STEVE EDWARDS

PHYSICS

A Discovery Approach

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PREFACE

This text has grown out of a one-term freshman physics course given by the author for a number of years as part of the General Education program at Florida State University. Only students who do not intend to major in any science take this course, and it is open to all entering freshmen with no prerequisites. The material therefore must be presented with a minimum of mathematical complication, and nothing more advanced than high school algebra is used.

Since students come to the course with little interest and often with downright antagonism, an effort has been made to develop interest in this captive audience by presenting the material in as nearly a narrative form as possible. Examples of contemporary interest have been used when appropriate, and presentations have been given in terms of simple pictures which draw upon the experience of such students for visualization. Much attention has been paid to motivation for each new topic. Some of the classical topics traditionally treated are not considered in any detail because these students so often find them dry and they are not essential to the general presentation.

The philosophy of the course is reminiscent of the PSSC high school course, and the teaching aids developed for that course have been used extensively. This modern approach has proved to be readily adaptable to the kind of qualitative presentation needed here. It is hoped that these features of the course have been carried over into the text successfully.

The study of light has been found to provide a good basis for the narrative approach because a presentation beginning with the earliest theories of Sir Issac Newton and finally reaching the most modern point of view can motivate the study of all the other major fields of physics. The material is divided into five parts, beginning with an Introduction covering mostly background material designed to prepare the student to be able to speak the language of the text. The other four parts are Light, Mechanics, Electricity and Magnetism, and Modern Physics.

All of the material presented can be covered adequately in one term, and the author has given one-semester, one-trimester, and one-quarter versions of it. An Instructor's Handbook prepared by the author is available which gives suggested course outlines for each version. Generally the sections can be covered in one lecture, and in some cases two sections can be combined into one lecture.

Demonstration experiments are extremely helpful in the presentation of the material. The use of the PSSC films is an exceptionally good method of providing these demonstrations, and the text has been designed so that these or an equivalent set of films can be incorporated into the course. The Instructor's Handbook gives a list of these films appropriate to the various sections. Demonstration experiments have also been described in some detail in the text, and discussions of some of these that use simple apparatus are included in the Handbook.

Although it is not the purpose of this text to develop a facility for solving physics problems, sets of problems and discussion questions have been included for each part. These are designed to aid the student to focus on the principles in the text by providing him with some familiarity in the manipulation of their mathematical descriptions. A list of references for further reading appropriate to each part is given in Appendix 3. The main goal of this presentation is to give the student the basis upon which to build a valid concept of the role of physics in contemporary culture.

I would like to thank Professors Robert A. Kromhout and Guenter Schwarz of Florida State University for many helpful discussions and suggestions during the development of the course upon which this text is based. I am also indebted to Professor Robert Resnick of Renssalaer Polytechnic Institute for reading the original manuscript and making many helpful suggestions for its improvement and to Professor L. Worth Seagondollar of North Carolina State University and Dr. William J. Thompson and Dr. Jack P. Aldridge of Florida State University for helping in the class testing of the preliminary edition. Finally, I would like to dedicate this book to my wife, Helen, whose outstanding typing ability made the preliminary edition possible and without whose devotion this text would not have been written.

Steve Edwards

Tallahassee, Florida
September 1970

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INTRODUCTION

1.1 PHYSICS AND PHYSICISTS

In the decade beginning around 1915, a small group of men associated with several universities in Europe engaged in a lively debate concerning the submicroscopic constituents of matter and whether they should be described as somewhat vague wavelike patterns of motion or as extremely small hard pieces of matter possessing definite properties. Most laymen did not even take note of these debates; those few who did probably placed them in the same category as the age-old discussion about how many angels can stand on the head of a pin and dismissed the debaters as impractical ivory tower intellectuals. After all, the members of this small group were not debating whether this subatomic world even existed, which would have been an understandable question for ordinary men; instead they were arguing the relative merits of two different ways of describing the subatomic world to each other should it indeed exist. What could be farther from the concern of most people?

To suggest that resolving the issues involved in these debates might change the world forever would have seemed absurd even to the debaters. In fact, however, one direct consequence of their conclusions has been the development of nuclear power and our entry into the *Atomic Age.* Some of the techniques developed during the process of their arriving at these conclusions about the subatomic world have led to the invention of radio, television, and computers, and to the exploration of space. The whole new age of medicine is founded on the modern biophysical and biochemical concepts that scientists formulated once they understood the problems that interested these debaters. Finally, our society owes its high level of technology to their curiosity about the structure of matter and their desire to understand this facet of nature. We who live in this society should therefore seek to know who these men were and to understand the thought processes and considerations that enabled them to so revolutionize our lives.

The science that these men studied is called *physics,* and they are called *physicists.* We can take as a working definition of physics that it is *the study of matter and radiation, including their motion in time and space and their mutual interaction.* This definition thus includes almost every natural phenomenon, and many people consider physics to be the fundamental natural science. Indeed, various other branches of science, such as chemistry and meteorology, can be considered areas of application of fundamental physical principles. They are often called *physical sciences* for this reason.

The main purpose of our present discussion is to gain a certain familiarity with what physics is and what physicists do, a familiarity any educated citizen in contemporary society should have. To attain a deep understanding of the principles of physics whereby one is able to apply these principles professionally requires a broad mathematical background. Acquiring such understanding is beyond our purposes, however. We wish simply to present a picture of physics that can be understood with no more preparation than high school algebra, some simple plane geometry, and a few other mathematical ideas to be introduced as needed. We shall stress understanding of the physical concepts rather than mathematical rigor, and in keeping with this approach we shall always endeavor to give descriptions that can be visualized in terms of common experiences.

The tools of the physicist are *observation* and *description.* He observes phenomena and then tries to describe what he has observed in such a way as to obtain some fundamental understanding of nature from the descriptions. A good description ought to make predictions of future observations possible, and those that do this are called *theories.* A theory that is successful in its prediction of most of the cases with which it is concerned is often designated a *law.* As our discussion develops we shall see how a description can become a theory and a law.

Visible light is the most common form of radiation. The study of light provides a foundation from which to range over all the main fields of physics, and we shall approach the subject in this way. Our general method will be to discuss the observations that led to the descriptions constituting the generally accepted theories of physics. In applying this method to the study of light, we shall see that we must consider all of nature from the wide expanse of the universe to the microscopic world of the atom itself.

Before we begin our treatment of physics in earnest, we must consider some background information to make certain we are speaking the same language. Some of this material will be mathematical background which may seem somewhat uncorrelated. We shall use our working definition of physics as a guide in this section, discussing space, time, motion, and matter. Because the remainder of Part 1 will be devoted to this necessary background, the general direction of our discussions may not seem clear until we actually begin our detailed analysis of the subject of physics in Part 2.

1.2 MEASUREMENT AND SYSTEMS OF UNITS

The observational branch of physics is called *experimental physics,* and *experimental physicists* devote themselves almost exclusively to making experimental observations, often guided by theory. One of their principal concerns is to design the apparatus used in this process. Since in the final analysis we must rely on our human senses to make our observations, the apparatus of physics is actually an extension of these senses. As we shall see later, much of this apparatus has found its way into our daily lives through applications not originally intended by its developers.

Most observations must be quantitative, and the process of quantitative observation is called *measurement.* Although you are probably already familiar with this process, it is worth our while to discuss it briefly from the point of view of a physicist. The physicist makes his measurements by making comparisons of unknown quantities with known quantities. The known quantities are called *standards* and are arbitrarily chosen for convenience.

Of course the physicist must be able to communicate the results of his observations to other scientists, and therefore he must be sure that other scientists know the standards he uses. The names given to standards of measurement are called *units;* several generally accepted *systems of units* have been developed over the years. For example, the standard of length in the system used by most scientists is called the *meter.* The meter is approximately equal to one ten-millionth of the distance from the North Pole to the equator of the earth. In fact, in 1791 a committee of French scientists chose this distance for the meter because it could be conveniently reproduced; this standard meter was adopted by the French Academy of Sciences in 1791. In 1889 the meter was redefined to be the distance between two marks on a platinum-iridium bar kept near Paris at the Bureau des Poids et Measures in Sèvres. Exact copies of this standard meter are kept in the bureaus of standards of all countries in the world. Thus when the results of a measurement of length are given in meters, all scientists throughout the world know exactly how long the new measurement is.

Actually, as the science of measurement developed further, it became apparent that for certain purposes the 1889 definition of the meter was not accurate enough. In 1960 the meter was again redefined by stating the distance between the two marks on the platinum-iridium bar in terms of a certain multiple of the wavelength of light emitted by the rare gas krypton. (We will discuss the wavelength of light in Section 2.6.)

Figure 1.1 illustrates the measurement process. The unknown length

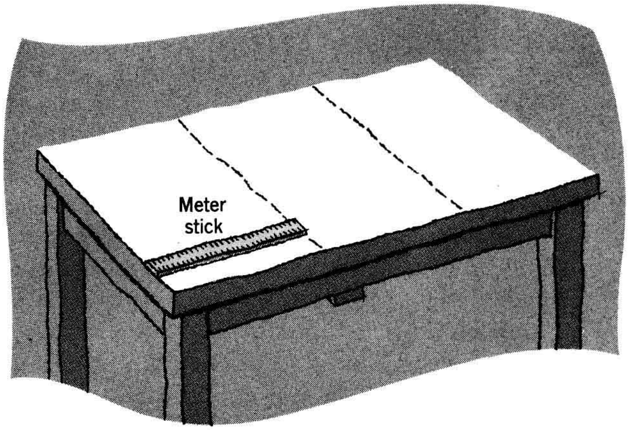

Fig. 1.1 Measuring the length of a table.

of the table is compared with that of a standard meterstick by counting the number of times its length fits into the length of the table. In this case it fits three times, and we report that the table is 3 meters long. Thus the measurement process is essentially a counting process. Although in some instances it may appear that the counting is done indirectly, all measurements are actually made in this way. The size of an unknown is determined by counting the number of times it contains a known and generally accepted standard.

Systems of units are identified by the names given to the standards for three fundamental quantities in each system. These quantities are length, time, and amount of matter (this last quantity we shall define and discuss in some detail in a later section). The unit of time in all systems is called the *second* which is chosen on the basis of daily rotations of the earth, a very convenient clock. In modern terms we define the second as the time between ticks on a clock that ticks 86,400 times in an average day. This definition, like that for the standard meter, is not accurate enough for certain purposes, and in 1967 an atomic standard for time was adopted. Today we set the rate of ticking of our clocks by comparing them with very stable atomic vibrations. This process of comparison is called *calibration.*

The second is not a convenient unit for most time spans in everyday life, and for this reason we give the most commonly used multiples of seconds special names. Sixty seconds is called a *minute,* sixty minutes an *hour,* twenty-four hours a *day,* three hundred sixty-five days a *year,* one hundred years a *century,* and so on. For scientific purposes, however, it is more convenient to use only one unit, the second, and we have developed convenient ways to write large multiples or small fractions of this unit.

The system of units adopted by the French has the great advantage that it is based on multiples of 10. For this reason it is called a *metric system.* The British also have a system based on multiples of 12. Its unit of length is the *foot,* which is now defined as exactly 0.3048 meter. Although the base 12 of the British system makes it inconvenient to apply, this system is still used in many English-speaking countries by everyone but scientists. In this book we shall use the metric system, except in certain instances where British units will help us relate our results to everyday experiences.

Multiples of metric units are also given special names which are often useful. The names of the multiples are formed by adding to the basic unit special prefixes denoting various powers of the factor 10 (the common base of all metric units). For example, 1000 meters is called a *kilometer.* The prefix "kilo" means 1000 or 10^3 in powers-of-ten notation. Table 1.1 lists some of these prefixes and the powers of ten to which they correspond. We have used the standard negative power notation for fractions like one-tenth and one-hundredth.

Although the standard systems of units are designed for convenience, the fact that they use only one unit for each quantity can be cumbersome, especially if we are dealing with very large or very small values. For example, the human race is thought to have developed about 1,000,000,000,000 seconds ago and the radius of an atom is about 1/10,000,000,000 of a meter. Numbers as large or as small as these are very awkward to write. We avoid such problems by writing all numbers in terms of powers of ten or *scientific notation.*

In scientific notation each number is written as the product of a decimal number and a power of ten. The decimal number is written with only one digit to the left of the decimal point. For example, the number 1700 would be 1.7×10^3. For numbers less than one we use the negative powers of ten. The number 0.0017, for example, would be written 1.7×10^{-3}.

TABLE 1.1 METRIC PREFIXES AND CORRESPONDING POWERS-OF-TEN

Prefix	Power of 10
mega	10^6
kilo	10^3
deci	10^{-1}
centi	10^{-2}
milli	10^{-3}
micro	10^{-6}

In this notation our age of the human race would be 10^{12} seconds and the atomic radius 10^{-10} meter. This notation also simplifies numerical calculations because the laws for adding, subtracting, multiplying, and dividing exponential numbers are relatively simple. Some facility with this system of notation will be useful in our discussions.

Another advantage of scientific notation is that it provides us with a fast way to round off numbers, called *orders of magnitude.* The order of magnitude of a number is the power of ten to which it is nearest. For example, 253 is between 100 and 1000, but it is nearer to 100 than 1000. Therefore its order of magnitude is 10^2. We indicate this by writing $253 \sim 10^2$ (where $\sim$ is read as "is of the order of"). In scientific notation $253 = 2.53 \times 10^2$, and we see that the order of magnitude is just the power-of-ten factor. For a number like 7×10^2, however, we must be careful. Its order of magnitude is 10^3 rather than the power-of-ten factor 10^2 because 700 is nearer to 1000 than it is to 100. Alternatively, we may say that 7 is nearer to 10 than it is to 1, so that 7×10^2 is nearer to 10×10^2 than it is to 1×10^2. In this example then the order of magnitude is the power of ten next higher than that of the power-of-ten factor in the number.

For numbers less than one we must exercise even more care. The order of magnitude of 7×10^{-2} is again the power of ten next higher than that of its power-of-ten factor because 7 is nearer to 10 than it is to 1, but in this case the next higher power is *not* 10^{-3}. Increasing the numerical value of the power for a negative power of ten will *decrease* the number rather than increase it. The next higher power is 10^{-1}, so the order of magnitude of 7×10^{-2} is 10^{-1} rather than 10^{-2} or 10^{-3}.

We often use orders of magnitude when comparing numbers. Rather than referring to two lengths as being about the same size, we say that they are of the *same order of magnitude.* This means that they agree to within a factor of ten. Using orders of magnitude, we can perform rough calculations rather easily as a check on our results. Since the orders of magnitude are all powers of ten, an *order-of-magnitude calculation* can be done quickly using them instead of the actual numbers involved. The answer obtained should then be the order of magnitude of the actual result. If the order of magnitude agrees with the expected order of magnitude of the result, we can proceed to the exact calculation with increased confidence.

1.3 MATHEMATICAL FUNCTIONS AND SCALING LAWS

The use of convenient systems of units, scientific notation, and orders of magnitude can simplify the problems of recording results of quantitative observations and communicating them to other scientists. To facilitate the development of useful descriptions of such results, however, we should be able to give as concise a summary of them as possible, which in turn means that a concise language in which to express our results is needed. Mathematics, an independent scientific discipline in its own right, provides physics and the other sciences with the concise language that is required.

To see how helpful mathematics can be, let us consider a very simple experiment. Suppose that we have a number of blocks of iron of various sizes and that for some reason we are interested in determining the weights that correspond to the different sizes. One way to indicate the sizes of the various blocks would be to give the volume of each. We could perform our experiment by first measuring the volume of each block and then weighing it. Since most of us are already familiar with the British unit of weight, the *pound*, we shall use the British system of units.

We have recorded the results of our experiment in Table 1.2. The volumes in cubic feet (ft^3) are listed in order of ascending size in the column on the left. The corresponding weights in pounds (lb) are listed in that on the right. This table already gives a concise and useful summary of our results. If we wish to determine the weight of a piece of iron whose volume is known, we need only look in the left column for the value of V and then move across the row to find the corresponding value of W in the right column.

Tables of this sort provide useful summaries of the data collected in various experiments, and books containing tables of data have been published for general use. We can present a more concise summary of this data, however. If we compare the values of W corresponding to increasing values of V, we notice that W increases as V does. In fact, it does so at the same rate. A mathematician describes this fact by saying that W is a *function* of V. The fact that W increases at the same rate as V, tells the mathematician the functional relationship between W and V.

From our table we see that if we double V we will double W, and if we triple V we will triple W, and so on. The mathematician says that

TABLE 1.2 RESULTS OF EXPERIMENT WITH BLOCKS OF IRON

Volume V (ft^3)	Weight W (lb)
1	440
2	880
3	1320
4	1760
⋮	⋮

W varies directly as V or that W is *directly proportional* to V. This statement is a concise summary of our table, and by using mathematical symbols we can be even more concise. We can write the statement as

$$W \propto V$$

where the symbol $\propto$ is read "is proportional to."

Although the proportionality statement is a great improvement, it does not replace our table; we still must use the table to find the values of W. The next step is to convert the proportionality into an *equation*. We do this by multiplying V by a *constant of proportionality* C as follows:

$$W = CV \tag{1.1}$$

We can determine C from the table. When V is 1 ft^3, W is 440 lb; thus

$$C = 440 \frac{\text{lb}}{\text{ft}^3} \tag{1.2}$$

Finally, our most concise summary of Table 1.2 is then

$$W = 440V \tag{1.3}$$

Equation 1.3 is a concise summary of all the information contained in Table 1.2. It tells us that W is a function of V, and it tells what the function is. To find the value of W in pounds corresponding to a given value of V in cubic feet, we just multiply that value of V by 440 lb/ft^3. Thus the equation is a rule for finding W if we know V. We can even generalize our results from this and guess that the same relation between V and W holds for substances other than iron with different values of C. In this case C is called the *weight density* of the material.

The function forms one of the basic concepts in mathematics. Its proper treatment in the most sophisticated mathematical formalisms requires a careful and rigorous definition. For our purposes, however, it is sufficient to think of a function as a rule that relates one set of numbers to another. Table 1.2 is one way of writing the function giving W in terms of V. Here the rule tells how to locate the appropriate values of W in the rows and columns of the table. The rule in Equation 1.3 is another way of writing this function. It is by far the most convenient and useful way. One goal of the physicist is usually to find the simplest mathematical function that will concisely describe the results of his observations.

It is useful for us to borrow a few more of the mathematician's symbolic descriptions of functions. When a quantity y is known to be a function of another quantity x, we write this fact as

$$y = f(x) \tag{1.4}$$

We read this as "y equals f of x." Sometimes we indicate it more simply by writing $y(x)$, read "y of x." The quantities x and y are called *variables*, with x the *independent variable* and y the *dependent variable*. In the example with W and V we write $W(V)$, indicating that W is a function of the independent variable V. We shall use this symbolism whenever convenient in our discussions.

Equation 1.3 is an example of a general class of functions occurring so often in physics that it is given a special name. We calculate W from V by multiplying the first power of V by the constant C. Other examples of this class of functions are provided by some simple geometric formulas with which we are all familiar. Figure 1.2 shows three common geometric figures: a circle of radius R; a cube of side L; and a rectangular solid of length L, width W, and height H.

The area of the circle in Figure 1.2 is given by

$$A = \pi R^2 \tag{1.5}$$

The volume of the cube is

$$V = L^3 \tag{1.6}$$

and that of the rectangular solid is

$$V = LWH \tag{1.7}$$

In each of these equations, as in Equation 1.3, we find the value of the dependent variable by raising the independent variable to some power. In Equation 1.7 L, W, and H are dimensions of length or *linear dimensions*, and so V is the third power of the linear dimensions (i.e., the product of three of them).

Functions of this type are called *power laws*, and most functions used in physics are power laws. As we shall see in later sections, the most important power law involves an inverse second power of the independent variable. An example of an inverse power law is afforded by the relationship

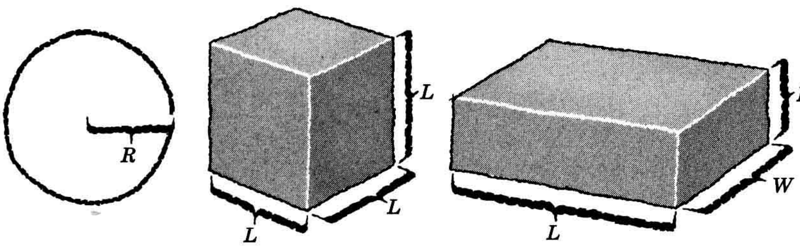

Fig. 1.2 Circle, cube, and rectangular solid.