A TEXT-BOOK

OF

PHYSICS

EDITED BY

A. WILMER DUFF

CONTRIBUTORS

A. WILMER DUFF
ALBERT P. CARMAN
E. PERCIVAL LEWIS
R. K. McCLUNG
CHARLES E. MENDENHALL

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PREFACE TO THE FIFTH EDITION

In this edition numerous minor improvements have been made, where experience has shown changes to be desirable. Brief accounts have also been given of some recent applications of Physics, such as instruments used in airplanes (p. 152), new methods in wireless telegraphy and telephony (pp. 481–485), sound-ranging in warfare (p. 529), zones of silence (p. 533), submarine detectors (p. 560), diffraction of X-rays (p. 629), and a note has been added on the principle of relativity (p. 577). A few problems referring to some of these topics have also been given. While the accounts of these important applications and principles are necessarily brief and inadequate, it seems desirable that students of college Physics should have some acquaintance with such new and live topics of scientific, and even popular, interest.

As in the past, corrections and criticisms from those who use or examine the book will be welcomed.

THE EDITOR.

WORCESTER, MASS.

EXTRACTS FROM PREFACE TO FIRST EDITION

The preparation of a work of this grade by the collaboration of several writers is a somewhat novel undertaking, and some explanation of its genesis will not be out of place. It represents the attempt of seven experienced teachers of college physics to prepare a text-book that would be more satisfactory to all of them than any existing one. It was, of course, hoped that such a book would also prove acceptable to other teachers. It seemed to the writers that there was a need, and there would be a place, for a work prepared in this way.

One or two remarks as to the character of the book may be permitted. It will in general be found that the writers, while aiming first of all at clearness and accuracy, have preferred terseness to diffuseness. Repetition and amplification are desirable in a lecture. In a printed statement, which may be reread and weighed until mastered, they often discourage thought; and a teacher of Physics might well begin his instruction with the words of Demosthenes, "In the name of the gods I beg you to think." The writers have endeavored to present their subjects simply and directly, avoiding, on the one hand, explanations obvious to any student of fair capacity, and, on the other hand, subtle distinctions and discussions suited to more advanced courses. Some may find the material included in the book too extensive for a single course. If so, a briefer course can be arranged by omitting all of the parts in small print together with as much of those in large print as may seem desirable. There may seem to be some duplication of topics in the work of two contributors. In such cases (which are very few), it will be found that the treatment is from different points of view, appropriate to the respective subdivisions of the subject.

THE EDITOR.

WORCESTER, MASS.

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TEXT-BOOK OF PHYSICS

MECHANICS AND THE PROPERTIES OF MATTER

By A. Wilmer Duff, D. Sc.

Professor of Physics in the Worcester Polytechnic Institute, Worcester, Mass.

INTRODUCTION

1. Physics as a Science.—From the evidence of our senses we infer the existence of a great variety of bodies in the physical universe around us. By the use of our senses we also learn that these bodies have various characteristics in common, such as inertia, weight, and elasticity, and these we attribute to the *matter* of which in various forms all bodies seem to consist. Matter in itself is inert; the mutual actions of bodies and the effects which they produce on our senses are due to the presence in them of something which is not matter and which is called *energy.* We shall define the word energy later; the thing denoted by it is known to all as the means which are supplied by the sun, fuels, and elevated bodies of water, and which are required for various familiar operations in nature and industry.

Physics is the Science of the Properties of Matter and Energy. This general description of Physics does not sharply distinguish it from Chemistry, and, in fact, no definite dividing line can be drawn between the two sciences, although, in a general way, it may be stated that chemistry deals chiefly with questions regarding the composition and decomposition of substances. The different branches of Engineering also treat of the properties of matter, but from the point of view of their useful applications.

A science is more than a large amount of information on some subject. In very early times men must have had much valuable information regarding the physical results of various actions and processes; but it was only when attempts were made to systematize and arrange this knowledge and to seek the relations between the different facts that the science of Physics began. The description of the phenomena of the physical world became more and more scientific as more numerous connections between physical phenomena were discovered and described. At the present time Physics has progressed farther in this direction than any other science, and, in seeking to give a brief account of the present state of the science of Physics, it must be our aim, not only to state the most important observed facts, but also to show the relations and interdependence of these facts.

It will be seen as we proceed that in some parts of the subject the relations between observed facts are better understood than in other parts. Thus in Mechanics the relations between phenomena have been so well ascertained that we are able to start from a few simple laws regarding the motions of bodies and from these deduce explanations of the most complicated motions. In other parts of the subject we must be content to take from time to time some one principle and trace the logical consequences of it as far as we can, and then proceed to do the same with other principles.

After classifying and studying a group of facts, the process by which we arrive at some underlying principle is called *Induction* Thus, the principle of gravitation was discovered by Newton after a careful comparison of the motions of falling bodies and of the moon and the planets. Having found a general principle underlying and binding together many phenomena, we may reason forward from it and deduce other known or unknown facts, as in Geometry we deduce one proposition from another. This process is called *Deduction.* In a brief account of Physics we must necessarily use deductive more frequently than inductive methods; but, where space will permit, the effort may be made to show how by induction important fundamental principles have been discovered.

2. Measurement.—The first condition for success in tracing the connection between the facts in any science is that these facts shall be ascertained as accurately as possible. A qualitative statement of the size or weight of a body, to the effect that it is large or small, is of very little use. A quantitative description of the same consists in giving the ratio of its size or weight to that of some accepted standard. Such a standard is called a *unit*, and the numerical ratio of the thing measured to the unit is called the *numerical measure* (or numeric) of the thing measured.

Some measurements are *direct*, that is, they are made by comparing the quantity to be measured directly with the unit of that kind, as when we find the length of a rod by placing a yard or meter scale beside it. But most measurements are *indirect*. For example, to measure the velocity of a train we measure the distance it travels and the time required, and by calculation we find the number of units of velocity in the velocity of the train.

3. Observation and Experiment.—In some branches of science mere *observation*, that is, taking note of circumstances and events, is the chief or only way of obtaining knowledge. For example, the astronomer cannot modify the motions of the heavenly bodies; he must be content to observe. Observation also plays an important part in Physics, but *experiment*, which consists in modifying circumstances or events with a view to making more valuable observations, plays a more important part. Thus, if we desire to know how the earth attracts a body and whether the attraction is different at different places, we cannot make much progress if we must confine ourselves to observing bodies falling freely from various heights; but, if we modify the fall by attaching the body to a cord and swinging it as a pendulum, we are able to make much more accurate observations, and to arrive at valuable information that we could probably never gain by observing free falling bodies. For this reason Physics is chiefly an experimental science, that is to say, the physicist relies on carefully planned experiments to find information, and then, by methods of reasoning, and especially the condensed accurate form of reasoning called Mathematics, he extracts from the results of the experiment all the information possible.

4. Hypotheses.—An event or phenomenon remains obscure or unexplained when its logical connection with other events or phenomena has not been traced. But it is *explained* when it is shown to be connected with other familiar phenomena, and the nature of the connection is made clear. Thus, the rising of mercury in an exhausted tube was obscure and unexplained until it was found to be different at different heights along a mountain side and to be connected with the pressure of the air on the mercury in the pool in which the tube stands. The explanation in such a case consists in tracing out the relation of cause and effect between the thing explained and other things. The latter may themselves be still unexplained. Thus the way in which air exercises pressure has only comparatively recently been explained.

A suggested explanation, while its correctness is still in doubt, is called an *hypothesis*. The hypothesis suggested to account for the pressure of air (or any gas) is that air consists of flying particles, which, by their bombardment of a surface, produce what we call the pressure on the surface; this suggested explanation is called the *kinetic hypothesis* of gases. The formation of an hypothesis plays a very important part in science, for it stimulates research to test its truth; and, even if this particular hypothesis turn out inadequate, in testing it many new facts are usually ascertained and the way is paved for arriving at the right explanation. The word *theory* is sometimes used in the same sense as hypothesis, but it is better to restrict it to meaning the extended discussion of an explanation or verified hypothesis. We shall use it in this sense later when speaking of the Kinetic Theory of Gases (§227).

5. Cause and Effect.[1]—When a certain event seems inevitably to be followed by a certain other event we are accustomed, in ordinary language, to speak of the former as the *cause* of the latter, and of the latter as the *effect* of the former. Thus the explosion of powder in a gun is spoken of as the cause of the projection of the bullet, and the latter event is described as the effect of the explosion. In speaking of the relation of two things as that of cause and effect, we do not merely mean that one has always been observed to follow the other, but we suppose that there is something invariable in the connection between them, that is, we imply our belief that nature will always act in the

[1] There is here no attempt to use terms in a critical philosophical sense. The use of such words cannot be avoided in an elementary work without confusing circumlocution and they must be used here in their ordinary sense.

same way when the circumstances are the same. There are, however, two circumstances which must be considered as of no importance as regards the connection between causes and effects. These are *time* and *place*. The time of an event is, of course, never repeated, and nothing, so far as we know, ever comes again to exactly the same place, since the sun and all the planets are moving rapidly through space.

6. Physical Laws.—A careful study of any phenomenon usually enables us to state in a general way what will happen in certain circumstances. Very ancient observation led to the conclusion that bodies when unsupported fall toward the earth. Such a generalization is a *physical law*. A still wider study usually leads to a more general law. Thus the study of falling bodies and of the motion of the moon and of the planets led Newton to the conclusion that each of two bodies is attracted toward the other. The aim of physical research is to obtain physical laws of increasing width and generality. Any such law is very imperfect until it can be stated in exact mathematical form, and this requires careful measurement. By measurement and calculation Newton arrived at the law of attraction between bodies called the Law of Universal Gravitation. Thus a physical law is simply a statement that, given a certain set of circumstances, certain events will follow.

The proof of a physical law is sometimes *direct*, that is, the law is deduced from certain facts of observation and experiment, as one proposition is deduced from another in Geometry. Thus the law of gravitation can be derived from the known motions of the moon and the planets (§144). But in many cases the proof of a law is *indirect* and consists in showing that all results deducible from such a law are in accord with observation and experiment. This is the proof of the fundamental laws of Mechanics (§36).

7. Subdivisions of Physics.—The Science of Physics may, for convenience, be divided into the following parts:

1. Mechanics.	**3. Heat.**	**6. Sound**
2. Wave Motion.	**4. Electricity and Magnetism.**	**7. Light.**
	5. Radioactivity.	

MECHANICS

8. **Mechanics** is the branch of Physics which treats of the motions of bodies and the causes of changes in these motions. It is divided into two parts, one, called **Kinematics,** in which the various kinds of motion are described and studied, and the other, called **Dynamics,** in which the causes of change of motion are studied. Kinematics, or the study of motion, differs from Geometry in having to consider the element of time. Dynamics is usually divided into two parts, **Kinetics** and **Statics,** the former dealing with bodies in motion and the latter with bodies which, though acted on by causes that tend to produce motion, remain at rest, owing to the fact that these influences counteract each other. (Some authors use the term Dynamics in the sense here assigned to Kinetics.) In the following elementary treatment of Mechanics it will not be convenient to treat the various parts of the subject quite separately; each will be taken up in turn as convenience and simplicity may seem to dictate.

KINEMATICS

The Geometry of Displacements

9. **Translation and Rotation.**—Motions may be divided into two kinds. A moving body has a motion of **translation** when every straight line in the body remains parallel to its original position. Thus, a train moving on a straight track and a sled moving down a uniform incline have motions of translation. In such a case all points in the body move in exactly the same way. Hence the motion of the body is completely described when the motion of any point in the body is given, and we may, therefore, in describing the motion of the body, treat it as a single particle.

A body has a motion of **rotation** when all points in the body travel in circles the centers of which lie in a straight line; the line is called the axis of rotation. This is the motion of a grindstone, a flywheel, or a swing. Any two points in such a body are at any moment moving differently (unless they lie in a plane through the axis and are equidistant from the axis); points farther from the axis move in larger circles and more rapidly than those nearer to the axis.

Many forms of motion are highly complex, but they may in all cases be considered as made up of translations and rotations.

Since the motion of a body which has translation without rotation is the same as that of a point, it is convenient to begin with a study of the motion of a point.

10. Position of a Point.—The position of a point is fixed by its distances, or distances and directions, from other points, lines, or surfaces. The simplest way of stating the position of a point is by giving its distance and direction from some other point which we may call the starting-point or *origin*.

When we confine our attention to points in a certain line, straight or curved, their positions may be assigned by giving the distance of each point from some assumed origin in that line. One direction away from the origin is taken as positive and the opposite direction as negative. For example, the position of any station on a railway line may be fixed by its distance, positive or negative, from some other station taken as origin.

When we confine our attention to points on a surface, plane or curved, the position of each point may be assigned by its distance and direction from some origin on the surface, or, what comes to the same thing, by its distance from each of two lines at right angles passing through the origin. For example, a point on the surface of the earth is described as being a certain distance east or west and a certain distance north or south from the origin.

For points not confined to any line or surface, the position of each may be assigned by its distance and direction from some assumed origin in space, or, what comes to the same thing, its distances, positive or negative, from each of three planes intersecting at right angles at the origin.

In the first case position is assigned by one number, in the second by two and in the third by three. A point is said to have one *degree of freedom* when its motion is confined to a definite line, two degrees of freedom when it is confined to a definite surface and three degrees of freedom when it is not restricted in any way.

The above statements of position are statements of *relative position*, that is, statements of the relation of the position of a point to that of some other point taken as origin. Absolute position, or the position of a point without any reference, stated or implied, to any other point or framework of lines, could not be described and no definite meaning could be attached to it. In what follows the word position will always mean relative position, and, unless otherwise stated or implied, the point of reference will be some point on the surface of the earth.

11. Displacements.—A change of position is called a **displacement.** In describing a displacement we do not need to make any reference to the time in which the point moves from one position to the other. A description of a displacement consists in a statement of the *length* and *direction* of the straight line drawn from the first position of the point to its second position. Thus, when a point has moved from A to B, it has received a displacement, the magnitude of which is the length of the straight line AB and the direction of which is the direction of AB. This displacement we may denote by the symbol $\overrightarrow{AB}$ or $\overline{AB}$, the arrow or stroke being placed above AB to indicate that we are referring not merely to the length of the line AB, but also to its direction from A to B.

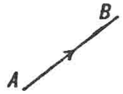

FIG. 1.—A displacement is represented by a directed line.

12. Units of Length.—To measure or specify a displacement we must use some unit of length. The unit chiefly employed in Physics is the *meter* or one of its multiples or submultiples. The meter is defined as the distance between two lines on a bar of platinum-iridium kept at the International Bureau of Weights and Measures near Paris, when the temperature of the bar is that of melting ice. It was intended by the designers that this length should be one ten-millionth of the distance from a pole of the earth to the equator. One one-hundredth of the meter is called the centimeter (0.01 m.), and this is the unit of length which we shall usually employ. Other decimal fractions of the meter are the decimeter (0.1 m.) and the millimeter (0.001 m.). For great distances the kilometer (1000 m.) is employed.

The unit of length popularly used in English-speaking countries is the *yard* or one of its well-known multiples or submultiples. The British yard is defined legally as the distance between two lines on a bronze bar kept at the office of the Exchequer in London. The legal definition of the yard in the United States is $\frac{3600}{3937}$ of a meter.[1]

13. The Addition of Displacements.—If the point that moved from A to B did not travel by the straight line AB but passed through points C and D, its final displacement was the same as if it had gone by the straight line AB; but the final displacement was the sum of a number of separate displacements, $\overline{AC}$, $\overline{CD}$, $\overline{DB}$. Thus $\overline{AB}$ is the *resultant* or sum of $\overline{AC}$, $\overline{CD}$, $\overline{DB}$, or we may say that by adding $\overline{AC}$, $\overline{CD}$, $\overline{DB}$, we get $\overline{AB}$, or briefly, $\overline{AB} = \overline{AC} + \overline{CD} + \overline{DB}$; but it must be carefully noted that the addition indicated by the sign + is a *geometrical* process, performed by placing the displacements end to end as the sides of a polygon and taking as the sum the displacement from the initial position to the final position.

If from C we draw a line CD' equal and parallel to DB, and from D' a line $D'B$ equal and parallel to CD, we shall have another path leading from A to B. The displacements $\overline{AC}$, $\overline{CD'}$, $\overline{D'B}$ added together give the same sum as the displacements $\overline{AC}$, $\overline{CD}$, $\overline{DB}$ added together, and for each step in one series there is an equal and parallel step in the other series. It is evident that, so far as addition of displacements is concerned, we may regard $\overline{CD'}$ and $\overline{DB}$ as the same displacement and $\overline{D'B}$ and $\overline{CD}$ as the same displacement. This is consistent with the definition of a displacement as a change of position; for, when a point goes from C to D, it has received the same *change* of position as another point has received when it has gone from D' to B, CD and $D'B$ being equal and parallel. Thus *all displacements which have the same magnitude and direction are equal.*

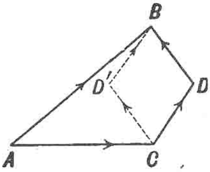

FIG. 2.—Geometrical addition of displacements.

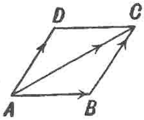

FIG. 3.

When two displacements are to be added, the addition may be performed by drawing a triangle. Thus to add $\overline{AB}$ and $\overline{BC}$ we complete the triangle ABC and the sum is $\overline{AC}$. This is called the **triangle method** of adding two displacements. Another method of performing the addition is to construct a parallelogram. If AD

[1] Vol. I of the *Bulletin of the Bureau of Standards*, Washington, D. C.

be drawn from A equal and parallel to BC, the displacement $\overline{AD}$ is the same as the displacement $\overline{BC}$ and the sum of $\overline{AB}$ and $\overline{AD}$ is $\overline{AC}$, where AC is the diagonal of the parallelogram of which AB and AD are adjacent sides drawn away from A. This is called **the parallelogram method** of adding two displacements. When several displacements are to be added, the addition is performed by constructing a polygon as in Fig. 2.

14. Resolution and Subtraction of Displacements.—As we may replace any number of displacements by their geometrical sum or resultant, so we may replace a displacement by any number of displacements which added together give the original displacement. This is called *resolving a displacement into components.* Thus, to resolve a displacement $\overline{AC}$ (Fig. 3) into two components in given directions, we draw from A lines in the given direction and then complete the parallelogram $ABCD$ on the diagonal AC; $\overline{AB}$ and $\overline{AD}$ are the components desired, since their sum is $\overline{AC}$.

Subtraction is the opposite of addition. To subtract 4 from 10 we must find the number, 6, which added to 4 will give 10. Similarly, to subtract a displacement, $\overline{PQ}$, from another, $\overline{PR}$, we must find the displacement which added to $\overline{PQ}$ will give $\overline{PR}$. From the triangle method of addition this is evidently $\overline{QR}$, or, if we complete a parallelogram $PQRS$, it is $\overline{PS}$ which is equal to $\overline{QR}$. Denoting subtraction by the minus sign $\overline{PR} - \overline{PQ} = \overline{QR} = \overline{PS}$.

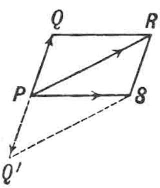

FIG. 4.—Subtraction of a displacement.

Subtraction may also be performed in a slightly different way. From the triangle method it is evident that $\overline{QP}$ added to $\overline{PR}$ will give $\overline{QR}$. Hence to subtract a displacement we may *reverse its direction and add.* This addition may also be performed by a parallelogram $PQ'SR$ where $\overline{PQ'} = \overline{QP}$. Since subtracting $\overline{PQ}$ is the same thing as adding $\overline{QP}$, $-\overline{PQ} = + \overline{QP}$ or the *minus sign before a displacement reverses its direction.*

15. Vector Quantities and Vector Diagrams.—Displacements belong to the class of quantities called **vector quantities,** that is, quantities which have *magnitude* and *direction.* Other vector quantities are velocities, forces, etc. The figures in the preceding sections are diagrams of displacements, that is, they are made up of lines representing the actual displacements in magnitude and direction. Thus the diagram might be regarded as a reduced or enlarged picture of the actual displacements. Other vector quantities, *e.g.*, a number of forces, may be similarly represented by a vector diagram by drawing lines each of which stands in magnitude and direction for one of the forces. The lines in such a diagram are called **vectors.** The lengths of any two vectors in such a diagram are to one another as the magnitudes of the forces represented, and the angle between the two vectors is the angle between these two forces. After we have defined the meaning of the resultant of a number of forces, it will be seen that it is represented as to magnitude and direction by the vector which is the sum of the vectors that represent the separate forces. Similar remarks apply to diagrams of velocities, accelerations, etc.

Quantities which imply no reference to direction are called **scalar** quantities. Such are mass, volume, etc. Each such quantity is assigned by a number without any idea of direction associated with it, and the addition or subtraction of such quantities is performed in the ordinary arithmetic or algebraic manner.

Velocity

16. Velocity is rate of change of position or *rate of displacement.* Since a displacement has a definite direction as well as a definite magnitude, a velocity also has a definite direction and a definite magnitude, or *velocities are vector quantities.* Thus "twenty miles an hour" is not a complete statement of a velocity since it gives only the magnitude of the velocity and does not specify its direction; but "twenty miles an hour eastward" is a complete statement of a velocity. For clearness such a phrase as "twenty miles an hour" may be called the statement of a *speed,* which means the mere magnitude of a velocity or a rate of change of position without reference to the direction of the change. When the motions considered are all in the same straight line, we do not need to distinguish speed and velocity.

17. Constant Velocity.—The velocity of a point is described as *constant* or *uniform* when the displacements of the point in all equal intervals of time are equal. By equal displacements must be understood displacements equal *in both magnitude and direc-*