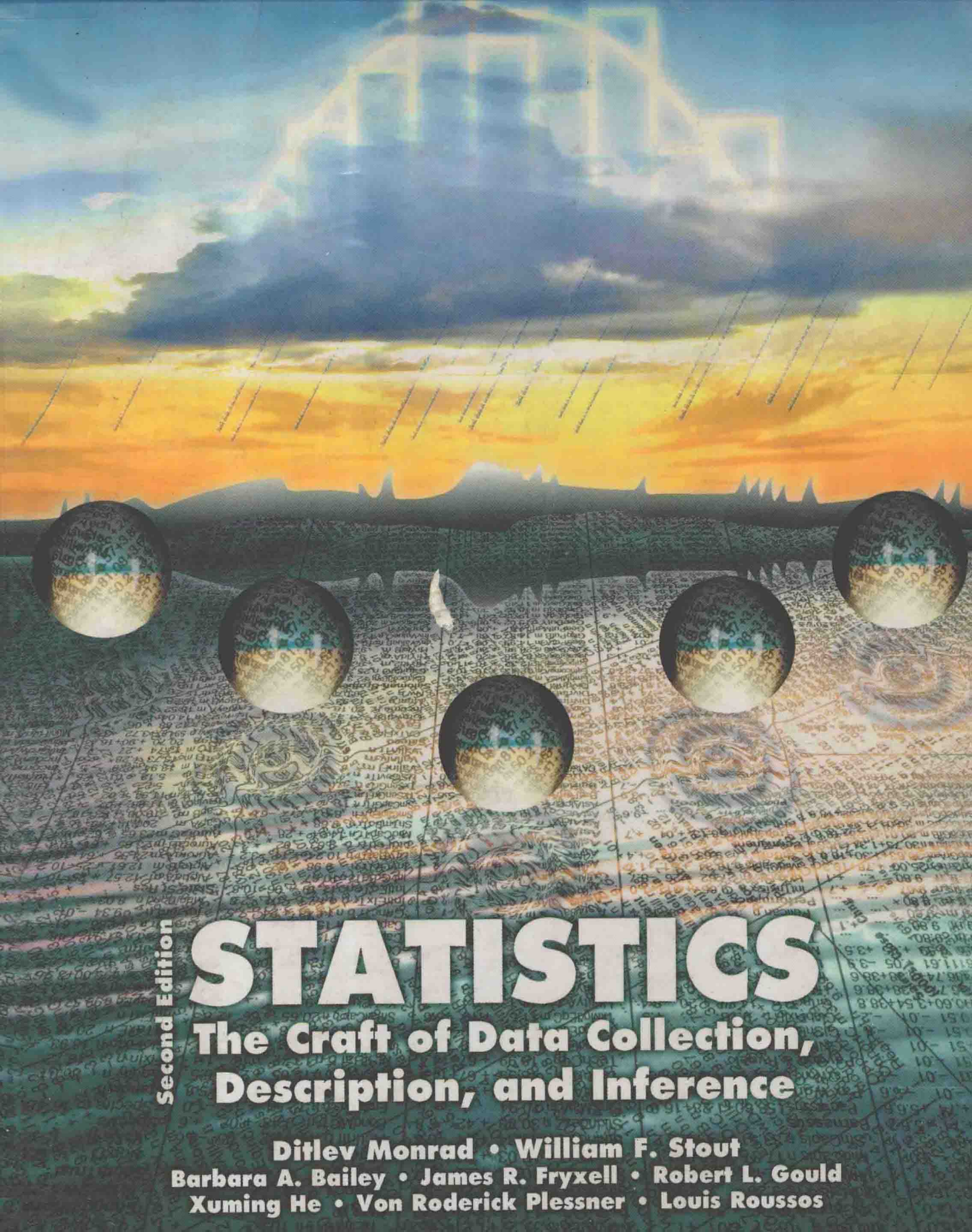

Second Edition

STATISTICS

The Craft of Data Collection, Description, and Inference

Ditlev Monrad • William F. Stout
Barbara A. Bailey • James R. Fryxell • Robert L. Gould
Xuming He • Von Roderick Plessner • Louis Roussos

MASTER STATISTICS

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With contributions from
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About the Authors

Ditlev Monrad is an Associate Professor in the Department of Statistics and the Department of Mathematics at the University of Illinois at Urbana-Champaign (UIUC). His research is in the area of theoretical probability. A dedicated teacher, Professor Monrad has also made important contributions in probability research. He has served as undergraduate and graduate advisor for statistics majors at the UIUC. He has extensive experience in teaching introductory statistics and probability at the 4-year college level.

William F. Stout is a Professor of Statistics at the University of Illinois at Urbana-Champaign (UIUC), where he has been on the faculty since 1967. He is an internationally acclaimed researcher in the application of statistics to the fields of educational and psychological measurement. As the founder of the University of Illinois Statistical Laboratory for Educational and Psychological Measurement, he has led the development of a new and widely applicable theory and methodology for improving standardized testing. Stout is an associate editor of two leading measurement journals: *Psychometrika* and *Journal of Educational and Behavioral Statistics*. He is president-elect of the Psychometric Society.

Dr. Stout is a sought-after instructor and mentor. Several times he has been on the UIUC's list of professors voted as outstanding instructors by their students. In the last five years, 10 students have received their doctorates in statistics under his guidance. Stout was the co-director of the NSF-funded Illinois Institute for Statistics Education, whose mission was to facilitate quality precollege statistics education nationwide. He is the author of over 50 scholarly books and papers.

Barbara A. Bailey is an Assistant Professor of Statistics at the University of Illinois at Urbana-Champaign. Dr. Bailey conducts research in the area of biomathematics and biostatistics with an emphasis on environmental statistics. From 1996 to 1998 she conducted postdoctoral research at the National Center for Atmospheric Research in Boulder, Colorado, concentrating on modeling the spatial and temporal distribution of cloud cover. She has taught mathematics and statistics at both the high school and college level.

James R. Fryxell is a Professor of Mathematics and Chairperson of the Mathematics Department at the College of Lake County, Grayslake, Illinois. He has taught statistics, mathematics, and computer science at the community college level and Advanced Placement statistics at the high-school level. Professor Fryxell was the creator and coordinator of the Mathematics Learning Center at the College of Lake County. Professor Fryxell lectures in math-

ematics and computer studies at Lake Forest College and has taught statistics in the Graduate School of Health Sciences at the Chicago Medical School.

Robert L. Gould is Director of the Center for Teaching Statistics in the Department of Statistics at the University of California at Los Angeles (UCLA). Dr. Gould's research has been in nonlinear estimation of random effects in a mixed model. Much of this research has been done in connection with the Alzheimer Disease Research Center at the University of California at San Diego. Other recent professional work has included the development (in cooperation with Professor Jane Friedman of the University of San Diego) of a high-school primer on statistical and probabilistic issues in DNA "fingerprinting." He is an amateur cellist. Dr. Gould takes an active leadership interest in statistics instruction at all levels. He is Vice-Chair of Undergraduate studies and Director of the Center for Teaching Statistics at UCLA.

Xuming He is an Associate Professor in the Department of Statistics at the University of Illinois at Urbana-Champaign. He is the Director of the department's statistical consulting service (Illinois Statistics Office). In addition, Dr. He serves as a consultant to the Argonne National Laboratory and is a member of the editorial board for the *Journal of Multivariate Analysis*, *Statistica Sinica*, and *Statistics and Probability Letters*.

Dr. He's principal research areas are regression models of large dimensions, regression splines and constrained models, robust methods in linear models, and asymptotics of IRT model estimation. Additional research has been conducted under grants from the National Security Agency and the University of Illinois Research Board.

A highly ranked instructor, Dr. He has taught statistics courses at both the undergraduate and graduate levels since 1989. Active within his department, Dr. He advises Ph.D. candidates and serves on committees for graduate student admissions and Ph.D. examinations.

Von Roderick Plessner is a Professor of Business Management, Accounting, and Computer Programming at Northwest State Community College and an Adjunct Professor of the same subjects at The Defiance College, both in Archbold, Ohio. Professor Plessner has served Northwest State as Dean of Instruction, Director of Business Technologies, and department chair.

Louis Roussos is a Research Scientist with the Law School Admission Council. His major research interest centers on analyzing educational and psychological tests and related constructs. A former aerospace engineer who developed mathematical models for acoustics and vibrations research, Dr. Roussos received the 1999 American Psychological Association's Division 5 Dissertation Award and the 1997 National Council of Measurement in Education Outstanding Dissertation Award.

With over a decade of statistics and mathematics teaching experience, Dr. Roussos has both pedagogical expertise and test analysis competence. He has developed new statistical techniques and software for dimensionality analysis of tests and test bias, and has designed computerized adaptive standardized tests. Since 1995, he has concentrated his research on the Law School Admission Test and conducted a large-scale national survey of law school students. During this same period, Dr. Roussos developed new theoretical insights and formulas that constitute a major advance in test bias detection.

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Preface to the First Edition

It is the authors' strongly held belief that the most effective way for beginning statistics students to learn statistics well is for them to directly experience its central concepts and standard procedures through closely observing and working with simulated and real data sets. The particular advantage of the use of simulated data is that the student knows precisely the underlying mechanism—that is, the probability model—producing the data. Thus the students can see how close the data come, when studied and analyzed with their evolving statistical expertise, to revealing their underlying model truths. The learning of statistics experientially by direct contact with data is facilitated in this textbook by the presentation and demonstration of statistical concepts using the five-step simulation method throughout, The same experiential pedagogical approach, with its emphasis on simulation-based demonstration of statistical concepts, was previously developed into a precollege textbook coauthored by William Stout. This book was used in a five-year National Science Foundation Educational Directorate national teacher training grant for high school teachers, with William Stout a principal investigator.

A vital complement to the experiential learning of statistical concepts is a clear and understandable verbal- and formula-based presentation of the formal, logical, and deductive aspects of the subject, using the minimum amount of mathematical formulation of concepts to make the concepts and procedures easy to understand. These presentation principles are used throughout this text. In most cases this theoretical component is presented after a thorough experiential immersion in and discussion of the topic of interest. For example, the basic aspects of probability—often a difficult set of principles for beginning students to master—are first presented mainly as empirical phenomena in Chapter 4 and 5 and then are abstracted and expanded into a body of probability tools and statistical models, mostly in Chapter 9 and 10. The textbook is deliberate in providing thorough explanations of statistical concepts and methods, because such verbal explanations are key to producing an in-depth understanding of statistics.

The textbook pedagogically stands on three legs: (i) verbal explanations of concepts and procedures; (ii) clear, formula-based descriptions and explanations as needed, and (iii) immersion in the world of chance phenomena and their statistical analyses, achieved through simulation studies and real-world examples.

To be most effective, an introductory statistics textbook must strike a balance between helping the student learn to reason statistically and exposing the student to the standard body of statistical procedures that are widely used in practice and are judged to constitute statistical literacy. This balance, a central goal of this book, equips a student with both real statistical discernment and the needed familiarity with the standard body of statistical procedures so widely used in science, business, and government, and so often reported in the media.

We have carefully crafted the textbook to function equally well for either of two rather different audiences: the concept-based liberal arts statistics courses and the "methods"-based introductory statistics courses for future statistics users. The concept-oriented course is improved by the inclusion of the standard core of statistical methods, and such a methods course is deepened by an emphasis on underlying concepts. As a basic principle of good statistics instruction, the authors assert that both kinds of courses are made better and more complete by this balancing synthesis of methods and concepts.

We believe that an introductory statistics textbook should be able to stand alone in educational settings where calculator and computer technology is not being used. In today's technology-rich learning environments, however, an introductory statistics textbook must be designed to make profound and meaningful use of available technology when the instructor desires. This book is designed with these two possible roles in mind. The book is totally self-contained for classrooms in which technology is not available or not desired. However, for those wishing to use computer software, the simulation approach of the textbook is ideal.

The textbook breaks new ground in content through its inclusion of bootstrap-based inferential procedures as an important component. The bootstrap approach is one of the most important statistical advances of the past 25 years and is rapidly becoming an essential component of the practicing statistician's toolbox. When presented appropriately, the bootstrap approach is intuitive and hence easily understandable by the beginning statistics student. Consistent with the instructional approach of the book, the bootstrap method is simulation based, and it seamlessly meshes with the five-step method used throughout. Most important, it provides the student with a powerful cutting-edge method of statistical inference that, together with small-sample, normal-population sampling inferential approaches and large-sample inferential approaches based on the central limit theorem and the analogous large-sample result for chi-square statistics provides the student with enormous inferential power.

The book is written to be accessible to all students having at least a modest exposure to algebra: "intermediate algebra" suffices. Although formulas and graphs appear frequently and students are encouraged to think deeply about what they are learning, the amount of formal mathematical background needed is minimal. The book should work very well in any non–calculus-based introductory statistics course at any two-year or four-year college or university. It can be effectively used at the precollege level, especially for Advanced Placement statistic courses. It can be taught to science and math majors and to humanities and social science majors with equal ease. It presumes no prior exposure to statistics.

Several influential nationally circulated reports have stressed the need for new emphasis in the teaching of statistics. For example, the widely influential American Statistical Association/Mathematical Association of America Cobb report recommends that the teaching of statistics be heavily data based and proposes that more emphasis be placed on statistical concepts than on abstract theory. Further, it stresses *active learning*. This textbook is tailor-made to address these valid recommendations because of the reasons stated above, and because of the numerous exercises provided after each section as review exercises at the end of each chapter. Students thus have ample opportunity to practice using the concepts learned in the text.

The book begins with three chapters describing how one summarizes data—data being the focus of statistics—graphically and by means of statistical indices. This includes an introduction to linear regression in Chapter 3. Chapters 4 and 5 then provide a heavily empirical introduction to probability through emphasis on probability and probability distributions, and their means and standard deviations. This is appropriate because probability is the logical underpinning of inferential statistics. In particular, probability and expected value are introduced as empirical concepts, numerically approximated using simulation studies with large numbers of simulators per study.

Chapter 6 tells the student how one obtains good data for statistical analyses through random sampling of populations and well-designed randomized statistical experiments, including a section on how students can validly collect their own data for statistical analysis.

Chapters 7 and 8 introduce hypothesis-testing inference, with the widely used and fascinating topic of chi-square testing appearing unusually early, as contrasted with the typical statistics textbook, in Chapter 8.

Chapters 9 and 10 deepen the student's understanding of probability, which is the source of statistical modeling. In this regard Chapter 9 presents the essentials of probability, while the optional chapter 10 presents probability tools necessary for a deeper understanding of statistics.

Chapters 11 and 12 cover statistical inference in depth, stressing estimation via confidence intervals and hypothesis testing, respectively. Chapter 13 complements the descriptive treatment of linear regression from Chapter 3 with an inference-based treatment of linear regression.

Finally, Chapter 14 provides a very accessible introduction to analysis of variance and multiple regression, which together provide the backbone to much of applied statistical practice.

The entire book can easily be covered in a two-semester (or three-quarter) course. If desired, the instructor can omit Chapter 14, or even Chapter 8 without loss of continuity. In a one-semeter course Chapters 1–7 and 9, and 11–12 can be covered, in which case the instructor is encouraged to monitor the ongoing cognitive progress of the class and set the pace accordingly. In a one-semester or one- or two-quarter course, the optional sections and other sections can be omitted to avoid undesirable time pressure, based on instructor tastes. In particular, Chapter 6 can be covered quite briefly if desired.

The apparent length of the textbook is a biased indicator of the pace that can be comfortably maintained through the textbook as the semester or quarter proceeds. Put simply, because of the space required for the textbook's emphasis on learning through simulation and space consumed by the throughness of its verbal explanations, it functions like a 650–700 page textbook would typically function.

This textbook has been heavily influenced by instructor and student input based on classroom use of an earlier textbook written by some of the authors. In particular, Chapter 6 on data collection, Chapter 14 on analysis of variance and multiple regression, and the annotated compilation of Formulas and Techniques were developed in response to such input.

We are confident that you will find teaching statistics from this textbook to be a rewarding experience. We look forward to interacting with instructors by means of the Möbius Web site for this textbook. We welcome queries

and are eager to assist in teaching statistics in this very exciting, effective and experientially based way.

It is worth noting that in addition to the college setting it was designed for, the textbook is also ideal for high school Advanced Placement statistic courses. Its coverage of the College Board's outline of topics covered by the AP exam in statistics is remarkably complete. Moreover, the College Board's recommended emphasis on taking a simulation approach, heavily using technology, and having students construct their own statistics knowledge base (through individual and group projects, etc.) mesh seamlessly with the textbook and its optional computer supplement.

PREFACE TO THE SECOND EDITION

All the misprints and errors that the authors have discovered have been corrected in this second edition. Also, Chapters 1 and 2 have been completely rewritten to produce a more intuitive and more data-centered presentation of descriptive statistics. Throughout the textbook, the text has been clarified and sometimes streamlined. On occasion, exercises have been modified or replaced, and sometimes new exercises have been created. The effect is to create a more readable book and in particular to better capture the flavor of descriptive statistics.

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PROFESSIONAL PROFILE

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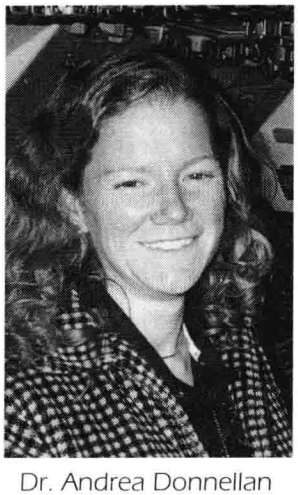
Dr. Andrea Donnellan on the ice in the Clark Mountains near a Global Positioning System station in Marie Byrd Land, Antarctica, November 1999



Dr. Andrea Donnellan

Earthquakes do more than destroy homes and businesses, endanger lives, and disrupt roads, communications, and power distribution. Earthquakes also change the surface of our planet, putting stresses in new locations. Dr. Andrea Donnellan studies what happens to the earth's crust before and after earthquakes. She helped spur the design and installation of the 250-station continuously recording Global Positioning System (GPS) network that monitors the San Andreas Fault and other faults in California.

Dr. Donnellan has also studied the deformation of the earth's surface in Mongolia, Antarctica, Bolivia, and Alaska. She looks at earthquake systems and how faults in the Earth's surface interact with each other. Her immediate goal is to gain an understanding of earthquake fault systems and the style and size of earthquakes that may occur over the next half-century. "We do not as yet," explains Dr. Donnellan, "understand enough to do short-term predictions."

In her work, Dr. Donnellan uses many types of data, including seismic data from the California Institute of Technology, synthetic aperture radar data from Japanese and European satellites, and information from the GPS satellites. Statistical analysis techniques allow her to make sense of this information and see how the earth deforms following a quake.

Dr. Donnellan also notes that the public can benefit from her work. By knowing where faults are and where the greatest risks for future quakes are located, we can set priorities for projects to retrofit buildings, bridges, and other structures to reduce the severity of structural damage in future quakes and perhaps save lives.

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