Engineering Mechanics

Volume 1

Statics

COPYRIGHTED MATERIAL

Ninth Edition

Engineering Mechanics

Volume 1

Statics

Ninth Edition

J.L. MERIAM

L.G. KRAIGE

Virginia Polytechnic Institute and State University

J.N. BOLTON

Bluefield State College

WILEY

On the cover: The Auditorio de Tenerife "Adán Martin" is located in Santa Cruz de Tenerife, the capital of the Canary Islands, Spain. It was designed by architect Santiago Calatrava Valls and was opened in 2003.

VICE PRESIDENT AND EXECUTIVE PUBLISHER:	Don Fowley
EXECUTIVE EDITOR:	Linda Ratts
SENIOR PRODUCT DESIGNER:	David Dietz
CONTENT EDITOR:	Adria Giattino
EDITORIAL ASSISTANT:	Adriana Alecci
SENIOR CONTENT MANAGER:	Valerie Zaborski
SENIOR PRODUCTION EDITOR:	Ken Santor
EXECUTIVE MARKETING MANAGER:	John Lavacca III
DESIGNER:	Wendy Lai
COVER DESIGN:	Wendy Lai
SENIOR PHOTO EDITOR:	Billy Ray
MEDIA SPECIALIST:	Aptara, Inc.
COVER PHOTO:	Novarc Images/Alamy Stock Photo

This book was set in 9.5/11.5 New Century Schoolbook Lt Std. by Aptara, Inc., and printed by Quad Graphics. The cover was printed by Quad Graphics.

This book is printed on acid-free paper. ∞

Copyright © 2018 John Wiley & Sons, Inc. All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning or otherwise, except as permitted under Sections 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, website www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030-5774, (201) 748-6011, fax (201) 748-6008, website http://www.wiley.com/go/permissions.

Library of Congress Cataloging-in-Publication Data

Names: Meriam, J. L. (James L.), author. | Kraige, L. G. (L. Glenn), author. | Bolton, J. N. (Jeffrey N.), author.

Title: Statics / J.L. Meriam, L.G. Kraige, Virginia Polytechnic Institute and State University, J.N. Bolton, Bluefield State College.

Description: Ninth edition. | Hoboken, NJ : Wiley, 2017. | Series: Engineering mechanics ; volume 1 | Includes index. |

Identifiers: LCCN 2017026647 (print) | LCCN 2017027881 (ebook) | ISBN 9781119392644 (pdf) | ISBN 9781119392620 (epub) | ISBN 9781119392804 (pbk.) | ISBN 9781119392620 (hardback)

Subjects: LCSH: Statics. | Mechanics, Applied.
Classification: LCC TA351 (ebook) | LCC TA351 .M4 2017 (print) | DDC 620.1/03--dc23

LC record available at https://lccn.loc.gov/2017026647

The inside back cover will contain printing identification and country of origin if omitted from this page. In addition, if the ISBN on the back cover differs from the ISBN on this page, the one on the back cover is correct.

ISBN: 978-1119-39262-0

1 0 9 8 7 6 5 4 3 2 1

Foreword

This series of textbooks was begun in 1951 by the late Dr. James L. Meriam. At that time, the books represented a revolutionary transformation in undergraduate mechanics education. They became the definitive textbooks for the decades that followed as well as models for other engineering mechanics texts that have subsequently appeared. Published under slightly different titles prior to the 1978 First Editions, this textbook series has always been characterized by logical organization, clear and rigorous presentation of the theory, instructive sample problems, and a rich collection of real-life problems, all with a high standard of illustration. In addition to the U.S. versions, the books have appeared in SI versions and have been translated into many foreign languages. These textbooks collectively represent an international standard for undergraduate texts in mechanics.

The innovations and contributions of Dr. Meriam (1917–2000) to the field of engineering mechanics cannot be overstated. He was one of the premier engineering educators of the second half of the twentieth century. Dr. Meriam earned the B.E., M.Eng., and Ph.D. degrees from Yale University. He had early industrial experience with Pratt and Whitney Aircraft and the General Electric Company. During the Second World War he served in the U.S. Coast Guard. He was a member of the faculty of the University of California—Berkeley, Dean of Engineering at Duke University, a faculty member at the California Polytechnic State University, and visiting professor at the University of California—Santa Barbara, finally retiring in 1990. Professor Meriam always placed great emphasis on teaching, and this trait was recognized by his students wherever he taught. He was the recipient of several teaching awards, including the Benjamin Garver Lamme Award, which is the highest annual national award of the American Society of Engineering Education (ASEE).

Dr. L. Glenn Kraige, coauthor of the *Engineering Mechanics* series since the early 1980s, 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 is Professor Emeritus of Engineering Science and Mechanics at Virginia Polytechnic Institute and State University. During the mid-1970s, I had the singular pleasure of chairing Professor Kraige's graduate committee and take particular pride in the fact that he was the first of my fifty-four Ph.D. graduates. Professor Kraige was invited by Professor Meriam to team with him, thereby ensuring that the Meriam legacy of textbook authorship excellence would be carried forward to future generations of engineers.

In addition to his widely 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 teaching awards at the departmental, college, university, state, regional, and national levels. These awards include the Outstanding Educator Award from the State Council of Higher Education for the Commonwealth of Virginia. In 1996, the Mechanics Division of ASEE bestowed upon him the Archie Higdon Distinguished Educator Award. The Carnegie Foundation for the Advancement of Teaching and the Council for Advancement and Support of Education awarded him the distinction of Virginia Professor of the Year for 1997. In his teaching, Professor Kraige stresses the development of analytical capabilities along with the strengthening of physical insight and engineering judgment. Since the early 1980s, he has worked on personal-computer software designed to enhance the teaching/learning process in statics, dynamics, strength of materials, and higher-level areas of dynamics and vibrations.

Continuing as coauthor for this edition is Dr. Jeffrey N. Bolton, Associate Professor of Mechanical Engineering Technology and Director of Digital Learning at Bluefield State College. Dr. Bolton earned his B.S., M.S., and Ph.D. in Engineering Mechanics from Virginia Polytechnic Institute and State University. His research interests include automatic balancing of six-degree-of-freedom elastically-mounted rotors. He has a wealth of teaching experience, including at Virginia Tech, where he was the 2010 recipient of the Sporn Teaching Award for Engineering Subjects, which is primarily chosen by students. In 2014, Professor Bolton received the Outstanding Faculty Award from Bluefield State College. Professor Bolton was selected as the 2016 West Virginia Professor of the Year by the Faculty Merit Foundation. He has the unusual ability to set

high levels of rigor and achievement in the classroom while establishing a high degree of rapport with his students. In addition to maintaining time-tested traditions for future generations of students, Dr. Bolton brings effective application of technology to this textbook series.

The Ninth 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. The faculty and students privileged to teach or study from the Meriam/Kraige/Bolton *Engineering Mechanics* series will benefit from several decades of investment by three highly accomplished educators. Following the pattern of the previous editions, this textbook stresses the application of theory to actual engineering situations, and at this important task it remains the best.

JOHN L. JUNKINS
Distinguished Professor of Aerospace Engineering
Holder of the Royce E. Wisebaker '39 Chair in
Engineering Innovation
Texas A&M University
College Station, Texas

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

Ninth 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 Ninth 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.

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, moments of inertia, and conversion factors are contained in Appendix D.

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. For the Ninth Edition, all homework problems have been moved to a special Student Problems section found after Appendix D in the Instructor Evaluation Copy, the enhanced e-text, and WileyPLUS. There is a Chapter Review at the end of each chapter which summarizes the main points in that chapter, and a corresponding Chapter Review Problem set found in the Student Problems section.

Problems

The 89 Sample Problems appear on specially designed pages by themselves. The solutions to typical statics problems are presented in detail. In addition, explanatory and cautionary notes (Helpful Hints) are number-keyed to the main presentation.

There are 898 homework exercises. 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 triangular symbol ▶. *Computer-Oriented Problems*, marked with an asterisk, appear throughout the problems and also in a special section at the conclusion of the Chapter Review Problems. Problems marked with the student-solution icon SS have solutions available on WileyPLUS. The answers to all 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 Ninth 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, the electronic version of 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 authors wish to restate the conviction that a high standard of illustration is critical to any written work in the field of mechanics.

Special Features

We have retained the following hallmark features of previous editions:

- All theory portions are constantly reexamined in order to maximize rigor, clarity, readability, and level of friendliness.
- Key Concepts areas within the theory presentation are specially marked and highlighted.
- The Chapter Reviews are highlighted and feature itemized summaries.
- All Sample Problems are printed on specially designed pages for quick identification.
- Within-the-chapter photographs are provided in order to provide additional connection to actual situations in which statics has played a major role.

Resources and Formats

The following items have been prepared to complement this textbook:

Instructor and Student Resources

The following resources are available online at *www.wiley.com/college/meriam*. There may be additional resources not listed.

WileyPLUS: A complete online learning system to help prepare and present lectures, assign and manage homework, keep track of student progress, and customize your course content and delivery. Newly added materials for WileyPLUS include step-by-step video solutions for approximately 200 problems, all of which are similar to those found in the textbook. These author-generated videos illustrate clear and concise solution strategies for students, further emphasizing key concepts and demonstrating sound principles of problem solving in mechanics.

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

All ***figures*** in the text are available in electronic format for use in creating lecture presentations.

All ***Sample Problems*** are available as electronic files for display and discussion in the classroom.

Formats

This Ninth Edition is available in a variety of formats, including conventional print, WileyPLUS standalone, standalone alone e-text (now with numerous enhancements), and other bundled formats. Please contact a Wiley representative (www.wiley.com/go/whosmyrep) for more information.

Acknowledgments

Special recognition is 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 early 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 authors 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.

We would like to thank the faculty members of the Department of Engineering Science and Mechanics at VPI&SU who regularly offer constructive suggestions. These include Saad A. Ragab, Norman E. Dowling, Michael W. Hyer (late), J. Wallace Grant, and Jacob Grohs. Scott L. Hendricks has been particularly effective and accurate in his extensive review of the manuscript and preparation of WileyPLUS materials. Michael Goforth of Bluefield State College is acknowledged for his significant contribution to supplementary textbook materials. Nathaniel Greene of Bloomfield State University of Pennsylvania is recognized for his careful reading and suggestions for improvement.

The contributions by the staff of John Wiley & Sons, Inc., reflect a high degree of professional competence and are duly recognized. These include Executive Editor Linda Ratts, Associate Developmental Editor Adria Giattino, Editorial Assistant Adriana Alecci, Senior Production Editor Ken Santor, Senior Designer Wendy Lai, and Senior Photograph Editor Billy Ray. We wish to especially acknowledge the long-term production efforts of Christine Cervoni of Camelot Editorial Services, LLC, as well as the editing of Helen Walden. The talented illustrators of Lachina continue to maintain a high standard of illustration excellence.

Finally, we wish to state the extremely significant contribution of our families for the patience and support over the many hours of manuscript preparation. In particular, Dale Kraige has managed the preparation of the manuscript for the Ninth Edition and has been a key individual in checking all stages of the proof.

We are extremely pleased to participate in extending the time duration of this textbook series well past the sixty-five-year mark. In the interest of providing you with the best possible educational materials over future years, we encourage and welcome all comments and suggestions.

L. Glenn Kraige

Blacksburg, Virginia Princeton, West Virginia

Contents

1 Introduction to Statics 1

1/1 Mechanics 1
1/2 Basic Concepts 2
1/3 Scalars and Vectors 2
1/4 Newton's Laws 5
1/5 Units 6
1/6 Law of Gravitation 9
1/7 Accuracy, Limits, and Approximations 10
1/8 Problem Solving in Statics 11
1/9 Chapter Review 14

2 Force Systems 17

2/1 Introduction 17
2/2 Force 17

Section A Two-Dimensional Force Systems 20
2/3 Rectangular Components 20
2/4 Moment 26
2/5 Couple 31
2/6 Resultants 34

Section B Three-Dimensional Force Systems 37
2/7 Rectangular Components 37
2/8 Moment and Couple 41
2/9 Resultants 48
2/10 Chapter Review 54

3 Equilibrium 55

3/1 Introduction 55

Section A Equilibrium in Two Dimensions 56
3/2 System Isolation and the Free-Body Diagram 56
3/3 Equilibrium Conditions 66

Section B Equilibrium in Three Dimensions 74
3/4 Equilibrium Conditions 74
3/5 Chapter Review 82

4 Structures 83

4/1 Introduction 83
4/2 Plane Trusses 84
4/3 Method of Joints 86
4/4 Method of Sections 92
4/5 Space Trusses 96
4/6 Frames and Machines 99
4/7 Chapter Review 105

5 Distributed Forces 106

5/1 Introduction 106

Section A Centers of Mass and Centroids 108
5/2 Center of Mass 108
5/3 Centroids of Lines, Areas, and Volumes 110
5/4 Composite Bodies and Figures; Approximations 118
5/5 Theorems of Pappus 122

Section B Special Topics 125
5/6 Beams—External Effects 125
5/7 Beams—Internal Effects 128
5/8 Flexible Cables 135
5/9 Fluid Statics 143
5/10 Chapter Review 153

6 Friction 154

6/1 Introduction 154

Section A Frictional Phenomena 155
6/2 Types of Friction 155
6/3 Dry Friction 155

Section B Applications of Friction in Machines **164**
6/4 Wedges **164**
6/5 Screws **165**
6/6 Journal Bearings **169**
6/7 Thrust Bearings; Disk Friction **169**
6/8 Flexible Belts **172**
6/9 Rolling Resistance **173**
6/10 Chapter Review **176**

7 Virtual Work **177**

7/1 Introduction **177**
7/2 Work **177**
7/3 Equilibrium **180**
7/4 Potential Energy and Stability **188**
7/5 Chapter Review **197**

APPENDIX **A** Area Moments of Inertia **198**
A/1 Introduction **198**
A/2 Definitions **199**
A/3 Composite Areas **206**
A/4 Products of Inertia and Rotation of Axes **209**

APPENDIX **B** Mass Moments of Inertia **214**

APPENDIX **C** Selected Topics of Mathematics **215**
C/1 Introduction **215**
C/2 Plane Geometry **215**
C/3 Solid Geometry **216**
C/4 Algebra **216**
C/5 Analytic Geometry **217**
C/6 Trigonometry **217**
C/7 Vector Operations **218**
C/8 Series **221**
C/9 Derivatives **221**
C/10 Integrals **222**
C/11 Newton's Method for Solving Intractable Equations **225**
C/12 Selected Techniques for Numerical Integration **227**

APPENDIX **D** Useful Tables **230**
Table D/1 Physical Properties **230**
Table D/2 Solar System Constants **231**
Table D/3 Properties of Plane Figures **232**
Table D/4 Properties of Homogeneous Solids **234**
Table D/5 Conversion Factors; SI Units **238**

INDEX **I-1**