# Speech

## The race to zero

Speech given by

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## 1. Introduction

Stock prices can go down as well as up. Never in financial history has this adage been more apt than on 6 May 2010. Then, the so-called "Flash Crash" sent shocks waves through global equity markets. The Dow Jones experienced its largest ever intraday point fall, losing $1 trillion of market value in the space of half an hour. History is full of such fat-tailed falls in stocks. Was this just another to add to the list, perhaps compressed into a smaller time window?

No. This one *was* different. For a time, equity prices of some of the world's biggest companies were in freefall. They appeared to be in a race to zero. Peak to trough, Accenture shares fell by over 99%, from $40 to $0.01. At precisely the same time, shares in Sotheby's rose three thousand-fold, from $34 to $99,999.99. These tails were not just fatter and faster. They wagged up as well as down.

The Flash Crash left market participants, regulators and academics agog. More than one year on, they remain agog. There has been no shortage of potential explanations. These are as varied as they are many: from fat fingers to fat tails; from block trades to blocked lines; from high-speed traders to low-level abuse. From this mixed bag, only one clear explanation emerges: that there is no clear explanation. To a first approximation, we remain unsure quite what caused the Flash Crash or whether it could recur.[1]

That conclusion sits uneasily on the shoulders. Asset markets rely on accurate pricing of risk. And financial regulation relies on an accurate reading of markets. Whether trading assets or regulating exchanges, ignorance is rarely bliss. It is this uncertainty, rather than the Flash Crash itself, which makes this an issue of potential systemic importance.

In many respects, this uncertainty should come as no surprise. Driven by a potent cocktail of technology and regulation, trading in financial markets has evolved dramatically during the course of this century. Platforms for trading equities have proliferated and fragmented. And the speed limit for trading has gone through the roof. Technologists now believe the sky is the limit.

This rapidly-changing topology of trading raises some big questions for risk management. There are good reasons, theoretically and empirically, to believe that while this evolution in trading may have brought benefits such as a reduction in transaction costs, it may also have increased abnormalities in the distribution of risk and return in the financial system. Such abnormalities hallmarked the Flash Crash. This paper considers some of the evidence on these abnormalities and their impact on systemic risk.

Regulation has thin-sliced trading. And technology has thin-sliced time. Among traders, as among stocks on 6 May, there is a race to zero. Yet it is unclear that this race will have a winner. If it raises systemic risk, it is

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[1] For a regulatory perspective see CFTC-SEC (2010), for a market perspective see Automated Trader (2010) and for an academic perspective see Easley et al (2011b).

possible capital markets could be the loser.  To avoid that, a redesign of mechanisms for securing capital market stability may be needed.

## 2. The Topology of Trading

During the course of this century, financial market trading has undergone a transformation.  This has been driven in part by technology and in part by regulation.   The key words are structure and speed.  Both the structure of the markets in which participants operate, and the behaviour of those participants, has undergone a phase shift.  That highly adaptive topology of trading has made understanding markets a more hazardous science than a decade ago.

Chart 1 plots equity market capitalisation relative to nominal GDP in the United States, Europe and Asia through this century.  On the face of it, it paints a rather unexciting picture.  Equity market values relative to GDP in the US are roughly where they started the century.  In Asia there is evidence of some deepening of equity markets relative to the whole economy but it is pretty modest.

Measures of equity market capitalisation to GDP have often been used as proxies for the contribution of financial development to economic growth.[2]  These effects are typically found to be significant.  By that metric, the contribution of equity markets to economic growth in the US, Europe and Asia has been static, at best mildly positive, during the course of this century.

Yet that picture of apparent stasis in equity markets conceals a maelstrom of activity beneath the surface.  To see this, Chart 2 plots stock market turnover in the US, Europe and Asia over the same period.  It shows a dramatic rise, especially in the world's most mature equity market, the United States.  Equity market turnover in the US has risen nearly fourfold in the space of a decade.  Put differently, at the end of the second World War, the average US share was held by the average investor for around four years.  By the start of this century, that had fallen to around eight months.  And by 2008, it had fallen to around two months.

What explains this story?  Regulation is part of it.  Two important, and almost simultaneous, regulatory developments on either side of the Atlantic changed fundamentally the trading landscape:  in the US, Regulation NMS (National Market System) in 2005;  and in Europe, MiFID (Markets in Financial Instruments Directive) in 2004.  Though different in detail, these regulatory initiatives had similar objectives:  to boost competition and choice in financial market trading by attracting new entrants.

Central exchanges for the trading of securities evolved from the coffee houses of Amsterdam, London, New York and Paris in the 17th century.  From those foundations emerged the physical exchanges which dominated the period from the 18th right through to the 20th centuries.  Central trading exchanges maintained

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[2]  Arestis and Demetriades (1997).

their near-monopoly status for 300 years.  In the space of a few years, that monopoly has been decisively broken.

A diverse and distributed patchwork of exchanges and multilateral trading platforms has emerged in its place.  These offer investors a range of execution characteristics, such as speed, cost and transparency, typically electronically.  Equity market trading structures have fragmented.  This has gone furthest in the US, where trading is now split across more than half a dozen exchanges, multilateral trading platforms and "dark pools" of anonymous trading (Charts 3 and 4).  Having accounted for around 80% of trading volume in NYSE-listed securities in 2005, the trading share of the NYSE had fallen to around 24% by February 2011.

A similar pattern is evident across Europe.  In the UK, the market share of the London Stock Exchange has fallen from two-thirds in June 2008 to less than one third today (Charts 5 and 6).  The same pattern is found in Germany and France.  In Asia, there is as yet less fragmentation.

Accompanying this structural evolution in trading has been a technological revolution.  Electronic trading is not new.  The first electronic exchange (NASDAQ) is already over forty years old.  But advances in computing power have shifted decisively the frontier of electronic, and in particular algorithmic, trading over the past few years.  That frontier is defined by speed.

The average speed of order execution on the US NYSE has fallen from around 20 seconds a decade ago to around one second today.  These days, the lexicon of financial markets is dominated by talk of High-Frequency Trading (HFT).  It is not just talk.  As recently as 2005, HFT accounted for less than a fifth of US equity market turnover by volume.  Today, it accounts for between two-thirds and three-quarters.

The picture is similar, if less dramatic, in Europe.  Since 2005, HFT has risen from a tiny share to represent over 35% of the equity market.  In Asia and in emerging markets, it is growing fast from a lower base.  What is true across countries is also true across markets.  HFT is assuming an ever-increasing role in debt and foreign exchange markets.  In some futures markets, it already accounts for almost half of turnover.  In the space of a few years, HFT has risen from relative obscurity to absolute hegemony, at least in some markets.

HFT itself is far from monolithic, comprising a range of strategies.[3]  Some involve high-speed liquidity provision, which is akin to market-making.  Others involve statistical arbitrage, using trading algorithms to detect and exploit pricing anomalies between stocks or markets.  Because these anomalies tend to be eliminated quickly, HFT algorithms have to be highly adaptive, not least to keep pace with the evolution of new algorithms.  The half-life of an HFT algorithm can often be measured in weeks.

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[3]  Mackenzie (2011) provides a brilliant recent account of the role of HFT, in particular in the context of the Flash Crash.  HFT is a sub-set of a broader class of algorithmic trading strategies.  See also Aldridge (2010).

One variant of these arbitrage strategies exploits pricing differences between common securities quoted on competing trading platforms. For that reason, HFT firms tend to have their tentacles spread across multiple trading venues, arbitraging tiny differences in price (Chart 7). These strategies have grown up as a direct response to the fragmentation of trading infrastructures. In other words, HFT is at least in part the (possibly unplanned) progeny of regulators pursuing competitive ends.

The ascent of HFT goes a long way towards explaining the rise in equity market turnover in the major equity markets and in particular the rise in number, and fall in the average size, of trades executed. Put differently, the trading behaviour of HFT has contributed to the downward fall in the average duration of stock holdings. HFT holding periods lie in a narrow time range. The upper bound is perhaps around one day. The lower bound is a perpetual downward motion machine, as computing capacity compresses the timeline for trading.

A decade ago, execution times on some electronic trading platforms dipped decisively below the one second barrier. As recently as a few years ago, trade execution times reached "blink speed" – as fast as the blink of an eye. At the time that seemed eye-watering, at around 300-400 milli-seconds or less than a third of a second. But more recently the speed limit has shifted from milli-seconds to micro-seconds – millionths of a second. Several trading platforms now offer trade execution measured in micro-seconds (Table 1).

As of today, the lower limit for trade execution appears to be around 10 micro-seconds. This means it would in principle be possible to execute around 40,000 back-to-back trades in the blink of an eye. If supermarkets ran HFT programmes, the average household could complete its shopping for a lifetime in under a second. Imagine.

It is clear from these trends that trading technologists are involved in an arms race. And it is far from over. The new trading frontier is nano-seconds – billionths of a second. And the twinkle in technologists' (unblinking) eye is pico-seconds – trillionths of a second. HFT firms talk of a "race to zero". This is the promised land of zero "latency" where trading converges on its natural (Planck's) limit, the speed of light.[4]

The race to zero seems like a million miles from the European coffee shop conversations of the 17th century and the noisy trading floors of the 18th, 19th and 20th centuries. The dawn of electronic trading coincided with the dusk for floor trading. Physical proximity lost its allure. As soon as computers processed faster than traders talked, the time was up for human interactions on physical exchanges. Trading became virtual, distance a dinosaur.

Or so it seemed. Latterly, however, HFT is turning that logic on its head. The race to zero has encouraged traders to eke out the last pico-second. And one way to do that is by limiting physical distance. The shorter

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[4] "Latency" refers to the time it takes from sending an order to it being executed.

the cable to the matching engine of the trading exchange, the faster the trade. Every 100 miles might add a milli-second to estimated execution times. For HFT, that is the difference between the tortoise and the hare.

The recognition of that has led to a phenomenon known as "co-location". HFT firms have begun to relocate their servers as close as physically possible to the trade-matching engine. That allows them to eke a pico over their (non co-located) competitors. For a price, a number of exchanges now offer co-located services, with a perimeter strictly enforced, including the NYSE, Euronext and the London Stock Exchange.

This has added a new dimension to the "adverse selection" problem in economics – of uninformed traders suffering at the hands of the informed. Being informed used to mean being smarter than the average bear about the path of future fundamentals – profits, interest rates, order flow and the like. Adverse selection risk meant someone having a better informed view on these fundamentals.

Adverse selection risk today has taken on a different shape. In a high-speed, co-located world, being informed means seeing and acting on market prices sooner than competitors. Today, it pays to be faster than the average bear, not smarter. To be uninformed is to be slow. These uninformed traders face a fundamental uncertainty: they may not be able to observe the market price at which their trades will be executed. This is driving through the rear-view mirror, stock-picking based on yesterday's prices.

Co-location speeds up the clock. But it has also had the effect of turning it back. Location matters once more. The race to zero has become a physical, as well as a virtual, one. Distance matters more than ever. The dinosaur has been resurrected, this time in high definition. In some ways, it is the ultimate contradiction.

In sum, through this century changes in the structure of trading, and in the behaviour of traders, have gone hand in hand. Liberalisation and innovation have delivered fragmentation of structure and transformation of speed. Both structure and speed have experienced a high-velocity revolution. So what impact has this race to zero had on market dynamics?

## 3. From Microstructure to Macrostructure

This is difficult detective work. But there are theoretical clues and empirical fingerprints. The theoretical clues come from a literature that flourished after the stock market crash of 1987 – the so-called market microstructure literature.[5] This departs from the notion of frictionless trading and information-efficient prices. In its place it introduces frictions in the price-setting process, which arise from characteristics of market participants (such as their trading speed) and of the trading infrastructure (such as its degree of fragmentation).

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[5]   For example, O'Hara (2004).

Frictions in pricing arise from the process of matching buyers and sellers. Here, the role of market-makers is key. The market-maker faces two types of problem. One is an inventory-management problem – how much stock to hold and at what price to buy and sell. The market-maker earns a bid-ask spread in return for solving this problem since they bear the risk that their inventory loses value.[6]

Market-makers face a second, information-management problem. This arises from the possibility of trading with someone better informed about true prices than themselves – an adverse selection risk. Again, the market-maker earns a bid-ask spread to protect against this informational risk.[7]

The bid-ask spread, then, is the market-makers' insurance premium. It provides protection against risks from a depreciating or mis-priced inventory. As such, it also proxies the "liquidity" of the market – that is, its ability to absorb buy and sell orders and execute them without an impact on price. A wider bid-ask spread implies greater risk in the sense of the market's ability to absorb volume without affecting prices.

This basic framework can be used to assess the impact of the changing trading topology on systemic risk, moving from analysing market microstructure to market *macro*structure. Take the effects of fragmentation. That heightens competition among trading platforms, offering differing execution options and wider access to participants. This would tend to attract liquidity providers, including cross-market arbitraging HFT. As new liquidity-providers enter the market, execution certainty and price efficiency might be expected to improve. Inventory and information risk would thereby fall and, with it, bid-ask spreads.

Some of the early empirical fingerprints suggest just such a pattern. For example, Brogaard (2010) analyses the effects of HFT on 26 NASDAQ-listed stocks. HFT is estimated to have reduced the price impact of a 100-share trade by $0.022. For a 1000-share trade, the price impact is reduced by $0.083. In other words, HFT boosts the market's absorptive capacity. Consistent with that, Hendershott et al (2010) and Hasbrouck and Saar (2011) find evidence of algorithmic trading and HFT having narrowed bid-ask spreads.

Chart 8 plots a measure of bid-ask spreads on UK equities over the past decade, normalising them by a measure of market volatility to strip out volatility spikes. It confirms the pattern from earlier studies. Bid-ask spreads have fallen by an order of magnitude since 2004, from around 0.023 to 0.002 percentage points. On this metric, market liquidity and efficiency appear to have improved. HFT has greased the wheels of modern finance.

But bid-ask spreads can sometimes conceal as much as they reveal. For example, by normalising on volatility, Chart 8 air-brushes out what might be most interesting: normalising volatility might normalise

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6  Stoll (1978).
7  Glosten and Milgrom (1985).

abnormality. It risks falling foul of what sociologists call "normalisation of deviance" – that is, ignoring small changes which might later culminate in an extreme event.[8]

So is there any evidence of increasing abnormality in market prices over the past few years? Measures of market volatility and correlation are two plausible metrics.[9] Chart 9 plots the volatility of, and correlation between, components of the S&P 500 since 1990. In general, the relationship between volatility and correlation is positive. Higher volatility increases the degree of co-movement between stocks.

Now consider how this volatility/correlation nexus has changed. This can be seen from the difference between the mass of blue dots (covering the period 1990 to 2004) and red dots (covering the period 2005 to 2010) in Chart 9. Two things have happened since 2005, coincident with the emergence of trading platform fragmentation and HFT.

First, both volatility and correlation have been somewhat higher. Volatility is around 10 percentage points higher than in the earlier sample, while correlation is around 8 percentage points higher. Second, the slope of the volatility / correlation curve is steeper. Any rise in volatility now has a more pronounced cross-market effect than in the past. Another way of making the same point is to plot measures of "excess correlation" – measured market correlation in excess of volatility. This is currently at historic highs (Chart 10).

Taken together, this evidence points towards market volatility being both higher and propagating further than in the past. Intraday evidence on volatilities and correlations appears to tell a broadly similar tale. Overnight and intraday correlations have risen in tandem.[10] And intra-day volatility has risen most in those markets open to HFT.[11]

Coincidence does not of course imply causality. Factors other than HFT may explain these patterns. Event studies provide one way of untangling this knitting. Recent evidence from the Flash Crash pinpoints the particular role played by HFT using transaction-level data. The official report on the Flash Crash, while not blaming HFT firms for starting the cascade, assigns them an important role in propagating it. For example, many HFT firms significantly scaled back liquidity and overall HFT firms were net sellers of stock.[12]

Taken together, this evidence suggests something important. Far from solving the liquidity problem in situations of stress, HFT firms appear to have added to it. And far from mitigating market stress, HFT appears to have amplified it. HFT liquidity, evident in sharply lower peacetime bid-ask spreads, may be illusory. In wartime, it disappears. This disappearing act, and the resulting liquidity void, is widely believed

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[8] This term has its origins in work by Diane Vaughan on NASA's decision-making in the run-up to the space shuttle Challenger disaster in 1986, where repeated oversight of small problems culminated in a big problem (Vaughan (1996)). It has since been found in a much broader range of phenomena, where small cognitive biases have had disastrous physical consequences (Cliff (2010), Harford (2011)).
[9] See also Brogaard (2010) and Zhang (2010).
[10] Lehalle et al (2010b).
[11] Lehalle et al (2010a).
[12] CFTC-SEC (2010), Kirilenko, Kyle, Samadi and Tuzun (2011).

to have amplified the price discontinuities evident during the Flash Crash.[13]  HFT liquidity proved fickle under stress, as flood turned to drought.

In some respects, this may sound like old news.  For example, an evaporation of liquidity, amplified by algorithmic trading, lay at the heart of the 1987 stock market crash.  And it is also well-known that stock prices exhibit non-normalities, with the distribution of asset price changes fatter-tailed and more persistent than implied by the efficient markets hypothesis at frequencies of years and months, perhaps weeks and days.[14]  But these abnormalities were thought to disappear at higher frequencies, such as hours and minutes.  Over shorter intervals, efficient market pricing restored itself.

Recent studies point, however, to a changing pattern.  Non-normal patterns in prices have begun to appear at much higher frequencies.  A recent study by Smith (2010) suggests that, since around 2005, stock price returns have begun to exhibit fat-tailed persistence at 15 minute intervals.  Given the timing, these non-normalities are attributed to the role of HFT in financial markets.

The measure of stock price abnormality used by Smith is the so-called "Hurst" coefficient.[15]  The Hurst coefficient is named after English civil engineer H E Hurst.  It was constructed by plotting data on the irregular flooding patterns of the Nile delta over the period 622-1469 AD.  Hurst found that flooding exhibited a persistent pattern.  Large floods were not only frequent, but came in clumps.  They had a long memory.

The Hurst coefficient summarises this behaviour in a single number.  For example, a measured Hurst equal to 0.5 is consistent with the random walk model familiar from efficient markets theory.  A Hurst coefficient above 0.5 implies fatter tails and longer memories.  In his study, Smith finds that the Hurst coefficient among a selection of stocks has risen steadily above 0.5 since 2005.  In other words, the advent of HFT has seen price dynamics mirror the fat-tailed persistence of the Nile flood plains.

To illustrate, Chart 11 plots the path of three simulated price series with Hurst coefficients of 0.5, 0.7 and 0.9.  A higher Hurst coefficient radically alters the probability of sharp dislocations in prices.  It also prolongs these dislocations.  Prices become de-anchored and drift;  their variance grows over time and is unbounded.  If this long-memory property of prices is emerging at ever-higher frequencies, it might provide an important clue to how HFT affects systemic risk.

## 4.  A Sketch Model of Market Macrostructure

To see that, consider a sketch model of market-making.  This builds on an analytical insight which is already more than 40 years old.  It owes to the late Benoit Mandelbrot, French-American mathematician and

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[13]  For example, Jarrow and Protter (2011, Cvitanic and Kirilenko (2010).
[14]  For example, Gopikrishnan et al (1999), Bouchaud et al (2009).
[15]  Blackledge (2008).

architect of fractal geometry. Mandelbrot found that a great many real-world topologies exhibited a fractal pattern. By this he meant that the basic pattern repeated itself, whatever the scale at which it was observed. They were "self-similar". Self-similarity appears to be present throughout the physical world, from coastlines to cauliflowers, from snowflakes to lightning bolts, from mountain ranges to river deltas.[16]

One of Mandelbrot's earliest applications of fractal geometry was to stock prices. In a 1967 paper, he argued that stock prices could best be understood by distinguishing between two measuring rods: clock time and volume time.[17] While empirical studies typically used the first measuring rod (days, hours, seconds, milli-seconds), stock prices were better understood by using the second.

Mandelbrot's explanation was relatively simple. If trading cannot occur within a given time window, price movements can only reflect random pieces of news – economic, financial, political. So, consistent with efficient market theory, price changes would be drawn from a normal distribution with a fat middle and thin tails when measured in clock time. They were a random walk.

But as soon as trading is possible within a period, this game changes. Strategic, interactive behaviour among participants enters the equation. Volumes come and go. Traders enter and exit. Algorithms die or adapt. Behaviour within that time interval may then no longer be random noise. Rather trading volumes will exhibit persistence and fat tails. This will then be mirrored in prices.[18] So when measured in clock time, prices changes will have thinner middles and fatter tails, just like a cauliflower, a coastline, or a cosmos.[19]

Subsequent studies have shown that this clock time / volume time distinction helps explain equity price dynamics, especially at times of market stress. For example, Easley et al (2011) show that the distribution of price changes during the Flash Crash was highly non-normal in clock time, with fat tails and persistence. But in volume time, normal service – indeed, near-normality – resumed. This fractal lens can be used to explain why market liquidity can evaporate in situations of market stress, amplifying small events across time, assets and markets. Fractal geometry tells us that what might start off as a snowflake has the potential to snowball.

**(a) Behaviour of High Frequency Traders**

HFT has had three key effects on markets. First, it has meant ever-larger volumes of trading have been compressed into ever-smaller chunks of time. Second, it has meant strategic behaviour among traders is occurring at ever-higher frequencies. Third, it is not just that the speed of strategic interaction has changed but also its nature. Yesterday, interaction was human-to-human. Today, it is machine-to-machine,

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[16] Peters (1994).
[17] Mandelbrot and Taylor (1967). See also Clark (1973).
[18] This finding can be given a variety of behavioural interpretations, including persistence in gaps in the limit order book (Bouchard et al (2009)). Empirical support for this hypothesis is found in Easley et al (2011a).
[19] Andrew Lo's "adaptive market hypothesis" is a more recent manifestation of essentially the same story.

algorithm-to-algorithm. For algorithms with the lifespan of a ladybird, this makes for rapid evolutionary adaptation.

Cramming ever-larger volumes of strategic, adaptive trading into ever-smaller time intervals would, following Mandelbrot, tend to increase abnormalities in prices when measured in clock time. It will make for fatter, more persistent tails at ever-higher frequencies. That is what we appear, increasingly, to find in financial market prices in practice, whether in volatility and correlation or in fat tails and persistence.

This change in price dynamics will in turn influence market-making behaviour. Consider the problem facing an HFT market-maker. They face inventory risk from market fluctuations and information risk from adverse selection. Pricing these risks means forming a guess about the future path of prices. The greater the potential range of future prices, the larger the insurance premium they will demand.

The future price range (maximum – minimum) for a price series at some future date T, *R(T),* can be written generically as:[20]

(1)
$$R(T) = \kappa \sigma_T T^H$$

where $\kappa$ is a constant and $\sigma_T$ is the standard deviation of the process up to time *T*. H is our old friend the Hurst coefficient, dredged up from the Nile; it can be thought to summarise the degree of fat-tailedness and persistence in prices.

When the holding period is short (say T=1), as with HFT, the future price range is the volatility of the series magnified by the Hurst coefficient. In other words, the fatter and more persistent the tails (H), the greater the market risk and the wider the bid-ask spread of the HFT.

This has implications for the dynamics of bid-ask spreads, and hence liquidity, among HFT firms. During a market crash, the volatility of prices (σ) is likely to spike. From equation (1), fractality heightens the risk-sensitivity of HFT bid-ask spreads to such a volatility event. In other words, liquidity under stress is likely to prove less resilient. This is because one extreme event, one flood or drought on the Nile, is more likely to be followed by a second, a third and a fourth. Reorganising that greater risk, market makers' insurance premium will rise accordingly.

This is the HFT inventory problem. But the information problem for HFT market-makers in situations of stress is in many ways even more acute. Price dynamics are the fruits of trader interaction or, more accurately, algorithmic interaction. These interactions will be close to impossible for an individual trader to observe or understand. This algorithmic risk is not new. In 2003, a US trading firm became insolvent in 16

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[20]   Equation (1) holds asymptotically in expectation for large T and for a broad range of statistical processes (see Peters (1994) and Qian and Rasheed (2004)).

seconds when an employee inadvertently turned an algorithm on. It took the company 47 minutes to realise it had gone bust.[21]

Since then, things have stepped up several gears. For a 14-second period during the Flash Crash, algorithmic interactions caused 27,000 contracts of the S&P 500 E-mini futures contracts to change hands. Yet, in net terms, only 200 contracts were purchased. HFT algorithms were automatically offloading contracts in a frenetic, and in net terms fruitless, game of pass-the-parcel. The result was a magnification of the fat tail in stock prices due to fire-sale forced machine selling.[22]

These algorithmic interactions, and the uncertainty they create, will magnify the effect on spreads of a market event. Pricing becomes near-impossible and with it the making of markets. During the Flash Crash, Accenture shares traded at 1 cent, and Sotheby's at $99,999.99, because these were the lowest and highest quotes admissible by HFT market-makers consistent with fulfilling their obligations. Bid-ask spreads did not just widen, they ballooned. Liquidity entered a void. That trades were executed at these "stub quotes" demonstrated algorithms were running on autopilot with liquidity spent. Prices were not just information inefficient; they were dislocated to the point where they had no information content whatsoever.

**(b) Behaviour of Low Frequency Traders**

If the story stopped here the ending would be an unhappy, but perhaps not critical, one. After all, the Flash Crash was done and dusted within an hour. But the framework developed suggests these effects need not, in general will not, be transient. To the contrary, these effects might actually magnify. To see why, consider now the behaviour of low frequency traders (LFT).

They face the same set of risks as the HFT market-maker – inventory and information risk. But persistence and fat tails in short-term price movement amplify these risks. From equation (1), the greater the holding period, T, the greater the potential dispersion in future prices. Intuitively, with fat-tailed persistence, a large shock is both more likely and its effects will linger longer. Slower trading increases the distance prices can travel once de-anchored.

Chart 12 illustrates this. The distribution of returns observed at a low frequency has far greater variance and kurtosis than that at a higher frequency. For example, the variance of prices faced by a LFT firm (trading at T=50) is around nine times greater than for a HFT firm (trading at T=1), for H=0.9.[23]

Given these price dynamics, HFT aggravates the market-making problem for LFT firms by magnifying the market risk they face.[24] And it is not just that LFT firms are slower to execute. In situations of stress, they

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[21] Clark (2010).
[22] CFTC-SEC (2010).
[23] Even once an adjustment has been made for the degree of time scaling associated with a standard Brownian motion.

may not even be able to see the prices at which they can trade.  Co-located traders may have executed many thousands of trades before LFT firms have executed their own.  LFT firms face intrinsic uncertainty about prices.  When volumes and price movements are large, LFT market-making is driving in the dark, stock-picking with a safety-pin.

During the Flash Crash, many traders suffered just this problem.  Message traffic resulted in delays in disseminating quotes for over 1000 stocks. These delays lasted for up to 35 seconds.  As a result, discrepancies emerged between the prices of common stocks trading on different exchanges (Chart 13).  Faced with such uncertainty, a number of market participants paused or halted trading.  The equilibrating force of long-term investors went missing.  Bargain-hunting shoppers simply had no price list.

The combined effects of these inventory and information problems is to widen the bid-ask spreads LFT market-makers charge.  Greater execution risk and uncertainty calls for a larger insurance premium.  This, too, may have an adverse feedback effect on financial market pricing.  That is because it is likely to render uncompetitive LFT firms relative to HFT firms able to charge tighter spreads.  Market-making will increasingly congregate around HFT firms proffering these lower spreads.

If the way to make money is to make markets, and the way to market markets is to make haste, the result is likely to be a race – an arms race to zero latency.  Competitive forces will generate incentives to break the speed barrier, as this is the passport to lower spreads which is in turn the passport to making markets.  This arms race to zero is precisely what has played out in financial markets over the past few years.

Arms races rarely have a winner.  This one may be no exception.  In the trading sphere, there is a risk the individually optimising actions of participants generate an outcome for the system which benefits no-one – a latter-day "tragedy of the commons".[25]  How so?  Because speed increases the risk of feasts and famines in market liquidity.  HFT contribute to the feast through lower bid-ask spreads.  But they also contribute to the famine if their liquidity provision is fickle in situations of stress.

In these situations, backstops sources of longer-term liquidity ought to ride to the rescue.  But HFT has also affected this outside option.  LFT market-making has been squeezed-out by competitive pressures from HFT.  And those LFT market makers that remain are at an acute informational disadvantage in situations of stress.  The result is a potentially double liquidity void.

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[24]   Indeed, with fractal price dynamics the variability of prices will potentially grow without bound over time.
[25]   Hardin (1968).

**(c) Behaviour across Assets and Markets**

So far the story has been confined to behaviour of one stock trading on a single exchange. But the changing structure of markets and trading mean it is unlikely that any stock-specific price dislocation will be localised. The new topology of trading makes contagion more of a potential bogeyman now than in the past.

One source of contagion is between stock prices and derivatives written on these stocks. HFT activity means that arbitrage opportunities between these markets are likely to be quickly removed. Or, put differently, price dislocations in the cash market are likely to be transmitted instantly to futures markets and vice-versa. That was the story of the Flash Crash, with order imbalances propagated through the futures market due to pass-the-parcel dynamics before ricocheting back to affect prices in the cash market.[26]

A second channel of contagion is between different exchanges and trading platforms. Here, too, HFT has changed the landscape. Because HFT strategies have emerged to arbitrage differences, price transmission across exchanges and platforms is near-instantaneous. It also has the potential to be more disruptive. Liquidity on these exchanges is no longer pooled and centralised. Instead it is distributed and localised, increasing the potential for illiquidity premia to emerge in periods of stress.

A third potential contagion channel is across stocks. HFT algorithms tend to amplify cross-stock correlation in the face of a rise in volatility due to their greater use of algorithmic trend-following and arbitrage strategies. That is consistent with the evidence in Chart 9, with heightened correlation per unit of volatility relative to the past.

Taken together, these contagion channels suggest that fat-tailed persistence in individual stocks could quickly be magnified to wider classes of asset, exchange and market. The micro would transmute to the macro. This is very much in the spirit of Mandelbrot's fractal story. Structures exhibiting self-similarity magnify micro behaviour to the macro level. Micro-level abnormalities manifest as system-wide instabilities.

In many respects, this is an unsurprising conclusion. The emergence of HFT in fragmented trading platforms makes for a financial market place exhibiting complexity and contagion. As the race for zero has gathered pace, those two features are likely to have grown in importance. The trading system has become increasingly complex and tightly knit. From the work of Charles Perrow, these are the two essential ingredients in the recipe for systemic failure.[27]

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[26] CFTC-SEC (2010).
[27] Perrow (1999), Harford (2011).

## 5. Market Macrostructure and Public Policy

The rapidly-adapting topology of trading poses a challenging set of questions for policymakers, particularly those safeguarding the resilience of financial markets. How is this changing market macrostructure best understood and monitored? And how, if at all, can it be modified to bolster systemic resilience?

This is unlikely to be an easy regulatory task. For the first time in financial history, machines can execute trades far faster than humans can intervene. That gap is set to widen. In some respects the 2010 Flash Crash and the 1987 stock market crash have common genes – algorithmic amplification of stress. But they differ in one critical respect. Regulatory intervention could feasibly have forestalled the 1987 crash. By the time of the Flash Crash, regulators might have blinked – literally, blinked – and missed their chance.

Nonetheless, the experience of managing large-scale, non-financial systems suggests risk-reducing regulatory intervention is possible. Drawing on that experience, two sets of policy tool are worth developing further.

### (a) Mapping Market Macrostructure

Many securities regulators collect transactional data for the markets they oversee, typically to help them detect instances of market abuse. But the transactional data collected internationally is about to be transformed. In future, a much larger array of over-the-counter transactions will be cleared through central counterparties (CCP). And transactions in a number of non-centrally cleared markets will be recorded and warehoused in so-called trade repositories.[28]

This presents a real opportunity. Prospectively over the next decade, securities regulators internationally will have at their disposal a database which is far richer in its frequency and scope than anything previously. For the first time ever, many of the raw ingredients will exist to map price and quantity dynamics within, and across, markets in close to real time.

To date, relatively little thought has been given to how best to put these data to work. They will certainly be useful as an archaeological site, allowing a detailed forensic sifting of the genealogy of historical market events. As with the Flash Crash, this may enable regulatory detectives to solve the whodunit: who did what when and, perhaps, why. It will allow DNA sampling of the victim.

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[28] In the United States, the Office of Financial Research, created under the Dodd Frank Act, is charged with collecting and analysing data submitted by US firms.

An altogether bigger prize would be to put these data to work before the fact, identifying the next victim pre-autopsy. That could mean using transactions data to help detect early warnings of systemic fault-lines and stresses. This is a potentially massive analytical and technical challenge.

The technical challenge is certainly surmountable. Advances in computer power over the past decade mean that storing and processing huge volumes of data poses no technological barrier. The answer lies in the clouds – conveniently enough, since they too exhibit fractal properties. If we can search and track the world wide web in close to real time, we can certainly do the same for its financial sub-component.

The analytical challenge is altogether greater. In essence, it is to find summary measures of billions of transactions data which are informative about impending market stress. There is serious needle-in-haystack risk with such an endeavour. And experience in economics and finance of finding robust early warning indicators is mixed. But here again, the market microstructure literature offers some tantalising clues.

For example, Easley et al (2011b) have suggested that measures of "order imbalance" may provide early warning signs of liquidity voids and price dislocations. Their measure of imbalance follows closely in Mandelbrot's footprints. It uses a volume-based metric of the proportion or orders from informed traders. Any imbalance towards informed traders causes potential liquidity problems down the line as a result of adverse selection risk. Easley et al show that their imbalance measure rose sharply ahead of the Flash Crash, contributing to an eventual evaporation of liquidity.

A more ambitious approach still would be to develop a system-wide model of financial market interaction. Cliff (2010) describes the trading infrastructure as an example of a "socio-technical system of systems". These involve a complex fusion between technology and human behaviour. This interaction increases the system's vulnerability to catastrophic failure. He proposes a "test rig" for such systems, using simulation techniques to unearth potential systemic fault-lines.

These techniques have already been applied to other large socio-technical systems, such as defence, space and weather systems. In each case, there have been some successes. The lessons from these exercises seem to be twofold. First, that although technology may pose a problem, it may also provide the solution. Second, that even if it ain't broke, there is a compelling strong case for fixing it. Not to do so today runs too great a risk of catastrophic failure tomorrow. We do not need to await a second Flash Crash to establish it was no fluke. To wait is to normalise deviance.

**(b) Modifying Market Macrostructure**

Regulators in the US and Europe are in the process of reviewing regulatory rules for trading. In the US, some changes to market rules have already been implemented, while others are the subject of ongoing research.[29] In Europe, a review is underway of MiFID with an early set of proposals tabled.[30] It is interesting to assess those proposals using the framework developed here.

(i) <u>Market-making guidelines</u>: In principle, a commitment by market-makers to provide liquidity, whatever the state of the market, would go to the heart of potential price discontinuity problems. Market-making commitments would not forestall the arms race. But they would lessen the chances of liquidity droughts and associated fat tails and persistence in prices. They would, in effect, lower the impact of H. Perhaps for that reason, there have been proposals in both the US and Europe for such a set of market-making commitments.[31]

The difficulty appears, first, in specifying these commitments in a precise enough fashion; and, relatedly and just as importantly, enforcing them. In a sense, even the market-makers offering their stub quotes on 6 May were fulfilling a market-making commitment, albeit a paper-thin one. If hard law commitments are too difficult to define or enforce, an alternative may be a set of soft law guidelines. A number of electronic broking platforms, notably in foreign exchange markets, have codes or rules of conduct - for example, around price-making and price-taking which control the extent to which any one firm can steal a technological march on others. If these codes were extended across trading platforms and assets, perhaps in time market-making behaviour might adapt.

(ii) <u>Circuit-breakers</u>: Circuit-breakers already exist on US and Europe exchanges. Indeed, circuit-breakers played an important role in stalling the Flash Crash. In the face of pass-the-parcel algorithmic dynamics, the Chicago Mercantile Exchange imposed an automatic 5-second pause on trading in its S&P 500 E-mini futures contracts.[32] It worked, providing time for human traders to take stock – and, as importantly, buy stock.

The rationale for such rules is well-understood. They temporarily impose a minimum execution time on trading, T. By calling a halt to trading, circuit-breakers provide a means of establishing a level informational playing field for all traders, long and short, fast and slow. In other words, they help solve the asymmetric information (risk and uncertainty) problem across traders of different types. The changing topology of trading, both speed and structure, has made these informational frictions more acute. So the case for circuit-breakers is perhaps stronger now than in the past.

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[29] European Commission (2010), CFTC-SEC (2011).
[30] CFTC-SEC (2011).
[31] European Commission (2010)
[32] MacKenzie and Demos (2011).

Circuit-breakers are also a means of heading-off suicidal spiralling, when algorithms join hands and chase each other over a cliff edge, as during the Flash Crash. Because they are automatic, circuit-breakers allow time for human intervention to catch-up with, and forestall, machine (summary) execution. They close the gap between man and machine, if only temporarily. Because HFT has widened this gap, the case for deploying circuit-breakers is stronger now than in the past.

Historically, circuit-breaking rules have been security or exchange-specific. But in a world of multiple exchanges, and increasingly correlated securities, rules of this type may not be restrictive enough. Contagion across securities and exchanges has become the rule. Recognising that, the US authorities have recently revised their circuit-breaking rules with all trading in a specified set of securities and futures now halted, irrespective of where trading is taking place.[33]

Although the pattern of trading fragmentation in Europe is similar to the US, current MiFID proposals do not envisage an automatic cross-market trading halt. But in a world of location-free, tightly arbitraged trading, cross-market circuit-breakers might become increasingly important. Indeed, these rules may potentially need to cross continents, as well as countries and platforms, if price dislocations are not to be redirected.

(iii) <u>Resting rules</u>: Circuit-breakers are an ex-post, state-contingent intervention rule, specifying a minimum T for a temporary period. A more ambitious proposal still would be to impose a minimum T, or resting period for trades, at all times. Minimum resting periods are an ex-ante, non-state contingent intervention rule. They tackle the arms race at source by imposing a speed limit on trading. Though mooted in both the US and Europe, they have not been implemented in either trading jurisdiction.

In some respects, it is easy to see why. From equation (1), imposing a minimum T will tend to result in a higher average bid-ask spread in all states. By increasing the per period transaction cost, the imposition of a minimum resting period would tend to widen bid-ask spreads and damage market liquidity in peacetime. HFT would be constrained in its offering to the liquidity feast.

That is of course only one side of the coin. Setting a minimum T would also tend to reduce the risk of liquidity drought. While raising the average bid-ask spread, it might also lower its variability at times of stress. Liquidity would on average be more expensive but also more resilient. So in determining whether there is a role for minimum resting periods, this trade-off between market efficiency and stability is key.

In calibrating this trade-off, a judgement would need to be made on the social value of split-second trading and liquidity provision and whether this more than counterbalances the greater market uncertainty it potentially engenders. At times, the efficiency of financial markets and their systemic resilience need to be

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[33] CFTC-SEC (2010).

traded off. This may be one such moment. Historically, the regulatory skew has been heavily towards the efficiency objective. Given today's trading topology, it may be time for that to change.

## 5. Conclusion

The Flash Crash was a near miss. It taught us something important, if uncomfortable, about our state of knowledge of modern financial markets. Not just that it was imperfect, but that these imperfections may magnify, sending systemic shockwaves. Technology allows us to thin-slice time. But thinner technological slices may make for fatter market tails. Flash Crashes, like car crashes, may be more severe the greater the velocity.

Physical catastrophes alert us to the costs of ignoring these events, of normalising deviance. There is nothing normal about recent deviations in financial markets. The race to zero may have contributed to those abnormalities, adding liquidity during a monsoon and absorbing it during a drought. This fattens tail risk. Understanding and correcting those tail events is a systemic issue. It may call for new rules of the road for trading. Grit in the wheels, like grit on the roads, could help forestall the next crash.

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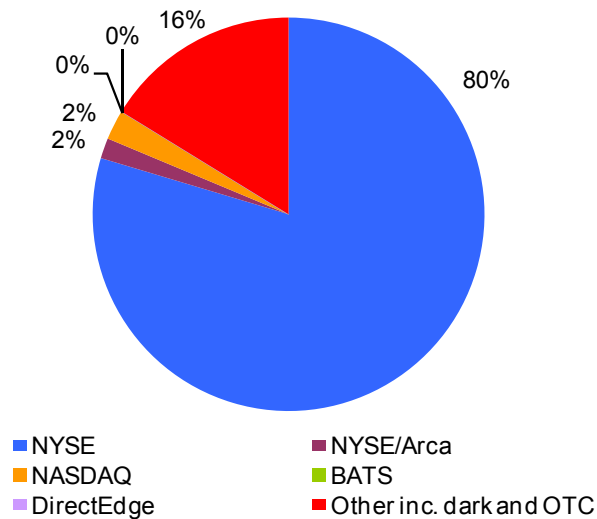**Chart 1: Market capitalisation by region, relative to GDP**
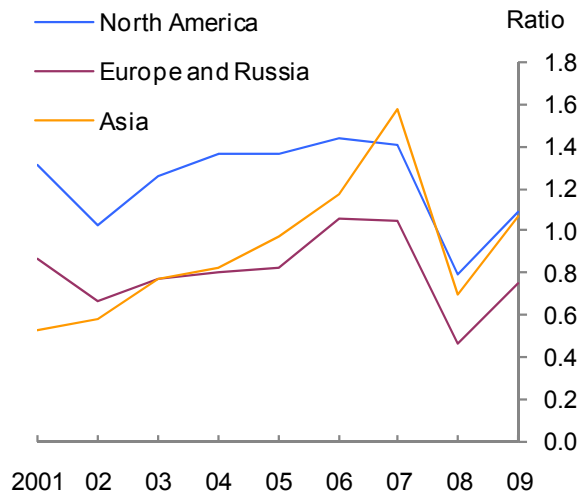


Source: World Federation of Exchanges.
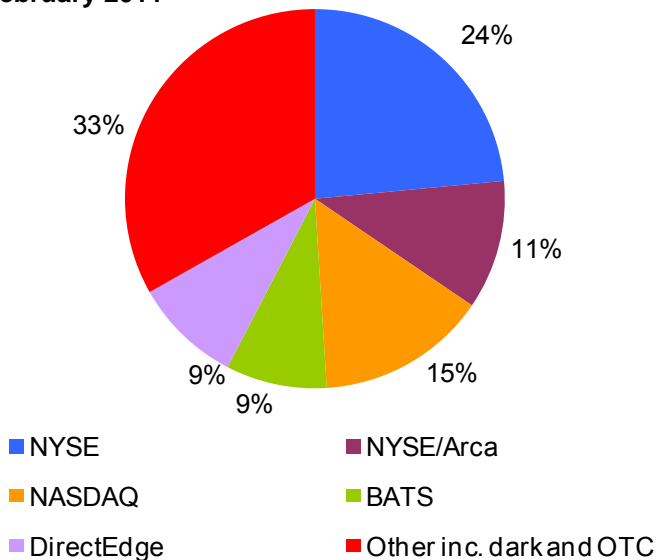
**Chart 2: Equity market turnover by region**
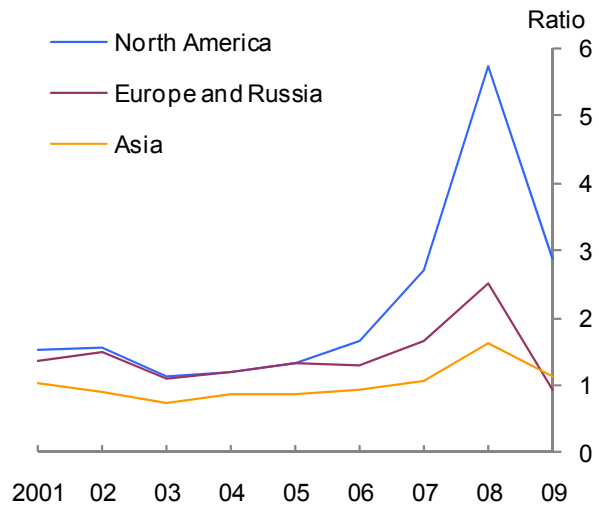


Source: World Federation of Exchanges.
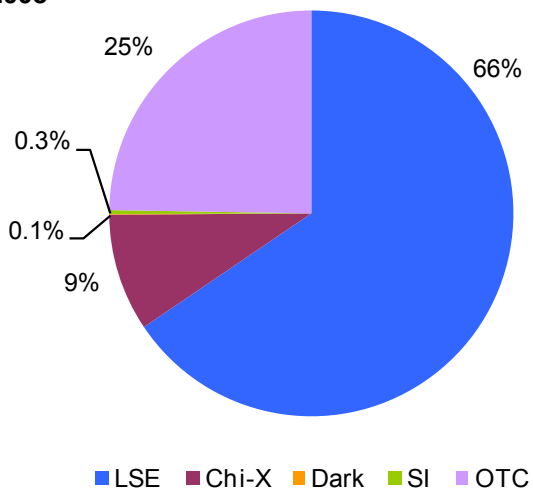
**Chart 3: NYSE-listed trading volume shares, January 2005**



- NYSE
- NYSE/Arca
- NASDAQ
- BATS
- DirectEdge
- Other inc. dark and OTC

Source: Fidessa.

**Chart 4: NYSE-listed trading volume shares, February 2011**



- NYSE
- NYSE/Arca
- NASDAQ
- BATS
- DirectEdge
- Other inc. dark and OTC

Source: Fidessa.

**Chart 5: FTSE 100 trading volume shares, June 2008**



- LSE 66%
- Chi-X 9%
- Dark 0.1%
- SI 0.3%
- OTC 25%

Legend: ■ LSE ■ Chi-X ■ Dark ■ SI ■ OTC

Source: Fidessa.

**Chart 6: FTSE 100 trading volume shares, June 2011**



- LSE 29%
- Chi-X 13%
- Bats Europe 4%
- Turquoise 4%
- Nyse Arca 0%
- Equiduct 0%
- Dark 2%
- SI 3%
- OTC 45%

Legend: ■ LSE ■ Chi-X ■ Bats Europe ■ Turquoise ■ Nyse Arca ■ Equiduct ■ Dark ■ SI ■ OTC
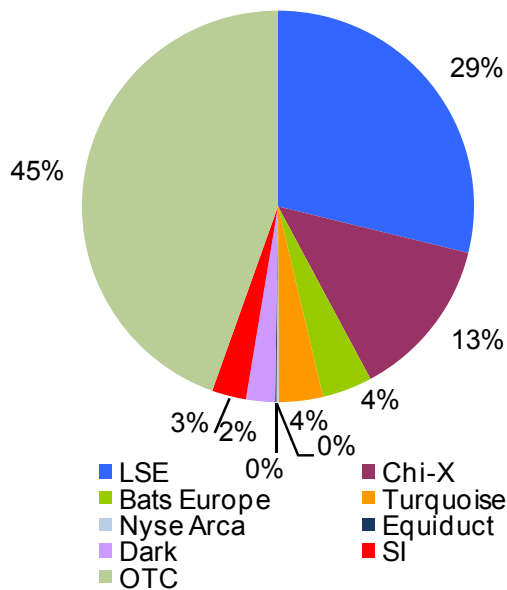
Source: Fidessa.

**Chart 7: Access to multiple trading venues by European HFTs**



- over 20 liquidity venues
- up to 20 liquidity venues
- up to 10 liquidity venues
- up to 5 liquidity venues
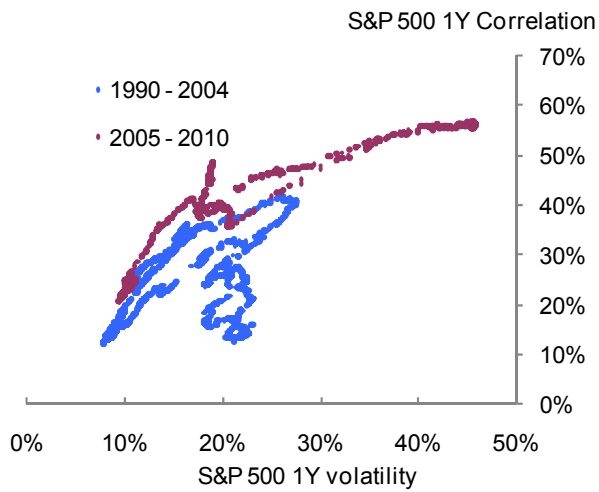- 2 liquidity venues
- 1 liquidity venue

Per cent
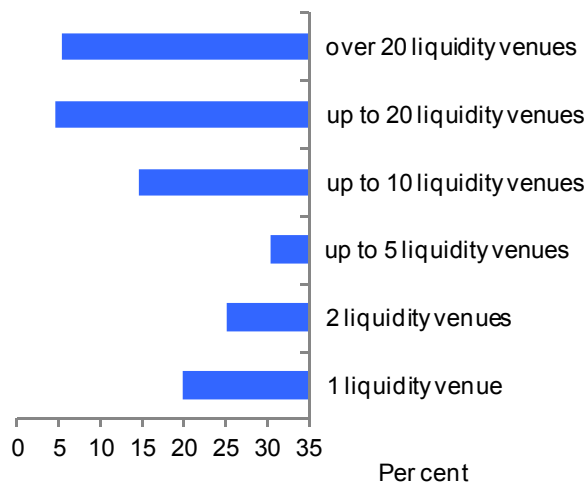
Source: Automated Trader.
Notes: Survey among 171 high frequency traders.

**Chart 8: Median end-of-day bid-ask spread for largest 20 stocks in FTSE 100 as a proportion of realised volatility[a]**
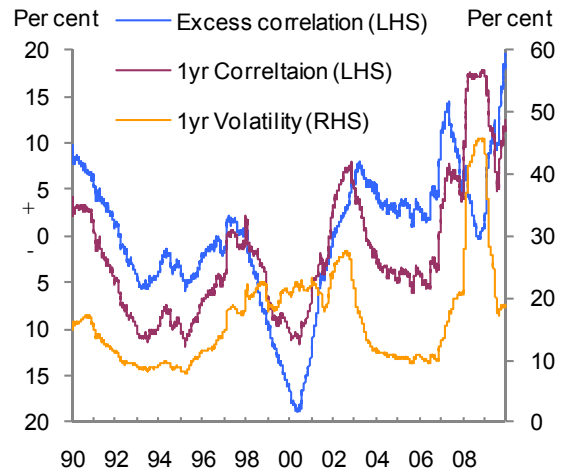


Percentage points
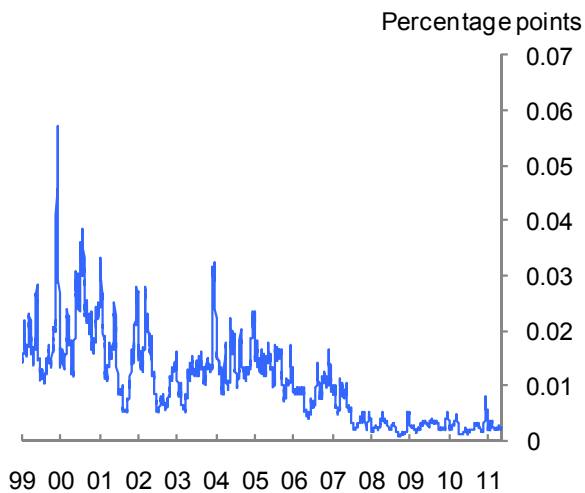
Source: Thomson Reuters Datastream.
[a] 22 day average. Largest stocks by market capitalisation. Selected stocks updated annually.

**Chart 9: Volatility and correlation of S&P 500**

S&P 500 1Y Correlation

- 1990 - 2004
- 2005 - 2010

S&P 500 1Y volatility

Source: JP Morgan and Bank calculations.

**Chart 10: Excess volatility**

Per cent

- Excess correlation (LHS)
- 1yr Correltaion (LHS)
- 1yr Volatility (RHS)

Per cent

Source: JP Morgan and Bank calculations.

**Chart 11: Simulated price series under different Hurst coefficients**

- H=0.5
- H=0.7
- H=0.9
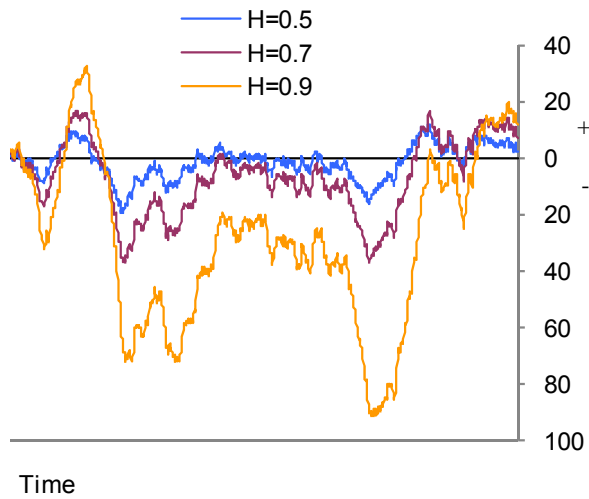
Time

Source: Bank of England.

**Chart 12: Distribution of simulated returns at different time horizons with H=0.9(a)**

- T=1
- T=20
- T=50
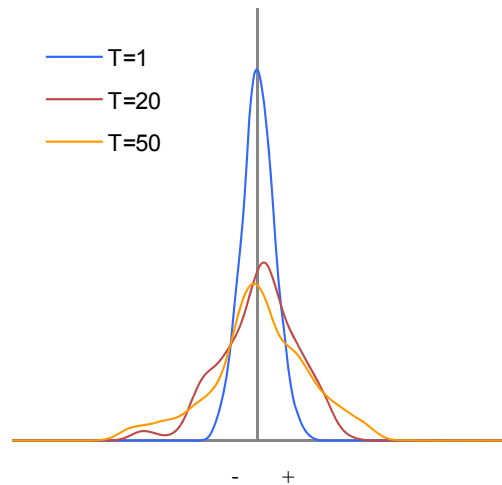
Source: Bank of England
(a) Returns at different time horizons have been scaled by the inverse of the square root of time, 1/sqrt(T).

**Chart 13: Difference in maximum and minimum price of
GE shares across different exchanges on 06 May 2010**

Price difference ($)

0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00

14:41    14:43    14:45    14:47    14:49

Time
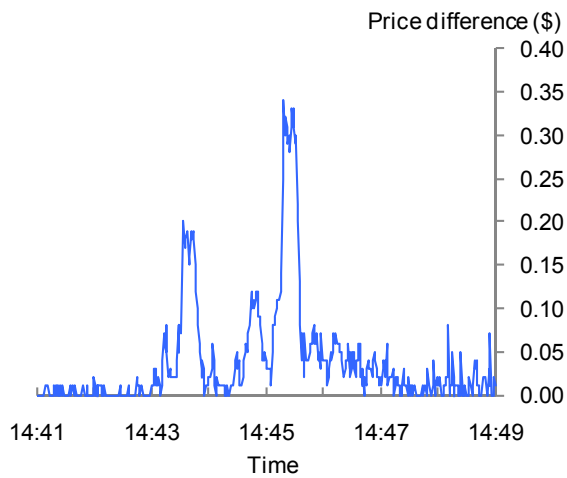
Source: NANEX.

Notes: Difference in bid prices across NASDAQ, NYSE and Pacific Exchange.

**Table 1: Round-trip latencies for selected exchanges, April 2010**

| Exchange | Average round-trip latency (microseconds) |
|---|---|
| Nasdaq OMX INET | 250 |
| Bats Europe | 270 |
| Chi-X Europe | 400 |
| NYSE Arca | 900 |
| LSE Tradelect | 2000 |
| TSE Assowhead | 5000 |

Source: http://mondivisione.com via AFM 2010.