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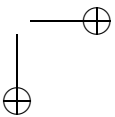
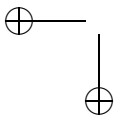
Applied Stochastic Processes and Control for Jump-Diffusions: Modeling, Analysis and Computation

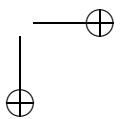
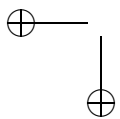
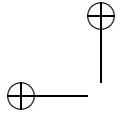
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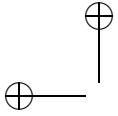
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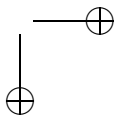
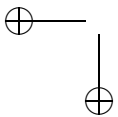
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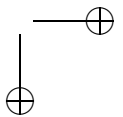
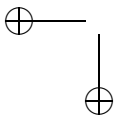
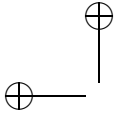






*To five generations of women in my life,
Margaret Geiger, Violet Bliss, Ethel Hutchins, Lisa Hanson
and Chiara Hanson Whitehurst*





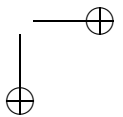
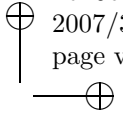
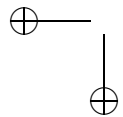
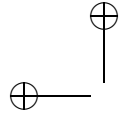
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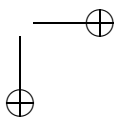
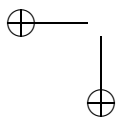
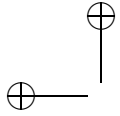
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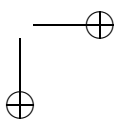
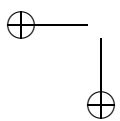
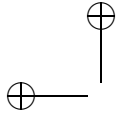
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Preface

*Everything should be as simple as it is,
but not simpler.*

—Albert Einstein (1879-1955).

*A mathematical theory is not to be considered complete
until you have made it so clear that you can explain it
to the first man whom you meet on the street.*

—David Hilbert (1862-1943).

*Always take a pragmatic view in applied mathematics:
the proof of the pudding is in the eating.*

—N. H. Bingham and Rüdiger Kiesel (2004) [33].

Overview of This Book

The aim of this book is to be a self-contained, practical, entry level text on stochastic processes and control for jump-diffusions in continuous time, technically Markov processes in continuous time.

The book is intended to be accessible to graduate students as well as a research monograph to researchers in applied mathematics, computational science and engineering. In fact, a number of colleagues have said that they would like to learn about stochastic processes, but have found it difficult to learn about it from the existing literature. Also, the book may be useful for practitioners of financial engineering who need fast and efficient answers to stochastic financial problems. Hence, the exposition is based upon integrated basic principles of applied mathematics, applied probability and computational science. The target audience includes mathematical modelers and students in many areas of science and engineering seeking to construct models for scientific applications subject to uncertain environments. The prime interest is in modeling and problem solving. The utility of the exposition, based upon systematic derivations along with essential proofs in the spirit of classical applied mathematics, is more important to setting up a stochastic model of an application than abstract theory. However, a lengthy last chapter is intended to

bridge the gap between the applied world and the abstract world in order to enable applied students and readers to understand the more abstract literature.

More rigorous theorem formulation and proving is not of immediate importance compared to modeling and solving an applied problem, although many proofs are given here. Many research problems deal with new applications and often these new applications require models beyond those in the existing literature. So, it is important to have a reasonably understandable derivation for a nearby model that can be perturbed to obtain a proper new model. The level of rigor here is embodied in correct and systematic derivations, with many proofs and results not available elsewhere, under reasonable conditions, not necessarily the tightest possible conditions. In fact, much of this book and the theory of Markov processes in continuous time is based upon modifying the formulations for continuous functions in regular and advanced calculus to extend them to the discontinuous and non-smooth functions of stochastic calculus.

Origin of the Book

The book is based upon the author's courses *Math 574 Applied Optimal Control*, *Math 590 Special Topics: Applied Stochastic Control*, *MCS 507 Mathematical, Statistical and Scientific Software for Industry* and partly on *MCS 571 Numerical Methods for Partial Differential Equations*. In addition, the results from research papers on computational stochastic dynamic programming, computational finance and computational biomedicine are included. Courses in asymptotic analysis and numerical analysis play a role as well. However, as with lectures, every attempt is made to keep the book self-contained through an integrated approach, without depending heavily on prerequisites, especially with a diverse readership and interdisciplinary topics.

This book integrates many of the research and exposition advances made in computational stochastic dynamic programming and stochastic modeling. They exhibit the broader impact of the applications and the computationally oriented approach. The stochastic applications are wide-ranging, including the optimal economics of biological populations in uncertain and disastrous environments, biomedical applications in cancer modeling and optimal treatment, and financial engineering with applications in option pricing and optimal portfolios.

How This Book is Organized and How to Use It

- The prerequisites are too numerous to expect of any reader of a wide-ranging interdisciplinary book such as this one, so a single online Appendix B on the essentials of probability theory, mathematical analysis, matrix algebra and other topics can be found at

<http://www.math.uic.edu/~hanson/math574/#Text>.

Over-specification of prerequisites tend to filter out too many students who could benefit from this material. This appendix is intended to bring all readers up to the same level by self-study, where necessary, of the basic concepts

and notations of probability and analysis needed for jump-diffusion processes and their deviations from continuity. It is not meant to be taught or read in sequence, but to include relevant results when needed and to make the presentation as self-contained as possible. Originally, this material as a pre-appended chapter, but became an appendix to reduce the size and cost of this book.

- Simple jump-diffusion Chapters 1, 2, 3 and 4 cover the basics for simple jump-diffusions, i.e., stochastic diffusion (Wiener or Brownian motion) and simple Poisson driven processes, including stochastic integration based upon Itô's computationally motivated mean square convergence for Markov processes and stochastic calculus for transformations of stochastic differential equations (SDEs). The speed and depth of coverage for the student or reader will depend on their level of knowledge, particularly with respect to prior knowledge of probability and diffusion processes which are more well known. The presentation is more elementary than that of later chapters to reduce the likelihood that readers will get lost at the basic level.
- Advanced and special topics are found in Chapters 5 to 12 and can be selected according to the instructor's or reader's interests. There are more chapters than can be covered in any one course.
 - Chapter 5 *Stochastic Calculus for General Markov SDEs* covers more advanced and general topics for SDEs. These include jumps driven by compound Poisson or Poisson random measure processes that allow randomly distributed jump-amplitudes, state-dependent jump-diffusions and multidimensional jump-diffusions.
 - Chapter 6 *Stochastic Optimal Control - Stochastic Dynamic Programming* and Chapter 8 *Computational Stochastic Control Methods* can form a stochastic control theory and computational components of a course. Also, if a chapter on deterministic control theory is desired for introduction and contrast to stochastic control, another online Appendix A *Deterministic Optimal Control* is available at the above listed URL. Appendix A gives a summary of deterministic optimal control results to provide a background for comparison to the stochastic optimal control results, but could be skipped if a deterministic control course is a prerequisite or if only stochastic optimal control are of interest. In Chapter 6 stochastic optimal control problems are introduced and the equation of stochastic dynamic programming is systematically derived from the basic principles of applied mathematics. Chapter 8 has treatments using either modified finite difference methods for optimal control problem or the Markov chain approximation methods. Computational methods are important for stochastic optimal control problems because there are so few exact analytical solutions. Computational methods are important for stochastic optimal control problems because there are so few exact analytical solutions.

- Chapter 7 *Kolmogorov Equations* concerns partial differential equation (PDE) methods for solving stochastic problems using the forward and backward Kolmogorov equations, Dynkin's integral formulas (also Feynmann-Kac's as Dynkin's with an integrating factor) that help provide PDE solutions without directly solving the PDE, boundary conditions and stopping time problems. Knowledge of partial derivatives from advanced courses in calculus is all that should be needed, a course in PDEs will be of little help, since a course is not essential and only these integral formulas are used in this chapter. PDE methods are an applied alternate to the abstract method of using martingales to solve stochastic problems, such as those in finance (see Chapter 12 for martingale and other abstract approaches.)
- Chapter 9 *Stochastic Simulations* contains treatments for direct simulations of SDEs and general simulations by the Monte Carlo method. This chapter along with Chapter 8 on computational dynamic programming could form a computational component of a course.
- Chapter 10 on financial applications and Chapter 11 on biomedical applications provide substantial examples of application of the theory and techniques treated in this book. Chapter 10 explains Merton's mathematical justification and generalization of the classical Black-Scholes option pricing problem in sufficient detail for those familiar with the diffusion processes properties in Chapters 1-4 and is a good motivating application for Chapter 5. Also treated are option pricing models for jump-diffusions, optimal portfolio and consumption models, and an important events model that modifies the jump-diffusion model with a quasi-deterministic jump model for scheduled announcements and random responses. Chapter 11 includes applications to stochastic optimal control or bioeconomic models, diffusion approximation models of tumor growth and a deterministic optimal control model of PDE-driven drug delivery model for the brain.
- Chapter 12 is an applied description of abstract probability methods, including probability measure, probability space, martingales and change in probability measure using either Radyn-Nikodým and Girsanov theorems. The last section is a generalization of jump-diffusions called Lévy processes that permit the jump-rate to be infinite. This chapter is meant to be a bridge between the applied view of stochastic processes and the abstract view to ease the transition to reading some of the more abstract literature on stochastic processes. However, depending on the instructor or reader, parts of this chapter can be woven into the coverage of the earlier chapters. For instance, a colleague said that Girsanov's measure change transformation was needed in his financial applications course and there are a pure diffusion version and a jump-diffusion version of the Girsanov theorem in this chapter.

Distinct Features of This Book

The book is based upon a number of distinct features:

- Both analytical and computational methods are emphasized based on the utility, with respect to the computational complexity, of the problems. Exercises and examples in the elementary chapters include both computational and analytic ones. Students need to have good analytic and computational skills to do well, since diverse skills are needed for many jobs.
- The treatment of jump and diffusion processes is balanced as well, rather than a stronger or nearly exclusive emphasis on diffusion processes. This is a unique feature of this book. This treatment of jump-diffusions is important for training graduate students to do research on stochastic processes, since the analysis of diffusion processes is so well-developed, there are many opportunities for open problems on jump-diffusions.
- It clearly shows the strong role that discontinuous as well as non-smooth properties of stochastic processes play compared to the random properties by emphasizing a concrete jump calculus, without much reliance on measure-theoretic constructs, except for the very useful random Poisson measure concept.
- Basic principles of probability theory in the spirit of classical applied mathematics are used to set up the practical foundations through clear and systematic derivations, making the book accessible as a research monograph to many who work with applications.
- It shows how analytical-canonical control problem models, such as the linear-quadratic, jump-diffusion (LQJD) problem and financial risk-adverse power utilities, can be used to reduce computational dimensional complexity of approximate solutions along with other computational techniques.
- Insightful and useful material are used so that the book can be readily used to model realistic applications and even modify the derivations when new applications do not quite fit the old stochastic model.
- Clear explanations for the entry level student are used. In particular, clear and consistent notation is used, such that the notation is clearly identified with the quantity it symbolizes, rather than arbitrarily selected. Sometimes this has meant some compromise on some standard notation, for instance, P is used for the Poisson process to be consistent with the W used for the Wiener process. This means that P could not be used for probability, so Prob is used in place of P (or Pr) and is clearer to a diverse audience. Similarly, probability distributions are denoted by Φ and densities by ϕ since P is used for Poisson and F is used for transformation functions throughout the book.

Target Audience

Colleagues and students have requested a more accessible, practical treatment of these topics. They are interested in learning about stochastic calculus and optimal stochastic control in continuous time, but reluctant to invest time to learn it from more advanced treatments relying heavily on abstract concepts. Hence, this book should be of interest to an interdisciplinary audience of applied mathematicians, applied probabilists, engineers (including control engineers dealing with deterministic problems and financial engineers needing fast as well as useful methods for modeling rapidly changing market developments), statisticians and other scientists. After this primary audience, a secondary audience would be mathematicians, engineers and scientists, using this book as a research monograph, seeking more intuition to more fully understand stochastic processes and how the more advanced analytical approaches fit in with important applications like financial market modeling.

Prerequisites

For optimal use of this book, it would be helpful to have had prior introduction to applied probability theory including continuous random variables, mathematical analysis at least at the level of advanced calculus. Ordinary differential equations, partial differential equations and basic computational methods would be helpful but the book does not rely on prior knowledge of these topics by using basic calculus style motivations. In other words, the more or less usual preparation for students of applied mathematics, science and engineering should be sufficient. However, the author has strived to make this book as self-contained as practical, not strongly relying on prior knowledge and explaining or reviewing the prerequisite knowledge at the point it is needed to justify a step in the systematic derivation of some mathematical result. Online Appendix B supplies essential preliminaries.

MATLAB™ Computation

As part of the theme of balancing computation and analysis, MATLAB™, the matrix laboratory computation system is used for almost all computational examples and figure illustrations. Simple MATLAB™ codes are described in class and the code for all text figures are given in online Appendix C at the URL previously cited in both listing and source forms. MATLAB™ greatly facilitates the development of code and is ideally suited to stochastic processes and control problems. Also, MATLAB™ now comes with the Maple™ kernel built into the MATLAB™ student package for including elementary symbolic computations with numeric computations. Beyond the initial elementary assignments, the students are required to submit their assignments with professionally done illustrations for which they can find examples in online Appendix C. Many students surveyed at the end of the class actually list MATLAB™ with the other topics that they were happy to learn. MATLAB™ is also helpful later for producing professional research papers and theses.

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Some of my students have used the SIAM Travel Fund, so half of the royalties of this book are to be donated to this fund.

My wife Ethel did a major job at the final proof-read.

This work has been influenced, consciously and subconsciously, from books and related works by many authors such as

Applebaum [12], Arnold [13], Bingham and Kiesel [33], Bliss [40], Çinlar [56], Clark [57], Cont and Tankov [60], Feller [84, 85], Fleming and Rishel [86], Gihman and Skorohod [95, 96], Goel and Richter-Dyn [99], Glasserman [97], Hammersley and Handscomb [105], D. Higham [140, 141], Hull [148], Itô [150], Jäkel [151] Jazwinski [155], Karlin and Taylor [162, 163, 265] Kirk [164], Kloeden and Platen [166], Kushner [174, 176], Kushner and Dupuis [179], Ludwig [187], Merton [203], Mikosch [209], Øksendal [222], Øksendal and Sulem, [223], Parzen [224], Protter [232], Runggaldier [239], Schuss [244], Snyder and Miller [252], Tuckwell [270], Steele [256], Wonham [286], and others. Although this influence may not be directly apparent here, some have shown how to make the presentation much simpler, while others have supplied the motivation to simplify the presentation, making it more accessible to a more general audience and other applications.

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Many of our national supercomputing centers have provided supercomputing time on the the currently most powerful supercomputers for continuing research for solving large scale stochastic control problems in *Advanced Computational Stochastic Dynamic Programming* and also for computational science education. In addition to Argonne National Laboratory, these were National Center for Supercomputing Applications (NCSA), Los Alamos National Laboratory's Advanced Computing Laboratory (LANL/ACL), Cornell Theory Center (CTC/CNSF), Pittsburgh Supercomputing Center (PSC) and the San Diego Supercomputing Center (SDSC/NPACI) during 1987-2003.

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Bibliography

- [1] M. L. ABELL AND J. P. BRASELTON, *The Maple V Handbook*, Academic Press, New York, NY, 1994.
- [2] M. ABRAMOWITZ AND I. A. STEGUN, (EDS.), *Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables*, Applied Mathematics Series 55, National Bureau of Standards, Washington, DC, 1964.
- [3] R. M. ABU-SARIS AND F. B. HANSON, *Computational Suboptimal Filter for a Class of Wiener-Poisson Driven Stochastic Process*, *Dynamics and Control*, vol. 7, no. 3, 1997, pp. 279-292.
- [4] N. AHMED AND K. TEO, *Optimal Control of Distributed Parameter Systems*, North Holland, New York, NY, 1981.
- [5] Y. AÏT-SAHALIA, *Disentangling Diffusion from Jumps*, *J. Financial Economics*, vol. 74, 2004, pp. 487-528.
- [6] T. G. ANDERSEN, L. BENZONI AND J. LUND, *An Empirical Investigation of Continuous-Time Equity Return Models*, *J. Finance*, vol. 57, no. 3, 2002, pp. 1239-1284.
- [7] B. D. O. ANDERSON AND J. B. MOORE, *Optimal Filtering*, Prentice-Hall, Englewood Cliffs, NJ, 1979.
- [8] B. D. O. ANDERSON AND J. B. MOORE, *Optimal Control: Linear Quadratic Methods*, Prentice-Hall, Englewood Cliffs, NJ, 1990.
- [9] P. ANDERSEN AND J. G. SUTINEN, *Stochastic Bioeconomics: A Review of Basic Methods and Results*, *Marine Res. Econ.*, vol. 1, 1982, pp. 1-10.
- [10] H. L. ANDERSON, *Metropolis, Monte Carlo Method, and the MANIAC*, Los Alamos Science, Fall 1986, pp. 96-107.
- [11] C. A. AOURIR, D. OKUYAMA, C. LOTT AND C. EGLINTON, *Exchanges - Circuit Breakers, Curbs, and Other Trading Restrictions*, URL:<http://invest-faq.com/articles/exch-circuit-brkr.html>.
- [12] D. APPLEBAUM, *Lévy Processes and Stochastic Calculus*, Cambridge University Press, Cambridge, UK, 2004.

- [13] L. ARNOLD, *Stochastic Equations: Theory and Applications*, John Wiley, New York, NY, 1974.
- [14] Y. ASHKENAZY, J. M. HAUSDORFF, P. C. IVANOV AND H. E. STANLEY, *A Stochastic Model of Human Gait Dynamics*, *Physica A*, vol. 316, 2002, pp. 662-670.
- [15] M. ATHANS AND P. L. FALB, *Optimal Control: An Introduction to the Theory and Its Applications*, McGraw-Hill Book Co., New York, NY, 1966.
- [16] L. BACHELIER, *Théorie de la Spéculation*, *Annales de l'Ecole Normale Supérieure*, vol. 17, 1900, pp. 21-86. English translation by A. J. Boness in *The Random Character of Stock Market Prices*, P. H. Cootner (Editor), MIT Press, Cambridge, MA, 1967, pp. 17-78.
- [17] A. BAIN, *Stochastic Calculus*, URL:<http://www.chiark.greenend.org.uk/~alanb/stoc-calc.pdf>.
- [18] C. A. BALL AND W. N. TOROUS, *On Jumps in Common Stock Prices and Their Impact on Call Option Prices*, *J. Finance*, vol. 40, 1985, pp. 155-173.
- [19] M. S. BARTLETT, *Stochastic Equations: Theory and Applications*, 3rd ed., Cambridge University Press, Cambridge, UK, 1978.
- [20] O. E. BARNDORFF-NIELSEN AND N. SHEPHERD, *Non-Gaussian Ornstein-Uhlenbeck-Based Models and Some of their Uses in Financial Economics*, ser. B, vol. 3, part. 2, 2001, pp. 167-241.
- [21] T. BASAR, *Twenty-five Seminal Papers in Control*, *IEEE Control Systems Magazine*, vol. 20, no. 1, February 2000, pp. 69-70.
- [22] M. BAXTER AND A. RENNIE, *Financial Calculus: An Introduction to Derivative Pricing*, Cambridge University Press, Cambridge, UK, 1996.
- [23] I. BEICHL AND F. SULLIVAN, *The Metropolis Algorithm*, *Computing in Sci. & Engineering*, vol. 2, no. 1, 2000, pp. 65-69.
- [24] D. J. BELL AND D. H. JACOBSON, *Singular Optimal Control Problems*, Academic Press, New York, NY, 1994.
- [25] R. E. BELLMAN, *Dynamic Programming*, Princeton University Press, Princeton, NJ, 1957.
- [26] R. E. BELLMAN, *Adaptive Control Processes: A Guided Tour*, Princeton University Press, Princeton, NJ, 1961.
- [27] R. BELLMAN AND R. KALABA, *Selected Papers on Mathematical Trends in Control Theory*, Dover Publications, New York, NY, 1964.
- [28] C. M. BENDER AND S. A. ORSZAG, *Advanced Mathematical Methods for Scientists and Engineers*, McGraw-Hill Book Co., New York, NY, 1978.

- [29] D. S. BERNSTEIN, *Feedback Control: An Invisible Thread in the History of Technology*, IEEE Control Systems Magazine, vol. 22, no. 2, April 2002, pp. 53-68.
- [30] J. T. BETTS, *Practical Methods for Optimal Control Using Nonlinear Programming*, SIAM, Philadelphia, PA, 2001.
- [31] A. T. BHARUCHA-REID, *Elements of the Theory of Markov Processes and their Applications*, McGraw-Hill Book Co., New York, NY, 1960.
- [32] P. BILLINGSLEY, *Probability and Measures*, 2nd Edition, John Wiley, New York, NY, 1986.
- [33] N. H. BINGHAM AND R. KIESEL, *Risk-Neutral Valuation: Pricing and Hedging of Financial Derivatives*, Springer-Verlag, New York, NY, 2004.
- [34] F. BLACK AND M. SCHOLES, *The Pricing of Options and Corporate Liabilities*, J. Political Economy, vol. 81, 1973, pp. 637-659.
- [35] F. BLACK, *How We Came Up with the Option Formula*, J. Portfolio Mgmt., vol. 15, Winter 1989, pp. 4-8.
- [36] A. BOKER, C. J. HABERMAN, L. GIRLING, R. P. GUZMAN, G. LOURIDAS, J. R. TANNER, M. CHEANG, M. MATH, B. W. MAYCHER, D. D. BELL AND G. J. DOAK, *Variable Ventilation Improves Perioperative Lung Function in Patients Undergoing Abdominal Aortic Aneurysmectomy*, Anesthesiology, vol. 100, no. 3, 2004, pp. 608-616.
- [37] G. E. P. BOX AND M. E. MULLER, *A Note on the Generation of Random Normal Deviates*, Ann. Math. Stat., vol. 29, 1958, pp. 610-611.
- [38] P. BOYLE, *Options: A Monte Carlo Approach*, J. Financial Economics, vol. 4, 1977, pp. 323-338.
- [39] P. BOYLE, M. BROADIE AND P. GLASSERMAN, *Monte Carlo Methods for Security Pricing*, J. Economic Dynamics and Control, vol. 21, 1997, pp. 1267-1321.
- [40] G. A. BLISS, *Lectures on the Calculus of Variations*, University Chicago Press, Chicago, IL, 1946.
- [41] P. BOSSAERTS, *The Paradox of Asset Pricing*, Princeton University Press, Princeton, NJ, 2002.
- [42] P. W. BRIDGEMAN, *Dimensional Analysis*, Yale University Press, New Haven, CT, 1963.
- [43] P. BRÉMAUD, *Point Processes and Queues: Martingale Dynamics*, Springer-Verlag, New York, NY, 1981.

- [44] A. E. BRYSON AND Y. C. HO, *Applied Optimal Control*, John Wiley, New York, NY, 1975.
- [45] T. G. BUCHMAN, *Nonlinear Dynamics, Complex Systems, and the Pathobiology of Critical Illness*, *Curr. Opin. Crit. Care*, vol. 10, no. 5, 2004, pp. 378-382.
- [46] P. CARR, H. GEMAN, D. B. MADAN AND M. YOR, *Stochastic Volatility for Lévy Processes*, *Math. Fin.*, vol. 13, no. 3, 2003, pp. 345-382.
- [47] P. CARR AND D. B. MADAN, *Option Valuation Using the Fast Fourier Transform*, *J. Comp. Fin.*, vol. 2, 1999, pp. 61-73.
- [48] S. P. CHAKRABARTY, *Optimal Control of Drug Delivery to Brain Tumors Using a Distributed Parameters Deterministic Model*, Ph.D. Thesis in Mathematics, Univ. Illinois at Chicago, Chicago, IL, 14 July 2006, 126 pages.
- [49] S. P. CHAKRABARTY AND F. B. HANSON, *Optimal Control of Drug Delivery to Brain Tumors for a Distributed Parameters Model*, in Proc. 2005 American Control Conference, 2005, pp. 973-978.
- [50] S. P. CHAKRABARTY AND F. B. HANSON, *Optimal Control of Drug Delivery to Brain Tumors for a PDE Driven Model Using the Galerkin Finite Element Method*, in Proc. 44th IEEE Conference on Decision and Control and European Control Conference 2005, 2005, pp. 1613-1618.
- [51] S. P. CHAKRABARTY AND F. B. HANSON, *Cancer Drug Delivery in Three Dimensions For a Distributed Parameter Control Model Using Finite Elements*, in Proc. 45th IEEE Conference on Decision, 2006, pp. 2088-2093; URL:<http://www.math.uic.edu/~hanson/pub/CDC2006/cdc06spcfhweb.pdf>.
- [52] G. CHICHILNISKY, *Fischer Black: The Mathematics of Uncertainty*, *Notices of the AMS*, vol. 43 (3), 1996, pp. 319-322.
- [53] S.-L. CHUNG AND F. B. HANSON, *Optimization Techniques for Stochastic Dynamic Programming*, in Proc. 29th IEEE Conference on Decision and Control, vol. 4, 1990, pp. 2450-2455.
- [54] S.-L. CHUNG AND F. B. HANSON, *Parallel Optimizations for Computational Stochastic Dynamic Programming*, in Proc. 1990 International Conference on Parallel Processing, vol. 3: Algorithms and Applications, P.-C. Yew, ed., 1990, pp. 254-260.
- [55] S.-L. CHUNG, F. B. HANSON AND H. H. XU, *Parallel Stochastic Dynamic Programming: Finite Element Methods*, *Lin. Alg. Applic.*, vol. 172, 1992, pp. 197-218.
- [56] E. ÇINLAR, *Introduction to Stochastic Processes*, Prentice-Hall, Englewood Cliffs, NJ, 1975.

- [57] C. W. CLARK, *Mathematical Bioeconomics: The Optimal Management of Renewable Resources*, 1st and 2nd Editions, John Wiley, New York, NY, 1976 and 1990.
- [58] C. W. CLARK AND R. LAMBERSON, *An Economic History and Analysis of Pelagic Whaling*, *Marine Policy*, vol. 6, 1982, pp. 103-120.
- [59] J. E. COHEN, *Mathematics Is Biology's Next Microscope, Only Better; Biology Is Mathematics' Next Physics, Only Better*, *PLoS Biology*, vol. 2, issue 12, 2004, p. 2017-2023.
- [60] R. CONT AND P. TANKOV, *Financial Modelling with Jump Processes*, Chapman & Hall/CRC, Boca Raton, FL, 2004.
- [61] E. T. COPSON, *Asymptotic Expansions*, Cambridge University Press, Cambridge, UK, 1965.
- [62] J. M. COURTAULT, Y. KABANOV, B. BRU, P. CRÉPEL, I. LEBON AND A. L. MARCHAND, *Louis Bachelier on the centenary of Théorie De La Spéculation*, *Mathematical Finance*, vol. 10, No. 3, 2000, pp. 341-353.
- [63] D. R. COX AND H. D. MILLER, *The Theory of Stochastic Processes*, Chapman and Hall, London, UK, 1965.
- [64] J. C. COX AND M. RUBINSTEIN, *Options Markets*, Prentice-Hall, Englewood Cliffs, NJ, 1985.
- [65] S. CYGANOWSKI, L. GRÜNE AND P. KLOEDEN, *Maple for Jump-Diffusion Stochastic Differential Equations in Finance*, *Programming Languages and Systems in Computational Economics and Finance*, S. S. Nielsen (Editor), Kluwer Academic Publishers, Amsterdam, 2002, pp. 233-269; URL:<http://www.uni-bayreuth.de/departments/math/~lgruene/papers/jumpfin.html>.
- [66] S. CYGANOWSKI AND P. KLOEDEN, *Maple Schemes for Jump-Diffusion Stochastic Differential Equations*, Proc. 16th IMACS World Congress, Lausanne 2000, M. Deville, R. Owens (Editors), Dept. Computer Science, Rutgers University, 2000, CD-ROM Paper 216-9, pp. 1-16; URL:<http://www.math.uni-frankfurt.de/~numerik/maplestoch/jumpdiff.pdf>.
- [67] S. CYGANOWSKI, P. KLOEDEN AND J. OMBACH, *Elementary Probability to Stochastic Differential Equations with Maple*, Springer-Verlag, New York, NY, 2002.
- [68] B. N. DATTA, *Numerical Linear Algebra and Applications*, Brooks/Cole, New York, NY, 1995.
- [69] J. DONGARRA AND F. SULLIVAN, *Guest Editor's Introduction: The Top Ten Algorithms*, *Computng in Sci. & Engineering*, vol. 2, no. 1, 2000, pp. 22-23.

- [70] J. L. DOOB, *Stochastic Processes*, John Wiley, New York, NY, 1953.
- [71] G. D. DOOLEN AND JOHN HENDRICKS, *Monte Carlo at Work*, Los Alamos Science, Special Issue Dedicated to S. Ulam, 1987, pp. 142-143; composite URL:<http://www.fas.org/sgp/othergov/doe/lanl/pubs/00326867.pdf>.
- [72] P. DORATO, C. ABDALLAH AND V. CERONE, *Linear-Quadratic Control: An Introduction*, Prentice-Hall, Englewood Cliffs, NJ, 1995.
- [73] J. DOUGLAS JR. AND T. DUPONT, *Galerkin Methods of Parabolic Equations*, SIAM J. Numerical Analysis, vol. 7, 1970, pp. 575-626.
- [74] J. DOUGLAS JR., *Time Step Procedures of Nonlinear Parabolic PDEs* in Mathematics of Finite Elements and Applications, MAFELAP, J. Whiteman (Editor), Academic Press, London, 1979, pp. 289-304.
- [75] D. DUFFIE, *Dynamic Asset Pricing Theory*, Princeton University Press, Princeton, NJ, 2001.
- [76] D. DÜVELMEYER *Untersuchungen zu Chancen und Risiken von Anti-Trend-Strategien am Beispiel des DAX-Futures*, Thesis, Fakultät für Mathematik, Technische Universität Chemnitz, Chemnitz, 2001; URL:http://www-usercg1.tu-chemnitz.de/~dana/diplom/_pdf/_dd.zip.
- [77] P. DYER AND S. R. MCREYNOLDS, *The Computation and Theory of Optimal Control*, Academic Press, New York, NY, 1970.
- [78] E. B. DYKIN, *Markov Processes I and II*, Academic Press, New York, NY, 1965.
- [79] R. ECKHARDT, *Ulam, John von Neumann, and the Monte Carlo Method*, Los Alamos Science, Special Issue Dedicated to S. Ulam, 1987, pp. 131-137. URL: <http://www.fas.org/sgp/othergov/doe/lanl/pubs/00326867.pdf>.
- [80] P. EMBRECHTS, *Multivariate Extremes and Market Risk Scenarios*, Bachelor Finance Society Third World Congress, Chicago, July 2004.
- [81] H. H. ENGELHARD, *Brain Tumors and the Blood-Brain Barrier*, Neuro-Oncology: The Essentials, Thieme Medical Publishers, Inc., New York 2000, pp. 49-53.
- [82] J. D. ESARY, F. PROSCHAN AND D. W. WALKUP, *Association of Random Variables, with Applications*, Annals of Mathematical Statistics, vol. 38, 1967, pp. 1466-1474.
- [83] M. EVANS, N. HASTINGS AND B. PEACOCK, *Statistical Distributions*, 3rd ed., John Wiley, New York, NY, 2000.
- [84] W. FELLER, *An Introduction to Probability Theory and Its Application*, vol. 1, 3rd ed., John Wiley, New York, NY, 1968.

- [85] W. FELLER, *An Introduction to Probability Theory and Its Application*, vol. 2, 2nd ed., John Wiley, New York, NY, 1971.
- [86] W. H. FLEMING AND R. W. RISHEL, *Deterministic and Stochastic Optimal Control*, Springer-Verlag, New York, NY, 1975.
- [87] J. J. FLORENTIN, *Optimal Control of Systems with Generalized Poisson Inputs*, ASME Trans., vol. 85D (also J. Basic Engr., vol. 2), 1963, pp. 217-221.
- [88] G. E. FORSYTHE, M. A. MALCOLM AND C. MOLER, *Computer Methods for Mathematical Computations*, Prentice-Hall, Englewood Cliffs, NJ, 1977.
- [89] B. FRIEDMAN, *Principles and Techniques of Applied Mathematics*, John Wiley, New York, NY, 1956.
- [90] FUTURE DIRECTIONS IN CONTROL THEORY PANEL, *Report of the Panel on Future Directions in Control Theory: A Mathematical Perspective*, W. H. Fleming (Chairman), Society for Industrial and Applied Mathematics, Philadelphia, PA, 1988.
- [91] FUTURE DIRECTIONS IN CONTROL, DYNAMICS, AND SYSTEMS PANEL, *Future Directions in Control in an Information Rich World: Report of the Panel on Future Directions in Control, Dynamics, and Systems*, R. M. Murray (Editor), Society for Industrial and Applied Mathematics, Philadelphia, PA, July 2003.
- [92] T. C. GARD, *Introduction to Stochastic Differential Equations*, Marcel-Dekker, New York, NY, 1988.
- [93] R. A. GATENBY AND E. T. GAWLINSKI, *A Reaction-Diffusion Model of Cancer Invasion*, Cancer Research, vol. 56, 1996, pp. 5745-5753.
- [94] S. B. GERSHWIN, *Manufacturing Systems Engineering*, Prentice-Hall, Englewood Cliffs, NJ, 1994.
- [95] I. I. GIHMAN AND A. V. SKOROHOD, *Stochastic Differential Equations*, Springer-Verlag, New York, NY, 1972.
- [96] I. I. GIHMAN AND A. V. SKOROHOD, *Controlled Stochastic Processes*, Springer-Verlag, New York, NY, 1979.
- [97] P. GLASSERMAN, *Monte Carlo Methods in Financial Engineering*, Springer-NY, New York, NY, 2003.
- [98] P. W. GLYNN AND W. WHITT, *The Asymptotic Efficiency of Simulation Estimators*, Operations Research, vol. 40, no. 3, 1992, pp. 505-520.
- [99] N. S. GOEL AND N. RICHTER-DYN, *Stochastic Models in Biology*, Springer-NY, New York, NY, 2003.
- [100] J. H. GOLDIE AND A. J. COLDMAN, *Drug Resistance in Cancer: Mechanisms and Models*, Cambridge University Press, Cambridge, UK, 1998.

- [101] M. S. GREWAL AND A. P. ANDREWS, *Kalman Filtering: Theory and Practice*, Prentice-Hall, Englewood Cliffs, NJ, 1993.
- [102] M. D. GUNZBURGER, *Perspectives in Flow Control and Optimization*, SIAM, Philadelphia, PA, 2003.
- [103] R. HABERMAN, *Elementary Applied Partial Differential Equations with Fourier Series and Boundary Value Problems*, Prentice-Hall, Englewood Cliffs, NJ, 1983.
- [104] W. HACKBUSCH, *A Numerical Method for Solving Parabolic Equations with Opposite Orientations*, *Computing*, vol. 20, 1978, pp. 229-240.
- [105] J. M. HAMMERSLEY AND D. C. HANDSCOMB, *Monte Carlo Methods*, Methuen, London, UK, 1964.
- [106] F. B. HANSON, *Bioeconomic Model of the Lake Michigan Alewife Fishery*, *Canadian Journal of Fisheries and Aquatic Sciences*, vol. 44, suppl. 2, 1987, pp. 298-305.
- [107] F. B. HANSON, *Stochastic Dynamic Programming: Advanced Computing Constructs*, in Proc. 28th IEEE Conference on Decision and Control, vol. 1, 1989, pp. 901-903.
- [108] F. B. HANSON, *Computational Dynamic Programming on a Vector Multiprocessor*, *IEEE Transactions on Automatic Control*, vol. 36, no. 4, 1991, pp. 507-511.
- [109] F. B. HANSON, *Computational Stochastic Dynamic Programming* in *Stochastic Digital Control System Techniques*, within series *Control and Dynamic Systems: Advances in Theory and Applications*, vol. 76, C. T. Leondes, ed., Academic Press, New York, NY, 1996, pp. 103-162.
- [110] F. B. HANSON, *Local Supercomputing Training in the Computational Sciences Using Remote National Centers*, *Future Generation Computer Systems: Special Issue on Education in the Computational Science*, vol. 19, 2003, pp. 1335-1347.
- [111] F. B. HANSON, *Computational Stochastic Control: Basic Foundations, Complexity and Techniques*, in Proc. 42nd IEEE Conference on Decision and Control, 2003, pp. 3024-3029.
- [112] F. B. HANSON AND K. NAIMIPOUR, *Convergence of Numerical Method for Multistate Stochastic Dynamic Programming*, in Proc. Int. Federation of Automatic Control 12th World Congress, vol. 9, 1993, pp. 501-504.
- [113] F. B. HANSON, C. J. PRATICO, M. S. VETTER, AND H. H. XU, *Multidimensional Visualization Applied to Renewable Resource Management*, in Proc. Sixth SIAM Conference on Parallel Processing for Scientific Computing, vol. 2, 1993, pp. 1033-1036.

- [114] F. B. HANSON AND D. RYAN, *Optimal Harvesting with Density Dependent Random Effects*, Natural Resource Modeling, vol. 2, 1988, pp. 439-455.
- [115] F. B. HANSON AND D. RYAN, *Mean and Quasideterministic Equivalence for Linear Stochastic Dynamics*, Mathematical Biosciences, vol. 93, 1989, pp. 1-14.
- [116] F. B. HANSON AND D. RYAN, *Optimal Harvesting with Both Population and Price Dynamics*, Mathematical Biosciences, vol. 148, 1998, pp. 129-146.
- [117] F. B. HANSON AND C. TIER, *An Asymptotic Solution to the First Passage Time Problem for Singular Diffusion Arising in Population Biology*, SIAM J. Appl. Math., vol. 40, 1981, pp. 113-132.
- [118] F. B. HANSON AND C. TIER, *A Stochastic Model of Tumor Growth*, Mathematical Biosciences, vol. 61, 1982, pp. 73-100.
- [119] F. B. HANSON AND H. C. TUCKWELL, *Persistence Times of Populations with Large Random Fluctuations*, Theor. Population Biol., vol. 14, 1978, pp. 46-61.
- [120] F. B. HANSON AND H. C. TUCKWELL, *Logistic Growth with Random Density Independent Disasters*, Theor. Population Biol., vol. 19, 1981, pp. 1-18.
- [121] F. B. HANSON AND H. C. TUCKWELL, *Diffusion Approximations for Neuronal Activity including Reversal Potentials*, J. Theoretical Neurobiology, vol. 2, 1983, pp. 127-153.
- [122] F. B. HANSON AND H. C. TUCKWELL, *Population Growth with Randomly Distributed Jumps*, J. Mathematical Biology, vol. 36, no. 2, 1997, pp. 169-187.
- [123] F. B. HANSON AND J. J. WESTMAN, *Optimal Consumption and Portfolio Policies for Important Jump Events: Modeling and Computational Considerations*, in Proc. American Control Conference, 2001, pp. 4456-4661.
- [124] F. B. HANSON AND J. J. WESTMAN, *Optimal Consumption and Portfolio Control for Jump-Diffusion Stock Process with Log-Normal Jumps*, in Proc. American Control Conference, July 2002, pp. 4256-4261; for corrected version see <ftp://www.math.uic.edu/pub/Hanson/ACC02/acc02webcor.pdf>.
- [125] F. B. HANSON AND J. J. WESTMAN, *Stochastic Analysis of Jump-Diffusions for Financial Log-Return Processes*, in Stochastic Theory and Control, Proceedings of a Workshop held in Lawrence, Kansas, October 18-20, 2001, Lecture Notes in Control and Information Sciences, vol. 280, B. Pasik-Duncan (Editor), Springer-Verlag, New York, pp. 169-184, 2002; for corrected version see <ftp://www.math.uic.edu/pub/Hanson/KU01/ku02hwfmcpr.pdf>.
- [126] F. B. HANSON AND J. J. WESTMAN, *Jump-Diffusion Stock Return Models in Finance: Stochastic Process Density with Uniform-Jump Amplitude*, in Proc. 15th Int. Sympos. Mathematical Theory of Networks and Systems, August 2002, pp. 1-7.

- [127] F. B. HANSON AND J. J. WESTMAN, *Portfolio Optimization with Jump-Diffusions: Estimation of Time-Dependent Parameters and Application*, in Proc. 41st Conference on Decision and Control, December 2002, pp. 377–382.
- [128] F. B. HANSON AND J. J. WESTMAN, *Jump-Diffusion Stock-Return Model with Weighted Fitting of Time-Dependent Parameters*, in Proc. American Control Conference, 2003, pp. 4869-4874.
- [129] F. B. HANSON, J. J. WESTMAN AND Z. ZHU, *Maximum Multinomial Likelihood Estimation of Market Parameters for Stock Jump-Diffusion Models*, in Mathematics of Finance: Proc. 2003 AMS-IMS-SIAM Joint Summer Research Conference on Mathematics of Finance, AMS Contemporary Mathematics, vol. 351, G. Yin and Q. Zhang (Editors), 2004, pp. 155-169.
- [130] F. B. HANSON AND J. J. WESTMAN, *Optimal Portfolio and Consumption Policies Subject to Rishel's Important Jump Events Model: Computational Methods*, IEEE Transactions on Automatic Control, vol. 48, no. 3, Special Issue on Stochastic Control Methods in Financial Engineering, 2004, pp. 326-337.
- [131] F. B. HANSON AND G. YAN, *American Put Option Pricing for Stochastic-Volatility, Jump-Diffusion Models*, Proc. 2007 American Control Conference, pp. 1-6, 11 July 2007, invited paper to appear. URL:<http://www.math.uic.edu/~hanson/pub/GYan/ACC07fhgywebpub.pdf> .
- [132] F. B. HANSON AND Z. ZHU, *Comparison of Market Parameters for Jump-Diffusion Distributions Using Multinomial Maximum Likelihood Estimation*, in Proc. 42nd IEEE Conference on Decision and Control, December 2004, pp. 3919-3924.
- [133] J. M. HARRISON AND S. R. PLISKA, *Martingales and Stochastic Integrals in the Theory of Continuous Trading*, Stochastic Processes & Appl., vol. 11, pp. 215-260, 1981.
- [134] J. M. HARRISON AND S. R. PLISKA, *A Stochastic Calculus Model of Continuous Trading: Complete Markets*, Stochastic Processes & Appl., vol. 15, pp. 313-316, 1983.
- [135] M. B. HAUGH AND A. W. LO, *Computational Challenges in Portfolio Management*, Computing in Sci. & Engr., pp. 54l-59, May/June 2000.
- [136] D. HEATH AND M. SCHWEIZER, *Martingales versus PDEs in Finance: An Equivalence Result with Examples*, J. Appl. Prob., vol. 37, pp. 947-957, 2000.
- [137] J. W. HELTON AND O. MERINO, *Classical Control Using H^∞ Methods: An Introduction to Design*, SIAM, Philadelphia, PA, 1998.
- [138] J. W. HELTON AND O. MERINO, *Classical Control Using H^∞ Methods: Theory, Optimization, and Design*, SIAM, Philadelphia, PA, 1998.

- [139] R. C. HENNEMUTH, J. E. PALMER AND B. E. BROWN, *A Statistical Description of Recruitment in Eighteen Selected Fish Stocks*, J. Northw. Atl. Fish Sci., vol. 1, pp. 101-111, 1980.
- [140] D. J. HIGHAM, *An Algorithmic Introduction to Numerical Simulation of Stochastic Differential Equations*, SIAM Review, vol. 43, no. 3, 2001, pp. 525-546.
- [141] D. J. HIGHAM, *An Introduction to Financial Option Valuation: Mathematics, Stochastics and Computation*, Cambridge University Press, Cambridge, UK, 2004.
- [142] D. J. HIGHAM, *Black-Scholes for Scientific Computing Students*, Computing in Science & Engineering, vol. 6, no. 6, pp. 72-79, November/December 2004.
- [143] D. J. HIGHAM AND N. J. HIGHAM, *MATLAB Guide*, SIAM, Philadelphia, PA, 2000.
- [144] D. J. HIGHAM AND P. E. KLOEDEN, *Maple and MATLAB for Stochastic Differential Equations in Finance*, in Programming Languages and Systems in Computational Economics and Finance, S. S. Neilsen (Editor), Kluwer, 2002, pp. 233-270. URL:<http://www.maths.strath.ac.uk/~aas96106/algfiles.html>.
- [145] D. J. HIGHAM AND P. E. KLOEDEN, *Numerical Methods for Nonlinear stochastic differential equations with jumps*, Numerische Mathematik, vol. 101, 2005, pp. 101-119.
- [146] D. J. HIGHAM AND P. E. KLOEDEN, *Convergence and Stability of Implicit Methods for Jump-Diffusion Systems*, Int. J. Numerical Analysis & Modeling, vol. 3, 2006, pp. 125-140.
- [147] D. J. HIGHAM, X. MAO AND A. M. STUART, *Strong Convergence of Euler-Type Methods for Nonlinear Stochastic Differential Equations*, SIAM J. Numer. Anal., vol. 40, no. 3, 2002, pp. 1041-1063.
- [148] J. C. HULL, *Options, Futures, & Other Derivatives*, 4th Edition, Prentice-Hall, Englewood Cliffs, NJ, 2000.
- [149] INTERNATIONAL PACIFIC HALIBUT COMMISSION, *Annual Reports*, Seattle, WA, 1984-1985.
- [150] K. ITÔ, *On Stochastic Differential Equations*, Mem. Amer. Math. Soc., no. 4, 1951, pp. 1-51.
- [151] P. JÄCKEL, *Monte Carlo Methods in Finance*, John Wiley, New York, NY, 2002.
- [152] D. H. JACOBSON AND D. Q. MAYNE, *Differential Dynamic Programming*, American Elsevier, New York, NY, 1970.

- [153] J. JACOD AND A. N. SHIRYAEV, *Limit Theorems for Stochastic Processes*, Springer-Verlag, Berlin, 1987.
- [154] R. A. JARROW AND E. R. ROSENFELD, *Jump Risks and the Intertemporal Capital Asset Pricing Model*, J. Business, vol. 57 (3), 1984, pp. 337-351.
- [155] A. H. JAZWINSKI, *Stochastic Processes and Filtering Theory*, Academic Press, New York, NY, 1970.
- [156] P. JORION, *On Jump Processes in the Foreign Exchange and Stock Markets*, Rev. Fin. Studies, vol. 88, no. 4, 1989, pp. 427-445.
- [157] R. E. KALMAN, *Contributions to the Theory of Optimal Control*, Bol. Soc. Mat. Mex., vol. 5, 1960, pp. 102-119.
- [158] M. H. KALOS AND P. A. WHITLOCK, *MONTE CARLO METHODS*, Volume I: Basics, John Wiley and Sons, NY, 1986.
- [159] M. I. KAMIEN AND N. L. SCHWARTZ, *Dynamic Optimization: The Calculus of Variations and Optimal Control in Economics and Management*, North-Holland, New York, NY, 1981.
- [160] I. KARATZAS, J. P. LEHOCZKY, S. P. SETHI AND S. E. SHREVE, *Explicit Solution of a General Consumption/Investment Problem*, Math. Oper. Res., vol. 11, 1986, pp. 261-294. (Reprinted in Sethi [245, Chapter 2].)
- [161] I. KARATZAS AND S. E. SHREVE, *Methods of Mathematical Finance*, Springer-Verlag, New York, NY, 1998.
- [162] S. KARLIN AND H. M. TAYLOR, *A First Course in Stochastic Processes*, 2nd ed., Academic Press, New York, NY, 1975.
- [163] S. KARLIN AND H. M. TAYLOR, *A Second Course in Stochastic Processes*, Academic Press, New York, NY, 1981.
- [164] D. E. KIRK, *Optimal Control Theory: An Introduction*, Prentice-Hall, Englewood Cliffs, NJ, 1970. (Reprinted by Dover Publications, Mineola, NY, 2004.)
- [165] F. C. KLEBANER, *Introduction to Stochastic Calculus with Applications*, Imperial College Press, London, UK, 1998.
- [166] P. E. KLOEDEN AND E. PLATEN, *Numerical Solution of Stochastic Differential Equations*, Springer-Verlag, New York, NY, 1992.
- [167] P. E. KLOEDEN, E. PLATEN AND H. SCHURZ, *Numerical Solution of SDE Though Computer Experiments*, Springer-Verlag, New York, NY, 1994.
- [168] P. KOKOTOVIĆ, H. K. KHALIL AND J. O'REILLY, *Singular Perturbation Methods in Control: Analysis and Design*, Academic Press, New York, NY, 1986.

- [169] A. N. KOLMOGOROV AND S. V. FOMIN, *Introductory Real Analysis*, R. A. Silverman (Translator), Dover Publications, New York, NY, 1970.
- [170] S. G. KOU, *A Jump Diffusion Model for Option Pricing*, Management Science, vol. 48, 2002, pp. 1086–1101.
- [171] S. G. KOU AND H. WANG, *Option Pricing Under a Double Exponential Jump Diffusion Model*, Management Science, vol. 50 (9), 2004), pp. 1178–1192.
- [172] K. KOYA, H. KIMURA AND M. KAWATO, *Neural Mechanisms of Learning and Control* IEEE Control Systems Magazine, vol. 21, no. 4, August 2001, pp. 42-54.
- [173] H. KUNITA AND S. WATANABE, *On Square-Integrable Martingales*, Nagoya Math. J., vol. 30, 1967, pp. 209-245.
- [174] H. J. KUSHNER, *Stochastic Stability and Control*, Academic Press, New York, NY, 1967.
- [175] H. J. KUSHNER, *A Survey of Some Applications of Probability and Stochastic Control Theory to Finite Difference Methods for Degenerate Elliptic and Parabolic Equations*, SIAM Review, vol. 18, 1976, pp. 545-577.
- [176] H. J. KUSHNER, *Numerical Methods for Stochastic Control in Continuous Time*, SIAM J. Control and Optimizations, vol. 28, 1990, pp. 999-1048.
- [177] H. J. KUSHNER, *Jump-Diffusions with Controlled Jumps: Existence and Numerical Methods*, J. Math. Anal. Applic., vol. 249, no. 1, 2000, pp. 179-198.
- [178] H. J. KUSHNER AND G. DIMASI, *Approximation for Functionals and Optimal Control Problems on Jump Diffusions Processes*, J. Math. Anal. Applic., vol. 63, 1978, pp. 772-800.
- [179] H. J. KUSHNER AND P. G. DUPUIS, *Numerical Methods for Stochastic Control Problems in Continuous Time*, 2nd Edition, Springer-Verlag, New York, NY, 2001.
- [180] H. J. KUSHNER AND D. J. JARVIS, *Large-Scale Computations for High Dimension Control Systems*, in Proc. 33rd IEEE Conference on Decision and Control, vol. 1, 1994, pp. 461-465.
- [181] H. J. KUSHNER AND G. G. YIN, *Stochastic Approximation Algorithms Recursive Algorithms and Applications*, Springer-Verlag, New York, NY, 2003.
- [182] R. E. LARSON, *A Survey of Dynamic Programming Computational Procedures*, IEEE Transactions on Automatic Control, vol. AC-16, 1967, pp. 767-774.
- [183] G. P. LEPAGE, *A New Algorithm for Adaptive Multidimensional Integration*, Journal of Computational Physics, vol. 27, no. 2, 1978, pp. 192-203.

- [184] F. L. LEWIS, *Optimal Estimation with an Introduction to Stochastic Control Theory*, John Wiley, New York, NY, 1986.
- [185] M. J. LIDTHILL, *Introduction to Fourier Analysis and Generalised Functions*, Cambridge University Press, Cambridge, UK, 1964.
- [186] A. LIPTON, *Mathematical Methods for Foreign Exchange: A Financial Engineer's Approach*, World Scientific, Singapore, 2001.
- [187] D. LUDWIG, *Stochastic Population Theories*, Springer-Verlag, New York, NY, 1974.
- [188] D. LUDWIG, *Persistence of Dynamical Systems Under Random Perturbations*, SIAM Review, vol. 17, 1979, pp. 605-640.
- [189] D. LUDWIG, *Optimal Harvesting of a Randomly Fluctuating Resource. I: Application of Perturbation Methods*, SIAM J. Applied Mathematics, vol. 37, 1979, pp. 166-184.
- [190] D. LUDWIG AND J. M. VARAH, *Optimal Harvesting of a Randomly Fluctuating Resource. II: Numerical Methods and Results*, SIAM J. Applied Mathematics, vol. 37, 1979, pp. 185-205.
- [191] Y. MAGHSOODI, *Mean Square Efficient Numerical Solution of Jump-Diffusion Stochastic Differential Equations*, Sankhyā: Indian J. Stat., vol. 58, ser. A, pt. 1, 1996, pp. 25-47.
- [192] Y. MAGHSOODI AND C. J. HARRIS, *In-Probability Approximation and Simulation of Nonlinear Jump-Diffusion Stochastic Differential Equations*, IMA J. Math Control & Info., vol. 4, 1996, pp. 65-492.
- [193] M. MANGEL, *Decision and Control in Uncertain Resource Systems*, Academic Press, New York, NY, 1985.
- [194] M. MARITON, *Jump Linear Systems in Automatic Control*, M. Dekker, New York, NY, 1990.
- [195] G. MARSAGLIA AND T. A. BRAY, *A Convenient Method for Generating Normal Variables*, SIAM Rev., vol. 6, 1964, pp. 260-264.
- [196] D. Q. MAYNE, *A Second-Order Gradient Method for Determining Optimal Control of Non-Linear Discrete Time Systems*, International Journal of Control, vol. 3, 1966, pp. 85-95.
- [197] D. Q. MAYNE, *Differential Dynamic Programming — A Unified Approach to the Optimization of Dynamical Systems*, Control and Dynamical Systems: Advances in Theory and Applications, vol. 10, C. T. Leondes, ed., Academic Press, New York, NY, 1973, pp. 179-254.

- [198] R. C. MERTON, *Lifetime Portfolio Selection Under Uncertainty: The Continuous-Time Case*, Rev. Econ. and Stat., vol. 51, 1969, pp. 247-257. (Reprinted in Merton [203, Chapter 4].)
- [199] R. C. MERTON, *Optimum Consumption and Portfolio Rules in a Continuous-Time Model*, J. Econ. Theory, vol. 3 (4), 1971, pp. 373-413. (Reprinted in Merton [203, Chapter 5].)
- [200] R. C. MERTON, *Eratum*, J. Econ. Theory, vol. 6, no. 2, 1973, pp. 213-214.
- [201] R. C. MERTON, *Theory of Rational Option Pricing*, Bell J. Econ. Mgmt. Sci., vol. 4, 1973 (Spring), pp. 141-183. (Reprinted in Merton [203, Chapter 8].)
- [202] R. C. MERTON, *Option Pricing When Underlying Stock Returns are Discontinuous*, J. Financial Economics, vol. 3, 1976, pp. 125-144. (Reprinted in Merton [203, Chapter 9].)
- [203] R. C. MERTON, *Continuous Time Finance*, Blackwell Publishers, Cambridge, MA, 1992.
- [204] R. C. MERTON AND M. S. SCHOLES, *Fischer Black*, J. Finance, vol. 50, no. 5, 1996, pp. 1359-1369.
- [205] W. C. MESSNER AND D. M. TILBURY, *Control Tutorials for MATLAB And Simulink: User's Guide*, Addison-Wesley Publ. Co., 2002; see also URL:<http://www.engin.umich.edu/group/ctm/>.
- [206] N. METROPOLIS, *The Beginning of the Monte Carlo Method*, Los Alamos Science, Special Issue Dedicated to S. Ulam, 1987, pp. 125-130. URL:<http://www.fas.org/sgp/othergov/doe/lanl/pubs/00326866.pdf>.
- [207] N. METROPOLIS, A. N. ROSENBLUTH, M. N. ROSENBLUTH, A. H. TELLER, AND E. TELLER' *Equation of State Calculation by Fast Computing Machines*, J. Chem. Phys., vol. 21, no. 6, 1953, 10871092.
- [208] N. METROPOLIS AND S. ULAM, *The Monte Carlo Method*, J. Amer. Stat. Assoc., vol. 44, no. 247, 1949, pp. 335-341.
- [209] T. MIKOSCH, *Elementary Stochastic Calculus: with Finance in View*, World Scientific, Singapore, 1998.
- [210] C. MOLER, ET AL., *Using MATLAB*, vers 6., Mathworks, Natick, MA, 2000.
- [211] F. MOSS, L. M. WARD AND W. G. SANNITA, *Stochastic Resonance and Sensory Information Processing*, Clinical Neurophysiology, vol. 115, 2004, pp. 267-281.
- [212] G. I. MURPHY, *Clupeoids*, in Fish Population Dynamics, J. A. Gulland (Editor), John Wiley, New York, NY, 1977, pp. 283-308.

- [213] J. D. MURRAY, *Mathematical Biology, I: An Introduction*, Springer-NY, New York, NY, 2002.
- [214] J. D. MURRAY, *Mathematical Biology, II: Spatial Models and Biomedical Applications*, Springer-NY, New York, NY, 2003.
- [215] R. M. MURRAY, K. J. ASTRÖM, R. W. BROCKETT AND G. STEIN, *Future Directions in Control in an Information Rich World: A Summary of the Report of the Panel on Future Directions in Control, Dynamics, and Systems*, IEEE Control Systems Magazine, vol. 23, no. 2, April 2003, pp. 20-33; see also URL:<http://www.cds.caltech.edu/~murray/cdspanel/>, California Institute of Technology, April 2002.
- [216] K. NAIMIPOUR AND F. B. HANSON, *Convergence of a Numerical Method for the Bellman Equation of Stochastic Optimal Control with Quadratic Costs and Constrained Control*, Dynamics and Control, vol. 3, no. 3, 1993, pp. 237-259.
- [217] S. N. NEFTCI, *Introduction to the Mathematics of Financial Derivatives*, 2nd ed., Academic Press, New York, NY, 2000.
- [218] H. NIEDERREITER, *Random Number Generation and Quasi-Monte Carlo Methods*, SIAM, Philadelphia, PA, 1989.
- [219] R. M. NISBET AND W. S. C. GURNEY, *Modelling Fluctuating Populations*, John Wiley, New York, NY, 1982.
- [220] N. S. NISE, *Control Systems Engineering*, John Wiley, New York, NY, 2000.
- [221] J. NOCEDAL AND S. J. WRIGHT, *Numerical Optimization*, Springer-Verlag, New York, NY, 1999.
- [222] B. ØKSENDAL, *Stochastic Differential Equations: An Introduction with Applications*, Fifth ed., Springer-Verlag, New York, NY, 1998.
- [223] B. ØKSENDAL AND A. SULEM, *Applied Stochastic Control of Jump Diffusions*, Springer-Verlag, Berlin, 2005.
- [224] E. PARZEN, *Stochastic Processes*, Holden-Day, San Francisco, CA, 1962.
- [225] S. R. PLISKA, *Introduction to Mathematical Finance: Discrete Time Models*, Blackwell Publishers, Cambridge, MA, 1997.
- [226] L. S. PONTRYAGIN, V. G. BOLTYANSKII, R. V. GAMKRELIDZE AND E. F. MISHCHENKO, *The Mathematical Theory of Optimal Processes*, Wiley-Interscience Publishers, New York, NY, 1962.
- [227] E. POLAK, *An Historical Survey of Computational Methods in Optimal Control*, SIAM Review, vol. 15, 1973, pp. 553-584.

- [228] C. J. PRATICO, F. B. HANSON, H. H. XU, D. J. JARVIS AND M. S. VETTER, *Visualization for the Management of Renewable Resources in an Uncertain Environment*, in Proc. Supercomputing '92, 1992, pp. 258-266, color plates p. 843.
- [229] W. H. PRESS AND G. R. FARRAR, *Recursive Stratified Sampling for Multidimensional Monte Carlo Integration*, Computers in Physics, vol. 4, no. 2, 1990, pp. 190-195.
- [230] W. H. PRESS, S. A. TEUKOLSKY, W. T. VETTERLING AND B. P. FLANNERY, *Numerical Recipes in C++: The Art of Scientific Computing*, 2nd ed., Cambridge University Press, Cambridge, UK, 2002.
- [231] A. PRIPLATA, J. NIEMI, M. SALEN, J. HARRY L. A. LIPSITZ AND J. J. COLLINS, *Noise-Enhanced Human Balance Control*, Phys. Rev. Lett., vol. 89, no. 23, 2002, pp. 2381011-2381014.
- [232] P. PROTTER, *Stochastic Integration and Differential Equations: A New Approach*, Springer-Verlag, Berlin, 2004.
- [233] D. W. REPPERGER, *Celebrating the 100th Anniversary of Controlled, Sustained, and Powered Air Flight*, in IEEE Control Systems Magazine, vol. 23, no. 6, 2003, pp. 12-16.
- [234] *Research Directions in Distributed Parameter Systems*, R. C. Smith and M. A. Demetriou (Editors), SIAM, Philadelphia, PA, 2003.
- [235] R. RISHEL, *Modeling and Portfolio Optimization for Stock Prices Dependent on External Events*, in Proc. 38th IEEE Conference on Decision and Control, 1999, pp. 2788-2793.
- [236] L. C. G. ROGERS AND D. WILLIAMS, *Diffusions, Markov Processes and Martingales*, Cambridge University Press, Cambridge, UK, 2000.
- [237] S. M. ROSS, *Stochastic Processes*, John Wiley, New York, NY, 1983.
- [238] S. M. ROSS, *Introduction to Probability Models*, 7th ed., Academic Press, 2000.
- [239] W. J. RUNGALDIER, *Jump-Diffusion Models*, in Handbook of Heavy Tailed Distributions in Finance, S. T. Rachev (Editor), Handbooks in Finance, Elsevier/North-Holland, New York, NY, 2003, pp. 169-209.
- [240] D. RUST, *Do People Behave According to Bellman's Principle Optimality?*, Hoover Institution Working Paper E-92-10, 65 pages, 1994.
- [241] D. RYAN AND F. B. HANSON, *Optimal Harvesting with Exponential Growth in an Environment with Random Disasters and Bonanzas*, Math. Biosci., vol. 74, 1985, pp. 37-57.

- [242] D. RYAN AND F. B. HANSON, *Optimal Harvesting of a Logistic Population in an Environment with Stochastic Jumps*, J. Math. Biol., vol. 24, 1986, pp. 259-277.
- [243] T. H. RYDBERG, *The Normal Inverse Gaussian Lévy Process: Simulation and Approximation*, Comm. Stat. Stoch. Models, vol. 13, 1997, pp. 887-910.
- [244] Z. SCHUSS, *Theory and Applications of Stochastic Differential Equations*, John Wiley, New York, NY, 1980.
- [245] S. P. SETHI, *Optimal Consumption and Investment with Bankruptcy* Kluwer Academic Publishers, Boston, MA, 1997.
- [246] S. P. SETHI AND M. TAKSAR, *A Note on Merton's "Optimum Consumption and Portfolio Rules in a Continuous-Time Model"* J. Econ. Theory, vol. 46 (2), 1988, pp. 395-401. (Reprinted in Sethi [245, Chapter 3].)
- [247] S. P. SETHI AND Q. ZHANG, *Hierarchical Decision Making in Stochastic Manufacturing Systems* Birkhäuser, Boston, MA, 1994.
- [248] S. E. SHREVE, *Stochastic Calculus Models for Finance II: Continuous-Time Models*, Springer-Verlag, New York, NY, 2004.
- [249] L. SIMPSON-HERREN AND H. H. LLOYD, *Kinetics Parameters and Growth Curves for Experimental Tumor Systems*, Cancer Chemo. Reps., vol. 54, 1970, pp. 143-174.
- [250] C. SINDERMANN, *Principal Diseases of Marine Fish and Shellfish*, Academic Press, New York, NY, 1970.
- [251] I. N. SNEDDON, *Elements of Partial Differential Equations*, McGraw-Hill Book Co., New York, NY, 1957.
- [252] D. L. SNYDER AND M. I. MILLER, *Random Point Processes in Time and Space*, 2nd ed., Springer-Verlag, New York, NY, 1991.
- [253] I. M. SOBOLOV, *On the Distribution of Points in a Cube and the Approximate Evaluation of Integrals* Comp. Math. and Math. Physics (Engl. Transl.), vol. 7, 1967, pp. 784-802.
- [254] H. W. SORENSEN (ED.), *Kalman Filtering: Theory and Application*, IEEE Press, New York, NY, 1985.
- [255] G. G. STEEL, *Growth Kinetics of Tumors*, Clarendon Press, Oxford, UK, 1977.
- [256] J. M. STEELE, *Stochastic Calculus and Financial Applications*, Springer-NY, New York, NY, 2001.
- [257] R. B. STEIN, *Nerve and Muscle: Membranes, Cells, and Systems*, Plenum Press, New York, NY, 1980.

- [258] R. STENGEL, *Stochastic Optimal Control: Theory and Application*, Dover Publications, New York, NY, 1994.
- [259] S. STOJANOVIC, *Computational Financial Mathematics using Mathematica: Optimal Trading in Stocks and Options*, Birkhäuser, Boston, MA, 2002.
- [260] R. L. STRATONOVICH, *A New Representation for Stochastic Integrals and Equations*, SIAM J. Control, vol. 4, 1966, pp. 362-371.
- [261] G. W. SWAN, *Applications of Optimal Control in Biomedicine*, Marcel Dekker, New York, NY, 1984.
- [262] K. R. SWANSON, *Mathematical Modeling of the Growth and Control of Tumors*, Ph.D. Thesis, University of Washington, Seattle, 1999.
- [263] A. E. TAYLOR AND W. R. MANN, *Advanced Calculus*, 2nd ed., Xerox College Publishing, Lexington, MA, 1972.
- [264] D. TAVELLA AND C. RANDALL, *Pricing Financial Instruments: The Finite Difference Method*, John Wiley, New York, NY, 2000.
- [265] H. M. TAYLOR AND S. KARLIN, *An Introduction to Stochastic Modeling*, 3rd ed., Academic Press, New York, NY, 1998.
- [266] C. TIER AND F. B. HANSON, *Persistence in Density Dependent Stochastic Populations*, Mathematical Biosciences, vol. 53, 1981, pp. 89-117.
- [267] H. C. TIJMS, *Stochastic Modelling and Analysis: A Computational Approach*, John Wiley, New York, NY, 1986.
- [268] D. M. TILBURY AND W. C. MESSNER, *Control Tutorials for Software Instruction over the World Wide Web*, IEEE Trans. Automatic Control, vol. 42, no. 4, 1999, pp. 237-246.
- [269] H. C. TUCKWELL, *Stochastic Processes in the Neurosciences*, SIAM, Philadelphia, PA, 1989.
- [270] H. C. TUCKWELL, *Elementary Applications of Probability Theory*, Chapman and Hall, London, UK, 1995.
- [271] M. TURELLI, *Random Environments and Stochastic Calculus*, Theor. Population Biol., vol. 12, 1977, pp. 140-178.
- [272] W. T. VETTERLING, S. A. TEUKOLSKY, W. H. PRESS AND B. P. FLANERY, *Numerical Recipes: Example Book [C++]*, 2nd ed., Cambridge University Press, Cambridge, UK, 2002.
- [273] J. VON NEUMANN, *Various Techniques Used in Connection with Random Digits*, in Applied Mathematics Series, vol. 12, U. S. National Bureau of Standards, 1951, pp. 36-38.

- [274] J. J. WESTMAN AND F. B. HANSON, *The LQGP Problem: A Manufacturing Application*, in Proc. American Control Conference, 1997, pp. 566-570.
- [275] J. J. WESTMAN AND F. B. HANSON, *Nonlinear State Dynamics: Computational Methods and Manufacturing Example*, International Journal of Control, 2000, vol. 73, pp. 464-480.
- [276] J. J. WESTMAN AND F. B. HANSON, *State Dependent Jump Models in Optimal Control*, in Proc. 38th IEEE Conference on Decision and Control, 1999, pp. 2378-2383.
- [277] J. J. WESTMAN AND F. B. HANSON, *Nonlinear State Dynamics: Computational Methods and Manufacturing Example*, International Journal of Control, vol. 73, 2000, pp. 464-480.
- [278] J. J. WESTMAN AND F. B. HANSON, *MMS Production Scheduling Subject to Strikes in Random Environments*, in Proc. American Control Conference, 2000, pp. 2194-2198.
- [279] J. J. WESTMAN, F. B. HANSON AND E. K. BOUKAS, *Optimal Production Scheduling for Manufacturing Systems with Preventive Maintenance in an Uncertain Environment*, in Proc. American Control Conference, 2001, pp. 1375-1380.
- [280] N. WIENER, *Differential Space*, Journal of Math. and Physics, vol. 2, 1923, pp. 132-174.
- [281] N. WIENER, *Generalized Harmonic Analysis*, Acta Mathematica, vol. 55, 1930, pp. 117-258.
- [282] P. WILMOTT, S. HOWISON AND J. DEWYNNE, *The Mathematics of Financial Derivatives: A Student Introduction*, Cambridge University Press, Cambridge, UK, 1996.
- [283] P. WILMOTT, *Derivatives: The Theory and Practice of Financial Engineering*, vols. 1 & 2, John Wiley, New York, NY, 2000.
- [284] P. WILMOTT, *Paul Wilmott on Quantitative Finance*, John Wiley, New York, NY, 1998.
- [285] S. WOLFRAM, *Mathematica: A System for Doing Mathematics by Computer*, Addison-Wesley, Reading, MA, 1988.
- [286] W. M. WONHAM, *Random Differential Equations in Control Theory*, in Probabilistic Methods in Applied Mathematics, vol. 2, Academic Press, New York, NY, 1970, pp. 131-212.
- [287] YAHOO! FINANCE, *Historical Quotes, S & P 500 Symbol ^SPC*, URL:<http://chart.yahoo.com/>, February 2001.

- [288] G. YAN, *Option Pricing for a Stochastic-Volatility Jump-Diffusion Model*, Ph.D. Thesis in Mathematics, Univ. Illinois at Chicago, Chicago, IL, 23 June 2006, 128 pages.
- [289] G. YAN AND F. B. HANSON, *Option Pricing for a Stochastic-Volatility Jump-Diffusion Model with Log-Uniform Jump-Amplitudes*, Proc. 2006 American Control Conference, 2006, pp. 2989-2994.
- [290] J. YONG AND X. Y. ZHOU, *Stochastic Controls: Hamiltonian Systems and HJB Equations*, Springer-Verlag, New York, NY, 1999.
- [291] Z. ZHU, *Option Pricing and Jump-Diffusion Models*, Ph.D. Thesis in Mathematics, Univ. Illinois at Chicago, Chicago, IL, 17 October 2005, 165 pages.
- [292] Z. ZHU AND F. B. HANSON, *A Monte-Carlo Option-Pricing Algorithm for Log-Uniform Jump-Diffusion Model* in Proc. 44nd IEEE Conference on Decision and Control and European Control Conference, 2005, pp. 5221-5226.
- [293] Z. ZHU AND F. B. HANSON, *Optimal Portfolio Application with Double-Uniform Jump Model* in Control Theory Applications in Financial Engineering and Manufacturing, International Series in Operations Research and Management Sciences, Springer/Kluwer, New York, NY, 2006, pp. 331-358, invited chapter.

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