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Robert C. Merton and the Science of Finance

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Abstract

Starting with his 1970 doctoral dissertation and continuing to today, Robert C. Merton has revolutionized the theory and practice of finance. In 1997, Merton shared a Nobel Prize in Economics "for a new method to determine the value of derivatives." His contributions to the science of finance, however, go far beyond that. In this article I describe Merton's main contributions. They include the following:

1. The introduction of continuous-time stochastic models (the Ito calculus) to the theory of household consumption and investment decisions. Merton's technique of dynamic hedging in continuous time provided a bridge between the theoretical complete-markets equilibrium model of Kenneth Arrow and the real world of personal financial planning and management.
2. The derivation of the multifactor Intertemporal Capital Asset Pricing Model (ICAPM). The ICAPM generalizes the single-factor CAPM and explains why that model might fail to properly account for observed market excess returns. It also provides a theory to identify potential forward-looking risk premia for use in factor-based investment strategies. It is therefore both a positive and normative theory.

3. The invention of Contingent Claims Analysis (CCA) as a generalization of option pricing theory. CCA applies the technique of dynamic replication to the valuation and risk management of a wide range of corporate and government liabilities. Merton's CCA model for the valuation and analysis of risky debt is known among scholars and practitioners alike as the Merton Model.
4. The development of financial engineering, which employs CCA to design and produce new financial products. Merton was the first to apply CCA to analyze government guaranty programs such as deposit insurance, and to suggest improvements in the way those programs are managed. He and his students have applied his insights at both the micro and macro policy levels.
5. And finally, the development of a theory of financial intermediation that explains and predicts how financial systems differ across countries and change over time. Merton has applied that theory, called functional and structural finance, to guide the design and regulation of financial systems at the levels of the firm, the industry, and the nation. He has also used it to propose reforms in pensions, sovereign wealth funds, and macrostabilization policy.

INTRODUCTION

Finance, a branch of economics, is an applied science that deals with the allocation of scarce resources over time under conditions of uncertainty. Financial activities consist of borrowing, lending, saving, investing, hedging, and insuring. Finance also concerns the institutions that intermediate these activities—banks, mutual funds, insurance companies, pension funds, securities exchanges, and regulatory agencies—which taken as a whole are called the financial system. Eight Nobel Prizes in Economics have so far been awarded for work in finance. Robert C. Merton received his prize in 1997 "for a new method to determine the value of derivatives" (R. Swed. Acad. Sci. 1997).[1] However, his contributions to the science of finance go far beyond that. Paul Samuelson, the first American to receive the Nobel Prize in Economic Sciences, compared Merton's influence on finance to Isaac Newton's impact on physics. In this article I describe his contributions.

A BRIEF HISTORY OF FINANCIAL SCIENCE BEFORE MERTON

In his chronological annotated bibliography of the history of the theory of finance, Mark Rubinstein (2006) starts with Fibonacci's *Liber Abaci* (*The Book of Calculation*) published in 1202, which contains four examples of numerical calculations of present value of future cash flows. From 1202 until today mathematicians, economists, and actuaries have been discovering and rediscovering important concepts that have been incorporated into the body of finance theory. The most important theorist was Irving Fisher (1930), who developed a complete intertemporal theory of consumption and production under conditions of certainty. Fisher labeled his theory of interest the impatience and opportunity theory that results from the interaction of two forces: the time preference people have for consumption now, and the investment opportunity principle (that income invested now will yield greater income in the future).

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[1] The announcement by the committee that awarded the prize went on to say: "Robert C. Merton and Myron S. Scholes have, in collaboration with the late Fischer Black, developed a pioneering formula for the valuation of stock options. Their methodology has paved the way for economic valuations in many areas. It has also generated new types of financial instruments and facilitated more efficient risk management in society."

Arrow (1953, 1970) extended the theory to include uncertainty in a general equilibrium framework of complete markets for all contingencies. In that theory there is a set of pure time-state securities—now known as Arrow securities—each of which pays one unit of consumption in a particular contingent state and point in time. Among economists, Arrow's complete-markets state-preference model is the ideal against which the efficiency of real-world financial systems should be judged.

At the same time that Arrow was developing his model, Markowitz (1952, 1959) developed his mean-variance theory of portfolio selection. With an important extension by Tobin (1958), it provided a tractable model for quantifying the risk-return trade-off among securities. Building on the Markowitz-Tobin fundamental work, Sharpe (1964), Lintner (1965), Mossin (1966), and Treynor (1962) investigated the resulting theoretical equilibrium structure of asset prices and expected returns, and the Capital Asset Pricing Model (CAPM) became the foundational quantitative model for measuring the risk of a security. The CAPM would later give rise to the multitrillion-dollar business of passive investing via market-capitalization-weighted index funds, and it became the foundation of performance attribution for professional investment managers. As we will see, Merton was able to reconcile the mean-variance model with Arrow's model using dynamic trading in continuous time. Merton also showed how Arrow securities, thought to be purely theoretical constructs, could be produced in the real world.[2]

The Modigliani & Miller (1958) propositions for the determinants of corporate capital structure provided a rational framework for thinking about debt and equity and established the "no-arbitrage principle" as a fundamental principle in the science of finance. Arbitrage is a basic force in asset pricing. It enforces the Law of One Price, which says that if two securities or portfolios have the same payoffs in all states of nature, then they must have the same price. The proof is that if the prices differed, there would be an arbitrage opportunity, that is, an opportunity to earn a profit with no net outlay of funds. An individual would buy the cheaper security and simultaneously sell the more expensive one, and would have money left over to spend.

Another milestone of the 1960s research on investment practice was the Samuelson (1965) and Fama (1965) Efficient Markets Hypothesis (EMH), which holds that, in a well-functioning and informed capital market, the best estimate of an asset's future price is its current price, adjusted for a fair expected rate of return. Under this hypothesis, attempts to use past price data or publicly available forecasts about future economic fundamentals to earn a rate of return higher than the fair rate are doomed to failure.[3]

The Fisher & Lorie (1964) study of historical stock returns drew practitioner attention to the EMH. Using the newly created database of the Chicago Center for Research in Security Prices, Fisher & Lorie showed that a randomly selected stock held from the mid-1920s to the mid-1960s would have earned, on average, a 9.4% annual compound return. Returns of this magnitude were believed to be considerably larger than those most professional managers had earned for their clients during that period. Rigorous scientific confirmation of this belief was provided by a host of empirical performance studies along lines set by Jensen (1968) who used the CAPM as a benchmark to test for superior performance among United States mutual funds in the postwar period.

PAUL SAMUELSON'S RESEARCH ASSISTANT

Merton attended Columbia University School of Engineering & Applied Science, receiving a B.S. in Engineering Mathematics in 1966. He took several undergraduate and graduate mathematics courses, both applied and pure. It was there that he encountered Paul Samuelson for the first time

[2] Financial economists call such a financial environment dynamically complete.

[3] Fama defines the fair rate as the one that satisfies the CAPM.

in the form of his famous introductory textbook in economics (for additional details regarding Merton's relationship with Paul Samuelson, see Kritzman 2018). After Columbia, Merton went west to pursue a PhD in applied mathematics at the California Institute of Technology. Sometime during the year, he decided to leave CalTech (and mathematics) to study economics. He applied to half a dozen good departments, but only one, MIT, accepted him, and it gave him a full fellowship.

When he arrived at MIT in the fall of 1967, he discovered that Harold Freeman, statistician and member of the economics department from pre-Samuelson days, had recognized some of the mathematicians who had written his letters of recommendation and convinced the department to take a flyer.

Freeman then advised Merton to take Paul Samuelson's mathematical economics course. He did, and he loved the course. Samuelson was impressed by Merton and offered him a job as Research Assistant. Merton has described it thus:

> One day Samuelson asked me if I would read over a paper he had drafted involving Hamiltonian optimization for the math (not for its economic content). I spent the whole night going over it and over it making sure that I got everything as good as I knew how. The next day I left it with him at his office trying to look as nonchalant as I could and certainly not a hint of the all-nighter. Next class he offered me a job as his RA, and I moved into a desk in his outer office where I was for the next 2.5 years before moving to my office as a faculty member at Sloan.
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> I did not get particularly good grades in my courses in the department, mainly because I spent much more of my time "playing with" research ideas and then working on joint research with Paul than on detailed studying of class assignments. The exception was Paul's course.... We had to do a paper.... I did a paper on optimal growth theory that was eventually published: R.C. Merton, A Golden Golden-Rule for Welfare-Maximization in an Economy with a Varying Population Growth Rate *Western Economic Journal* 4 (December 1969): 307–318. (Merton 1970, chapter III)

In the course of his work for Samuelson, Merton discovered shared interests and some common knowledge about the stock market, warrants, and convertible securities. In the summer of 1968, they began a joint effort to advance Paul's 1965 theory of warrant pricing, which was subsequently published in 1969 (Samuelson & Merton 1969; Merton 1970, chapter IV; Merton 1990c, chapter 7).

Later in October, Merton would have his first experience presenting in a formal seminar. Merton writes:

> "My coauthor decided that I, the second-year grad student, and not he, the Institute Professor, would give our paper at the *inaugural* session of the MIT-Harvard Mathematical Economics seminar at Harvard. With a full audience of Harvard economics faculty including Kenneth Arrow, Wassily Leontief, and Hendrik Houthakker, it was surely a memorable baptism" (R. Swed. Acad. Sci. 1997)

CONTINUOUS-TIME FINANCE

That summer Merton also made his first major contribution to the theory of finance—he attacked, on his own, the lifetime dynamic consumption-portfolio selection problem in continuous time. There was a long tradition of life-cycle consumption models in economics, but none that incorporated uncertainty and included the portfolio selection decision.[4] He solved it using stochastic dynamic programming. Merton solving this problem motivated Samuelson to do a discrete-time version to investigate the effect of time horizon on the demand for stocks versus bonds over the life cycle. These two papers were published as companion papers in 1969, and Merton's paper became Chapter II in his dissertation (Merton 1969, Samuelson 1969; see also Merton 1970, chapter II).

[4] Franco Modigliani and Milton Friedman each received Nobel Prizes for their work on lifetime consumption behavior.

Merton's continuous-trading, dynamic portfolio theory resolved a serious challenge to the Markowitz-Tobin mean-variance model. Markowitz-Tobin was inconsistent with the generally accepted von Neumann-Morgenstern expected utility theory of rational choice, unless security returns were normally distributed. But normally distributed returns allow prices to be negative. In Merton's 1969 model, prices are lognormally distributed (which ensures non-negative prices) with means, variances, and covariances constant through time. The instantaneous optimal portfolio demand functions are identical to those in Markowitz-Tobin. Thus, by creating a more realistic dynamic/multiperiod model, Merton made the Markowitz-Tobin mean-variance results consistent with generally accepted economic theory.[5]

With the Markowitz-Tobin asset demand functions justified in continuous time, it followed immediately that if applying equilibrium pricing conditions to this special case, as Sharpe had done, one arrives at the same CAPM specification of equilibrium expected returns but holding over a specified infinitesimal interval of continuous trading.

In writing his MIT doctoral dissertation between 1968 and 1970, Merton became the first economist to use the Ito stochastic calculus to model the continuous-time dynamics of asset prices and portfolios.[6] Ito's lemma was introduced first in a March 1970 draft of "Optimum Consumption and Portfolio Rules in a Continuous-Time Model," Chapter 1 of his 1970 PhD dissertation, which was circulated as MIT Department of Economics Working Paper #58, in August 1970, and later published in the *Journal of Economic Theory* in 1971.

In that paper (Merton 1971), Merton applied Ito's lemma to derive much richer versions of the lifetime consumption-portfolio selection model with generalizations such as stochastic wages, mean reversion in returns, uncertain lifetime, and even jump diffusion defaults—all rendered tractable by positing the continuous-time assumption for the trading interval.

Unlike his 1969 paper that derived the Markowitz-Tobin portfolio allocation rules for expected utility and lognormality of asset returns, this paper shows that those rules would no longer apply in the intertemporal context if the investment opportunity set is not constant. Thus, Merton showed that the special case of constant mean, variance, and interest rate was the intellectual watershed connector case between the Markowitz-Tobin static one-period model and a richer set of portfolio rules, arising from a dynamic intertemporal model. His application of Ito's lemma in modeling portfolio dynamics was also the foundation tool he later applied to the Black-Scholes trading rules in his continuous-time model framework to demonstrate that their trading rule and resulting pricing formula obtained because of no-arbitrage.

DECEMBER 1970 MIT WORKING PAPER

Thanks to a job offer arranged by Franco Modigliani, Merton was hired and started teaching at MIT's Sloan School of Management in the fall of 1970. He already had several publications, but perhaps the most important one appeared as a working paper in December 1970, "A Dynamic General Equilibrium Model of the Asset Market and Its Application to the Pricing of the Capital Structure of the Firm" (Merton 1990a).[7] It contained early versions of at least three

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[5] The reason Merton succeeded in rationalizing the mean-variance approach was that he specified the trading interval to be continuous and not an arbitrary t, t+1, t+2…, where the arbitrary time interval between trades could be a nanosecond or 5 years.

[6] Despite all the mathematics courses that Merton had taken as a PhD student in applied mathematics, he had seen neither stochastic dynamic programming nor the Ito calculus, both of which turned out to be key mathematical tools needed for this research. Instead, driven by need, he found them and learned them on his own.

[7] The paper was not formally published until 1990 (Merton 1990, chapter 11).

groundbreaking papers on key aspects of finance theory: ICAPM (Merton 1973a), Rational Option Pricing (Merton 1973b), and Risky Corporate Debt (Merton 1974).

Among the other original insights presented in this same December 1970 working paper is a predecessor model of the term structure of interest rates to the well-known models of Vasicek (1977) and Cox, Ingersoll & Ross (CIR) (1985). The dynamic structure of the risk-free asset's stochastic changes include the posited dynamics in the Vasicek and CIR interest-rate models, although it did not specify and solve either of those specific model's dynamics.

In Section 5 of his 1970 working paper, Merton derived the Fundamental Partial Differential Equation of Security Pricing (including derivatives), where he also described the concept of what was later called risk-neutral pricing. His first derivation of the derivative pricing formula was based on a continuous-time, ICAPM two-factor version of the equilibrium pricing approach, which followed the original equilibrium CAPM formulation by Black and Scholes. Then Merton went on to derive the same formula with continuous trading, using Ito's lemma. He showed that there is no risk in the hedging portfolio, and therefore the Black-Scholes equation holds because of the Law of One Price and the force of arbitrage. Thus, the concept of a replicating portfolio was born, and the methodology was called Contingent Claims Analysis (CCA). We will return to the difference between the two derivations—Black-Scholes versus Merton—below in the section on Option Pricing and Contingent Claims Analysis.

In addition to the pricing of options, Merton's 1970 working paper also lays out four specific examples of pricing of the capital structure of the firm with the same CCA methodology: 1. debt and equity; 2. debt and equity plus warrants (which includes the dilution effect that makes warrants issued by the firm more complicated to value than options on the firm's stock issued in an external-to-the-firm market); 3. equity and convertible debt (which makes the same point about dilution); and 4. the pricing of Dual Funds—actually traded in the markets at that time—in which a closed-end fund with a definite future liquidation date (e.g., 10 years after issue) had two claims on it, income shares and capital shares. The income shares were structurally equivalent to risky debt and the capital shares to leveraged equity. Dual Funds were a good strategic research site to explore the CCA approach because the two were traded continuously in the market, the market value of the assets was observable, and the contractual terms were precisely defined. Indeed, Jonathan Ingersoll, an MIT doctoral student working under Merton, later did his thesis on the theory and empirical pricing of dual funds (Ingersoll 1976).

THE INTERTEMPORAL CAPITAL ASSET PRICING MODEL

In Merton's model of consumption and portfolio selection, the desire to hedge against a risk gives rise to a demand for securities that are correlated with that risk. For example, a desire to hedge against adverse changes in short-term interest rates induces a demand for long-term bonds. In equilibrium, a security's risk premium will reflect not only its beta on the market portfolio but also its betas on commonly shared hedging portfolios. The result of these hedging demands is Merton's multifactor ICAPM (Merton 1973c). Instead of the single market risk premium of the CAPM, there are several factors in the ICAPM, each of which corresponds to the correlation of a security's return with a hedging portfolio. Merton (1973c, 1975, 1982; see also 1990b,c) developed the general m-factor version of his three-factor, continuous-time portfolio and equilibrium asset pricing model (including an m+2 Fund Separation Theorem).[8]

Merton's ICAPM demonstrates that the CAPM could "fail" as a pricing model even in an informationally efficient and frictionless, perfect asset market. It thus provides a theoretical

[8]Merton (1982) was prepared at the request of Kenneth J. Arrow for a handbook volume on mathematical economics for which he was Co-Editor. It was later republished as Merton (1990b).

justification for a multifactor investment strategy[9] and a rationale for investment firms to offer a "family" of hedging portfolios that could be combined to suit the needs of different clienteles. Merton's ICAPM and his continuous-time technology were foundational for the development of consumption-based asset pricing models (CCAPM), which have been widely used by researchers in the subsequent four decades following Merton's initial breakthroughs.[10]

OPTION PRICING AND CONTINGENT CLAIMS ANALYSIS

The discovery that resulted in the awarding of the 1997 Nobel Prize was the Black & Scholes (1973) and Merton (1973b) model for option pricing.[11] Black & Scholes derived their pricing formula by showing that investors could create a portfolio of stocks and options that has a beta of zero. In equilibrium, the CAPM implies that such a portfolio must have an expected rate of return equal to the risk-free rate. Given this equality, Black & Scholes were able to derive their formula:

$$C = N(d_1)S - N(d_2)Ee^{-rT},$$

$$d_1 = \frac{ln\left(\frac{S}{E}\right) + \left(r + \frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}},$$

$$d_2 = d_1 - \sigma\sqrt{T},$$

where C = price of the call, S = price of the stock, E = exercise price, r = riskless interest rate (the annualized continuously compounded rate on a safe asset with the same maturity as the option), T = time to maturity of the option in years, σ = standard deviation of the annualized continuously compounded rate of return on the stock, ln = natural logarithm, e = the base of the natural log function (approximately 2.71828), and $N(d)$ = the probability that a random draw from a standard normal distribution will be less than d.

The Black-Scholes formula has five parameters, four of which are directly observable: S, E, r, and T. The fifth parameter is the volatility of the underlying stock price, σ, and it is not directly observable.

Merton's contribution was his alternative derivation of the formula applying his continuous-trading dynamic portfolio model using Ito's lemma. He showed that following the Black-Scholes dynamic strategy they used to create a zero-beta portfolio results in a portfolio that has no risk at all. Therefore, with continuous trading, the Black-Scholes trading rule in the stock and risk-free asset will exactly replicate the payoff to the option for every possible sample path of the underlying stock. Hence, in Merton's model, the Black-Scholes formula holds because of the Law of One Price and "no-arbitrage." The absence of arbitrage is a necessary condition for equilibrium. The formula thus must obtain in all equilibrium models, not just in the CAPM, which is a far more robust conclusion.[12]

[9]Fama and French have cited Merton's ICAPM as a possible theoretical rationale for their 1992 multifactor empirical findings.

[10]The CCAPM was the work of Merton's MIT student Douglas Breeden (1979).

[11]Merton deliberately delayed the publication date of his Rational Option Pricing paper to ensure simultaneous publication with the Black & Scholes paper in the spring of 1973. For the story of how they developed their model, see Bernstein (1992), Black (1989), Scholes (1998), and Merton (1998).

[12]Because he did not believe in continuous trading, Black maintained that the CAPM equilibrium justification for the formula was preferable to the no-arbitrage argument. Real-world practice today is converging to the theory with latencies in high-frequency algorithmic trading measured in microseconds.

Merton showed how to synthesize an option contract through the technique of dynamic replication. This is a theory of production and the formula gives the cost of producing an option for an intermediary that has no trading costs. In a competitive market this will also be the selling price of the option. Merton's dynamic replication approach had the greater impact on subsequent developments in finance theory and practice.[13]

Merton (1973b, section 9) also solved the pricing of a "down-and-out" option, which he learned about from Donaldson, Lufkin & Jenrette (DLJ), where he and Scholes were consultants. DLJ was trading down-and-out options in Hong Kong and wanted to know how to price and hedge them. It turned out that the down-and-out option was the first example of what later came to be known as Exotic Options (Bermuda options, Asian options, Russian options, and look-back options). This ultimately became a very large and significant industry that is still ongoing today.

Virtually from the day the Black-Scholes and Merton papers were published, their models were put into practice. The Chicago Board Options Exchange (CBOE) began trading the first listed options in the United States in April 1973, a month before the official publication of the Black-Scholes paper. By 1975, traders on the CBOE were using the model to both price and hedge their options positions. Indeed, Texas Instruments created a handheld calculator that was specially programmed to produce Black-Scholes/Merton option prices and hedge ratios.

Early on, Merton recognized that his continuous-time replicating-portfolio approach could be applied to the pricing of general derivative securities with arbitrary nonlinear payoffs contingent on one or more traded-security prices. His replicating-portfolio approach thus became the basis for a theory of the supply of custom-designed contingent contracts. The formula gives the cost of replicating the derivative's payoffs for a producer who has zero transaction costs.[14] The method used to derive the formula can also be used to synthesize and find the prices of Arrow time-state securities (see "Superfund Securities" in Hakansson 1976; Breeden & Litzenberger 1978 showed how Arrow prices could be derived from the prices of options). Thus it makes possible the creation of a dynamically complete market environment.

Hence, while his work was closing the gates on fundamental research on options, it was opening new gates by setting the foundation for a new branch of finance called CCA. The applications of CCA range from the pricing of complex financial securities to the evaluation of corporate capital budgeting and strategic decisions, and include, for instance, a unified theory for pricing corporate liabilities and the evaluation of loan guarantees and deposit insurance. Indeed, the theory and mathematical modeling of CCA for these applications have become even more important to finance practice than the original options applications.

MONEY MARKET/OPTIONS INVESTMENTS

In February1976, Merton and Scholes created the first mutual fund to hold options as a core asset. It was called Money Market/Options Investments. Ninety percent of the assets were invested in money market instruments and 10% in call options, with a 6-month rebalancing period. The call options were listed on national securities exchanges, and the money market securities were all high grade. The idea was to offer investors the upside potential of a portfolio of common stocks with complete downside protection. It was motivated by the nearly 50% decline in real terms in the

[13] Ironically, it was Merton who named the formula after Black and Scholes.

[14] But if the market is not competitive, it is not necessarily the equilibrium market price the derivative will sell for.

stock market that took place in 18 months between 1973 and 1974. Although the fund performed as expected, it was not a retail commercial success.

FINANCIAL ENGINEERING

Another extension of CCA that occurred in the 1970s was the application of option-pricing theory to analyzing real investment opportunities and making capital-budgeting decisions involving drug discovery; oil fields leases; mineral rights; alternative production processes; multiple-fuel power plants; patents; and the option to commence, delay, or abandon a project. Financial engineering is the term used to describe all these activities, and the investment opportunities are called real options.

Although Black, Scholes, and Merton were certainly aware of the broader applications of their framework, even they did not fully appreciate the breadth with which option-pricing theory could and would be applied in the 45 years following the publication of their papers. Today, the term financial engineering has come to mean the practical application of modern financial science to solving a wide array of economic problems facing individuals, businesses, financial institutions, or governments (see Merton 2002, Mason et al. 1995).[15]

THEORY OF FINANCIAL INTERMEDIATION

In 1987, Merton took his first-ever sabbatical year to write a book based on his work in continuous-time finance (Merton 1990d). This sabbatical year was a watershed, both for his research and for where that research would take place. In effect, *Continuous-Time Finance* was the synthesis of his earlier work. Chapter 14 on intermediation and institutions, however, represented a bridge to a new direction of his research. From that time until the present, he has focused on understanding the financial system with special emphasis on the dynamics of institutional change. In particular, he is studying the role of financial technology and innovation in driving changes in financial institution and market design, the management of financial-service firms, and the role of regulatory and accounting systems in supporting these changes.

There is, however, continuity of this line of inquiry with the past: his derivative-security research provided much of the foundation for the contracting and security-design technology that is central to the extraordinary wave of real-world financial innovation of the past 45 years. The principle that underlies Merton's theory of financial intermediation is contingent-contract equivalence. This principle maintains that for every dynamic trading strategy, there exists an equivalent contingent contract that can be derived by running the option-pricing derivation in reverse (this type of procedure is developed in Merton 1989).

In reality, most investors face substantial transaction costs and cannot trade even approximately continuously, as is done in the theoretical models. But in a modern, well-developed financial system, the lowest-cost transactors may have marginal trading costs close to zero, and can trade almost continuously. Thus, the lowest-cost producers of contingent contracts can approximate reasonably well the dynamic trading strategy, and in a competitive environment their cost of replicating the contingent contract is approximately the theoretical price.

From contingent-contract equivalence it follows that a low-transaction-cost financial intermediary can sell to high-transaction-cost customers fully hedged ("immunized") contracts that have the contingent payoffs associated with an optimized portfolio strategy. The intermediary pursues

[15] In 1993, Merton received the inaugural Financial Engineer of the Year Award from the International Association of Financial Engineers (now the International Association for Quantitative Finance).

the dynamic trading strategy at its lower transaction costs and provides the specified contractual benefits to its customers (an example of this process is the model developed in the paper by Bodie, Ruffino & Treussard 2008).

THE FUNCTIONAL PERSPECTIVE

For a variety of reasons—including differences in size, complexity, and available technology, as well as differences in political, cultural, and historical backgrounds—financial institutions generally differ across borders. They also change over time. Even when the names of institutions are the same, the functions they perform often differ dramatically. For example, banks in the United States today are very different from what they were in 1928 or in 1958, and banks in the United States today are very different from the institutions called banks in Germany or the United Kingdom today.

To analyze how and why financial institutions differ across borders and change over time, Merton adopted a framework he called the functional perspective (Merton 1993; for an alternative description and extension of the functional perspective, see Wilson & Campbell 2016).[16] The key element in the framework is its focus on functions rather than on institutions as the conceptual "anchor" (see Merton 1995, 2007a). The functional perspective rests on two basic premises:

- Financial functions are more stable than financial institutions—that is, functions change less over time and vary less across borders.
- Institutional form follows function—that is, innovation and competition among institutions ultimately result in greater efficiency in the performance of financial system functions.

From the most aggregated level of the single primary function of efficient resource allocation, Merton distinguishes six basic or core functions performed by the financial system:

- To provide ways to transfer economic resources through time, across borders, and among industries.
- To provide ways of managing risk.
- To provide ways of clearing and settling payments to facilitate trade.
- To provide a mechanism for the pooling of resources and for the subdividing of ownership in various enterprises.
- To provide price information to help coordinate decentralized decision making in various sectors of the economy.
- To provide ways of dealing with the incentive problems created when one party to a transaction has information that the other party does not or when one party acts as agent for another.

THE FINANCIAL INNOVATION SPIRAL

Merton describes the evolution of the financial system as an innovation spiral in which organized markets and intermediaries compete in a static sense and complement each other in a dynamic sense (the description here draws heavily on Merton & Bodie 1995a). The emergence of new trading markets in standardized securities, such as futures, options, and swaps, makes possible the creation of a wide range of new financial products, many of them custom-designed and sold over the counter (OTC) by financial intermediaries to meet selected needs of investors and corporate

[16]Merton's functional perspective is likely a legacy from his father, the famous sociologist Robert K. Merton. Robert C. Merton uses concepts and terminology coined by his father: manifest and latent functions, theory of the middle range, self-fulfilling prophecy, and many more.

issuers. Once these new products exist, volume in the new markets expands as the intermediaries themselves trade simply to hedge their own exposures from the products they sold. In turn, this increased volume reduces marginal transaction costs and thereby makes possible the further implementation of new products and trading strategies, which, in turn, leads to still more volume.

New markets also evolve as some successful products become standardized, and their source of distribution moves from intermediaries to markets. Success of these trading markets and custom products then encourages investment in creating additional markets and products, and so on it goes, spiraling toward the theoretically limiting case of zero marginal transaction costs and dynamically complete markets.

THE GLOBAL FINANCIAL SYSTEM PROJECT

Merton refined and applied his functional perspective in a series of working papers, published articles, and book chapters. In 1992, Merton and his Harvard Business School colleague and former MIT student, Carliss Baldwin, led the way to the creation of the Global Financial System Project (the project is described in detail in Merton & Tufano 1998). The project, which involved several of his finance colleagues working together with senior management from 15 global financial-service firms, expanded the research effort devoted to applying the functional approach to the financial system and to the management of financial institutions. The main result of the project was a volume published in 1995 that devoted a chapter to each of the six functions of the financial system discussing how it was performed in the past and likely to be performed in the future (Crane et al. 1995).

In the final chapter, the authors considered the changes in financial infrastructure necessary to support welfare-improving financial innovation (Merton & Bodie 1995b). The authors warned that financial crises were liable to occur in the future because the pace of financial product innovation exceeds the rate of change in infrastructure needed to accommodate it:

> "Separate and discrete innovations in products and services can be implemented in an entrepreneurial way and rather quickly. Innovations in financial infrastructure, however, must be more coordinated; they therefore take longer to implement and will occur more gradually. Successful public policy depends importantly on recognizing the limits of what government can do to improve efficiency and on recognizing when government inaction is the best choice. Government regulatory actions can do much to either mitigate or aggravate the dysfunctional aspects of financial innovations. By analogy, hurricanes are inevitable, but government policy can either reduce their devastation by encouraging early warning systems or it can aggravate the damage by encouraging the building of housing in locations that are especially vulnerable to such storms. Similarly, well-intentioned government policies aimed at reducing the systemic risks of a crisis in the global financial system may have the unintended and perverse consequence of actually increasing the risk of such a crisis."

Although the authors made no explicit forecasts, implicitly they were anticipating the Great Financial Crisis of 2007–2008.

TOWARD A SYNTHESIS OF FUNCTION AND STRUCTURE

After the Global Financial System Project ended, Merton and Bodie continued to develop a multidisciplinary functional approach to analyzing changes in the institutional structure of the financial systems of countries, regions, firms, households, and other entities (Merton & Bodie 2005). The term institutional structure, as used by us, includes financial institutions, financial markets, products, services, organization of operations, and supporting infrastructure such as regulatory rules and the accounting system. The financial functions may be provided by private-sector, governmental, and family institutions. The proposed framework can be applied both as a descriptive theory to predict the design structure of existing financial systems and as a prescriptive one to explore how such systems should be designed. Our central methodological thesis is a synthesis of the neoclassical, the new institutional, and the behavioral perspectives on finance. This attempt to synthesize these three perspectives is called functional and structural finance (FSF).

Neoclassical theory is an ideal driver to link science and global practice in finance because its prescriptions are robust across time and geopolitical borders. By itself, however, neoclassical theory provides little prescription or prediction of the institutional structure of financial systems, that is, the specific kinds of financial intermediaries, markets, and regulatory bodies that will or should evolve in response to underlying changes in technology, politics, demographics, and cultural norms. The neoclassical model, therefore, offers important, but incomplete, guidance to decision makers seeking to understand and manage the process of institutional change.

In accomplishing this task, the neoinstitutional and behavioral perspectives can be very useful. In the proposed synthesis of the three approaches, institutional structure is endogenous. When particular transaction costs or behavioral patterns produce large departures from the predictions of the ideal frictionless neoclassical equilibrium for a given institutional structure, new institutions tend to develop that partially offset the resulting inefficiencies. In the longer run, after institutional structures have had time to fully develop, the predictions of the neoclassical model will be approximately valid for asset prices and resource allocations.

FUNCTIONAL REGULATION

The FSF approach to financial system reform envisions an important role for government as regulator, guarantor, and innovator. It recognizes the need for government to complete some markets, stabilize the system, and prevent and respond to crises. The dominant approach generally adopted by regulators is to treat the existing institutional structure as given, and to view the objective of public policy as helping the institutions currently in place to survive and flourish.[17] In contrast, FSF takes as given the functions to be performed, and asks instead, "What institutional structure can best perform these functions?"

Increasingly sophisticated trading technologies, together with low transaction cost markets to implement them, tend to blur the lines among financial products and services. The existence of these technologies and markets also implies easier entry into the financial services. As a result, distinctions among financial institutions are likely to become even less clear in the future. Functional regulation promises more consistent treatment for all providers of functionally equivalent products or services, and thereby reduces the opportunities for rent-seeking and regulatory capture. Furthermore, functional regulation can facilitate necessary changes in institutional structures by not requiring a simultaneous revision of the regulations or the regulatory bodies surrounding them as is often required with an institutionally based regulatory structure.

In joint research with Bodie and other scholars, Merton has applied the functional framework to several public policy issues: regulation of banks, deposit insurance (Merton & Bodie 1993), pension guarantees (Bodie & Merton 1993), international diversification (Merton & Bodie 2002), and economic stabilization (Draghi, Giavazzi & Merton 2003). In most cases of dysfunctional structures and rules the source of the problem is the mismanagement of guarantees against the risk of default (Merton & Bodie 1992).

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[17]The thrust of policymaker thinking is perhaps reflected in the titles given to government reports. For instance, the US Treasury entitled its February 1991 detailed proposals for financial system reform *Modernizing the Financial System: Recommendations for Safer, More Competitive Banks.*

FINANCIAL GUARANTEES, MISMATCH RISK, AND FINANCIAL CRISES

Financial guarantees, such as insurance against credit risk and contract default, serve an important function for virtually every player in the global economy—households, businesses, and governments. Without such guarantees—both implicit and explicit—many economic activities would be less efficiently performed. Merton and Bodie have focused on the special role that guarantees play in the financial system and the harm that is caused when government mismanages its explicit and implicit guarantees of institutions that are "too big to fail" (TBTF). Typically, the mismanagement involves forbearance, as was the case with the Federal Savings and Loan (S&L) crisis in the 1980s [we analyze the S&L debacle in Merton & Bodie (1992)].

For financial intermediaries, the efficient management of implicit and explicit guarantees is critical to business success. The customers of many types of financial intermediaries receive a promise of services in the future in return for payments to the firm now. Those promised future services are liabilities of the firm, both economically and in the accounting sense. There are essentially three ways for an intermediary to provide assurances against default risk to the customers who hold its liabilities:

1. By having investors put in additional capital beyond that required for funding of the physical investments and working capital needed to run the business.
2. By purchasing guarantees of its customer liabilities from a private third party. This might be accomplished by a confederation of private parties as in the reinsurance market. This approach works best for covering customer liabilities where the risk is diversifiable—as in the case of mortality risk—or where the risk can be hedged in the capital markets—as in the case of stock market or interest rate risk.
3. By government guarantees of its customer liabilities. This approach may be best where the risk cannot be diversified or hedged through the capital markets.

There are three basic methods for a guarantor of liabilities to manage its business operations on a sound basis:

1. Monitoring. This method requires the guarantor to frequently mark to market the assets and liabilities of the insured party and be ready and able to seize the collateral as soon as the party's net worth falls below a predetermined maintenance target.
2. Asset restrictions. This method of controlling costs requires the insured party to (at least partially) hedge its guaranteed liabilities and limits the volatility of its net worth.
3. Risk-based premiums. Under this method the guarantor charges a fee that is commensurate with the riskiness of the guarantee.

In practice, guarantors (whether private-sector or government) use combinations of all three methods. Not one of the three methods can be effective if used alone. They do, however, substitute for each other in varying degrees. Hence, there is room for trade-offs among them. Depending on the context, some mixes will be more efficient than others.

When government serves as a guarantor, there are benefits but also often special problems. Governments are subject to constant pressures from various interest groups to subsidize their activities. The provision of cheap government guarantees is a less visible form of subsidy than outright cash payments, price supports, or other forms that require either immediate cash outlays or budget allocations.

If faced with a political constraint limiting the size of the premiums that it can charge, the government can still adopt procedures using the other tools of management to maintain the solvency of its guarantee activity, prevent excessive risk-taking, and avoid unintended subsidies. If it can, for instance, establish an effective system of monitoring, then premiums can be kept low with the system solvent. But, if it can neither charge adequate risk-based premiums nor monitor effectively, then the only route left open is asset restrictions. Reductions or increases in asset restrictions and monitoring of insured institutions should not be classified as acts of deregulation or reregulation. All guarantors, whether government or private-sector providers, must apply some feasible combination of such controls to remain viable.

As an important example, Bodie & Merton (1993) applied their functional analysis to the Pension Benefit Guaranty Corporation (PBGC), the government entity that guarantees private-sector defined-benefit pension plans. The PBGC has to date all but ignored the impact of an insured pension fund's asset mix on the PBGC's exposure. Yet when there is a mismatch between the pension assets and liabilities, the economic value of the guarantee provided by the PBGC, even for well-funded pension plans, can be quite significant.

The risk-related premium must therefore also be related to the future variability of the difference between the value of the pension assets (excluding the value of the guarantee) and the present value of guaranteed benefits. For risk-based premiums to work, the variability of net worth need not be reduced to zero, but it does have to be known (or at least bounded) and not subject to significant unilateral change by the insured pension plan after the premium has been set. If the insured pension plan sponsor can unilaterally change the composition of its pension asset portfolio ex post, then the guarantor faces a problem of moral hazard.

Failure to take account of the mismatch between the assets in defined-benefit pension plans (primarily equities) and the liabilities (deferred fixed annuities) has long been a major unrecognized source of financial instability. The underfunding problems now facing state and local government pension plans and the PBGC are a direct consequence of this conceptual failure. Yet the source of the problems and the policies needed to correct them remain unrecognized by many, if not most, mainstream economists (Bodie 2011).

The destabilizing feedback loop caused by government guarantees of TBTF financial institutions, moral hazard, forbearance, and ever bigger government bailouts is familiar to analysts of the US banking system. It is less familiar, but no less pernicious, in the case of the pension system. In the case of pensions, however, the vicious cycle is less transparent because of the fallacious belief that the risk of equities goes away in the long run. Until there is a recognition that equities are not a match for the fixed liabilities of defined-benefit pension liabilities, it will remain a serious source of financial instability for the US economy.

FINANCIAL ECONOMICS TEXTBOOK

Conceived at the outset as a parallel development to Merton's joint research with Bodie, and completed in 1997, was a textbook on basic finance that applies the functional perspective and presents the subject as a set of principles much like first courses in economics and the physical sciences (Bodie, Merton & Cleeton 2010). *Financial Economics* was intended for use in its current form anywhere in the world. The book is written so that its concepts are as relevant and understandable to a student in Argentina, France, Japan, or China as they are to a student in the United States. The international aspects of finance are integrated throughout the book, not confined to specific separate international chapters. It has been translated into eight foreign languages: Chinese, French, Japanese, Korean, Polish, Portuguese, Russian, and Spanish.

ANNUAL REVIEW OF FINANCIAL ECONOMICS

In 2009, Merton and his MIT colleague Andrew Lo became Co-Editors of a new scientific journal, *Annual Review of Financial Economics* (Lo & Merton 2009). Annual Reviews is a nonprofit publisher dedicated to synthesizing and integrating knowledge for the progress of science and the benefit of society. It was founded in 1932 by J. Murray Luck, then Professor of Chemistry, Stanford University, who brought his colleagues together to publish the first *Annual Review of Biochemistry*. Luck was overwhelmed by the amount of time it would take to read all the relevant literature in his field. *Annual Reviews* now covers 51 disciplines in the biomedical, life, physical, and social sciences.

The *Annual Review of Financial Economics* provides comprehensive, forward-looking and critical reviews of the most significant theoretical, empirical, and experimental developments in financial economics, including the fields of capital markets, corporate finance, financial institutions, market microstructure, and behavioral and experimental finance. In the inaugural volume of the *Annual Review of Financial Economics*, Lo & Merton (2009, p. 1) wrote:

> "One of the most exciting aspects of this discipline is the constant interplay between theory and practice that is unique among the social sciences. Despite its use of rather arcane mathematics, and unlike other mathematically sophisticated branches of economics, financial economics has found its way into the mainstream of financial practice."

FROM THEORY TO PRACTICE: LARGE-SCALE PROJECTS TO IMPROVE FINANCIAL SERVICES

Merton summarized his current approach to using theory to improve the practice of finance in a presentation entitled "Design Process for Development and Implementation of Large-Scale Innovation Projects to Improve Financial Services":

Step 1. Identify the purpose or goal of the project and the financial functions that the project is to serve. What challenges is it intended to solve?

Step 2. Define the objective function for determining the ranking of alternative potential solutions for implementing the project.

Step 3. Determine the best technologically feasible solution for performing the identified functions that you can find, without the constraints of existing regulations, practices, and institutions. This best solution, when implemented, represents the ultimate—Nirvana—for the project because it is the unconstrained optimum.

Step 4. Determine how the financial functions to be served by the project are currently being executed—the institutional specification of current practice for performing the identified functions. This is current practice.

Step 5. Determine the desired time/state-contingent path for implementation of the project between the two fixed points: current practice (where we are now) and Nirvana (where we want to be).

Determining the North Star to Nirvana (Step 3):

- Establish a set of key/essential/core design criteria such that any candidate solution must satisfy them all, or otherwise the candidate is not eligible for consideration. These criteria must be carefully crafted to arrive at consensus by producers, regulators, and consumers. Proposed solutions that satisfy those criteria should be openly considered and evaluated seriously, allowing full flexibility for negotiation on other nonkey design issues.
- Best practice is not good enough. Considering only best practices is not good enough for this solution. It is like driving by looking in the rearview mirror. Because best practice is in place, it is already a legacy system, subject to constraints. Finance science plays a critical role in identifying feasible solutions that have not yet been put into practice for this application and enables the new system to leapfrog over the best current practice system.

- The agreed-upon solution design in Step 3 sets the boundary condition that determines the future path of the project development. It enables project development to get back on course whenever the inevitable shocks/crises cause the project to go off course in unanticipated ways. It is the continuity reference point for all who interface with the project. It thus serves the function of a North Star to guide the team to achieving Nirvana from wherever it is at the moment.

And finally, "Determine the Optimal Path for Implementation of the Project Between Current Practice and Nirvana (Step 5)":

- At each point in time, do the best that can be done, on a cost-benefit basis, to perform the functions served by the project, subject to meeting the constraints in force at that time.
- Evaluate the impact/cost of each of the current constraints and proactively work to reduce them with priority set on the ones with the largest shadow cost of impeding implementation of Nirvana. This is the means for achieving the necessary changes in regulations, taxes, accounting, and financial institutions needed to get to Nirvana for performing the functions served by the project.
- Continue the process, keeping the beneficiaries of the project informed as to the current status of what is being delivered in terms of service in terms of the ultimate goal. The purpose is for the beneficiaries to see where they are being taken and are assured that is the best that can be done under current constraints. This manages expectations and shows the path to future improvement.

ILLUSTRATION: RETIREMENT SYSTEM REFORM

To see how the above process works in practice, consider the question of pension reform. Merton has long been concerned with the efficient design of retirement income systems (Merton 2014). In his early papers, he envisioned a reformed Social Security system, in which benefits would be linked to national per capita consumption. In his recent published work, he is concerned with improving the design of defined contribution retirement plans around the world (Merton 2007b, Merton & Muralidhar 2017). In addition to his scholarly activities as a professor at MIT's Sloan School of Management,[18] he is engaged in putting his theory into practice as Resident Scientist at Dimensional Holdings, Inc., where he is the creator of Target Retirement Solution, a global integrated retirement-funding solution system. Here is how he describes it:

1. Set retirement replacement income goal…and not wealth accumulation. The retirement goal is to sustain standard of living enjoyed in latter part of work life. Standard of living is characterized by inflation-protected income for life.
2. Offer robust, scalable low-cost investment strategies that make efficient use of all dedicated retirement assets to maximize the chances of achieving the retirement income.
3. Manage the shortfall risk of not achieving this goal. Risk is measured by retirement income volatility and not wealth volatility.
4. Be effective for participants who are and remain completely unengaged.
5. Goals individually customized for each participant based on salary, age, gender, plan accumulation, and other retirement-dedicated assets.
6. Integrate all sources of retirement savings into an individually tailored dynamic portfolio strategy informed by changes in market and personal conditions.

[18] Merton retired from Harvard and returned to MIT in 2010.

7. Provide only meaningful information and choices with easy implementation to participants who do engage.
8. Offer seamless transition at retirement from accumulation phase to postretirement payout phase with flexible options to combine annuities, long-maturity government bond portfolio, risk asset portfolio for goal-based future real income growth, and deferred annuities that start at age 85 as tail insurance for longevity, according to individual retiree profile.

SYSTEMIC RISK

In the wake of the Great Financial Crisis of 2007–2008, Merton, Amir Khandani, and Andrew Lo initiated a joint research effort to understand the causes of the crisis in order to avoid repeating it. Their research found that the combination of rising home prices, declining interest rates, and near-frictionless refinancing opportunities created unintentional synchronization of homeowner leverage, leading to a ratchet effect on leverage because homes are indivisible and owner-occupants cannot raise equity to reduce leverage when home prices fall (Khandani, Lo & Merton 2013). Their simulation of the US housing market yielded potential losses of $1.7 trillion from June 2006 to December 2008 with cash-out refinancing versus only $330 billion in the absence of cash-out refinancing. They concluded that while each of the three elements—rising home prices, declining interest rates, and more efficient refinancing services—was by itself a benign-to-favorable development, the combination of the three led to a kind of resonance that created instability and vulnerability capable of producing an enormous dysfunctional impact on the system, although no individual participant was engaged in dysfunctional behavior. Their message is that it is not adequate to monitor each of the silos of the financial system for systemic risk. Therefore, in screening for systemic risks, attention must be paid across the silos to their combinations as well.

MEASURING AND MANAGING SOVEREIGN RISK

Following the lead of Dale Gray, Merton and Bodie proposed a new approach to measure, analyze, and manage sovereign risk based on the theory and practice of modern CCA (Gray, Bodie & Merton 2007). Their paper provides a new framework for adapting the CCA model to the sovereign balance sheet in a way that can help forecast credit spreads and evaluate the impact of market risks and risks transferred from other sectors. This new framework is useful for assessing vulnerability, policy analysis, sovereign credit risk analysis, and design of sovereign risk mitigation and control strategies. CCA was also employed by Merton et al. (2013) to develop a modeling tool to identify potential systemic risk exposures in the global financial markets from connectedness among sovereigns, banks and insurance companies.

CONCLUSION

No individual has contributed more to the beneficial relationship between finance theory and practice than Robert C. Merton. In the first part of his career, he revolutionized the modeling of asset price dynamics and intertemporal optimization, pioneering the field of CCA. In the second part of his career, he has successfully applied the functional perspective to the theory and practice of financial intermediation—the design of financial systems. Working with his colleagues at MIT's Golub Center for Finance and Policy, Merton continues to pursue FSF. He teaches it at MIT and lectures around the world. The title of one of his lectures to an audience in China describes his central theme: "Solving Global Challenges Using Finance Science" (Merton 2018). Amen.

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