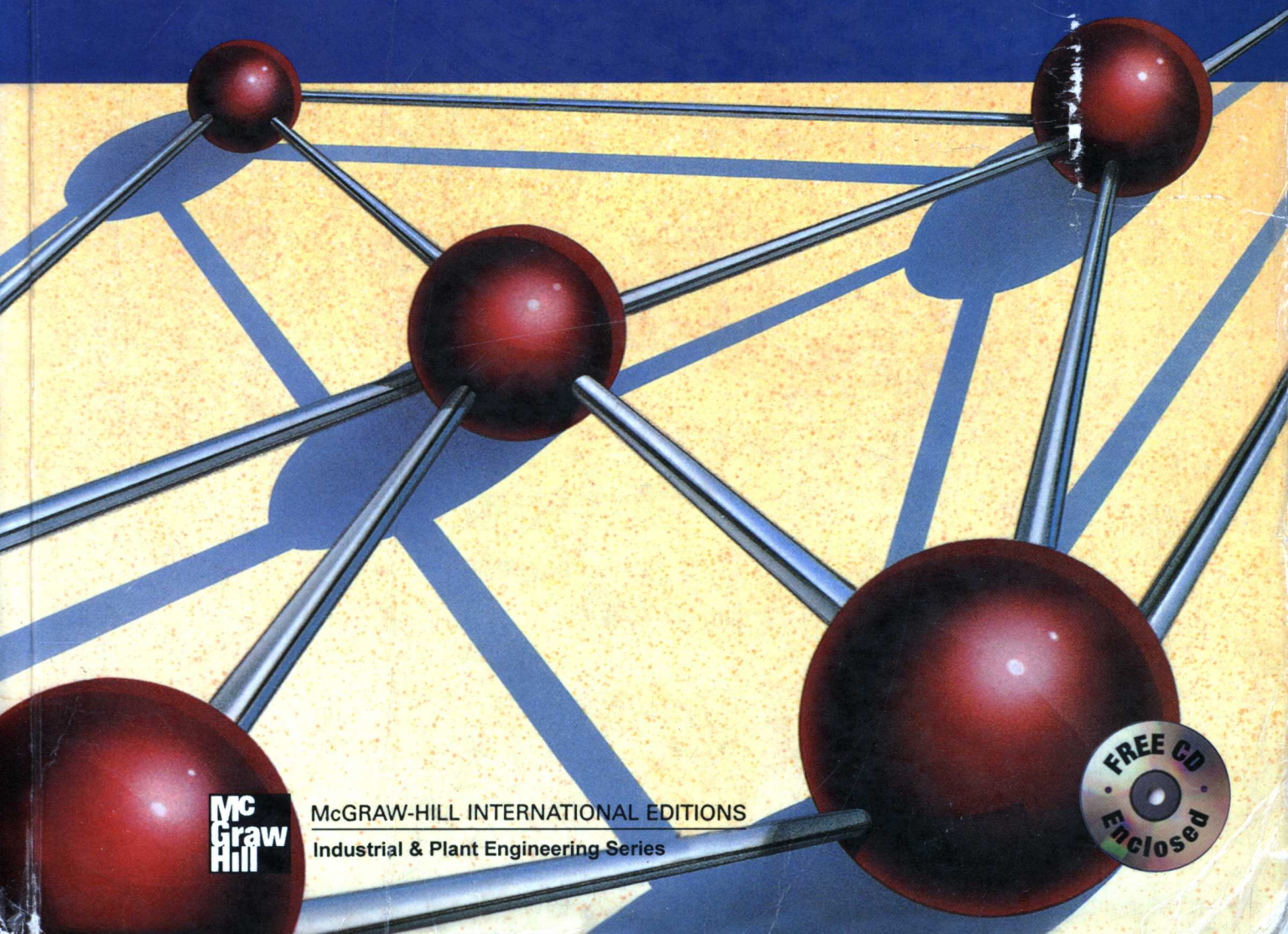
# INTRODUCTION TO OPERATIONS RESEARCH

Seventh Edition

Hillier / Lieberman




McGRAW-HILL INTERNATIONAL EDITIONS
Industrial & Plant Engineering Series

# INTRODUCTION TO OPERATIONS RESEARCH

Seventh Edition

FREDERICK S. HILLIER,
*Stanford University*

GERALD J. LIEBERMAN,
*Late of Stanford University*

Cases developed by Karl Schmedders and Molly Stephens

Tutorial software developed by Mark Hillier and Michael O'Sullivan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# ADVANCE PRAISE FOR INTRODUCTION TO OPERATIONS RESEARCH, SEVENTH EDITION

Reviewers seem to agree that this is clearly the best edition yet. Here is a sampling of comments:

*"The new edition seems to contain the most current information available."*

*"The new edition of Hillier/Lieberman is very well done and greatly enhances this classic text."*

*"The authors have done an admirable job of rewriting and reorganizing to reflect modern management practices and the latest software developments."*

*"It is a complete package."*

*"Hillier/Lieberman has recaptured any advantage it may have lost (to other competitors) in the past."*

*"The changes in this new edition make Hillier/Lieberman the preeminent book for operations research and I would highly recommend it."*

# INTRODUCTION TO OPERATIONS RESEARCH

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# ABOUT THE AUTHORS

**Frederick S. Hillier** was born and raised in Aberdeen, Washington, where he was an award winner in statewide high school contests in essay writing, mathematics, debate, and music. As an undergraduate at Stanford University he ranked first in his engineering class of over 300 students. He also won the McKinsey Prize for technical writing, won the Outstanding Sophomore Debater award, played in the Stanford Woodwind Quintet, and won the Hamilton Award for combining excellence in engineering with notable achievements in the humanities and social sciences. Upon his graduation with a B.S. degree in Industrial Engineering, he was awarded three national fellowships (National Science Foundation, Tau Beta Pi, and Danforth) for graduate study at Stanford with specialization in operations research. After receiving his Ph.D. degree, he joined the faculty of Stanford University, and also received visiting appointments at Cornell University, Carnegie-Mellon University, the Technical University of Denmark, the University of Canterbury (New Zealand), and the University of Cambridge (England). After 35 years on the Stanford faculty, he took early retirement from his faculty responsibilities in 1996 in order to focus full time on textbook writing, and so now is Professor Emeritus of Operations Research at Stanford.

Dr. Hillier's research has extended into a variety of areas, including integer programming, queueing theory and its application, statistical quality control, and the application of operations research to the design of production systems and to capital budgeting. He has published widely, and his seminal papers have been selected for republication in books of selected readings at least ten times. He was the first-prize winner of a research contest on "Capital Budgeting of Interrelated Projects" sponsored by The Institute of Management Sciences (TIMS) and the U.S. Office of Naval Research. He and Dr. Lieberman also received the honorable mention award for the 1995 Lanchester Prize (best English-language publication of any kind in the field of operations research), which was awarded by the Institute of Operations Research and the Management Sciences (INFORMS) for the 6th edition of this book.

Dr. Hillier has held many leadership positions with the professional societies in his field. For example, he has served as Treasurer of the Operations Research Society of America (ORSA), Vice President for Meetings of TIMS, Co-General Chairman of the 1989 TIMS International Meeting in Osaka, Japan, Chair of the TIMS Publications Committee, Chair of the ORSA Search Committee for Editor of *Operations Research*, Chair of the ORSA Resources Planning Committee, Chair of the ORSA/TIMS Combined Meetings Committee, and Chair of the John von Neumann Théory Prize Selection Committee for INFORMS.

He currently is serving as the Series Editor for the International Series in Operations Research and Management Science being published by Kluwer Academic Publishers.

In addition to *Introduction to Operations Research* and the two companion volumes, *Introduction to Mathematical Programming* and *Introduction to Stochastic Models in Operations Research*, his books are *The Evaluation of Risky Interrelated Investments* (North-Holland, 1969), *Queueing Tables and Graphs* (Elsevier North-Holland, 1981, co-authored by O. S. Yu, with D. M. Avis, L. D. Fossett, F. D. Lo, and M. I. Reiman), and *Introduction to Management Science: A Modeling and Case Studies Approach with Spreadsheets* (Irwin/McGraw-Hill, co-authored by M. S. Hillier and G. J. Lieberman).

The late **Gerald J. Lieberman** sadly passed away shortly before the completion of this edition. He had been Professor Emeritus of Operations Research and Statistics at Stanford University, where he was the founding chair of the Department of Operations Research. He was both an engineer (having received an undergraduate degree in mechanical engineering from Cooper Union) and an operations research statistician (with an A.M. from Columbia University in mathematical statistics, and a Ph.D. from Stanford University in statistics).

Dr. Lieberman was one of Stanford's most eminent leaders in recent decades. After chairing the Department of Operations Research, he served as Associate Dean of the School of Humanities and Sciences, Vice Provost and Dean of Research, Vice Provost and Dean of Graduate Studies, Chair of the Faculty Senate, member of the University Advisory Board, and Chair of the Centennial Celebration Committee. He also served as Provost or Acting Provost under three different Stanford presidents.

Throughout these years of university leadership, he also remained active professionally. His research was in the stochastic areas of operations research, often at the interface of applied probability and statistics. He published extensively in the areas of reliability and quality control, and in the modeling of complex systems, including their optimal design, when resources are limited.

Highly respected as a senior statesman of the field of operations research, Dr. Lieberman served in numerous leadership roles, including as the elected President of The Institute of Management Sciences. His professional honors included being elected to the National Academy of Engineering, receiving the Shewhart Medal of the American Society for Quality Control, receiving the Cuthbertson Award for exceptional service to Stanford University, and serving as a fellow at the Center for Advanced Study in the Behavioral Sciences. In addition, the Institute of Operations Research and the Management Sciences (INFORMS) awarded him and Dr. Hillier the honorable mention award for the 1995 Lanchester Prize for the 6th edition of this book. In 1996, INFORMS also awarded him the prestigious Kimball Medal for his exceptional contributions to the field of operations research and management science.

In addition to *Introduction to Operations Research* and the two companion volumes, *Introduction to Mathematical Programming* and *Introduction to Stochastic Models in Operations Research*, his books are *Handbook of Industrial Statistics* (Prentice-Hall, 1955, co-authored by A. H. Bowker), *Tables of the Non-Central t-Distribution* (Stanford University Press, 1957, co-authored by G. J. Resnikoff), *Tables of the Hypergeometric Probability Distribution* (Stanford University Press, 1961, co-authored by D. Owen), *Engineering Statistics*, Second Edition (Prentice-Hall, 1972, co-authored by A. H. Bowker), and *Introduction to Management Science: A Modeling and Case Studies Approach with Spreadsheets* (Irwin/McGraw-Hill, 2000, co-authored by F. S. Hillier and M. S. Hillier).

# ABOUT THE CASE WRITERS

**Karl Schmedders** is assistant professor in the Department of Managerial Economics and Decision Sciences at the Kellogg Graduate School of Management (Northwestern University), where he teaches quantitative methods for managerial decision making. His research interests include applications of operations research in economic theory, general equilibrium theory with incomplete markets, asset pricing, and computational economics. Dr. Schmedders received his doctorate in operations research from Stanford University, where he taught both undergraduate and graduate classes in operations research. Among the classes taught was a case studies course in operations research, and he subsequently was invited to speak at a conference sponsored by the Institute of Operations Research and the Management Sciences (INFORMS) about his successful experience with this course. He received several teaching awards at Stanford, including the university's prestigious Walter J. Gores Teaching Award.

**Molly Stephens** is currently pursuing a J.D. degree with a concentration in technology and law. She graduated from Stanford University with a B.S. in Industrial Engineering and an M.S. in Operations Research. A champion debater in both high school and college, and president of the Stanford Debating Society, Ms. Stephens taught public speaking in Stanford's School of Engineering and served as a teaching assistant for a case studies course in operations research. As a teaching assistant, she analyzed operations research problems encountered in the real world and the transformation of these problems into classroom case studies. Her research was rewarded when she won an undergraduate research grant from Stanford to continue her work and was invited to speak at an INFORMS conference to present her conclusions regarding successful classroom case studies. Following graduation, Ms. Stephens worked at Andersen Consulting as a systems integrator, experiencing real cases from the inside, before resuming her graduate studies.

# DEDICATION

To the memory of our parents

and

To the memory of one of the true
giants of our field, Jerry Lieberman,
whose recent passing prevented him
from seeing the publication
of this edition

# SUPPLEMENTS ON THE BOOK'S WEBSITE, WWW.MHHE.COM/HILLIER

*Some of these supplements are password protected, but are available to all instructors who adopt this textbook.*

**SUPPLEMENT TO APPENDIX 3.1**
**More about LINGO**

**SUPPLEMENT TO CHAPTER 8**
**An Algorithm for the Assignment Problem**

**SUPPLEMENT TO CHAPTER 18**
**The Evaluation of Travel Time**

**CHAPTER 23**
**Additional Special Types of Linear Programming Problems**

23.1 The Transshipment Problem
23.2 Multidivisional Problems
23.3 The Decomposition Principle for Multidivisional Problems
23.4 Multitime Period Problems
23.5 Multidivisional Multitime Period Problems
23.6 Stochastic Programming
23.7 Chance-Constrained Programming
23.8 Conclusions
Selected References
Problems

**CHAPTER 24**
**Probability Theory**

24.1 Sample Space
24.2 Random Variables
24.3 Probability and Probability Distributions
24.4 Conditional Probability and Independent Events

# PREFACE

It now is 33 years since the first edition of this book was published in 1967. We have been humbled by having had both the privilege and the responsibility of introducing so many students around the world to our field over such a long span of time. With each new edition, we have worked toward the goal of meeting the changing needs of new generations of students by helping to define the modern approach to teaching the current status of operations research effectively at the introductory level. Over 33 years, much has changed in both the field and the pedagogical needs of the students being introduced to the field. These changes have been reflected in the substantial revisions of successive editions of this book. We believe that this is true for the current 7th edition as well.

The enthusiastic response to our first six editions has been most gratifying. It was a particular pleasure to have the 6th edition receive honorable mention for the 1995 INFORMS Lanchester Prize (the prize awarded for the year's most outstanding English-language publication of any kind in the field of operations research), including receiving the following citation. "This is the latest edition of the textbook that has introduced approximately one-half million students to the methods and models of Operations Research. While adding material on a variety of new topics, the sixth edition maintains the high standard of clarity and expositional excellence for which the authors have long been known. In honoring this work, the prize committee noted the enormous cumulative impact that the Hillier-Lieberman text has had on the development of our field, not only in the United States but also around the world through its many foreign-language editions."

As we enter a new millennium, the particular challenge for this new edition was to revise a book with deep roots in the 20th century so thoroughly that it would become fully suited for the 21st century. We made a special effort to meet this challenge, especially in regard to the software and pedagogy in the book.

## A WEALTH OF SOFTWARE OPTIONS

The new CD-ROM that accompanies the book provides an exciting array of software options that reflect current practice.

One option is to use the increasingly popular spreadsheet approach with Excel and its Solver. Using spreadsheets as a key medium of instruction clearly is one new wave in

the teaching of operations research. The new Sec. 3.6 describes and illustrates how to use Excel and its Solver to formulate and solve linear programming models on a spreadsheet. Similar discussions and examples also are included in several subsequent chapters for other kinds of models. In addition, the CD-ROM provides an Excel file for many of the chapters that displays the spreadsheet formulation and solution for the relevant examples in the chapter. Several of the Excel files also include a number of Excel templates for solving the models in the chapter. Another key resource is a collection of Excel add-ins on the CD-ROM (Premium Solver, TreePlan, SensIt, and RiskSim) that are integrated into the corresponding chapters. In addition, Sec. 22.6 describes how some simulations can be performed efficiently on spreadsheets by using another popular Excel add-in (@RISK) that can be downloaded temporarily from a website.

Practitioners of operations research now usually use a modeling language to formulate and manage models of the very large size commonly encountered in practice. A modeling language system also will support one or more sophisticated software packages that can be called to solve a model once it has been formulated appropriately. The new Sec. 3.7 discusses the application of modeling languages and illustrates it with one modeling language (MPL) that is relatively amenable to student use. The student version of MPL is provided on the CD-ROM, along with an extensive MPL tutorial. Accompanying MPL as its primary solver is the student version of the renowned state-of-the-art software package, CPLEX. The student version of CONOPT also is provided as the solver for nonlinear programming. We are extremely pleased to be able to provide such powerful and popular software to students using this book. To further assist students, many of the chapters include an MPL/CPLEX file (or MPL/CPLEX/CONOPT file in the case of the nonlinear programming chapter) on the CD-ROM that shows how MPL and CPLEX would formulate and solve the relevant examples in the chapter. These files also illustrate how MPL and CPLEX can be integrated with spreadsheets.

As described in the appendix to Chaps. 3 and 4, a third attractive option is to employ the student version of the popular and student-friendly software package LINDO and its modeling language companion LINGO. Both packages can be downloaded free from the LINDO Systems website. Associated tutorial material is included on the CD-ROM, along with a LINDO/LINGO file for many of the chapters showing how LINDO and LINGO would formulate and solve the relevant examples in the chapter. Once again, integration with spreadsheets also is illustrated.

Complementing all these options on the CD-ROM is an updated version of the tutorial software that many instructors have found so useful for their students with the 5th and 6th editions. A program called OR Tutor provides 16 demonstration examples from the 6th edition, but now with an attractive new design based on JavaScript. These demos vividly demonstrate the evolution of an algorithm in ways that cannot be duplicated on the printed page. Most of the interactive routines from the 6th edition also are included on the CD-ROM, but again with an attractive new design. This design features a spreadsheet format based on VisualBasic. Each of the interactive routines enables the student to interactively execute one of the algorithms of operations research, making the needed decision at each step while the computer does the needed arithmetic. By enabling the student to focus on concepts rather than mindless number crunching when doing homework to learn an algorithm, we have found that these interactive routines make the learning process *far* more efficient and effective as well as more stimulating. In addition to these

routines, the CD-ROM includes a few of the automatic routines from the 6th edition (again redesigned with VisualBasic) for those cases that are not covered by the software options described above. We were very fortunate to have the services of Michael O'Sullivan, a talented programmer and an advanced Ph.D. student in operations research at Stanford, to do all this updating of the software that had been developed by Mark S. Hillier for the 5th and 6th editions.

Microsoft Project is introduced in Chap. 10 as a useful tool for project management. This software package also is included on the CD-ROM.

## NEW EMPHASES

Today's students in introductory operations research courses tend to be very interested in learning more about the relevance of the material being covered, including how it is actually being used in practice. Therefore, without diluting any of the features of the 6th edition, the focus of the revision for this edition has been on increasing the motivation and excitement of the students by making the book considerably more "real world" oriented and accessible. The new emphasis on the kinds of software that practitioners use is one thrust in this direction. Other major new features are outlined below.

Twenty-five elaborate new cases, embedded in a realistic setting and employing a stimulating storytelling approach, have been added at the end of the problem sections. All but one of these cases were developed jointly by two talented case writers, Karl Schmedders (a faculty member at the Kellogg Graduate School of Management at Northwestern University) and Molly Stephens (recently an operations research consultant with Andersen Consulting). We also have further fleshed out six cases that were in the 6th edition. The cases generally require relatively challenging and comprehensive analyses with substantial use of the computer. Therefore, they are suitable for student projects, working either individually or in teams, and can then lead to class discussion of the analysis.

A complementary new feature is that many new problems embedded in a realistic setting have been added to the problem section of many chapters. Some of the current problems also have been fleshed out in a more interesting way.

This edition also places much more emphasis on providing perspective in terms of what is actually happening in the practice of operations research. What kinds of applications are occurring? What sizes of problems are being solved? Which models and techniques are being used most widely? What are their shortcomings and what new developments are beginning to address these shortcomings? These kinds of questions are being addressed to convey the relevance of the techniques under discussion. Eight new sections (Secs. 10.7, 12.2, 15.6, 18.5, 19.8, 20.1, 20.10, and 22.2) are fully devoted to discussing the practice of operations research in such ways, along with briefer mentions elsewhere.

The new emphases described above benefited greatly from our work in developing our recent new textbook with Mark S. Hillier (*Introduction to Management Science: A Modeling and Case Studies Approach with Spreadsheets,* Irwin/McGraw-Hill, 2000). That book has a very different orientation from this one. It is aimed directly at business students rather than students who may be in engineering and the mathematical sciences, and it provides almost no coverage of the mathematics and algorithms of operations research. Nevertheless, its applied orientation enabled us to adapt some excellent material developed for that book to provide a more well-rounded coverage in this edition.

## OTHER FEATURES

In addition to all the new software and new emphases just described, this edition received a considerable number of other enhancements as well.

The previous section on project planning and control with PERT/CPM has been replaced by a complete new chapter (Chap. 10) with an applied orientation. Using the activity-on-node (AON) convention, this chapter provides an extensive modern treatment of the topic in a very accessible way.

Other new topics not yet mentioned include the SOB mnemonic device for determining the form of constraints in the dual problem (in Sec. 6.4), 100 percent rules for simultaneous changes when conducting sensitivity analysis (in Sec. 6.7), sensitivity analysis with Bayes' decision rule (in Sec. 15.2), a probability tree diagram for calculating posterior probabilities (in Sec. 15.3), a single-server variation of the nonpreemptive priorities model where the service for different priority classes of customers now have different mean service rates (in Sec. 17.8), a new simpler analysis of a stochastic continuous-review inventory model (Sec. 19.5), the mean absolute deviation as a measure of performance for forecasting methods (in Sec. 20.7), and the elements of a major simulation study (Sec. 22.5).

We also have added much supplementary text material on the book's new website, www.mhhe.com/hillier. Some of these supplements are password protected, but are available to all instructors who adopt this textbook. For the most part, this material appeared in previous editions of this book and then was subsequently deleted (for space reasons), to the disappointment of some instructors. Some also appeared in our *Introduction to Mathematical Programming* textbook. As delineated in the table of contents, this supplementary material includes a chapter on additional special types of linear programming problems, a review or primer chapter on probability theory, and a chapter on reliability, along with supplements to a few chapters in the book.

In addition to providing this supplementary text material, the website will give updates about the book, including an errata, as the need arises.

We made two changes in the order of the chapters. The decision analysis chapter has been moved forward to Chap. 15 in front of the stochastic chapters. The game theory chapter has been moved backward to Chap. 14 to place it next to the related decision analysis chapter. We believe that these changes provide a better transition from topics that are mainly deterministic to those that are mainly stochastic.

Every chapter has received significant revision and updating, ranging from modest refining to extensive rewriting. Chapters receiving a particularly major revision and reorganization included Chaps. 15 (Decision Analysis), 19 (Inventory Theory), 20 (Forecasting), and 22 (Simulation). Many sections in the linear programming and mathematical programming chapters also received major revisions and updating.

The overall thrust of all the revision efforts has been to build upon the strengths of previous editions while thoroughly updating and clarifying the material in a contemporary setting to fully meet the needs of today's students.

We think that the net effect has been to make this edition even more of a "student's book"—clear, interesting, and well-organized with lots of helpful examples and illustrations, good motivation and perspective, easy-to-find important material, and enjoyable homework, without too much notation, terminology, and dense mathematics. We believe

and trust that the numerous instructors who have used previous editions will agree that this is the best edition yet. This feeling has been reinforced by the generally enthusiastic reviews of drafts of this edition.

The prerequisites for a course using this book can be relatively modest. As with previous editions, the mathematics has been kept at a relatively elementary level. Most of Chaps. 1 to 14 (introduction, linear programming, and mathematical programming) require no mathematics beyond high school algebra. Calculus is used only in Chaps. 13 (Nonlinear Programming) and in one example in Chap. 11 (Dynamic Programming). Matrix notation is used in Chap. 5 (The Theory of the Simplex Method), Chap. 6 (Duality Theory and Sensitivity Analysis), Sec. 7.4 (An Interior-Point Algorithm), and Chap. 13, but the only background needed for this is presented in Appendix 4. For Chaps. 15 to 22 (probabilistic models), a previous introduction to probability theory is assumed, and calculus is used in a few places. In general terms, the mathematical maturity that a student achieves through taking an elementary calculus course is useful throughout Chaps. 15 to 22 and for the more advanced material in the preceding chapters.

The content of the book is aimed largely at the upper-division undergraduate level (including well-prepared sophomores) and at first-year (master's level) graduate students. Because of the book's great flexibility, there are many ways to package the material into a course. Chapters 1 and 2 give an introduction to the subject of operations research. Chapters 3 to 14 (on linear programming and on mathematical programming) may essentially be covered independently of Chaps. 15 to 22 (on probabilistic models), and vice versa. Furthermore, the individual chapters among Chaps. 3 to 14 are almost independent, except that they all use basic material presented in Chap. 3 and perhaps in Chap. 4. Chapter 6 and Sec. 7.2 also draw upon Chap. 5. Sections 7.1 and 7.2 use parts of Chap. 6. Section 9.6 assumes an acquaintance with the problem formulations in Secs. 8.1 and 8.3, while prior exposure to Secs. 7.3 and 8.2 is helpful (but not essential) in Sec. 9.7. Within Chaps. 15 to 22, there is considerable flexibility of coverage, although some integration of the material is available.

An elementary survey course covering linear programming, mathematical programming, and some probabilistic models can be presented in a quarter (40 hours) or semester by selectively drawing from material throughout the book. For example, a good survey of the field can be obtained from Chaps. 1, 2, 3, 4, 15, 17, 19, 20, and 22, along with parts of Chaps. 9, 11, 12, and 13. A more extensive elementary survey course can be completed in two quarters (60 to 80 hours) by excluding just a few chapters, for example, Chaps. 7, 14, and 21. Chapters 1 to 8 (and perhaps part of Chap. 9) form an excellent basis for a (one-quarter) course in linear programming. The material in Chaps. 9 to 14 covers topics for another (one-quarter) course in other deterministic models. Finally, the material in Chaps. 15 to 22 covers the probabilistic (stochastic) models of operations research suitable for presentation in a (one-quarter) course. In fact, these latter three courses (the material in the entire text) can be viewed as a basic one-year sequence in the techniques of operations research, forming the core of a master's degree program. Each course outlined has been presented at either the undergraduate or the graduate level at Stanford University, and this text has been used in the manner suggested.

To assist the instructor who will be covering only a portion of the chapters and who prefers a slimmer book containing only those chapters, all the material (including the supplementary text material on the book's website) has been placed in McGraw-Hill's PRIMIS