

THE ANNALS of PROBABILITY

AN OFFICIAL JOURNAL OF
THE INSTITUTE OF MATHEMATICAL STATISTICS

Articles

Critical phenomena for Spitzer's reversible nearest particle systems	DAVID GRIFFEATH AND THOMAS M. LIGGETT	881
Spatial growth of a branching process of particles living in \mathbb{R}^d	KÔHEI UCHIYAMA	896
A central limit theorem for k-means clustering	DAVID POLLARD	919
Limit theorems for some random variables associated with urn models	L. FLATTO	927
Moments and error rates of two-sided stopping rules	ADAM T. MARCINSEK	935
Renewal theory for Markov chains on the real line	ROBERT W. KEENER	942
A lower bound of the asymptotic behavior of some Markov processes	TZUU-SHUH CHIANG	955
Invariance principles for mixing sequences of random variables	MAGDA PELIGRAD	968
Berry-Esseen theorems for simple linear rank statistics under the null-hypothesis	RONALD J. M. M. DOES	982
Limit theorems for estimators based on inverses of spacings of order statistics	PETER HALL	992
Bounds on the rate of convergence of moments in the central limit theorem	PETER HALL	1004
The expected ratio of the sum of squares to the square of the sum	D. L. MCLEISH AND G. L. O'BRIEN	1019

Short Articles

First hitting time of curvilinear boundary by Wiener process	M. I. TAKSAR	1029
Moment and probability bounds with quasi-superadditive structure for the maximum partial sum	F. A. MÓRICZ, R. J. SERFLING AND W. F. STOUT	1032
Finite Markov chains in stationary random environments	KURT NAWROTZKI	1041
On the central limit theorem for stationary mixing random fields	E. BOLTHAUSEN	1047
Some characterizations of strong laws for linear functions of order statistics	DAVID M. MASON	1051
Strong limiting bounds for maximal uniform spacings	PAUL DEHEUVELS	1058
Generalization and application of a result of C. C. Heyde	R. MICHEL	1066
A limit theorem on a subcritical Galton-Watson process with immigration	K. N. VENKATARAMAN AND K. NANTHI	1069
Some limit theorems on a supercritical simple Galton-Watson process	K. N. VENKATARAMAN AND K. NANTHI	1075
Some limit theorems on reversed Brownian motion	RONG WU	1079
Martingales with given convex image	P. PRINZ	1085
Multiplicative decomposition of non-singular matrix valued continuous semimartingales	RAJEEVA L. KARANDIKAR	1088

Corrections and Notes

The Natural Median	D. LANDERS AND L. ROGGE	1092
--------------------	-------------------------	------

Vol. 10, No. 4—November 1982

THE INSTITUTE OF MATHEMATICAL STATISTICS

(Organized September 12, 1935)

The purpose of the Institute of Mathematical Statistics is to encourage the development, dissemination, and application of mathematical statistics.

OFFICERS

President:

Patrick Billingsley, Department of Statistics, University of Chicago, Chicago, Illinois 60637

President-Elect:

Ingram Olkin, Department of Statistics, Stanford University, Stanford, California 94305

Past-President:

Mark Kac, Department of Mathematics, University of Southern California, Los Angeles, California 90007

Executive Secretary:

Kjell Doksum, Department of Statistics, University of California, Berkeley, California 94720

Treasurer:

Bruce E. Trumbo, Department of Statistics, California State University, Hayward, California 94542

IMS Business Office, 3401 Investment Blvd., Suite 6, Hayward, California 94545

Program Secretary:

Richard Johnson, Department of Statistics, University of Wisconsin, 1210 West Dayton St., Madison, Wisconsin 53706

Editor: *Annals of Statistics*

David V. Hinkley, Department of Applied Statistics, University of Minnesota, St. Paul Campus, St. Paul, Minnesota 55108

Editor: *Annals of Probability*

Harry Kesten, Department of Mathematics, Cornell University, Ithaca, N.Y. 14853

Editor: *IMS Bulletin*

William C. Guenther, University of Wyoming, Box 3332, University Station, Laramie, Wyoming 82071

Editor: *IMS Lecture Notes—Monograph Series*

Shanti S. Gupta, Department of Statistics, Purdue University, West Lafayette, Indiana 47907

Managing Editor:

Jagdish S. Rustagi, Department of Statistics, The Ohio State University, Columbus, Ohio 43210

Membership. Membership dues including a subscription to one *Annals* and *The Institute of Mathematical Statistics Bulletin* are \$37 per year for all members. Special rates of \$17.00 per year are available to students. The dues are approximately 25% higher for members who wish both *Annals* as well as the *Bulletin*. Inquiries regarding membership in the Institute should be sent to the Treasurer at the business office.

Subscription Rates. Current volumes (four issues per calendar year) of the *Annals of Probability* are \$48.00. Single issues are \$13 each. Current volumes (four issues per calendar year) of the *Annals of Statistics* are \$55.00. Single issues are \$15.00 each. Members of the Institute of Mathematical Statistics pay different rates (see above). Back numbers of both *Annals* and the *Annals of Mathematical Statistics* (Volumes 1 through 43) may be purchased from the Treasurer.

The Annals of Probability, Volume 10, Number 4, November 1982. Published in February, May, August, and November by The Institute of Mathematical Statistics, IMS Business Office, 3401 Investment Blvd., Suite 6, Hayward, California 94545.

Mail to the *Annals of Probability* should be addressed to the Treasurer at the IMS Business Office as described above. It should not be addressed to Waverly Press.

Printed at the
WAVERLY PRESS, INC., BALTIMORE, MARYLAND 21202 U.S.A.

Second-class postage at Hayward, California and at additional mailing offices
Copyright © 1982 by the Institute of Mathematical Statistics

NOTICE

Beginning with the calendar year 1982, the two journals of The Institute of Mathematical Statistics will be printed quarterly. The total numbers of pages per volume will be approximately the same as before. Months of publication for 1982 and 1983 are as follows.

Annals of Probability: February, May, August and November

Annals of Statistics: March, June, September and December

THE ANNALS OF PROBABILITY

INSTRUCTIONS FOR AUTHORS

Submission of Papers. Papers to be submitted for publication should be sent to the Editor of the *Annals of Probability*. (For current address, see the latest issue of the *Annals*.) The original (or xerox copy) should be submitted with two additional copies on paper that will take ink corrections. The manuscript will *not* normally be returned to the author; when expressly requested by the author, one copy of the manuscript will be returned.

Preparation of Manuscripts. Manuscripts should be typewritten, entirely double-spaced, including references, with wide margins at sides, top and bottom. Dittoed or mimeographed papers are acceptable only if completely legible; xerox copies are preferable. When technical reports are submitted, all extraneous sheets and covers should be removed.

Submission of Reference Papers. Copies (preferably two) of unpublished or not easily available papers cited in the manuscript should be submitted with the manuscript.

Title and Abbreviated Title. This title should be descriptive and as concise as is feasible, i.e., it should indicate the topic of the paper as clearly as possible, but every word in it should be pertinent. An abbreviated title to be used as a running head is also required, and should be given below the main title. This should normally not exceed 35 characters. For example, a title might be "A Limit Theorem for Conditioned Recurrent Random Walk Attracted to a Stable Law," with the running head "Limit Theorem for Recurrent Random Walk" or possibly "Recurrent Random Walk Attracted to a Stable Law," depending on the emphasis to be conveyed.

Summary. Each manuscript is required to contain a summary which will be printed immediately after the title, clearly separated from the rest of the paper. Its main purpose is to inform the reader quickly of the nature and results of the paper; it may also be used as an aid in retrieving information. The length of a summary will clearly depend on the length and difficulty of the paper, but in general it should not exceed 150 words. It should be typed on a separate page, under the heading "Summary," followed by the title of the paper. Formulas should be used as sparingly as possible. The summary should not make reference to results or formulas in the body of the paper—it should be self-contained.

Footnotes. Footnotes should be reduced to a minimum and, where possible, should be replaced by remarks in the text or in the references; formulas in footnotes should be avoided. Footnotes in the text should be identified by superscript numbers and typed together, double-spaced on a separate page.

Key Words. Included as the first footnote on page 1 should be the headings:

American Mathematical Society 1980 subject classifications. Primary —; Secondary—. Key words and phrases.

The classification numbers representing the primary and secondary subjects of the article may be found with instructions for its use in the *Mathematical Reviews Annual Subject Index-1980*. The key words and phrases should describe the subject matter of the article; generally they should be taken from the body of the paper.

Identification of Symbols. Manuscripts for publication should be clearly prepared to insure that all symbols are properly identified. Distinguish between "oh" and "zero"; "ell" and "one"; "epsilon" and "element of"; "kappa" and "kay," etc. Indicate also when special type is required (Greek, German, script, boldface, etc.); other letters will be set in italics. Acronyms should be introduced sparingly.

Figures and Tables. Figures, charts, and diagrams should be prepared in a form suitable for photographic reproduction and should be professionally drawn twice the size they are to be printed. (These need not be submitted until the paper has been accepted for publication.) Tables should be typed on separate pages with accompanying footnotes immediately below the table.

Formulas. Fractions in the text are preferably written with the solidus or negative exponent;

thus, $(a + b)/(c + d)$ is preferred to $\frac{a + b}{c + d}$, and

$(2\pi)^{-1}$ or $1/(2\pi)$ to $\frac{1}{2\pi}$. Also, $a^{b(c)}$ and $a_{b(c)}$ are

preferred to a^{b^c} and a_{b_c} , respectively. Complicated exponentials should be represented with the symbol \exp . A fractional exponent is preferable to a radical sign.

References. References should be typed double-spaced and should follow the style:

[5] Doob, J. L. (1944). The elementary Gaussian processes. *Ann. Math. Statist.* 15 229–282.

In textual material, the format "... Doob (1944) ..." is normally referred to "... Doob [5] ..." Multiple references can be distinguished as "... Doob (1944a) ..." Abbreviations for journals should be taken from a current index issue of *Mathematical Reviews*.

Proofs. Author will ordinarily receive galley proofs. Corrected galley proofs should be sent to the Managing Editor of the *Annals of Probability*. (For current address, see the latest issue of the *Annals*.)

EDITORIAL STAFF

EDITOR

HARRY KESTEN

ASSOCIATE EDITORS

DAVID ALDOUS

SIMEON M. BERMAN

RENÉ CARMONA

BURGESS DAVIS

C. A. DOLÉANS-DADE

H. O. GEORGI

PRISCILLA GREENWOOD

MARJORIE G. HAHN

PETER HALL

RICHARD HOLLEY

NOBUYUKI IKEDA

THOMAS G. KURTZ

THOMAS M. LIGGETT

P. WARWICK MILLAR

MARK A. PINSKY

HERMANN ROST

STANLEY SAWYER

MICHAEL J. SHARPE

STEVEN E. SHREVE

MICHAEL WOODROOFE

EDITORIAL ASSISTANT

NORMA PRENDERGAST

MANAGING EDITOR

JAGDISH S. RUSTAGI

EDITORIAL ASSISTANTS

DOROTHY GARVIN TONJES

LINDALEE W. BROWNSTEIN

PAST EDITORS

ANNALS OF MATHEMATICAL STATISTICS

H. C. CARVER, 1930–1938

S. S. WILKS, 1938–1949

T. W. ANDERSON, 1950–1952

E. L. LEHMANN, 1953–1955

T. E. HARRIS, 1955–1958

WILLIAM KRUSKAL, 1958–1961

J. L. HODGES, JR., 1961–1964

D. L. BURKHOLDER, 1964–1967

Z. W. BIRNBAUM, 1967–1970

INGRAM OLKIN, 1970–1972

ANNALS OF PROBABILITY

RONALD PYKE, 1972–1975

PATRICK BILLINGSLEY, 1976–1978

R. M. DUDLEY, 1979–1981

ANNALS OF STATISTICS

INGRAM OLKIN, 1972–1973

I. R. SAVAGE, 1974–1976

RUPERT G. MILLER, JR., 1977–1979

EDITORIAL POLICY

The main purpose of the *Annals of Probability* and the *Annals of Statistics* is to publish contributions to the theory of probability and statistics and to their applications. The emphasis is on importance and interest, not formal novelty and correctness. Especially appropriate are authoritative expository papers and surveys of areas in vigorous development. All papers are refereed.

IMS INSTITUTIONAL MEMBERS

AEROSPACE CORPORATION
El Segundo, California

ARIZONA STATE UNIVERSITY
Tempe, Arizona

BELL TELEPHONE LABORATORIES, TECHNICAL
LIBRARY
Murray Hill, N.J.

BOWLING GREEN STATE UNIVERSITY, DEPT.
OF MATHEMATICS
Bowling Green, Ohio

CALIFORNIA STATE UNIVERSITY, FULLERTON,
DEPARTMENT OF MATHEMATICS
Fullerton, California

CALIFORNIA STATE UNIVERSITY, HAYWARD,
DEPARTMENT OF STATISTICS
Hayward, California

CASE WESTERN RESERVE UNIVERSITY, DE-
PARTMENT OF MATHEMATICS
Cleveland, Ohio

CORNELL UNIVERSITY, DEPARTMENT OF
MATHEMATICS
Ithaca, New York

FLORIDA STATE UNIVERSITY, DEPARTMENT OF
STATISTICS
Tallahassee, Florida

GENERAL MOTORS CORPORATION, RESEARCH
LABORATORIES
Warren, Michigan

GEORGE WASHINGTON UNIVERSITY, DEPART-
MENT OF STATISTICS
Washington, D.C.

INDIANA UNIVERSITY, MATHEMATICS DEPT.
Bloomington, Indiana

INTERNATIONAL BUSINESS MACHINES CORPO-
RATION
Armonk, New York

IOWA STATE UNIVERSITY, STATISTICAL LABO-
RATORY
Ames, Iowa

JOHNS HOPKINS UNIVERSITY, DEPARTMENT OF
BIostatistics, DEPARTMENT OF MATHE-
MATICAL SCIENCES
Baltimore, Maryland

KANSAS STATE UNIVERSITY, STATISTICS DE-
PARTMENT
Manhattan, Kansas

MARQUETTE UNIVERSITY, MATHEMATICS AND
STATISTICS DEPARTMENT
Milwaukee, Wisconsin

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
MATHEMATICS DEPARTMENT
Cambridge, Massachusetts

MIAMI UNIVERSITY, DEPARTMENT OF MATH-
EMATICS
Oxford, Ohio

MICHIGAN STATE UNIVERSITY, DEPARTMENT
OF STATISTICS AND PROBABILITY
East Lansing, Michigan

NATIONAL SECURITY AGENCY
Fort George G. Meade, Maryland

NEW MEXICO STATE UNIVERSITY, DEPART-
MENT OF MATHEMATICAL SCIENCES
Las Cruces, New Mexico

NORTHERN ILLINOIS UNIVERSITY, DEPART-
MENT OF MATHEMATICAL SCIENCES
De Kalb, Illinois

NORTHWESTERN UNIVERSITY, DEPARTMENT
OF MATHEMATICS
Evanston, Illinois

OHIO STATE UNIVERSITY, DEPARTMENT OF
STATISTICS
Columbus, Ohio

OREGON STATE UNIVERSITY, DEPARTMENT OF
STATISTICS
Corvallis, Oregon

PENNSYLVANIA STATE UNIVERSITY, DEPART-
MENT OF STATISTICS
University Park, Pennsylvania

PRINCETON UNIVERSITY, DEPARTMENT OF
STATISTICS
Princeton, New Jersey

PURDUE UNIVERSITY LIBRARIES
Lafayette, Indiana

QUEEN'S UNIVERSITY, DEPT. OF MATHEMATICS
AND STATISTICS
Kingston, Ontario, Canada

RICE UNIVERSITY, DEPARTMENT OF MATHE-
MATICAL SCIENCES
Houston, Texas

THE ROCKEFELLER UNIVERSITY
New York, New York

SANDIA CORPORATION, SANDIA BASE
Albuquerque, New Mexico

SIMON FRASER UNIVERSITY, MATHEMATICS
DEPARTMENT
Burnaby, Canada

SOUTHERN ILLINOIS UNIVERSITY, MATHEMATI-
CAL STUDIES
Edwardsville, Illinois

SOUTHERN METHODIST UNIVERSITY, DEPART-
MENT OF STATISTICS
Dallas, Texas

STANFORD UNIVERSITY, GIRSHICK MEMORIAL
LIBRARY
Stanford, California

STATE UNIVERSITY OF NEW YORK, BUFFALO,
DEPARTMENT OF STATISTICS
Amherst, New York

TEMPLE UNIVERSITY, MATHEMATICS DEPART-
MENT
Philadelphia, Pa.

TEXAS TECH UNIVERSITY, DEPARTMENT OF
MATHEMATICS
Lubbock, Texas 79409

THE TOBACCO INSTITUTE
Washington, D.C.

UNION OIL COMPANY OF CALIFORNIA, UNION
RESEARCH CENTER
Brea, California

UNIVERSITY OF ALBERTA, DEPARTMENT OF
MATHEMATICS
Edmonton, Alberta, Canada

UNIVERSITY OF ARIZONA, DEPARTMENT OF
MATHEMATICS AND COMMITTEE ON STA-
TISTICS
Tucson, Arizona

UNIVERSITY OF BRITISH COLUMBIA, DEPART-
MENT OF MATHEMATICS
Vancouver, B.C., Canada

UNIVERSITY OF CALGARY, MATHEMATICS DE-
PARTMENT
Calgary 44, Alberta, Canada

UNIVERSITY OF CALIFORNIA, BERKELEY, STA-
TISTICAL LABORATORY
Berkeley, California

UNIVERSITY OF CALIFORNIA, DAVIS, DIVISION
OF STATISTICS
Davis, California

UNIVERSITY OF CINCINNATI, DEPARTMENT OF
MATHEMATICAL SCIENCES
Cincinnati, Ohio

UNIVERSITY OF GUELPH, MATHEMATICS AND
STATISTICS DEPARTMENT
Guelph, Ontario, Canada

UNIVERSITY OF ILLINOIS AT CHICAGO CIRCLE,
DEPARTMENT OF MATHEMATICS
Chicago, Illinois

UNIVERSITY OF ILLINOIS, MATHEMATICS DEPT.
Urbana, Illinois

UNIVERSITY OF IOWA, DIVISION OF MATHE-
MATICAL SCIENCES
Iowa City, Iowa

UNIVERSITY OF MANITOBA, DEPARTMENT OF
STATISTICS
Winnipeg, Manitoba, Canada

UNIVERSITY OF MARYLAND, DEPARTMENT OF
MATHEMATICS
College Park, Maryland

UNIVERSITY OF MICHIGAN, DEPARTMENT OF
STATISTICS
Ann Arbor, Michigan

UNIVERSITY OF MINNESOTA, SCHOOL OF STA-
TISTICS
Minneapolis, Minnesota

UNIVERSITY OF MISSOURI, DEPARTMENT OF
STATISTICS
Columbia, Missouri

UNIVERSITY OF MISSOURI AT ROLLA, DEPART-
MENT OF MATHEMATICS
Rolla, Missouri

UNIVERSITY OF MONTREAL, DEPARTMENT OF
MATHEMATICS
Montreal, Quebec, Canada

UNIVERSITY OF NEBRASKA, MATHEMATICS
AND STATISTICS DEPARTMENT
Lincoln, Nebraska

UNIVERSITY OF NEW MEXICO, DEPARTMENT
OF MATHEMATICS AND STATISTICS
Albuquerque, New Mexico

UNIVERSITY OF NORTH CAROLINA, DEPART-
MENT OF STATISTICS
Chapel Hill, North Carolina

UNIVERSITY OF OREGON, MATHEMATICS DE-
PARTMENT
Eugene, Oregon

UNIVERSITY OF OTTAWA, DEPARTMENT OF
MATHEMATICS
Ottawa, Ontario, Canada

UNIVERSITY OF SOUTH CAROLINA, DEPART-
MENT OF MATHEMATICS AND COMPUTER
SCIENCE
Columbia, South Carolina

UNIVERSITY OF TEXAS, DEPARTMENT OF
MATHEMATICS
Austin, Texas

UNIVERSITY OF TEXAS, MATHEMATICS DEPT.
San Antonio, Texas

UNIVERSITY OF VICTORIA, DEPT. OF MATHE-
MATICS
Victoria, British Columbia, Canada

UNIVERSITY OF VIRGINIA, DEPT. OF MATHE-
MATICS
Charlottesville, Virginia

UNIVERSITY OF WASHINGTON, DEPARTMENT
OF MATHEMATICS
Seattle, Washington

UNIVERSITY OF WATERLOO, STATISTICS DE-
PARTMENT
Waterloo, Ont., Canada

UNIVERSITY OF WISCONSIN, MADISON, DE-
PARTMENT OF STATISTICS
Madison, Wisconsin

UNIVERSITY OF WISCONSIN, MILWAUKEE, DE-
PARTMENT OF MATHEMATICS
Milwaukee, Wisconsin

VIRGINIA COMMONWEALTH UNIVERSITY, DE-
PARTMENT OF MATHEMATICAL SCIENCES
Richmond, Virginia

WAYNE STATE UNIVERSITY, DEPARTMENT OF
MATHEMATICS
Detroit, Michigan

WESTINGHOUSE ELECTRIC CORPORATION, RE-
SEARCH LABORATORIES
Pittsburgh, Pennsylvania

The Institute of Mathematical Statistics

announces the publication of

Directions in Time Series

Table of Contents

Keynote Address

Can We Predict Where "Time Series" Should Go Next? John W. Tukey

Time Series Models

Parametric Time Series with Some Applications George E. P. Box

Maximum Likelihood Estimation for Vector Autoregressive Moving Average Models T. W. Anderson

Computer Packages and Graphics

What Will Your Time Series Analysis Computer Package Do? David J. Pack

Time Series Modeling, Spectral Analysis, and Forecasting Emanuel Parzen

Some Remarks on Time Series Graphics William S. Cleveland and Douglas M. Dunn

Econometric Models

Some Recent Developments in Seasonal Adjustment David A. Pierce

Comments. John Geweke

On the Synthesis of Time Series and Econometric Models C. W. J. Granger

Comments. John Geweke

Comments. Kenneth F. Wallis

Control Theory and Engineering Applications

On the Identification of State Space Models and Their Use in Control Hirotugu Akaike

System Identification, Kalman Filtering, and Stochastic Control M. B. Priestley

Self-Tuning Algorithms for Control, Prediction and Smoothing Bjorn Wit-tenmark

Robust Methods

Robust Estimation of Autoregressive Models R. Douglas Martin

Comments. Robert B. Miller

Continuous Processes and Periodic Models

Continuous Model Fitting from Discrete Data P. M. Robinson

Comments. David A. Dickey

Some Recent Advances in Autoregressive Processes Marcello Pagano

Comments. Herbert T. Davis

List Price \$20.00

(Members) \$15.00

Order Pre-paid from:

**The Institute of Mathematical Statistics
3401 Investment Boulevard, Suite 6
Hayward, California 94545 (USA)**