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ROBERT C. MERTON AND THE SCIENCE OF FINANCE
A COLLECTION

LUIS GARCIA-FEIJÓO, CFA, CIPM,
LAURENCE B. SIEGEL, AND
TIMOTHY R. KOHN, EDITORS

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CFA Institute
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Statement of Purpose

CFA Institute Research Foundation is a not-for-profit organization established to promote the development and dissemination of relevant research for investment practitioners worldwide.

Updated July 2020 to include "Robert C. Merton's Seminal Insights, Revisited" by Robert A. Jarrow

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FOREWORD: ROBERT C. MERTON AND HIS IMPACT ON THE SCIENCE OF FINANCE

David Booth
Dimensional Fund Advisors

Dimensional Fund Advisors was proud to cosponsor the 2019 MIT symposium honoring Robert C. Merton that is faithfully summarized in this CFA Institute Research Foundation publication.

Dimensional is dedicated to translating academic research into practical investment solutions. Since 2010, Bob has been our resident scientist working on retirement income solutions. His effort to link science and the practice of finance was groundbreaking when he started his career, and today, he remains committed to the power of ideas and putting them to work to solve real challenges.

It is easy to think of Bob Merton as the father of financial engineering. His continuous-time models laid the foundation for an entirely new branch of finance that revolutionized the way financial firms manage risk. We endorse and share his belief that best practice is not good enough; we must all continually innovate to improve outcomes for our clients and investors—and for future generations.

The speeches in this volume make abundantly clear that Bob has had a profound impact both as a financial science pioneer and as a teacher and mentor. And I can attest, based on my years as his colleague, that his influence as a friend is no less profound.

INTRODUCTION

Luis Garcia-Feijóo, CFA, CIPM, and Laurence B. Siegel

Robert C. Merton, winner of the 1997 Nobel Prize in economics, is one of the most influential scholars in the history of financial economics. His work on continuous-time finance, option pricing, financial services firms, and retirement security is central to the current state of knowledge.

On August 5 and 6, 2019, MIT hosted a symposium in honor of Merton's 75th birthday. The idea for this symposium originated with several of Merton's former students, whose careers were shaped by his influence. Realizing that he was about to turn 75 on July 31, 2019, Zvi Bodie took the initiative to organize a celebratory symposium with a steering committee consisting of Eric Rosenfeld, Leonid Kogan, and Andrew Lo as well as Professor Bodie. They invited former students and colleagues to prepare papers and presentations explaining the influence that Merton had on their ideas, careers, and lives.

Every one of the people invited to make a presentation accepted enthusiastically. The MIT finance department, represented by Kelly Nixon, coordinated the logistics, and Dimensional Fund Advisors (DFA) and Convexity Wines jointly funded the event. We thank David Booth and Tim Kohn at DFA, and Chi-fu Huang, John Meriwether, and Eric Rosenberg at Convexity Wines for their generosity and support.

Roughly a hundred people—former students, colleagues, and Merton's family—gathered at MIT for the symposium. The result was an intellectually stimulating and heartwarming event that is summarized in this brief. There is also a complete set of videos of the entire event, which can be found at https://www.youtube.com/watch?v=zLYlMi83o5Y.

The brief begins with an overview of Merton's work and career, authored by Zvi Bodie. It then presents edited transcripts of some of the speeches and panel discussions that took place at the symposium. The authors of these pieces graciously contributed their time following the conference to make this brief possible.[1] Professor Bodie organized and put some structure into the conference by asking the presenters to focus on a specific aspect of Merton's work so that summed across the presenters, the audience would gain a full picture of Merton's influence while avoiding repetition. The presentations illustrate the impact that Merton had, and continues to have, on the profession not only as an author but also as a teacher, mentor, and adviser to financial practice.

Some readers may not know that Merton's father, Robert K. Merton, was one of the most important sociologists of the last half of the 20th century. As Harriet Zuckerman, who is the elder Merton's widow as well as a sociologist of great accomplishment, mentions in her presentation, he is the originator of the concept of role models, of unanticipated consequences, and of self-fulfilling prophecies, just to give a few examples. His ideas on functions laid the foundation for the younger Merton and Zvi Bodie's work on the functional perspective of the financial system.

[1]This brief includes selected conference presentations. We are grateful to everyone who presented, including those whose excellent presentations are not available for inclusion herein.

Robert C. Merton's current interests include the role of trust in financial markets, a classic topic that regained relevance following the global financial crisis. Richard Thakor, a professor of economics and psychology at the University of Minnesota Carlson School of Management, describes his and Merton's recent theoretical work on trust. Thakor explains that the combination of their model and Merton's functional perspective offers a powerful framework for analyzing topics such as the financial crisis, the impact of technology on financial advising, and the future of lending.

The MIT economics professor James Poterba's presentation highlights the interplay between economics and finance and shows Merton's role in connecting financial with economic topics. He offers several examples through Merton's work as an author and as a teacher.

Arun Muralidhar, an investment manager, presents Merton's contributions on retirement security, a pressing challenge in today's world. Their joint work on SeLFIES, which Muralidhar describes, promises to be one of the most important financial innovations of recent times. SeLFIES are engineered securities that guarantee a lifetime income to their purchaser.

A panel discussion then follows. It includes comments by Zvi Bodie, the Harvard professors Carliss Baldwin and André Perold, the MIT professor Deborah Lucas, and Peter Tufano, who is the dean of the Saïd Business School at Oxford. The panel covers issues such as continuous-time finance, the payment system, credit guarantees, reverse mortgages, and thinking functionally rather than institutionally. The topics are treated in the context of Robert C. Merton as a mentor of the many distinguished panel participants.

Marti Subrahmanyam, a finance professor at NYU, presents a research project that allows him to illustrate some of Merton's teachings. In his article, Subrahmanyam and coauthors show theoretically that the optimal contract between an entrepreneur and a financier takes the form of a convertible security, as it is common in practice, but in their model they do not assume information asymmetry, contrary to existing models. He notes that today, it is nearly impossible to develop a theoretical model in financial economics without relying on Merton's contributions.

In lieu of his presentation, André Perold asked us to include some prepared remarks. In them, he reflects on the influence Merton has had on him, at the same time describing some of Merton's most important contributions.

Robert Jarrow reflects on the fact that his own work has been, by and large, an extension of Merton's work on topics as diverse as the option-pricing model, the intertemporal CAPM, and bubbles. He explains the origins of these concepts in Merton's writings as well as his own modifications and extensions of them.

Andrew Lo makes the case that financial engineering is essential for the science of finance because engineering is what makes science practical and that Merton was the first financial engineer. With humor and strong evidence, Lo eloquently defends his case in an engaging presentation.

The brief celebrates Robert C. Merton's past and ongoing impact on the science of finance. This series of presentations describes his family background, his personal path to the field of finance and to MIT, his intellectual contributions, and especially his impact on former students, coauthors, and colleagues. A tone of gratitude and celebration permeates all the presentations, coupled with the generous acknowledgment of Merton's influence on the practice and theory of finance.

CFA Institute Research Foundation is extraordinarily pleased to present this account of a memorable event in honor of a great thinker.

ROBERT C. MERTON AND THE SCIENCE OF FINANCE

Zvi Bodie
Professor Emeritus, Boston University

From his pioneering work on optimal portfolio selection to options pricing and retirement security, Robert C. Merton, the 1997 Nobel laureate in economics, continues to seek innovative solutions for complex financial problems.

Paul Samuelson, the first American to receive the Nobel Prize in Economic Sciences, once compared Merton's influence on finance to Isaac Newton's impact on physics. Put another way, starting with his 1970 doctoral dissertation and continuing today, Merton has revolutionized the theory and practice of finance.

For many years I have worked with Merton on a variety of research initiatives. Here, I offer a detailed look at selected highlights of his career and the overarching body of work that I refer to as "The Mertonian Revolution in Finance."

PAUL SAMUELSON'S RESEARCH ASSISTANT

Merton attended the Columbia University School of Engineering and Applied Science, receiving a BS in engineering mathematics in 1966. It was there that he encountered Samuelson—who in 1970 would become the first American Nobel laureate in economics—in the form of his famous introductory textbook on economics. Merton then went to the California Institute of Technology to pursue a PhD in applied mathematics. But he soon decided to leave Caltech (and mathematics) to study economics, applying to a half-dozen good departments. Only one—the Massachusetts Institute of Technology (MIT)—accepted him and gave him a full fellowship.

When he arrived at MIT in the fall of 1967, Merton took Samuelson's mathematical economics course and loved it. Samuelson offered him a job as a research assistant. "I did not get particularly good grades in my courses in the department," Merton recalls, "mainly because I spent much of my time 'playing with' research ideas and working on joint research with Paul."

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 Samuelson's 1965 theory of warrant pricing, subsequently published in 1969.

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." (Lifetime dynamic consumption refers to how individuals' spending varies over time. The portfolio selection problem refers, in simple terms, to the best way to diversify a portfolio and balance its expected return against its risks. Continuous time refers to the idea that these decisions are made continuously, not just at successive points in time.) There was a long tradition of life-cycle consumption models in economics but none that incorporated uncertainty and included the portfolio selection decision.[2] Merton addressed this problem, and his paper became Chapter 2 in his doctoral dissertation.[3]

1970 MIT WORKING PAPER

Thanks to a job offer arranged by Franco Modigliani, an MIT professor at the time, Merton was hired and started teaching at MIT's Sloan School of Management in the fall of 1970. His work on "A Dynamic General Equilibrium Model of the Asset Market and Its Application to the Pricing of the Capital Structure of the Firm" (Merton 1970) appeared as MIT Working Paper No. 497-70. It contained early versions of at least three groundbreaking papers on key aspects of finance theory: the Intertemporal Capital Asset Pricing Model or ICAPM (Merton 1973a), Rational Option Pricing (Merton 1973b), and Risky Corporate Debt (Merton 1974). In over 30 years of studying and teaching finance, never have I seen one paper so rich in its academic ideas, theories, and future contributions to the science of finance.

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

[3]Merton (1969). This paper was paired in *The Review of Economics and Statistics* with a closely related paper by Samuelson (1969).

THE INTERTEMPORAL CAPM (ICAPM)

In Merton's model of consumption and portfolio selection, the desire to *hedge* against a risk gives rise to a demand for securities 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 volatility relative to the market but also its volatility relative to commonly shared hedging portfolios. The result of these hedging demands is Merton's multifactor ICAPM. Instead of the single market risk premium of the Capital Asset Pricing Model (CAPM)—a theory developed in the 1960s by William Sharpe, Jack Treynor, John Lintner, and Jan Mossin—there are several factors in the ICAPM, each of which corresponds to the correlation of a security's return with a hedging portfolio.[4]

Merton's ICAPM provides a theoretical rationale for investment firms to offer a family of hedging portfolios that could be combined to suit the needs of different types of clients as well as a theoretical justification for a multifactor investment strategy.[5]

The ICAPM and Merton's continuous-time technology were foundational for the development of consumption-based asset pricing models (CCAPM), which researchers have used widely to price risky securities in the subsequent four decades.[6]

[4]Merton (1973a).

[5]Eugene F. Fama, a professor at the University of Chicago Booth School of Business and a consultant to Dimensional Fund Advisors, has cited Merton's ICAPM as a possible theoretical rationale for the Fama–French multifactor empirical findings.

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

OPTIONS PRICING

The research that Merton is most known for—and the discovery that led to his Nobel Prize two decades later—is the model for options pricing.[7]

The Chicago Board Options Exchange (CBOE) began trading the first listed options in the US in April 1973—a month before the official publication of the famous paper "The Pricing of Options and Corporate Liabilities" in the *Journal of Political Economy*, penned by Fischer Black and Myron Scholes (Black and Scholes 1973). Simultaneously, Merton published his "Theory of Rational Option Pricing" in the *Bell Journal of Economics and Management Science* (Merton 1973b).[8] By 1975, traders on the CBOE were using the model to both price and hedge their options positions. Indeed, Texas Instruments created a hand-held calculator that was specially programmed to produce Black–Scholes/Merton option prices and hedge ratios.

Merton's work in this area also set the foundation for a new branch of finance called Contingent Claims Analysis (CCA), a technique for determining the price of a security whose payoffs depend on the prices of one or more other securities (Merton 1977). The applications of CCA range from the pricing of complex financial securities to the evaluation of corporate capital budgeting and strategic decisions. The theory and mathematical modeling of CCA for such applications have become even more important to finance practice than the original options applications.

[7]Merton shared the Nobel with Myron Scholes. For the story of how Merton, Scholes, and Fischer Black developed their model, see Bernstein (1991), Black (1989), and Scholes (1998).

[8]Merton deliberately delayed his "Theory of Rational Option Pricing" paper's publication date until the paper by Black and Scholes was published in spring 1973.

FINANCIAL ENGINEERING

Another development 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. These investment opportunities are called "real options."

Black, Scholes, and Merton 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. The term "financial engineering" has come to mean the practical application of modern financial science as a tool to solve economic challenges faced by individuals, businesses, financial institutions, or governments.[9]

THEORY OF FINANCIAL INTERMEDIATION

In 1990, Merton published *Continuous-Time Finance*, a synthesis of his earlier work. Chapter 14 on intermediation and institutions represented a bridge to a new direction in his research. From that time until the present, he has focused on understanding the financial system and has put a special emphasis on the dynamics of institutional change.

In particular, he is studying how financial technology and innovation drive changes in the design of financial institutions and markets and the management of financial services firms, as well as the role of regulatory and accounting systems in supporting these changes. The role fintech (and other new ways of engaging

[9]See Merton (2002).

investors and plan participants) is of special interest. His thoughts and consultations with regulators and service providers are helping to shape how we interact with the stewards of our financial dreams.

A FUNCTIONAL PERSPECTIVE

Today, decision makers around the world face many issues that concern institutional change. In China, for example, decentralization and privatization of large parts of the economy during the past decade produced remarkable improvements in standards of living.[10] Public officials and business leaders now see an urgent need to create a financial infrastructure that supports continued economic development. Japan is considering fundamental changes to the structure of its banking system in an effort to overcome economic stagnation.[11] And in Asia, Europe, and the US, pension, Social Security, and defined contribution reform have become a top priority. A critical issue everywhere is controlling the risk of default by financial institutions.

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. To analyze how and why financial institutions differ across borders and change over time, Merton adopted a framework he called the "functional perspective."[12] Its key element is a focus on functions rather than institutions as the conceptual "anchor."[13] 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.

GLOBAL FINANCIAL SYSTEM PROJECT

Merton refined and applied his functional perspective in a series of working papers, published articles, and book chapters. In 1992, he and Carliss Baldwin, his Harvard Business School (HBS) colleague and a former MIT student, led the creation of the Global Financial System Project at HBS.[14] This initiative, which involved several finance colleagues working together with senior management from 15 global financial services firms, expanded the research effort devoted to applying the functional approach to the financial system and the management of financial institutions. The main result was a volume published in 1995 (Crane et al. 1995) that discussed how the financial system had performed in the past and was likely to perform in the future.

[10] See "China's Economic Rise: History, Trends, Challenges, and Implications for the United States," Congressional Research Service (February 2018).

[11] See "Japan Financial System Stability Assessment," International Monetary Fund Country Report No. 17/244 (July 2017).

[12] 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.

[13] See Merton (1993, 1995) and Chapter 4 in Bernstein (2007).

[14] The project is described in detail in Merton and Tufano (1998).

The final chapter considered the changes in financial infrastructure necessary to support welfare-improving financial innovation,[15] warning 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. Although no explicit forecasts were made, the authors were implicitly anticipating a global financial crisis.

SYSTEMIC RISK

In the wake of the 2008–09 financial crisis, Merton, his MIT colleague Andrew Lo, and Amir Khandani initiated a joint research effort to understand the causes in order to avoid a repeat. They found that a 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.[16]

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 the refinancing ratchet effect exemplifies a new type of systemic risk in the financial system in which individual elements viewed in isolation are each seen as "good" or "functional" but when interacting together they can be dysfunctionally destabilizing, leading to crisis. Thus, preventive policy requires integrating across silos.

[15]Chapter 8 in Crane et al. (1995).

[16]See Khandani, Lo, and Merton (2013).

GLOBAL RETIREMENT SYSTEM REFORM

Among the most pressing policy issues around the world is pension, social security, and defined contribution reform. Merton has long been concerned with the efficient design of retirement income systems.[17] For over four decades, he has been contemplating, researching, and speaking about this topic around the world. 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 (Merton 2007 and Merton and Muralidhar 2017), he is concerned with improving the design of defined contribution retirement plans. In addition to his scholarly activities as a professor at MIT Sloan,[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.

"Insofar as addressing the retirement income shortfall is a problem, it is one of engineering, not science," Merton says. "We already have the tools to fix this issue. We know how to make the system sustainable and increase people's chances of a good retirement. Essentially, this new system comes down to making smarter products rather than trying to make consumers smarter about finance."

The answer, in Merton's view, is to adopt a liability-driven investment (LDI) strategy that is equivalent to how an insurer hedges an annuity contract or how pension funds hedge their liabilities for future retirement payments to members.

[17]See Merton (2014).

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

Several companies in Europe started implementing Merton's retirement solution in the mid-2000s, and the idea continues to gain traction around the globe.

The goal is to grow the savings of plan participants during their accumulation phase and manage income uncertainty by using long-term inflation-linked bonds as the lowest-risk hedge leading up to and during their decumulation phase. This approach gives participants a clearer view of the income that a portfolio may provide in retirement.

"Most target date or risk-based DC solutions tend to put employees nearing retirement in shorter-maturity bonds. But short-term bonds are more risky than almost any other asset if the goal is retirement income," Merton explains. "A better way to manage income risk is to use inflation-protected instruments, such as Treasury Inflation-Protected Securities (TIPS), that can match the duration of the retirement income need (the liability). This approach isn't new. In fact, defined benefit (DB) plans have long regarded income risk as the most important risk to manage."

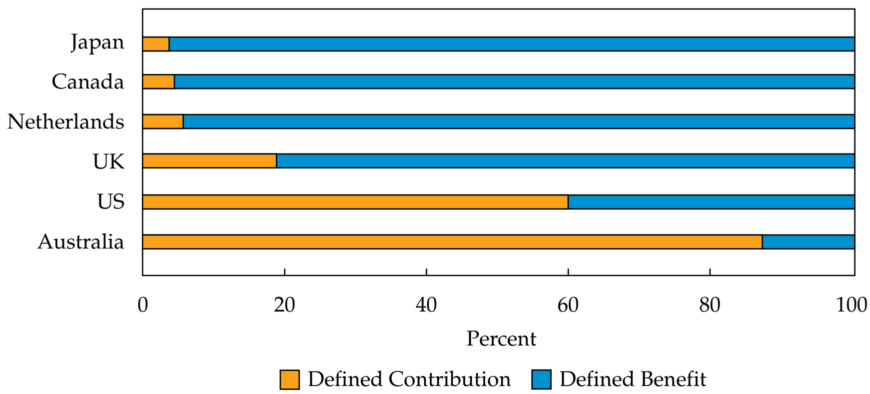
See **Exhibit 1** for the DB/DC split among a group of countries that account for most of the world's pension money. Global pension systems, not unlike the US system, face funding and sustainability challenges as they move from more DB-oriented to more DC-oriented systems. Merton has been at the forefront of addressing this trend—and its implications for participants—with regulators, central banks, and academics alike.

Several companies in Europe started implementing Merton's solution in the mid-2000s, and the idea continues to gain traction around the globe, including in the US and also South Africa and Canada. "It's built on financial science," Merton says, "and these principles work everywhere independent of culture or the design of the financial system."

POSTSCRIPT

In my view, no individual has contributed more to the beneficial relationship between finance theory and practice than Robert C. Merton. Today, he still teaches at MIT and often lectures around the world. Not only has "The Mertonian

EXHIBIT 1. ASSETS IN DEFINED CONTRIBUTION VS. DEFINED BENEFIT



Source: Global Pension Assets Study 2018, Thinking Ahead Institute, Willis Towers Watson, February 2018.

Revolution in Finance" helped shape modern finance, it has also provided us with insights, theories, and models for our collective future. The title of one of Merton's recent lectures to an audience in China describes his central theme: "Solving Global Challenges Using Finance Science."[19]

To that, I say "Amen!"

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[19]Delivered at the China International Conference in Finance, Tianjin, China, July 11, 2018.

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ROBERT K. MERTON, ROBERT C. MERTON, FUNCTIONAL SOCIAL SCIENCE, AND FINANCE

Harriet Zuckerman
Andrew W. Mellon Foundation

ROBERT MERTON, FATHER AND SON

Harriet Zuckerman: Robert K. Merton and Robert C. Merton were father and son. They were also remarkably close. They talked by phone every day, for decades. In order to keep the two Bobs straight for all of you, Zvi [Bodie] and I have decided to call them RKM and RCM, but I confess that it's hard to talk about my husband as RKM, and about [my stepson] Bob as RCM. So if I get it tangled, you'll understand.

Audience: [Chuckling]

Harriet Zuckerman: According to RCM, their phone calls dealt with his work and his father's work: with the stock market, with sports, politics, his children, about nearly everything. This essay is about the influence of RKM on RCM when RCM was growing up, on his research, and through a medley of stories about their joint lives.

Not all of you are going to be familiar with who RKM was. To locate RKM chronologically, he was born in 1910 and died in 2003. He was arguably the most significant sociologist of the last half of the 20th century. He was a theorist, and he did empirical research. He examined a vast variety of subjects, as Zvi and I can attest. We have not counted his papers and books. His bibliography covers some 15 closely printed pages. It ranges over the sciences, social sciences, and humanities.

So much so that RCM could say, "Although my research is very mathematical, very quantitative, and seemingly very far away from what my father did, nonetheless I found myself using many of his ideas." RCM has drawn on RKM's concepts. RCM has written in his publications and spoken about his father's ideas of manifest and latent functions, functions and dysfunctions, unanticipated consequences, functions and structures, which RCM calls "institutions" in both his teaching and in the papers that he and Zvi have published, providing a functional perspective on the finance system.[20]

[20]A brief primer on sociological jargon is in order. Study.com writes, "Robert Merton's contribution to sociology is one of great importance in regards to the *functional perspective* of society. Merton and other functionalists viewed society as an organism with various parts, and each part has a function to perform. Merton recognized that some functions were intentional and other functions were not. He also acknowledged that some functions actually disrupted society. These...are known as the manifest [intentional] and latent [unintended] functions and dysfunctions" [editor's parentheticals].

Editor's note: Harriet Zuckerman is Robert C. Merton's stepmother. She is a sociologist and foundation executive.

"PARADIGMS" AND THE SOCIOLOGY OF SCIENCE

These papers [a list of RCM's contributions was shown] lay out the principal concepts needed for understanding how the financial system works. In that sense, these papers aren't altogether different from RKM's paradigm for functional analysis. Paradigm, I might add, was a notion he used about 10 to 15 years before Tom Kuhn made it so popular.[21] RKM was also known for his studies of bureaucracy, crime and its origins, the effects of mass communications and propaganda, the effect of communities on their residents, and the professions.

This list is just the tip of his research iceberg. He was the father of the sociology of science, now a full-grown specialty, but one that didn't even exist when he wrote his doctoral dissertation on the role Puritanism played in the establishment of modern science. He was especially interested in the implications and effects of the emphasis in science on *priority*, on being first, on making a discovery before anyone else. And he went on to lay out both its positive and negative consequences.

We all know that scientists don't always agree on who made a discovery first, and that absence of agreement has led to conflicts over priority, to very hard feelings among scientists who are participants in such discoveries. They have sometimes gotten into open conflict, and have made claims of plagiarism against their competitors, and have even alleged that fraud has taken place.

Some of you may have heard of the Matthew effect. That was RKM's analysis of why well-known scientists tend to get more than their fair share of recognition. It's not simply that the wealthy get wealthier—not at all. They get wealthier, given the contributions they make, than their less-advantaged co-discoverers get for the same work. This is for a number of reasons, including the greater attention paid to the work of well-known authors. On another tack altogether, RKM's last book was on serendipity in science, how scientists came to make discoveries they never intended to make.

That gives you a sense of the breadth of his interests. His ideas have so penetrated the public mind that it's simply hard to escape reading the front page of the *New York Times* without encountering one of them. He is the originator of the concept of role models, of unanticipated consequences, of self-fulfilling prophecies, of influentials, of bureaucratic personalities—these for starters. These phenomena did not exist in the collective mind until he had the wit to perceive that they were real phenomena, to analyze why they occur, and to create evocative terms for them. He was University Professor at Columbia for 50 years. He received both the Presidential Medal of Science and the American Council of Learned Societies award for distinguished scholarship in the humanities—both ends of the continuum of scholarship.

RKM was a member of the US National Academy of Sciences, the British Academy, the Royal Swedish Academy, the American Philosophical Society, and the American Academy of Arts and Sciences. He received over 30 honorary degrees, from Oxford, Bologna, Rome, Leiden, Krakow, Hebrew University, and Athens; and in the United States from Harvard, Yale, Chicago, and of course Columbia. His work has been continuously cited, and it's continuously influential.

And, as you know, he was the very proud father of Robert C. Merton.

[21]See Thomas Kuhn, *The Structure of Scientific Revolutions* (Chicago: University of Chicago Press, 1962). This work is almost universally regarded as a fundamental text of how change occurs in science.

THE INFLUENCE OF ROBERT K. MERTON ON ROBERT C. MERTON

Zvi was, of course, RCM's student, worked with him for 45 years, and they continue to collaborate. Zvi also knew RKM and liked and admired him, and RKM liked and admired Zvi, too. For my part, over some 40 years, RKM was my teacher, collaborator, and ultimately my partner and husband. You'd be right to think that I'm biased. And add to this the fact that when I married RKM, I happily acquired RCM as a stepson, so I too am doubly biased.

Now, at the same time, Zvi and I are both card-carrying social scientists. We're obliged to keep our biases under control, and we'll try to tell the story of the influence of RKM on RCM as it was then and as it is now. Personal influence is a complicated business. People are inclined to think that similarities between father and son arise from one influencing the other. But, influence is more complicated than that. It is easy to assume that similarities in question wouldn't have existed without some active effort, but that's not necessarily so.

We'll not get into the weeds of determining how the influence occurred, or even who influenced whom. Rather, we've elected to draw upon RCM's testimony about his father in an interview we did with him several weeks ago. But, of course, such testimony is unreliable. Skepticism about the validity of memories, some of them more than 50 years old, is justified. RCM also noted that what he assumed at the time his father thought or believed also might not have been correct. It was helpful, though, for Zvi and me to be able to draw on RKM's copious files to corroborate our impressions, some going back to when RCM was a small boy. The great majority of materials we drew on, though, came in a set of file folders labeled "Bob"—no last name.

We were lucky to find this file. We read an accumulation of letters, faxes, manuscripts, clippings, and invitations that were exchanged between them in 1994. One year's file measured between nine and ten inches thick. And this didn't even include emails, of which there are no copies. But it was before Bob got the Nobel and after his options-pricing work, so the subjects of that particular year were not wildly unrepresentative.

THE YOUNG ROBERT C. MERTON

We also drew on knowledge that both Zvi and I had of the work of the two of them, just in case we missed similarities that hadn't surfaced otherwise. We call this section "Before RCM became a financial economist." According to RCM, his father, RKM, was no "tiger father." I was struck at the time when you said this how contemporary a term that is, but the meaning of "no tiger father" is very clear. RKM never insisted that RCM read specific books, never insisted he pursue certain activities, never told him to study harder, or to get better grades.

In fact, his grades were uneven. And he never told him that certain ideas should be adopted and others, rejected. According to RCM, his father's child-rearing policy, if there was one, relied almost entirely on example. His father liked to read, and read a lot. "There were lots of books around the house," RCM said, including a large number of dictionaries. Judging from what I knew about RKM's personal library, "lots of books" clearly meant thousands. RCM said that when he was a child, he liked dipping into those dictionaries.

He also "liked looking at his father's old books." He liked going to the local library with his father. But the two of them never read together. Despite being bookish, RKM was no literary snob. He read detective stories and mysteries, as well as novels, biographies, histories, essays, and poetry, and everything he thought might be germane to his work. And he often returned to the Bible, Old and New Testament, of course. RCM does not describe himself as bookish, but books were a part of his life.

There were three activities RKM deliberately introduced to RCM: magic or sleight of hand, poker, and the stock market. RKM's enthusiasm for magic goes back to his teenage years, when he mastered sleight of hand well enough to be paid to perform. For RCM, however, magic was a total loss, as he put it. He recalls standing in front of the mirror, trying to learn the moves his father had learned decades before. That effort was tedious and frustrating. He decided then that there was no comparative advantage, a concept he must've had as a child, to justify the effort. Magic held no magic for him.

Not so for poker and the market. RCM took up poker early. As far as I knew, he didn't play with RKM very much after he, RCM, had mastered the game, which he evidently did by his teenage years. We take seriously Paul Samuelson's testimony that RCM "routinely emptied out the pockets of any and all fellow students" who played with him. He later went on to play in far more challenging games with far richer players.

RKM's introduction of RCM to the stock market suited RCM's very early interest in money.

ENCOUNTERING FINANCE

As a child, he balanced his mother's checkbook. He also founded—and you'll love this; I do—the RCM Savings Bank of Dollars and Cents, as he called it. He sought deposits from family and friends, which, when they reached a certain level, he and his mother would deposit in the local savings bank. He then paid depositors somewhat less than what he had earned—

Audience: [Laughter]

Harriet Zuckerman: —thus becoming a sort of second-order banker.

But it was the stock market that really intrigued him. Even before he was 10, his father took him to the local brokerage house in White Plains. They watched the ticker together, and they talked about the prospects of particular stocks. During these visits, RCM says he soaked up a lot of market lore. It's not clear when he learned all the ticker-tape abbreviations for the stocks listed on the American and the New York exchanges; that must have started earlier.

In any event, he learned about convertible bonds from one of the other men that frequented the brokerage house. He learned about the risks of excessive leveraging from another. He recalled that the man who was "the ultimate leverager" earned a lot and lost a lot, so much in one year that he had to borrow money for Christmas presents. This clearly deeply impressed RCM, who we know would later go on to be highly sensitive to investment risk. RCM made his first stock purchase when he was 10, and he undertook his first risk arbitrage at about 15.

He was lucky that one worked out. He had no idea that maybe the merger he anticipated wouldn't go through. By the time he was a college student at Columbia, he was a sophisticated investor. And by the time he got to Caltech as a graduate student in applied math, he was getting up early, well before his classes began, to trade on the markets that were already open in the East. One might think that this immersion in the market would have led him to consider a career as a trader, or something of that sort, but it didn't.

He says it never occurred to him that his interest in investing could lead to it becoming a day job. Nor did it occur to him, given his relationship with his father, to become a professor. Based on observations he made of one of his father's colleagues, he decided that professors were arrogant and were people he wanted nothing to do with. He excluded his father from this observation, he said recently; he said his father was "a gem," different from the rest.

During his second semester at Caltech, RCM decided that he wasn't really interested in being an applied mathematician. Instead, he thought of going to graduate school in economics even though he'd taken no courses in economics. It's now a famous story that he was rejected by all the graduate departments to which he applied but one, MIT, which also awarded him a fellowship. In his talk at RCM's 50th birthday party here at MIT, Paul Samuelson put to rest the idea that academic nepotism explained RCM's admission to MIT.

No one responsible for admissions at MIT, Paul said, had any idea that the RCM from Caltech had any relationship with RKM from Columbia. Well, so much for paternal influences. Now on to RCM's functional perspective on the financial system.

THE SIX FUNCTIONS OF ANY FINANCIAL SYSTEM

Zvi Bodie: Harriet is very modest, so she doesn't want to explain the financial concepts that Bob Merton invented and developed. I did my best to put together a list of his greatest hits.

First, the six functions of any financial system. I will not go through all six, but they form the basis for a lot of the work that he's done and that we've done together. Synthesis of neoclassical transaction costs and behavioral paradigms started with him, and he convinced me rather easily that there really is no conflict between the behavioral approach and the neoclassical approach.

In the neoclassical approach to finance, there are no institutions. Individuals transact directly in markets. And you get some fantastic, powerful results from that. However, in the real world, institutions have to develop. We tried our hands at a synthesis of the approach, and I think that's a major contribution. The fact that in studying financial institutions—in fact any firm, any organization—the *risk balance sheet* is just as important as the accounting balance sheet (which shows at a point in time the value of assets and liabilities). This means that one has to think in terms of exposure to risk, or changes in the risk-balance-sheet items. Bob developed an approach based on option pricing theory, or its extension, contingent claims analysis—I'll just say that term once and leave it at that, but today in academic circles it's known as contingent claims analysis.

Another key concept is the financial innovation spiral, the idea that institutions are constantly changing. Products move from institutions, where they typically are innovated, to markets, where they become more homogeneous. And then, from markets with homogeneous products, new institutions can develop. It's like a spiral, moving up, sometimes collapsing. Crises occur periodically, but fundamentally there's an upward movement over time.

Contingent claims equivalence to dynamic replication—now that probably sounds like gobbledygook to many of you, but the basic idea here is the fundamental insight that comes from option pricing theory—namely, that one can use basic instruments to replicate the payoffs from other contracts. To replicate stock options, you can use stocks and risk-free bonds. That gives you a theory of the production of new financial instruments, and it also gives you a price, because the no-arbitrage principle says the option price has to be equal to the cost of replicating the option dynamically in that fashion.

Now, that's a very powerful principle, and in fact Bob once said to me that at the first presentation he made while still a graduate student, the great Ken Arrow came up to him afterward. This was at a seminar at Harvard and MIT where many of the greats of economic theory were present. And Ken Arrow came over to Bob, who was 25 or 26 years old, and said, "Y'know, it occurred to me that that might be the case, that by trading dynamically you don't have to have complete markets for all contingencies."

Customers versus investors in financial firms—it's a very important principle for understanding the evolution of financial institutions. When one buys an insurance policy, as a customer, you don't want to be exposed to the default risk of the institution. So investors have to put up risk capital in order to satisfy the demand of the customers. That may now seem rather obvious, but in the theory of financial institutions, it's nowhere to be found until Bob introduced it. So we'll leave it at that, and now I turn it back to Harriet.

FATHER–SON COLLABORATION: AN EFFORT YET TO BE COMPLETED

Harriet Zuckerman: I had no idea [Zvi] was going to pull me out of the depths. But this is just not my world. I think I get most of the words, but none of the music. Even though RCM thinks it's presumptuous to identify ways in which he and Zvi extended his father's views on functional analysis, I can say as an outsider who knows more about the RKM side that they not only extended his ideas by looking very closely at one system, they also clarified a number of them—for example, that financial systems have to provide means for dealing with functions such as clearing and settling payments or pooling and subdividing resources. Such functions are far less changeable than the ways institutions in various times and places are organized to provide for such functions.

Their ideas are and were very powerful. I am quite sure that RKM would have applauded those extensions as they apply to financial systems. By no means would he have objected. As you'll hear, extending his ideas was something he cared a lot about. Now, did RCM and his father differ in some respects? Yes, they did. But RCM believes that the differences were more a matter of degree than of kind. What did RKM think about the functional perspective on the financial system? Zvi reported to me that RKM said he was very impressed.

He thought it might be still another one of RCM's major contributions. But he asked Zvi whether these ideas were new. He was very concerned that they not be repetitions of anybody else's work. He was worried about the priority of discovery.

RKM often mentioned wanting to publish with each of his offspring. In fact, he and his lawyer daughter, Vanessa, did publish together in 1983. They wrote a paper that dealt with the ambivalence that clients experience when they seek professional help from strangers.

Half-seriously, RKM also mentioned wanting to publish with RCM and Bob Solow so that the authorship could read, "Robert Merton Solow and Robert Merton Duo."

Audience: [Laughter]

Harriet Zuckerman: Alas, that paper never materialized. But I understand that Bob Solow liked the idea.

In the 1990s, RCM and RKM decided seriously to work together on a paper that would deal with the reward system of science—that is, on how it affects the choices scientists make among problems on which to do research. Their plan was to identify the conditions under which the reward system gives scientists incentives to work on important and hard problems more than it does for them to work on less important but easy problems.

But the question is, how do scientists actually make these choices? What they were doing was making *problem choice* a problem choice, a telling case of what RKM called self-exemplification in science. The idea behind it was that RCM would produce mathematical models of the choice of problems under specified conditions, and RKM would provide his vast knowledge of the reward system and concrete cases of instances of RCM's conditions. Now, RCM did what he was supposed to do. He worked through models of problem choice under two conditions and had plans for two more. The two talked about the paper daily.

According to RCM, his father understood the mathematics, and he also liked the outcomes of the models. However, this 40-page draft we have shows no signs of RKM's very identifiable writing style. It bristles with equations. When we mentioned this to RCM, he said, "Well, of course. I wrote it."

Audience: [Laughter]

Harriet Zuckerman: Now, RKM must have mentioned the paper to his former student James Coleman. By this time, Jim Coleman was a very distinguished sociologist, and he was a doyen of mathematical sociology. He was also the editor of a journal called *Rational Choice Theory*, and he accepted the paper immediately. But it wasn't ever published. Why was this? RKM had a history of withdrawing completed and accepted manuscripts from publication.

Almost always, the reason he gave for doing this was he didn't think the work was good enough. Now, was this the case here? RCM thinks not. He said RKM thought the results of the models were illuminating. RCM believes—and it strikes me as being probably true—that his father didn't think he had contributed enough to merit authorship of the draft as it then existed. The paper remains unpublished. As far as we know, no published equivalent exists. RCM has left the door open to future publication. He might return to it . . . sometime.

BLACK–SCHOLES–MERTON AND THE PRICING OF OPTIONS

I'll now return to another episode of RCM and RKM's joint life. We come to the simultaneous publication of Black–Scholes on the pricing of options and corporate liabilities and of RCM's theory of rational option pricing. These are papers very likely to be familiar to you. You know from Peter Bernstein's engaging book *Capital Ideas* that RCM put the brakes on publication of his paper on option pricing to make sure it came out at the same time that Black–Scholes did.

I'm going to quote from a longish email that RCM sent us. "As you know, Fischer Black and Myron worked together on the options pricing problem, and I worked on it alone, in friendly competition. Myron shared some of what they were doing with me occasionally. All my technical work, and much more, was done by

December 1970, when I distributed an MIT working paper. I created a narrower version called the rational theory of option pricing as an MIT working paper in 1971.

"Fischer and Myron were trying to get their paper published in the *Journal of Political Economy*. It was initially rejected, but by this time it had the strong support from Merton Miller and Gene Fama. However, resistance to publishing had continued on the basis that it was too specialized, and because finance and certainly options were not mainstream or important in economics." Again, this is RCM talking.

"I was approached by Paul McAvoy, my Sloan economics colleague, who had been named as editor of the newly created *Bell Journal of Economics*, with an offer to publish any paper I wanted, with as much space as I wanted, and rapid publication, and $500.00. My MIT salary at the time was something like $11,000.00." Peter Bernstein says it was $11,500.00. "I'd agreed to do it, but I imposed the condition that McAvoy could not publish the paper until I gave the okay.

"Now, here's the point of the story. I knew, from being around my dad, that if my paper came out with a 1971 imprint, or 1972, and Myron's and Fischer's came out later, as it did, in 1973, my paper would have been given the edge, that is, priority. This would be the case even if I wrote in the opening credits that my result could not have been done without theirs. Without their insights, my work would not have been the same, although I derived the results in a different fashion, and in my opinion my assumptions were considerably more general.

"When I found out when their paper would appear, I notified the *Bell Journal*, and both papers came out at the same time, in the spring of 1973." The following should be in boldface in Bob's email to us. "I am pretty sure that without the sensitivity that my dad instilled in me, I would have just published the paper. It's notable that when Black–Scholes published their paper, they published their derivation and mine as two ways. They did insert a footnote that gave me credit for the second way. Without that little note, maybe no Nobel? Who knows?"

Did RCM regret having delayed publication? No. In fact he said he sleeps better at night for having done so. Now, RKM was clearly standing in the wings of this drama.

How much fatherly advice did RKM actually give RCM? The documents we've seen show that the generally restrained RKM didn't shrink from responding when RCM asked for help. RCM did ask for his father's editorial assistance on his nontechnical papers.

He sought advice on dealing with publishers and, early on, on what to charge for consulting. This was well before he became far more experienced at it than his father was. In each of these instances, RKM was in his element. I'll describe only his propensity to edit other people's work. He made it tighter logically, more graceful, and with some frequency added good ideas the authors originally didn't have. It was said, in my world, that he performed literary alchemy, that he turned written dross into publishable gold.

TRISTRAM SHANDY TO THE RESCUE

Now, according to RCM, he and RKM also were alike in a particular speech habit. They both liked to digress. After making a statement, each would veer off into a verbal footnote, which then got its own verbal footnote, and then that footnote got a third footnote, leaving listeners anxiously wondering, would they ever get back to the original statement? And if they would, how would they do it?

This habit of digressing RCM describes as speaking in a "Shandean style," after Tristram Shandy, the subject of Laurence Sterne's nine-volume 18th-century novel, *The Life and Opinions of Tristram Shandy, Gentleman*. RKM was a dedicated Shandean. His book *On the Shoulders of Giants* is full of digressions. Indeed, the subtitle is *A Shandean Postscript*. It deals with the origins of the aphorism, "If I have seen farther, it's because I have stood on the shoulders of giants."

Now, most of you probably think that this should be attributed to Isaac Newton; that's wrong, as RKM demonstrated. Read the book. What accounts for their shared impulse to digress? Is it influence? Imitation? A totally independent practice, both enjoying following down the paths of their thoughts wherever they take them? I can't say. But it's unusual enough to comment on.

WHAT, OR WHO, IS A MERTONIAN?

Another verbal aspect we want to comment on is the term "Mertonian." You probably know that eponymy—that is, naming an effect or an equation or, at the most extreme, an era, like the Freudian or the Darwinian era—is the most significant reward scientists can get. Zvi told me not long ago that RCM's admirers are called "Mertonians," and he asked me if RKM had admirers, and were they called Mertonians? I said yes, of course. That led me to remember that the *Oxford English Dictionary (OED)*, the definitive history of the English language, has a listing on the word "Mertonian."

It says, "From the proper name of Robert King Merton, 1910 to 2003, U.S. sociologist and humanist regarded as the founder of the sociology of science." The first use of "Mertonian," according to the *OED* in this sense, appeared in print in 1960. The *OED* goes on to say, "It is still in current use." Now, we await a revision of the *OED* that will revise that definition by noting that it now also applies to individuals and ideas associated with Robert C. Merton.

CONCLUSION: A WORLD WITH FOUR ROBERT MERTONS

So much for Mertonians, because we have more coming. There are four Roberts Merton. You may have noted that RCM is not RKM, Jr. RKM would never have named his male offspring Junior. Too ordinary, and unacceptably self-referential. Now, according to RKM, he never told RCM why he was not RKM, Jr. Being obvious was not his style. He wanted to give RCM a puzzle to solve, and RCM did. When RCM telephoned his father to report the birth of his first son, he declared that the baby would be called Robert Frederick, and said no more.

Now Robert F. has his own son, and he is Robert A. We now have four Robert Mertons, and the possibilities for confusion multiply as each new generation comes into the world. RCM has been confused with RKM. I was sent a textbook that dealt with RKM's work, and RCM's picture is in the textbook. Once, when RKM encountered a colleague at Columbia at an elevator, he said, "Oh, Bob, I had no idea you knew so much mathematics!"

Audience: [Chuckling]

Harriet Zuckerman: I'll close with the observation that RCM has said how much it pleases him that when he types "Robert Merton" into Google, his father's name, not his, comes up first, this being a mechanical outcome of the number of queries the Google machinery receives. Now, why does RKM's presence please him so? He responded, "Well, my father has now been dead for 16 years, and with the Nobel, one might have thought my name would have displaced his. But it hasn't."

This pleases RCM because he knows what really mattered to his father. It was that his ideas would live on after him, that they would be of interest to others, not obscure references long since stale and outmoded. RCM knew his father very well. By drawing, in his own research, on his father's ideas, RCM has shown that those contributions still have value. In doing so, he's also increased the chances that his father's contributions would remain useful as others are stimulated by the ideas his son has used.

Paul Samuelson once described RCM and RKM as "a worthy son of a worthy father." In our view, they're also a deserving pair. Thank you.

TRUST AND THE FUNCTIONAL PERSPECTIVE

Richard Thakor
University of Minnesota Carlson School of Management

It's really an honor to be here. Bob has been a tremendous influence and mentor. A mentor both in terms of intellectual ideas, but also in terms of generosity with his time, even when I was just a PhD student.

My presentation is going to focus on Bob's work on trust and its key role in the financial system. At an intuitive level, we understand that trust in financial products and institutions is essential for financial markets to function. What Bob has emphasized is that a functional perspective of trust creates a very powerful framework to understand recent developments in the financial system and the economy that are difficult to explain in our traditional frameworks.

DEFINITION OF TRUST

A challenge in the literature has been to provide a formal definition of trust. Bob emphasizes two basic components. The first component is competence, which is about skills. And the second component is trustworthiness, which is about intent.

You can think of the first component as asking if a company or person has the skills to act in a good manner. Bob mentioned to me that a good way to think about the first component is that a completely honest but incompetent firm can make decisions that are just as bad as an untrustworthy firm. Bob gave me example, which stuck in my mind, which is that you may trust your children, but you would not trust them to perform surgery on you unless they're trained medical doctors.

The second component of trust is trustworthiness. Will a person or company, given that they *can* act in a good manner, *choose* to act in a good manner? A person may be competent, but you may still choose not to transact or interact with them if they're not trustworthy.

Trustworthiness is related to the existing notion of reputation and the associated statistical framework of Bayesian updating, but there are some features of trustworthiness that are not well captured by this framework. First, trust is a zero-one property—so you either trust someone or you don't. Second, if you trust someone, you'll think that there's no possibility that they'll act badly. In fact, you may ignore some evidence consistent with them acting badly. Third, if trust is broken, it's completely unexpected and results in a paradigm shift, in the sense that you feel the world does not work in the way that you previously thought.

THEORETICAL FRAMEWORK

In our recent joint work, we attempt to incorporate these observations formally in a theoretical framework. You first start by ascertaining whether an entity is competent or not competent; and if they're not competent, you don't contract with them. If they're competent, you then evaluate if they're trustworthy or not. There are two different models of the world in this case.

In model 1, you think the firm will never engage in bad behavior. If you trust the firm, you'll assign prices and negotiate contracts accordingly and the firm will get the best contract terms. If you then observe an outcome that is good, you'll continue to trust the firm. If the outcome is bad, which would be inconsistent with the model, you will think the outcome is due to bad luck or some other circumstance but not due to the firm behaving badly, and you will continue operating as if you trust the firm. Any evidence that is slightly inconsistent with the model may be ignored.

In the second model of the world, you think there is some chance the firm will engage in bad behavior, so you don't trust the firm. You'll assign prices and contracts accordingly, and the terms from the firm's perspective will be *ex ante* worse than if you trusted the firm. Any evidence that a firm behaved badly will be consistent with the model; and if you observe a good outcome, you will think that the firm just chose not to act badly.

In this framework, losing trust can be understood as a paradigm shift between model 1 and model 2. If you operate under model 1 and observe an outcome that is so bad that it is completely inconsistent with the model, trust can be broken. You will re-evaluate your view of that firm and you may shift to model 2. We argue that this is such a big shift that it's discontinuous in terms of prices and other consequences.

To emphasize, the key takeaways here are that first, a trusted individual or firm will be able to get contract terms or prices at favorable terms. Second, trust will insulate the firm from the adverse reputational consequences of bad outcomes. Third, trust can be lost. And if trust is lost, it will cause a large and discontinuous shift. Finally, losing trust will be easier than regaining it once trust has been lost.

APPLICATIONS OF A FRAMEWORK BASED ON TRUST AND THE FUNCTIONAL PERSPECTIVE

In my remaining time, I'll discuss some applications if we combine trust with Bob's work on the functional perspective, which aims to understand financial institutions, for example, not in terms of the labels we put on them, but on the basis of the core economic functions they perform. What I want to underscore is that this gives a practical framework for understanding a number of changes that many people have hypothesized are fundamental shifts in the financial system.

The first application is the 2007–08 financial crisis. There are a few stylized facts about the crisis. First, there was a very sharp and discontinuous increase in risk premiums, in particular in markets such as bilateral repos. Second, markets froze. Companies were relying on markets like the European interbank market to fund themselves and suddenly those markets froze and the companies could no longer get funding. And third, risks that were penalized during the crisis were not even contemplated before the crisis.

I'll argue that this is all consistent with the framework of trust that Bob has been developing. It's consistent with discontinuities in pricing and risk and in the supply of credit that we can understand within the context of trust. Investors initially placed trust in the functioning of various technologies and various markets, and they had their trust broken when they observed events that were incompatible with trust.

FINTECH AND FINANCIAL ADVISING

The second application is financial advising and wealth management, where there has been a big influx of financial technology. Trust is going to be fundamental in understanding how these areas may evolve in the future. Bob highlights three main points. The first is that a client and adviser share the objective that their relationship will, they hope, last a long time. However, while the client will tolerate some level of bad performance, if the performance becomes bad enough, the client will leave the wealth adviser. Put differently, the greater the degree of trust the client has in the adviser, the higher the threshold of tolerable bad performance. Trust is therefore a valuable asset for a financial adviser to retain clients against competition. And elements that foster trust for financial advisers—minimizing conflicts of interest or having fee-only independent advisers—will tend to disrupt traditional product-based wealth management models.

The second point he emphasizes is that the introduction of fintech into wealth management will be limited to the extent that it relies inherently on opaque products and technology alone. In this case, verification of investment performance may be especially difficult, so the ability of fintech to disrupt and survive in this environment will depend on its ability to generate and maintain trust.

The final point is that we can view regulation as one way to cultivate and strengthen trust, such as fiduciary responsibility for financial advisers. To the extent that information is not inherently opaque or complex, mandated disclosures can encourage transparency and foster trust.

LENDING

Another area of application is lending, where we've seen peer-to-peer platforms and the use of technology to originate loans that don't flow from traditional banks. This situation can also be viewed within a framework of trust, which Bob and I have explored in our joint work. The starting point is that the lending *functions* of banks and nonbanks are the same—both provide debt financing or loans to clients. But their institutional features differ. Deposits provide banks with a valuable source of financing, but the depositors are also customers that don't want their service provision—for example, safekeeping—to be jeopardized by the bank's credit risk. A key result is that trust will allow a lender to raise financing at the best possible terms.

A second point is that banks have endogenous incentives to develop and maintain trust through making good loans, as opposed to bad loans, because of their ability to collect deposits that provide the funding. Third, loan defaults in good times can cause a loss of trust. If you observe that a loan defaults when the economy is healthy, it's very likely that the loan defaulted because the bank made a bad loan. In contrast, if the loan defaults when the economy is doing poorly, you can attribute the default to economic conditions and bad luck. Finally, if trust is lost—if there is another crisis that erodes trust—a prediction from the framework is that banks will be better able to survive this loss of trust than nonbanks such as fintech firms.

Bob also notes that block chain and digital currencies can potentially have a large impact on financial markets, but trust is important for these currencies to function as well. Block chain, for example, uses a consensus mechanism along different record keepers. The conclusion is that block chain and digital currencies will not be able to succeed unless they're widely accepted, and they won't be widely accepted unless they're trusted.

In ongoing work that Bob and I are collaborating on, trust can interact in interesting ways with respect to companies' information environment. Companies can choose a level of informational transparency through disclosures to investors and to the market in general. We want to understand how this can potentially substitute for trust. The main idea is that information disclosure allows access to more financing and better terms, but the trade-off is that information may also get to your competitors. One insight here is that trusted institutions may be able to afford being more opaque. It may be that if you trust a firm more, it will actually disclose less information. The second is that transparency may substitute for trust. So if you don't have trust, there may be some cases where you can disclose more information and get some of the benefits of trust, as long as that information is not too complex. And third, a mitigating factor is verification. Simply put, if you see that something works, it may be an alternative for both. An implication is that in situations where you can't verify or make something transparent, trust is your only answer.

Bob has been actively promoting many of these ideas in his presentations as well as some of the joint work that I've had the privilege of collaborating on with him. Thank you very much.

QUESTIONS AND ANSWERS

Audience: Have you thought about the role of regulation in establishing and maintaining trust?

Richard Thakor: One of the purposes of regulation can be to foster more trust. Regulation can help investors trust firms, in which case, firms will have access to the benefits of trust that I discussed earlier.

Audience: But you need competent regulators.

Richard Thakor: Yes, you do need competent regulators. And of course there are a lot of complex issues such as regulatory capture, but if regulation is designed in a certain way, I think that it does have the potential to enhance some of the functions that we see.

Audience: How are you taking into account all the other factors that influence trust other than performance? I'm thinking in my own work what leads my clients to trust me or not. Secondly, how are you taking into account the variability in the capacity of people to assess performance and to evaluate all the factors, including the uncertainties that go into performance?

Richard Thakor: I completely agree with you. This certainly is not meant to encompass everything, but I think that performance itself is, at least in our economic and finance models, one of the things that we emphasize based on outcomes we observe, such as loan defaults, financial strength of the company, and so on and so forth.

Audience: You did not mention too much about the legal and regulative framework. For instance, you made a comment about banks versus nonbanks. I think one important distinction is the fact that banks are highly regulated. Also, when you look at it across different countries, why is it that the United States has the most successful financial system despite missteps? I think it has to do with the fact that it has, despite some issues, the strongest regulatory environment. I think it's very useful to explore your arguments in the context of international comparisons.

Richard Thakor: I completely agree with you. That would be very interesting to explore. Some regulation, I think, can foster trust, but there's also the sense that if you already have trust, you don't necessarily need regulation.

THE RELATIONSHIP BETWEEN ECONOMICS AND FINANCE

James Poterba
Massachusetts Institute of Technology and National Bureau of Economic Research

Eric Rosenfeld: Our lunchtime speaker is Jim Poterba, the Mitsui Professor of Economics here at MIT. He's also the head of the National Bureau of Economic Research (NBER). His research focuses on the impact of incentives, especially tax incentives, on households and firms. He's going to talk about the history of the collaboration between economics and finance—but given the events of the day, you should feel free to quiz him on optimal tariff policy.

James Poterba: Thanks, Eric. It's really great to be part of this wonderful celebration and to see so many friends and colleagues gathered together. Like Robert Jarrow [who spoke earlier], I received a clear set of marching orders from Zvi [Bodie]. I was to speak about the relationship between the fields of economics and finance and to reconcile any tensions between the two over the course of lunch. [*Laughs*] Unlike Robert, I did not follow my orders, but pushed back and said, "This is lunch, give me a break." No slides, no discussion of Itô calculus, and a few stories—then we'll talk about the interplay between economics and finance.

MIT REALLY DOES HAVE AN ECONOMICS DEPARTMENT

I want to start by saying that I am here as a representative of the MIT economics department, which is incredibly proud of its distinguished graduate Bob. Jerry Hausman is also here representing our department, which has never hesitated to bask in the reflected glory of Bob's accomplishments.

When Ben Bernanke came to MIT in 2006 to deliver the commencement address, he began his talk by explaining to the gathered MIT community, much of which probably had no idea we had an economics department, that MIT had been teaching economics since the 1880s when Francis Amasa Walker was president of the Institute. Bernanke also pointed to the accomplishments of economic research and the way this had transformed the world. He emphasized the work that led to the financial economics revolution, which in an important sense began in this building. Bernanke said, "The global financial industry has been transformed by quantitative approaches to pricing complex financial instruments such as derivatives, and to managing and measuring risk. This transformation stemmed from the application of formal tools of mathematical economics by the faculty of the Sloan School, including Fischer Black, Bob Merton, and Myron Scholes."

That was a way to explain that the economic tools developed here at MIT had consequences for industry and commerce in the wider world.

BOB MERTON BECOMES AN ECONOMIST

This important revolution, however, owes at least a bit to good fortune. It was not a foregone conclusion that Bob Merton was going to graduate school in economics. He applied to something like six different schools and was admitted by only one. Harriet [his stepmother] mentioned the word *serendipity* this morning. There's a wonderful book by Robert K. Merton [his father] and Elinor Barber, which is called *Serendipity*. Serendipity is not good luck. It is the result of a trained observer finding something he wasn't expecting to find while doing something else. When a scientist discovers, by her powers of observation and deduction, that something else interesting is happening in her experiment, that's serendipity.

I don't think Bob being admitted to the MIT economics department was an act of serendipity. I think it was just a bit of random good luck. MIT doesn't always discover promising economists at a young age. They passed on [the early and very influential Nobel Prize winner] Ken Arrow.

There is a lot of history behind Bob's arrival at MIT, but as this is lunchtime, I will skip over it and highlight the start of his studies. Bob arrived on registration day, and Bob Solow was the graduate registration officer. There was a long line outside Solow's door. There was no line at the next door over, so—arbitrage in action—Bob decided to walk through that door to see what or who he found. That was Paul Samuelson's office. *[Laughs]*

MERTON AND SAMUELSON

So the Samuelson–Merton connection begins early on. This is where serendipity comes into play. Harold Freeman, the MIT economics department chairperson who had originally recruited Samuelson, convinced Bob that he needed to enroll in Paul Samuelson's mathematical economics course. Paul soon realized the gift the gods had brought him and turned Bob into his research assistant and then his collaborator.

Paul would have loved to be here as part of this celebration. Fortunately, we have Paul's descriptions of Bob and his critical role in their joint work. Paul Samuelson wrote the foreword to Bob's *Continuous-Time Finance* book, and I'll just read you his tribute:

> Robert Merton is known as an expert amongst experts . . . [and] I am proud to have figured in the Mertonian march to fame. . . . One of the great pleasures in academic life is to see a younger savant develop, evolving into a colleague and coauthor—and then best of all the rare sight of a companion at arms who forges ahead of you, as you were able to do at the inflection point in your own career.

Coming from Paul Samuelson, that's pretty strong praise.

I want to dwell a bit longer on the Samuelson–Merton interaction. In 1969, when Harvard introduced a seminar in economic theory, Paul Samuelson was invited to be the first speaker. He began his presentation by saying: "Our speaker today will not be me. It will not be a full professor. It will not be an associate professor. It will not be an assistant professor. Rather, it will be one of the graduate students who's back in the bleachers. I would like to introduce you to Robert Merton, my coauthor for this paper, who will do the presentation today." Paul Samuelson clearly enjoyed delivering that introduction, and we know from Zvi's remarks this morning that the seminar went brilliantly. The rest, in some sense, is history.

BRINGING FINANCE INTO ECONOMICS

Let me now move to the interaction between the fields of economics and finance. Paul Samuelson did a lot to bring *finance* into *economics*. He was very interested in financial topics. He used to say that the stock market and personal finance are the catnip that attract people to introductory economics. My thesis today is that Bob has played an incredibly important role in continuing to build bridges between finance and economics and that he has been bringing the fields closer for nearly 50 years.

It's difficult to try to distinguish finance versus economics. Fortunately, back in the days of the yellow-covered NBER working papers that had white holes in the middle, Stanley Fischer, who was one of Bob's office mates in graduate school, wrote a paper with Bob entitled "Macroeconomics and Finance." They defined finance as "the study of household behavior in the intertemporal allocation of resources in an environment of uncertainty and the role of private sector economic organizations in facilitating these allocations." Using that definition, there are many parts of economics that are not finance. It is harder to find parts of finance that could not be included in economics.

Fischer and Merton lamented that macroeconomics at the time was ignoring financial economics, particularly the role of the stock market as a key pricing mechanism that affected macroeconomic outcomes such as investment and consumption. There's a wonderful passage in which they describe, more practically, the difference between finance and economics. In traditional macroeconomics, they argue, the emphasis is on the explanatory variables and the residuals are treated as noise, which you would prefer not be there. By contrast, in finance, it is precisely the noise, the residuals, that represents the uncertainties that significantly influence economic behavior. In short, if there were no residuals, then there would be no subject of finance.

The Fischer–Merton paper was written in 1984. The situation today is quite different. If you were to go to a macroeconomics conference today, you would discover that the events of the last 15 years have turned most macroeconomists into students of financial intermediation, imperfect credit markets, and the intermediates who link the household sector and the corporate sectors.

If you go to a *monetary* economics conference, in particular, you would find that since most of the unusual monetary policy of the last decade has involved using policy tools to try to inflate asset values in the hope that this will spur consumer spending, macro- and monetary economists now realize that they must understand what determines asset values. In this century there's been an enormous shift toward integration between finance and macro.

Bob's work has been central in connecting research in financial economics to that in macroeconomics. There are some questions in financial economics that are largely "within finance" questions. Examples might include the relative pricing of securities or securities market microstructure. These questions might not intersect with issues that macroeconomists or labor economists study. Bob's work, in contrast, brings the toolkit of financial economics to bear on large topics that are broadly of interest in economics.

I'm going to support my thesis in several ways, starting with the theory of intertemporal portfolio selection and optimal consumption. In Bob's classic papers on this topic, the consumption-planning problem drives the portfolio choice problem. Bob takes Frank Ramsey's (1927) optimal lifetime consumption–planning problem, recognizes that there are many different assets to hold and asks, "What should the consumer/investor do?"[22] That is a hard problem, but it is also a central problem for both economics and finance.

LIFE-CYCLE FINANCE AND RETIREMENT INVESTING

The same theme is evident as we move forward from the early 1970s, when Bob published his lifetime portfolio selection paper,[23] to the mid-1980s, when Bob published a remarkable paper on optimal social security in an NBER conference volume.[24] Public finance economists, the subgroup that usually studies social security, are not, in general, well versed in the use of Itô calculus. Bob's contribution to the conference essentially said, "Here's the way to develop the optimal social security structure." His answer involved an annuity stream with payouts indexed to aggregate consumption: a postretirement consumption-indexed annuity product that will be available once you reach retirement.

Peter Diamond, like Bob an MIT-trained and MIT faculty winner of the Nobel Prize in Economics, has observed that one of the key missing markets in the economy is that for a price-level indexed annuity market. Social Security can replace that market. In practice, inflation-indexed annuities are very rare. One of Bob's central insights is that an inflation-indexed annuity is not the security, or at least not the only security, that an individual would choose to hold in retirement. Lifetime portfolio selection indicates that even in retirement, an individual should bear some risk in exchange for a higher expected return. The key challenge is to design and develop products for this group of individuals.

Arun [Muralidhar] will talk more this afternoon about retirement income product design, but let me call attention to Bob's 1984 paper that lays out key principles for optimizing a retirement system. This paper offers practical guidance on a very important economics problem: drawdown of assets in retirement.

Fast-forward another 10 years. Bob was one of the first to point out that defined benefit pension plans were very costly and placed a great deal of risk on the firms or other entities that sponsored them. He explained clearly that many of the firms offering them didn't understand their risks and that going forward, firms would either have to pay more for their pension product or would have to move to a different environment, for example, one in which defined contribution plans dominate. That is the situation today.

TURNING DEFINED CONTRIBUTION BALANCES INTO RETIREMENT INCOME

Bob also recognized, along with Zvi Bodie, that in the defined contribution world, baby boomers, when they were in the labor force, were

[22]Frank P. Ramsey, "A Contribution to the Theory of Taxation," *The Economic Journal* 37 (1927): 47–61.

[23]Robert C. Merton, "Optimum Consumption and Portfolio Rules in a Continuous-Time Model," *Journal of Economic Theory* 3, no. 4 (1971): 373–413; Robert C. Merton, "Lifetime Portfolio Selection under Uncertainty: The Continuous-Time Case," *Review of Economics and Statistics* 51, no. 3 (August 1969): 247–57.

[24]Robert C. Merton, "On the Role of Social Security as a Means for Efficient Risk Sharing in an Economy Where Human Capital Is Not Tradeable," in *Financial Aspects of the United States Pension System*, ed. Zvi Bodie and John B. Shoven, 259–90 (Chicago: University of Chicago Press, 1983).

primarily focused on how much they could accumulate in their pension account. They were asking the wrong question! The right question was, how large a stream of income or consumption in retirement they could purchase with their accumulated balance. As someone who had fully absorbed the lessons about the importance of changes in the opportunity set for investments from Bob's 1971 paper would recognize, just knowing the asset balance did not answer that question.

Defined contribution plan participants need to think about how they would transform the wealth accumulated for retirement into a stream of consumption that they can live on in their retirement years. That leads to a critical insight regarding the definition of the riskless asset for somebody planning future consumption.

Today in the pension world we're seeing that as the baby boomers have moved from the accumulation phase to the early days of retirement and are thinking about what comes next, the focus has shifted from asset accumulation to what to do with those assets at retirement. The work that Arun and Bob have been doing on SeLFIES brings a helpful perspective to thinking about how you want to manage accumulated retirement assets. This underscores how the work Bob has done on intertemporal consumption planning, which then leads to the work on optimal retirement product design, brings together the fields of economics and financial economics in a very fundamental way. I think it illustrates for anyone who's an outside observer the important symbiosis between those two fields, because it shows how you can use the tools and technology of financial economics to tackle problems that are very difficult but central to the way households go about their problem of consumption planning.

ON OPTIMAL GROWTH

Let me offer a second example of linking finance and economics. This one's a little bit farther off the beaten track. One of the chapters in Bob's dissertation was on optimal growth. Those of you who've been around MIT know that it was pretty hard to be an economics graduate student at MIT in the 1960s and not to write a dissertation on optimal growth. This was what Bob Solow was working on, and Bob Merton's dissertation committee was Paul Samuelson, Bob Solow, and Frank Fisher. This was in the air. Bob Merton's dissertation chapter is on what happens if the growth rate of population depends on per capita wealth. You can think of various reasons why the level of economic development as measured by wealth per capita might affect the population growth rate.

Bob Merton also wrote a second paper on optimal growth, which appeared in the *Review of Economic Studies* in 1975.[25] It brings stochastic calculus to bear on the problem of optimal growth. Most of the work on optimal growth is done in a world of certainty—for example, about the rate of technological change and population growth—and the question is what the steady state will be. Bob brought in stochastic population growth, which means that the steady state that generations of economics graduate students have learned how to find is replaced by a steady-state distribution of outcomes. That is a much more complicated situation, both mathematically and economically. It opens the door to a lot of additional work in the theory of optimal growth.

Nobel laureate James Mirrlees also worked on stochastic growth. He was a Cambridge-trained

[25]Robert C. Merton, "An Asymptotic Theory of Growth under Uncertainty," *Review of Economic Studies* 42, no. 3 (July 1975): 375–93 (Chapter 17 in *Continuous-Time Finance*).

mathematician, and no mathematical slouch![26] He studied the problem of optimal growth in the presence of shocks during the 1960s as an unpublished paper that Bob cites. Mirrlees never felt that he got enough traction to be able to go forward and publish that paper. I recently asked Bob Solow why stochastic growth research did not take off after Bob Merton's paper. His answer was that "it was just too hard." *[Laughs]* I thought that option pricing with stochastic calculus was hard, too, but there was more of an incentive for the financial sector to figure that out than there was for a development economist to figure out optimal stochastic growth in the presence of an Itô process for population growth.

By the way, I emailed Bob Solow this morning. He will be celebrating his 95th birthday later this month. He asked that I share this message with this gathering: "Please convey that one of the things Paul Samuelson and I shared is fondness and admiration for both Bob Mertons, the elder and younger. Between them, they covered most of the human virtues. To have known them both is serendipity at its best."

OPTION VALUATION AND CONTINGENT CLAIMS ANALYSIS

My last illustration of Bob's role in unifying economics and financial economics focuses on contingent claim valuation. In this area, one can see the tools of financial economics being used to tackle all manner of economics problems.

One of my litmus tests for figuring out whether someone is a finance economist or not, in terms of intellectual perspective, is to ask how they think about capital gains taxation. Public finance economists usually focus on the fact that the capital gains tax rate is lower than the ordinary income tax rate that applies to dividends and interest, and the distortions that may create. Financial economists almost invariably point to the embedded options provided by a realization-based capital gains system, which enables you to decide when to take gains and when to take losses, and thus gives you the opportunity to optimize against the government, which plays a passive role. Work by George Constantinides, Chester Spatt, and others points to the fact that when you have a realization-based tax, the economic consequences of the tax system can be quite different from what a simple analysis without embedded options would suggest. The effective tax burden is much lower when investors have the option to selectively realize gains than when they don't. Contingent claims analysis allows you to reach that conclusion easily.

In labor economics, Bob Hall, who was part of the MIT economics faculty in the 1970s, has described the decision to hire a worker as the decision to exercise an option. There is always the option to wait another quarter to make the hire. The option to delay an action, or not to take it at all, is valuable, and by hiring the worker you've extinguished it. Not only is that important for labor economics, it's also fundamental for thinking about economic fluctuations and for trying to understand how unemployment and hiring fluctuate over the course of the business cycle.

Of course, there are contingent claims in all kinds of different financial instruments and transactions. Bob's paper on corporate debt lays out the framework for how to think about these embedded claims providing guidance for all of us in trying to understand the financial system.

[26]Sir James Mirrlees won the 1996 Nobel Prize in Economics.

BOB MERTON AS A TEACHER

I want to close with a different but very important theme: Bob as a teacher. One thing Bob did here at MIT and also at Harvard was to be an incredibly effective salesperson for financial economics as a toolkit for studying a wide range of other topics. My wife, Nancy, who was a graduate student at MIT in the early 1980s, took Bob's course, 15.415, and she was part of a large group of graduate students in the economics department who took that course because they realized that they were learning a set of useful tools. Whether they were industrial organization economists, finance economists, or macroeconomists, the lessons in that course helped them tackle various issues that were on their research agendas.

That era was the time when Fischer Black was also teaching PhD students interested in finance. A joke that I believe the students told was that if you were taking the finance general exam, you had to figure out which were Bob's questions and which were Fischer's. If it was Bob's question, you knew that the answer was to apply contingent claim valuation; you just had to figure out how to do it. Fischer's questions, in contrast, were often the same from year to year, but the acceptable answers changed.

To conclude, Bob has played a central role in advancing, not just research, but pedagogy in finance and economics. We all appreciate the work he has done to bring students into the field of financial economics and the bridge he has built between nonfinancial economics and financial economics. Today, that bridge is a very firm and well-trod structure. Bob has been a role model for generations of economics graduate students, and it's really a pleasure to celebrate his accomplishments today. Thank you.

ROBERT MERTON'S IMPACT ON RETIREMENT SECURITY: FINANCE SCIENCE, SELFIES, AND THE MMM PLAN

Arun Muralidhar
Mcube Investment Technologies

I've been asked to compress 35 years of Bob Merton's work on retirement security into 35 minutes. As a result, this is going to feel a little bit like speed dating. I've had the pleasure of working with both Franco Modigliani and Bob Merton.[27] There are many similarities between them—their brilliance, the number of ideas that they send to you. But there's one thing that distinguishes the two: Bob has never called me up at 6:00 in the morning. I can't say that about Franco!

Franco's favorite cartoon was one from *The New Yorker* that said, "Forget about me. Save Social Security." Given the occasion, I was trying to think about what would be an appropriate cartoon for Bob, but all I could come up with was, "Forget about me. Ensure retirement security." While this might seem like just a little tweak, it's a high compliment to Bob because his work on retirement security goes even beyond what Franco did.

I got my PhD from MIT in 1992, and I wrote my thesis on using real options to value the financial flexibility of multinational enterprises, so essentially leveraging Myron Scholes's and Professor Merton's ideas on options and applying them to valuing real and financial decisions of firms. But then I went nonacademic, and I ended up at the World Bank issuing structured bonds. Within the first few months I was able to use Merton's students' models, especially those of Robert Jarrow, to save the World Bank millions of dollars because of the embedded optionality in structured bonds.

In 1995, the World Bank moved me over to the pension fund. At the time, the World Bank was on a path to privatize social security globally. While not my primary responsibility, I started to apply finance science, as Bob calls it, to look at the privatization model. I suddenly realized it made no sense at all. Privatization was based on myth and people's personal biases, but it wasn't based on finance science and was likely to lead to bad outcomes and transfer wealth from the poor to the rich—the exact opposite of the World Bank's mandate!

I began to question the economists at the World Bank who were pressuring countries to adopt privatization, and they, in turn, accused me of not knowing anything about savings. I then called Franco, who was having a similar discussion in Italy, and we ended up writing a book titled *Rethinking Pension Reform*.[28] That's how

[27]The late Franco Modigliani was the recipient of the 1985 Nobel Prize in economics and served at MIT with Robert Merton.

[28]Franco Modigliani and Arun Muralidhar, *Rethinking Pension Reform* (London: Cambridge University Press, 2004).

I first got formally introduced to Bob because Bob kindly wrote the back-cover material for the book.

I then went to the dark side in the late 1990s and I now manage institutional money for a living. But about seven years ago I again started to do pro bono work on retirement security. I started to assist various US states in their attempt to ensure that poor people have access to secure pensions without having to pay a lot of money for this privilege.

The first thing you do if you're going to work in that area is to read everything Bob's ever written, along with a lot of Zvi Bodie's work, too. As a result, I sent Bob an email out of the blue, asking if he remembered me from the Franco connection and mentioning that I had a few questions about his work. Not only did I get a very kind and immediate reply but I also got about two-and-a-half pages of ideas to think about. Fortunately, we've been exchanging emails ever since, leading to a number of collaborations that I will discuss today.

I recently published a book on this work to help US states, titled *50 States of Gray*.[29] I figured nobody's going to buy a book on pension security, but they might buy it if they think it's an erotic thriller. This book includes a new instrument that we designed. The new instrument combines an absolutely brilliant idea that Bob articulated in a 1983 paper—to create consumption-linked bonds—with a paper I coauthored called "The Relative Asset Pricing Model,"[30] in which I made the case for a new class of safe assets when one invests relative to stochastic goals.

A NEW BOND DESIGN FOR RETIREMENT SECURITY

When you combine these two ideas, you get this new bond design, which I'll call SeLFIES—and I'll explain why we call it SeLFIES a little later—which helps improve the retirement security problem around the world. Further, if you combine SeLFIES with Bob's retirement income model and another brilliant idea that Franco had articulated about 20 years ago, you can create a very interesting pension plan that achieves the goals of a diverse group of stakeholders—the Flex MMM Plan.[31]

THE FIRST PILLAR OF RETIREMENT: SOCIAL SECURITY

Taking a step back, in the last generation we've gone from a pension system that was paternalistic, with the government providing you with Social Security benefits or your company providing you with a guaranteed defined benefit (DB) pension if you worked with them for some time, to a model where we're now loading up all that risk on the individual through defined contribution (DC) plans. The problem with Social Security—and I'm going to simplify it greatly—is that the pay-as-you-go DB system, which is the way Social Security is designed, requires taxing the young to pay for the benefits of the old. If you don't have sufficient population growth, have low productivity growth, and people are living longer, something's going to break. You have to either raise taxes or cut

[29]Arun Muralidhar, *50 States of Gray: An Innovative Solution to the Defined Contribution Retirement Crisis* (Greenwood Village, CO: Investments & Wealth Institute, 2018).

[30]Arun Muralidhar, Kazuhiko Ohashi, and Sung Hwan Shin, "The Relative Asset Pricing Model: Toward a Unified Theory of Asset Pricing," *Journal of Investment Consulting* 15, no. 1 (2014): 51–66, papers.ssrn.com/sol3/papers.cfm?abstract_id=2480183.

[31]MMM stands for Merton, Muralidhar, and Modigliani.

benefits. The first pillar of retirement security, the social security–type design, globally, is thus in bad shape.

THE SECOND PILLAR: PENSION FUNDS HAVE MISPRICED RISK

The second pillar used to be your employer looking after you through a DB pension plan. Bob wrote about how pension plan sponsors mispriced DB plan risks. In my opinion, it was the improper use of finance theory to manage these assets that caused the DB pension crisis because investors were using an asset-centric model for a liability-centric problem. Stated differently, holding portfolios with large equity allocations relative to a long-duration bondlike liability implies high asset–liability mismatch risk.

The mispricing of risk was first exposed by the tech bubble blowing up in 2000–2002. The later global financial crisis pushed these pension funds over the edge. And I think the Federal Reserve and central banks around the world are nailing the coffin shut, with historically low interest rates. As a result, employers and governments no longer want to sponsor such plans because they do not want to bear these risks. As a friend has noted, DB now stands for "Dead and Buried." The decline of DB plans thus forces almost all retirement assets into the DC space, where risk is loaded onto the individual. In the interest of brevity, I focus the rest of this presentation on the defined contribution challenge.

A FINANCIAL INNOVATION THAT WOULD HELP PRESERVE RETIREES' STANDARD OF LIVING

Recall that Social Security is a public, mandatory DB system, with little to no accumulation. You work for a number of years; your benefit gets calculated based on your lifetime income and number of years of service, and you get an adjustment for the cost of living. What Bob Merton was recommending back in 1983 was the following: If that system is shaky, countries should revert to a capitalized system or a DC system, where the system is still going to be public, participation is still going to be mandatory, but the benefit amount is not guaranteed because now it depends on the performance of the assets that the system accumulates.

In his 1983 paper,[32] Bob recommended connecting people's contributions to the pension system based on their consumption. Under the existing system, you're required to put a portion of your income into Social Security. The amount is a fixed percentage; but with the gig economy, Bob's suggestion back in 1983 of connecting the contribution amount to consumption is actually a stroke of genius because income with the gig generation is often interrupted, whereas consumption typically is not. When you hit retirement, this new public DC plan, unlike the current DB payout formula, would promise you a payment stream that was indexed to *per capita* consumption, or the standard of living.

The reason for this recommendation is simple—individuals like to maintain their pre-retirement standard of living through retirement as well. Therefore, if you've been saving for 40 years and you're going to live in retirement for 20 years, an effective pension system should have a payout that keeps you at or near the standard of living you've been used to. How does this new public pension plan do that? Bob suggested that

[32]Robert C. Merton, "On Consumption-Indexed Public Pension Plans," in *Financial Aspects of the U.S. Pension System*, ed. Zvi Bodie and John B. Shoven, 259–90 (Chicago: University of Chicago Press, 1983), www.nber.org/chapters/c6035.pdf.

this fund would invest in a diversified portfolio on the one hand. But then, to enable this public fund to hedge future changes in the cost of maintaining an individual's living standard, the government should issue bonds that are linked to per capita consumption. By buying such bonds, the public DC plan can hedge the risk of what the government has promised to pay out being adequate to maintain the retiree's consumption stream. Clearly, Douglas Breeden's Consumption CAPM has influenced this thinking.

But what is most fascinating to me is Bob's recognition back in 1983 of the government's role in completing markets, where there is an incomplete market to begin with. There are a lot of innovative ideas that come out of this beautiful paper, but I'm just going to focus on two.

First, as Jim Poterba mentioned, the most significant contribution of that paper was the recognition that the biggest risk in retirement is, not inflation, but the standard of living in an economy. In a survey done earlier this year, people were asked, "How many of you feel that you don't have the same standard of living in retirement as you did pre-retirement?" The number of people who felt that way is pretty staggering (and often in excess of 35% in developed and developing countries), which means that this risk is still unmanaged 35 years after Bob started to write about it.

CHALLENGES OF DC PLANS, AND WHY WE NEED A CONSUMPTION-INDEXED BOND

The second interesting contribution of this paper is the recommendation that we can create a new instrument, in this case the consumption-indexed bond, that satisfies a goal we are trying to achieve by saving money.[33] Put differently, if an instrument doesn't exist that helps us achieve the goal, why don't we create one? This reform of Social Security that Bob recommended back in 1983, along with the proposal with Franco, were sadly ignored, and Social Security's finances continue to deteriorate.

Switching gears, let's examine the challenge in DC plans. The beauty of having a DB plan, managed by the government or your employer, is that it's a multigenerational institution that can smooth risk over many generations. The moment you get the scope or timeline of the plan down to the individual, which is what DC plans do, you now have to solve a lot of issues in one lifetime.

DC plans force people to make complex decisions in three key areas: how much to save, how to invest the savings, and how to decumulate it when you get to retirement. However, you're dealing with an audience that can't even calculate the effect of inflation or compound interest; globally, 60% of people tested can't answer three out of four questions on basic financial literacy. We have, unfortunately, transferred all these difficult decisions about saving for retirement to people who are unqualified to make them.

Additionally, in DC plans, you accumulate with one vendor. But when you retire, unless you want to manage the spend-down yourself and also forgo the benefits of mortality risk pooling, you have to go to an insurance company and buy an annuity. More parties, higher cost! It just makes for a disastrous outcome. But if we fix the fact that the industry has focused on the wrong goal and potentially the wrong financial instruments, a case that Bob's been making for 15 years, you could actually solve this problem quite easily.

[33] Today, we refer to this as "goals-based investing."

The goal, whether in a DB or DC system, is for people to preserve their pre-retirement lifestyle. Imagine a chart of what these real cash flows look like for a 25 year old—let's pick an arbitrary number, $50,000 a year in today's dollars. Assume that this is in addition to what you receive from Social Security.[34]

What's interesting is that there are no cash flows needed for the first 40 years while you're working until age 65. After that, you just want a steady stream of 20 years of fixed real payments.[35] And if the payments are guaranteed, then you can retain your pre-retirement lifestyle. But this doesn't look like any bond that's in your portfolio today. It's definitely not the cash flow you get from stocks, which means just about every asset you hold in your DC pension plan is a risky asset relative to your DC pension goal!

WHAT IS THE "SAFE ASSET"?

Now, you can argue that maybe I can buy an annuity that could give me this payout. But as Franco Modigliani noted in his 1986 Nobel Prize lecture, there's an "annuity puzzle": Although, objectively speaking, holding annuities is welfare improving, less than 10% of the population actually buys these instruments. I'll explain why in a second.

This leads us to a critical point—that the true metric of retirement security is not the level of accumulated assets (or wealth), but rather the real income they can generate. This change in perspective from wealth to income has interesting implications for a number of topics. First, consider finance theory. On the top of **Exhibit 1**, you have the volatility of Treasury bills, which are considered the safe asset in the classic CAPM and modern portfolio theory (MPT). But when you look at the life annuity cash flows that Treasury bills generate—"annuity income units," in Bob Merton's words—the asset that we believed was safe because it protected our principal, nominal Treasury bills, produces highly volatile retirement outcomes. In other words, the safe asset from a wealth perspective is risky from an income perspective.

Second, consider various product offerings and regulation. Now we know that this asset, a portfolio of nominal bills or bonds, is the "safe asset" in many (if not all) target date or life-cycle funds (the "risky" asset being stocks). Much as with Bob's prediction about DB plans, you have the starting point for a crisis because of mismatched risks. Essentially, the products are loading up the portfolio entirely with risky assets relative to the goal. Moreover, the US Department of Labor has provided safe harbor for this product, which means you cannot sue the company that provides the target date fund. Such a fund guarantees you neither an income level nor a wealth number. Yet if you end up poor by having invested in one of these products, you cannot sue the vendor. In short, we're basically setting up people to fail (or bear enormous risk) in their retirement accounts.

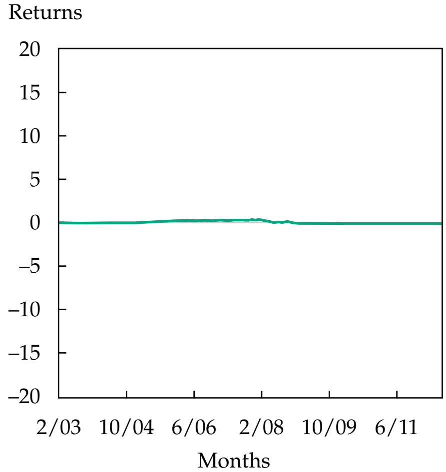
Third, this revised income (not wealth) perspective affects not only planning for retirement but also monetary policy. What the Fed was doing when it was lowering rates was to try to boost wealth to stimulate consumption—the "wealth effect." *But the Fed actually boosted the value of liabilities of pensions by much more than it boosted the value of assets.* Pension funds went from being 100% funded to being seriously underfunded. Bob and I wrote a paper called

[34]The average annual Social Security check in the United States is approximately $18,000/year as of June 2019.

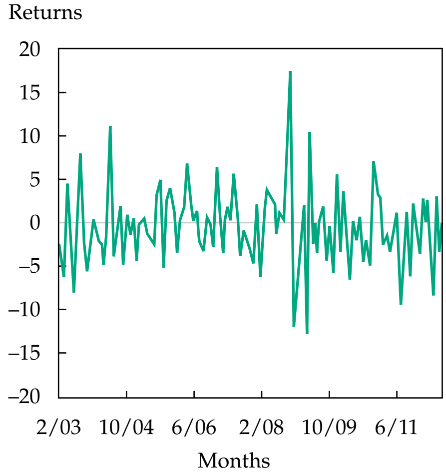
[35]This assumes life expectancy at retirement is 20 years, or that this individual dies at age 85.

EXHIBIT 1. MEASURING TREASURY BILL RISK FROM AN ABSOLUTE AND RELATIVE VOLATILITY (AIU) PERSPECTIVE

A. Three-Month US T-Bill (USD)



B. Three-Month US T-Bill (AIU Units)



Note: Panel A shows month-to-month returns on a Treasury bill portfolio. Panel B shows month-to-month changes in annuity income units (AIU)—that is, the payout amount of a life annuity one can buy for an amount equal to the value of the Treasury bill portfolio.

Source: Robert C. Merton and Arun S. Muralidhar, "SeLFIES: A New Pension Bond and Currency for Retirement," preprint, https://www.researchgate.net/publication/339674296, March 2020, based on earlier work by Robert C. Merton.

"Monetary Policy: It's All Relative," explaining this.[36] Lowering rates raised wealth, but this action also lowered the ability of pensions to pay their liabilities (i.e., retirement income for individuals).

Some may quibble with Exhibit 1 and argue that longer-dated inflation-linked bonds are the safe asset. TIPS (Treasury inflation-protected securities) and other inflation-indexed securities have weaknesses too. First, although they hedge almost perfectly against changes in consumer prices, they do not hedge standard-of-living risk. Second, they produce coupon income the investor doesn't want while he or she is still working; such income may be taxable if the bonds aren't held in a tax-deferred retirement account. More important, these coupons have to be reinvested. Third, if individuals buy the actual TIPS, they receive a stub principal amount at maturity (say at the 30th year); once again, this amount isn't needed in that year and it is mismatched relative to the goal.

Finally, another weakness is that the maturity of the longest TIPS (e.g., 30 years in the United States) is too short for young investors to hedge the retirement cash flows (as retirement planning and execution could be as long as a 60-year exercise). It takes a lot of transactions to keep the hedge on, and Bob has estimated that if a 25-year-old buys a 30-year TIPS, he or she then needs to engage in at least 61 more transactions to transform the TIPS cash flows to a retirement income stream. In short, there are major cash flow mismatches and reinvestment risks, so TIPS cannot be the safe asset for retirement.

[36]Robert C. Merton and Arun Muralidhar, "Monetary Policy: It's All Relative," *Pensions and Investments* (April 16, 2015), www.pionline.com/article/20150416/ONLINE/150419916/monetary-policy-its-all-relative.

THE MERTON RETIREMENT INCOME MODEL

I'm now going to switch briefly to Bob's retirement income model. It starts with the idea that financial illiteracy is a real challenge. So, rather than asking people what portfolio they want to hold, why don't we ask them what they're competent to answer, which is the level of retirement income that they would like and when they hope to retire? Then you could ask them how much they plan to save and the level of risk that they want to take.

Thereafter, fintech and finance science can help individuals. Asset managers and financial institutions could do all the calculations and asset management and deliver the outcome to the saver. This would work as follows: The first step is to create the *relative safe asset*. It's the asset that delivers the goals-based cash flows that you desire. One option is to purchase a deferred inflation-linked life annuity. But it could be something else: a portfolio of swaps, bonds, and so forth that are financially engineered, at some cost, to match the cash flow that people want for their specific goal.

One can then derive a formula for rebalancing this "safe" asset against the risky portfolio, for example, the global equity market portfolio—a portfolio with a high Sharpe ratio—to ensure, to the greatest extent possible, that the retirement goal is met. Finance science requires that one's *funded status* be used to determine how much of each to hold. Funded status is the ratio of the value of the assets to the value of the liabilities, where the latter is the present value of your projected retirement cash flow.

If you're young and you're not willing to save a lot but you're willing to take a lot of risk, you are invested substantially in risky assets. If your funded status is extremely high, maybe above 100%, and you don't want to take a lot of risk, then you put 100% into the safe asset. The dynamic rebalancing continues throughout one's life as one's financial situation, the markets (especially interest rates), and one's goals change.

IMPLICATIONS OF THE RELATIVE ASSET PRICING MODEL

This is the basic structure I'm advocating. But how do we hedge people who might be 25 or 35 years old and who don't want to take risk, if the longest TIPS bond matures in 30 years, before they retire and way before their last retirement income dollar is needed?

The beginning of an answer is in Bill Sharpe and Larry Tint's very interesting paper that says asset allocation has to be liability-centric (presuming you have liabilities) for goals-based investing.[37] But Professor Sharpe never went the extra step of asking, If asset allocation is liability-centric and people are actually holding a portfolio that defeases (prepays) liabilities, how does that affect asset pricing? This bothered me for a number of years when I helped manage the World Bank's DB plan in the late 1990s, but I just never wrote it up until one day I basically found the relative utility or "keeping up with the Joneses" models of Andrew Abel, and Haim Reisman and Beni Lauterbach.[38]

To simplify my formal work quite a bit, CAPM and MPT ignore this practical nuance of goals-based investing and do not regard the goal as stochastic. Fundamentally, wealth for wealth's sake has no value; it is useful for satisfying a goal like a secure retirement (or paying for a child's college). Implicitly, CAPM and MPT assume that the goal is deterministic. If we assume, as Bob does, that investors care about funded status (assets divided by stochastic liabilities), the asset pricing and asset allocation model changes meaningfully and one can derive a Relative Asset Pricing Model (RAPM), where the impact of the stochastic liability can be seen on both the "relative beta" and the "relative market premium." This means that an investor's liability, in this case retirement spending goals, should be discounted by the rate on the relative risk-free asset (which is stochastic or volatile) and asset pricing should be liability-centric. This may seem like a trivial tweak, but the implications are serious.

When you work through RAPM, in this new "relative" paradigm, the traditional absolute risk-free asset (T-bills) is now a risky asset (as Professor Merton has shown in Exhibit 1) and is now part of the risky relative market portfolio. What gets kicked out of the traditional market portfolio is the liability-defeasing portfolio because it's being used as the relative safe asset. In short, you get three-fund separation, which again should be credited to Bob, wherein any individual should split his or her money between cash (the absolute risk-free asset), the relative risk-free asset, and the (relative) risky market portfolio as we've just redefined it.

In a footnote in Kahneman and Tversky's 1979 classic paper is a little comment that they don't explore at all: "The utility function of an individual who needs $60,000 to purchase a house may reveal an exceptionally steep rise near the critical value." The purchase price of the house is a goal, or liability (and its value changes over time

[37]William F. Sharpe and Lawrence G. Tint, "Liabilities—A New Approach," *Journal of Portfolio Management* 6, no. 2 (Winter 1990): 5–10.

[38]Andrew B. Abel, "Asset Prices under Habit Formation and Catching Up with the Joneses," *American Economic Review* 80, no. 2 (1990): 38–42; Haim Reisman and Beni Lauterbach, "Preferences on Relative Return: A Potential Explanation for Some Pricing Anomalies," *Advances in Financial Economics* 7 (2002): 95–103.

because of changing market conditions and changes in interest rates, among other factors). This footnote ties prospect theory to MPT and RAPM. When pension funds are overfunded—that is, when the value of assets exceeds the critical value of liabilities—they tend to be risk averse. When they start to get underfunded and start to lose value relative to the liabilities, they crank up the risk in their portfolios.

The IMF found this behavior in US public DB pension plans,[39] and the phenomenon is well known to all industry practitioners and verified in a simple survey conducted on global institutional chief investment officers.[40] It's not unreasonable to think that individual investors do something similar.

This is a type of loss aversion behavior. And the Fed, by lowering rates, is pushing investors even more into risky assets. But that issue is for another day. For me the most interesting thing about the RAPM is that if this goal replicating safe asset doesn't exist, somebody needs to create it—the goals-based investor establishes the demand, but you ideally need a supplier too.

TAKE A SELFIES!

Bob and I came up with SeLFIES, which is the offspring of the RAPM and the consumption-indexed bond. SeLFIES stands for Standard of Living indexed, Forward-starting, Income-only Securities.

SeLFIES are government-issued series of bonds for each retirement cohort. The bond pays nothing until the investor turns 65. If I am 64 years old, I'll buy the bond that starts paying one year from now. If I'm 50 years old, I'll buy the bond that starts paying in 15 years. It pays me nothing until I get to 65, and then it pays me a coupon of, say, $5.00 per year, in real terms—that is, adjusted each month, quarterly, semiannually, or each year for the inflation or standard of living index used, as described below.

Why did we pick $5.00 real? A traditional bond would have a coupon of 3-3/8%, or 1-7/8%, or some number that few people on the street understand (but picked to price the bond close to par). By specifying the coupon as $5.00 real per year, you can convert a person's retirement income goal into a number of bonds to buy, using grade-school arithmetic. If your retirement income goal is $50,000 per year in real terms, your goal is to buy 10,000 of these bonds by the time you turn 65 (i.e., 50,000 divided by 50). That's it. No complicated calculations. No forecasting expected returns (which is a highly problematic activity). And if you have 6,000 of the bonds already, you're at 60% of your goal. If you have 11,000, you have more than what your goal was originally, and you can increase your goal.[41]

WHAT IS STANDARD-OF-LIVING INDEXING? HOW DOES IT DIFFER FROM INFLATION INDEXING?

I've been referring to standard-of-living indexing—the SeL in SeLFIES—without saying

[39]International Monetary Fund (IMF), Chapter 1, "Acute Risks Reduced: Actions Needed to Entrench Financial Stability," in *Global Financial Stability Report* (April 2013), doi.org/10.5089/9781475589580.082.

[40]Arun Muralidhar, "Modern Prospect Theory: The Missing Link in PT and MPT" (SSRN Working Paper, 2014), papers.ssrn.com/sol3/papers.cfm?abstract_id=2492603.

[41]The original paper on this topic is by me; one of Andy Lo's students, Sung-hwan Shin; and one of Chi-fu Huang's students, Kazuhiko Ohashi. We called the bond "Bonds for Financial Security." Arun Muralidhar, Kazuhiko Ohashi, and Sung-hwan Shin, "The Most Basic Missing Instrument in Financial Markets: The Case for Forward-Starting Bonds," *Journal of Investment Consulting* 16, no. 2 (2016): 34–47.

much about it except to note earlier that globally many retirees have a standard of living in retirement below what they had in their working lives. Let me spend a moment on that.

Per capita consumption measures the changes in standard of living in an economy by capturing how the level of consumption by citizens changes. With economic growth, typically, nominal consumption grows faster than consumer prices. As a result, if a retirement cash flow is indexed solely to the rate of increase in consumer prices, retirees' standard of living will fall farther and farther behind the standard of living of younger, working people over time, especially in high-growth emerging markets. The SeLFIES design would eliminate that problem and protect individuals from the biggest risk they face in retirement.[42]

Bob and I have extended the SeLFIES concept to show how you can hedge longevity risk if the instrument is designed well. That is a topic for another day. We've also taken the idea to a number of countries, in both the developed and the developing world, and talked to the governments about why this instrument makes sense. A friend of ours in Colombia (Professor Daniel Garcia Mantilla) asked, "If we had created SeLFIES in Colombia, what would have happened in terms of their annualized rate of return?" The answer was that it would have had a pretty interesting rate of return relative to investing in the local stock market or even in the S&P 500 because Colombia has experienced a very high growth rate in the last 15 years.

But to me that's not the important part. The key point is that it's the safe asset in retirement. It actually gives people a guaranteed income tied to standard of living. Bob has run similar numbers for South Korea to show how solely indexing to inflation trails indexation to per capita consumption. And it's fascinating that again, this bond performs reasonably well, even though the bar is high because it has to keep up with a rapidly rising standard of living and competes with a strong stock market.

THE DEMAND: WHO WILL BUY SELFIES?

Going back to the idea that SeLFIES is the safe asset, their safety is the most important attribute and the compounded growth rates are a bonus (as compounding and inflation are embedded in the instrument, allowing financially unsophisticated individuals to achieve their real goals). But now that we have this idea for a bond, is there demand for it? And who is going to supply it? There is likely to be a lot of demand from individuals in this country, where, shockingly, a large fraction of the population doesn't participate in any kind of pension plan. They often don't even have access to a plan; but even if they do, they don't participate.

So the beauty of buying SeLFIES is that you now immediately get an "individual DB" plan. SeLFIES don't need to be part of a formal 401K plan. Buying the security actually buys you a pension. Alternatively, you could be participating in a plan but not getting enough benefits, so this could be a top-up on the side. Creating this instrument allows individuals to create the retirement income profile they want.

In my business, I deal a lot with corporate and public pension funds that offer DC plans. They could buy SeLFIES in bulk for their participants.

[42]See Merton (2018), which analyzes this problem for South Korea, a country that has had much faster economic growth than the United States. Robert C. Merton, "SeLFIES—A Globally Applicable Bond Innovation to Improve Retirement Funding and Lower Government Financing Cost" (paper presented at the World Knowledge Forum, Seoul, October 18, 2018), jinrong.swufe.edu.cn/info/1127/3901.htm.

SeLFIES don't have to be limited to retail distribution. They could be institutional, as well. And smart asset managers could create interesting products for clients whereby you can guarantee a specific level of retirement income by shifting between the risky asset and the safe asset.[43] Insurance companies would find these instruments very helpful in hedging their annuity offerings. In short, there's potential demand on both the retail and the institutional side, not just in the United States, but globally. The institutional market will establish the price through both the auction and the aftermarket trading process, and these market prices could be used as the basis for TreasuryDirect (low-cost) sales to individuals.

THE SUPPLY: WHO WILL ISSUE SELFIES?

Who issues the bond? I think the government as issuer makes eminent sense for getting the ball rolling, for two reasons. One is that if you have a retirement crisis, the government has to bail out citizens anyway. If the current debt held in DC plans is risky relative to the retirement goal as shown earlier, to continue to issue the same bonds raises the risk of the domestic retirement system. If many retire poor, the government will have to increase welfare payments. In short, governments are carrying that conditional liability implicitly on their balance sheet. Why not replace the existing debt that they're issuing with a much better instrument that lessens the risk of a future retirement crisis?

A lot of the emerging market countries we've talked to like this idea because it de-dollarizes their balance sheet. For example, India is planning to issue debt in foreign markets because of negative interest rates. But the currency risk is enormous, and capital flight is a real problem. If you can fund your debt locally with long-term savings, you can make your country's financing situation a lot more stable. Additionally, for countries with value-added taxes (VAT), SeLFIES improve the asset-liability matching of government debt. And finally, countries need to invest in infrastructure and have struggled to raise funds for these long-term projects. SeLFIES provide synergistic cash flows for such long-term needs.

OPTIMAL DESIGN OF DC PLANS: THE MERTON–MODIGLIANI–MURALIDHAR PLAN

Finally, there's a lot of debate in the US and even in countries like the Netherlands about the optimal design for these DC plans. If one uses finance science and incorporates all the objectives of the stakeholders for a national plan (i.e., objectives of individuals, employers, governments, asset managers, and regulators), you can come up with an acronym—"SUPER ACCESSIBLE."[44] Once you articulate these objectives, Bob's retirement income model is clearly the one that you want to start with because it corrects for the goal. And it corrects for the method by which you achieve it. SeLFIES complement Bob's retirement income

[43]This idea is explored in more detail in Ádám Kóbor and Arun Muralidhar, "Ensuring Retirement Security with Simple GLIDeS" (SSRN Working Paper, May 7, 2019), ssrn.com/abstract=3384140 or doi.org/10.2139/ssrn.3384140. This paper demonstrates how a simple, heuristic-based, linear rebalancing rule produces more secure retirement income than current products as the rebalancing tries to achieve full funding relative to the retirement income target. Alternatively, one could use portfolio insurance concepts to provide a floor income while participating in the upside, but now the formula becomes a bit more complex.

[44]Robert C. Merton and Arun Muralidhar, "An Effective DC Plan for Uncovered Workers: The Flex MMM Plan," *Plan Sponsor Magazine* (February 8, 2017).

model with a very liquid, low-cost asset to allow for goals-based rebalancing.

And finally, individuals want liquidity from the pension plan to pay for emergencies and other contingencies. Franco had a similar idea 20 years ago—he argued that it made no sense for people to be borrowing at 18% on their credit cards or for payday lending when they were saving in a retirement account which was earning probably 5% or 6%. So he patented an idea to have a "credit" card against your 401(k) balance, with very strict repayment provisions as well.

If you lock everything up in a pension fund and say, "You cannot get it until you're 65," people don't even want to put money into a pension fund. In short, combining Franco's idea of being able to borrow against your plan with Bob's retirement income model and my relative safe asset bond idea would give you the MMM plan. The "Flex" aspect of the Flex MMM plan allows for each state or country to design its plan to meet its specific objectives.

SUMMARY

To sum up, before I open this up to questions, Bob Merton has been working on this topic for 35 years, creating innovation after innovation. I've focused on just a few papers, but you could pick another 10 more that convey lovely ideas we can still work with today. The critical ideas discussed today are that

- standard-of-living risk is the most important risk in retirement,
- governments can play a role in completing markets, and
- people are focusing on the wrong goal (wealth versus income) and the wrong safe asset in their retirement accounts (T-bills versus SeLFIES).

And so far Bob and I have worked on SeLFIES and the MMM plan.

I'm hoping that when we come back 10 years from now, we'll have solved the "home pensions" problem, which is term that Bob likes to use in place of "reverse mortgages," and maybe a paper on monetary policy, and a few others as well. To sum up the experiences I've had with Bob, here is a beautiful quote from Confucius: "Knowledge is merely brilliance in organization of ideas, not wisdom. The truly wise person goes beyond knowledge."

And, Bob, it's been a real honor to ride with you on this journey. Happy birthday. My family and especially my sons have a little present for you. You might not be too surprised that it's a selfie stick! Hopefully it will be a selfie-fulfilling prophecy.

QUESTIONS AND ANSWERS

Deborah Lucas: I'm generally worried about governments as financial innovators. They can offer anything for sale, but if people really don't want it or if it's hard to price, people are only going to buy it if the price is very low. And it's always the taxpayer who is standing on the other side, paying the losses if there are any.

This was a debate I had back when the government was introducing inflation-indexed bonds. At the time I was in Chicago, not Cambridge, so it was very natural to me to push back against what most people here were saying, which was, "It's great because the government is completing the market." But, I thought, what if people don't really want these bonds, or they don't want to pay much for them? And in fact, if you look at the early history of inflation-linked bonds, the yields were very high and the prices low. "You should invest in these things," I was told, "because the return is phenomenal."

I followed this advice, and it was very good for my portfolio for over a decade. But it was not good for the issuer. It was not free for the government to innovate. And—more importantly—if they innovate and they make a mistake, it's very hard for them to undo it. So I hope that the government would be, possibly, a back-end insurer for private issuers because that pushes the pricing to the private sector. When the government is kind of the front line of the pricing, it becomes more problematic. What is your reaction to that?

Arun Muralidhar: One danger of this bond is that if a lot of people buy it, it gives the government massive short-term budget relief. The government gets money and doesn't have to pay back anything—not even interest—for 20 years.

So you are right that we need some mechanism by which you don't allow governments to go crazy in terms of what they can do with this instrument. You've got so much money in defined contribution plans—$7.7 trillion in the US alone—it's going to be hard for the private sector to issue not only this volume but also the range of maturities you'd like to have. So what we recommended to some countries is, if you're going to get the insurance companies to do the issuance, maybe they should start just with the 60-year-olds and 55-year-olds. That reduces the credit risk to the issuer during the introduction period.

Larry Siegel: I have two related comments. My first is that the problem appears to be financial, so we're trying to financially engineer our way out of it—but the problem is in the real economy. You just can't work for 30 years to consume for 100. The numbers don't add up. So people need to work longer at both ends, youth and older age.

People are starting adult work later and later in life, but they still want to retire at 55 or 65. So my thought is that anything that will induce people to work and save for more years will produce a radically more favorable result. The reason is not just more years of saving and more years of compounding in the market, but fewer years of retirement to pay for.

My second comment is, a plan that pays off until you're 85 years old is fine for a population, but not for an individual. You could live to 107. So I just don't see how this problem can be solved without some form of annuitization or longevity insurance. How do you respond?

Arun Muralidhar: Let me take the second one first. Clearly, if you just issued SeLFIES and stopped, which means that payments to retirees stop at age 85, you could try to financially engineer a whole ladder of these and get whatever length of retirement income you want. Or you could buy a deferred annuity, which would then be much cheaper to buy because you're buying it during your working years to start paying only at age 85, having been covered by the SeLFIES from the age of retirement up to that point. Bob and I wrote a follow-up piece where we showed that if you have a well-run insurance company with a broad customer base, which thus has the average life expectancy of the country as its risk, then individuals who have bought these SeLFIES should be able to exchange one SeLFIE for one equally paying life annuity.[45]

And the difference between the price of the SeLFIES and the price of the annuity will tell you how diversified the insurance company is or whether the SeLFIE has been designed optimally. That is, is the SeLFIE paying for long enough for the insurance company to actually

[45]R. C. Merton and A. Muralidhar, "Taking a Closer Look at SeLFIES: Added Thoughts, Clarifications," *Pensions and Investments* (May 27, 2019), www.pionline.com/article/20190527/PRINT/190529910/taking-a-closer-look-at-selfies-added-thoughts-clarifications.

want to hold it as a hedging instrument for the annuity the company has issued? Once you start to get SeLFIES into the market, you can greatly improve longevity risk hedging, which is incredibly hard to hedge today because you can't lay it off onto anybody else.

I've proposed a slightly different bond, which I won't describe in detail here, that I call the LIVE bond—Longevity Indexed Variable Expiration bond, which would start payouts after age 85.[46] This LIVE bond, again issued by the government, is cohort-specific and pays coupons based on the life expectancy of the cohort. This bond can be used to hedge individual-specific longevity risks, but it is a bit more complex to do so. Note that the government is hedged too: It would start paying only after the cohort reaches the age of 85 years, and then would have the desired cash flow for the declining number of surviving members of the cohort.

To your first point, the real problem is clearly people are not saving enough. And SeLFIES are not going to cure that. There's no easy way to solve that without either saving a much higher proportion of their income, working longer, or some combination of these two. But I think that's where the work on reverse mortgages, which I prefer to call "home pensions," becomes absolutely critical. Home equity is the only asset today that is in large supply and that you can potentially grab and convert into a retirement income stream.

Marti Subramanyam: This is more a suggestion than a question. The point was made that there's no way a pension system can cater to rapidly rising longevity. People can't work, as Larry put it, for 30 years and be enjoying retirement for 50. I think there has to be something in the structure that incentivizes people to work longer. That should be part of the product, something that says, "If you work one more year, you'll get this much more." I think that will help. And I think that will make it much more attractive for governments to take the risk of issuing these bonds.

Arun Muralidhar: There are ways to do that, that don't have to be embedded in the bond.

Marti Subramanyam: I want it to be embedded in the bond because if the investor has too many variables to deal with, that will make it more complicated. It could be a very simple adjustment that puts in an incentive to work for one extra year. If you work for an extra year, instead of $50,000 a year or whatever you talked about, you'll get $52,000.

Arun Muralidhar: My bias is that people look at their balance and see 100,000 pesos when they're 64, and they think they're incredibly rich. They spend 20,000 immediately. Changing that to an accumulation of income credits, that is, SeLFIES, raises the investor's awareness that his or her current accumulation is going to give them only so much. It starts to change their behavior to "I need to save more. I need to work more."

[46]Arun Muralidhar, "Managing Longevity Risk: The Case for Longevity-Indexed Variable Expiration Bonds," *Retirement Management Journal* 8, no. 1 (2019): 31–44.

PANEL

Zvi Bodie, Carliss Baldwin, Deborah Lucas, Peter Tufano, and André Perold

Zvi Bodie: Professor Emeritus, Boston University

Carliss Baldwin: Harvard Business School

Deborah Lucas: MIT Sloan School of Management

Peter Tufano: Saïd Business School

André Perold: Harvard Business School and HighVista Strategies

Leonid Kogan (conference leader and moderator): On the panel this afternoon we have Debbie Lucas, Carliss Baldwin, and André Perold, who has been Bob's colleague at Harvard in the past. So, Zvi, please take it away.

Zvi Bodie: Thank you, Leonid. This has been a great honor for me. Payback time to Bob for all that he has done for me and my career. We can all say that to some degree. This panel is meant to be an informal discussion. Imagine that we're all sitting in the same living room reminiscing because we go back quite a few years. Bob started teaching at MIT in 1970—almost 50 years ago. Wow. And he's not emeritus yet. He's still full-time faculty.

I think it makes sense to start with Carliss Baldwin, because she was an undergrad in 1971 and took one of Bob's finance classes. I should add that Bob admitted, last night at dinner, that he was learning finance as he was teaching it. Carliss?

A VIEW FROM AN UNDERGRADUATE

Carliss Baldwin: I was actually the second member of my family to take Bob's course. My husband, who will be here for dinner, took the course in 1970. And consistent with what Jim Poterba said, Bob is a brilliant teacher. I was then a live-in girlfriend, and the word-of-mouth advice was, "Take the course."

So I took the course in 1971. I believe it was in the fall, which would have been the second time it was taught. That was before the big papers were published. But we had mimeograph, the purple machine. So we had notes. My notes are now in the Baker Library Archive, at Harvard, where many of Bob's papers are, preserved for eternity.

To say I was blown away by the vision of continuous-time economics is a totally inadequate understatement. It seemed to me—and I'm an undergraduate senior at that point—everything a theory should be. Even though I struggled with the math, the logical structure of the theory was impeccable.

I wanted to write a thesis, which was required in the econ department. (I was not in the Sloan School of Management.) I wanted to do one in finance because, frankly, I wasn't all that interested in consumption. I wanted to understand wealth, and finance is about wealth. So, Bob suggested that valuing convertible preferred stock, because there was no time horizon, was a tractable problem, and maybe I could write a thesis on that.

But the econ department did not allow economics students to write their theses for people out of the department. I had to petition to have a supervisor from the Sloan School because Bob had moved over there. I'm an undergraduate and just totally afraid that my petition is going to be denied, because what is it that people do but deny petitions?

So, I creep into Professor Cary Brown's office and propose my exception. He asked, "Who are you proposing as your supervisor?" And I said, "Professor Merton." And to this day I remember this big smile on E. Cary Brown's face and he said, "Bob is one of us."

From which I inferred that even then the economics department viewed Bob as a missionary and a colonizer preaching the true faith to the heathens in the Sloan School.

Audience: [Laughter]

Carliss Baldwin: So I think I can claim to be the oldest student here, until my husband arrives, and he's an even older student.

Zvi Bodie: Great. Thank you. We'll come back to you. André comes next. The Harvard years.

BOB MERTON AS A MENTOR

André Perold: The Harvard years. I think of myself less as a baby boomer and more of a Merton baby. I was just extraordinarily fortunate to start my academic career at a time when Bob was in his heyday, and every second there was something that he was contributing.

I met him here first at MIT when I was on the job market in 1978. It feels like forever ago. But I really got to know him over the 22 years that Bob was a colleague of mine at Harvard Business School. He joined us in 1988 and he spent the first year or two writing his book *Continuous-Time Finance*.[47] And I was fortunate that he was across this little corridor from me, so I saw him every single day.

When Zvi asked me to speak here, I thought I would talk about how Bob has affected me. The most profound way in which Bob has affected me is that I'm always asking myself, "What would Bob say?" when I do things out there professionally and otherwise. And every time I do that it helps—it keeps me out of trouble. There have been many "aha!" moments because of it. And the profundity is as much in the concepts and ideas that Bob has endowed us with as it is the applicability of those to everyday situations in the professional world of finance.

But I must say I think the first thing I think of with Bob always is as a mentor. I noticed—and I don't think it's an accident—that Merton and mentor are anagrams of one another. There's something very real that is there.

Bob would always say to write things down. If you couldn't write it down, then whatever you were thinking probably wasn't going to fly. And Bob not only wrote everything down but his footnotes alone would contain whole papers. As young faculty we would live in fear that anything we thought of was already contained in those footnotes, so reading the footnotes was absolutely necessary if you wanted to make progress in this field.

CONTINUOUS-TIME FINANCE

Bob would give credit where due, and he'd say that to everyone else: "Give credit where due."

[47]Robert C. Merton, *Continuous-Time Finance* (Oxford: Blackwell, 1990).

He's a stickler for doing that, and he would go overboard to make sure that the antecedents of his work were recognized and placed in context. I'll never forget when he was writing his book *Continuous-Time Finance* how much effort he put into creating and arranging the bibliography. The bibliography was as important to him as the actual substance of his work.

Then, of course, there's Bob's work itself. Bob said, "Think in continuous time." That is, think of the long run as a sequence of short runs, and understand how the short runs add cumulatively to where you end up. Or, because it's continuous time, how they multiply out to where you end up. Bob's view was if you can't see [an economic problem] in continuous time, you're probably going to make some mistakes and you're going to omit some first-order effect.

The continuous-time world of Bob is actually very weird, because what you think is first order is really second order, and what seems to be second order is really first order. In other words, in the short run the mean matters very little and the variance dominates, and it's all because dz^2 is zero. I had no idea that something nonzero, when squared, could be zero.

ARITHMETIC VERSUS GEOMETRIC MEAN RETURNS

In continuous time you can see clearly how variance can factor into the mean return, and significantly so. An everyday example, one you see all day long, is the difference between the arithmetic and the geometric mean of a series of stock market returns or an estimate of future returns. People don't understand it, but it's an enormous difference. The difference is equal to $\sigma^2/2$. If σ, the standard deviation of annual percentage returns, is 16%, which is the average for equities, the difference between the arithmetic and geometric means is 1.3% per year. So, if you use the geometric return instead of the arithmetic, you're going to underestimate the return by 1.3% a year. And especially today, when real interest rates are zero or negative, 1.3% is even bigger. It's a mistake people make all the time.

Thinking in small increments of time is really important, especially in any situation where there's asymmetry or nonlinearity. That's how σ^2 pops out. I noticed Fischer Black doing that when we were working on a paper together, and he said, "That's the only way I think. And I learned it from Bob." In that case, Fischer was working on an exchange rate hedging problem, and he figured out that the sum of the returns of exchange rate movements had to add up to σ^2 across all participants. That meant there was a positive drift. So, if you were currency hedging, you were always going to bear a pretty significant drift cost that wasn't understood.

Bob also said that it's a lot easier to estimate risk, the variance, than expected return. While this is mathematically incontrovertible, I'm often shocked to see investment practitioners attach false precision to the mean while all but ignoring the variances and covariances.

IS THERE A PRESENT TENSE IN INVESTMENT FINANCE?

Bob recommended thinking of price paths as nondifferentiable and subject to discontinuous jumps with processes that had nonstationary coefficients. In other words, the market environment is random and dynamic. If we ever needed a reminder of this, it was the great financial crisis and all the events that occurred then. There was nothing stationary about that period of time.

The nondifferentiability of price paths is a particularly sad fact of everyday life in the market.

What it means is that prices are never falling or rising. You can say only that they have fallen or have risen and that they might fall or might rise. In other words, there's no present participle in finance, according to Bob. If prices were ris*ing* or fall*ing*—emphasis on the "-ing"—we'd all be amazingly rich from arbitrage. So, Bob, just think about what you could have done for us if you would have come up with differentiable instead of nondifferentiable price paths. None of us would be sitting here today.

THINKING FUNCTIONALLY

As Zvi and Richard Thakor already discussed, the functional approach is one of Bob's very big contributions. Once you've heard Bob say, "Think functionally rather than institutionally," the power of it is striking and it becomes hard to think about finance and many other things differently.

Part of thinking functionally is to think holistically and enterprise-wide. Bob has done so in almost everything he's done. He included consumption in his models. But he's also included other assets. So, he's done work with Zvi where they include human capital as an asset, and they take into consideration the covariance of your human capital with the markets. He did that with contingent claims analysis, where he priced risky debt, and in endowment investing, where he said, "You should really think about the gifts that universities get as a shadow asset, and consider the covariance of those gifts with other assets and risks when you think about how endowments should invest."

It was Bob's functional framework for understanding the financial system that underpinned our global financial system project at Harvard Business School. Carliss was part of it. Bob was our leader. Zvi was part of it, and we had other colleagues as well. It was an ambitious undertaking in the mid-1990s, a time of rapid change in financial firms and markets. It was a time when people would say, "In the end, after all this change, there will be four banks, three insurance companies, and two investment banks standing." Bob would reply, "That's complete nonsense. You can't think that way. You cannot anchor the evolution of institutions, taking institutions as the unit of analysis." You had to think functionally, how those functions would be performed most efficiently, and how competition and technology would lead to an evolving set of ways in which functions would be performed. And, thereby, you can see how institutions might evolve.

Out of this project came a book with eight coauthors, a conference.[48] We had 15 major financial institutions take part. And Bob's second-year MBA course called Functional and Strategic Finance, which was very quickly oversubscribed, also came out of this project.

THE PAYMENT SYSTEM AND THE ROLE OF DERIVATIVES

My own focus in the project was to think about the payment system as a core financial function. There's no financial system that doesn't have a payment system—but what is it? How does the payment system work? Why does it matter, and how might it evolve over time? So, I chose to include securities clearing and settlement as part of the payment system and very quickly discovered how costly, risky, and inefficient the payment system actually was. You had pervasive amounts of delayed settlement in the system.

[48]D. B. Crane, Kenneth A. Froot, Scott P. Mason, André Perold, Robert C. Merton, Zvi Bodie, E. R. Sirri, and Peter Tufano, *The Global Financial System: A Functional Perspective* (Boston: Harvard Business School Press, 1995).

But delayed settlement really was just a derivative contract. It was a forward contract because you were postponing the day when you would actually exchange physical securities for cash. And you could see that if you included the most heavily traded derivative instruments, such as interest rate swaps and index futures, there was actually much less burden placed on the financial system because of those than you would have had if you were trading in the underlying physical securities, because derivatives include small amounts of money being exchanged frequently and over time, whereas physical instruments involved large amounts of money being exchanged less frequently but in very large amounts, where the risks are much greater. The insight there was that derivative instruments are actually a mitigating effect on risk in the payment system, not an exacerbating effect, as some would say.

The only way to see that and understand all that was through a functional lens. It's work that I for sure would not have done without the urging of Bob.

APPLYING FUNCTIONAL THINKING TO INVESTMENT COMMITTEES

I'll say just a couple more things. When you're in the real world and you see how it functions, you wonder why functional thinking is not more pervasive and more commonly used. I'll give you two simple examples. I sit on investment committees, and consultants and advisers often tell investment committee members, "You need to have an inflation hedge." What they're thinking is that you need to invest in things like energy projects. Drill for oil and gas, or something like that, to get an inflation hedge.

And I of course ask myself, "What would Bob do?" He would say, "Just buy an inflation swap. You don't have to put much money down. You get an r^2 of 1.0 with inflation, and if that's what you want, there it is, instead of very expensively investing in illiquid assets where you have no idea what you're going to get back and the r^2 with inflation is very low."

The same with bonds. People caution, "Don't invest in bonds because the returns are very low." But bonds have a very desirable feature: They have a negative covariance with equities, so they're the one hedging instrument that will, in many scenarios, hedge against equities. If you don't want to own them, you don't have to. You can just buy bond futures. It's very simple. Try to tell that to people in the real world. They cannot think this way. It is a surprise.

So we have a long way to go to get people to think functionally. But I want to personally thank you for what I've learned from you and still apply every day.

Leonid Kogan: Thank you, André. And now back to MIT. Debbie?

PUBLIC FINANCE AND PUBLIC POLICY

Deborah Lucas: Thank you, Zvi. I'm a relative newcomer, but for almost the last 10 years I've had an office about three doors down from Bob. It has probably been the best learning experience I've had since I left graduate school. My conversations with Bob have changed how I look at a lot of things, some of which I'd like to touch on now. I was a little worried about getting to this part of the day because I thought, "Surely by now anything that I'd have to say would have been said already by someone else." But it speaks to Bob's range that although what

I have to say picks up on some of the themes that you've already heard, there's really not that much overlap.

I will frame my comments in terms of Bob's contributions to financial policy. He has an enviable *modus operandi*, which is to contribute to the fields he works in, not only by making conceptually path-breaking contributions but also by making the effort to have far-reaching effects on their use and practice. Bob is the person who has done the most to put the "finance" into public finance, and that contribution has actually made him one of the greatest *public* financial economists who are out there, although not too many people have recognized that.

CREDIT GUARANTEES AS PUT OPTIONS

Bob wrote a paper in 1978 with an unassuming title, "On the Cost of Deposit Insurance When There Are Surveillance Costs."[49] He had also written a 1977 paper on deposit insurance.[50] Both of those papers, which applied finance to the policy of deposit insurance, grew naturally out of his groundbreaking work a few years earlier on the valuation of risky debt and guarantees. He demonstrated that you could look at either a risky bond or a credit guarantee as a put option. So, you could use the tools he developed for pricing options to answer the question, "What is the real cost of credit risk?"

Not only did Bob derive these pricing formulas—which, I should mention, are still being widely used today in practice—but his analysis made it crystal clear that as a matter of public policy, writing a guarantee is not a benign thing to do. In fact, it represents a highly levered position in the underlying asset and is therefore filled with cost and risk.

So, those of you who know me have heard me say many times, governments are the world's largest financial institutions. They are also the most profligate writers of exotic options, and they get to do that without a regulator or a board of directors staring over their shoulders.

So, starting in the 1980s, Bob's insights on pricing credit guarantees and government guarantees gave rise to a significant literature that expanded on his models, that calibrated them with data, and that gave plausible and significant estimates on the costs and risks of institutions like deposit insurance, agricultural guarantees, and Fannie Mae and Freddie Mac. This work was developed by his students, several of whom are in the room today. I would shout out to Alan Marcus, George Pennachi, Bob McDonald—maybe Zvi has others to add to the list. And I think it's fair to say that my own work these days is continuing to walk down that same path. I am also trying to bring younger scholars down that path to complete a piece of what I consider a very important unfinished project of Bob's.

In any case, I wish I could say that governments have now seen the light and that they use Bob's methods to price all their guarantees as put options. But even Bob can't work that kind of miracle. It's still a work in progress. But I believe that work has changed the conversation. It's changed the way many people, including many policy makers, view these sorts of guarantees. And that has been an enormous contribution.

[49]Robert C. Merton, "On the Cost of Deposit Insurance When There Are Surveillance Costs," *Journal of Business* 51, no. 3 (July 1978): 439–52.

[50]Robert C. Merton, "Analytic Derivation of the Cost of Deposit Insurance and Loan Guarantees: An Application of Modern Option Pricing Theory," *Journal of Banking and Finance* 1 (June 1977): 3–11.

VIEWING REVERSE MORTGAGES THROUGH AN OPTION LENS

Many people have talked about the functional approach and how important it is to interpreting what they work on. It turns out it's also very important in public finance and policy, especially retirement policy. For the last several years now, Bob and I have been discussing reverse mortgages and the prospects for that market, and why it will or won't take off in various places.

I was determined to convince him that the flaws in current US policy are hobbling that market and that this is a serious problem, but I wasn't convincing him. So, I went away and wrote a long paper on reverse mortgages, and I even included some options pricing in it.[51] I wasn't just pandering to Bob; reverse mortgages are in fact filled with a lot of embedded options. But Bob remained politely indifferent to the institutional details of the reverse mortgage market.

So I asked myself, "How could someone who was so enthusiastic about the prospects of reverse mortgages for making retirements better for hundreds of millions of people around the world be so indifferent to these institutional details?" I think I figured it out in preparing for today: When Bob sees an unmet financial need, he instinctively thinks, "Someone should design a product or an institution to fix it." And in fact, someone will . . . eventually. And Bob is a patient man. He's also agnostic about whether the solution will come from government or from the private sector. What he's interested in is the best functional form.

[51]Deborah Lucas, "Hacking Reverse Mortgages" (September 1, 2016), https://gcfp.mit.edu/wp-content/uploads/2016/09/ReverseMortgagesV11.pdf.

MERTON'S ADDITIONAL CONTRIBUTIONS TO PUBLIC POLICY

As was mentioned before, SeLFIES—which Arun talked about earlier—are another example where functional requirements have led Bob and Arun to promote a design that's essentially a public-private partnership, agnostic on whether the private or the public sector is the best place to do things. (SeLFIES are securities, capable of being purchased by an individual, that are intended to mimic the payout of a defined benefit pension plan.)

But bringing it closer to home here at MIT, Bob, along with Andrew Lo, generated the idea that Sloan should have a new center that would focus on research, education, and financial policy. It was that vision that brought me to MIT and the Golub Center for Finance and Policy, which has been a going concern for the last six years. I view the center as just another financial engineering innovation of Bob's. It's a way to institutionalize, at Sloan, his functional approach to finance and policy by taking an attitude that's agnostic in terms of what the best answer is, but religious about the importance of facts and the use of financial science to find answers to those important questions.

THE HARVARD GLOBAL FINANCIAL SYSTEM PROJECT

Zvi Bodie: Thank you. Shall we tell the story of the Harvard global financial system project? Carliss, you were the actual instigator of it, so why don't you start? Several global financial institutions came to the Harvard Business School and said, "The world of finance is changing."

Carliss Baldwin: I went to a dinner at the dean's house and Bill Edgerly from State Street, recently retired as CEO, was talking about how State Street had a different function in banking because it had focused on payments, and in using technology to streamline the payment system. You basically froze the physical assets in somebody's vault, you put that information in a computer ledger, and then you could do the transfers very cheaply via computer, just by making adjustments on the electronic balance sheets.

In that way, at a time when many banks were suffering, State Street had created a new business. It turned out to be a huge growth business. And Bill was telling those of us at the dinner that somebody should be studying this. I said, "This has a feeling of functionalism, and that's what Bob is talking about. Maybe we could create some bridge, some synergy between this state-of-the-art concept and the question that Bill was posing."

It was difficult for Harvard Business School and Harvard University to overturn policies and procedures and practices to collaborate with businesses, nor did we ask for funding from businesses. So Harvard laid down a condition that the institutions, as a condition for Harvard taking their money, would have to have their CEOs participate by meeting twice a year in a working session.

CUSTOMERS VS. INVESTORS

André Perold: Bob has this idea of customers versus investors. Customers expect things to work as advertised. Investors take risks. They're not sure what they're going to get. They can diversify away specific risks and manage risk that way. But customers expect things to work. It relates to the question of trust we heard about this morning.

When it comes to customers, you think of the rating agencies. The whole function of a rating agency is to avoid us all incurring the cost of research over and over again when you can centralize that cost and have a rating agency perform it for us. And when they say a bond is AAA, the whole point is that we can assume it's default-free.

Now let's apply this principle to the global financial crisis. Through this functional lens you see what happens when you violate the performance of a function. And the rating agencies rated securities AAA that were absolutely not AAA and that later traded at 50 cents on the dollar with lousy recoveries.

To me, this was the greatest crime of the crisis. I think that a lot of the crisis stemmed from messing up this one single function. When you say something is AAA and it isn't, all hell breaks loose, because everyone relies on the rating and we will buy things, sight unseen, because they're rated AAA. That functional perspective is one of the things Bob taught us all that I'll never forget.

Zvi Bodie: I should add that Bob warned of a potential crisis because the pace of financial innovation was accelerating. The nature of financial innovation is you can have one-off innovations that occur very quickly, but to change the regulatory infrastructure takes a long time. Bob came up with this analogy: "Suppose we develop a new type of train that is super fast, but you need to upgrade the track. If you try to run the train on the old track, you're going to have a lot of destruction. Not just the train; it's going to destroy the track as well." And, in that first Global Financial System conference volume (Crane et al. [1995]), he warned of the potential for crisis.[52]

[52]D.B. Crane, Kenneth A. Froot, Scott P. Mason, André Perold, Robert C. Merton, Zvi Bodie, E. R. Sirri, and Peter Tufano, *The Global Financial System: A Functional Perspective* (Boston: Harvard Business School Press, 1995).

Frankly, I think that's a lot of the reason for the global financial crisis: Infrastructure was not prepared for all these new innovations.

André Perold: Zvi, I would add that new tracks are being laid. In China, Alibaba and Tencent have created whole payment systems on their platforms, constituting a vast chunk of Chinese GDP. They have laid new tracks. And the implications for economic growth in that country are profound. We may also see it with Facebook's Libra coin. We don't know. But that is also an attempt to lay track of a certain kind.

MERTON AND SAMUELSON

Hélyette Geman: I'd like to give an anecdote, a scientific one, from the other side of the ocean. In 2000, exactly one century after Louis Bachelier's dissertation was published, I had the honor of organizing the first World Congress of the Bachelier Financial Society. Three years earlier, in June 1997, I had given a doctorate *honoris causa* at the Université Paris-Dauphine to Robert Merton. And the day after my talk, where I was referring to the other Robert Merton—because for my colleagues Robert K. Merton and Robert C. Merton would have been too complicated—I received an email from the other Robert Merton thanking me for my talk and asking for the details of it. That was beautiful, and this was two months before the Nobel Prize. My colleagues at Dauphine were happy with the good timing.

So, back to 2000, when I organized the first World Congress of the Bachelier Financial Society. Obviously, I invited Robert Merton. I also invited Henry McKean, a professor at Courant Institute. With two major cards in my hands called Robert Merton and Henry McKean, I got in touch with Paul Samuelson and I said, "Professor Samuelson, you need to come to this event at Collège de France—Amphithéâtre Marguerite de Navarre." And he kindly accepted.

The conference took place, and Paul Samuelson was the first speaker. He was 85. He flew on the Concorde the day before and opened the conference with a talk entitled "Portfolio Selection in One's Lifetime." His talk was beautiful and very well followed. Then we got Henry McKean presenting beautiful mathematics around time and scale. Finally, Robert C. Merton gave his talk.

The morning had been fairly busy for Paul Samuelson, who was 85 years old, so I proposed to drive him back to the Plaza Athénée. Bob was staying at the Crillon. We got into the car, and I had done a lot of research and had read a paper written in 1965 by Paul Samuelson with an appendix by Henry McKean on the valuation of American options, wherein one can see clearly that the arithmetic Brownian motion of Bachelier has been transformed into geometric Brownian motion and then Black–Scholes–Merton.

And, in the car, I said to Paul Samuelson, "Very few people know that geometric Brownian motion belongs to you." He turned to me and said, "Yes, Hélyette, I had the process but they got the formula." So obviously, Robert C. Merton had not only a beautiful father but also a beautiful PhD adviser, Paul Samuelson, the greatest economist of the century.

Zvi Bodie: Thank you. Peter Tufano just arrived. He was supposed to be here for this panel but his flight got canceled from the UK. Yet here he is. Peter was a central player in the global financial system project at Harvard and is now dean of the Saïd Business School at Oxford University, on the other side of the Atlantic Ocean. Come on up.

Peter Tufano: When Zvi told me you were doing this, there was no way I was going to miss this, Bob. You had no reason to be kind to me when I was a doctoral student and when I was a young professor, but you were extraordinarily kind. And as part of that kindness, in addition to all the other gifts that you gave—I think you've probably been talking about the functional perspective a fair bit?

Leonid Kogan: We have, yes.

CLOSING THOUGHTS: ON KINDNESS AND IMPACT

Peter Tufano: I'd like to address that. The functional perspective has been probably the single most powerful concept that I've used. I'm still in the classroom every once in a while. I'm teaching a fintech class online, and one of the things I'm teaching is how to use the functional perspective to understand what's going on in fintech. As you know, I founded an organization which was called Doorways to Dreams and is now called buildcommonwealth.org. Most of what we do uses fintech. So, for that professional debt, it was worth a slightly elongated trip here. But the personal debt is even more important.

Zvi Bodie: Could you please describe that organization and indicate whom it's designed to serve?

Peter Tufano: It is an organization that I set up more than 20 years ago that was intended to support low-income families in America, especially in financial services.

But, Bob, you have influenced how I'm a dean in other ways. I never forget that you had no reason whatsoever to take me under your wing. I wasn't well trained in a technical way. I liked history and case studies and a bunch of other things that weren't your cup of tea. And that kindness is what I've tried to pattern as I think about what I do as a dean toward my students and toward my faculty members. There's no one who is unworthy of that, and that is a lesson I will forever take.

I would like to say a word about impact. At Harvard one of the roles that I had was to run the appointments process for a period of time. In that process we lay out evidentiary standards that determine whether somebody gets appointed professor or not. I run those processes at Oxford as well. And I think you'd be pleased to know that we've just changed our standards at Oxford to explicitly acknowledge impact, because, Bob, you taught me, Bob, that it's important to do great scientific research, get published, and get the word out among academics, but you also encouraged me in a way that very few others did to turn that work into impact. That's what I've done through our nonprofit, and that's what we've done in our work in the UK as well.

Zvi Bodie: Thank you, Peter. I am so happy that you made it in time. We will wrap this up and move on to the next inning.

DEVELOPING A THEORY OF CONVERTIBLE SECURITIES

Marti Subrahmanyam
New York University Stern School of Business

Zvi Bodie: Our next speaker is Bob Merton's first doctoral student and coauthor, Marti Subrahmanyam, who has gone on to an illustrious career of his own.

Marti Subrahmanyam: It's such a privilege and an honor to be here today to publicly acknowledge the debt of gratitude I owe to Bob. Studying under Bob, Myron [Scholes], Stewart [Myers], and all the other greats of the MIT economics department in the 1970s was an incredibly good fortune. Bob was among the masters of economics of the second half of the 20th century and he continues to be today, and he took me under his wing as a PhD student. It's hard for me not to get emotional about it.

The paper I'm going to present, entitled "Security Design with Status Concerns," illustrates what I learned from Bob, but also how his ideas have become fundamental finance language, to the point that people don't know they come from him. The paper is a joint work with Süleyman Başak, Dmitry Makarov, and Alex Shapiro.[53] The paper was inspired by one of Bob's pet peeves best expressed in his presidential address at the American Finance Association years ago. Bob noted that it's easy to appeal to asymmetry of information or behavioral assumptions to explain observed phenomena but that before we do so, we should first examine market frictions to explain the very same phenomena.

ON LOTTERY TICKETS AND CONVERTIBLE SECURITIES

The paper's intuition is that it's commonly observed that many people buy lottery tickets. Everybody knows this is an unfair gamble, and yet people buy them. Why? The argument is that if you have an extra dollar, you can buy maybe an additional loaf of bread, which gives you some utility, but really not much more. But if you participate in this unfair gamble, you have a very tiny probability of getting over the hump and buying your dream car or dream house, for example.

We apply the argument to convertible securities, which are securities that are part debt, part equity. For instance, compensation schemes are often a combination of fixed salary and some kind of equity option. We ask, "Why do convertible securities exist?" We offer an explanation that does not rely on asymmetric information or behavioral assumptions. We use a dynamic framework in the spirit of Bob's work and also work by Milton Friedman and Leonard Savage in the 1940s where they posited a convex/concave utility function. The utility functions are concave for the most part, but there is a segment where they are convex, which actually motivates participation in unfair gambles.

[53]Süleyman Başak, Dmitry Makarov, Alex Shapiro, and Marti G. Subrahmanyam, "Security Design with Status Concerns" (August 22, 2019), ssrn.com/abstract=2556344 or doi.org/10.2139/ssrn.2556344.

In our setup, the entrepreneur chooses how to finance and how to manage the firm. The financing is provided by a risk-averse financier, but the entrepreneur is key to the functioning of this firm or this project, in the sense that without [him or] her the project cannot be undertaken by the financier. We use the setup to solve for the optimum security and show it is very much a convertible security. Our model can explain why convertibles are used by startups and small firms, is widely used in venture capital, and also by firms that have highly volatile payoffs. Our results are also useful for structural credit modeling, because as Bob has shown, credit risk is an important consideration in security design.

MODEL DESCRIPTION

We follow Bob's classic framework, which has been adopted by many people in finance and economics, but we introduce a choice variable that determines the firm's riskiness. The entrepreneur has flexibility in choosing the variable. Our interpretation of the variable is product novelty. An increase in novelty affects both the drift and the diffusion term.

Then we use the Friedman/Savage framework in which status is captured by preferences that switch from the usual concavity to convexity around some wealth threshold. For very low and very high levels of wealth around the threshold, the entrepreneur behaves like any other risk-averse investor, but at threshold level there is a kink that actually makes the investor behave differently. In the model, there is a status barometer whose parameterization leads to different utility shapes above the kink and which affects the investor's willingness to participate in unfair gambles.

To finance the firm, the entrepreneur issues a security with a certain payoff. The entrepreneur's optimization problem is to choose the payoff function as well as the risk parameter, which is the dynamically adjustable novelty parameter. Firm value is a function of the novelty parameter. At low levels of firm value, the riskiness is maintained constant; but at levels close to that kink, in the convex region, the entrepreneur would want to increase risk. Above the threshold, optimal risk will come down again to more or less a constant level. That's essentially the pattern of the dynamic adjustment of this novelty parameter in conjunction with the payoff function. The optimal payoff solution looks like a convertible. What are the features? There is an initial region over which the payoff is linearly increasing with firm value, then at some threshold it gets flattish, and again it becomes linearly increasing beyond a point.

EMPIRICAL EVIDENCE AND ALTERNATIVE SETTINGS

In the model, project volatility affects that nature of the kink, and the greater the project volatility, the more akin to the convertible security payoff we will get. This is consistent with highly volatile and speculative firms using convertibles and with venture capital firms using such structures widely.

We also solve for the optimal contract problem when the firm is completely inflexible and the technology cannot be changed dynamically as in our first version. In the optimal solution, the entrepreneur still wants to increase risk in the middle region and so it offers the financier a negative stake in the firm. At the other extreme, when security design is given and the entrepreneur can optimize only with regard to firm riskiness, results are similar to the main model for the two calibrations we considered of young and mature firms.

A comparison of the issuance and no-issuance cases highlights the impact of two opposite forces that arise with security issuance. One is that risk sharing between the financier and the entrepreneur allows the entrepreneur to take more risk. That is very much in line with classical risk sharing. The other is that the participation constraint requires the financier get his [or her] minimum reservation utility, which dampens the incentives to take risk. Depending on firm maturity, either force can dominate.

CONCLUSION

The paper illustrates the power of Bob's ideas. One is, of course, the pioneering introduction of stochastic optimization. The other is using linear versus nonlinear sharing rules, which is part of the design of the contract, and the influence of credit risk in motivating security design, which is a much broader topic. And another idea is how you can, through dynamic replication, mimic the characteristics of a complete market. Today, it is impossible to write down a theoretical model in financial economics without relying heavily on one or other of Bob's many contributions. Thank you.

WHAT WOULD BOB MERTON SAY OR DO?

André Perold
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To be able to celebrate Bob Merton is a special honor at any time, and certainly so on this occasion. For me, it's not that Bob has shaped the field of mathematical finance, practically as well as academically—which he has profoundly—or that he received the Nobel Prize for doing so—which he did—but that he also had such an enduring influence on those who got to know him.

I feel less a baby boomer than I am a Merton baby. I first met Bob here at MIT when I was on the job market in 1978 (gasp). But I really got to know him over the 22 years that he spent at Harvard Business School. He joined us in 1988 and spent the first year or two writing his book *Continuous-Time Finance*. I was fortunate that Bob's office was right next to mine. To me, he has been a colleague, a coauthor, and most importantly a friend, a teacher, and a mentor.

In the spirit of this session, I am going to focus my remarks on some of the ways in which Bob came to occupy a special place in my professional life—be it researcher, teacher, or investment practitioner. I am going to reflect on the question, "What Would Bob Say or Do"? I frame it this way because when confronted with an issue, small or large, I constantly find myself asking "What Would Bob Say or Do?" It's been the source of many "aha!" moments, and I've discovered that when I don't think this way, I am more prone to make a mistake. The profundity is as much in the concepts and ideas as it is in the applicability to everyday situations.

The first thing I think of that Bob would say is to *be a mentor*. He would often talk about the influence of his father and the mentoring he received from Paul Samuelson. There are countless students and faculty—including a great many of us in this audience—who would say that they have benefited from him in much the same way. As others have already said, he proactively takes an interest in his colleagues' work and offers helpful unsolicited advice with no expectation of a *quid pro quo*. His door would always be open, and he was always extraordinarily generous with his time. I don't think it's an accident that "Merton" and "mentor" are anagrams of each other. Importantly, I certainly can trace the most fruitful and satisfying relationships I have with students and colleagues to situations where I in turn have been able to serve as a mentor for them.

Second, Bob would always say to *write it down*. If you did not or could not write it down, whatever you were thinking probably was not going to fly. In Bob's case, he not only wrote everything down, but his footnotes alone would contain the substance of whole papers. As young faculty, we would live in fear that anything we thought of was already contained in one of his footnotes. Reading those footnotes was absolutely necessary if you wanted to make progress in this field.

As for writing it down, Bob's handwritten lecture mimeos were legendary—because the notes were so carefully produced, comprehensive, and in beautiful handwriting. They would be all you'd need, and I treasure my collection of those notes.

Bob would also say to *give credit where due*. He is a stickler for doing so and would go overboard to make sure that the antecedents of his work were recognized and placed in context. I'll never forget how much effort he put into creating and arranging the bibliography of his book (*Continuous-Time Finance*). The bibliography was as important to him as the actual substance of his own work.

Then there's Bob's work itself.

Bob would say to *think in continuous time*, in other words, to think of the long run as a sequence of short runs and to understand how the short runs cumulatively would add up—or in his case multiply up. The point is that if you can't see it in continuous time, you'll be open to omitting important first-order effects.

This continuous-time world of Bob's is weird indeed, because what you'd think might be first order is really second order and vice versa—where in the short term the mean return matters little and the variance dominates. And all because dt^2 = zero. Until studying Bob's work, I had no idea that something nonzero when squared could be zero!

It is in continuous time where you see clearly how the variance itself can factor into the mean return, and significantly so. An everyday example includes the misunderstanding and misuse of the geometric versus arithmetic return, which differ by $5 \times \sigma^2 = 1.3\%$ for equities. An error of 1.3% *per annum* in estimating the expected return matters enormously in making portfolio allocation decisions, and yet sophisticated practitioners do it all the time. An error of 1.3% *per annum* matters even more in today's world where the real risk-free rate is essentially zero. No student of Bob's would ever be confused about this. All you have to ask is, What would Bob say?

Thinking in small increments of time is really important, including in any situation where there is asymmetry or nonlinearity. I noticed Fischer Black doing that when we were working on a paper together, and he said, "That's the only way I think, and I learnt it from Bob." Fischer very elegantly showed how the mean return from exchange rate exposure across participants had to sum to σ^2 and therefore that exchange rates would necessarily have a positive drift term and therefore that currency hedging would be inherently costly. And he said that Bob gave him the tools to figure it out.

Bob would also say that it's a lot easier to estimate risk (the variance) than return. While this is mathematically incontrovertible, I am constantly shocked to see how investment practitioners attach false precision to the mean while all but ignoring the variances and covariances.

Bob would also say to *think of price paths as nondifferentiable and subject to discontinuous jumps and with processes that had nonstationary coefficients*—in other words, the market environment is random and dynamic. If we ever we needed a reminder of the nonstationarity of markets, just reflect back to the tumultuous period of 2008–2009.

The nondifferentiability of price paths is a particularly sad fact of everyday life in the markets. What it means is that prices are never falling or rising. You can say only that they have fallen or risen and that they might fall or rise. In other words, there is no present participle in finance. If prices were rising or falling, we would all be amazingly rich from the arbitrage possibilities. Bob, think what you could have done for us if you had instead come up with differentiable price paths!

As Zvi and Richard Thakor have already discussed, the functional approach is one of Bob's very big contributions. Once you have heard Bob say to *think functionally rather than institutionally*, the power of it is striking and it becomes hard to think about finance (and many other things) any differently.

As part of thinking functionally, Bob would also say that it is important to *think holistically and enterprise-wide*, to be thoughtful about the full set of assets and liabilities, whether pertaining to an institution or an individual. This thinking is manifest in Bob's work, for example, regarding the pricing of corporate liabilities, and his analysis of personal investing—where you should include the risk of your human capital and its covariance with markets—and in endowment investing, where you should include alumni donations as a shadow asset and, of course, the covariance of those gifts with other risks. Thinking enterprise-wide is just another example of a powerful framework that all too often is eschewed for a focus that is unhelpfully narrow and institutionally siloed.

It was Bob's functional framework for understanding the financial system (how it could and likely would evolve) that underpinned our Global Financial System (GFS) project at Harvard Business School. It was an ambitious undertaking in the mid-1990s—a time of rapid evolution of financial firms and market structures—when people would wonder, when the dust settled, which and how many banks, investment banks, and insurance companies would exist. His and our answer was that that was a dumb question. A framework that took particular institutional forms as the unit of analysis could not answer how institutions should evolve, nor how they should be regulated. What would matter was how competition and technology would drive the financial system to better perform its functions and, in any given moment, that is what would determine the form the financial system would take and what should drive regulation.

The GFS project produced among other things a jointly authored book (eight coauthors), a conference and an executive education program, the involvement of 15 major financial institutions, and a new MBA elective year course—Bob's course on functional and strategic finance that very quickly became oversubscribed. It was a prime example not only of Bob's ability to come up with an abstraction that was useful and powerful but also of his colleagueship, his way of exciting us, his way of gently cajoling us to get the work done, and his willingness to share the credit as well as the ideas. He cared first and foremost about getting it right and having impact. After the GFC and in today's world of shadow banking and blockchain, the framework is as relevant as ever.

My own focus in this project was to think about the payment system as a core financial function—there is no financial system that does not have a payment system—with a view to developing a functional understanding of how it was constructed and intended to work. I included securities clearing and settlement as part of the payment system and quickly discovered how costly, risky, and inefficient it could be. Among the insights gained were to see how pervasive delayed settlement actually was in the system and that delayed settlement really was functioning as a forward contract. Furthermore, you could see that derivative instruments more broadly, including the highest-volume ones such as interest rate swaps and index futures, actually placed significantly less of a burden on the payment system than would trading in the underlying physical securities. They did so because derivatives transformed payment demands from a small number of large payments, when trading physical securities, to a large number of small payments spread over time when trading derivative instruments. Through this lens, you could see how derivatives actually were an important part of the payment system and how they played an important role in risk mitigation, rather than risk propagation as is so often claimed. It would have been hard to see that without a functional lens. It's work I would not have done without the urging of Bob.

The payments function is an exciting area of innovation today—aside from blockchain, just look at the whole new parts of the world economy that are being created on payments platforms like the ones built by gig economy giants like Alibaba, Tencent, and now perhaps Facebook. Through a purely institutional lens, you would not have seen these coming.

Zvi earlier mentioned risk-based capital and Bob's notion of customers versus investors. Bob and I coauthored a paper on risk capital in financial institutions where our goal was to provide a framework for how financial firms should think about risk capital, how to think about the allocation of risk capital, and what should govern how to charge for that risk capital. The idea was very simple—that a firm's capital providers, not customers, should bear the risks the firm is taking, and that the firm's risk capital really and functionally was just an insurance policy, or a put option on those risks. The put option is always there; it's a matter of who's writing it. It's a version of put–call parity. If there's a risk out there, someone is bearing it. The put is something you could buy from an external provider, and if you do nothing you're in effect buying it from yourself. Once you understand that there's always a firm-wide put option embedded in its balance sheet, it's then straightforward to understand the drivers of risk capital, including the covariances among individual business activities that determine overall firm economic risk. Like Bob's other work, the paper changed how firms thought about this important topic and had an impact on their practices in this area.

I'll conclude by saying that it always surprises me how slow and reluctant organizations are to adopt functional thinking. As one example, I sit on a number of investment committees where consultants and advisers are constantly urging us to invest in energy and other real asset projects as a hedge against inflation. Or to eliminate our bond exposures because yields today are so low. I of course ask what would Bob say, and the answer then is very simple. If you want an inflation hedge, buy an inflation swap, which you can do with little money down, with an R^2 to inflation of 1.0 rather than use precious cash to make costly, illiquid investments that will at best be a noisy hedge. As for bonds, if you don't want to invest cash in these instruments because they have low returns, buy bond futures that use minimal cash, while preserving the important hedging function that these instruments provide. These are obvious things to do, but the institutional rigidities to thinking functionally are large indeed.

Bob, in myriad situations I am always asking what you would say. I hope it is clear that your impact on all of us and the world has been enormous and enduring. Congratulations on your extraordinary achievements, and thanks for your wonderful mentorship, colleagueship, and friendship.

ROBERT C. MERTON'S SEMINAL INSIGHTS, REVISITED

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To honor Robert Merton's impact on my own career as his student, I will reflect on the extensions to his work that I have studied. In a real sense that will shortly become obvious, much of my life's work can be characterized as a modest attempt to extend and apply Robert Merton's seminal insights.

THE BLACK–SCHOLES–MERTON MODEL

The Black–Scholes–Merton (BSM) model provides an analytic formula for a European call option on a traded risky asset. More important, however, the BSM methodology provides a blueprint for pricing and hedging derivatives on arbitrary collections of assets. Its assumptions are (i) a continuous-time model with a finite horizon, (ii) competitive and frictionless markets, (iii) no arbitrage, (iv) a constant default-free spot rate of interest, (v) no counterparty risk in the execution of financial contracts, and (vi) the risky asset price follows a geometric Brownian motion (a constant volatility).

The only assumption here that may need clarification is "competitive and frictionless markets." A competitive market is one where traders' transactions have no quantity impact on the market price, and a frictionless market is one where there are no transaction costs and no trading restrictions, such as collateral/margin requirements.

Under these assumptions, the BSM model prices a European call option by synthetically constructing the call's payoffs using a self-financing trading strategy in the underlying risky asset and a default-free money market account. The cost of constructing this synthetic call is the option's arbitrage-free value. Synthetic construction is the key insight of the BSM model.

The model works well when these assumptions are a reasonable approximation. It applies well for short-dated options on equities and foreign currencies in non-volatile and large-volume markets dominated by financial institutions. Short-dated options guarantee that interest rate risk is minimal. Large-volume markets are approximately competitive, and non-volatile markets imply that a constant volatility is a reasonable approximation. And, for financial institutions, transaction costs, trading constraints, and counterparty risks are minimal.

Some thought reveals, however, that these assumptions are not reasonable for all markets and all times. In particular, they are less reasonable for long-dated derivatives on assets correlated with interest rates, markets with less trading volume, friction-filled markets, and volatile markets where constant volatilities do not apply. My research has been to relax the BSM model's assumptions.

The Heath–Jarrow–Morton Model

The BSM model assumes that interest rates are constant. In the 1980s, I helped create the Heath–Jarrow–Morton (HJM) model (Heath, Jarrow, and Morton 1992) for pricing and hedging derivatives under stochastic interest rates. The HJM model determines necessary and sufficient conditions for the evolution of a term structure of interest rates to be arbitrage-free, and it then uses synthetic construction to value and to hedge the derivative's cash flows. The assumptions of the HJM model are similar to the BSM model, and they are (i) a continuous-time model with a finite horizon, (ii) competitive and frictionless markets, (iii) no arbitrage, (iv) stochastic interest rates, and (v) no counterparty risk in the execution of financial contracts.

I have applied the HJM model to many securities over the years: to non-maturity demand deposits at banks, Treasury inflation-protected securities (TIPS), and interest rate caps and floors, as well as to understand convenience yields from holding Treasury securities due to specials in repurchase agreements. I have even explored the relaxation of the competitive market assumption to understand the effectiveness of the US Federal Reserve's 2008–2011 quantitative easing program. All of these applications are based on the fundamental insights first presented in the BSM model.

Asset Price Bubbles

It has been shown that asset price bubbles can exist in an arbitrage-free and complete market under the standard frictionless and competitive markets assumptions (Jarrow, Protter, and Shimbo 2010). But when bubbles exist, option pricing theory changes! Indeed, in the presence of an asset price bubble, put–call parity and the "risk-neutral" valuation formula for pricing derivatives may fail. Call option prices can reflect the underlying asset's price bubble, whereas put options (whose payoffs are bounded) do not. The BSM model, by construction, excludes asset price bubbles.

To detect asset price bubbles in real time, I helped create a methodology for doing this. The trick is to recognize that an asset price process's local moments exhibit different behaviors with and without bubbles, and these differences can be detected empirically (see Jarrow 2016). Interestingly, asset prices with bubbles typically exhibit stochastic volatilities that increase with the level of the asset's price, which explains why geometric Brownian motion excludes bubbles. These new bubble detection methodologies await serious empirical investigation to evaluate their usefulness in practice.

THE CONTINGENT CLAIMS MODEL

Merton's contingent claims model is a model for the pricing and hedging of credit risk. This model takes a firm's balance sheet as given, and its purpose is to value the firm's liabilities and equity. The present value of all of the firm's assets is called the firm's value.

The contingent claims model's assumptions are (i) a continuous-time model with a finite horizon, (ii) competitive and frictionless markets, (iii) no arbitrage, (iv) a constant default-free spot rate of interest, (v) all of the firm's assets trade, and (vi) the firm's value process follows a geometric Brownian motion (a constant volatility).

The firm's liabilities and equity are valued, as in the BSM model, by the cost of synthetically constructing the payoffs to the liabilities and equity via a self-financing trading strategy in the firm's asset value process and a default-free money market account.

The restrictive assumptions are (iv) constant interest rates and (v) all of the firm's assets trade. My research relaxed these two assumptions. This relaxation is known as the reduced-form credit risk model (Jarrow and Turnbull 1992, 1995), which makes the following assumptions: (i) a continuous-time model with a finite horizon, (ii) competitive and frictionless markets, (iii) no arbitrage, (iv) stochastic interest rates (an HJM model), (v) various collections of the firm's liabilities trade, and (vi) a firm's default and recovery rate process are specified.

We replaced assumption (v) all of the firm's assets trade with only a subset of the firm's liabilities trade and assumption (vi) constant volatility with the firm's default and recovery rate process are exogenously specified. Under these assumptions, in a complete market, one can price and hedge a firm's liabilities using synthetic construction.

I have applied the reduced-form model in practice to credit default swaps, commercial mortgage-backed securities, corporate callable bonds, corporate debt, and microfinance loans. It has even motivated me to estimate the firm's intensity process using historical default data and to estimate the recovery rate process using market prices.

The literature applying and extending Merton's contingent claims model is voluminous, and its impact, especially with respect to the risk management of financial institutions, has been profound.

THE INTERTEMPORAL CAPITAL ASSET PRICING MODEL

Merton's intertemporal capital asset pricing model (ICAPM; Merton 1973a) transformed our understanding of equilibrium asset pricing from the static to a dynamic world. Merton's ICAPM assumed the following: (i) a continuous-time model with a finite horizon, (ii) competitive and frictionless markets, (iii) symmetric information and beliefs, (iv) equilibrium pricing (supply equaling demand and investors attaining their optimal portfolios), (v) regular preferences over consumption (increasing, concave, time separable), and (vi) risky asset prices follow a diffusion process with a finite number of Brownian motions.

The three most important results from this model are (1) a mutual fund theorem, (2) a characterization of systematic risk—an expected return relation between a risky asset and the covariances of various risk factors with the risky asset, and (3) a multiple-factor model—a relation between the expected (realized) excess return on a risky asset and a weighted sum of the excess expected (realized) returns of a finite number of risk factors.

The third result is perhaps the most extensively used implication of the ICAPM in the financial and academic industries. The financial industry uses multi-factor models for active portfolio management—the discovery of positive alpha trading strategies—and they form the basis for much of the empirical asset pricing literature that characterizes an asset's realized returns. My most recent research studies the relaxation of the ICAPM's assumptions.

Arbitrage-Free Markets

First, I replaced assumption (iv) equilibrium pricing with just the assumption of no arbitrage. I deleted assumption (v) concerning preferences, and I replaced assumption (vi) diffusion process with arbitrary jump plus diffusion process. Here, we were able to obtain all of the ICAPM's results (see Jarrow and Protter 2016).

This research shows that the ICAPM's implications are robust to these modifications and that the form of the multi-factor model estimated in the empirical literature is consistent with markets that are in disequilibrium and/or where investors do not satisfy the strong rationality assumptions assumed in the original ICAPM.

Equilibrium with Bubbles

I studied whether an extended ICAPM would allow price bubbles to exist in equilibrium (see Jarrow 2017a). The assumptions were (i) a continuous-time model with a finite horizon, (ii) competitive and frictionless markets, (iii) symmetric information and differential beliefs, (iv) equilibrium pricing (supply equaling demand and investors attaining their optimal portfolios), (v) regular preferences over consumption (increasing, concave, time separable), and (vi) risky asset prices following a general semimartingale process (jumps plus diffusions).

In this setting, I could show that rational price bubbles can exist in an ICAPM equilibrium. I also showed that including trading constraints introduces even more types of price bubbles into the economy (Jarrow 2017b). Perhaps surprisingly, in both of these models, Merton's insights on the characterization of systematic risk and the form of the multi-factor model extend again. The only difference is that price bubbles may introduce an additional non-diversifiable risk that earns a risk premium.

Equilibrium with Liquidity Risk and Bubbles

Lastly, I was interested in relaxing the competitive market assumption. To do this, I added a structure so that the more of an asset a trader buys, the larger the average price paid. I studied two different economies, one with a stochastic quantity impact on the price (Jarrow 2018a) and one with additional trading constraints (Jarrow 2018b). Again, in both models, Merton's insights extend and I was able to characterize systematic risk and generate a multi-factor model. In both cases, systematic risk was augmented to include non-diversifiable liquidity risk resulting from the randomness in the quantity impact on the price. In the trading constraint version, asset price bubbles appear, introducing another non-diversifiable risk.

MARKET EFFICIENCY

One of Merton's insights was to use the assumption of no dominance to prove various relations across different options. This assumption was forgotten for almost 20 years. Interestingly, the assumption of no dominance is crucially important to another topic central to finance: that of an informationally efficient market, in which prices "fully reflect" available information.

Recently, a former student and I formalized the definition of an efficient market (Jarrow and Larsson 2012). Roughly speaking, a market is defined to be efficient with respect to an information set if the market prices can be supported by some equilibrium model. Given this definition, we proved the following theorem (roughly stated):

> The market is efficient with respect to an information set if and only if the market satisfies no arbitrage and no dominance.

The relevance of Merton's no-dominance assumption to market efficiency is now obvious.

The importance of this theorem for applications is that it provides an alternative method to test for an efficient market. To prove a market is efficient with respect to the information set generated by prices, one needs only to show that the observed price process is consistent with no arbitrage and no dominance. This is possible using the mathematical finance notion of an equivalent martingale measure, which is a topic better left to the literature.

Robert Merton's impact on my career is far greater than just his influence on the selection of topics that I have discussed herein. His mentorship formed my entire research philosophy—how to construct and to solve problems. His rigorous use of mathematics to solve open questions in finance and economics became my approach too. One can say that as a scholar, I am who I am today because of Robert Merton.

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ROBERT C. MERTON: THE FIRST FINANCIAL ENGINEER

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INTRODUCTION

It's a pleasure and an honor to be a participant at Bob Merton's 75th birthday celebration, a wonderful occasion to consider the remarkable contributions of one of the giants of modern finance. However, as the last speaker in an extraordinary roster of otherwise distinguished guests, including several other giants of modern finance, I feel wholly inadequate and intimidated. What else can I add to the many insights and accolades about Bob's work that other speakers have spoken about?

Moreover, by now, most of you are probably pretty tired of hearing about Bob. Bob this, Bob that, Bob, Bob, Bob! Even Bob may be tired of hearing about Bob! So I'm going to change the theme. I'm going to talk about me. I'm going to tell you what *I* think of Bob.

Specifically, my remarks will be more of a personal reflection on my somewhat idiosyncratic views of Bob's contributions to finance theory and practice. Like many of you, I believe I owe my career to Bob, not just professionally, but also personally through the many ways he and his entire family have encouraged and supported me over the years. And I'll point out a few of those things over the course of the next half hour or so.

But I'd like to do so by taking a very different perspective than those of the other talks at this conference. I want to consider Robert C. Merton, the "financial engineer." The very *first* financial engineer, as a matter of fact. Now I realize that this is a somewhat loaded term these days. I don't use it lightly and will spend some time unpacking it and describing exactly what I mean by financial engineer and why financial engineering as a concept is so important for the *science* of finance.

ECONOMICS: THE BLACK SHEEP OF THE SCIENCES

Before turning to that topic, let me share my view about why Bob is unique. To do so, I need to tell you a bit about my background. I come from a family of three in which I'm the youngest;

Author's Note: This is an edited version of a talk given at the Robert C. Merton 75th Birthday Celebration Conference held at MIT on August 5–6, 2019 (please see https://bit.ly/2nvITM6 for the video of the talk). I thank Zvi Bodie, Bob Merton, Larry Siegel, and Harriet Zuckerman for helpful comments and discussion and Jayna Cummings for editorial support.

I have an older brother and sister. I grew up in New York City, in a typical immigrant family and a single-parent household, and as long as I can remember, my older siblings were focused on science, math, and engineering. Both of them went to the Bronx High School of Science, the best education that money didn't need to buy. My sister received a BS in biology at MIT and a PhD in molecular biology from Rockefeller University, and now chairs the Department of Developmental Biology at the University of Pittsburgh Medical School. My brother received a BS in mathematics from Caltech and a PhD in mathematics from Cornell University, and is now a (real) rocket scientist at Caltech's Jet Propulsion Lab.

I tell you this not to brag—these aren't *my* accomplishments—but to tell you the kind of neuroses that I developed, growing up in that kind of household. Our dinner conversations were generally very difficult for me because, no matter what we were talking about, I knew the least and was frequently reminded of this fact in no uncertain terms. No matter what topic I brought up, my older and smarter siblings had more things to say about it than I did. And as I began to take an interest in economics, I quickly became the black sheep of the family because, obviously, from their perspective, economics was not a science. In fact, the 2013 Nobel Prize has often been used by critics as proof that economics is not a science because in what field of scientific endeavor could Nobel Prizes be awarded in the same year to two people whose research claims the exact opposite things (Bob Shiller and Gene Fama)?!

So that's the intellectual cauldron in which my world view was forged, focusing on science, math, and engineering. And this is where economics falls short.

ENGINEERING VS. SCIENCE

Now, over the years, I've developed what I think are a number of good arguments as to why economics and finance *are* bona fide sciences, but I'd like to first consider the distinction between science and engineering. What's the difference between the two?

When I first got to MIT, I learned almost immediately through a story from one of my engineering colleagues that even among engineering subfields, there are important distinctions. Apparently, after a department party in which some faculty members had a little too much to drink, a group of them started debating which kind of an engineer God must be. The electrical engineer said, "Obviously God is an electrical engineer because of all the electrical connections in the brain and throughout all the body's nerve cells." Then the mechanical engineer said, "No, no, God is a mechanical engineer because the body has all sorts of joints, muscles, and pulley systems that allow us to engage in a wide range of motion." Finally, the civil engineer piped up and said, "You're both wrong; God is a civil engineer!" His puzzled colleagues both turned to him and asked why, and he replied, "Who else would run a toxic waste pipeline through a recreational area?!" This was my introduction to how engineers think.

But if we consider engineering generically and ask the question, "What's the difference between a scientist and an engineer," we can identify a number of differences that most of us seem to agree on (at least here at MIT).

Scientists want to understand things; engineers want to build things. Scientists observe the world; engineers seek to change the world. Scientists tend to be very theoretical; engineers tend to be more practical. Scientists embrace ambiguity; engineers are often frustrated by it.

And finally, engineers work hard, whereas scientists work free (I realize that this last point is somewhat more controversial).

When you go down the list, a theme emerges: science is about developing a body of knowledge that provides some beautiful results about the underlying structure of things. Engineers, in contrast, take that underlying structure and do things with it. And the doing is often much messier.

But I want to make a somewhat different argument today. I want to propose a new definition of science that's intimately tied to the relationship between science and engineering: *I believe that a body of knowledge only becomes a science when a corresponding field of engineering emerges from it*. In other words, I don't believe you can call a body of knowledge "science" until and unless it becomes practically useful. And that's what engineering is all about.

Yesterday, we spoke of finance science as beginning with Harry Markowitz. But I would like to suggest that Markowitz was also part of financial engineering, the moment that Barr Rosenberg introduced the BARRA model to the industry. Rosenberg took Markowitz's theoretical ideas and showed the world that you can actually construct real live portfolios with them. And then these tools became really useful. So much so that they're now used every day by virtually every large asset management company around the world. Before that moment, finance theory was just a bunch of math. Afterwards, finance became useful.

I want to focus on this theme of science versus engineering through the rest of my talk and show how Bob is *both* scientist and engineer.

There are many excellent scientists who aren't engineers. And there are many excellent engineers who aren't scientists. But there are very few who can do both, and do them at the very highest levels. When they do, they change the world. Now, we already know that Bob is a scientist. Paul Samuelson said as much—he called Bob "the Isaac Newton of finance." So, clearly, finance science is one of Bob's accomplishments.

As an aside, Isaac Newton also dabbled in finance. From 1699 until his death in 1727, Newton served as England's Master of the Royal Mint. He also speculated in the stock market, made a small fortune, and then lost much of it by investing in the South Sea Company, the hottest stock in England at the time and which ultimately went bust. Newton muttered afterwards that "I could calculate the motions of the heavenly bodies, but not the madness of the people." This proves the proposition that finance is more difficult than physics.

But getting back to the theme that Bob Merton is, in fact, also an engineer, I can make this argument easily just by considering Bob's resume: a bachelor of science from the School of Engineering and Applied Sciences at Columbia University—not the School of Social Sciences or the School of Science—with a degree in engineering math; a master's degree in applied math from Caltech; and then a PhD from an engineering school in economics.

So, just considering his educational background, one could make the case that, of course, he's an engineer.

But that would be too easy. I want to prove my point by considering several specific examples from Bob's career. There are many, but the following four will suffice: (1) his teaching, (2) his research methodology, (3) his work on derivative pricing models, and finally (4) some of the practical applications Bob has been recently involved in.

So let me start with Bob as a teacher and tell you about the role he played in my choosing finance for my career.

BOB MERTON: EDUCATOR

I already mentioned the science background in my family, so you won't be surprised to learn that I also attended the Bronx High School of Science and was fully prepared to major in math, physics, or biology in college. Those were the three fields that interested me most, and they were also considered "respectable" by my siblings.

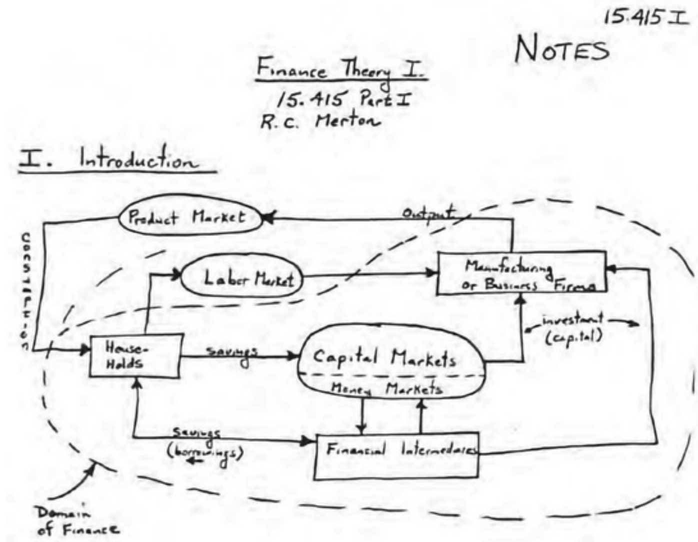
It was only because I happened to take an introductory economics class that I needed to fulfill my humanities requirements that I became interested in economics. I took one or two more courses after that captivating intro class, and was hooked! I'm sure it was largely because I had the great fortune of having a series of charismatic teachers: Pradeep Dubey, Paul Krugman, Saul Levmore, Sharon Oster, Herb Scarf, and Martin Shubik, to name just a few. I became enthralled with the idea of being able to use mathematics and statistics to predict human behavior. In high school, I devoured the *Foundation* trilogy, three mesmerizing volumes of science fiction by Isaac Asimov in which the main protagonist, a brilliant mathematician named Hari Seldon, developed remarkably accurate predictions of major sociopolitical trends using "psychohistory," a new fictional branch of mathematics and statistics that he invented. I thought, "wow, this could really be done with economics."

So, I enrolled as an economics PhD student at Harvard, but after the first semester, I was so discouraged about the subject that I decided to apply to law school. The key faculty I was hoping to work with—Ken Arrow and Jerry Green—both were on leave at Stanford. The faculty member who was assigned the task of teaching first-year microeconomics was drafted at the last minute, and none too pleased about this assignment, so you can imagine how that course went. But the most disappointing aspect of that first semester was the fact that all the models we covered were pretty much the same ones I had learned as an undergraduate. I was expecting much more sophisticated models that would get me closer to psychohistory, but after six months of graduate school, I realized that economics was nowhere near what Asimov had envisioned.

So, at the end of the fall of 1980, I made plans to leave economics, but a high school classmate of mine, Lei-Ching Chou, who happened to be a senior at MIT and to whom I complained about my disenchantment with economics, suggested that I sit in on an MIT Sloan School of Management class on finance theory. At the time, I had no idea what finance was about and thought it involved balancing one's checkbook, but my friend encouraged me by telling me that the class involved a lot of math and that it was taught by a really engaging instructor, someone I had never heard of named "Merton." I took her advice and went to the first class, and then the second, and the third. After two weeks, I decided that this was what I wanted to do for the rest of my life.

Merton's class, known at the time as "15.415" in MIT-speak, was nothing short of an epiphany for me. Let me give you a simple example of just how remarkable his lectures were. In the very first class, he began with a simple diagram that described the entire economy (**Exhibit 1a**). Despite the fact that I had already taken many courses in microeconomics, macroeconomics, econometrics, game theory, and general equilibrium theory—at both graduate and undergraduate levels—this was the first time that any economics professor had taken the time to describe the entire economy from a

EXHIBIT 1A. FLOW DIAGRAM OF THE FINANCIAL SYSTEM'S ROLE IN THE ECONOMY FROM 15.415, SPRING 1981



Source: Robert C. Merton. Reproduced by permission.

systems perspective, and explain "This is what we're studying, this is how all the parts are connected; now let's focus on each of these parts and try to understand how it works." It was transformational.

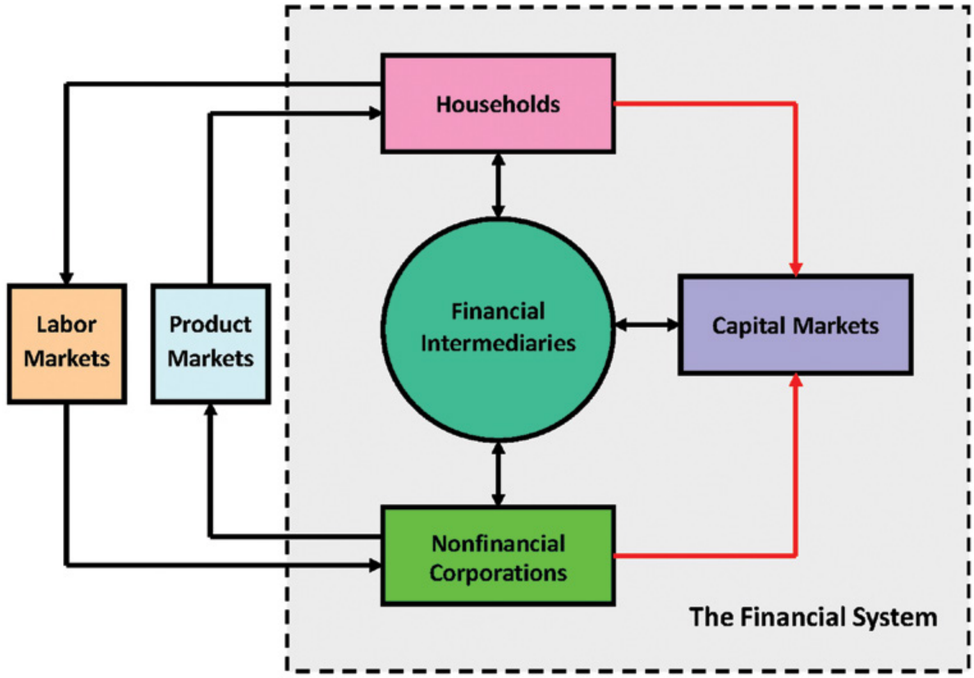
Years later, after I joined the MIT Sloan finance faculty and was given the honor of teaching this very same course that changed my life, I also started my first day of class with a flow diagram of the economy (**Exhibit 1b**). It should look familiar.

It also helped that we had two terrific teaching assistants for the course—Bob Ariel and Saman Majd—and I was privileged to start my academic career with Saman when he and I both joined the Wharton School as assistant professors of finance at the same time.

In Bob's Finance Theory class, the subject just came alive for me. I was fascinated, and couldn't get enough. I took all the other courses taught by Bob, as well as those offered by Fischer Black, Franco Modigliani, and other MIT finance luminaries. But among all of those luminaries, I still found Bob's approach to finance particularly engaging, even though I couldn't have told you why at the time. But now I can.

To see why, let me show you another of Bob's systems flowcharts (see **Exhibit 2**), one that came from his course on capital markets, 15.433. This diagram describes the organizational structure of an asset management company, one that offers both passive and active investment products and services. At this point in the course, we had just completed a unit on mean-variance portfolio optimization, and then a more sophisticated intertemporal version using stochastic dynamic programming, so our heads were in the mathematical clouds of modern portfolio theory. In fact, I had to take a graduate course

EXHIBIT 1B. UPDATED FLOW DIAGRAM OF THE FINANCIAL SYSTEM'S ROLE IN THE ECONOMY FROM 15.401, FALL 2018



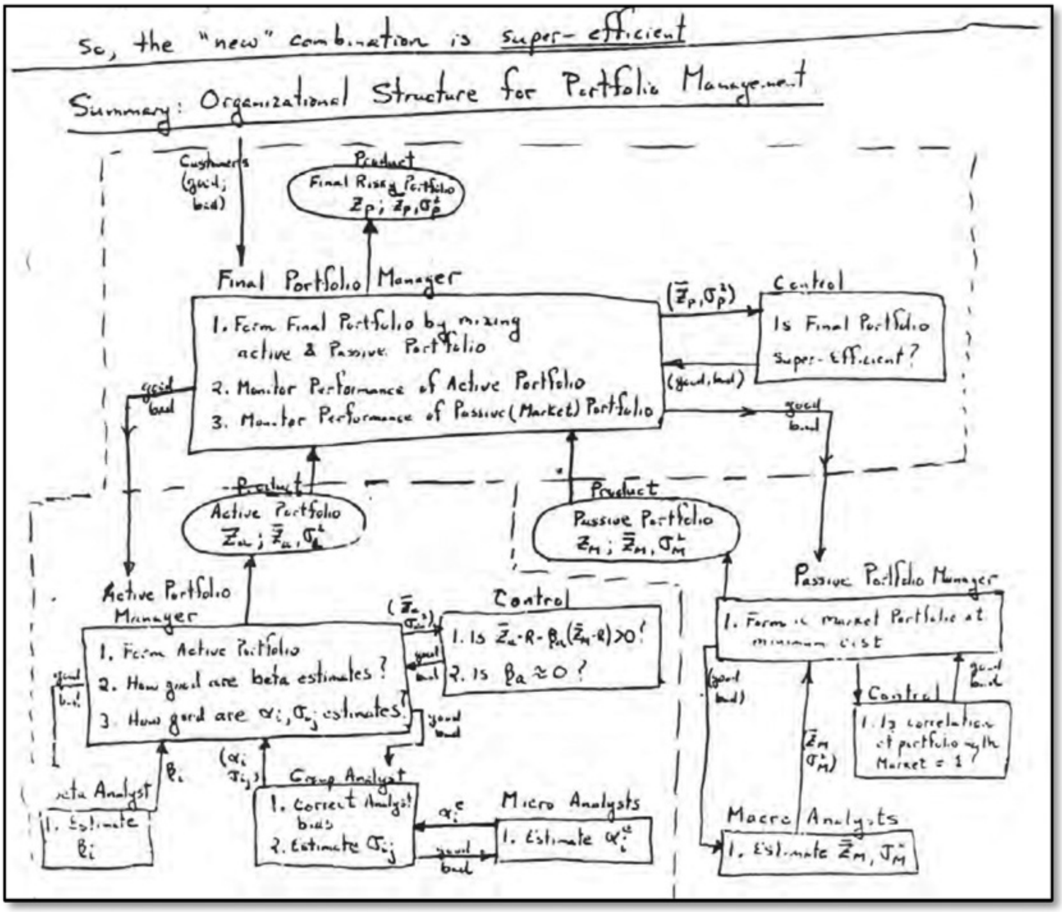
Source: Andrew W. Lo. Reproduced by permission.

on stochastic control theory (taught by Roger Brockett at Harvard's School of Engineering) just to be able to fully appreciate the techniques that Bob used so nonchalantly in 15.433.

And yet Bob brought us back down to Earth by explaining how these very esoteric tools could actually be implemented in practice to create value for investors and shareholders. It was only years later, after starting my own asset management company, AlphaSimplex Group, along the lines of Exhibit 2 (we offered both active and passive products), did I come to realize that Bob wasn't describing current best practices at the time; he was designing the ideal institutional asset management organization of the future. From scratch. When I asked him recently about his tendency to bring cutting-edge research into the classroom—in some cases challenging conventional wisdom and existing institutional practice—Bob observed that "sometimes best practice simply isn't good enough." Amen.

Exhibit 2 convinced me that I'd made the right choice in deciding to focus on finance because, for the first time in my young graduate school career, I saw on one page, in one diagram, how all of finance science could be made practical. The different boxes illustrated all the necessary ingredients for building a modern asset management company: a passive portfolio management unit, an active portfolio management unit, macro- and microanalysis units, super-efficient portfolio construction, and centralized

EXHIBIT 2. FLOW DIAGRAM OF A PORTFOLIO MANAGEMENT ENTERPRISE FROM 15.433, FALL 1982



Source: Robert C. Merton. Reproduced by permission.

services such as risk management, trading, and compliance.[54]

Today, these are common buzzwords, but in 1981 when I took the course, many of these ideas were still academic musings. For example, the idea of super-efficient portfolio construction was published just a few years earlier in an academic journal by Jack Treynor and Fischer Black (1973). They showed how to combine unique insights about mispriced stocks with a passive portfolio to maximize the gains from those insights.

There was science behind their approach, but at the end of the day, it was engineering. Financial engineering.

[54]The super-efficient portfolio is the portfolio on the efficient frontier that is at the point of tangency to the capital market line.

I was completely blown away by the ideas in Exhibit 2. The more I thought about it, the more I came to realize what the most important part of this diagram is. What would you choose as the most important? Would it be the active part, the passive, the micro/macro analysts, beta analysis, monitoring?

From my perspective, the most important part of the diagram is not the boxes. *It's the arrows.* It's how all these pieces connect with each other—the dynamics.

That's an aspect of Bob's work that took me a while to fully appreciate. I knew when I sat in his classes that there was something special about him and his work. At first I thought it was just the subject matter, but then I attended lectures by other financial economists, and they weren't the same. Something was different. And ultimately, I realized what it was: the arrows, the dynamics.

BOB MERTON: SCIENTIST

In economics, as most of you know, we're devoted to the notion of "equilibrium," the idea that everything is in perfect balance—supply equals demand. I spent a lot of time as an undergraduate and in my first year of graduate school studying "general equilibrium," in which supply equals demand in all markets across all industries at all times. But when you look at the real world, almost nothing is in equilibrium. Equilibrium is a static concept, a snapshot: Right now, things might be in balance, but then something changes and we're out of balance. Economists have tried to make this concept dynamic—as in a "dynamic equilibrium" where you transition from one equilibrium to the next—but that's a very cheap and not particularly realistic way of studying dynamics.

When you observe the actual dynamics of financial markets, you understand how important they are, and how difficult they are to model. But that's how things work in the real world. Now for us to have a meaningful discussion about dynamics, we need to turn to the second topic, which is Bob's research methodology. I want to focus in particular on Bob's use of Itô calculus.

Itô calculus was introduced in 1964 by two mathematicians, Kiyoshi Itô, of the University of Kyoto, and Henry P. McKean, who actually spent some time at MIT and collaborated with Paul Samuelson but spent most of his career at New York University's famed Courant Institute. The two of them came up with a generalization of calculus that can be applied to random variables, and not just random variables, but *sequences* of random variables over time, which is particularly important for finance because that's exactly what stock and bond markets are.

To understand the magnitude of their contributions, and then Bob's contributions, we need to understand what stochastic calculus is.

I'd like to turn to some of the ideas that were first developed in a paper that Bob wrote in 1971, titled "Optimum Consumption and Portfolio Rules in a Continuous Time Model." This is a remarkable publication for a variety of reasons. It's a technological *tour de force*, and took me probably a year to get through, and I had to take that course in stochastic control theory to really get inside this paper and understand it. And I'm not sure I fully understand all of it, even to this day. In fact, I'm sure there are subtleties that I still don't fully appreciate.

This article was probably the first to introduce stochastic calculus to the economics profession in a serious way. Bob had published a paper in 1969 on dynamic portfolio optimization (a companion piece to Paul Samuelson's discrete-time version of the same problem),[55] wrote a technical appendix extending Samuelson's discrete-price model of asset prices to continuous time,[56] and also applied stochastic calculus to modeling economic growth.[57] But none of these contributions were nearly as expansive a treatment of stochastic calculus and its applications to solving important problems in finance. His 1971 paper did just that, offering a complete exposition of these techniques in the context of an individual's optimal consumption and investment decisions.

By "complete," I'm referring to the fact that he led readers by the hand with respect to this relatively new branch of mathematics. For example, the title of Section 2 of the 1971 paper is "A Digression on Itô Processes," which was an excellent overview of stochastic calculus for the uninitiated.

Which isn't to say that this section was easy reading—it took me three months to fully understand footnote 7. And the gist of this footnote is a warning that the rules governing derivatives and integrals with respect to Brownian motion are similar to *but different from* the rules for the usual derivatives and integrals of ordinary calculus. It was an important footnote. And in case you haven't already figured this out about Bob's publications, there are gems buried in his footnotes. Even though it might take you months and perhaps years to understand them, it's well worth the effort.

I want to explain a bit more about this footnote on stochastic calculus to illustrate my main thesis that Bob is also an engineer. However, I first have to tell you a little bit about ordinary calculus, since not all of you are familiar with it. Calculus, as most of you know, was invented by Isaac Newton and, independently, Gottfried Leibnitz in the mid-17th century. It was invented as a set of mathematical tools to do certain computations that would be difficult to do any other way.

Consider the curve in the upper right of **Exhibit 3**. Suppose we want to calculate the area under it. We know how to calculate areas for things like rectangles (base times height) and triangles (one-half base times height), but how do we calculate the area of an irregular shape like Exhibit 3?

Even if I gave you the formula for the curve, it's not obvious how to compute the area below it. Well, calculus gives us a very sensible way to do it. We start by approximating this area using a bunch of rectangles, and we'll put the rectangles at various different spacings underneath the curve. We know how to calculate the area of each of those rectangles, and if we do so and sum them up, we now have an approximation to the value we're looking for. If we now put more and more rectangles under the curve that are each thinner and thinner, they'll give us better and better approximations to the area under that curve. Eventually, if we go to the limit of an infinite number of rectangles, each infinitesimally thin, we'll reach a perfect approximation to the area under the curve. That's ordinary calculus!

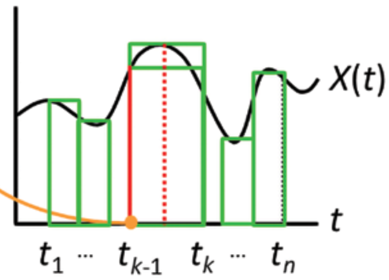
Now imagine that the curve in Exhibit 3 represents one possible path of the evolution of a sequence of random variables over time and that there are many such paths that are possible, each one representing a different realization of that sequence of random variables, also known as a "stochastic process." This is the sense in which the calculus we're about to consider is

[55]Merton (1969).
[56]Merton (1973).
[57]Merton (1975).

EXHIBIT 3. BASICS OF STOCHASTIC INTEGRAL CALCULUS

$$\int_0^t F(X(\tau),\tau)dB(\tau) \equiv$$

$$\lim_{\Delta\to 0}\sum_{k=1}^{n} F\left(\overbrace{X(t_{k-1})\ ,\ t_{k-1}}\right)\times\left(B(t_k)-B(t_{k-1})\right)$$



$$\oint_0^t F(X(\tau),\tau)dB(\tau) \equiv$$

$$\lim_{\Delta\to 0}\sum_{k=1}^{n} F\left(\frac{X(t_k)+X(t_{k-1})}{2}\ ,\ \frac{t_k+t_{k-1}}{2}\right)\times\left(B(t_k)-B(t_{k-1})\right)$$

Source: Andrew W. Lo. Reproduced by permission.

"stochastic," so now you can begin to develop an appreciation for what Itô and McKean accomplished. They proposed a precise and elegant method for calculating areas under the curve for stochastic processes. To do that, we need to make a decision. We need to decide how to calculate the areas of those rectangles. We all know that it's base times height, right?

But when we're approximating the function with these rectangles, we have to choose the point of the function at which we measure the height. So let's just take a look at that one rectangle in Exhibit 3, the one outlined in green between t_{k-1} and t_k. One way to calculate the area of this rectangle is to multiple the base $t_k - t_{k-1}$ by the height of the curve, which we measure by evaluating the function at the midpoint of that base, $(t_k + t_{k-1})/2$. That's how it's usually done in ordinary calculus.

But we could have chosen a different point. We could have chosen, say, the left endpoint of that interval, t_{k-1}. We'd get a shorter rectangle as a result if we had done that, but as the number of rectangles goes to infinity, it would matter less and less. It turns out that this is exactly what Itô and McKean proposed when they came up with the definition of a stochastic integral—they used the left endpoint, not the midpoint as ordinary calculus would do. But before I explain why they made this rather odd choice, you should know there's an alternative to Itô calculus and that's what Merton was getting at in footnote 7 of his 1971 paper.

The other way of defining a stochastic integral is to use the midpoint, and this is known as the "Stratonovich integral," after the Russian mathematician Ruslan L. Stratonovich, who first proposed this definition in 1966.[58] The main difference between the Itô and Stratonovich integrals can be seen more clearly when you compare their differential versions (**Exhibit 4**). Let me explain what this means.

[58]See Stratonovich (1966). This definition was independently proposed by Fisk (1963).

EXHIBIT 4. BASICS OF STOCHASTIC DIFFERENTIAL CALCULUS

$$dF(X(t),t) = F_x dX + F_t dt + \frac{1}{2}F_{xx}(dX)^2 \qquad \text{Itô formula}$$

$$d_sF(X(t),t) = F_x d_sX + F_t dt \qquad \text{Stratonovich formula}$$

The version of ordinary calculus I described earlier—adding up rectangles to approximate the area under a curve—is typically called "integral calculus" because it involves combining or integrating lots of small rectangles. But there's a flip side to integral calculus that involves starting with quantities like the area under the curve and calculating how quickly it grows or declines over time. This calculation is known as "differential calculus" because it involves measuring differences, so rather than adding up infinitesimally small rectangles, we're actually taking first differences of such rectangles. Those differences are called "derivatives" (which shouldn't be confused with derivative securities, a topic I'll turn to shortly), and they measure rates of change of various quantities. These rates of change are often the first step in developing an understanding of dynamics (for example, is the stock market rising or falling today and how quickly?).

The concept of a derivative from ordinary or differential calculus also has an analogue in stochastic calculus. The differential version of the Itô integral is given by the first formula in Exhibit 4, and the corresponding version of the Stratonovich integral is given by the second formula. These formulas tell us how an arbitrary function, $F(X(t), t)$, changes over an infinitesimally small increment of time.

Now you wouldn't know this unless you're familiar with ordinary calculus; but if you are, you'll see that the Itô formula looks different than the ordinary-calculus version and contains an extra term at the end, $\frac{1}{2}F_{xx}(dX)^2$. This third term arises because we're dealing with stochastic processes, not deterministic functions, and also because we're using the left endpoint to compute our rectangles. It turns out that when the midpoint is used, as in the case of the Stratonovich integral, this third term disappears, as we see from the second expression in Exhibit 4. Physicists use the Stratonovich integral all the time, and one of the reasons is that it doesn't have that annoying extra third term.

So who cares? And why am I discussing this in connection with Bob's 75th birthday celebration?

BOB MERTON: ENGINEER

Well, Bob, for one, cares. In that same 1971 article, Section 3, titled "Asset Price Dynamics and the Budget Equation"—a boring-sounding title for one of the most important sections of one of the most important publications in modern finance—he describes why the left endpoint is so special. In this section, Bob shows us how to define and derive the dynamics of our wealth over time. In the practice of finance, one of the most basic tasks is to be able to relate changes in our total wealth to changes in stock and bond market prices. We often refer to this as computing our "profit and loss," or "P&L" for short. This is the connection between stochastic calculus—the analysis of variables that change randomly—and finance.

How is wealth changing over time? Bob derives this relation initially in discrete time via the expression:

$$W(t+h) = \sum_{1}^{n} N_i(t) P_i(t+h),$$

in which our wealth at time $t + h$ is simply equal to the number of shares of each security i at time t multiplied by the price at time $t + h$. Now this might seem like a trivial accounting relation, but it turns out that it's an absolutely critical link in the chain of logic that leads us to the inescapable conclusion that we have to use the Itô integral instead of the Stratonovich integral. The reason is this: The horizontal axis in most financial applications of stochastic calculus is time, so using the left endpoint in computing P&L simply means that we aren't assuming that we can see into the future, which would be the case if we used the midpoint instead.

Referring back to Exhibit 3, if we use the left endpoint, this means we're making decisions and choices for the future based on information that we actually have at time t. In contrast, the Stratonovich integral implicitly assumes that, at time t, when we make a decision, we're using information that becomes available only at time $t + h/2$, which is in the future. In other words, we would be using information that we couldn't possibly have, unless we could see into the future. If we could do that, we would quickly conclude that there were tremendous arbitrage opportunities available to us. We would be able to implement Will Rogers' famous dictum for how to make money in the stock market: "Buy a stock and sell it when the price goes up; if the price never goes up, then don't buy it."

So this is an important idea, but you might still think it's just mathematical mumbo jumbo and not something that could affect you. You would be wrong. I promise that if you were asked to compute the P&L of a hypothetical trading strategy, say, a simple equity market–neutral mean-reversion trading strategy, you would probably get it wrong the first time around because you would calculate the return based on prices in the CRSP data and then multiply those prices by portfolio weights formed on the same day.[59] That method implicitly assumes that you know the future, so it's not surprising that when academics simulate trading strategies, they often achieve tremendous profits in their backtests. But when you take into account the constraint that you can only use information that's truly available to you on the date you consummate a trade, those profits often vanish.

I appreciated the depth of this section of Bob's 1971 paper only after I made that same mistake myself years later and calculated trading strategies that were enormously profitable on paper. At that moment, I realized that when Bob wrote Section 3, he must have known how to calculate P&L correctly and built that into the mathematics he used. How did he know this as an economics PhD student?

It's because as an undergraduate and graduate student, Bob traded stocks fairly regularly and calculated his own P&L. This is yet another manifestation of Bob the financial engineer. As dense and esoteric as the mathematics are in his 1971 paper, there's some very practical engineering behind it.

[59]CRSP is the Center for Research in Security Prices, part of the Booth School of Business at the University of Chicago.

DERIVATIVE PRICING AS FINANCIAL ENGINEERING

Now I'd like to turn to the third aspect of Bob as financial engineer, which is his research on derivative securities. This body of work has been considered in many other forums, including other presentations in this conference, so I won't repeat those wonderful expositions. Instead, I want to argue that the Black–Scholes/Merton formula—the breakthrough that Fischer Black, Myron Scholes, and Bob collectively achieved—was the beginning, the real epicenter of financial engineering (see **Exhibit 5**).

Moreover, this beginning was a unique contribution of Bob's that's distinct from those of Myron Scholes and Fischer Black. Myron is here in the audience, so he can speak for Black and Scholes and correct me if I'm wrong. But the reason I feel somewhat confident in this distinction is because I gave a talk at Goldman Sachs years ago when Fischer was in the audience, and he made some interesting remarks that I'll share with you shortly.

So let's revisit the famous Black and Scholes 1973 paper, "The Pricing of Options and Corporate Liabilities," and consider yet another interesting footnote, footnote 3, in which the authors write, "This was pointed out to us by Robert Merton." What was pointed out? If you refer back to the main text, footnote 3 comes after the following sentence: "In fact, the return on the hedged position becomes certain." We need to unpack this sentence to fully appreciate the footnote's significance.

What Black and Scholes showed was that we can create a portfolio of stocks, bonds, and options that collectively had no systematic risk, and therefore it had to earn the risk-free rate. That, in turn, gave us the famous Black–Scholes partial differential equation for the price of an option, the same equation that the French mathematician Joseph Fourier derived a century and a half ago to explain the physics of heat conduction. Black and Scholes were first to derive the

EXHIBIT 5. BLACK–SCHOLES/MERTON FORMULA FOR PRICING AN OPTION

If σ^2 = constant, then the solution to (218)–(219) is:

(220) $$F(S,\tau;E,r,\sigma^2) = S\,\Phi(X_1) - E e^{-r\tau}\,\Phi(X_2)$$

where: $$X_1 \equiv \left[\log\left(\frac{S}{E}\right) + \left(r + \tfrac{1}{2}\sigma^2\right)\tau\right] / \sigma\sqrt{\tau}$$

$$X_2 \equiv X_1 - \sigma\sqrt{\tau}$$

and $$\Phi(y) \equiv \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{y} e^{-\frac{1}{2}u^2}\,du =$$ Standard Normal Cumulative Density Function

Source: Robert C. Merton. Reproduced by permission.

option-pricing formula by solving this equation, and that's why it's the "Black–Scholes/Merton" formula instead of the "Merton/Black–Scholes" formula.

But what Bob showed is that not only can we eliminate the systematic risk of this portfolio of stocks, bonds, and options, we can eliminate *all* the risk if we trade continuously in time. He proved this fact using Itô calculus, and to someone focused on practical applications—financial engineering—this fact makes all the difference in the world. Why?

Let me explain using Bob's own words from his 15.433 lecture notes. There's a passage in those notes on page 116 (**Exhibit 6**) that I just found stunning—I still remember the precise moment when I read those words as a graduate student and being awestruck by their implications. ". . . we have created a 'security' with an identical payoff structure to the option. . . . The investor always has the right to 'manufacture' an option if it is cheaper." It's no exaggeration to say that this passage launched thousands of careers in the financial industry.

What this observation implies is that if an option doesn't yet exist, we have the recipe for creating it. We can *build* it. That's engineering. The science tells us this is what the price ought to be. But it's the continuous trading, the delta hedging, that tells us how to manufacture it. And it was manufactured in spades.

Several multi-trillion-dollar industries are based on the idea that you can manufacture it. If the security you want doesn't yet exist, no problem—we'll make it for you (and, by the way, we'll charge you a small fee for it).

EXHIBIT 6. THE BEGINNINGS OF FINANCIAL ENGINEERING IN MERTON'S 15.433 LECTURE NOTES

–116– 15.433 Merton

By following the ($W_1^* = F_1 S$, $W_3^* = F - F_1 S$) strategy, the value of the stock-riskless borrowing portfolio will always be $F(S,\tau;E)$. Clearly, at the end of τ-periods, the portfolio will have value of $F(S,0;E) = \mathrm{Max}[0, S-E]$. Thus, by combining the stock with riskless borrowing in the above strategy, we have created a "security" with an identical payoff structure to the option. So, even without the "perfect markets" assumptions, we can deduce $F(S,\tau;E)$ as the "right price" for an option by using dominance. The investor always has the right to "manufacture" an option if it is cheaper.

Back to the hedging: If the option is selling for more than

Source: Robert C. Merton. Reproduced by permission.

Exchange-traded derivatives are one example, of course, but the over-the-counter (OTC) derivatives markets are even larger. In 2018, there were $544 trillion of notional OTC derivative contracts outstanding. More than half a quadrillion dollars of notional value.

Black, Scholes, and Merton have provided us with the means for understanding, creating, and managing these instruments. This is financial engineering at work.

THE ALBERT EINSTEIN OF FINANCE

The fourth and final topic that I'd like to consider is some of Bob's efforts in taking his ideas from theory into practice.

It's clear that Black, Scholes, and Merton have transformed several industries with the ability to manufacture derivative securities synthetically. In fact, an industry association emerged years ago that used to be called the "International Association of Financial Engineers," or IAFE. The organization is now known as the "International Association of Quantitative Finance" because of the unfortunate negative connotations associated with the term "financial engineering."

However, they still offer an award known as "Financial Engineer of the Year." Last year, for example, Francis Longstaff was honored with this award. The award was first offered in 1993, and who do you think was the inaugural Financial Engineer of the Year? Bob Merton. So I rest my case for the title of my talk.

But many people now think of derivative securities as "financial weapons of mass destruction," a phrase first used by Warren Buffett and popularized by the media, even though it was taken out of context. In fact, Buffett uses derivatives all the time, but he was sincere and thoughtful when he used the term in his annual report because there are certain contexts where financial derivatives are extraordinarily dangerous and could have catastrophic consequences.

This critique of financial engineering has even been embraced by one of the founding fathers of quantitative finance, Paul A. Samuelson. In a PBS interview recorded on December 26, 2008, about the financial crisis unfolding that year, Samuelson offered the following mea culpa: "Fiendish Frankenstein monsters of financial engineering had been created, a lot of them at MIT, some of them by people like me."

I never had the privilege of speaking with Samuelson about this comment, but I wish I had because I strongly disagree with him about his conclusion. In the wrong hands, any tool can be abused. But even if we agree that derivatives are, in fact, financial weapons of mass destruction, then by analogy, it follows that Fischer Black, Myron Scholes, and Bob Merton must be the equivalent of Albert Einstein.

I take this analogy quite seriously, and let me start by making the argument that Einstein was not only a scientist of the first order, but he was also an engineer. By now, everyone is familiar with the fact that after receiving his PhD in physics, Einstein began his career as a patent clerk. From 1902 to 1909, he worked in the patent office in Bern, Switzerland, because he wasn't able to secure an academic job in physics.

But in the midst of those seven years he spent examining patents, he published a series of extraordinary scientific papers that forever changed the way we think about the physical world. In 1905, his *annus mirabilis*, or miracle year, he produced four amazing articles on the photoelectric effect, Brownian motion, special relativity, and what was to become the theoretical basis of the first true weapon of mass destruction, $E = mc^2$. He made all these breakthroughs during evenings, weekends, and vacations, while employed full-time sorting through other people's inventions. This story is reminiscent of Bob's early years—while there may not have been one year that was his *annus mirabilis*, there were probably two or three years that came close.

But to continue with my claim that Einstein was also an engineer, let me tell you about an aspect of his life that most people don't know about. Einstein was actually an inventor. He held a number of patents, several of which he filed jointly with a physicist colleague named Leo Szilard for a new method of refrigeration.[60] At the time, refrigeration was a relatively new technology, and a number of deaths occurred when poisonous refrigerants—ammonia, sulfur dioxide, or methyl chloride—leaked. In 1926, an entire family in Berlin, including several children, died from such a leak and this tragedy greatly affected Einstein, so he set out to develop a safer alternative.

He and Szilard ultimately received several patents for an ingenious method of refrigeration requiring no moving parts such as a compressor, and no need for any toxic gases. Unfortunately, they never made a commercial success of their invention, mainly because a nontoxic refrigerant (freon) was introduced by the industry in 1930. However, they did sell their patents to the Swedish company Electrolux for about $10,000 in today's currency. In a beautiful twist of karmic fate, in 1950 the Einstein–Szilard design finally found a commercial application—as the cooling mechanism for nuclear breeder reactors.

[60]Dannen (1997).

Because patents are designed to deal with practical problems, they generally require some forms of engineering. And by starting out as a patent clerk, Einstein was immersed in engineering at the very outset of his career.[61] Although I'm no expert in the history of science, I conjecture that Einstein's early introduction to such practical problems was critical for his intellectual development as a theoretician.

Of course, because most practical problems are dynamic, not static, the solutions are considerably more complex than theory suggests. And because this complexity means we can't possibly anticipate the myriad potential unintended consequences of a given engineering design, it's inevitable that we're going to fail on occasion, as in space shuttle explosions, nuclear meltdowns, plane crashes, train wrecks, chemical plant failures, and so on. The sociologist Charles Perrow refers to these problems as "normal accidents" because of their frequency.[62] He and others have observed that what matters most is how we respond to those disasters. Do we learn from our mistakes and improve?

This has been a research topic of the well-known engineer Henry Petroski,[63] an expert in failure analysis and how the study of failure is inextricably linked to engineering advances. He argues that an important part of engineering is experimentation and understanding failure. To illustrate this theme, he cites the compelling example of the failure of the Tacoma Narrows Bridge in 1940. This bridge opened on July 1 and almost immediately, it became clear that there were serious flaws in its design as it swayed in

[61]In fact, Einstein's exposure to engineering came much earlier from his father and uncle, who jointly founded an electrical engineering company that produced parts for direct-current electric power companies.
[62]Perrow (1984).
[63]I thank Zvi Bodie for introducing me to his work.

response to windy conditions. This tendency quickly led to the moniker "Galloping Gertie," and on the morning of November 7, 1940, in the face of 40 mph winds, the bridge finally collapsed.[64]

At the time it opened, this bridge was the third-longest suspension bridge in the world, 2,800 feet from span to span. Since then, engineers have studied the causes of the bridge's failure, and we now routinely build suspension bridges of this length and greater. For example, a bridge in Kobe, Japan, was opened in 1998 that runs 6,800 feet between the central spans, more than twice as long as the Tacoma Narrows Bridge, and there hasn't been a single problem with it since its debut.

WEAPONS OF MASS DESTRUCTION: THE ATOMIC KIND

So part of engineering is studying and learning from failure. But another part of engineering is applying knowledge to address important issues of the day, as in the case of weapons of mass destruction. The origin of nuclear weapons can be traced back to 1939, the year in which Einstein coauthored a letter with Szilard to President Roosevelt. Let me quote one passage from that letter:

> In the course of the last four months, it has been made probable through the work of Joliot in France as well as Fermi and Szilard in America that it may become possible to set up a nuclear chain reaction in a large mass of uranium by which vast amounts of power and large quantities of new radium-like elements would be generated. This new phenomenon would also lead to the construction of bombs, and it is conceivable, though much less certain, that extremely powerful bombs of a new type may thus be constructed.

The letter goes on to point out something that with the benefit of hindsight, I found incredibly chilling, and this is ultimately what motivated the United States to launch the Manhattan Project to create the first nuclear weapon:

> I understand that Germany has actually stopped the sale of uranium from the Czechoslovakian mines which she has taken over. That she should have taken such early action might perhaps be understood on the ground that the son of the German Under-Secretary of State, von Weizsäcker, is attached to the Kaiser-Wilhelm-Institut in Berlin where some of the American work on uranium is now being repeated.

The Kaiser-Wilhelm-Institut für Physik was the most prestigious physics research institute in Germany at the time, an institute that Einstein knew well because he served as its founding director from 1917 to 1933. In 1939, this institute had started trying to replicate some of the experiments that Szilard and others in the United States were conducting on splitting the atom.

This is why Einstein wrote the letter to the president. This is why we have weapons of mass destruction. And, fortunately for us, we prevailed.

[64]See the remarkable newsreel footage of Galloping Gertie at https://www.youtube.com/watch?v=nFzu6CNtqec.

WEAPONS OF MASS DESTRUCTION: THE FINANCIAL KIND

Sometimes engineering is called on to address urgent policy issues of the day, and in the case of financial engineering, Bob has responded to these calls. In the period since the 2008 financial crisis, Bob has given countless talks and written a number of research papers—two of which I've been privileged to coauthor—focused on measuring and managing systemic risk so we can better address future threats to financial stability.

The first publication Bob and I collaborated on shows that the combination of rising home prices, declining interest rates, and near-frictionless refinancing opportunities can create unintentional synchronization of homeowner leverage.[65] This leads to a "ratchet" effect on leverage because homes are indivisible and owner-occupants cannot raise equity to reduce leverage when home prices fall. Our simulation of the US housing market generated 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. This refinancing ratchet effect is a new type of systemic risk in the financial system and does not rely on any dysfunctional behaviors.

Our second publication argues that monetary, fiscal, and financial stability policies have to be integrated in order to be effective.[66] One key reason has to do with the credit risk associated with government guarantees, which can be modeled as put options and, as such, can be highly nonlinear and subject to tremendous losses during periods of financial distress. We apply several econometric techniques such as Granger causality networks to credit default swaps data for banks, insurance companies, and sovereign government debt that allow us to construct early warning indicators of potential threats to financial stability.

Bob pursued this need for more data and better analytics one step farther by lending his name, reputation, and knowledge—along with several other Nobel laureates in finance, and John Liechty and Allan Mendelowitz—in a letter to Congressman Jack Reed persuading him to formulate legislation to create the Office of Financial Research. This new branch of government is charged with the mission of collecting data from the financial industry and monitoring systemic risk in the financial system, a mission designed explicitly to deal with the risks of financial weapons of mass destruction. Sound familiar? While this letter may not have had the same degree of life-and-death urgency as the Einstein–Szilard letter, from the financial system's perspective, its eventual impact could touch as many lives.

If that weren't enough, Bob has been a tireless participant in the effort that Lars Hansen and I initiated on macro-financial modeling in which we focus on catalyzing new research at the intersection of macroeconomics and finance—with a particular emphasis on developing better analytics for measuring systemic risk. He has spoken at several of our meetings, participated in our organizational activities, and inspired an entire generation of younger scholars to join this emerging field of systemic risk measurement and management.

And you have already seen what Bob is working on together with Arun Muralidhar about SeLFIES. This could be the most important

[65]Khandani, Lo, and Merton (2013).

[66]Merton, Billio, Getmansky, Gray, Lo, and Pelizzon (2013).

practical application of financial engineering that Bob has ever undertaken, with the potential to help hundreds of millions of individuals secure better retirements.

At 75 years of age, Bob has not slowed down one bit!

CONCLUSION

Human civilization has had a remarkable run for the last 100,000 years. That run has been largely the result of technological innovations—agricultural technology, medical technology, manufacturing technology, and most recently, information technology.

But all those technologies have one theme in common: They all needed financing. Therefore, financial technology is central to innovation and progress. We're now facing some of the biggest challenges ever to confront humanity. With climate change, flu pandemics and other infectious diseases, Alzheimer's, cancer, and the eventual exhaustion of fossil fuels, I'm not at all sure that *Homo sapiens* will survive the next 100,000 years. But I do know one thing for sure: The technologies we'll need to develop to deal with these challenges will all require financial engineering.

And that's why I'm so grateful that we have, right here at MIT, the motivation, inspiration, and expertise of the very first financial engineer.

Thank you, Bob, and happy birthday!

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