

The High-Frequency Trading Arms Race: Frequent Batch Auctions as a Market Design Response

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- ▶ Analogous races occurring at level of microseconds and nanoseconds, estimated at \$bn’s per year (also substantial human capital)

The HFT Arms Race: Market Design Perspective

- ▶ We examine the HFT “Arms Race” from the perspective of market design.
 - ▶ We assume that HFT’s are optimizing with respect to market rules as they’re presently given
 - ▶ But, ask whether these are the right rules
 - ▶ Avoids much of the “is HFT good or evil?” that seems to dominate the discussion of HFT
- ▶ Central point: HFT arms race is a *symptom* of a basic flaw in modern financial market design: continuous-time trading.
- ▶ Proposal: replace continuous-time limit order books with discrete-time frequent batch auctions
 - ▶ Frequent batch auctions: uniform-price sealed-bid double auctions conducted at frequent but discrete time intervals, e.g., every 1 second.

Frequent Batch Auctions

A simple idea: replace (continuous-time) limit-order books with (discrete-time) frequent batch auctions

1. Continuous limit-order books don't actually “work” in continuous time: market correlations break down at high frequency
2. Correlation breakdown → Technical arbitrage opportunities → Arms Race. Arms Race is a “constant” of the market design.
3. Model: costs of the arms race
 - ▶ Harms liquidity (spreads, depth)
 - ▶ Socially wasteful
4. Frequent Batch Auctions as a market design response
 - ▶ Benefits: eliminates arms race, enhances liquidity, enhances market stability
 - ▶ Cost: fundamental traders must wait a small amount of time to trade

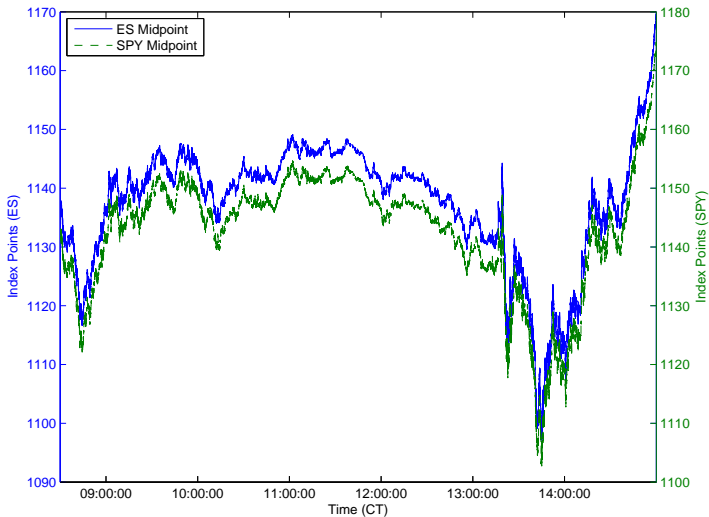
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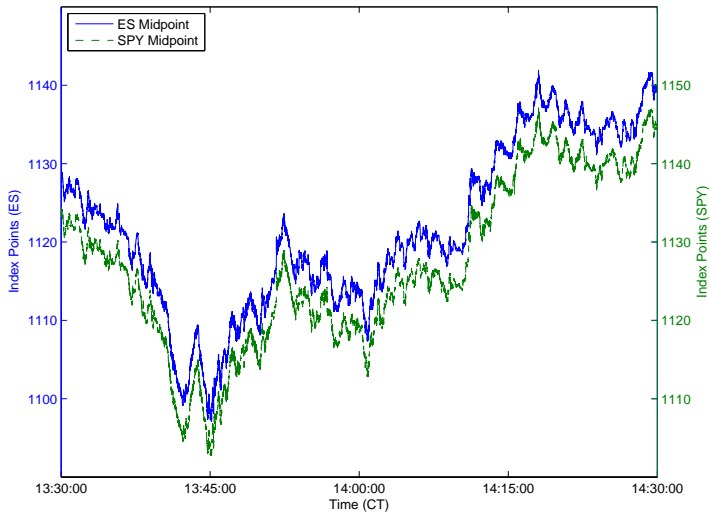
Market Correlations Break Down at High Frequency

ES vs. SPY: 1 Day



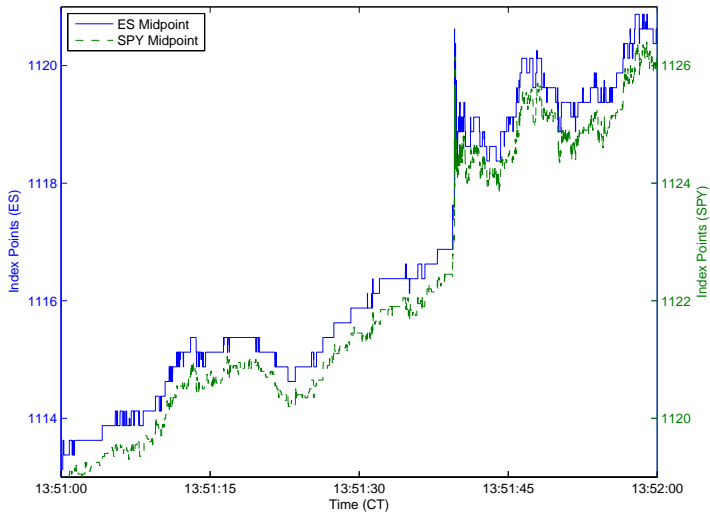
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ES vs. SPY: 1 hour



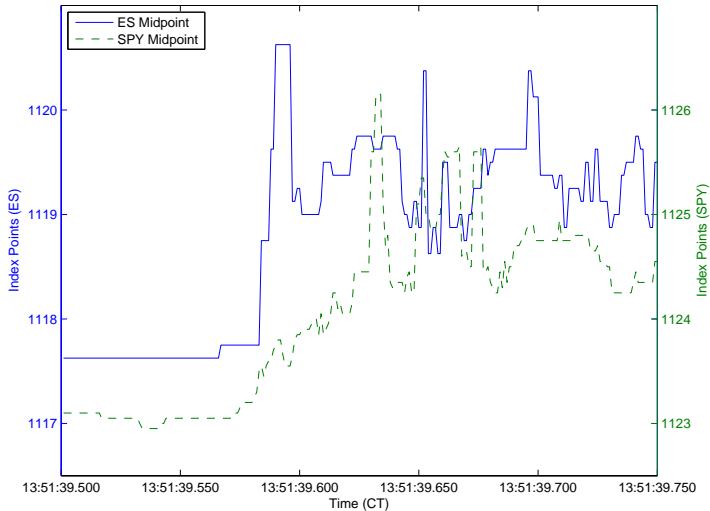
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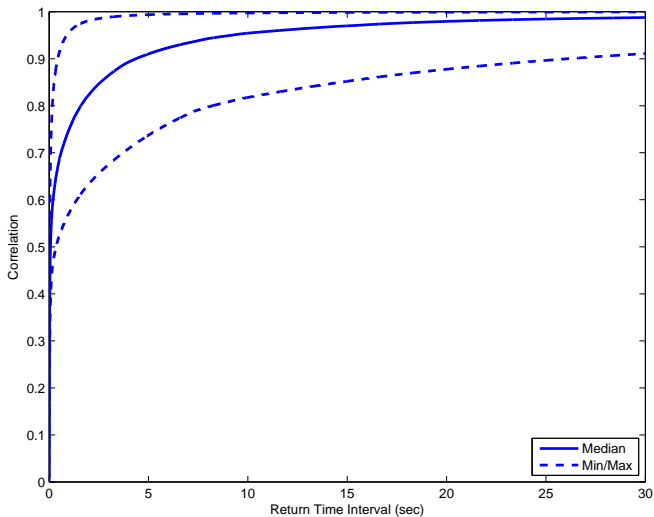
Market Correlations Break Down at High Frequency

ES vs. SPY: 250 milliseconds



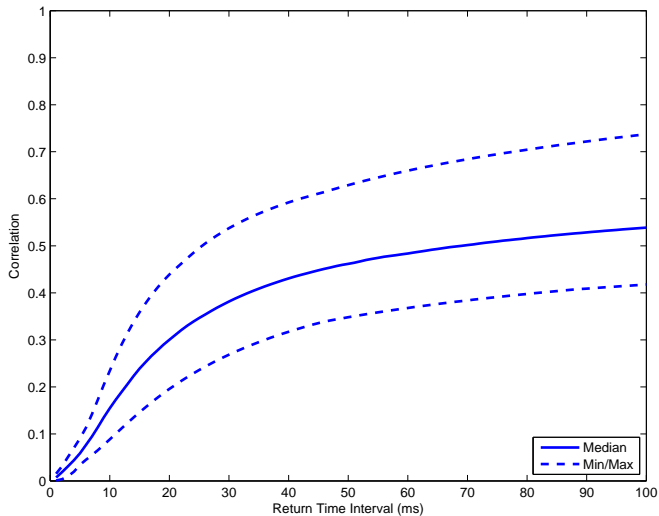
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ES vs. SPY: Correlations by Time Interval in 2011

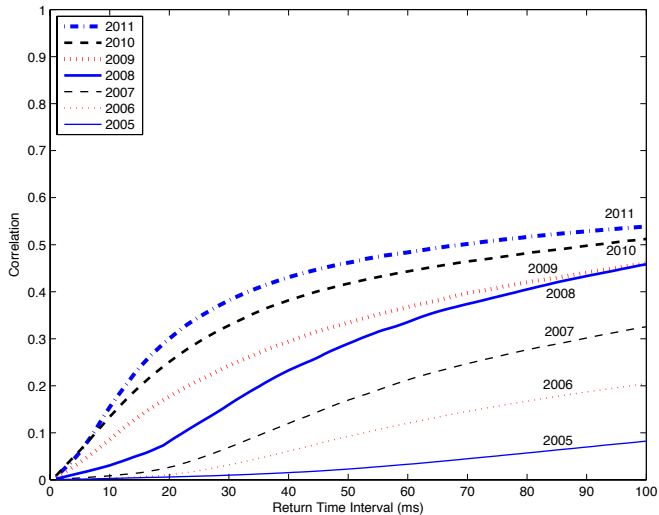


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ES vs. SPY: Correlations by Time Interval in 2011



Correlation Breakdown Over Time



Correlation Breakdown: Equities Correlation Matrix

	1 ms	100 ms	1 sec	10 sec	1min	10 min	30 min
HD-LOW	0.008	0.101	0.192	0.434	0.612	0.689	0.704
GS-MS	0.005	0.094	0.188	0.405	0.561	0.663	0.693
CVX-XOM	0.023	0.284	0.460	0.654	0.745	0.772	0.802
AAPL-GOOG	0.001	0.061	0.140	0.303	0.437	0.547	0.650

Correlation Breakdown: Equities Correlation Matrix

	AAPL	XOM	GE	JNJ	IBM
	1 ms				
AAPL	1.000				
XOM	0.005	1.000			
GE	0.002	0.005	1.000		
JNJ	0.003	0.010	0.004	1.000	
IBM	0.002	0.005	0.002	0.004	1.000

	30 Min				
AAPL	1.000				
XOM	0.495	1.000			
GE	0.508	0.571	1.000		
JNJ	0.349	0.412	0.440	1.000	
IBM	0.554	0.512	0.535	0.464	1.000

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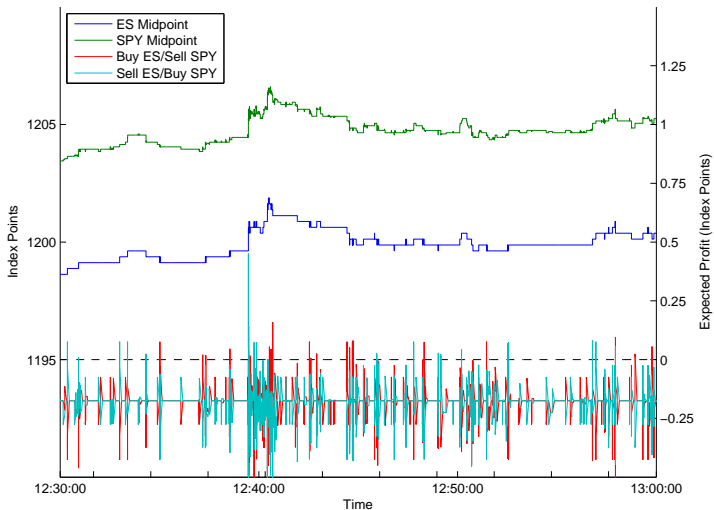
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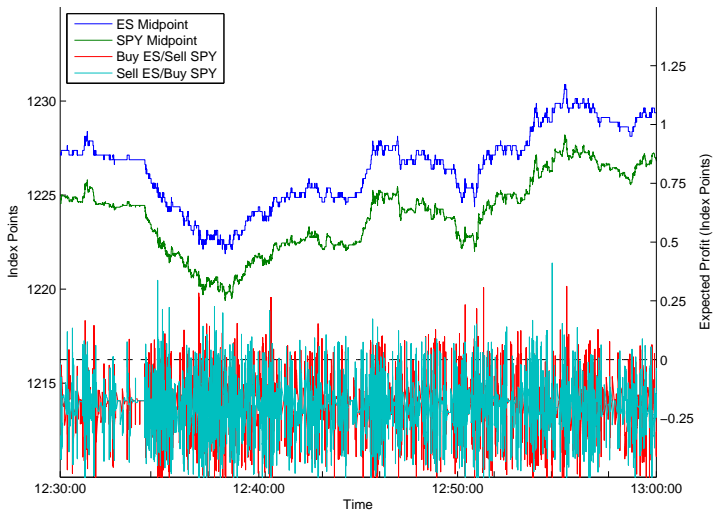
Correlation Breakdown Creates an Arms Race

- ▶ Correlation breakdown is obvious ex-post
 - ▶ Nothing in current financial market design that would enable correlated securities' prices to move at *exactly* the same time
 - ▶ In auction design terminology, financial markets are a collection of separate single-product auctions, rather than a single combinatorial auction.
- ▶ Might seem like a theoretical curiosity, safe to ignore
 - ▶ Analogy: Newtonian mechanics breaks down at the quantum level, but we can safely ignore quantum physics and rely on the Newtonian model in most of day-to-day life
- ▶ But it matters: creates purely technical arbitrage opportunities, which in turn create an arms race

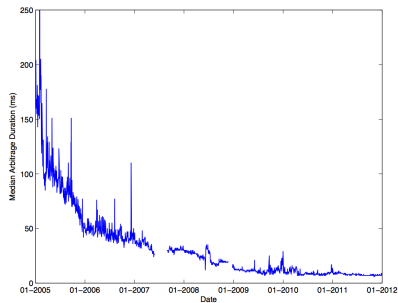
Technical Arbitrage: Illustrated



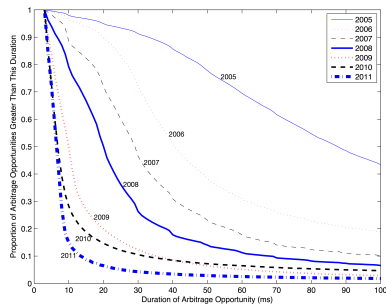
Technical Arbitrage: Financial Crisis



Arb Durations over Time: 2005-2011

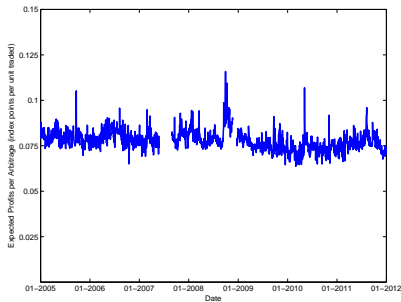


(a) Median over time

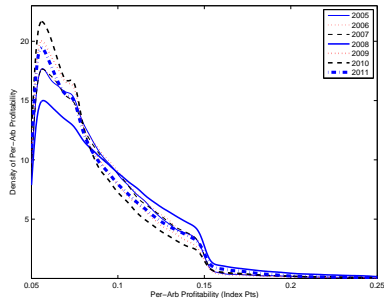


(b) Distribution by year

Arb Per-Unit Profits over Time: 2005-2011

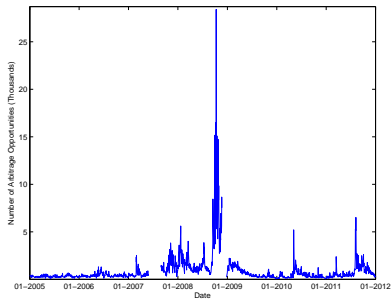


(c) Median over time

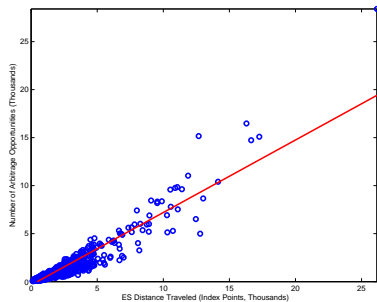


(d) Distribution by year

Arb Frequency over Time: 2005-2011



(e) Median over time



(f) Frequency vs. Volatility

Arms Race is a “Constant” of the Market Design

- ▶ Results suggest that the arms race is a mechanical “constant” of the continuous limit order book.
 - ▶ Rather than a profit opportunity that is competed away over time
- ▶ Competition does increase the speed requirements for capturing arbs (“raises the bar”)
- ▶ Competition does not reduce the size or frequency of arb opportunities
- ▶ These facts both inform and are explained by our model

Total Size of the Arms Race Prize

- ▶ Estimate annual value of ES-SPY arbitrage is \$75mm (we suspect underestimate, details in paper)
- ▶ And ES-SPY is just the tip of the iceberg in the race for speed:
 1. Hundreds of trades very similar to ES-SPY: highly correlated, highly liquid
 2. Fragmented equity markets: can arbitrage SPY on NYSE against SPY on NASDAQ! Even simpler than ES-SPY.
 3. Correlations that are high but far from one can also be exploited in a statistical sense. Example: GS-MS
 4. Race to top of book (artifact of minimum tick increment)

We don't attempt to put a precise estimate on the total prize at stake in the arms race, but common sense extrapolation from our ES-SPY estimates suggest that the sums are substantial

Technical Arbitrage: Other Highly Correlated Pairs

Partial List

E-mini S&P 500 Futures (ES) vs. SPDR S&P 500 ETF (SPY)	Australian Dollar Futures (6B) vs. Spot AUDUSD
E-mini S&P 500 Futures (ES) vs. iShares S&P 500 ETF (SPV)	Swiss Franc Futures (6S) vs. Spot USDCHF
E-mini S&P 500 Futures (ES) vs. Vanguard S&P 500 ETF (VOO)	Canadian Dollar Futures (6C) vs. Spot USDCAD
E-mini S&P 500 Futures (ES) vs. ProShares Ultra (2x) S&P 500 ETF (SSO)	Gold Futures (GC) vs. miNY Gold Futures (QO)
E-mini S&P 500 Futures (ES) vs. ProShares UltraPro (3x) S&P 500 ETF (UPRO)	Gold Futures (GC) vs. Spot Gold (XAUUSD)
E-mini S&P 500 Futures (ES) vs. ProShares Short S&P 500 ETF (SH)	Gold Futures (GC) vs. E-micro Gold Futures (MGC)
E-mini S&P 500 Futures (ES) vs. ProShares Ultra (2x) Short S&P 500 ETF (SDS)	Gold Futures (GC) vs. SPDR Gold Trust (GLD)
E-mini S&P 500 Futures (ES) vs. ProShares UltraPro (3x) Short S&P 500 ETF (SPXU)	Gold Futures (GC) vs. iShares Gold Trust (IAU)
E-mini S&P 500 Futures (ES) vs. 500 Constituent Stocks	miNY Gold Futures (QO) vs. E-micro Gold Futures (MGC)
E-mini S&P 500 Futures (ES) vs. 9 Select Sector SPDR ETFs	miNY Gold Futures (QO) vs. Spot Gold (XAUUSD)
E-mini S&P 500 Futures (ES) vs. E-mini Dow Futures (YM)	miNY Gold Futures (QO) vs. SPDR Gold Trust (GLD)
E-mini S&P 500 Futures (ES) vs. E-mini Nasdaq 100 Futures (NQ)	miNY Gold Futures (QO) vs. iShares Gold Trust (IAU)
E-mini S&P 500 Futures (ES) vs. E-mini S&P MidCap 400 Futures (EMD)	E-micro Gold Futures (MGC) vs. SPDR Gold Trust (GLD)
E-mini S&P 500 Futures (ES) vs. Russell 2000 Index Mini Futures (TF)	E-micro Gold Futures (MGC) vs. iShares Gold Trust (IAU)
E-mini Dow Futures (YM) vs. SPDR Dow Jones Industrial Average ETF (DIA)	E-micro Gold Futures (MGC) vs. Spot Gold (XAUUSD)
E-mini Dow Futures (YM) vs. ProShares Ultra (2x) Dow 30 ETF (DDM)	Market Vectors Gold Miners (GDX) vs. Direxion Daily Gold Miners Bull 3x (NUGT)
E-mini Dow Futures (YM) vs. ProShares UltraPro (3x) Dow 30 ETF (UDOW)	Silver Futures (SI) vs. miNY Silver Futures (QI)
E-mini Dow Futures (YM) vs. ProShares Short Dow 30 ETF (DOG)	Silver Futures (SI) vs. iShares Silver Trust (SLV)
E-mini Dow Futures (YM) vs. ProShares Ultra (2x) Short Dow 30 ETF (DXD)	Silver Futures (SI) vs. Spot Silver (XAGUSD)
E-mini Dow Futures (YM) vs. ProShares UltraPro (3x) Short Dow 30 ETF (SDOW)	miNY Silver Futures (QI) vs. iShares Silver Trust (SLV)
E-mini Dow Futures (YM) vs. 30 Constituent Stocks	miNY Silver Futures (QI) vs. Spot Silver (XAGUSD)
E-mini Nasdaq 100 Futures (NQ) vs. ProShares QQQ Trust ETF (QQQ)	Platinum Futures (PL) vs. Spot Platinum (XPTUSD)
E-mini Nasdaq 100 Futures (NQ) vs. Technology Select Sector SPDR (XLK)	Palladium Futures (PA) vs. Spot Palladium (XPDUSD)
E-mini Nasdaq 100 Futures (NQ) vs. 100 Constituent Stocks	Eurodollar Futures Front Month (ED) vs. (12 back month contracts)
Russell 2000 Index Mini Futures (TF) vs. iShares Russell 2000 ETF (IWM)	10 Yr Treasury Note Futures (ZN) vs. 5 Yr Treasury Note Futures (ZF)
Euro Stoxx 50 Futures (FESX) vs. Xetra DAX Futures (FDAX)	10 Yr Treasury Note Futures (ZN) vs. 30 Yr Treasury Bond Futures (ZB)
Euro Stoxx 50 Futures (FESX) vs. CAC 40 Futures (FCE)	10 Yr Treasury Note Futures (ZN) vs. 7-10 Yr Treasury Note
Euro Stoxx 50 Futures (FESX) vs. iShares MSCI EAFE Index Fund (EFA)	2 Yr Treasury Note Futures (ZT) vs. 1-2 Yr Treasury Note
Nikkei 225 Futures (NIY) vs. MSCI Japan Index Fund (EWJ)	2 Yr Treasury Note Futures (ZT) vs. iShares Barclays 1-3 Yr Treasury Fund (SHY)
Financial Sector SPDR (XLF) vs. Constituents	5 Yr Treasury Note Futures (ZF) vs. 4-5 Yr Treasury Note
Financial Sector SPDR (XLF) vs. Direxion Daily Financial Bull 3x (FAS)	30 Yr Treasury Bond Futures (ZB) vs. iShares Barclays 20 Yr Treasury Fund (TLT)
Energy Sector SPDR (XLE) vs. Constituents	30 Yr Treasury Bond Futures (ZB) vs. ProShares UltraShort 20 Yr Treasury Fund (TBT)
Industrial Sector SPDR (XLI) vs. Constituents	30 Yr Treasury Bond Futures (ZB) vs. ProShares Short 20 Year Treasury Fund (TBF)
Cons. Staples Sector SPDR (XLP) vs. Constituents	30 Yr Treasury Bond Futures (ZB) vs. (6 back month contracts)
Materials Sector SPDR (XLB) vs. Constituents	Crude Oil Futures Front Month (CL) vs. (6 back month contracts)
Utilities Sector SPDR (XLU) vs. Constituents	Crude Oil Futures (CL) vs. ICE Brent Crude (B)
Technology Sector SPDR (XLK) vs. Constituents	Crude Oil Futures (CL) vs. United States Oil Fund (USO)
Health Care Sector SPDR (XLV) vs. Constituents	Crude Oil Futures (CL) vs. ProShares Ultra DJ-UBS Crude Oil (UCO)
Cons. Discretionary Sector SPDR (XLY) vs. Constituents	Crude Oil Futures (CL) vs. iPath S&P Crude Oil Index (OIL)
SPDR Homebuilders ETF (HXB) vs. Constituents	ICE Brent Crude Front Month (B) vs. (6 back month contracts)
SPDR S&P 500 Retail ETF (XRT) vs. Constituents	ICE Brent Crude (B) vs. United States Oil Fund (USO)
Euro FX Futures (6E) vs. Spot EURUSD	ICE Brent Crude (B) vs. ProShares Ultra DJ-UBS Crude Oil (UCO)
Japanese Yen Futures (6J) vs. Spot USDJPY	ICE Brent Crude (B) vs. iPath S&P Crude Oil Index (OIL)
British Pound Futures (6B) vs. Spot GBPUSD	Natural Gas (Henry Hub) Futures (NG) vs. United States Nat Gas Fund (UNG)

Frequent Batch Auctions

A simple idea: replace (continuous-time) limit-order books with (discrete-time) frequent batch auctions

1. Continuous limit-order books don't actually “work” in continuous time: market correlations break down at high frequency
2. Correlation breakdown → Technical arbitrage opportunities → Arms Race. Arms Race is a “constant” of the market design.
3. **Model: costs of the arms race**
 - ▶ **Harms liquidity (spreads, depth)**
 - ▶ **Socially wasteful**
4. Frequent Batch Auctions as a market design response
 - ▶ Benefits: eliminates arms race, enhances liquidity, enhances market stability
 - ▶ Cost: fundamental traders must wait a small amount of time to trade

Model: Key Idea

Key idea: the arms race profits come at the expense of liquidity providers, which ultimately harms liquidity (bid-ask spreads, market depth)

- ▶ Why? Consider the race from a liquidity provider's perspective
 - ▶ Suppose there is a publicly observable news event that causes his quotes to become “stale”
 - ▶ E.g., a change in the price of a highly correlated security, Fed announcement
 - ▶ 1 of him, trying to adjust his stale quotes
 - ▶ Many others, trying to “pick off” his stale quotes
 - ▶ In a continuous limit order book, messages are processed one-at-a-time in serial ...
 - ▶ so the 1 usually loses the race against the Many ...
 - ▶ Even if they are all equally fast
- ▶ Glosten-Milgrom (1985) adverse selection ... but with completely symmetric information. The adverse selection is “built in” to the market design.

Model: Key Idea

- ▶ This “picking off” cost of providing liquidity is incremental to the usual fundamental costs of providing liquidity
 - ▶ Asymmetric information, inventory costs, search costs
- ▶ In a competitive market, picking off costs get passed on to fundamental investors
 - ▶ Thinner markets, wider bid-ask spreads
- ▶ Ultimately, in equilibrium of our model, all of the \$ spent in the arms race come out of the pockets of fundamental investors

What's the Market Failure?

Chicago question: isn't the arms race just healthy competition?
what's the market failure? Our model yields two responses

1. Model shows that the arms race can be interpreted as a prisoners' dilemma
 - ▶ If all HFTs could commit not to invest in speed, they'd all be better off
 - ▶ But, each individual HFT has incentive to deviate and invest in speed
2. Model shows that a violation of the efficient market hypothesis is built in to the market design
 - ▶ Violations of the the weak-form EMH are intrinsic to the continuous limit order book market design
 - ▶ You can make money from purely technical information (and HFTs do!)

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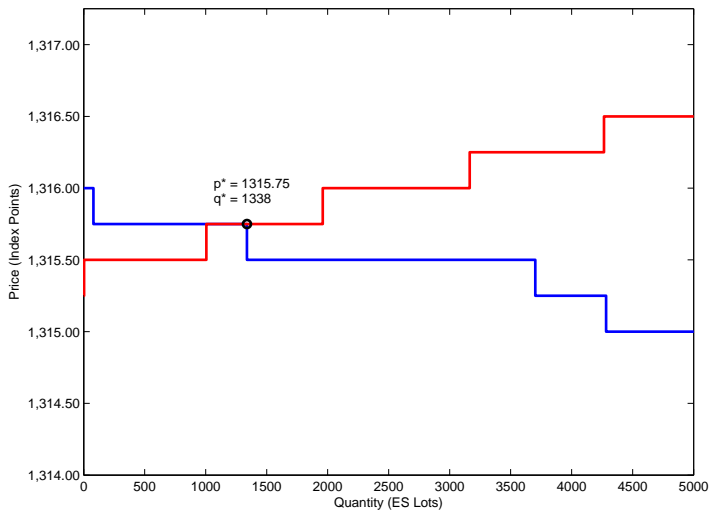
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Frequent Batch Auctions: Definition

- ▶ The trading day is divided into a finite number of equal-length discrete intervals, each of length $\tau > 0$.
- ▶ During the batch interval (eg 1 second), traders submit bids and asks as price-quantity pairs
 - ▶ Just like standard limit orders
- ▶ At the conclusion of each batch interval, the exchange “batches” all of the received orders, and computes market-level supply and demand curves
- ▶ If supply and demand intersect, then all transactions occur at the same market-clearing price (“uniform price”)
 - ▶ Bids and asks of exactly the market-clearing price may get rationed (pro-rata)
 - ▶ If there is a range of market-clearing prices, choose the midpoint (knife-edge case)
- ▶ Information policy: orders are not visible during the batch interval. Aggregate demand and supply are announced at the end.
 - ▶ Analogous to current practice under the continuous limit-order book

Frequent Batch Auctions: Illustrated



Why and How Batching Eliminates the Arms Race

There are two reasons why batching eliminates the arms race:

1. Batching reduces the value of a tiny speed advantage
 - ▶ If the batch interval is 1 second, a 1 millisecond speed advantage is only $\frac{1}{1000}$ th as useful
2. Batching transforms competition on speed into competition on price
 - ▶ Ex: the Fed announces policy change at 2:00:00.000pm ...
 - ▶ Continuous market: competition manifests in a race to react. *Someone is always first.*
 - ▶ Batched market: competition simply drives the price to its new correct level for 2:00:01.000. Lots of orders reach the exchange by the end of the batch interval.

Equilibrium Costs and Benefits of Frequent Batching

- ▶ Benefits

- ▶ Enhanced liquidity
 - ▶ Narrower spreads
 - ▶ Increased depth
- ▶ Eliminate socially wasteful arms race

- ▶ Costs

- ▶ Fundamental investors must wait until the end of the batch interval to transact

Questions About Batching Left Unanswered

- ▶ Practical implementation questions
 - ▶ Optimal batch interval, and how this varies by security
 - ▶ Tick sizes?
 - ▶ Circuit breakers?
 - ▶ Further details of information policy
- ▶ Competition among exchanges
 - ▶ Especially salient given fragmentation of US equity markets
- ▶ Effect of batching on market stability

Market Stability Benefits of Frequent Batching

1. Computationally simple for exchanges
 - ▶ Given discrete block of time to compute auction, report outcomes
 - ▶ Prevents order backlog, incorrect time stamps (Facebook IPO, Flash Crash)
 - ▶ Simplifies systems design (NASDAQ outage)
2. Batching gives trading algos a discrete period of time to process recent prices before deciding on their next trades
 - ▶ Observe t outcome, discrete block of time to make $t + 1$ decisions
 - ▶ Reduces incentive to trade off code robustness for speed (Knight)
3. Improved transparency for regulators
 - ▶ Continuous market leaves a paper trail that regulators can't follow (Flash Crash)
4. Market depth theory results can also be interpreted as a stability result
 - ▶ Thin markets more vulnerable to “mini flash crashes”

Market Stability Benefits of Frequent Batching

Conceptual point

- ▶ Continuous markets implicitly assume that computers and communications technology are infinitely fast
- ▶ Computers are fast but not infinitely so
- ▶ Frequent batching respects the limits of computers

Summary

- ▶ We take a market design perspective to the HFT arms race. What incentivizes HFTs to invest billions in tiny speed advantages? Can we improve financial market design?
 - ▶ Propose a simple idea: replace (continuous-time) limit-order books with (discrete-time) frequent batch auctions.
1. Show that continuous-time markets are a fiction: market correlations break down at high frequency
 2. Correlation breakdown → Technical arbitrage opportunities → Arms Race. Arms Race is a “constant” of the market design.
 3. Costs of the arms race
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 - ▶ Costs: fundamental investors must wait a small amount of time to trade, law of unintended consequences