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Robert C. Merton: The First Financial Engineer

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Abstract

This is an edited version of a talk given at the Robert C. Merton 75th Birthday Celebration Conference held at MIT on August 5 and 6, 2019. A video of the talk is available at **https://bit.ly/2nvITM6**.

This article is one of a pair of articles published in this volume about Robert C. Merton's contributions to the science of financial economics. The other article in this pair is "Robert C. Merton and the Science of Finance" by Zvi Bodie.

INTRODUCTION

It's a pleasure and an honor to be a participant at Bob Merton's 75th Birthday Celebration Conference, 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. I'll point out a few of those things over the course of the next half-hour or so.

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; 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. 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)?!

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 VERSUS SCIENCE

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, 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 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. Afterward, 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 that ultimately went bust. Newton muttered afterward 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.

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 degree from the School of Engineering and Applied Sciences at Columbia University—not the School of Social Sciences or the School of Science—in engineering math; a master's degree in applied math from Caltech; and then a PhD in economics from an engineering school. 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: (*a*) his teaching, (*b*) his research methodology, (*c*) his work on derivative pricing models, and finally (*d*) some of the practical applications Bob has been recently involved in.

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."

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 6 months of graduate school, I realized that economics was nowhere near what Asimov had envisioned.

So, at the end of fall 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 2 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 (**Figure 1*a***). 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 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 (**Figure 1*b***). 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 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 (**Figure 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 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 **Figure 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.

Figure 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; superefficient portfolio construction; and centralized services such as risk management, trading, and compliance.[1]

[1]The superefficient portfolio is the portfolio on the efficient frontier that is at the point of tangency to the capital market line.

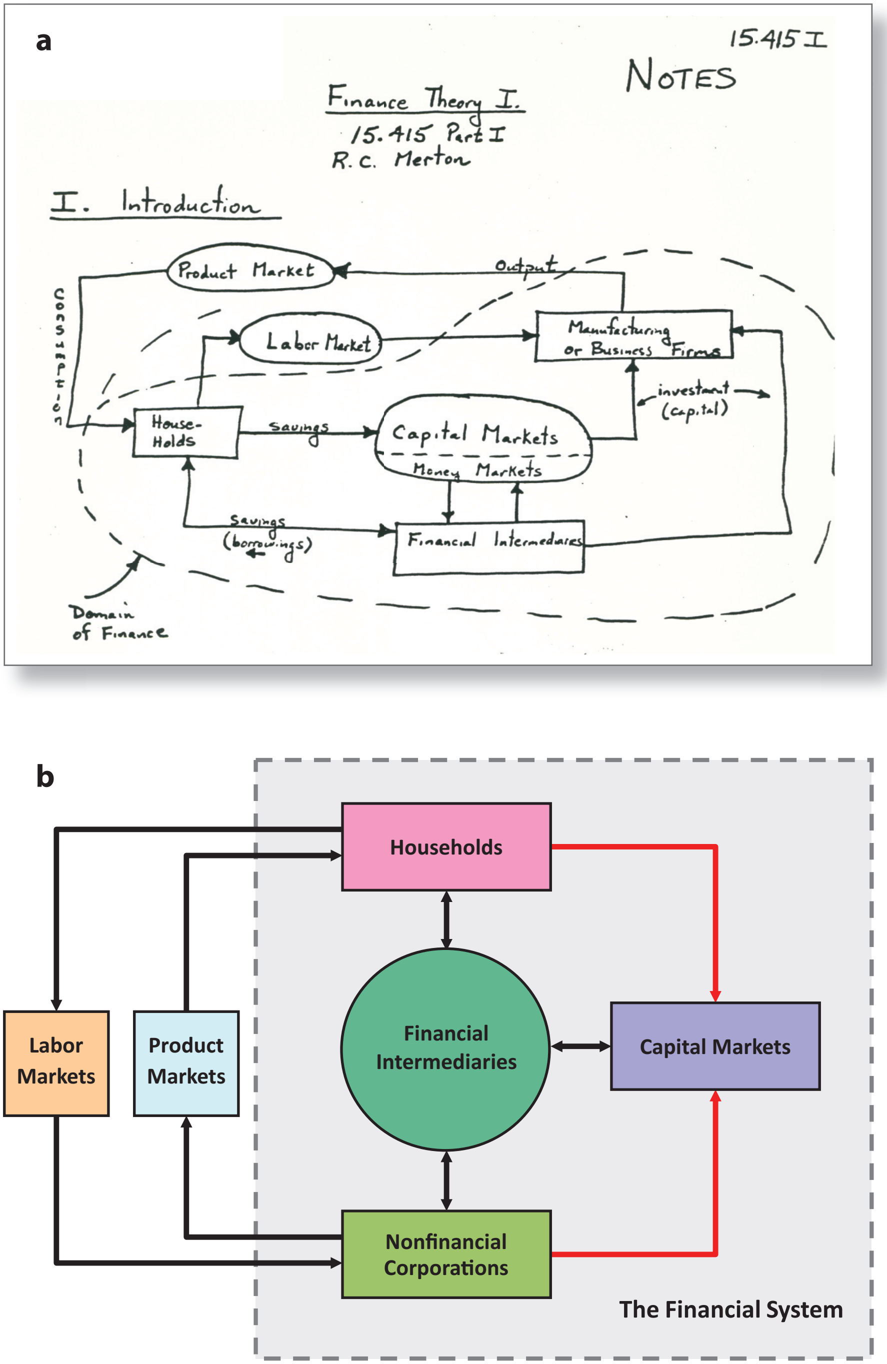


Figure 1

(*a*) Flow diagram of the financial system's role in the economy from MIT course 15.415, spring 1981. (*b*) Updated flow diagram of the financial system's role in the economy from course 15.401, fall 2018. Panel *a* adapted with permission from Robert C. Merton. Panel *b* adapted with permission from Andrew W. Lo.

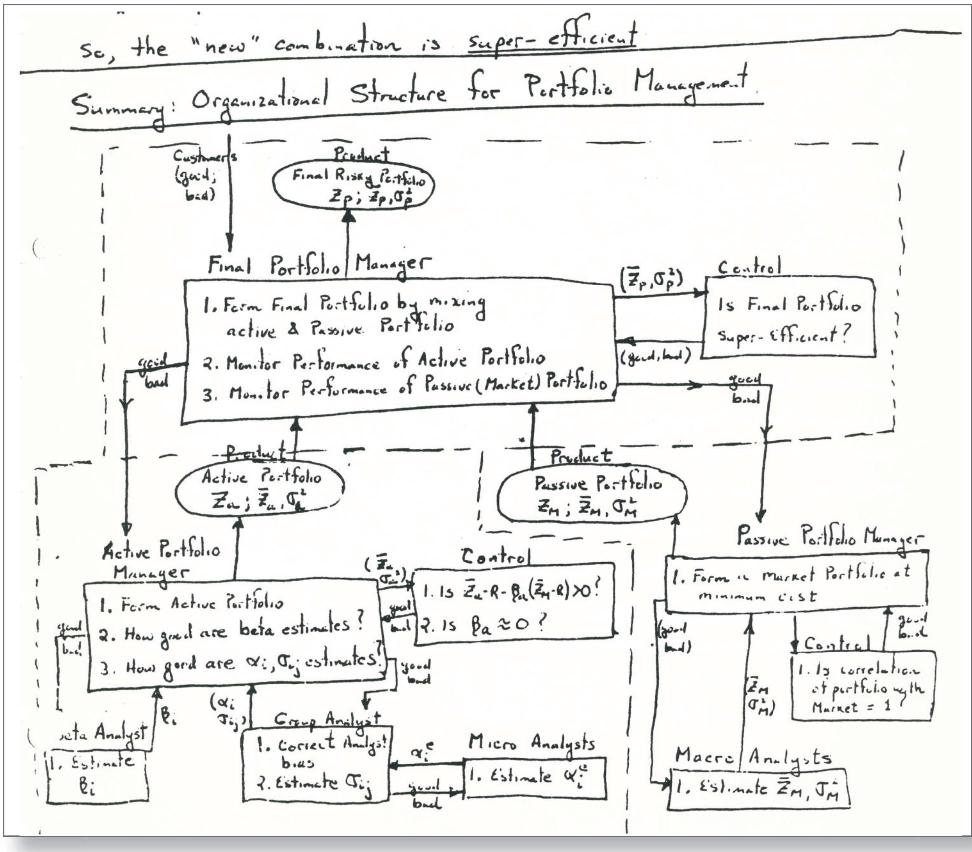


Figure 2

Flow diagram of a portfolio management enterprise from MIT course 15.433, fall 1982. Figure adapted with permission from Robert C. Merton.

Today, these are common buzzwords, but in 1982, when I took this course, many of these ideas were still academic musings. For example, the idea of superefficient portfolio construction was published just a few years earlier in an academic journal by Jack Treynor and Fischer Black (Treynor & Black 1973). They showed how to combine unique insights into 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.

I was completely blown away by the ideas in **Figure 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 part, 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 of 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. 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 first developed in the 1940s by Kiyosi Itô (1944, 1946, 1951) of the University of Kyoto, and disseminated more broadly in a 1965 textbook he coauthored with Henry P. McKean (Itô & McKean 1965), a Courant Institute mathematician who, early in his career, spent some time at MIT and collaborated with Paul Samuelson. Itô calculus, also known as stochastic calculus, is a generalization of the calculus of Newton and Leibniz 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 involve.

To understand the magnitude of this contribution, 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" (Merton 1971). 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. 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 (Merton 1969) on dynamic portfolio optimization (a companion piece to Paul Samuelson's discrete-time version of the same problem), wrote a technical appendix extending Samuelson's discrete-price model of asset prices to continuous time (Merton 1973), and also applied stochastic calculus to modeling economic growth (Merton 1975). But none of these contributions provided 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.

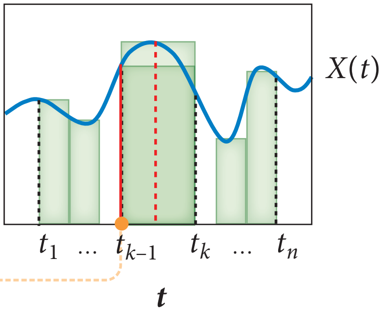
By "complete," I'm referring to the fact that he led readers by the hand with respect to this relatively new branch of mathematics. For example, the title of section 2 of the 1971 paper is "A Digression on Itô Processes," which was an excellent overview of stochastic calculus for the uninitiated.

This isn't to say that this section was easy reading—it took me 3 months to fully understand footnote 7. 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. 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.

Stochastic Calculus

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

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



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

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

Figure 3

Basics of stochastic integral calculus. Figure adapted with permission from Andrew W. Lo.

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 Leibniz in the mid-seventeenth 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 **Figure 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 the one in **Figure 3**?

Even if I give 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 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 **Figure 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 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. Let's take a look at that one rectangle in **Figure 3**,

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

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

Figure 4

Basics of stochastic differential calculus.

the one 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 (Merton 1971).

The other way of defining a stochastic integral is to use the midpoint, which is known as the Stratonovich integral, after the Russian mathematician Ruslan L. Stratonovich, who first proposed this definition in 1966 (see Stratonovich 1965, 1966; this definition was independently proposed in Fisk 1963). The main difference between the Itô and Stratonovich integrals can be seen more clearly when you compare their differential versions (**Figure 4**). Let me explain what this means.

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 **Figure 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.

You wouldn't know this unless you were familiar with ordinary calculus, but if you are, you'll see that the Itô formula looks different from the ordinary-calculus version and contains an extra term at the end, $(1/2)F_{xx}(dX)^2$. 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 **Figure 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.

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 (Merton 1971). 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 (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

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

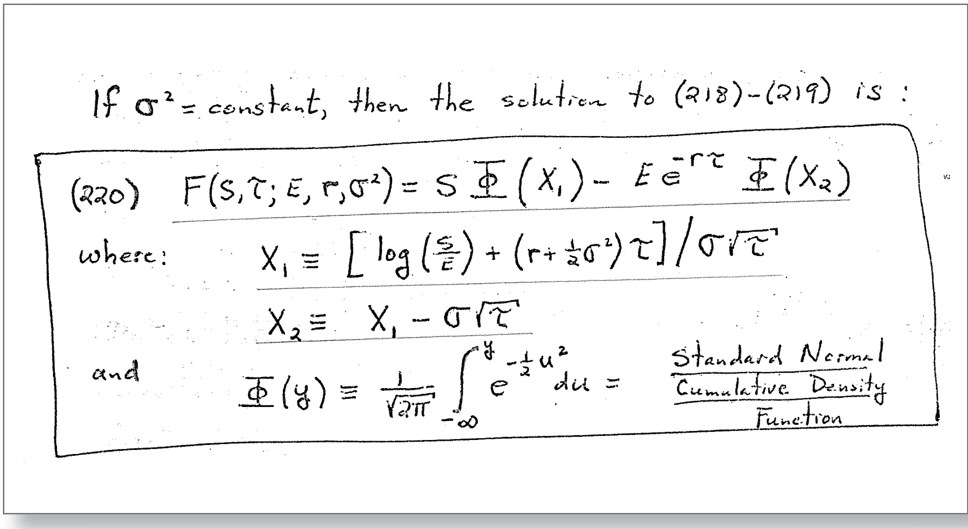
in which our wealth at time $t+h$ is simply equal to the number of shares of each security i at time t multiplied by the price at time $t+h$. This might seem like a trivial accounting relation, but it turns out that it's an absolutely critical link in the chain of logic that leads us to the inescapable 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 **Figure 3**, if we use the left endpoint, this means we're making decisions and choices for the future based upon 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 only becomes available 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's 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."

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.[2] 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 only appreciated the depth of this section of Bob's 1971 paper 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

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


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

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

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

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

Figure 5

Black–Scholes/Merton formula for pricing an option. Figure adapted with permission from Robert C. Merton.

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.

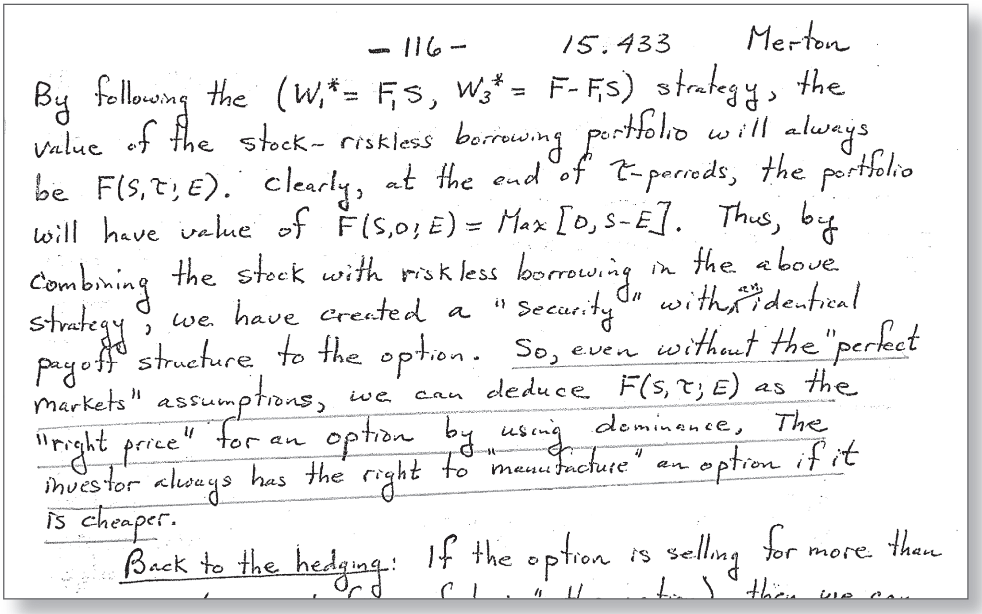
DERIVATIVE PRICING AS FINANCIAL ENGINEERING

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 at 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 (**Figure 5**).

Moreover, this beginning was a unique contribution of Bob's that is 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.

Let's revisit the famous Black & 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 have no systematic risk, and therefore it has to earn the risk-free rate. That, in


– 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 $F(S, 0; E) = Max[0, S - E]$. 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

Figure 6

The beginnings of financial engineering in Merton's MIT course 15.433 lecture notes. Figure adapted with permission from Robert C. Merton.

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 the first to derive the 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.[3] 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 (**Figure 6**) that I found stunning—I still remember the precise moment when

[3]Merton relates a fascinating story about the connection between the origin of Itô calculus and finance. At a 1994 conference held at MIT in honor of Norbert Wiener's 100th birthday, Merton met Itô and asked if he created his calculus based on Wiener's work. Itô responded no, the inspiration did not at all come from Wiener's work but instead from the French mathematician Louis Bachelier. This surprising connection is meaningful because of Bachelier's role in the history of option-pricing theory, which was rescued from obscurity by Paul Samuelson in the 1960s. It turns out that Bachelier's Sorbonne thesis—written under the direction of the mathematical giant Henri Poincaré and published in 1900—developed the first formal mathematical theory of continuous-time stochastic processes, now known as Brownian motion, for the sole purpose of pricing options on the Paris Bourse where he was employed prior to his graduate studies. Merton recalls that Samuelson had compared this thesis with Einstein's (1905) paper on Brownian motion, and concluded that Bachelier's version was mathematically at least as rigorous and general as Einstein's. The importance of this story, and Bachelier, to economists is clear: This is perhaps the only case in which a financial application has motivated the development of a theory before the physicists got to it (5 years before, to be precise).

I read those words as a graduate student, and being awestruck by their implications: "[W]e 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 and trillions of dollars in trading volume in the financial industry.

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. 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 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 7 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 of 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 2 or 3 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 (Dannen 1997). 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. 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.

Because patents are designed to deal with practical problems, they generally require some forms of engineering. By starting out as a patent clerk, Einstein was immersed in engineering at the very outset of his career.[4] 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. Bob acknowledged as much in 1994 with respect to financial theory and practice when, in writing about the role of mathematical models in finance, he observed (Merton 1994, p. 451): "The scientific breakthroughs in financial modelling both shaped and were shaped by the extraordinary flow of financial innovation which coincided with revolutionary changes in the structure of world financial markets and institutions during the past two decades."

Of course, because most practical problems are dynamic, not static, the solutions are considerably more complex than theory suggests. 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—for example, Space Shuttle explosions, nuclear meltdowns, plane crashes, train wrecks, chemical plant failures, and so on. The sociologist Charles Perrow (1984) refers to these problems as "normal accidents" because of their frequency. 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,[5] 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 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.[6]

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

[4]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.

[5]I thank Zvi Bodie for introducing me to Petroski's work.

[6]See the remarkable newsreel footage of Galloping Gertie at **https://www.youtube.com/watch?v=j-zczJXSxnw**.

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

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 Franklin Delano Roosevelt. Let me quote one passage from that letter (Einstein 1939):

> 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.

WEAPONS OF MASS DESTRUCTION: THE FINANCIAL KIND

Sometimes, engineering is called upon 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 be included on as a 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 (Khandani, Lo & Merton 2013). 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 (Merton et al. 2013). 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 further 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 macrofinancial 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.

You have already seen what Bob is working on together with Arun Muralidhar about SeLFIES (Standard-of-Living indexed, Forward-starting, Income-only Securities). This could be the most important 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 of 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.

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!

DISCLOSURE STATEMENT

The author is a faculty colleague of the subject at the MIT Sloan School of Management and the Laboratory for Financial Engineering, and both are co-founders of QLS Advisors, LLC.

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