JERRY B. MARION

ESSENTIAL PHYSICS IN THE WORLD AROUND US

Essential Physics in the World Around Us

JERRY B. MARION
University of Maryland

JOHN WILEY & SONS
New York/Santa Barbara/London/Sydney/Toronto

Cover design: Eileen Thaxton
Cover photo: Monument Valley Arizona,
Pete Turner/The Image Bank

Library of Congress Cataloging in Publication Data

Marion, Jerry B
Essential physics in the world around us.

1. Physics. I. Title.
QC23.M358 530 76-46545
ISBN 0-471-56905-4

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Preface

The familiar, everyday world around us abounds in examples of physical ideas and principles at work. Even the most casual observers can easily make a long list of questions about phenomena and devices they see regularly. What goes on inside a refrigerator to produce cooling? Why does an electric bulb emit white light whereas a neon sign produces red light? How is a rocket launched on a mission to the Moon? Questions like these raise points about the fundamental behavior of physical systems. Moreover, answers to these questions can be given without complicated mathematics. This is the spirit in which physics is approached in this book. My purpose is to provide a nonmathematical survey of some of the basic concepts of physics by closely relating these ideas to everyday things.

This book is not a compendium of facts. Instead, I have elected to concentrate on a relatively small number of important physical ideas. Each chapter poses a question about a familiar phenomenon or device. The answers are developed by introducing and explaining in simple terms the background physics while keeping before the reader the notion that we are building step by step the answer to a specific question. Thus, each chapter has a definite theme. Although a good deal of physics can be introduced in this way, there is always a central focus for the discussion.

The approach used here necessarily bypasses many interesting and important physical phenomena. But there is no attempt here to be comprehensive or exhaustive. Rather, I believe that it is more important to provide nonscience students, toward whom this book is directed, with an in-depth look at a few of the ways that physics appears in the world around them rather than to deluge them with an endless series of facts. The emphasis here is on the forest, not on the trees.

This book has been designed as a textbook for a one-semester course that has no mathematical prerequisites except for the usual one year of required high-school mathematics. (Alternatively, the book is easily adapted for one- or two-quarter courses, as well.) Because the emphasis is conceptual instead of mathematical, the use of mathematics has been maintained at a minimum level. The *Questions and Exercises* sections at the end of each chapter, for example, are almost entirely nonnumerical. For those few mathematical exercises that are included, the answers are always given. Students who wish to pursue a topic further will find at the end of each chapter a section entitled *Additional Details for Further Study*. These sections do not include material that is required for the following chapters and are therefore entirely optional.

Jerry B. Marion

Contents

How far? How long? How much?

1

OUR SYSTEM OF MEASUREMENT

We see in the world around us an astounding variety of natural processes and man-made things at work. Natural events do not happen by sheer accident, nor are our technical gadgets designed by guesswork. We like to say that all of these processes and things are governed by the laws of nature. By this we mean that through many years—indeed, many centuries—of observation, experiment, and reasoning, we have discovered a number of rules that seem always to be followed when particular classes of events take place or when certain kinds of operations are carried out. We search for these rules or laws not only because they permit us to understand what *has* happened around us, but also because they allow us to predict what *will* happen in particular circumstances. From the study of gravitation, for example, we have learned why an apple falls downward from a tree and why the Earth follows its characteristic path around the Sun. The development of these ideas also permits us to predict with precision the occurrence of solar eclipses and to plan the launch of a communications satellite so that it has the greatest usefulness to us. We seek to discover the laws of nature not only to satisfy our curiosity about the way the world works, but also to provide for the greater benefit of mankind.

We live in a technological society. Essentially every household contains a refrigerator, a television set, an automobile, a transistorized radio, and many other electrical and mechanical gadgets. The electricity we use is produced in huge and complex generating plants; much of our commerce depends on electronic computers; and our national security is ensured (we hope) by highly sophisticated radar systems, laser devices, and nuclear weapons. Each of these things is an outgrowth of some fundamental discovery about the way nature behaves. The design of a refrigerator depends on a knowledge of the behavior of gases under changing conditions of pressure and temperature. The study of the way electrons move in solid materials resulted in the invention of the transistor. And nuclear power plants could be constructed only after thorough studies had been made of the nuclear fission process.

In this book we will discuss some of the natural laws that govern the world in which we live. We will be concerned particularly with basic physical concepts and the way in which they relate to everyday things around us. By connecting every physical idea with some process or device that we have seen or used or heard about, we will gain a better appreciation of how natural phenomena influence our lives.

The emphasis in this book is on *ideas,* not *mathematics.* However, we cannot completely divorce physics from numbers, even in this elementary survey. Otherwise, how could we ever describe in a quantitative way a physical object or physical event? We must, from time to time, be able to discuss the *size* of a thing, or how *much* it weighs, or how *long* a process takes. Actually, we are accustomed to relating numbers to physical ideas in many situations. You drive 8.4 miles from home to class at an average speed of 28 miles per hour in an automobile that has a 90-horsepower engine. You buy potatoes in 5-pound bags, milk in half-gallon cartons, and aspirin in 100-milligram tablets. These are all familiar units of measure. When we state that a speed is 28 miles per hour, the number "28" is the *amount* or *value* of the speed and "miles per hour" is the *unit.* All physical quantities—quantities such as length, force, and energy—have units, and these units must be specified before we can report a meaningful result. It makes no sense to state that a certain distance is "60" unless we also state whether the unit is feet or meters or miles.

Fortunately, in science we use a restricted set of units. The unit (or *dimension*) of every physical quantity is made up of combinations consisting, at most, of the units for length, mass, and time. A simple example of the combination of units is in the quantity *speed* (which we will discuss later in this chapter). We are accustomed to measuring speed in units of miles per hour or feet per second. That is, the units for speed consist of a *length* unit divided by a *time* unit.

The fundamental units of measure in science are those of *length, mass,* and *time.* These are familiar concepts, but because they are so basic to the description of physical events and phenomena, we will briefly describe the units of measure for each of these quantities. In so doing, we will list several numbers. Do not be dismayed at this; these numbers are collected together here primarily as a matter of convenience. You will see more numbers in the next section than in any chapter that follows!

Length, Mass, and Time

Most Americans are accustomed to thinking about distance and length in terms of inches, feet, yards, and miles. And we are familiar with ounces, pounds, and tons for the measurement of mass. These are all units in the *British system* of measurement. Today, the scientific community universally uses the *metric system* of measurement. Indeed, even for everyday matters, most of the world (with the primary exception of the United States) uses metric measure. In this country we are gradually making a change away from the outdated and cumbersome British system, but several decades will probably be required before we will be using the metric system exclusively.

The basic unit of length in the metric system is the *meter* (m). Various multiples of the meter are also commonly used. For example,

1000 m = 1 kilometer (km)
$\frac{1}{100}$ = 1 centimeter (cm)
$\frac{1}{1000}$ m = 1 millimeter (mm)

The correspondence between the metric length units and those in the British system is as follows (see also Fig. 1-1):

1 inch (in.) = 2.54 cm = 25.4 mm
1 yard (yd) = 3 feet (ft) = 0.9144 m
1 mile (mi) = 5280 ft = 1.609 km

Approximately, we have

1 in. = 2.5 cm	1 cm = 0.4 in.
1 yd = 0.9 m	1 m = 1.1 yd
1 mi = 1.6 km	1 km = 0.6 mi

While adjusting to thinking in metric terms, it will be helpful to use these approximate figures. For example, if you see a road sign that states the distance to a certain city is 100 km (such signs are beginning to appear here), then you know that the distance in miles is approximately 0.6 (or $\frac{3}{5}$) of this figure, or 60 miles. (For better accuracy, use a factor of 0.62 or $\frac{5}{8}$ to convert from kilometers to miles.)

The metric unit of mass is the *kilogram* (kg), which is about twice as large as the *pound* (lb). In fact,

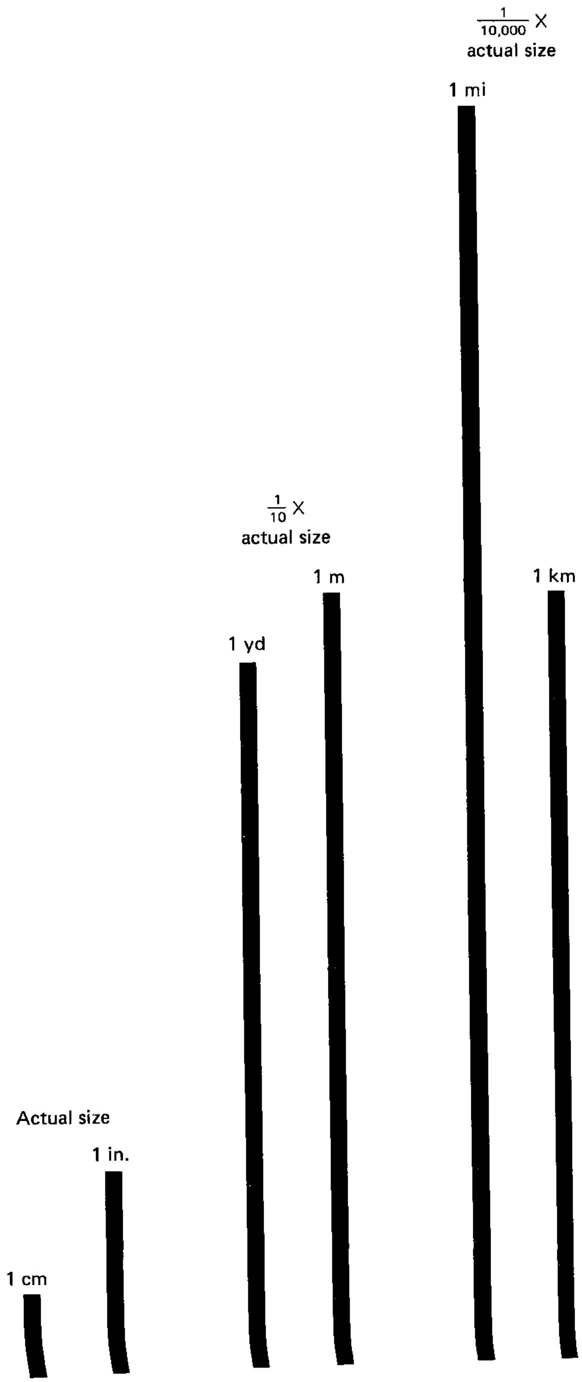
1 lb = 0.454 kg

or, approximately,

1 kg = 2.2 lb

as illustrated in Fig. 1-2. Smaller and larger metric units of mass are the *gram* (g), the *milligram* (mg), and the *metric ton* (or *tonne*):

Figure 1-1 *Correspondences between British and metric length units.*



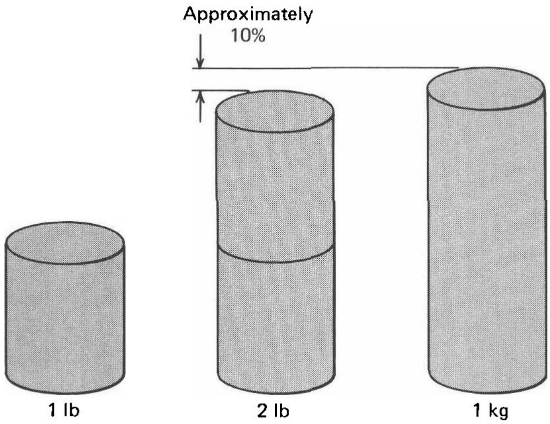


Figure 1-2 *A kilogram is approximately 10 percent greater than 2 pounds: 1 kg = 2.2 lb.*

$$\tfrac{1}{1000}\ \text{kg} = 1\ \text{g}$$
$$\tfrac{1}{1\,000\,000}\ \text{kg} = \tfrac{1}{1000}\ \text{g} = 1\ \text{mg}$$
$$1000\ \text{kg} = 1\ \text{tonne}$$

If you have examined the labels on various products lately, you will have noticed that metric units of mass are being used on more and more items. Grocery products are frequently labeled with the mass in pounds and in kilograms. And pharmaceutical products are now almost always measured in milligrams.

Time is measured in the same units in both the British and the metric systems. The basic unit of time is the *second* (s). Several other time units are also used in everyday and scientific matters:

$$1\ \text{minute (min)} = 60\ \text{s}$$
$$1\ \text{hour (h)} = 3600\ \text{s}$$
$$1\ \text{day} = 86\,400\ \text{s}$$
$$1\ \text{year (y)} = 31\,600\,000\ \text{s}$$

The numbers collected in this section have been included for your convenience in adjusting your thinking from British to metric units. How many of these numbers must you remember? Actually, only a few. First of all, the various metric units for length and mass differ only by simple multiples of 10, and these multiples are indicated by *prefixes;* for example,

centi- (c) means $\tfrac{1}{100}$: 1 centimeter (cm) = $\tfrac{1}{100}$ m
milli- (m) means $\tfrac{1}{1000}$: 1 millimeter (mm) = $\tfrac{1}{1000}$ m
kilo- (k) means 1000: 1 kilogram (kg) = 1000 g

Two other prefixes often used are *micro-* (μ, 1 *millionth*) and *mega-* (M, 1 *million*).

The basic number that allows the conversion between British and metric units of length is

1 in. = 2.54 cm

All other length relationships can be obtained from this number together with the familiar expressions, 1 ft = 12 in., 1 mi = 5280 ft, and so forth. In this way, you can obtain, for example, the connection between miles and kilometers. However, it is probably easier to remember this relationship than to compute it each time it is needed:

1 mi = 1.6 km

Finally, the connection between the units for mass is

1 kg = 2.2 lb

These are the three key relationships that will permit you to shift between the British and metric systems of units. (Notice that these expressions are all stated in such a way that each numerical factor is approximately 2.)

Mass and Weight

We have indicated that kilograms and pounds are the units of measure for *mass*. You are probably accustomed to giving your *weight* as a certain number of pounds. Are mass and weight therefore the same? No, they are not. *Mass* and *weight* actually refer to two different physical ideas. *Mass* is a measure of the amount of matter in an object. We could specify the mass of an iron bar in terms of the number of iron atoms in the bar. This would not be practical, however, because the number of atoms in a bar is enormous and there is no way by which they can be counted accurately. But the number of atoms in the bar does not change if we move the bar from place to place or change its size or shape. The number of atoms in an object—that is, the *mass* of the object—is a property of that object and does not depend on what we might do to the object. We say that *mass is an intrinsic property of an object.*

The *weight* of an object is a measure of how strongly gravity pulls on the object. The gravitational attraction of the Earth for an object is nearly the same at any position on or near the Earth's surface. Because most of us (astronauts are exceptions) spend our lives close to the surface of the Earth, we never experience any substantial change in the pull of gravity. The weight of an object therefore seems to be the same whatever its location. Away from the surface of the Earth, however, the pull of gravity and, hence, the weight of an object *does* change. When an astronaut is on the surface of the Moon, he experiences a much smaller effect due to the Moon's gravity than he does due to the Earth's gravity on the Earth's surface. Thus, an astronaut on the Moon has a smaller weight than he does on Earth (about one-sixth as great). The weight of an object is a variable quantity, whereas mass is not.

In scientific terms we say that mass is *mass* but that weight is *force*. Indeed, mass and weight, being different physical concepts, have different physical units. Mass and weight are definitely *not* the same thing. (For more details, see the discussion on page 76.)

Speed

Many of the quantities that are useful in science (and often in everyday matters as well) are measured in units that are combinations of the basic units, meters, kilograms, and seconds. The quantity of this type that is easiest to understand is probably *speed*. We are all familiar with the measurement of speed in units of miles per hour (otherwise written as mi/h or mph). The speedometer in an automobile is an instrument that automatically gives the vehicle's speed in these units (or in kilometers per hour, km/h, in European cars not intended for export to the United States). The standard automotive speed unit is not the only possible unit for specifying speed. We could, in fact, use *any* length unit divided by *any* time unit. Some possible speed units are feet per minute (ft/min), centimeters per hour (cm/h), or furlongs per fortnight. In the metric system we usually measure speed in meters per second (m/s), kilometers per second (km/s), or kilometers per hour (km/h).

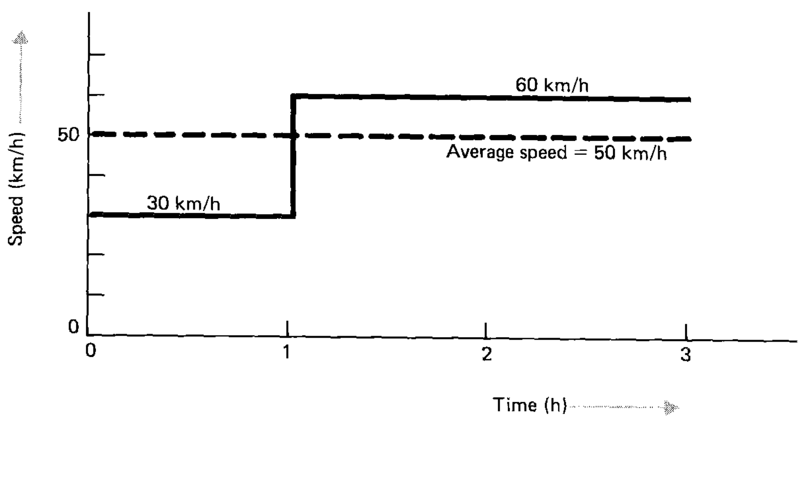
How do we determine the speed in a particular situation? If we make a 40-km trip in 1 h, we say that our speed has been 40 km/h. Or, if the same trip required 4 h, the speed was 10 km/h. That is, we specify speed by dividing the distance traveled by the time required for the trip:

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

and the units for speed are automatically those of length divided by time.

To make the computation of speed according to this procedure, we need only the total distance traveled and the total time required. But we know that in any automobile trip from one place to another we rarely make the entire journey with the speedometer reading a steady value. Most trips involve starts, stops, periods of slow driving, and periods of fast driving. What do we mean by the *speed* for such a trip? If we divide the *total* distance traveled by the *total* time required, we obtain a value that we call the *average speed* for the trip. The average speed applies to the trip *as a whole*. In a particular case we may have a certain average speed for the entire trip and yet no appreciable part of the distance will have been covered at that speed. For example, suppose that you undertake a trip of 150 km. You travel the first 30 km in 1 h at a steady speed of 30 km/h. Then, you are able to increase your speed and you travel the remaining 120 km in 2 h at a steady speed of 60 km/h. Now, if you consider the trip as a whole, the total distance traveled was 150 km and the total elapsed time was 3 h. Therefore, the average speed was 50 km/h, a value different from that for either segment of the trip (see Fig. 1-3). The *average speed* is that speed, which if maintained constant

Figure 1-3 *The average speed for an entire trip is not necessarily the speed during any segment of the trip. Here, there are two segments with speeds of 30 km/h and 60 km/h; the average speed for the trip as a whole is 50 km/h.*



during the trip, would allow completion of the trip in the same total time as for the actual trip.

To state the average speed for a trip gives useful information, but it must be remembered that the average speed applies only for the time or distance interval that is specified and not necessarily to smaller intervals. This is always the way with average values: Very few members of the group for which an average is calculated (or even none at all) will have the average value. For example, the class average for an examination may be 76.8, but probably no member of the class will have received this score.

The average speed for a long trip tells us very little about how the trip was actually made. How do we obtain more information? One way would be to divide the trip into a number of segments and to give the average speed for each segment. The larger the number of segments, the greater the amount of information that is given about the trip. We can imagine that the intervals during which the average speeds are measured are made extremely small. We could have intervals of 1 s, or $\frac{1}{10}$ s, or $\frac{1}{1000}$ s, or even smaller. In fact, we could make the intervals so small that we can specify the speed essentially at one *instant* of time. We call such a value the *instantaneous speed*. The value of the speed that we read from a speedometer is just the instantaneous speed of the automobile at that instant. Usually, when we refer to *the* speed of an object, we mean the instantaneous speed.

Acceleration

When you "step on the gas" in your automobile, you cause the speed to increase. Or, when you step on the brake, you cause the speed to decrease. In both cases, the essential feature of the motion is that the speed *changes*. Whenever the speed of an object changes, we say that the object has undergone *acceleration*. Indeed, the gas pedal in an automobile is appropriately called the *accelerator*. (The brake pedal could be called a "decelerator" or "negative accelerator.") Acceleration is familiar in other situations as well. If you drop an object from a height, it is easy to see that the object gains speed as it falls. The greater the distance of fall, the greater will be the final speed. An automobile is accelerated by the push of the engine; a falling object is accelerated by the downward pull of the Earth's gravity.

How do we measure acceleration? Just as we measure speed as the change in *position* per unit of time, we measure acceleration as the change in *speed* per unit of time:

$$\text{acceleration} = \frac{\text{change in speed}}{\text{time}}$$

Also in analogy with the case of speed, we can define *average* acceleration and *instantaneous* acceleration.

What are the units of acceleration? These are less familiar than the units for speed, but they are easy to find from the definition of acceleration. The definition of speed is distance divided by time and the units for speed are a length unit divided by a time unit. Similarly, the definition of acceleration is speed change divided by time, so the units for acceleration must be a speed unit divided by a time unit. If the speed of an object increases from 2 m/s to 10 m/s, the speed change is 8 m/s. If this change took place during a time interval of 2 s, the acceleration would be 8 m/s per 2 s, or 4 meters per second per second. That is, during each second of acceleration the speed increased by 4 m/s. We usually write this kind of result using a shorthand notation:

$$\text{4 meters per second per second} = 4\ \text{m/s/s} \quad \text{or} \quad 4\ \text{m/s}^2$$

Do not be confused by this kind of notation. We would read 4 m/s^2 as "4 meters per second squared." There is, of course, no physical significance to a unit of 1 s^2 (1 square second) as there is for a unit of 1 m^2 (1 square meter). But in the combination m/s^2, we mean "meters per second per second."

If we were to drop an object from a tall building and measure the object's instantaneous speed at the end of each second of fall, we would find a steady increase in speed. At the end of 1 s the speed would be 10 m/s; at the end of 2 s the speed would be 20 m/s; at the end of 3 s the speed would be 30 m/s; and so forth. During each second of fall the speed increases by 10 m/s. That is, the acceleration is 10 m/s per second, or 10 m/s^2. (If we performed such an experiment we would actually find a value of 9.8 m/s^2.)

In discussing speed and acceleration we have found that the units used to measure a physical quantity can always be obtained directly from the definition of the quantity in terms of