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Mathematizing Risk: Markets, Arbitrage and Crises

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Two moments in the financial history of high modernity:

Monday, August 17, 1998. The government of Russia declares a moratorium on interest payments on most of its ruble denominated bonds, announces that it will not intervene in the markets to protect the exchange rate of the ruble, and instructs Russian banks not to honour forward contracts on foreign exchange for a month. Elements of the decision are a surprise: countries in distress usually do not default on domestic bonds, since these can be honoured simply by printing more money. That Russia was in economic difficulties, however, was well known. Half of its government income was being devoted to interest payments, and investors – some fearing a default – had already pushed the yield on GKOs, short-term ruble bonds, to 70% by the beginning of August. Nor is the news on August 17 entirely bad: Russia manages to avoid a default on its hard currency bonds. And Russia, for all its size and nuclear arsenal, is not an important part of the global financial system. "I do not view Russia as a major issue," says Robert Strong of Chase Manhattan Bank. Wall Street is unperturbed. On August 17, the Dow rises almost 150 points.[1]

Tuesday, September 11, 2001. Two hijacked planes destroy the World Trade Center in Manhattan, and a third hits the Pentagon, the heart of American military power. Thousands – the exact number may never be known – die. It is a blow to the heart of the global financial system, both geographically and economically: the American economy, the world's largest, has already been sliding into recession. Within seconds of the news reaching Chicago, S & P index futures fall 3%, and, before further panic becomes evident, the markets close. Says a hedge fund manager: "This is your one-in-

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[1] See Dunbar (2000, pp. 200-201) and Lowenstein (2000, p. 144); the quotation from Strong is taken from the latter. An earlier version of this paper was presented to the Colloque International, Centre Alexandre Koyré, "Modèles et Modélisations, 1950-2000: Nouvelles pratiques, nouveaux enjeux."

a-billion scenario. ... You have to wonder about all the derivatives. Anyone who has leveraged positions may be destroyed."[2]

Now let us move forward a month from those two events. Thursday, September 17, 1998: the Russian default has amplified through the financial system. "It's like a blanket of fear has descended over the market," said one options trader (Lowenstein 2000, p. 168). The prices of risky assets have, in general, plummeted: for some assets, a market scarcely exists, because no-one will buy at other than distressed prices. At the core of the spreading crisis is one of the world's most sophisticated hedge funds, Long-Term Capital Management (LTCM). LTCM's large, complex portfolio, which had been constructed to be extremely safe, is losing value almost every day: half a billion dollars have been lost over the previous week. It is becoming clear that LTCM's bankruptcy is inevitable, with imponderable consequences. If it failed, as William J. McDonough, President of the Federal Reserve Bank of New York, later put it, "there was a likelihood that a number of credit and interest rate markets would experience extreme price moves and possibly cease to function for a period of one or more days and maybe longer" (McDonough 1998, p. 1052). Should that have happened, said Alan Greenspan, it "could have potentially impaired the economies of many nations, including our own" (Greenspan 1998, p. 1046).

Thursday, October 11, 2001: the war in Afghanistan has scarcely begun, and its outcome is still quite unclear. Economic indicators increasingly point to recession. Yet the main global equity markets, having plunged following the September 11 atrocities, have recovered to the level they were at prior to that dreadful morning: "Within the space of a month, equity markets seem to have gone from assuming that the effects of the terrorist attacks would be politically and economically catastrophic to assuming that, after allowing for the easing of monetary policy, the effect will be neutral or broadly

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[2] See, for example, Chaffin and Clow (2001), from whom the quotation is taken. A derivative is an asset (such as a swap, future or option: see below), the value of which depends on the price of another, "underlying," asset.

positive" (Coggan 2001). The bonds of "emerging market" countries have fallen, but by a surprisingly small average 2.5%. Joyce Chang, analyst at J.P. Morgan, comments that "the sell-off has been very orderly compared with other crises" (Ostrovsky and Wiggins 2001). The U.S. government bond market has been hit both financially and in human terms: the broker and market-maker Cantor Fitzgerald, with its offices high in the World Trade Center, has suffered dreadfully. But even a week after the atrocities, it is becoming clear that the crisis in the bond market is less severe than three years previously. "Traders stressed ... that the bond market was not undergoing the turmoil it endured in 1998 after the Long Term Capital Management hedge-fund crisis. ... 'The market is by no means locked up,'" said one (Wiggins and Boland 2001).

The chain of events set in motion on September 11 has not yet run its course. Here, I shall use its early phase simply as a counterpoint to the 1998 crisis. It may seem callous to discuss the financial consequences of an event whose human aspects were so dreadful, but I make no apologies for doing so. Economic crises, after all, have their own way of killing: undramatic, unnoticed, individual; through despair, dislocation, and disease. Their effects are at their worst, not in the heartland countries of the global financial system, but in its peripheries. Understanding the robustness of the financial system in the face of shocks of different kinds is not unimportant.

Because Long-Term Capital Management was at their heart, the events of August and September 1998 have also a significance of quite a different kind. The near-failure of LTCM (it was rescued from bankruptcy by a consortium of the world's leading banks coordinated by the Federal Reserve Bank of New York) has been taken as a verdict upon the modern theory of finance and on the mathematical models at its core. Amongst LTCM's partners were Robert C. Merton and Myron Scholes, winners of the 1997 Nobel Prize in Economics for their fundamental contributions to the theory of finance, and others in the firm were also well versed in the theory and had often been important contributors to it. Typical is the conclusion of the most influential work on LTCM:

> The professors ... sent their mathematical Frankenstein gamely into the world as if it could tame the element of chance in life itself. No self-doubt tempered them; no sense of perspective checked them as they wagered such staggering sums. (Lowenstein 2000, p. 235).

To those, like myself, on the more "humanistic," qualitative rather than quantitative, side of the social sciences, such a conclusion is seductive. But as I have investigated the episode and its intellectual and economic context, I have learned that Lowenstein's verdict, comforting as it is to those with my inclinations, is false. Indeed, ultimately it trivializes what took place. If LTCM really had been guilty of blind faith in mathematical models and of reckless risk-taking, its crisis would have been predictable and of little interest. But it was guilty of neither; and its fate is therefore the more interesting. We need a far more nuanced view of finance theory, of mathematical models of financial risk, of LTCM, and of the events of 1998. This paper, which represents work in progress rather than any definitive statement, attempts to sketch this more nuanced view.

The paper has four parts. The first describes the development of the modern theory of finance, focusing especially on the crucial role in that theory of arbitrage. Arbitrage is the exploitation of differences between the prices of the same or similar assets; it is the key mechanism that drives prices towards their theoretical values. This section of the paper will inevitably be somewhat "tough going" for readers without a background in finance. They can be reassured that all that is required to understand the later parts of this paper is the overall gist of this section (in particular the pivotal assumption that arbitrage will close price discrepancies), not its details. The second section explores the possibility that finance theory is performative: that it helps bring into being the world that its models describe, rather than simply describing an already-existing external world. The third section describes Long-Term Capital Management, its trading strategies, and the crisis of 1998. The fourth section suggests some general conclusions about the 1998 encounter with risk, the contrast with 2001, and about

financial models, imitation, and arbitrage.

Finance, Models and Arbitrage

In 1950, financial economics scarcely existed, and only the most elementary and most partial mathematical models of financial processes were available. Finance was taught, but in business schools, not economics departments, and economists would not generally have regarded professors of finance as contributors to economics. John Maynard Keynes, for example, told his colleagues at Kings College Cambridge in 1939 that "the management of stock exchange investments of any kind is a low pursuit ... from which it is a good thing for most members of our Society to be free" (quoted in Bernstein 1992, p. 48). There is an element of self-deprecating humour here – Keynes was actually a successful stock market investor – but economists seem in general to have shared for many years what Roberts (1959, p. 3) called "the traditional academic suspicion about the stock market as an object of scholarly research." At the start of the 1950s, the PhD thesis by Harry Markowitz, now seen as beginning modern finance theory (and eventually to win its author the Nobel Prize in economics), was seen by Milton Friedman as "not economics." He told Markowitz at the beginning of his PhD defence: "Harry, I don't see anything wrong with the math here, but I have a problem. This isn't a dissertation in economics, and we can't give you a PhD in economics for a dissertation that's not economics" (quoted in Bernstein 1992, p. 60).[3]

Even as the "respectability" of the financial markets as a topic for economists grew, Markowitz's work was not entirely universally embraced, for reasons I shall explore elsewhere. Closer to "heartland" neoclassical economics was a 1958 paper by Franco Modigliani and Merton Miller, who demonstrated that in a "perfect market" (Modigliani and Miller 1958, p. 268) the total value of a firm is not affected by its "capital structure," that is, by its degree of leverage, the extent to which it chooses to finance its activities by the issuance of debt rather than equity. What was of

[3] There is a nice history of the intellectual background to Markowitz's work in Pradier (2000).

significance was not just Modigliani and Miller's proposition, but the way they proved it: arbitrage proof. They showed that if two firms with different capital structures but identical expected future income streams were valued differently by the market, "arbitrage will take place and restore the stated equalities." In other words, "an investor could buy and sell stocks and bonds in such a way as to exchange one income stream for another stream, identical in all relevant respects but selling at a lower price. ... As investors exploit these arbitrage opportunities, the value of the overpriced shares will fall and that of the underpriced shares will rise, thereby tending to eliminate the discrepancy between the market values of the firms" (Modigliani and Miller 1958, p. 269).

Arbitrage proof was also at the core of the argument that won Myron Scholes and Robert C. Merton their Nobel Prizes (their colleague Fischer Black died prematurely in 1995). The problem solved by Black, Scholes, and Merton was the pricing of options.[4] Again assuming a perfect market (for example, the capacity both to borrow and to lend indefinite amounts at the risk-free rate of interest), they showed that an option on an asset could be replicated completely by a continuously-adjusted portfolio of the asset and cash, so long as the returns on the asset followed the by-then-standard model of a log-normal[5] random walk in continuous time.[6] If the price of the asset diverges from the cost of the replicating portfolio, arbitrageurs will buy the

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[4] An option is a contract that confers the right, but not the obligation, to buy ("call") or sell ("put") a given asset at a given price, at (or up to) a given future date.

[5] Stock prices themselves cannot be normally distributed, since that would imply a non-zero probability of negative prices, and limited liability means that stock prices cannot be negative. Log-normality of price changes was a more attractive assumption because it avoided this problem (a variable is log-normal if its natural logarithm follows a normal distribution).

[6] I am here oversimplifying a complex historical development, to which I will return elsewhere.

cheaper and short sell[7] the dearer of the two, and in so doing their purchases would raise the lower price and their sales reduce the higher one, restoring equality. More generally, Black's, Scholes's, and Merton's analyses suggested a methodology for the rational pricing and hedging of derivative products of all kinds: identify the replicating portfolio of more basic assets (if it exists), and use its cost to price the derivative, and (if desired) to hedge its risks.

Commentary on LTCM has often drawn a connection between the events of August and September 1998 and the assumption of log-normality in Black-Scholes-Merton option pricing: some of the price movements of those months were indeed wildly improbable on the hypothesis of log-normality (see MacKenzie, forthcoming). To focus upon log-normality, however, is to focus on a less-than-central aspect of Black, Scholes, and Merton's contribution to finance theory (that stock price changes were not in practice log-normal was known even in 1973, when their work was published). As Bouleau (1998, p. 63) puts it, the "epistemological rupture" is the idea of the replicating portfolio and consequent possibility of pricing by arbitrage. Merton himself, and other finance theorists such as Steve Ross, John Cox, Mark Rubinstein, and William Sharpe, soon showed how to extend the basic framework of Black-Scholes-Merton derivative pricing to worlds in which the dynamics of asset pricing was not log-normal.

The work of Black and Scholes on option pricing was first circulated in October 1970;[8] by 1979, J. Michael Harrison and David M. Kreps had established the form of derivative pricing theory that is most attractive to mathematicians (Harrison and Kreps 1979; Harrison and Pliska 1981). Crucial was the link they drew to the theory of

[7] To "short sell" or "short" an asset is to borrow it, sell it, and later repurchase and return it.

[8] This version is in box 28 of the Fischer Black papers at MIT (Institute Archives, MC505).

martingales. (A martingale is a stochastic process for which the expected future value of a variable, conditional upon its current value, is its current value. Loosely, a martingale is a "fair game": in a game of chance which is a martingale, a player's expectation of gain or loss is zero.) Others had previously realised that financial markets could be modeled as martingales, but it was Harrison, Kreps (and Stanley R. Pliska) who brought to bear the full power of modern martingale theory, especially the ultra-abstract theory of martingales and stochastic integration developed by Paul-André Meyer and his Strasbourg school. Martingale theory freed option pricing from dependence upon any *particular* stochastic process: it could encompass the log-normal random walk posited by Black, Scholes, and Merton; the Poisson, "jump," process investigated by Cox, Ross, and Merton; and the finite-time models of Sharpe, Cox, Ross, and Rubinstein. In a "frictionless" market with no opportunities for arbitrage, Harrison and Kreps showed that there existed an "equivalent martingale measure," a way of assigning probabilities to the path followed by the price of an asset such that the value of a derivative contract on that asset was simply the conditional expectation of its payoff discounted back to the present. If the market was complete – in other words, if every contingent claim[9] could be replicated – then the equivalent martingale measure was unique. Harrison and Krep's conclusions gave general form to perhaps the most surprising of the findings of the earlier work: that arbitrage pricing meant that all sorts of complications, notably the degree of risk aversion of investors, could be abstracted away. Derivatives could be priced as if investors were risk-neutral, in other words as if they demanded no premium for holding risky assets.

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[9] A contingent claim (such as an option) is a contract the value of which depends on some future state of the world (for example, the value of an option at its expiry depends on the price of the underlying asset).

These developments in 1970-79 in derivative pricing theory were connected to major economic changes. In 1970, there was a tiny market in options; effectively no market in financial futures; and swaps[10] had yet to be invented. By June 2000, the total notional amount of derivative contracts outstanding worldwide was $108 trillion, the equivalent of nearly $18,000 for every human being on earth.[11] (Large though it was, LTCM's portfolio represented less than 2% of the global derivatives market.) The theory of contingent-claim pricing developed by Black, Scholes, and Merton, and added to by Cox, Ross, Rubinstein, Harrison, Kreps, and others, formed an essential part of this huge high-modern industry, guiding participants both in the pricing of derivative products and in hedging the risks involved. The theory, and its accompanying mathematical models, are built deep into the economic structure of high modernity, no less so after the crisis of 1998 than before.

Arbitrage – or to be more precise, the assumption that pricing discrepancies will be closed by arbitrage – plays a central role in the theory of contingent claim pricing. Arbitrage is also highly significant in the justification of the overall notion of "market efficiency," which has shaped not just financial economics, but also, via the plausibility it lends to notions of rational expectations, economics as a whole. Loosely, a market is

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[10] A swap is a contract to exchange two income streams, for example fixed-rate interest and floating-rate interest on the same notional principal sum.

[11] Data from the Bank for International Settlements http://www.bis.org/publ/otc_hy0011.pdf This figure arguably overstates the economic significance of derivatives, for example by valuing swaps by total notional principal sums. Because the principal does not actually change hands, and because swap positions are normally closed out by entering into exactly offsetting swaps, adding total notional amounts is, under most circumstances, misleading. Nevertheless, derivatives trading remains a major activity if $108 trillion is deflated by a factor of ten or even 100.

efficient if prices in it reflect all publicly-known information. What might make markets efficient? For some of the central figures in modern financial economics, to assume that all investors are perfectly rational and perfectly well-informed has been just too heroic. It is, for example, difficult on that assumption to explain the high volumes of trading in the financial markets. If all traders are perfectly rational and perfectly well-informed, why should they continue to trade once they have diversified their portfolios satisfactorily? "Noise trading," said Fischer Black (1986, p. 531) "provides the essential missing ingredient. Noise trading is trading on noise as if it were information. People who trade on noise are willing to trade even though from an objective point of view they would be better off not trading. Perhaps they think the noise they are trading on is information. Or perhaps they just like to trade."

If the empirical presence of noise trading and other departures from rationality is hard to deny, and if its denial leads to incorrect predictions (markets with far less trading than in reality), does this then mean that the thesis of market efficiency must be rejected, and some version of "behavioural finance"[12] adopted? Not so, argues Steve Ross (2001, p. 4):

> I, for one, never thought that people – myself included – were all that rational in their behavior. To the contrary, I am always amazed at what people do. But, that was never the point of financial theory.

The absence of arbitrage requires that there be enough well financed and smart investors to close arbitrage opportunities when they appear. ... Neoclassical finance is a theory of

[12] In "behavioural finance," market participants are assumed to be less than entirely rational, for example to be subject to various systematic biases, normally psychological in their nature.

sharks and not a theory of rational homo economicus, and that is the principal distinction between finance and traditional economics. In most economic models aggregate demand depends on average demand and for that reason, traditional economic theories require the average individual to be rational. In liquid securities markets, though, profit opportunities bring about infinite discrepancies between demand and supply. Well financed arbitrageurs spot these opportunities, pile on, and by their actions they close aberrant price differentials. ... Rational finance has stripped the assumptions [about the behaviour of investors] down to only those required to support efficient markets and the absence of arbitrage, and has worked very hard to rid the field of its sensitivity to the psychological vagaries of investors.

Performing Theory

Modern finance theory, in particular the theory of contingent claim pricing, is elegant and powerful. What is the relationship of that theory and its accompanying models to "reality"? They are, of course, an abstraction from it, and, *pace* the conventional interpretation, quoted above, of LTCM's near-failure, are *known to be such by all involved*. At this point, this paper begins to draw upon a set of sixty interviews conducted by the author with finance theorists and market participants, in LTCM and elsewhere, between October 1999 and October 2001. This paper will present only summary conclusions from these interviews, but more detail will be found in MacKenzie and Millo (2001) and MacKenzie (forthcoming).

No-one I have spoken to believed in the literal truth of finance theory's assumptions. Does that lack of verisimilitude mean that, as much of the commentary on LTCM suggests, the theory is a hopelessly flawed endeavour? Two points suggest not. The first was spelled out by Milton Friedman in his famous essay, "The Methodology of

Positive Economics" (Friedman 1953). The test of an economic theory, Friedman argued, was not the accuracy of its assumptions but the accuracy of its predictions. That viewpoint has become fundamental not just to modern neoclassical economics but also to finance theory: indeed, one of the distinguishing features of the modern theory of finance is that it abandoned the earlier attitude that the job of the scholar in finance was accurately to describe what people in the finance industry actually did. When Black-Scholes-Merton option pricing theory, for example, was first propounded in the early 1970s, its assumptions were wildly unrealistic. Not only was it already known by then that empirical stock price distributions had "fat tails" (in other words, that the probabilities of extreme events were considerably greater than implied by the log-normal model), but transaction costs were high (not zero as assumed in the model), there were significant restrictions on short-selling stocks, etc. By the late 1970s and early 1980s, however, the differences between empirical option prices and best-fit Black-Scholes theoretical prices was remarkably good, with residual discrepancies typically less than 2% (Rubenstein 1985). "When judged by its ability to explain the empirical data," commented Steve Ross (1987, p. 332), Black-Scholes-Merton option pricing theory and its variants formed "the most successful theory not only in finance, but in all of economics." (Interestingly, the fit between empirical data and the Black-Scholes-Merton model deteriorated after 1987, but that is a matter, which, for reasons of space, I must set aside here: see Rubinstein 1994 and MacKenzie and Millo 2001.)

The second point is that the empirical accuracy of finance theory's typical assumptions has increased considerably since the 1970s. This is perhaps most apparent in regard to the speed of transactions (the Black-Scholes-Merton model assumes the possibility of instantaneous adjustment of the replicating portfolio) and transaction costs. Because of technological change and institutional reform (in particular, the

abolition of fixed commissions on the New York Stock Exchange and other leading exchanges), for major players in the main equities markets transaction costs are now close to zero,[13] and significant adjustments to portfolios can now be made, if not instantaneously, at least in seconds. Finance theory models are still idealizations of market realities, but less radical idealizations than they were in 1970.

Has the crucial assumption that price discrepancies will be closed by arbitrage, like the other assumptions of finance theory, also become more true with the passage of time? The prevalence of arbitrage opportunities is a more difficult point to investigate than, for example, the decline in transaction costs. There is a strong motivation to exploit such opportunities, rather than reveal them in the academic literature, so they may be underreported. Conversely, however, what may *appear* to be an arbitrage opportunity may actually disappear as soon as one seeks to exploit it. The typical mechanism by which this happens is what market participants call "slippage": the movement of prices against one as soon as one starts to trade in significant quantities. Because of slippage and other practicalities, one cannot simply investigate statistically: in a sense, to determine the presence of arbitrage opportunities one must become an arbitrageur. As Ross puts it: "To find the [arbitrage] opportunities one must put oneself in the shoes of the arbitrageurs which is difficult and expensive" (2001, p. 4).

The testimony of actual arbitrageurs (in interview) is not entirely unequivocal, but all tend to agree that arbitrage opportunities which are relatively easy to identify tend to diminish. The action of arbitrageurs may not close them completely – there may be predator-prey dynamics (see below), so that as arbitrage opportunities diminish so

[13] Amongst the reasons is that brokers will offer to transact large trades effectively free of commission because of the informational advantages such transactions offer them. Note, however, that slippage (see text) is still a significant issue, and it can also be seen as a transaction cost.

too does the commitment of arbitrage capital to exploiting them – and the expansion of the global financial system into new geographical territories and new products creates new opportunities to replace diminished ones. But, overall, it seems reasonable to conclude that in the core financial markets of the Euro-American world the assumption that price discrepancies will be closed by arbitrage has a tendency to become more realistic.

Note that some of the increasing realism of the assumptions of finance theory is due to the very development and acceptance of the theory. As Callon (1998) has pointed out, economic theory has a performative dimension. It does not simply describe an already-existing external world, but can help that world come into being. (The classic study of neoclassical economics creating a market in its own image is Garcia 1986.) Take, for example, option pricing theory. The close empirical fit between observed option prices and their Black-Scholes values resulted at least in part from the use of option pricing theory to detect and exploit arbitrage opportunities.[14] The growing prestige of Black-Scholes-Merton theory also directly affected the validity of one of its key assumptions, as my student Yuval Millo (forthcoming) has discovered. When the theory was initially formulated, its assumption that stocks could be bought entirely on credit was empirically false: in the United States, stock purchases on credit were

[14] The classic arbitrage was "spreading": using option pricing theory to identify relatively "over-priced" and relatively "under-priced" options on the same underlying asset, selling over-priced options and hedging their risk by buying under-priced ones. The effect of the strategy was to push prices in the direction of satisfying the key econometric test of the validity of the Black-Scholes-Merton model: that the "implied volatilities" of all the options with the same expiry on the same underlying asset should be identical. This is discussed in more detail in MacKenzie and Millo (2001), which also examines why option prices since 1987 differ from prices prior to 1987 in this respect.

governed by the Federal Reserve's Regulation T, which strictly limited the availability of credit for share purchases. The Black-Scholes-Merton model, however, was used to delineate "*bona fide* hedges" which were exempted from Regulation T and therefore could be implemented using stocks purchased entirely on credit!

If finance theory already had its performative aspects by 1980, by the 1990s it was, as noted above, built into the very fabric of the high-modern financial world. Thus Walter (1996, p. 904) describes the role of Itô's lemma, the key bridging result between "ordinary" calculus and the stochastic calculus of finance. Without the lemma, "no trading room could now manage its options market positions."[15] The key players in the markets of high-modern finance perform, not just general notions of market efficiency, but highly sophisticated mathematical formulations. Strasbourg martingale theory, for example, is no longer simply "pure mathematics," but is performed in flesh, blood, and silicon on the markets. Finance theory is a world-making, and not just a world-describing, endeavour.

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[15] My translation. In fact, there may be rather greater dependence on discrete-time models such as Cox-Ross-Rubinstein than on continuous-time models to which Itô's lemma applies, but Walter's generic point is undoubtedly correct.

Long-Term Capital Management[16]

LCTM was an investment partnership set up in 1993 by John Meriwether, previously head of Salomon Brothers' bond arbitrage desk and a senior manager in the bank. Meriwether recruited to LTCM from Salomon and elsewhere an impressive team of experienced traders and specialists in mathematical finance. Much of LTCM's trading was with leading banks, and it largely avoided risky "emerging markets," preferring well-established ones such as those in government bonds of the leading industrial nations (though active in the U.S. and Japan, as Salomon had been, LTCM was more heavily involved than Salomon had been in European bond markets), in swaps, in options, in mortgage derivatives, and in certain very restricted categories of stock.[17] Following the tradition established by Meriwether at Salomon, the fund eschewed speculation based upon intuitive hunches. It invested in a way designed to be insulated from overall stock market movements, interest rate changes, and so on, seeking pricing anomalies around which to base arbitrage strategies.

LTCM's market positions were varied, but a common theme underlay many of them. Using extensive statistical databases and theoretical reasoning, the firm would identify pairs of assets the prices of which ought to be closely related, which should

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[16] This section draws on an earlier treatment of LTCM (MacKenzie 2000), but that treatment is in some respects in error. MacKenzie (forthcoming; shortly to be made available at http://www.ed.ac.uk/Research/Staff/mcknz.htm) discusses the LTCM case fully – it contains, for example, quantitative tests of the explanation of 1998 that is sketched here – and it should be consulted for details, discussion of sources, etc. In the interests of brevity and accessibility, I describe here only the outline of the episode.

[17] See, for example, the list of LTCM's major positions on August 21, 1998 given in Perold (1999, pp. C6-7).

over the long run converge (and in some cases *had* to do so), but which for contingent reasons had diverged: perhaps one was temporarily somewhat easier to trade than the other, and therefore more popular, or perhaps institutions had a particular need for one rather than the other. The fund would then buy the underpriced, less popular asset, and borrow and sell the overpriced, more popular asset (or take positions equivalent to these by use of derivatives, especially swaps). The close relation between the two assets would mean that general market changes such as a rise or fall in interest rates or in the stock market would affect the prices of each nearly equally, and long-run convergence between their prices would create a small but very low-risk profit for LTCM. By "levering" its own capital – in other words, performing arbitrage using borrowed funds and/or securities – LTCM could turn this small profit into a larger one; this also increased risk, but only to modest levels. The partnership knew perfectly well that over the short and medium term prices might diverge further, but the probabilities and the consequences of them doing so were carefully calculated by a statistical "value-at-risk" model, which measures the potential losses from adverse market movements (by the late 1990s such models were used by all the sophisticated institutional participants in the financial markets).

Pace standard accounts of LTCM, however, the firm did not simply assume that past price patterns would continue into the future, nor did it display an uncritical attitude to its risk model. Observed volatilities and correlations were increased by explicitly judgement-based "safety factors" to take account of possible changes in markets and of possible deficiencies in the model. A consequence of this conservatism was that LTCM's risk model predicted risk levels that were substantially higher than those actually experienced (until the 1998 crisis). The model predicted an annual volatility of net asset value of 14.5%; the actual volatility was 11%; both figures were considerably

less than the 20% investors in LTCM had been warned to expect. LCTM also "stress-tested" its trading positions to gauge the effect on them of extreme events not captured by standard statistical models or recent historical experience, events such as the failure of European economic and monetary union or stock exchanges crashing by a third in a day. LTCM balanced its portfolio to minimize the consequences of such events, and sometimes purchased explicit insurance against their consequences. With a considerable presence in the Italian capital markets, for example, LTCM decided it was prudent to buy insurance against bond default by the government of Italy.

Default by Russia was much more probable than default by Italy, but LTCM had only a minor exposure to Russia. The precise form of Russia's actions on August 17, 1998, however, caused significant losses to western banks. A hedge fund called High Risk Opportunities failed, and (quite unfounded) rumours began that Lehman Brothers, an established investment bank, was also about to do to. Suddenly, market unease turned into self-feeding fear. A "flight-to-quality" took place, as a host of institutions sought to liquidate investments that were seen as difficult to sell, and potentially higher risk, replacing them with lower risk, more liquid, alternatives. Because LTCM's arbitrage generally involved holding the former, and short selling the latter, the result was a substantial market movement against the fund.

A similar flight to quality was triggered by the atrocities of September 11, 2001. The key difference between the events of 1998 and 2001 is that the 1998 flight to quality was amplified, overlain, and in some instances[18] contradicted by a much more

[18] In a minority of instances, LTCM (and, most likely, its imitators) held the *more* liquid asset and was short the illiquid one. In Germany and France, for example, LTCM held (highly liquid) government bonds, hedged by paying fixed interest in (less liquid) interest-rate swaps. This kind of case is crucial in allowing the effects of a flight to quality to be distinguished analytically from those of the more

specific process. LTCM's very success had encouraged imitation: other hedge funds, and many of the world's leading banks, notably Wall Street investment banks, had either taken up similar arbitrage trading, or devoted more capital to it. In aggregate, this body of arbitrageurs held broadly similar positions to those of LTCM, but some of them had greater exposure to Russia than LTCM had. To cover losses incurred there, they had to liquidate other positions, similar to LTCM's. As the prices of these moved against the arbitrageurs, they found themselves having to liquidate further positions, thus further worsening price pressures, and so on. The arbitrage "superportfolio" (the aggregate of arbitrage positions similar to LTCM's) began to unravel.

Paradoxically, the process seems to have been intensified by risk management practices in banks. Banks employed value-at-risk models not just as LTCM did (to gauge the overall risks faced by the fund), but also as a management tool (see, e.g., Dunbar 2000). By allocating value-at-risk limits to individual traders and trading desks, banks can prevent the accumulation of over-risky positions while giving traders flexibility within those limits. In 1996, the significance of value-at-risk models was increased when the Basle Committee on Banking Supervision permitted banks to use these models to help determine capital adequacy ratios. This reduced the amount of capital that banks had to set aside, but had the consequence that as volatility increased and prices moved against a bank, it faced a choice between setting aside more capital

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specific process discussed in the test. Swap spreads (the difference between the fixed interest rate at which swaps can be entered into and the yield of government bonds of equivalent maturity denominated in the same currency) should rise in a flight to quality. They did indeed do so sharply in the U.S., U.K., and Sweden in 1998, but much less so in Japan (where LTCM had no net position), while in France and Germany they fell during much of the crisis. For further details, see MacKenzie (forthcoming).

and liquidating its positions. In August 1998, many seem to have chosen the latter option. Value-at-risk became a stop-loss rule: the traders involved had no alternative but to try to cut their losses and sell, even if it was an extremely unfavourable time to do so. In August 1998, widespread efforts, driven by risk models, to liquidate broadly similar positions in roughly the same set of markets intensified the adverse market movements that were the initial problem. Crucially, these various processes unravelling the arbitrage superportfolio led to greatly enhanced correlations between what historically had been only loosely related markets, across which risk had seemed to be reduced by diversification.

When used as management and capital adequacy tools, value-at-risk models (intended to describe the market as if it were an external thing) thus became part of a process that magnified adverse market movements, which reached levels far beyond those anticipated by these models. LTCM's loss in August 1998 was a -10.5σ event on the firm's risk model, and a -14σ event in terms of the actual previous price movements: both have probabilities that are vanishingly small. Value-at-risk models with stop-loss rules, other forms of stop-loss, management nervousness, fears by hedge fund managers of investor withdrawals, the need to liquidate positions to cover losses and meet margin calls combined to cause a failure of arbitrage. As "spreads" (the difference between prices of related assets) widened, and thus arbitrage opportunities grew more attractive, arbitrageurs did not move into the market, narrowing spreads and restoring "normality." Instead, potential arbitrageurs continued to flee, widening spreads and intensifying the problems of those who remained, such as LTCM.

LTCM, however, was constructed so robustly that these problems, though they caused major losses, were not fatal. In September 1998, though, LTCM's difficulties became public. For example, on September 2, Meriwether sent a private fax to LTCM's

investors, giving the fund's August results, and seeking to raise further capital to exploit what (quite reasonably) he described as attractive arbitrage opportunities.[19] The fax was posted almost immediately on the Internet and seems to have been read as evidence of desperation. The nervousness of the markets crystallized as fear of LTCM's failure. Almost no-one could be persuaded to buy, at any reasonable price, an asset that LTCM was known or believed to hold, because of the concern that the markets were about to be saturated by a fire sale of the fund's positions. In addition, LTCM's counterparties – the banks and other institutions that had taken the other side of its trades – protected themselves as much as possible against LTCM's failure by a mechanism that seems to have sealed the fund's fate. LTCM had constructed its trades so that solid collateral, typically government bonds, moved backwards and forwards between it and its counterparties as market prices moved in favor of one or the other. Under normal circumstances, when market prices were unequivocal, it was an eminently sensible way of controlling risk. But in the fear-chilled, illiquid markets of September 1998, prices lost their character as external facts. LTCM's counterparties marked against LTCM: that is, they chose prices that were prices that were predicated on LTCM's failure.[20] That minimized the consequences for their balance-sheets of LTCM's failure by getting hold of as much of the firm's collateral as possible, but made that failure inevitable by draining the firm of its remaining capital.

[19] The fax is reproduced in Perold (1999, pp. D1-D3).

[20] LTCM could have appealed unfavourable marks, but the market makers from whom quotations would have been obtained to arbitrate such a dispute would also have priced in an LTCM bankruptcy, so appeal would have been to no avail.

Conclusions

The crisis of 1998 was not the result of reckless risk-taking on LTCM's part, nor of blind faith in models. The background to the crisis was a "flight to quality" involving sharp rises in the relative prices of safe and liquid instruments, and sharp declines in those that were perceived as risky and illiquid. But the flight to quality was only part of the process that generated the crisis. A similar flight took place in September 2001, but its effects were different and more limited. By then, the capital devoted to the kind of convergence and relative value arbitrage pursued by LTCM was tiny by comparison with three years previously (perhaps a tenth as large). There was no massive superportfolio of overlapping arbitrage positions, and no internal mechanism amplifying the crisis.[21] No major hedge fund failed; no investment bank – not even Morgan Stanley, a major occupant of the World Trade Center – was threatened. The overall returns for September 2001 of JWM Partners, the successor fund set up by John Meriwether and several of his former colleagues at LTCM, were

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[21] There was a bottleneck in the U.S. repo market caused by disruption to the Bank of New York, the main Treasury bond settlement agent, whose headquarters were close to the World Trade Center. (Repo is a contract in which party A borrows money from party B to buy securities such as bonds from B. B holds the securities as collateral for the loan, and undertakes to buy back the securities at a given price on a given future date.) On October 4, 2001, the Treasury Department decided on an *ad hoc* auction of $6 billion of ten-year bonds to alleviate the bottleneck (Ip and Zuckerman, 2001). On September 11 – in response to earlier stock market falls, not the terrorist attacks – the U.K. Financial Services Agency had also suspended another potential source of amplification, the "resilience test" imposed on U.K. insurance companies. The test requires insurers to be able to meet their obligations following a 25% drop in share prices and an increase of 3 percentage points in interest rates. The Agency's fear was that the test would force insurers to sell into an already falling market, so exacerbating its fall (Bolger 2001).

"basically flat." August and September 1998 devastated the world of the arbitrageurs; September 2001 was but a relatively minor disturbance of it.

LTCM's success, and imitation of that success by others, had created by the summer of 1998 a "global microstructure" (in the sense of Knorr Cetina and Bruegger, forthcoming). A superportfolio had been created, in part deliberately (because of conscious imitation of LTCM), in part inadvertently (independent discovery of, and efforts to exploit, the same pricing anomalies). Once the holders of part of this superportfolio had to unwind their positions, they caused price movements that impacted negatively on the other holders of the portfolio. LTCM was structured precisely so as to avoid having to liquidate positions in the face of such pressures, and indeed it did not do so on any large scale (although the sheer size of its positions would in any case have made it extremely difficult to liquidate them quickly). But the large losses LTCM suffered in August 1998 set in motion, in September, what was in effect a run on the bank. The prophecy of LTCM's failure became self-fulfilling (Merton 1949), or, at least, would have done so had the Federal Reserve not intervened.

Debate over the adequacy of mathematical models of financial risk, or about the efficient market hypothesis and wider theoretical framework of modern financial economics, has a curiously static, ahistorical character.[22] Financial economics, and the models it proposes, affect the reality that it and

[22] See, e.g., the most important recent contribution to this debate (Shleifer 2000). On many particular topics, including the limits of arbitrage (see below), it is insightful. But the book's central question, the validity of the efficient market hypothesis, is largely construed as if that question had an ahistorically correct answer, at least for the last thirty years. Almost certainly, it does not.

they describe. Most of the time, I would conjecture, the effects of this reflexive connection serve to increase the veracity of finance theory's assumptions and the accuracy of its models' predictions. For example, as noted above, the availability of the Black-Scholes-Merton model of option prices, predicated as it was on the assumption that arbitrage would close pricing discrepancies, assisted arbitrageurs in identifying, exploiting, and thus reducing those discrepancies. The adoption of the model, in other words, helped make it more true. The events of 1998, in contrast, suggest a reflexive loop that was anti-performative rather than performative. The exploitation of arbitrage opportunities, using mathematical models (albeit ad hoc models, often quite simple and typically involving estimated parameters) grew to such a level that it became unstable. As spreads began to widen, instead of arbitrageurs entering the market to reduce them, they found themselves forced to flee the market, thus widening spreads. The assumption that arbitrage would close pricing discrepancies was, paradoxically, undermined by the very popularity that arbitrage had come to enjoy.

Part of the process that undermined arbitrage in 1998 was identified and modelled in a prescient article by Andrei Shleifer and Robert Vishny (1997: see also Shleifer 2000). While, in economic theory, arbitrage may be riskless, real-world arbitrage involves risk and cannot be conducted entirely using borrowed capital. If those who invest in arbitrageurs (hedge fund investors, senior management in investment banks, etc.) are influenced by the performance of these investments, then a price movement against arbitrageurs can become self-

reinforcing, as the latter are forced by investor withdrawals to abandon even excellent arbitrage opportunities. Another, more explicitly sociological part of the process leading to the crisis of 1998 was, as I have suggested, imitation. Imitation – "herd behaviour" it is sometimes called – in financial markets if often noted, but typically assumed to be the characteristic of naïve, uninformed, lay investors, and to be irrational. If the hypothesis presented here is correct, however, the preconditions of the 1998 crisis were created by skilled, professional investors imitating each other. Nor, furthermore, should we regard imitation as necessarily irrational. André Orléan suggests an appropriate metaphor. Imagine you and another person are in a room in which a fire breaks out. The room has two exits, one which leads to a dead-end (if you take it, you will die), and one through which you can safely escape, but you do not know which is which. Nor do you know whether the other person knows. With no time to communicate, you decide simply to imitate the other person, following him or her through whichever door he or she chooses. It is herd behaviour – at least with a herd numbering two – but is it irrational? No, says Orléan. If the other person knows which exit leads to safety, one has assured one's safety. If he or she does not know, you are no worse off than if you had on your own taken a random decision (Orléan 1998 p. 39).[23] Relative-value

[23] Fans of the television game show "Who wants to be a millionaire?" will note the structural parallel with the option of the contestant, who has to choose the right answer amongst four possibilities, to "ask the audience": in other words, to poll the studio audience. "Ask the audience" is a valuable resource – participants can use it only once – because the answers of those who do not know will tend to distribute randomly, so the most popular answer is probably right.

arbitrageurs in August 1998, and a wider range of market participants in September 1998, were in a sense in the room postulated by Orléan, with the added complication that the safety of the different courses of action was not a given, but was affected by the ensemble of their own behaviour. Their behaviour was rational, but in a profound sense it was also social.

The key, fatal, consequence of imitation was the disastrous increase in correlations of August and September 1998. LTCM's arbitrage positions were geographically diverse, in disparate asset classes, and in spreads that at the level of economic "fundamentals" were often quite unrelated. Yet correlations that had historically been at the level of 0.1 or lower jumped during the crisis to around 0.7 as the holders of the imitative superportfolio started to liquidate its components simultaneously. This – the "social," imitative, correlational nature of financial risk – interestingly is the lesson that LTCM's principals have learned from their 1998 encounter with risk. The risk model of LTCM's successor fund, JWM Partners, incorporates the possibility that an extreme event can trigger all correlations to become 1.0. Paradoxically, though, the very fact of the unpopularity of relative-value and convergence arbitrage since 1998 meant that even the extreme event of September 11 did not provoke the imitation-based, superportfolio crisis that JWM's risk modelling now anticipates.

Arbitrage is an historically situated process in two senses. First, as noted above, there is an interaction between arbitrage as market practice and arbitrage as theoretical presupposition, an interaction that generally is performative.

Second, however, there is an interaction between the popularity of arbitrage and its success. Mostly, this interaction is also positive: arbitrage's success leads it to become more widely practised. But there is perhaps a potential instability, akin to the sudden tipping point in models of predator-prey dynamics.[24] If arbitrageurs are foxes, and arbitrage opportunities are rabbits, then a small number of foxes will flourish in a world of many rabbits. Arbitrageurs make markets more efficient, just as in conventional ecological thinking predators are necessary to "nature's balance," preventing prey populations from outstripping the resources on which they in turn depend. But just as fox populations can outstrip those of rabbits, and suddenly collapse, so arbitrage can become too popular. That in a sense was the cause of the encounter with risk in 1998: LTCM on its own could have survived the events of that year, but in a world of imitators it could not survive without recapitalization. After a collapse of predator numbers, predation can again become a flourishing activity. So, it seems, with arbitrage. The crisis of 1998 greatly reduced the amount of capital devoted to convergence and relative value arbitrage. Subsequently, arbitrage seems once again to have become stably profitable, surviving the crisis of September 2001 without difficulty.

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[24] I owe the analogy to a conversation with Doyne Farmer. See also Farmer (1998). It is not a complete analogy: it fails fully to capture the processes of August and September 1998, which, as noted in the text, were characterized by an increase, not a decrease, in arbitrage opportunities. The years from 1994 to early summer 1998, however, were characterized by an increase in arbitrage leading to a diminution in arbitrage opportunities: see MacKenzie (forthcoming).

How do the two aspects of the historical situatedness of arbitrage interact? The answer may vary from market to market, and between pricing discrepancies of different types, and in any case I can only speculate, but one possibility is this: that in some circumstances[25] arbitrage can succeed reliably as a practical activity only when the amounts of capital devoted to it are insufficient substantially to close pricing discrepancies. So any historical tendency for arbitrage to make markets more efficient may remain only that: a tendency, always vulnerable to reverse.

[25] See Shleifer and Vishny (1997, pp. 49-54) for some interesting suggestions in respect to the bearing on these circumstances of the risk they analyze, of investors withdrawing capital from arbitrage in response to adverse price movements.

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