sears
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university physics

fourth edition

complete

UNIVERSITY PHYSICS

Fourth Edition

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Preface

University Physics is available in one complete volume or as two separate parts: Part I covers the subjects of mechanics, heat, and sound; Part II includes electricity and magnetism, light, and atomic physics. The total number of topics is small enough so that the complete text may be taught in two semesters.

The text is intended for students of science and engineering who are taking a course in calculus concurrently and to whom calculus is still a new tool. The emphasis is on physical principles; historical background and practical applications have been given a place of secondary importance.

Three systems of units are used: the British gravitational system because it is the one used in engineering work throughout the 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 to eventually supplant the cgs system. The symbols and terminology, with few exceptions, are those recommended by the Committee on Letter Symbols and Abbreviations of the American Association of Physics Teachers as listed in the American Standard, ASA-Z10, published in 1947.

In this fourth edition, many of the features of the third edition are retained. Numerous illustrative problems are worked out in the body of the text; in each of them, all physical quantities are expressed by numerics along with the appropriate units. The problems at the end of each chapter deal with physical topics in the same order as in the body of the text; they are graded in difficulty and are designed to provide opportunities for routine drill as well as for independent thinking.

The level of mathematical and physical sophistication has been slightly reduced. The concept of the vector product has been removed from the treatment of elementary statics and postponed until the subject of angular momentum is encountered in Chapter 9. The relativistic treatment of relative velocity and the detailed diagrammatic analysis of length contraction and time dilation have been removed from elementary kinematics. Only the variation of mass with velocity has been retained in order to illuminate the Einstein relation between mass and energy. The concept of a magnetic field is introduced in the same manner as that of the second edition, without using relativistic principles.

Some of the more advanced topics that the students will meet in their later intermediate courses have been removed. Chief among these are the concept of circulation in a velocity field, details concerned with radiative heat transfer, and treatments of Maxwellian velocity distribution, mean free path, and viscosity, in the kinetic theory of gases. The mathematical treatment of the propagation of electromagnetic waves has been simplified and shortened.

In the early 1960's the level of difficulty of first-year physics for colleges and universities underwent a notable rise. Sparked by activities of the Commission on College Physics, by increased use of the materials prepared by the Physical Science Study Committee, and by wishful thinking, new courses were developed which went beyond the mathematical and physical limits imposed by the previous preparation of the average entering freshman. Unfortunately this preparation on the part of many students has not increased to the level demanded by the more difficult texts. As a result, some readjustment is necessary, and this fourth edition of *University Physics* may be regarded as a slight move in an attempt to reach the most realistic level.

It is with a feeling of sincere gratitude that we acknowledge the help we have received from the following teachers of physics: J. G. Anderson, J. D. Barnett, H. H. Barschall, A. C. Braden, P. Catranides, D. S. Duncan, D. Frantszog, J. L. Glathart, R. A. Kromhout, Robert J. Lee, Gerald P. Leitz, James A. Richards, Jr., T. L. Rokoske, M. Russel Wehr, L. W. Seagondollar, Lester V. Whitney, Jack Willis, and R. E. Worley.

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1

Composition and Resolution of Vectors

分解

矢量 向量

动力

力学

1-1 THE FUNDAMENTAL INDEFINABLES OF MECHANICS

Physics has been called the science of measurement. To quote from Lord Kelvin (1824–1907), "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."

A definition of a quantity in physics must provide a set of rules for calculating it in terms of other quantities that can be measured. Thus, when momentum is defined as the product of "mass" and "velocity," the rule for calculating momentum is contained within the definition, and all that is necessary is to know how to measure mass and velocity. The definition of velocity is given in terms of length and time, but there are no simpler or more fundamental quantities in terms of which length and time may be expressed. *Length and time are two of the indefinables of mechanics.* It has been found possible to express all the quantities of mechanics in terms of only three indefinables. The third may be taken to be "mass" or "force" with equal justification. *We shall choose mass as the third indefinable of mechanics.*

In geometry, the fundamental indefinable is the "point." The geometer asks his disciple to build any picture of a point in his mind, provided the picture is consistent with what the geometer *says* about the point. In physics, the situation is not so subtle. Physicists from all over the world have international committees at whose meetings the rules of measurement of the indefinables are adopted. The rule for measuring an indefinable takes the place of a definition.

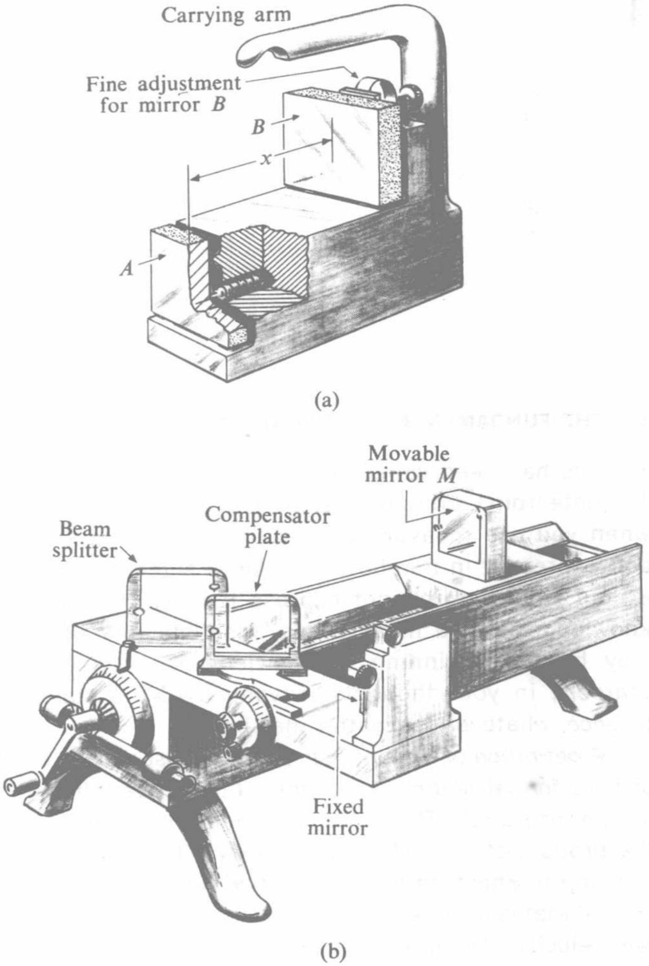
1-2 STANDARDS AND UNITS

The set of rules for measuring the indefinables of mechanics is determined by an international committee called the *General Conference on Weights and Measures*, to which all the major countries send delegates. One of the chief functions of the Conference is to decide on a standard for each indefinable. A standard may be an actual object, in which case its main characteristic must be *durability*. Thus in 1889 when the meter bar of platinum-iridium alloy was chosen as the standard of length, it was felt that this alloy was particularly stable in its chemical structure. If, instead of platinum-iridium, a glass bar had been chosen, its length would have changed throughout the years because of the unavoidable crystallization that glass undergoes as it ages. Although platinum-iridium is an unusually stable alloy, the preservation of a bar of this material as a world standard entails a number of cumbersome provisions, such as making a large number of replicas for all the major countries and comparing these replicas with the world standard at periodic intervals. On October 14, 1960, the General Conference changed the standard of length to an *atomic constant*, namely, the *wavelength of the orange-red light emitted by the individual atoms of krypton-86* in a tube filled with krypton gas in which an electrical discharge is maintained.

The standard of mass is the mass of a *cylinder of platinum-iridium*, designated as *one kilogram*, and kept

TABLE 1-1 STANDARDS AND UNITS AS OF 1969

	Standard	Measuring device	Unit
Length	Wavelength of orange-red light from krypton-86	Optical interferometer	1 meter = 1,650,763.73 wavelengths
Mass	Platinum-iridium cylinder, 1 kilogram	Equal-arm balance	1 kilogram
Time	Periodic time associated with a transition between two energy levels of cesium-133 atom	Atomic clock	1 second = 9,192,631,770 cesium periods



1-1 (a) Etalon and (b) Michelson interferometer for use in measuring the distance x in terms of the wavelength of light.

at the International Bureau of Weights and Measures at Sèvres, near Paris.

Before 1960, the standard of time was the interval of time between successive appearances of the sun overhead, averaged over a year, and called the *mean solar day*. Between ~~1960 and 1967~~ it was changed to the *tropical year 1900*, that is, the time it took the sun to move from a certain point in the heavens, known as the *vernal equinox*, back to the same point in 1900. In October 1967, the standard was changed again to the *periodic time of the radiation corresponding to the transition between the two hyperfine levels of the fundamental state of the atom of cesium-133*.

The three standards are listed in Table 1-1.

After the choice of a standard, the next step is to decide upon an instrument and a technique for comparing the standard with an unknown. Consider, for example, the distance x between two mirrors, A and B, of the device called an *etalon*, shown in Fig. 1-1(a). To find the number of wavelengths of orange-red light of krypton-86 in the distance x requires the use of an *optical interferometer*, one type of which, due to Michelson, is shown in Fig. 1-1(b). A movable mirror M on the Michelson interferometer is first made to coincide in position with A on the etalon. Then the mirror is moved slowly to coincide with B, during which time gradations of orange and black, known as *interference fringes*, move past the cross hair in the field of view of a telescope and are counted. The motion of one complete fringe corresponds to a motion of mirror M of exactly one-half a wavelength. A length known as *one meter* is defined in this way as

1 meter = 1,650,763.73 wavelengths of orange-red light of krypton-86.

Other units of length frequently used in pure science are:

1 angstrom unit = 1 Å = 10^{-10} m (used by spectroscopists),
1 nanometer = 1 nm = 10^{-9} m (used by optical designers),

TABLE 1-2 PREFIXES FOR POWERS OF TEN

Power of ten	10^{-12}	10^{-9}	10^{-6}	10^{-3}	10^{-2}	10^{3}	10^{6}	10^{9}	10^{12}
Prefix	pico-	nano-	micro-	milli-	centi-	kilo-	mega-	giga-	tera-
Abbreviation	p	n	μ	m	c	k	M	G	T

$$\begin{array}{ll} \text{1 micrometer} & = 1\ \mu\text{m} = 10^{-6}\ \text{m} \\ & \text{(used commonly in biology),} \\ \text{1 millimeter} & \left.\begin{array}{l} = 1\ \text{mm} = 10^{-3}\ \text{m} \\ = 1\ \text{cm} = 10^{-2}\ \text{m} \end{array}\right\} \text{(used most often),} \\ \text{1 centimeter} & \\ \text{1 kilometer} & = 1\ \text{km} = 10^{3}\ \text{m} \\ & \text{(a common European unit of distance).} \end{array}$$

The words "nanometer," "micrometer," and "kilometer" are all accented on the *first* syllable, *not* the second, just like the words "millimeter" and "centimeter." The prefix "nano" is pronounced "nanno." Units of length used in everyday life and in engineering in both the United States and the United Kingdom are defined as follows:

$$\text{1 inch} = \text{1 in.} = \begin{cases} \text{41,929.399 wavelengths of Kr light,} \\ \text{2.54 cm,} \end{cases}$$

1 foot = 1 ft = 12 in.,
1 yard = 1 yd = 3 ft,
1 mile = 1 mi = 5280 ft.

The device used to subdivide the standard of mass, the kilogram, into equal submasses is the *equal-arm balance*, which will be discussed in Chapter 5. Frequently used units of mass are:

$$\begin{aligned} \text{1 microgram} &= 1\ \mu\text{g} = 10^{-9}\ \text{kg}, \\ \text{1 milligram} &= 1\ \text{mg} = 10^{-6}\ \text{kg}, \\ \text{1 gram} &= 1\ \text{g} = 10^{-3}\ \text{kg}, \\ \text{1 pound mass} &= 1\ \text{lbm} = 0.45359237\ \text{kg}. \end{aligned}$$

The clock making use of the standard time interval is the *cesium clock*, a large, complex, and expensive laboratory instrument. It is extraordinarily precise and maintains its frequency constant to one part in one hundred billion (10^{11}) or better. Furthermore, it may be compared with other high-precision clocks in an hour or so as against the years required for comparison with the old astronomical standard. In the atomic clock, a beam of cesium-133 atoms passes through a long metal cylinder and interacts with microwaves brought in by a wave guide from a generator controlled by a quartz oscillator. The *unit* of time used throughout the world is called the *second* and is defined to be

$$\text{1 second} = 1\ \text{s} = 9{,}192{,}631{,}770\ \text{Cs periods.}$$

Other common units of time are:

$$\begin{aligned} \text{1 nanosecond} &= 1\ \text{ns} = 10^{-9}\ \text{s}, \\ \text{1 microsecond} &= 1\ \mu\text{s} = 10^{-6}\ \text{s}, \\ \text{1 millisecond} &= 1\ \text{ms} = 10^{-3}\ \text{s}, \\ \text{1 minute} &= 1\ \text{min} = 60\ \text{s}, \\ \text{1 hour} &= 1\ \text{hr} = 3600\ \text{s}, \\ \text{1 day} &= 1\ \text{day} = 86{,}400\ \text{s}. \end{aligned}$$

It will be found useful to memorize the prefixes and abbreviations for the various powers of ten which are collected in Table 1-2. (The prefix "giga" is pronounced "jeega.")

1-3 SYMBOLS FOR PHYSICAL QUANTITIES

We shall adopt the convention that an algebraic symbol representing a physical quantity, such as F, p, or v, stands for both a *number* and a *unit*. For example, F might represent a force of 10 lb, p a pressure of 15 lb ft^{-2}, and v a velocity of 15 ft s^{-1}.

When we write

$$x = v_0 t + \tfrac{1}{2}at^2,$$

if x is in feet, then the terms $v_0 t$ and $\frac{1}{2}at^2$ must be in feet also. Suppose t is in seconds. Then the units of v_0 must be ft s^{-1} and those of a must be ft s^{-2}. (The factor $\frac{1}{2}$ is a *pure number*, without units.) As a numerical example, let $v_0 = 10$ ft s^{-1}, $a = 4$ ft s^{-2}, $t = 10$ s. Then the preceding equation would be written

$$x = 10\ \text{ft}\ \cancel{\text{s}}^{-1} \times 10\ \cancel{\text{s}} + \tfrac{1}{2} \times 4\ \text{ft}\ \cancel{\text{s}}^{-2} \times 10\ \cancel{\text{s}}^{2}.$$

The units are treated like algebraic symbols. The s's cancel in the first term and the s^2's in the second, and

$$x = 100 \text{ ft} + 200 \text{ ft} = 300 \text{ ft}.$$

The beginning student will do well to include the units of all physical quantities, as well as their magnitudes, in all his calculations. This will be done consistently in the numerical examples throughout the book.

1-4 FORCE

Mechanics is the branch of physics which deals with the motion of material bodies and with the forces that bring about the motion. Since motion is best described by the methods of calculus and many readers of this book are just beginning their study of this subject, we shall postpone a discussion of motion until Chapter 4, and start with a study of forces.

When we push or pull on a body, we are said to exert a *force* on it. Forces can also be exerted by inanimate objects: 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 it is drawing. The force of which we are most aware in our daily lives is the force of gravitational attraction exerted on every body by the earth, and is called the *weight* of the body. Gravitational forces (and electrical and magnetic forces also) can act through empty space without contact. In this respect they differ from the forces mentioned above, where the body doing the pushing or pulling must make contact with the body being pushed or pulled.

We are not yet in a position to show how a unit of force can be defined in terms of the units of mass, length, and time. This will be done in Chapter 5. For the present, a unit of force can be defined as follows. We select as a standard body the standard pound, defined in Section 1-2 as a certain fraction (approximately 0.454) of a standard kilogram. The force with which the earth attracts this body, at some specified point on the earth's surface, is then a perfectly definite, reproducible force and is called a force of *one pound* (avoirdupois). A particular point on the earth's surface must be specified, since the attraction of the earth for a given body varies slightly from one point to another. If great precision is not required, it suffices to take any point 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 such effect 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 forces. In this chapter we shall consider only the former; the latter will be discussed in Chapter 5.

The instrument most commonly 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 changes the length of the spring. The balance can be calibrated as follows. The standard pound is first suspended from the balance at sea level and 45° latitude and the position of the pointer is marked 1 lb. Any number of duplicates of the standard can then be prepared by suspending a body from the balance and adding or removing material until the index again 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 assumption about the elastic properties of the spring except that the force exerted on it is always the same when the pointer stands at the same position. The calibrated balance can then be used to measure an unknown force.

Fig. 1-2

1-5 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. 1-2. 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 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. 1–3 is the force diagram corresponding to Fig. 1–2. (There are other forces acting on the box, but these are not shown in the figure.)

Fig. 1–3

Force is not the only physical quantity which requires the specification of a direction in space as well as a magnitude. For example, the velocity of an aircraft is not completely specified by stating that it is 300 miles per hour; we need to know the direction also. The concept of volume, on the other hand, has no direction associated with it.

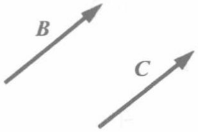
Quantities like volume, which involve a magnitude only, are called *scalars*. Those like force and velocity, which involve both a magnitude and a direction in space, are called *vector quantities*. Any vector quantity can be represented by an arrow, and this arrow is called a vector (or if a more specific statement is needed, a force vector or a velocity vector).

Some vector quantities, of which force is one, are not *completely* specified by their magnitude and direction alone. Thus the effect of a force depends also on its *line of action* and its *point of application*. (The line of action is a line of indefinite length, of which the force vector is a segment.) For example, if one is pushing horizontally against a door, the effectiveness of a force of given magnitude and direction depends on the distance of its line of action from the hinges. If a body is deformable, as all bodies are to a greater or lesser extent, the deformation depends on the point of application of the force. However, since many actual objects are deformed only very slightly by the forces acting on them, we shall assume for the present that all objects considered are perfectly rigid. The point of application of a given force acting on a rigid body may be transferred to any other point on the line of action without altering the effect of the force. Thus *a force applied to a rigid body may be regarded as acting anywhere along its line of action.*

A vector quantity is represented by a letter in boldface type. The same letter in ordinary type represents the magnitude of the quantity. Thus the magnitude of a force ***F*** is represented by *F*.

1–6 VECTOR ADDITION. RESULTANT OF A SET OF FORCES

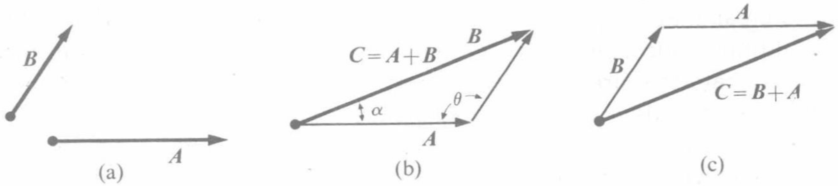
The sciences of arithmetic and algebra deal with pure numbers. Similarly, in the science of *vector analysis*, another branch of pure mathematics, a vector is considered simply as an arrow or a "directed line segment," without any physical significance. However, just as the laws of arithmetic and algebra are found to describe certain operations that can be carried out with some physical quantities, so the laws of vector algebra are found to represent some (but not all) aspects of the behavior of other physical quantities.



1–4 The vectors, ***A***, ***B***, and ***C*** are mathematically equal.

For example, two (mathematical) vectors are considered equal, by definition, if they have the same magnitude and direction. Thus in Fig. 1–4 the vectors ***A***, ***B***, and ***C*** are all equal. It follows that in mathematics a given vector may be moved around at will, provided its length and direction are not changed. However, if the vectors in Fig. 1–4 represent forces acting on a body, the forces are not physically equivalent, since they have different points of application and different lines of action.

The *vector sum* of two (mathematical) vectors is defined as follows. Let ***A*** and ***B*** in Fig. 1–5(a) be two given



1-5 Vector ***C*** is the vector sum of vectors ***A*** and ***B***. $\boldsymbol{C} = \boldsymbol{A} + \boldsymbol{B} = \boldsymbol{B} + \boldsymbol{A}$.

vectors. Draw the vectors as in (b) at any convenient point, with the initial point of ***B*** at the endpoint of ***A***. The vector sum ***C*** is then defined as the vector from the initial point of ***A*** to the endpoint of ***B***. The symbol for vector addition is the same as for algebraic addition, and we write

$$\boldsymbol{C} = \boldsymbol{A} + \boldsymbol{B}.$$

Alternatively, the given vectors can be drawn as in Fig. 1-5(c), with the initial point of ***A*** at the endpoint of ***B***. The vector ***C*** has the same magnitude and direction as in (b) and hence the two vector sums are mathematically equal. The order in which the vectors are added is therefore immaterial, and vector addition obeys the same commutative law as algebraic addition:

$$\boldsymbol{A} + \boldsymbol{B} = \boldsymbol{B} + \boldsymbol{A}.$$

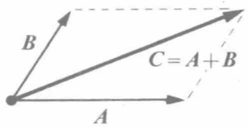
The magnitude and direction of the vector sum ***C*** can be found from measurements on a carefully drawn diagram. They can also be computed by the methods of trigonometry. Thus if θ represents the angle between vectors ***A*** and ***B***, as in Fig. 1-5(b), the magnitude of ***C*** is given by

$$C^2 = A^2 + B^2 - 2AB\cos\theta.$$

The angle α between ***C*** and ***A*** can be found from the relation

$$\frac{\sin\alpha}{B} = \frac{\sin\theta}{C}.$$

Another useful method of finding the sum of two vectors is shown in Fig. 1-6, where vectors ***A*** and ***B*** are both drawn from a common point. The vector sum ***C*** is the concurrent diagonal of a parallelogram of which the given vectors form two sides.



1-6 Parallelogram method for obtaining the vector sum of two vectors.

Figure 1-7 illustrates a special case in which two vectors are parallel, as in (a), or antiparallel, as in (b). If they are parallel, the magnitude of the vector sum ***C*** equals the sum of the magnitudes of ***A*** and ***B***. If they are antiparallel, the magnitude of the vector sum equals the difference of the magnitudes of ***A*** and ***B***. (The vectors in Fig. 1-7 have been displaced slightly sidewise from their line of action to show them more clearly. Actually, all vectors lie along the same geometrical line.)

When more than two vectors are to be added, we may first find the vector sum of any two, add this vectorially to the third, and so on. This process is illustrated in Fig. 1-8, which shows in part (a) four vectors ***A***, ***B***, ***C***, and ***D***. In Fig. 1-8(b), vectors ***A*** and ***B*** are first added by the triangle method, giving a vector sum ***E***; vectors ***E*** and ***C*** are then added by the same process to obtain the vector sum ***F***; finally, ***F*** and ***D*** are added to obtain the vector sum

$$\boldsymbol{G} = \boldsymbol{A} + \boldsymbol{B} + \boldsymbol{C} + \boldsymbol{D}.$$

Evidently the vectors ***E*** and ***F*** need not have been drawn; we need only draw the given vectors in succession, with the tail of each at the head of the one preceding it, and complete the polygon by a vector ***G*** from the tail of the first to the head of the last vector. The order in which

1-7 Vector sum of (a) two parallel vectors, (b) two antiparallel vectors.