George Fishman's Professional Career

Christos Alexopoulos, David Goldsman, and James R. Wilson

Abstract In this lead article for *Advancing the Frontiers of Simulation: A Festschrift in Honor of George Samuel Fishman*, we survey briefly George's professional career, summarizing his most significant contributions to the disciplines of operations research and the management sciences. We give special emphasis to George's remarkable accomplishments in helping to lay the foundation for the field of computer simulation and advancing that field over the past five decades.

1 A Brief Biography

George Fishman was born to Louis and Gertrude Fishman on July 3, 1937, in Everett, Massachusetts. Eight months later his father died of cancer, leaving his mother to bring up George and his six-year-old sister Estelle. He spent his early years in the West End of Boston near the Longfellow Bridge. In 1950, his family moved first to Roxbury and then a year later to Chelsea. George graduated from Chelsea High School in 1955 and matriculated that fall at the Massachusetts Institute of Technology (MIT). Unsure of his commitment to engineering, he took a leave of absence in November 1956 and spent the next ten months working for the Whiting Milk Company in Charlestown, Massachusetts. The nightly experience of lifting and pouring 100 forty-quart jugs of heavy cream into a tank for bottling was enough to convince George that college was worth completing. He completed his course work in December 1959 and was graduated from MIT in 1960 with a bachelor of science degree in economics.

While awaiting decisions from graduate schools, George spent January through August 1960 working as a research assistant at MIT for Professors Morris Adelman, E. Cary Brown, and Robert Solow of the Economics Department, and also for Professor Ithiel deSola Pool, chair of the Political Science Department. In many

C. Alexopoulos (✉)
H. Milton Stewart School of Industrial and Systems Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA
e-mail: christos@isye.gatech.edu

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respects, George's experience as a research assistant during the winter, spring, and summer of 1960 persuaded him that research was his preferred career path.

In the fall of 1960, George enrolled in the Ph.D. program of the Department of Economics at Stanford University, serving as research assistant to Professors Kenneth Arrow and Marc Nerlove. In the spring of 1962, he was invited to be a summer intern in the Logistics Department of the RAND Corporation in Santa Monica, California. The latter opportunity turned out to be fortuitous. In the summer of 1962, George was offered a full-time position as a research analyst at RAND, and he left Stanford with a master's degree in economics.

RAND was an exceptionally stimulating place, and the decision to go there was not hard for George to make. In the early 1960s, RAND's Logistics Department could have easily staffed several university-level departments in operations research. During the 1950s, RAND had been in the forefront of new developments in mathematical programming, Monte Carlo simulation, and discrete-event simulation, topics in which George had limited experience prior to joining RAND. In December 1963, Murray Geisler, then chair of the Logistics Department, asked George to referee a RAND report on statistical aspects of simulation. After reading the review, Geisler encouraged George to examine the many outstanding statistical issues in simulation. During the next seven years at RAND, George wrote a collection of publications with a focus on estimating the statistical accuracy of simulation results. Several of these papers were coauthored with Philip Kiviat, who at that time was actively engaged with Harry Markowitz in the development of the SIMSCRIPT II simulation programming language. The collaboration with Kiviat gave George a considerably broader understanding of the component parts of simulation methodology: modeling, computer languages, and statistical considerations.

By 1967, George had decided that a university setting would work best for his research interests. He enrolled in the Biostatistics Program at the University of California, Los Angeles (UCLA), from which he received a Ph.D. degree in March 1970. Shortly thereafter he and his young wife, Sue, moved to New Haven, Connecticut, where he joined the Administrative Sciences Department at Yale University as an associate professor and associate director of the Health Services Research Training Program in Yale's Institution for Social and Policy Studies. At that time, Yale's Administrative Sciences Department had an exceptionally accomplished operations research faculty, including Gordon Bradley, Eric Denardo, Matt Sobel, Harvey Wagner, and Ward Whitt.

The RAND experience, especially the collaboration with Kiviat, had provided George with an excellent preparation for teaching a graduate-level course in simulation. The notes from this course led to his book *Concepts and Methods in Discrete Event Simulation* (Fishman 1973). George's scholarly work now broadened to encompass pseudorandom number generation, random variate generation, and a new way to analyze sample path data based on the theory of regenerative processes.

In July 1974, George, Sue, and their children, Becky and Matt, moved to Chapel Hill, North Carolina, where George had accepted a professorship at the University of North Carolina (UNC) in its recently established Curriculum in Operations Research and Systems Analysis. His work on several areas of simulation methodology continued, with special emphasis on decision rules for how to make the batch-means method of analysis statistically valid in practice.

Although Sue had grown up in a small Mississippi town, George's New England roots made the warm North Carolina summers more of a challenge for him. To the family's delight, George received and accepted an invitation from Matt Sobel to spend part of the summer of 1976 at the Ecology Center of the Marine Biological Laboratory in Woods Hole, Massachusetts, to study the harvesting of elephants in African national parks. The problem called for mathematical and statistical modeling and was of sufficient interest to Dan Botkin, a principal researcher at the Center, to warrant a return the next summer. George found that Woods Hole was a delightful place to do research and spend summers.

Grants from the North Carolina Sea Grant program allowed George and his family to repeat the experience closer to home in the summers of 1978 and 1979 at the UNC Marine Research Laboratory in Morehead City, North Carolina, and the U.S. National Marine Fisheries Laboratory in Beaufort, North Carolina. The challenge was to formulate a policy for optimally determining the opening date for shrimp fishing in North Carolina intercoastal waters.

In January 1981, George became chair of the Curriculum in Operations Research and Systems Analysis at UNC. University resources for academic program development were relatively plentiful in the early 1980s; and during George's ten-year tenure as chair, the program grew in reputation within UNC, nationally, and internationally. Its core faculty, originally consisting of David Rubin, Jon Tolle, and George, was enhanced by the recruitment of Vidyadhar Kulkarni, Scott Provan, Sandy Stidham, and Mark Hartmann. In 1987, UNC acknowledged this growth in size and reputation by elevating the Curriculum in Operations Research and Systems Analysis to the status of the Department of Operations Research within the UNC College of Arts and Sciences.

Scott Provan gives a concise summary of George's contributions to the growth of the Operations Research program and the development of its faculty.

> [George] joined UNC in 1974, having been hired specifically to form the nucleus for operations research as an academic discipline within the College of Arts and Sciences. He originally occupied the sole funded position in an interdisciplinary program whose faculty included members from mathematics, statistics, biostatistics, computer science, and business. George was tenacious in his development of the program, and worked from a crystal-clear vision of its mission within the college. UNC took a farsighted position in those years of encouraging high-quality graduate programs to flourish and draw top-flight faculty and students, and George took excellent advantage of that. I joined the program in 1982 precisely because the research atmosphere was so exciting. Under his chairmanship the program gained 3.5 more funded faculty lines, and in 1987 it became a full-fledged department. George chaired the department until 1990, all the time continuing to garner international acclaim for his own research in simulation theory.
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> It is safe to say that George single-handedly built the OR program into a nationally-respected and intellectually vibrant department during his tenure. He was relentless in his pursuit of resources, and I was constantly surprised at what he could coax out of the college for a program of our size. Just as significantly, he was able to shield the faculty from many distractions that make it difficult to pursue high-quality research by maintaining a consistent set of expectations and boundaries. I always said that he was a great guy to be behind, and a tough one to be in front of.

Vidyadhar Kulkarni, the current chair of the Department of Statistics and Operations Research at UNC adds a personal touch.

> Professor Fishman acted as my academic mentor: I learned how to write research papers and research grants under the helpful advice of George. He served as a role model of an effective chairman that helped me later. I was truly amazed at his ability of time management: his research productivity did not diminish one bit during his tenure as the chairman. I have found myself using his administrative strategies many times during my own stint as a chairman. I am thankful to him for all that I learned from him.
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> George is now retired, but comes to the department regularly and provides the most enjoyable and erudite conversational company during our lunches. He is still a valuable resource for research problems that I continue to mine regularly. I wish him a long and productive life.

David Rubin, a professor of operations research with a primary appointment in UNC's Kenan-Flagler Business School offers a view from a slightly different angle.

> When George Fishman arrived at UNC in 1974, the Curriculum in Operations Research and Systems Analysis had control of one full position (George's) and two half positions that were joint in the mathematics and statistics departments. In addition, there were roughly eight "affiliated" faculty, like me, whose home appointments were in business, computer science, economics, and statistics. Six years later, when George became Curriculum Chair, he had control of only 2.5 faculty positions. I remember often being asked exactly what a curriculum was at UNC. My stock answer: "It's either a nascent or stillborn Department, and only time will tell." George's almost ten years as chair were a time of great growth and success for operations research at UNC. Under his able and forceful leadership, the Curriculum became the Department of Operations Research, home to 5.5 faculty members at the end of his term.

The early 1980s saw a shift in George's focus toward the application of the Monte Carlo method to networks, especially the development of efficiency-improvement (variance-reduction) techniques for estimating reliability and the distribution of maximal flow. In 1986 he began writing the text *Monte Carlo: Concepts, Algorithms, and Applications* (Fishman 1996), followed by *Discrete-Event Simulation: Modeling, Programming, and Analysis* (Fishman 2001).

In 2001, George retired from UNC; however, thanks to the generosity of the department chair, Vidyadhar Kulkarni, George was able to maintain a shared office in the department. Fortuitously, his office mate from 2001 through the summer of 2008 was Charles Dunn, whom George had as a student at Yale over thirty years earlier. Since the fall of 2008, Sandy Stidham, a friend and colleague for at least as long, has been his office mate. It was the convenience of this space that made possible publication of his latest book, *A First Course in Monte Carlo* (Fishman 2005).

Sandy Stidham succeeded George as department chair in 1990. Sandy provides a keen insight into George's leadership style and its effect on all his colleagues.

> After I came to North Carolina, it soon became apparent to me that, under George's leadership, the Curriculum in Operations Research and Systems Analysis at UNC-CH had achieved a status that is rare in academic life: it was an interdisciplinary, interdepartmental program with an independent budget and dedicated faculty lines, which had maintained vital connections with other academic units through joint faculty positions. Just as important, and just as rare, was the collegiality of the faculty, the mutual respect among its members, and the close, congenial relations between the faculty and students.

> Soon after I joined the faculty in 1986, the Curriculum attained departmental status as the Department of Operations Research. George continued to provide steady leadership as Chair of the Department until 1990. I like to call it "leadership by encouragement." One of George's favorite phrases has always been "I encourage you to . . .." More than a rhetorical device, it was an emblem of his leadership style: he encouraged his colleagues to see things the way he saw them. Because he always thought through his own decisions with logic and sensitivity, the rest of us (almost always) ended up seeing things the same way.
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> While devoting himself to the growth and flourishing of OR at UNC-CH, George maintained an active research program and a growing international reputation in the fields of discrete-event simulation and Monte Carlo. When these subjects come up during conversations with friends, I have found myself saying (with pride): "My friend and colleague, George Fishman, is the preeminent expert on simulation and Monte Carlo, and I encourage you to look at his books, *Monte Carlo: Concepts, Algorithms, and Applications* and *Discrete-Event Simulation: Modeling, Programming, and Analysis*."
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> During our mutual retirement, George and I have made a habit of going out for coffee about once a week. We discuss music, politics, religion, economics, and, of course, the joys of grandchildren. The friendship that has developed between us is, and will continue to be, one that I cherish.

During the course of his career, George has made major contributions in laying the foundations for the field of computer simulation and in advancing that field. From 1972 to 1974, he served as the chair of the College on Simulation and Gaming of The Institute of Management Sciences (TIMS), an organization subsequently named TIMS/College on Simulation and later renamed the Simulation Society of the Institute for Operations Research and the Management Sciences (INFORMS). From 1978 to 1980, George served as the representative of TIMS/College on Simulation and Gaming on the Board of Directors of the Winter Simulation Conference. Moreover, from 1978 to 1987, he served as the founding editor of the Simulation Department of the journal *Management Science*. From the perspective provided by the passage of almost three decades, it is now clear that George's service as founding editor of the Simulation Department of *Management Science* was critical to the establishment and initial advancement of the simulation literature as we know it today. It can be argued that this development coupled with George's own research contributions to the simulation literature were two of the key factors in the survival of the field of simulation as a separate, recognizable subject with its own body of relevant theory, methodology, and applications.

From 1989 to 1992, George served on the Editorial Advisory Board of *ACM Transactions on Modeling and Computer Simulation*, a flagship publication of the Association for Computing Machinery. Further, over the years, George served on numerous committees of professional societies and international conferences.

George has received numerous forms of professional recognition for his remarkable contributions to simulation and the larger disciplines of operations research and the management sciences over the past five decades. In 1990 he received the Distinguished Service Award from TIMS/College on Simulation. For his book *Monte Carlo: Concepts, Algorithms, and Applications* (Fishman 1996), he received two awards—the Frederick W. Lanchester Prize from INFORMS in 1996, and the Outstanding Simulation Publication Award from the INFORMS Simulation Society in 1997. In 2003 George was elected a Fellow of INFORMS. In 2004 George received the INFORMS Simulation Society's Lifetime Professional Achievement Award (LPAA), the highest honor given by that organization. This award recognizes major contributions to the field of computer simulation that are sustained over a professional career, with the critical consideration being the total impact of those contributions on the field.

In a supporting letter for the LPAA nomination, Russell Cheng (University of Southampton) wrote:

> Discrete-event simulation has seen substantial growth both in terms of its theoretical base and in terms of its huge range of application. Professor Fishman has been at the forefront of these developments. On a worldwide basis, I would rank him in the top few in terms of both range and the scholastic quality of his contributions, many of which have been seminal.

John Charnes (Senior Vice President, Bank of America) concurred:

> When I look at Prof. Fishman's vita, I am amazed that he has done so much. With contributions to research in so many different fields, mentorship of so many students, and service to the profession in so many ways, he is certainly qualified to be awarded the LPAA.

2 Contributions to Computer Simulation

George is a scholar and researcher of the first rank, a stimulating colleague, a thoughtful mentor, and a steadfast friend to those individuals fortunate enough to have worked with him. Over the course of a career spanning five decades, George has made fundamental contributions to both the theory and practice of simulation, dissemination of knowledge, service to the profession, and the advancement of the status of the field. In the sections that follow, we give a synopsis of George's impact on the field of computer simulation.

2.1 Contributions to Research

George has made numerous groundbreaking contributions to the following methods for simulation output analysis:

- the spectral method;
- the autoregressive method;
- the regenerative method; and
- the batch-means method.

Moreover, George has made seminal contributions to the following areas within the field of simulation:

- efficiency-improvement (variance-reduction) techniques;
- estimation of network performability measures;
- pseudorandom number generation; and
- random variate generation.

Although George's first archival journal article (Fishman 1964) and his first book (Fishman 1969) were in the field of economics, much of his subsequent work focused on simulation analysis methodology and the design of efficient simulation experiments. In the rest of this section, we survey George's contributions in the areas listed above.

2.1.1 Spectral Method

George's first major contribution to simulation output analysis was the development with Phil Kiviat of the spectral method (Fishman and Kiviat 1967). The name of this method is based on the following property of a stationary stochastic process, presumably generated by a simulation in steady-state operation: if we compute the power spectrum of the process (that is, the Fourier cosine transform of the associated autocovariance function), then the power spectrum evaluated at frequency zero is equal to the variance parameter of the process (that is, the sum of the autocovariances at all lags). Moreover, the variance of the sample mean is asymptotically equal to the variance parameter divided by the sample size as the sample size increases. Hence, for large sample sizes, the estimation of the variance parameter and the construction of a valid confidence interval for the steady-state mean reduces to the estimation of the power spectrum of the process at zero frequency.

As formulated by Fishman and Kiviat (1967), the spectral method for simulation analysis estimates the variance parameter (and hence the variance of the sample mean) by a weighted average of estimators of the autocovariance function, with appropriately chosen weights. The methodology was revisited in the early 1980s by Heidelberger and Welch (1983), and its relationship to the methods of nonoverlapping and overlapping batch means is discussed by Welch (1987). This variance-estimation approach has regained attention recently with the development of wavelet-based methods for estimation of the power spectrum (Lada and Wilson 2006).

2.1.2 Autoregressive Method

In Fishman (1971) and Fishman (1973), George pioneered the autoregressive method for simulation output analysis. This technique is based on the following properties:

- A mixed autoregressive–moving average (ARMA) process of order (p, q) (where $0 \le p, q < \infty$) that is stationary and invertible often provides an adequate model for many time series encountered in practice—including many simulation-generated times series.
- A stationary invertible ARMA(p, q) process can be approximated in quadratic mean to any prespecified accuracy by a stationary autoregressive (AR) process of sufficiently large order p' (that is, an AR(p') model).

George formulated a comprehensive method for determining an appropriate order of the pure autoregressive model as an approximation to a given simulation-generated process and for estimating the coefficients of that model. A simplified variant of the autoregressive method has resurfaced recently as a key ingredient of automated batch-means methods for simulation analysis (Steiger et al. 2005, Lada et al. 2008, Tafazzoli et al. 2008).

2.1.3 Regenerative Method

George's next fundamental contribution to simulation analysis was the estimation of steady-state means and quantiles based on the regenerative method (Fishman 1974a, Fishman and Moore 1979, Seila 1976). If a stationary stochastic process has the regenerative property, then the process has regeneration points defined by transitions out of a distinguished state—for example in a stable single-server queueing system, a regeneration point occurs each time an arriving customer finds the system empty and thus triggers a transition out of the empty-and-idle state. At each regeneration point, the probabilistic mechanism governing the evolution of the process is restarted independently of the previous history of the process. The regenerative property enables us to obtain independent and identically distributed blocks of data on which to apply relevant central limit theorems. By coincidence, Crane and Iglehart (1974a, b) published similar results on the regenerative method for simulation analysis simultaneously with Fishman (1974a); in fact, all three papers appeared in the January 1974 issue of *Operations Research*. George relates the following story:

> A copy of my technical report on the regenerative method was sent to Gerry Lieberman, Chair of the Operations Research Department at Stanford University. Interestingly, a copy of a technical report from Stanford University, authored by Don Iglehart and Michael Crane and describing a similar methodology arrived at Yale University one week later. Apparently, the Stanford group and I had been working on the same problem, unaware of the other's work.

Since the appearance of these seminal papers on the regenerative method, hundreds of papers have been published on this approach to the analysis of simulation output.

2.1.4 Batch Means Method

George's pathbreaking contributions to the batch-means method for simulation analysis were motivated by the difficulties that arise in practical applications of the regenerative method. In general, it can be difficult to identify regeneration points in a simulation-generated output process. Moreover, even when such regeneration points can be identified, their recurrence frequency may be so small that an excessive simulation run length is required to accumulate a sufficiently large number of complete regenerative cycles so as to estimate long-run average performance measures with acceptable precision.

Although the method of batch means was known to the simulation community since the early 1960s (Conway 1963), George's groundbreaking work on this method in the 1970s (Fishman 1978a, b) provides the first comprehensive batch-means procedure for computing valid confidence intervals for the steady-state mean. In particular, the discussion on pp. 245–246 of Fishman (1978a) explains how a perusal of the plot of the batch means can give good insights into the effect of the simulation's initial condition, as well as the approach to independence and normality of the batch means with increasing batch size.

In the early 1990s, George revisited the method of batch means with the development of ABATCH and LBATCH, two implementations of the batch-means method that yield not only a consistent estimator of the variance parameter but also asymptotically valid confidence intervals for the steady-state mean as the batch size and the number of batches both tend to infinity at suitable rates (Fishman and Yarberry 1997). ABATCH and LBATCH are the only batch-means algorithms that require $O(n)$ time and $O(\log_2 n)$ space for the total sample size n accumulated with each additional iteration of the overall procedure. Although linear time complexities are known for algorithms based on fixed batch and sample sizes, the dynamic setting of the ABATCH and LBATCH algorithms offers an important additional advantage not present in static approaches: as the analysis evolves with the availability of additional data, ABATCH and LBATCH allow the user to assess visually and quantitatively how the batch-means estimate of the variance parameter converges to the desired limiting value, in linear computation time and sublinear space (that is, computer memory). Such direct assessment enables the user to gauge the quality of the variance estimate and the confidence interval for the mean.

Peter Glynn (Stanford University) applauds George's contributions in this area, while also crediting him as a codeveloper of the regenerative method.

> [George] played a major role in providing a rigorous analysis of the method of batch means, and in developing practical implementations of the method. Given the important role of this output analysis procedure in the steady-state simulation setting, this stands as a significant accomplishment. But this is only one of several fundamental contributions to the output analysis problem. George also introduced the regenerative method (along with Don Iglehart), and developed means of producing confidence bounds that are non-asymptotic (and are thereby guaranteed to hold for any fixed sample size). Each of these contributions has stimulated an extensive amount of follow-on research.

2.1.5 Efficiency-Improvement (Variance-Reduction) Techniques

Throughout his professional career, George has had a particular interest in methods to improve the efficiency of simulation experiments. In Fishman (1968), he addressed the relationship between the computing budget and the accuracy and precision of the resulting simulation-based estimators. In Fishman (1974b), George laid the foundation for the use of common random numbers and antithetic variates to improve the efficiency of estimation of linear simulation metamodels, thereby anticipating the correlation-induction strategy of Schruben and Margolin (1978) and all the follow-up work on correlation-induction strategies for simulation metamodel estimation. In his groundbreaking papers on efficiency-improvement techniques for the simulation of Markov chains (Fishman 1983a, b; Fishman and Huang 1983), George anticipated the recent explosive growth in the use of Markov Chain Monte Carlo (MCMC) (Gilks et al. 1996), especially in the implementation of Bayesian statistical methods. George's work on efficiency-improvement techniques in the 1970s and early 1980s were precursors to his influential contributions on network reliability estimation and his work in the 1990s. Fishman and Rubin (1992a, b) and Fishman et al. (1992) exploit the availability of bounds on the underlying distribution (prior information) to obtain best- and worst-case bounds on the variance and coefficient of variation of the corresponding Monte Carlo–based estimators. Fishman and Kulkarni (1992) describe necessary and sufficient conditions for MCMC sampling to perform more efficiently than Monte Carlo sampling based on independent trials.

2.1.6 Network Reliability

In the early 1980s, George focused much of his research on the development of Monte Carlo sampling plans for estimating performability measures of networks whose components have random characteristics (e.g., lengths, durations, and capacities). This development was funded by a research grant from the Air Force Office of Scientific Research and spanned a period of about ten years. The sampling plans developed by George and his collaborators typically use bounds on the measures under study to construct conditional distributions defined on a subset of the system's state space. The resulting estimators are unbiased, have substantially smaller variance than estimators based on standard Monte Carlo and equal computing effort (encompassing sample size and sampling time), and have bounded relative error as the sample size grows; see, for example, Fishman (1986a, b; 1989b, c). Although bounds existed since the early 1970s (Frank and Frisch 1970, Van Slyke and Frank 1972), they did not permit the construction of effective sampling distributions.

Fishman (1986a) and Fishman (1986b) are landmark papers on the problem of computing network reliability with binary state components. In Fishman (1986b), George exploits bounds based on disjoint minimal path sets and minimal cut sets. In Fishman (1986a), he takes advantage of bounds on the coefficients of the polynomial reliability function when all components have equal reliabilities.

To estimate the distribution of two-terminal maximum flow in networks with discrete arc capacities, George and his collaborators achieve striking increases in estimator efficiency by exploiting bounds based on minimal paths and cuts (Fishman 1987a, b; Fishman 1989a, c; Alexopoulos and Fishman 1991, 1993). An alternative approach is proposed by Fishman and Shaw (1989) and Alexopoulos and Fishman (1992) in which the bounds result from iterative partitions of the system state space, and the corresponding estimators are based on a combination of importance and stratified sampling. The work of George and his coauthors in this area is referenced prominently in the handbook chapter by Ball et al. (1995).

Concerning George's work on Monte Carlo–based analysis of network performability, Peter Glynn offers the following perspective.

> He has made fundamental contributions to the development of special-purpose methods for efficiently computing various performance measures in the stochastic networks context. This class of networks arises naturally in many applied settings, and is of great practical interest. The tools that George has developed in this setting make possible computations that would be difficult (or perhaps even impossible) if attacked using naïve algorithms.

2.1.7 Generation of Pseudorandom Numbers and Variates

George has authored three widely cited studies of pseudorandom number generators (Fishman and Moore 1982, 1986; Fishman 1990) and six papers on random variate generation. In the latter area, the paper by Fishman and Moore (1984) is worthy of special mention. Although the alias method of Walker (1977) is the most frequently cited approach for generating samples from a discrete distribution in bounded time, it fails to provide a monotonic functional dependence of each generated sample on the corresponding random number, a fundamental property required by the methods of common random numbers and antithetic variates. The cutpoint method of Fishman and Moore overcomes this limitation of the alias method, is easier to understand, and shows how to ensure a fixed bound on variate-generation time regardless of the number of points in the distribution.

Pierre L'Ecuyer (Université de Montréal) talks about the influence that George's random number generation work had on his career.

> My first and closest encounter with his work was his papers with Louis R. Moore on search and evaluation of linear congruential generators. These papers had a very strong influence on my own work on uniform random number generators, especially at the earliest stages. In particular, the figure of merit I adopted to select the famous combined [linear congruential generator] of my 1988 *CACM* paper was taken from these papers. In their 1982 *JASA* paper, they introduced a normalized spectral test measure which has become the standard for the theoretical evaluation of linear congruential and multiple recursive random number generators.

In the above quotation, L'Ecuyer (1988) is the article referred to as the "1988 *CACM* paper"; and Fishman and Moore (1982) is the article referred to as the "1982 *JASA* paper."

2.2 Dissemination of Knowledge and Advancement of the Field

Of course, many of us in the simulation community have grown up on George's simulation texts. George authored one monograph on the application of spectral methods in econometrics, three books on discrete-event simulation and two books on the Monte Carlo methodology.

His first simulation text, *Concepts and Methods in Discrete Event Digital Simulation* (Fishman 1973), served as the state-of-the-art reference for many researchers. Barry Nelson (Northwestern University) relates the following story that summarizes the value of this text.

> For me, personally, George's work joins the work of Jim Wilson as having the most impact on the direction of my own career. To illustrate this point, I want to single out his 1973 book *Concepts and Methods in Discrete Event Digital Simulation*. I first encountered this book in Bruce Schmeiser's office when I was a graduate student at Purdue in 1981. Bruce used this book as a reference for his IE680 class, and it was this material (along with Bruce) that persuaded me to stay for my Ph.D. rather than leave Purdue after my M.S., as originally planned. The book was already out of print, but I made it a priority to find a copy, and I eventually obtained one from a used book store for $10 (perhaps the highest value per dollar of any purchase I have ever made!). In addition to being one of the first comprehensive books on simulation, covering modeling, programming, and analysis, *Concepts and Methods in Discrete Event Digital Simulation* was the first formal mathematical treatment of "analysis methodology" that I encountered. For many years after I left Purdue, it was one of the first books I pulled from my shelf when I tackled a new research problem.

His second simulation text, *Principles of Discrete Event Simulation*, appeared in 1978. This text incorporated the methodological advancements in simulation output analysis during the 1970s and, most importantly, contained SIMSCRIPT II.5 codes for computing point and confidence interval estimates based on the regenerative and batch-means methods.

In 2001, George published *Discrete-Event Simulation: Modeling, Programming, and Analysis*. Of particular import are the excellent chapter on efficient execution of simulation programs (appropriately entitled "Search, Space, and Time") and the chapter on output data analysis. In addition to the description and implementation of sequential methods based on batch means, the latter chapter contains an enlightening discussion regarding the potential deleterious effects of the initialization bias inherent in steady-state simulation experiments on the validity of confidence intervals obtained by the method of replication/deletion. This discussion directly inspired the paper by Alexopoulos and Goldsman (2004), recipient of the INFORMS Simulation Society's Outstanding Simulation Publication Award in 2007.

The monograph *Monte Carlo: Concepts, Algorithms, and Applications* (Fishman 1996), winner of the Frederick W. Lanchester Prize from INFORMS in 1996, as well as the INFORMS Simulation Society's Outstanding Simulation Publication Award in 1997, is perhaps the tour de force of George's career.

Stunningly complete and comprehensive, the text is a must-read for anyone in the field. In fact, the book has found great use in a number of wide-ranging fields: operations research and industrial engineering, mathematics, probability and statistics, computer science, financial engineering, and physics, just to name a few. The book is unparalleled in scope and content; yet, remarkably, it is a self-contained piece that requires little previous exposure to the field. It begins with a number of methods for estimating volumes and counts, including classical (but difficult) problems involving network reliability, multidimensional integration, sensitivity analysis, bounds for simultaneous confidence intervals, estimation of the expected value of the ratio of random variables, and sequential estimation. The book then presents an encyclopedic discussion on random variate generation techniques. Not only does the list encompass the "usual" random variables; it also includes problems involving the generation of points constrained by interesting geometric shapes including convex polytopes—thus making the book tremendously useful for researchers in mathematical optimization. The text goes on to discuss methods such as correlated sampling, control variates, importance sampling, and stratified sampling to increase sampling efficiency. These topics are in the spirit of Hammersley and Handscomb (1964), albeit at a more-rigorous and more-modern level. A particularly significant chapter is that on random tours, encompassing random walks (and generalizations thereof) on a variety of domains. The book devotes a chapter to simulation output analysis—how should one report the results of an experiment in a statistically rigorous way? The text is in fact the first to treat sequential, commercially useful output analysis methods (LBATCH and ABATCH). The tome concludes with a state-of-the-art treatment on pseudorandom number generation, in which we see how to generate the underlying uniform random variates that drive the stochastic simulation. The overall result is that the book is a beautiful compendium covering everything that one needs to know about the Monte Carlo method; the Lanchester Prize certainly underscores this obvious fact.

The primary target of his 1996 book on Monte Carlo methods is, of course, researchers. This realization led George to author the primer *A First Course on Monte Carlo* (Fishman 2005), for purposes of exposing the methodology to a wider, less-mathematically sophisticated audience. The main contributions of this text are the simplicity of the exposition, the detailed algorithmic description of the various techniques, the plethora of real-world examples from various application areas, and the inclusion of "hands-on" exercises that enable the reader to try the techniques and identify the most-effective ones for the underlying problems.

2.3 Development of Software

George and Louis Moore developed comprehensive computer programs for evaluating the performance of random-number generators using statistical and geometric tests. In addition, George and Stephen Yarberry developed and implemented the only sequential batch means algorithms (LBATCH and ABATCH) that run in linear time and logarithmic space. The algorithms in the LABATCH.2 package have been used by numerous researchers in the operations research and computer science communities. The LABATCH.2 package is available online via

`www.or.unc.edu/~gfish/labatch.2.html` .

3 George's Academic Family Tree

George has a distinguished academic pedigree. His doctoral research advisor was Dr. Robert Jennrich, who is currently a Professor in the Department of Mathematics at UCLA. In reverse chronological order, one path of George's academic ancestry includes Paul Hoel, Dunham Jackson, Edmund Landau, Georg Frobenius, Lazarus Fuchs, Ernst Kummer, Karl Weierstrass, Friedrich Bessel, Christoph Gudermann, and Carl Gauss. A second path can be traced directly to Nicolaus Copernicus and a third path originates from Georgios Gemistos Plethon, a Greek neoplatonist philosopher from Constantinople.

George served on many doctoral dissertation committees both as an advisor and reader. He advised the following students:

- Andrew F. Seila, dissertation: "Quantile estimation methods in discrete event simulations of regenerative systems," Operations Research, UNC (1976).
- Veena G. Adlakha, dissertation: "Starting and stopping rules for data collection in queueing simulations," Operations Research, UNC (1979).
- Louis R. Moore, dissertation: "Quantile estimation in regenerative processes," Statistics, UNC (1979).
- Bao-Sheng Huang, dissertation: "Antithetic sampling method: A variance reduction technique in computer simulation," Operations Research, UNC (1980).
- Kenneth J. Risko, dissertation: "Binomial population selection procedures for fixed unequal sampling costs," Statistics, UNC (1982).
- Tien-Yi Shaw, dissertation: "Monte Carlo methods for reliability analysis of stochastic flow networks," Operations Research, UNC (1988).
- Christos Alexopoulos, dissertation: "Maximum flows and critical cutsets in stochastic networks with discrete arc capacities," Operations Research, UNC (1988).
- L. Stephen Yarberry, dissertation: "Incorporating a dynamic batch size selection mechanism in a fixed-size batch means procedure," Operations Research, UNC (1993).
- M. Cristina Arguelles, dissertation: "Exploiting special structure to enhance efficiency of manufacturing simulation," Operations Research, UNC (1997).

Currently, Andy Seila is a professor emeritus in the Department of Management Information Systems of the Terry College of Business at the University of Georgia. Veena Adlakha is a professor in the Management Department of the Merrick School of Business at the University of Baltimore. Lou Moore is a senior operations researcher with the RAND Corporation in Santa Monica, California. From 1980 to 2000, Bao-Sheng Huang worked for Bell Labs, where he became a distinguished member of the technical staff and technology consultant for his contributions in the areas of network modeling and simulation; and since 2004 he has served as director of systems engineering for Wide Area Network Design Laboratory (WANDL). Kenneth J. Risko is a senior manager in the regulatory and capital markets consulting practice for the financial services industry at Deloitte & Touche LLP. Danny Shaw is an operations research specialist in the Operations Research and Development Department of the SAS Institute Inc. Christos Alexopoulos is an associate professor in the H. Milton Stewart School of Industrial and Systems Engineering at the Georgia Institute of Technology and the director of the Modeling and Simulation Research and Education Center at Georgia Tech. L. Stephen Yarberry is currently the chief information officer at Practice Plus/Arkansas Health Group and chief information security officer at Baptist Health in Little Rock, Arkansas. In addition, he owns Yarberry & Associates, a management and telecommunications consulting company; and he serves as an adjunct professor at both Webster University and the University of Central Arkansas. Cristina Arguelles Tasker is a client business manager with i2 Technologies in London.

Despite his heavy administrative duties and research agenda, George was a resourceful teacher and a wonderful academic advisor. Veena Adlakha comments on George's dedication to his students.

> I have always considered it as a great honor and privilege to have had Dr. George Fishman as my Ph.D. thesis advisor. Working with him as his research assistant and as his student was a great learning process. His office was always open and he always had time for his students—whether to debug a program, improve the flow of logic, or simply answer a question. Dr. Fishman was unrelenting in his demand for hard work and perfection, but he always guided his students with patience. I recall vividly how he made me rewrite the first chapter of my thesis seven times. It was only when I would write my own research papers later that I appreciated the effect that his persistence had on improving my writing abilities.
>
> Being Dr. Fishman's student certainly had its perks. In 1979 I attended the ORSA/TIMS conference with Dr. Fishman, where I received several job offers even though I was not seeking a job at the time, no doubt simply because I was Dr. Fishman's student.
>
> Dr. Fishman was a very gracious man and became a good family friend. I wish nothing but the best for George in his well-deserved retirement.

Stephen Yarberry offers a similarly memorable view of what it means to be one of George's former students.

> While George pushed his students to excel, he never had higher expectations of us than he had for himself. He was so much more than just an advisor and a mentor—he was, and still is, my friend. I count it a honor and a privilege to have received tutelage from a man whom many refer to as the father of our field.

4 Recapitulation

George Fishman is remarkable not only for his exceptional level of scholarly productivity sustained over five decades but also for this long-standing dedication to the advancement of the professions of simulation, operations research, and the management sciences. David Rubin gives the following assessment of George's contributions from the perspective of a faculty colleague and frequent collaborator.

> While shepherding the curriculum/department, George maintained his very active scholarly career. I need not recount here the list of monographs, texts and journal articles he wrote, nor the roster of Ph.D. theses and MS expository papers he directed over the past 40+ years. He recently commented to me about how much he enjoyed doing joint research with colleagues who had skills complementary to his own. I was a beneficiary of that outlook. It was my great pleasure to be a coauthor with him on four of those journal articles. George's work in simulation led him to questions about the size of samples needed to guarantee specified precision in estimating quantities whose exact distributions were unknown. He recognized that there were optimization problems at the base of these questions, I knew something about structured optimization problems, and a fruitful collaboration ensued.
>
> For almost 35 years I have been fortunate to count George among my colleagues, mentors, and special friends. On the occasion of this Festschrift, I wish him many more happy and productive years.

Andy Seila (University of Georgia) gives what is perhaps the best high-level summary of George's professional achievements over the past five decades.

> In order to understand George's contributions to the field of simulation, you have to go back to the early 1970s and examine the status of computing in general and simulation in particular. At that time, two processes were developing that would have a profound influence on the development of simulation as a tool for systems analysis: computers were becoming powerful enough—both in raw size and speed, and in the availability of compilers and other tools—to move simulation from a niche tool to one that would be available to engineers, statisticians and scientists with a modest amount of training. Discrete event simulation modeling tools such as SIMULA, SIMSCRIPT II.5, GPSS, and GASP were widely available and relatively easy to use. At the time, the focus was on modeling methodology, and analysis of output data (as well as input data) was an ad-hoc process. George had the insight to see that, in order for simulation to become a tool that managers would use with confidence, reliable statistical methodology had to be developed. This is the area in which George made his initial contribution and continues to contribute. Thanks to his work and that of others who were influenced by him, we now have a foundation of statistical methodology for the analysis of simulation output data that enables practitioners to compute estimates of performance measures and, more importantly, to assess the usefulness of the estimates. The combination of modeling methodology and data analysis methodology, contributed by George, has provided the fuel to power the explosion in simulation applications we have seen in the past three decades.

On a more personal level, we (the authors of this paper) can trace virtually every line of research we have pursued individually or collectively over the past three decades back to George's seminal papers and books on computer simulation that are surveyed in this article. More important, however, is that many others in the international simulation community spanning several generations of academics, practitioners, and researchers acknowledge a similar debt to the intellectual heritage they received from George Fishman.

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