Carnegie Mellon University and the Quantification of Finance

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By awarding Harry Markowitz, William Sharpe and Merton Miller the 1990 Nobel Prize in Economics, the Nobel Prize Committee brought to world-wide attention the fact that the last forty years have seen the emergence of a new scientific discipline, the "theory of finance." This theory attempts to understand how financial markets work, how to make them more efficient, and how they should be regulated. It explains and enhances the important role these markets play in reducing risk associated with economic activity. Without losing its application to practical aspects of trading and regulation, the theory of finance has become increasingly mathematical, to the point that problems in finance are now driving research in mathematics.

Harry Markowitz's 1952 Ph.D. thesis "Portfolio Selection" laid the groundwork for the mathematical theory of finance. Markowitz developed a notion of mean return and covariances for common stocks which allowed him to quantify the concept of "diversification" in a market. He showed how to compute the mean return and variance for a given portfolio and argued that investors should hold only those portfolios whose variance is minimal among all portfolios with a given mean return. Although the language of finance now involves Ito calculus, minimization of risk in a quantifiable manner underlies much of the modern theory.

In 1969 Robert Merton introduced stochastic calculus into the study of finance. Merton was motivated by the desire to understand how prices are set in financial markets, which is the classical economics question of "equilibrium," and in later papers he used the machinery of stochastic calculus to begin investigation of this issue.

At the same time as Merton's work and with Merton's assistance, Fischer Black and Myron Scholes were developing their celebrated option pricing formula. This work won the 1997 Nobel Prize in Economics. It provided a satisfying solution for an important practical problem, that of finding a fair price for a European call option, i.e., the right to buy one share of a given stock at a specified price and time. Such options are frequently purchased by investors as a risk-hedging device. In 1981, Harrison and Pliska used the general theory of continuous-time stochastic processes to put the Black-Scholes option pricing formula on a solid theoretical basis, and as a result, showed how to price numerous other "derivative" securities.

Many of the theoretical developments in finance have found immediate application in financial markets. To understand how they are applied, attention must be paid to the role of financial institutions. A principal function of the nation's financial institutions is to act as a risk-reducing intermediary among customers engaged in production. For example, the insurance industry pools premiums of many customers and must pay off only the few who actually incur losses. Risk, however, arises in situations for which pooled-premium insurance is unavailable. For instance, as a hedge against higher fuel costs, an airline might want to buy securities whose value will rise if oil prices rise. But who wants to sell such securities? The role of a financial institution is to design such a security, determine a "fair" price for it, and sell it to the airline. The security thus sold is usually "derivative," i.e., its value is based on the value of other, identified securities. "Fair" in this context means that the financial institution earns just enough from selling the security to enable it to trade in other securities whose relation with oil prices is such that, if oil prices do indeed rise, the firm can pay off its increased obligation to the airlines. An "efficient" market is one in which risk-hedging securities are widely available at "fair" prices.

The Black-Scholes option pricing formula provided, for the first time, a theoretical method of fairly pricing a risk-hedging security. If an investment bank offers a derivative security at a price which is higher than "fair," it may be underbid. If it offers the security at less than the "fair" price, it runs the risk of substantial loss. This makes the bank reluctant to offer many of the derivative securities which would contribute to market efficiency. In particular, the bank only wants to offer derivative securities whose "fair" price can be determined in advance. The mathematical theory growing out of the Black-Scholes option pricing formula has permitted the creation and pricing of a host of specialized derivative securities.

Going hand in hand with the mathematical theory of finance is the advent of computer trading, which has accelerated the pace and expanded the information base for decision-making, much of which is now being automated. In such an environment, the trader who bases decisions solely on "feel" for the market is at a decided disadvantage. Even during the retrenchments on Wall Street in the late 1980s, high technology trading operations and their supporting research groups grew. In the 1990s, these operations expanded at an increasing rate.

As these developments proceed, the issues of regulation and risk appraisal become more complex. Banks are trading in exotic derivative securities whose associated risk must be measured. Private corporations are discovering an increased need to do their own financial analysis. The Society of Actuaries reports that "The actuary of the future will be a financial architect and manager of enterprises built on the applications of financial analysis and risk appraisal." Major accounting firms are hiring persons who can build mathematical models to assess the positions of their clients. Despite the Enron fiasco, electric and natural gas utilities continue to build mathematical models to guide trading.

Disciplines Inextricably Linked

The disciplines of finance, mathematics, statistics and computer science are now inextricably linked. A corporation whose risk management policy compels it to lock in a foreign exchange rate must deal with a foreign currency futures trader. The trader bases his pricing and hedging decisions on the behavior of a Brownian motion, determined by statistical estimation of parameters and simulated under probabilities that differ from those of the real world, a simulation justified by the profound mathematical and financial dual ideas of change-of-measure and risk-neutral pricing.

The determination of prices and hedges down to one one-hundredth of a percent require sophisticated scientific computation, and the data collection for the computation and the execution of the trade takes place within a globally integrated information technology system. Similar activities occur whenever a mortgage is securitized, bonds are issued, an electric utility contracts for future fuel supply, a farmer agrees to deliver crops, and when countless other financial transactions are conducted.

Finance has been modeled, computerized and, in general, "quantified." The "quants" who practice this brand of finance are slowly but surely moving into positions of power in investment banking, insurance, asset management, commodities trading, and regulation.

Overcoming the Barriers

Universities wishing to retain preeminence in finance are called to draw the disciplines of mathematics, statistics and computing into the main stream of their finance research and education. At many universities, including Carnegie Mellon, these disciplines are housed not only in different departments, but in different colleges. The challenge is to overcome cultural and institutional barriers to bring them together.

Because of its small size, Carnegie Mellon cannot afford barriers. The university has developed a strategy of carefully choosing areas in which to excel. As these areas span more than one discipline, the university has found it necessary to provide an environment in which interdisciplinarity can flourish. Faculty who successfully reach outside their own departments to find collaborators are rewarded. Deans have seen from experience the value of building innovative programs at the points where their colleges interface. Moreover, entrepreneurship is rewarded because revenues generated by successful programs are reinvested in those programs.

In addition to providing a fertile environment for the development of quantitative finance, Carnegie Mellon has benefited since 1980 from having faculty in three departments, Mathematical Sciences, Statistics, and the Tepper School of Business whose research programs include a substantial finance component. In the past ten years each of these departments has made additional hires to build their quantitative finance faculties.

For example, the Department of Mathematical Sciences now has three faculty whose primary research interests are in quantitative finance, and two other faculty with secondary interests in the field. These are all regular (tenured or tenure-track) faculty. This has enabled the creation of a Ph.D. degree in Mathematical Finance, which has graduated seven students in the past six years and has twelve students currently in residence. These students take courses in and are advised by faculty in Statistics, the Business School and Mathematical Sciences. Mathematical Sciences faculty also assist with teaching and advising students in Statistics and the Tepper School.

Risk management has emerged as a focus of research at Carnegie Mellon. A team of eight faculty, four in Statistics and four in Mathematical Sciences, are seeking to develop sound tools for measuring and controlling financial risk.

Decision-making by individuals within a firm is being studied, both theoretically and experimentally. This work is informed by on-going discussions with risk managers at investment banks and through faculty membership on boards of directors of financial firms.

Faculty at the Tepper School have taken the lead in designing and conducting experiments to determine how traders might react to various forms of risk limits. These experiments use Carnegie Mellon's Financial Analysis and Security Trading (FAST) software as a platform for simulated trading by human subjects. The development of the FAST software, beginning in 1989, was the first initiative on the part of an educational institution to replicate the live international data feeds and sophisticated software of Wall Street's top trading firms. It is now licensed to over seventy-five universities worldwide, and it continues to support the educational mission of Carnegie Mellon.

The research collaboration among faculty from multiple departments led to the formation in 2000 of the Center for Computational Finance, directed by David Heath. The inaugural conference of this center brought 170 participants to campus in July of that year. Since that time, the Center has sponsored workshops on Risk Management, Market Incompleteness and Credit Risk. The Center has a regular seminar series with external and internal speakers, and faculty and graduates students from Mathematical Sciences, Statistics and the Tepper School participate. In addition, the Center has appointed a post-doctoral fellow and supports graduate students.