Life Sketch of Professor C. R. Rao

-Bikas K Sinha, Editor-in-Chief, IJSS

There are many articles available in the published literature on the Life and Work of Late Professor C R Rao.

Here we quote from one such article written by Professor T J Rao, Retired Professor of Statistics, ISI, Kolkata.

CALYAMPUDI RADHAKRISHNA RAO—A Living Legend in Statistical Science, IISA News Letter, Spring (2023), 7-11. by PROF. T.J. RAO, RETIRED PROFESSOR, INDIAN STATISTICAL INSTITUTE, CALCUTTA

About Professor T J Rao

TJ Rao is an expert in survey sampling – theory and methodology. He spent almost 50 years at ISI Kolkata in different positions and also served in various expert committees. He visited RUDS in connection with an Int'l Conference and participated actively in the deliberations. He has closely collaborated with me [BKS] and a host of other statisticians in India and abroad.

We quote from the above published article on Prof. C R Rao with due acknowledgement to Prof. T J Rao.

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Around seven decades ago, a passenger travelling to Calcutta by the Madras-Howrah Mail was asked what he did for a living. Perhaps, feeling that an accurate reply would not be understood, he seems to have replied:

"I work in a school and I am the Head Master of the school."

The school referred to is the world-famous Research and Training School (RTS) of the Indian Statistical Institute (ISI) and the unassuming passenger was none other than the living legend Professor C.R. Rao, who was indeed the Head of the School for almost a quarter of a century, whose Centennial Birthday was celebrated in September 2020 [in all corners of the globe].

TODAY WITH A HEAVY HEART WE BRING OUT THIS MEMORIAL VOLUME IN THE MEMORY OF A PERSON WHO WAS THE LIVING LEGEND IN THE FIELD OF STATISTICAL SCIENCE.

Prof. C R Rao's work over 75 years continues to exert a profound influence on science and he has been awarded the prestigious 2023 International Prize in Statistics.'

Childhood and Education:

Calyampudi Radhakrishna Rao, well known as C.R. Rao (and Dr. Rao to his students) was born on 10 September, 1920 in Huvanna Hadagali, now in the Indian state of Karnataka. He studied in various schools in Andhra Pradesh wherever his father, working as an Inspector of Police, got posted. He had a flair for numbers even from the days of elementary school and when he was six,

his teacher would ask him to recite multiplication tables (which young Rao had memorized up to twentieth table) and the other students would repeat after him. At the age of sixteen, Mrs AVN College (Visakhapatnam) magazine had a caption under his photo saying "he has had the unique distinction of knocking off the most coveted prizes in every class until now. We hope he will continue to maintain the high efficiency of his mental and academic facilities in the years to come." And indeed he did so with 14 books, 470 plus research papers, 51 Ph.D. students, 48 edited Volumes of Handbook of Statistics and 39 honorary doctorates from universities in 19 countries spanning 6 continents.

Rao did the 3 year post graduate B.A. (Hons.) degree in Mathematics from Andhra University, the course being popular among bright students in South India at that time and was awarded M.A. degree (First Class First) by efflux of time after one year in 1941. His (sole) application for a research scholarship at Andhra University was rejected by both the Principal and Vice Chancellor on official grounds. (Little did Rao know that the same University would offer him a Professorship a few years later and after some years an honorary doctorate). He then responded to an advertisement from army for a mathematician and when called for a test and interview went to Calcutta where he was found to be under-aged and not accepted. Alas! A Loss to the Army, but a Glorious Gain to the Statistics Fraternity! In the hotel he was staying, he came to know of the Indian Statistical Institute (ISI) which was being run from a room in the Presidency College by Prof. Mahalanobis who by then introduced the subject of Statistics in India by way of organizing large scale sample surveys and experimental designs which are speedy, cost effective and efficient. Mahalanobis also started the Masters Course in Statistics in Calcutta University in which Rao, who had already joined as a trainee at ISI, got admitted as a student of the first batch and obtained an M.A. degree in Statistics, again with a First Class First. Soon after, he joined the ISI as a technical apprentice and started working in the areas of Design of Experiments and Multivariate Analysis having been inspired by RC Bose, KR Nair and SN Roy who were senior scholars at the Institute. He collaborated with the anthropologist DN Majumdar and analysed the anthropometric data based on a survey of the United Provinces using the concept of Mahalanobis' D^2, a measure of distance between two populations. At the request of JC Trevor, a Cambridge University anthropologist, C.R. Rao was deputed to Cambridge University to apply Mahalanobis Distance analysis on skeletal data from North Africa collected by the university museum. Rao also worked in the Genetics laboratory of RA Fisher, the founder of Modern Statistics and under his guidance obtained the Ph. D. degree in 1948 from the University of Cambridge. Later on, by peer review of published work, the same university awarded him the Sc.D. degree.

For a detailed Biography of CR Rao, we refer to Nalini Krishnankutty's "Putting Chance to Work....a Life in Statistics" and Julian Champkin's article "C.R. Rao-a Life in Statistics" which appeared in Significance, 2011, 175-178 and the ET interview by Anil Bera, Econometric Theory, 19, 2003, 331–400, among others.

Positions held:

Rao started as a Superintending Statistician (1944- 48) on a meagre salary of Rs. 75 per month at the ISI. He worked for almost 40 years till he retired at the mandatory age of 60 holding important positions as Professor and Head, Research and Training School, widely known as RTS (1949-63),Director and Secretary of ISI (1972-76, an unsatisfactory period for Rao when he decided to move to the Delhi Campus), Jawaharlal Nehru Professor (1976-84), National Professor (1987-92). Throughout his tenure, world class research facilities were made available at ISI. He arranged long

and short time visits by renowned experts, organized lecture series, encouraged publication of monographs and thus this period came to be known as the Golden Period of ISI. Since post retirement scenario in India was not much conducive for continuing research, he moved to USA and continued research with renewed vigour, first to the University of Pittsburgh and later to Pennsylvania State University where he was the Director of Center for Multivariate Analysis as well as Eberly (Chair) Professor of Statistics. In the US, he is currently a Research Professor at the University at Buffalo.

Awards: [IISA Newsletter www.intindstat.org Β newsletter@intindstat.org Page 7]

Dr. Rao received numerous international and national awards. He was elected to the Royal Society, UK as a Fellow (FRS), National Academy of Sciences, USA, Third World Academy of Sciences, Lithuanian Academy of Science, and three major science academies in India. Kings College, Cambridge gave him an exclusive Honorary Life Membership (given to only eleven persons at any time). He was awarded Padma Vibhushan, the second highest civilian award by the Government of India. As a recipient of Shanti Swaroop Bhatnagar Memorial Award at a time when the China-India war was waging on, he donated the entire prize money to Prime Minister's National Defence Fund saying that "the country's need is greater than that of an individual scientist in times of war." At the Berlin Session of the International Statistical Institute, Rao was awarded the Mahalanobis Prize in recognition of lifetime achievements in Statistics in 2003. The Government of Andhra Pradesh conferred the prestigious 'Genome Valley Excellence Award 2010' to CR Rao for his research contributions to statistical methods towards better understanding of health and disease. He has also received the 'Sardar Patel Life Time Achievement Award', 2015. Right from the school and college days, CR Rao was collecting numerous Medals. He received the Gold Medal from Calcutta University, Wilk's Memorial Medal from American Statistical Society, Wilks' Army Medal (USA), Guy Medal in Silver from Royal Statistical Society (UK), Meghnath Saha and Ramanujan Medals of the National Science Academy (India), JC Bose Gold Medal of Bose Institute, Mahalanobis Centenary Gold Medal of the Indian Science Congress, University of Zielona Go'ra Medal (Poland).

Special Awards:

C.R. Rao was honoured by President Bush as a "prophet of a better age" at the White House and was awarded the National Medal of Science, USA "for his pioneering contributions to the foundations of statistical theory and multivariate statistical methodology, and their applications, enriching the physical, biological, mathematical, economic, and engineering sciences." Former Prime Minister Dr. Manmohan Singh conferred on C.R. Rao the highest and most prestigious INDIA SCIENCE AWARD in recognition of "his significant contributions to the field of statistical science that had profound influence on the Theory and Application of Statistics, well recognized all over the world." For his outstanding achievements, C.R. Rao has been honoured with the establishment of an institute named after him C.R. Rao Advanced Institute of Mathematics, Statistics and Computer Science (CRRAO AIMSCS). The Institute, located in the campus of the University of Hyderabad, is expected to play an important role in improving the quality of teaching, encouraging basic research in mathematical and social sciences, and promoting applications of science and technology in all areas of human endeavour. Within the Institute there is a 'C.R.Rao Gallery', designed by Rao's daughter, Dr. Tejaswini Rao, which was inaugurated by Nobel Laureate Sir Venkataraman in 2013. The Gallery is open to visitors and students. "C.R. Rao,

an Indian professor whose work over 75 years ago continues to exert a profound influence on science, has been awarded the 2023 International Prize in Statistics." Thus the recent announcement on www.statprize.org starts. It continues, "In his remarkable 1945 paper published in the Bulletin of the Calcutta Mathematical Society, Calyampudi Radhakrishna (C.R.) Rao demonstrated three fundamental results that paved the way for the modern field of Statistics and provided statistical tools heavily used in science today. These are 'Cramér–Rao lower bound', Rao–Blackwell Theorem and the third result now flourished as 'information geometry'." "In awarding this prize, we celebrate the monumental work by C.R. Rao that not only revolutionized statistical thinking in its time but also continues to exert enormous influence on human understanding of science across a wide spectrum of disciplines," said Guy Nason, Chair of the International Prize in Statistics Foundation.

Significant Contributions:

It would be an impossible task to write about CR Rao's research contributions in a couple of paragraphs in an article of few pages. We shall attempt to briefly indicate some of his contributions known to have made significant impact in different fields of science as well as official statistics. Mathematical Statistics: At the very young age of 24, C.R. Rao completed a landmark paper which appeared in the 1945 Bulletin of Calcutta Mathematical Society, now regarded as one of the Breakthroughs in Statistics that gave rise to so many technical terms bearing Rao's name such as Cramér-Rao Lower Bound (CRLB) with applications in Statistics, Signal Processing, Bayesian Risk Theory. In the sixties, during RTS tea club sessions, Dr. Rao used to say, if you need a grant, use the terms 'Signal and Noise'. Little did he know then, that his CRLB of the 1945 Breakthrough paper is quoted in a number of papers on Signal Processing. Terms unknown to some of us, statisticians, such as pixel array detectors, spectroscopic measurements, PET detector designs, SBP methods for 3D event positioning and quantum physics which use CRLB are popular now. Again, applications of the other Breakthrough work popularized as Rao-Blackwellization are abundantly used in addition to improving estimators in conventional sampling theory, in adaptive sampling, link-tracing, size-biased sampling theories, Dynamic Bayesian Networks, Post Simulation Improvement of Monte Carlo Methods, Cross Validation and Non Parametric Bootstrap, particle filtering, stereology, data compression, Quantum Rao-Blackwell Theorem, RaoBlackwellized Gaussian Smoothing, Rao-Blackwellized Parts-Constellation Tracker, Rao-Blackwellized Tempered Sampling (RTS), Assessment of California Condor recover, Rao-Blackwellized Field Goal percentage estimator (RB-FG%), and a host of others including possibly Rao-Blackwellized WhatsApp (RB-WA).

Rao's 1945 results IISA Newsletter m www.intindstat.org B newsletter@intindstat.org Page 8 now known as 'Information Geometry' had an application at the Large Hadron Collider at the CERN in understanding the Higgs Boson measurements. (also, see Information Geometry, Vol. 45(2021) (eds.: ASR Rao, CR Rao, A Plastino), Elsevier). His work in Multivariate Analysis led to Rao's F-test, Rao's U-test and Canonical Coordinates while his results in Testing of Hypotheses produced Rao's Score Test, a member of the Holy Trinity (besides Likelihood Ratio and Wald's Tests) which again found place in Breakthroughs in Statistics. Some other terms that appear in text books are Fisher-Rao Theorem, Rao's Theorem on Second Order Efficiency, Kagan-Linnik-Rao Characterizations, Lau-Rao-Shanbhag Theorem, Rao's Damage Model, Rao-Rubin theorem, Khatri-Rao inequalities, Burbea-Rao Divergence Measures, Rao's paradox in multivariate analysis , just to quote a few. Dr. Rao is known as the 'Scientist's Statistician' and some of his statistical

tests and other contributions continue to guide scientists all over the globe. It may be interesting to the readers who are nor aware of this anecdote as narrated by Dr. Rao himself to Anil Bera (Econometric Theory, 19, 2003, 331–400): "...I may mention some anecdotes in connection with the Rao–Blackwell theorem and Rao–Blackwellization. Blackwell independently discovered this method two years after the publication of my paper. In 1953, I attended a conference where Berkson presented a paper using conditional expectation with respect to a sufficient statistic to improve an estimate, attributing the method to Blackwell and calling the method Blackwellization. When I told him that the method was first given by me, Berkson remarked that Raoization by itself does not sound nice; in a later paper I found that Berkson used the term Rao–Blackwellization. Another instance was a review of a book by Lindley, where he attributed my result on the use of a sufficient statistic to Blackwell only. When I wrote to him about my priority of the result, he replied, "Yes, I read your paper. Although the result was in your paper, you did not realize its importance because you did not mention it in the introduction to your paper." I replied to Lindley saying that it was my first full-length paper and I did not know that the introduction to a paper is written for the benefit of those who read only the introduction and do not go through the paper..."

Applied Statistics:

Rao's early contributions consisted of problems of Confounding and Factorial Experiments. It is interesting to note that a couple of early papers of 1943 and 1945 on experimental arrangements in Quasi Latin Squares and Familial Correlations respectively, appeared in the Indian journal Current Science. C.R. Rao introduced Orthogonal Arrays (OA) in the late forties which in the hands of Taguchi, who visited ISI around that time had a profound effect on industrial experimentation for determining the optimum combination of factors. OA have been referred to as a new Mantra for American Industries in an article published in Forbes magazine in 1996. OA have an important application in Cryptology as well. Influence of Rao on Theory and Practice of Sample Surveys was discussed by T.J. Rao in the Jour. Ind. Soc.Prob.Stat. (2021)This paper notes that Rao's justification of their sample selection in the 1941 United Provinces Anthropometric Survey is a prelude to Randomized Permutation Model Theory. CR Rao is also the first to notice that the design of the Bengal Anthropometric Survey, 1945 amounted to stratified sampling and not a simple random sampling technique, there by heralding the need for Analysis of Complex Survey Data. Rao's Paradox in Sample Surveys refers to the situation that "if one wants to use the likelihood principle, it pays to throw away part of the observed data." Rao edited 4 of the Volumes in Sample Surveys in the Elsevier Series Handbook of Statistics. The review of his book "Advanced Statistical Methods in Biometric Research" (ASMBR), first published by Wiley in 1952 and later by Hafner Press in (1970,74) by CAB Smith (The Eugenics Review,1953) says "It is one of the best books in this series; Indeed, it is one of the best text books in statistics available anywhere.... ASMBR will be of especial interest to those human geneticists who have occasion to use multivariate analysis." Cabdirect review states "In the latter part of the book the author is dealing with his own researches, but it is an advantage to the reader that difficult multidimensional mathematical problems are written round actual data, which are worked through in illustration of the methods."

C.R. Rao's contributions to Econometrics were discussed in detail by T Krishna Kumar, HD Vinod and S Deman in 2010 (dx.doi.org/10.2139/ssrn.1722743). The Volume No. 41 of Handbook of Statistics, 2019 (eds.: HD Vinod and C. R. Rao) is devoted for Financial, Macro and Micro Econometrics using R shows his interest in the use of software. Rao's sequential tests of Null

Hypothesis have an application in Quality Control. Some of his other applied work includes: Problems in Biological Classification, Methods of Scoring on Linkage data in Genetics, Prinicipal Component Analysis and Factor Analysis in Psychometry, Quantitative Studies in Sociology ,and the list goes on.

Official Statistics:

We start by quoting Rao (2001): "...When I joined the Indian Statistical Institute (ISI) in 1941, there was considerable activity in conducting sample surveys. Mahalanobis was designing a large scale sample survey for estimating the acreage under jute crop in Bengal..." It was but natural that CR Rao should get attracted to the survey operations. Subsequently Mahalanobis established the National Sample Survey (NSS) in 1950 at the Indian Statistical Institute, Calcutta. CR Rao joined the team comprising DB Lahiri, S Raja Rao, MN Murthy among others and took an active part in "designing sample surveys, preparing schedules for recording data and collecting data as an investigator." Post independence of India, Mahalanobis initiated country wide National Sample Survey in 1950. He also created the Central Statistical Organisation in 1951 to coordinate the data collected by various official channels of the states of India. Dr. Rao recalls "...I remember Prof. Mahalanobis sending me to different states in India to help the local governments in setting up State Statistical Bureaus (SSB's) and district level statistical offices, and training the required staff." "...Nothing is more frustrating to the investigator than to discover that the observations collected at a considerable expense of money and energy are worthless because of obvious inconsistencies or failure to furnish complete details," he warns the investigators. Mahalanobis established the International Statistical Education Centre (ISEC) at the Indian Statistical Institute (ISI), Calcutta in 1950 under the auspices of UNESCO and Government of India (GoI) and was the Chairman of Board of Directors till 1973 and then CR Rao became the Chairman and continued to act so till 2016.With the growing need for modernizing the Official Statistics and training of the officers, especially in South East Asia, a UN Committee for development of Statistics was constituted by the Secretary-General, chaired by CR Rao and thus the Asian Statistical Institute (ASI) was inaugurated in 1970 in Tokyo. This is now renamed as Statistical Institute for Asia and the Pacific (SIAP) and from 1999 shifted to Chiba. At home, Dr. Rao chaired or acted as a member of several committees of the government namely Committee on Statistics, Committee on Demographic and Communication for Population Control, Committee on Science and Technology and also advised Reserve Bank of India, Atomic Energy Commission and the Indian Heart Association. He also acted as the Chairman of the Science and Health Allied Research and Education (SHARE), an organisation set up in Hyderabad and initiated Longitudinal Health Surveys on the lines of Framingham Surveys. Data from these surveys supplements NFHS data (Kusneniwar et al., Int. Jour. Epidem., 46,788–789, 2016). In 1948 after his return from Cambridge, Rao himself got an attractive offer from ECAFE - UN office in Bangkok. However, since he was deputed by Mahalanobis to Cambridge, he told the Professor about his offers and expressed his desire to work at the ISI. In an ET interview by A Bera in 2003, CR Rao said: "...I had some interest in econometrics and was instrumental in founding the Indian Econometric Society and developing its activities. I served as president and chairman of the society for a number of years. I had also organized a series of seminars on the database of the Indian Economy, to assess gaps and deficiencies in government statistics and suggest methods of utilizing the data for policy purposes. My early research on estimation and linear models is a part of econometrics literature and also, perhaps, the score test...." Controversy relating to National Accounts Statistics versus National Sample Survey estimates of household consumption expenditure has been

addressed many times. It is interesting to note that Cross Entropy and extensions studied by CR Rao have been used in the case of Official Statistics as well. Reconciliation of household survey data and national accounts data using CE was successfully attempted by Robilliard and Robinson(Rev. Income and wealth, 49, 395-406, 2003) using the General Algebraic Modeling System (GAMS) software for Madagascar data. Reweighting of data from two sources to create a consistent time series using CE method discussed by Branson(Working Paper Series # 38, 2009, SALDRU and assessment of spatial distribution of crop areas by CE method by You and Wood (Int. Jour.Appl. Earth Observations and Geo information, 7, 310-323, 2005) to quote a few show a successful application of CE. The possibility of reconciliation of NSS Household Consumer Expenditure (HCE) data and National Accounts data on Private Final Consumption Expenditure (PFCE) in the Indian context using GAMS would perhaps be a good project.

Mathematics:

Dr. Rao acknowledges his teacher at Andhra University Professor Vommi Ramaswamy for introducing him to the rigour of mathematical proofs, inculcating a spirit of enquiry and kindling a research interest in him. Rao was the first to introduce differential geometric concepts in statistics which gave rise to technical terms such as Fisher-Rao Metric, Rao Distance, Rao Measure and Cramér-Rao Functional. Quantum Physicists developed the Quantum Cramér-Rao Bound giving a more precise estimate of uncertainty than Heisenberg's Principle. His work on generalized inverse (g-inverse) of a matrix (singular or rectangular) resulted in several innovative results in linear models. One of his very early contributions on Orthogonal Arrays (OA) in Combinatorial Mathematics, already referred to in the previous paragraph, was published in the Proceedings of the Edinburgh Mathematical Society. This work though mathematical in nature found its extensive use in Japanese and American Industrial experimentation. Rao's work on Quadratic Entropy and his recent interest in Cross Entropy led to the construction of dissimilarity measures.

Course development, Teaching and Training of Statistics to students and officers:

Together with Mahalanobis and Haldane, CR Rao devised the syllabi for B.Stat. and M.Stat. degree courses of ISI in 1960. He included a field visit for the students to the ISI campus in Giridih for firsthand experience in conducting crop cutting experiments and collecting data for a short socio economic survey. The syllabus also included a visit to the Central Statistical Organization (CSO) for training in Official Statistics with a grade in a test at the end of the training. During the initial years of the ISEC, officers from the participating countries used to be sponsored by the respective governments. Some had difficulty with English and some had school level mathematics only. While teaching a course on Sample Surveys, Dr. Rao made it a point not to use complicated notations or theorems. He devised simple techniques to explain the concepts. He would rather show a sum in a full form than use sigma notation. For their level, he believed that 'the best way of teaching sample surveys [IISA Newsletter m www.intindstat.org B newsletter@intindstat.org Page 10] is to choose some problem and let the students conduct a survey going through the various stages' involved in a sample survey. True to his belief, during a course on sample surveys for international officers and senior graduate students, he made them participate in conducting the 'Radio listeners' preference survey' in the city of Calcutta and acted as a project director in 1965. Senior students acted as 'supervisors', a concept created by Mahalanobis in NSS or 'crew leaders', a concept of Hansen.

Other Interests:

CR Rao was the Editor of Sankhya, Journal of Multivariate Analysis, for several decades and 40 plus Volumes of Handbook of Statistics. He acted as the President of all prestigious International Statistical Organisations as well as Founder of Indian Econometric Society and Indian Society for Medical Statistics. He was associated with the Quality Control Movement in India and organised Courses in Industrial Quality during the late forties at the Institute. Dr. Rao followed his teacher of Andhra University, Professor Vommi Ramaswami in his teaching style by calling the student to the board and making him work out the problems, guiding him only with essential steps. Students were thus always alert and had a mastery over the subject. To create awareness of Statistics and to encourage those with an aptitude for numbers and numerical reasoning, to study Statistics, C.R. Rao suggested organizing Statistics Olympiad on lines similar to Mathematics Olympiad. Following his suggestion, a team of statisticians headed by T.J. Rao and S. Bendre organized the FIRST STATISTICS OLYMPIAD, for the first time in India and probably in the whole world, in June 2009 by administering tests to students at the high school/junior college level. For the first time in 2014, the same test was held in Sri Lanka as well, at the same time and same date and thus it became an international event and it continues to be so. Each year, the top students are felicitated at a function held on June 29, the birth date of Professor Mahalanobis which also happens to be the National Statistics Day of India. Rao started planning for the establishment of a Museum in Statistics, registered as Sankhya: The National Museum of Statistics, the first one of its kind. Dr APJ Abdul Kalam, former President of India laid the foundation stone for the museum on 30 March 2011 to be built on a 5 acre land donated by University of Hyderabad. Through this medium CR Rao wishes to demonstrate the applicability of Statistics in a variety of fields and spread numerical literacy.

Some of the rare honours that C.R. Rao received include a National Award in his name instituted by the Government of India, Roads adjacent to University of Hyderabad and Andhra University named after him, a Special Postal Cover released in celebration of his 90th Birthday in 2010.

Rao's hobbies include photography, playing badminton, long walks and writing humorous essays. A Living Legend in Statistics, Rao spent forty years of his prime life at the Indian Statistical Institute developing statistical activities in India, and then left for USA. Rao was in regular touch with the activities at CRRAO Advanced Institute of Mathematics Statistics and Computer Science (AIMSCS) named after him, guiding and advising the Institute as well as various National and International Statistical Organisations and University Departments of Statistics.