UNIVERSITY PHYSICS

Fifth Edition

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ADDISON-WESLEY PUBLISHING COMPANY
Reading, Massachusetts • Amsterdam • London • Manila
Singapore • Sydney • Tokyo

WORLD STUDENT SERIES EDITION
FIRST PRINTING 1976

Printed in the United States of America. Published simultaneously in Canada. Library of Congress Catalog Card No. 75-20989.

Preface

University Physics is intended for students of science and engineering who are taking an introductory calculus course concurrently. The complete text may be taught in an intensive two- or three-semester course and is also adaptable to a variety of shorter courses. Primary emphasis is on physical principles and problem solving; historical background and specialized practical applications have been given a place of secondary importance. Many worked-out examples and an extensive collection of problems are included with each chapter. *University Physics* is available as a single volume or as two separate parts. Part I includes mechanics, heat, and sound, and Part II includes electricity and magnetism, optics, and atomic and nuclear physics.

In this new edition, the basic philosophy and outline and the balance between depth of treatment and breadth of subject-matter coverage are unchanged from previous editions. We have tried to preserve those features that users of previous editions have found desirable, while incorporating a number of changes that should enhance the book's usefulness. Here are the most important changes.

1. The mks system of units, with the conventions and nomenclature of the Système Internationale, has become the principal unit system in the book. In this system the joule is the fundamental unit of energy of all forms, including heat. In the first half of the book, however, some examples and problems using English units have been retained.

2. The material on atomic and nuclear physics (Chapters 44 through 46) has been completely rewritten and expanded into three chapters, now including an elementary discussion of physics of solids, high-energy physics, and elementary particles.

3. A new chapter on relativistic mechanics has been added. Positioned somewhat arbitrarily at the end of the mechanics material, this chapter can be taken up earlier or later, or may be omitted completely if desired.

4. The chapter on electromagnetic waves has been completely rewritten, to exhibit more clearly and in simpler context the relation of wave propagation to the basic principles of electromagnetism.

5. Several sections have been added to broaden subject coverage. Among these are: 16–7 Examples (of calorimetric calculations), 19–25 (practical aspects of) Energy Conversion, 23–5 Musical Intervals and Scales, 23–7 Applications of Acoustic Phenomena, 28–10 Physiological Effects of Electric Currents, 38–7 Absorption (of light), 38–8 Illumination, 41–10 Defects of Vision, 42–1 Coherent Sources (of light), 42–13 Holography, 45–7 Semiconductors, 45–8 Semiconductor Devices, and 46–11 Radiation and the Life Sciences.

6. Some material has been reorganized. The material on surface tension has been shortened and incorporated into the hydrostatics chapter; the treatment of thermoelectricity has been shortened to a single section. The chapter on electromagnetic in-

duction has been rearranged to exhibit more clearly the various applications of Faraday's law to moving conductors and to stationary conductors in varying fields. The material on inductance and associated problems has been removed from this chapter and placed in a separate chapter.

7. Many sections have been completely rewritten for improved clarity and pedagogical effectiveness. These include the beginning of Chapter 7 (Work and Energy), Chapter 8 (Impulse and Momentum), Chapter 11 (Harmonic Motion); Section 25–4 (Gauss's Law); Chapter 26 (Potential); Section 27–7 (Polarization and Electric Displacement); Section 29–7 (*R–C* Circuits); Section 32–6 (Ampère's Law); and Chapter 35 (Magnetic Properties of Matter), to cite only a few examples. In a few cases, such as the opening sections of Chapters 7 and 8, the rewriting may create the illusion of de-emphasizing the use of calculus. Not so; the treatment is just as rigorous as in previous editions, but has been rearranged to follow the pedagogical principle of moving from the simple to the complex.

8. About 300 new problems have been added, bringing the total to over 1400. The added problems provide greater variety and also broader subject coverage than in previous editions. The authors have resisted the temptation to key problems to specific sections of text. Learning to select the principles appropriate for a specific problem is, after all, part of learning to solve problems. In addition, many problems require material from more than one section.

9. In every case where material has been rewritten, sound pedagogical principles and the authors' own teaching experience have guided the revision. In some instances we have shifted from a sequence in which a principle or concept is presented initially in its full generality to one that begins with special cases and then progresses to the more general statement. We hope thus to help the student attain the same final level of sophistication as previously by climbing a less steep slope.

The text is adaptable to a wide variety of course outlines. The entire text can be used for an intensive course two or three semesters in length. For a less intensive course, many instructors will want to omit certain chapters or sections to tailor the book to their individual needs. The format of this edition facilitates this kind of flexibility. For example, any or all of the chapters on relativity, hydrostatics, hydrodynamics, acoustics, magnetic properties of matter, electromagnetic waves, optical instruments, and several others can be omitted without loss of continuity.

Conversely, however, many topics that were regarded a few years ago as of peripheral importance and were purged from introductory courses have now come to the fore again in the life sciences, earth and space sciences, and environmental problems. An instructor who wishes to stress these kinds of applications will find this text a useful source for discussion of the appropriate principles.

In any case, it should be emphasized that instructors should not feel constrained to work straight through the book from cover to cover. Many chapters are, of course, inherently sequential in nature, but within this general limitation instructors should be encouraged to select among the contents those chapters that fit their needs, omitting material that is not relevant for the objectives of a particular course.

Again, we wish to thank our many colleagues who have contributed suggestions for this new edition. In particular, Prof. Robert Folk, Prof. Shelden H. Radin, and Prof. Charles W. Smith have read the entire manuscript, and their critical and constructive comments are greatly appreciated.

Hanover, New York, F.W.S.
and Pittsburgh M.W.Z.
November 1975 H.D.Y.

During the final stages of production of this book, word was received of the sudden death of Francis Weston Sears on November 13, 1975, at the age of 77. His shining example of excellence in physics education was an inspiration to colleagues and students alike, and he will be sorely missed.

Mark W. Zemansky
Hugh D. Young

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Chapter 1

Composition and Resolution of Vectors

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 state 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, with equal justification, be taken to be "mass" or "force." *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 staff 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, and such a rule is sometimes called an *operational 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 a meter bar of platinum-iridium alloy was chosen as the *standard of length,* because this alloy is particularly stable in its chemical structure. However, 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

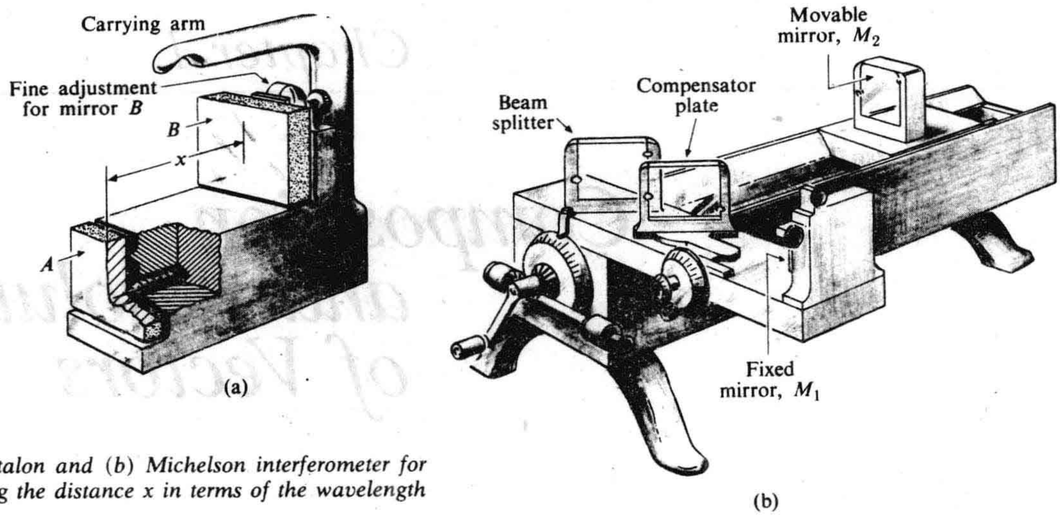

Fig. 1–1 (a) Etalon and (b) Michelson interferometer for use in measuring the distance x in terms of the wavelength of light.

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. Such a standard is much more readily reproducible than one based on a specific material object.

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

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

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

ble mirror M on the Michelson interferometer is first made to coincide in position with A on the etalon. Then the mirror is moved slowly until it coincides 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 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.

The metric system of units is used exclusively in defining the standards of mass, length, and time. Most nations other than the United States and Great Britain also use the metric system exclusively for commerce and industry as well; Britain is making long-range plans to convert to the metric system, and many well-informed people believe it would be very advantageous for the United States to convert. One advantage of the metric system is that the various units for a quantity are always related by factors of ten. Thus, some units of length in common use in science and technology are:

1 angstrom unit = 1 Å = 10^{-10}m (used by spectroscopists),

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

1 micrometer = 1 μm = 10^{-6}m (used commonly in biology),

1 millimeter = 1 mm = 10^{-3}m and

1 centimeter = 1 cm = 10^{-2}m (used most often),

1 kilometer = 1 km = 10^{3}m (a common European unit of distance).

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." A common set of prefixes is used with all units. These and their standard abbreviations are shown in Table 1–2. Thus,

1 kilometer = 1 km = 10^{3} meter = 10^{3}m,

1 kilogram = 1 kg = 10^{3} grams = 10^{3}g,

1 kilowatt = 1 kW = 10^{3} watts = 10^{3}W.

It is convenient to memorize Table 1–2, to have the information available when needed.

Units of length used in everyday life and in engineering in both the United States and the United Kingdom are defined as follows:

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

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:

1 microgram = 1 μg = 10^{-9}kg,

1 milligram = 1 mg = 10^{-6}kg,

1 gram = 1 g = 10^{-3}kg,

1 pound mass = 1 lbm = 0.45359237 kg.

The clock used to define 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, instead of 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

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

Other common units of time are:

1 nanosecond = 1 ns = 10^{-9} s,
1 microsecond = 1 μs = 10^{-6} s,
1 millisecond = 1 ms = 10^{-3} s,
1 minute = 1 min = 60 s,
1 hour = 1 hr = 3600 s,
1 day = 1 day = 86,400 s.

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 N (where N stands for newton), p a pressure of 15 N m^{-2}, and v a velocity of 15 m s^{-1}.

When we write

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

if x is in meters, then the terms $v_0 t$ and $\frac{1}{2}at^2$ must be in meters also. Suppose t is in seconds. Then the units of v_0 must be m s^{-1} and those of a must be m s^{-2}. (The factor $\frac{1}{2}$ is a *pure number*, without units.) The units of v_0 could be written as m/s rather than m s^{-1}, but the negative-exponent form is usually more convenient and will be used in all such expressions in this book.

As a numerical example, let $v_0 = 10$ m s^{-1}, $a = 4$ m s^{-2}, $t = 10$ s. Then the preceding equation would be written

$$x = (10 \text{ m } \cancel{\text{s}}^{-1}) \cdot (10 \ \cancel{\text{s}}) + \tfrac{1}{2} \cdot (4 \text{ m } \cancel{\text{s}}^{-2}) \cdot (10 \ \cancel{\text{s}})^2.$$

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

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

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 this 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. 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 pulling or pushing. The force of which we are most aware in our daily lives is the force of gravitational attraction exerted on every physical body by the earth, called the *weight* of the body. Gravitational forces (and electrical and magnetic forces also) can act through empty space without contact. A force on an object resulting from direct contact with another object is called a *contact force*; viewed on an atomic scale, contact forces arise chiefly from electrical attraction and repulsion of the electrons and nuclei making up the atoms of material.

To describe a force, we need to describe the *direction* in which it acts, as well as its *magnitude*, which is a quantitative description of "how much" or "how hard" the force pushes or pulls, in terms of a standard unit of force. In Chapter 5 we shall see how a unit of force can be defined in terms of the units of mass, length, and time. In the meter-kilogram-second (mks) system, this unit is the *newton*, abbreviated N. A more familiar unit is the *pound*, which can be defined as the force with which the earth attracts a standard body (i.e., its weight) with a mass of 1 pound-mass as defined in Section 1–2. A particular location on the earth's surface must be specified, since the attraction of the earth for a given body varies by as much as 0.5% 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 for an unknown force to be compared with the force unit and thereby *measured*, some observable 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 can be used in the measurement of forces. In this chapter we shall consider only the former; the latter will be discussed in Chapter 5.

An instrument 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, and the change can be read on the scale. 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 the magnitude of an unknown force. An analogous procedure can be used to calibrate a spring balance in newtons

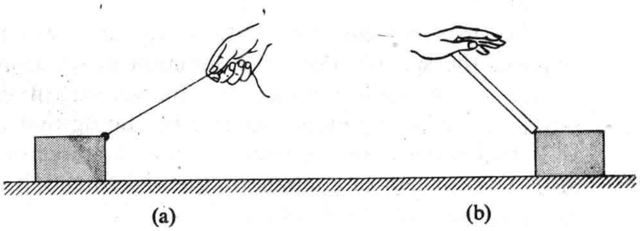

Fig. 1–2

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 N. To write "10 N" on the diagram would not completely describe the force, since it would not indicate the *direction* in which the force acts. One might write "10 N, 30° above horizontal to the right," or "10 N, 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 such as volume, which involve a magnitude only, are called *scalar quantities.* Those such as 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 perpendicular distance of its line of action from the hinges. If a body is deformable, as all are to some extent, the deformation depends upon 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 $\boldsymbol{F}$ is represented by F.

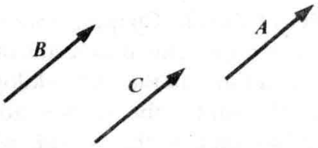

Fig. 1-4 *The vectors* **A, B,** *and* **C** *are mathematically equal.*

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

Two vector quantities are said to be equal if they have the same magnitude and direction. In Fig. 1–4 the vectors **A, B,** and **C,** which may represent physical quantities, are all equal, and we may write symbolically

$$\mathbf{A} = \mathbf{B} = \mathbf{C}.$$

Two vector quantities which are equal need not have the same physical effect. For example, as already pointed out, two forces with the same magnitude and direction may have different points of application, and a complete description must include the point of application in addition to the magnitude and direction. Thus vector equality has a rather specialized meaning, and in this text boldface "equals" signs will be used as a reminder of this meaning.

The *vector sum* of two vector quantities is defined as follows. Let **A** and **B** in Fig. 1–5(a) be two given 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.** This relationship may be expressed symbolically as:

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

Clearly, vector addition is not the same operation as addition of ordinary numbers; in this book a

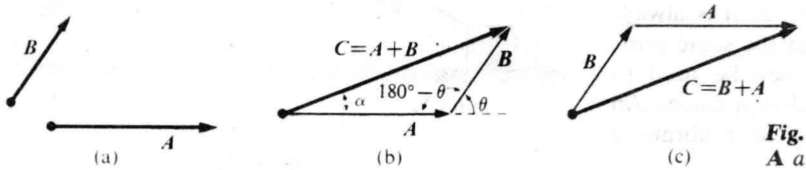

Fig. 1–5 *Vector* **C** *is the vector sum of vectors* **A** *and* **B.** $\mathbf{C} = \mathbf{A} + \mathbf{B} = \mathbf{B} + \mathbf{A}$.