

Book Review

Continuous-Time Finance. Robert C. Merton. Oxford, U.K.: Basil Blackwell, 1990. 700 pp., \$56.95 (cloth). ISBN 0-631-15847-2.

In his essay on “Ramsey as an Economist,” John Maynard Keynes alludes to economics in the following terms:¹ “. . . the delightful paths of our own most agreeable branch of moral sciences, in which theory and fact, intuitive imagination and practical judgment, are blended in a manner comfortable to the human intellect.” Robert C. Merton’s book entitled “*Continuous-Time Finance*,” which comes to us more than 20 years after his first paper appeared in the *Review of Economics and Statistics*, squarely fits this description.

During these two decades, Merton published several path-breaking papers spanning a broad spectrum of topics in economics and finance, including options, corporate debt, consumption portfolio rules, stochastic growth theory, capital asset pricing, and financial intermediation. Some of these papers are classics and on the required reading lists of most Ph.D. programs in finance and economics around the world.

This book pulls together several of his papers in a pedagogical sequence supplemented by Merton’s analysis and reflections on some recent research that has a bearing on the issues studied. In particular, the book has devoted a fair amount of attention and pages to analyzing recent developments in martingale representation theory as applied to arbitrage-free asset pricing and to optimal consumption and portfolio rules with explicit nonnegativity restrictions. In addition, the book also contains several new results pertaining to general equilibrium models of exchange and production economies and their applications to pricing and financial intermediation.

The publication of this book provides an opportunity to reflect on Merton’s seminal contributions to the area of continuous-time methods in finance and economics. To this end, Section 1 of this review will offer a survey of the evolution of this discipline in economics and finance. This brief survey will also serve as a frame of reference for the review of the book (also contained in Section 1). The concluding section offers some suggestions as to the manner in which this book may be used in advanced courses in finance and economics.

I thank Chester Spatt for his detailed and painstaking comments that significantly improved the style and substance of this review. My thanks are also due to Fernando Zapatero for his comments.

¹ *Economic Journal*, March 1930. Reprinted in “The Collected Writings of John Maynard Keynes,” Volume X. *Essays in Biography*, Macmillan, St. Martin’s Press, The Royal Economic Society.

Survey and Review

This book is about continuous-time methods and their contributions in finance. Although Bachelier's (1900) paper was probably the first paper ever to utilize continuous-time methods to study issues in financial economics, the power and beauty of this tool was brought to the attention of economists by Merton's early papers [e.g., Merton (1969, 1971)]. It is now a standard and invaluable methodological tool for economists interested in intertemporal or dynamic models of economies and markets. Indeed, this tool has become the workhorse for research in a number of areas in financial economics, including options pricing and contingent claims analysis.

The first part of the book begins with a chapter on "Modern Finance," which is an overview of the discipline as well as the book. Chapter 2 develops the basic tools and results for the static portfolio theory, mutual funds separation theorems, and equilibrium considerations that lead to the Sharpe-Lintner-Mossin capital asset pricing model (CAPM). Further, it develops the concept of spanning portfolios and contains a discussion of the arbitrage pricing theory (APT) model of asset pricing [Ross (1976)]. Chapter 3 contains an accessible treatment of continuous-time stochastic processes with emphasis on the mathematical and economic assumptions that underlie their construction. Together, these chapters provide the reader with a broad overview of the discipline and a quick "working knowledge" of continuous-time processes. A deeper understanding of continuous-time stochastic processes will require significant investments in probability theory and stochastic processes. Such an investment is necessary to carry out research in this area, but to understand and appreciate the contributions in the literature, a less rigorous exposure is probably sufficient.

The contributions in continuous-time finance may be collected in six distinct areas. The book addresses these six areas in different levels of depth and hence such a classification provides a nice frame of reference from which to evaluate the book.

Optimal consumption and portfolio rules. The second part of the book is anchored around this topic. This literature derived and characterized optimal consumption and portfolio behavior of expected (separable) utility maximizing individuals. For the hyperbolic absolute risk aversion (HARA) class of utility functions, Merton (1969, 1971) examined the consumption and savings decisions using stochastic dynamic programming techniques. He also investigated the

² In discrete time, Hakansson (1970) derived results that are of a similar flavor.

impact of a stochastic opportunity set on consumption and portfolio decisions.² These papers provide the foundation for the second part of the book. Chapters 4 and 5 are based on Merton (1969) and Merton (1971), respectively. This strand of literature laid the groundwork for subsequent developments in the area of asset pricing and the term structure of interest rates. Much of this work ignored the possibility that for some members of the HARA family, nonnegativity restrictions may be binding. In Cox and Leland (1982), such nonnegativity restrictions were accounted for explicitly and optimal consumption and portfolio rules derived *without recourse to the stochastic dynamic programming approach*.³ This paper was a precursor to a number of important papers in this area that reduced the dynamic problem to a static problem using the martingale representation theory. The notable paper of Cox and Huang (1989) contains a comprehensive treatment of this approach and significantly generalizes the results of Cox and Leland (1982). In a recent paper, Karatzas, Lehoczky, and Shreve (1987) extend these results to a richer class of processes. Duffie and Huang (1985, 1986) have shown how such approaches may be used to implement the complete market welfare results using a few long-lived securities that may be traded continuously. Chapter 6 of the book contains an insightful treatment of martingale representation theory and the growth-optimum portfolio construction. This chapter examines Cox and Huang (1989) and studies the impact of nonnegativity restrictions on consumption and portfolio rules. Much of the analysis in this context is also followed up in Chapters 15 and 16. For readers who have not had a good exposure to the martingale representation theory, this chapter, coupled with Cox and Leland (1982), might provide the necessary groundwork and motivation to pursue this important strand of research. More advanced papers by Cox and Huang (1989) and Karatzas, Lehoczky, and Shreve (1987) require a solid grounding in martingale representation theory, but these papers are quite important for a deeper understanding of this approach.

In addition, Chapter 6 also considers multiple-good economies and utility functions that are state dependent. Merton briefly explores the impact of introducing money balances as an argument in the utility function and considers transactions cost technologies. A number of recent papers have explored inter-temporally dependent preferences with a view to study the effect of such preferences on optimal consumption and portfolio behavior and asset pricing. Articles by Sundaresan (1989), Constantinides (1990), and Huang and Kreps (1987) fall in this category. Multiple-good economies and their implications

³ Papers by Karatzas et al. (1986) and Lehoczky, Sethi and Shreve (1983) also examined such constraints.

for pricing derivative assets and term structure also have been explored in Breeden (1979) and Richard and Sundaresan (1981). Chapter 6 provides a good summary of multigood economies and state-dependent utility functions.

Options pricing. This strand is probably the most well-known application of continuous-time methods. Black and Scholes (1973) and Merton (1973b) provided the initial breakthroughs in options pricing. The power of the no-arbitrage condition in pricing securities was pioneered in these papers. The third part of the book focuses on options and warrants pricing. Chapter 7 considers the pricing of warrants and is drawn from Samuelson and Merton (1969). Chapter 8 is based on the classic Merton (1973b). The insights of these papers are still being refined and generalized in many directions. One of the refinements is the pricing of options when the underlying security returns are discontinuous. This is treated in Chapter 9 and is based on Merton (1976), which provides an options pricing formula when the jump risk is diversifiable. In a recent article, Naik and Lee (1990) provide an equilibrium model of option pricing in which jump risk is not diversifiable. Another refinement is the risk-neutral valuation technique. A lucid exposition of arbitrage pricing techniques related to options is to be found in Cox and Ross (1976b), which builds on the insights of Merton (1973b) and provides new results on pricing operators. The risk-neutral pricing procedure is also formulated by Cox and Ross (1976a) and subsequently shown to be a rather general feature of arbitrage-free economies by Harrison and Kreps (1979). In the risk-neutral pricing principle, the pricing operator is an expectation taken with respect to a martingale measure. Linearity of the pricing operator was also derived by Ross (1976, 1978) in discrete-time settings. Chapter 10 surveys recent developments in options pricing with special emphasis on the Cox and Ross (1976a) risk-neutral valuation procedure and options on futures contracts. Chapters 7 and 8, together with Black and Scholes (1973), will provide the basic introduction to options pricing theory. This is a necessary first step. This should be followed by Cox and Ross (1976a), Harrison and Kreps (1979), and Harrison and Pliska (1981) to get a deeper appreciation of the basic pricing operator, which is an expectation of the terminal cash flows taken with respect to a martingale measure. The concepts of "doubling strategies," "admissible trading strategies," etc., are best learned in this context. It is also useful to review the material in the third part with the discrete-time options pricing approach of Cox, Ross, and Rubinstein (1979) as well as the recent work of Nelson and Ramaswamy (1990), which provides useful discrete-time approximations for options pricing by incorporating a richer

set of stochastic processes than was considered in Cox, Ross, and Rubinstein (1979).

CCA and corporate finance applications. One of the major offshoots of options pricing theory is contingent claims analysis (CCA). Part IV of the book investigates CCA and financial intermediation. The recognition that many corporate liabilities may be thought of as positions in options on the underlying assets of the firm led to several important contributions. In part IV, these contributions are reviewed. Chapter 11 provides a general equilibrium treatment of asset markets and applies it to value the capital structure of the firm. Chapter 12 applies the CCA to value the risk structure of interest rates. This chapter is drawn from Merton (1974). An ideal companion paper is that of Black and Cox (1976), which considers subordinated debt and safety covenants. Chapter 13 illustrates the power of CCA and surveys applications ranging from the “value of waiting to invest”, to “mutual fund insurance.” This is an ideal chapter to motivate students about the broad range of CCA. Chapter 14 develops a theory of financial intermediation in a continuous-time setting with applications to derivative securities pricing. The valuation of other derivative assets such as forward contracts and futures contracts has also been grounded largely in a continuous-time setting [see Black (1976), Cox, Ingersoll, and Ross (1981a), and Richard and Sundaresan (1981)]. The CCA has been used in the context of capital budgeting applications as well. This strand of research fits in nicely with the material in part IV.

Intertemporal asset pricing models. Part V of the book is devoted to the development of equilibrium pricing theory. Three major papers in this area are Merton (1973a), Breeden (1979), and Cox, Ingersoll, and Ross (1985a). The generalization of Sharpe-Lintner-Mossin CAPM to inter-temporal settings (multibeta CAPM) was a major step first undertaken in Merton (1973a). Its simplification to a single (consumption) beta consumption CAPM was achieved in Breeden (1979). Cox, Ingersoll, and Ross (1985a) embedded such models in production economies in a rational expectations equilibrium framework. Merton’s paper was the first to aggregate the portfolio demands to derive the equilibrium intertemporal capital asset pricing model (ICAPM). The impact of a stochastic opportunity set on asset pricing was clearly identified. Breeden (1979) showed that what mattered in pricing is really the optimal consumption path. The envelope condition, which links the marginal utility of consumption to the marginal (derived) utility of wealth, provided the clue to collapse the multibeta ICAPM to a single consumption beta CAPM for separable utility functions. *The asset price processes were specified exogenously*

in these models. No closure was offered to endogenize the price processes. Cox, Ingersoll, and Ross (1985a) offered a rational expectations closure in the context of a stochastic production economy. The resulting equilibrium price processes were intertemporally consistent and endogenous.⁴ Each paper in its own way is a landmark. Chapter 15 is drawn from the ICAPM model of Merton (1973a). Chapter 16 follows up the development of financial intermediation in complete markets and develops optimal consumption and portfolio policies in markets that are dynamically complete. In addition, this chapter develops general equilibrium models of exchange and, production economies. ICAPM is derived in the context of a general equilibrium production economy. Part V is the core for teaching asset pricing theory. Supplemented by Breeden (1979), Cox, Ingersoll, and Ross (1985a), Lucas (1978), Rubinstein (1976), Huang (1985), Duffie and Huang (1985), and Prescott and Mehra (1980), this part could be the basis for understanding the contributions made by asset pricing theory.

Term structure of interest rates. The application of continuous-time methods to term structure was anticipated in Merton (1973b, 1975a). Much of the earlier work was cast in partial equilibrium settings in which “factor risk premia” were specified exogenously in an ad hoc manner. Richard (1978) is an example of such an approach. A full general equilibrium model of the term structure was developed in Cox, Ingersoll, and Ross (1985b) based on their general equilibrium pricing theory. Several of the traditional term structure hypotheses have been reexamined in a continuous setting. Cox, Ingersoll, and Ross (1981b) show that only the local expectations hypothesis (LEH) is free from arbitrage. The last part of the book contains a collection of papers that span stochastic growth theory, consumption-indexed pension plans, and deposit insurance. The growth theory paper contains the kernel of term structure analysis in a stochastic production economy, although not pursued to its logical conclusion by Merton. It also shows how the stationary distribution of stock of goods in the economy will influence the evolution of spot rate of interest and hence the term structure of interest rates. Much of the term structure theory has been developed in a continuous-time setting. Issues concerning the term structure are sufficiently distinct (relative to options pricing) that a chapter on the term structure might have rounded out the spectrum of topics nicely. Having said this, I recognize that the book is already 700 pages long and topics on

⁴ Major asset pricing developments in discrete-time settings during this period include Lucas (1978) and Prescott and Mehra (1980).

transactions costs and term structure may be studied by supplementing from either Bhattacharya and Constantinides (1989) or other relevant papers.

Transactions costs, taxes, and frictions. In his address, Merton (1975b) has articulated the effective use of continuous-time methods in treating transactions costs? Rather than specifying uniformly spaced trading intervals (as done in discrete time), it is useful to start with the possibility of continuous trading where the presence of transactions costs will result in *endogenously determined trading intervals*. Given an opportunity to trade continuously, the consumer will choose to trade only at random intervals in the presence of transactions costs. The trading intervals are determined by times at which certain threshold levels of an economic variable are reached. Regulated Brownian motion methods have been used recently in the economics literature to explain stickiness in economic variables of interest. Applications of this tool are to be found in Dixit (1989) and Bentalola and Bertola (1990), for example. Grossman and Laroque (1990) provide an insightful analysis of the consumer's adjustment of durable good stock. An equilibrium treatment of this problem may be a key step toward understanding the manner in which the durable good accumulation process affects equity risk premia. This is yet another topic that falls within the subject matter addressed by the book. Constantinides (1983) treats taxes in a continuous-time setting. Merton touches upon some of the issues in this area, but has not devoted a chapter to this topic. Two factors might have contributed to this outcome. First, absent such imperfections, it is possible to present a coherent concept of equilibrium grounded in a common set of assumptions in exchange and production economies as done in the book. Such equilibrium models are naturally the backdrops for much of the analysis offered in the text. Second, given the nature of evolution of this strand of research, only recently have we seen satisfactory treatments of transactions costs. The article by Davis and Norman (1990) is surely a major step in characterizing the consumption portfolio problems with transactions costs. This article treats both continuous consumption and transactions that are subject to proportional transactions costs.⁶ It is an ideal companion article to Merton (1969, 1971) and hence could be used in conjunction with the text to remedy this deficiency. In this context, the book by Harrison (1985) might also serve as a companion text.

⁵ Merton's address in the distinguished speaker series at the Western Finance Association Meetings (1975) contains a general perspective on continuous-time methods in finance.

⁶ Duffie and Sun (1990) treat fixed plus proportional transactions costs.

The review in this section illustrates clearly the breadth of coverage. All topics, with the exception of term structure of interest rates (topic 5) and taxes, transaction costs, and frictions (topic 6), are dealt with in considerable detail in the text. The extensive treatment of topics on optimal consumption and portfolio theory, asset pricing, options pricing, the martingale representation ideas, and CCA is not replicated easily by combinations of other books and articles without losing the tractability and accessibility offered in this book. These topics are handled in considerable depth as well. A graduate student with adequate exposure to microeconomics and probability theory will not only get a sweeping perspective on these topics, but also a solid grounding concerning the economic issues and modeling considerations in these topics, which are intertemporal in their scope.

2. Conclusions

Given its breadth and depth, this book is an ideal text to introduce Ph.D. students to continuous-time finance. It could be used in either of the following ways.

- (i) As the basic text in a Ph.D. course that introduces students to the power of continuous-time methods in tackling dynamic problems in finance and economics. The book is (a) self-contained in developing an accessible treatment of continuous-time-state stochastic processes and stochastic control and (b) powerful in illustrating its applications to a broad range of economic problems. Used this way, the book's effectiveness as a text will be enhanced by supplementing it with major papers in transactions costs, the martingale representation ideas, etc. This book might also be combined with Bhattacharya and Constantinides (1989), which has two chapters on transactions costs and a more detailed treatment of term structure of interest rates and arbitrage pricing theory. Under this suggested alternative, students who wish to develop additional grounding in continuous-time methods will have to take an advanced course in continuous-time methods.
- (ii) Alternatively, this book might be used in conjunction with a broader menu of papers or a more technical book such as Duffie (1988) or Karatzas and Shreve (1987) in an advanced course on continuous-time methods. Used this way, this text will play the role of illustrating how the literature has evolved over time and provide a backdrop and a perspective on more recent developments and contributions.

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