Reprinted from

The Craft of Probabilistic Modelling
A Collection of Personal Accounts

Edited by J. Gani

Applied Probability Series
J. Gani and C.C. Heyde, Editors

Springer-Verlag
New York Berlin Heidelberg
London Paris Tokyo

Probability Modelling Across the Continents

1. Academic Background

I was born at Calicut, Kerala State, India and attended high school and (two-year) intermediate college there. I wanted to study mathematics, but in those days there was supposed to be no future for arts and science graduates, so I applied for admission to an engineering college. As it turned out, I failed to get this admission, and so I joined the Loyola College of Arts and Science, Madras, where I studied for a bachelor's degree (with honours) in mathematics.

The programme at this college consisted of courses in pure mathematics (analysis, algebra and geometry) and applied mathematics (statics, dynamics and astronomy); in addition I took two optional papers—potential theory and complex analysis. A strong feature of the programme was the interconnection between various branches of mathematics that the instructors stressed constantly. A typical example was the manner in which the proof of the following statement in astronomy:

"The equation of time vanishes four times a year"

was reduced analytically to that of the statement in geometry:

"From a point within the ellipse, four normals can be drawn to it."

The professor of mathematics at the college was Fr C. Racine, a young energetic Jesuit priest who had recently arrived from France with new (for the 1940s) mathematics. He taught analysis out of the book by De la Vallée Poussin. This course and the one on complex variables (based on the book by Goursat) were an important part of my training in mathematics.

Mathematics in India at that time (but probably much less now) was influenced by British mathematics, and consisted mainly of classical pure and applied mathematics with emphasis on problem solving. However, the training in mathematics that I received taught me to appreciate fully its conceptual foundations and to use its techniques skillfully and wisely. In addition I developed a perspective on the discipline of mathematics that has moulded my attitude towards the craft of probability modelling.

After receiving my BA (Hons.) degree in 1946 I taught mathematics for two years at colleges affiliated with the University of Bombay. I found teaching interesting enough, but the position itself did not hold many prospects. Therefore when in August 1948 the University of Bombay opened its post-graduate department of statistics, I gave up my position and enrolled in that programme. The curriculum included courses in topics such as statistical inference, multivariate analysis, experimental designs and sample surveys, but was rather weak in probability theory. Some training in the handling of statistical data was also a part of the programme. I was truly impressed with the vastness of the conceptual framework of mathematical statistics, but probability theory was going to be my chosen field of interest.

I received the MA degree in 1950 and worked as lecturer in mathematics and statistics at Gauhati University, Assam State, for two years and then as reader in statistics and head of the Department of Statistics at Karnatak University, Karnataka State.

2. Visits to England and Australia

During my tenure at Karnatak (1955) I was awarded a British Council scholarship for higher studies and went to work with Maurice Bartlett at the University of Manchester, England. It turned out that my choice of university was perhaps not ideal, as Bartlett's probability proved to be too heuristic for my taste. However, that year Joe Gani came to Manchester as a Nuffield Fellow from Australia and I started to do research on the probability theory of dams under his direction. During the limited duration of my scholarship I was able to fulfill the requirements of the M.Sc. degree at Manchester.

The statistics courses taught at Manchester did not contain any material that was new to me, but I did take a couple of mathematics courses, one of which was on functional analysis and Markov processes taught by Harry Reuter. I enjoyed this course immensely and it influenced my later work on Wiener–Hopf factorization. Also I became acquainted with David Kendall who expressed interest in my work on the theory of dams.

My own academic temperament had much in common with Joe Gani's, and our early student–advisor relationship rapidly developed into successful research collaboration (at the University of Western Australia which I visited during the 1957 academic year) and also led to a close personal friendship.

I returned to my position at Karnatak University in 1958. The Department of Statistics that I had started in 1952 continued to expand, and a modest attempt was made to start a Ph.D. programme. My research continued on an active basis. However, circumstances forced me to leave my position in 1961 and accept the position of reader in mathematical statistics at the University of Western Australia.

In 1961 there was still only moderate activity in the area of probability in Australia; however, since then a group of very fine probabilists and statisticians has emerged. The group in Western Australia, started earlier by Joe Gani, was very active in terms of research publications and graduate students. This activity continued under my tenure as reader. I completed work on two books—on queueing theory [21] and stochastic processes [22]. Also I became acquainted with Pat Moran, who pioneered the probability theory of dams. The academic climate in Australia was indeed to my liking, but unfortunately the political climate of those times was not favourable to my continued stay in that country.

3. Migration to the USA; Some Reflections on my Career

I came to the USA in 1964 as a visiting associate professor of statistics at Michigan State University. This was my first experience of American academe, and it was not an entirely happy one. Since 1965 I have been at Cornell University—as associate professor in 1965–7 and as professor since 1967. In 1972 my wife, our two daughters and I became naturalized U.S. citizens, and it looks as though my wanderings have come to an end.

The applied probability group at Cornell is a part of the School of Operations Research and Industrial Engineering, which is a unit of the College of Engineering. I have tried to develop this subject area according to my philosophical inclinations. My experience is that the environment provided by the engineering college is not entirely conducive to the growth of applied probability to its full stature. I am completing my twentieth year at Cornell, and this is perhaps an opportune time to reflect a little over some aspects of my career.

The scientific community is a truly international one, sharing its concerns over matters of mutual interest and participating in cooperative ventures such as conferences and journals. Membership of this vast international community is one of the privileges of our profession. This is an aspect that I have enjoyed most in my career; it has been my objective to play my part in international activities in the domain of probability.

Teaching and research are important parts of an academic career. I like teaching, but derive less satisfaction from it here in the USA, than I have in Australia and India. I have had excellent rapport with my research students, many of whom have become my close friends and associates. My own research has been in the area of what I have designated as stochastic storage processes [23]. This area was in its developing stage when I started my research career, and my contributions to it have brought me immense enjoyment.

In this section I describe my views on various aspects of the craft of probability modelling in general, and the modelling of queues and storage systems in particular. My views have evolved through various stages, being influenced by my experiences in India, England, Australia, and the USA, and are therefore somewhat personal. In particular, I have found that in most parts of the world academics consider themselves to be members of an élite class, enjoying social if not financial privileges. I am ill-at-ease with this notion, and would not claim for myself any special status. In a society where jealousy is almost institutionalized I consider myself an uncompetitive person.

4. Mathematical Models

Let me begin with some comments on mathematical modelling. The term "mathematical model" is used to describe a quantitative approach to various phenomena. Such models abound in classical physics and applied mathematics (in the British sense of the term). They are all deterministic; the physicists were apparently slow in recognizing the role of chance in model-building. The paper by Kac [9] contains interesting references to some of the controversies that raged between the classical and modern physicists. Neyman [18] in his address over 25 years ago to the American Statistical Association drew statisticians' attention to the role of indeterminism in science and the consequent demands on them. To make the perspective somewhat broader, one might perhaps also emphasize the concept of stochastic control in this connection.

Probability models may be characterized as mathematical models that involve a random element. An older term is *statistical*, used in connection with statistical physics and related areas. At the early stages of development of mathematical statistics considerable attention was paid to fitting curves to observed data. (Kendall's book [14]) contains several examples of this.) Even that may be viewed as probability modelling, but the curve-fitting was carried out rather uncritically, with no attempt to explain the possible *a priori* reasons why a certain curve and not some other might have been fitted to the data. Probability modelling in the current sense of the term emerged during what Neyman [18] calls the era of *dynamic indeterminism*, starting with Mendelism, statistical mechanics, epidemiology and other areas, and now extending to all branches of the natural, physical and social sciences.

5. The Scope of Applied Probability

The subject areas that probabilists seek to model are diverse, and each has its own technical background. Applied probabilists, on the other hand, are usually trained in mathematics, probability and in some cases, statistics. Their intended audience consists of theoretical experts in their various areas, or practitioners (the consumers of applied probability). This is very different from the classical situation when the boundaries across disciplines such as mathematics and physics were not rigidly drawn. Probability modelling consists of the following important steps:

(i) Describe the phenomenon under investigation in fairly non-mathematical terms.

(ii) Set up reasonable hypotheses (assumptions) to translate the above description into mathematical (probabilistic) terms. This constitutes the probability model.

(iii) Ask appropriate questions concerning the phenomenon, and formulate these questions in terms of the stochastic process that arises from the model.

(iv) Test the appropriateness of the assumptions made in (ii). This involves the testing of the model.

(v) Communicate the results of the investigation to the scientist or the practitioner who first proposed the problem, and to the wider audience of all applied probabilists.

The ideal environment for applied probabilists' work is provided by organizations such as the scientific and industrial research organizations of Australia, India and the United Kingdom, and Bell Laboratories and IBM in the USA. The environment provided by a university for collaborative research between probabilists and biologists (for example) has its limitations. In any case, whether or not an applied probabilist is able to perform his chosen task successfully in terms of the steps (i)–(v) described above will depend entirely on his environment.

First and foremost an applied probabilist has to understand the subject matter of his study thoroughly and grasp its technical nature, with a view to explaining the problem to a wide audience. Unfortunately the very important step (i) above is neglected by several authors, who begin their analysis of the model with a rather uncritical mathematical description of the situation and thereby raise questions concerning the genuineness of the model itself. In all branches of applied mathematics the practitioner is usually prepared to allow the mathematician considerable latitude in introducing sophistication in his modelling effort for the sake of mathematical maneuvrability, but it is essential that the real-life features of the situation should be carefully described in step (i) before introducing the necessary sophistication in step (ii).

A probability model gives rise to a stochastic process and the analysis of the model reduces to solution of problems within the theoretical framework of this process. Thus in his pioneering papers on queueing theory, Kendall [12, 13] uses discrete-time Markov chains, while in his recent book on the subject Brémaud [3] uses martingale dynamics. It very frequently happens that in order to carry out step (iii) described above, namely to answer questions concerning the phenomenon under investigation, the applied probabilist expands his theoretical framework considerably, and discovers new properties of known processes or even finds a new class of stochastic processes. Thus the work of Lindley [15] and Smith [31] on queueing theory opened up new vistas on random walks (fluctuation theory, Wiener–Hopf factorization, etc.).

Incorporating a large number of real-life factors into a model usually makes it complex to the extent that the existing theory of stochastic processes becomes inapplicable. In such situations computer simulations of the model might be the only recourse and might lead to broad tentative conclusions.

The questions asked of the model are in the first instance solved by calculating the system characteristics, and at an advanced level involve statistical inference, design, and control. The analytical techniques used by applied probabilists are drawn from several branches of mathematics such as real and complex analysis, linear algebra, functional analysis and even mathematical programming and game theory. Thus Rouché's theorem has many uses in applied probability, and properties of linear operators in Banach spaces are also needed. For problems that defy analytical treatment, computers are being used fairly extensively. Exactly which of these techniques should be used depends on the problem in hand, and to indulge in a concerted effort to discredit any one set of techniques amounts to an anti-intellectual activity.

Except perhaps in a few classes of probability models, real-life data are hard to obtain, and testing of models as suggested in step (iv) above is not always possible. The theory of statistical inference for stochastic processes has made great advances in recent years (see Basawa and Prakasa Rao [1]), and should prove useful to applied probabilists.

6. Communication Problems in Applied Probability

Initially, applied probabilists published the results of their research in mathematics and statistics journals; this was very natural, as their academic background was in these subject areas. It is doubtful whether the readership of these journals was the authors' intended audience, and in any case the journals became increasingly reluctant to publish papers on applied probability. The founding of the *Journal of Applied Probability* in 1964 and *Advances in Applied Probability* in 1969 by Joe Gani was a most timely and welcome development, and these two journals have since provided a major venue for the publication of applied probability research.

In the USA the main concerns of applied probabilists were the directions in which the field of applied probability was developing, and the status of applied probabilists in the general scientific community. Efforts to address these problems led to the starting of a series of conferences on stochastic processes and their applications (SPA) in 1971, and to a journal of the same title in 1973. The committee that was set up to plan the conferences was affiliated in 1975 with the International Statistical Institute's Bernoulli Society for Mathematical Statistics and Probability as a subject area committee. The journal *Stochastic Processes and Their Applications*, published by the North-Holland Publishing Company, became an official publication of the Bernoulli Society in 1980. In [25] and [26] I have recorded brief histories of these developments, with which it was my privilege to be associated from the very beginning.

7. The Status of Applied Probabilists

Some applied probabilists seem to feel that they do not always get the recognition they deserve for their work. It is tempting to blame this on the continuing reluctance of classical scientists to recognize the role of chance in physical and natural phenomena. However, there are other, more valid reasons. It is possible that an applied probabilist is viewed as a technician, a problem-solver, rather than as a scientist in his own right. This is clearly a mistaken view. It is true that a considerable part of an applied probabilist's work consists of problem-solving, and I believe this amounts to a significant contribution, of importance to all parties involved. However, applied probabilists are also basically probabilists; they are inclined to ask whether the results obtained in specific models have implications concerning a larger class of stochastic processes, and very often find that they do. Thus they are able to make significant contributions to the theory of stochastic processes, which entitle them to the status of scientists in their own right.

Are applied probabilists trying to "reach the moon without learning Newton's laws of gravitation"? The early applied probabilists emerged from among mathematicians and statisticians with a good background in pure and applied mathematics and mathematical statistics. It was appropriate at that time to designate them as probabilists. In recent times most applied probabilists have been graduates of departments of operations research or of mathematical sciences. Their training includes mathematical programming, game theory and combinatorics (which perhaps constitute modern applied mathematics), besides probability and statistics. This training is broader in the sense that it is appropriate to the needs of current times, but it may perhaps lack depth in mathematics, probability and statistics. Is a person with this background an applied probabilist *per se*, or rather an applied mathematician specializing in probability models?

In the 1950s and early 1960s when applied probability was emerging, it was subject to the criticism of pure mathematicians and mathematical statisticians, who did not fully appreciate the significance of the new discipline. Against this criticism the small community of applied probabilists built a common defence, and the applied probability journals which started their publication at this time provided them with a strong sense of identity. This professional camaraderie was, however, shortlived. As the community grew larger the differences in the academic backgrounds of its members (as explained above) became more evident, and resulted in disparities in their approach to the craft of probability modelling. Trends and fashions emerged, as is so common in other branches of science—the very same factors that applied probabilists had earlier felt they were victims of. Thus events have completed a full cycle.

In the USA financial support from the national research agencies for research projects on applied probability has not been forthcoming to the extent that this area deserves. One cannot blame the agencies for this deficiency, because they do not have an accurate perception of the role of applied probability in the general domain of scientific endeavour, and it would be futile to look to them for any leadership in this matter. In my opinion the factors responsible for this lack of support are the continuing reluctance of mathematicians and statisticians to give applied probability its due place, and the prevailing attitudes of applied probabilists themselves in making some areas of research less fashionable than others. This competition for financial support is of course an essential feature of American scientific effort; one might take some comfort from the fact that the quality of the research accomplished is not always positively correlated with the extent of support received from the research agencies.

The social unrest of the late 1960s and the 1970s in the USA and the resulting challenge to mathematicians (and other scientists) made considerable impact on their subject areas, specifically prompting a heightened awareness of real-life problems. Thus mathematicians have become increasingly interested in problems of biology, operations research, economics and other subject areas. The availability of high-speed computers has made problem-solving a less tedious and perhaps even an interesting exercise. In the broad spectrum of applied science, applied probability has a well-deserved place; perhaps it is not as large as applied probabilists in their pioneering enthusiasm once claimed for it, but it is undoubtedly a significant place.

8. Probability Modelling of Queueing and Storage Systems

In his pioneering survey paper, Kendall [12] stated that the theory of queues has a special appeal for the mathematician interested in stochastic processes. The truth of Kendall's statement has been borne out by the developments of the last 34 years, and queueing theory continues to fascinate mathematicians at least as a source of convenient examples for various concepts of stochastic processes. It provides motivation to applied probabilists to seek new directions for their research, and poses problems of inference and control to operations researchers. Indeed the richness of structure of queueing systems is shared by only a few other areas of applied probability.

The stochastic processes arising from simple queueing models (those with Poisson arrivals and service times having exponential density) turn out to be birth-and-death processes, and the standard properties of these processes are used to answer questions concerning these systems. In somewhat more advanced models (such as those with group arrivals or bulk service), the processes are still Markovian, but not of the birth-and-death type. Their analysis is still standard, attention being concentrated on the limit behaviour of the processes. When non-Markovian processes were encountered, dire warnings were at first issued as to the complications that occur in their analysis, and later, two remedies for the situation were offered. One remedy is A. K. Erlang's method of phases for the system $M/E_k/1$, where one is asked to investigate $Q_1(t)$, the number of service phases present in the system, there being k for each arrival; it turns out that the process $\{Q_1(t)\}$ is Markovian, while the queue-length process $\{Q(t)\}$ is not. However, Erlang's method results in loss of information on $Q(t)$, and it is in fact quite unnecessary to use it. The appropriate procedure for the $M/E_k/1$ system is to consider $\{Q(t), R(t)\}$, where $R(t)$ is 0 if the system is empty, and the residual number of phases of the customer being served otherwise. This two-dimensional process is Markovian, and its analysis is no more difficult than that of $Q_1(t)$. A second remedy for the non-Markovian situation is the technique of imbedding proposed by Kendall [12, 13]. Here, instead of the given continuous-time process one investigates a suitable Markov chain imbedded in it. I used to think that the concept of imbedding had retarded the progress of queueing theory by at least 10 years, because attention was diverted from continuous-time non-Markovian processes (such as point processes and martingales). However, my more recent experience has convinced me that imbedded chains are perhaps the natural processes to observe in control procedures, where controls are usually (but not always) imposed at certain special points of time, such as arrival or departure epochs. The end of this Markovian era is marked by the appearance of the important paper by Takács [35] on the virtual waiting time in the system $M/G/1$.

More general queueing systems in which the independence assumptions on interarrival times and service times are suitably weakened give rise to Markov renewal processes. However, no significant results seem to emerge from this class of models, qualitatively different from those of the standard models.

Early investigations of the general single-server queueing systems were concerned with the waiting time of an arriving customer (as opposed to virtual waiting time). In the pioneering paper of Lindley [15] the basic process is again a (discrete-time) Markov chain, and its limit distribution is of main interest. Here Wiener–Hopf techniques were used by Smith [31] in a non-probabilistic context, and later by Spitzer [32], [33] in a probabilistic context. This led to the surprising discovery of the close connections between queueing problems and random walks. In particular, it turned out that the problems concerning the waiting time and accumulated idle time reduce to those concerning the maximum and minimum functionals of the associated random walk. Combinatorial techniques used in random walks became a standard tool of queueing theory, and were used by Bhat [2] to investigate bulk queueing systems.

The continuous-time analogue of the random walk is of course a process with stationary independent increments (Lévy process). However, the fact that Lévy processes are basic to queueing models was not easily recognized. The compound Poisson process lurking behind the virtual waiting-time process $\{W(t); t \geq 0\}$ of the $M/G/1$ system was used by Reich [28], [29] to formulate his integral equation for $W(t)$, and I obtained the distribution of the busy period of that system by recognizing it as a first-passage time for this compound Poisson process [19]. The theory of dams, which reached a vigorous state of development about this time, gave considerable impetus to the study of continuous-time stochastic processes arising in queues. In particular it led to appropriate formulations of single-server queueing models with static and dynamic priorities (Hooke and Prabhu [8], Goldberg [7]) and also to a new approach to the insurance risk problem (Prabhu [20]). Unification of the theories of queues, dams and insurance risk was also achieved, and it became evident that it would be appropriate to include all of these models under the broad title of stochastic storage models, characterized by inputs constituting Lévy processes. In [24] I presented a comprehensive treatment of these models.

The probability theory of dams had a modest beginning, with Moran's [17] discrete-time, finite-capacity model with additive inputs. Models with correlated inputs were proposed by Lloyd [16]. Continuous-time models with inputs forming a Lévy process were first investigated by Gani and myself [6]. This area of probability models developed very rapidly. In particular a study of continuous-time storage models with Markovian inputs was undertaken by Çinlar [4]. Insurance risk models with claims occurring in a Markov renewal process have recently received considerable attention from European actuaries.

My research on queueing problems within the framework of random walks and on continuous-time dam models motivated my interest in the fluctuation-theoretic aspects of Lévy processes. This led to the theory of ladder phenomena (Rubinovitch [30]) and Wiener–Hopf factorization for Lévy processes (Prabhu [23]), for Markov additive processes (Kaspi [10]) and for Markov processes (Prabhu [27]). This was a most rewarding experience, and it confirmed my belief that applied probability research can indeed lead to significant contributions to the theory of stochastic processes.

In other work on continuous-time storage models the net input process is assumed to be a Brownian motion. Now since the net input equals gross input minus amount demanded, both quantities being nonnegative, it is clear that the net input process is necessarily of bounded variation with probability 1, and so it cannot be Brownian. I therefore question the validity of such models. In the Brownian setting, control problems in storage reduce to familiar problems in stochastic control theory and other problems reduce to those involving entrance or exit times for the Brownian motion (in one or more dimensions) into or from certain regions. These problems are difficult, and presumably they are interesting and even important. However, it would be more honest to formulate them directly as problems on Brownian motion, rather than as problems arising from genuine storage models.

Research on queueing networks started along conventional lines, using the standard theory of Markov processes, most of the work being motivated by computer applications. This subject area has become increasingly important, and more advanced concepts and techniques such as time-reversibility and properties of Poisson flows have been used (see, for example, Kelly [11]). The other newly emerged areas of research use the theory of point processes and martingales (Brémaud [3], Franken et al. [5]) and concepts of stochastic ordering (Stoyan [34]).

A due concern with the practical applications of queueing and storage models has forced applied probabilists to come to grips with the complexities of the stochastic processes arising from the models, and their labours have been amply rewarded. These models have indeed made significant contributions to the general theory of stochastic processes in terms of concepts and techniques; I am happy to have been among the contributors.

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N. U. Prabhu

Professor Prabhu was born in Calicut, India on 25 April 1924 and received his university education at Loyola College, Madras, where he studied mathematics. After teaching for two years in the University of Bombay, he enrolled in its statistics programme and obtained his MA there in 1950. He began lecturing at Gauhati University, Assam, and soon moved to the Department of Statistics at Karnatak University in 1952 as reader and head of department, a position he held for nine years.

In 1955, he visited the University of Manchester, England, as a British Council scholar, and was awarded an M.Sc. in 1957 for his research on dam theory. In 1961 he was appointed to a readership in mathematical statistics at the University of Western Australia, where he completed the writing of his two books.

He emigrated to the USA in 1964, and after a year at Michigan State University, he moved to Cornell University, where he has been a professor of operations research since 1967. He has been closely involved in the development of stochastic processes, as editor of *Advances in Applied Probability* (1973–82) and as principal editor (1973–9) and editor (1980–4) of *Stochastic Processes and Their Applications*. He has written over 40 research papers and four books.

Professor Prabhu has received recognition for his many contributions to the field of applied probability. He is a fellow of the Institute of Mathematical Statistics and an elected member of the International Statistical Institute. He also served as chairman of the Committee for Conferences on Stochastic Processes between 1975 and 1979.

He married his wife Sumi in 1951 and has two daughters, Vasundhara and Purnima. He is interested in literature (including detective fiction), cinema, music and travel.