

THE ANNALS *of* PROBABILITY

AN OFFICIAL JOURNAL OF
THE INSTITUTE OF MATHEMATICAL STATISTICS

Articles

Long range exclusion processes	THOMAS M. LIGGETT	861
On the growth of one dimensional contact processes	RICHARD DURRETT	890
Markov chains in random environments: the case of Markovian environments	ROBERT COGBURN	908
Further limit theorems for the range of a two-parameter random walk in space	NASROLLAH ETEMADI	917
Rates of convergence for conditional expectations	SANDY ZABELL	928
On the transmission of Bernoulli sources over stationary channels	JOHN C. KIEFFER	942
Asymptotically mean stationary measures	ROBERT M. GRAY AND J. C. KIEFFER	962
A duality theorem for phase type queues	V. RAMASWAMI AND MARCEL F. NEUTS	974

Short Communications

A strong law for linear functions of order statistics	W. R. VAN ZWET	986
Joint limit laws of sample moments of a symmetric distribution	HOWARD G. TUCKER	991

Correction Notes

Correction to "Sojourns and extremes of Gaussian processes"	SIMEON M. BERMAN	999
Correction to "On the range of recurrent Markov chains"	LEO CHOSID AND RICHARD ISAAC	1000
Correction to "The uniform dimension of the levels sets of a Brownian sheet"	ROBERT J. ADLER	1001

Vol. 8, No. 5—October 1980

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:

George E. P. Box, Department of Statistics, University of Wisconsin, 1210 W. Dayton St., Madison, Wisconsin 53706

President-Elect:

Peter Bickel, Department of Statistics, University of California, Berkeley, California 94720

Past-President:

Samuel Karlin, Department of Mathematics, Stanford University, Stanford, California 94305

Executive Secretary:

Martin Fox, Department of Statistics and Probability, Michigan State University, East Lansing, Michigan 48824

Treasurer:

Heebok Park, Department of Statistics, California State University, Hayward, California 94542
IMS Business Office, 3401 Investment Blvd., Suite 6, Hayward, California 94545

Program Secretary:

William L. Harkness, Pennsylvania State University, University Park, Pennsylvania 16801

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*

R. M. Dudley, Department of Mathematics, Room 2-245, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139.

Managing Editor:

Donald R. Truax, Department of Mathematics, University of Oregon, Eugene, Oregon 97403.

Membership. Membership dues including a subscription to one *Annals* and *The Institute of Mathematical Statistics Bulletin* are \$32 per year for all members. Special rates of \$15.00 per year are available to students. Rates in each category are one-third 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 (six issues per calendar year) of the *Annals of Probability* are \$40.00. Current volumes (six issues per calendar year) of the *Annals of Statistics* are \$45.00. Members of the Institute of Mathematical Statistics pay different rates (see above). Single issues are \$8.00. 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 8, Number 5, October 1980. Published bimonthly in February, April, June, August, October, and December 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 either the Editor, Managing Editor or the Treasurer, 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 © 1980 by the Institute of Mathematical Statistics

EDITORIAL STAFF

EDITOR

R. M. DUDLEY

ASSOCIATE EDITORS

ALEXANDRA BELLOW
SIMEON M. BERMAN
RABI BHATTACHARYA
MIKLÓS CSÖRGŐ
C. A. DOLÉANS-DADE
VÁCLAV FABIAN

C. C. HEYDE
NARESH C. JAIN
MARK KAC
HARRY KESTEN
THOMAS G. KURTZ
M. R. LEADBETTER

THOMAS M. LIGGETT
WALTER PHILIPP
STANLEY SAWYER
DAVID O. SIEGMUND
JOHN B. WALSH
STEPHEN JAMES WOLFE

EDITORIAL ASSISTANT

CYNTHIA FRIEDMAN

MANAGING EDITOR

D. R. TRUAX

EDITORIAL ASSISTANTS

RALPH KRUMDIECK

ESTHER ELLEN NOVITSKI

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

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, DEPARTMENT 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, DEPARTMENT OF STATISTICS
Washington, D.C.

INDIANA UNIVERSITY, MATHEMATICS DEPT.
Bloomington, Indiana

INSTITUTE FOR DEFENSE ANALYSES
Arlington, Virginia

INTERNATIONAL BUSINESS MACHINES CORPORATION
Armonk, New York

IOWA STATE UNIVERSITY, STATISTICAL LABORATORY
Ames, Iowa

JOHNS HOPKINS UNIVERSITY, DEPARTMENT OF BIostatISTICS, DEPARTMENT OF MATHEMATICAL SCIENCES
Baltimore, Maryland

KANSAS STATE UNIVERSITY, STATISTICS DEPARTMENT
Manhattan, Kansas

MARQUETTE UNIVERSITY, MATHEMATICS AND STATISTICS DEPARTMENT
Milwaukee, Wisconsin

MASSACHUSETTS INSTITUTE OF TECHNOLOGY MATHEMATICS DEPARTMENT
Cambridge, Massachusetts

MIAMI UNIVERSITY, DEPARTMENT OF MATHEMATICS
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, DEPARTMENT OF MATHEMATICAL SCIENCES
Las Cruces, New Mexico

NORTHERN ILLINOIS UNIVERSITY, DEPARTMENT 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, DEPARTMENT OF STATISTICS
University Park, Pennsylvania

PRINCETON UNIVERSITY, DEPARTMENT OF STATISTICS
Princeton, New Jersey

PURDUE UNIVERSITY LIBRARIES
Lafayette, Indiana

QUEEN'S UNIVERSITY, DEPT. OF MATHEMATICS, KINGSTON
Ontario, Canada

RICE UNIVERSITY, DEPARTMENT OF MATHEMATICAL 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, MATHEMATICAL STUDIES
Edwardsville, Illinois

SOUTHERN METHODIST UNIVERSITY, DEPARTMENT 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 DEPARTMENT
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 UTAH, DEPT. OF MATHEMATICS
Salt Lake City, Utah

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

WEST CHESTER STATE COLLEGE
West Chester, Pennsylvania

WESTINGHOUSE ELECTRIC CORPORATION, RE-
SEARCH LABORATORIES
Pittsburgh, Pennsylvania

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. The 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 1970 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, as an Appendix to *Mathematical Reviews* Index to Volume 39, June 1970. (See, also, *The Notices of the American Mathematical Society*, June 1970; *Bulletin of the Institute of Mathematical Statistics*, September 1974; or a current index issue of *Mathematical Reviews*.) 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"; "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 pre-

ferred to a^{bc} and a_{bc} , 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 preferred 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*.)