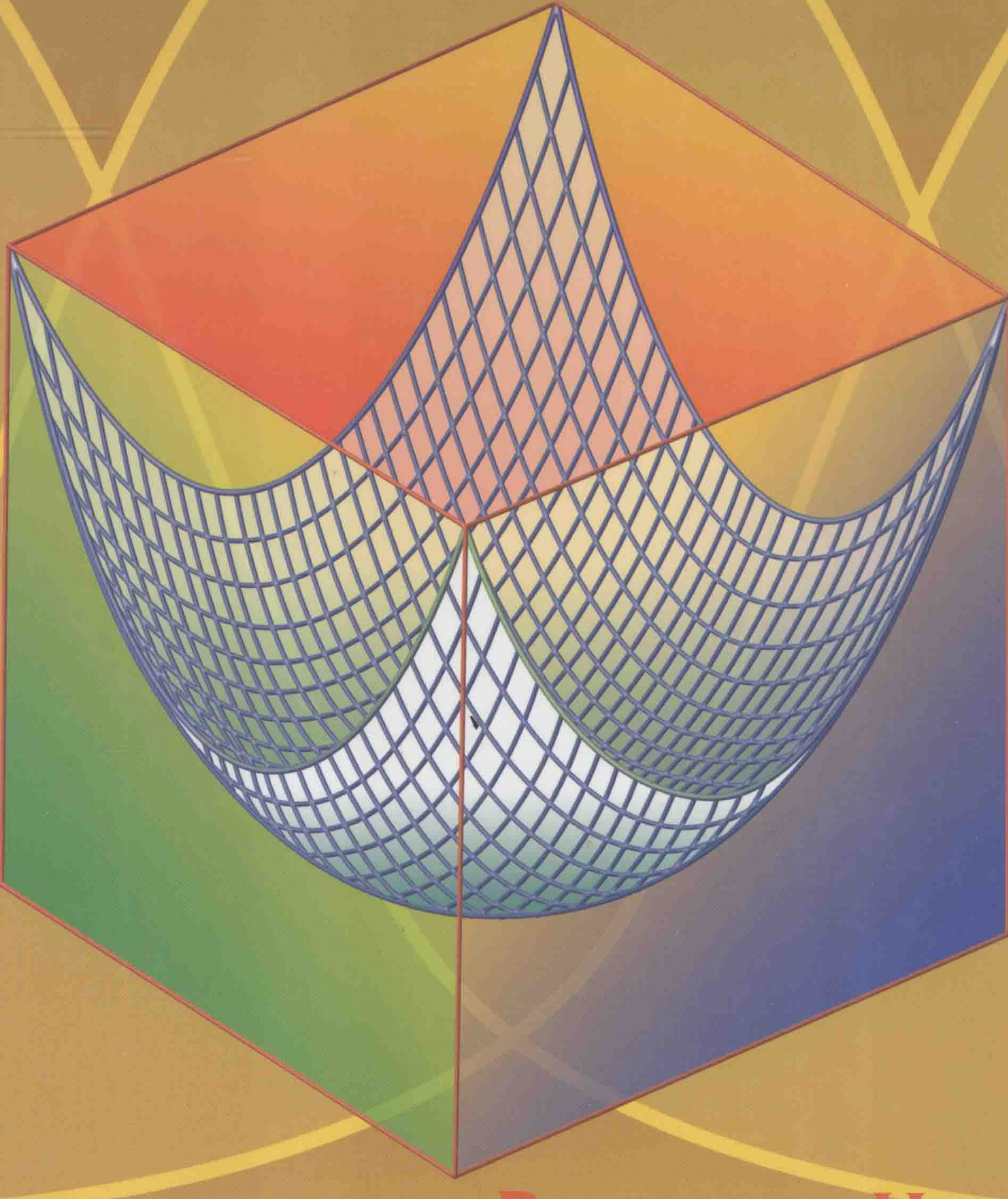
FOURTH EDITION

ENGINEERING STATISTICS



MONTGOMERY RUNGER HUBELE

Engineering Statistics

Fourth Edition

Douglas C. Montgomery
George C. Runger
Norma Faris Hubele
Arizona State University

BICENTENNIAL 1807 WILEY 2007 BICENTENNIAL

John Wiley & Sons, Inc.

ACQUISITIONS EDITOR *Jenny Welter*
SENIOR PRODUCTION EDITOR *Sujin Hong*
MARKETING MANAGER *Frank Lyman*
SENIOR DESIGNER *Kevin Murphy*
COVER PHOTO *Norm Christiansen*
ANNIVERSARY LOGO DESIGN *Richard Pacifico*

This book was set in Times New Roman by TechBooks and printed and bound by R. R. Donnelley. The cover was printed by Phoenix Colors.

This book is printed on acid-free paper. ∞

To order books or for customer service, please call 1-800-CALL WILEY (225-5945).

Library of Congress Cataloging-in-Publication Data

Montgomery, Douglas C.
Engineering statistics/Douglas C. Montgomery, George C. Runger, Norma Faris Hubele.—4th ed.
p. cm.
Includes index.
ISBN-13: 978-0-471-73557-1 (cloth)

1. Statistics. 2. Probabilities. I. Runger, George C. II. Hubele, Norma Faris, 1953- III. Title.
QA276.12.M6453 2006b
519.5′024′62—dc22 2006030759

Printed in the United States of America
10 9 8 7 6 5 4 3

Applications in Examples and Exercises

Chemical and Biological

Civil, Industrial, and Mechanical

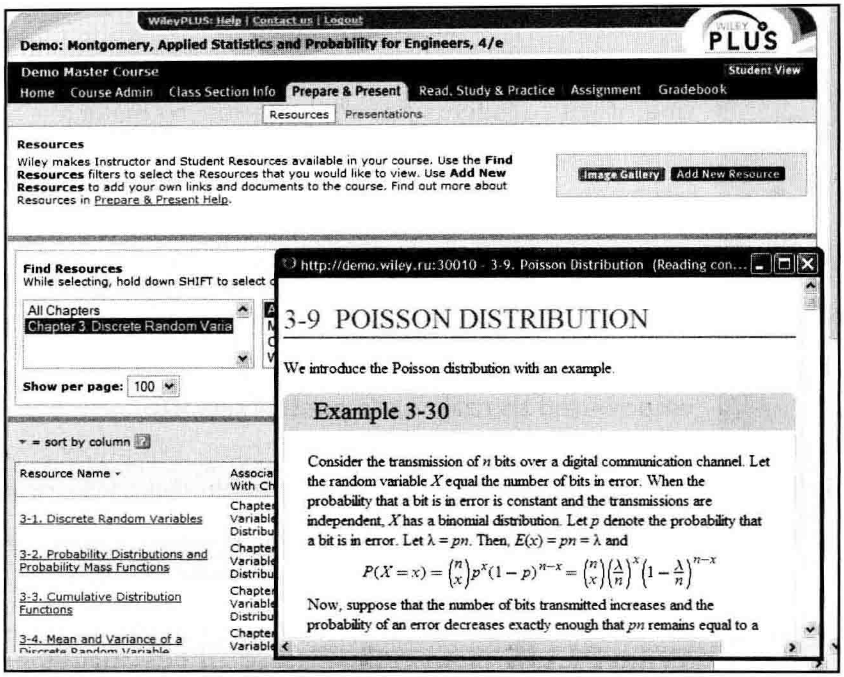
Electrical, Computers, and Communication Networks

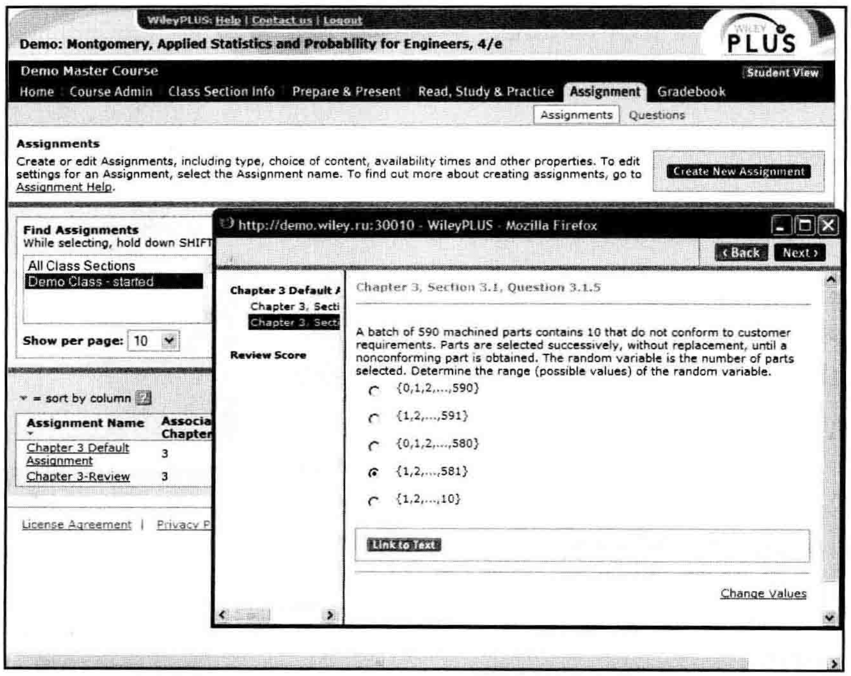
TO THE INSTRUCTOR

WileyPLUS is built around the activities you perform

Prepare & Present

Create outstanding class presentations using a wealth of resources, such as PowerPoint™ slides, image galleries, interactive simulations, and more. Plus you can easily upload any materials you have created into your course, and combine them with the resources Wiley provides you with.





Create Assignments

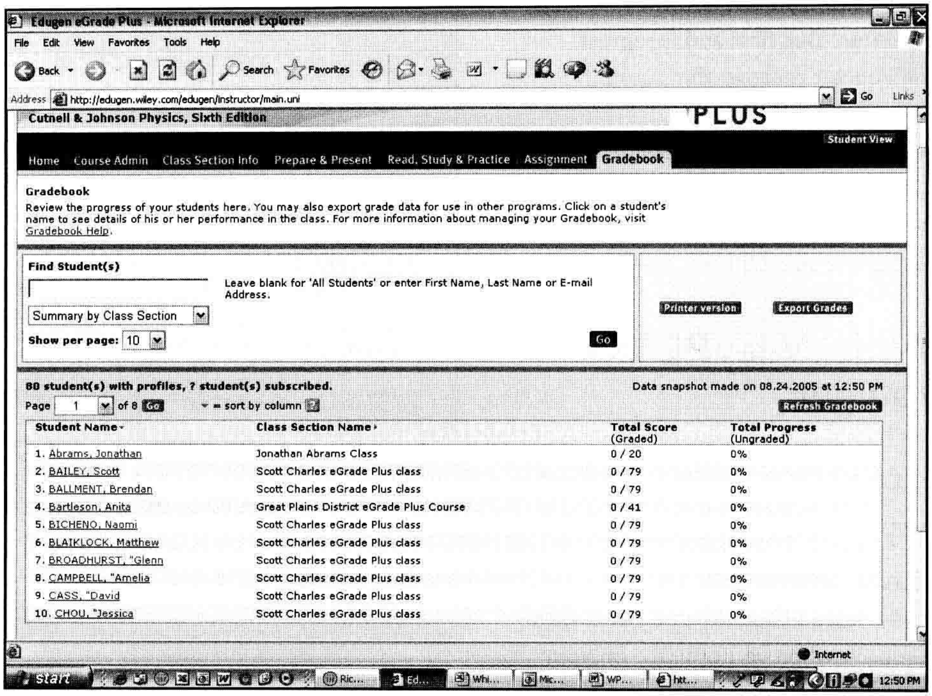
Automate the assigning and grading of homework or quizzes by using the provided question banks, or by writing your own. Student results will be automatically graded and recorded in your gradebook. *WileyPLUS* also links homework problems to relevant sections of the online text, hints, or solutions—context-sensitive help where students need it most!

*Based on a spring 2005 survey of 972 student users of *WileyPLUS*

in your class each day. With Wiley**PLUS** you can:

Track Student Progress

Keep track of your students' progress via an instructor's gradebook, which allows you to analyze individual and overall class results. This gives you an accurate and realistic assessment of your students' progress and level of understanding.



Now Available with WebCT and Blackboard!

Now you can seamlessly integrate all of the rich content and resources available with *WileyPLUS* with the power and convenience of your WebCT or BlackBoard course. You and your students get the best of both worlds with single sign-on, an integrated gradebook, list of assignments and roster, and more. If your campus is using another course management system, contact your local Wiley Representative.

WebCT

Bb Blackboard

"I studied more for this class than I would have without *WileyPLUS*."

Melissa Lawler, *Western Washington Univ.*

For more information on what *WileyPLUS* can do to help your students reach their potential, please visit

www.wiley.com/college/wileyplus

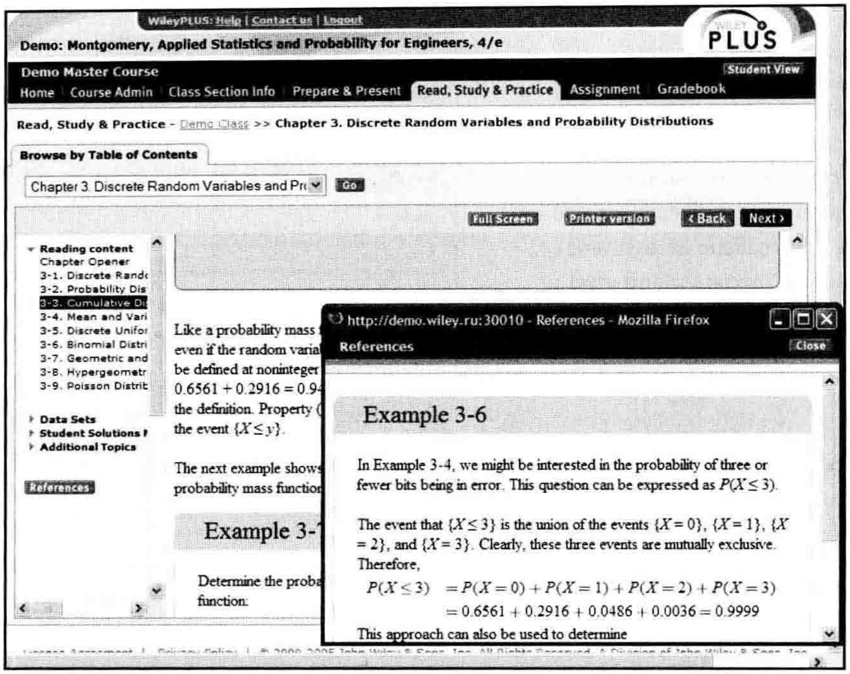
76% of students surveyed said it made them better prepared for tests.*

TO THE STUDENT

You have the potential to make a difference!

Will you be the first person to land on Mars? Will you invent a car that runs on water? But, first and foremost, will you get through this course?

WileyPLUS is a powerful online system packed with features to help you make the most of your potential, and get the best grade you can!



With Wiley**PLUS** you get:

A complete online version of your text and other study resources

Study more effectively and get instant feedback when you practice on your own. Resources like self-assessment quizzes, tutorials, and animations bring the subject matter to life, and help you master the material.

Problem-solving help, instant grading, and feedback on your homework and quizzes

You can keep all of your assigned work in one location, making it easy for you to stay on task. Plus, many homework problems contain direct links to the relevant portion of your text to help you deal with problem-solving obstacles at the moment they come up.

The ability to track your progress and grades throughout the term.

A personal gradebook allows you to monitor your results from past assignments at any time. You'll always know exactly where you stand.

If your instructor uses *WileyPLUS*, you will receive a URL for your class. If not, your instructor can get more information about *WileyPLUS* by visiting www.wiley.com/college/wileyplus

"It has been a great help, and I believe it has helped me to achieve a better grade."
Michael Morris, *Columbia Basin College*

69% of students surveyed said it helped them get a better grade.*

WILEY PLUS

Engineering Statistics

Fourth Edition

THE WILEY BICENTENNIAL–KNOWLEDGE FOR GENERATIONS

Each generation has its unique needs and aspirations. When Charles Wiley first opened his small printing shop in lower Manhattan in 1807, it was a generation of boundless potential searching for an identity. And we were there, helping to define a new American literary tradition. Over half a century later, in the midst of the Second Industrial Revolution, it was a generation focused on building the future. Once again, we were there, supplying the critical scientific, technical, and engineering knowledge that helped frame the world. Throughout the 20th Century, and into the new millennium, nations began to reach out beyond their own borders and a new international community was born. Wiley was there, expanding its operations around the world to enable a global exchange of ideas, opinions, and know-how.

For 200 years, Wiley has been an integral part of each generation's journey, enabling the flow of information and understanding necessary to meet their needs and fulfill their aspirations. Today, bold new technologies are changing the way we live and learn. Wiley will be there, providing you the must-have knowledge you need to imagine new worlds, new possibilities, and new opportunities.

Generations come and go, but you can always count on Wiley to provide you the knowledge you need, when and where you need it!

William J. Pesce
President and Chief Executive Officer

Peter Booth Wiley
Chairman of the Board

To

Meredith, Neil, Colin, and Cheryl

Rebecca, Elisa, George, and Taylor

Yvonne and Joseph Faris, My Parents

Other Wiley Books by These Authors

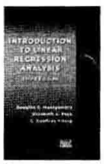
Website: www.wiley.com/college/montgomery

Engineering Statistics, Fourth Edition
By Montgomery, Runger and Hubele
Introduction to engineering statistics, with topical coverage appropriate for a one-semester course. A modest mathematical level, and an applied approach, with frequent use of computational software. One chapter coverage of probability.

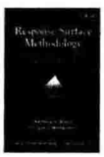
Applied Statistics and Probability for Engineers, Fourth Edition
By Montgomery and Runger
Introduction to engineering statistics, with topical coverage appropriate for either a one- or two-semester course. An applied approach to solving real-world engineering problems, with a strong focus on data analysis. Four chapters coverage of probability.

Introduction to Statistical Quality Control, Sixth Edition
By Douglas C. Montgomery
For a first course in statistical quality control. A comprehensive treatment of statistical methodology for quality control and improvement. Some aspects of quality management are also included, such as the six-sigma approach.

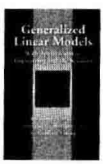
Design and Analysis of Experiments, Fifth Edition
By Douglas C. Montgomery
An introduction to design and analysis of experiments, with the modest prerequisite of a first course in statistical methods. For senior and graduate students, and practitioners, to design and analyze experiments for improving the quality and efficiency of working systems.



Introduction to Linear Regression Analysis, Third Edition
By Montgomery, Peck, and Vining
A comprehensive and thoroughly up-to-date look at regression analysis, still the most widely used technique in statistics today.

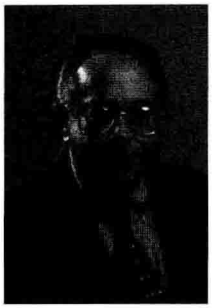


Response Surface Methodology: Process and Product Optimization Using Designed Experiments, Second Edition
By Myers and Montgomery Website: www.wiley.com/college/myers
The exploration and optimization of response surfaces, for graduate courses in experimental design, and for applied statisticians, engineers, and chemical and physical scientists.

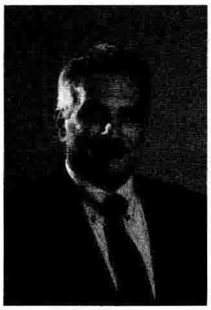


Generalized Linear Models: With Applications in Engineering and the Sciences
By Myers, Montgomery, and Vining Website: www.wiley.com/college/myers
An introductory text or reference on Generalized Linear Models (GLMs). The range of theoretical topics and applications appeals both to students and practicing professionals.

About the Authors



Douglas C. Montgomery, Regents' Professor of Industrial Engineering and Statistics at Arizona State University, received his B.S., M.S., and Ph.D. degrees in engineering from Virginia Polytechnic Institute. He has been a faculty member of the School of Industrial and Systems Engineering at the Georgia Institute of Technology and a professor of mechanical engineering and director of the Program in Industrial Engineering at the University of Washington, where he held the John M. Fluke Distinguished Chair of Manufacturing Engineering. The recipient of numerous awards including the Stewart Medal of the American Society for Quality, two Brumbaugh Awards, the William G. Hunter Award, and two Shewell Awards from the ASQ. He is the editor of *Quality and Reliability Engineering International* and a former editor of the *Journal of Quality Technology*.



George C. Runger, Ph.D., is a Professor in the department of Industrial Engineering at Arizona State University. His research is on data mining, real-time monitoring and control, and other data-analysis methods with a focus on large, complex, multivariate data streams. His work is funded by grants from the National Science Foundation and corporations. In addition to academic work, he was a senior engineer at IBM. He holds degrees in industrial engineering and statistics.

Norma Faris Hubele, Professor of Engineering and Statistics at Arizona State University, and Director of Strategic Initiatives for the Ira A. Fulton School of Engineering, holds degrees in mathematics, operations research, statistics and computer and systems engineering. She is co-owner and serves as vice-president for Quality Control and Statistical Analysis at the Phoenix-based Refrac System. She is on the editorial board of the *Journal of Quality Technology* and *Quality Technology & Quantity Management*, as a founding member. Her specializations include capability analysis, transportation safety and statistics in litigation.

Preface

INTENDED AUDIENCE

Engineers play a significant role in the modern world. They are responsible for the design and development of most of the products that our society uses, as well as the manufacturing processes that make these products. Engineers are also involved in many aspects of the management of both industrial enterprises and business and service organizations. Fundamental training in engineering develops skills in problem formulation, analysis, and solution that are valuable in a wide range of settings.

Solving many types of engineering problems requires an appreciation of variability and some understanding of how to use both descriptive and analytical tools in dealing with variability. Statistics is the branch of applied mathematics that is concerned with variability and its impact on decision making. This is an introductory textbook for a first course in engineering statistics. Although many of the topics we present are fundamental to the use of statistics in other disciplines, we have elected to focus on meeting the needs of engineering students by allowing them to concentrate on the applications of statistics to their disciplines. Consequently, our examples and exercises are engineering based, and in almost all cases, we have used a real problem setting or the data either from a published source or from our own consulting experience.

Engineers in all disciplines should take at least one course in statistics. Indeed, the Accreditation Board on Engineering and Technology is requiring that engineers learn about statistics and how to use statistical methodology effectively as part of their formal undergraduate training. Because of other program requirements, most engineering students will take only one statistics course. This book has been designed to serve as a text for the one-term statistics course for all engineering students.

The Fourth edition has been extensively revised and includes some new examples and many new problems. In this revision we have focused on rewriting topics that our own teaching experience or feedback from others indicated that students found difficult.

ORGANIZATION OF THE BOOK

The book is based on a more comprehensive text (Montgomery, D. C., and Runger, G. C., *Applied Statistics and Probability for Engineers*, Fourth Edition, Hoboken, NJ: John Wiley & Sons, 2006) that has been used by instructors in a one- or two-semester course. We have taken the key topics for a one-semester course from that book as the basis of this text. As a result of this condensation and revision, this book has a modest mathematical level. Engineering students who have completed one semester of calculus should have no difficulty reading nearly all of the text. Our intent is to give the student an understanding of statistical methodology and how it may be applied in the solution of engineering problems, rather than the mathematical theory of statistics. Margin notes help to guide the student in this interpretation and understanding. Throughout the book, we provide guidance on how statistical methodology is a key part of the problem-solving process.

Chapter 1 introduces the role of statistics and probability in engineering problem solving. Statistical thinking and the associated methods are illustrated and contrasted with other engineering modeling approaches within the context of the engineering problem-solving method. Highlights of the value of statistical methodologies are discussed using simple examples. Simple summary statistics are introduced.

Chapter 2 illustrates the useful information provided by simple summary and graphical displays. Computer procedures for analyzing large data sets are given. Data analysis methods such as histograms, stem-and-leaf plots, and frequency distributions are illustrated. Using these displays to obtain insight into the behavior of the data or underlying system is emphasized.

Chapter 3 introduces the concepts of a random variable and the probability distribution that describes the behavior of that random variable. We introduce a simple 3-step procedure for structuring a solution to probability problems. We concentrate on the normal distribution, because of its fundamental role in the statistical tools that are frequently applied in engineering. We have tried to avoid using sophisticated mathematics and the event–sample space orientation traditionally used to present this material to engineering students. An in-depth understanding of probability is not necessary to understand how to use statistics for effective engineering problem solving. Other topics in this chapter include expected values, variances, probability plotting, and the central limit theorem.

Chapters 4 and 5 present the basic tools of statistical inference: point estimation, confidence intervals, and hypothesis testing. Techniques for a single sample are in Chapter 4, and two-sample inference techniques are in Chapter 5. Our presentation is distinctly applications oriented and stresses the simple comparative-experiment nature of these procedures. We want engineering students to become interested in how these methods can be used to solve real-world problems and to learn some aspects of the concepts behind them so that they can see how to apply them in other settings. We give a logical, heuristic development of the techniques, rather than a mathematically rigorous one. In this edition, we have focused more extensively on the *P*-value approach to hypothesis testing because it is relatively easy to understand and is consistent with how modern computer software presents the concepts.

Empirical model building is introduced in *Chapter 6*. Both simple and multiple linear regression models are presented, and the use of these models as approximations to mechanistic models is discussed. We show the student how to find the least squares estimates of the regression coefficients, perform the standard statistical tests and confidence intervals, and use the model residuals for assessing model adequacy. Throughout the chapter, we emphasize the use of the computer for regression model fitting and analysis.

Chapter 7 formally introduces the design of engineering experiments, although much of Chapters 4 and 5 was the foundation for this topic. We emphasize the factorial design and, in particular, the case in which all of the experimental factors are at two levels. Our practical experience indicates that if engineers know how to set up a factorial experiment with all factors at two levels, conduct the experiment properly, and correctly analyze the resulting data, they can successfully attack most of the engineering experiments that they will encounter in the real world. Consequently, we have written this chapter to accomplish these objectives. We also introduce fractional factorial designs and response surface methods.

Statistical quality control is introduced in *Chapter 8*. The important topic of Shewhart control charts is emphasized. The $\overline{X}$ and R charts are presented, along with some simple control charting techniques for individuals and attribute data. We also discuss some aspects of estimating the capability of a process.

The students should be encouraged to work problems to master the subject matter. The book contains an ample number of problems of different levels of difficulty. The end-of-section exercises