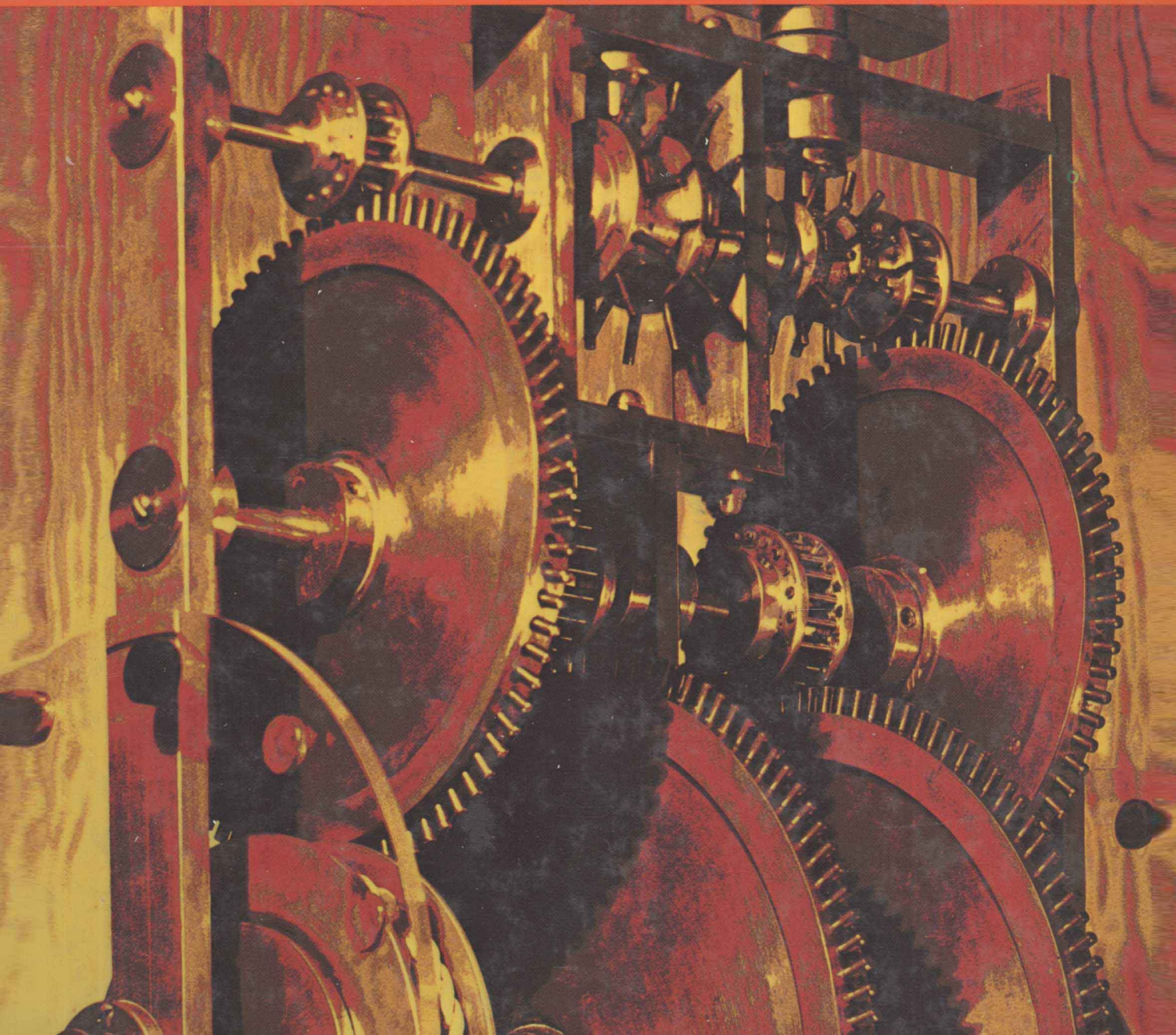
Ferdinand P. Beer and E. Russell Johnston, Jr.

Vector Mechanics for Engineers

STATICS

Fourth Edition



Vector Mechanics for Engineers

STATICS

Fourth Edition

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One of the many inventions sketched in Leonardo da Vinci's notebooks is a mechanical, weight-driven clock. IBM maintains and exhibits a collection of working models made from the sketches, and our cover is derived from a photograph of the clock model. The clock has two separate escapements, one for minutes and one for hours. We thank IBM for their permission to photograph the model, and especially appreciate the cooperation of Mr. Herbert E. Pedersen, director of the IBM Touring Exhibition Program. (Photograph by Felix Cooper.)

VECTOR MECHANICS FOR ENGINEERS: **Statics**

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Preface

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. It is hoped that this text, designed for the first course in statics offered in the sophomore year, and the volume that follows, *Vector Mechanics for Engineers: Dynamics*, will help the instructor achieve this goal.†

Vector algebra is introduced early in the text and used in the presentation and the discussion of the fundamental principles of mechanics. Vector methods are also used to solve many problems, particularly three-dimensional problems where their application results in a simpler and more concise solution. 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 algebra is presented chiefly as a convenient tool.‡

One of the characteristics of the approach used in these volumes is that the mechanics of *particles* has been 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 more difficult concepts. In this volume, for example, the statics of particles is treated first (Chap. 2); after the rules of addition and subtraction of vectors have been 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. In the volume on 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 may 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.

† Both texts are also available in a single volume, *Vector Mechanics for Engineers: Statics and Dynamics*, fourth edition.

‡ In a parallel text, *Mechanics for Engineers: Statics*, third edition, the use of vector algebra is limited to the addition and subtraction of vectors.

Since this text is designed for a first course in statics, new concepts have been presented in simple terms and every step explained in detail. On the other hand, by discussing the broader aspects of the problems considered, a definite maturity of approach has been achieved. For example, the concepts of partial constraints and of static indeterminacy are introduced early in the text and used throughout.

The fact that mechanics is essentially a *deductive* science based on a few fundamental principles has been 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 have been considered first. Thus the statics of particles precedes the statics of rigid bodies, and problems involving internal forces are postponed until Chap. 6. Also, 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.

Free-body diagrams are introduced early, and their importance is emphasized throughout the text. Color has been used to distinguish forces from other elements of the free-body diagrams. 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. Free-body diagrams 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. This approach is particularly useful as a preparation for the study of the dynamics of rigid bodies. As will be shown in the volume on dynamics, 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 may be achieved.

Because of the current trend among American engineers to adopt the international system of units (SI metric units), the SI units most frequently used in mechanics have been introduced in Chap. 1 and are used throughout the text. Approximately half the sample problems and 60 percent of the problems to be assigned have been stated in these units, while the remainder retain U.S. customary units. The authors believe that this approach will best serve the needs of the students, who will be entering the engineering profession during the period of transition from one system of units to the other. It also should be recognized that the passage from one system to the other 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

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be required to determine its mass in slugs (or lb · sec²/ft). The authors, therefore, believe that problem assignments should include both systems of units. The actual distribution of assigned problems between the two systems of units, however, has been left to the instructor, and a sufficient number of problems of each type have been provided so that four complete lists of assignments may be selected with the proportion of problems stated in SI units set anywhere between 50 and 75 percent. If so desired, two complete lists of assignments may also be selected from problems stated in SI units only and two others from problems stated in U.S. customary units.

A large number of optional sections have been included. These sections are indicated by asterisks and may thus easily be distinguished from those which form the core of the basic statics course. They may be omitted without prejudice to the understanding of the rest of the text. Among the topics covered in these additional sections are 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. 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 motion of rigid bodies in three dimensions.

The material presented in the text and most of the problems require no previous mathematical knowledge beyond algebra, trigonometry, and elementary calculus, and all the elements of vector algebra necessary to the understanding of the text have been carefully presented in Chaps. 2 and 3. In general, a greater emphasis has been placed on the correct understanding of the basic mathematical concepts involved 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. The presentation of numerical solutions takes into account the universal use of calculators by engineering students and instructions on the proper use of calculators for the solution of typical statics problems have been included in Chap. 2.

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. The body of the text has been 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 may 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 sample problems have been set up in much the same form that students will use in solving the assigned problems. They thus serve the double purpose of amplifying the text and demonstrating the type

of neat and orderly work that students should cultivate in their own solutions. Most of the problems to be assigned 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 basic principles of mechanics. The problems have been grouped according to the portions of material they illustrate and have been arranged in order of increasing difficulty. Problems requiring special attention have been indicated by asterisks. Answers to all even-numbered problems are given at the end of the book.

The authors wish to acknowledge gratefully the many helpful comments and suggestions offered by the users of the previous editions of *Mechanics for Engineers* and of *Vector Mechanics for Engineers.*

Ferdinand P. Beer
E. Russell Johnston, Jr.

List of Symbols

a	Constant; radius; distance
A, B, C, . . .	Reactions at supports and connections
$A, B, C, \ldots$	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
$I, I_x, \ldots$	Moment of inertia
$\bar{I}$	Centroidal moment of inertia
$I_{xy}, \ldots$	Product of inertia
J	Polar moment of inertia
k	Spring constant
k_x, k_y, k_O	Radius of gyration
$\bar{k}$	Centroidal radius of gyration
l	Length
L	Length; span
m	Mass
M	Couple; moment
$\mathbf{M}_O$	Moment about point O
$\mathbf{M}_O^R$	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
$\mathbf{S}$	Force; vector
t	Thickness
$\mathbf{T}$	Force
T	Tension
U	Work
$\mathbf{V}$	Vector product; shearing force
V	Volume; potential energy; shear
w	Load per unit length
$\mathbf{W}$, W	Weight; load
x, y, z	Rectangular coordinates; distances
$\bar{x}$, $\bar{y}$, $\bar{z}$	Rectangular coordinates of centroid or center of gravity
α, β, γ	Angles
γ	Specific weight
δ	Elongation
$\delta\mathbf{r}$	Virtual displacement
δU	Virtual work
$\boldsymbol{\lambda}$	Unit vector along a line
η	Efficiency
θ	Angular coordinate; angle; polar coordinate
μ	Coefficient of friction
ρ	Density
ϕ	Angle of friction; angle

Contents

Preface xi
List of Symbols xv

CHAPTER ONE INTRODUCTION 1
1.1 What Is Mechanics? 1
1.2 Fundamental Concepts and Principles 2
1.3 Systems of Units 5
1.4 Conversion from One System of Units to Another 10
1.5 Method of Problem Solution 11
1.6 Numerical Accuracy 13

CHAPTER TWO STATICS OF PARTICLES 14
2.1 Introduction 14

Forces in a Plane 14
2.2 Force on a Particle. Resultant of Two Forces 14
2.3 Vectors 15
2.4 Addition of Vectors 16
2.5 Resultant of Several Concurrent Forces 18
2.6 Resolution of a Force into Components 19
2.7 Rectangular Components of a Force. Unit Vectors 24
2.8 Addition of Forces by Summing *x* and *y* Components 26
2.9 Equilibrium of a Particle 31
2.10 Newton's First Law of Motion 32
2.11 Problems Involving the Equilibrium of a Particle. Free-Body Diagram 32

Forces in Space 39
2.12 Rectangular Components of a Force in Space 39
2.13 Force Defined by Its Magnitude and Two Points on Its Line of Action 42
2.14 Addition of Concurrent Forces in Space 43
2.15 Equilibrium of a Particle in Space 48

CHAPTER THREE RIGID BODIES: EQUIVALENT SYSTEMS OF FORCES 55
3.1 Introduction 55
3.2 External and Internal Forces 56

3.3 Principle of Transmissibility. Equivalent Forces 57
3.4 Vector Product of Two Vectors 58
3.5 Vector Products Expressed in Terms of Rectangular Components 60
3.6 Moment of a Force about a Point 62
3.7 Varignon's Theorem 64
3.8 Rectangular Components of the Moment of a Force 64
3.9 Scalar Product of Two Vectors 72
3.10 Mixed Triple Product of Three Vectors 74
3.11 Moment of a Force about a Given Axis 76
3.12 Moment of a Couple 82
3.13 Equivalent Couples 83
3.14 Addition of Couples 86
3.15 Couples May Be Represented by Vectors 86
3.16 Resolution of a Given Force into a Force at *O* and a Couple 87
3.17 Reduction of a System of Forces to One Force and One Couple 95
3.18 Equivalent Systems of Forces 96
3.19 Equipollent Systems of Vectors 97
3.20 Further Reduction of a System of Forces 97
*3.21 Reduction of a System of Forces to a Wrench 100

CHAPTER FOUR EQUILIBRIUM OF RIGID BODIES 114
4.1 Introduction 114
4.2 Free-Body Diagram 115

Equilibrium in Two Dimensions 116
4.3 Reactions at Supports and Connections for a Two-dimensional Structure 116
4.4 Equilibrium of a Rigid Body in Two Dimensions 118
4.5 Statically Indeterminate Reactions. Partial Constraints 120
4.6 Equilibrium of a Two-Force Body 132
4.7 Equilibrium of a Three-Force Body 133

Equilibrium in Three Dimensions 138
4.8 Reactions at Supports and Connections for a Three-dimensional Structure 138
4.9 Equilibrium of a Rigid Body in Three Dimensions 140

CHAPTER FIVE DISTRIBUTED FORCES: CENTROIDS AND CENTERS OF GRAVITY 154
5.1 Introduction 154

Areas and Lines 155
5.2 Center of Gravity of a Two-dimensional Body 155
5.3 Centroids of Areas and Lines 156

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5.4 First Moments of Areas and Lines 157
5.5 Composite Plates and Wires 160
5.6 Determination of Centroids by Integration 170
5.7 Theorems of Pappus-Guldinus 172
*5.8 Distributed Loads on Beams 181
*5.9 Forces on Submerged Surfaces 182

Volumes 188
5.10 Center of Gravity of a Three-dimensional Body. Centroid of a Volume 188
5.11 Composite Bodies 191
5.12 Determination of Centroids of Volumes by Integration 191

CHAPTER SIX ANALYSIS OF STRUCTURES 202
6.1 Introduction 202

Trusses 204
6.2 Definition of a Truss 204
6.3 Simple Trusses 206
6.4 Analysis of Trusses by the Method of Joints 207
*6.5 Joints under Special Loading Conditions 209
*6.6 Space Trusses 211
6.7 Analysis of Trusses by the Method of Sections 216
*6.8 Trusses Made of Several Simple Trusses 217

Frames and Machines 224
6.9 Structures Containing Multiforce Members 224
6.10 Analysis of a Frame 224
6.11 Frames Which Cease to Be Rigid When Detached from Their Supports 226
6.12 Machines 239

CHAPTER SEVEN FORCES IN BEAMS AND CABLES 254
*7.1 Introduction 254
*7.2 Internal Forces in Members 254

Beams 259
*7.3 Various Types of Loading and Support 259
*7.4 Shear and Bending Moment in a Beam 260
*7.5 Shear and Bending-Moment Diagrams 262
*7.6 Relations among Load, Shear, and Bending Moment 267

Cables 275
*7.7 Cables with Concentrated Loads 275
*7.8 Cables with Distributed Loads 276
*7.9 Parabolic Cable 277
*7.10 Catenary 284

CHAPTER EIGHT FRICTION 291
8.1 Introduction 291
8.2 The Laws of Dry Friction. Coefficients of Friction 292
8.3 Angles of Friction 294
8.4 Problems Involving Dry Friction 295
8.5 Wedges 308
8.6 Square-threaded Screws 308
*8.7 Journal Bearings. Axle Friction 315
*8.8 Thrust Bearings. Disk Friction 317
*8.9 Wheel Friction. Rolling Resistance 318
8.10 Belt Friction 324

CHAPTER NINE DISTRIBUTED FORCES: MOMENTS OF INERTIA 333
9.1 Introduction 333

Moments of Inertia of Areas 334
9.2 Second Moment, or Moment of Inertia, of an Area 334
9.3 Determination of the Moment of Inertia of an Area by Integration 336
9.4 Polar Moment of Inertia 337
9.5 Radius of Gyration of an Area 338
9.6 Parallel-Axis Theorem 343
9.7 Moments of Inertia of Composite Areas 344
*9.8 Product of Inertia 354
*9.9 Principal Axes and Principal Moments of Inertia 355
*9.10 Mohr's Circle for Moments and Products of Inertia 358

Moments of Inertia of Masses 366
9.11 Moment of Inertia of a Mass 366
9.12 Parallel-Axis Theorem 368
9.13 Moments of Inertia of Thin Plates 369
9.14 Determination of the Moment of Inertia of a Three-dimensional Body by Integration 370
9.15 Moments of Inertia of Composite Bodies 370
*9.16 Moment of Inertia of a Body with Respect to an Arbitrary Axis through *O*. Mass Products of Inertia 380
*9.17 Ellipsoid of Inertia. Principal Axes of Inertia 381

CHAPTER TEN METHOD OF VIRTUAL WORK 388
*10.1 Introduction 388
*10.2 Work of a Force 389
*10.3 Principle of Virtual Work 391
*10.4 Applications of the Principle of Virtual Work 392
*10.5 Real Machines. Mechanical Efficiency 394

*10.6 Work of a Force during a Finite Displacement 404
*10.7 Potential Energy 406
*10.8 Potential Energy and Equilibrium 407
*10.9 Stability of Equilibrium 408

Index 417
Answers to Even-Numbered Problems 421

CHAPTER ONE
Introduction

1.1. What Is Mechanics? Mechanics may 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 liquids.

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* may 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 may 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.

We shall 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 may 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 may 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 we shall see in Sec. 12.2, this law may be stated as

$$\mathbf{F} = m\mathbf{a} \tag{1.1}$$

where $\mathbf{F}$, m, and $\mathbf{a}$ 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 $\mathbf{F}$ and $-\mathbf{F}$ (Fig. 1.1) of magnitude F given by the formula

$$F = G\frac{Mm}{r^2} \tag{1.2}$$

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 $\mathbf{F}$ and the reaction $-\mathbf{F}$ in Fig. 1.1 are equal and opposite, and they have the same line of action.

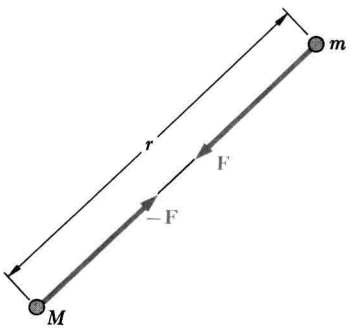

Fig. 1.1

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