PHYSICS FOR THE LIFE SCIENCES

Second Edition

ALAN H. CROMER

PHYSICS FOR THE LIFE SCIENCES

Second Edition

ALAN H. CROMER

Professor of Physics
Northeastern University

McGRAW-HILL BOOK COMPANY
New York St. Louis San Francisco Auckland Bogotá Düsseldorf
Johannesburg London Madrid Mexico Montreal New Delhi
Panama Paris São Paulo Singapore Sydney Tokyo Toronto

PHYSICS
FOR
THE LIFE
SCIENCES

1 2 3 4 5 6 7 8 9 0 DODO 7 8 3 2 1 0 9 8 7 6

This book was set in Helvetica by York Graphic Services, Inc.
The editors were C. Robert Zappa, Alice Macnow,
and James W. Bradley;
the designer was Jo Jones;
the production supervisor was Dennis J. Conroy.
New drawings were done by Felix Cooper.
The cover illustration was done by Cheryl Cooper.
R. R. Donnelley & Sons Company was printer and binder.

Library of Congress Cataloging in Publication Data

Cromer, Alan H date
Physics for the life sciences.

Includes index.
1. Physics. I. Title.
QC23.C917 1977 530 76-16167
ISBN 0-07-014434-6

INDEX OF MAJOR LIFE-SCIENCE APPLICATIONS

PREFACE

The purpose of this book is to give students in biology, pharmacy, premedicine, physical therapy, physical education, and the allied health sciences the physics background they need for their professional work. The selection of material has been made on the basis of its appropriateness to the life sciences and its suitability for an introductory physics course. These criteria have resulted in some shifts in the customary emphasis of topics, but they have not limited the broad scope expected of a general physics textbook.

Since life science students often do not understand why they are required to take a physics course, the pertinence of the material to life processes is stressed at every opportunity by use of realistic biological examples to illustrate each physical principle and by inclusion of many problems that relate the physics to the life sciences. I have found that this approach increases the interest of students who otherwise have no motivation to study physics.

The mathematics in this book is limited to elementary algebra and trigonometry because many students, even those who have studied calculus, are not sufficiently proficient in advanced mathematics to benefit from its use The use of only simple mathematics enables the student to concentrate directly on the physics.

In response to the suggestions of users of the first edition, the following topics have been added: simple harmonic motion, momentum, heat transfer, lens aberrations, and instrumentation. To make room for these additions, the following topics have been deleted: simple machines, derivation of the speed of sound, relativity, and thick lenses. Other major changes are: rewriting of Chap. 5 (Energy), deferring any mention of heat until Chap. 11, where it can be treated properly, and increasing the discussion of biomagnetism to include contemporary research.

The book is divided into six parts: Mechanics, Properties of Matter, Heat and Thermodynamics, Wave Phenomena (including optics), Electricity and Magnetism (including instrumentation), and Modern Physics.

Chapters 2, 4, 5, and 6 in Part I (Mechanics) cover the basic concepts of force, acceleration, energy, and momentum that are required for the rest of the book. Chapters 2 and 3 constitute a self-contained unit on statics suitable for students of physical therapy and physical education. The concept of similarity scaling, first introduced in Chap. 1, is used again in Chap. 5 to derive interesting relations between size and function in animals.

Chapter 7 in Part II (Properties of Matter) covers the static and dynamic properties of fluids and applies them to respiration and circulation. The specific properties of gases, liquids, and solids relevant to biology are given in Chaps. 8 to 10.

Part III (Heat and Thermodynamics) is divided into a chapter on heat (Chap. 11), which discusses the first law of thermodynamics, specific heat, and heat transfer, and a chapter on thermodynamics (Chap. 12), which discusses thermodynamic transformations, the second law of thermodynamics, and entropy. Chapter 12 goes beyond the usual introductory discussion of thermodynamics in order to develop the concepts of entropy and free energy, which are so important for understanding the dynamics of chemical reactions.

Sound, light, and optics are covered in Part IV (Wave Phenomena). Since this section is largely independent of Part II, it can be studied before Part II.

The principles of electricity and magnetism developed in Part V are applied to bioelectric phenomena (Chap. 18), biomagnetic phenomena (Chap. 19), and biomedical instrumentation (Chap. 20).

The fundamentals of quantum physics and their significance for chemistry are covered in Chap. 21 of Part VI (Modern Physics). Chapter 22 develops the concepts of nuclear physics needed for an understanding of modern developments in nuclear medicine.

The last section or two in most chapters contains advanced material or specialized applications that can be omitted without significant loss of continuity. By the inclusion or omission of these sections, the length and level of the course can be adjusted to the needs of the class. A variety of problems is included at the end of each chapter, with the more challenging ones marked with an asterisk (*).

I wish to thank the many users of the first edition who took the time to send me their thoughts on how to improve the book. Every suggestion was carefully considered, and most of them have been incorporated into this edition. The final manuscript was carefully reviewed by Ms. Alice Macnow (McGraw-Hill), Professors Rexford E. Adelberger (Guilford College), Charles D. Teague (Eastern Kentucky University), Eugene A. McGinnis (University of Scranton), and John E. Mulhern, Jr. (University of New Hampshire). I am very grateful for their help in correcting errors and clarifying obscure passages. The responsibility for the final product, with any uncorrected errors, is entirely mine.

Alan H. Cromer

CONTENTS

PART II PROPERTIES OF MATTER

PART III HEAT AND THERMODYNAMICS

PART IV WAVE PHENOMENA

PART V ELECTRICITY AND MAGNETISM

PART VI MODERN PHYSICS

MECHANICS I

For thousands of years natural philosophers have speculated about the nature of the physical world. More than 2000 years ago ancient Greek scientists made considerable progress on some isolated problems, but it was not until the laws of mechanics were established by Galileo and Newton that a coherent understanding of all physical phenomena became possible. Mechanics is the study of the conditions under which objects remain at rest (*statics*) and the laws governing objects in motion (*dynamics*). These laws are universal in scope, applying as well to the motion of a satellite about the earth as to the motion of a runner about a track. More significant, mechanics is the foundation on which the rest of physics is built.

CHAPTER 1 MEASUREMENT

The human mind ascribes many different attributes to people and things, such as length, weight, color, beauty, and patriotism. Some attributes are clearly measurable, and others are not. Thus there exist well-defined procedures for measuring length and weight, but not beauty or patriotism. [Color is an intermediate case, for while a numerical value can be assigned to every color (Sec. 15.4), color cannot be ranked in order.] Physics is the study of the measurable attributes of things. The basic concepts of physics are defined in terms of measurements, and the purpose of physical theories is to correlate the results of measurements. A physical theory, no matter how abstractly it may be stated, is ultimately a statement about concrete operations performed in a laboratory.

1.1 THE INTELLECTUAL ORIGINS OF PHYSICS

Modern physics is the confluence of two rather different intellectual streams. One stream can be traced back to the early philosophers of Asia Minor, who were the first people in recorded history to ask questions about the fundamental nature (*physis*) of the material world. Their reasoning often tended to be speculative rather than scientific, but it was free of much of the mythology that beclouded the minds of most people in those days.

In the Greek colonies of Asia Minor (Ionia), especially the city of Miletus, the philosophers Thales (640?–546 B.C.), Anaximander (610–545 B.C.), Anaximenes (?–525 B.C.), and others developed the concept of unity in the natural world. They believed that in spite of the apparent differences between material objects such as rocks, trees, clouds, and horses, there is an underlying sameness to all things. Each one had a different idea about the nature of this universal essence (Thales thought it was water, and Anaximenes thought it was air), but their great concept of the unity of matter remains a major doctrine of physics today.

The Ionian philosophers were also true scientists, and borrowing from the earlier work of the Egyptians and Babylonians, they made important advances in mathematics, astronomy, geology, and biology. Their work was continued on the Greek mainland in the fifth century B.C. and in the Hellenistic cities (especially Alexandria) in the fourth and third centuries B.C. The great Archimedes of Syracuse (287–212 B.C.) lived in this later period. His work in statics and hydrostatics is very modern in approach, and so little progress was made in the following 1800 years that he would have had no difficulty in understanding the work of Galileo (A.D. 1564–1642). In fact Archimedes might have started the second stream of ideas that, together with the early Greek search for the fundamental nature of things, constitutes modern physics. But unfortunately most of his written work was lost to Europe for a long time, and it was not until Galileo that the second stream clearly emerged.

It was Galileo who developed the modern method of studying simple systems by means of experimental measurement and mathematical analyses. He studied the motion of objects sliding down inclined planes and disentangled the relevant from the irrelevant features of the motion. The relevant feature was usually a measurable quantity such as the mass of the object or the time required to move a fixed distance. He tried to find the relation between these numerical measurements and to express the results in mathematical terms. It turned out that the results of an investigation could often be summarized in very simple terms, such as: The distance traveled down an incline is proportional to the square of the elapsed time. Galileo showed that the laws of nature (or some of them at least) obey simple mathematical equations, and ever since then physicists have continued the search for the mathematical relations connecting the results of their measurements.

So what is physics? It is a motivation and a method. The motivation is the same as that of the Greeks: to find the fundamental nature of things. But the method is that of Galileo: to investigate simple systems by means of experimentation and mathematical analysis. The problems under investigation sometimes seem childish and sometimes esoteric: Galileo rolls balls down an incline, Joule spins a paddle wheel in water, Rutherford experiments with rare radioactive elements. But time and again the results lead to deep and profound insights into the nature of things, fulfilling the aim of the Greek philosophers in ways they could only dream about.

In this book we shall study the method of physics and some of the results it has obtained in the 400 years since Galileo. These results are important for anyone interested in the nature of things because they apply universally to the whole material universe, including living organisms. Indeed, as we shall see in this book, physics is essential for understanding the mechanism of many biological processes, such as body movement, blood flow, and speech. Furthermore, the mystery of life itself may some day be understood in terms of the fundamental laws of physics.

1.2 MEASUREMENT

Physics deals with the things that can be measured. What can be measured depends to a large degree on the current state of technology. For instance, the radiation emitted by radioactive substances could not be measured before the invention of devices to detect such radiation. The scope of physics continually increases as new inventions expand the range of possible measurements.

All sciences rely on measurements to some degree, but usually the measurement is auxiliary to the main purpose. Thus a zoologist might carefully measure the weight of the mice used in a drug experiment in order to determine the effect of the drug on their growth. This measurement is incidental to the problem of the drug's metabolic function. In physics, however, the measurement itself is a primary object of interest, because a particular concept, such as length, time, or temperature, is understood only in terms of the method used to measure it. This way of defining things is called *operationalism,* and its use avoids assigning unwarranted metaphysical meaning to a concept and introducing extraneous and possibly false connotations.

Consider for instance the concept of length. Operationally the length of something is defined as the number obtained when a specific set of operations, called *measuring its length,* is performed. These operations can be illustrated by examining the steps required to measure the length of a room:

1 Mark two points, one at either end of the room, to define the exact interval to be measured (points A and B in Fig. 1.1*a*).
2 Stretch a surveyor's chain (a piece of string will do) between these two points to define the straight line between them (Fig. 1.1*b*).
3 Take a meterstick and lay it along the stretched chain with one end at point A. Mark where the other end of the stick touches the chain (point C in Fig. 1.1*c*) and move the stick along the chain until the front end is lined up with this mark (Fig. 1.1*d*). Repeat this step until point B is reached.
4 When point B is reached, the stick will be in the position shown in Fig. 1.1*e*. Mark the point on the stick that touches B.
5 The *length* (in meters) is the number of marks on the chain plus the fraction of the stick required to reach from the last mark (E) on the chain to B.

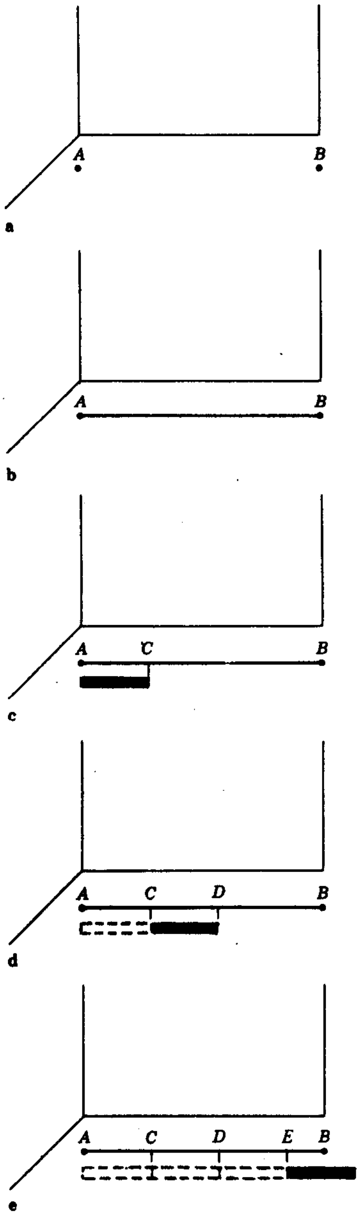

FIGURE 1.1
The steps required to measure the length of a room.

We see that by detailing the actual procedure used to measure a length we can avoid having to say anything about the essential nature of space or distance (which would be metaphysics). Length is what is measured with a ruler, and we never need to know any more about it in order to do physics.

Measurements are always made relative to some standard, called a *unit*. In the present example the unit is the meter, and the final result is given as so many meters, say 3.7 m. This can be converted into other units if the length of the meter is known in terms of these units. For instance, the conversion from meters to centimeters is

$$1 \text{ m} = 100 \text{ cm}$$

so the length of the room can be given as

$$(3.7 \text{ m})(100 \text{ cm/m}) = 370 \text{ cm}$$

The conversion from meters to feet is

$$1 \text{ m} = 3.28 \text{ ft} \qquad \text{or} \qquad 1 = 3.28 \text{ ft/m}$$

so the length can also be given as

$$(3.7 \text{ m})(3.28 \text{ ft/m}) = 12.1 \text{ ft}$$

Example 1 Given that a liter equals 0.264 gallon, how many liters is 20 gallons?

The usual difficulty in converting units is knowing whether to multiply or divide by the conversion factor. To see what to do in this case, we first write the equation for the relation between liters (l) and gallons (gal):

$$1\ \text{liter} = 0.264\ \text{gal}$$

Since we want to convert from gallons to liters, we must find the number of liters in 1 gal by dividing both sides of the equation by 0.264 gal

$$\frac{1\ \text{liter}}{0.264\ \text{gal}} = \frac{0.264\ \text{gal}}{0.264\ \text{gal}}$$

or

$$1 = 3.79\ \text{l/gal}$$

Thus there are 3.79 liters per gallon (3.79 l/gal) and

$$20\ \text{gal} = (20\ \cancel{\text{gal}})(3.79\ \text{l}/\cancel{\text{gal}}) = 75.8\ \text{liters}$$

Notice that by treating the units as algebraic symbols, the correct unit appears in the final answer after some cancellation.

Similarly, to convert from liters to gallons, we multiply the number of liters by the factor

◇

$$1 = 0.264\ \text{gal/l}$$

At one time the meter and the foot were the respective national standards of length of France and England. Today the meter is the scientific standard of length in all countries and the national standard in most countries except the United States. (Even the United Kingdom has converted to the metric system.) The metric system is described in Appendix V, and conversions between English and metric units are given inside the front cover.

There are many cases of interest in which the direct measurement of a length using a meterstick is not possible, and indirect methods must be employed. However, even in an indirect measurement, a meterstick type of measurement must be made at some stage.

For example, to measure the distance d between two points A and B on opposite sides of a river, a surveyor's transit is used (Fig. 1.2). A third point C is picked on the surveyor's side of the river, and sightings are taken with the transit at B and C to measure the angles† θ_1 and θ_2. The length b of the base line BC is measured with a chain and meterstick, as previously described. From these measurements the length d can be found using the law of sines.

In this book, however, trigonometry will be avoided as much as possible, and problems like this will be solved *graphically* by making a scale drawing.

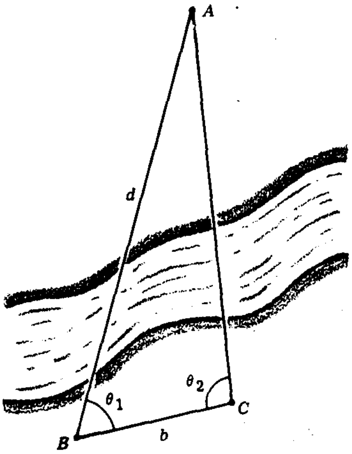

FIGURE 1.2
The distance d between the two points A and B on opposite sides of a river is found by measuring the distance b and the angles θ_1 and θ_2.

Example 2 What is the distance d in Fig. 1.2, given that $b = 0.50$ km, $\theta_1 = 80°$, and $\theta_2 = 85°$?

---

† θ is the Greek letter theta.

A scale drawing is begun by choosing a suitable scale, say

$$10 \text{ cm} = 1 \text{ km}$$

With this scale the baseline BC would be drawn 5 cm long. A protractor is next used to draw lines at 80 and 85° to BC from points B and C, respectively. These lines are extended until they intersect at point A. Finally, the distance AB is measured with a ruler and converted back into the original units. In this case AB will be found to be about 19.2 cm. According to our scale, 1 cm = 0.1 km, so

$$19.2 \text{ cm} = (19.2 \text{ cm})(0.1 \text{ km/cm}) = 1.92 \text{ km}$$

◇

The graphical method is not as accurate as the trigonometric method, but it is conceptually much simpler and accurate enough for most of our purposes. Some surveying problems are given at the end of this chapter to prepare you for vectors in the next chapter.

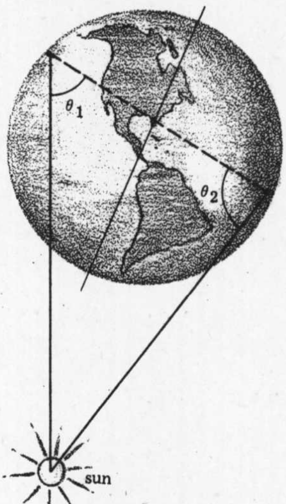

FIGURE 1.3
The distance to the sun is found by measuring the angles θ_1 and θ_2 from two points on the earth that are a known distance apart.

Large distances on the earth are measured by a sequence of such small-distance *triangulations*, and the size of the earth itself is ultimately determined in this way. Once the size of the earth is known, the distance to the sun can be found by measuring the angle of the sun from two different points on the earth at the same time and using the known distance between these points as the base line (Fig. 1.3). The distance to the sun is then used to measure the distance to a (nearby) star by taking the diameter of the earth-sun orbit as the base line (Fig. 1.4). Thus even astronomical measurements are related, often through a large number of intermediate steps, to a direct measurement of distance with chain and meterstick.

Other concepts require other methods of measurement. Time is particularly subtle. To measure time a device is needed that continually repeats some event, so that the interval between two events can be taken as the unit of time. The rotation of the earth on its axis is very convenient for this purpose, and the unit of time might be one sidereal day, the time between the passing of a given star through its highest position in the sky, the zenith, on two successive nights. (This is not the same as the mean solar, or 24-hour, day, which is the time between two successive passings of the sun through the zenith averaged over 1 year.)

Clocks are mechanical devices constructed to repeat some event over and over. They are calibrated against the earth's rotation, and discrepancies between the clock and the earth are attributed to inaccuracies in one or the other. Atomic clocks are more accurate than the earth, which does not rotate with absolute uniformity because of tidal friction between the oceans and the ocean floor.

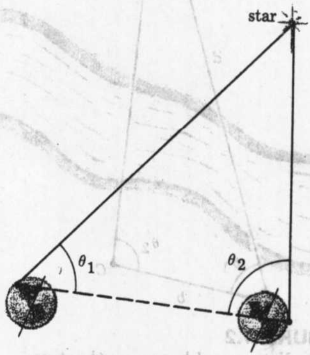

FIGURE 1.4
The distance to a star is found by using the diameter of the earth-sun orbit as a base line.

The standard unit of time is the *second* (s), which until 1967 was defined as 1/86,400 of the mean solar day in the year 1900. This is not the same as 1/86,400 of a current 24-hour day because the rate of the earth's rotation has changed since 1900. As a clock, the earth runs a little slow, and an extra second was added to July 30, 1972 to correct for this.†

---

† Since 1967 the second has been defined by the cesium clock, an atomic clock controlled by electronic transitions in cesium. Likewise the meter is now defined as 1,650,763.73 times the wavelength of the orange light emitted by the gas krypton when electrically excited.