ENGINEERING MECHANICS

DYNAMICS

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ENGINEERING MECHANICS: DYNAMICS

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Dedicated to our children:
Jennifer, Annette, and Nancy
Marshall, Charles, and Catherine

TO THE INSTRUCTOR

Our intention in writing this book is to provide a thorough, rigorous presentation of mechanics, augmented with proven learning techniques for the benefit of instructor and student. Our first objective is to present the topics thoroughly and directly, allowing fundamental principles to emerge through applications to real-world problems. We emphasize concepts, derivations, and interpretations of the general principles, and we discuss the applicability and limitations of each principle. We illustrate that general rules frequently have exceptions; however, we do not dwell on these to the extent that they become a distraction. This book presents, in the clearest form possible, more theorems, more proofs, and more explanation than you will find in most introductory engineering mechanics texts.

Our second objective is unique. We have attempted to integrate learning principles and teaching techniques that improve students' ability to grasp and absorb concepts. In general, texts in engineering mechanics focus exclusively on the technical principles, with no structure to increase student comprehension. The integrated use of learning aids in this book is based on our experience that students can be taught effective study habits while they learn mechanics.

Each chapter in this book is organized around the SQ3R study-reading method.[1] This structured approach to reading directs the student to:

- develop a global view of the course material one section or chapter at a time,
- organize the material into manageable pieces and read each piece for content and comprehension, and
- review the material as a coherent whole.

Details of the SQ3R method are described in *To the Student*, which also offers tips on note taking and presents a formal strategy for problem solving. The SQ3R method offers an integrated approach to studying mechanics that requires no additional preparation or follow-up by the instructor.

FEATURES AND DESIGN

To maximize students' success, instructors must capture their interest and attention. The instructor's task is to cultivate students' interest, while educating them in the fundamentals and broad applications of mechanics. To facilitate that task, we attempt to present mechanics in the most exciting and relevant context possible. Since the study of mechanics is not limited to engineering practice, we include examples and illustrations of mechanics at work in many different applications. For a wider perspective and a sense of tradition, we include historical references to balance the technical presentation.

Much of engineering mechanics involves the development of mathematical models of the physical world. In particular, visualization of three-dimensional physical systems and development of appropriate models are of paramount importance. We facilitate this process throughout the text by including pertinent photographs and figures emphasizing a wide range of applications from simple to complex.

1. SQ3R is an acronym for Survey, Question, Read, Recite, and Review (Robinson, 1970).

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Throughout the text, we integrate *Problem-Solving Techniques.* These are not step-by-step solution methods to be used mechanically by the students, but rather summaries of the key concepts and issues that must be considered to solve particular types of problems.

A large number of example and homework problems provide students with ample opportunities to apply concepts and principles to familiar, meaningful situations. The homework problems include relatively simple introductory problems that test students' basic understanding, as well as more challenging problems requiring a deeper grasp of concepts and techniques. They also include problems that are best solved with the aid of computer-based tools (spreadsheets, equation solvers, and plotting tools) and problems that are design-oriented. The design problems are intended to introduce students to the kinds of decisions that will be expected of them throughout their engineering studies and in professional practice and to give them an appreciation for the importance of engineering mechanics in the design process. These problems do not cover all aspects of design, but are intended to introduce students to the challenge of creating a part or a system that will perform a particular function. Icons identify these three types of homework problems:

Challenging

Computer-based

Design-oriented

Solving numerical problems alone is not sufficient to allow students to learn the fundamental concepts that underlie the equations and solution techniques used in mechanics. So, we have included in each chapter *Survey Questions, Checkpoints,* and *Review Questions* that challenge students' understanding of fundamental concepts. These short-answer questions, appropriate for homework assignments or examinations, help students develop a balance between understanding concepts and applying them to problem solving.

TEXT ORGANIZATION

In this book, the dynamics of particles is covered before the dynamics of rigid bodies. That is, particle kinematics is followed immediately by particle kinetics. Next, work-energy and impulse-momentum principles of particles are developed. This sequence is then repeated for planar rigid bodies. This organization allows one type of system to be studied thoroughly before moving on to another.

- Chapter 13 presents a brief introduction to the study of dynamics, followed by an extensive discussion of the concepts of kinematics of particles. Although we emphasize the mathematical basis for the relationships among position, velocity, and acceleration, physical interpretations are offered where appropriate.
- Chapter 14 discusses particle kinetics. The relationship between Newton's law of universal gravitation and his second law of motion is developed. Extensive examples illustrate the application of Newton's laws. We compare the use of Newtonian reference frames with the inertial force method (D'Alembert's principle) and then present an extensive treatment of planetary motion.
- Chapter 15 covers work-energy principles of particles, while Chapter 16 discusses impulse-momentum principles. We have presented these topics in separate chapters in order to clearly identify the main features of each.
- Chapter 17 begins the study of the dynamics of rigid bodies by considering their kinematics. Both two-dimensional and three-dimensional motion are addressed.

- The kinetics of planar motion of rigid bodies is covered in Chapter 18.
- Chapter 19 discusses the work-energy and impulse-momentum principles related to planar motion of rigid bodies.
- As an introduction to vibration of mechanical systems and structural dynamics, Chapter 20 discusses elastic vibrations.
- Chapter 21 covers dynamics of rigid bodies in three dimensions. We discuss energy and momentum principles and derive the relationships for three-dimensional kinetics from the momentum equations.
- Appendices provide reference material on simultaneous algebraic equations and determinants; geometric and trigonometric relations; centroids of lines, areas, and volumes; area moments of inertia; numerical integration; and mass moments of inertia.

HOMEWORK PROBLEMS AND SOLUTIONS

Each homework problem in this book was solved by both the authors and students. We used student problem solvers to help us test the clarity of the problem statements, identify the relative difficulty of the problems, and obtain approximate solution times. As a result of this process, we edited or rewrote some problems. Each section of the Problems at the end of each chapter is arranged approximately in order of increasing time required to obtain the solution. The solution times are given in the *Solution Manual.*

We developed the solutions presented in the *Solution Manual* to be used by students as teaching aids after they have attempted to solve the problems. For the most part, the solutions are fairly detailed and similar in format to those presented in the text for the Examples. This approach allowed us to outline the problem-solving process, as well as give correct answers. The Preface to the *Solution Manual* describes more completely the process used to develop the problems and their solutions.

We believe that we have developed homework problems that are student-tried and student-tested, with solutions that are correct and complete. Nevertheless, we are solely responsible for any errors that exist. So, we welcome any feedback that you may wish to offer. Send corrections, comments, or suggestions for improvements to:

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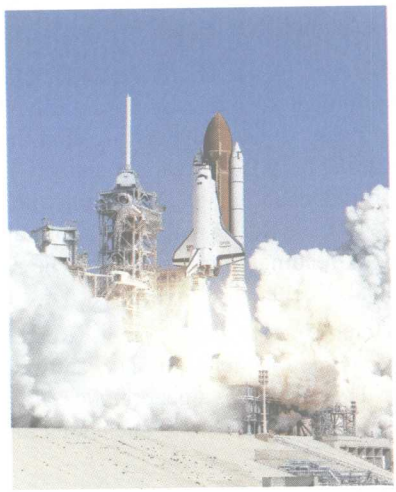
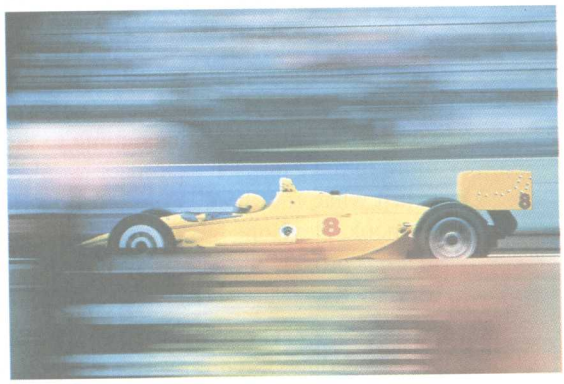
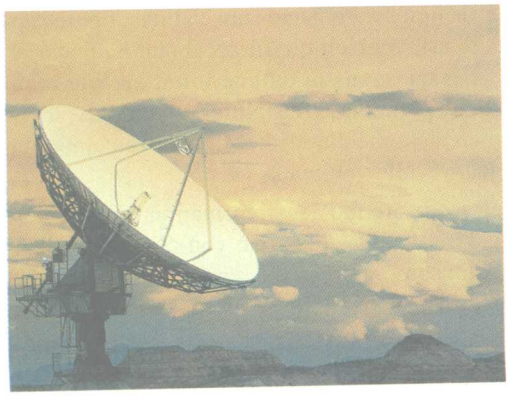
TO THE STUDENT

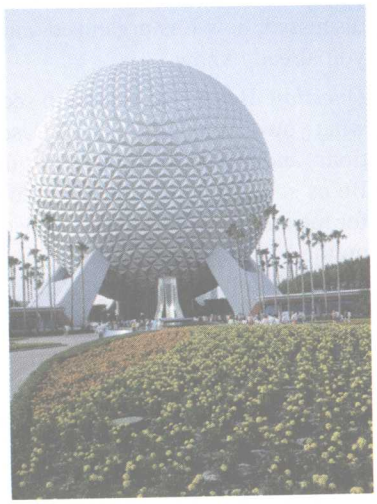
The purpose of this book is to start you on the road to becoming a good engineer. Although fundamentals of physics and mathematics are important in this endeavor, we emphasize applications of physical and mathematical principles to engineering. While physicists are interested primarily in understanding the principles that govern the natural world and mathematicians focus on developing mathematical models to describe natural phenomena, engineers seek to create what does not exist in nature and to enrich people's lives by solving problems that confront modern society. Indeed, an engineer is a problem solver. To be an effective engineer, you must develop a thorough understanding of physical and mathematical principles and their application to the world around you.

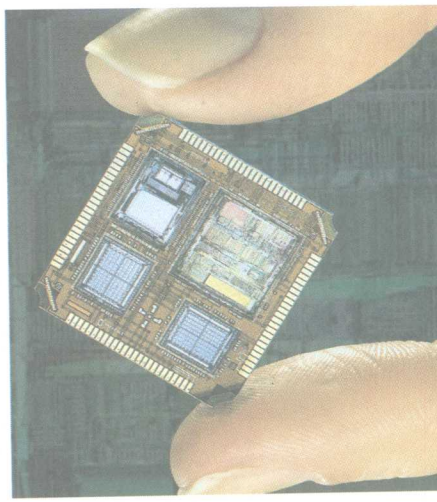
Statics and dynamics form the basis for a large part of your study in engineering. The importance of these fields cannot be overstated. For many of you, the study of statics and dynamics will be your first opportunity to formally apply your skills in algebra, trigonometry, and calculus and to expand your understanding of how the laws of physics apply to real-world problems.











The designs of all engineering systems—from massive space vehicles to tiny microprocessor chips—are based on the fundamental laws of mechanics.

A systematic approach facilitates the solution of problems in mechanics. Knowledge of a set of mathematical tools and techniques for solving problems is not sufficient: You must also have motivation, ingenuity, and an organized strategy for attacking new problems. Our first objective in writing this book on engineering mechanics is to present the topics in a thorough and systematic way so that fundamental principles become evident through application to real-world problems, including examples from everyday engineering practice. We emphasize concepts, derivations, and interpretations of the general principles. Our goal is to give you a clear grasp of major concepts by presenting the simplest and most elementary derivations that are consistent with the demands of rigor. Then, we apply those concepts and derivations in example problems to illustrate their use.

Our second objective is to help you develop your study skills and problem-solving abilities. These cannot always be developed intuitively, but the use of problem-solving strategies can accelerate their development. We present such strategies, which you can apply to become a more efficient problem solver.

STUDYING AND LEARNING TOOLS

Engineering is a challenging field, both as a student and as a professional. To succeed, you must develop effective study habits, adding structure and discipline to your routine. We offer the following tools designed to help you accomplish this goal.

Reading—The SQ3R Method The process of reading a textbook for understanding is not the same as that of reading a novel for entertainment. One does not ordinarily skim over a novel to get the high points, jump to the last pages to learn the ending, and then go back to fill in the gaps. This approach would defeat the purpose of reading a novel. However, it is just what you should do to maximize your understanding and retention when reading a textbook. Developed by Francis Robinson (1970), the SQ3R method is a formal procedure that has proven effective in improving textbook reading comprehension. The name SQ3R (or SQRRR) stands for Survey, Question, Read, Recite, and Review.

- *Survey.* The best way to begin a new chapter is to skim over it.[2] Read the section headings, figure captions, highlighted items, chapter summary, and other emphasized material that indicates key ideas. This gives you a general idea of what will be discussed, how it is organized, and how the topics relate to one another and to what you already know.
- *Question.* Before reading each section, ask yourself what the section will cover and what you should learn from it. Use the section heading and subheadings, figure captions, and highlighted items as guides to ask yourself questions about the material. Be as specific as possible. Jot down your questions in outline form, leaving room for the answers. The questions need not be particularly insightful or complex; focus on the basics. This step allows you to create a mental framework for remembering the detailed information you need to learn while you read.
- *Read.* Once you have prepared yourself to absorb the new information, read the text and think about what you are reading. Are the questions that you raised being answered? Do you understand the relationships among the topics? Read a small amount of material at a time. If the material seems difficult or confusing, don't go

2. Here we use the word "chapter." However, in engineering courses, you will generally be given reading assignments that involve less than a whole chapter.

on. Go back and reread the section, maybe just a paragraph or two at a time, until it makes sense.

- *Recite.* At the end of each section, stop. In your own words, recite the major ideas. Answer the questions on your outline. If your initial set of questions is incomplete, ask—and answer—further questions. Don't go on to the next section until you have stated the main ideas in your own words. If you cannot answer some of your questions, take them to class and discuss them with your instructor.
- *Review.* At the end of the chapter, review all of its material and your notes; then ask and answer your questions again. You should be able to see the topical relationships within each section and among the sections. Once you have grasped the main concepts, individual facts become easier to remember. It may be helpful to work with a classmate and quiz each other. Finally, combine your SQ3R notes with your lecture notes to create a coherent, well-organized package for the chapter. Then, take a break and relax. Approach each chapter with a fresh outlook.

Note Taking Taking notes during a classroom lecture is far different from being a court stenographer. A stenographer records every word spoken, but the point of note taking in class is to capture the main points accurately and in an organized way so that you can use your notes later as a study aid. Students who develop a mental outline of a lecture's main ideas and concentrate on capturing those in a few words typically remember more than students who try to write down every detail.

Here are some simple hints for effective note taking:

- Come to class prepared. Do the assigned reading before class and bring your SQ3R notes. Ask your questions when the instructor is discussing the topic that confuses you. Jot down his or her answer on your outline. Use the lecture time to fill in the gaps in your own understanding, not to provide you with your first exposure to the topic. If you prepare for the lecture ahead of time, you will already have your general outline, and you will recognize important points.
- Every day, imagine that you are taking notes for your best friend who could not attend class that day. Your objective is to give your friend an organized set of notes that record the *key points* of the lecture. Your lecture notes should be a supplement to your SQ3R notes.
- During the lecture, listen for key words that signal main ideas ("The three primary reasons that . . ."), an alternative explanation ("In other words, . . ."), a conclusion or summary statement ("Finally, we can say that . . ."), or a change of direction ("On the other hand . . .").
- Do not assume that the instructor will write on the board everything that you are expected to know. Read everything that is written, and listen to everything that is said; but be selective in what you write down in your notes. Note taking takes concentration. Take brief notes so that you are not distracted from the lecture for long periods of time.
- After class and before the next class, combine your SQ3R notes and your lecture notes into a single, organized unit. This is another opportunity to review the material and solidify your understanding. If you missed a point or two during the lecture, leave space in your rewritten notes for additional detail. Then talk to your instructor to fill in the gaps. When the time comes for an exam, your rewritten notes will be well-organized and complete—perfect for exam preparation.

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Developing Problem-Solving Skills To be an effective problem solver, you must follow an organized strategy.

- *Define the problem.* Read the given information thoroughly and carefully before working the problem. Unnecessary, incorrect, or misleading information could distract you from the real problem.
- *Think about it.* Be sure you have an accurate understanding of the problem. Don't jump into the solution process without identifying the facts and features of the problem situation. Summarize and organize what is given. Do you have enough information to solve the problem? Have you solved a similar problem before?
- *Plan your approach.* Make a flowchart outlining the solution process. Decide where to start and what sequence of steps to follow to reach the solution. Break the problem down into manageable pieces that can be solved one at a time. Think about alternate plans in case your first plan does not succeed.
- *Carry out your plan.* Persevere, and do not lose confidence in your plan.
- *Look back and evaluate.* Make sure you solved the problem that was posed. Determine whether your solution is reasonable. Does it agree with what your intuition tells you? Check all calculations for math errors, correct signs, decimal place locations, transposed digits, proper units, and so on. Be certain that your solution and the answer are presented in a readable, logical form that will not be misinterpreted.[3]

CHAPTER ORGANIZATION

We have organized this book to facilitate use of the SQ3R method. Features of each chapter include the following:

- *A Look Forward* provides a general perspective on the chapter. The main topics are introduced in relatively nontechnical terms so that you can get a sense of what is important before you begin detailed study.
- *Survey Questions* are included to start you on the SQ3R method. These questions are fairly simple and are based on an overview of the contents of the chapter. You are encouraged to perform your own survey and develop additional questions.
- *Key Terms* are printed in the margins of the text as signposts to recognize during reading. On completing a chapter, you should be able to define each of its key terms.
- *Key Concepts* are highlighted statements of the chapter's main ideas that appear throughout the text. They are relatively general so that you can grasp the big picture, then fill in the details from the text discussion.
- *Learning Objectives* are specific, performance-related statements at the beginning of each section. They help you assess your learning by telling you specifically what you should know or understand after you have studied a section.

3. In Section 1.5, we expand on these ideas and apply them explicitly to problem solving in engineering mechanics. Throughout this book, we include step-by-step strategies, called *Problem-Solving Techniques*, to help you develop your own methods of problem solving.

- *Checkpoints* at the ends of sections present true/false or short-answer questions that remind you to recite a section's main points. As you answer these questions, work on your chapter outline and check your survey questions. Answers are given below each Checkpoint box, but try to answer the questions before looking at the answers.
- *Chapter Highlights* are provided at the end of each chapter for your survey and review.
- *Problems* are grouped at the end of each chapter rather than immediately after the text and examples to which they relate. This organization preserves the continuity and flow of the text material and emphasizes that problem solving should follow thorough study of the chapter. However, we have divided the problems by section and have arranged the problems for each section in increasing order of difficulty. Icons next to problem numbers identify three special types of problems:

  Problems that are more challenging

  Problems that are best solved using computer-based tools

  Problems that are design-oriented

- *Review Questions* at the end of each chapter allow you to explain the concepts in your own words. Your ability to paraphrase key concepts will help you apply them during problem solving.

FINAL WORDS

An old saying goes: "What I hear, I forget; what I see, I may remember; what I experience, I know for life." Many engineers are visual, sensory learners, relying on examples, demonstrations, and illustrations to help them generalize and understand fundamental, often abstract, concepts. For this reason, this book is illustrated with photographs and drawings to enliven and enrich your study of mechanics. Apply what you learn to your own life, and know it for life. We have done all that we can to get you off on the right foot. The rest is up to you. Now start your study of mechanics with our best wishes for your success.

Arthur P. Boresi
Richard J. Schmidt

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