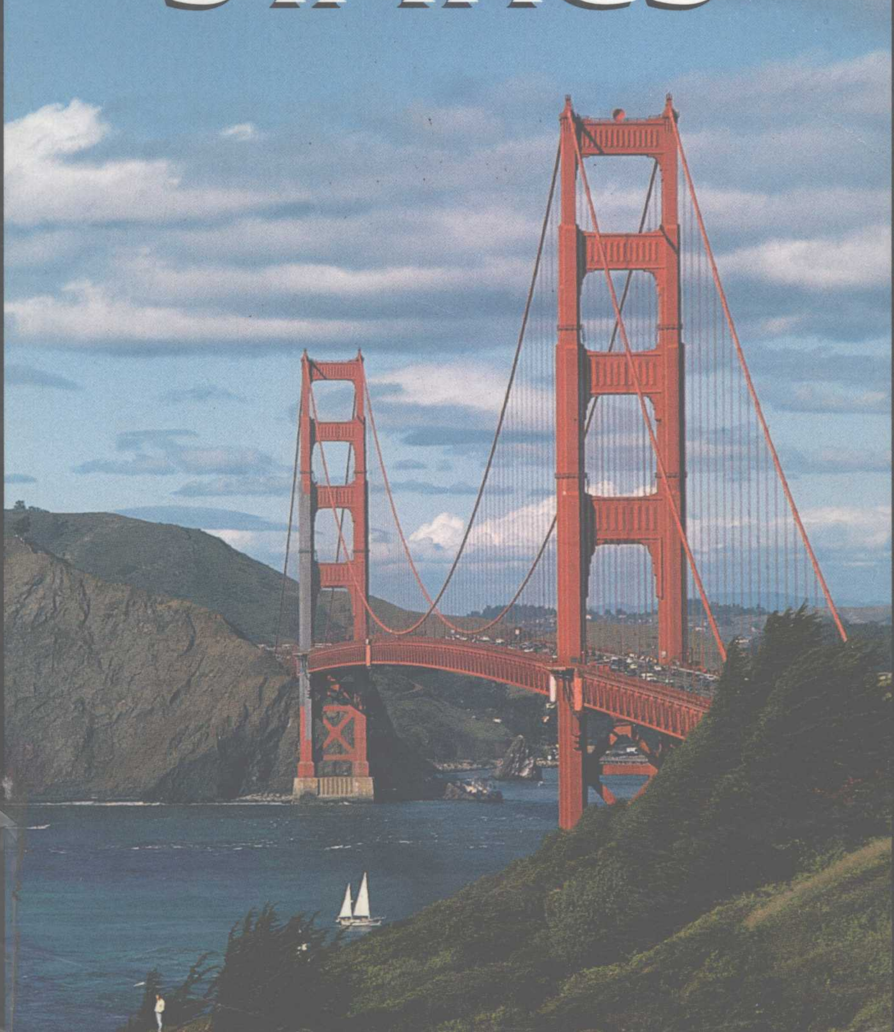
J.L. MERIAM L.G. KRAIGE

ENGINEERING MECHANICS

Volume One

Third Edition

STATICS



ENGINEERING MECHANICS

VOLUME 1

STATICS

THIRD EDITION

J.L. MERIAM
University of California
Santa Barbara

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Virginia Polytechnic Institute and
State University

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FOREWORD

The innovations and contributions of Dr. James L. Meriam to the field of engineering mechanics cannot be overstated. He has undoubtedly had as much influence on instruction in mechanics during the last forty years as any one individual. His first books on mechanics in 1951 literally reconstructed undergraduate mechanics and became the definitive textbooks for the decades that followed. His texts were logically organized, easy to read, directed to the average engineering undergraduate, and were packed with exciting examples of real-life engineering problems which were superbly illustrated. These books became the model for other engineering mechanics texts in the 1950s and beyond.

Dr. Meriam began his work in mechanical engineering at Yale University where he earned his B.E., M. Eng., and Ph.D. degrees. He had early industrial experience with Pratt and Whitney Aircraft and the General Electric Company, which stimulated his first contributions to mechanics in mathematical and experimental stress analysis. During the Second World War he served in the U.S. Coast Guard.

Dr. Meriam was a member of the faculty of the University of California, Berkeley, for twenty-one years where he served as Professor of Engineering Mechanics, Assistant Dean of Graduate Studies, and Chairman of the Division of Mechanics and Design. In 1963 he became Dean of Engineering at Duke University where he devoted his full energies to the development of its School of Engineering. In 1972 Professor Meriam followed his desire to return to full-time teaching and served as Professor of Mechanical Engineering at California Polytechnic State University, where he retired in 1980. During the following ten years he served as visiting professor at the University of California, Santa Barbara, retiring for the second time in 1990. Professor Meriam has always placed great emphasis on teaching, and this trait has been recognized by his students wherever he has taught. At Berkeley in 1963 he was the first recipient of the Outstanding Faculty Award of Tau Beta Pi, given primarily for excellence in teaching, and in 1978 he received the Distinguished Educator Award for Outstanding Service to Engineering Mechanics Education from the American Society for Engineering Education.

Professor Meriam was the first author to show clearly how the method of virtual work in statics can be employed to solve a class of problems largely neglected by previous authors. In dynamics, plane motion became understandable, and in his later editions, three-dimensional kinematics and kinetics received the same treatment. He is credited with original developments in the theory of variable-mass dynamics, which are contained in his *Dynamics, Second Edition* (1971). Professor Meriam has also been a leader in promoting the use of SI units, and his *SI Versions* of *Statics* and *Dynamics* (1975) were the first mechanics textbooks in SI units in this country.

Dr. L. Glenn Kraige, coauthor for the second time in the *Engineering Mechanics* series, has also made significant contributions to mechanics education. Dr. Kraige earned his B.S., M.S., and Ph.D. degrees at the University of Virginia, principally in aerospace engineering, and he currently serves as Professor of Engineering Science and Mechanics at Virginia Polytechnic Institute and State University.

In addition to his recognized research and publications in the field of spacecraft dynamics, Professor Kraige has devoted his attention to the teaching of mechanics at both introductory and advanced levels. His outstanding teaching has been widely recognized and has earned him several awards, including, in 1988, an AT&T award for outstanding teaching in the Southeastern Section of the American Society for Engineering Education and, also in 1988, the Outstanding Educator Award from the State Council of Higher Education for the Commonwealth of Virginia. In his teaching, Professor Kraige stresses the development of analytical capabilities along with the strengthening of physical insight and engineering judgment. In the mid 1980s, he was a leader in the development of motion simulation software for use on personal computers. More recently, he has begun a long-term effort in the area of multimedia approaches to the instruction and learning of statics and dynamics.

The third edition of *Engineering Mechanics* continues the same high standards set by previous editions and adds new features of help and interest to students. It contains a vast collection of interesting and instructive problems. Analysis and applications are the cornerstones of a successful learning experience in engineering mechanics, and J. L. Meriam and L. G. Kraige have shown again that they are the best at melding these essential characteristics.

Robert F. Steidel, Jr.
Professor Emeritus of Mechanical Engineering
University of California, Berkeley

PREFACE
To the Student

As you undertake the study of engineering mechanics, first statics and then dynamics, you will be building a foundation of analytical capability for the solution of a great variety of engineering problems. Modern engineering practice demands a high level of analytical capability, and you will find that your study of mechanics will help you immensely in developing this capacity.

In engineering mechanics we learn to construct and to solve mathematical models which describe the effects of force and motion on a variety of structures and machines that are of concern to engineers. In applying our principles of mechanics we formulate these models by incorporating appropriate physical assumptions and mathematical approximations. In both the formulation and solution of mechanics problems you will have frequent occasion to use your background in plane and solid geometry, scalar and vector algebra, trigonometry, analytic geometry, and calculus. Indeed, you are likely to discover new significance to these mathematical tools as you make them work for you in mechanics.

Your success in mechanics (and throughout engineering) will be highly contingent on developing a well-disciplined method of attack from hypothesis to conclusion in which the applicable principles are applied rigorously. Years of experience in teaching and engineering disclose the importance of developing the ability to represent one's work in a clear, logical, and concise manner. Mechanics is an excellent place in which to develop these habits of logical thinking and effective communication.

Engineering Mechanics contains a large number of sample problems in which the solutions are presented in detail. Also included in these examples are helpful observations that mention common errors and pitfalls to be avoided. In addition, the book contains a large selection of simple, introductory problems and problems of intermediate difficulty to help you gain initial confidence and understanding of each new topic. Also included are many problems that illustrate significant and contemporary engineering situations to stimulate your interest and help you to develop an appreciation for the many applications of mechanics in engineering.

We are pleased to extend our encouragement to you as a student of mechanics. We hope this book will provide both help and stimulation as you develop your background in engineering.

J. L. Meriam
Santa Barbara, California
February 1992

L. Glenn Kraige
Blacksburg, Virginia
February 1992

PREFACE
To the Instructor

The primary purpose of the study of engineering mechanics is to develop the capacity to predict the effects of force and motion in the course of carrying out the creative design function of engineering. Successful prediction requires more than a mere knowledge of the physical and mathematical principles of mechanics. Prediction also requires the ability to visualize physical configurations in terms of real materials, actual constraints, and the practical limitations that govern the behavior of machines and structures. One of our primary objectives in teaching mechanics 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.

Courses in mechanics are often regarded by students as a difficult requirement and frequently as an uninteresting academic hurdle as well. The difficulty stems from the extent to which reasoning from fundamentals, as distinguished from rote learning, is required. The lack of interest that is frequently experienced is due primarily to the extent to which mechanics is presented as an academic discipline often lacking in engineering purpose and challenge. This attitude is traceable to the 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 much of the 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 of interest and purpose in providing the strongest possible motive for learning cannot be overemphasized. Furthermore, we should stress the view 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.

During the past thirty years there has been a strong trend in engineering education to increase the extent and level of theory in the engineering-science courses. Nowhere has this trend been more evident than in mechanics courses. To the extent that students are prepared to handle the accelerated treatment, the trend is beneficial. There is evidence and justifiable concern, however, that a significant disparity has more recently appeared between coverage and comprehension. Among the contributing factors we note three trends. 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 that depends on geometric and physical perception, and we should increase our efforts to develop this ability.

One of our responsibilities as teachers of mechanics is to use the mathematics that is most appropriate for the problem at hand. The use of vector notation for one-dimensional problems is usually trivial; for two-dimensional problems it is often optional; but for three-dimensional problems it is usually essential. As we introduce vector operations in two-dimensional problems, it is especially important that their geometric meaning be emphasized. A vector equation is brought to life by a sketch of the corresponding vector polygon, which often discloses through its geometry the shortest solution. There are, of course, many mechanics problems where the complexity of variable interdependence is beyond the normal powers of visualization and physical perception, and reliance on analysis is essential. Nevertheless, our students become better engineers when their abilities to perceive, visualize, and represent are developed to the fullest.

As teachers of engineering mechanics, we have the strongest obligation to the engineering profession to set reasonable standards of performance and to uphold them. In addition, we have a serious responsibility to encourage our students to think for themselves. Too much help with details that students should be reasonably able to handle from prerequisite subjects can be as bad as too little help and can easily condition them to become overly dependent on others rather than to exercise their own initiative and ability. Also, when mechanics is subdivided into an excessive number of small compartments, each with detailed and repetitious instructions, students can have difficulty seeing the "forest for the trees" and, consequently, will fail to perceive the unity of mechanics and the far-reaching applicability of its few basic principles and methods.

This third edition of *Engineering Mechanics,* as with previous editions, 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 that 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 that these few ideas will solve. A major feature of the book is the extensive treatment of sample problems, which are presented in a single-page format for convenient self-study. In addition to presenting the solution in detail, each sample problem also contains comments and cautions keyed to salient points in the solution and printed in colored type.

Volume 1, Statics, contains 75 sample problems and 950 unsolved problems from which a wide choice of assignments can be made. Of these problems, more than 50 percent are new to the Third Edition. In recognition of the need for the predominant 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. Many practical problems and examples of interesting engineering situations drawn from a wide range of applications are represented in the problem collection.

In a feature new to the Third Edition, most problem sets are divided into two sections entitled *Introductory Problems* and *Representative Problems.* In the first section are 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 arranged generally in order of increasing difficulty; near the end of the *Representative Problems* are more difficult exercises, which are marked with the symbol ▶. Computer-oriented problems are 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. Simple numerical values have been used throughout so as not to complicate the solutions and divert attention from the principles. All numerical solutions have been carried out and checked with an electronic calculator without rounding intermediate values. Consequently, the final answers should be correct to within the number of significant figures cited.

A special note on the use of computers is in order. We wish to emphasize that 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, we believe that computer usage must be carefully controlled. At the present time, the processes of 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 via 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 in mind as we have designed the computer-oriented problems in the Third Edition. To conserve adequate time for problem formulation, it is suggested that the student be assigned only a limited number of the computer problems.

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 belaboring unnecessarily 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 before three-dimensional problems are treated. The vast majority of students acquire a greater physical insight and understanding of mechanics by first gaining confidence in two-dimensional analysis before coping with the third dimension.

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 is 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 where 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 distributed forces.

Chapter 7 presents a consolidated introduction to virtual work with application 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 that the student should be prepared to use in computer-solved problems.

We wish to specially cite the outstanding contributions to this series of mechanics books over a period of twenty-five years by illustrator John Balbalis, who died in October 1991. His dedication to high standards of illustrative achievement greatly increased the educational potential of the *Engineering Mechanics* series by providing clarity, reality, and interest to the many thousands of students who have been challenged by his efforts.

Special recognition is due Dr. A. L. Hale of the 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 to all previous versions in this entire series of mechanics books, and his input has been a great asset. Appreciation is expressed to Professor J. M. Henderson of the University of California, Davis, for helpful comments and suggestions of selected problems. Also acknowledged are the observations and constructive comments over a period of years of Professor Alfonso Diaz-Jiménez of Bogota, Colombia. A number of members of the Department Engineering Science and Mechanics at Virginia Polytechnic Institute and State University have offered helpful suggestions, including Professors Norman E. Dowling, J. Wallace Grant, Scott L. Hendricks, Arpad A. Pap, Saad A. Ragab, and George W. Swift. The contribution by the staff of John Wiley & Sons, Inc., including editor Charity Robey, reflects a high degree of professional competence and is duly recognized. The support, in the form of a study-research leave, of VPI & SU is acknowledged. Finally, we acknowledge the patience, support, and assistance of our wives, Julia and Dale, during the many hours required to prepare this manuscript.

J. L. Meriam

Santa Barbara, California
February 1992

L. Glenn Kraige

Blacksburg, Virginia
February 1992

Structures that support and produce large forces depend on the principles of mechanics. The ship-loading cranes of the Port of Seattle are examples of the many applications of the principles of statics.

CONTENTS

1 INTRODUCTION TO STATICS	**1**
1/1 Mechanics	1
1/2 Basic Concepts	2
1/3 Scalars and Vectors	3
1/4 Newton's Laws	6
1/5 Units	7
1/6 Law of Gravitation	9
1/7 Accuracy, Limits, and Approximations	11
1/8 Description of Statics Problems	13
2 FORCE SYSTEMS	**19**
2/1 Introduction	19
2/2 Force	19
Section A. Two-Dimensional Force Systems	22
2/3 Rectangular Components	22
2/4 Moment	34
2/5 Couple	44
2/6 Resultants	52
Section B. Three-Dimensional Force Systems	61
2/7 Rectangular Components	61
2/8 Moment and Couple	70
2/9 Resultants	84
2/10 Problem Formulation and Review	95
3 EQUILIBRIUM	**101**
3/1 Introduction	101
Section A. Equilibrium in Two Dimensions	102
3/2 Mechanical System Isolation	102
3/3 Equilibrium Conditions	113
Section B. Equilibrium in Three Dimensions	142
3/4 Equilibrium Conditions	142
3/5 Problem Formulation and Review	163
4 STRUCTURES	**173**
4/1 Introduction	173
4/2 Plane Trusses	174
4/3 Method of Joints	176

4/4 Method of Sections 189
4/5 Space Trusses 200
4/6 Frames and Machines 208
4/7 Problem Formulation and Review 228

5 DISTRIBUTED FORCES **239**

5/1 Introduction 239
Section A. Centers of Mass and Centroids 241
5/2 Center of Mass 241
5/3 Centroids of Lines, Areas, and Volumes 243
5/4 Composite Bodies and Figures; Approximations 263
5/5 Theorems of Pappus 275
Section B. Special Topics 282
5/6 Beams—External Effects 282
5/7 Beams—Internal Effects 289
5/8 Flexible Cables 301
5/9 Fluid Statics 315
5/10 Problem Formulation and Review 336

6 FRICTION **345**

6/1 Introduction 345
Section A. Frictional Phenomena 346
6/2 Types of Friction 346
6/3 Dry Friction 347
Section B. Application of Friction in Machines 368
6/4 Wedges 368
6/5 Screws 370
6/6 Journal Bearings 380
6/7 Thrust Bearings; Disk Friction 381
6/8 Flexible Belts 389
6/9 Rolling Resistance 390
6/10 Problem Formulation and Review 398

7 VIRTUAL WORK **407**

7/1 Introduction 407
7/2 Work 407
7/3 Equilibrium 410
7/4 Potential Energy and Stability 428
7/5 Problem Formulation and Review 444

APPENDIX A AREA MOMENTS OF INERTIA **451**

A/1 Introduction 451
A/2 Definitions 452
A/3 Composite Areas 467
A/4 Products of Inertia and Rotation of Axes 475

APPENDIX B MASS MOMENTS OF INERTIA 489

APPENDIX C SELECTED TOPICS OF MATHEMATICS 491

C/1 Introduction 491
C/2 Plane Geometry 491
C/3 Solid Geometry 492
C/4 Algebra 492
C/5 Analytic Geometry 493
C/6 Trigonometry 493
C/7 Vector Operations 494
C/8 Series 497
C/9 Derivatives 497
C/10 Integrals 498
C/11 Newton's Method for Solving Intractable Equations 501
C/12 Selected Techniques for Numerical Integration 503

APPENDIX D USEFUL TABLES 507

Table D/1 Physical Properties 507
Table D/2 Solar System Constants 508
Table D/3 Properties of Plane Figures 509
Table D/4 Properties of Homogeneous Solids 511

PHOTO CREDITS 515

INDEX 517

INTRODUCTION TO STATICS 1

1/1 MECHANICS

Mechanics is that branch of physical science which deals with the state of rest or motion of bodies under the action of forces. No one subject plays a greater role in engineering analysis than mechanics. The early history of this subject is synonymous with the very beginnings of engineering. Modern research and development in the fields of vibrations, stability and strength of structures and machines, robotics, rocket and spacecraft design, automatic control, engine performance, fluid flow, electrical machines and apparatus, and molecular, atomic, and subatomic behavior are highly dependent on the basic principles of mechanics. A thorough understanding of this subject is an essential prerequisite for work in these and many other fields.

Mechanics is the oldest of the physical sciences. The earliest recorded writings in this field are those of Archimedes (287–212 B.C.) which concern the principle of the lever and the principle of buoyancy. Substantial progress awaited the formulation of the laws of vector combination of forces by Stevinus (1548–1620), who also formulated most of the principles of statics. The first investigation of a dynamic problem is credited to Galileo (1564–1642) in connection with his experiments with falling stones. The accurate formulation of the laws of motion, as well as the law of gravitation, was made by Newton (1642–1727), who also conceived the idea of the infinitesimal in mathematical analysis. Substantial contributions to the development of mechanics were also made by da Vinci, Varignon, Euler, D'Alembert, Lagrange, Laplace, and others.

The principles of mechanics as a science embody the rigor of mathematics on which they are highly dependent. Thus, mathematics plays an important role in achieving the purpose of engineering mechanics, which is the application of these principles to the solution of practical problems. In this book we shall be concerned with both the rigorous development of principles and their application. The basic principles of mechanics are relatively few in number, but they have exceedingly wide application, and the methods employed in mechanics carry over into many fields of engineering endeavor.