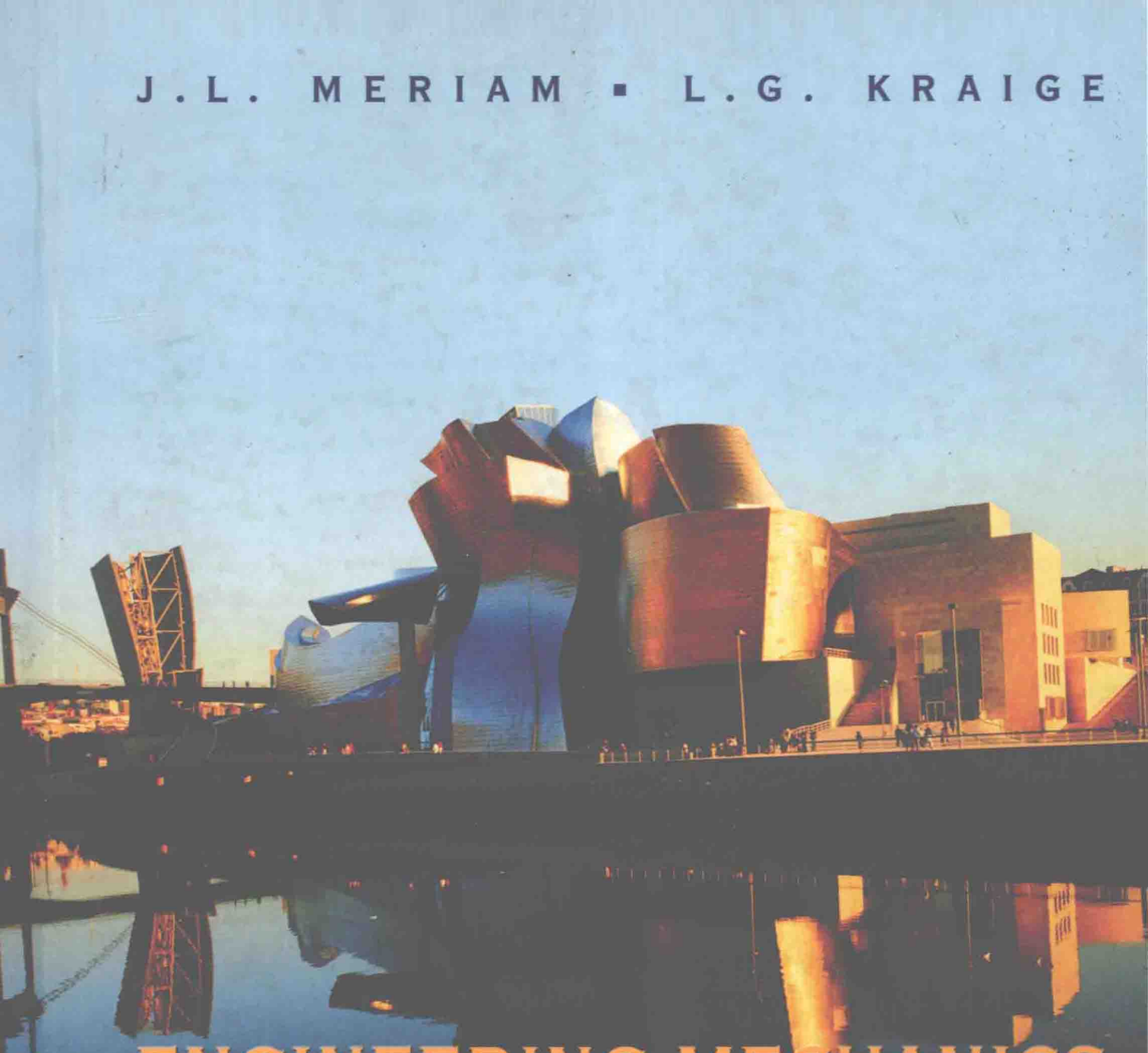
J. L. MERIAM ▪ L. G. KRAIGE



# ENGINEERING MECHANICS

# STATICS

FIFTH EDITION

# ENGINEERING MECHANICS

## VOLUME 1

# STATICS

**FIFTH EDITION**

**J. L. MERIAM**

**L. G. KRAIGE**

*Virginia Polytechnic Institute and State University*

With Special Contributions by

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WILEY

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# ENGINEERING MECHANICS
# STATICS

# JAMES LATHROP MERIAM

## *1917–2000*

Dr. James Lathrop Meriam, internationally known author of engineering mechanics textbooks and distinguished professor of engineering, died at his Santa Barbara home on July 18, 2000. Because of his numerous and significant contributions to the engineering profession, Dr. Meriam is regarded as one of the premier engineering educators of the twentieth century. Dr. Meriam (known as Lath to his friends) received three degrees from Yale University, ending with the Ph.D. in 1942. He served in the U.S. Coast Guard during World War II. His early industrial experience came at Pratt and Whitney Aircraft and the General Electric Company.

Dr. Meriam was a member of the faculty of the University of California—Berkeley for twenty-one years. During this period he served as Professor of Engineering Mechanics, Assistant Dean of Graduate Studies, and Chairman of the Division of Mechanics and Design. From 1963 to 1972, he was Dean of Engineering at Duke University. In 1972 he returned to full-time teaching at California Polytechnic State University—San Luis Obispo, and retired in 1980. Subsequently, he was visiting professor at the University of California—Santa Barbara and retired for a second time in 1990.

Recognition of his superb teaching abilities followed him wherever he went. At Berkeley in 1963, he was the first recipient of the Outstanding Faculty Award of Tau Beta Pi. In 1978 he received the Distinguished Educator Award from the Mechanics Division of the American Society for Engineering Education (ASEE). In 1992 he received the Benjamin Garver Lamme Award from ASEE. He was a fellow member of both ASEE and the American Society of Mechanical Engineers (ASME).

Dr. Meriam began his *Engineering Mechanics* textbook series in 1950. The *Statics* and *Dynamics* texts reshaped undergraduate mechanics and became the definitive textbooks in the field for the next five decades. In addition to the U.S. version, the books have appeared in SI versions and have been translated into many foreign languages. His books have been characterized by clear and rigorous presentation of the theory, instructive sample problems, and numerous and realistic homework exercises. From the outset, a high standard of illustration has distinguished the series.

In the early 1980s, Dr. Meriam designed and hand-built, over a period of more than three years, a 23-foot wooden sailboat named *Mele Kai,* which is Hawaiian for *Song of the Sea.* Over the next several years, he and his fortunate sailing companions spent many happy hours sailing off the coast of Santa Barbara. Dr. Meriam also designed and built four homes, including a vacation home on the island of Kauai.

In addition to his many professional accomplishments, Lath Meriam will be long remembered for his open friendliness, gentlemanly demeanor, mature judgment and leadership, generosity, and absolute commitment to the highest educational standards.

# PREFACE

Engineering mechanics is both a foundation and a framework for most of the branches of engineering. Many of the topics in such areas as civil, mechanical, aerospace, and agricultural engineering, and of course engineering mechanics itself, are based upon the subjects of statics and dynamics. Even in a discipline such as electrical engineering, practitioners, in the course of considering the electrical components of a robotic device or a manufacturing process, may find themselves first having to deal with the mechanics involved.

Thus, the engineering mechanics sequence is critical to the engineering curriculum. Not only is this sequence needed in itself, but courses in engineering mechanics also serve to solidify the student's understanding of other important subjects, including applied mathematics, physics, and graphics. In addition, these courses serve as excellent settings in which to strengthen problem-solving abilities.

## PHILOSOPHY

The primary purpose of the study of engineering mechanics is to develop the capacity to predict the effects of force and motion while carrying out the creative design functions of engineering. This capacity requires more than a mere knowledge of the physical and mathematical principles of mechanics; also required is the ability to visualize physical configurations in terms of real materials, actual constraints, and the practical limitations which govern the behavior of machines and structures. One of the primary objectives in a mechanics course is to help the student develop this ability to visualize, which is so vital to problem formulation. Indeed, the construction of a meaningful mathematical model is often a more important experience than its solution. Maximum progress is made when the principles and their limitations are learned together within the context of engineering application.

There is a frequent tendency in the presentation of mechanics to use problems mainly as a vehicle to illustrate theory rather than to develop theory for the purpose of solving problems. When the first view is allowed to predominate, problems tend to become overly idealized and unrelated to engineering with the result that the exercise becomes dull, academic, and uninteresting. This approach deprives the

student of valuable experience in formulating problems and thus of discovering the need for and meaning of theory. The second view provides by far the stronger motive for learning theory and leads to a better balance between theory and application. The crucial role played by interest and purpose in providing the strongest possible motive for learning cannot be overemphasized.

Furthermore, as mechanics educators, we should stress the understanding that, at best, theory can only approximate the real world of mechanics rather than the view that the real world approximates the theory. This difference in philosophy is indeed basic and distinguishes the *engineering* of mechanics from the *science* of mechanics.

Over the past several decades, several unfortunate tendencies have occurred in engineering education. First, emphasis on the geometric and physical meanings of prerequisite mathematics appears to have diminished. Second, there has been a significant reduction and even elimination of instruction in graphics, which in the past enhanced the visualization and representation of mechanics problems. Third, in advancing the mathematical level of our treatment of mechanics, there has been a tendency to allow the notational manipulation of vector operations to mask or replace geometric visualization. Mechanics is inherently a subject which depends on geometric and physical perception, and we should increase our efforts to develop this ability.

A special note on the use of computers is in order. The experience of formulating problems, where reason and judgment are developed, is vastly more important for the student than is the manipulative exercise in carrying out the solution. For this reason, computer usage must be carefully controlled. At present, constructing free-body diagrams and formulating governing equations are best done with pencil and paper. On the other hand, there are instances in which the *solution* to the governing equations can best be carried out and displayed using the computer. Computer-oriented problems should be genuine in the sense that there is a condition of design or criticality to be found, rather than "makework" problems in which some parameter is varied for no apparent reason other than to force artificial use of the computer. These thoughts have been kept in mind during the design of the computer-oriented problems in the Fifth Edition. To conserve adequate time for problem formulation, it is suggested that the student be assigned only a limited number of the computer-oriented problems.

As with previous editions, this Fifth Edition of *Engineering Mechanics* is written with the foregoing philosophy in mind. It is intended primarily for the first engineering course in mechanics, generally taught in the second year of study. *Engineering Mechanics* is written in a style which is both concise and friendly. The major emphasis is on basic principles and methods rather than on a multitude of special cases. Strong effort has been made to show both the cohesiveness of the relatively few fundamental ideas and the great variety of problems which these few ideas will solve.

## Pedagogical Features

The basic structure of this textbook consists of an article which rigorously treats the particular subject matter at hand, followed by one or more Sample Problems, followed by a group of Problems. There is a Chapter Review at the end of each chapter which summarizes the main points in that chapter, followed by a Review Problem set.

**Problems.** The 80 Sample Problems appear on specially colored pages by themselves. The solutions to typical statics problems are presented in detail. In addition, explanatory and cautionary notes (Helpful Hints) in blue type are number-keyed to the main presentation.

There are 963 homework exercises, of which approximately 50 percent are new to the Fifth Edition. The problem sets are divided into *Introductory Problems* and *Representative Problems*. The first section consists of simple, uncomplicated problems designed to help students gain confidence with the new topic, while most of the problems in the second section are of average difficulty and length. The problems are generally arranged in order of increasing difficulty. More difficult exercises appear near the end of the *Representative Problems* and are marked with the symbol ►. *Computer-Oriented Problems,* marked with an asterisk, appear in a special section at the conclusion of the *Review Problems* at the end of each chapter. The answers to all odd-numbered problems and to all difficult problems have been provided.

In recognition of the need for emphasis on SI units, there are approximately two problems in SI units for every one in U.S. customary units. This apportionment between the two sets of units permits anywhere from a 50–50 emphasis to a 100-percent SI treatment.

A notable feature of the Fifth Edition, as with all previous editions, is the wealth of interesting and important problems which apply to engineering design. Whether directly identified as such or not, virtually all of the problems deal with principles and procedures inherent in the design and analysis of engineering structures and mechanical systems.

**Illustrations.** In order to bring the greatest possible degree of realism and clarity to the illustrations, this textbook series continues to be produced in full color. It is important to note that color is used consistently for the identification of certain quantities:

- *red* for forces and moments,
- *green* for velocity and acceleration arrows,
- *orange dashes* for selected trajectories of moving points.

Subdued colors are used for those parts of an illustration which are not central to the problem at hand. Whenever possible, mechanisms or objects which commonly have a certain color will be portrayed in that color. All of the fundamental elements of technical illustration which have been an essential part of this *Engineering Mechanics* series of textbooks have been retained. The author wishes to restate the conviction that a high standard of illustration is critical to any written work in the field of mechanics.

**Features New to this Edition.** While retaining the hallmark features of all previous editions, we have incorporated these improvements:

- The theory portions were rewritten for clarity and readability, with a higher level of friendliness and a more active voice.
- Sections have been shortened and more subheads added to make information easier to find.

- Key Concepts areas within the theory presentation have been specially highlighted with blue screens.
- The Chapter Reviews have been revised and highlighted, and feature itemized summaries.
- Approximately 50 percent of the homework problems are new to this Fifth Edition, and include new problems in the area of biomechanics.
- New Sample Problems have been added.
- All Sample Problems are printed on specially colored pages for quick identification.
- The text has been printed in a new, larger format for a more open look.

## ORGANIZATION

In Chapter 1, the fundamental concepts necessary for the study of mechanics are established.

In Chapter 2, the properties of forces, moments, couples, and resultants are developed so that the student may proceed directly to the equilibrium of nonconcurrent force systems in Chapter 3 without unnecessarily belaboring the relatively trivial problem of the equilibrium of concurrent forces acting on a particle.

In both Chapters 2 and 3, analysis of two-dimensional problems is presented in Section A before three-dimensional problems are treated in Section B. With this arrangement, the instructor may cover all of Chapter 2 before beginning Chapter 3 on equilibrium, or the instructor may cover the two chapters in the order 2A, 3A, 2B, 3B. The latter order treats force systems and equilibrium in two dimensions and then treats these topics in three dimensions.

Application of equilibrium principles to simple trusses and to frames and machines is presented in Chapter 4 with primary attention given to two-dimensional systems. A sufficient number of three-dimensional examples are included, however, to enable students to exercise more general vector tools of analysis.

The concepts and categories of distributed forces are introduced at the beginning of Chapter 5, with the balance of the chapter divided into two main sections. Section A treats centroids and mass centers; detailed examples are presented to help students master early applications of calculus to physical and geometrical problems. Section B includes the special topics of beams, flexible cables, and fluid forces, which may be omitted without loss of continuity of basic concepts.

Chapter 6 on friction is divided into Section A on the phenomenon of dry friction and Section B on selected machine applications. Although Section B may be omitted if time is limited, this material does provide a valuable experience for the student in dealing with both concentrated and distributed friction forces.

Chapter 7 presents a consolidated introduction to virtual work with applications limited to single-degree-of-freedom systems. Special emphasis is placed on the advantage of the virtual-work and energy method for interconnected systems and stability determination. Virtual work provides an excellent opportunity to convince the student of the power of mathematical analysis in mechanics.

Moments and products of inertia of areas are presented in Appendix A. This topic helps to bridge the subjects of statics and solid mechanics. Appendix C contains a summary review of selected topics of elementary mathematics as well as several numerical techniques which the student should be prepared to use in computer-solved problems. Useful tables of physical constants, centroids, and moments of inertia are contained in Appendix D.

## SUPPLEMENTS

The following items have been prepared to complement this textbook:

**Instructor's Manual.** Prepared by the authors, fully worked solutions to all problems in the text are available to faculty by contacting their local Wiley representative.

***Solving Mechanics Problems with. . . .*** A series of booklets introduces the use of computational software in the solution of mechanics problems. Developed by Brian Harper at Ohio State University, the booklets are available for Matlab, MathCAD, and Maple.

***Wiley Website (www.wiley.com/college/meriam).*** Items on this site include:

- *Electronic figures* for most of the figures from the text are available electronically for use in creating lectures.
- *Electronic transparencies* for over 100 solved problems, similar to those in the text, are available for use in lecture or in self-study by students.
- *On-line problem solving,* a program called eGrade, provides over 400 problems in mechanics for students to solve, featuring step-by-step procedures and immediate feedback. These were developed by Joe Torok at Rochester Institute of Technology.
- *Extension sample problems* build on sample problems from the text and show how computational tools can be used to investigate a variety of "what if" scenarios. Available to both students and faculty, these were developed by Brian Harper at Ohio State University.

## ACKNOWLEDGMENTS

The contribution of Professor William J. Palm, III, of the University of Rhode Island merits special acknowledgment for his excellent and careful review of the entire text. Professor Palm has inspected the structure of every sentence and, where necessary, has made modifications so that the presentation is clear, direct, concise, and friendly. He has carefully modified the heading structure in order to make the text more easily readable, and reorganized the Chapter Review sections so that the student can efficiently survey what has been presented. Professor Palm has worked under a number of constraints and has done so in a friendly and timely manner.

Special recognition is again due Dr. A. L. Hale, formerly of Bell Telephone Laboratories, for his continuing contribution in the form of invaluable suggestions and accurate checking of the manuscript. Dr. Hale has rendered similar service for all previous versions of this entire series of mechanics books, dating back to the 1950s. He reviews all aspects of the books, including all old and new text and figures. Dr. Hale carries out an independent solution to each new homework exercise and provides the author with suggestions and needed corrections to the solutions which appear in the *Instructor's Manual*. Dr. Hale is well known for being extremely accurate in his work, and his fine knowledge of the English language is a great asset which aids every user of this textbook.

Professor J. Wallace Grant of VPI&SU has kindly provided several excellent equilibrium problems in the area of biomechanics. These new problems serve to strengthen the textbook in this important application field.

The following individuals (listed in alphabetical order) provided feedback on the Fourth Edition, reviewed samples of the Fifth Edition, or otherwise contributed to the Fifth Edition:

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Finally, I wish to state the extremely significant contribution of my family. In addition to providing patience and support for this project, my wife Dale has managed the preparation of the manuscript for the Fifth Edition and has been a key individual in checking all stages of the proof. In addition, my daughter Stephanie and son David (both of whom are currently engineering students) have contributed both problem ideas and have helped with the illustrations.

I am extremely pleased to participate in extending the time duration of this textbook series to the fifty-year mark. In the interest of providing you with the best possible educational materials over future years, I encourage and welcome all comments and suggestions. Please address your comments to kraige@vt.edu.

L. Glenn Kraige

Blacksburg, Virginia

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