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# IMPLICATIONS OF HIGH-FREQUENCY TRADING
# FOR SECURITY MARKETS

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High frequency trading (HFT) has grown substantially in recent years, due to fast-paced technological developments and their rapid uptake, particularly in equity markets. This paper investigates how HFT could evolve and, by developing a robust understanding of its effects, to identify potential risks and opportunities that it could present in terms of financial stability and other market outcomes such as volatility, liquidity, price efficiency and price discovery. Despite commonly held negative perceptions, the available evidence indicates that HFT and algorithmic trading (AT) may have several beneficial effects on markets. However, they may cause instabilities in financial markets in specific circumstances. Carefully chosen regulatory measures are needed to address concerns in the shorter term. However, further work is needed to inform policies in the longer term, particularly in view of likely uncertainties and lack of data. This will be vital to support evidence-based regulation in this controversial and rapidly evolving field.

# Implications of High-Frequency Trading for Security Markets

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### Abstract

High frequency trading (HFT) has grown substantially in recent years, due to fast-paced technological developments and their rapid uptake, particularly in equity markets. This paper investigates how HFT could evolve and, by developing a robust understanding of its effects, to identify potential risks and opportunities that it could present in terms of financial stability and other market outcomes such as volatility, liquidity, price efficiency and price discovery. Despite commonly held negative perceptions, the available evidence indicates that HFT and algorithmic trading (AT) may have several beneficial effects on markets. However, they may cause instabilities in financial markets in specific circumstances. Carefully chosen regulatory measures are needed to address concerns in the shorter term. However, further work is needed to inform policies in the longer term, particularly in view of likely uncertainties and lack of data. This will be vital to support evidence-based regulation in this controversial and rapidly evolving field.

## 1    Introduction

Are computerized trading systems delivering good outcomes for investors, speculators, hedgers, and other market participants? Computer-based trading including Algorithmic Trading (AT) and High Frequency Trading (HFT) are the predominant feature in current financial markets due to technological advances and market structure developments. HFT is thought to be responsible for as much as 75 percent of trading volume in the United States in 2009 (see Hendershott, Jones, and Menkveld (2011) and Biais and Woolley (2011)). Computers allow one to automate any trading strategy, and therefore to do it faster, to engage in much more complicated versions of strategies that already existed, and in some cases to do things that were simply not feasible before. They do what they are told to do and they don't complain about their bonus. They have clearly improved many back office functions. In the late 1960's the NYSE experienced an increase in trading that lead to a mountain of paperwork related to the clearing and settlement process; this crisis

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lead to the closing of the entire stock market on Wednesdays and reduced trading hours on other days in the week to allow staff to clear their desks. The level of trading volume then was less than 1% of what it is now, but computer technology is generally able to process all the current information flows in a timely fashion and with high accuracy. Many authors have argued that bid ask spreads and the cost of transacting has decreased to both retail investors and institutional investors in the last thirty years, see Jones (2013) and O'Hara (2015). These sound like improvements that we should celebrate. But there is also a dark side. The impact of HFT on market functioning has garnered increasing scrutiny, with particular impetus stemming from events such as the May 6, 2010 Flash Crash and the October 15, 2014 bond market flash event. In the former event, nearly a trillion US dollars temporarily evaporated in a matter of minutes. In the latter event, the market for US Treasuries (the bedrock instrument of international finance) had it fourth-largest trading day in history with most volatility concentrated in a half-hour period, with no apparent macroeconomic catalyst.

It is therefore a central issue to better understand the economic role of HFT's and their impact on market functioning, which is our purpose. The title of our paper suggests a one way causality from HFT to security markets whereas it is more accurate to think of them as evolving together. The existence, viability, innovation, and development of HFT depends intimately on the market structure and technology. We survey the academic, industry, and government literature on computer-based trading and evaluate the evidence on the functioning of financial markets. In Section 2 we discuss the nature of HFT and AT. In Section 3 we present some critiques of HFT, while in Section 4 we discuss the role of speed and information in understanding the role of HFT and AT in financial markets, and in Section 5 we discuss the issue of profitability. In Section 6 we discuss the empirical evidence about the effects of HFT on market quality in normal times and in extreme times. In Section 7 we discuss the issue of market manipulation. In Section 8 we discuss the role of big data in HFT and AT. Section 9 concludes.

## 2    The Ontology of HFT and AT

In this section we try to make precise what is meant by HFT and AT. The SEC Concept Release of 2010 (SEC (2010)) defined HFT thus: (1) Professional traders acting in a proprietary capacity that generate a large number of trades on a daily basis; (2) Use of extraordinarily high speed and sophisticated programs for generating, routing, and executing orders; (3) Use of co-location services and individual data feeds offered by exchanges and others to minimize network and other latencies; (4) Very short time-frames for establishing and liquidating positions; (5) Submission of numerous orders that are cancelled shortly after submission; (6) Ending the trading day in as close to a flat position as possible (that is, not carrying significant, unhedged positions overnight). This definition was the result of many man hours of committee work by top experts, which has been replicated by other regulatory authorities around the world with similar results, see Foresight (2012). It emphasizes the high degree of technological sophistication and short time frames. In principle

AT includes HFT, but in practice what is often meant by the term AT when in juxtaposition with the term HFT is the part of AT that is not HFT or rather the application of computer technology for the purpose of establishing a longer term position in the underlying securities.

According to Jobs (2016), the top fifteen HFT firms worldwide in 2016 were, in order: KCG, Sun Trading, Jump Trading, Tower Research Capital, Tradebot Systems, Virtu, XR Trading, DRW Trading, GSA Capital Partners, Maven Securities, Two Sigma International, Allston Trading, IMC, Hudson River Trading, and Spot Trading. We could add Susquehanna and Citadel to this list of major firms; many banks have electronic trading desks that act similarly. This list includes regulated and even stock market listed firms (which are therefore subject to substantial regulatory oversight) with hundreds of employees. In addition to these major firms there are many smaller firms with not such well established online presences that might satisfy some or all of the SEC criteria. There is quite a bit of variation in speed within the category of traders who might call themselves HFT. Some for example pay for co-location, while others do not. Clearly, some of the larger firms are not purely acting in a proprietary capacity.

Perhaps a useful categorization can be based on the different strategies that HFT firms pursue. These include: Market making; Cross venue/cross asset arbitrage; News based trading; Short term directional trading. These strategies have always existed in financial markets, but regulation and technology have affected how these strategies are currently executed. We discuss next these trading strategies.

*Market making.* A "market maker" is a firm that stands ready to buy and sell a particular stock on a regular and continuous basis at a publicly quoted price (According to the SEC). They make profits by capturing the spread between a buy order and a sell order, and the difficulty they face is that buy and sell orders may not arrive at the same time or at the same rate. In the past, such market makers may have had a monopolistic position, knowing the order flow for their particular stock or stocks in advance of others and having little direct competition. Nowadays this monopolistic structure has long gone. Nevertheless, exchanges like to advertise their "Market Maker" structure. On the NYSE, there are Designated Market Makers who: "Have obligations to maintain a fair and orderly market in their stocks, quote at the National Best Bid and Offer (NBBO) price a specified percentage of the time, and facilitate price discovery throughout the day as well as at the open, close and in periods of significant imbalances and high volatility"; and Supplemental liquidity providers who have to commit to quoting a minimum quantity at the NBBO on each side of the market to meet incoming market orders in each assigned security for a certain percentage of the trading day. In return these firms may get some advantages in terms of fees and rebates or exemption from short sale restrictions, or even direct payments from exchanges or issuers, but they do not have exclusive or even necessarily superior access to the order flow information. Typically, these are large technologically savvy firms who may participate in these arrangements for thousands of securities. In addition, there may be many participants who do not formally take part in such exchange programs for a specific security, but quote on both sides of the market in a similar way to official market makers, although they have the flexibility of not being required to always be in that particular market.

Unlike their textbook alter ego, current market makers use both active and passive orders types, i.e., they are alternately supplying and demanding liquidity, in order to control their inventory and risk. They need to be able to update their quotes rapidly, and across all the securities they are active in. New information about one stock suggests quotes should be updated on that stock but also on all other correlated (in practice all) securities. Market makers hope to capture the spread and don't want to be offering stale quotes that give away value. Before 1999, the tick size (the minimum price increment) in the US was 1/8th of a dollar, now it is $0.01 for most stocks. This represents a big reduction in the lower bound of spreads that could accrue to market makers. In the more competitive environment that now operates, making markets with 1cent spreads and no further advantage seems like a losing proposition. Assuming that market makers provide some valuable service, they need to be compensated. We may compare with retail FX as provided by Travelex at airports around the world. They typically set quotes for a whole day at a time but their spreads are very wide, perhaps even 30% the day before an election for example, so as to compensate for the longer resting time they operate. They rely on the impatience and risk aversion of travellers to generate order flow and profits.

*Arbitrage Activities.* One popular arbitrage is between the Emini futures contract traded on the Chicago Mercantile Exchange (CME) in Chicago and the S&P500 index ETF (SPDR) traded on the NYSE in New York, Budish, Cramton, and Shim (2015). Index arbitrage exploits index tracker funds that are bound to buy and sell large volumes of securities in proportion to their changing weights in indices. If a HFT firm is able to access and process information that predicts these changes before the tracker funds do so, they can buy up securities in advance of the trackers and sell them on to them at a profit. In the FX markets, the triangular arbitrage between currencies is popular, for example: buy Yen with Dollars, sell Yen for Euros, and sell Euros for Dollars. If the quoted currency values are out of line, this strategy can generate profits, see Chaboud et al. (2014) and Mahmoodzadeh, Tseng, and Gencay (2017).

*News-based trading.* Company news in electronic text format is available from many sources including commercial providers like Bloomberg, public news websites, and Twitter feeds. Automated systems can identify company names, keywords and sometimes semantics in online text, which can be used to trade news or sentiment before human traders can process it. Automated systems can also rapidly digest the implications from scheduled stock specific and macroeconomic announcements, Jiang and Valente (2013).[1]

*Direction-based Trading.* Some firms predict short term price movements based on information embedded in market data, such as quotes, transaction prices, and volumes, as well as other sources. By buying when they predict prices will rise and then selling when they predict prices will fall, they hope to make profits from short term movements. Momentum and contrarian strategies have been operated by many investment funds over different frequencies for a long time with mixed success, Khandani and Lo (2007).

To summarize, HFT is fast trading with a short term horizon, which is achieved through advanced

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[1] Although perhaps interpreting the subtleties of interpreting central bankers press conferences are beyond the current ambit of machine learning techniques.

technology.

# 3   Some Critiques of High Frequency Trading

In this section we discuss some often repeated criticisms of HFT from different quarters. There have been a number of criticisms of HFT by industry participants. The following list was taken from a survey of the "buy-side" conducted by Oliver Wyman [2012]:

1. The liquidity they supply is ephemeral. Current bid ask spreads are narrow, but this is an illusion created by flickering quotes, i.e., the liquidity is not accessible to humans or slower traders. The high volume of trading  we see reflects "pass the parcel trading" between HFT (intermediation chains) rather than genuine risk transfer between final users. Furthermore, their liquidity supply evaporates rapidly during crisis times e.g., the Flash Crash.

2. There is a lot of implicit front running/back running of large institutional orders, whereby fast traders can identify incoming large orders and move ahead of them. They are more like ticket touts who block buy a section of the stadium before selling on to the people who actually want to go to the game.

3. There is too much messaging, i.e., order cancellations and revisions, which imposes a negative externality on other traders. The current system requires big investments in technology (Smart Order Routers, Co-location, Algos for order slicing) to keep up. There is an arms race for speed, Haldane (2011).

4. The quoting and trading activities of HFT increase volatility relative to what it used to be

5. They engage in market abuse and manipulation: quote stuffing, spoofing, layering, smoking, etc.

Many well known economists and commentators have added their voices to the debate including Paul Krugman (in the NY Times, 03/08/09):

"It's hard to imagine a better illustration [of social uselessness] than high frequency trading. The stock market is supposed to allocate capital to its most productive uses, for example by helping companies with good ideas raise money. But it's hard to see how traders who place their orders one-thirtieth of a second faster than anyone else do anything to improve that social function ...  we've become a society in which the big bucks go to bad actors, a society that lavishly rewards those that make us poorer".

Michael Lewis in his (2015) book emphasizes that HFT make money by front running others orders inside the stock market by being well informed about incoming orders and being faster to react and profit

from them. It is convenient to have use of a label such as HFT about which to make allegations, since if one attacks any single firm or participant, then one would be subject to litigation.

We will discuss further below the question of speed and information that are at the heart of some of these critiques. We then discuss profitability as this bears on the potential size of the damage being done by HFT.

# 4    Speed and Information

Since speed is the subject of much criticism, we review its role in financial markets. In fact, speed has always mattered to investors. A well known example is the legend of Nathan Mayer Rothschild profiting from news of the British/Prussian victory at Waterloo. He had news about the outcome of the battle ahead of the British government (the fantasy version has it that he received the information by carrier pigeons, other versions say by personal couriers). There are also two versions of how he made money. In the first, he just bought bonds on news of victory, while in the second version of events he "Spoofed" the market by himself publicly selling bonds while having his agents buy them and keep on buying as the prices dropped. In any case, he made lots of money from having the key information 24 hours before other participants. He was the High Frequency Trader of his day.

We have benefitted in the last fifty years from remarkable technological improvements. In 1965 Gordon Moore predicted that the number of transistors in a dense integrated circuit would double approximately every two years, and this prediction has been pretty accurate since then (although it has been claimed that it will cease to operate from 2025). This development has led to a rapid increase in computing power and speed and improved all the applications of technology. The following table illustrates the evolution of speed in the last 20 years as measured by the "system latency" of the London Stock Exchange's matching engine. This roughly follows Moore's law, with an approximate halfing of latency every two to three years. The result of this is that the trading system itself can handle many more messages and deliver execution very much faster than it could prior to 2000 and of course much faster than any human intermediated system as was common prior to the 1980s. Of course traders have developed systems and approaches to take advantage of this technological improvement, just as academics have also improved their productivity by making use of faster computers and better software.

| System | Implementation | Latency$^2 10^{-6}$ |
|---|---|---|
| SETS | <2000 | 600000 |
| SETS1 | Nov 2001 | 250000 |
| SETS2 | Jan 2003 | 100000 |
| SETS3 | Oct 2005 | 55000 |
| TradElect | June 18, 2007 | 15000 |
| TradElect 2 | October 31, 2007 | 11000 |
| TradElect 3 | September 1, 2008 | 6000 |
| TradElect 4 | May 2, 2009 | 5000 |
| TradElect 4.1 | July 20, 2009 | 3700 |
| TradElect 5 | March 20, 2010 | 3000 |
| Millenium | February 14, 2011 | 113 |

Table 1. System latency of the London Stock Exchange matching engine

This shows that the trading infrastructure has become faster, which means that the costs of delivering a given speed has declined too. HFT is a phenomenon that has arisen throughout this technological development, while all trading related activity has speeded up. Since 2011 there has been a trend to use microwaves to transmit data across key connections such as the one between New York City and Chicago. This is because microwaves travelling in air suffer a less than 1% speed reduction compared to light travelling in a vacuum, whereas with conventional fiber optics light travels over 30% slower. On the other hand microwaves are more fragile, for example in storms, Shkilko and Sokolov (2016). As everything speeds up, the physical distance between locations starts to matter much more. Knowing the latency delay factor is important in determining which of two messages from different exchanges truly was issued first. In this calculation, random variation in latency and clock accuracy can also be a big factor. This makes perfect calculations impossible, and guaranteeing being first also impossible, although one may obtain a systematic advantage by having the best technology, Kirilenko and Lamacie (2015). Academics and regulators working with post trade data face major problems in scrutinizing markets. For this analysis one also needs to know that the clocks on each exchange are synchronized so as to work out which message came first, or since they are not in fact synchronized at all, what is the precise time delay between the clocks on the exchanges.

How do we measure the benefits of speed in electronic markets? Posting limit orders on the exchange gives options to trade to other traders, since they have the right but not the obligation to execute against you, Copeland and Galai (1983). The Black and Scholes call option price can be used to value the option. In a standard notation, the price of the call option $C$ in terms of the underlying price $S$ is

$$C(S, X, \tau, r_f, \sigma) = S \cdot \Phi(d_+) - X \cdot e^{-r_f \cdot \tau} \cdot \Phi(d_-),$$

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[2] For comparison, the time for light to travel round trip from London to New York is around 37200 microseconds.

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$$d_{\pm} = \frac{\log \frac{S}{X} + \left(r_f \pm \frac{\sigma^2}{2}\right) \cdot \tau}{\sigma \cdot \sqrt{\tau}},$$

where $\Phi$ is the standard normal cdf, while $r_f$ is the interest rate, $\tau$ is the time to maturity, $X$ is the strike price, and $\sigma$ is volatility. A competitive limit order can be considered as "At the money", i.e., $S = X$; furthermore, intraday interest rates $r_f$ are zero. Letting $\tau \to 0$, we obtain the approximation

$$\frac{C(S, X, \tau, r_f, \sigma)}{S} = \frac{1}{\sqrt{2\pi}} \sigma \sqrt{\tau} + O(\tau^{3/2}). \tag{1}$$

This says that there is a positive albeit small value in a single order that sits for a small time (If there are many orders, then the total value being given away can be large). Also, (1) says that the value being given away increases with volatility measured by the parameter $\sigma$, so that in times of market stress the value per unit time increases. The posters of limit orders should be compensated for their service to the market by for example the bid ask spread. The faster the limit order poster is at updating his quotes, the less compensation he would require for posting them in the first place. Note that the value in (1) scales with the square root of time: millisecond to microsecond value shrinks by $1/30$ not by $1/1000$.

The classical Glosten and Milgrom (1985) microstructure model of a dealer market explains the bid ask spread in terms of adverse selection. The dealer is uninformed, and he posts limit orders for informed and uninformed traders who arrive randomly. In this model if the dealer can update quotes in response to new information faster than the informed trader can act, then he will be able to set narrower spreads than if he is slow and keeps stale quotes on the table. On the other hand, if the informed trader is faster than the dealer, then the dealer will have to set wider spreads to protect himself. In the classical dealer market, the dealer alone new the order flow and they alone set prices, "investors" had to take it or leave it. They earned a profit from providing the service of immediacy. In the new system, that advantage has been eliminated, and without some advantage the human and physical capital that would have gone to the market making activity would find better employ elsewhere. Speed of action and superior information about order flow from datafeeds is the advantage that the new market makers seek, Menkveld (2013).

The classic inventory models, e.g., Ho and Stoll (1981,1983), explain the spread as the cost of providing immediacy to impatient investors. In their models, the spread varies positively with the degree of the monopoly power of the dealer, the volatility of the asset price, the trade size, and the horizon of the dealer. This class of models predicts that competition between dealers would lead to small spreads. It also predicts that small sized orders would require small spreads whereas larger orders would face wider spreads, ceteris paribus. Also, if the dealer has a short horizon, then spreads should be narrow. All these suggest that dealers who can quote and cancel faster will benefit the market. Aït-Sahalia and Saglam (2013) extend this literature to analyze the consequences for liquidity provision of competing market makers operating at high frequency. They find that competition increases overall liquidity and deters the fast market maker's use of order flow signals. They show that the market maker provides more liquidity as he gets faster but shies away as volatility increases.

There has been a lot of recent work extending microstructure models to give a special role to High Frequency traders. In some cases, their presence delivers positive outcomes, while in others they do damage to market quality metrics: Jarrow and Protter (2011), Biais, Foucault, and Moinas (2015), Pagnotta and Philippon (2015), Cartea and Penalva (2011), Jovanovic and Menkveld (2011), Aït-Sahalia and Saglam (2013), and Foucault, Khozan and Tham (2016). These new models allow HFT to affect the functioning of the trading system by: Being better informed agents (i.e., subscribing to news feeds) (+); Being faster acting but uninformed (-); Preying on large informed traders (-); Preying on large uninformed traders (+); Run games in context of multiple markets (-); Use mixed strategy over prices leads to endogenous quote flickering (-);

These are all "could happens"; there is no dominant agreed-on model yet. By their nature, economic models have to be simplifications, and in this setting the type of simplifications that must be made are somewhat extreme and fragile in the sense that small changes in modelling assumptions can predict quite different outcomes. Many models have no explicit time scale (for example there are two or three periods, or the evolution of time is discrete and exogenous), when time is the key and often endogenous feature here. The interpretation of some models is not unique, since they present some traders with an advantage that could represent speed or just being smarter.[3] Models often involve a simplified strategy space for traders that capture some "key" feature of interest. A common feature of many models is that traders are either informed or uninformed (about the true value of the security) and in many cases this is the key feature that differentiates participants. This is quite a drastic simplification, and it is not clear that it is justified as the main driver of outcomes. In FX markets for example, where there are no retail traders, it is not so clear whether this binary classification is useful. Kirilenko, Samadi, Kyle, and Tuzun (2017) record more than 15,000 trading accounts for the Emini futures contract around the time of the Flash Crash. For their empirical analysis they collapse these traders into around ten broad categories based on their observed "trading styles" (in terms of their attitude to inventory and holding periods) over the four days including the flash crash. In practice, the "HFT" category is consistent with a number of different trading strategies such as market making, arbitrage, and short term directional trading, which can have quite different effects on markets.

## 5 Profitability

One key question is whether HFT activity is a significant and pernicious factor in the market as a whole. The TABB Group (2012) estimated that the HFT sector earned $20billion profits in 2008, which raised some concerns about their trading practices, see also Budish, Cramton, and Shim (2015). Although HFT makes a small profit per trade on average, since they make many trades they may extract a large amount of rent from the intermediation sector, which would negatively impact end users. Kearns, Kulesza, and Nevmyvaka

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[3]Perhaps we should be worrying about High Intelligence Traders, especially in the era of Artificial Intelligence.

(2012) investigated the potential profitability of HFT. They argued that the negative consequences of HFT seem primarily to come from their use of aggressive market orders. They used the so-called *Omniscient Trader Methodology* to try to estimate an upper bound on the potential profits being made by HFT through this strategy. They reconstructed the entire limit order book of Nasdaq in 2008 for 19 big names (this was a major computational undertaking). The omniscient trader who can see the entire evolution of the market uses market orders with variable direction and quantity and holds for time period $\in \{0.01, \ldots, 10\}$. The calculation is repeated every 10 milliseconds. They extrapolate to the entire equity universe by regression methodology. They find that the potential profits achievable for this strategy are quite small, quite a bit less than \$2billion per year over the equity space for this strategy. Others have argued that competition has further reduced profits in this space. Chordia, Green and Kottimukkalur (2016) argue that HFT profits based on trading quickly after macroeconomic announcements has declined in recent years consistent with more competition between HFT or Low Latency Traders (LLT) as they call them.

In fact, one can obtain further information on the actual profits earned by HFT. For example, KCG and Virtu are both regulated and listed on the NYSE and have to file regular accounts. Their stock prices does not imply extreme profitability, and their annual reports further show that gross revenues and executive compensation are also not as high as implied by the Tabb group's estimates. On the other hand, some stock exchanges have made lots of money since 2007 (in many cases by selling data and technology) judging by their stock prices and annual reports.

To summarize, HFT are believed by some to be the devil's spawn and to be creaming off huge profits from innocent asset managers and retail investors. In fact, profitability of the sector has fallen through increased competition. There are economics arguments why HFT can cause bad outcomes for the market as a whole and there are economic arguments why HFT can cause good outcomes. The question of their value is ultimately an empirical one, and we turn to this next.

# 6   Empirical Evidence about Market Quality

In this section we review the empirical evidence about the effects of HFT on the functioning of markets, i.e., so-called "Market Quality".

Institutional networks introduced the first automated trading system in 1969 and in 1977 the Green screen, which displayed quotes from the NYSE. Glosten (1994) asked whether the electronic limit order book (ELOB) was inevitable, and by 2000 it was a substantial part of the landscape. It is commonly assumed that the era of HFT began around about 2005, although given the difficulties in defining HFT this is not so firm a dating.[4]

In order to determine the effect of HFT on outcomes, one could compare the market outcomes before and

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[4]According to google trends, the term High Frequency Trading became very searched on around July 2009, and continued to increase and reached its peak in 2014..

after 2005. But this would surely be oversimplified, because the Global Financial Crisis (GFC) of 2007-2010 affected many financial and economic outcomes over the same time period and in a much bigger way than HFT.[5]

Financial markets have changed in many ways to reflect the technological advances and regulatory changes. The encouragement of competition between trading venues brought about by reg NMS in the United States and *Directive concernant les services d'investissement*/MiFid in Europe lead to a more diverse financial ecosystem, which lead to improvements in market quality, Gresse (2011) and O'Hara and Ye (2011). There are more trading venues than there were twenty years ago, and the diversity of trading venue type has also increased. Best execution policy in the US forces some integration of the trading venues by imposing the law of one price for a small quantity. It fosters competition so that for example NYSE can't just trade through a better quote placed elsewhere. This integration is accomplished by smart order routing technology that links markets together, Foucault and Menkveld (2008). There has been a substantial development of algorithmic software to effectuate a variety of trading strategies. These algorithms are given names such as "Stealth", "Iceberg", "Dagger", "Guerrilla", "Sniper", and "Sniffer". They are routinely bought or rented by a range of participants along with the technology to implement them. There has also been the development of electronic dark pools. These are alternative trading systems that are private in nature—and thus do not interact with public order flow—and seek instead to provide undisplayed liquidity to large blocks of securities. In dark pools trading takes place anonymously, prices and quantities are not displayed as in the "lit" venues of standard exchanges, and execution prices are usually set at the midpoint of the best bid and offer from some lit venue or venues. Some authors have questioned whether dark pools degrade the overall market quality by impeding price discovery, Degryse, de Jong, and van Kervel (2015). More recently, there has been concern as to whether the transaction prices achieved in dark pools are accurately pegged to current best quoted prices, Aquilina, Diaz-Rainey, Ibikunle, and Sun (2017).

There have been many other changes in markets before and after 2005. The decimalization process in the US markets which saw the tick size reduce from 12.5 cents to 1 cent for large stocks around 2000 is a significant factor in the decline of bid ask spreads, since in the old regime, no matter how much competition there was the spread could not go below 12.5 cents, Bessembinder (2003) and Aït-Sahalia and Yu (2009).[6] The demutualization process of the exchanges themselves who are now listed companies rather than owned by their users has lead to them aggressively pursuing pricing strategies to encourage trading on their marketplace, Malinova and Park (2011), and to improve their technology. The introduction of competition between exchanges in Europe in 2007 after MiFID and the intensification of competition between exchanges in the USA following the introduction of reg NMS is potentially a factor in explaining the improvement in

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[5] If HFT has a role to play in the large swings in market conditions, it is relatively small and insignificant in comparison with the huge negative effects of the banking and sovereign debt crises that happened during the financial crisis.

[6] In the EBS FX market after 2011, the tick size was reduced by a factor of 10 from 0.0001 (pips) to 0.00001 (decimal pips). In Bitcoin, the minimum price increment is $10^{-8}$.

market quality metrics, Storkenmaier and Wagener (2011).[7] The growth of the economies and stock markets of Brazil, Russia, India, and China on the other hand has lead to more sensitivity of prices to news from around the world.

## 6.1 Measurement of HFT and Market Quality

We have discussed already the difficulty in defining HFT. In the empirical literature there are generally two ways to measure HFT activities. There are proxies (like message traffic) that are related to the intensity of trading activity. Large volumes of order placements and cancellations indicate the involvement of computers at the least. Examples using U.S. data can be found in Brogaard, Hendershott, and Riordan (2014) and Hendershott, Jones, and Menkveld (2011). One issue with this approach is that it can be a poor guide to the presence or absence of HFT.

A key issue in identifying the consequences of HFT for market quality is endogeneity. That is, property $x$ may be both a cause of HFT activity and a consequence of HFT activity. The question is whether HFT caused more volatility or whether volatility caused higher activity by HFT (this can be the case since volatility offers profitable trading opportunities to some HFT). The econometric methods available to identify the direction of causation or rather to control for endogeneity are as follows. In a first approach, differences in differences may be taken, that is, the difference between treated and untreated outcomes before and after the treatment are compared. This approach eliminates common time-specific and firm-specific effects that may contaminate our view of the effects. However, sometimes it is difficult to find a proper control group and to justify the parallel trends assumption, Bertrand, Duflo, and Mullainathan (2004). A second approach is to use an instrumental variable; that is, a variable that is related to the input variable (for example, HFT activity) but unrelated to the output variable (for example, market quality) except directly through the input variable HFT. The main problem with this approach is finding credible instruments, that is, those that are not correlate with the error term. Popular such instrument variables include latency upgrade events, such as listed in Table 1, or using the time at which an exchange first adopted automation.

## 6.2 Liquidity

Liquidity is a fundamental property of a well-functioning market, and lack of liquidity is generally at the heart of many financial crises and disasters. Is HFT associated with a decrease or increase in liquidity during regular market conditions? There have been some substantial and well documented changes to some important features of stock market trades and quotes in the last twelve years: the average size of transactions has decreased; the number of transactions has increased; the number of quotes has increased and the number of quotes per transaction has increased; the average holding period of stocks has decreased (although maybe not the "11 seconds" of internet rumor), Chordia, Roll, and Subrahmanyam (2011). However, these metrics

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[7]MiFID2 will be implemented in January 2018. It will bring more trading onto electronic venues (from OTC) and impose larger minimum size orders for dark pools, with a view to improving transparency.

are not generally interpreted by themselves as measures of liquidity or market quality. Common ways of measuring liquidity include bid-ask spreads, effective spreads, realized spreads, depth, and weighted depth, transaction volume, and Amihud illiquidity, see Goyenko, Holden, and Trzcinka (2009).

There are a number of studies that try to identify computerised trading and its consequences on the order book and transactions. Hendershott, Jones, and Menkveld (2011) use the automation of the NYSE quote dissemination as an implicit experiment to measure the causal effect of algorithmic trading on liquidity. In 2003, the NYSE began to phase in the auto-quote system, which empowered computerised trading, initially for six large active stocks and then slowly over the next five months to all stocks on NYSE. They found that this change narrowed spreads which was interpreted as increased algorithmic trading improving liquidity, and reducing adverse selection. The evidence was strongest for large stocks. Another study by Chaboud et al. (2014) also reports results on liquidity in the Electronic Broking Services (EBS) exchange rate market. They found that even though some algorithmic traders appear to restrict their activity in the minute following macroeconomic data releases, they increased their supply of liquidity over the hour following each release.

Hasbrouck and Saar (2013) investigate order book data from NASDAQ during the trading months of October 2007 and June 2008. Looking at 500 of the largest firms, they construct a measure of HFT activity by identifying "strategic runs" - which are linked submissions, cancellations, and executions. These are likely to be parts of a dynamic strategy adopted by such traders. Their conclusion is that increased low-latency activity improves traditional market quality measures such as spreads and displayed depth in the limit order book, as well as reducing short-term volatility.

Brogaard (2010) also investigated the impact of high frequency trading on market quality in US markets. High frequency traders were found to participate in 77% of all trades and tended to engage in a price-reversal strategy. There was no evidence to suggest that high frequency traders were withdrawing from markets in bad times or engaging in abnormal front-running of large non-HFT trades. High frequency traders demanded liquidity for 50.4% of all trades and supplied liquidity for 51.4% of all trades. They also provided the best quotes approximately 50% of the time.

Turning to Europe, Menkveld (2013) studied in some detail the entry of a new high frequency trader into trading on Dutch stocks at Euronext and a new market Chi-X in 2007 and 2008. He shows that the inventory of the high frequency trader ends the day close to zero but varies throughout the day, which is consistent with the SEC definition of HFT. All the trader's earnings arose from passive orders (liquidity supply). He also found that the bid-ask spreads were reduced by about 30% within a year when compared with Belgian stocks that were not traded by the HFT entrant. Brogaard and Garriott (2017) show similarly improved spread metrics on the Alpha exchange in Canada post the arrival of 11 HFT firms.

There are also studies reporting trends in liquidity without specifically linking them to algorithmic or high frequency trading. Castura et al. (2010) investigated trends in bid-ask spreads on the Russell 1000 and 2000 stocks over the period 2006 to 2010. They show that bid-ask spreads have declined over this period and that available liquidity (defined as the value available to buy and sell at the inside bid and ask) improved

over time. Angel, Harris and Spatt (2010) show a slow decrease in the average spread for S&P500 stocks over the period 2003-2010 (subject to some short-term up-side fluctuations in 2007/2008). They also find that depth has increased slowly over the relevant period. The evidence also shows that both the number of quotes per minute and the cancellation to execution ratio have increased, while market order execution speed has increased considerably.

Friedrich and Payne (2012) compare the operation of HFT in equities and foreign exchange (FX). They find that penetration of algorithmic, dynamic agency flow (i.e. best execution of trades on behalf of clients) on multilateral order books in FX is small relative to equities, perhaps because FX is more liquid and therefore orders do not need to be broken up. They report no trend in volume (the traded value) of FTSE100 stocks traded between 2006 and 2011, but find that bid-ask spreads have decreased while depth has increased. The number of trades, on the other hand, has increased more than five times over this period, implying that the average trade size is now only 20% of its former level. For small UK stocks there are different results. First, the average trade size has not changed as much over the period 2006 to 2011, which suggests that HFT is not so actively involved in their trading. Secondly, there has been little improvement in the liquidity of small cap stocks.

## 6.3   Transaction Costs

Trading with computers is cheaper than trading with humans, so transaction costs have fallen steadily in recent years as a result of the automation of markets. Jones (2002) reports the average relative one-way costs paid for trading Dow Jones stocks between 1935 and 2000. He finds the total cost of trading has fallen dramatically in the period 1975-2000. Angel, Harris and Spatt (2010) show that average retail commissions in the USA have decreased between 2003 and 2010, a period more relevant for inferring the effects of computer trading. They also make a cross-country comparison of trading costs at the end of 2009. According to this study, the United States large cap stocks are the cheapest to trade in the world with a roughly 40 basis point cost. They also have the market place most impacted by technology and HFT.

Menkveld (2013) argues that new entry, often designed to accommodate HFT, had profound effects on transaction costs. For example, the entry of Chi-X into the market for Dutch index stocks had an immediate and substantial effect on trading fees for investors, first through the lower fees that Chi-X charged and then through the consequent reduction in fees that Euronext offered. The strongest effect however was a reduction in clearing fees. A new clearing house entered, EMCF, and this triggered a price war that ended up with a 50% reduction in clearing fees. This reduction in clearing fees seems to have been replicated across European exchanges to the benefit of investors.

The interests of institutional investors are of great importance. Brogaard, Hendershott, Hunt, and Ysusi (2012) examines the direct effects of HFT on the execution costs of long-term investors. The authors use a new UK dataset obtained from the detailed transaction reports of the Financial Services Authority over the period 2007-2011 to provide a better measurement of HFT activity. They combine this with Ancerno

data on institutional investors' trading costs. To test whether HFT has impacted the execution costs of institutional traders, the authors conduct a series of event studies around changes in network speeds on the London Stock Exchange to isolate sudden increases in HFT activity. This study found that the increases in HFT activity have no measurable effect on institutional execution costs. Of course additional studies linking HFT and institutional trading costs in other market settings would be helpful in determining the generality of this finding.

## 6.4 Price Discovery and Efficiency

The usual method of measuring the degree of market inefficiency is through the predictability of prices based on past price information alone. In practice, widely used measures such as variance ratios and autocorrelation coefficients estimate the predictability of prices based on linear rules. Hendershott (2012) describes the meaning of price efficiency in the context of high-speed markets, and presents the arguments why HFT may improve market efficiency by enabling price discovery through information dissemination. Brogaard, Hendershott, and Riordan (2014) find that high frequency traders play a positive role in price efficiency by trading in the direction of permanent price changes and in the opposite direction of transitory pricing errors on average days and the days of highest volatility. Negative effects on efficiency can arise if high frequency traders pursue market manipulation strategies, see below. However, it is clear that price efficiency-reducing strategies, such as manipulative directional strategies, are more difficult to implement effectively if there are many firms following the same strategies. Thus, the more competitive the HFT industry, the more efficient will be the markets in which they work.

There is a variety of evidence suggesting that price efficiency has generally improved with the growth of computer-based trading. Castura et al. (2010) investigate trends in market efficiency in Russell 1000/2000 stocks traded on NYSE and Nasdaq over the period 1 January 2006 to 31 December 2009. They compared the variances of stock returns computed at one second, ten seconds, one minute and ten minutes. Prior to the automation of the NYSE in 2006-2007 the NYSE had much slower trading than Nasdaq, which meant it was less attractive to HFT. As the automation proceeded, penetration by HFT increased on NYSE. Based on evidence from intraday variance ratios, they argue that markets became more efficient in the presence of and increasing penetration by HFT. In summary, the preponderance of evidence suggests that HFT has not harmed, and may have improved, price efficiency.

## 6.5 Volatility and Stability

There is a concern that some HFT systems, like other novel trading systems in the past, could be making a steady stream of small profits but at the risk of causing very big losses if (or when) things go wrong, picking up pennies before steamrollers, as the saying goes. Even if each individual HFT system is considered to be stable, it is well known that groups of stable systems can, in principal, interact in highly unstable ways.

Price volatility is a fundamental measure useful in characterizing financial stability, since wildly volatile prices are a possible indicator of instabilities in the market and may discourage stock market participation.

There are a number of studies that have argued that HFT increases volatility, meaning essentially that volatility is higher in faster markets. One of the key issues that needs to be addressed in making such a comparison is the time frame under consideration. For example, retail FX providers such as Travelex keep their midquote constant throughout a trading day, and common measures of intraday volatility calculated from this price would be zero, whereas the spot or futures FX market would reveal nontrivial and time varying intraday volatility. However, day to day variability on Travelex midquotes would essentially track the volatility on the spot market. The time frame for comparison is critical.

Many authors have argued that the introduction of computerized trading and the increased prevalence of HFT strategies in the period post 2005 has lead to an increase in volatility, see Boehmer, Fong, and Wu (2015), Zhang (2010), Benos and Sagade (2012), and Caivano (2015). How to test this hypothesis? There are a number of studies that have investigated this question with natural experiments methodology, Hendershott and Riordan (2013) and Brogaard et al (2014), but the conclusions one can draw from such work are event specific. One implication of this hypothesis is that ceteris paribus the ratio of intraday to overnight volatility should have increased during this period because trading is not taking place during the market close period. Linton and Wu (2016) show that for large stocks the reverse has happened, i.e., the ratio of overnight to intraday volatility has increased over the period 2001-2016. This finding seems to be hard to reconcile with the view that trading has increased volatility. Hasbrouck (2016) compares the volatility of quoted prices over the 2001-2011 period. At subsecond horizons bids and offers in U.S. equity markets are more volatile than what would be implied by long-term fundamentals. He suggests that traders' random latencies interact with quote volatility to generate execution price risk and relative latency costs and that this volatility is more likely to arise from recurrent cycles of undercutting, rather than mixed strategies of limit order placement. He also shows that this quote volatility does not display a strong trend despite the high growth in quote traffic. Overall, the evidence does not support the view that HFT has increased volatility in normal times.

We now turn to the discussion of extreme events or flash crashes. Flash crashes are short and relatively deep price movements that are not apparently driven by fundamentals or rather the movement in prices is in excess of what would be warranted based on fundamentals, according to hindsight anyway. Unlike some other market crashes (e.g., 1929 and 1987) one may not easily identify a prior period where the market was dominated by bubbles. Also, in many cases they are not contagioned globally unlike say the 1929 and 1987 crashes, which were worldwide phenomena. Some argue that in certain specific circumstances, self-reinforcing nonlinear feedback loops (the effect of a small change looping back on itself and triggering a bigger change, which again loops back and so on) within well-intentioned management and control processes can amplify internal risks and lead to undesired interactions and outcomes, Danielsson and Shin (2013). These feedback loops can involve risk-management systems, and can be driven by changes in market volume

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or volatility, by market news and by delays in distributing reference data. HFT has the potential to lead to a qualitatively different and more obviously nonlinear financial system in which crises and critical events are more likely to occur in the first place, even in the absence of larger or more frequent external fundamental shocks. In the Glosten and Milgrom (1985) class of models, Flash crashes may be caused by increased "toxic" order flow from informed agents or a misinterpretation of a large temporary directional order flow as being permanent.

We first consider the Flash Crash in the US stock market on May 6th, 2010. In Figure 1 we show the trajectory of the Emini futures price in the hour containing the peak declines and rise, along with the change in consecutive transaction prices in terms of ticks. This shows the rapidity of the price changes and the incredible volatility that was present during the crash. Even a half hour before the crash most price changes between consecutive transactions took place within one tick, but during the most intense period there were price changes of upto 40 ticks in both directions.
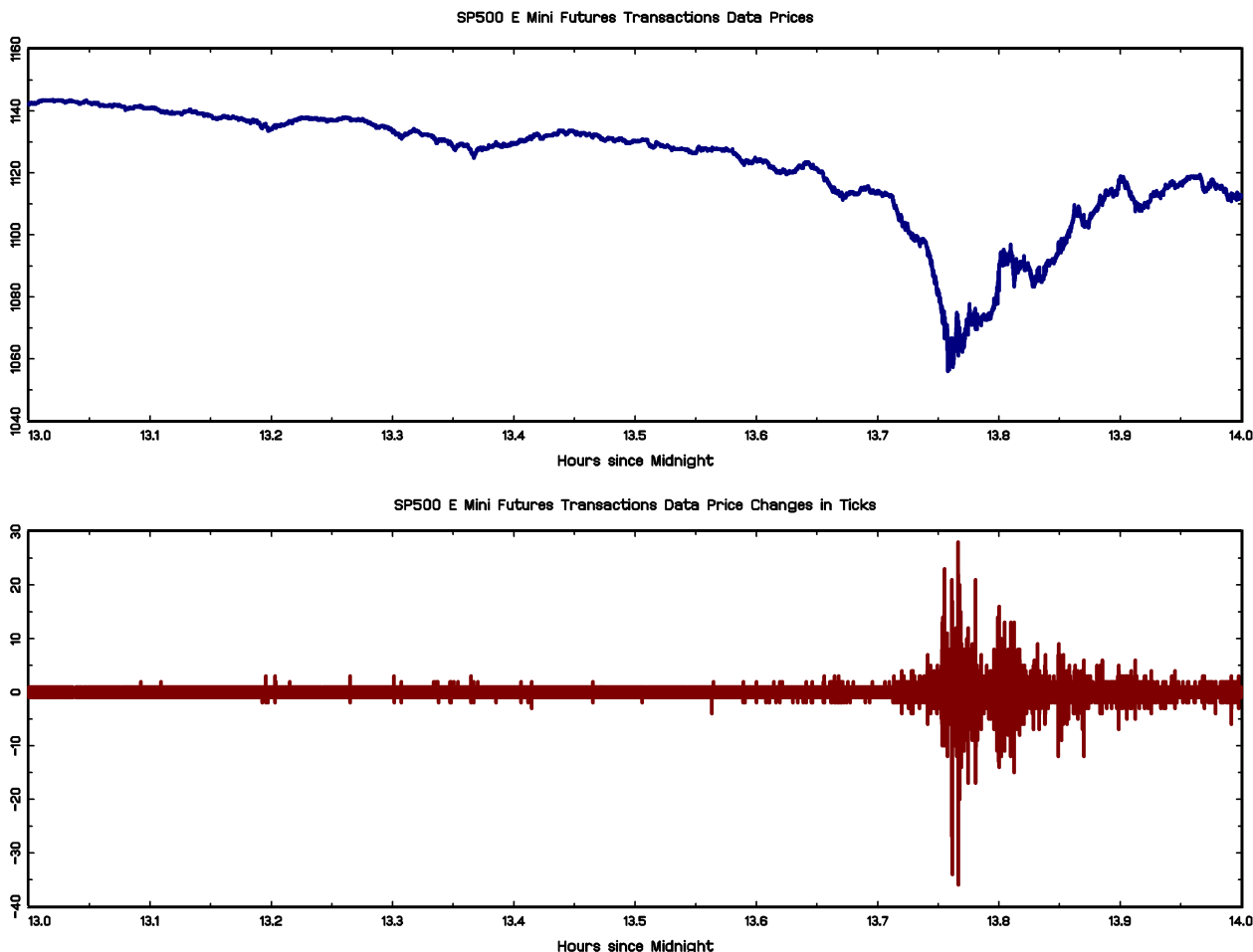


Figure 1. Price level of the Emini near term futures contract during the flash crash along with changes in

prices between consecutive transactions measured in ticks.

The SEC/CFTC (2010) report on the Flash Crash suggested some explanations for the initiation and promulgation of the Flash crash. They argued that a starting point was a large parent sell order by Waddell & Reed for 75,000 emini contracts that was divided into "price insensitive" market orders and fed into the market at a rate proportional to the transaction volume that had occurred in the most recent period. This lead to a dynamic interaction between different types of traders as they tried to absorb the large volume by trading amongst themselves which in turn raised the transaction volume which led to more selling by the Waddell & Reed algo. At some point, the loop broke and HFT's "withdrew liquidity". Kirilenko, Samadi, Kyle, and Tuzun (2017) conclude that HFTs did not trigger the Flash Crash, but their responses to the unusually large selling pressure on that day exacerbated market volatility. Easley, Lopez de Prado, and O'Hara (2011) argue that historically high levels of order toxicity forced market makers to withdraw during the Flash Crash.[8] Others have disputed some parts of this narrative, Hunsader (2010), Madhavan (2011), Andersen and Bondarenko (2013) and Menkveld and Yueshen (2017).

Some other recent technological/market disasters include: the Facebook IPO (#Faceplant) on May 18, 2012 when trading was delayed for half an hour; the BATS IPO (the stock opened at $15.5 but traded down to a penny in 1.4 seconds); and the Google (#Pending Larry) mistaken early earnings announcement in 2012 (price went down 10% in 8 minutes). The so-called Knightmare on Wall street on August 1, 2012: Knight Capital was a market maker/HFT firm, listed on the NYSE. A "trading error" caused widespread disruption on NYSE, and the firm lost $450m in a few minutes, see Nanex (2012). Subsequently, they were bought out by another HFT. The so-called Hash Crash on April 23rd, 2013: there was a hack of Reuters twitter account and a story tweeted about a bomb at the White house, which resulted in a rapid drop in the Dow Jones index, and subsequent rapid recovery when the hack was uncovered. The Treasury Flash "event" (where prices went up rapidly and yields went down equally rapidly) of October 15th, 2014, was a very big event where it has proven difficult to explain the magnitude of the short term price changes.

Foreign exchange (FX) markets have some different features from equity markets. They have a large OTC component where the identity of the transacting parties is common knowledge (unlike in the electronic order book where price and quantity are displayed but identity is hidden), and they are "lightly regulated". There have been a number of recent rule changes on EBS, one of the largest electronic platforms, with a view to limiting and mitigating the actions of anonymous HFT participants. EBS introduced a minimum quote life (MQL) in 2009, where quotes must remain tradable for at least a minimum amount of time (e.g. 500ms) to permit most participants the opportunity to trade on them. A "latency floor" was introduced in 2014 in which orders arriving with a period (which is itself random in length and random in start time) are kept within one or more batches, and their priority within the batch is randomised (ParFX and Reuters also have versions of this). Nevertheless, flash crashes have occurred in FX markets. One major event was

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[8]Order flow is considered toxic when it adversely selects market makers who are unaware that they are providing liquidity at their own loss.

the Swiss Franc depegging event of 15th January, 2015 whereby the Swiss authorities removed their large limit order on EBS that was supporting the desired price level. After a short while, this resulted in a rapid increase in the Swiss France from 1.20 to 0.80, and a subsequent recovery to 1.05. The downward trajectory was chaotic and there was gapping, meaning that many price points in between were not visited. Although the primary cause of the "crash" is obvious and reflecting fundamental information, the way it transpired is worrisome.



Figure 2. Swiss franc against the euro and dollar on the day of the depegging announcement

The Sterling Flash Crash on 20161007 is a more recent example. The GBP/USD currency, the third most liquid currency pair in the world, dropped by 9.66%, from 1.2601 to 1.1491, within 40 seconds. Most of this movement was reversed within the ten minutes that followed. The Bank for International Settlements provided a report, BIS (2017), on the sterling flash episode. Rather than pointing to any single driver, it found the movement in the currency pair to have resulted from a "confluence of factors". These included larger-than-normal trading (predominantly selling) volumes at a typically illiquid part of the trading day, as well as demand to sell sterling to hedge options positions and execute client orders in response to the initial fall in the exchange rate. The report also notes the potential amplifying role played by trading halts in USD/GBP futures contracts on the CME futures exchange. This may have created larger price pressure on other platforms and increased the price impact of trades in the spot market because many trading systems rely on the linkage between the spot and futures markets.

Kyle and Obizhaeva (2016a) propose a comprehensive model of trading in markets as transfers of risk in business time. Kyle and Obizhaeva (2016b) apply their findings to explain crashes of market in October 1929, October 1987, January 2008, and the flash crash of May 2010. They define the concept of *bets* as a parent sell or buy order that can be decomposed into many small trades. The bet does not have to be placed by a single person but can be composed of multiple orders acting on the same impulse or information. An example of this is when a price decline forces a liquidation of positions made on margin in a given security.

The advantage of this approach is that it does not suffer from biases caused by analyzing all the decomposed small trades (which individually have small impact) separately. Tobek, Linton, Noss, Crowley-Reidy and Pedace (2017) argue that the first part of the sterling flash crash was broadly consistent with the Kyle and Obizhaeva (2016b) impact model given the large directional order flow, but subsequent price developments went beyond that countenanced by the impact model.

There has been an increase in the deployment of and variety of circuit breakers and other market controls that limit price movements or halt trading on exchanges. Their purpose is to reduce the risk of a market collapse induced by a sequence of cascading trades. Circuit breakers can take many forms. There have been three types of circuit breakers in the U.S. equity markets: the market wide circuit breaker, the single stock circuit breaker, and the limit up-limit down trading halt. The market wide circuit breaker shuts down all trading, when triggered by a large movement in the stock price index. The single stock circuit breaker shuts down trading (or switches trading to an auction mechanism) when there is a large movement in the individual stock price. The limit up limit down mechanism prohibits trade outside upper and lower bounds, however trade of the stock can continue within the limits. Some authors have found positive effects of circuit breakers on market quality, Brugler and Linton (2017).

Circuit breakers are no panacea. Price discovery is a natural feature of markets, and bad news can induce (sometimes large) price drops to new efficient values. Halting markets can interfere with this natural process, and may simply postpone the inevitable. An empirically documented effect of circuit breakers is the so-called magnet or gravitational effect whereby traders rush to carry out trades when a halt becomes imminent, accelerating the price change process and forcing trading to be halted sooner or moving a price more than it otherwise would have moved, Subrahmanyam (1994), Arak and Cook (1997). During the sterling flash crash some have argued that the implementation of trading halts in the CME futures market contributed to the collapse of the spot market. In January 2016 China suspended its recently implemented circuit-breaker system after it experienced two days in close succession when trading in Chinese stocks had been halted because of a plunge in prices. The China Securities Regulatory Commission has used the halts and other measures to control downward pressure amid volatility. However, some observers felt the system as designed could have increased investor jitters about the health of markets.

## 7    Market Manipulation

Markham (2014) describes the long history of market manipulation including squeezes, pump and dump schemes, and insider trading in the era before and including electronic trading. The following types of market manipulation are of particular concern in electronic markets.

*Front running* ('pre-hedging') Traditionally, this arises when a broker who is charged with executing a large order on behalf of a client, trades on his own account ahead of the client trades selling back or buying back to them at worse prices (from the clients perspective). Nowadays, this refers to the practice whereby a

trader learns about a large order through the electronic marketplace and trades ahead of that order, thereby profiting from the momentum induced by the clients trades. One way of learning about the presence of large order is through *Phishing or Pinging.* This is quoting or placing orders, usually in small size, to uncover hidden orders or intentions of other participants, and then trading to take advantage of the information obtained; this technique is particularly effective on trading platforms where order confirmations are sent immediately, but market data updates are sent afterwards or even at regular, low sampled intervals

*Quote stuffing* This involves placing a large number of orders and then immediately cancelling them. The purpose of this is to make things difficult for rival firms by adding lots of noise into the system that the stuffer knows is not real but other participants do not. There are claims that this happened during the flash crash and at other times. This seems to be particularly an issue in the US stock market system due to the large number of trading venues and the logic of the National Market System, which requires routing of orders to obtain the best price wherever that is, Elder (2010). On the LSE for example, there are message throttling schemes to prevent over messaging relative to some prior agreed quantity. Of course, in times of market crisis when trading volumes increase massively relative average daily volume, these limits may be relaxed by the trading venue.

*Smoking/Flashing/Strobing.* Offering attractive limit orders (better than current top-of-book) and then quickly amending these orders to worse prices to exploit slower participants' market orders.

*Layering and spoofing.* A series of visible limit orders on one side of the market (the fake side) entered in a sequence to create the impression of increased demand/supply but far enough away form the touch to have small execution risk (or if close to the touch, small enough in size for execution not to matter), followed by or preceded by a limit order away from the touch on the other side (or a market order at the right time). For the spoofing to work, other participants have to improve their quotes in response to the fake side activity, thereby creating a better price on that side, which then is hit by the spoofers other side orders. This is then followed by cancellation of the fake side orders, and perhaps reversal of the strategy to complete a round trip. The Dodd-Frank Act prohibits "disruptive" trading such as spoofing.

The academic literature on modern market manipulations is relatively thin. There are some classic theoretical treatments of Allen and Gorton (1992) and Kyle and Viswanathan (2008) who discussed the economics of manipulation. There are a number of empirical studies documenting manipulation of closing prices (*banging the close*), see Putnins (2012), but relatively few documenting say spoofing. One exception is Lee, Eom and Park (2013) who investigated the Korean exchange ELOB, which until the end of 2001 disclosed the best prices and the total quantity without regard to where that quantity was priced. The authors document spoofing strategies on this market: big orders placed away from the touch that conveyed the impression of increased activity on one side of the market followed by market orders on the other side that captured the subsequent price movement.

There have been a number of market manipulation cases in the US and UK that lead to legal action. Navinder Sarao (the *Hound of Hounslow*) was convicted in February 2017 of spoofing in the E-mini futures

market including during the Flash crash day. He was trading from his parents' house in West London through a US broker's account. Similarly, two recent cases in the UK involved traders who spoofed stocks on the LSE using a combination of algorithmic execution and manual intervention and were relatively small and technologically mediocre players. The relative lack of HFT-related cases is consistent with the interpretation that HFT is not giving rise to more abuse, or alternatively that such abuse is much harder to detect. It is certainly the case that the few penalties related to HFT pale into insignificance when compared to the fines imposed to date on the firms implicated in the low frequency LIBOR fixing scandal uncovered in 2012, and the FX fixing scandal in 2014. There is some evidence (Aitken et al. (2012)) that closing price manipulation has reduced due to the presence of HFT.

## 8  Big Data and Financial Markets

The amount of data created and consumed by humanity has increased exponentially and will continue to do so in the near future. Recent developments in "Machine Learning" technology promises to be able to analyze this data rapidly and accurately. The success of the computer programme AlphaGo in beating the world Go champion in 2016 at this very complex and subtle game has demonstrated the value of machine learning techniques. This was considered the most complex of human games, more difficult for a computer to win at than chess, which was already conquered ten years ago. In this case, the data are quite complex in type although rather small in volume, but the strategy space over which the software has to search is huge, as there are approximately $361!=10^{700}$ different games on a $19 \times 19$ board. There are many other successes of this new data mining methodology in medicine, marketing, and security services. A lot of the basic techniques used in machine learning are easy to acquire and deploy and are publicly available in open source depositaries such as GitHub.

The objective of High Frequency Trading is to make many round trip trades in as short a time as possible with small expected profit per trade, which involves making very short term predictions. Their approach is a bit like taking AlphaGo and requiring it to make a move every nanosecond. In that case it would make very simple moves that would not have any educational value ex post. It would still win if the human opponent was required to move in nanosecond frequency also or forfeit his move, but it would win ugly. Some algorithmic traders on the other hand are trying to buy or sell a large quantity of stock and seek to do this in a way that gets the best price within some fairly long time frame. This is an objective that may be achieved better using more complicated techniques based on big data. There is an increase in the number of fintech companies that provide such services. Could we ever expect big data techniques to be able to predict financial markets better than was possible in the past?

Economic models usually employ a dichotomy between informed individuals and uninformed individuals and draw various conclusions from this. Grossman and Stiglitz (1980) develop a model of stock prices in

the presence of costly information acquisition. They establish that

$$1 - \rho_\theta^2 = \frac{\exp\left(\gamma c\right) - 1}{\sigma_\theta^2/\sigma_\varepsilon^2}, \tag{2}$$

where the signal noise ratio is $\sigma_\theta^2/\sigma_\varepsilon^2$, the cost of signal acquisition is $c$, $\gamma$ is the risk aversion, and $\rho_\theta^2$ is the squared correlation between the signal and the equilibrium price, which measures the informativeness of the price system. This allows some comparative statics. One could argue that the cost of acquiring basic historical data has decreased, and generally the quality and quantity of data has improved, although given the vast quantity of data being produced, finding the relevant information from the noisy chatter is challenging (and perhaps the cost of the most relevant and timely data has even increased). Anyway, suppose that $\sigma_\theta^2/\sigma_\varepsilon^2$ increases and $c$ decreases in (2). Then $\rho_\theta^2$ should rise and the price system should be more informative. On the other hand, one might imagine a more complex scenario in which both the signal and the noise increase and where it is not the absolute cost of information but the relative cost of information (cost per unit of $\sigma_\theta^2$) in which case the predictions are ambiguous. One thing should be clear, that the Grossman and Stiglitz model sets limits on the amount of predictability that can be achieved in financial markets for any given cost/signal noise ratio. In practice, there are also many issues raised about the sensitivity of the market system to herding induced by automated systems.

## 9 Conclusions

High frequency trading can improve the quality of markets, fostering greater liquidity, narrowing spreads, and increasing efficiency. Yet these benefits may come with associated costs: the rates at which current systems can interact autonomously with each other raises the risk that rare but extreme adverse events can be initiated and then proceed at speeds very much faster than humans can comfortably cope with, generating volumes of data that can require weeks of computer-assisted analysis by teams of skilled analysts before they are understood. Although they may happen only very rarely, there is a clear danger that very serious situations can develop at extreme speed. We next discuss a number of proposals to alter market design to mitigate some of the negative outcomes associated with HFT.

Some have argued that the order priority rules which determine the sequence in which submitted orders are executed on equity markets are at fault and prioritize speed. The policy issue is whether time-price priority unduly rewards high frequency traders and leads to over-investment in an unproductive technology arms race, Haldane (2011) and Baron, Brogaard, and Kirilenko (2014). The greatest benefit of a time-price priority rule is that it treats every order equally. Using other priorities, such as a pro rata rule where every order at a price gets a partial execution, gives greater benefits to large traders over small traders. In addition, time-price priority provides a stronger incentive to improve the quote than a pro rata rule, enhancing liquidity dynamics. Limit order providers face risks in that traders with better information can profit at their expense. Time-price priority encourages risk-taking by giving priority in execution to limit

order providers willing to improve their quotes. The IEX exchange was established with a view to offer equity traders an alternative priority scheme, as discussed in Lewis (2015). They also claim to offer protection from "crumbling quotes", i.e. to protect orders from trading during unstable, i.e., fast moving, and potentially adverse conditions.[9] They have gained some market share but are still far behind NYSE, Nasdaq, and BATS.

Budish, Cramton, and Shim (2015) have proposed to replace the continuous ELOB by periodic auctions, which can be designed to minimize the advantage of speed and to mitigate other negative outcomes of the continuous trading model such as manipulative strategies. The main benefit of periodic call auctions would be a reduction of the speed of trading and the elimination of the arms race for speed discussed above. The speed of trading could be controlled through the timing and frequency parameters, which could be tuned to individual and market conditions. One issue with this proposal is how to foster competition and allow dynamic hedging, which requires synchronization between securities on the same and competing venues. Many markets have auctions at the open and the close and now are introducing midday auctions, in addition to the continuous trading segment. The auction mechanism was the primary mechanism for stock trading in many markets before the ELOB arrived, and there are a number of studies documenting the benefits of adding the ELOB from this period, Amihud, Mendelsohn, and Lauterbach (1997).

The worlds' financial markets are engines of economic growth, enabling corporations to raise funds and offering investors the opportunity to achieve their preferred balance of expected risks and rewards. It is important that they remain fair and orderly. Deciding how best to ensure this, in light of the huge growth in both the uptake and complexity of high frequency trading that has occurred in the last decade, and which can be expected to continue in the next, requires careful thought and discussion.

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