PREFACE

This volume has been created to honor Professor David Blackwell of the University of California at Berkeley by his students, colleagues, friends and admirers. Most of the papers of this volume are on topics connected with areas in which Blackwell has played a major role. There are review articles on Comparison of Experiments, on Games of Timing, on Merging of Opinions, on Associate Memory Models, and SPLIF's etc. There are historical views of Carnap, of von Mises, and of the Berkeley Statistics Department. But the bulk of the articles are research articles in Probability, Statistics, Gambling, Game Theory, Markov Decision Processes, Set Theory and Logic. Special care has been taken to achieve a wide variety of readable and interesting papers from outstanding scholars.

We present a brief biography of Blackwell, followed by a short review of his research accomplishments. We also include a bibliography of his publications, which, as may be seen from the first article of this volume, becomes out of date with the publication of this volume!

Biography of David Blackwell

David Blackwell was born in Centralia, Illinois, on April 24, 1919. After completing his early education there, he entered the University of Illinois in 1935, where he obtained his A.B. in 1938, his M.A. in 1939, and then his Ph.D. in Mathematics in 1941 at the young age of 22. His thesis was in the area of probability theory written under the direction of J. L. Doob. After spending a year at the Institute for Advanced Study at Princeton, and a summer as an Assistant Statistician for the OPA, he started his career in the educational field as an instructor at two Black universities in the South, in 1942 at Southern University in Baton Rouge, Louisiana, and the following year at Clark College in Atlanta, Georgia. In 1944, he moved to Howard University in Washington, D.C., and in three years he was promoted to full professor and chairman of the mathematics department. In spite of the heavy teaching load and administrative duties this entailed, Blackwell published a substantial amount of outstanding research. He spent several summers at RAND Corporation during this period and the 1950-51 academic year at Stanford as a Visiting Professor of Statistics. In 1954, he joined the Statistics Department of the University of California at Berkeley, where he remains to this day.

By 1954, Blackwell's reputation in probability, statistics, and game theory had grown to such an extent that he was invited to give the address

in probability at the International Congress of Mathematicians held in Amsterdam that year. In 1955, he was elected President of the Institute of Mathematical Statistics.

From this time in his career, Blackwell has received numerous honors and awards. He has received honorary degrees from the University of Illinois, Michigan State University, Southern Illinois University, Carnegie-Mellon University, National University of Lesthos, Amherst College, Harvard University, Yale University, University of Warwick, Syracuse University and the University of Southern California. He has been elected to the National Academy of Science, and to the American Academy of Arts and Sciences.

He was twice elected to the Council of the Institute of Mathematical Statistics, and he has served on the Board of Directors for the American Association for the Advancement of Science. He been Vice President of the American Mathematical Society, of the American Statistical Association and of the International Statistical Institute. He has served as President of the Bernoulli Society and of the International Association for Statistics in the Physical Sciences. He is an Honorary Fellow of the Royal Statistical Society. He has received the R. A. Fisher Award from the Committee of Presidents of Statistical Societies and was awarded the von Neumann Theory Prize by the Institute of Management Sciences and the Operations Research Society of America.

Blackwell's clarity and effectiveness as a lecturer is well known. He has given the Rietz Lecture and the Wald Lectures for the Institute of Mathematical Statistics. Of special note is the fact that he was one of the select, small group of mathematicians chosen by the AMS-MAA to be filmed lecturing on topics accessible to undergraduates. These films have received wide distribution to colleges across the country and make available for posterity the chance to see Blackwell in action.

Blackwell's dedication as a teacher is shown by his books, his many enthusiastic graduate students and his involvement in many educational activities in the field of mathematics. His Ph.D. students number at least 53, and five of them, L. H. Koopmans, I. Mielijson, J. Rolph, G. Roussas, and H. G. Tucker, are represented in this volume. He has served on the American Mathematical Society's Council on the teaching of mathematics. He has twice participated in U.N. supported on-site Conferences for Educational Development in African Mathematics, during the summer of 1962 in the conference on teaching in Uganda, and during the summer of 1965 in the working conference on teaching in Kenya. In 1959-60, he was selected by the Mathematical Association of America as Visiting Lecturer in a program designed to enhance mathematical education in undergraduate colleges. In this instance, in one semester he visited 30 colleges, giving 120 lectures mostly in the Southern United States. It is hard to overestimate the value of this

experience for the many people in predominantly black colleges who heard him.

Along with his many other accomplishments, it is worth noting his ability as an administrator and leader. From 1957 to 1961, he served as Chairman of the Statistics Department at Berkeley. (See the paper of E. L. Lehmann in this volume.) In addition to his chairmanships and his service on numerous Academic Senate Committees at the University of California, he has served as Assistant Dean of the College of Letters and Science for 1964-68, a particularly difficult period in the University's long history. He has also served in London as Director of the University of California Study Center for the United Kingdom and Ireland, 1973-1975.

Finally, there is the matter of David Blackwell, the man and his personality. The editors of this volume have known Dave for a combined total of over 130 years and have many nice things to say on this subject. We instead refer the reader for a personal view of Blackwell to two excellent interviews, one in *Mathematical People – Profiles and Interviews* (1985),17-32, eds. Donald J. Albers and G. L. Alexanderson, Contemporary Books Inc., Chicago, and the other in the very first issue of *Statistical Science* (1986) **1**, 40-53.

The Blackwell Publications.

It is the mark of an outstanding scientist to be influential in a variety of fields. David Blackwell has made fundamental contributions in each of the several fields he has touched. This is well reflected in the fact that in many instances basic theorems or ideas go under his name. His published work falls mainly into five categories: probability theory, statistical theory, game theory, dynamic programming, and set theory and logic. We review each field in turn.

Probability Theory. In terms of numbers of publications, Blackwell's main field of research is probability theory. His early interest in this field, starting with his thesis, centered on Markov chains and processes. The investigation into non-homogeneous Markov chains begun by Blackwell in [3] is alive and well today and is described in the paper of Sonin #23. In the area of renewal theory, Blackwell obtained the definitive result, [8] and [18], now known as Blackwell's Renewal Theorem. In a basic paper [26] on measure spaces underlying modern probability theory, he introduced the concept of Lusin spaces, now sometimes called Blackwell spaces (see Paul-André Meyer, *Probabilités et Potentiel*, Hermann, Paris, 1966). His view of the Dirichlet Process in [65] with MacQueen and in [66] has important implications today as described in the paper of Pitman #18. Among the many other topics of probability theory he has treated, one should specifically mention his pioneer work on functions of Markov chains in [30] with L. Koopmans and in [31],

and also the work on the probability in the tail of a convolution [34] with J. L. Hodges, Jr. Of considerable importance is his very interesting work, some in collaboration with L. Breiman and A. Thomasian, on Information Theory, [33,35,36,37,41].

Mathematical Statistics. In terms of general renown, Blackwell's main field of research would have to be considered statistical theory. He was among the first to recognize the importance of Wald's theory of statistical decision functions, and he has played an important role in the development of that theory. The fundamental paper of Arrow, Blackwell and Girshick [9] helped lay the foundation for Bayesian sequential analysis. His book with Girshick [22] is important not only because of the structured synthesis of the field and the new results it contains, but because it set the style for the next generation of statisticians. The famous Rao-Blackwell Theorem, discovered by C. R. Rao and independently by Blackwell [6] in a form applicable to sequential problems, occupies a central position in the theory of estimation. The practical procedure of improving estimates afforded by this theory is now called Rao-Blackwellization. In [11] and [19], Blackwell introduced the theory of comparison of experiments, and a basic theorem in this area now goes by his name. The paper of Le Cam #11 contains a review of the continuing work in this area. The area of merging of opinions with increasing information was initiated in the paper of Blackwell with Lester Dubins [43]. For an up to date view of this field see the paper of Lehrer and Smorodinsky #13. Other areas in statistical theory on which Blackwell has made an impact include admissibility of estimates for a location parameter [15], randomization of decision rules [12], [13], [17], and design for the control of selection bias [29] with Hodges.

Game Theory. Blackwell started work in game theory while spending his summers at RAND Corporation in the late 1940's. There he authored and coauthored a number of unpublished RAND memorandorum. Among these were several on games of timing or "duels". The modern theory of this field is presented in the survey paper of Radzik #19. The connection between statistical decision functions and game theory, pointed out by Wald, was made closer with the publication of Blackwell's book with Girshick [22]. Since the appearance of the book, Blackwell has made several important contributions to game theory proper. In [25] and [27] he extends the fundamental minimax theorem to vector valued payoffs by introducing the theory of approachability and excludability. This theory is important today in the field of repeated games of incomplete information. In [23], he introduces the class of games of attrition. His paper [59] with T. S. Ferguson provided impetus in the study of stochastic games. (See the paper of Evangelista, Raghavan and Vrieze #3.)

Markovian Decision Processes. Earlier work of Bellman, Karlin and Howard was developed into the modern theory of Markovian decision pro-

cesses by Blackwell in [42] and [53]. The concept of a decision rule that is simultaneously optimal for all sufficiently small discount rates is now described by the name "Blackwell optimal". (See the paper of Yuskevich #26.) In [54], he introduces the concepts of positive and negative dynamic programs. These papers have had a deep impact on the area, and papers of Feinberg #4 and Filar and Liu #5 are concerned with certain modern aspects of the theory.

Set Theory and Logic. Blackwell's impact on these fields has come mainly from his work on infinitely long games. In [56] Blackwell used the determinacy of certain infinite games of perfect information to give a new proof of the reduction principle for coanalytic sets. Blackwell's idea had a major impact on descriptive set theory. Many questions in that subject were known to be unanswerable on the basis of the standard ZFC axioms for set theory. In the decade or so after Blackwell's paper, logicians discovered that the hypothesis that certain infinite games are determined could be used to answer most of these unanswerable questions. (Interaction between game theory and logic is two-way: in the paper of Maitra and Sudderth #15, logic and descriptive set theory are applied to game theory.) In [62] Blackwell introduced a general class of infinitely long games of imperfect information and proved the determinacy of such games for G_δ winning sets. In [80] he gave a new proof of this result. Recently logicians have become interested in these games, and Vervoort's paper #24 at long last generalizes Blackwell's theorem to $G_{\delta\sigma}$ winning sets.

THOMAS S. FERGUSON
DEPARTMENT OF MATHEMATICS
UNIVERSITY OF CALIFORNIA
LOS ANGELES, CA 90095-1555
tom@math.ucla.edu

LLOYD S. SHAPLEY
DEPARTMENT OF ECONOMICS
DEPARTMENT OF MATHEMATICS
UNIVERSITY OF CALIFORNIA
LOS ANGELES, CA 90095-1555
shapley@math.ucla.edu

JAMES B. MACQUEEN
DEPARTMENT OF STATISTICS
UNIVERSITY OF CALIFORNIA
LOS ANGELES, CA 90095-1555
jmacquee@asgm.ucla.edu