As publishers of the books by Ferd Beer and Russ Johnston we are often asked how they happened to write their books together with one of them at Lehigh and the other at the University of Connecticut.

The answer to this question is simple. Russ Johnston’s first teaching appointment was in the Department of Civil Engineering and Mechanics at Lehigh University. There he met Ferd Beer, who had joined that department two years earlier and was in charge of the courses in mechanics.

Ferd was delighted to discover that the young man who had been hired chiefly to teach graduate structural engineering courses was not only willing but eager to help him reorganize the mechanics courses. Both believed that these courses should be taught from a few basic principles and that the various concepts involved would be best understood and remembered by the students if they were presented to them in a graphic way. Together they wrote lecture notes in statics and dynamics, to which they later added problems they felt would appeal to future engineers, and soon they produced the manuscript of the first edition of *Mechanics for Engineers* that was published in June 1956.

The second edition of *Mechanics for Engineers* and the first edition of *Vector Mechanics for Engineers* found Russ Johnston at Worcester Polytechnic Institute and the next editions at the University of Connecticut. In the meantime, both Ferd and Russ assumed administrative responsibilities in their departments, and both were involved in research, consulting, and supervising graduate students—Ferd in the area of stochastic processes and random vibrations and Russ in the area of elastic stability and structural analysis and design. However, their interest in improving the teaching of the basic mechanics courses had not subsided, and they both taught sections of these courses as they kept revising their texts and began writing the manuscript of the first edition of their *Mechanics of Materials* text.

Their collaboration spanned more than half a century and many successful revisions of all of their textbooks, and Ferd’s and Russ’s contributions to engineering education have earned them a number of honors and awards. They were presented with the Western Electric Fund Award for excellence in the instruction of engineering students by their respective regional sections of the American Society for Engineering Education, and they both received the Distinguished Educator Award from the Mechanics Division of the same society. Starting in 2001, the New Mechanics Educator Award of the Mechanics Division has been named in honor of the Beer and Johnston author team.

**Ferdinand P. Beer.** Born in France and educated in France and Switzerland, Ferd received an M.S. degree from the Sorbonne and an Sc.D. degree in theoretical mechanics from the University of Geneva. He came to the United States after serving in the French army during
the early part of World War II and taught for four years at Williams College in the Williams-MIT joint arts and engineering program. Following his service at Williams College, Ferd joined the faculty of Lehigh University where he taught for thirty-seven years. He held several positions, including University Distinguished Professor and chairman of the Department of Mechanical Engineering and Mechanics, and in 1995 Ferd was awarded an honorary Doctor of Engineering degree by Lehigh University.

**E. Russell Johnston, Jr.** Born in Philadelphia, Russ holds a B.S. degree in civil engineering from the University of Delaware and an Sc. D. degree in the field of structural engineering from the Massachusetts Institute of Technology. He taught at Lehigh University and Worcester Polytechnic Institute before joining the faculty of the University of Connecticut where he held the position of Chairman of the Civil Engineering Department and taught for twenty-six years. In 1991 Russ received the Outstanding Civil Engineer Award from the Connecticut Section of the American Society of Civil Engineers.

**David F. Mazurek.** David holds a B.S. degree in ocean engineering and an M.S. degree in civil engineering from the Florida Institute of Technology and a Ph.D. degree in civil engineering from the University of Connecticut. He was employed by the Electric Boat Division of General Dynamics Corporation and taught at Lafayette College prior to joining the U.S. Coast Guard Academy, where he has been since 1990. He has served on the American Railway Engineering and Maintenance of Way Association's Committee 15—Steel Structures for the past eighteen years. His professional interests include bridge engineering, tall towers, structural forensics, and blast-resistant design.

**Phillip J. Cornwell.** Phil holds a B.S. degree in mechanical engineering from Texas Tech University and M.A. and Ph.D. degrees in mechanical and aerospace engineering from Princeton University. He is currently a professor of mechanical engineering at Rose-Hulman Institute of Technology where he has taught since 1989. His present interests include structural dynamics, structural health monitoring, and undergraduate engineering education. Since 1995, Phil has spent his summers working at Los Alamos National Laboratory where he is a mentor in the Los Alamos Dynamics Summer School and does research in the area of structural health monitoring. Phil received an SAE Ralph R. Teetor Educational Award in 1992, the Dean’s Outstanding Scholar Award at Rose-Hulman in 2000, and the Board of Trustees Outstanding Scholar Award at Rose-Hulman in 2001.

**Elliot R. Eisenberg.** Elliot holds a B.S. degree in engineering and an M.E. degree, both from Cornell University. He has focused his scholarly activities on professional service and teaching, and he was recognized for this work in 1992 when the American Society of Mechanical Engineers awarded him the Ben C. Sparks Medal for his contributions to mechanical engineering and mechanical engineering technology education and for service to the American Society for Engineering Education. Elliot taught for thirty-two years, including twenty-nine years at Penn State where he was recognized with awards for both teaching and advising.
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OBJECTIVES

The main objective of a first course in mechanics should be to develop in the engineering student the ability to analyze any problem in a simple and logical manner and to apply to its solution a few, well-understood, basic principles. This text is designed for the first courses in statics and dynamics offered in the sophomore or junior year, and it is hoped that it will help the instructor achieve this goal.†

GENERAL APPROACH

Vector analysis is introduced early in the text and is used throughout the presentation of statics and dynamics. This approach leads to more concise derivations of the fundamental principles of mechanics. It also results in simpler solutions of three-dimensional problems in statics and makes it possible to analyze many advanced problems in kinematics and kinetics, which could not be solved by scalar methods. The emphasis in this text, however, remains on the correct understanding of the principles of mechanics and on their application to the solution of engineering problems, and vector analysis is presented chiefly as a convenient tool.‡

Practical Applications Are Introduced Early. One of the characteristics of the approach used in this book is that mechanics of particles is clearly separated from the mechanics of rigid bodies. This approach makes it possible to consider simple practical applications at an early stage and to postpone the introduction of the more difficult concepts. For example:

- In Statics, the statics of particles is treated first (Chap. 2); after the rules of addition and subtraction of vectors are introduced, the principle of equilibrium of a particle is immediately applied to practical situations involving only concurrent forces. The statics of rigid bodies is considered in Chaps. 3 and 4. In Chap. 3, the vector and scalar products of two vectors are introduced and used to define the moment of a force about a point and about an axis. The presentation of these new concepts is followed by a thorough and rigorous discussion of equivalent systems of forces leading, in Chap. 4, to many practical applications involving the equilibrium of rigid bodies under general force systems.

†This text is available in separate volumes, Vector Mechanics for Engineers: Statics, ninth edition, and Vector Mechanics for Engineers: Dynamics, ninth edition.

‡In a parallel text, Mechanics for Engineers: fifth edition, the use of vector algebra is limited to the addition and subtraction of vectors, and vector differentiation is omitted.
In *Dynamics*, the same division is observed. The basic concepts of force, mass, and acceleration, of work and energy, and of impulse and momentum are introduced and first applied to problems involving only particles. Thus, students can familiarize themselves with the three basic methods used in dynamics and learn their respective advantages before facing the difficulties associated with the motion of rigid bodies.

**New Concepts Are Introduced in Simple Terms.** Since this text is designed for the first course in statics and dynamics, new concepts are presented in simple terms and every step is explained in detail. On the other hand, by discussing the broader aspects of the problems considered, and by stressing methods of general applicability, a definite maturity of approach is achieved. For example:

- In *Statics*, the concepts of partial constraints and statical indeterminacy are introduced early and are used throughout statics.
- In *Dynamics*, the concept of potential energy is discussed in the general case of a conservative force. Also, the study of the plane motion of rigid bodies is designed to lead naturally to the study of their general motion in space. This is true in kinematics as well as in kinetics, where the principle of equivalence of external and effective forces is applied directly to the analysis of plane motion, thus facilitating the transition to the study of three-dimensional motion.

**Fundamental Principles Are Placed in the Context of Simple Applications.** The fact that mechanics is essentially a *deductive* science based on a few fundamental principles is stressed. Derivations have been presented in their logical sequence and with all the rigor warranted at this level. However, the learning process being largely *inductive*, simple applications are considered first. For example:

- The statics of particles precedes the statics of rigid bodies, and problems involving internal forces are postponed until Chap. 6.
- In Chap. 4, equilibrium problems involving only coplanar forces are considered first and solved by ordinary algebra, while problems involving three-dimensional forces and requiring the full use of vector algebra are discussed in the second part of the chapter.
- The kinematics of particles (Chap. 11) precedes the kinematics of rigid bodies (Chap. 15).
- The fundamental principles of the kinetics rigid bodies are first applied to the solution of two-dimensional problems (Chaps. 16 and 17), which can be more easily visualized by the student, while three-dimensional problems are postponed until Chap. 18.

**The Presentation of the Principles of Kinetics Is Unified.** The ninth edition of *Vector Mechanics for Engineers* retains the unified presentation of the principles of kinetics which characterized the previous eight editions. The concepts of linear and angular momentum are introduced in Chap. 12, so that Newton’s second law of motion can be presented not only in its conventional form \( \mathbf{F} = m \mathbf{a} \), but also as a law relating, respectively, the sum of the forces acting on a particle and the
sum of their moments to the rates of change of the linear and angular momentum of the particle. This makes possible an earlier introduction of the principle of conservation of angular momentum and a more meaningful discussion of the motion of a particle under a central force (Sec. 12.9). More importantly, this approach can be readily extended to the study of the motion of a system of particles (Chap. 14) and leads to a more concise and unified treatment of the kinetics of rigid bodies in two and three dimensions (Chaps. 16 through 18).

**Free-Body Diagrams Are Used Both to Solve Equilibrium Problems and to Express the Equivalence of Force Systems.** Free-body diagrams are introduced early, and their importance is emphasized throughout the text. They are used not only to solve equilibrium problems but also to express the equivalence of two systems of forces or, more generally, of two systems of vectors. The advantage of this approach becomes apparent in the study of the dynamics of rigid bodies, where it is used to solve three-dimensional as well as two-dimensional problems. By placing the emphasis on “free-body-diagram equations” rather than on the standard algebraic equations of motion, a more intuitive and more complete understanding of the fundamental principles of dynamics can be achieved. This approach, which was first introduced in 1962 in the first edition of *Vector Mechanics for Engineers*, has now gained wide acceptance among mechanics teachers in this country. It is, therefore, used in preference to the method of dynamic equilibrium and to the equations of motion in the solution of all sample problems in this book.

**A Four-Color Presentation Uses Color to Distinguish Vectors.** Color has been used, not only to enhance the quality of the illustrations, but also to help students distinguish among the various types of vectors they will encounter. While there is no intention to “color code” this text, the same color is used in any given chapter to represent vectors of the same type. Throughout *Statics*, for example, red is used exclusively to represent forces and couples, while position vectors are shown in blue and dimensions in black. This makes it easier for the students to identify the forces acting on a given particle or rigid body and to follow the discussion of sample problems and other examples given in the text. In *Dynamics*, for the chapters on kinetics, red is used again for forces and couples, as well as for effective forces. Red is also used to represent impulses and momenta in free-body-diagram equations, while green is used for velocities, and blue for accelerations. In the two chapters on kinematics, which do not involve any forces, blue, green, and red are used, respectively, for displacements, velocities, and accelerations.

**A Careful Balance Between SI and U.S. Customary Units Is Consistently Maintained.** Because of the current trend in the American government and industry to adopt the international system of units (SI metric units), the SI units most frequently used in mechanics are introduced in Chap. 1 and are used throughout the text. Approximately half of the sample problems and 60 percent of the homework problems are stated in these units, while the remainder
are in U.S. customary units. The authors believe that this approach will best serve the need of students, who, as engineers, will have to be conversant with both systems of units.

It also should be recognized that using both SI and U.S. customary units entails more than the use of conversion factors. Since the SI system of units is an absolute system based on the units of time, length, and mass, whereas the U.S. customary system is a gravitational system based on the units of time, length, and force, different approaches are required for the solution of many problems. For example, when SI units are used, a body is generally specified by its mass expressed in kilograms; in most problems of statics it will be necessary to determine the weight of the body in newtons, and an additional calculation will be required for this purpose. On the other hand, when U.S. customary units are used, a body is specified by its weight in pounds and, in dynamics problems, an additional calculation will be required to determine its mass in slugs (or \( \text{lb} \cdot \text{s}^2/\text{ft} \)). The authors, therefore, believe that problem assignments should include both systems of units.

The Instructor's and Solutions Manual provides six different lists of assignments so that an equal number of problems stated in SI units and in U.S. customary units can be selected. If so desired, two complete lists of assignments can also be selected with up to 75 percent of the problems stated in SI units.

**Optional Sections Offer Advanced or Specialty Topics.** A large number of optional sections have been included. These sections are indicated by asterisks and thus are easily distinguished from those which form the core of the basic mechanics course. They may be omitted without prejudice to the understanding of the rest of the text.

The topics covered in the optional sections in statics include the reduction of a system of forces to a wrench, applications to hydrostatics, shear and bending-moment diagrams for beams, equilibrium of cables, products of inertia and Mohr’s circle, mass products of inertia and principal axes of inertia for three-dimensional bodies, and the method of virtual work. An optional section on the determination of the principal axes and the mass moments of inertia of a body of arbitrary shape is included (Sec. 9.18). The sections on beams are especially useful when the course in statics is immediately followed by a course in mechanics of materials, while the sections on the inertia properties of three-dimensional bodies are primarily intended for the students who will later study in dynamics the three-dimensional motion of rigid bodies.

The topics covered in the optional sections in dynamics include graphical methods for the solution of rectilinear-motion problems, the trajectory of a particle under a central force, the deflection of fluid streams, problems involving jet and rocket propulsion, the kinematics and kinetics of rigid bodies in three dimensions, damped mechanical vibrations, and electrical analogues. These topics will be found of particular interest when dynamics is taught in the junior year.

The material presented in the text and most of the problems require no previous mathematical knowledge beyond algebra, trigonometry, and elementary calculus; all the elements of vector algebra
necessary to the understanding of the text are carefully presented in Chaps. 2 and 3. However, special problems are included, which make use of a more advanced knowledge of calculus, and certain sections, such as Secs. 19.8 and 19.9 on damped vibrations, should be assigned only if students possess the proper mathematical background. In portions of the text using elementary calculus, a greater emphasis is placed on the correct understanding and application of the concepts of differentiation and integration than on the nimble manipulation of mathematical formulas. In this connection, it should be mentioned that the determination of the centroids of composite areas precedes the calculation of centroids by integration, thus making it possible to establish the concept of moment of area firmly before introducing the use of integration.

CHAPTER ORGANIZATION AND PEDAGOGICAL FEATURES

Chapter Introduction. Each chapter begins with an introductory section setting the purpose and goals of the chapter and describing in simple terms the material to be covered and its application to the solution of engineering problems. Chapter outlines provide students with a preview of chapter topics.

Chapter Lessons. The body of the text is divided into units, each consisting of one or several theory sections, one or several sample problems, and a large number of problems to be assigned. Each unit corresponds to a well-defined topic and generally can be covered in one lesson. In a number of cases, however, the instructor will find it desirable to devote more than one lesson to a given topic. The Instructor’s and Solutions Manual contains suggestions on the coverage of each lesson.

Sample Problems. The sample problems are set up in much the same form that students will use when solving the assigned problems. They thus serve the double purpose of amplifying the text and demonstrating the type of neat, orderly work that students should cultivate in their own solutions.

Solving Problems on Your Own. A section entitled Solving Problems on Your Own is included for each lesson, between the sample problems and the problems to be assigned. The purpose of these sections is to help students organize in their own minds the preceding theory of the text and the solution methods of the sample problems so that they can more successfully solve the homework problems. Also included in these sections are specific suggestions and strategies which will enable students to more efficiently attack any assigned problems.

Homework Problem Sets. Most of the problems are of a practical nature and should appeal to engineering students. They are primarily designed, however, to illustrate the material presented in the
text and to help students understand the principles of mechanics. The problems are grouped according to the portions of material they illustrate and are arranged in order of increasing difficulty. Problems requiring special attention are indicated by asterisks. Answers to 70 percent of the problems are given at the end of the book. Problems for which the answers are given are set in straight type in the text, while problems for which no answer is given are set in italic.

**Chapter Review and Summary.** Each chapter ends with a review and summary of the material covered in that chapter. Marginal notes are used to help students organize their review work, and cross-references have been included to help them find the portions of material requiring their special attention.

**Review Problems.** A set of review problems is included at the end of each chapter. These problems provide students further opportunity to apply the most important concepts introduced in the chapter.

**Computer Problems.** Each chapter includes a set of problems designed to be solved with computational software. Many of these problems provide an introduction to the design process. In *Statics*, for example, they may involve the analysis of a structure for various configurations and loading of the structure or the determination of the equilibrium positions of a mechanism which may require an iterative method of solution. In *Dynamics*, they may involve the determination of the motion of a particle under initial conditions, the kinematic or kinetic analysis of mechanisms in successive positions, or the numerical integration of various equations of motion. Developing the algorithm required to solve a given mechanics problem will benefit the students in two different ways: (1) it will help them gain a better understanding of the mechanics principles involved; (2) it will provide them with an opportunity to apply their computer skills to the solution of a meaningful engineering problem.

**SUPPLEMENTS**

An extensive supplements package for both instructors and students is available with the text.

**Instructor’s and Solutions Manual.** The *Instructor’s and Solutions Manual* that accompanies the ninth edition features typeset, one-per-page solutions to all homework problems. This manual also features a number of tables designed to assist instructors in creating a schedule of assignments for their courses. The various topics covered in the text are listed in Table I, and a suggested number of periods to be spent on each topic is indicated. Table II provides a brief description of all groups of problems and a classification of the problems in each group according to the units used. Sample lesson schedules are shown in Tables III, IV, and V.
McGRAW-HILL CONNECT ENGINEERING

McGraw-Hill Connect Engineering is a web-based assignment and assessment platform that gives students the means to better connect with their coursework, their instructors, and the important concepts that they will need to know for success now and in the future. With Connect Engineering, instructors can deliver assignments, quizzes, and tests easily online. Students can practice important skills at their own pace and on their own schedule.

Connect Engineering for Vector Mechanics for Engineers is available at www.mhhe.com/beerjohnston and includes algorithmic problems from the text, Lecture PowerPoints, an image bank, and animations.

Hands-on Mechanics. Hands-on Mechanics is a website designed for instructors who are interested in incorporating three-dimensional, hands-on teaching aids into their lectures. Developed through a partnership between the McGraw-Hill Engineering Team and the Department of Civil and Mechanical Engineering at the United States Military Academy at West Point, this website not only provides detailed instructions for how to build 3-D teaching tools using materials found in any lab or local hardware store but also provides a community where educators can share ideas, trade best practices, and submit their own demonstrations for posting on the site. Visit www.handsonmechanics.com.

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E. Russell Johnston, Jr.
David Mazurek
Phillip Cornwell
Elliot R. Eisenberg
### List of Symbols

- **a**: Constant; radius; distance
- **A, B, C, . . .**: Reactions at supports and connections
- **A, B, C, . . .**: Points
- **A**: Area
- **b**: Width; distance
- **c**: Constant
- **C**: Centroid
- **d**: Distance
- **e**: Base of natural logarithms
- **F**: Force; friction force
- **g**: Acceleration of gravity
- **G**: Center of gravity; constant of gravitation
- **h**: Height; sag of cable
- **i, j, k**: Unit vectors along coordinate axes
- **I, I_x, . . .**: Moments of inertia
- **\( \bar{I} \)**: Centroidal moment of inertia
- **I_{xy}, . . .**: Products of inertia
- **J**: Polar moment of inertia
- **k_x, k_y, k_O**: Radii of gyration
- **\( \bar{k} \)**: Centroidal radius of gyration
- **l**: Length
- **L**: Length; span
- **m**: Mass
- **M**: Couple; moment
- **M_O**: Moment about point \( O \)
- **M_O**: Moment resultant about point \( O \)
- **M**: Magnitude of couple or moment; mass of earth
- **M_{OL}**: Moment about axis \( OL \)
- **N**: Normal component of reaction
- **O**: Origin of coordinates
- **p**: Pressure
- **P**: Force; vector
- **Q**: Force; vector
- **r**: Position vector
- **r**: Radius; distance; polar coordinate
- **R**: Resultant force; resultant vector; reaction
- **R**: Radius of earth
- **s**: Position vector
- **s**: Length of arc; length of cable
- **S**: Force; vector
- **t**: Thickness
- **T**: Force
- **T**: Tension
- **U**: Work
List of Symbols

**V** Vector product; shearing force

**V** Volume; potential energy; shear

**w** Load per unit length

**W**, **W** Weight; load

**x, y, z** Rectangular coordinates; distances

**x̅, y̅, z̅** Rectangular coordinates of centroid or center of gravity

**α, β, γ** Angles

**γ** Specific weight

**δ** Elongation

**δr** Virtual displacement

**δU** Virtual work

**λ** Unit vector along a line

**η** Efficiency

**θ** Angular coordinate; angle; polar coordinate

**μ** Coefficient of friction

**ρ** Density

**φ** Angle of friction; angle
In the latter part of the seventeenth century, Sir Isaac Newton stated the fundamental principles of mechanics, which are the foundation of much of today’s engineering.
CHAPTER 1

Introduction
Chapter 1  Introduction

1.1  WHAT IS MECHANICS?

Mechanics can be defined as that science which describes and predicts the conditions of rest or motion of bodies under the action of forces. It is divided into three parts: mechanics of rigid bodies, mechanics of deformable bodies, and mechanics of fluids.

The mechanics of rigid bodies is subdivided into statics and dynamics, the former dealing with bodies at rest, the latter with bodies in motion. In this part of the study of mechanics, bodies are assumed to be perfectly rigid. Actual structures and machines, however, are never absolutely rigid and deform under the loads to which they are subjected. But these deformations are usually small and do not appreciably affect the conditions of equilibrium or motion of the structure under consideration. They are important, though, as far as the resistance of the structure to failure is concerned and are studied in mechanics of materials, which is a part of the mechanics of deformable bodies. The third division of mechanics, the mechanics of fluids, is subdivided into the study of incompressible fluids and of compressible fluids. An important subdivision of the study of incompressible fluids is hydraulics, which deals with problems involving water.

Mechanics is a physical science, since it deals with the study of physical phenomena. However, some associate mechanics with mathematics, while many consider it as an engineering subject. Both these views are justified in part. Mechanics is the foundation of most engineering sciences and is an indispensable prerequisite to their study. However, it does not have the empiricism found in some engineering sciences, i.e., it does not rely on experience or observation alone; by its rigor and the emphasis it places on deductive reasoning it resembles mathematics. But, again, it is not an abstract or even a pure science; mechanics is an applied science. The purpose of mechanics is to explain and predict physical phenomena and thus to lay the foundations for engineering applications.

1.2  FUNDAMENTAL CONCEPTS AND PRINCIPLES

Although the study of mechanics goes back to the time of Aristotle (384–322 B.C.) and Archimedes (287–212 B.C.), one has to wait until Newton (1642–1727) to find a satisfactory formulation of its fundamental principles. These principles were later expressed in a modified form by d’Alembert, Lagrange, and Hamilton. Their validity remained unchallenged, however, until Einstein formulated his theory of relativity (1905). While its limitations have now been recognized, newtonian mechanics still remains the basis of today’s engineering sciences.

The basic concepts used in mechanics are space, time, mass, and force. These concepts cannot be truly defined; they should be accepted on the basis of our intuition and experience and used as a mental frame of reference for our study of mechanics.

The concept of space is associated with the notion of the position of a point $P$. The position of $P$ can be defined by three lengths measured from a certain reference point, or origin, in three given directions. These lengths are known as the coordinates of $P$. 
To define an event, it is not sufficient to indicate its position in space. The *time* of the event should also be given.

The concept of *mass* is used to characterize and compare bodies on the basis of certain fundamental mechanical experiments. Two bodies of the same mass, for example, will be attracted by the earth in the same manner; they will also offer the same resistance to a change in translational motion.

A *force* represents the action of one body on another. It can be exerted by actual contact or at a distance, as in the case of gravitational forces and magnetic forces. A force is characterized by its *point of application*, its *magnitude*, and its *direction*; a force is represented by a *vector* (Sec. 2.3).

In newtonian mechanics, space, time, and mass are absolute concepts, independent of each other. (This is not true in *relativistic mechanics*, where the time of an event depends upon its position, and where the mass of a body varies with its velocity.) On the other hand, the concept of force is not independent of the other three. Indeed, one of the fundamental principles of newtonian mechanics listed below indicates that the resultant force acting on a body is related to the mass of the body and to the manner in which its velocity varies with time.

You will study the conditions of rest or motion of particles and rigid bodies in terms of the four basic concepts we have introduced. By *particle* we mean a very small amount of matter which may be assumed to occupy a single point in space. A *rigid body* is a combination of a large number of particles occupying fixed positions with respect to each other. The study of the mechanics of particles is obviously a prerequisite to that of rigid bodies. Besides, the results obtained for a particle can be used directly in a large number of problems dealing with the conditions of rest or motion of actual bodies.

The study of elementary mechanics rests on six fundamental principles based on experimental evidence.

**The Parallelogram Law for the Addition of Forces.** This states that two forces acting on a particle may be replaced by a single force, called their *resultant*, obtained by drawing the diagonal of the parallelogram which has sides equal to the given forces (Sec. 2.2).

**The Principle of Transmissibility.** This states that the conditions of equilibrium or of motion of a rigid body will remain unchanged if a force acting at a given point of the rigid body is replaced by a force of the same magnitude and same direction, but acting at a different point, provided that the two forces have the same line of action (Sec. 3.3).

**Newton’s Three Fundamental Laws.** Formulated by Sir Isaac Newton in the latter part of the seventeenth century, these laws can be stated as follows:

**FIRST LAW.** If the resultant force acting on a particle is zero, the particle will remain at rest (if originally at rest) or will move with constant speed in a straight line (if originally in motion) (Sec. 2.10).
**SECOND LAW.** If the resultant force acting on a particle is not zero, the particle will have an acceleration proportional to the magnitude of the resultant and in the direction of this resultant force.

As you will see in Sec. 12.2, this law can be stated as

\[
F = ma
\]  

(1.1)

where \( F \), \( m \), and \( a \) represent, respectively, the resultant force acting on the particle, the mass of the particle, and the acceleration of the particle, expressed in a consistent system of units.

**THIRD LAW.** The forces of action and reaction between bodies in contact have the same magnitude, same line of action, and opposite sense (Sec. 6.1).

**Newton’s Law of Gravitation.** This states that two particles of mass \( M \) and \( m \) are mutually attracted with equal and opposite forces \( F \) and \(-F\) (Fig. 1.1) of magnitude \( F \) given by the formula

\[
F = G \frac{Mm}{r^2}
\]  

(1.2)

where \( r \) = distance between the two particles

\( G \) = universal constant called the *constant of gravitation*

Newton’s law of gravitation introduces the idea of an action exerted at a distance and extends the range of application of Newton’s third law: the action \( F \) and the reaction \( -F \) in Fig. 1.1 are equal and opposite, and they have the same line of action.

A particular case of great importance is that of the attraction of the earth on a particle located on its surface. The force \( F \) exerted by the earth on the particle is then defined as the *weight* \( W \) of the particle. Taking \( M \) equal to the mass of the earth, \( m \) equal to the mass of the particle, and \( r \) equal to the radius \( R \) of the earth, and introducing the constant

\[
g = \frac{GM}{R^2}
\]  

(1.3)

the magnitude \( W \) of the weight of a particle of mass \( m \) may be expressed as†

\[
W = mg
\]  

(1.4)

The value of \( R \) in formula (1.3) depends upon the elevation of the point considered; it also depends upon its latitude, since the earth is not truly spherical. The value of \( g \) therefore varies with the position of the point considered. As long as the point actually remains on the surface of the earth, it is sufficiently accurate in most engineering computations to assume that \( g \) equals 9.81 m/s\(^2\) or 32.2 ft/s\(^2\).

†A more accurate definition of the weight \( W \) should take into account the rotation of the earth.
The principles we have just listed will be introduced in the course of our study of mechanics as they are needed. The study of the statics of particles carried out in Chap. 2, will be based on the parallelogram law of addition and on Newton's first law alone. The principle of transmissibility will be introduced in Chap. 3 as we begin the study of the statics of rigid bodies, and Newton's third law in Chap. 6 as we analyze the forces exerted on each other by the various members forming a structure. In the study of dynamics, Newton's second law and Newton's law of gravitation will be introduced. It will then be shown that Newton's first law is a particular case of Newton's second law (Sec. 12.2) and that the principle of transmissibility could be derived from the other principles and thus eliminated (Sec. 16.5). In the meantime, however, Newton's first and third laws, the parallelogram law of addition, and the principle of transmissibility will provide us with the necessary and sufficient foundation for the entire study of the statics of particles, rigid bodies, and systems of rigid bodies.

As noted earlier, the six fundamental principles listed above are based on experimental evidence. Except for Newton's first law and the principle of transmissibility, they are independent principles which cannot be derived mathematically from each other or from any other elementary physical principle. On these principles rests most of the intricate structure of Newtonian mechanics. For more than two centuries a tremendous number of problems dealing with the conditions of rest and motion of rigid bodies, deformable bodies, and fluids have been solved by applying these fundamental principles. Many of the solutions obtained could be checked experimentally, thus providing a further verification of the principles from which they were derived. It is only in the twentieth century that Newton's mechanics was found at fault, in the study of the motion of atoms and in the study of the motion of certain planets, where it must be supplemented by the theory of relativity. But on the human or engineering scale, where velocities are small compared with the speed of light, Newton's mechanics has yet to be disproved.

1.3 SYSTEMS OF UNITS

With the four fundamental concepts introduced in the preceding section are associated the so-called kinetic units, i.e., the units of length, time, mass, and force. These units cannot be chosen independently if Eq. (1.1) is to be satisfied. Three of the units may be defined arbitrarily; they are then referred to as basic units. The fourth unit, however, must be chosen in accordance with Eq. (1.1) and is referred to as a derived unit. Kinetic units selected in this way are said to form a consistent system of units.

International System of Units (SI Units†). In this system, which will be in universal use after the United States has completed its conversion to SI units, the base units are the units of length, mass, and time, and they are called, respectively, the meter (m), the kilogram (kg), and the second (s). All three are arbitrarily defined. The second,

†SI stands for Système International d’Unités (French).
which was originally chosen to represent 1/86,400 of the mean solar
day, is now defined as the duration of 9,192,631,770 cycles of the radia-
tion corresponding to the transition between two levels of the funda-
mental state of the cesium-133 atom. The meter, originally defined as
one ten-millionth of the distance from the equator to either pole, is
now defined as 1,650,763.73 wavelengths of the orange-red light cor-
responding to a certain transition in an atom of krypton-86. The kilo-
gram, which is approximately equal to the mass of 0.001 m$^3$ of water,
is defined as the mass of a platinum-iridium standard kept at the Inter-
national Bureau of Weights and Measures at Sèvres, near Paris, France.
The unit of force is a derived unit. It is called the newton (N) and is
defined as the force which gives an acceleration of 1 m/s$^2$ to a mass of
1 kg (Fig. 1.2). From Eq. (1.1) we write

$$1 \text{ N} = (1 \text{ kg})(1 \text{ m/s}^2) = 1 \text{ kg} \cdot \text{m/s}^2$$  

The SI units are said to form an absolute system of units. This means
that the three base units chosen are independent of the location where
measurements are made. The meter, the kilogram, and the second
may be used anywhere on the earth; they may even be used on another
planet. They will always have the same significance.

The weight of a body, or the force of gravity exerted on that body,
should, like any other force, be expressed in newtons. From Eq. (1.4)
it follows that the weight of a body of mass 1 kg (Fig. 1.3) is

$$W = mg$$

$$= (1 \text{ kg})(9.81 \text{ m/s}^2)$$

$$= 9.81 \text{ N}$$

Multiples and submultiples of the fundamental SI units may be
obtained through the use of the prefixes defined in Table 1.1. The
multiples and submultiples of the units of length, mass, and force most
frequently used in engineering are, respectively, the kilometer (km) and
the millimeter (mm); the megagram† (Mg) and the gram (g); and
the kilonewton (kN). According to Table 1.1, we have

$$1 \text{ km} = 1000 \text{ m} \quad 1 \text{ mm} = 0.001 \text{ m}$$

$$1 \text{ Mg} = 1000 \text{ kg} \quad 1 \text{ g} = 0.001 \text{ kg}$$

$$1 \text{ kN} = 1000 \text{ N}$$

The conversion of these units into meters, kilograms, and newtons,
respectively, can be effected by simply moving the decimal point	hree places to the right or to the left. For example, to convert
3.82 km into meters, one moves the decimal point three places to the
right:

$$3.82 \text{ km} = 3820 \text{ m}$$

Similarly, 47.2 mm is converted into meters by moving the decimal
point three places to the left:

$$47.2 \text{ mm} = 0.0472 \text{ m}$$

†Also known as a metric ton.
Using scientific notation, one may also write

\[3.82\, \text{km} = 3.82 \times 10^3\, \text{m}\]
\[47.2\, \text{mm} = 47.2 \times 10^{-3}\, \text{m}\]

The multiples of the unit of time are the minute (min) and the hour (h). Since 1 min = 60 s and 1 h = 60 min = 3600 s, these multiples cannot be converted as readily as the others.

By using the appropriate multiple or submultiple of a given unit, one can avoid writing very large or very small numbers. For example, one usually writes 427.2 km rather than 427 200 m, and 2.16 mm rather than 0.002 16 m.†

**Units of Area and Volume.** The unit of area is the square meter (m²), which represents the area of a square of side 1 m; the unit of volume is the cubic meter (m³), equal to the volume of a cube of side 1 m. In order to avoid exceedingly small or large numerical values in the computation of areas and volumes, one uses systems of subunits obtained by respectively squaring and cubing not only the millimeter but also two intermediate submultiples of the meter, namely, the decimeter (dm) and the centimeter (cm). Since, by definition,

\[1\, \text{dm} = 0.1\, \text{m} = 10^{-1}\, \text{m}\]
\[1\, \text{cm} = 0.01\, \text{m} = 10^{-2}\, \text{m}\]
\[1\, \text{mm} = 0.001\, \text{m} = 10^{-3}\, \text{m}\]

†It should be noted that when more than four digits are used on either side of the decimal point to express a quantity in SI units—as in 427 200 m or 0.002 16 m—spaces, never commas, should be used to separate the digits into groups of three. This is to avoid confusion with the comma used in place of a decimal point, which is the convention in many countries.
the submultiples of the unit of area are

\[ 1 \text{ dm}^2 = (1 \text{ dm})^2 = (10^{-1} \text{ m})^2 = 10^{-2} \text{ m}^2 \]
\[ 1 \text{ cm}^2 = (1 \text{ cm})^2 = (10^{-2} \text{ m})^2 = 10^{-4} \text{ m}^2 \]
\[ 1 \text{ mm}^2 = (1 \text{ mm})^2 = (10^{-3} \text{ m})^2 = 10^{-6} \text{ m}^2 \]

and the submultiples of the unit of volume are

\[ 1 \text{ dm}^3 = (1 \text{ dm})^3 = (10^{-1} \text{ m})^3 = 10^{-3} \text{ m}^3 \]
\[ 1 \text{ cm}^3 = (1 \text{ cm})^3 = (10^{-2} \text{ m})^3 = 10^{-6} \text{ m}^3 \]
\[ 1 \text{ mm}^3 = (1 \text{ mm})^3 = (10^{-3} \text{ m})^3 = 10^{-9} \text{ m}^3 \]

It should be noted that when the volume of a liquid is being measured, the cubic decimeter (dm³) is usually referred to as a liter (L).

Other derived SI units used to measure the moment of a force, the work of a force, etc., are shown in Table 1.2. While these units will be introduced in later chapters as they are needed, we should note an important rule at this time: When a derived unit is obtained by dividing a base unit by another base unit, a prefix may be used in the numerator of the derived unit but not in its denominator. For example, the constant \( k \) of a spring which stretches 20 mm under a load of 100 N will be expressed as

\[ k = \frac{100 \text{ N}}{20 \text{ mm}} = \frac{100 \text{ N}}{0.020 \text{ m}} = 5000 \text{ N/m} \quad \text{or} \quad k = 5 \text{ kN/m} \]

but never as \( k = 5 \text{ N/mm} \).

**TABLE 1.2 Principal SI Units Used in Mechanics**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Unit</th>
<th>Symbol</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration</td>
<td>Meter per second squared</td>
<td>...</td>
<td>m/s²</td>
</tr>
<tr>
<td>Angle</td>
<td>Radian</td>
<td>rad</td>
<td>†</td>
</tr>
<tr>
<td>Angular acceleration</td>
<td>Radian per second squared</td>
<td>...</td>
<td>rad/s²</td>
</tr>
<tr>
<td>Angular velocity</td>
<td>Radian per second</td>
<td>...</td>
<td>rad/s</td>
</tr>
<tr>
<td>Area</td>
<td>Square meter</td>
<td>...</td>
<td>m²</td>
</tr>
<tr>
<td>Density</td>
<td>Kilogram per cubic meter</td>
<td>...</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Energy</td>
<td>Joule</td>
<td>J</td>
<td>N·m</td>
</tr>
<tr>
<td>Force</td>
<td>Newton</td>
<td>N</td>
<td>kg·m/s²</td>
</tr>
<tr>
<td>Frequency</td>
<td>Hertz</td>
<td>Hz</td>
<td>s⁻¹</td>
</tr>
<tr>
<td>Impulse</td>
<td>Newton-second</td>
<td>...</td>
<td>kg·m/s</td>
</tr>
<tr>
<td>Length</td>
<td>Meter</td>
<td>m</td>
<td>†</td>
</tr>
<tr>
<td>Mass</td>
<td>Kilogram</td>
<td>kg</td>
<td>†</td>
</tr>
<tr>
<td>Moment of a force</td>
<td>Newton-meter</td>
<td>...</td>
<td>N·m</td>
</tr>
<tr>
<td>Power</td>
<td>Watt</td>
<td>W</td>
<td>J/s</td>
</tr>
<tr>
<td>Pressure</td>
<td>Pascal</td>
<td>Pa</td>
<td>N/m²</td>
</tr>
<tr>
<td>Stress</td>
<td>Pascal</td>
<td>Pa</td>
<td>N/m²</td>
</tr>
<tr>
<td>Time</td>
<td>Second</td>
<td>s</td>
<td>†</td>
</tr>
<tr>
<td>Velocity</td>
<td>Meter per second</td>
<td>...</td>
<td>m/s</td>
</tr>
<tr>
<td>Volume</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solids</td>
<td>Cubic meter</td>
<td>...</td>
<td>m³</td>
</tr>
<tr>
<td>Liquids</td>
<td>Liter</td>
<td>L</td>
<td>10⁻³m³</td>
</tr>
<tr>
<td>Work</td>
<td>Joule</td>
<td>J</td>
<td>N·m</td>
</tr>
</tbody>
</table>

†Supplementary unit (1 revolution = \( 2\pi \) rad = 360°).
†Base unit.
U.S. Customary Units. Most practicing American engineers still commonly use a system in which the base units are the units of length, force, and time. These units are, respectively, the foot (ft), the pound (lb), and the second (s). The second is the same as the corresponding SI unit. The foot is defined as 0.3048 m. The pound is defined as the weight of a platinum standard, called the standard pound, which is kept at the National Institute of Standards and Technology outside Washington, the mass of which is 0.45359243 kg. Since the weight of a body depends upon the earth's gravitational attraction, which varies with location, it is specified that the standard pound should be placed at sea level and at a latitude of 45° to properly define a force of 1 lb. Clearly the U.S. customary units do not form an absolute system of units. Because of their dependence upon the gravitational attraction of the earth, they form a gravitational system of units.

While the standard pound also serves as the unit of mass in commercial transactions in the United States, it cannot be so used in engineering computations, since such a unit would not be consistent with the base units defined in the preceding paragraph. Indeed, when acted upon by a force of 1 lb, that is, when subjected to the force of gravity, the standard pound receives the acceleration of gravity, \( g = 32.2 \text{ ft/s}^2 \) (Fig. 1.4), not the unit acceleration required by Eq. (1.1). The unit of mass consistent with the foot, the pound, and the second is the mass which receives an acceleration of 1 ft/s\(^2\) when a force of 1 lb is applied to it (Fig. 1.5). This unit, sometimes called a slug, can be derived from the equation \( F = ma \) after substituting 1 lb and 1 ft/s\(^2\) for \( F \) and \( a \), respectively. We write

\[ F = ma \quad 1 \text{ lb} = (1 \text{ slug})(1 \text{ ft/s}^2) \]

and obtain

\[ 1 \text{ slug} = \frac{1 \text{ lb}}{1 \text{ ft/s}^2} = 1 \text{ lb} \cdot \text{s}^2/\text{ft} \quad (1.6) \]

Comparing Figs. 1.4 and 1.5, we conclude that the slug is a mass 32.2 times larger than the mass of the standard pound.

The fact that in the U.S. customary system of units bodies are characterized by their weight in pounds rather than by their mass in slugs will be a convenience in the study of statics, where one constantly deals with weights and other forces and only seldom with masses. However, in the study of dynamics, where forces, masses, and accelerations are involved, the mass \( m \) of a body will be expressed in slugs when its weight \( W \) is given in pounds. Recalling Eq. (1.4), we write

\[ m = \frac{W}{g} \quad (1.7) \]

where \( g \) is the acceleration of gravity (\( g = 32.2 \text{ ft/s}^2 \)).

Other U.S. customary units frequently encountered in engineering problems are the mile (mi), equal to 5280 ft; the inch (in.), equal to \( \frac{1}{12} \text{ ft} \); and the kilopound (kip), equal to a force of 1000 lb. The ton is often used to represent a mass of 2000 lb but, like the pound, must be converted into slugs in engineering computations.

The conversion into feet, pounds, and seconds of quantities expressed in other U.S. customary units is generally more involved and
requires greater attention than the corresponding operation in SI units. If, for example, the magnitude of a velocity is given as \( v = 30 \text{ mi/h} \), we convert it to \( \text{ft/s} \) as follows. First we write

\[
v = 30 \frac{\text{mi}}{\text{h}}
\]

Since we want to get rid of the unit miles and introduce instead the unit feet, we should multiply the right-hand member of the equation by an expression containing miles in the denominator and feet in the numerator. But, since we do not want to change the value of the right-hand member, the expression used should have a value equal to unity. The quotient \( \frac{5280 \text{ ft}}{1 \text{ mi}} \) is such an expression. Operating in a similar way to transform the unit hour into seconds, we write

\[
v = \left( 30 \frac{\text{mi}}{\text{h}} \right) \left( \frac{5280 \text{ ft}}{1 \text{ mi}} \right) \left( \frac{1 \text{ h}}{3600 \text{ s}} \right)
\]

Carrying out the numerical computations and canceling out units which appear in both the numerator and the denominator, we obtain

\[
v = 44 \frac{\text{ft}}{\text{s}} = 44 \text{ ft/s}
\]

### 1.4 Conversion from One System of Units to Another

There are many instances when an engineer wishes to convert into SI units a numerical result obtained in U.S. customary units or vice versa. Because the unit of time is the same in both systems, only two kinetic base units need be converted. Thus, since all other kinetic units can be derived from these base units, only two conversion factors need be remembered.

**Units of Length.** By definition the U.S. customary unit of length is

\[
1 \text{ ft} = 0.3048 \text{ m} \quad (1.8)
\]

It follows that

\[
1 \text{ mi} = 5280 \text{ ft} = 5280(0.3048 \text{ m}) = 1609 \text{ m}
\]

or

\[
1 \text{ mi} = 1.609 \text{ km} \quad (1.9)
\]

Also

\[
1 \text{ in.} = \frac{1}{12} \text{ ft} = \frac{1}{12}(0.3048 \text{ m}) = 0.0254 \text{ m}
\]

or

\[
1 \text{ in.} = 25.4 \text{ mm} \quad (1.10)
\]

**Units of Force.** Recalling that the U.S. customary unit of force (pound) is defined as the weight of the standard pound (of mass 0.4536 kg) at sea level and at a latitude of 45° (where \( g = 9.807 \text{ m/s}^2 \)) and using Eq. (1.4), we write
or, recalling Eq. (1.5),

$$1 \text{ lb} = 4.448 \text{ N}$$ \hspace{1cm} (1.11)

**Units of Mass.** The U.S. customary unit of mass (slug) is a derived unit. Thus, using Eqs. (1.6), (1.8), and (1.11), we write

$$1 \text{ slug} = 1 \text{ lb} \cdot s^2/\text{ft} = \frac{1 \text{ lb}}{1 \text{ ft}/s^2} = \frac{4.448 \text{ N}}{0.3048 \text{ m}/s^2} = 14.59 \text{ N} \cdot s^2/\text{m}$$

and, recalling Eq. (1.5),

$$1 \text{ slug} = 1 \text{ lb} \cdot s^2/\text{ft} = 14.59 \text{ kg}$$ \hspace{1cm} (1.12)

Although it cannot be used as a consistent unit of mass, we recall that the mass of the standard pound is, by definition,

$$1 \text{ pound mass} = 0.4536 \text{ kg}$$ \hspace{1cm} (1.13)

This constant may be used to determine the mass in SI units (kilograms) of a body which has been characterized by its weight in U.S. customary units (pounds).

To convert a derived U.S. customary unit into SI units, one simply multiplies or divides by the appropriate conversion factors. For example, to convert the moment of a force which was found to be $M = 47 \text{ lb} \cdot \text{in.}$ into SI units, we use formulas (1.10) and (1.11) and write

$$M = 47 \text{ lb} \cdot \text{in.} = 47(4.448 \text{ N})(25.4 \text{ mm})$$

$$= 5310 \text{ N} \cdot \text{mm} = 5.31 \text{ N} \cdot \text{m}$$

The conversion factors given in this section may also be used to convert a numerical result obtained in SI units into U.S. customary units. For example, if the moment of a force was found to be $M = 40 \text{ N} \cdot \text{m}$, we write, following the procedure used in the last paragraph of Sec. 1.3,

$$M = 40 \text{ N} \cdot \text{m} = (40 \text{ N} \cdot \text{m}) \left( \frac{1 \text{ lb}}{4.448 \text{ N}} \right) \left( \frac{1 \text{ ft}}{0.3048 \text{ m}} \right)$$

Carrying out the numerical computations and canceling out units which appear in both the numerator and the denominator, we obtain

$$M = 29.5 \text{ lb} \cdot \text{ft}$$

The U.S. customary units most frequently used in mechanics are listed in Table 1.3 with their SI equivalents.

## 1.5 METHOD OF PROBLEM SOLUTION

You should approach a problem in mechanics as you would approach an actual engineering situation. By drawing on your own experience and intuition, you will find it easier to understand and formulate the problem. Once the problem has been clearly stated, however, there is
no place in its solution for your particular fancy. The solution must be based on the six fundamental principles stated in Sec. 1.2 or on theorems derived from them. Every step taken must be justified on that basis. Strict rules must be followed, which lead to the solution in an almost automatic fashion, leaving no room for your intuition or “feeling.” After an answer has been obtained, it should be checked. Here again, you may call upon your common sense and personal experience. If not completely satisfied with the result obtained, you should carefully check your formulation of the problem, the validity of the methods used for its solution, and the accuracy of your computations.

The statement of a problem should be clear and precise. It should contain the given data and indicate what information is required. A neat drawing showing all quantities involved should be included. Separate diagrams should be drawn for all bodies involved, indicating clearly the forces acting on each body. These diagrams are known as free-body diagrams and are described in detail in Secs. 2.11 and 4.2.

TABLE 1.3  U.S. Customary Units and Their SI Equivalents

<table>
<thead>
<tr>
<th>Quantity</th>
<th>U.S. Customary Unit</th>
<th>SI Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration</td>
<td>ft/s²</td>
<td>0.3048 m/s²</td>
</tr>
<tr>
<td></td>
<td>in./s²</td>
<td>0.0254 m/s²</td>
</tr>
<tr>
<td>Area</td>
<td>ft²</td>
<td>0.0929 m²</td>
</tr>
<tr>
<td></td>
<td>in²</td>
<td>645.2 mm²</td>
</tr>
<tr>
<td>Energy</td>
<td>ft · lb</td>
<td>1.356 J</td>
</tr>
<tr>
<td>Force</td>
<td>kip</td>
<td>4.448 kN</td>
</tr>
<tr>
<td></td>
<td>lb</td>
<td>4.448 N</td>
</tr>
<tr>
<td></td>
<td>oz</td>
<td>0.2780 N</td>
</tr>
<tr>
<td>Impulse</td>
<td>lb · s</td>
<td>4.448 N · s</td>
</tr>
<tr>
<td>Length</td>
<td>ft</td>
<td>0.3048 m</td>
</tr>
<tr>
<td></td>
<td>in.</td>
<td>25.40 mm</td>
</tr>
<tr>
<td></td>
<td>mi</td>
<td>1.609 km</td>
</tr>
<tr>
<td>Mass</td>
<td>oz mass</td>
<td>28.35 g</td>
</tr>
<tr>
<td></td>
<td>lb mass</td>
<td>4.536 kg</td>
</tr>
<tr>
<td></td>
<td>slug</td>
<td>14.59 kg</td>
</tr>
<tr>
<td></td>
<td>ton</td>
<td>907.2 kg</td>
</tr>
<tr>
<td>Moment of a force</td>
<td>lb · ft</td>
<td>1.356 N · m</td>
</tr>
<tr>
<td></td>
<td>lb · in.</td>
<td>0.1130 N · m</td>
</tr>
<tr>
<td>Moment of inertia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Of an area</td>
<td>in⁴</td>
<td>0.4162 × 10⁶ mm⁴</td>
</tr>
<tr>
<td>Of a mass</td>
<td>lb · ft · s²</td>
<td>1.356 kg · m²</td>
</tr>
<tr>
<td>Momentum</td>
<td>lb · ft · s</td>
<td>4.448 kg · m/s</td>
</tr>
<tr>
<td>Power</td>
<td>ft · lb/s</td>
<td>1.356 W</td>
</tr>
<tr>
<td></td>
<td>hp</td>
<td>745.7 W</td>
</tr>
<tr>
<td>Pressure or stress</td>
<td>lb/ft²</td>
<td>47.88 Pa</td>
</tr>
<tr>
<td></td>
<td>lb/in² (psi)</td>
<td>6.895 kPa</td>
</tr>
<tr>
<td>Velocity</td>
<td>ft/s</td>
<td>0.3048 m/s</td>
</tr>
<tr>
<td></td>
<td>in./s</td>
<td>0.0254 m/s</td>
</tr>
<tr>
<td></td>
<td>mi/h (mph)</td>
<td>0.4470 m/s</td>
</tr>
<tr>
<td></td>
<td>mi/h (mph)</td>
<td>1.609 km/h</td>
</tr>
<tr>
<td>Volume</td>
<td>ft³</td>
<td>0.02832 m³</td>
</tr>
<tr>
<td></td>
<td>in³</td>
<td>16.39 cm³</td>
</tr>
<tr>
<td>Liquids</td>
<td>gal</td>
<td>3.785 L</td>
</tr>
<tr>
<td></td>
<td>qt</td>
<td>0.9464 L</td>
</tr>
<tr>
<td>Work</td>
<td>ft · lb</td>
<td>1.356 J</td>
</tr>
</tbody>
</table>
The fundamental principles of mechanics listed in Sec. 1.2 will be used to write equations expressing the conditions of rest or motion of the bodies considered. Each equation should be clearly related to one of the free-body diagrams. You will then proceed to solve the problem, observing strictly the usual rules of algebra and recording neatly the various steps taken.

After the answer has been obtained, it should be carefully checked. Mistakes in reasoning can often be detected by checking the units. For example, to determine the moment of a force of 50 N about a point 0.60 m from its line of action, we would have written (Sec. 3.12)

\[ M = Fd = (50 \text{ N})(0.60 \text{ m}) = 30 \text{ N} \cdot \text{m} \]

The unit N \cdot m obtained by multiplying newtons by meters is the correct unit for the moment of a force; if another unit had been obtained, we would have known that some mistake had been made.

Errors in computation will usually be found by substituting the numerical values obtained into an equation which has not yet been used and verifying that the equation is satisfied. The importance of correct computations in engineering cannot be overemphasized.

1.6 NUMERICAL ACCURACY

The accuracy of the solution of a problem depends upon two items: (1) the accuracy of the given data and (2) the accuracy of the computations performed.

The solution cannot be more accurate than the less accurate of these two items. For example, if the loading of a bridge is known to be 75,000 lb with a possible error of 100 lb either way, the relative error which measures the degree of accuracy of the data is

\[ \frac{100 \text{ lb}}{75,000 \text{ lb}} = 0.0013 = 0.13 \text{ percent} \]

In computing the reaction at one of the bridge supports, it would then be meaningless to record it as 14,322 lb. The accuracy of the solution cannot be greater than 0.13 percent, no matter how accurate the computations are, and the possible error in the answer may be as large as \((0.13/100)(14,322 \text{ lb}) \approx 20 \text{ lb}\). The answer should be properly recorded as 14,320 ± 20 lb.

In engineering problems, the data are seldom known with an accuracy greater than 0.2 percent. It is therefore seldom justified to write the answers to such problems with an accuracy greater than 0.2 percent. A practical rule is to use 4 figures to record numbers beginning with a “1” and 3 figures in all other cases. Unless otherwise indicated, the data given in a problem should be assumed known with a comparable degree of accuracy. A force of 40 lb, for example, should be read 40.0 lb, and a force of 15 lb should be read 15.00 lb.

Pocket electronic calculators are widely used by practicing engineers and engineering students. The speed and accuracy of these calculators facilitate the numerical computations in the solution of many problems. However, students should not record more significant figures than can be justified merely because they are easily obtained. As noted above, an accuracy greater than 0.2 percent is seldom necessary or meaningful in the solution of practical engineering problems.
Many engineering problems can be solved by considering the equilibrium of a “particle.” In the case of this excavator, which is being loaded onto a ship, a relation between the tensions in the various cables involved can be obtained by considering the equilibrium of the hook to which the cables are attached.
Chapter 2

Statics of Particles
Chapter 2 Statics of Particles

2.1 Introduction

In this chapter you will study the effect of forces acting on particles. First you will learn how to replace two or more forces acting on a given particle by a single force having the same effect as the original forces. This single equivalent force is the resultant of the original forces acting on the particle. Later the relations which exist among the various forces acting on a particle in a state of equilibrium will be derived and used to determine some of the forces acting on the particle.

The use of the word “particle” does not imply that our study will be limited to that of small corpuscles. What it means is that the size and shape of the bodies under consideration will not significantly affect the solution of the problems treated in this chapter and that all the forces acting on a given body will be assumed to be applied at the same point. Since such an assumption is verified in many practical applications, you will be able to solve a number of engineering problems in this chapter.

The first part of the chapter is devoted to the study of forces contained in a single plane, and the second part to the analysis of forces in three-dimensional space.

2.2 Force on a Particle. Resultant of Two Forces

A force represents the action of one body on another and is generally characterized by its point of application, its magnitude, and its direction. Forces acting on a given particle, however, have the same point of application. Each force considered in this chapter will thus be completely defined by its magnitude and direction.

The magnitude of a force is characterized by a certain number of units. As indicated in Chap. 1, the SI units used by engineers to measure the magnitude of a force are the newton (N) and its multiple the kilonewton (kN), equal to 1000 N, while the U.S. customary units used for the same purpose are the pound (lb) and its multiple the kilopound (kip), equal to 1000 lb. The direction of a force is defined by the line of action and the sense of the force. The line of action is the infinite straight line along which the force acts; it is characterized by the angle it forms with some fixed axis (Fig. 2.1). The force itself is represented by a segment of
that line; through the use of an appropriate scale, the length of this segment may be chosen to represent the magnitude of the force. Finally, the sense of the force should be indicated by an arrowhead.

It is important in defining a force to indicate its sense. Two forces having the same magnitude and the same line of action but different sense, such as the forces shown in Fig. 2.1a and b, will have directly opposite effects on a particle.

Experimental evidence shows that two forces $\mathbf{P}$ and $\mathbf{Q}$ acting on a particle $A$ (Fig. 2.2a) can be replaced by a single force $\mathbf{R}$ which has the same effect on the particle (Fig. 2.2c). This force is called the resultant of the forces $\mathbf{P}$ and $\mathbf{Q}$ and can be obtained, as shown in Fig. 2.2b, by constructing a parallelogram, using $\mathbf{P}$ and $\mathbf{Q}$ as two adjacent sides of the parallelogram. The diagonal that passes through $A$ represents the resultant. This method for finding the resultant is known as the parallelogram law for the addition of two forces. This law is based on experimental evidence; it cannot be proved or derived mathematically.

### 2.3 VECTORS

It appears from the above that forces do not obey the rules of addition defined in ordinary arithmetic or algebra. For example, two forces acting at a right angle to each other, one of 4 lb and the other of 3 lb, add up to a force of 5 lb, not to a force of 7 lb. Forces are not the only quantities which follow the parallelogram law of addition. As you will see later, displacements, velocities, accelerations, and momenta are other examples of physical quantities possessing magnitude and direction that are added according to the parallelogram law. All these quantities can be represented mathematically by vectors, while those physical quantities which have magnitude but not direction, such as volume, mass, or energy, are represented by plain numbers or scalars.

Vectors are defined as mathematical expressions possessing magnitude and direction, which add according to the parallelogram law. Vectors are represented by arrows in the illustrations and will be distinguished from scalar quantities in this text through the use of boldface type ($\mathbf{P}$). In longhand writing, a vector may be denoted by drawing a short arrow above the letter used to represent it ($\vec{P}$) or by underlining the letter ($\hat{P}$). The last method may be preferred since underlining can also be used on a typewriter or computer. The magnitude of a vector defines the length of the arrow used to represent the vector. In this text, italic type will be used to denote the magnitude of a vector. Thus, the magnitude of the vector $\mathbf{P}$ will be denoted by $P$.

A vector used to represent a force acting on a given particle has a well-defined point of application, namely, the particle itself. Such a vector is said to be a fixed, or bound, vector and cannot be moved without modifying the conditions of the problem. Other physical quantities, however, such as couples (see Chap. 3), are represented by vectors which may be freely moved in space; these
vectors are called free vectors. Still other physical quantities, such as forces acting on a rigid body (see Chap. 3), are represented by vectors which can be moved, or slid, along their lines of action; they are known as sliding vectors.†

Two vectors which have the same magnitude and the same direction are said to be equal, whether or not they also have the same point of application (Fig. 2.4); equal vectors may be denoted by the same letter.

The negative vector of a given vector \( \mathbf{P} \) is defined as a vector having the same magnitude as \( \mathbf{P} \) and a direction opposite to that of \( \mathbf{P} \) (Fig. 2.5); the negative of the vector \( \mathbf{P} \) is denoted by \( -\mathbf{P} \). The vectors \( \mathbf{P} \) and \( -\mathbf{P} \) are commonly referred to as equal and opposite vectors. Clearly, we have

\[
\mathbf{P} + (-\mathbf{P}) = 0
\]

### 2.4 ADDITION OF VECTORS

We saw in the preceding section that, by definition, vectors add according to the parallelogram law. Thus, the sum of two vectors \( \mathbf{P} \) and \( \mathbf{Q} \) is obtained by attaching the two vectors to the same point \( A \) and constructing a parallelogram, using \( \mathbf{P} \) and \( \mathbf{Q} \) as two sides of the parallelogram (Fig. 2.6). The diagonal that passes through \( A \) represents the sum of the vectors \( \mathbf{P} \) and \( \mathbf{Q} \), and this sum is denoted by \( \mathbf{P} + \mathbf{Q} \). The fact that the sign \(+\) is used to denote both vector and scalar addition should not cause any confusion if vector and scalar quantities are always carefully distinguished. Thus, we should note that the magnitude of the vector \( \mathbf{P} + \mathbf{Q} \) is not, in general, equal to the sum \( \mathbf{P} + \mathbf{Q} \) of the magnitudes of the vectors \( \mathbf{P} \) and \( \mathbf{Q} \).

Since the parallelogram constructed on the vectors \( \mathbf{P} \) and \( \mathbf{Q} \) does not depend upon the order in which \( \mathbf{P} \) and \( \mathbf{Q} \) are selected, we conclude that the addition of two vectors is commutative, and we write

\[
\mathbf{P} + \mathbf{Q} = \mathbf{Q} + \mathbf{P}
\]  
(2.1)

†Some expressions have magnitude and direction, but do not add according to the parallelogram law. While these expressions may be represented by arrows, they cannot be considered as vectors.

A group of such expressions is the finite rotations of a rigid body. Place a closed book on a table in front of you, so that it lies in the usual fashion, with its front cover up and its binding to the left. Now rotate it through 180° about an axis parallel to the binding (Fig. 2.3a); this rotation may be represented by an arrow of length equal to 180 units and oriented as shown. Picking up the book as it lies in its new position, rotate
From the parallelogram law, we can derive an alternative method for determining the sum of two vectors. This method, known as the **triangle rule**, is derived as follows. Consider Fig. 2.6, where the sum of the vectors \( \mathbf{P} \) and \( \mathbf{Q} \) has been determined by the parallelogram law. Since the side of the parallelogram opposite \( \mathbf{Q} \) is equal to \( \mathbf{Q} \) in magnitude and direction, we could draw only half of the parallelogram (Fig. 2.7a). The sum of the two vectors can thus be found by **arranging \( \mathbf{P} \) and \( \mathbf{Q} \) in tip-to-tail fashion and then connecting the tail of \( \mathbf{P} \) with the tip of \( \mathbf{Q} \)**. In Fig. 2.7b, the other half of the parallelogram is considered, and the same result is obtained. This confirms the fact that vector addition is commutative.

The **subtraction** of a vector is defined as the addition of the corresponding negative vector. Thus, the vector \( \mathbf{P} - \mathbf{Q} \) representing the difference between the vectors \( \mathbf{P} \) and \( \mathbf{Q} \) is obtained by adding to \( \mathbf{P} \) the negative vector \( -\mathbf{Q} \) (Fig. 2.8). We write

\[
\mathbf{P} - \mathbf{Q} = \mathbf{P} + (-\mathbf{Q}) \tag{2.2}
\]

Here again we should observe that, while the same sign is used to denote both vector and scalar subtraction, confusion will be avoided if care is taken to distinguish between vector and scalar quantities.

We will now consider the **sum of three or more vectors**. The sum of three vectors \( \mathbf{P}, \mathbf{Q}, \) and \( \mathbf{S} \) will, **by definition**, be obtained by first adding the vectors \( \mathbf{P} \) and \( \mathbf{Q} \) and then adding the vector \( \mathbf{S} \) to the vector \( \mathbf{P} + \mathbf{Q} \). We thus write

\[
\mathbf{P} + \mathbf{Q} + \mathbf{S} = (\mathbf{P} + \mathbf{Q}) + \mathbf{S} \tag{2.3}
\]

Similarly, the sum of four vectors will be obtained by adding the fourth vector to the sum of the sum of the first three. It follows that the sum of any number of vectors can be obtained by applying repeatedly the parallelogram law to successive pairs of vectors until all the given vectors are replaced by a single vector.

\[
\text{it now through } 180^\circ \text{ about a horizontal axis perpendicular to the binding (Fig. 2.3b); this second rotation may be represented by an arrow 180 units long and oriented as shown. But the book could have been placed in this final position through a single } 180^\circ \text{ rotation about a vertical axis (Fig. 2.3c). We conclude that the sum of the two } 180^\circ \text{ rotations represented by arrows directed respectively along the } z \text{ and } x \text{ axes is a } 180^\circ \text{ rotation represented by an arrow directed along the } y \text{ axis (Fig. 2.3d). Clearly, the finite rotations of a rigid body do not obey the parallelogram law of addition; therefore, they cannot be represented by vectors.}
\]
If the given vectors are coplanar, i.e., if they are contained in the same plane, their sum can be easily obtained graphically. For this case, the repeated application of the triangle rule is preferred to the application of the parallelogram law. In Fig. 2.9 the sum of three vectors $\mathbf{P}$, $\mathbf{Q}$, and $\mathbf{S}$ was obtained in that manner. The triangle rule was first applied to obtain the sum $\mathbf{P} + \mathbf{Q}$ of the vectors $\mathbf{P}$ and $\mathbf{Q}$; it was applied again to obtain the sum of the vectors $\mathbf{P} + \mathbf{Q}$ and $\mathbf{S}$. The determination of the vector $\mathbf{P} + \mathbf{Q}$, however, could have been omitted and the sum of the three vectors could have been obtained directly, as shown in Fig. 2.10, by arranging the given vectors in tip-to-tail fashion and connecting the tail of the first vector with the tip of the last one. This is known as the polygon rule for the addition of vectors.

We observe that the result obtained would have been unchanged if, as shown in Fig. 2.11, the vectors $\mathbf{Q}$ and $\mathbf{S}$ had been replaced by their sum $\mathbf{Q} + \mathbf{S}$. We may thus write

$$\mathbf{P} + \mathbf{Q} + \mathbf{S} = (\mathbf{P} + \mathbf{Q}) + \mathbf{S} = \mathbf{P} + (\mathbf{Q} + \mathbf{S}) \quad (2.4)$$

which expresses the fact that vector addition is associative. Recalling that vector addition has also been shown, in the case of two vectors, to be commutative, we write

$$\mathbf{P} + \mathbf{Q} + \mathbf{S} = (\mathbf{P} + \mathbf{Q}) + \mathbf{S} = \mathbf{S} + (\mathbf{P} + \mathbf{Q}) = \mathbf{S} + (\mathbf{Q} + \mathbf{P}) \quad (2.5)$$

This expression, as well as others which may be obtained in the same way, shows that the order in which several vectors are added together is immaterial (Fig. 2.12).

**Product of a Scalar and a Vector.** Since it is convenient to denote the sum $\mathbf{P} + \mathbf{P}$ by $2\mathbf{P}$, the sum $\mathbf{P} + \mathbf{P} + \mathbf{P}$ by $3\mathbf{P}$, and, in general, the sum of $n$ equal vectors $\mathbf{P}$ by the product $n\mathbf{P}$, we will define the product $n\mathbf{P}$ of a positive integer $n$ and a vector $\mathbf{P}$ as a vector having the same direction as $\mathbf{P}$ and the magnitude $n\mathbf{P}$. Extending this definition to include all scalars, and recalling the definition of a negative vector given in Sec. 2.3, we define the product $k\mathbf{P}$ of a scalar $k$ and a vector $\mathbf{P}$ as a vector having the same direction as $\mathbf{P}$ (if $k$ is positive), or a direction opposite to that of $\mathbf{P}$ (if $k$ is negative), and a magnitude equal to the product of $P$ and of the absolute value of $k$ (Fig. 2.13).

### 2.5 RESULTANT OF SEVERAL CONCURRENT FORCES

Consider a particle $A$ acted upon by several coplanar forces, i.e., by several forces contained in the same plane (Fig. 2.14a). Since the forces considered here all pass through $A$, they are also said to be concurrent. The vectors representing the forces acting on $A$ may be added by the polygon rule (Fig. 2.14b). Since the use of the polygon rule is equivalent to the repeated application of the parallelogram law, the vector $\mathbf{R}$ thus obtained represents the resultant of the given concurrent forces, i.e., the single force which has the same effect on
the particle \( A \) as the given forces. As indicated above, the order in which the vectors \( \mathbf{P} \), \( \mathbf{Q} \), and \( \mathbf{S} \) representing the given forces are added together is immaterial.

2.6 Resolution of a Force into Components

We have seen that two or more forces acting on a particle may be replaced by a single force which has the same effect on the particle. Conversely, a single force \( \mathbf{F} \) acting on a particle may be replaced by two or more forces which, together, have the same effect on the particle. These forces are called the components of the original force \( \mathbf{F} \), and the process of substituting them for \( \mathbf{F} \) is called resolving the force \( \mathbf{F} \) into components.

Clearly, for each force \( \mathbf{F} \) there exist an infinite number of possible sets of components. Sets of two components \( \mathbf{P} \) and \( \mathbf{Q} \) are the most important as far as practical applications are concerned. But, even then, the number of ways in which a given force \( \mathbf{F} \) may be resolved into two components is unlimited (Fig. 2.15). Two cases are of particular interest:

1. One of the Two Components, \( \mathbf{P} \), Is Known. The second component, \( \mathbf{Q} \), is obtained by applying the triangle rule and joining the tip of \( \mathbf{P} \) to the tip of \( \mathbf{F} \) (Fig. 2.16); the magnitude and direction of \( \mathbf{Q} \) are determined graphically or by trigonometry. Once \( \mathbf{Q} \) has been determined, both components \( \mathbf{P} \) and \( \mathbf{Q} \) should be applied at \( A \).

2. The Line of Action of Each Component Is Known. The magnitude and sense of the components are obtained by applying the parallelogram law and drawing lines, through the tip of \( \mathbf{F} \), parallel to the given lines of action (Fig. 2.17). This process leads to two well-defined components, \( \mathbf{P} \) and \( \mathbf{Q} \), which can be determined graphically or computed trigonometrically by applying the law of sines.

Many other cases can be encountered; for example, the direction of one component may be known, while the magnitude of the other component is to be as small as possible (see Sample Prob. 2.2). In all cases the appropriate triangle or parallelogram which satisfies the given conditions is drawn.
SAMPLE PROBLEM 2.1

The two forces $P$ and $Q$ act on a bolt $A$. Determine their resultant.

SOLUTION

**Graphical Solution.** A parallelogram with sides equal to $P$ and $Q$ is drawn to scale. The magnitude and direction of the resultant are measured and found to be

$$ R = 98 \text{ N} \quad \alpha = 35^\circ 
\Rightarrow R = 98 \text{ N} \angle 35^\circ 

The triangle rule may also be used. Forces $P$ and $Q$ are drawn in tip-to-tail fashion. Again the magnitude and direction of the resultant are measured.

$$ R = 98 \text{ N} \quad \alpha = 35^\circ 
\Rightarrow R = 98 \text{ N} \angle 35^\circ 

**Trigonometric Solution.** The triangle rule is again used; two sides and the included angle are known. We apply the law of cosines.

$$
R^2 = P^2 + Q^2 - 2PQ \cos B
R^2 = (40 \text{ N})^2 + (60 \text{ N})^2 - 2(40 \text{ N})(60 \text{ N}) \cos 155^\circ
R = 97.73 \text{ N}

Now, applying the law of sines, we write

$$
\frac{\sin A}{Q} = \frac{\sin B}{R} \quad \Rightarrow \quad \frac{\sin A}{60 \text{ N}} = \frac{\sin 155^\circ}{97.73 \text{ N}}
$$

Solving Eq. (1) for $\sin A$, we have

$$
\sin A = \frac{(60 \text{ N}) \sin 155^\circ}{97.73 \text{ N}}
$$

Using a calculator, we first compute the quotient, then its arc sine, and obtain

$$ A = 15.04^\circ \quad \alpha = 20^\circ + A = 35.04^\circ 

We use 3 significant figures to record the answer (cf. Sec. 1.6):

$$ R = 97.7 \text{ N} \angle 35.0^\circ 

**Alternative Trigonometric Solution.** We construct the right triangle $BCD$ and compute

$$ CD = (60 \text{ N}) \sin 25^\circ = 25.36 \text{ N} 
BD = (60 \text{ N}) \cos 25^\circ = 54.38 \text{ N} 

Then, using triangle $ACD$, we obtain

$$
\tan A = \frac{25.36 \text{ N}}{94.38 \text{ N}} \quad \Rightarrow \quad A = 15.04^\circ 
R = \frac{25.36 \text{ N}}{\sin A} \quad \Rightarrow \quad R = 97.73 \text{ N} 
$$

Again,

$$ \alpha = 20^\circ + A = 35.04^\circ \quad R = 97.7 \text{ N} \angle 35.0^\circ $$
SAMPLE PROBLEM 2.2

A barge is pulled by two tugboats. If the resultant of the forces exerted by the tugboats is a 5000-lb force directed along the axis of the barge, determine (a) the tension in each of the ropes knowing that \( \alpha = 45^\circ \), (b) the value of \( \alpha \) for which the tension in rope 2 is minimum.

SOLUTION

a. Tension for \( \alpha = 45^\circ \). Graphical Solution. The parallelogram law is used; the diagonal (resultant) is known to be equal to 5000 lb and to be directed to the right. The sides are drawn parallel to the ropes. If the drawing is done to scale, we measure

\[
T_1 = 3700 \text{ lb} \quad T_2 = 2600 \text{ lb}
\]

Trigonometric Solution. The triangle rule can be used. We note that the triangle shown represents half of the parallelogram shown above. Using the law of sines, we write

\[
\frac{T_1}{\sin 45^\circ} = \frac{T_2}{\sin 30^\circ} = \frac{5000 \text{ lb}}{\sin 105^\circ}
\]

With a calculator, we first compute and store the value of the last quotient. Multiplying this value successively by \( \sin 45^\circ \) and \( \sin 30^\circ \), we obtain

\[
T_1 = 3660 \text{ lb} \quad T_2 = 2590 \text{ lb}
\]

b. Value of \( \alpha \) for Minimum \( T_2 \). To determine the value of \( \alpha \) for which the tension in rope 2 is minimum, the triangle rule is again used. In the sketch shown, line 1-1' is the known direction of \( T_1 \). Several possible directions of \( T_2 \) are shown by the lines 2-2'. We note that the minimum value of \( T_2 \) occurs when \( T_1 \) and \( T_2 \) are perpendicular. The minimum value of \( T_2 \) is

\[
T_2 = (5000 \text{ lb}) \sin 30^\circ = 2500 \text{ lb}
\]

Corresponding values of \( T_1 \) and \( \alpha \) are

\[
T_1 = (5000 \text{ lb}) \cos 30^\circ = 4330 \text{ lb}
\]

\[
\alpha = 90^\circ - 30^\circ = 60^\circ
\]
SOLVING PROBLEMS ON YOUR OWN

The preceding sections were devoted to the parallelogram law for the addition of vectors and to its applications.

Two sample problems were presented. In Sample Prob. 2.1, the parallelogram law was used to determine the resultant of two forces of known magnitude and direction. In Sample Prob. 2.2, it was used to resolve a given force into two components of known direction.

You will now be asked to solve problems on your own. Some may resemble one of the sample problems; others may not. What all problems and sample problems in this section have in common is that they can be solved by the direct application of the parallelogram law.

Your solution of a given problem should consist of the following steps:

1. **Identify which of the forces are the applied forces and which is the resultant.** It is often helpful to write the vector equation which shows how the forces are related. For example, in Sample Prob. 2.1 we would have

   \[ \mathbf{R} = \mathbf{P} + \mathbf{Q} \]

   You may want to keep that relation in mind as you formulate the next part of your solution.

2. **Draw a parallelogram with the applied forces as two adjacent sides and the resultant as the included diagonal** (Fig. 2.2). Alternatively, you can use the triangle rule, with the applied forces drawn in tip-to-tail fashion and the resultant extending from the tail of the first vector to the tip of the second (Fig. 2.7).

3. **Indicate all dimensions.** Using one of the triangles of the parallelogram, or the triangle constructed according to the triangle rule, indicate all dimensions—whether sides or angles—and determine the unknown dimensions either graphically or by trigonometry. If you use trigonometry, remember that the law of cosines should be applied first if two sides and the included angle are known [Sample Prob. 2.1], and the law of sines should be applied first if one side and all angles are known [Sample Prob. 2.2].

If you have had prior exposure to mechanics, you might be tempted to ignore the solution techniques of this lesson in favor of resolving the forces into rectangular components. While this latter method is important and will be considered in the next section, use of the parallelogram law simplifies the solution of many problems and should be mastered at this time.