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WHAT HAPPENED TO THE QUANTS IN AUGUST 2007?

Amir E. Khandani[a] *and Andrew W. Lo*[b]

During the week of August 6, 2007, a number of quantitative long/short equity hedge funds experienced unprecedented losses. Based on TASS hedge-fund data and simulations of a specific long/short equity strategy, we hypothesize that the losses were initiated by the rapid "unwind" of one or more sizable quantitative equity market-neutral portfolios. Given the speed and price impact with which this occurred, it was likely the result of a forced liquidation by a multi-strategy fund or proprietary-trading desk, possibly due to a margin call or a risk reduction. These initial losses then put pressure on a broader set of long/short and long-only equity portfolios, causing further losses by triggering stop/loss and de-leveraging policies. A significant rebound of these strategies occurred on August 10th, which is also consistent with the unwind hypothesis. This dislocation was apparently caused by forces outside the long/short equity sector—in a completely unrelated set of markets and instruments—suggesting that systemic risk in the hedge-fund industry may have increased in recent years.

1 Introduction and summary

The months leading up to August 2007 were a tumultuous period for global financial markets, with events in the US sub-prime mortgage market casting long shadows over many parts of the financial industry. The blow-up of two Bear Stearns credit strategies funds in June, the sale of Sowood Capital Management's portfolio to Citadel after losses exceeding 50% in July, and mounting problems at Countrywide Financial—the nation's largest home lender—throughout the second and third quarter of 2007 set the stage for further turmoil in fixed-income and credit markets during the month of August.

But during the week of August 6th, something remarkable occurred. Several prominent hedge funds experienced unprecedented losses that week; however, unlike the Bear Stearns and Sowood funds, these hedge funds were invested primarily in

[a]Department of Electrical Engineering and Computer Science, and Laboratory for Financial Engineering, MIT.

[b]Corresponding author. MIT Sloan School of Management, 50 Memorial Drive, E52-454, Cambridge MA 02142; director, MIT Laboratory for Financial Engineering; and Chief Scientific Officer, AlphaSimplex Group, LLC.

exchange-traded equities, not in sub-prime mortgages or credit-related instruments. In fact, most of the hardest-hit funds were employing long/short equity market-neutral strategies—sometimes called "statistical arbitrage" strategies—that, by construction, did not have significant "beta" exposure, and which were supposed to be immune to most market gyrations. But the most remarkable aspect of these hedge-fund losses was the fact that they were confined almost exclusively to funds using quantitative strategies. With laser-like precision, model-driven long/short equity funds were hit hard on Tuesday August 7th and Wednesday August 8th, despite relatively little movement in fixed-income and equity markets during those two days and no major losses reported in any other hedge-fund sectors. Then, on Thursday August 9th when the S&P 500 lost nearly 3%, most of these market-neutral funds continued their losses, calling into question their market-neutral status.

By Friday, August 10th, the combination of movements in equity prices that caused the losses earlier in the week had reversed themselves, rebounding significantly, but not completely. However, faced with mounting losses on the 7th, 8th, and 9th that exceeded all the standard statistical thresholds for extreme returns, many of the affected funds had cut their risk exposures along the way, which only served to exacerbate their losses while causing them to miss out on a portion of the reversals on the 10th. And just as quickly as it descended upon the quants, the perfect financial storm was over. At least for the moment.

The following week, the financial press surveyed the casualties and reported month-to-date losses ranging from −5% to −30% for some of the most consistently profitable quant funds in the history of the industry.[1] David Viniar, Chief Financial Officer of Goldman Sachs argued that "We were seeing things that were 25-standard deviation moves, several days in a row…. There have been issues in some of the other quantitative spaces. But nothing like what we saw last week" (Thal Larsen, 2007).

What happened to the quants in August 2007?

In this paper, we attempt to shed some light on this question by examining some indirect evidence about the profitability of long/short equity strategies over the past decade and during August 2007. We simulate the performance of a specific long/short equity strategy to see if we can capture the performance swings during the week of August 6, 2007, and then use this strategy to compare and contrast the events of August 2007 with those of August 1998. We then turn to individual and aggregate hedge-fund data from the TASS database and the Credit Suisse/Tremont hedge-fund indexes to develop a broader understanding of the evolution of long/short equity strategies over the past decade.

From these empirical results, we have developed the following tentative hypotheses about August 2007:

1. The losses to quant funds during the second week of August 2007 were initiated by the temporary price impact resulting from a large and rapid "unwinding" of one or more quantitative equity market-neutral portfolios. The speed and magnitude of the price impact suggests that the unwind was likely the result of a sudden liquidation of a multi-strategy fund or proprietary-trading desk, perhaps in response to margin calls from a deteriorating credit portfolio, a decision to cut risk in light of current market conditions, or a discrete change in business lines.
2. The price impact of the unwind on August 7–8 caused a number of other types of equity funds—long/short, 130/30, and long-only—to cut their risk exposures or "de-leverage," exacerbating the losses of many of these funds on August 8th and 9th.

3. The majority of the unwind and de-leveraging occurred on August 7–9, after which the losses stopped and a significant—but not complete—reversal occurred on the 10th.
4. This price-impact pattern suggests that the losses were the short-term side-effects of a sudden (and probably forced) liquidation on August 7–8, not a fundamental or permanent breakdown in the underlying economic drivers of long/short equity strategies. However, the coordinated losses do imply a growing common component in this hedge-fund sector.
5. Likely factors contributing to the magnitude of the losses of this apparent unwind were: (a) the enormous growth in assets devoted to long/short equity strategies over the past decade and, more recently, to various 130/30 and other active-extension strategies; (b) the systematic decline in the profitability of quantitative equity market-neutral strategies, due to increasing competition, technological advances, and institutional and environmental changes such as decimalization, the decline in retail order flow, and the decline in equity-market volatility; (c) the increased leverage needed to maintain the levels of expected returns required by hedge-fund investors in the face of lower profitability; (d) the historical liquidity of US equity markets and the general lack of awareness (at least prior to August 6, 2007) of just how crowded the long/short equity category had become; and (e) the unknown size and timing of new sub-prime-mortgage-related problems in credit markets, which created a climate of fear and panic, heightening the risk sensitivities of managers and investors across all markets and style categories.
6. The fact that quantitative funds were singled out during the week of August 6, 2007 had less to do with a breakdown of any specific quantitative algorithms than the apparent sudden liquidation of one or more large quantitative equity market-neutral portfolios. Because such portfolios consist primarily of exchanged-traded instruments, the price impact of the rapid unwind was quickly transmitted to other funds, with the most severe losses experienced by portfolios with the largest overlap to the portfolio that initiated the unwind. Not surprisingly, the portfolios with the largest overlap were those constructed using similar methods, i.e., quantitative equity market-neutral methods. But the fact that these portfolios are typically highly diversified—involving several hundred positions on any given day—suggests that the impact of the unwind could be much broader, affecting many other types of portfolios.
7. The differences between the behavior of our test strategy in August 2007 and August 1998, the increase in the number of funds and the average assets under management per fund in the TASS hedge-fund database, the increase in average absolute correlations among the CS/Tremont hedge-fund indexes, and the growth of credit-related strategies among hedge funds and proprietary trading desks suggest that systemic risk in the hedge-fund industry may have increased in recent years.
8. The ongoing problems in the sub-prime mortgage and credit sectors may trigger additional liquidity shocks in the more liquid hedge-fund style categories such as long/short equity, global macro, and managed futures. However, the severity of the impact to long/short equity strategies is likely to be muted in the near future given that market participants now have more information regarding the size of this sector and the potential price-impact of another firesale liquidation of a long/short equity portfolio.

We wish to emphasize at the outset that these hypotheses are tentative, based solely on indirect evidence, and without the benefit of very much hindsight given the recency of these events. For these reasons, this paper should be interpreted more like an evolving case study, not formal academic research. We are focusing on a rather timely topic, which does not afford the luxury of multiple rounds of critical review and revision through which more enduring research findings are typically forged.

However, we wish to highlight another distinction between academic research and this paper. Original research typically offers novel answers to questions that have yet to be resolved. There is little point, and no credit given, to answering questions for which the answers are already known. But the answer to the question of what happened to the quants in August 2007 is indeed known, at least to a number of industry professionals who were directly involved in these markets and strategies in August 2007.

Therefore, it is an odd task that we have undertaken—to attempt to explain something that, at least to a subset of potential readers, needs no explanation. And as a case study, our endeavor may seem even more misguided because we do not have ready access to any of the primary sources: the hedge funds, proprietary trading desks, and their prime brokers and major credit counterparties. For obvious reasons, such sources are not at liberty to disclose any information about their strategies—indeed, any disclosure of proprietary information is clearly not in the best interests of their investors or shareholders. Therefore, it is unlikely we will ever obtain the necessary information to conduct a *conclusive* study of the events of August 2007.

It is precisely this well-known lack of transparency of hedge funds, coupled with genuine intellectual curiosity and public-policy concerns regarding systemic risks in this dynamic industry, that led us to undertake this effort. Because the relevant hedge-fund managers and investors are not able to disclose their views on what happened in August 2007, we propose to construct a simple simulacrum of a quantitative equity market-neutral strategy and study its performance, as well as to use other publicly available hedge-fund data to round out our understanding of the long/short equity sector during this challenging period. However, we recognize the difficulty for outsiders to truly understand such complex issues, and do not intend to be self-appointed spokesmen for the quants.

Accordingly, we acknowledge in advance that we may be far off the mark given the limited data we have to work with, and caution readers to be appropriately skeptical of our analysis, as we are. While some academics may have warned that systemic risk in the hedge-fund industry has been on the rise (see, for example, Carey and Stulz (2007)), none of the academic literature has produced any timely forecasts of when or how such shocks might occur. Indeed, by definition, a true "shock" is unforecastable. Nevertheless, it is our hope that the tentative hypotheses suggested by our empirical results, and the simple tools that we use to derive them, will stimulate additional investigations—especially by those who do have access to the data—that may lead to a deeper understanding of financial market dynamics under stress.

We begin in Section 2 with a brief discussion of terminology, and in Section 3 we describe the specific quantitative test strategy that we plan to use as our "microscope" to study the effects of August 6–10, 2007 on long/short equity strategies. We show in Section 4 that this test strategy does indeed capture the losses that affected so many quants during that week. By comparing August 2007 to August 1998, in Section 5 we observe that, despite the many similarities between the two periods, there is one significant difference that may be cause for great concern regarding the current level of systemic risk in the hedge-fund industry—our microscope revealed not a single sign of stress in August 1998, but has shown systematic deterioration year by year since then until the outsized losses in August 2007. We attempt to trace the origins of this striking difference to various sources. In particular, in

Section 6, we consider the near-exponential growth of assets and funds in the long/short equity category, the secular decline in the expected rate of return of our test strategy over the years, and the increases in leverage that these two facts imply. With the appropriate leverage assumptions in hand, we are able to produce a more realistic simulation of the test strategy's performance in August 2007, and in Section 7 we lay out our "unwind hypothesis." This hypothesis relies on the assumption that long/short equity strategies are less liquid than market participants anticipated, and in Section 8 we estimate the illiquidity exposure of long/short equity funds in the TASS database. We find evidence that over the past two years, even this highly liquid sector of the hedge-fund industry has become less liquid. And in Section 9, we investigate the changes in simple correlations across broad-based hedge-fund indexes over time and find that the hedge-fund industry is a more highly "connected" network now than ever before. We conclude by discussing the broader issue of whether "quant" failed in August 2007 (Section 10), some of the limitations of our analysis and possible extensions (Section 11), and our current outlook for systemic risk in the hedge-fund industry (Section 12).

2 Terminology

Among experienced hedge-fund investors and managers, there is a clear distinction between the terms "statistical arbitrage," "quantitative equity market-neutral," and "long/short equity" strategies. The first category refers to highly technical short-term mean-reversion strategies involving large numbers of securities (hundreds to thousands, depending on the amount of risk capital), very short holding periods (measured in days to seconds), and substantial computational, trading, and IT infrastructure. The second category is more general, involving broader types of quantitative models, some with lower turnover, fewer securities, and inputs other than past prices such as accounting variables, earnings forecasts, and economic indicators. The third category is the broadest, including any equity portfolios that engage in shortselling, that may or may not be market-neutral (many long/short equity funds are long-biased), that may or may not be quantitative (fundamental stock-pickers sometimes engage in short positions to hedge their market exposure as well as to bet on poor-performing stocks), and where technology need not play an important role. In most hedge-fund databases, this is by far the single largest category, both in terms of assets and the number of funds.

More recently, a fourth category has emerged, the "130/30" or "active extension" strategies, in which a fund or, more commonly, a managed account of, say \$100MM, maintains \$130MM of long positions in one set of securities and \$30MM of short positions in another set of securities. Such a strategy is a natural extension of a long-only fund where the long-only constraint is relaxed to a limited extent. It is currently one of the fastest-growing areas in the institutional money management business, and because the portfolio construction process is rather technical by design, the managers of such products are primarily quantitative.

For the purposes of this paper, we sometimes refer to all of these strategies as "long/short equity" for several reasons. First, these seemingly disparate approaches are beginning to overlap. A number of statistical arbitrage funds are now pursuing lower-turnover sub-strategies to increase their funds' capacities, while many long/short equity funds have turned to higher-turnover sub-strategies as they develop more trading infrastructure and seek more consistent returns. This natural business progression has blurred the distinction between the long/short equity sub-specialties. Second, as long/short equity managers have grown in size, technology has naturally begun to play a more important role, even among fundamental stock-pickers who find that they cannot expand their business unless they make more efficient use of their time and skills. Such managers have begun to rely on stock-screening software and portfolio-construction tools that allow them to leverage their qualitative stock-selection skills, and automated trading platforms that allow them to execute their stock picks more cost-effectively. These new tools have made quants out of many fundamental stock-pickers. Indeed, even among the long-only equity managers, 130/30 strategies are transforming the multi-trillion-dollar equity enhanced-index business into a quantitative endeavor. We argue that all four investment categories were impacted by the events of August 6–10, 2007, largely because their growth has pushed them into each other's domains. Accordingly, in the event of a rapid unwind of any equity portfolio, all four types of strategies are likely to be affected in one way or another.

Therefore, throughout the remainder of this paper, we shall use the broader term "long/short equity" to refer generically to all of these distinct activities, making finer distinctions when appropriate.

3 Anatomy of a long/short equity strategy

To gauge the impact of the events of August 6–10, 2007 on long/short equity portfolios, we consider a specific strategy—first proposed by Lehmann (1990) and Lo and MacKinlay (1990)—that we can analyze directly using individual US equities returns. Given a collection of N securities, consider a long/short market-neutral equity strategy consisting of an equal dollar amount of long and short positions, where at each rebalancing interval, the long positions consist of "losers" (underperforming stocks, relative to some market average) and the short positions consist of "winners" (outperforming stocks, relative to the same market average). Specifically, if ω_{it} is the portfolio weight of security i at date t, then

$$\omega_{it} = -\frac{1}{N}(R_{it-k} - R_{mt-k}),$$

$$R_{mt-k} \equiv \frac{1}{N}\sum_{i=1}^{N} R_{it-k} \qquad (1)$$

for some $k > 0$.

Note that the portfolio weights are the negative of the degree of outperformance k periods ago, so each value of k yields a somewhat different strategy. For our purposes, we set $k = 1$ day. By buying yesterday's losers and selling yesterday's winners at each date, such a strategy actively bets on mean reversion across all N stocks, profiting from reversals that occur within the rebalancing interval. For this reason, (1) has been called a "contrarian" trading strategy that benefits from market overreaction, i.e., when underperformance is followed by positive returns and vice-versa for outperformance (see Appendix A.1 for further details).

However, another source of profitability of contrarian trading strategies is the fact that they provide liquidity to the marketplace. By definition, losers are stocks that have underperformed relative to some market average, implying a supply/demand imbalance, i.e., an excess supply that caused the prices of those securities to drop, and vice-versa for winners. By buying losers and selling winners, contrarians are adding to the demand for losers and increasing the supply of winners, thereby stabilizing supply/demand imbalances. Traditionally, designated marketmakers such as the NYSE/AMEX specialists and NASDAQ dealers have played this role, for which they are compensated through the bid/offer spread. But over the last decade, hedge funds and proprietary trading desks have begun to compete with traditional marketmakers, adding enormous amounts of liquidity to US stock markets and earning attractive returns for themselves and their investors in the process.

In providing liquidity to the market, contrarian trading strategies also have the effect of reducing market volatility because they attenuate the movement of prices by selling stocks for which there is excess demand and buying stocks for which there is excess supply. Therefore, an increasing amount of capital dedicated to market-making strategies is one potential explanation for the secular decline in US equity-market volatility during the past 10 years. Once this market-making capital is withdrawn from the marketplace, volatility should pick up, as it has over the past several months.

If mean reversion implies that contrarian trading strategies will be profitable, then momentum implies the reverse. In the presence of return persistence, i.e., positively autocorrelated returns, Lo and MacKinlay (1990) show that the contrarian trading strategy (1) will exhibit negative profits. As with other market-making strategies, the contrarian strategy loses when prices exhibit trends, either because of private information, which the market microstructure literature calls "adverse selection," or a sustained liquidation in which the market-maker bears the losses by taking the other side and losing value as prices move in response to the liquidation. Therefore, whether or not (1) is an interesting strategy in its own right, it can serve as a valuable indicator of broad-based strategy liquidations of long and/or short positions, and we will return to this interpretation in Section 7.

Note that the weights (1) have the property that they sum to 0, hence (1) is an example of an "arbitrage" or "market-neutral" portfolio where the long positions are exactly offset by the short positions.[2] As a result, the portfolio "return" cannot be computed in the standard way because there is no net investment. In practice, however, the return of such a strategy over any finite interval is easily calculated as the profit-and-loss of that strategy's positions over the interval divided by the initial capital required to support those positions. For example, suppose that a portfolio consisting of \$100MM of long positions and \$100MM of short positions generated profits of \$2MM over a one-day interval. The return of this strategy is simply \$2MM divided by the required amount of capital to support the \$100MM long/short positions. Under Regulation T, the minimum amount of capital required is \$100MM (often stated as 2 : 1 leverage, or a 50% margin requirement), hence the return to the strategy is 2%. If, however, the portfolio manager is a broker/dealer, then Regulation T does not apply (other regulations govern the capital adequacy of broker/dealers), and higher levels of leverage may be employed. For example, under certain conditions, it is possible to support a \$100MM long/short portfolio with only \$25MM of capital—leverage ratio of 8 : 1—which implies a portfolio return of $\$2/\$25 = 8\%$.[3] Accordingly, the gross dollar investment I_t of the portfolio (1) and its unleveraged (Reg T) portfolio return R_{pt} are given by

$$I_t \equiv \frac{1}{2}\sum_{i=1}^{N}|\omega_{it}|, \quad R_{pt} \equiv \frac{\sum_{i=1}^{N}\omega_{it}R_{it}}{I_t}. \tag{2}$$

To construct leveraged portfolio returns $L_{pt}(\theta)$ using a regulatory leverage factor of $\theta : 1$, we simply multiply (2) by $\theta/2$:[4]

$$L_{pt}(\theta) \equiv \frac{(\theta/2)\sum_{i=1}^{N}\omega_{it}R_{it}}{I_t}. \tag{3}$$

Lo and MacKinlay (1990) provide a detailed analysis of the unleveraged returns (2) of the contrarian trading strategy, tracing its profitability to mean reversion in individual stock returns as well as positive lead/lag effects and cross-autocorrelations across stocks and across time. However, for our purposes, such decompositions are of less relevance than simply using (1) as an instrument to study the impact of market events on long/short equity strategies during the second week of August 2007. To that end, we apply this strategy to the daily returns of all stocks in the University of Chicago's CRSP

Database, and to stocks within 10 market-cap deciles, from January 3, 1995 to August 31, 2007.[5]

Before turning to the performance of the contrarian strategy in August 2007, we summarize the strategy's historical performance to develop some intuition for its properties. Table 1 provides year-by-year average market capitalizations and share prices of stocks in each decile from 1995 to 2007,[6] and Table 2 reports the year-by-year average daily return of (1) when applied to stocks within market-cap deciles, as well as for all stocks in our sample. The results are impressive. In the first year of our sample, 1995, the strategy produced an average daily return of 1.38% per day, or 345% per year assuming a 250-day year! Of course, this return is unrealistic because it ignores a number of market frictions such as transactions costs, price impact, shortsales constraints, and other institutional limitations. In particular, a daily rebalancing interval would imply extraordinarily high turnover across the set of 4,781 individual stocks, which was simply not feasible in 1995. However, we intend to use this strategy to gauge the impact of market movements in August 2007 relative to its typical performance, hence we are not as concerned about whether the results are achievable in practice.

The high turnover and the large number of stocks involved also highlight the importance that technology plays in strategies like (1), and why funds that employ such strategies are predominantly quantitative. It is nearly impossible for human portfolio managers and traders to implement a strategy involving so many securities and trading so frequently without making substantial use of quantitative methods and technological tools such as automated trading platforms, electronic communications networks, and mathematical optimization algorithms. Indeed, part of the liquidity that such strategies seem to enjoy—the short holding periods, the rapid-fire implementation of trading signals, and the diversification of profitability across such a large number of instruments—is directly related to technological advances in trading, portfolio construction, and risk management. It is no wonder that the most successful funds in this discipline have been founded by computer scientists, mathematicians, and engineers, not by economists or fundamental stock-pickers.

Table 2 confirms a pattern long recognized by long/short equity managers—the relation between profitability and market capitalization. Smaller-cap stocks generally exhibit more significant inefficiencies, hence the profitability of the contrarian strategy in the smaller deciles is considerably higher than in the larger-cap portfolios. For example, the average daily return of the strategy in the smallest decile in 1995 is 3.57% in contrast to 0.04% for the largest decile. Of course, smaller-cap stocks typically have much higher transactions costs and price impact, hence they may not be as attractive as the data might suggest. The trade-off between apparent profitability and transactions costs implies that the intermediate deciles may be the most opportune from a practical perspective, a conjecture that we shall revisit below.

Table 2 also exhibits a strong secular trend of declining average daily returns, a feature that many long/short equity managers and investors have observed. In 1995, the average daily return of the contrarian strategy for all stocks in our sample is 1.38%, but by 2000, the average daily return drops to 0.44% and the year-to-date figure for 2007 (up to August 31) is 0.13%. Figure 1 illustrates the near-monotonic decline of the expected returns of this strategy, no doubt a reflection of increased competition, changes in market structure, improvements in trading technology and electronic connectivity, the growth in assets devoted to this type of strategy, and the corresponding decline in US equity-market volatility over the last decade.[7] This secular decline in profitability has significant implications for the use of leverage, which we will explore in Section 6.

Table 1 Year-by-year average market capitalizations and share prices of US common stocks (CRSP share codes 10 and 11) with share prices above $5 and below $2,000 within market-capitalization deciles from January 3, 1995 to August 31, 2007.

	Deciles by market capitalization											All
Year	Smallest	Decile 2	Decile 3	Decile 4	Decile 5	Decile 6	Decile 7	Decile 8	Decile 9	Largest	All	Count
	Panel A: Average market capitalization ($MM)											
1995	17	34	57	86	127	190	305	556	1,269	8,250	1,121	4,781
1996	18	38	61	92	140	210	334	591	1,349	9,599	1,293	5,273
1997	22	47	74	109	164	248	407	708	1,539	12,401	1,628	5,393
1998	24	49	78	115	172	274	444	773	1,735	16,011	2,088	5,195
1999	23	50	83	126	200	310	507	905	2,086	22,002	2,764	4,736
2000	22	53	92	148	249	398	647	1,145	2,545	26,050	3,361	4,566
2001	25	60	106	181	288	440	723	1,268	2,863	26,007	3,348	3,782
2002	27	64	111	188	289	450	711	1,235	2,696	23,463	3,082	3,486
2003	31	73	130	213	327	498	795	1,371	2,951	24,185	3,146	3,376
2004	37	86	149	244	363	569	875	1,554	3,268	26,093	3,425	3,741
2005	40	97	171	266	408	651	1,026	1,772	3,811	28,164	3,741	3,721
2006	44	105	187	298	452	717	1,145	1,907	4,073	30,154	3,988	3,764
2007	47	109	195	313	472	739	1,188	2,120	4,387	33,152	4,363	3,623
	Panel B: Average price ($)											
1995	11.07	11.55	13.37	14.84	16.96	18.90	22.54	26.49	32.45	45.14	21.55	4,781
1996	11.30	11.92	13.06	14.36	17.11	20.12	23.47	28.29	33.02	47.95	22.40	5,273
1997	12.39	13.33	14.42	15.88	18.52	22.21	26.20	31.07	36.52	52.16	24.56	5,393
1998	11.37	13.15	14.34	15.55	17.94	21.76	25.40	29.97	36.55	54.06	24.53	5,195
1999	10.31	11.79	12.87	14.14	16.58	21.01	24.13	31.62	36.99	54.04	23.80	4,736
2000	9.74	11.59	12.31	13.85	17.86	21.85	25.89	34.03	40.49	60.25	25.39	4,566
2001	11.34	13.10	13.66	15.47	18.47	20.70	25.37	31.47	34.96	42.71	23.04	3,782
2002	12.15	14.20	15.02	16.16	18.88	21.38	25.35	28.43	33.18	39.52	22.73	3,486
2003	13.65	15.56	16.55	17.15	19.89	21.25	26.12	28.53	33.86	41.83	23.61	3,376
2004	13.81	16.33	16.88	17.84	20.33	24.37	28.21	32.54	38.68	46.92	25.84	3,741
2005	13.48	16.40	16.34	18.01	20.84	25.01	29.25	38.51	42.50	51.14	27.42	3,721
2006	13.06	16.08	16.28	19.33	21.56	25.95	30.44	40.08	45.42	51.94	28.24	3,764
2007	12.61	15.18	16.75	18.30	22.32	27.32	30.30	38.70	48.70	56.56	28.94	3,623

Table 2 Year-by-year average daily returns, standard deviations of daily returns, and annualized Sharpe ratios ($\sqrt{250}$ × (average daily return/standard deviation)) of Lo and MacKinlay's (1990) contrarian trading strategy applied to all US common stocks (CRSP share codes 10 and 11) with share prices above \$5 and less than \$2,000, and market-capitalization deciles, from January 3, 1995 to August 31, 2007.

	Market capitalization deciles										
Year	Smallest	Decile 2	Decile 3	Decile 4	Decile 5	Decile 6	Decile 7	Decile 8	Decile 9	Largest	All (%)
	Average daily returns (%)										
1995	3.57	2.75	1.94	1.62	1.07	0.61	0.21	−0.01	−0.02	0.04	1.38
1996	3.58	2.47	1.82	1.34	0.84	0.52	0.19	−0.11	−0.04	0.02	1.17
1997	2.83	1.94	1.34	1.02	0.62	0.28	0.04	−0.12	0.06	0.14	0.88
1998	2.38	1.45	1.11	0.62	0.29	0.03	−0.04	−0.12	0.03	0.10	0.57
1999	2.56	1.41	0.82	0.38	−0.01	−0.11	−0.21	−0.35	−0.01	0.06	0.44
2000	2.58	1.59	0.92	0.14	0.03	−0.02	−0.14	0.16	0.00	0.03	0.44
2001	2.15	1.25	0.57	0.24	−0.01	0.06	0.13	−0.10	−0.11	−0.11	0.31
2002	1.67	0.85	0.53	0.29	0.28	0.26	0.28	0.20	0.11	0.09	0.45
2003	1.00	0.26	−0.07	0.04	0.11	0.20	0.18	0.15	0.04	0.05	0.21
2004	1.17	0.48	0.31	0.38	0.25	0.29	0.22	0.15	0.05	−0.01	0.37
2005	1.05	0.39	0.13	0.11	0.09	0.11	0.05	0.08	0.01	0.02	0.26
2006	0.86	0.26	0.11	0.06	0.05	−0.02	−0.02	0.05	0.06	0.00	0.15
2007	0.57	0.09	0.08	0.18	0.16	−0.08	0.04	−0.04	0.00	−0.04	0.13
	Standard deviation of daily returns (%)										
1995	0.92	0.88	0.81	0.82	0.78	0.77	0.73	0.67	0.63	0.65	0.40
1996	1.07	1.00	0.79	0.81	0.88	0.84	0.90	0.90	0.83	0.73	0.48
1997	1.04	0.98	0.96	0.96	1.12	1.00	0.91	0.99	0.98	0.77	0.68
1998	1.59	1.67	1.23	1.22	1.57	1.25	1.29	1.43	1.08	1.00	0.84
1999	1.66	1.82	1.44	1.44	1.79	1.57	1.71	1.70	1.57	1.07	1.02
2000	1.57	1.69	2.06	1.89	1.76	2.15	2.18	2.29	2.44	2.56	1.68
2001	1.33	1.26	1.46	1.62	1.65	1.64	1.83	1.91	2.28	2.29	1.43

Table 2 (*Continued*)

Year	Market capitalization deciles										
	Smallest	Decile 2	Decile 3	Decile 4	Decile 5	Decile 6	Decile 7	Decile 8	Decile 9	Largest	All (%)
2002	1.17	0.89	1.14	1.07	1.25	1.11	1.30	1.42	1.50	1.50	0.98
2003	1.11	0.81	0.95	0.89	0.86	0.81	0.77	0.76	0.75	0.56	0.54
2004	1.35	1.01	0.87	0.76	0.76	0.78	0.80	0.74	0.69	0.57	0.53
2005	1.35	0.80	0.89	0.70	0.77	0.77	0.65	0.73	0.57	0.56	0.46
2006	1.07	0.90	0.83	0.84	0.70	1.07	0.68	0.68	0.64	0.61	0.52
2007	0.96	1.02	1.00	0.99	1.06	1.44	1.00	0.87	0.67	0.56	0.72
	Annualized Sharpe ratio (0% riskfree rate)										
1995	61.27	49.20	37.79	31.26	21.49	12.68	4.62	−0.22	−0.54	0.87	53.87
1996	53.08	39.12	36.27	26.10	15.17	9.85	3.38	−1.89	−0.69	0.36	38.26
1997	43.15	31.19	22.00	16.66	8.67	4.45	0.74	−1.88	0.95	2.79	20.46
1998	23.61	13.78	14.22	8.09	2.92	0.39	−0.54	−1.32	0.43	1.58	10.62
1999	24.32	12.25	9.05	4.22	−0.11	−1.08	−1.93	−3.23	−0.09	0.82	6.81
2000	25.96	14.91	7.04	1.18	0.31	−0.18	−1.04	1.14	0.01	0.21	4.17
2001	25.56	15.68	6.15	2.30	−0.05	0.57	1.09	−0.79	−0.79	−0.73	3.46
2002	22.54	15.10	7.30	4.28	3.57	3.68	3.38	2.24	1.13	0.98	7.25
2003	14.32	5.19	−1.11	0.63	1.94	3.91	3.64	3.09	0.89	1.33	5.96
2004	13.76	7.55	5.60	7.96	5.11	5.90	4.27	3.20	1.12	−0.33	11.07
2005	12.33	7.72	2.26	2.42	1.95	2.29	1.31	1.74	0.36	0.62	8.85
2006	12.72	4.49	2.08	1.18	1.14	−0.26	−0.56	1.08	1.60	−0.03	4.47
2007	9.40	1.45	1.33	2.93	2.40	−0.84	0.69	−0.74	−0.05	−1.03	2.79

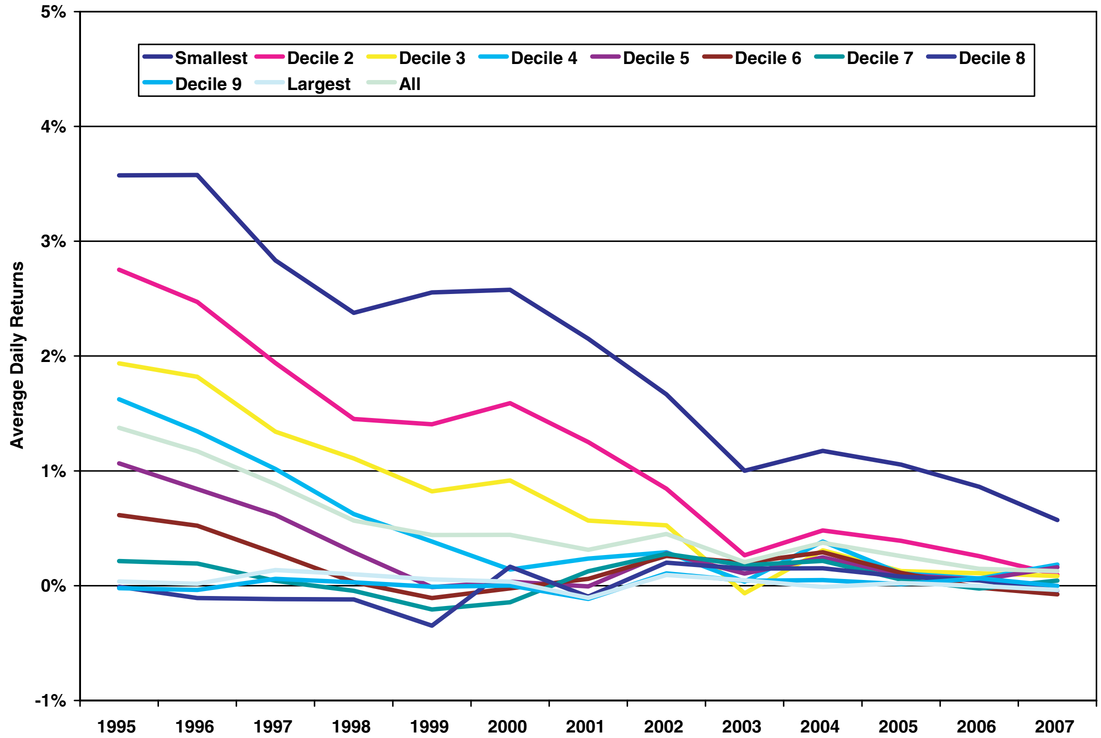


Figure 1 Year-by-year average daily returns of Lo and MacKinlay's (1990) contrarian trading strategy applied to all US common stocks (CRSP share codes 10 and 11) with share prices above \$5 and less than \$2,000, and market-capitalization deciles, from January 3, 1995 to August 31, 2007.

The third panel of Table 2 reports the annualized ratio of the contrarian strategy's daily mean return to its daily standard deviation, where the annualization is performed by multiplying the ratio by $\sqrt{250}$. This is the Sharpe ratio relative to a 0% risk-free rate, and is one simple measure of the strategy's expected return per unit risk. Although a Sharpe ratio of 53.87 in 1995 may seem absurdly high, it should be kept in mind that in 1995, this strategy calls for the daily rebalancing of a portfolio with 4,781 stocks on average (see Table 1). The transactions costs involved in such rebalancing would have been formidable, but if one had the ability or technology to engage in such broad-based market-making, extraordinary Sharpe ratios may not be so unrealistic.[8] Indeed, we expect the Sharpe ratios of more formal market-making activities such as specialist profits on the New York Stock Exchange to be quite high given the economics of price discovery. Therefore, the Sharpe ratios in Table 2 may be somewhat inflated because we have not incorporated transactions costs, but they are probably not off by an order of magnitude, and their attractive levels provide one explanation for the popularity of statistical arbitrage strategies among investors and hedge-fund managers.

4 What happened in August 2007?

Table 3 presents the unleveraged daily returns of the contrarian strategy over the five-week period from Monday, July 30 to Friday, August 31, 2007 applied to our entire universe of stocks and to market-cap deciles. The three days in the second week—August 7th, 8th, and 9th—are the outliers, with losses

Table 3 Daily returns of Lo and MacKinlay's (1990) contrarian trading strategy applied to all US common stocks (CRSP share codes 10 and 11) with share prices above $5 and less than $2,000, and market-capitalization deciles, from Monday July 30, 2007 to Friday August 31, 2007.

	Deciles by market capitalization (%)										
Date	Smallest	Decile 2	Decile 3	Decile 4	Decile 5	Decile 6	Decile 7	Decile 8	Decile 9	Largest	All (%)
7/30/2007	−0.07	0.02	1.96	−0.36	0.07	0.23	0.26	0.38	0.51	0.18	0.44
7/31/2007	0.19	1.10	0.28	0.55	−0.63	0.02	−0.80	0.49	−0.31	0.06	0.36
8/1/2007	1.53	0.45	−1.39	0.35	0.95	−0.88	−0.71	−0.63	−2.02	−0.22	0.11
8/2/2007	0.88	−0.76	−0.12	−0.67	−0.94	−2.70	2.16	1.53	−0.74	−0.19	−0.30
8/3/2007	−0.95	−0.62	−0.78	0.06	0.88	0.01	−0.62	−1.09	−0.57	−0.68	−0.02
8/6/2007	−0.83	−1.77	−0.39	−1.03	1.37	−1.37	−1.19	−0.72	0.27	0.77	0.50
8/7/2007	0.75	0.26	−1.64	−2.91	−1.50	−0.70	0.36	−1.02	−1.72	−0.67	−1.16
8/8/2007	0.88	−1.33	−2.59	−3.65	−4.27	−2.16	−2.23	−3.46	−1.26	−1.48	−2.83
8/9/2007	0.91	−1.86	−3.87	−2.77	−3.18	−3.95	−3.27	−4.33	−2.58	−1.31	−2.86
8/10/2007	−0.33	3.65	6.08	7.90	8.77	7.67	7.52	6.70	4.68	2.39	5.92
8/13/2007	1.36	−0.31	−0.63	−1.07	−1.55	−0.22	−1.29	−2.01	−2.14	−1.25	−0.76
8/14/2007	1.16	0.91	−0.26	0.34	0.56	−0.28	0.69	−0.29	0.16	0.17	0.08
8/15/2007	0.88	1.19	−0.61	−0.58	−0.17	−0.97	−0.24	−1.34	−0.57	−1.18	−0.38
8/16/2007	−1.26	−0.54	0.15	−0.59	−0.60	−0.99	−1.73	−1.27	0.27	−1.83	−0.81
8/17/2007	3.57	2.49	0.10	1.26	1.33	−0.52	0.12	−0.39	0.31	0.11	0.38
8/20/2007	3.75	1.75	0.35	1.35	0.51	0.44	1.22	0.56	0.39	1.17	1.14
8/21/2007	1.24	0.11	0.01	−0.45	0.02	−0.63	−0.08	−0.05	0.19	0.11	0.06
8/22/2007	−0.85	−0.31	−0.52	−0.51	−0.17	−0.83	−0.18	−0.56	0.39	0.09	−0.38
8/23/2007	−0.03	0.70	0.70	−0.16	0.38	1.04	0.26	−0.33	0.32	0.31	0.33
8/24/2007	0.62	−0.28	−0.07	0.23	0.92	−0.06	−0.07	0.09	−0.35	0.61	0.43
8/27/2007	1.10	0.70	0.11	0.20	1.25	−0.16	0.39	0.71	0.71	0.03	0.75
8/28/2007	0.41	0.32	0.08	−0.61	−0.64	−0.50	−0.33	−0.44	−0.47	0.25	−0.76
8/29/2007	1.45	0.08	1.27	2.08	1.94	−0.53	1.42	1.60	0.91	0.98	1.76
8/30/2007	1.07	0.04	0.62	0.40	0.89	0.10	−0.03	−0.04	0.12	−0.05	0.50
8/31/2007	1.69	0.97	0.95	−0.55	0.05	0.52	−0.08	−0.67	0.01	0.14	0.36

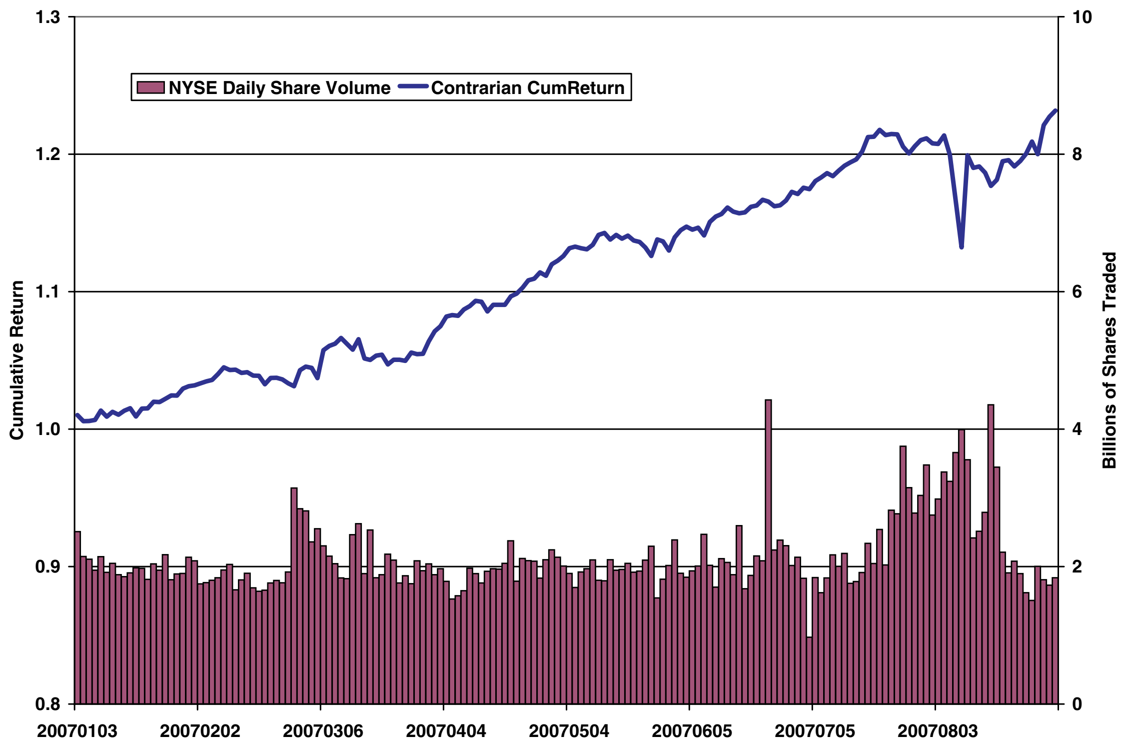


Figure 2 Cumulative return of the contrarian trading strategy from January 3 to August 31, 2007, and the NYSE daily share volume during this same period.

of −1.16%, −2.83%, and −2.86%, respectively, yielding a cumulative three-day loss of −6.85%.[9] Although this three-day return may not seem that significant—especially in the hedge-fund world where volatility is a fact of life—note from Table 2 that the contrarian strategy's 2006 daily standard deviation is 0.52%, so a −6.85% cumulative return represents a loss of 7.6 standard deviations assuming independently and identically distributed daily returns![10] Moreover, many long/short equity managers were employing leverage (see Section 6 for further discussion), hence their realized returns were magnified several-fold.

Curiously, a significant fraction of the losses was reversed on Friday, August 10th, when the contrarian strategy yielded a return of 5.92%, which was another extreme outlier of 11.4 standard deviations. In fact, the strategy's cumulative return for the entire week of August 6th was −0.43%, not an unusual weekly return in any respect. This reversal is a telltale sign of a liquidity trade. In fact, the plot in Figure 2 of the cumulative return of the contrarian strategy from January 3 to August 31, 2007 shows a reasonably steady positive trend interrupted by a prominent dip during the second week of August, after which the trend seems to continue. The elevated levels of NYSE share volume during the latter part of July and the first half of August, along with a mini-dip in July in the contrarian cumulative return series, suggest the possibility that liquidations may have started several weeks prior to the August 7–10 event. We shall return to this interpretation in Section 7.

The decile returns in Table 3 show that the losses on August 7–9 were even more pronounced in some of the intermediate deciles, with cumulative three-day returns of −8.09% in decile 3, −9.33% in decile 4, −8.95% in decile 5, and −8.81% in decile 8.

But as in the main strategy, these decile portfolios experienced sharp increases on Friday, August 10th, in most cases recouping a significant fraction of the losses. We shall return to this empirical fact in Section 7 when we consider various interpretations for the pattern of losses on August 7–9.

What makes this pattern of loss and gain so puzzling is the fact that there were virtually no signs of market turmoil outside the world of quantitative equity market-neutral funds on August 7th and 8th. For example, Table 4 reports the daily returns of 9 major market indexes spanning a broad array of asset classes (stocks, bonds, currencies, commodities, and volatility) from July 30 to August 31, 2007, and nothing remarkable occurred on August 7th and 8th when the contrarian strategy first began to suffer extreme losses. On August 9th, the S&P 500 did lose 2.95% and the VIX jumped by 5.03, significant one-day moves for both indexes. But these changes cannot explain the losses earlier in the week, nor can they explain the outsized losses of many genuinely market-neutral equity hedge funds, i.e., funds that had virtually no beta exposure to the S&P 500 and positive exposure to volatility.

The one remaining explanation for these extraordinary return patterns is that they were the result of broad-based momentum due to a large-scale strategy liquidation, as discussed in Section 3, and when the liquidation had run its course, the liquidation-driven momentum turned into a strong burst of mean reversion that caused Friday's reversal. We shall return to this explanation in Section 7, after we explore the differences between August 1998 and August 2007 and the implications for expected returns and leverage.

5 Comparing August 2007 with August 1998

The behavior of the contrarian strategy during the second week of August 2007 becomes even more significant when compared to the performance of the same strategy during August 1998, around the time of the Long Term Capital Management (LTCM) debacle. On August 17, 1998 Russia defaulted on its GKO government bonds, causing a global flight to quality that widened credit spreads which, in turn, generated extreme losses in the days that followed for LTCM and other fixed-income arbitrage hedge funds and proprietary trading desks. The specific mechanism that caused these losses—widening credit spreads that generated margin calls, which caused the unwinding of illiquid portfolios, generating further losses and additional margin calls, leading ultimately to a fund's collapse—is virtually identical to the sub-prime mortgage problems that affected Bear Stearns and other credit-related hedge funds in 2007.

However, there is one significant difference between August 1998 and August 2007. Table 5 reports the daily returns of the contrarian strategy (1) during the months of August and September 1998, which show that the turmoil in fixed-income markets had little or no effect on the profitability of our long/short equity strategy. In contrast to August 2007 where an apparent demand for liquidity caused a firesale liquidation that is easily observed in the contrarian strategy's daily returns, the well-documented demand for liquidity in the fixed-income arbitrage space of August 1998 had no discernible impact on the very same strategy. This is a significant difference that signals a greater degree of financial-market integration in 2007 than in 1998. While this may be viewed positively as a sign of progress in financial markets and technology, along with the many benefits of integration is the cost that a financial crisis in one sector can have dramatic repercussions in several others, i.e., contagion.

There are several possible explanations for the difference between August 1998 and August 2007. One interpretation is that in 1998, there were

Table 4 Daily returns of various market indexes from Monday July 30, 2007 to Friday August 31, 2007. With the exception of the Goldman Sachs Commodities Index and the Trade Weighted USD Index, which are obtained from the Global Financial Database, all other data series are obtained from Datastream. In all cases the total returns index is used, which capture the effects of any coupons and/or dividends that would accrue to an investor in the underlying assets of these indexes.

Date	S&P 500 Index (%)	S&P Small Cap 600 Index (%)	MSCI Emerging Markets Index (%)	MSCI World ex. US Index (%)	Lehman Aggregate US Gov. Index (%)	Lehman US Universal Corp. High-Yield Index (%)	Goldman Sachs Commodity Index (%)	Trade Weighted USD Index (%)	CBOE Volatility Index (VIX) Change
7/30/2007	1.03	0.94	0.87	0.14	−0.04	0.18	0.11	−0.12	−3.30
7/31/2007	−1.26	−0.88	1.67	1.36	0.17	0.61	1.18	−0.10	2.65
8/1/2007	0.73	0.19	−3.42	−1.70	0.04	−0.15	−1.34	0.13	0.15
8/2/2007	0.46	0.98	0.61	0.62	0.04	0.53	0.00	−0.20	−2.45
8/3/2007	−2.65	−3.48	−0.05	−0.37	0.29	0.08	−1.10	−0.66	3.94
8/6/2007	2.42	1.35	−1.99	−0.57	−0.14	−0.29	−2.76	0.10	−2.56
8/7/2007	0.62	0.71	0.45	0.56	−0.04	0.38	0.34	0.28	−1.04
8/8/2007	1.44	1.52	2.83	1.88	−0.48	0.84	−0.20	−0.17	−0.11
8/9/2007	−2.95	−1.38	−1.28	−1.52	0.31	−0.07	−0.37	0.54	5.03
8/10/2007	0.04	1.01	−3.30	−2.85	0.07	−0.29	−0.03	−0.12	1.82
8/13/2007	−0.03	−0.84	1.01	1.08	0.04	0.34	0.27	0.46	−1.73
8/14/2007	−1.81	−1.87	−1.42	−1.10	0.23	−0.10	0.35	0.54	1.11
8/15/2007	−1.36	−1.45	−2.39	−1.52	0.15	−0.56	0.80	0.41	2.99
8/16/2007	0.33	1.70	−5.63	−2.91	0.58	−0.59	−3.01	−0.11	0.16
8/17/2007	2.46	2.30	0.12	0.96	−0.28	0.24	1.49	−0.37	−0.84
8/20/2007	−0.03	0.30	3.78	1.23	0.23	0.24	−1.65	−0.03	−3.66
8/21/2007	0.11	0.21	−0.18	0.61	0.24	0.19	−1.14	0.11	−1.08
8/22/2007	1.18	1.19	2.58	1.27	−0.16	0.37	0.04	−0.30	−2.36
8/23/2007	−0.11	−1.16	1.76	1.16	−0.01	0.22	0.96	−0.13	−0.27
8/24/2007	1.16	1.44	0.44	0.51	−0.10	0.04	1.10	−0.59	−1.90
8/27/2007	−0.85	−1.07	1.90	0.29	0.23	0.17	0.28	0.09	2.00
8/28/2007	−2.34	−2.70	−0.85	−1.26	0.34	−0.07	−0.17	0.02	3.58
8/29/2007	2.22	2.28	−0.23	0.04	−0.09	−0.06	1.40	−0.07	−2.49
8/30/2007	−0.41	−0.38	1.31	0.80	0.29	0.06	0.15	0.12	1.25
8/31/2007	1.12	1.28	2.39	1.58	−0.16	0.01	0.48	0.00	−1.68

Table 5 Daily returns of Lo and MacKinlay's (1990) contrarian trading strategy applied to all US common stocks (CRSP share codes 10 and 11) with share prices above $5 and less than $2,000, and market-capitalization deciles, from Monday August 3, 1998 to Friday September 30, 1998. Highlighted dates are: August 17 (default of Russian GKO bonds), August 21 (LTCM loses $550MM in one day), September 3 (first LTCM letter to investors regarding their losses), and September 24 (news about the bailout by the consortium).

	Deciles by market capitalization (%)										
Date	Smallest	Decile 2	Decile 3	Decile 4	Decile 5	Decile 6	Decile 7	Decile 8	Decile 9	Largest	All (%)
8/3/1998	3.35	1.75	1.68	0.15	3.25	−0.33	0.40	0.06	0.62	0.16	1.01
8/4/1998	−0.29	2.16	1.64	−1.35	−1.18	−0.51	−0.82	−0.07	−1.22	−0.16	−0.18
8/5/1998	2.75	1.93	0.68	2.60	2.04	0.93	−0.57	0.38	−0.59	2.56	1.27
8/6/1998	2.25	1.68	2.01	0.36	0.17	−0.33	−1.35	0.15	0.85	1.34	0.66
8/7/1998	3.05	2.99	0.79	0.26	−0.23	0.03	0.12	0.39	2.93	−0.10	0.67
8/10/1998	3.48	1.69	1.53	0.91	0.48	2.23	1.03	−0.23	0.68	0.27	1.27
8/11/1998	2.34	1.72	0.81	−0.24	0.60	1.18	−0.36	0.79	−0.29	−0.14	0.59
8/12/1998	4.83	2.88	2.71	1.31	0.96	0.58	2.01	0.93	1.00	0.68	2.04
8/13/1998	3.74	2.24	0.88	2.72	0.37	0.39	1.03	0.48	−0.11	0.04	1.33
8/14/1998	2.25	1.64	3.57	1.42	−0.46	−0.05	0.66	−0.07	0.77	−0.42	0.94
8/17/1998	2.46	2.48	1.81	0.11	−0.32	1.66	−0.01	−0.80	0.11	0.49	0.96
8/18/1998	4.31	1.85	1.75	3.86	0.35	−0.16	−2.12	0.03	0.29	0.12	0.87
8/19/1998	2.60	2.15	1.16	0.45	−0.65	−0.36	0.34	−0.80	0.06	−0.13	0.63
8/20/1998	1.60	3.04	1.49	0.42	−0.64	0.55	0.87	−0.61	−0.55	−1.47	0.46
8/21/1998	2.26	4.06	2.18	1.79	1.03	−0.06	−0.28	−0.51	0.06	−0.36	1.04
8/24/1998	5.35	1.84	4.13	0.63	−0.83	0.13	−1.57	−1.02	−0.68	0.73	0.90
8/25/1998	2.05	2.19	1.76	0.85	−0.45	−0.34	0.91	−1.46	−0.48	−0.56	0.36
8/26/1998	4.02	1.39	1.78	0.81	−0.31	0.06	−0.43	1.03	−0.65	−0.26	0.61
8/27/1998	1.69	1.15	0.24	−1.16	−2.02	−0.47	−1.54	−1.91	−0.63	−2.20	−0.78
8/28/1998	2.52	2.29	1.33	1.35	0.11	1.12	−1.29	−1.32	−1.18	−0.36	0.39
8/31/1998	3.31	1.79	0.51	−0.36	−3.44	−1.97	−3.08	−4.47	−2.73	−2.82	−1.62
9/1/1998	4.96	4.42	6.04	4.67	9.06	6.68	6.71	6.67	4.90	6.10	6.59

Table 5 *(Continued)*

Date	Smallest	Decile 2	Decile 3	Decile 4	Decile 5	Decile 6	Decile 7	Decile 8	Decile 9	Largest	All (%)
	Deciles by market capitalization (%)										
9/2/1998	4.43	2.74	1.90	0.82	−1.33	0.25	0.86	−0.39	0.45	0.33	0.63
9/3/1998	3.89	3.78	2.08	2.09	0.23	−0.03	0.79	0.15	0.51	0.76	1.41
9/4/1998	5.10	3.95	2.09	0.75	−0.33	−0.84	−1.33	−1.61	−1.15	−3.68	0.26
9/8/1998	3.53	3.40	3.82	0.57	0.60	0.82	1.35	1.05	0.97	3.73	2.08
9/9/1998	1.99	3.62	1.38	1.15	1.12	1.66	1.70	2.10	2.32	2.92	2.42
9/10/1998	4.26	2.68	0.08	2.05	0.96	−0.27	0.64	−0.86	−0.67	−2.16	0.29
9/11/1998	3.34	3.17	2.15	0.77	0.20	0.50	−0.95	1.28	−0.18	0.15	1.24
9/14/1998	3.53	3.58	1.54	0.83	−0.20	−0.42	−0.47	−0.50	0.02	−0.23	0.33
9/15/1998	3.62	2.36	1.34	0.77	−0.17	−0.98	−0.52	−1.15	−0.95	−0.63	0.14
9/16/1998	2.71	3.33	0.89	1.48	0.58	0.83	0.00	0.05	1.53	−0.04	1.01
9/17/1998	3.70	2.24	1.54	1.56	−0.95	0.23	1.10	−0.40	−0.86	0.38	0.79
9/18/1998	4.01	3.94	2.67	1.27	2.55	1.20	−1.17	−1.41	−0.51	−0.45	1.07
9/21/1998	3.22	1.28	1.86	−0.61	−0.87	−0.09	−2.22	1.08	−0.47	−0.32	0.19
9/22/1998	3.26	2.15	1.68	1.76	−0.21	−0.16	−0.62	−2.06	−1.46	0.16	0.42
9/23/1998	4.24	2.16	0.78	−1.66	−0.34	−2.33	−3.08	−3.27	−0.60	−0.42	−0.71
9/24/1998	2.54	1.47	3.13	1.60	0.63	−0.38	−0.06	−0.27	0.59	1.63	1.21
9/25/1998	2.28	3.27	0.16	0.86	0.28	−0.90	−0.66	0.67	1.16	0.36	0.61
9/28/1998	4.24	1.24	1.81	2.64	0.52	−1.30	0.47	−1.58	−0.59	0.16	0.60
9/29/1998	2.75	1.48	−0.07	0.81	−0.83	−1.61	−1.58	−0.83	−1.19	−0.83	−0.29
9/30/1998	2.98	0.41	0.33	−0.96	0.01	−1.00	−1.78	−0.41	−0.10	−0.74	−0.33

fewer multi-strategy funds and proprietary-trading desks engaged in both fixed-income arbitrage and long/short equity, so the demand for liquidity caused by deteriorating fixed-income arbitrage strategies did not spill over as readily to long/short equity portfolios. Another possible explanation is that the amount of capital engaged in long/short equity strategies, particularly statistical arbitrage strategies, was not large enough to cause any significant dislocation even if such strategies were unwound quickly in August 1998. A third possibility is that in 1998, long/short equity funds did not employ as much leverage as they were apparently using in 2007.

We argue in the remaining sections that all three of these interpretations may be correct to some degree.

6 Total assets, expected returns, and leverage

To see how crowded the long/short equity category has become in recent years, we consider the growth in the number of funds and assets under management (AUM) in the Long/Short Equity Hedge and Equity Market Neutral categories of the TASS hedge-fund database.[11] The TASS database is divided into two parts: "Live" and "Graveyard" funds. Hedge funds are recorded in the Live database if they are considered active as of the date of the snapshot. Once a hedge fund decides not to report its performance, liquidates, closes to new investment, restructures, or merges with other hedge funds the fund is transferred into the Graveyard database. A hedge fund can only be listed in the Graveyard database after having been listed in the Live database.[12]

Figure 3 shows that the Long/Short Equity Hedge funds are the most numerous, with over 600 funds in the Live database during the most recent months.[13] However, the number of Equity Market Neutral funds has clearly grown rapidly over the last two years, with just over 100 live funds in the most recent months. Combining these two categories and dividing the total assets under management by the total number of funds in both Live and Graveyard databases, we see from Figure 3 that the average assets per fund has increased exponentially since 1994, starting out at \$62MM in January 1994 and ending at \$229MM in July 2007.

These assets do not reflect the inflows to active extension strategies such as 130/30 funds, which is one of the fastest growing products in the institutional asset management industry. A recently published research report estimates that \$75 billion is currently devoted to such strategies, and in five years this could grow to \$1 trillion (see Merrill Lynch, 2007). Although such strategies are net long by construction, the fact that they hold short positions of up to 30% of their sizable asset base has significant implications for long/short equity hedge funds. For example, because of the increase in shortselling due to 130/30 strategies, shorting "hard-to-borrow" securities has become harder, more securities now fall into the hard-to-borrow category, short positions are less liquid, and "short squeezes" are more likely.

Of course, it is possible that the securities shorted by 130/30 strategies are held long by other long/short equity hedge funds and vice versa, which would enhance liquidity. But the factors causing 130/30 strategies to short a security (e.g., financial ratios, price patterns, bad news) are likely to be the same factors causing hedge funds to short that security. Moreover, the naturally quantitative nature of 130/30 strategies creates an unavoidable commonality between them and quantitative equity market-neutral strategies. For example, the use of commercially available factor-based portfolio optimizers such as those of MSCI/BARRA, Northfield Information Systems, and APT by both 130/30 managers and equity market-neutral

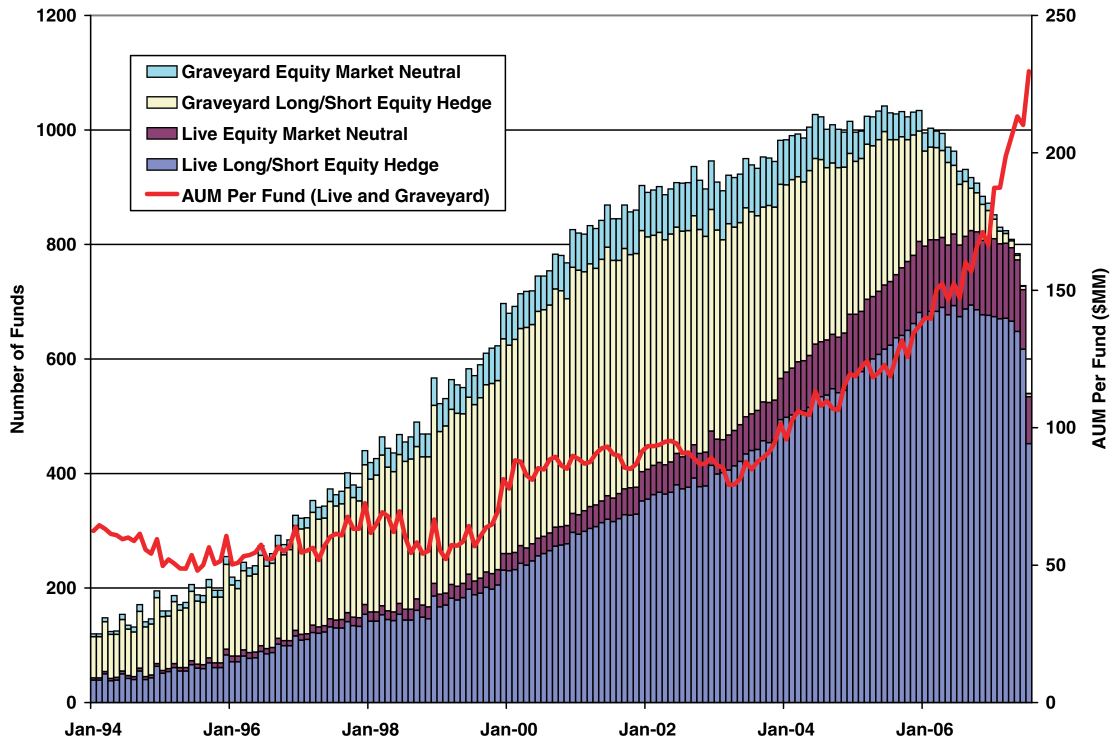


Figure 3 Number of funds in the Long/Short Equity Hedge and Equity Market Neutral categories of the TASS database, and average assets under management per fund, from January 1994 to July 2007.

managers can create common factor exposures between 130/30 and market-neutral portfolios.

The simultaneous increase in the number of long/short equity funds, average assets per fund, and the growth of related strategies like 130/30, imply greater competition and, inevitably, reduced profitability of the strategies employed by such funds. This implication is confirmed in the case of the contrarian trading strategy (1), as Figure 4 illustrates. As the total assets in the Long/Short Equity Hedge and Equity Market Neutral categories grow, the average daily return of the contrarian strategy declines, reaching a low of 0.13% in 2007, and where the total assets in these two categories are at an all-time high of over $160 billion at the beginning of 2007.

It may seem counterintuitive that assets would flow into hedge-fund strategies with declining expected returns. However, recall that the average daily returns reported in Table 2 and plotted in Figure 4 are based on *unleveraged* returns. As these strategies begin to decay, hedge-fund managers have typically employed more leverage so as to maintain the level of expected returns that investors have come to expect, particularly when the volatilities of the underlying instruments have experienced the kind of secular decline in volatility that US equities have during this time period.[14] And because many hedge funds rely on leverage, the size of the positions are often considerably larger than the amount of collateral posted to support those positions. Leverage has the effect of a magnifying glass, expanding small profit opportunities into larger ones, but also expanding small losses into larger losses. And when adverse changes in market prices reduce the market value of collateral, credit is withdrawn quickly, and the subsequent sudden liquidation of large positions over short periods of time can lead to widespread

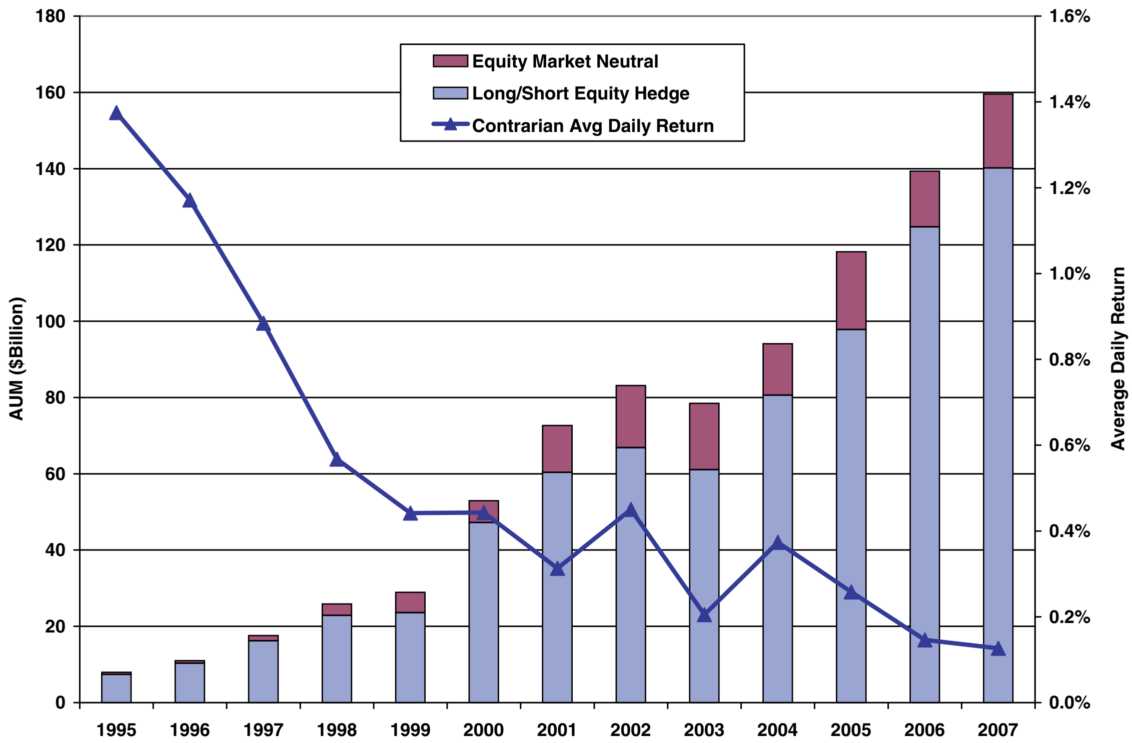


Figure 4 Beginning-of-year assets under management for funds in Long/Short Equity Hedge and Equity Market Neutral categories of the TASS database, from 1995 to 2007, and year-by-year average daily returns of Lo and MacKinlay's (1990) contrarian trading strategy applied to all US common stocks (CRSP share codes 10 and 11) with share prices above \$5 and less than \$2,000, from January 3, 1995 to August 31, 2007.

financial panic, as in the aftermath of the default of Russian government debt in August 1998.

To see how significant an effect this might be in the long/short equity sector, we compute the necessary amount of leverage required in each year after 1998 to yield an expected return for the contrarian strategy that is equal to 1998's level. In other words, we seek values θ^* for the leverage ratio such that:

$$\mathrm{E}[L_{pt}] \equiv \frac{\theta^*}{2}\,\mathrm{E}[R_{pt}] = \mathrm{E}[R_{p,1998}] \tag{4a}$$

$$\theta^* = \frac{2\,\mathrm{E}[R_{p,1998}]}{\mathrm{E}[R_{pt}]}, \qquad t = 1999, \ldots, 2007 \tag{4b}$$

where (4) follows from the definition of leveraged returns (3) and the factor of 2 follows from the definition of leverage as the sum of the gross long and short positions (which are equal in the case of market-neutral portfolios) divided by the investment capital. Table 6 shows that there has been significant "alpha decay" of the contrarian strategy between 1998 and 2007, so much so that a leverage ratio of almost 9:1 was needed in 2007 to yield an expected return comparable to 1998 levels!

We can now simulate a more realistic version of the contrarian strategy in August 2007 using the 2006 leverage ratio of approximately 8:1 as suggested by Table 6, simply by multiplying the entries in Table 3 by $8/2 = 4$, which we do in Table 7 and Figure 5.[15] These returns illustrate the potential

Table 6 Year-by-year average daily returns of Lo and MacKinlay's (1990) contrarian trading strategy applied to all US common stocks (CRSP share codes 10 and 11) with share prices above \$5 and less than \$2,000, from 1998 to 2007, and the return multipliers and leverage factors needed to yield the same average return as in 1998.

Year	Average daily return (%)	Return multiplier	Required leverage ratio
1998	0.57	1.00	2.00
1999	0.44	1.28	2.57
2000	0.44	1.28	2.56
2001	0.31	1.81	3.63
2002	0.45	1.26	2.52
2003	0.21	2.77	5.53
2004	0.37	1.52	3.04
2005	0.26	2.20	4.40
2006	0.15	3.88	7.76
2007	0.13	4.48	8.96

losses that affected long/short equity managers during the week of August 6th. A naive statistical arbitrage strategy like (1), with a leverage ratio of 8:1, would have lost −4.64% on August 7th, followed by daily returns of −11.33% and −11.43%, respectively, on August 8th and 9th. By the close of business on August 9th, the leveraged contrarian strategy would have lost a little over a quarter of the assets it started with three days before!

The fact that the strategy recovered sharply on August 10th with a leveraged return of 23.67% is small comfort for managers and investors who cut their risks on Wednesday and Thursday in response to the unusual size and speed of the losses over those two days. For those with the fortitude (and the credit lines) to maintain their positions throughout the week, they would have experienced an arithmetically compounded weekly return of −1.72%, which is not an unusual return in any respect.[16] However, with cumulative losses of −25% between the 6th and the 9th, many managers capitulated and were forced to de-leverage prior to Friday's reversal.

7 The unwind hypothesis

With the empirically more plausible results of Table 7 in hand, we are now in a position to develop some additional hypotheses about the events of August 2007, which we shall refer to collectively as the "unwind hypothesis."

The fact that the leveraged contrarian strategy lost −4.64% on Tuesday August 7th, and continued to lose another −11.33% on the 8th, suggests a sudden liquidation of one or more sizable market-neutral equity portfolios. Only a sudden liquidation would cause the strategy to lose close to −5% in the absence of any other significant market developments. And the logic behind the inference that market-neutral funds were being liquidated is the fact that both the S&P 500 and MSCI-ex-US indexes showed gains on August 7th and 8th, hence it is unlikely that sizable long-biased funds were unwound on these two days.

The timing of these losses—shortly after month-end of a very challenging month for many hedge-fund strategies—is also suggestive. The formal process of marking portfolios to market typically takes several business days after month-end, and August 7–9 may well be the first time managers and investors were forced to confront the extraordinary credit-related losses they suffered in July, which may have triggered the initial unwind of their more liquid investments, e.g., their equity portfolios, during this period.

The large losses on Tuesday and Wednesday—amounting to −15.98% for our leveraged contrarian strategy—would almost surely have spilled

Table 7 Leveraged daily returns of Lo and MacKinlay's (1990) contrarian trading strategy applied to all US common stocks (CRSP share codes 10 and 11) with share prices above $5 and less than $2,000, and market-capitalization deciles, from Monday July 30, 2007 to Friday August 31, 2007, with 8:1 leverage or a return multiplier of 4.

	Deciles by market capitalization (%)										
Date	Smallest	Decile 2	Decile 3	Decile 4	Decile 5	Decile 6	Decile 7	Decile 8	Decile 9	Largest	All (%)
7/30/2007	−0.28	0.08	7.85	−1.43	0.29	0.91	1.04	1.51	2.05	0.71	1.77
7/31/2007	0.77	4.41	1.12	2.20	−2.53	0.09	−3.19	1.94	−1.23	0.22	1.46
8/1/2007	6.10	1.78	−5.55	1.39	3.79	−3.52	−2.83	−2.52	−8.06	−0.90	0.43
8/2/2007	3.54	−3.04	−0.46	−2.68	−3.77	−10.79	8.63	6.12	−2.97	−0.77	−1.22
8/3/2007	−3.79	−2.49	−3.12	0.24	3.52	0.05	−2.49	−4.35	−2.29	−2.74	−0.10
8/6/2007	−3.33	−7.06	−1.57	−4.12	5.47	−5.47	−4.75	−2.86	1.06	3.08	2.01
8/7/2007	3.00	1.03	−6.55	−11.65	−6.01	−2.79	1.42	−4.08	−6.86	−2.67	−4.64
8/8/2007	3.52	−5.30	−10.36	−14.58	−17.07	−8.65	−8.94	−13.85	−5.06	−5.91	−11.33
8/9/2007	3.66	−7.42	−15.46	−11.08	−12.72	−15.78	−13.06	−17.33	−10.32	−5.22	−11.43
8/10/2007	−1.32	14.62	24.32	31.58	35.08	30.67	30.07	26.79	18.73	9.55	23.67
8/13/2007	5.42	−1.24	−2.53	−4.26	−6.20	−0.88	−5.15	−8.04	−8.58	−4.99	−3.05
8/14/2007	4.65	3.64	−1.02	1.35	2.23	−1.12	2.74	−1.16	0.66	0.67	0.33
8/15/2007	3.52	4.74	−2.42	−2.33	−0.69	−3.89	−0.97	−5.36	−2.29	−4.73	−1.53
8/16/2007	−5.03	−2.16	0.59	−2.36	−2.39	−3.95	−6.94	−5.08	1.08	−7.31	−3.24
8/17/2007	14.30	9.94	0.41	5.04	5.32	−2.07	0.47	−1.56	1.24	0.44	1.53
8/20/2007	15.02	7.02	1.42	5.40	2.03	1.74	4.88	2.22	1.57	4.67	4.58
8/21/2007	4.98	0.43	0.02	−1.80	0.09	−2.54	−0.33	−0.20	0.74	0.43	0.24
8/22/2007	−3.39	−1.23	−2.07	−2.05	−0.67	−3.31	−0.74	−2.26	1.57	0.37	−1.51
8/23/2007	−0.14	2.79	2.79	−0.64	1.51	4.15	1.04	−1.33	1.28	1.23	1.31
8/24/2007	2.47	−1.13	−0.26	0.92	3.70	−0.23	−0.29	0.37	−1.42	2.43	1.73
8/27/2007	4.38	2.80	0.46	0.78	5.01	−0.63	1.58	2.85	2.84	0.10	2.99
8/28/2007	1.64	1.26	0.34	−2.45	−2.56	−1.99	−1.33	−1.77	−1.88	0.99	−3.04
8/29/2007	5.79	0.31	5.07	8.32	7.75	−2.14	5.67	6.39	3.63	3.94	7.06
8/30/2007	4.27	0.16	2.46	1.61	3.55	0.41	−0.11	−0.16	0.47	−0.19	2.01
8/31/2007	6.75	3.86	3.80	−2.21	0.21	2.08	−0.32	−2.68	0.02	0.58	1.46

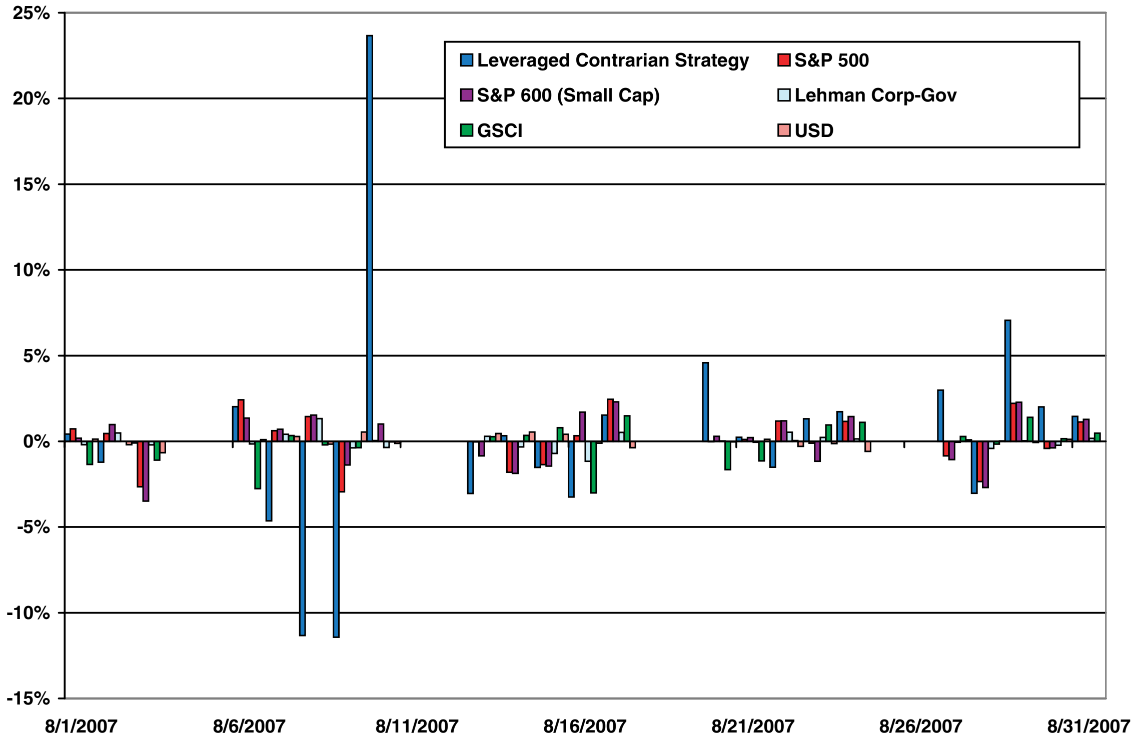


Figure 5 Leveraged daily returns of Lo and MacKinlay's (1990) contrarian trading strategy applied to all US common stocks (CRSP share codes 10 and 11) with share prices above \$5 and less than \$2,000, and miscellaneous indexes, for the month of August 2007, with 8 : 1 leverage or a return multiplier of 4.

over to long/short equity funds as well as to certain quantitative long-only funds. In particular, if our hypothesis is correct that the losses on August 7th and 8th were caused by the unwinding of large equity market-neutral portfolios, then any explicit factors used to construct that portfolio would have generated a loss for other portfolios with the same factor exposures. For example, if the portfolios that were unwound happened to be long low-P/E stocks and short low-dividend-yield stocks, the unwind will cause low-P/E stocks to decline and low-dividend-yield stocks to rise (albeit temporarily, until the unwind is complete). All other portfolios with these same factor exposures will suffer losses during the unwind process as well.

How likely is it that other funds would have the same factor exposures? If they use similar quantitative portfolio construction techniques, then more often than not, they will make the same kind of bets because these techniques are based on the same historical data, which will point to the same empirical anomalies to be exploited, e.g., the value premium, the size premium, the January effect, six-month momentum, one-month mean reversion, earnings surprise, etc. Moreover, the widespread use of standardized factor risk models such as those from MSCI/BARRA, Northfield Information Systems, and APT by many quantitative managers will almost certainly create common exposures among those managers to the risk factors contained in such platforms.

But even more significant is the fact that many of these empirical regularities have been incorporated into non-quantitative equity investment processes, including fundamental "bottom-up" valuation approaches like value/growth characteristics, earnings quality, and financial ratio analysis. Therefore, a sudden liquidation of a quantitative equity market-neutral portfolio could have far broader repercussions, depending on that portfolio's specific factor exposures.

Table 7 contains another interesting pattern that is consistent with a statistical arbitrage unwind—the fact that the losses on August 7th and 8th were most severe for some of the intermediate-decile portfolios (deciles 3–5 and 8 each experienced cumulative losses greater than the other deciles and the entire universe of securities). Given the pattern of average daily returns of the contrarian strategy in decile portfolios (see Table 2), it is the intermediate-decile portfolios that should be most attractive to statistical arbitrage funds. Securities in the larger deciles do not exhibit sufficient profitability, and securities in the smaller deciles are too illiquid to trade in large volume, hence they will not be of interest to the larger funds.

In the face of the large losses of August 7–8, most of the affected funds—which includes market-neutral, long/short equity, 130/30, and certain long-only funds—would likely have cut their risk prior to Thursday's open by reducing their exposures or "de-leveraging," either voluntarily or because they exceeded borrowing and risk limits set by their prime brokers and other creditors. This was both prudent and, unfortunately, disastrous. The unintentionally coordinated efforts of so many equity managers to cut their risks simultaneously led to additional losses on Thursday August 9th, −11.43% in the case of our leveraged contrarian strategy. But this time, the S&P 500 was no longer immune, and dropped by −2.95% by Thursday's close, presumably partly a reflection of the risk reduction by long-biased and long-only managers.[17]

By Thursday's close, the economic forces behind the unwind were apparently balanced by countervailing forces—either because the unwind and risk reductions were complete, or because other market participants identified significant mispricings due to the rapid liquidations earlier in the week—and the losses stopped. Friday's massive reversal, which generated a one-day return of 23.67% for the leveraged contrarian strategy, is the final piece of evidence that the losses of the previous three days were due to a sudden liquidation, and not caused by any fundamental change in the equilibrium returns of long/short equity strategies, which would presumably have had a more permanent impact on price levels.

This pattern of short-term temporary price-impact for purely liquidity-motivated trades is a classic consequence of market equilibrium with information asymmetries between buyers and sellers. When large blocks of securities are executed quickly, equilibrium prices will exhibit greater moves to induce the contra-parties to consummate the trades and bear the risk that they are less informed about the securities' true values.[18] If it is subsequently revealed that the trades were not based on information, but merely liquidity trades, prices move back to their pre-block-trade equilibrium levels. And if there is lingering uncertainty as to whether the trades were motivated by information or liquidity, prices may only partially revert back to their pre-block-trade levels. This partial-adjustment property of the price-discovery process is one compelling reason for "sunshine" trades, the practice of pre-announcing a large trade so as to identify oneself as a liquidity trader with no proprietary information, so as to reduce the price impact of the trade (see Admati and Pfleiderer (1991), and Gennotte and Leland (1990)).

The particular dynamics of the bounce-back on August 10th may have taken several forms. One possibility is that the unwind and subsequent risk reductions were largely achieved by August 9th, and the resulting cumulative price impact of the previous three days would have created even stronger trading signals for those long/short equity strategies that experienced the most significant losses.[19] In the absence of further unwind-motivated price momentum, the natural mean-reverting tendencies of equities that yield positive expected returns for long/short equity strategies during "normal" times would return. Moreover, the price impact of the previous days' unwind and risk-reduction trades would naturally revert to some degree as the fraction of market participants attributing such price movements to liquidity trades increases. However, only a partial reversal should be expected because not everyone would come to the same conclusion, and also because the de-leveraging of August 7–9 leaves a lower amount of capital to be deployed by long/short equity strategies on the 10th.

Another possibility is that the price impact of August 7–9 was so severe that it drew the attention of new investors who: (1) recognized that the closing prices on August 9th were temporarily out of equilibrium due purely to a liquidity crunch; and (2) had access to significant sources of capital to seize the opportunity to buy (sell) securities at artificially deflated (inflated) prices. This injection of new capital—deployed in the opposite direction of the unwind—could have turned the tide, supporting the strong reversal on August 10th.

These two possibilities are not mutually exclusive, but they both suggest that long/short equity strategies are not as liquid as we thought. Alternatively, the common factors driving these strategies have now become a significant source of risk, and the "phase-locking" behavior described in Lo (2001) apparently can cause as much dislocation in long/short equity strategies as in other parts of the hedge-fund industry. To verify this possibility, we turn next to specific measures of illiquidity in long/short equity hedge funds in the TASS database.

8 Illiquidity exposure

The rapid growth in the number of long/short equity funds and assets per fund, coupled with the likely increase in the amount of leverage each fund now employs (see Section 6), suggest a significant decrease in liquidity of long/short equity strategies over the last decade. To explore this possibility, we propose to measure the illiquidity exposure of funds in the Long/Short Equity Hedge and Equity Market Neutral categories of the TASS database using the first-order autocorrelation coefficient of their monthly returns as suggested by Lo (1999) and Getmansky *et al.* (2004). Specifically, using the monthly returns of each fund in the TASS database, we compute:

$$\hat{\rho}_{1i} \equiv \frac{(T-2)^{-1}\sum_{t=2}^{T}(R_{it}-\hat{\mu}_i)(R_{it-1}-\hat{\mu}_i)}{(T-1)^{-1}\sum_{t=1}^{T}(R_{it}-\hat{\mu}_i)^2},$$

$$\hat{\mu}_i \equiv T^{-1}\sum_{t=1}^{T} R_{it} \tag{5}$$

which is simply the correlation between fund *i*'s return and its lagged return from the previous month. Getmansky *et al.* (2004) show that funds with large positive values for $\hat{\rho}_{1i}$ tend to be less liquid,[20] and using a rolling window to estimate these autocorrelation coefficients for various asset return series allows us to capture changes in estimated illiquidity risk for those assets.

A striking example of the autocorrelation coefficient as a proxy for illiquidity is given in Figure 6, which plots the 90-day rolling-window autocorrelations of the first-differences of daily spreads between the March and April 2007 natural-gas futures contracts from August 9, 2004 through November 9, 2006. The time series of first-differences of the March/April 2007 spreads is a proxy for the daily returns of one of the largest strategies that Amaranth Advisors was allegedly engaged in, and in which they were alleged to have built up a large and

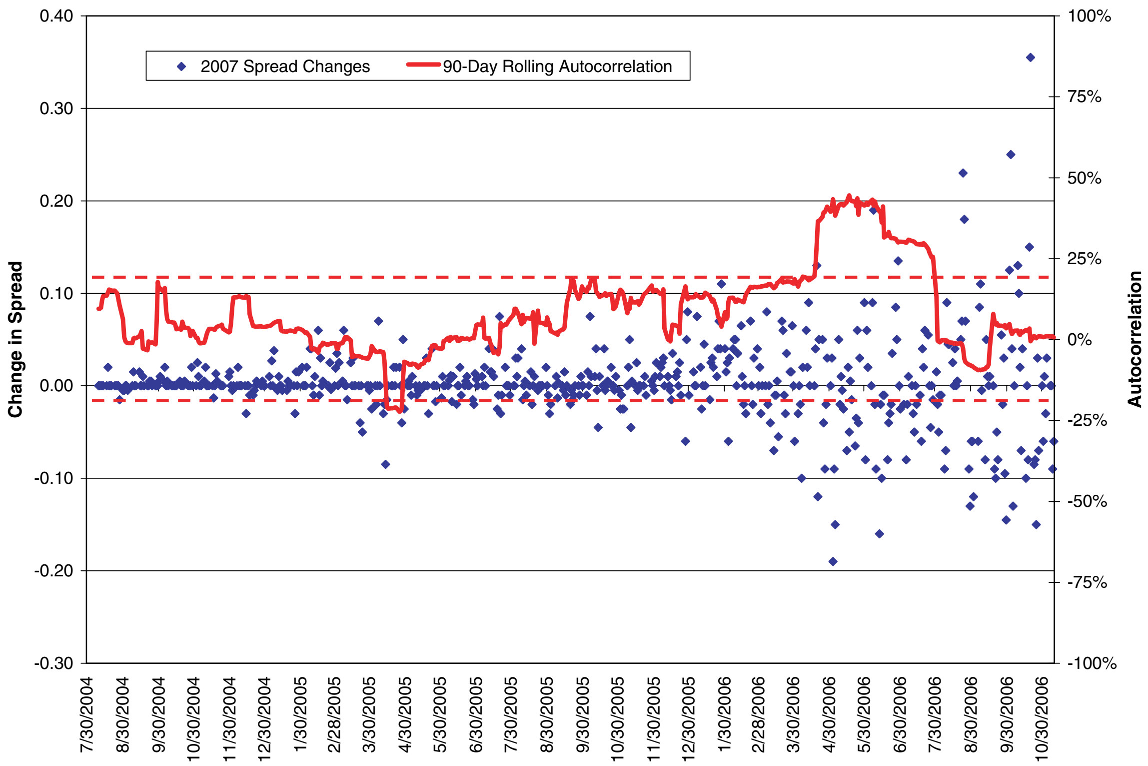


Figure 6 First-differences of March/April 2007 natural-gas futures spreads (dots), and 90-day rolling-window first-order autocorrelations $\hat{\rho}_1$ (solid line) of those first-differences, from August 9, 2004 to November 9, 2006. Dotted lines indicate the two-standard-deviation confidence band for the rolling-window autocorrelations under the null hypothesis of zero autocorrelation.

illiquid position prior to their demise in September 2006. Figure 6 shows that the rolling autocorrelations began climbing throughout 2005, nearly breached the 95% confidence interval in September and October 2005, and did breach this threshold on April 18, 2006, staying well above this level until August 2006 when Amaranth and other similarly positioned hedge funds were presumably forced to unwind this spread trade.

Using $\hat{\rho}_{1i}$ as a measure of the illiquidity of each fund i, we can construct three aggregate measures of the illiquidity exposure of long/short equity funds along the lines of Chan *et al.* (2006, 2007), i.e., by computing the mean and median of rolling-window $\hat{\rho}_{1i}$'s over all funds i in the TASS Long/Short Equity Hedge and Equity Market Neutral categories month by month:

$$\hat{\rho}_{at} \equiv \frac{1}{n}\sum_{i=1}^{n} \hat{\rho}_{1it} \text{ (equal-weighted mean)} \tag{6a}$$

$$\hat{\rho}_{bt} \equiv \sum_{i=1}^{n} \frac{\text{AUM}_{it}}{\sum_j \text{AUM}_{jt}} \hat{\rho}_{1it} \text{ (asset-weighted mean)} \tag{6b}$$

$$\hat{\rho}_{ct} \equiv \text{Median}(\hat{\rho}_{11t}, \ldots, \hat{\rho}_{1nt}). \tag{6c}$$

In Figure 7, the equal-weighted and asset-weighted means and the median of 60-month rolling-window autocorrelations of individual hedge-fund returns are plotted from December 1994 to June 2007 using all funds in the two equity categories in both Live and Graveyard databases that report assets under management in US dollars, and with at

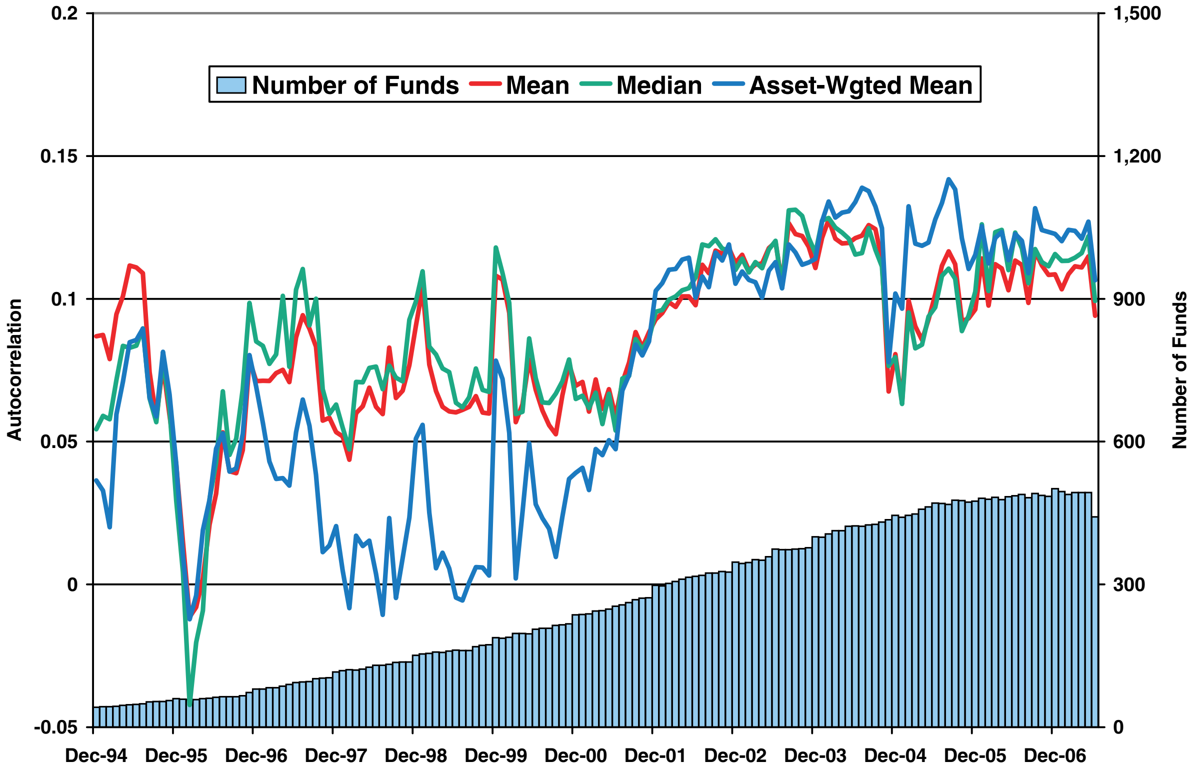


Figure 7 Mean, median, and asset-weighted mean 60-month rolling autocorrelations of funds in the TASS Live and Graveyard database in the Long/Short Equity Hedge and Equity Market Neutral categories, from December 1994 to June 2007.

least 60 months of non-missing returns.[21] These three series tell the same story: except for a brief decline in late 2004, the aggregate autocorrelation of Long/Short Equity Hedge and Equity Market Neutral funds has been on the rise since 2000, implying a significant decline in the liquidity of this sector over the past 6 years.[22]

Of course, the absolute level of illiquidity exposure in these two categories is still considerably lower than in many other categories, e.g., Convertible Arbitrage or Emerging Markets (see Getmansky *et al.* (2004) and Chan *et al.* (2006, 2007) for further details). But the fact that the autocorrelations have increased at all in the most populous and, traditionally, among the most liquid of all sectors in the hedge-fund industry, is certainly noteworthy. This is another indication that systemic risk in the hedge-fund industry has increased recently.

9 A network view of the hedge-fund industry

A common theme surrounding the "unwind" phenomenon in the hedge-fund industry is credit and liquidity. Although they are separate sources of risk exposures for hedge funds and their investors—one type of risk can exist without the other—nevertheless, credit and liquidity have been inextricably intertwined in the minds of most investors because of the problems encountered by LTCM and many other fixed-income relative-value hedge funds in August 1998. There has been much progress in the recent literature in modeling credit and illiquidity risk,[23] but the complex network of creditor/obligor relationships, revolving credit agreements, and other financial interconnections is still largely unmapped. Perhaps some of the newly developed techniques in the mathematical theory of networks will allow us to construct systemic measures for liquidity and credit exposures and the robustness of the global financial system to idiosyncratic shocks. The "small-world" networks considered by Watts and Strogatz (1998) and Watts (1999) seem to be particularly promising starting points. However, given the lack of transparency in the hedge-fund industry, we have no direct way of gathering the data required to estimate the "network topology" that is the starting point of these techniques.

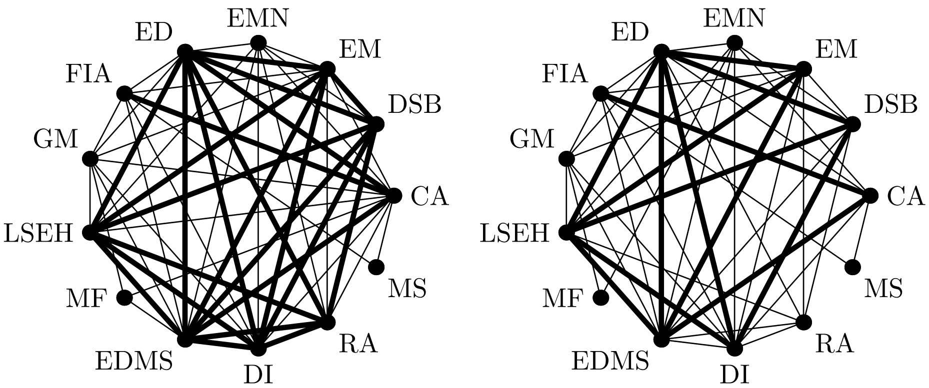
One indirect and crude measure of the change in the "degree of connectedness" in the hedge-fund industry is to calculate the changes in the absolute values of correlations between hedge-fund indexes over time.[24] Using 13 indexes from April 1994 to June 2007 constructed by CS/Tremont,[25] we compare their estimated pairwise correlations between the first and second half of our total sample period: April 1994 to December 2000 versus January 2001 to June 2007. If, for example, the absolute correlation between Multi-Strategy and Emerging Markets was 7% over the first half of the sample and 52% over the second half, as it was, this might be a symptom of increased connectedness between those two categories.

Figure 8 provides a graphical depiction of this network for the two sub-samples, where we have used thick lines to represent absolute correlations greater than 50%, thinner lines to represent absolute correlations between 25% and 50%, and no lines for absolute correlations below 25%. For the earlier sub-sample, we estimate correlations with and without August 1998, and the difference is striking. Omitting August 1998 decreases the correlations noticeably, which is no surprise given the ubiquity and magnitude of the LTCM event. But a comparison of the two sub-periods shows a significant increase in the absolute correlations in the more recent sample. The hedge-fund industry has clearly become more closely connected.

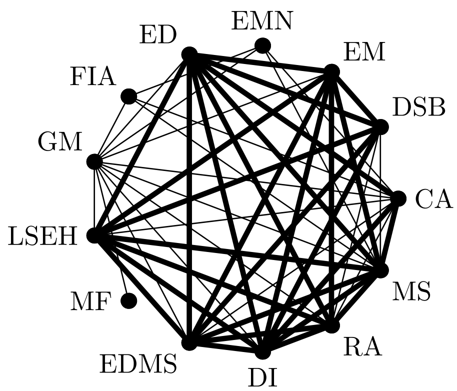
Perhaps the most significant indicator of increased connectedness is the fact that the Multi-Strategy category is now more highly correlated with almost every other index, a symptom of the large influx of assets into the hedge-fund industry. This increased correlation is also consistent with the hypothesis that forces outside the long/short equity sector may have caused an unwind of statistical arbitrage strategies in August 2007. In August 1998, multi-strategy funds were certainly impacted by their deteriorating fixed-income arbitrage positions, and no doubt many of them liquidated their statistical arbitrage portfolios to meet fixed-income margin calls. But because multi-strategy funds were not as significant a market force in 1998 as they evidently are now, their correlations to other strategies were not as large as they are today.

Table 8 contains a more detailed comparison of the two correlation matrices. The absolute correlation matrix from the earlier sample is subtracted from that of the more recent sample, hence a positive entry represents an increase in the absolute correlation in the more recent period, and is highlighted in red if it exceeds 20% (negative entries less than −20% are highlighted in blue). Table 8 confirms the patterns of Figure 8: absolute correlations among the various different hedge-fund categories have indeed increased in the more recent sample, with considerably more positive entries than negative ones.

To capture the dynamics of these changes in correlation structure among the CS/Tremont Indexes, in Figure 9 we plot the means and medians of the



(a) April 1994 to December 2000, with (left) and without (right) August 1998



(b) January 2001 to June 2007

Figure 8 Network diagrams of correlations among 13 CS/Tremont hedge-fund indexes over two subperiods, April 1994 to December 2000 (with and without August 1998) and January 2001 to June 2007. Thicker lines represent absolute correlations greater than 50%, thinner lines represent absolute correlations between 25% and 50%, and no connecting lines correspond to correlations less than 25%. CA: Convertible Arbitrage, DSB: Dedicated Short Bias, EM: Emerging Markets, EMN: Equity Market Neutral, ED: Event Driven, FIA: Fixed Income Arbitrage, GM: Global Macro, LSEH: Long/Short Equity Hedge, MF: Managed Futures, EDMS: Event Driven Multi-Strategy, DI: Distressed Index, RA: Risk Arbitrage, and MS: Multi-Strategy.

absolute values of 36-month rolling-window correlations between the indexes, with and without the month of August 1998.[26] These graphs show that the mean and median absolute correlations among the indexes have been steadily increasing in recent years, especially after 2004. The inordinate amount of influence that August 1998 has on these correlations underscores the potential for system-wide shocks in the hedge-fund industry.

The increase in correlations among hedge-fund returns can be attributed to at least two potential sources: increased exposure of hedge funds to standard factors such as the S&P 500, the US 10-Year Treasury bond, and the US dollar index, and increased linkages due to more complex channels such as liquidity and credit relationships through multi-strategy funds and proprietary trading desks. Unfortunately, without more detailed data from

Table 8 The difference of the absolute correlation matrices of CS/Tremont Hedge-Fund Indexes using recent data (January 2001 to June 2007) and earlier data (April 1994 to December 2000), where the earlier correlation matrix is estimated with and without August 1998.

	Convertible arbitrage (%)	Dedicated short bias (%)	Emerging markets (%)	Equity market neutral (%)	Event driven (%)	Fixed income arbitrage (%)	Global macro (%)	Long short equity (%)	Managed futures (%)	Event driven multi-strategy (%)	Distressed (%)	Risk arbitrage (%)	Multi-strategy (%)
					With August 1998 Included								
Convertible arbitrage		−1	−24	−4	−7	−38	11	6	−18	−14	1	−3	31
Dedicated short bias	−1		3	−35	−6	2	4	−12	−15	0	−11	−5	46
Emerging markets	−24	3		−6	−10	−25	−2	11	−9	−11	−10	6	45
Equity market neutral	−4	−35	−6		−33	32	6	−15	−18	−25	−40	−7	16
Event driven	−7	−6	−10	−33		−18	−6	4	−16	3	−3	0	69
Fixed income arbitrage	−38	2	−25	32	−18		1	−5	−1	−25	−9	−5	−3
Global macro	11	4	−2	6	−6	1		−14	15	−13	−2	12	34
Long/short equity	6	−12	11	−15	4	−5	−14		20	10	−7	12	69
Managed futures	−18	−15	−9	−18	−16	−1	15	20		−16	−12	−23	19
Event driven multi-strategy	−14	0	−11	−25	3	−25	−13	10	−16		1	−2	67
Distressed	1	−11	−10	−40	−3	−9	−2	−7	−12	1		3	57
Risk arbitrage	−3	−5	6	−7	0	−5	12	12	−23	−2	3		53
Multi-strategy	31	46	45	16	69	−3	34	69	19	67	57	53	

Table 8 *(Continued)*

	Convertible arbitrage (%)	Dedicated short bias (%)	Emerging markets (%)	Equity market neutral (%)	Event driven (%)	Fixed income arbitrage (%)	Global macro (%)	Long short equity (%)	Managed futures (%)	Event driven multi-strategy (%)	Distressed (%)	Risk arbitrage (%)	Multi-strategy (%)
						Excluding August 1998							
Convertible arbitrage		17	−9	2	5	−37	15	21	−8	−2	20	15	27
Dedicated short bias	17		14	−31	7	3	11	−7	−2	19	3	11	47
Emerging markets	−9	14		1	0	−20	1	20	−3	0	5	25	46
Equity market neutral	2	−31	1		−33	34	9	−10	−27	−21	−39	1	15
Event driven	5	7	0	−33		−19	−8	10	3	10	4	23	63
Fixed income Arbitrage	−37	3	−20	34	−19		3	2	4	−26	−4	5	−4
Global Macro	15	11	1	9	−8	3		−11	8	−14	2	21	34
Long/short equity	21	−7	20	−10	10	2	−11		15	19	3	27	67
Managed futures	−8	−2	−3	−27	3	4	8	15		3	−13	−6	18
Event driven multi-strategy	−2	19	0	−21	10	−26	−14	19	3		25	20	60
Distressed	20	3	5	−39	4	−4	2	3	−13	25		32	54
Risk arbitrage	15	11	25	1	23	5	21	27	−6	20	32		53
Multi-strategy	27	47	46	15	63	−4	34	67	18	60	54	53	

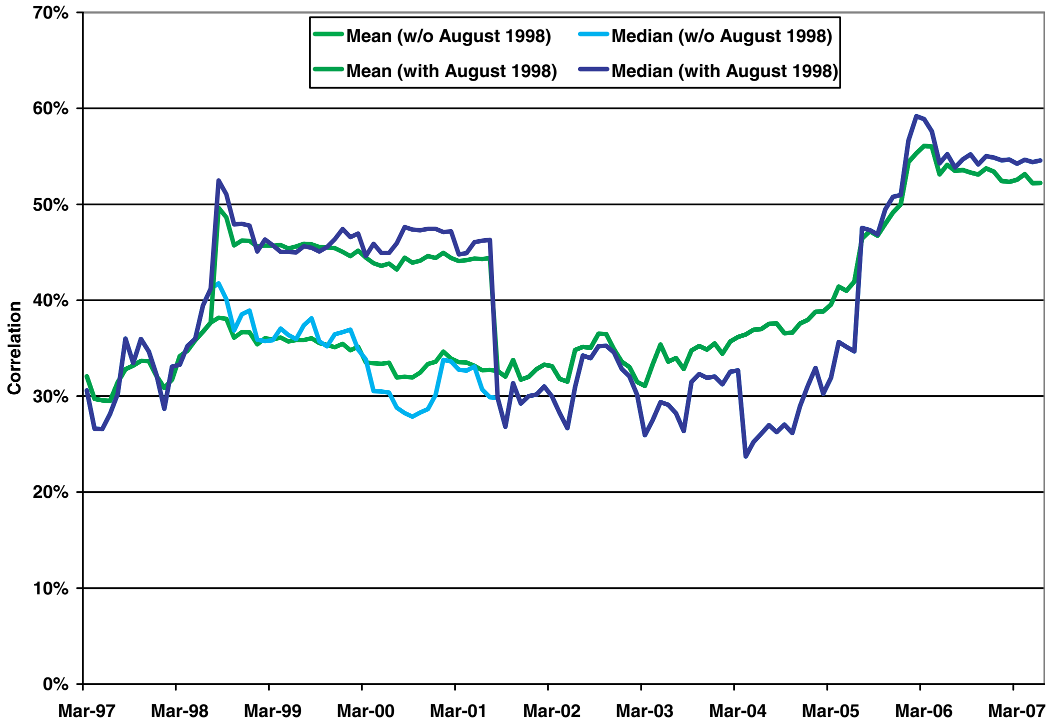


Figure 9 Mean and median absolute 36-month rolling-window correlations among CS/Tremont hedge-fund indexes from March 1997 to June 2007, with and without August 1998.

hedge funds and their creditors and obligors, we have no way of distinguishing between these two sources of commonality.

One subtlety in interpreting the time variation in correlations is the possibility that the changes are due to volatility shifts, not to changes in the covariances of returns. This distinction may not be particularly relevant from the perspective of systemic risk exposures because an increased correlation between variables X and Y does imply higher co-movement of two variables per unit of $\sigma_x\sigma_y$, irrespective of whether that increase has come about from an increase in the numerator or a decrease in the denominator. For example, suppose that the volatility in X declines suddenly, but the covariance between X and Y remains unchanged, yielding an increase in the absolute value of the correlation between X and Y. This increased absolute correlation is not spurious, but is the direct result of the volatility of X declining while the covariance between X and Y remained unchanged, and this combination of facts does imply a more "significant" relation between X and Y, where significance is measured in units of $\sigma_x\sigma_y$.[27] Nevertheless, from the portfolio-construction perspective, increases in correlation need not imply increased portfolio risk, simply because the portfolio variance is the weighted sum of all the pairwise covariances of the constituent assets. Specifically, a decrease in the volatilities of all assets while covariances are held constant would imply a lower portfolio volatility, despite the fact that all pairwise correlations have increased in absolute value due to the lower asset-volatility levels.

Figure 10 plots the 36-month rolling-window pairwise covariances between the CS/Tremont Multi-Strategy Index and other CS/Tremont Sector Indexes from December 1996 to June 2007, where

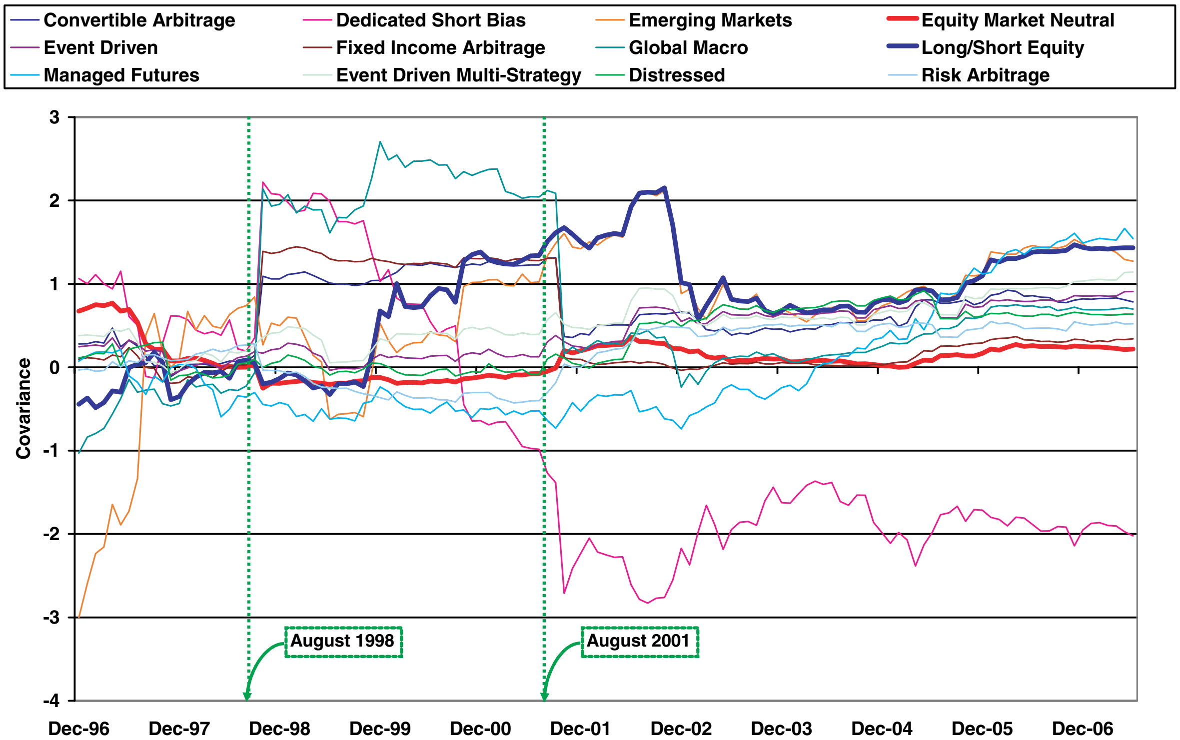


Figure 10 36-month rolling-window pairwise covariances between the CS/Tremont Multi-Strategy Index and other CS/Tremont Sector Indexes from December 1996 to June 2007.

the rolling covariances to the Long–Short Equity and Equity Market Neutral Indexes are highlighted using thicker lines. The 36-month window following August 1998 is also marked with dotted lines to highlight the impact this period has on our rolling estimates. These plots show that in the 1990's, pairwise covariances between Multi-Strategy and other sectors were quite heterogeneous and noisy, but in the last seven years, the covariances have clustered together, with the exception of Dedicated Short Bias (as expected), and exhibit upward trends.

The fact that Multi-Strategy did not have a reliably negative covariance to Dedicated Short Bias in the 1990's is notable, particularly in light of the strong negative covariance in the last half of the sample. One interpretation of this shift is that Multi-Strategy did not have a significant equity component in the 1990's, but this has changed over the past seven years, and is consistent with the increased covariance between Multi-Strategy and the two equity indexes since 1999.

Of course, volatility in US equity markets has declined over the past seven years, so a significant portion of the increased correlations between Multi-Strategy and the two equity indexes is due to smaller denominators, not just increased numerators. But both shifts have important implications for the systemic risk of the hedge-fund industry, and neither should be ignored or dismissed.

Of course, pairwise correlations of indexes are very crude measures of the connectedness of the hedge-fund industry. Moreover, the network map of the global financial system is considerably more complex, involving many different types of organizations (banks, hedge funds, prime brokers, investors, regulators, etc.), and different types of relationships between these organizations. Although a number of recent papers have applied the mathematical theory of networks to financial markets,[28] there is virtually no data with which to calibrate such models. In an industry that protects its intellectual property primarily through trade secrets, it may be impossible to collect the necessary information to map the network topology without additional regulatory oversight.

10 Did "Quant" fail?

In light of Section 7's unwind hypothesis, what can we conclude about whether or not quantitative equity market-neutral strategies failed en masse in August 2007? We have a specific definition of failure in mind: Do the losses of August 2007 signal a breakdown in the basic economic relationships that yield attractive risk/reward profiles for such strategies, or is August 2007 an unavoidable and integral aspect of those risk/reward profiles?

An instructive thought experiment is to consider a market-neutral portfolio strategy in which US equities with odd-numbered CUSIP identifiers are held long and those with even-number CUSIPs are held short. Suppose such a portfolio strategy is quite popular and a number of large hedge funds have implemented it. Now imagine that one of these large hedge funds decides to liquidate its holdings because of some liquidity shock. Regardless of this portfolio's typical expected return during normal times, in the midst of a rapid and large unwind, all such portfolios will experience losses, with the magnitudes of those losses directly proportional to the size and speed of the unwind. Moreover, it is easy to see how such an unwind can generate losses for other types of portfolios, e.g., long-only portfolios of securities with prime-number CUSIPs, dedicated shortsellers that short only those securities with CUSIPs divisible by 10, etc. If a portfolio is of sufficient size, and it is based on a sufficiently popular strategy that is broadly implemented, then unwinding even a small fraction of it can cascade into a major market dislocation.

Therefore, it is tempting to conclude that the events of August 2007 are not particularly relevant to the efficacy of quantitative investing. The losses were more likely the result of a firesale liquidation of quantitatively constructed portfolios rather than the specific shortcomings of quantitative methods. In this respect, the dislocation experienced by quantitative equity market-neutral managers in August 2007 resembles the dislocation experienced by US equityholders in October 1987, fixed-income arbitrage managers in August 1998, sub-prime mortgage-related managers in 2007, Japanese real-estate investors in the 1990's, internet-stockholders in March 2000, and Dutch tulip-bulb investors in February 1637.[29] What played out in August 2007 was not new at all, but may be an age-old dynamic of risk-taking opportunism punctuated by occasional flights to safety and liquidity.

However, a successful investment strategy should include an assessment of the risk of ruin, and that risk should be managed appropriately. Moreover, the magnitude of tail risk should, in principle, be related to a strategy's expected return given the inevitable trade-off between risk and reward. Therefore, it is disingenuous to assert that "a strategy is successful except in the face of 25-standard-deviation events." Given the improbability of such events, we can only conclude that either the actual distribution of returns is extraordinarily leptokurtic, or the standard deviation is time-varying and exhibits occasional spikes.

In particular, as Montier (2007) observed, risk has become "endogenous" in certain markets—particularly those that are recently flush with large inflows of assets—which is one of the reasons that the largest players can no longer assume that historical estimates of volatility and price impact are accurate measures of current risk exposures. Endogeneity is, in fact, an old economic concept illustrated by the well-known theory of imperfect competition—if an economic entity, or group of coordinated entities, is so large that it can unilaterally affect prices by its own actions, then the standard predictions of microeconomics under perfect competition no longer hold. Similarly, if a certain portfolio strategy is so popular that its liquidation can unilaterally affect the risks that it faces, then the standard tools of basic risk models such as Value-at-Risk and normal distributions no longer hold. In this respect, quantitative models may have failed in August 2007 by not adequately capturing the endogeneity of their risk exposures. Given the size and interconnectedness of the hedge-fund industry, we may require more sophisticated analytics to model the feedback implicit in current market dynamics.

For example, from a purely statistical perspective, the mere threat of a forced liquidation of a given strategy should increase the theoretical volatility of the entire class of such strategies, and the more illiquid the underlying assets and the larger the potential liquidation, the larger the increase in volatility. But theoretical volatilities are not observable, and must be estimated, which is the crux of the problem: if the historical record contains no realizations of an extreme event, statistical estimators based on that record alone cannot reflect the possibility of such events. Moreover, by definition tail events are rare, hence any statistical estimator of such events will be based on very small samples and subject to large estimation error.

Therefore, August 2007 offers a number of insights for improving the quantitative methods for measuring and managing risks. One of the most important lessons is the need for measures of illiquidity risk, and that volatility is an inadequate measure of risk, especially for relative-value strategies like quantitative equity-market neutral where the market-making characteristics of the strategy tend to attenuate market fluctuations, yielding lower volatility estimates that are used to justify higher amounts of leverage. In the case of August 2007, traditional risk measures could have been augmented with estimates of factor and illiquidity exposures in the Long/Short Equity and Equity Market Neutral categories of the TASS database to yield a broader assessment of the risks facing managers in this sector. To the extent that we can develop a better framework and a set of analytics for measuring illiquidity and other risk exposures in financial markets—perhaps along the lines of Gennotte and Leland (1990), Lo (1999, 2001, 2002), Getmansky *et al.* (2004), Getmansky *et al.* (2004), and Chan *et al.* (2006, 2007)—we may be able to reduce the impact of future liquidity events.

Another important issue is the role that investment horizon played in the market reaction to August 2007. Short-term investors that reduced their risks intra-month suffered the most, while many long-term investors enjoyed positive returns for the month, and this difference bears further study. A related issue is the differences between strategies employing exchange-traded securities that are marked-to-market continuously, versus strategies with OTC contracts or highly illiquid securities whose valuations are not observed as frequently. This distinction may well explain why the aftermath of August 2007 was so different than that of August 1998. One possible explanation is that the infrequent valuation of illiquid assets yields a certain degree of flexibility for portfolio managers that exchange-traded instruments do not allow. This flexibility comes from the fact that credit lines provided by prime brokers and other creditors are often contingent on the valuation of the corresponding collateral, and any material change in that valuation can trigger margin calls and, ultimately, a reduction or withdrawal of credit. For portfolios of continuously marked-to-market securities, margin calls can occur more frequently by definition than for portfolios with hard-to-value securities.[30] We conjecture that a major reason for the quick reversal of quantitative portfolios on August 10th is the fact that the securities involved were mostly exchange-traded equities, for which the price-discovery mechanism allowed market participants to better understand the dynamics of the losses during August 7–9. Had the alleged unwind of August 2007 involved illiquid OTC contracts, we suspect that the losses would have been considerably larger and any reversal would have taken much longer to materialize.

While market participants will no doubt learn from August 2007 and improve their strategies and risk management protocols, it is unlikely that the possibility of future dislocations can be completely eliminated by such improvements. Events like August 2007 may simply be unavoidable features of quantitative equity market-neutral strategies. In fact, the profit-and-loss patterns these strategies in August 2007 are consistent with those of a broader set of market-making and relative-value strategies: small but steady positive returns most of the time, coupled with occasional short-lived bursts of significant loss. Such risk/reward profiles are quite attractive to a certain set of investors—those that understand the nature of "tail risk" and can withstand the inevitable rare event. For example, which of the following two gambles is best?:

$$G_1 = \begin{cases} \$75{,}000 & \text{with probability } 50\% \\ \$25{,}000 & \text{with probability } 50\% \end{cases}$$

$$G_2 = \begin{cases} \$100{,}000 & \text{with probability } 98\% \\ -\$1{,}000{,}000 & \text{with probability } 2\% \end{cases}$$

The first gamble entails less risk of loss (the worst case is a gain of $25,000) but has an expected return of $50,000, which is lower than the expected return of $78,000 for the second gamble. The second gamble is almost sure to yield a higher payoff than the first, but has a small probability of a very significant loss. There is no correct answer to which is best—the optimal choice depends entirely on an individual's risk preferences (see Lo (1999)).

A less contrived example is the catastrophe-insurance industry, in which insurers routinely bet against tail events, and most of the time, they enjoy steady cashflows from their policyholders. However, on occasion, they suffer great losses when disaster strikes, but they are adequately capitalized so such events typically do not cause widespread dislocation in that industry. The one circumstance in which problems can arise in the catastrophe-insurance industry is when there is too much capital, causing so much downward pressure on insurance premia that a number of insurers cannot cover their costs, i.e., they become under-capitalized and cannot survive a tail event. In such cases, the demand for catastrophe insurance cannot support the excess supply, and the occurrence of a tail event causes an industry shake-out where only the most well-capitalized insurers survive. In the aftermath of such a shake-out, premiums will rise, creating great profit opportunities for the remaining players which, in turn, will attract new insurers to the industry, and the cycle begins again. The correspondence of this insurance cycle to the quantitative equity market-neutral business is no accident.[31]

There is also a competitive and strategic element to whether a given manager or prime broker should reduce leverage given the actions of other managers and brokers. If we all agree to reduce leverage so as to decrease the likelihood of a major market dislocation due to forced liquidation, then each manager and prime broker has an incentive to deviate from this agreement and reap the benefits of increasing leverage while everyone else cuts back. Without a mechanism for enforcing cooperation, such agreements are not stable, and unlikely to arise in practice.[32] In fact, because of the lack of transparency and coordination within the hedge-fund industry, and the strong relationship between performance and business viability, competitive pressures will lead managers and prime brokers to *increase* leverage in an "arms race" for generating better returns.

This perspective provides further support for the Adaptive Markets Hypothesis of Farmer and Lo (1999) and Lo (2004, 2005), in which financial markets are not always and everywhere efficient, but where competition, mutation, adaptation, and natural selection jointly determine the dynamics of market prices and quantities. The growth in hedge-fund assets, the growth in the number of new hedge funds, the apparent increase in leverage, and the proliferation of hedge-fund products and services are the most recent manifestations of the relentless search for investment performance and economic gain, i.e., the survival instinct. As a particular type of strategy becomes "crowded"—meaning too much capital deployed relative to the returns generated per unit risk—capital will leave this sector to seek out more attractive risk/reward profiles, thereby improving the risk/reward profile for the remaining population, which then attracts new capital and restarts the cycle.

Such cycles are commonplace in ecological models of population dynamics, and the Adaptive Markets Hypothesis is an application of this framework to the population of investors, managers, and creditors. If August 2007 is to be viewed as a failure, it was a failure to recognize the ineluctable cycle of profit and loss that all types of investment strategies seem to exhibit over time. But to expect individual market participants to identify and avoid such cycles is not only unrealistic, it flies in the face of basic economics. In the absence of any reason for coordination, market participants will seek to maximize their own welfare, and doing so implies that each will push the limits of his investments to the point at which the risk-adjusted expected returns are equalized across all investment opportunities. With limited information regarding the nature and extent of other market participants' investments, each participant must estimate the risk/reward profile of each strategy and determine the appropriate level of capital to deploy. Since such estimates are subject to error, the natural feedback of losses and gains, i.e., action is spurred by losses and complacency is induced by gains, implies the waxing and waning of strategies and the cyclical flow of capital described above.

A remaining open question is whether investors truly understood and preferred the particular risks of quantitative equity market-neutral strategies in recent years. While only "qualified investors" are meant to have access to hedge funds, the ubiquity of delegated financial management suggests that the dislocation of August 2007 may well have spilled over to less sophisticated investors' pension funds and other retirement assets. Whether this type of spill-over effect is appropriate touches upon a series of complex policy issues surrounding the implicit paternalism of pension-fund management by fiduciaries. Can a pension plan sponsor make investment decisions that are in the "best interests" of all of the plan participants, even when those participants have widely varying risk preferences and financial objectives? Unfortunately, we have little to add to this controversy, other than to acknowledge its relevance for the question of whether quantitative equity market-neutral managers should or should not have reduced their risk levels prior to August 2007. If all three sets of stakeholders—managers, investors, and creditors—were aware of the risks and willing to bear them, then August 2007 is merely the cost of doing business. If not, then August 2007 signalled another kind of failure in this industry.

11 Qualifications and extensions

Although the unwind hypothesis of Section 7 seems to be consistent with our empirical results, we emphasize the caveat of Section 1: all of our inferences are indirect, tentative, and without the benefit of much hindsight given the recency of these events. We have no inside information about the workings of the many hedge funds that were affected in August 2007, nor do we have any proprietary access to prime brokerage records, trading histories, or industry leverage data. Therefore, our academic perspective of the events during the week of August 6–10 should be interpreted with some caution and a healthy dose of skepticism.

In particular, our empirical findings are based on only one very simple strategy applied to US stocks, which may be representative of certain short-term market-neutral mean-reversion strategies, but is not likely to be as good a proxy for the broader set of quantitative long/short equity products that involve both United States and international equities, and other securities. For example, we apply our naive strategy indiscriminately to an undistinguished universe of US securities, using no other factors besides past returns, and with no consideration of execution costs or risk-adjusted return contributions. This test strategy is clearly missing many other features of long/short equity funds. To continue the microscope analogy, we have used just one lens of rather limited magnification to look at August 2007. A more refined analysis using multiple lenses with different resolutions will no doubt yield a more complex and accurate picture of the very same events. For example, the contrarian strategy does not contain any factor-based selection algorithms, hence its performance may not reflect as clearly the unwind of factor-based portfolios.

More importantly, even if our hypothesis is correct that an unwind initiated the losses on August 7th, we cannot say much about the ultimate causes of such an unwind. It is tempting to conclude that a multi-strategy proprietary trading desk's increased exposure to sub-prime mortgage portfolios caused it to reduce leverage by liquidating a portion of its most liquid positions, e.g., a statistical arbitrage portfolio, thereby initiating the losses on August 7th that cascaded into the subsequent rout. However, another possible scenario is that several quantitative equity market-neutral managers decided at the beginning of August that it would be prudent to reduce leverage in the wake of so many problems facing credit-related portfolios. They de-leveraged accordingly, not realizing that this strategy was so crowded and that the price impact of their liquidation would be so severe. Once this price impact had been realized, other funds employing similar strategies may have decided to cut their risks in response to their losses, which then led to the kind of "death spiral" that we witnessed in August 1998 as managers attempted to unwind their fixed-income arbitrage positions to meet margin calls.

Whether or not the initial losses on August 7th were caused by a forced liquidation or a voluntary reduction in risk is impossible to determine from our outsider's perspective. But the fact that an entire category of strategies as liquid as Long/Short Equity could suffer such significant losses in the absence of any real market news suggests that the current level of liquidity is less than we thought. Alternatively, we learned in August 2007 that there is more commonality among long/short equity strategies than we anticipated. This commonality may be even broader, as suggested by the fact that all the CS/Tremont Hedge-Fund Indexes yielded losses in August 2007 (see Table 9).

Our use of the TASS hedge-fund database also requires some qualification. The TASS database consists entirely of funds that have voluntarily agreed to be included, with no legal obligations to report either regularly or accurately. In fact, many of the high-profile managers that made headlines in

Table 9 CS/Tremont hedge-fund index returns for the month of August 2007.

Index/sub strategies	August 2007 (%)
Credit suisse/tremont hedge-fund index	−1.53
Convertible arbitrage	−1.08
Dedicated short bias	−1.14
Emerging markets	−2.37
Equity market neutral	−0.39
Event driven	−1.88
Distressed	−1.73
Multi-strategy	−2.03
Risk arbitrage	−0.65
Fixed income arbitrage	−0.87
Global macro	−0.62
Long/short equity	−1.38
Managed futures	−4.61
Multi-strategy	−1.40

Source: www.hedgeindex.com

August 2007 are not included in TASS, and while we hope that this database contains an unbiased cross-section of funds in the industry, we have no way to ensure that it is representative.[33] And all of our inferences are indirect since we are unable to obtain direct information from hedge funds or their prime brokers. Accordingly, we cannot be any more definitive in our conclusions than to say that, for the moment, the empirical facts seem to be consistent with our hypotheses.

Finally, we conjecture that liquidations of various strategies and asset classes may have started earlier. For example, Figure 2 shows that the contrarian strategy exhibited a smaller dip during the second half of July, with NYSE daily volume at elevated levels during this period and into the first half of August. Other liquid investment categories such as global macro, managed futures, and currency strategies may have experienced similar unwinds during July and August as problems in the subprime mortgage markets became more prominent in the minds of managers and investors. For example, the so-called "carry trade" among currencies was supposedly unwound to some extent in July and August 2007, generating losses for a number of global macro and currency-trading funds. Obviously, our long/short equity microscope is incapable of detecting dislocation among currency strategies, but a simple carry-trade simulation—similar to our simulation of the contrarian trading strategy—could shed considerable light on the dynamics of the foreign exchange markets in recent months. Indeed, a collection of simulated strategies across all of the hedge-fund categories can serve as a kind of multi-resolution microscope, one with many lenses and magnifications, with which to examine the full range of financial-market activity. We plan to explore such extensions in future research.

12 The current outlook

In this paper, we have argued through indirect means that the events of August 6–10, 2007 may have been the result of a rapid unwinding of one or more large long/short equity portfolios, most likely initially a quantitative equity market-neutral portfolio. This unwind created a cascade effect that ultimately spread more broadly to long/short equity portfolios, 130/30 and other active-extension strategies, and certain long-only portfolios (those based primarily on quantitative stock-selection and systematic portfolio-construction methods). By August 9th, this unwind and de-leveraging process was over, and the affected portfolios and strategies experienced a significant but not complete rebound on the 10th.

With the caveats of Section 11 in mind, we draw three broad conclusions from our indirect inferences.

The first is that the contrast between August 1998 and August 2007 has important ramifications for the connectedness of the global financial system. In August 1998, default of Russian government debt caused a flight to quality that ultimately resulted in the demise of LTCM and many other fixed-income arbitrage funds. This series of events caught even the most experienced traders by surprise because of the unrelated nature of Russian government debt and the broadly diversified portfolios of some of the most successful fixed-income arbitrage funds. Similarly, the events of August 2007 caught some of the most experienced quantitative equity market-neutral managers by surprise. But August 2007 may be far more significant because it provides the first piece of evidence that problems in one corner of the financial system—possibly the sub-prime mortgage sector and related credit markets—can spill over so directly to a completely unrelated corner: long/short equity strategies. This is precisely the kind of "shortcut" described in the theory of mathematical networks that generates the "small-world phenomenon" of Watts (1999) in which a small random shock in one part of the network can rapidly propagate throughout the entire network.

The second implication of August 2007 is that the notion of "hedge-fund beta" described in Hasanhodzic and Lo (2007) is now a reality. The fact that the entire class of long/short equity strategies moved together so tightly during August 2007 implies the existence of certain common factors within that class. Although more research is needed to identify those factors (e.g., liquidity, volatility, value/growth, etc.), there should be little doubt now about their existence. This is reminiscent of the evolution of the long-only index-fund industry, which emerged organically through the realization by most institutional investors that they were invested in very similar portfolios, and that a significant fraction of the expected returns of such portfolios could be achieved passively and, consequently, more cheaply. Of course, hedge-fund beta replication technology is still in its infancy and largely untested, but the intellectual framework is well-developed and a few prominent broker/dealers and asset-management firms are now offering the first generation of these products. To the extent that the demand for long/short equity strategies continues to grow, the increasing amounts of assets devoted to such endeavors will create its own common factors that can be measured, benchmarked, managed, and, ultimately, passively replicated.

Finally, the events of August 2007 have some implications for regulatory reform in the hedge-fund sector. Recent debate among regulators and legislators have centered around the registration of hedge funds under the Investment Advisers Act of 1940. While there may be compelling arguments for registering hedge funds, these arguments are generally focused on investor protection which is, indeed, the main impetus behind the '40 Act. But investor protection is not directly related to systemic risk, and the best ways to deal with the former may not be optimal for the latter. In particular, registration does not address the systemic risks that hedge funds pose to the global financial system and currently, no regulatory body has a mandate to monitor, much less manage, such risks in the hedge-fund sector.[34] Given the role that hedge funds have begun to play in financial markets—namely, significant providers of liquidity and credit—they now impose externalities on the economy that are no longer negligible.

In this respect, hedge funds are becoming more like banks. The fact that the banking industry is so highly regulated is due to the enormous social externalities banks generate when they succeed, and when they fail. But unlike banks, hedge funds can decide to withdraw liquidity at a moment's notice, and while this may be benign if it occurs rarely and randomly, a coordinated withdrawal of liquidity among an entire sector of hedge funds could have disastrous consequences for the viability of the financial system if it occurs at the wrong time and in the wrong sector.

This observation should not be taken as a criticism of the hedge-fund industry. On the contrary, hedge funds have created tremendous economic and social benefits by supplying liquidity, engaging in price discovery, improving risk transfer, and uncovering non-traditional sources of expected return. If hedge funds have increased systemic risk, the relevant questions are "by how much?" and "do the benefits outweigh the risks?" No one would argue that the optimal level of systemic risk for the global financial system is zero. But then what is optimal, or acceptable?

The first step to addressing this issue is to develop a better understanding of the likelihood and proximate causes of systemic risk; one cannot manage that which one cannot measure. The proposal by Getmansky *et al.* (2004) to establish a National Transportation Safety Board-like organization for capital markets is one possible starting point. By establishing a dedicated and experienced team of forensic accountants, lawyers, and financial engineers to monitor various aspects of systemic risk in the financial sector, and by studying every financial blow-up and developing guidelines for improving our methods and models, a Capital Markets Safety Board may be a more direct way to deal with the systemic risks of the hedge-fund industry than registration.

In the aftermath of the Second World War, a group of socially minded physicists joined to form the Bulletin of Atomic Scientists to raise public awareness of the potential for nuclear holocaust. To illustrate their current assessment of the appropriate state of alarm, they published a "Doomsday Clock" indicating how close we are to "midnight," i.e., nuclear annihilation.[35] Originally set at 7 min to midnight in 1947, the clock has changed from time to time as we have moved closer to (2 min to midnight in 1953) or farther from (17 min to midnight in 1993) the brink of nuclear disaster. If we were to develop a Doomsday Clock for the hedge-fund industry's impact on the global financial system, calibrated to 5 min to midnight in August 1998, and 15 min to midnight in January 1999, then our current outlook for the state of systemic risk in the hedge-fund industry is about 11:51pm.

For the moment, markets seem to have stabilized, but the clock is ticking…

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A Appendix

Throughout the Appendix, the following conventions are maintained: (1) all vectors are column vectors unless otherwise indicated; (2) vectors and matrices are always typeset in boldface, i.e., X and μ are scalars and $\mathbf{X}$ and $\boldsymbol{\mu}$ are vectors or matrices. In Section A.1 we provide a more detailed exposition of the contrarian trading strategy in Lehmann (1990) and Lo and MacKinlay (1990). Section A.2 contains a derivation of the asymptotic standard errors of the aggregate autocorrelations of Section 8. And in Section A.3 we include the definitions of the various hedge-fund categories on which the CS/Tremont Indexes are based.

A.1 A contrarian trading strategy

Consider a collection of N securities and denote by $\mathbf{R}_t$ the $N \times 1$-vector of their period t returns $[R_{1t} \cdots R_{Nt}]'$. For convenience, we maintain the following assumption:

(A1) $\mathbf{R}_t$ is a jointly covariance-stationary stochastic process with expectation $\mathrm{E}[\mathbf{R}_t] = \boldsymbol{\mu} \equiv [\mu_1\ \mu_2\ \cdots\ \mu_N]'$ and autocovariance matrices $\mathrm{E}[(\mathbf{R}_{t-k} - \boldsymbol{\mu})(\mathbf{R}_t - \boldsymbol{\mu})'] = \boldsymbol{\Gamma}_k$ where, with no loss of generality, we take $k \geq 0$ since $\boldsymbol{\Gamma}_k = \boldsymbol{\Gamma}'_{-k}$.[36]

In the spirit of virtually all contrarian strategies, consider buying at time t stocks that were "losers" at time $t - k$, and selling at time t stocks that were "winners" at time $t - k$, where winning and losing is determined with respect to the equal-weighted return on the market. More formally, if $\omega_{it}(k)$ denotes the fraction of the portfolio devoted to security i at time t, let:

$$\omega_{it}(k) = -\frac{1}{N}(R_{it-k} - R_{mt-k}) \quad i = 1, \ldots, N, \tag{A.1}$$

where $R_{mt-k} \equiv \sum_{i=1}^{N} R_{it-k}/N$ is the equally-weighted market index. By construction, $\boldsymbol{\omega}_t(k) \equiv [\omega_{1t}(k)\, \omega_{2t}(k) \cdots \omega_{Nt}(k)]'$ is a "dollar-neutral" or "arbitrage" portfolio since the weights sum to zero. Accordingly, the weights have no natural scale since any multiple of the weights will also sum to zero. Therefore, it is most convenient to define the weights to be the actual dollar positions in each security, in which case the total dollar investment long (or short) at time t is given by $\mathrm{I}_t(k)$ where:

$$\mathrm{I}_t(k) \equiv \frac{1}{2}\sum_{i=1}^{N} |\omega_{it}(k)|. \tag{A.2}$$

Since the portfolio weights are proportional to the differences between the market index and the returns, securities that deviate more positively from the market at time $t - k$ will have greater negative weight in the time t portfolio, and vice-versa. Such a strategy is designed to take advantage of stock market overreaction, but Lo and MacKinlay (1990) show that this need not be the only reason that contrarian investment strategies are profitable. In particular, if returns are positively cross-autocorrelated, they show that a return-reversal strategy will yield positive profits on average, even if individual security returns are *serially independent*! The presence of stock market overreaction, i.e., negatively autocorrelated individual returns, enhances the profitability of the return-reversal strategy, but is not required for such a strategy to earn positive expected returns.

Because of the linear nature of the strategy, its statistical properties are particularly easy to derive. For example, Lo and MacKinlay (1990) show that the strategy's profit-and-loss at date t is given by:

$$\pi_t(k) = \boldsymbol{\omega}'_t(k)\mathbf{R}_t \tag{A.3}$$

and re-arranging (A.3) and taking expectations yields the following:

$$E[\pi_t(k)] = \frac{\boldsymbol{\iota}'\boldsymbol{\Gamma}_k\boldsymbol{\iota}}{N^2} - \frac{1}{N}\text{trace}(\boldsymbol{\Gamma}_k) - \frac{1}{N}\sum_{i=1}^{N}(\mu_i - \mu_m)^2, \quad \text{(A.4)}$$

which shows that the contrarian strategy's expected profits are an explicit function of the means, variances, and autocovariances of returns. See Lo and MacKinlay (1990, 1999) for further details of this strategy's statistical properties and an empirical analysis of its historical returns.

A.2 Statistical significance of aggregate autocorrelations

To gauge the statistical significance of the aggregate autocorrelations in Section 8, recall that under the null hypothesis of no autocorrelation, the autocorrelation coefficient $\hat{\rho}_{1i}$ is asymptotically normal with zero mean and variance $\sigma_\rho^2 \equiv 1/T$. Therefore, we can derive the asymptotic variance of the mean autocorrelation $\hat{\rho}$ in the usual manner:

$$\text{Var}\left[n^{-1}\sum_{i=1}^{n}\hat{\rho}_{1i}\right] = n^{-2}\,\boldsymbol{\iota}'\boldsymbol{\Omega}\boldsymbol{\iota}, \quad \text{(A.5)}$$

where $\boldsymbol{\Omega}$ is the covariance matrix of the vector of n first-order autocorrelation coefficients $[\,\hat{\rho}_{11}\cdots\hat{\rho}_{1n}\,]'$. If we assume that the $\hat{\rho}_{1i}$'s are uncorrelated, then $\boldsymbol{\Omega}$ is a diagonal matrix with $1/T$'s on the diagonal. Therefore, the asymptotic variance and standard error of $\hat{\rho}$ is given by

$$\text{Var}[\hat{\rho}] \approx \frac{1}{nT}, \quad \text{SE}[\hat{\rho}] \approx \frac{1}{\sqrt{nT}}. \quad \text{(A.6)}$$

For $n = 400$ and $T = 60$, the standard error for $\hat{\rho}$ is 0.65%, hence a two-standard-deviation confidence interval around the null hypothesis of zero correlation is the range $[-1.3\%, +1.3\%]$ which is clearly breached by the graphs in Figure 7 for most of the sample.

A.3 CS/Tremont category descriptions

The following is a list of descriptions of the categories for which CS/Tremont constructs indexes, taken directly from the CS/Tremont website (www.hedgeindex.com):

Convertible Arbitrage. This strategy is identified by investment in the convertible securities of a company. A typical investment is to be long the convertible bond and short the common stock of the same company. Positions are designed to generate profits from the fixed income security as well as the short sale of stock, while protecting principal from market moves.

Dedicated Short Bias. This strategy is to maintain net short as opposed to pure short exposure. Short biased managers take short positions in mostly equities and derivatives. The short bias of a manager's portfolio must be constantly greater than zero to be classified in this category.

Emerging Markets. This strategy involves equity or fixed income investing in emerging markets around the world. Because many emerging markets do not allow short selling, nor offer viable futures or other derivative products with which to hedge, emerging market investing often employs a long-only strategy.

Equity Market Neutral. This investment strategy is designed to exploit equity market inefficiencies and usually involves being simultaneously long and short matched equity portfolios of the same size within a country. Market neutral portfolios are designed to be either beta or currency neutral, or both. Well-designed portfolios typically control for industry, sector, market capitalization, and other exposures. Leverage is often applied to enhance returns.

Event Driven. This strategy is defined as "special situations" investing designed to capture price movement generated by a significant pending corporate event such as a merger, corporate restructuring, liquidation, bankruptcy or reorganization. There are three popular sub-categories in event-driven strategies: risk arbitrage, distressed securities, and multi-strategy.

Risk Arbitrage. Specialists invest simultaneously in long and short positions in both companies involved in a merger or acquisition. Risk arbitrageurs are typically long the stock of the company being acquired and short the stock of the acquiring company. The principal risk is deal risk, should the deal fail to close.

Distressed. Hedge Fund managers invest in the debt, equity or trade claims of companies in financial distress and general bankruptcy. The securities of companies in need of legal action or restructuring to revive financial stability typically trade at substantial discounts to par value and thereby attract investments when managers perceive a turn-around will materialize. Managers may also take arbitrage positions within a company's capital structure, typically by purchasing a senior debt tier and short-selling common stock, in the hopes of realizing returns from shifts in the spread between the two tiers.

Multi-Strategy. This subset refers to Hedge Funds that draw upon multiple themes, including risk arbitrage, distressed securities, and occasionally others such as investments in micro and small capitalization public companies that are raising money in private capital markets. Hedge Fund managers often shift assets between strategies in response to market opportunities.

Fixed Income Arbitrage. The fixed income arbitrageur aims to profit from price anomalies between related interest rate securities. Most managers trade globally with a goal of generating steady returns with low volatility. This category includes interest rate swap arbitrage, the United States and non-US government bond arbitrage, forward yield curve arbitrage, and mortgage-backed securities arbitrage. The mortgage-backed market is primarily US-based, over-the-counter and particularly complex.

Global Macro. Global macro managers carry long and short positions in any of the world's major capital or derivative markets. These positions reflect their views on overall market direction as influenced by major economic trends and or events. The portfolios of these Hedge Funds can include stocks, bonds, currencies, and commodities in the form of cash or derivatives instruments. Most Hedge Funds invest globally in both developed and emerging markets.

Long/Short Equity. This directional strategy involves equity-oriented investing on both the long and short sides of the market. The objective is not to be market neutral. Managers have the ability to shift from value to growth, from small to medium to large capitalization stocks, and from a net long position to a net short position. Managers may use futures and options to hedge. The focus may be regional, such as long/short US or European equity, or sector specific, such as long and short technology or healthcare stocks. Long/short Equity Hedge Funds tend to build and hold portfolios that are substantially more concentrated than those of traditional stock Hedge Funds.

Managed Futures. This strategy invests in listed financial and commodity futures markets and currency markets around the world. The managers are usually referred to as Commodity Trading Advisors, or CTAs. Trading disciplines are generally systematic or discretionary. Systematic traders tend to use price and market specific information (often technical) to make trading decisions, while discretionary managers use a judgmental approach.

Multi-Strategy. Multi-Strategy Hedge Funds are characterized by their ability to dynamically allocate capital among strategies falling within several traditional Hedge Fund disciplines. The use of many strategies, and the ability to reallocate capital between strategies in response to market opportunities, means that such Hedge Funds are not easily assigned to any traditional category. The Multi-strategy category also includes Hedge Funds employing unique strategies that do not fall under any of the other descriptions.

Notes

1 For example, the *Wall Street Journal* reported on August 10, 2007 that "After the close of trading, Renaissance Technologies Corp., a hedge-fund company with one of the best records in recent years, told investors that a key fund has lost 8.7% so far in August and is down 7.4% in 2007. Another big fund company, Highbridge Capital Management, told investors its Highbridge Statistical Opportunities Fund was down 18% as of the 8th of the month, and was down 16% for the year. The \$1.8 billion publicly traded Highbridge Statistical Market Neutral Fund was down 5.2% for the month as of Wednesday…Tykhe Capital, LLC—a New York-based quantitative, or computer-driven, hedge-fund firm that manages about \$1.8 billion—has suffered losses of about 20% in its largest hedge fund so far this month…" (see Zuckerman *et al.*, 2007), and on August 14, the *Wall Street Journal* reported that the Goldman Sachs Global Equity Opportunities Fund "…lost more than 30% of its value last week…" (Sender *et al.*, 2007).

2 Such a strategy is more accurately described as a "dollar-neutral" portfolio since dollar-neutral does not necessarily imply that a strategy is also market-neutral. For example, if a portfolio is long \$100MM of high-beta stocks and short \$100MM of low-beta stocks, it will be dollar-neutral but will have positive market-beta exposure. In practice, most dollar-neutral equity portfolios are also constructed to be market-neutral, hence the two terms are used almost interchangeably, which is sloppy terminology but usually correct.

3 The technical definition of leverage—and the one used by the US Federal Reserve, which is responsible for setting leverage constraints for broker/dealers—is given by the sum of the absolute values of the long and short positions divided by the capital, so

$$\frac{|\$100| + |-\$100|}{\$25} = 8.$$

4 Note that Reg-T leverage is, in fact, considered 2:1 which is exactly (2), hence θ:1 leverage is equivalent to a multiple of $\theta/2$.

5 Specifically, we use only US common stocks (CRSP share code 10 and 11), which eliminates REIT's, ADR's, and other types of securities, and we drop stocks with share prices below \$5 and above \$2,000. To reduce unnecessary turnover in our market-cap deciles, we form these deciles only twice a year (the first trading days of January and July). Since the CRSP data are available only through December 29, 2006, decile memberships for 2007 were based on market capitalizations as of December 29, 2006. For 2007, we constructed daily close-to-close returns for the stocks in our CRSP universe as of December 29, 2006 using adjusted closing prices from finance.yahoo.com. We were unable to find prices for 135 stocks in our CRSP universe, potentially due to ticker symbol changes or mismatches between CRSP and Yahoo. To avoid any conflict, we also dropped 34 other securities that are mapped to more than one CRSP PERMNO identifier as of December 29, 2006. The remaining 3,724 stocks were then placed in deciles and used for the analysis in 2007. Also, Yahoo's adjusted prices do not incorporate dividends, hence our 2007 daily returns are price returns, not *total returns*. This difference is unlikely to have much impact on our analysis.

6 The market capitalizations reported in Table 1 for the year 2007 are based on shares outstanding as of December 29, 2006 and should be interpreted as estimates for the average market cap in these deciles. The "All Count" column is the daily average number of stocks in our universe in each year. As stocks go bankrupt, delist, change from CRSP share code 10 or 11 to any other share code (prior to 2007), or fall outside of the \$5-to-\$2,000 price range, they are taken out of our universe.

7 Equity market-making profits are usually positively correlated with the level of volatility, and most quantitative equity market-neutral strategies have a significant

market-making component to their returns, especially at higher trading frequencies.

[8] In particular, in 1995 the minimum price-variation on most stock exchanges was 12.5 cents per share, and while this may seem like a very high hurdle for any high-turnover strategy to overcome, recall that the contrarian strategy tends to be a *supplier* of liquidity, hence it will be earning the spread on average, not paying it.

[9] For simplicity, we use arithmetic compounding to arrive at the three-day cumulative return, which is a reasonable approximation to geometrically compounded returns when the return values are relatively small in magnitude, and is also consistent with the typical way that long/short equity market-neutral portfolios are implemented in practice.

[10] We use the strategy's standard deviation in 2006 instead of 2007 as the unit of comparison to provide a cleaner comparison between 2007 and previous years. In particular, if 2007 is viewed as "unusual" because of the phenomena we are studying in this paper, it is presumably unusual relative to some benchmark other than its 2007 performance.

[11] We use the August 20, 2007 snapshot of the TASS database, and consider only those funds reporting their AUM in US dollars.

[12] The voluntary nature of reporting to TASS and other commercially available hedge-fund databases obviously imparts a selection bias, so our results should be interpreted with this bias in mind. See the review papers by Agarwal and Naik (2005) and Fung and Hsieh (2006) for comprehensive discussions of the impact of this and other biases in hedge-fund databases.

[13] The fact that the number of funds drops in the most recent month is a common feature of the TASS data that is typically caused by reporting lags, not necessarily a genuine decline in the number of funds in the category, hence the most recent month or two of data should be discounted.

[14] In fact, one can argue that the growth of quantitative equity market-neutral strategies played a role in the downward trend in US equity-market volatility because most of these strategies are mean-reversion based, hence they tend to attenuate market fluctuations rather than accentuate them as momentum strategies might.

[15] We use the leverage ratio of 8:1 instead of the 2007 level to capture the expectations of investors at the end of 2006 which, in turn, is taken into account by the portfolio managers. In particular, the average daily return of the strategy in 2007 was not known to either the investors or the managers at the start of 2007.

[16] The corresponding geometrically compounded weekly return is −5.52% for the week, which is so different from the arithmetic case because of the magnitude of returns on August 8–10. This is certainly a bad return but not a terrible one under the circumstances. Whether geometric or arithmetic compounding is appropriate depends on how the strategy is implemented—some portfolio managers rebalance their positions each day to a fixed notional long/short exposure within the month, irrespective of daily profits-and-losses, in which case arithmetic compounding is the more appropriate method for aggregating daily returns.

[17] On Friday August 10th, the *Wall Street Journal* also cited growing concern about the sub-prime mortgage market, the move by BNP Paribas to suspend redemptions to three of its mortgage-related investment funds, and the injection of cash into money markets by the European and US central banks as major factors in Thursday's market decline. See Zuckerman *et al.* (2007).

[18] See, for example, Kyle (1985), Easley and O'Hara (1987), O'Hara (1995, Chapter 6), and Gennotte and Leland (1990) for theories of equilibrium price dynamics with asymmetric information, and Barclay and Litzenberger (1988), Barclay and Warner (1993), Chan and Lakonishok (1993, 1995), and Holthausen *et al.* (1987, 1990) for empirical evidence regarding the price impact of large trades. Ironically, Gennotte and Leland (1990) show that portfolio insurance and related hedging behavior—which includes mean-reversion trades like our contrarian strategy—can increase the likelihood of market crashes.

[19] For example, in the case of the contrarian strategy (1), consider the contribution of security i to the profits at date t, $\omega_{it}R_{it} = -R_{it}(R_{it-1} - R_{mt-1})/N$. Suppose this is an unusually large losing position for a given portfolio weight ω_{it}, which implies either that R_{it-1} is larger than R_{mt-1} and R_{it} is large and positive, or R_{it-1} is less than R_{mt-1} and R_{it} is large and negative. In either case, the loss is due to persistence or momentum in security i's price—the bigger the loss, the more significant the momentum. This, in turn, implies a much bigger position of the same sign for security i at date $t+1$ on average since $\omega_{it+1} = -(R_{it} - R_{mt})/N$ and R_{mt} has much lower volatility than R_{it}. Therefore, large losses will, on average, yield bigger bets for the contrarian strategy (1).

[20] They provide several arguments, both theoretical and empirical, but the basic intuition is straightforward: large positive autocorrelation in asset returns is usually a sign of informational inefficiencies in frictionless markets, but given how efficient hedge-fund strategies tend to be, the

only remaining explanation for such autocorrelation is significant market frictions, i.e., illiquidity. For example, it is well known that the historical returns of residential real-estate investments are considerably more highly autocorrelated than, say, the returns of the S&P 500 index during the same sample period. Similarly, the returns of S&P 500 futures contracts exhibit less autocorrelation than those of the index itself. In both examples, the more liquid instrument exhibits less autocorrelation than the less liquid, and the economic rationale is a modified version of Samuelson's (1965) argument—predictability in asset returns will be exploited and eliminated only to the extent allowed by market frictions. Despite the fact that the returns to residential real estate are highly predictable, it is impossible to take full advantage of such predictability because of the costs associated with real-estate transactions, the inability to shortsell real properties, and other market realities. These frictions have, in turn, led to the creation of real-estate investment trusts, and the returns to these securities—which are considerably more liquid than the underlying assets on which they are based—exhibit much less autocorrelation.

[21] If a fund's AUM is missing in any given month, we use the fund's most recent non-missing AUM instead.

[22] In particular, the approximate standard error for the equal-weighted mean of 400 60-month rolling autocorrelations is 0.65% under the assumption of cross-sectionally independently and identically distributed autocorrelations. Therefore, statistical significance of the recent levels of autocorrelation in Figure 7 is quite high. See Appendix A.2 for details.

[23] See, for example, Bookstaber (1999, 2000, 2007), Getmansky *et al.* (2004), Lo (1999, 2001, 2002), Kao (2002), and their citations.

[24] Because most hedge-fund strategies involve shortselling of one type or another, the correlations between the returns of various hedge funds can be positive or negative and are less constrained than, for example, those of long-only vehicles such as mutual funds. And because in our context, "connectedness" can mean either large positive or large negative correlation, we focus on the absolute values of correlations in this analysis.

[25] Specifically, we use CS/Tremont's Convertible Arbitrage, Dedicated Short Bias, Emerging Markets, Equity Market Neutral, Event Driven, Fixed Income Arbitrage, Global Macro, Long/Short Equity, Managed Futures, Event Driven Multi-Strategy, Distressed Index, Risk Arbitrage, and Multi-Strategy indexes. See Appendix A.3 for the definitions of these categories, and www.hedgeindex.com for more detailed information about their construction. All indexes start in January 1994 except Multi-Strategy, which starts in April 1994.

[26] We use a shorter rolling window in this case because the index returns are less noisy than the individual fund returns used to estimate the rolling autocorrelations in Figure 7.

[27] In particular, recall that the numerator of the correlation coefficient, the covariance, is given by the expectation of the cross product $(X_t - \mu_x)(Y_t - \mu_y)$. If σ_x were to decrease merely through a change in units (e.g., raw return instead of percentage return), then $(X_t - \mu_x)$ would undergo the same decrease, thereby leaving the correlation coefficient unchanged. Therefore, if σ_x were to decrease without a corresponding change in $(X_t - \mu_x)$, then it can be argued that there has been a genuine change in the relationship between X and Y.

[28] See, for example, Allen and Gale (2000), Freixas *et al.* (2000), Furfine (2003), Boss *et al.* (2004), Degryse and Nguyen (2004), Upper and Worms (2004), and Leitner (2005).

[29] The differences in recovery times for these dislocations seem to be related to the liquidity of the underlying instruments and the breadth of participation in the specific strategies involved. This intriguing pattern bears further investigation, and is one of the directions of our ongoing research.

[30] For example, suppose a margin call is triggered by a decline of 20% or more in the value of a given portfolio. If this portfolio contains exchange-traded instruments that are continuously marked to market, the first instance of a 20% decline will trigger a loss of credit even if the portfolio's value improves dramatically immediately after reaching this critical level. If, on the other hand, the portfolio contains OTC contracts that are valued only once a month, margin calls will occur less frequently.

[31] However, an important difference is that the risks of the catastrophe insurance business are exogenously determined, hence the primary source of variability in that business is the amount of risk capital available. In the case of hedge-fund strategies, both the risks and the risk capital are endogenous and jointly determined, which significantly increases the complexity of the dynamics.

[32] More formally, they are not Nash equilibria, and suffer from the "Prisoner's Dilemma." See Luce and Raiffa (1957). Moreover, the possibility of Brunnermeier and Pedersen's (2005) "predatory trading" becomes more likely in periods of financial distress, as in August 1998

and 2007, and in these cases, risks become endogenous in the sense of Montier (2007).

[33] See Agarwal and Naik (2005) and Fung and Hsieh (2006) for excellent overviews of the hedge-fund industry and some of the pitfalls with various hedge-fund databases.

[34] A number of organizations have been actively involved in addressing systemic risk in the hedge-fund industry including the Federal Reserve System (especially the New York Fed and the Board of Governors), the Office of the Comptroller of the Currency, the International Monetary Fund, the SEC, the Treasury Department, and the President's Working Group. However, none of these organizations have any regulatory authority over the largely unregulated hedge-fund industry, and cannot even obtain the necessary data from hedge funds or their credit counterparties to compute direct measures of systemic risk. Even the very influential New York Fed exercises its influence primarily through moral suasion.

[35] Specifically, "The Bulletin of the Atomic Scientists' Doomsday Clock conveys how close humanity is to catastrophic destruction—the figurative midnight—and monitors the means humankind could use to obliterate itself. First and foremost, these include nuclear weapons, but they also encompass climate-changing technologies and new developments in the life sciences and nanotechnology that could inflict irrevocable harm." See www.thebulletin.org for further information.

[36] Assumption (A1) is made for notational simplicity, since joint covariance-stationarity allows us to eliminate time-indexes from population moments such as $\boldsymbol{\mu}$ and $\boldsymbol{\Gamma}_k$; the qualitative features of our results will not change under the weaker assumptions of weakly dependent heterogeneously distributed vectors $\mathbf{R}_t$. This would merely require replacing expectations with corresponding probability limits of suitably defined time-averages. See Lo and MacKinlay (1990) for further discussion.

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