A FIRST COURSE IN PHYSICS FOR COLLEGES

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PREFACE

It is now more than two decades since the appearance of "A First Course in Physics," — a text designed to serve as a brief general introduction to the subject of physics wherever taught, but of such length and character as to occupy a year if given in the secondary school or two quarters if given in college. These are two uses to which "A First Course" has continually been put, for all beginning courses cover necessarily much the same ground and in general the presentation is better for the college student if the secondary-school pupil has been kept in mind in the writing.

However, "A First Course" was not originally well adapted to the *full year* of work usually assigned to beginning physics in most colleges, and a considerable number of college teachers have urged the authors to make such additions and modifications as would better adapt it to this purpose. The present time has been found one which is peculiarly opportune for responding to this request. The fourth rewriting of "A First Course" has just been completed. During the last twenty years physics has undergone extraordinary changes, — changes which the authors have been in a rather favored position for understanding, appraising, and reflecting. This they have endeavored to do in the repeated revisions, or, better, entire rewritings, now four in number, that "A First Course" has undergone. More important still, the authors have had the inestimable benefit of the experience and coöperation of a large number of teachers, who have helped them in eliminating, condensing, perfecting, and choosing, so that the final product of the last rewriting, represented in "The Elements of Physics," done in collaboration with W. R. Pyle, is the result of twenty years of continuous coöperative effort to improve the teaching and presentation of beginning physics. It is just now particularly opportune to utilize that experience for meeting the *college* demand for a beginning course.

The additions and modifications which have been deemed desirable for the expansion of the course so as to make it cover a full year of college work have recently been organized, and the manuscript in mimeographed form has for two years, in the hands of six successful college teachers, been given the crucial test of actual classroom experience. In this form it has been read in part by a number of teachers who have in the past used "The First Course" with college students. Their suggestions have been of great value in preparing the manuscript for the press. To each of these the authors are very grateful and regret that the roll of names to which acknowledgments are now due is too long for inclusion here. In addition to those who have contributed in an important way to the success of "The Elements of Physics," and whose services have been acknowledged in that book, we are under special obligations to Professor L. L. Hendren, head of the Department of Physics in the University of Georgia, who has arranged a number of problems for this text and has made other important contributions. Professor C. C. Hatley of Duke University and Professor James L. Lake of Wake Forest College have read a large portion of the manuscript and have contributed materially to the accuracy of the text.

The course as organized in "A First Course in Physics for Colleges" is designed to meet a rather urgent need for a text which may profitably be presented to any freshman without the omission of a paragraph. Any course in general physics is built up through a process of selection from a very great variety of available topics. In three times the available time no college student could possibly assimilate all the subject matter presented in various textbooks of general physics. In this text only those topics have been incorporated which are teachable to the class of students in view and which seem to give to the general student the most significant picture of the present status of the science of physics as a whole. Comprehensive tests indicate definitely that only a very small percentage of the subject matter presented in the typical college course is ever assimilated by the majority of its students. It is hoped that this will not be true of the present course, and that, further, the selection of material and mode of treatment here used will make the study of physics attractive to a larger number of students, develop a greater interest, and hence result in more of self-education. For those in whom is aroused a desire to extend their knowledge of physics other courses are available in which more exhaustive and more mathematical treatments are employed.

Opinions differ as to the advisability of supplying answers to problems. A sufficient number of representative problems have been selected to meet the requirements of the usual course, and answers to these are given at the end of the text. All the supplementary problems given in Appendix A and a considerable number distributed throughout the text have been left without answers for the use of those preferring this procedure.

R. A. M.
H. G. G.
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CHAPTER I

THE STUDY OF PHYSICS

1. Physics. The study of physics deals with all the phenomena of the world about us except those involving the complex life of animals and vegetables and those invisible changes which alter the nature of matter. Everything that we can see, hear, or feel, as well as much which does not affect our senses, is the subject matter of physics.

In a certain sense many of us have been studying physics all our lives, since human nature is ever concerned with the reasons *why* natural phenomena occur. We even try, in a crude way, to correlate the facts that we observe, but in the main we are considering only the raw material out of which physics is built. In the study of physics we shall try to observe with open minds the facts of nature; we shall try to explain intelligently the facts observed and to answer the question Why? for each of them. In so doing we shall correlate the observed phenomena and establish definite laws of nature which account for them and which enable us to predict what will happen under certain conditions not yet observed. Jules Henri Poincaré said, "A science is made out of facts, just as a house is made out of stones, but a mere collection of facts is not a science, any more than a pile of stones is a house." When we begin to relate one observation to another, and establish laws, then our former aimless wonderings become a definite, organized, systematized science.

For example, you have observed innumerable instances in which bodies stay where they are put unless some force moves them. If you leave a chair in the middle of the room and return to find it on the porch, you are convinced that some force moved it there. Again, should you strike a ball with a bat, picture your astonishment to see it stop in mid-air a few feet from your bat. You do not expect an automobile going at high speed to stop the instant the explosions of gas cease. You apply the brakes because you believe that the car will continue in motion unless some force is applied to stop it, and you apply the brakes in proportion to the urgency. These conditions are all based on very numerous personal observations, and you unconsciously establish for yourself a law regarding them.

Sir Isaac Newton merely crystallized such observations into his first law of motion: *Every body continues in its state of rest or uniform motion in a straight line unless impelled by external force to change that state.*

After a law of nature has once been established by careful observations and deductions, then new phenomena may be predicted as a result of given conditions. Leverrier and Adams, each making an independent study of the planet Uranus, could not account for its actual motion through a consideration of all the known forces acting upon it. The combined attraction of the sun, the earth, and all the planets would cause it to follow a different path from the one actually taken; so a new body had to be assumed in the heavens in order that the observed phenomena should conform to known laws. This line of reasoning led to the discovery of the planet Neptune. The electromagnetic waves by which the messages of wireless telegraphy and telephony are transmitted were predicted by Maxwell by inference from physical laws some twenty years before they were detected experimentally. So in all the divisions of physics new phenomena will be discovered which will advance the civilization of mankind through the application of laws based on observation and measurement.

Physics is frequently defined as *the science of matter and energy.* Since in the beginning of our study we have little conception of the complete meaning of the terms "matter" and "energy," this definition probably serves only to give a general idea of the field. Matter is generally regarded as the vehicle of energy, and one might say without fear of disproof that *physics is the science of energy.* A better definition has been given in this form : *Physics is essentially a system of explanations — answers to the question Why? — of the behavior of inanimate things.* Time and again we shall busy ourselves with relating one fact of nature to another more fundamental fact until no further simplification is possible. To use Poincaré's figure, each stone in the house will be given its particular place in relation to all the others.

2. Divisions of physics. Since the study of physics involves a consideration of an almost infinite number of related phenomena, it is desirable, from the standpoint of clarity, first to classify the phenomena into very broad groups according to the dominant form of energy involved. To accomplish this six divisions are frequently employed : *mechanics, heat, magnetism, electricity, sound,* and *light.* These terms have passed into everyday use and have some sort of meaning to everyone. But our important task will be that of reaching as definite conceptions as possible of these divisions. While definite, unambiguous meanings must always be employed in physics, we must not expect nature to act in such nicely arranged groups. One kind of phenomenon is never produced without the simultaneous production of one or more phenomena of the other groups.

Since it is the task of physics to answer questions about nature, let us at the outset get some conception of the questions that will arise for our consideration. Our answers or explanations will rarely be ultimate in their nature. Frequently the process consists in explaining phenomena in terms of simpler yet still unexplained concepts.

Under the division of mechanics we consider, in general, force and its action on matter. Sir Isaac Newton considered mechanics as the study of machines and structures, thus giving the term a more or less limited meaning. It is this division of physics which appeals most directly and most universally to our senses. The questions arising here are such as the following : Why can you lift a thousand pounds with a pinch bar, a block and tackle, or a jack? Why cannot you lift yourself by your bootstraps? Why does the coal go on into the furnace when your shovel stops? Why does a piece of cardboard stick closer to a spool the harder you blow against it through the spool? Why does a loop of chain suspended vertically from a string spread out into a hoop and assume a horizontal position when the string is twisted rapidly? Why can a man stand on the slope of a roof? Why does a baseball curve? Why does a steel ship float? Why does a spring balance measure weight? Why does an air rifle shoot? Why is the strength of a dam independent of the weight of the water in the pond?

Under the division of heat we are led into a consideration of the energy possessed by the particles of matter too small to be seen even through the most powerful microscope, particles which we call molecules. Here we endeavor to answer such questions as these: Why can a Boy Scout light a fire by rubbing two sticks together? Why does the motion of a train develop a hot box? Why does a balloon rise? Why will fittings on a steam pipe break if there are no loops or bends in its length? Why will hot water sometimes crack a bottle? Why does a snowball "pack" when you squeeze it in your hands? Why does a boiler-maker use red-hot rivets? Why does a lake freeze on the surface only, instead of all the way through? Why is climate more temperate near large bodies of water? Why is it cooler on the mountain top than near the sea? How are tornadoes produced? Why does the same vacuum bottle keep a liquid either hot or cold?

The study of the molecule is not confined to heat. In sound we also deal with this exceedingly small particle; but this time our primary interest is not in the energy of the molecules, but in certain *wave motions* in which the molecules take part in large groups. In our study of sound we shall find occasion to answer such questions as these: What makes a sound? Why do you see the lightning before you hear the thunder? Why do you hear a train sooner with your ear placed to the track than when you stand upright? What causes an echo? Why is it more difficult to hear a speaker out of doors than in a hall, and why may one hear a speaker better in one hall than in another of the same volume? What determines the loudness of a sound at a given point? What is necessary to reflect a sound? Why are not all sounds alike to us? Why do we regard certain sound combinations as harmonious and others as discordant? Why are some voices more pleasing than others? Why will a phonograph reproduce music? How does a player piano work?

Similar questions arise in connection with magnetism and light.

3. Objectives of the study of physics. It is worth while in the beginning to justify to ourselves the time and effort involved in the study of physics. Our objectives will much more certainly be attained if we have, as we go along, a clear conception of just what we wish to accomplish. There are many advantages to be derived from such a study, and we may, without placing special emphasis anywhere, mention three that will appeal to the majority of students. Physics is worth while because of its use in the study of other subjects, because of its value as a mental discipline, and, finally, because of its enrichment of our lives by giving us a real appreciation of the world in which we live.

We say that physics is the fundamental science because the progress of the other sciences depends largely upon the observation of physical phenomena. When we burn sugar and from it make charcoal, when we mix two clear liquids and find a colored solid precipitated, or when two invisible gases are brought together to form a white cloud, all that we see is a matter of physics, and all the processes, such as filtration, evaporation, ignition, weighing, and dialysis, used for further investigation are physical. It is true that chemical changes have been brought about, but all that is chemistry has been utterly invisible and is only a matter of deduction from the physical phenomena observed. Chemistry uses the methods and language of physics in arriving at her truths, and, in the words of the late Alexander Smith, professor of chemistry at Columbia University, is "deaf, dumb, and blind" except for the aid of physics.

In a general way biology is more directly dependent upon chemistry than upon physics, but at many critical points it finds physical instruments and processes of fundamental importance. What would biological science do without the microscope or the microtome or the thermostat? The field of biophysics is developing at a rapid pace, and the labors of the trained physicist in the field of biology promise to transform certain phases of medicine.

Engineering and astronomy are really the study of physics in special fields. The former is primarily the application of physics to man's material needs; the latter is an application of physics to meet his intellectual craving to know the facts of the universe. The laboratory of experimental psychology is, in reality, a physical laboratory in which the experimental methods of physics are employed to obtain the truth about the working of the mind.

Physics is also worth while because of its severe discipline in the use of words and in the statement of ideas. Such words as "mass," "weight," "elasticity," "work," "pressure," and "density" have vague meaning to the average mind. To the student of physics they have perfectly definite and exact meaning. The study of physics develops the habit of accurate and exact description.

Finally, the most important reason why one should study physics is that it leads to a closer and more accurate observation of the world about us and to a deeper enjoyment of life. We see and understand things in art, in literature, and in nature to which we were previously blind, and from our greater faith in the inevitable effect of given causes we are led to a saner life.

CHAPTER II

MEASUREMENTS

4. The three fundamental quantities. One may say that a physical quantity is anything that can be measured, and in a general survey of all measurable phenomena we find three quantities in terms of which all other quantities may be expressed. Yet it is impossible to express any one of these in terms of either of the other two. These three quantities are *length, mass,* and *time,* and are therefore called *fundamental quantities.*

The *mass* of a body is the *quantity of matter* that it contains.

The *length* of a body is the *distance between its extremities.*

Time is the *measure of duration.*

Any other quantities than these, then, must be *derived quantities.*

5. Standard units for fundamental quantities. To avoid confusion and error in the use of various types of measuring devices, such as yardsticks or clocks, located as they are in many different countries, it is necessary that there be for each type some universally accepted standard to which all similar devices may be referred for their validity. Since there are only three fundamental quantities, there need be only three of these standards: one for length, one for mass, and one for time. As a matter of fact, English-speaking people established one set of standards, and the French established the "metric" standards which have been adopted by the rest of the world. Therefore there is one British standard and one metric standard of mass and one British standard and one metric standard of length; one standard of time serves for both the British and the metric system.

Standards of length. The British government preserves at London a bronze bar having near each end a fine transverse scratch on a gold plug. The distance between these two scratches at a temperature of 62° F. is taken as the *standard yard*. At the International Bureau of Weights and Measures near Paris is a platinum bar designed to be $\frac{1}{10,000,000}$ of the distance between the equator and the north pole. This is called the *standard meter* and is equivalent to a little more than a yard.

The meter is first divided into ten parts called *decimeters*. Each decimeter is divided into ten parts called *centimeters*, and each centimeter is divided into ten parts called *millimeters*. Taking the dollar as the standard unit, we may compare its subdivisions with the subdivisions of the standard meter. The *dime* corresponds to the *deci*meter, the *cent* to the *cent*imeter,

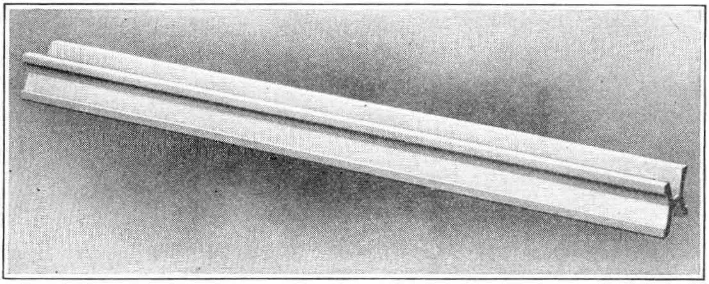

FIG. 1. The standard meter

and the *mill* to the *mill*imeter. As there are a thousand mills, a hundred cents, and ten dimes in a dollar, so there are a thousand millimeters, a hundred centimeters, and ten decimeters in a meter. In this book distances will generally be expressed either as meters and decimal fractions of a meter or in terms of centimeters and decimal fractions of a centimeter.

Standards of mass. The metric standard of mass is the mass of a cylinder of platinum made equal to that of 1000 cubic centimeters of water at a temperature of 4° C. This cylinder is deposited with the standard meter at the International Bureau and is called the *standard kilogram*. The British standard of mass is a cylinder of platinum called the *standard pound*, which is kept at London.

Standard of time: the mean solar day. The solar day is the time which elapses between successive "transits" of the sun, or the interval between the instants at which the sun crosses the meridian on successive days. Because of the variable velocity of the earth in its elliptical orbit about the sun, this day is variable. If we add together the lengths of all the days in the year and divide the sum by the number of days, we obtain the mean solar day. The second is defined as $\frac{1}{86,400}$ of this standard mean solar day. Astronomers use as a day the interval between one star noon and the succeeding star noon. Because of the enormous distance of the stars from the earth the

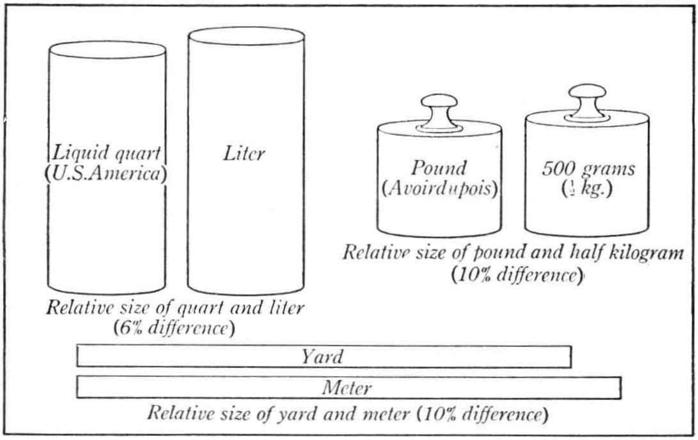

FIG. 2. Metric units in comparison with the British units

effect on this interval of the motion of the earth in its orbit is negligible, so that the star day, or *sidereal day*, is constant throughout the year.

6. The British and metric systems of units. On the basis of the standard units just discussed, two widely used systems of units have been built up. The system in common use in America and in the British Empire is called the British system and is too familiar to require explanation here. The system employed elsewhere throughout the civilized world originated in France and is called the metric, or C.G.S. (centimeter-gram-second), system. This is superior to the British system in that it is far simpler and more easily used in computation. The units used for the measurement of length and mass are in the ratio of 10 or some multiple of 10, such as 100, 1000, etc. Thus 10 milligrams = 1 centigram, 10 centigrams = 1 decigram, and 10 decigrams = 1 gram. If the student is not familiar with the metric units, a careful study should be made of Table II of Appendix B.

7. The fundamental units. Corresponding to the British and metric *standard* units of the fundamental quantities mass, length, and time, we have in common use two sets of *fundamental* units of mass, length, and time. The fundamental units of the metric system are the centimeter, the gram, and the second (C.G.S.); the corresponding units of the British system are the foot, the pound, and the second.

8. Conversion of units. Since the student is more or less familiar with the English system of measurement, and since he will be required frequently to use both the British and the metric unit, it will be advisable for him to acquire some knowledge of how to convert one into the other. This can usually be done best by reference to conversion tables, but it is suggested that he memorize the following relations: 1 inch is equivalent to 2.54 centimeters; 1 kilogram (1000 grams) equals 2.2046 pounds, or approximately 2.2 pounds; 1 meter contains 39.37 inches. The relation between all the other units can be found if these ratios are known. For complete conversion tables see Appendix B.

9. Measurement of length. Measuring the length of a body consists simply in comparing its length with that of the standard meter bar kept at the International Bureau. In order that this may be done conveniently, great numbers of rods of the same length as this standard meter bar have been made and scattered all over the world. They are our common meter sticks. They are divided into 10, 100, or 1000 equal parts, great care being taken to have all the parts of exactly the same length. The method of making a measurement with such a bar is more or less familiar to everyone.

10. Measurement of mass. Similarly, measuring the mass of a body consists in comparing its mass with that of the standard kilogram. In order that this might be done conveniently, it was first necessary to construct bodies of the same mass as this kilogram and then to make a whole series of bodies whose masses were $\frac{1}{2}$, $\frac{1}{10}$, $\frac{1}{100}$, $\frac{1}{1000}$, etc. of the mass of this kilogram; in other words, to construct a set of standard masses commonly called a *set of weights*.

With the aid of such a set of standard masses, the determination of the mass of any unknown body is made by first placing the body upon the pan A (Fig. 3), counterpoising with shot, paper, etc., then replacing the unknown body by as many of the standard masses as are required to bring the pointer back to O again. The mass of the body is equal to the sum of these standard masses. This is the rigorously correct method of weighing, and is called the *method of substitution*.

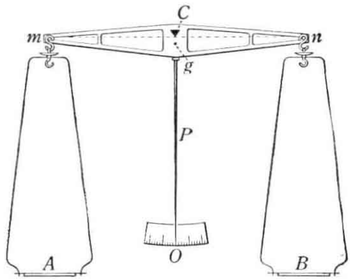

FIG. 3. The simple balance

If a balance is well constructed, however, a weighing may usually be made with sufficient accuracy by simply placing the unknown body upon one pan and finding the sum of the standard masses which must then be placed upon the other pan to bring the pointer again to O. This is the usual method of weighing. It gives correct results, however, only when the knife-edge C is exactly midway between the points of support m and n of the two pans. The method of substitution, on the other hand, is independent of the position of the knife-edge.

Note on physical units in physical equations. It should be noted that in equations the proper units are carried along with the numbers telling how many of these units are involved. Physical equations are relations between physical things and not between numbers alone, as in pure mathematics. If the units are carried through the equations properly, they can be canceled out by the same rules that apply to numbers or algebraic symbols, and thus the correct unit for the answer is indicated.