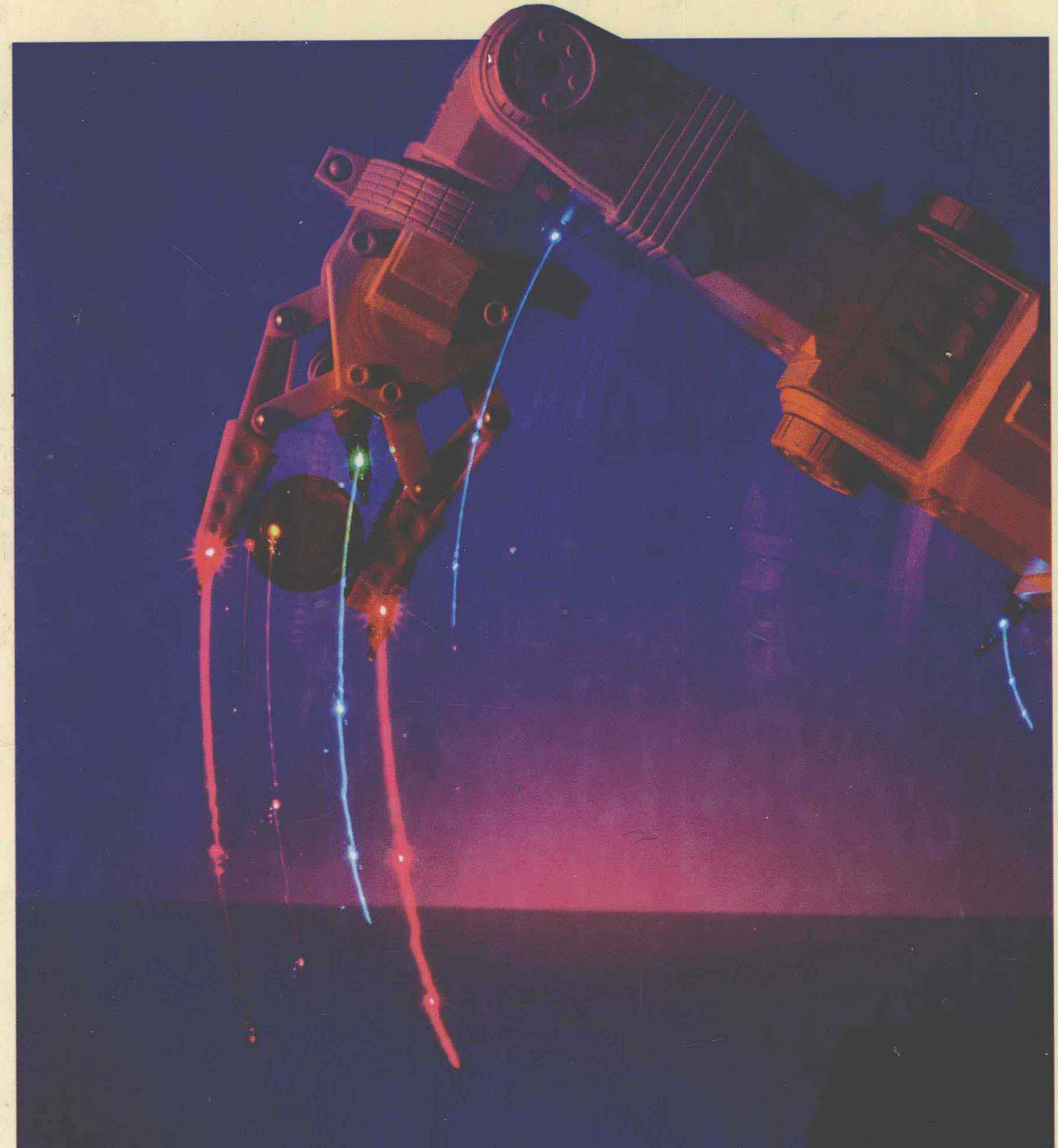
ENGINEERING MECHANICS
DYNAMICS

Seventh Edition



R. C. HIBBELER

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TO THE STUDENT

With the hope that this work
will stimulate an interest in Engineering Mechanics
and provide an acceptable guide to its understanding.

Preface

The main purpose of this book is to provide the student with a clear and thorough presentation of the theory and applications of engineering mechanics. To achieve this objective the author has by no means worked alone, for to a large extent this book has been shaped by the comments and suggestions of more than a hundred reviewers in the teaching profession as well as many of the author's students.

Continued improvements have been made to this the seventh edition. Previous users of the book may first notice that the art work has been enhanced in a multi-color presentation in order to provide the reader with a more realistic and understandable sense of the material. Also, the problem sets have been greatly expanded. Often, several problem statements refer to the same drawing, so that the instructor can reinforce concepts discussed in class. The problem sets also provide a wider variation in the degree of difficulty in problem solutions, and instructors can now select problems that focus on design rather than on analysis.

Although the contents of the book have remained in the same order, the details of some topics have been expanded, some examples have been changed and others have been replaced with new ones. Also, the explanation of many topics has been improved by a careful rewording of selected sentences. The hallmarks of the book, however, remain the same: where necessary, a strong emphasis is placed on drawing a free-body diagram, and the importance of selecting an appropriate coordinate system and associated sign convention for vector components is stressed when the equations of mechanics are applied.

Organization and Approach. The contents of each chapter are organized into well-defined sections. Selected groups of sections contain an explanation of specific topics, illustrative example problems, and a set of homework problems. The topics within each section are placed into subgroups defined by boldface titles. The purpose of this is to present a structured method for introducing each new definition or concept, and to make the book convenient for later reference and review.

A ''procedure for analysis'' is given at the end of many sections of the book in order to provide the student with a review or summary of the material and a logical and orderly method to follow when applying the theory. As in the previous editions, the example problems are solved using this outlined method in order to clarify its numerical application. It is to be understood, however, that once the relevant principles have been mastered and enough confidence and judgment have been obtained, the student can then develop his or her own procedures for solving problems. In most cases, it is felt that the first step in any procedure should require drawing a diagram. By doing so, the student forms the habit of tabulating the necessary data while focusing on the physical aspects of the problem and its associated geometry. If this step is correctly performed, applying the relevant equations of mechanics becomes somewhat methodical, since the data can be taken directly from the diagram. This step is particularly important when solving problems involving equilibrium, and for this reason, drawing a free-body diagram is strongly emphasized throughout the book.

Since mathematics provides a systematic means of applying the principles of mechanics, the student is expected to have prior knowledge of algebra, geometry, trigonometry, and, for complete coverage, some calculus. Vector analysis is introduced at points where it is most applicable. Its use often provides a convenient means for presenting concise derivations of the theory, and it makes possible a simple and systematic solution of many complicated three-dimensional problems. Occasionally, the example problems are solved using more than one method of analysis so that the student develops the ability to use mathematics as a tool whereby the solution of any problem may be carried out in the most direct and effective manner.

Problems. Numerous problems in the book depict realistic situations encountered in engineering practice. It is hoped that this realism will both stimulate the student's interest in engineering mechanics and provide a means for developing the skill to reduce any such problem from its physical description to a model or symbolic representation to which the principles of mechanics may be applied. As in the previous edition, an effort has been made to include some problems which may be solved using a numerical procedure executed on either a desktop computer or a programmable pocket calculator. Suitable numerical techniques along with associated computer programs are given in Appendix B. The intent here is to broaden the student's capacity for using other forms of mathematical analysis *without* sacrificing the time needed to focus on the application of the principles of mechanics. Problems of this type which either can or must be solved using numerical procedures are identified by a ''square'' symbol (■) preceding the problem number.

Throughout the text there is an approximate balance of problems using either SI or FPS units. Furthermore, in any set, an attempt has been made to arrange the problems in order of increasing difficulty.* The answers to all but every fourth problem are listed in the back of the book. To alert the user to a problem without a reported answer, an asterisk (*) is placed before the problem number.

Contents. The book is divided into 11 chapters.† In particular, the kinematics of a particle is discussed in Chapter 12, followed by a discussion of particle kinetics in Chapter 13 (equation of motion), Chapter 14 (work and energy), and Chapter 15 (impulse and momentum). The concepts of particle dynamics contained in these four chapters are then summarized in a ''review'' section and the student is given the chance to identify and solve a variety of different types of problems. A similar sequence of presentation is given for the planar motion of a rigid body: Chapter 16 (planar kinematics), Chapter 17 (equations of motion), Chapter 18 (work and energy), and Chapter 19 (impulse and momentum), followed by a summary and review set of problems for these chapters. If desired, it is possible to cover Chapters 12 through 19 in the following order with no loss in continuity: Chapters 12 and 16 (kinematics), Chapters 13 and 17 (equations of motion), Chapters 14 and 18 (work and energy), and Chapters 15 and 19 (impulse and momentum).

Time permitting, some of the material involving three-dimensional rigid-body motion may be included in the course. The kinematics and kinetics of this motion are discussed in Chapters 20 and 21, respectively. Chapter 22 (vibrations) may be included if the student has the necessary mathematical background. Sections of the book which are considered to be beyond the scope of the basic dynamics course are indicated by a star (★) and may be omitted. As in *Statics,* however, this more advanced material provides a suitable reference for basic principles when it is covered in other courses.

Acknowledgments. I have endeavored to write this book so that it will appeal to both the student and instructor. Through the years many people have helped in its development and I should like to acknowledge their valued suggestions and comments. Specifically, I wish to thank all the reviewers who contributed to this edition. A particular note of thanks is also given to Professor Will Lidell, Jr., Auburn University at Montgomery for his help and support.

*Review problems, wherever they appear, are presented in random order.

†The first eleven chapters of this sequence form the contents of *Engineering Mechanics: Statics.*

Many thanks are also extended to all my students and to members of the teaching profession who have freely taken the time to offer their suggestions and comments. Since the list is too long to mention, it is hoped that those who have given help in this manner will accept this anonymous recognition. Lastly, I should like to acknowledge the assistance of my wife, Conny, during the time it has taken to prepare the manuscript for publication.

Russell Charles Hibbeler

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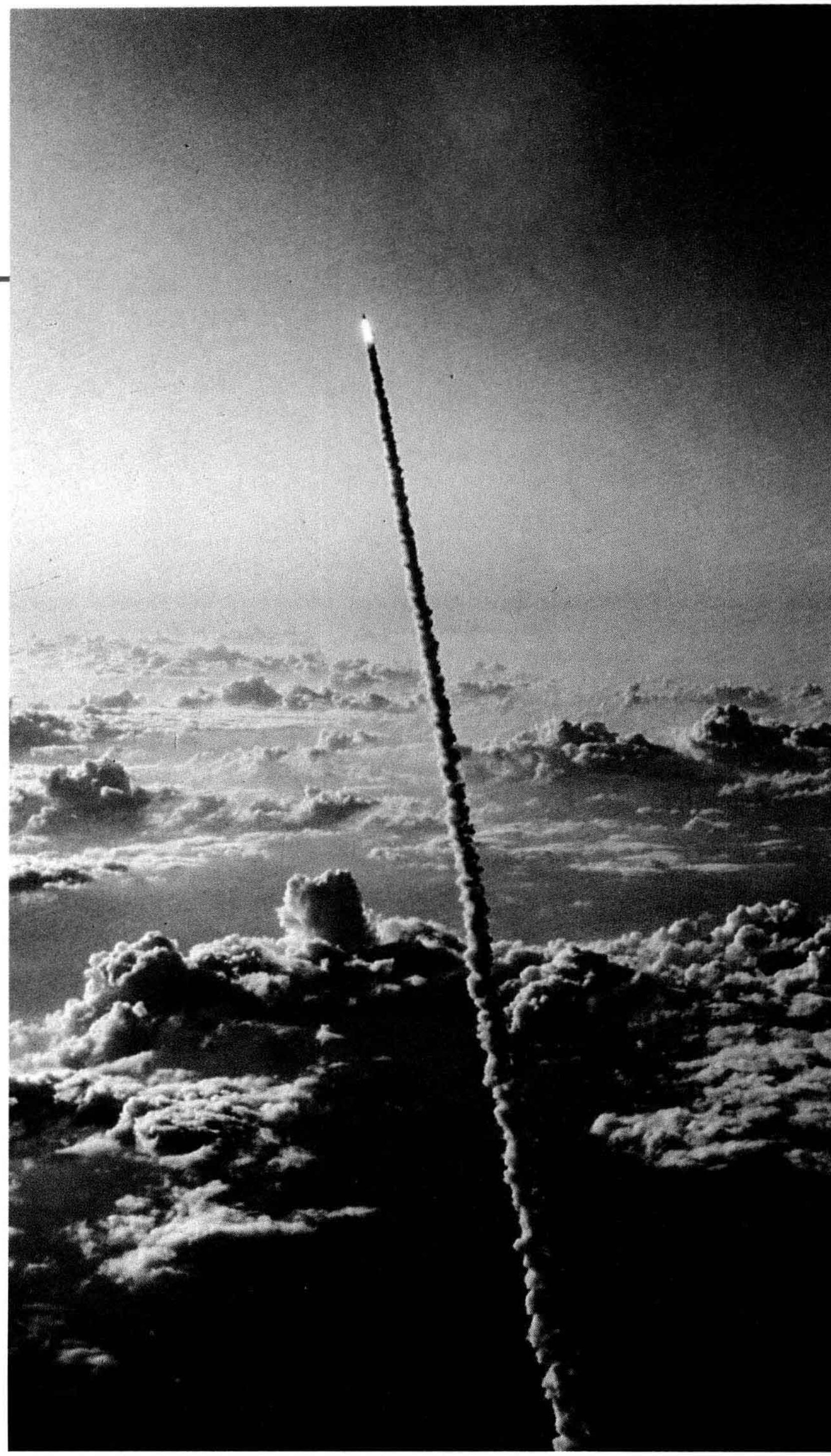
APPENDIXES

Dynamics

Although the space shuttle is a very large object, from a distance its motion can be modeled as a particle. In this chapter we will analyze the geometry of its motion.



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Kinematics of a Particle

In this chapter we will study the geometric aspects of the motion of a particle, measured with respect to both fixed and moving reference frames. The path will be described using several different types of coordinates systems, and the components of the motion along the coordinate axes will be determined. For simplicity, motion along a straight line will be considered before the more general study of motion along a curved path. Once these ideas are fully understood, the analysis of the forces that cause the motion will be presented in the following chapters.

12.1 Rectilinear Kinematics: Continuous Motion

The first part of the study of engineering mechanics is devoted to *statics,* which is concerned with the equilibrium of bodies at rest or moving with constant velocity. The second part is devoted to *dynamics,* which is concerned with bodies having accelerated motion. In this text, the subject of dynamics will be presented in two parts: *kinematics,* which treats only the geometric aspects of motion; and *kinetics,* which is the analysis of the forces causing the motion. In order to understand better the principles involved, particle dynamics will be discussed first, followed by topics in rigid-body dynamics presented in two and then three dimensions.

We will begin our study of dynamics by discussing particle kinematics. Recall that a *particle* has a mass but negligible size and shape. Therefore we must limit application to those objects that have dimensions that are of no consequence in the analysis of the motion. In most problems, one is interested in bodies of finite size, such as rockets, projectiles, or vehicles. Such objects may be considered as particles, provided motion of the body is characterized by motion of its mass center and any rotation of the body is neglected.

Rectilinear Kinematics. A particle can move along either a straight or a curved path. In order to introduce the kinematics of particle motion, we will begin with a study of *rectilinear* or straight-line motion. The kinematics of this motion is characterized by specifying, at any given instant, the particle's position, velocity, and acceleration.

Position. The straight-line path of the particle can be defined using a single coordinate axis s, Fig. 12–1a. The origin O on the path is a fixed point, and from this point the *position vector* $\mathbf{r}$ is used to specify the position of the particle P at any given instant. For *rectilinear motion,* however, the *direction* of $\mathbf{r}$ is *always* along the s axis, and so it never changes. What will change is its magnitude and its sense or arrowhead direction. For analytical work it is therefore convenient to represent $\mathbf{r}$ by an *algebraic scalar s,* representing the *position coordinate* of the particle, Fig. 12–1a. The magnitude of s (and $\mathbf{r}$) is the distance from O to P, usually measured in meters (m) or feet (ft), and the sense (or arrowhead direction of $\mathbf{r}$) is defined by the algebraic sign of s. Although the choice is arbitrary, in this case s is positive since the coordinate axis is positive to the right of the origin. Likewise, it is negative if the particle is located to the left of O.

Displacement. The *displacement* of the particle is defined as the *change* in its *position.* For example, if the particle moves from P to P', Fig. 12–1b, the displacement is $\Delta\mathbf{r} = \mathbf{r}' - \mathbf{r}$. Using algebraic scalars to represent $\Delta\mathbf{r}$, we also have

$$\Delta s = s' - s$$

Here Δs is *positive* since the particle's final position is to the *right* of its initial position, i.e., $s' > s$. Likewise, if the final position is to the *left* of its initial position, Δs is *negative.*

Since the displacement of a particle is a vector quantity, it should be distinguished from the distance the particle travels. Specifically, the *distance traveled* is a *positive scalar* which represents the total length of path traversed by the particle.

Velocity. If the particle moves through a displacement $\Delta\mathbf{r}$ from P to P' during the time interval Δt, Fig. 12–1b, the *average velocity* of the particle during this time interval is

$$\mathbf{v}_{\text{avg}} = \frac{\Delta\mathbf{r}}{\Delta t}$$

If we take smaller and smaller values of Δt, the magnitude of $\Delta\mathbf{r}$ becomes smaller and smaller. Consequently, the *instantaneous velocity* is defined as $\mathbf{v} = \lim_{\Delta t\to 0} (\Delta\mathbf{r}/\Delta t)$, or