PRINCIPLES OF PHYSICS SERIES

MECHANICS, HEAT, AND SOUND

by

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PREFACE

This book is the first volume of a series of texts written for a two-year course in general physics. It is assumed that students using the book have completed a course in calculus or that they are studying calculus concurrently.

The title of the series, Principles of Physics, has been chosen deliberately to indicate that its emphasis is on physical principles. Historical background and practical applications have been given a place of secondary importance.

This volume opens with several chapters on statics in order that kinematics may be postponed until the student has acquired some familiarity with the concepts and notation of calculus. Beginning with Chapter 4, simple differentiation and integration are introduced to supplement and extend the algebraic development of the equations of linear motion with constant acceleration. From that point on, the calculus is used freely wherever its inclusion is warranted.

Three systems of units are used: the English gravitational because it is the one used in engineering work throughout this country, the cgs system because some familiarity with it is essential for any intelligent reading of the literature of physics, and the mks system because of its increasing use in electricity and magnetism as well as because it seems destined eventually to supplant the cgs system.

The author is particularly indebted to Professor M. Stanley Livingston for many stimulating and informative discussions and for his encouragement in the task of developing a set of lecture notes into this book.

The multiflash photographs were taken with the advice and assistance of Professor Harold E. Edgerton, to whom the author is duly grateful. Collective acknowledgment is made to numerous contributors to the *American Journal of Physics* (formerly the *American Physics Teacher*) since its inception.

F.W.S.

Cambridge, Mass.
March 1944.

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CHAPTER 1

COMPOSITION AND RESOLUTION OF VECTORS

1–1 Force. Mechanics is the branch of physics and engineering which deals with the interrelations of force, matter, and motion. We shall begin with a study of forces. The term force, as used in mechanics, refers to what is known in everyday language as a *push* or a *pull.* We can exert a force on a body by muscular effort; a stretched spring exerts forces on the bodies to which its ends are attached; compressed air exerts a force on the walls of its container; a locomotive exerts a force on the train which it is drawing. In all of these instances the body exerting the force is in contact with the body on which the force is exerted, and forces of this sort are known as *contact* forces. There are also forces which act through empty space without contact, and are called *action-at-a-distance* forces. The force of gravitational attraction exerted on a body by the earth, and known as the *weight* of the body, is the most important of these for our present study. Electrical and magnetic forces are also action-at-a-distance forces, but we shall not be concerned with them for the present.

All forces fall into one or the other of these two classes, a fact that will be found useful later when deciding just what forces are acting on a given body. It is only necessary to observe what bodies are in contact with the one under consideration. The only forces on the body are then those exerted by the bodies in contact with it, together with the gravitational force or the weight of the body.

Those forces acting on a given body which are exerted by other bodies are referred to as *external* forces. Forces exerted on one part of a body by other parts of the same body are called *internal* forces.

1–2 Units and standards. The early Greek philosophers confined their activities largely to speculations about Nature, and to attempts to reconcile the observed behavior of bodies with theological doctrines. What has been called the *scientific method* began to appear in the time of Galileo Galilei (1564–1642). Galileo's studies of the laws of freely falling bodies were made not in an attempt to explain *why* bodies fell toward the earth, but rather to determine *how far* they fell in a given time, and *how fast* they moved. Physics as it exists today has been called the science of measurement, and the importance of quantitative knowledge and reasoning has been expressed by Lord Kelvin (1824–1907) as follows: "I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of *Science*, whatever the matter may be."

The first step in the measurement of a physical quantity consists in choosing a *unit* of that quantity. As the result of international collaboration over a long period, practically all of the units used in physics are now the same throughout the world. The second step is an experiment that determines the ratio of the magnitude of the quantity to the magnitude of the unit. Thus, when we say that the length of a rod is 10 centimeters, we state that its length is ten times as great as the unit of length, the centimeter.

It is possible to simplify many of the equations of physics by the proper choice of units of physical quantities. Any set of units which is chosen so that these simplified equations can be used is called a *system* of units. We shall use three such systems in this book. They are, first, the *English gravitational* system; second, the meter-kilogram-second or *mks* system; and third, the centimeter-gram-second or *cgs* system. The units of these systems will be defined as the need for them arises.

Most of the fundamental units of physics are embodied in a physical object called a *standard*. One of the functions of the National Bureau of Standards in Washington, D. C. is to maintain in its vaults standards of various quantities with which commercial and technical measuring instruments can be compared for accuracy.

1–3 The pound. The unit of force which we shall use for the present is the English gravitational unit, the *pound*. Other units will be discussed in Chapter 5. This unit is embodied in a cylinder of platinum-iridium called the *standard pound*. The unit of force is defined as the weight of the standard pound. That is, it is a force equal to the force of gravitational attraction which the earth exerts on the standard pound. Since the earth's gravitational attraction for a given body varies slightly from one point to another on the earth's surface it is further stipulated that the unit force shall equal the weight of the standard pound *at sea level and 45° latitude.**

In order that an unknown force can be compared with the force unit (and thereby measured) some measurable effect produced by a force must be used. One common effect of a force is to alter the dimensions or shape of a body on which the force is exerted; another is to alter the state of motion of the body. Both of these effects are used in the measurement of

*See Section 15–3 for a more precise definition.

forces. In this chapter we shall consider only the former; the latter will be discussed in Chapter 5.

The instrument used to measure forces is the spring balance, which consists of a coil spring enclosed in a case for protection and carrying at one end a pointer that moves over a scale. A force exerted on the balance increases the length of the spring. The balance can be calibrated as follows. The standard pound is first suspended from the balance and the position of the pointer marked 1 lb. Any number of duplicates of the standard can then be prepared by suspending each of them in turn from the balance and removing or adding material until the index stands at 1 lb. Then, when two, three, or more of these are suspended simultaneously from the balance, the force stretching it is 2 lb, 3 lb, etc., and the corresponding positions of the pointer can be labeled 2 lb, 3 lb, etc. This procedure makes no assumptions about the elastic properties of the spring, except that the force exerted on it is always the same when its index stands at the same point. The calibrated balance can then be used to measure any unknown force.

1-4 Graphical representation of forces. Vectors. Suppose we are to slide a box along the floor by pulling it with a string or pushing it with a stick, as in Fig. 1-1. That is, we are to slide it by exerting a force on it. The point of view which we now adopt is that the motion of the box is caused not by the *objects* which push or pull on it, but by the *forces* which these exert. For concreteness assume the magnitude of the push or pull to be 10 lb. It is clear that simply to write "10 lb" on the diagram would not completely describe the force, since it would not indicate the direction in which the force was acting. One might write "10 lb, 30° above horizontal to the right," or "10 lb, 45° below horizontal to the right," but all of the above information may be conveyed more briefly if we adopt the convention of representing a force by an arrow. The length of the arrow, to some chosen scale, indicates the size or magnitude of the force, and the direction in which the arrow points indicates the direction of the force. Thus Fig. 1-2 (in which a scale of $\frac{1}{8}$ in = 1 lb has been chosen) is the force diagram corresponding to Fig. 1-1. (There are other forces acting on the box, but these are not shown in the figure.)

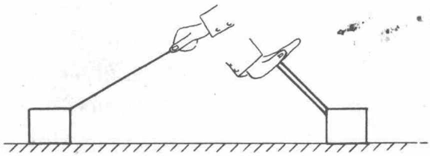

FIG. 1-1. The box is pulled by the string or pushed by the stick.

Force is not the only physical quantity which requires the specification of direction as well as magnitude. For example, the velocity of a plane is not completely specified by stating that it is 300 miles per hour; we need

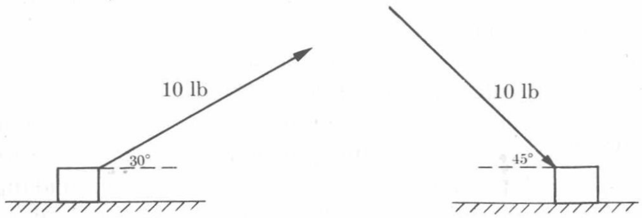

FIG. 1–2. The force diagram corresponding to Fig. 1–1.

to know the direction also. The concept of density, on the other hand, has no direction associated with it.

Quantities like force and velocity, which involve both magnitude and direction, are called *vector* quantities. Those like density, which involve magnitude only, are called *scalars*. Any vector quantity can be represented by an arrow, and this arrow is called a vector (or if a more specific statement is needed, a force vector or a velocity vector). We shall first consider force vectors only, but the ideas developed in dealing with them can be applied to any other vector quantity.

1–5 Components of a vector. When a box is pulled or pushed along the floor by an inclined force as in Fig. 1–1, it is clear that the effectiveness of the force in moving the box along the floor depends upon the direction in which the force acts. Everyone knows by experience that a given force is more effective for moving the box the more nearly the direction of the force approaches the horizontal. It is also clear that if the force is applied at an angle, as in Fig. 1–1, it is producing another effect in addition to moving the box ahead. That is, the pull of the string is in part tending to lift the box off the floor, and the push of the stick is in part forcing the box down against the floor. We are thus led to the idea of the *components* of a force, that is, the effective values of a force in directions other than that of the force itself.

The component of a force in any direction can be found by a simple graphical method. Suppose we wish to know how much force is available for sliding the box in Fig. 1–1 if the applied force is a pull of 10 lb directed 30° above the horizontal. Let the given force be represented by the vector OA in Fig. 1–3, in the proper direction and to some convenient scale. Line OX is the direction of the desired component. From point A drop a perpendicular to OX, intersecting it at B. The vector OB, to the same scale as that used for the given vector, represents the component of OA in the direction OX. Measurements of the diagram show that if OA represents a force of 10 lb, then OB is about 8.7 lb. That is, the 10-lb force at an angle of 30° above the horizontal has an effective value of only about 8.7 lb in producing forward motion.

The component OB may also be computed as follows. Since OAB is a right triangle, it follows that

$$\cos 30° = \frac{OB}{OA},$$

$$OB = OA \cos 30°.$$

The lengths OB and OA, however, are proportional to the magnitudes of the forces they represent. Therefore the desired component OB, in pounds, equals the given force OA, in pounds, multiplied by the cosine of the angle between OA and OB. The magnitude of OB is therefore

$$\begin{aligned} OB \text{ (lb)} &= OA \text{ (lb)} \times \cos 30° \\ &= 10 \text{ lb} \quad \times 0.866 \\ &= 8.66 \text{ lb}. \end{aligned}$$

This result agrees as well as could be expected with that obtained from measurements of the diagram. The superiority of the trigonometric method is evident, however, since it does not depend for accuracy on the careful construction and measurement of a scale diagram.

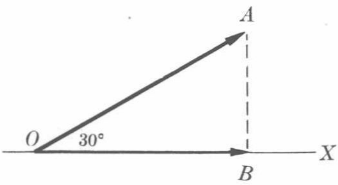

FIG. 1–3. Vector OB is the component of vector OA in the direction OX.

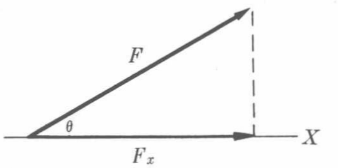

FIG. 1–4. $F_x = F \cos \theta$ is the X-component of F.

The line OX in Fig. 1–3 is called the X-axis, and the foregoing analysis may be generalized as follows. If a force F makes an angle θ with the X-axis (Fig. 1–4), its component F_x along the X-axis is

$$F_x = F \cos \theta. \tag{1–1}$$

It should be obvious that if the force F is at right angles to the X-axis, its component along that axis is zero (since $\cos 90° = 0$), and if the force lies along the axis, its component is equal to the force itself (since $\cos 0° = 1$).