Perwez Shahabuddin, 1962–2005: A Professional Appreciation

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Perwez Shahabuddin was an accomplished researcher, teacher, and participant in the simulation community. This article provides an overview of his career and a summary of some of his many professional accomplishments.

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Perwez Shahabuddin died tragically on November 17, 2005. He was an accomplished researcher and teacher who was respected and liked by all around him. He leaves behind his wife Soophia and children Zoha and Zain, and will be greatly missed by his family, friends, students, and colleagues. This issue of *ACM Transactions on Modeling and Computer Simulation* is dedicated to his memory.

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In the sections that follow, we describe some of Perwez's accomplishments, with emphasis on his substantial contributions to the simulation literature. We comment on the period when he was a Ph.D. student at Stanford University (1985–1990), when he has a researcher at IBM (1990–1995), and when he was a faculty member in the Department of Industrial Engineering and Operations Research at Columbia University (1995–2005). We also summarize his research accomplishments in the areas of highly reliable systems and importance sampling (conducted while he was at Stanford and IBM), splitting, heavy-tailed importance sampling, and finance. These topics represent the central focus of Perwez's research: developing and analyzing efficient algorithms for rare event simulation.

1. THE STANFORD YEARS

Perwez graduated from the Indian Institute of Technology Delhi with a degree in mechanical engineering in 1984. An important early influence on Perwez was Professor Kiran Seth, with whom Perwez published two articles, Seth and Shahabuddin [1989; 1990].

Perwez joined Stanford's Department of Operations Research as a Ph.D. student in 1985, and is fondly remembered by faculty there both as an exceptional student and for the enthusiasm and energy that he brought into the classroom and his interactions with both his fellow students and the faculty. Following his second year of study, he went to IBM Research as a summer intern and spent time working on a system availability software package that was under development at that time (under the leadership of IBM researchers Ambuj Goyal, Steve Lavenberg, and Philip Heidelberger). As a result of his coursework and this summer research opportunity, he decided to focus his dissertation research on stochastic modeling issues and became one of Professor Peter W. Glynn's first Ph.D. students at Stanford.

The System Availability Estimation (SAVE) package under development at IBM at that time was intended as a design tool for the analysis of fault-tolerant computing systems. When Perwez arrived at IBM, SAVE had numerical solution algorithms and only rudimentary simulation capability. One of the numerical difficulties inherent in the models that arise in this area is that they result in stochastic models with an enormous number of states, even in the presence of simplifying exponential distribution assumptions. This has to do with the fact that in a system with r components, the system state must minimally keep track of whether each of the r components is currently "up" or "down," leading to a state descriptor that takes on at least 2^r different values. Given that IBM's goal was to produce a design package capable of dealing with Markovian systems having 40 or 50 components, this produced a family of models with very large state spaces, and made simulation a particularly attractive solution tool. The fault tolerance was typically achieved either by using highly reliable individual components or by adding component redundancy using either "hot" or "cold" stand-by modes. This led to system designs that failed rarely, and created difficulties when applying conventional simulation to such problems. Perwez began looking at how to incorporate effective simulation algorithms into SAVE.

A natural approach to rare event simulation is to apply importance sampling, which biases the simulation towards the rare event and unbiases the estimate by multiplying the result by a likelihood ratio. In Glynn et al. [1992] a unified framework was developed for estimating a wide variety of reliabilty and availability metrics using importance sampling. As to the crucial choice of which importance sampling approach to apply, a prior paper by Lewis and Bohm [1984] had used an importance sampling technique called failure biasing that appeared promising in the SAVE rare event context. Perwez began experimenting with this technique and found that sometimes it worked well, but often it did not. At the end of his second summer at IBM in 1988, he gave a beautiful presentation in which he showed, using a very simple example and writing out the likelihood ratios for some sample paths, exactly why failure biasing sometimes worked poorly. He proposed a different importance sampling algorithm and showed that it did not suffer from this defect on this example.

IBM went on to provide financial support for Perwez's dissertation work at Stanford. His Ph.D. research developed a theoretical framework that helped explain the empirical results on importance sampling that were accumulating over the many test problems generated at IBM and to suggest new and more robust algorithms. A key idea was to develop the theory on the basis of an asymptotic framework in which the component failure rates were sent to zero in the limit (thereby corresponding to real-world models in which the components were highly reliable). Perwez used this framework to develop an importance sampling algorithm called "balanced failure biasing." He proved, in the context of highly reliable Markovian systems, that balanced failure biasing algorithms enjoy a particularly strong form of asymptotic optimality, that he termed *bounded relative error*. Unlike conventional simulation, in which the number of replications required to achieve a certain level of accuracy increases as the component reliability gets higher (and the system failure event becomes rarer), an estimator with the bounded relative error property requires only a fixed number of replications, no matter how reliable the individual components.

This elegant result, which formed the basis of his 1990 Ph.D. thesis, *Simulation and Analysis of Highly Reliable Systems*, was the first provably successful application of importance sampling to a broad class of models in the operations research literature. This was a landmark result that became the "gold standard" in rare event simulation, and stimulated much additional research by Perwez, his colleagues, and other researchers. A paper based on his thesis [Shahabuddin 1994b] won the 1990 Nicholson Prize (awarded by the Institute for Operations Research and the Management Sciences (INFORMS) for the best student paper) and also the 1996 Outstanding Simulation Publication Award given by the INFORMS College on Simulation.

It will come as no surprise that Perwez's strong scientific talents were apparent to both the faculty and his fellow students during his student days at Stanford. However, this period was also one of significant personal growth. He explored his Indian heritage through yoga and music, even learning to play the sitar. He was also eager to learn about Western culture and civilization, and could happily discuss a wide range of cultural and political ideas. He made many friends who remember him for his broad interests, helpfulness, sense of humor, and, most of all, for his big smile.

2. THE IBM YEARS

Perwez joined IBM Research in 1990, after completing his Ph.D. His research at IBM was mostly focused on developing effective rare event simulation techniques for ever broader classes of stochastic models. We highlight several results in this area. For highly available systems, his thesis was extended in two major ways. First, the assumption of exponentially distributed failure and repair times was relaxed to distributions with bounded hazard rates in Heidelberger et al. [1994] for estimating transient reliability measures. Second, Perwez observed that balanced failure biasing may not work for highly reliable Markovian systems when practically important general repair policies such as group and simultaneous repair were allowed. Perwez, along with Sandeep Juneja in Juneja and Shahabuddin [1992], then developed and analyzed some importance sampling algorithms for a broader class of Markovian models that could efficiently simulate models with general repair policies. A more elaborate version appeared in Juneja and Shahabuddin [2001b]. Nakayama and Shahabuddin [1998] established conditions under which likelihood ratio–based derivative estimates are valid for transient performance measures in generalized semi-Markov processes.

In work on queueing networks, Chang et al. [1994] investigated the relationship between "effective bandwidths" and rare event simulation for estimating tail probabilites in queues arising in telecommunications networks. Asymptotically optimal estimators were derived for a broad class of single node queues fed by multiple, light-tailed sources; and bounds on efficiency were derived for such nodes in tree-structured networks.

At IBM Perwez took over the development of the SAVE package and implemented balanced failure biasing. He consulted on the use of SAVE in modeling workstation (RS/6000) availability. He also worked on performance analysis and algorithms in several systems related areas including multimedia servers [Dan et al. 1995] and FDDI networks [Willebeek-LeMair and Shahabuddin 1997]. Perwez had two patents issued in computer sytems and another in financial modeling [Shahabuddin and Sitaram 1995; Dan et al. 1998; Glasserman et al. 2002].

3. THE COLUMBIA YEARS

Perwez moved to the Department of Industrial Engineering and Operations Research at Columbia in 1995. Although he was generally happy with the work environment at IBM Research, he was eager to have greater freedom to pursue his research interests, and a move to an academic position would allow that. Columbia's IEOR Department had substantial teaching needs in simulation and, as a research topic, simulation had very little representation in the department. Perwez was highly recommended by others in the field, and he had already established a promising research record. But he had no teaching experience, and his speech impediment raised the question—for Perwez as well as the department—of whether he would be happy and successful in teaching. The IEOR Department invited Perwez to teach a course as an adjunct professor while he continued to work at IBM. The experience was a success and was followed by Perwez's move to Columbia as a full-time assistant professor in 1995.

Columbia was quickly rewarded for adding Perwez to its faculty. In 1996, Perwez received the Outstanding Simulation Publication Award mentioned above, and he received the National Science Foundation's prestigious CAREER Award for early career development. While at Columbia, Perwez continued to collaborate with researchers at IBM on both simulation and on systems issues, e.g., aspects of systems management in Web servers [Hellerstein et al. 2001]. To support his work, IBM granted him a Faculty Development Award in 1998; and Perwez spent a sabbatical at IBM's India Research Lab during the academic year 2001–2002.

Perwez also proved to be an excellent teacher. He taught both graduate and undergraduate courses in discrete-event simulation, often teaching very large sections. His exceptional dedication to his students was recognized with the 1997 Distinguished Faculty Teaching Award given by Columbia's Engineering School Alumni Association for excellence in teaching undergraduates. In 2004, he received the Great Teacher Award from the Society of Columbia Graduates.

Perwez's career blossomed at Columbia along all dimensions. As a productive scholar and award-winning teacher, he was promoted to associate professor in 1998, granted tenure in 2000, and promoted to full professor in 2003. He was active professionally, serving on the editorial boards of *IEEE Transactions on Reliability*, *IIE Transactions on Operations Engineering*, *Management Science*, and *Stochastic Models*. He was a regular contributor to the Winter Simulation Conference, and frequently served the simulation community and the applied probability community in numerous professional capacities.

Among Perwez's lasting contributions to Columbia's IEOR Department is his work for the department's doctoral program. He led the department's efforts to attract the best doctoral students and to design an outstanding program of study. Perwez served as the primary thesis advisor for several doctoral students, but he was also an informal mentor and guide to many other students. Perwez was known in the department for his ready willingness to provide extra help and guidance to all students.

4. RARE EVENT SIMULATION VIA MULTILEVEL SPLITTING

In 1995, just as Perwez was moving from IBM to Columbia, Perwez, Paul Glasserman, and Phil Heidelberger received a grant with joint funding from the NSF and IBM to study rare event simulation problems in queueing systems. This grant enabled the hiring of a postdoctoral fellow, Tim Zajic. At the time, an alternative approach to importance sampling that appeared attractive was a form of multilevel splitting, which had received renewed interest under the name "RESTART" given by Villen-Altamirano and Villen-Altamirano [1991]. In this method, additional sample paths are spawned (split) each time the simulation enters a subset along the way to the rare event of interest. The method can be applied recursively to nested subsets, thereby obtaining a multilevel splitting algorithm. The method is attractive because, at first glance, one need only define subsets that a sample path must pass through on the way to the rare event, rather than devising an efficient importance sampling change of measure. Intuitively, it seems easier to pick good subsets than changes of measure.

In Glasserman, Heidelberger, Shahabuddin, and Zajic (GHSZ) [1999], a formal work-variance efficiency measure for splitting was defined and analyzed using branching theory techniques. In this paper, two-dimensional Markovian models were analyzed in which the first dimension is infinite, representing, e.g., the queue length, and the second dimension is finite, representing, e.g., a Markovian dependency in the number of arrivals per time slot. The rare event of interest is a large queue length. This paper established asymptotic properties as a function of the number of split paths generated at each level. A simple expression for the optimal split factor was derived and asymptotic optimality of the resulting procedure was shown.

In GHSZ [1998], more general state spaces were considered and the relationship between large deviation paths and the subsets was studied. Under appropriate technical conditions, this paper showed that a necessary condition for splitting to be asymptotically optimal is that the subsets must be consistent with the large deviation paths to both the subset and the final rare event. Roughly speaking, the method cannot be optimal unless the large deviations path to the subset coincides with the large deviations path to the rare event. This suggests that for the method to be effective in practice, a rather deep knowledge of the process is required in both splitting and importance sampling.

5. RARE EVENT SIMULATION WITH HEAVY-TAILED RANDOM VARIABLES

In the summer of 1997, Perwez initiated work on rare events associated with heavy-tailed random variables along with Sandeep Juneja, who was visiting him at Columbia. While the literature on rare event simulation involving light-tailed random variables was relatively well developed at that time, that on heavy-tailed random variables was at a nascent stage. (Roughly speaking, the tail probability of light-tailed random variables decays at an exponential or faster rate, while for heavy-tailed random variables it decays at a subexponential rate; for instance, at a polynomial rate.) Asmussen and Binswanger [1997] was the only work in the literature that addressed the issue of fast simulation involving heavy-tailed random variables. Asmussen and Binswanger [1997] considered the problem of efficient estimation of a level crossing probability for a random walk in which each increment has a negative mean and a heavy positive tail. Direct efficient estimation for such a probability turns out to be a difficult problem. Asmussen and Binswanger [1997] instead worked with a ladder height representation of this probability, effectively reducing it to estimating the probability that a sum of a geometrically distributed number of independent heavy-tailed random variables takes unusually large values.

Importance sampling techniques involving exponential twisting of underlying distributions have found wide success in rare event simulation involving sums of light-tailed random variables. These however are not applicable for heavy-tailed random variables, as they fundamentally require that the random variables be light-tailed. Perwez, Sandeep, and A. Chandra (Juneja et al. [1999], also Juneja and Shahabuddin [2002]) introduced *hazard rate twisting* and its variant *delayed* hazard rate twisting for asymptotically optimal simulation-based estimation of the probabilities considered by Asmussen and Binswanger [1997] for a wide class of heavy-tailed distributions. Asmussen et al. [2000] had also developed asymptotically optimal importance sampling techniques for these probabilities using a different approach.

Later, Perwez worked with his student N. K. Boots (in Boots and Shahabuddin

[2001]) to address the efficient estimation of the level crossing probability problem using a more direct approach involving hazard rate twisting. Boots and Shahabuddin [2001] proposed that the random walk be truncated after a specified number of transitions, and they developed an asymptotically valid upper bound on the bias resulting from this truncation. Empirically, they observed that this approach was effective when the tails of the constituent random variable decayed at a subexponential rate but faster than polynomial rate (for instance, when the random variables had tails similar to a Weibull distribution with shape parameter less than 1). However, it did not work well when the tails of constituent random variables decayed at a polynomial rate.

Perwez also worked with his student Z. Huang on the problem of estimating small tail probabilities of general functions of a finite number of heavy-tailed random variables. In Huang and Shahabuddin [2004], they proposed applying an appropriate uniform hazard rate twist to distributions of all random variables to obtain asymptotic optimality of the resultant estimator. Huang and Shahabuddin [2003] observe that transforming a heavy-tailed random variable via its hazard function converts it to an exponential random variable. They further note that exponentially twisting the transformed random variable is equivalent to hazard rate twisting of the original random variable.

In the last few years, Perwez again teamed up with Sandeep and with Rajeeva Karandikar to generalize hazard rate twisting (in Juneja et al. [2007]). This was done in three ways:

(a) They showed that in estimating the tail probability of a sum of a fixed number of random variables, hazard rate twisting can be applied successfully to light-tailed random variables as well.

(b) They observed that often the hazard function may not have a simple closed form, although it may be asymptotically similar to a simple function. With this in mind, they showed that even asymptotic approximations to hazard functions yield asymptotically optimal estimators both in light- and heavy-tailed settings.

(c) They generalized the importance sampling techniques to efficiently estimate tail probabilities of delays in PERT networks.

6. FINANCE AND RISK MANAGEMENT

In late 1997 and early 1998, Perwez began to work on simulation problems arising in finance and risk management. His involvement in this area began in collaboration with Paul Glasserman and Phil Heidelberger. Columbia's IEOR Department was in the process of launching a master's program in financial engineering, so this was a natural topic for Perwez to explore; IBM Research was interested in investigating computational problems in finance, both as a research area and as a potentially expanding market for IBM, so Phil was also interested in the topic; and Paul had already begun to work on other problems involving simulation and finance. Their initial collaboration led to a series of papers on pricing path-dependent options by simulation.

In Glasserman, Heidelberger, and Shahabuddin (GHS) [1999a], the authors developed a method that combined importance sampling and stratified sampling. Their importance sampling method applies a deterministic change of drift to the Brownian motion driving the underlying assets in an option pricing problem; the new drift is selected by solving an optimization problem. The method is asymptotically optimal in a limiting regime that focuses on the linear part of the log payoff of an option. The stratificiation procedure in the paper is designed to focus on the corresponding second-order contribution. In GHS [1999b], the authors applied the method in the Heath-Jarrow-Morton framework for interest rate modeling.

The same three authors then turned their attention from option-pricing applications to risk management applications—in particular, the calculation of portfolio Value at Risk (VaR). A portfolio's VaR is a percentile of its loss distribution. For example, a 99% one-day VaR is a loss level that is exceeded over a single day with a 1% probability. GHS [2000] developed another combination of importance sampling and stratified sampling for this problem. Both techniques are based on a widely used quadratic ("delta-gamma") approximation to portfolio value. The importance sampling procedure is asymptotically optimal for estimating the tail of the loss distribution under the quadratic approximation at large loss thresholds.

GHS [2000] is based on using a multivariate normal distribution to model changes in the values of a portfolio's assets. In practice, market returns are often observed to have heavier tails than a normal distribution would predict. GHS [2002] therefore addresses the problem of estimating portfolio VaR when the underlying returns have a multivariate heavy-tailed distribution. The method developed circumvents difficulties associated with applying importance sampling in a heavy-tailed context by working with distributions that can be represented as scale mixtures of normal distributions—in particular, the multivariate Student's t-distribution. The method in GHS [2002] applies a change of distribution to the normal distribution and to the mixing random variable (a chi-square random variable in the case of Student's t-distribution). As in GHS [2000], the method is designed to take advantage of the delta-gamma approximation to portfolio value, both for importance sampling and stratified sampling. These ideas were further developed in Huang and Shahabuddin [2004].

In one of Perwez's last research projects, he cosupervised the dissertation of Wanmo Kang in Columbia's IEOR department with Paul Glasserman. Perwez, Wanmo, and Paul collaborated on simulation problems arising in portfolio credit risk. In Glasserman et al. [2004a], they analyzed the tail behavior of the loss distribution in a portfolio subject to losses from default. Dependence between default times leads to a rather intricate combinatorial structure to the problem of finding the "most likely" scenario leading to large losses. In Glasserman et al. [2004b], the authors applied this structure to develop an asymptotically optimal importance sampling procedure for estimating the tail of the loss distribution.

The Glasserman-Kang-Shahabuddin papers work within the Gaussian copula model of portfolio credit risk. This model is sometimes faulted for lacking "extreme tail dependence." Alternatives that capture extreme tail dependence include models that replace the Gaussian copula with, e.g., a Student's t-copula. In one of his last pieces of work, Perwez published a conference paper (Kang and Shahabuddin [2005]) that addressed this case. Perwez's other papers with Wanmo and his other coauthors will appear posthumously, including two in this special issue.

7. CONCLUDING REMARKS

Perwez Shahabuddin has left a lasting mark on the field of simulation through his research publications and his influence on his many students and colleagues. We are fortunate to have had the opportunity to know and work with Perwez during his much-too-brief life.

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