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# International Encyclopedia of Statistical Science

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Miodrag Lovric  
Editor

# International Encyclopedia of Statistical Science

Second Edition

With 310 Figures and 141 Tables

 Springer

*Editor*

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*To my lovely wife Vesna Lovric (nee Jovandic),  
our children Tara and Andrej,  
my brother Dragan (1955–1970), and my mother Julijana  
(1924–1997)*

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## Foreword by Bradley Efron

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### The Future of Statistics II

The first edition of this Encyclopedia came out in 2010, and in it I published an article titled “The Future of Statistics.” Now I’ve been asked to write on the same topic for the new 2023 Encyclopedia. From a 2010 point of view, the years 2011–2023 constitute 13 years of “future,” which offer an opportunity to test how prescient I was in 2010.

Not very, I have to say. Among other things, I missed the rising interest in causality, an intense surge of development of Lasso-related model-building methods, and, most glaringly, the triumph of the large-scale prediction algorithms, particularly “deep learning.”

Deep learning and other pure prediction algorithms, such as random forests, gbm, and support vector machines, are recognizable as regression programs, but ones that operate in a different spirit from traditional methods such as linear regression. If prediction algorithms are the future of statistics, it’s going to be a different discipline than the one we’re used to.

Statisticians have traditionally operated at two levels, an algorithmic one and an inferential one. The algorithms usually happen first. Some new class of problems comes to the fore, where older data analytic methods seem inadequate. A new algorithm is proposed to provide useful statistical results. Then theoretical analysis is done to put those results into context of previous statistical theory. This is the inferential part. An inspiring example is Cox’s proportional hazard algorithm, subsequently justified by partial likelihood.

Classical statistical algorithms, of the Fisher-Neyman-Hotelling brand, were developed with the needs of scientists in mind, working in a world of small data sets where results were hard won. Inferential statistics at its best shows researchers how to wring every drop of information out of their studies.

The Prediction Community, to use Leo Breiman’s term, works best in a world of huge data sets where, if anything, there is too much information, pointing in too many directions. The goal of algorithms like deep learning is to filter out the information stream toward some predictive purpose: image recognition, language translation, medical diagnosis, etc. Algorithmic construction has been all-important in this world, with little in the way of inferential development. Scientists have not been the principal target audience for the pure prediction algorithms, which were developed less by statisticians and more from a computer engineering and commercial impetus.

There is a magnetic attraction to the Prediction Community, enhanced by an avalanche of breathless news stories concerning deep learning and its descendent “chatGPT.” During my student years in the 1960s, mathematics was the prestige field, but today’s young students are pulled toward computer science. My poor batting average in 2010 has made me cautious about predicting the future of Statistics. I’ll hedge my bets this time by predicting two possible futures, quite different but both plausible.

In Future 1, the Prediction Community comes to dominate Statistics and Statistics departments. Algorithms for analyzing large-scale databases become of primary importance, with reduced emphasis on inferential justification. Prediction becomes the central goal, not estimation or testing. Leo Breiman’s influential Statistical Science article (2001), “Statistical Modeling: the two cultures,” puts it bluntly: “The theory in this field shifts from data models to the properties of algorithms.”

By “data models” Leo meant classical parametric modeling: normal distributions, exponential families, etc. These are mostly missing from current Prediction Community work. Bayesian statistics relies heavily on parametric modeling, making Future 1 an unhappy prospect for Bayesians. Without progress on estimation and testing, there may be reduced contact with the physical and biological sciences, where prediction is only a small part of the story, and more connections with high-tech commercial applications. Something like this happened to Operations Research in the later decades of the 1900s.

In Future 2, the Prediction Community continues to grow in influence but not to the point where it dominates statistical discourse. Parametric models don’t fade from the graduate curriculum, and inference continues to be the measuring stick for algorithmic success. In fact, inferential justification for prediction algorithms becomes a central project of the statistics world. There are at least four such algorithms, deep learning, random forests, boosting, and support vector machines, all successful but different from each other, reflecting a lot of clever ad hoc constructions waiting for a unifying theory. Current theory can’t even say what is a “good” prediction, only that a new proposal does better than its predecessors.

A successful theoretical basis for prediction would be a good start on a bigger project: a theory of biased estimation, something Fisher et al. failed to provide us. Bias is a word that scientists hate, but large-scale analyses, as in genomics studies, reward biasing individual cases for the sake of the whole. The James-Stein estimate, 1961, was a dramatic proof of concept for deliberately induced bias. The empirical Bayes literature has provided a framework for biased estimation, but getting the theory into a form that scientists can routinely use, the way they use ANOVA for instance, remains a project for Future 2. A theory of Relevance—that is, a way to choose which other cases provide useful information for any one particular case of interest—seems like an essential missing link.

One prediction seems obvious, and it applies to both Futures 1 and 2: the emergence of a popular AI-based statistical package. Let’s call it “chatstat.” Chatstat might be impressive and dangerous at the same time. The danger is the same one encouraged by today’s statistical packages, but now more

seductively presented: to take chatstat's answer as final, and not look carefully within one's own data set to unveil its intricacies and special structures. Applied statistics is a creative and pain-staking business, and I can see our future colleagues having to argue with management on why chatstat's beautifully packaged report isn't the last word.

I gave my 2012 article poor marks for prediction but I got at least one thing right: the continued growth in size and complexity of the data sets statisticians are called upon to deal with. "Big Data," now a slightly quaint-sounding term, hasn't been the sole property of the prediction algorithms. A typical GWAS ("genome wide attribution study") can now top 200,000 subjects, each measured at 2.5 million genomic positions. Unlike the pure prediction algorithms, GWAS analyses include testing and estimation, and make essential use of parametric models. Perhaps the 2036 edition of this encyclopedia, 13 more years from now, will include articles insightfully combining GWAS inference with prediction algorithms, a melding of Future 1 and Future 2.

Stanford University  
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Bradley Efron  
Max H. Stein Professor of Statistics  
and Biostatistics

[Dr. Efron is "one of the most eminent living statisticians" (David Zierler, director of the Caltech heritage project, in the interview "Bradley Efron (BS '60, Statistician)," September 7, 2022). Bradley Efron is Professor Emeritus of Statistics and Professor Emeritus of Biomedical Data Science, Stanford University. He is past President, American Statistical Association (2004), Past President, Institute of Mathematical Statistics (1987–1988), and Founding Editor, *The Annals of Applied Statistics*. Professor Efron is a member of American Academy of Arts and Sciences (1983) and National Academy of Sciences (1985). He has been awarded the Ford Prize, Mathematical Association of America (1978), MacArthur award (1983), Wilks Medal, American Statistical Association (August 1990), Fisher Prize, Committee of Presidents of Statistical Societies (July 1996), Parzen Prize for Statistical Innovation, Texas A&M University (1998), and Noether Prize, American Statistical Association (2006). On May 29, 2007, he was awarded the National Medal of Science, the highest scientific honor by the United States "for his contributions to theoretical and applied statistics, especially the bootstrap sampling technique; for his extraordinary geometric insight into nonlinear statistical problems; and for applications in medicine, physics, and astronomy." In 2014, he was awarded the Guy Medal in Gold, and in 2018 he received the International Prize in Statistics.

"Brad Efron is renowned as a quintessential, theoretical, mathematical, interdisciplinary, and applied statistician. His foreseeing the onset of cheap and fast computation inspired his most famous breakthrough in 1979, the bootstrap, which marks the onset of the computer intensive age in statistics" (Professor Carl Morris, Harvard University, *Notices of the AMS*, 2007, p. 999).]

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## Foreword by James J. Heckman

The second edition of the *International Encyclopedia of Statistical Science* marks a significant milestone in the field of statistical science. As a contributor and a Nobel Laureate in Economics, I am honored to be part of this monumental work that brings together the expertise of 700 authors from 110 countries. This diverse assembly of minds showcases the universal appeal and applicability of statistical science, making this encyclopedia a global endeavor of unparalleled scale.

The profound influence of statistics on econometrics and economics is undeniable. In these fields, statistical methods are not just tools but the very foundation upon which economic theories and policies are built and evaluated. This encyclopedia, through its extensive coverage, provides insights into the intricate relationship between statistical science and economic analysis, highlighting their interdependence.

The collaborative effort that has culminated in this edition is a testament to the spirit of international cooperation that defines our scientific community. Each author, by contributing their unique perspective and knowledge, has enriched the encyclopedia, making it a comprehensive and invaluable resource for anyone interested in the multifaceted world of statistics. To the readers, whether you are a seasoned researcher, practitioner, or a student just beginning your journey, this encyclopedia offers a panoramic view of the field of statistics. It is a source of inspiration, a beacon guiding your intellectual pursuits, and a bridge connecting theoretical knowledge with real-world application.

As you explore these pages, let them ignite your curiosity and drive your passion for statistical science. May this edition continue to serve as a cornerstone in the evolution of statistical understanding and a tool for unlocking the vast potential of data in shaping our world.

Henry Schultz Distinguished Service  
Professor of Economics at the University of Chicago  
John Bates Clark Medal (1983)  
Nobel Memorial Prize in Economics (2000)  
Frisch Medal (2014)

James J. Heckman

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## Foreword by Neil Sigmon

I am honored to be asked to contribute this forward for the second edition of the *International Encyclopedia of Statistical Science*. In 2018, I had the pleasure of meeting Dr. Miodrag Lovric when he joined our faculty at Radford University. I have found Dr. Lovric's strong commitment to teaching and introducing statistics to students at all levels at our university very admirable. I was made aware of his additional efforts to spread statistical knowledge through the first edition of the Statistics Encyclopedia. The goal of this encyclopedia is to expose students and scientists throughout the world to the field of statistics. The first edition of the *International Encyclopedia of Statistical Science* was especially designed to revive statistics education in parts of the world where it has been in crisis. A great deal of the motivation behind this work came from the fact that much statistical education and expertise had been lost due to the breakup of the former Yugoslavia. Through his efforts, Dr. Lovric was able to bring together researchers from multiple countries that had been part of the former Yugoslavia. In addition, he helped expand the project to include reviving statistics education in many developing countries throughout the world. Now, the publication of the second edition of the Statistics Encyclopedia will further expand this outstanding mission.

*In the symphony of knowledge, the collaboration of minds from 110 nations composes a transformative opus that transcends borders—a resounding testament to the unity that has the power to reshape the world through the harmonious chords of mathematical and statistical wisdom.*

As we embark on the second edition of the Statistics Encyclopedia, I am delighted to extend a heartfelt welcome to our esteemed community of scholars and researchers spanning 110 countries. This ambitious endeavor not only showcases the global reach of statistical inquiry but also exemplifies the transformative potential that arises when diverse minds unite in a common pursuit.

This Encyclopedia serves as a beacon, illuminating the collaborative efforts of scientists from varied backgrounds, transcending geographical boundaries. The collective wisdom contained within its pages reflects a shared commitment to advancing statistical knowledge and its pivotal role in shaping our understanding of the world.

In a world where challenges recognize no borders, this collaborative venture symbolizes the unification of intellects dedicated to overcoming obstacles and addressing global issues. The threads of knowledge woven into this edition contribute to a tapestry of insights that extend far beyond the confines of any single discipline.

I extend my sincere gratitude to the contributors, whose passion and expertise have enriched this comprehensive compendium. May this edition inspire future generations to continue the tradition of collaboration, fostering a spirit of unity that propels scientific inquiry forward.

Chair of the Department of Mathematics and  
Statistics Radford University, VA, USA

Neil Sigmon, Professor

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## Foreword by Steven Bachrach

*In the face of an increasingly divided world, the imperative to unite for a better future emerges as a radical act, echoing the transformative power of collaboration and the pursuit of world peace.*

The second edition of the Statistics Encyclopedia unfolds as a remarkable odyssey, where ideas continue to emerge, converge, and evolve. As we delve into this intellectual achievement, I invite our esteemed community of scholars, a mosaic of diverse perspectives spanning 110 countries, to embark on a journey of discovery.

This monumental compendium serves as a nexus of statistical discourse. Here, the collaborative spirit of scientists, united in purpose and fueled by curiosity, transforms the complex into the comprehensible. It is more than a collection of entries; it is a testament to the collaborative power of collective thought.

Our contributors have crafted a narrative that defies constraints. This edition is not merely a repository of statistical facts; it is an unfolding story, revealing the evolving landscape of statistical inquiry and its profound impact on our understanding of the world.

As we navigate this reservoir of knowledge, I extend profound gratitude to the minds behind the entries, whose creativity and rigor have shaped this edition. May this work kindle the flames of inquiry, inspire future generations, and stand as a testament to the boundless possibilities that arise when diverse minds unite in pursuit of knowledge.

Dean, Artis College of Science and  
Technology Radford University, VA, USA

Steven Bachrach, Ph.D.

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# Initial Insights: Forewords and Foundations in the First Edition

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## Foreword in the First Edition

*Inventas vitam iuvat excoluisse per artes*

—Vergil

In the Republic of Srpska, and in the Federation of Bosnia and Herzegovina, we need to encourage statistics both as a science and as an aid to developing the economy of our region. This *Encyclopedia* goes a significant way towards meeting that challenge. It provides us with international visibility in statistics, it demonstrates our unity, energy, and judgment, and it shows our capacity for collaboration.

However, the *Encyclopedia* does much more than that. This storehouse of the knowledge and wisdom of statisticians from around the world displays the unity of the broad international statistics community, and provides a resource of substantial scientific benefit to all nations. It demystifies the concepts and philosophy of statistics, not just to students and researchers in the field but to their many non-statistician colleagues in other areas, who need to understand statistics in order to make progress in their own disciplines. As the historian Theodore Porter wrote, “statistics . . . is evidently among the products of science whose influence on public and private life has been most pervasive.”

For all these reasons we believe that the *Encyclopedia* will become the starting point for still further development of scientific knowledge, and be of influence for many years to come. At least in our region we feel that time, in the statistics community, will henceforth be designated as BE or AE—before the *Encyclopedia*, or after it.

Speaking personally, it is with unconcealed pride in this achievement that I take this opportunity to express my great satisfaction with the project, and my deep gratitude to the scientists and scholars who have contributed so generously to it. I believe that the *Encyclopedia* will inspire a younger

generation of statistical scientists to study and dedicate themselves to the discipline. It will draw them closer to researchers in many other fields, and closer too to their colleagues in other nations.

President Academy of Sciences and Arts  
Republic of Srpska  
Academician Rajko Kuzmanović, Ph.D.

Rajko Kuzmanović

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## Preface and Acknowledgments from the First Edition

*Statistical thinking will one day be as necessary for efficient citizenship as the ability to read and write.*

—Samuel Wilks (paraphrasing Herbert G. Wells)

*The quiet statisticians have changed our world—not by discovering new facts or technical developments, but by changing the ways we reason, experiment and form our opinions about it.*

—Ian Hacking, Contemporary Philosopher

Why is there a need for one more encyclopedia and *what is so special and unique* with the book that you have just started reading? After perusing the prefaces to at least 300 encyclopedias, I can provide 10 distinctive arguments and answers:

1. As you will see more in the next section the main objective of this project, **help reviving statistics education in developing countries**, is very different and broader and has a valuable social dimension. This goal has attracted and united many leading world statisticians, four Nobel Laureates, many eminent mathematicians, psychologists, philosophers, econometricians, economists, academicians, Presidents and founders of Statistical societies, and Editors and Associate Editors of many reputed international journals, who have decided to participate.
2. One of the hallmarks of the Encyclopedia is its international scope, it has **609 contributors from 106 countries** making this assignment one of the largest international scientific projects ever undertaken (from the perspective of the number of countries involved), not only in Statistics, but also in other branches of Science. We have shown that statistical science does not recognize and cares for country borders and customs; this united world effort encompasses countries that overall include more than 90% of the world population altogether, in a way we have fulfilled John Lennon's dream: "and the world will be as one."
3. Many of our papers have resulted as collaborations of authors coming from different countries, for example, we have a paper written by authors from the USA and Russia, paper by authors from the USA, the Philippines, and Spain; from Serbia and Croatia; Australia, the UK, and Switzerland, to mention a few.

4. For the first time authors from many developing countries have had an opportunity to work together on the same project with the leading world authorities in statistics and quantitative methods.
5. Almost all leading experts from many developing countries have been involved, including presidents of their statistical societies. This encyclopedia has contributors from almost all countries in the world that have statistics departments or professors in statistics.
6. Many papers from this encyclopedia have been selected to provide the backbone of **StatProb**, the **free** online encyclopedia of statistics, sponsored by statistics and probability societies (<http://statprob.com>).
7. This project has several contributors whose papers can be regarded as conveying an encouraging and mesmerizing message “never say never” to all of us, for example, one author has been blind since 1993 and yet provided a paper with many formulas, several most distinguished authors are over 90 and one is even 101 years old.
8. In contrast to almost all other encyclopedias, this one includes achievement biographies of many contributed authors.
9. To overcome pervasive stereotyped public images that Statistics is dull and boring, I invited many authors to write non-standard papers with our joint vision: to show not only that Statistics is a “grammar of science” but also a fascinating, attractive, stimulating, beautiful, almost magical discipline with plenty of room for fundamental improvements. For example, instead of standard foreword, Professor Bradley Efron has given his vision on the future of statistics. Former President of the American Statistical Association, Jon R. Kettenring, has written the paper on “The Rise of Statistics in the Twenty First Century” mentioning the headline that appeared on the front page of *The New York Times*: “**For today’s graduate, just one word: statistics.**” Professor Shlomo Sawilowsky has written a paper “Statistical Fallacies, Misconceptions, and Myths,” Professor Jan Kmenta “Econometrics: a failed science?”, Professor Jagdish Srivastava “Clinical Trials: Some Aspects of Public Interest,” Professor William Notz “Statistics - Resolving Controversies in Practice,” Professors Bruno Lecoutre and Shlomo Sawilowsky contrast their views on hypothesis testing, and Professors John Nelder and Herman Rubin give their different views on statistics, etc.
10. This encyclopedia includes last papers and words written by four eminent statisticians who had made great contribution to our science.

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## The Origin of the Encyclopedia and Its Goal

This project started to correct the lacuna in Statistics education in Macedonia, Serbia, Montenegro, and Bosnia that were once part of former Yugoslavia. After long discussions, an Organizational Committee was formed for writing and promoting a **Dictionary of Statistics** and as many such dictionaries were on the market, the title was changed to **Lexicon of Statistics**.

The Organizational Committee was structured such that from each of the former Yugoslavian republics (except Monte Negro) a president was elected (in alphabetical order):

Bosnia: Professor *Jasmin Komić* (also the President of the Committee),

Croatia: Professor *Ksenija Dumičić*,

Macedonia: Professor *Kalina Trenevska Blagoeva*,

Serbia: Professor *Milan Merkle* and

Slovenia: Professor *Jože Rován*.

Initially, the idea was to invite only the statisticians from the former Yugoslavian republics. It had been regarded as a significant success to realize a project with authors coming from all these republics, for the first time after the “third Balkan war.” The choice of the language was very difficult because of the different dialects (languages), and finally we decided to select English as the official Lexicon language. Later, some of the eminent statisticians and professors (in chronological order) *Peter Hall*, *Bradley Efron*, *James Hamilton*, *Robert Tibshirani*, *David Moore*, *Ronald Iman*, *Peter Diggle*, and *E.L. Lehmann* have submitted brief definitions of some statistical terms. However, a few like *Thomas Hettmansperger*, *Peter Kennedy*, *Geert Molenberghs*, *Hirotougu Akaike*, and *Alan Agresti* submitted brief articles. This reshaped my vision to strive for brief articles rather than definitions. Sir *David Cox* who pointed to some important statisticians in Europe provided the major impetus for this idea.

In preparing for this expanded project the committee realized that Statistics education is also on the decline in many developing countries. After I exchanged more than 5000 emails with statisticians from all over the world, the scope of the project was further broadened to **revive interest in Statistics in developing countries**. The response was so unprecedented and unbelievable that the title of this project was changed from Lexicon of Statistics into *International Encyclopedia of Statistical Science*.

I have decided to include the Lexicon part and the interested reader can find it in the Vol. 3.

All the contributors have committed themselves to giving our readers the best, despite the imperfections that inhere in any human endeavor. We hope that those who use this encyclopedia experience the pleasure and insight that we have worked to provide.

*If this united world effort ignite a spark of enthusiasm about statistics and henceforth revitalize interest in statistics education in developing countries and also inspire many high school students to study statistics we will consider mission fulfilled.*

Finally, I should mention that during this process, four of our esteemed contributors have passed away, Professor **Hirotougu Akaike**, Nobel Laureate Sir **Clive Granger**, Professor **Erich Lehmann**, and Professor **John Nelder**. Each of these figures has made considerable contributions to our discipline, and will be sadly missed. I feel it appropriate to **dedicate the Encyclopedia to their memory**.

## List of Articles by the Reader's Background

This encyclopedia has 636 entries arranged in alphabetical order. In contrast to many other encyclopedias, we have many co-authored papers. At the same time many authors have written two or more papers, Professor Sander Greenland even nine. The Encyclopedia includes extensive cross-referencing of two types: inline (included within a body of a paper) and "external" (provided at the end of the entry). Responsibility for these cross-references lies ultimately with me, though I am thankful to those authors who have suggested cross-references for their own papers. This work was designed to provide useful **up-to-date trustworthy** information, including the **latest advances** in statistics, for different categories of users:

*High school students* (they are strongly advised to read the papers "Statistics: An Overview," "Careers in Statistics," "Rise of Statistics in the Twenty First Century," "Statistics: Nelder's view," and the "Role of Statistics," among others).

*Undergraduate students* in almost any field (they can start reading this encyclopedia by finding the paper on the relation of statistics and their particular field of study).

*Businesspersons* (they can find valuable information in the following entries, among others: "Business Forecasting Methods," "Forecasting Principles," "Business Statistics," "Economic Statistics," "Detection of Turning Points in Business Cycles," "Business Intelligence," "Data Mining," and "Business Surveys").

*Researchers* in all branches of science (they are urged to start reading the following entries: "Research Designs," "Statistical Significance," "Statistical Evidence," "Null-Hypothesis Significance Testing: Misconceptions," "Effect Size," "P-Values," "Bayesian Versus Frequentist Statistical Reasoning," "Statistical Fallacies: Misconceptions, and Myths," "Significance Tests: A Critique," and "Frequentist Hypothesis Testing: A Defense").

*Authors of the introductory university statistics textbooks* (they could start by reading the following entries: "Statistics: An Overview," "Statistical Literacy, Reasoning, and Thinking," "Statistical Inference: An Overview," "Bayesian Versus Frequentist Statistical Reasoning," "Bayesian Statistics," "Psychology, Statistics in," "Misuse of Statistics," "Statistical Fallacies: Misconceptions, and Myths," "Statistics: Controversies in Practice," "Null-Hypothesis Significance Testing: Misconceptions," "Effect Size," "Role of Statistics," "Statistics Education," "Data Mining," "Online Statistics Education," "Measurement Scales and Choice of Statistical Method," "Harmonic Mean," "Sturges' and Scott's Rules," "Skewness," and "Significance Testing: An Overview." They will certainly find a wealth of information and many issues that they could cover or amend in their future editions, and many new angles on all those topics, that they could not find in standard textbooks).

*All other readers* can start using the encyclopedia by reading the entries “Statistics: An Overview,” “Clinical Trials: Some Aspects of Public Interest,” or “Rise of Statistics in the Twenty First Century.” We believe that any non-statistician will be able to obtain quick and yet comprehensive and highly understandable view on certain statistical terms, methods or applications. Additionally, we trust that all researchers, managers, and practitioners will regard this encyclopedia as a highly valuable resource that will help them refreshing their knowledge in Statistics, especially in certain controversial fields.

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## Acknowledgments

I would like to express my profound thanks to all our contributors who have made substantial and Herculean efforts and devoted their valuable time to support this project. This is neither a Serbian nor a Yugoslavian Encyclopedia, but a **joint work** of many leading statisticians, economists, philosophers, engineers, sociologists, econometricians, psychologists, and other scientists from all over the world, and is truly a **World Encyclopedia**. Throughout the progress of this work almost all authors have given many invaluable ideas to improve some entries and to include other topics, or suggestions to invite other eminent scholar.

The **Ministry of Science of the Republic of Srpska, President Rajko Kuzmanović, Prime Minister Milorad Dodik, and the University of Banja Luka** accorded formal recognition to this project and helped me substantially to complete it.

I would also like to especially thank Presidents and Past Presidents of many statistical associations for their support and contributed papers, including the ones from the following countries (alphabetically): Argentina, Armenia, Austria, Belarus, Belgium, Brazil, Canada, Chile, China, Estonia, Germany, Hong Kong, India, Ireland, Israel, Italy, Japan, Korea, Kyrgyzstan, Mexico, Nepal, New Zealand, Palestine, Saudi Arabia, Slovenia, South Africa, Sweden, The Netherlands, Turkey, Uganda, the UK, and the USA.

I am indebted to Presidents, Past Presidents, Directors, and Chairmen of many reputed international scientific organizations for their decisions to take part in this project, including: *Academy of Marketing Science, African Centre for Statistics, Bachelier Finance Society, Bernoulli Society, European Consortium for Mathematics in Industry, European Consortium of Sociological Research, European Society for Mathematical and Theoretical Biology, Eurostat, Institute of Mathematical Statistics, International Association for Statistics Education, International Association of Survey Statisticians, International Biometric Society, International Chinese Statistical Association, International Federation of Classification Societies, International Federation of Nonlinear Analysts, International Indian Statistical Association, International Society for Bayesian Analysis, International Society for the Study of Work and Organizational Values, International Society on Multiple Criteria Decision Making, International Sociological Association, International Statistical Institute,*

*Islamic Countries Society of Statistical Sciences, Omega Rho, Psychometric Society, Scandinavian Demographic Society, Sensometrics Society, Society for Applied Multivariate Research, Society for Marketing Advances, Statistical Modelling Society, and United Nations Statistical Commission.*

The major help throughout the realization of this project I received is from the following Organizational Committee members: Professor **Jasmin Komić**, Professor **Ksenija Dumičić**, and Professor **Milan Merkle**. It is fair to say that the whole idea of *Lexicon* came out in my long stimulating discussions with Dr. Komić, after we published our joint statistics textbook for the university students in Republic of Srpska. Also, I would like to mention my close friend, Professor *Vladislav Milošević* who was not fortunate enough to see this book as he passed away in 2009. He was always there to encourage me and to share the ideas.

I am extremely grateful to all of our reviewers whose constructive comments greatly improved many entries. In this project *peer-to-peer reviewing process* was applied, and many of our contributors took a dual role and reviewed papers from their field of expertise. Their valuable help is here acknowledged with gratitude. In the reviewing process, however, many papers had to be rejected, since the highest possible standard was applied. Additionally, I am sorry to say that for many papers I could not find the scholars that had time and willingness to provide me a report on these papers. As a result we have about 50 papers still waiting for the referees, and hopefully some will be published in the next edition.

Very special thanks are offered to the following (external) reviewers:

Alexei Stepanov—Professor, Kaliningrad State Technical University, Russia  
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 Edward Waymire—Professor, Oregon State University, USA  
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 Russia  
 William G. Faris—Professor, University of Arizona, USA

In particular, I am indebted to the Dean of my faculty, Professor *Slobodan Malinić* for his great support, especially for giving me a special permission to work continuously during the nights (till 7 am) at my faculty office for more than a year. Thanks are also due to my teaching assistants Marina Milanović and Milan Stamenković for the long hours they spent during the corrections of the papers converted to LaTeX. The draft conversion was done by the postgraduate student Srdjan Radovanović, he did a marvelous job by converting several hundred mainly difficult papers into LaTeX.

Thanks are also due to Springer's editors Dr. Niels Peter Thomas and Jennifer A. Carlson for many invaluable suggestions, support, organization, efficiency, and kindness throughout the entire project. This encyclopedia would hardly have been possible without their participation.

It would be highly inappropriate to single out any of the contributed authors. I would only like to mention that the first paper was written by Professor Peter Hall and the last one by Professor C.R Rao.

There were many ups and downs, and also many critical moments during the realization of this huge project. I succeeded (better to say survived) owing to two factors.

1. I was very fortunate to have had never-ending support of my wife and family.
2. Whenever there was a crisis or some extremely difficult phase (like for example building cross-references, there are about 4500 “external” and few thousand inline ones), I received an unprecedented support and encouragements from our authors that gave me the additional energy and strength to carry on.

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 September 2010

Miodrag Lovric  
 Editor-in-Chief

*Pro Statistica Scientia, Pace et Fraternitate Gentium*

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## Preface to the Second Edition

Standing at the threshold of the second edition of the *International Encyclopedia of Statistical Science*, an overwhelming sense of gratitude and enthusiasm courses through my veins. As Samuel Wilks eloquently stated, statistical thinking is as essential for efficient citizenship as reading and writing, echoing the sentiments of Herbert G. Wells. Within the intricate tapestry of human knowledge, statisticians emerge as the quiet architects of transformative change, a sentiment beautifully articulated by Ian Hacking. The journey ahead is not a mere compilation of facts; it is a living testament to the evolving nature of statistical understanding and its pivotal role in shaping our worldview.

Our inaugural edition, published by Springer in 2011, proved to be a resounding success. Accessed 350,000 times and garnering 4060 citations, it set a precedent in statistics by engaging recognized international authors, including prominent figures from developing countries. However, the passage of time has seen the departure of many statisticians and great minds, including luminaries like C.R. Rao, Sir David Cox, Nobel Laureate Sir Clive Granger, Nobel Laureate Harry Markowitz, Erich Leo Lehmann, John Nelder, Professor Lotfi A. Zadeh, G.E.P. Box, D.A.S. Fraser, Hirotugu Akaike, Peter Hall, Shlomo Sawilowsky, Joseph M. Hilbe, Peter Kennedy, Jan Kmenta, Alastair Scott, Scott Armstrong, Stephen E. Fienberg, Theodore Anderson, and Venkatarama Krishnan, among others. Each page echoes the collective endeavor to demystify, celebrate, and advance statistical science. In honoring the memory of luminaries, we pay tribute to their enduring contributions, ensuring their legacy lives on in the minds of future statisticians.

As the custodians of statistical knowledge, our overarching objective has been to revive statistics education in developing countries. This endeavor transcends borders and customs, embodying a united world effort that includes over 90% of the global population. In the spirit of John Lennon's dream, "and the world will be as one," our first edition united 617 authors from 105 countries, including five Nobel Laureates, earning recognition as the largest *international* scientific project in history by AMSTATNEWS in May 2011.

The resonance of collaborative effort that defined the first edition now crescendos in the second, reaching unprecedented heights of inclusivity and depth. With an impressive roster of 700 contributors from 110 countries and featuring 766 entries, this encyclopedia represents a monumental international scientific endeavor. Its scope transcends the boundaries of

statistics, encompassing an array of scientific domains and marking it as a truly comprehensive and global academic achievement. The threads of collaboration weave a rich tapestry, connecting minds from Alaska to New Zealand, from the United States to Russia, the Philippines to Spain, Serbia to Croatia, and beyond. It is a manifestation of the universal principles that underpin statistical science.

In embracing a broader conception of statistics, this edition becomes a reflection of the evolving definition put forth by Miodrag Lovric. The virtual realm, a powerful force shaping our world, finds a prominent place within the pages of this encyclopedia. There is a deliberate emphasis on the analysis of material culture, both real and virtual, situated within diverse cultural landscapes. The inclusion of biographies, especially those highlighting the achievements of non-English-speaking statisticians, adds a layer of richness, providing insight into lives intricately woven with statistical advancements.

At its core, the goal of reviving statistics education in developing countries remains a guiding light, illuminating the profound social dimension underscoring this collective endeavor. The collaborative force behind this encyclopedia unites Nobel Laureates, mathematicians, psychologists, philosophers, economists, and esteemed academicians. It is a testimony to the inclusive and universal nature of statistical science, transcending geographical borders and cultural customs. The impact of the first edition, marked by over 400,000 downloads and 4000 citations, solidifies the belief that this encyclopedia is not a mere reference work but a catalyst for inspiration and learning.

Within the virtual and real landscapes of statistical science, this edition transcends data points to unveil narratives of resilience, innovation, and unwavering commitment. It is a living legacy that spans from statistical fallacies to clinical trials, capturing the rise of statistics in the twenty-first century and delving into the controversies within the discipline.

This edition is not just a compendium of statistical knowledge; it is a global overture inviting readers from diverse backgrounds to explore the intricate melodies of statistical wisdom. From high school students to seasoned researchers, from businesspersons to educators, each entry resonates with the potential to spark curiosity, challenge perceptions, and inspire a lifelong appreciation for the grammar of science. As we unveil this second edition, gratitude extends to the 700 contributors whose Herculean efforts have shaped this monumental work, coupled with the invaluable support of institutions, societies, and colleagues.

Embark on this odyssey through statistical science and discover the richness, diversity, and enduring relevance of our discipline. May this encyclopedia serve not only as a comprehensive reference but as a source of inspiration, sparking a renewed passion for statistics that transcends borders, defies stereotypes, and illuminates the boundless possibilities within our grasp. With unwavering dedication to statistical enlightenment, we invite you to join us on this shared journey of discovery and knowledge.

As the editor of this distinguished compilation, I personally reflect on the immense effort and collaboration that have culminated in this second edition. This journey, from the initial conception to the final publication, has been one of immense learning, challenge, and fulfillment. Witnessing the coming

together of experts from around the world to contribute to this monumental work has been an incredibly humbling and enriching experience. This edition is a testament to the power of collective knowledge and the unyielding spirit of inquiry that characterizes the statistical community.

We extend a special invitation to the younger generation—the emerging statisticians, data scientists, and analysts of tomorrow. You are inheriting a rich legacy, a tapestry woven with the wisdom of the past and the innovations of the present. We urge you to delve into this encyclopedia not just as a source of knowledge but as a springboard for inspiration, a catalyst for innovation, and a call to action.

The challenges and opportunities that lie ahead in our increasingly data-driven world are immense. From tackling global health crises to addressing climate change, from enhancing technological advancements to strengthening economic structures, your role in shaping the future with statistical acumen has never been more critical.

We encourage you to ask bold questions, seek new frontiers in research, and apply your statistical expertise to solve real-world problems. Embrace the legacy of those who came before you and contribute your unique perspective to expand the boundaries of what is possible.

Let this encyclopedia be your guide, your companion, and your inspiration as you embark on your own statistical journey. Together, let's continue to unravel the mysteries of data, to make informed decisions, and to contribute to the betterment of our world. The future of statistical science is in your hands, and we are excited to see the paths you will forge and the marks you will leave on the ever-expanding horizon of knowledge.

Designed to offer valuable, **current, and reliable** insights, this edition encompasses the **forefront of statistical advancements**, serving a wide spectrum of readers.

**Educators, Students, and Academic Researchers:** The Encyclopedia's second edition is a treasure trove of knowledge for those in academia. High school and undergraduate students will find “Data Science, Data Mining, Machine Learning,” and “Big Data and Statistics” particularly enlightening, offering a glimpse into the cutting-edge of statistical application. For those grappling with the nuances of scientific research, “Navigating the Replication Crisis in Science: Striving for Solutions” provides critical insights into the challenges of reproducibility in research, a must-read for graduate students and postdoctoral researchers aiming to adopt robust research methodologies. Additionally, “The Note on Pitfalls of Misformulating One-Sided Null Hypotheses” clarifies a common misconception in hypothesis testing, an essential read for authors of statistical textbooks and curriculum designers. The comprehensive coverage of topics like “Bayesian Disease Mapping” and “Functional Data Analysis” makes the encyclopedia an indispensable resource for researchers across various scientific domains, urging them to delve into contemporary statistical debates and methodologies.

**Business and Industry Professionals:** Business leaders and professionals in the healthcare industry can gain valuable insights from entries like “Business Analytics,” “Statistical Modeling of Parkinson's Disease,” and “Cybersecurity: Recent Developments—Statistical Analysis and Predictive

Models.” These entries provide an understanding of how statistical analysis is pivotal in decision-making and strategy formulation in business contexts. The entry “Big Data” is particularly relevant, given its increasing significance in the business world.

**Philosophers, Ethicists, and Social Scientists:** The second edition also addresses the intersection of statistics with ethical and philosophical questions. “Ethics in Statistical Science” and “Navigating the Ethical Terrain: Principles and Practices in Machine Learning” are crucial for understanding the ethical implications of data analysis and statistical practices. “Deciphering Life’s Origins: A Statistical Odyssey in Evolution Versus Intelligent Design” offers a statistical perspective on a long-standing philosophical debate, making it an intriguing read for theologians, philosophers, and educators.

**Researchers in Science and Technology:** Urged to read “Modeling Probabilistic and Statistical Prediction of Risks Based on Monitoring System Data,” “Empirical Bayes,” “The P-Value Chronicles: Unmasking Thirteen Widespread Misconceptions,” “Bayes Factor,” “Jeffreys-Lindley Paradox,” and “Rao-Lovric Zero Probability Theorem.” These entries offer deep insights into contemporary statistical debates and methodologies.

**Data Scientists and Technology Experts:** For professionals and enthusiasts in the rapidly evolving fields of data science and machine learning, entries like “Python in Focus: Exploring the Intersection of Simplicity, Versatility, and Innovation” and “Deep Learning” are invaluable. These entries not only cover the technical aspects but also explore the broader implications and applications of these technologies in various fields.

**Policy Makers and Public Health Leaders:** In a world increasingly driven by data, policymakers and leaders in public health will find entries like “Practical and Adaptive Modeling for SARS-CoV-2,” “Statistical Model for Pancreatic Cancer Disease,” and “Vaccine Efficacy Trials” particularly relevant. These entries provide statistical perspectives on crucial public health issues, aiding in informed policy-making and public health strategies.

**Scientists Exploring New Frontiers:** For those interested in the frontiers of science, such as the search for extraterrestrial life or understanding the origins of life on Earth, entries like “Beyond the Horizon: A Statistical Odyssey in the Quest for Extraterrestrial Life” and “Unveiling the Integral Role of Statistical Inference in Scientific Advancements: A Comprehensive Rebuttal” offer a blend of statistical analysis with existential and cosmic inquiries. These topics are not only academically stimulating but also encourage readers to contemplate the broader implications of statistical findings in unconventional realms.

In summary, the second edition of the *International Encyclopedia of Statistical Science* stands as a beacon of knowledge, catering to a diverse array of interests and professional needs. Its comprehensive coverage of both foundational concepts and cutting-edge developments makes it an essential resource for anyone seeking to deepen their understanding of statistical science and its myriad applications in our modern world.

## Acknowledgments

This second edition stands as a testament to what can be achieved through collaboration, dedication, and a shared passion for statistical science. As we look to the future, we are inspired by the collective effort that has brought this edition to life and are excited for the journey ahead.

As we bring to fruition the second edition of the *International Encyclopedia of Statistical Science*, our hearts are full of gratitude. This monumental task, now a tangible reality, would not have been possible without the dedication, expertise, and passion of countless individuals whose contributions have been invaluable.

First and foremost, we extend our deepest thanks to every author who contributed their knowledge and insights. Your scholarly work forms the backbone of this encyclopedia, and your commitment to advancing statistical science is truly inspiring. Your individual contributions coalesce into this comprehensive resource, reflecting the diversity and richness of our field.

We are profoundly grateful to the peer reviewers, whose keen eyes and expert perspectives have immensely enhanced the quality of this work. Your rigorous evaluations, insightful feedback, and unwavering commitment to academic excellence have not only sharpened the content but also upheld the highest standards of scholarly integrity.

Special thanks go to the following esteemed reviewers for their invaluable input:

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Their commitment to maintaining scholarly standards and providing constructive critiques has been instrumental in shaping the final form of this work. I express my sincere gratitude for their dedication to academic excellence.

Gratitude is also extended to Springer's editors, Michael Hermann and Eva Hiripi, for their numerous invaluable suggestions, unwavering support, meticulous organization, efficient contributions, and gracious kindness throughout the entire project. The realization of this encyclopedia would have been considerably more challenging without their essential participation. I am also deeply indebted to Ms. Sindhuja Sakthivel, Production Supervisor, and Mr. Daniel Diwakar, Production Editor, whose tireless efforts, patience, and technical expertise over the course of more than a year have been instrumental in transforming this vast and complex manuscript into its final published form. Their professionalism, precision, and dedication to excellence played a crucial role in the successful production of this expanded second edition, now comprising more than 3,100 pages and involving contributions from over 700 authors across 110 countries.

Ultimately, the realization of this second edition owes its existence to the invaluable support extended by my Chair, Professor Neil Sigmon, and my Dean, Professor Steven Bachrach.

Radford, USA  
April 2025

Miodrag Lovric

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## In Memoriam: A Tribute to the Luminaries of Statistics

As we turn the pages of the second edition of the *International Encyclopedia of Statistical Science*, we pause to reflect with deep respect and admiration on the lives and legacies of those towering figures who have left an indelible mark on the field of statistics. Their intellectual rigor, pioneering spirit, and relentless pursuit of truth through numbers have not only shaped the discipline but also enriched the very fabric of scientific inquiry.

We fondly recall C.R. Rao, a legendary figure in the field of statistics, renowned for his remarkable achievement of acquiring 39 honorary doctorates from distinguished universities spanning 19 countries across six continents. His groundbreaking work in statistical theory and multivariate analysis has laid a lasting and influential groundwork in the sphere of statistical knowledge. Sir David Cox, whose name is synonymous with the Cox proportional hazards model, has left a legacy that continues to influence survival analysis and the study of risk. Nobel Laureate Sir Clive Granger, whose work on cointegration transformed our understanding of time series analysis, remains a guiding star in the field of econometrics.

Nobel Laureate Harry Markowitz's seminal work on portfolio theory laid the groundwork for financial econometrics, reshaping the world of finance and investment. The profound insights of Erich Leo Lehmann into testing hypotheses and estimation theory continue to illuminate the path for new generations of statisticians. John Nelder's co-creation of the Generalized Linear Model has become a staple tool for statisticians worldwide.

We recall Professor Lotfi A. Zadeh, the father of fuzzy logic, whose innovative thinking pushed the boundaries of binary classification and opened new realms of reasoning under uncertainty. G.E.P. Box's wisdom, "All models are wrong, but some are useful," continues to remind us of the humility and creativity required in statistical modeling. D.A.S. Fraser's contributions to statistics, particularly to the field of inference and likelihood theory, continue to inspire.

The groundbreaking work of Hirotugu Akaike with his information criterion encourages us to seek models that balance complexity with information. Peter Hall's extensive work in theoretical statistics has left a profound impact on the development of modern statistical methods. The legacy of these luminaries, along with the contributions of Shlomo Sawilowsky, Joseph M. Hilbe, Peter Kennedy, Jan Kmenta, Alastair Scott, Scott Armstrong, Stephen E. Fienberg, Theodore Anderson, and Venkatarama Krishnan, among others, remains a beacon of excellence.

Their collective endeavors to demystify the complex and to unravel the stochastic fabric of nature have paved the way for future breakthroughs. In honoring their memory, we commit to carrying forward the torch of inquiry and enlightenment they have bequeathed to us. Their pioneering work continues to inspire countless researchers and practitioners, and their teachings resonate in classrooms and laboratories across the globe.

Let us celebrate their achievements and honor their memories by dedicating ourselves to the pursuit of knowledge and the advancement of statistical science. They have passed the baton to us, and it is our privilege and responsibility to continue the race with the same passion and perseverance that they exemplified. In their remembrance, we pledge to uphold the standards of excellence and innovation they set, ensuring their legacy lives on for generations to come.

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## About the Editor



**Dr. Miodrag Lovric** embarked on his academic journey at the Department of Statistics, University of Belgrade, culminating in the completion of his Ph.D. in Statistical Science in 1986. His doctoral research focused on the efficiency and robustness of nonparametric rank tests, with a particular emphasis on the relevance of the Pitman asymptotic relative efficiency, especially in the context of moderate sample sizes. His early career involved teaching and research in Belgrade, but the turbulent times during the war in Yugoslavia prompted him to make a significant decision—to leave Serbia and relocate to New Zealand. In 1995, Dr. Lovric became part of the Open Polytechnic of New Zealand, contributing to distance education. The following year, he joined Wellington Polytechnic, later integrated into Massey University, where he delivered diverse courses, ranging from programming languages and data analysis to quality assurance and applied statistics. His commitment to conveying the relevance, beauty, and universal value of statistical thinking led him to envision and develop user-friendly statistical software named EduStat.

The year 1999 marked a move to Australia, where Dr. Lovric joined the School of Mathematics and Statistics at the University of South Australia, Adelaide. Responsible for teaching statistics across various disciplines, he encountered student feedback indicating a need for a fresh approach to statistical education. This realization inspired him to spend several years designing and developing EduStat, aiming to create a friendlier attitude toward statistics. Returning to Serbia in 2002, Dr. Lovric assumed the role of Professor of Statistics at the University of Belgrade, extending to the University of Kragujevac from 2008. Despite the widespread use of his statistical software at more than 30 faculties in the region and its exposure on numerous Serbian TV channels, he observed a crisis in statistics education in the former Yugoslavian republics. In response, he dedicated himself to a new project, resulting in the creation of the *International Encyclopedia of Statistical Science*.

In 2018, Miodrag Lovric embarked on a significant new chapter in his professional journey, moving from New Zealand to the United States. This transition marked a pivotal point in his career, bringing new opportunities and collaborations. Upon joining the Department of Mathematics and Statistics at Radford University in the United States, Miodrag was met with an extraordinary welcome and an outpouring of support from his colleagues, a testament to the inclusive and collegial atmosphere of the academic community there. At the heart of this warm reception was the faculty at the Artis College of Science, who extended their support and camaraderie, playing a crucial role in his smooth integration into the academic fabric of the institution. Professor Neil Sigmon, the Chair of the Department of Mathematics and Statistics, stood out for his guidance and encouragement, providing Miodrag with invaluable insights and assistance as he acclimated to his new environment. His Dean, Steven Bachrach, Ph.D., was instrumental in fostering an environment where Miodrag's talents and experiences were not only recognized but also celebrated. Under Dean Bachrach's leadership, Miodrag found a conducive and vibrant setting for both teaching and research, enabling him to thrive and contribute significantly to the department.

Most importantly, the enthusiasm and engagement of his students in the United States have been a source of great joy and inspiration for Miodrag. Their curiosity, eagerness to learn, and ability to challenge conventional thinking have greatly enriched his experience as an educator and a mentor. It is this interaction with his students that Miodrag cherishes the most, as it represents the core essence of his passion for teaching and statistical science. Journey to Radford University significantly enhanced Dr. Lovric's conception, vision, and knowledge of Statistical Science. After contributing six joint papers in the first edition of *IESS*, his involvement grew substantially in the second edition, revising these papers and authoring 12 new joint papers and 17 as a single author. Additionally, he updated many papers from the first edition, showcasing his dedication to maintaining the Encyclopedia's relevance and accuracy.

Dr. Lovric's research interests span a wide spectrum, covering Statistical Science, Philosophy of Statistical Inference, Bayesian vs. Frequentists Controversy, Controversies and Paradoxes in Statistical Testing, History of Statistics, Statistics Education, Statistical Computing, Computational Statistics, Statistics Software, Data Science, Social Statistics, Nonparametric Statistics, Robustness of Statistical Tests, Big Data and Simulation Techniques, and initiatives to revive interest in statistics education in developing countries. Dr. Lovric's professional affiliations include membership in the New Zealand Statistical Association, Statistical Society of Australia, Fellowship in the Royal Statistical Society, and membership in the American Statistical Association. He has served as a peer reviewer for various journals and authored numerous papers and books. A pinnacle in his career was a joint paper published with the eminent world statistician, Professor C.R. Rao, in 2016.

He has delivered research seminars and speeches at universities worldwide, including Australia, New Zealand, Malta, the USA, Brazil, India, Japan, and Serbia. In 2013, Dr. Lovric received a Nobel Peace Prize nomination, supported by commendations from the Provost (Rector) of Wayne State University, USA, senators from Michigan, the Rector (Chancellor) of Hyderabad University, India, the President of Bosnia, and the President of the Republic of Srpska, along with nominators from Spain and Serbia. Subsequently, in 2014, he received nominations from Brazil and Botswana. His monumental work, the *International Encyclopedia of Statistical Science* (3 volumes, Springer reference work), was recognized as the largest international scientific project in history (AMSTAT NEWS, May 2011 edition, page 14). As of January 2024, it has garnered 4060 citations. In December 2018, the Encyclopedia was translated into Japanese and published by the Statistical Society of Japan in five volumes, comprising 2130 pages.

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