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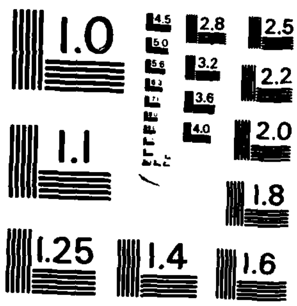
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REPORT ON

THE JACK KIEFER - JACOB WOLFOWITZ MEMORIAL

STATISTICAL RESEARCH CONFERENCE

held at

CORNELL UNIVERSITY, ITHACA, NEW YORK

July 6-9, 1983

Robert E. Bechhofer

Conference Chairman

December 1983

Cornell University

This is a report on the Jack Kiefer-Jacob Wolfowitz Statistical Research Conference held at Cornell University, Ithaca, New York, July 6-9, 1983. The report consists of the following sections.

1. Introduction and summary

2. Program of the Conference

3. Abstracts of papers presented at the Conference

4. List of participants in the Conference

APPENDIX

1. Introduction and summary

The Jack Kiefer-Jacob Wolfowitz Memorial Statistical Research Conference was held at Cornell University, Ithaca, New York on July 6-9, 1983. Financial support for the Conference was provided by the Army Research Office-Durham, the National Science Foundation and the Office of Naval Research. Financial support and services were also provided by various academic units at Cornell including the College of Arts and Science, the College of Engineering, the College of Agriculture and Life Sciences, the Mathematics Research Center, the Statistics Center, the School of Operations Research and Industrial Engineering, and the Office of Sponsored Programs. The statistical community at Cornell is grateful to the various agencies and academic units which provided funds and services, all of which contributed to making this a highly successful conference.

The Conference was designated as a Special Meeting of the Institute of Mathematical Statistics, and was co-sponsored by the American Statistical Association (see copies of relevant letters in the Appendix.) It was publicized through items in AMSTAT NEWS, the Bulletin of the Institute of Mathematical Statistics, the Newsletter of the International Statistical Institute, the Newsletter of the Statistical Society of Canada, the News and Notes of the Royal Statistical Society, among others.

A copy of the program of the Conference is contained in Section 2. Thirty-five papers were presented in plenary sessions at the Conference. The topics covered included admissibilty and inference, → p2 combinatorial design, information and coding theory, multivariate analysis, optimal design, selection theory, and sequential analysis. all of these are areas in which Kiefer and Wolfowitz made substantial contributions. Abstracts of the papers presented at the Conference are contained in Section 3. We are indebted to all of the speakers for their fine presentations.

More than 125 individuals attended the Conference including the speakers and several of their co-authors, the moderators, researchers from various universities and organizations and 24 Cornell statistics students. Full financial support for travel and local expenses was provided to all speakers (except for one foreign speaker who received partial travel support from his own sources). Partial financial support was also provided to 22 junior (and a few more senior) research workers who had particular interests in the topics being discussed. A complete list of the participants is contained in Section 4.

We are particularly grateful to Dr. Aryeh Dvoretzky of the Hebrew University, Israel, and Professor Jerome Sacks of Northwestern University who spoke at a banquet at which Lillian Wolfowitz and Doolie Kiefer, widows of the "two Jacks" were present. Dvoretzky and Sacks were close friends and professional colleagues of Wolfowitz and Kiefer; they reminisced about early research together at Cornell and elsewhere.

Last but certainly not least, the writer would like to express his great indebtedness to the advisory committee and the local committee of statisticians who helped plan the Conference and, in particular, to three of his statistical colleagues at Cornell, Professors George Cascella, Thomas Santner and Bruce Turnbull, who labored long, hard and effectively to make this Conference a great success.

Section 2

PROGRAM OF THE CONFERENCE

THE
JACK KIEFER - JACOB WOLFOWITZ
MEMORIAL STATISTICAL RESEARCH CONFERENCE

PROGRAM

WEDNESDAY, JULY 6

7:30-10:00 a.m. **Registration**

8:20-8:40 a.m. **Welcome**

R.E. Bechhofer, Conference Chairman
W. Keith Kennedy, Provost, Cornell University

8:40-10:00 a.m. **Optimal Design**

Moderator: E. Seiden (Hebrew University)

1. H.P. Wynn (Imperial College, London)
   "Using Discrete Stationary Sequences to Generate Neighbour Designs"

2. T.J. Mitchell (Union Carbide)
   "Computer Algorithms for Designing Experiments Under Multiple Criteria"

10:00-10:15 a.m. **Coffee**

10:15-12:15 p.m. **Admissibility and Inference**

Moderator: B. Turnbull (Cornell University)

1. J. Sacks (Northwestern University)
   "Uniform Confidence Bounds for Functions"

2. M.B. Woodroofe (University of Michigan)
   "Estimating a Distribution Function with Missing Data"

3. A. Cohen* and H.B. Sackrowitz (Rutgers University)
   "Double Sample Procedures"

1:30-3:30 p.m. **Sequential and Multivariate Analysis**

Moderator: A. Tamhane (Northwestern University and Cornell University)

1. G. Lorden (California Institute of Technology)
   "Multi-stage Testing and Design"

2. R.H. Farrell (Cornell University)
   "A Lower Bound on the Risk of Sequential Estimators of the Value of a Density Function"

3. C.-F. Wu (University of Wisconsin)
   "Efficient Model-based Sequential Designs for Sensitivity Experiments"

3:30-3:45 p.m. **Refreshments**

3:45-5:05 p.m. **Combinatorial Design**

Moderator: K.-C. Li (Purdue University)

1. J.N. Srivastava (Colorado State University)
   "On the Criteria of Sensitivity, Revealing Power, and Optimality in the Statistical Design of Multifactor Experiments"

2. W.T. Federer* (Cornell University) and J.P. Mandeli (Virginia Commonwealth University)
   "Orthogonal F-rectangles, Orthogonal Arrays, and Codes"

6:15 p.m. **Barbecue at the Big Red Barn**

THURSDAY, JULY 7

8:00-10:00 a.m. **Sequential Analysis**

Moderator: T. Santner (Cornell University)

1. D. Siegmund (Stanford University)
   "Boundary Crossing Probabilities for Conditioned Processes"

2. W.J. Hall (University of Rochester)
   "Sequential Tests for Bessel Processes: Likelihood Ratio, Wald, and Rao Procedures"

3. T.L. Lai* and H. Robbins (Columbia University)
"Adaptive Allocation of Treatments in Sequential Experiments and the Multi-armed Bandit Problem"

10:00-10:15 a.m. **Coffee**

10:15-11:35 p.m. **Multivariate Analysis**

Moderator: C. Blyth (Queen's University)

1. J.I. Marden (University of Illinois, Champaign-Urbana) and M.D. Perlman* (University of Washington)
"On the Admissibility of Step-down Procedures"

2. I. Olkin (Stanford University)
"Modeling Bivariate Data"

1:30-2:50 p.m. **Admissibility and Inference**

Moderator: J.T. Hwang (Cornell University)

1. P.J. Huber (Harvard University)
"Some Problems Arising in Projection Pursuit"

2. L.D. Brown (Cornell University)
"Comments on the Hunt-Stein Theorem"

2:55-3:30 p.m. **Group Photographs**

3:30-3:45 p.m. **Refreshments**

3:45-5:05 p.m. **Admissibility and Inference**

Moderator: G. Casella (Cornell University)

1. W.E. Strawderman* and J. Natarajan (Rutgers University)
"Sequential Estimation of a Multivariate Normal Mean"

2. J.O. Berger (Purdue University)
"Admissibility and Conditionality"

6:30 p.m. **Banquet in the Memorial Room, Williard Straight Hall**

FRIDAY, JULY 8

8:00-10:00 a.m. **Combinatorial Design**

Moderator: S. Zacks (SUNY, Binghamton)

Section 3

ABSTRACTS OF PAPER DELIVERED AT THE CONFERENCE

GEOMETRIC SINGLE-LETTERISATION TECHNIQUES FOR AV-CHANNELS

R. Ahlswede (Bielefeld University)

There has been a considerable effort during the last 25 years to find the capacities of AV-channels under various assumptions on the communicators' or jammer's strategies and side information. Several of the problems studied originated with [1], [2], and [6].

Our reason for an intensive study of these channels is the fact that they have proved to be a fruitful environment for the discovery of general principles in information theory and new coding methods which often find applications to other coding problems, in particular those arising for multi-user systems.

In the first part of the lecture, we give a brief survey.

The Elimination Technique of [5] has found many applications. It leads to a formula for the average error capacity if this capacity is positive. This leaves us with the task to decide when a capacity is positive. Mathematically this leads to several nice geometric problems about convex sets. We solve some of the seemingly most basic among them. Finally, these investigations should lead to a new algebraic theory of convex sets under Kronecker products.

Most coding problems for AV-channels can be divided into two subproblems: the problem of the capacity formula and the problem of positivity. We observed a remarkable phenomenon: there is a certain tradeoff between the complexities of the two subproblems. It never occurs that both subproblems are easy, if one is easy the other turns out to be very hard or "undoable." (For instance, Shannon's zero-error capacity problem.) Usually, if both are hard, we can (with some effort) get a full answer. There are several such cases, among them the case where the sender knows the state sequence before transmission.

[1] D. Blackwell, L. Breiman and A.J. Thomasian, "The Capacities of Certain Channel Classes under Random Coding," Ann. Math. Statist., 31, pp. 558-567 (1960).

[2] J. Kiefer and J. Wolfowitz, "Channels with Arbitrarily Varying Channel Probability Functions," Information and Control, 5, pp. 44-54 (1962).

[3] R. Ahlswede and J. Wolfowitz, "The Capacity of a Channel with Arbitrarily Varying Channel Probability Functions and Binary Output Alphabet," Z. Wahrscheinlichkeitstheorie, u. verw. Geb., 15, pp. 186-194 (1970).

[4] R. Ahlswede, "Channel Capacities for List Codes," J. Appl. Prob., 10, pp. 824-836 (1973).

[5] R. Ahlswede, "Elimination of Correlation in Random Codes for Arbitrarily Varying Channels," Z. Wahrscheinlichkeitstheorie, u. verw. Geb., 44, pp. 159-175 (1978).

[6] C.E. Shannon, "The Zero Error Capacity of a Noisy Channel," IRE Trans. on Information Theory, IT-2, pp. 8-19 (1956).

[7] L. Lovasz, "On the Shannon Capacity of a Graph," IEEE Trans. on Information Theory, 25, pp. 1-7 (1979).

[8] R. Ahlswede, "Coloring Hypergraphs: A New Approach to Multi-user Source Coding," Part I, J. Comb. Inf. & Syst. Sc., 4, pp. 76-115 (1979); Part II ib., 5, pp. 220-268 (1980).

[9] R. Ahlswede, "A Method of Coding and an Application to Arbitrarily Varying Channels," J. Comb. Inf. & Syst. Sc., 5, pp. 10-35 (1980).

[10] R.L. Dobrushin and S.Z. Stambler, "Coding Theorems for Arbitrarily Varying Discrete Memoryless Channels," Problemi Peredachi Informatsii, 11, pp. 3-22 (1975).

SOME NEW RESULTS FOR A BERNOULLI SEQUENTIAL SELECTION PROCEDURE

R.E. Bechhofer (Cornell University),

C. Jennison (Durham University) and

R.V. Kulkarni (University of North Carolina, Chapel Hill)

In a recent paper, Purdue Symposium III (1982), Bechhofer and Kulkarni proposed "Closed adaptive sequential procedures for selecting the best of $k \geqq 2$ Bernoulli populations." At that time the procedures were known to have various optimal properties. Since then the procedures have been proved to possess additional optimal properties, and have been shown to have highly desirable performance characteristics as well. These will be discussed, and current directions of research will be described.

ADMISSIBILITY AND CONDITIONALITY

J.O. Berger (Purdue University)

The following two questions will be considered:

(i) Is the frequentist concept of admissibility of any use to a conditionalist?

(ii) Could a badly inadmissible decision rule be satisfactory conditionally?

Examples will be discussed which suggest that the answers to both questions are - yes.

THE THEORY OF OPTIMAL DIVERSITY CODING

T. Berger and Z. Zhang (Cornell University)

In communication theory parlance diversity means the provision of more than one link between transmitter and receiver in order to provide protection against intermittent channel dropouts. Instead of naively sending the same information over each link, it is of interest to develop a theory of optimal diversity. Such a theory would specify what information should be sent over the separate links in order to achieve as satisfactory performance as possible given that links may be severed at times. Since each subchannel either is noisefree or disabled at any particular moment, optimal diversity is a source coding problem. Another name for the theory of optimal diversity is "multiple descriptions" theory.

Let $\{X_k\}$ be a sequence of i.i.d.r.v. with finite alphabet X. An m-diversity block encoder with blocklength n and rate vector $\underline{R} = (R_1,\ldots,R_m)$ is a collection of mappings $f_i\colon X^n \to \{1,2,\ldots,M_i\}$, where M_i is the integer part of 2^{nR_i}, $1 \le i \le m$. Let $S \subset \{1,2,\ldots,m\}$, and let $f_S = \{f_i\colon i \in S\}$. The decoder $g_S\colon f_S(X^n) \to \hat{X}^n$ generates an approximation to $\underline{X} = (X_1,\ldots,X_n)$ based on the information available to the receiver when the operative links are $\{\text{link } i\colon i \in S\}$. Here $\hat{X}$ is another finite alphabet perhaps distinct from X. The expected distortion D_S achieved by g_S is $E[d_n(\underline{X},\underline{\hat{X}}(S);S)]$, where $\underline{\hat{X}}(S) = g_S(f_S(\underline{X}))$, $d_n(\underline{x},\underline{\hat{x}};S) = n^{-1}\sum_{k=1}^{n} d_S(x_k,\hat{x}_k)$, and $d_S\colon X\times\hat{X} \to [0,\infty)$. If for any $\epsilon > 0$ there exists for n sufficiently large an $(n,\underline{R})$-encoder and a corresponding collection of 2^m-1 decoders

$\{g_S, \phi \neq S \subset \{1,\ldots,m\}\}$, such that the expected distortion achieved by g_S does not exceed $D_S+\varepsilon$, we say that $\underline{D} = (D_S, \phi \neq S \subset \{1,\ldots,m\})$ is $\underline{R}$-achievable (or equivalently that $\underline{R}$ is $\underline{D}$-admissible). The optimum diversity problem is to determine $\mathcal{D}(\underline{R}) = \{\underline{D}: \underline{D}$ is $\underline{R}$-achievable$\}$.

We prove a general coding theorem that provides a new inner bound to $\mathcal{D}(\underline{R})$. We also precisely specify portions of the boundary of $\mathcal{D}(\underline{R})$ in interesting special cases.

THE ROLE OF THE DISCRIMINATION FUNCTION

R. E. Blahut (IBM Owego)

The expected value of the log-likelihood ratio is a function that appears many times in information theory and in statistics, and under many different names. It deserves to be better recognized. This tutorial paper is intended to show the central role of this function and to explore its many applications.

COMMENTS ON THE HUNT-STEIN THEOREM

L.D. Brown (Cornell University)

This talk will survey the development and current status of the Hunt-Stein Theorem, (The Hunt-Stein Theorem guarantees the existence under suitable regularity conditions of an invariant minimax procedure.) Kiefer (1957) Invariance, minimax sequential estimation, and continuous time processes, Ann. Math. Statist. 28, 573-601, contains the most comprehensive version of the Hunt-Stein

Theorem in the standard statistical literature. However, there is an alternative version and proof, due to L. Le Cam. Only special cases of this have previously been published. We will describe the general statement, and sketch the proof, and explain its relation to Kiefer's results. Some unresolved questions will be mentioned.

AN OPTIMIZATION PROBLEM WITH APPLICATIONS

C.-S. Cheng (University of CA, Berkeley)

The problem of minimizing $\sum_{i=1}^{n} f(x_i)$ subject to the constraints $\sum_{i=1}^{n} x_i$ = constant, $\sum_{i=1}^{n} g(x_i)$ = constant, and $x_i \geq 0$, is considered, where f and g are real-valued functions. It turns out that the solutions are different depending on whether f''/g'' is an increasing or decreasing function. The results can be applied to solve some problems in optimum weighing and block designs. Another application is to the problem of maximizing the total number of spanning trees in a graph.

DOUBLE SAMPLE ESTIMATION PROCEDURES

A. Cohen and H.B. Sackrowitz (Rutgers University)

Bayes double sample procedures are given for estimating the mean of exponential family distributions. The distribution can be multiparameter and so the case of a normal mean with unknown variance is included. Linear combination loss functions are usually assumed. Stein's double sample procedure, and other intuitive double sample procedures for estimating a binomial parameter are studied both theoretically and computationally. Recommendations are given including guidelines for the size of the initial samples. Further theoretical results regarding complete classes, inadmissibility of intuitive procedures, and unbiasedness are given for the binomial case.

INFORMATION INEQUALITIES AND THEIR IMPLICATIONS FOR STATISTICS

T. Cover (Stanford University)

We shall develop a formal similarity between the entropy power inequality and the Brunn-Minkowski inequality. Just as independent normal random variables of given entropies minimize the entropy of the sum, so do spheres of given volumes minimize the volume of the set sum. The isoperimetric inequality says that surface area for a given volume is minimized by spheres. Similarly we shall find that Fisher information for a given entropy is minimized by the normal density. These results are immediate consequences of the aforementioned inequalities.

Another consequence of the entropy power inequality is that $H(\frac{X_1+X_2}{\sqrt{2}}) \geq H(X_1)$, where X_1 and X_2 are independent identically distributed random variables. This may lead to a new proof of the central limit theorem.

We then examine the known inequality $H(X_1,X_2,\ldots,X_n) \geq \Sigma H(X_i)$ for $\underline{X}$ multivariate normal to prove Hadamard's inequality by inspection.

Finally, we shall examine the role of minimum Kullback-Leibler information in large sample theory and discuss some conditional limit theorems. In particular, it will be argued that if $X_1, X_2, \ldots, X_n$ are i.i.d. uniform random variables, and if the first p sample correlations $\frac{1}{n} \Sigma X_i X_{i+k} = \alpha_k$ are observed, then the conditional density of X is given asymptotically by that of the p-th order Gauss-Markov process satisfying covariance constraints $\alpha_0, \alpha_1, \ldots, \alpha_p$. Some of the above is the result of joint work with M. Costa and B.S. Choi.

A LOWER BOUND ON THE RISK OF SEQUENTIAL ESTIMATORS OF THE VALUE OF A DENSITY FUNCTION

R. H. Farrell (Cornell University)

A special parametric family $f(\cdot,\delta)$ of density functions is constructed. For this family the sequential Cramer-Rao lower bound is computed for estimators of $f(0,\delta)$ when squared error loss is used, and δ is the parameter. The resulting differential inequality is related to a differential equation, study of which yields a lower bound to the risk. For the special family of density functions constructed, it is shown that kernel type estimators adaptively modified do not have an asymptotic risk that achieves the lower bound but within a factor of 1.25 the lower bound is attained by the improved estimators. The differential inequalities were studied by means of a related nonlinear differential equation which is solved numerically.

ORTHOGONAL F-RECTANGLES, ORTHOGONAL ARRAYS, AND CODES

W. T. Federer (Cornell University) and

J. P. Mandeli (Virginia Commonwealth University)

There is a 1:1 relationship between sets of t pairwise orthogonal Latin squares, POLS(v,t), and orthogonal arrays, $OA(v^2,t+2,v,2)$ of strength two; there is also a 1:1 relationship between either of the preceding and error correcting codes having v^2 words composed from v symbols, of length $t+2$, and having a distance of $t+1$. Recent developments in orthogonality of F-squares, F-rectangles, Latin cubes, and hyper F-rectangles may be utilized to construct new orthogonal arrays and codes. Orthogonal Latin square theory limits construction of orthogonal arrays to $v^2,t+2,v,2$ types and of codes with v^2 words of length $t+2$ from v symbols. Orthogonal F-square and F-rectangle theory allows construction of orthogonal arrays having different numbers of symbols in the rows as well as having more than $t+2$ rows (constraints). Likewise, codes can be constructed with v^{n+1} words of length v^n using v symbols. Thus, the length of a word (or message) can be made as long as desired, i.e., v^n. A number of results for special cases allows construction of additional orthogonal arrays, and hence codes. Latin and F-hyperrectangle theory allows construction of other orthogonal arrays and codes.

THE SEARCH FOR OPTIMUM WEIGHING DESIGNS: WHERE STATISTICS, COMBINATORICS AND COMPUTATION MEET

Z. Galil (Tel Aviv University)

This paper surveys techniques, results and open problems concerning the computation of optimum weighing designs.

ON TWO-STAGE BAYES SELECTION PROCEDURES

S. S. Gupta (Purdue University)
and K. J. Miescke (University of Illinois, Chicago)

Given k normal populations with unknown means and a common known variance, two-stage selection procedures with screening at the first stage to find the population with the largest mean are considered. A typical procedure of this type can be described as follows: At Stage 1, after samples of size n have been taken from all populations, a non-empty subset of populations is selected. If it consists of only one single population, this one will be selected, and the procedure stops. Otherwise, at Stage 2, additional samples of size m are taken only from those populations which have been selected previously, and one of them is then selected finally. Under a symmetric normal prior, a Bayes procedure is derived with respect to a certain loss function which takes into account the selected population mean's deviation from the largest mean, as well as the costs of sampling at Stage 2. Of special interest herein is the form of the subset selection rule at Stage 1, which is studied in greater detail. Also, comparisons are made to several stage subset selection procedures existing in the literature.

EXTREMAL SPLITTINGS OF POINT PROCESSES

B. Hajek (University of Illinois, Champaign-Urbana)

The binary sequence with nth term defined by [(n+1)p]-[np] is the "most deterministic" binary sequence of density p in the following sense (for example): If a fraction p of customers from a Poisson arrival stream are sent to an exponential server queue according to a prespecified binary sequence, then the long term average delay is minimized when the above sequence is used.

The proof involves the minimization over a class of probability measures of the integral of a fixed function on R^n (with arbitrarily large n). The measures are supported on the integer lattice Z^n and have a specified mean which need not be a lattice point. A broad family of functions is identified for which the extremal measures are completely characterized.

SEQUENTIAL TESTS FOR BESSEL PROCESSES: LIKELIHOOD RATIO, WALD, AND RAO PROCEDURES

W.J. Hall (University of Rochester)

Thirty years ago, Jack Kiefer and Jacob Wolfowitz, jointly with A. Dvoretzky (Ann. Math. Statist. 24 (1953)), introduced sequential tests for the parameter of certain continuous-time stochastic processes, such as the drift parameter of a Wiener process. Using notions of sufficiency and invariance, we extend their work, constructing tests for the non-centrality parameter of a Bessel process. Such a process is the continuous-time analog of a sequence of quadratic-form statistics, based on increasing amounts of data. Hence, applications include sequential versions of likelihood ratio, Wald, and Rao tests--of multidimensional hypotheses, with or without nuisance parameters--and corresponding rank tests as well. As with other invariant sequential tests, formulas are not available for such characteristic properties as OC functions and mean stopping times; however, tables are being prepared based on numerical computations. Finally, conditional P-values are introduced for various component hypotheses when the null hypothesis of centrality is rejected.

DESIGNS FOR CONTROLLED ΠPS SAMPLING

A.S. Hedayat and B.Y. Lin (University of Illinois, Chicago)

Any survey sampling design, d, of size n without replacement based on a finite population u of size N units or clusters can be formally presented by a pair (S_d, P_d), where S_d, called the support of d, is any set of subsets of size n each based on the elements of u such that the (set theoretic) union of these subsets, called samples, is u and P_d is a strictly positive probability distribution on S_d. A survey sampling design, d, is said to be probability proportional to size, denoted by PPS(N,n), if the probability that the unit i is selected (customarily, this probability is denoted by Π_i) in a random sample under d is proportional to a known positive quantity associated with the unit $i = 1,2,\ldots,N$. The literature of survey sampling offers a PPS(N,n) with S_d consisting of all

$\binom{N}{n}$ possible samples. This paper provides a technique called UTEQ for constructing PPS survey sampling designs. The UTEQ produces all the existing PPS survey sampling designs as special cases. Indeed, no more PPS survey designs can be constructed beyond the ones produced by UTEQ. For each pair of N and n the list of produced PPS survey sampling designs includes survey designs whose supports do not include all samples of size n. Survey designs of the latter type are needed for controlled samplings when some samples are undesirable to be chosen. In addition, a procedure called "max procedure" is introduced to be utilized along with the UTEQ for manipulating probabilities (increasing or decreasing) over desirable or undesirable samples while dealing with controlled survey samplings.

SOME PROBLEMS ARISING IN PROJECTION PURSUIT

P.J. Huber (Harvard University)

Projection pursuit methods are among the most intriguing and promising new techniques of multivariate analysis. I shall describe some of their proposed uses: (1) finding "interesting" low-dimensional projections, and (2) lifting univariate methods to higher dimensions with applications to robust estimation, non-parametric smoothing and density estimation. Their sampling properties are largely unexplored. I shall comment on preliminary results and on conceptual and mathematical problems.

ADAPTIVE ALLOCATION OF TREATMENTS IN SEQUENTIAL EXPERIMENTS AND THE MULTI-ARMED BANDIT PROBLEM

T.L. Lai and H. Robbins (Columbia University)

Let $\pi_1,\ldots,\pi_k$ denote k statistical populations (treatments, manufacturing processes, gambling machines or "bandits," etc.) specified respectively by density functions $f(x,\theta_1),\ldots,f(x,\theta_k)$ with respect to some measure ν, where f is known and $\theta_1,\ldots,\theta_k$ are unknown parameters belonging to some set Θ. Assume that $\int_{-\infty}^{\infty} |x| f(x,\theta) d\nu < \infty$ for all $\theta \in \Theta$. How should we sample $x_1, x_2, \ldots$ sequentially from the k populations if our objective is to achieve the greatest possible expected value of the sum $S_n = x_1 + \ldots + x_n$? This is often called the "multi-armed bandit problem" in the engineering and statistical literature, and there have been several different formulations of the notion of "greatest possible" expected reward. We review these different formulations and earlier results in the literature, provide a unified approach to these formulations, and describe a simple adaptive allocation rule which is asymptotically optimal for each of these formulations.

MULTI-STAGE TESTING AND DESIGN

G. Lorden (University of California at Los Angeles)

A new method of constructing 3-stage hypothesis tests yields asymptotic optimality among all tests (including sequential ones) as in recently published results by the author. The method has the advantage of facilitating construction of tests that achieve (approximately) prescribed error probabilities. Similar methods apply to problems of asymptotically optimal sequential design and yield, for example, results like those of Kiefer and Sacks (1963).

ON THE ADMISSIBILITY OF STEP-DOWN PROCEDURES

J. I. Marden (University of Illinois at Champaign-Urbana)
and M. D. Perlman (University of Washington)

J. Roy (1958 Annals of Mathematical Statistics) proposed step-down procedures in various multivariate testing problems. In the Hotelling T^2 problem of testing that a p-dimensional normal mean vector is zero based on a sample of i.i.d. multivariate normal observations, the step-down procedure accepts the null hypothesis if and only if $F_i \equiv (T_i - T_{i-1})/(1+T_i) \leq c_i$, $i = 1,\ldots,p$, where T_i is the Hotelling T^2 statistic based on the first i variables. Under the null hypothesis, the F_i's are independent scaled F variables. The problem and the step-down procedures are invariant under the upper triangular group G. We have characterized the minimal complete class of G-invariant tests, and have obtained the following results:

(a) If $p = 2$, the step-down procedure is admissible among G-invariant tests;

(b) If $p > 2$ and at least three c_i's are strictly positive, then the procedure is inadmissible among G-invariant tests, hence is inadmissible at large;

(c) If some $c_i = 0$, then there exists a sequence of parameter values going to infinity for which the power of the test does not approach 1, i.e., the test is not parameter consistent.

Admissibility results are also obtained for the step-down procedure in testing for independence, and for the modified procedures in which the step sizes may exceed one, i.e., where the component tests $(F_i \leq c_i)$ are based on blocks of variables rather than one variable each (cf. Mudholkar and Subbaiah (1980), Annals Inst. Statist. Math.)

COMPUTER ALGORITHMS FOR DESIGNING EXPERIMENTS UNDER MULTIPLE CRITERIA

T. J. Mitchell (Union Carbide Corporation, TN)

Current computer algorithms for designing experiments are based on the assumption that the expectation (η) of the response variable (y) is related to p design variables $\underset{\sim}{x}$ through the linear model:

$$\eta = \underset{\sim}{\beta}_1' \underset{\sim}{f}_1(\underset{\sim}{x}) \qquad (1)$$

where $\underset{\sim}{\beta}_1$ is a k_1-vector of unknown coefficients and $\underset{\sim}{f}_1(\underset{\sim}{x})$ is a k_1-vector of known functions of $\underset{\sim}{x}$. The design criterion is usually a function of the $k_1 \times k_1$ variance-covariance matrix of the least squares estimator $\hat{\underset{\sim}{\beta}}_1$. Such criteria focus on precise estimation of $\underset{\sim}{\beta}_1$, given that the model assumption (1) holds. Unfortunately, designs that are optimal with respect to these criteria are often virtually incapable of assessing the adequacy of the proposed model. Similarly, algorithms that focus only on the ability to detect lack of fit may not produce designs that are good for estimating β_1.

Assuming that the true response has the form $\eta = \beta_1' f_1(x) + \beta_2' f_2(x)$, we propose a method for constructing "compromise designs" that are good with respect to two kinds of criteria: C_1 for precise estimation of β_1 given $\beta_2 = 0$ and C_2 for detection of lack of fit of (1). Here C_1 is log D-optimality and C_2 is the Jones-Mitchell Λ_2-optimality criterion. An "admissible" design is defined to be one that cannot be beaten with respect to both criteria by some other design. Concavity arguments are used to show that any design that maximizes the mixed criterion $C_\alpha = (1-\alpha)C_1 + \alpha C_2$, for some α, is admissible. An exchange algorithm for constructing designs to maximize C_α is discussed. Some results are given for polynomial models in one dimension and also for the two-level factorial design setting. Approaches to finding the remaining admissible designs (i.e., those not optimal with respect to any C_α) are also discussed.

MODELING BIVARIATE DATA

I. Olkin (Stanford University)

Distribution theory for univariate random variables is very well developed. In contrast, the development of multivariate distribution theory, except for the multivariate normal distribution, is quite sparse. In particular, there is little theory of how to construct bivariate distributions with particular types of dependencies. In this paper we describe several general procedures and then show how to generate a coherent family of distributions using sums and limits of bivariate Bernoulli random variables.

APPROXIMATE THEORY OF MULTI-WAY BLOCK DESIGNS

F. Pukelsheim (University of Freiburg)

Exact multi-way block designs are embedded into J. Kiefer's approximate theory of experimental design. Optimality properties of block designs are deduced then from the general results of the approximate design theory. This is carried out under variation of

(1) the class of competing designs,

(2) the optimality criterion,

(3) the parameters of interest, and

(4) the statistical model.

It turns out that the designs which are optimal are uniform designs, and designs whose two-dimensional marginals are products of the one-dimensional marginals.

The situation gets more involved when the support sets of the two-dimensional marginals is prescribed in advance: Generalized Youden designs, and C.-S. Cheng's more general Pseudo-Youden-Designs turn out to be optimal with respect to a relatively small class of competing designs, only. This contrasts with the setting in one-way models where the classical Balanced Incomplete Block Designs do maintain their optimality also with respect to restricted sets of support points.

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[1] C.-S. Cheng, "Optimal designs for the elimination of multi-way heterogeneity. Ann. Statist. 6, pp. 1262-1272 (1978).

[2] ______, "Optimality and construction of Pseudo-Youden designs. Ann. Statist. 9, pp. 201-205 (1981).

[3] J. Kiefer, "General equivalence theory for optimum designs (approximate theory). Ann. Statist. 2, pp. 849-879 (1974).

[4] F. Pukelsheim, "On linear regression designs which maximize information. J. Statist. Plann. Inference 4, pp. 339-364 (1980).

[5] ______, "On optimality properties of simple block designs in the approximate design theory. J. Statist. Plann. Inference, forthcoming.

UNIFORM CONFIDENCE BOUNDS FOR FUNCTIONS

J. Sacks (Northwestern University)

Uniform confidence bounds for regression functions are described for situations covered by standard linear model assumptions (for example, the function is a cubic on an interval) and also when the function is in an infinite dimensional class controlled by some bound on its smoothness (for example $|f''| \leq m$). The bounds obtained are conservative but are very close to the exact bounds obtained by Wynn and Bloomfield in the linear model settings they treat, thus indicating the bounds' utility in the nonparametric regression settings.

BOUNDARY CROSSING PROBABILITIES FOR CONDITIONED PROCESSES

D. Siegmund (Stanford University)

Techniques originally developed for approximating the power functions of sequential tests will be applied to a number of problems inside and outside of sequential analysis: notably statistics involving the maximum deviation of a (weighted) empirical distribution function and statistics which test for a change point. As a focal point I shall sketch a derivation of the following asymptotic expansion of the tail of a distribution which was computed exactly by J. Kiefer (1959) in terms of an infinite series of Bessel functions. Let $W_0(t)$, $0 \le t \le 1$, denote a two-dimensional Brownian bridge. As $k \to \infty$

$$(*) \quad P\{\max_{0 \le t \le 1} \|W_0(t)\| \ge x\} = 2(2\pi)^{1/2} \times e^{-2x^2}(1-(8x^2)^{-1} + o(x^{-2})).$$

For $x = 1$, Kiefer gives the value .588 for this probability. The approximation (*) yields .594.

LIKELIHOOD PROCEDURES FOR SELECTING A SUBSET

M. Sobel* and H.-F. Wu (University of California, Santa Barbara)

A general method for sequential selection and/or identification problems based on updating at each stage the likelihoods associated with various decisions (and stopping when any one of them reaches a preassigned P*-value) was developed in Bechhofer, Kiefer and Sobel (1968). This sequential method also applies to the problem of subset selection, although this application was never developed. In this paper this application is developed and preliminary results based on both asymptotic theory and Monte Carlo studies are used to make fair comparisons between fixed-sample-size results and sequential results obtained by the above procedure. Although the numerical differences are not significant, the procedures are quite different. The fact that the sequential procedure represents an application of a general technique with other possible applications is important.

ON THE CRITERIA OF SENSITIVITY, REVEALING POWER, AND OPTIMALITY IN THE STATISTICAL DESIGN OF MULTIFACTOR EXPERIMENTS

J.N. Srivastava (Colorado State University)

"Sensitivity" and "Revealing Power" were recently advanced by the author as statistical design criteria, which should be reckoned with, along with "optimality." Briefly speaking, the question of sensitivity arises when there are major nuisance factors present which influence the outcome of the experiment, but whose levels and nature cannot be identified either "at all" or "partially." The question of revealing power arises when there are factors present in which we are "completely" or "partially" interested, but whose "levels" or "influence parameters" are not known, either "wholly" or "partially." It was shown that such situations do arise in the earlier stages of most experimentation. In such situations, optimality may get overshadowed by the above criteria, since in general, optimality refers to situations with "well defined models." In the present paper the criteria are further elaborated and results are presented on designs satisfying one or more of the three criteria. It will be shown how some of the popular classes of designs fall short of the needs, and how certain other classes could replace them.

SEQUENTIAL ESTIMATION OF A MULTIVARIATE NORMAL MEAN

W. E. Strawderman and J. Natarajan (Rutgers University)

Stein showed that the usual estimator of a vector of normal means is inadmissible for quadratic loss if the dimension is at least 3. We go somewhat further and produce a sequential procedure which never takes more observations than the usual procedure (and takes substantially fewer observations with high probability for θ close to the origin) and has uniformly smaller risk.

Similar results for estimating several Poisson means and for estimating the variance of a normal distribution will also be discussed.

OPTIMAL DESIGNS FOR TRIGONOMETRIC REGRESSION FUNCTIONS USING CANONICAL MOMENTS

W.J. Studden and T.-S. Lau (Purdue University)

D-optimal designs are considered for trigonometric regression functions using canonical moments. A short proof of the D-optimality of the uniform design will be given for the full set of coefficients. The relationship with the ordinary polynomial case is considered and D_s-optimal designs are obtained for certain subsets of the coefficients.

A MULTIDIMENSIONAL CLT FOR MAXIMA OF NORMED SUMS

H. Teicher (Rutgers University)

and C. Hagwood (University of Virginia)

It is shown that $S_{k,j} = \sum_{i=1}^{k} X_{ij}$, $1 \leq j \leq d$, $k \geq 1$ where $(X_{i1},\ldots,X_{id})$, $i \geq 1$ are i.i.d. random vectors with positive mean vector $(\mu_1,\ldots,\mu_d)$ and finite covariance matrix $\sum$, then for any choice of α_j in $[0,1)$, $1 \leq j \leq d$ the random vector whose jth component is $n^{\alpha_j - 1/2}\left(\max_{1 \leq k \leq n} \frac{S_{k,j}}{k^{\alpha_j}} - \mu_j n^{1-\alpha_j}\right)$ converges in law to a multinormal distribution with mean vector zero and covariance matrix $\sum$.

SOME OPTIMUM NON-ADAPTIVE HYPERGEOMETRIC GROUP TESTING DESIGNS FOR IDENTIFYING TWO DEFECTIVES

C.A. Weideman and D. Raghavarao (Temple University)

A systematic study of non-adaptive hypergeometric group testing designs for identifying two defectives is presented. Bounds are given for the number of items that can be tested in a given number of tests. Constructions of some classes of designs are presented.

ESTIMATION WITH A GAUSSIAN GAIN FUNCTION

L. Weiss (Cornell University)

The random vector X has a distribution depending on the unknown parameters $\theta_1,\ldots,\theta_m$, which are to be estimated. If the values of the estimates are $D_1,\ldots,D_m$, the following loss function is proposed:

$$C[1 - \exp\{ - \sum_{i,j=1}^{m} B_{ij}(\theta_1,\ldots,\theta_m)(D_i-\theta_i)(D_j-\theta_j)\}]$$

where C is a positive constant, $B_{ij}(\theta_1,\ldots,\theta_m)$ is a continuous function of its arguments, and the matrix $\{B_{ij}(\theta_1,\ldots,\theta_m)\}$ is positive definite for all $\theta_1,\ldots,\theta_m$. It is mathematically equivalent, and more convenient, to use the "gain function" defined as 1 - (1/C)(Loss function). Because of its form, this will be called a "Gaussian gain function." It is shown that for several common estimation problems the maximum likelihood estimator has an expected gain function uniformly arbitrarily close to the expected gain function of an admissible decision rule.

ESTIMATING A DISTRIBUTION FUNCTION WITH MISSING DATA

M.B. Woodroofe (University of Michigan)

Let P be a finite population with $N \geq 1$ elements; for each $e \in P$, let X_e and Y_e be independent, positive random variables with unknown distribution functions F and G and suppose that the pairs (X_e,Y_e), $e \in P$, are i.i.d. We consider the problem of estimating F and G when the data consist of those pairs (X,Y) for which $Y \leq X$. The non-parametric maximum likelihood estimators of F and G are described, and asymptotic properties as $N \to \infty$ are derived. It is shown that the maximum likelihood estimators are consistent against continuous alternatives F and G for which $G^{-1}(0) \leq F^{-1}(0)$ and

$G^{-1}(1) \leq F^{-1}(1)$. Asymptotic distributions of the estimation errors are considered. Here $\sqrt{n}$ x estimation error may fail to converge to a Gaussian process, if $\int (1/G)dF = \infty$.

EFFICIENT MODEL-BASED SEQUENTIAL DESIGNS FOR SENSITIVITY EXPERIMENTS

C.F.J. Wu (University of Wisconsin)

A sequential design for estimating the percentiles of a quantal response curve is proposed. Its updating rule is based on an efficient summary of all the data available via a parametric model. Its efficiency in terms of saving the number of runs and its robustness against the distributional assumption are demonstrated heuristically and in a simulation study. A linear approximation to the "logit-MLE" version of the proposed sequential procedure is shown to be equivalent to an asymptotically optimal stochastic approximation method, thereby providing a large sample justification. For sample size between 12 and 35, the simulation study shows that the "logit-MLE" version of the general sequential procedure substantially outperforms an adaptive (and asymptotically optimal) version of the Robbins-Monro method, which in turn outperforms the nonadaptive Robbins-Monro and Up-and-Down methods.

USING DISCRETE STATIONARY SEQUENCES TO GENERATE NEIGHBOR DESIGNS

H.P. Wynn (Imperial College, London)

Recent joint work with the late Professor Jack Kiefer stressed the importance of stationary discrete processes in understanding the allowable neighbor structures of designs used for spatial processes with a superimposed treatment structure. There has also been a growth of activity in recent years on neighbor designs more generally. There is a close connection with the theory of two dimensional codes and with image processing which both study the evolution of binary patterns. This paper attempts to tie together these different areas with particular reference to the generation of new methods of finding optimum neighbor designs and new classes of pseudo-random sampling schemes. As a bi-product some remarks are made about the analysis of spatial binary data.

1. F. Pukelsheim (University of Freiburg)
   "Approximate Theory of Multi-way Block Designs"

2. C.-S. Cheng (University of California, Berkeley)
   "An Optimization Problem with Applications"

3. C.A. Weideman and D. Raghavarao* (Temple University)
   "Some Optimum Non-adaptive Hypergeometric Group Testing Designs for Identifying Two Defectives"

10:00-10:15 a.m. **Coffee**

10:15-12:15 p.m. **Optimal Design**

Moderator: W.I. Notz (Purdue University)

1. Z. Galil (Tel Aviv University)
   "The Search for Optimum Weighing Designs: Where Statistics, Combinatorics, and Computation Meet"

2. W.J. Studden* and T.-S. Lau (Purdue University)
   "Optimal Designs for Trigonometric Functions Using Canonical Moments"

3. A.S. Hedayat* and B.Y. Lin (University of Illinois, Chicago)
   "Designs for Controlled πPS Sampling"

1:30-3:30 p.m. **Information and Coding Theory**

Moderator: J.P.M. Schalkwijk (University of Technology, Eindhoven)

1. R. Ahlswede (Bielefeld University)
   "Geometric Single-letterisation Techniques for AV-channels"

2. T. Berger* and Z. Zhang (Cornell University)
   "The Theory of Optimal Diversity Coding"

3. T.M. Cover (Stanford University)
   "Information Inequalities and Their Implications for Statistics"

3:30-3:45 p.m. **Refreshments**

3:45-5:05 p.m. **Information and Coding Theory**

Moderator: J. Abrahams (Office of Naval Research)

1. R.E. Blahut (IBM Owego)
   "The Role of the Discrimination Function"

2. B. Hajek (University of Illinois, Champaign-Urbana)
   "Extremal Splittings of Point Processes"

SATURDAY, JULY 9

8:00-10:00 a.m. **Selection Theory**

Moderator: R. Launer (Army Research Office, Durham)

1. S.S. Gupta* (Purdue University) and K.J. Miescke (University of Illinois, Chicago)
   "On Two-stage Bayes Selection Procedures"

2. R.E. Bechhofer* (Cornell University), C. Jennison (Durham University) and R.V. Kulkarni (University of North Carolina, Chapel Hill)
   "Some New Results for a Bernoulli Sequential Selection Procedure"

3. M. Sobel* and H.-F. Wu (University of California, Santa Barbara)
   "Likelihood Procedures for Selecting a Subset"

10:00-10:15 a.m. **Coffee**

10:15-11:35 a.m. **Convergence and Estimation**

Moderator: D. Robson (Cornell University)

1. H. Teicher* (Rutgers University) and C. Hagwood (University of Virginia)
   "A Multidimensional CLT for Maxima of Normed Sums"

2. L. Weiss (Cornell University)
   "Estimation with a Gaussian Gain Function"

*Designates presenter

Section 4

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December 1, 1982

Mr. Robert Bechhofer
School of Operations Research and Industrial Engineering
Cornell University
Upson Hall
Ithica, New York 14853

Dear Bob:

I respond to your letter of November 23, 1982.

It is obvious to me that the IMS should be a sponsor of the Kiefer-Wolfowitz Research Conference, to be held in Ithica, July 6-9, 1983. I am confident that the council would approve if called upon to vote on the issue, and in the interest of speed, I take it upon myself to designate your conference as a special IMS meeting. Please do mention our sponsorship in further notices of the meeting that you publish.

Very truly yours,

Pat

Patrick Billingsley
1982-83 IMS President

cc: Kjell Doksum, IMS Secretary
Richard Johnson, IMS Program Secretary
William C. Guenther, Editor, IMS Bulletin

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November 11, 1982

Professor Robert Bechhofer
Cornell University
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Upson Hall
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Dear Bob:

I regret very much that we have been so slow in coming to a final conclusion concerning the Kiefer-Wolfowitz Symposium at Cornell. Let me quote from the minutes of the October 15 Executive Committee meeting:

> "It was moved and seconded that ASA co-sponsor the Symposium at Cornell in honor of Jack Kiefer and Jacob Wolfowitz.
>
> "The motion carried.
>
> The general Chairman of the Symposium is Professor Robert Bechhofer. He will be asked to act as the ASA representative."

Hence, Bob, please consider this as final approval for ASA cosponsorship and with the understanding that you are representing us on the committee. This latter point is really a technicality but it makes us feel good that we have a representative, knowing full well that the final program will be assembled in fine fashion by our colleagues.

Finally, Bob, you have approval from ASA and as far as I am concerned there is no further action on our part. Please keep us informed as the program develops. We should have some representation from the ASA Board at the meeting. Possibly, I will attend.

Sincerely,

Fred

Fred C. Leone
Executive Director

cc: W. H. Kruskal
R. L. Anderson

Unclassified

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18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Admissability and inference, combinatorial design, information and coding theory, multivariate analysis, optimal design, selection theory, sequential analysis.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This is a report on the Jack Kiefer-Jacob Wolfowitz Statistical Research Conference held at Cornell University, Ithaca, New York, July 6-9, 1983. The report consists of the following sections: 1. Introduction and Summary, 2. Program of the Conference, 3. Abstracts of papers presented at the Conference, 4. List of participants in the Conference and Appendix.

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