



NORTH-HOLLAND

**A Brief Biography and Appreciation
of Calyampudi Radhakrishna Rao,
With a Bibliography of His Books and Papers**

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ABSTRACT

We present a brief biography and appreciation of Calyampudi Radhakrishna Rao, to whom this Fifth Special Issue on Linear Algebra and Statistics of *Linear Algebra and Its Applications* is dedicated in celebration of his 75th birthday; a bibliography of his books and papers is also included.

Calyampudi Radhakrishna Rao was born on 10 September 1920, in a small town in south India called Huvvinna Hadagalli, then in the integrated Madras Province of British India but now in the state of Karnataka. CR (as we affectionately call him) was the eighth child (out of ten: six boys and four girls) of his parents, C. D. Naidu and Laxmikanthamma; following a general custom in South India, CR was named Radhakrishna after the god Krishna who, according to mythology, was the eighth child.

C. R. Rao dedicates his book [18] *Statistics and Truth: Putting Chance to Work* to his mother, Laxmikanthamma, "who, in my younger days, woke me up every day at four in the morning and lit the oil lamp for me to study in the quiet hours of the morning when the mind is fresh."



FIG. 1. C. R. Rao: Delhi, India, December 1992.

Laxmikanthamma was a great disciplinarian and used to punish CR when he refused to go to school. At first, CR was shy and afraid to go to school, but soon he overcame this fear and eventually did well in all his school examinations. The college magazine in 1935 carried his photograph with the caption: "...C. Radhakrishna Rao has won the Chandrasekara scholarship [in physics] this year; he has had the unique distinction of knocking off the most coveted prize throughout his school career..." Fifty-three years later, on 31 December 1988, C. R. Rao was chosen by the *Times of India* as one of the top ten scientists of modern India, considering all disciplines and the impact of the work done by each scientist.

C. R. Rao's father, C. D. Naidu, was an inspector of police and unusually peripatetic; he was transferred from place to place every two or three years, and the family moved with him. He retired in 1931 and settled down in Visakhapatnam (in Andhra Pradesh), where CR joined the Mrs. A. V. N. College and finished his high school and the two-year intermediate course, with mathematics, physics, and chemistry as his special subjects. C. D. Naidu had little direct contact with his children until he retired, as he took the duties of policing seriously. After retirement, however, he paid attention to the progress of his children and used to say that CR was "his pride, hope, and joy." Though CR was doing well in physics, his father's

suggestion prompted him to study mathematics. He earned an M.A. degree with first-class honors (and with first rank) in mathematics at Andhra University in 1940.

After completing his M.A., C. R. Rao applied for a research scholarship in mathematics, but this application was turned down due to late submission; he then applied for a variety of jobs without success. In those days there were not many jobs available for people with a degree in mathematics. At that time CR casually visited the Indian Statistical Institute (ISI), an institute established by Prasanta Chandra Mahalanobis (1893–1972) in Calcutta in 1931, and people there said that statistics was a subject of the future. At that time the ISI offered only a one-year training course, and CR joined the ISI in January 1941 for “training in statistics.” Six months later, C. R. Rao joined Calcutta University, which had just started a Master’s degree program in statistics, the first of its kind in India. He completed the program with first-class honors (and with first rank) and a gold medal in 1943, and so was among the first five people to receive an M.A. degree in statistics from any Indian University.

In August 1946, C. R. Rao sailed for England (in a steamship taking Italian prisoners of war from Bombay to Naples), heading for Cambridge, where, at the invitation of J. C. Trevor, a Cambridge University anthropologist, he was to work in the Anthropological Museum. He joined King’s College (later being elected a Life Fellow with the privilege of walking on the lawns) and registered for a Ph.D. degree under Ronald Aylmer Fisher (1890–1962). Professor Fisher suggested that CR should conduct some experiments with mice for mapping of chromosomes, which he then did in addition to full-time work at the Museum. The work in the Anthropological Museum involved the statistical analysis of measurements made on skeletons excavated in Jebel Moya in the Sudan. Based on the work he did at the Museum, C. R. Rao received the Ph.D. degree from Cambridge University in 1948 with the thesis entitled “Statistical Problems of Biological Classification.” In 1965 he received the Sc.D. degree from Cambridge based on his overall contributions to statistical theory and applications.

C. R. Rao returned to India in August 1948, marrying Bhargavi on 9 September 1948. Professor Mahalanobis then offered CR a professorship at the Indian Statistical Institute as well as the headship of its Research and Training School: it was very unusual in India in those days to become a professor at the young age of 28. Under his leadership, the Research and Training School gradually expanded its teaching and research activities. Soon it earned a reputation as a center for advanced study, research, and consultation, and attracted brilliant students and statistical practitioners for courses in statistical theory and applications in various areas. As its only professor, C. R. Rao had the responsibility of guiding the work of

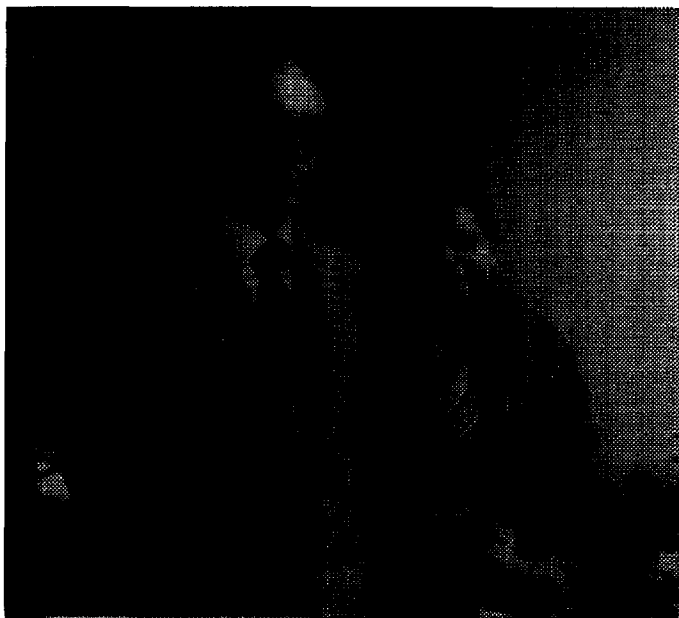


FIG. 2. C. R. Rao and Bhargavi: Tampere, Finland, August 1983.

all the research scholars. He quickly earned a reputation as an inspiring teacher, and over the years about 50 students have completed Ph.D. theses under his guidance.

In 1959, the Indian Parliament declared the Indian Statistical Institute an Institute of National Importance and empowered it to award its own degrees. The ISI then developed undergraduate, graduate, and research programs and started giving B.Sc., M.Sc., and Ph.D. degrees in statistics; it became known internationally for research in statistics, attracting famous statisticians and scientists from all over the world, including J. L. Doob, Ronald A. Fisher, Ragnar Frisch, J. Kenneth Galbraith, J. B. S. Haldane, A. N. Kolmogorov, Simon Kuznets, Richard Stone, and Norbert Wiener.

C. R. Rao served as Professor and the Head of the Research and Training School from 1949 to 1963, and then as Director from 1963 to 1972. After the death of P. C. Mahalanobis in 1972, CR was appointed Director and Secretary of the Indian Statistical Institute, the position he held from 1972 to 1976. He then continued to work in the ISI as a Jawaharlal Nehru Professor, 1976–1984. During the period 1987–1992, C. R. Rao also held the prestigious National Professorship in India (the total number of National Professors being limited to 12 at any one time). CR took leave from ISI in 1979 (finally retiring from there in 1984) and went to the United States

to accept a University Professorship at the University of Pittsburgh. He moved to The Pennsylvania State University in 1988, where he was offered the Eberly Family Chair in Statistics. He continues to work in the Statistics Department at Penn State as Professor and holder of the Eberly Chair, as well as being the Director of the Center for Multivariate Analysis.

In 1954 C. R. Rao received some data collected in Japan in order to study the long-term effects of radiation on atom-bomb casualties in Hiroshima and Nagasaki. The statistical analysis involved finding a matrix to replace the inverse of $X'X$, where X is the model or design matrix in the usual linear model; here the matrix $X'X$ was singular and so the inverse was not defined. This led to a *pseudoinverse*, which C. R. Rao introduced in his 1955 paper [113] in *Sankhyā*. This was the same year that R. A. Penrose published his paper on generalized inverses [*Proc. Cambridge Philos. Soc.* 51:406–413 (1955)]. C. R. Rao then discovered that the key condition for a generalized inverse G of a matrix A was the equation $AGA = A$, introducing the notation $G = A^-$. The calculus of g-inverses (an abbreviation CR invented for generalized inverses) and the unified theory of linear estimation were then presented in 1962 in [141]. The subject of g-inverses was further developed with the help of his colleagues at the ISI, leading to the full-length monograph with Sujit Kumar Mitra, *Generalized Inverse of Matrices and its Applications* [14], published in 1971; see also [188, 195, 196, 205, 208, 217], and [346]. Using the concept of g-inverse, C. R. Rao developed a unified theory for linear estimation, noting that g-inverses were particularly helpful with explicit expressions for projectors; also in 1971, in *Sankhyā*, he introduced [189] the inverse partitioned matrix (IPM) method for computing summary statistics for the general linear model. Linear models, which have wide applications in statistics, have also provided outlets for some basic research in linear algebra: the special issues on linear algebra and statistics of *Linear Algebra and its Applications* [Vols. 67 (1985), 70 (1985), 82 (1986), 127 (1990), 176 (1992), 210 (1994)] bear witness to this. Some of C. R. Rao's contributions are a general matrix inequality [323], separation theorems for singular values and eigenvalues [236], matrix approximations and reduction of dimensionality [241], and Kantorovich-type inequalities [283], as well as [245] and [253] with Chinubhai Ghelabhai Khatri (1931–1989).

C. R. Rao has developed statistical estimation theory in small samples, extending the scope of statistical methods in practice. Many results in this area bear his name, such as the Cramér-Rao lower bound, Rao-Blackwell theorem, Rao-Blackwellization, Fisher-Rao theorem, Rao's second-order efficiency, and the Geary-Rao theorem on the Pitman closeness criterion. Rao's orthogonal arrays were a major contribution to research in coding theory and in experimental design—especially in industrial experimenta-

tion as developed by Genichi Taguchi [cf. *Quality Engineering Using Robust Design* by Madhav S. Phadke, Prentice-Hall, 1989]. C. R. Rao has made pioneering contributions to the development of multivariate statistical analysis, especially with the concept of Rao's quadratic entropy, Rao's U -test, Rao's F -approximation to the likelihood-ratio criterion, and canonical coordinates. He has also introduced a broad class of asymptotic tests of hypotheses, including Rao's score statistic and the Neyman-Rao statistic; he has used differential-geometric techniques in discussing problems of statistical inference, based on Rao's distance function.

C. R. Rao was elected Fellow of the Royal Society, London, in 1967, and Member of the National Academy of Sciences, U.S.A., in 1995. He is also an Honorary Fellow of the Royal Statistical Society (1969), the Calcutta Statistical Association (1985), the Finnish Statistical Society (1990), and the Institute of Combinatorics and Applications (1995), and an Honorary Member of the International Statistical Institute (1983) and the International Biometric Society (1986). He has served as President of the Indian Econometric Society (1971–1976), the International Biometric Society (1973–1975), the Institute of Mathematical Statistics (1976–1977), the International Statistical Institute (1977–1979), and the Forum for Interdisciplinary Mathematics (1982–1984).

C. R. Rao has been awarded 19 honorary doctoral degrees: Andhra University, Waltair (1967), Leningrad University (1970), Delhi University (1973), University of Athens (1976), Osmania University, Hyderabad (1977), Ohio State University, Columbus (1979), Universidad Nacional de San Marcos, Lima (1982), University of the Philippines, Manila (1983), University of Tampere (1985), Indian Statistical Institute (1989), Université de Neuchâtel (1989), Colorado State University, Fort Collins (1990), University of Hyderabad (1991), Agricultural University of Poznań (1991), Slovak Academy of Sciences, Bratislava (1994), University of Barcelona (1995), University of Munich (1995), Sri Venkateswara University, Tirupati (1996), and University of Guelph (1996).

C. R. Rao has received numerous other awards, including the Guy Medal in Silver of the Royal Statistical Society, London (1965), the Megnadh Saha Medal of the Indian National Science Academy (1969), the Jagdish Chandra Bose Gold Medal and cash award (1979), the Silver Plate bearing the monogram of the Andhra Pradesh Academy of Sciences (1984), the S. S. Wilks Medal of the American Statistical Association (1989), and the Mahalanobis Birth Centenary Gold Medal awarded by the Indian Science Congress (1996). The government of India honored C. R. Rao in 1968 by awarding him the title of Padma Bhushan, a high civilian award.

C. R. Rao has published over 30 books in statistics, mathematics, and econometrics and over 350 research papers in statistics, probability, and



FIG. 3. C. R. Rao and G. P. H. Styan: Säijä, Lempäälä, Finland, August 1983.

mathematics, specializing in statistical estimation theory, multivariate analysis, characterization problems, combinatorics and design of experiments, differential-geometric methods in statistics and mathematical genetics, and, of course, generalized inverses of matrices and matrix methods for linear models. His book [16] entitled *Linear Statistical Inference and Its Applications*, which is one of the most frequently cited books in the statistical and social sciences literature, has been translated into six languages and includes a rather substantial collection of linear-algebraic and matrix-theoretic “complements.” There is a very useful 40-page appendix on matrix algebra in his new book with Helge Toutenburg, *Linear Models: Least Squares and Alternatives* [15].

When C. R. Rao was young, he was interested in music and other cultural activities, but his parents wanted him to concentrate on studies rather than on extracurricular activities which might be distracting. However, he continued to pursue his cultural interests and became, for example, the president of the Kuchipudi Dance Academy in Delhi, 1970–1976. His daughter Tejaswini went to a dance school in Calcutta and now runs a dance school called Natya in Buffalo, New York, besides teaching at SUNY–Buffalo. CR is well known for his accomplishments in photography, with several prizes won in competitions. His other hobbies now include gardening, writing humorous essays, and Indian cooking.

We begin the bibliography below with some biographical articles about C. R. Rao, followed by a list of books published in his honor. We then present books written by C. R. Rao, followed by books edited by him; these books are listed alphabetically by title (in each category). We conclude with a list of research papers (starting with books of reprints); these papers are grouped by year of publication and arranged alphabetically by journal (or collection) within each year. References to *Mathematical Reviews* (abbreviated MR) are given whenever available.

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