CloudEx: Experiments with Building a Financial Exchange in the Cloud
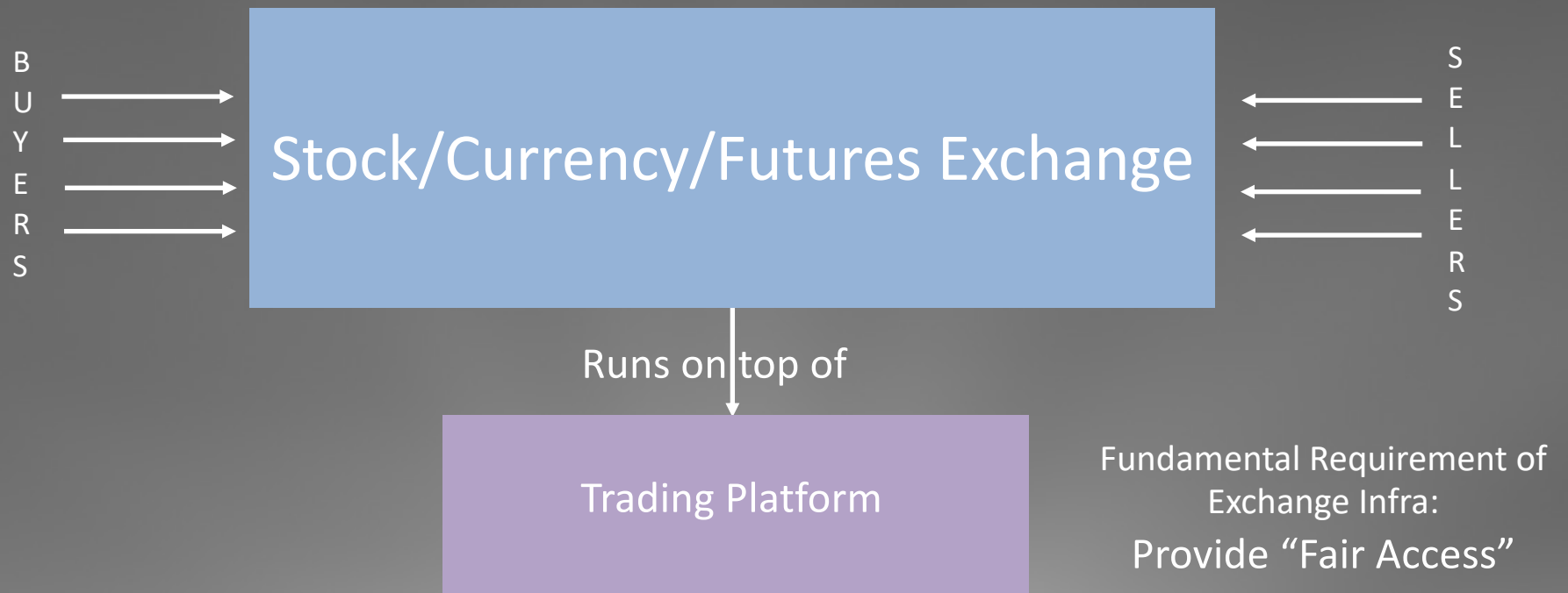
Balaji Prabhakar

Professor of EE and CS, Stanford University
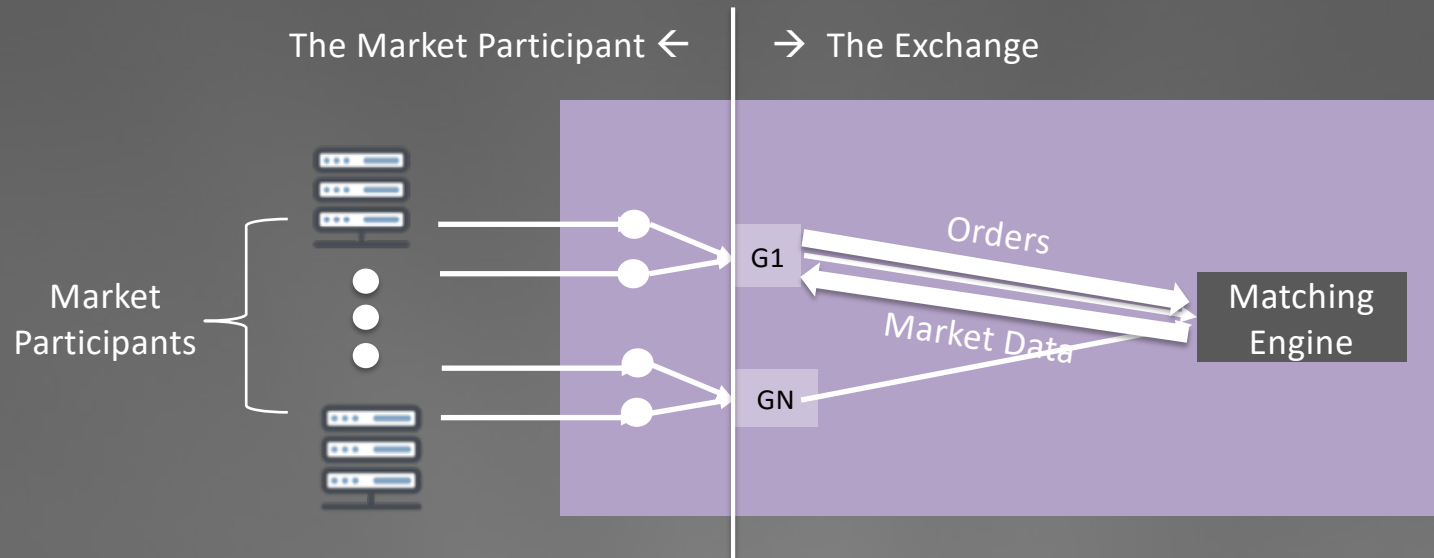
Co-Founder, Tick Tock Networks

Exchanges and Trading Platforms

Fundamental Operation Performed by Exchange:
Price Discovery!

B U Y E R S

Stock/Currency/Futures Exchange

S E L L E R S

Runs on top of

Trading Platform

Fundamental Requirement of
Exchange Infra:
Provide "Fair Access"

The Exchange Loop Must Be **Fair**

The Market Participant ←   → The Exchange

Market Participants
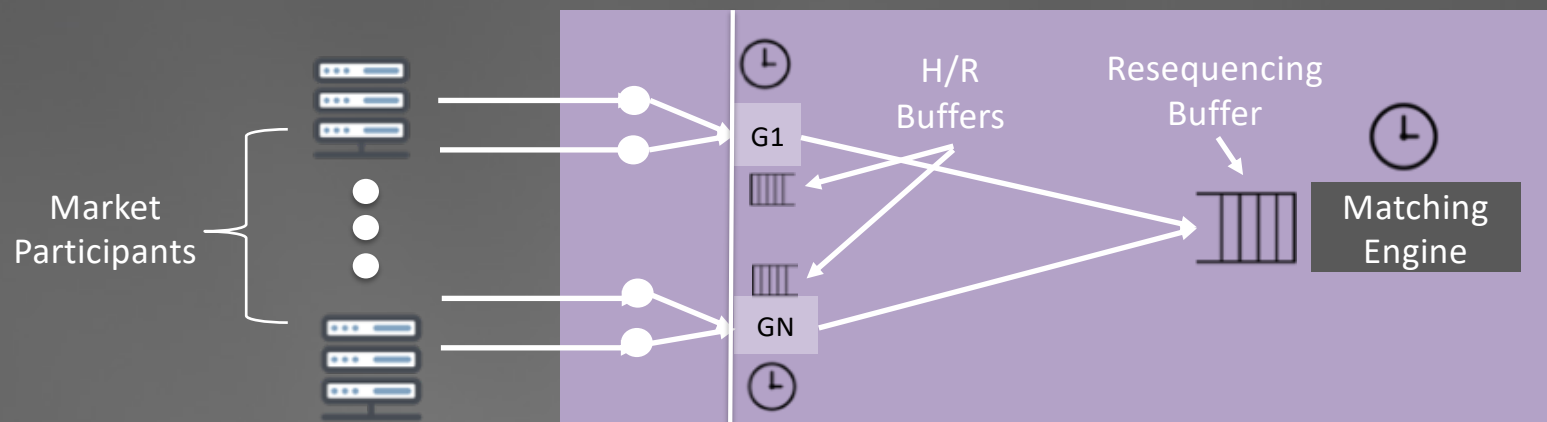
G1

GN

Orders

Market Data

Matching Engine

Definition of Fairness

Inbound Fairness: *Orders must be processed in a globally FIFO manner*, regardless of GW through which they enter the exchange

Outbound Fairness: The *Market Data shall reach* all MPs (GWs) at *exactly the same time*

Providing Fairness using Accurate Clocks

Inbound Fairness (recall: GW and ME clocks are synchronized)

Timestamp orders when the arrive at the gateways to establish order of arrival

Resequence orders according to their gateway timestamps before executing them at the ME

Outbound Fairness

Timestamp market data at the ME

Hold-and-release market data at the gateways using the H/R buffers to ensure simultaneous delivery

→ See STAC talk from Oct 2019: https://stacresearch.com/STAC-Summit-17-Oct-2019-tick-tock

"All the News That's Fit to Print"

The New York Times

Late Edition

Today, sunny to partly cloudy, hot, humid, high 94. **Tonight,** clear, very warm, humid, low 78. **Tomorrow,** hazy sunshine, very hot, humid, high 98. Weather map, Page A20.

VOL. CLXVII ... No. 58,009 © 2018 The New York Times Company   NEW YORK, SATURDAY, JUNE 30, 2018 $3.00

KREMLIN'S LINKS TO BREXIT PUSH GET A NEW LOOK

COURTING BANKROLLERS

Parallels to U.S. Inquiry as Investigators Focus on 2016 Meeting

By DAVID D. KIRKPATRICK and MATTHEW ROSENBERG

LONDON — Arron Banks, a British financier who bankrolled the campaign for Britain to leave the European Union, has long bragged about his "boozy six-hour lunch" with the Russian ambassador eight months before the vote.

Some also wondered about Mr. Banks's Russian-born wife and their custom license plate, X MI5 SPY, after the British intelligence agency, MI5. But Mr. Banks always laughed off questions about his ties to the Kremlin.

Now, a leaked record of some of Mr. Banks's emails suggest that he and his closest adviser had more engaged relationship with Russian diplomats than he has disclosed.

While Mr. Banks was spending more than eight million British pounds to promote a break with the European Union — an outcome the Russians eagerly hoped for — his contacts at the Russian Embassy in London were opening the door to at least three potentially lucrative investment opportunities in Russian-owned gold or diamond mines.

One of Mr. Banks's business partners, and a fellow backer of Britain's exit from the European Union, or Brexit, took the Russians up on at least one of the deals.

The extent of these business discussions, which have not been previously reported, raises new questions about whether the Kremlin sought to reward critical figures in the Brexit campaign. Much as in Washington, where investigations are underway into the possibility that Donald J. Trump's campaign may have cooperated with the Russians, Britain is now grappling with whether Moscow tried to use its close ties with any British citizens to promote its interests.

In Washington, the investigators for the special prosecutor, Robert S. Mueller III, and Democrats on the House Intelligence Committee have obtained records of Mr. Banks's communications, including some with Russian diplomats and about Russian business deals.

And they have taken a special interest in close ties Mr. Banks and other Brexit leaders built to

Continued on Page A9

Battling Tanks, Troops and Twisted Truths
American soldiers in Eastern Europe holding training exercises to combat Russia's military might and manipulation tactics. Page A7.

Once Deemed Too Radical for Mexico, He Now May Be President

By AZAM AHMED

GUADALAJARA, Mexico — Andrés Manuel López Obrador nodded at the sea of red T-shirts and flag-waving devotees jammed into a plaza in Guadalajara.

Never before had such a crowd welcomed him here. In his previous campaigns for the president's office, residents of Guadalajara, the wealthy capital of the state of Jalisco, shunned him, considering him leftist platform too radical.

But this time, only days before one of Mexico's most important elections in decades, the cheers reflected a nationwide shift — and the ability of Mr. López Obrador to ride it.

"We have had three transformations in the history of our country: our independence, the reform and the revolution," he told the crowd. "We are going to pull off the fourth."

As corruption and violence gnaw at Mexico's patience, voters have turned to a familiar face in Mr. López Obrador, a three-time candidate for president who once shut down Mexico City for months after a narrow loss, refusing to accept defeat.

Brandishing a deep connection with the poor, built over more than a decade of visits to every corner of this country of 120 million, he has managed a staggering lead ahead of Sunday's vote.

If the poll numbers bear out on Election Day, Mr. López Obrador — who has promised to sell the presidential plane and convert the opulent presidential palace into a public park — could win by a landslide, putting a leftist leader in charge of Latin America's second-largest country for the first time in decades.

He is currently 20 to 30 percentage points ahead of his closest rival, a stunning reversal for a politician whose future was far from clear just a few years ago. But a broad disgust with Mexico's political establishment has brought

Continued on Page A17

The presidential candidate Andrés Manuel López Obrador during the closing rally of his campaign on Wednesday in Mexico City.

Firing of Comey Left Rosenstein Feeling 'Shaken' and Exploited

By MICHAEL S. SCHMIDT and ADAM GOLDMAN

WASHINGTON — In the days after the F.B.I. director James B. Comey was fired last year, the deputy attorney general, Rod J. Rosenstein, repeatedly expressed anger about how the White House used him to rationalize the firing, saying the experience damaged his reputation, according to four people familiar with his outbursts.

In public, Mr. Rosenstein has shown no hint that he had second thoughts about his role — writing a memo about Mr. Comey's performance that the White House used to justify firing him. "I wrote it. I believe it. I stand by it," Mr. Rosenstein said to Congress last year.

But in meetings with law enforcement officials in the chaotic days immediately after Mr. Comey's dismissal, and in subsequent conversations with colleagues and friends, Mr. Rosenstein appeared conflicted, according to the four people.

He alternately defended his involvement, expressed remorse at the tumult it unleashed, said the White House had manipulated him, fumed how the news media had portrayed the events and said the full story would vindicate him, said the purging of events and news weeks described the previously undisclosed episodes.

According to one person with whom he spoke shortly after Mr. Comey's firing, Mr. Rosenstein was "shaken," "unsteady" and "overwhelmed."

Another person in touch with

Continued on Page A14

Whittling a New York Minute To 100 Billionths of a Second

By JOHN MARKOFF

SAN FRANCISCO — Computer scientists at Stanford University and Google have created technology that can track time down to 100 billionths of a second. It could be just what Wall Street is looking for.

System engineers at Nasdaq, the New York-based stock exchange, recently began testing an algorithm and software that they hope can synchronize a giant network of computers with that nanosecond precision. They say they have built a prototype, and are in the process of deploying a bigger version.

For an exchange like Nasdaq, such refinement is essential to accurately order the millions of stock trades that are placed on their computer systems every second.

Ultimately, this is about money. With stock trading now dominated by computers that make buying and selling decisions and execute them with blazing speed, keeping that order also means protecting profits. So-called high-frequency trading firms place trades in a fraction of a second, sometimes in a bet that they can move faster than bigger competitors.

Continued on Page A17

In Gunman's Rage, Something Eerily Familiar for Newsrooms

By TIM ARANGO and JOHN HERRMAN

Years ago, Joe Kieta was out to dinner at a nice restaurant with his wife, celebrating their second anniversary.

Mr. Kieta, then the editor of The Merced Sun-Star in Merced, Calif., had just published a series of articles that led to the ouster of the local district attorney. As he was eating, a friend of the district attorney showed up and asked Mr. Kieta to go outside.

He was "challenged me to a fight right in the middle of this fancy restaurant," Mr. Kieta, now the editor of The Fresno Bee in California, said on Friday.

The fatal shooting a day earlier at The Capital Gazette in Annapolis, Md., reverberated throughout newsrooms across the country, not only for its tragedy but also for the familiarity of conflicts like the suspected gunman's long-standing feud with the paper. Many reporters and editors, especially at the local level, have stories of being confronted or harassed by a resident upset by something in the newspaper. Unlike Thursday's shooting, in which five people were killed, few of those situations end in violence.

The suspect, Jarrod W. Ramos, 38, had hounded the paper for years, after the publication of an article about his conviction in a criminal harassment case involving online threats against a former classmate. He filed lawsuits, posted highly personal comments about reporters online and routinely intimated violence on social

Continued on Page A14

INTERNATIONAL A4-9

E.U. Reaches Migration Deal
Despite making no commitments, the agreement seemed to be enough to save Chancellor Angela Merkel of Germany while appeasing Italy.   PAGE A7

NATIONAL A10-17

Medicaid Work Rule Blocked
A ruling in a Kentucky case may affect other states' efforts to require the poor to work to get health care.   PAGE A16

Riding an Outsider Wave
Midterm voters brought a wave of progressive female candidates powered by strong personal narratives.   PAGE A11

NEW YORK A18-20

9/11 Safety Chief Laid to Rest
Chief Ronald R. Spadafora, who kept rescue workers safe at ground zero, died of blood cancer at 63.   PAGE A18

Tough Math in School Plan
The mayor's proposal to drop the test for the city's elite high schools could upend its elite middle schools.   PAGE A18

BUSINESS DAY B1-8

Mission: Crispy for an Hour
As delivery services ramp up, one giant company's goal is to keep your fries succulent for up to 60 minutes.   PAGE B1

China Curtails Lending Spree
A bold plan to gain greater global influence by funding big projects is lagging as China grows cautious.   PAGE B1

ARTS C1-7

In a Pixar Short, a Dark Twist
"Bao," running with "Incredibles 2," is about a Chinese dumpling and a mother's love. The director says, "Part of me wanted to shock audiences."   PAGE C1

SPORTSSATURDAY D1-6

The N.B.A.'s Decider
LeBron James might join a new team, instantly boosting the fortunes of a city and its N.B.A. franchise. Or he might stay in Cleveland.   PAGE D1

THIS WEEKEND

Special Section
Months after accusing powerful men of abuse, 20 people, including Ashley Judd, above, share how saying #MeToo changed their lives.

EDITORIAL, OP-ED A22-23

Dave Eggers   PAGE A23

G.M. TELLS TRUMP TARIFF PLAN PUTS U.S. JOBS AT RISK

CAUGHT IN TRADE WAR

Warns Auto Prices Could Rise by Thousands, Sapping Demand

By TIFFANY HSU

General Motors warned Friday that if President Trump pushed ahead with another wave of tariffs, the move could backfire, leading to "less investment, fewer jobs and lower wages" for its employees.

The automaker said that the president's threat to impose tariffs on imports of cars and car parts — along with an earlier spate of penalties — could drive vehicle prices up by thousands of dollars. The "hardest hit" cars, General Motors said in comments submitted to the Commerce Department, are likely to be the ones bought by consumers who can least afford an increase. Demand would suffer and production would slow, all of which would lead to a smaller G.M.

The president has promoted tariffs as a way to protect American businesses and workers, aiming at dozens of nations with metal tariffs, as well as broader trade levies against Chinese goods. But companies, which rely on other markets for sale of production and materials, have grown increasingly vocal about the potential damage from his policies.

The warning by G.M., echoed in comments by trade groups and other automakers, could test the president's aggressive approach to trade and his commitment to business. In the past, Mr. Trump has hauled General Motors for its decisions and vowed to defend the auto industry.

A G.M. spokeswoman, Dayna Hart, said the company had no contingency plans calling for job cuts, but that such a move was "something that could happen."

"We are still assessing the impact," she added.

The White House did not respond to a request for comment.

G.M. and other industry leaders are caught in the middle of an escalating trade war that has prompted retaliation from the European Union, Mexico, Canada and China.

Last month, Mr. Trump ordered an investigation into whether imported cars and automotive components pose a national security risk, calling for penalties expected to be as high as 25 percent. The administration has already put levies on imported steel and aluminum, and is about place tariffs

Continued on Page A14

Whittling a New York Minute To 100 Billionths of a Second

By JOHN MARKOFF

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The pressure to manage these high-speed trades grows when the stock market becomes more volatile, as it has been in recent months, in part to prevent the fastest traders from taking unfair advantage of slower firms. High-frequency traders typically ac-

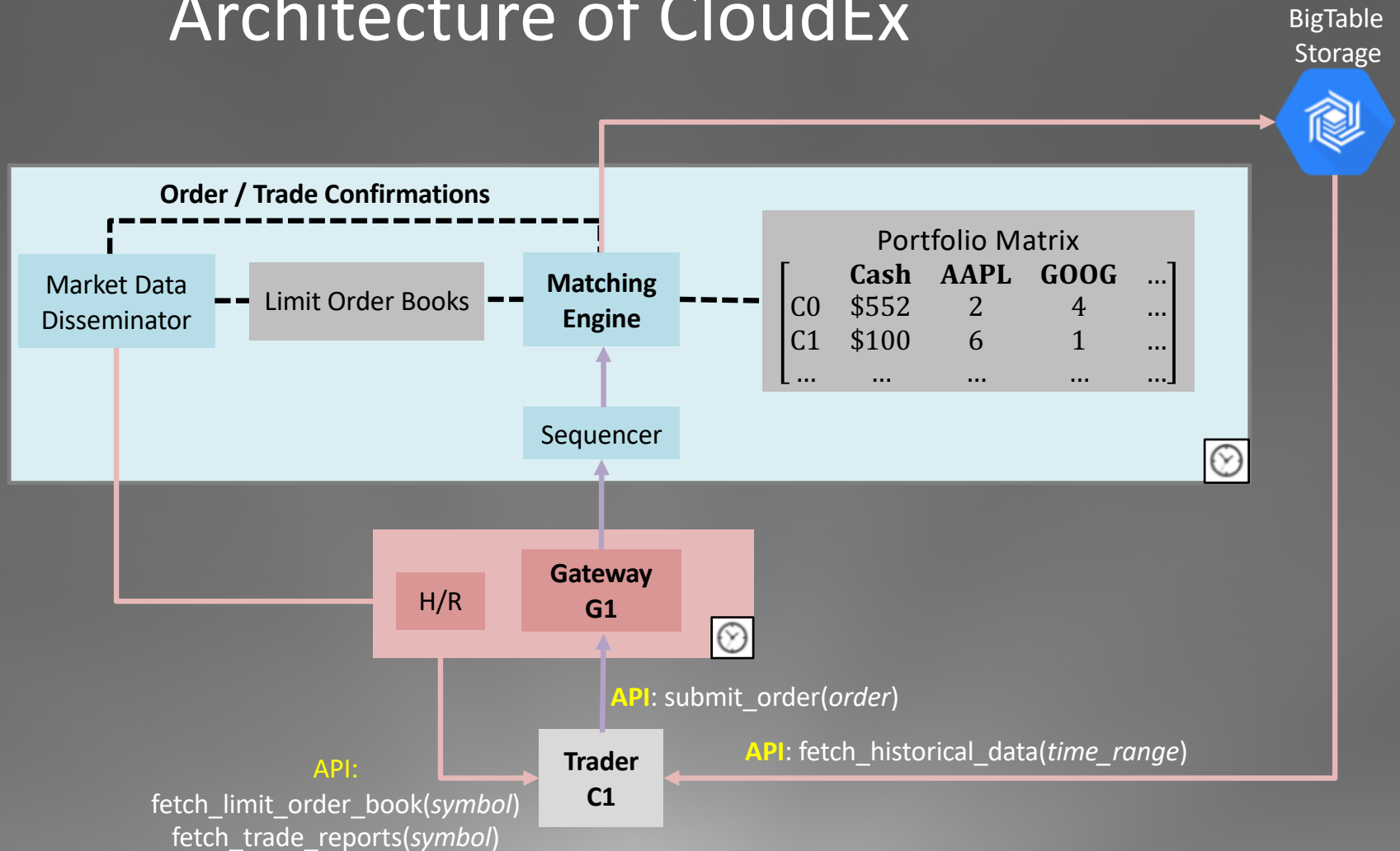*Continued on Page A17*

Motivation for CloudEx

- Study feasibility of building fair and highly performant financial exchanges in the public cloud

- Research tool
  - Fully configurable end-to-end exchange; can experiment with infra changes, matching engine algos, etc

- Teaching tool
  - Prototype system for learning about (i) infrastructure, (ii) trading algorithms, and (iii) matching algorithms
  - Used in a course at Stanford this Autumn; student teams will compete as HF traders

- Joint work with
  - Vinay Sriram, Jinkun Geng, Ahmad Ghalayini, Vig Sachidananda, Yilong Geng, Mendel Rosenblum and Anirudh Sivaraman

Architecture of CloudEx

BigTable
Storage

Order / Trade Confirmations

Market Data Disseminator	Limit Order Books	**Matching Engine**

Portfolio Matrix

$$\begin{bmatrix} & \textbf{Cash} & \textbf{AAPL} & \textbf{GOOG} & ... \\ C0 & \$552 & 2 & 4 & ... \\ C1 & \$100 & 6 & 1 & ... \\ ... & ... & ... & ... & ... \end{bmatrix}$$

Sequencer

H/R

Gateway G1

API: submit_order(*order*)

API: fetch_historical_data(*time_range*)

Trader C1

API:
fetch_limit_order_book(*symbol*)
fetch_trade_reports(*symbol*)

Order Messages
Currently restricted to Market and Limit Orders

Appended by Gateway

Format

Symbol	Action	Shares	Type	Bid/Ask Price	Timestamp	Client ID	Order ID

Examples

Symbol	Action	Shares	Type	Bid/Ask Price	Timestamp	Client ID	Order ID
AAPL	Buy	100	Limit	$210	1569290045000	C1	SAD651GH
GOOG	Buy	50	Market	$1200	1569290048121	A2	3AS5SDF2
MSFT	Sell	325	Limit	$140	1569290053007	B2	A22S134H

CloudEx Testbed Setup and Numbers

Testbed Setup
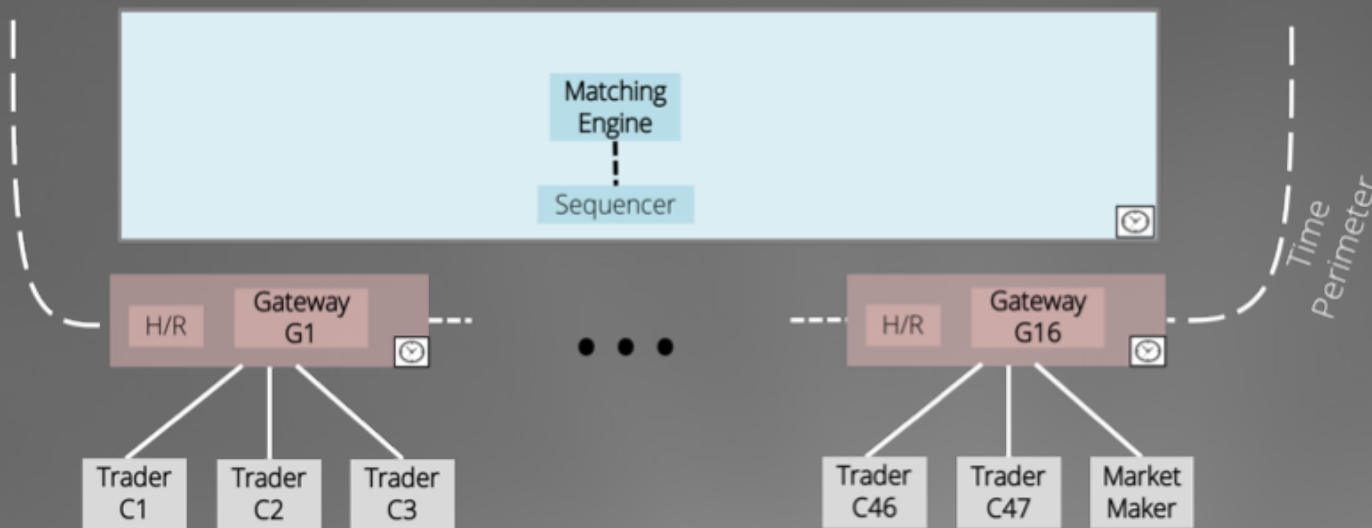
- 1 Matching Engine
- 48 Traders, 3 per Gateway

- 10 symbols to trade
- Each trader starts with 5M cash and 10k shares per symbol

Traders

1 Market Maker

Trader C48

- Has a large amount of resources that allows it to transact in high volume and drive the price of a symbol towards some predetermined price

43 Random Traders

Trader C21

- Models traders that perform trades without reacting to instantaneous market data

4 Algorithmic Traders

Trader C1

- Uses a **mean reversion strategy** to profit on volatility in certain symbols
- Also support other strategies such as Pairs Trading and Momentum Trading

CloudEx Testbed Specs

- VMs rented in Google Cloud; heterogeneous capabilities, as follows:
  - Matching Engine:
    - n1-standard-64 (64 vCPUs, 240 GB memory, 32Gbps Bandwidth Maximum)
  - Market Maker:
    - n1-standard-32 (32 vCPUs, 32 GB memory, 32 Gbps Bandwidth Maximum)
  - Gateway:
    - n1-standard-8 (8 vCPUs, 30 GB memory, 16 Gbps Bandwidth Maximum)
  - Trader:
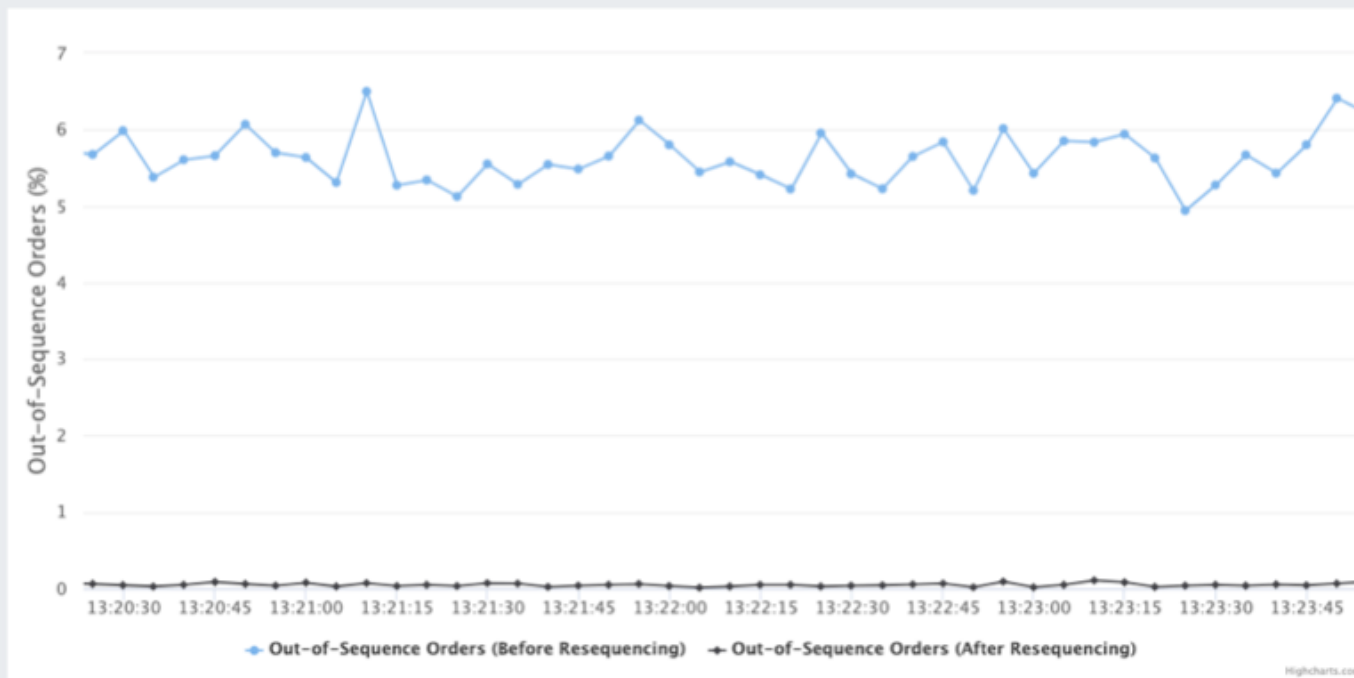   - n1-standard-2 (2 vCPUs, 7.5 GB memory, 10 Gbps Bandwidth Maximum)

Dashboard Plots

Inbound Fairness	Queue Length	System Delays

Inbound Fairness

Out-of-Sequence Orders.

Out-of-Sequence Orders (Before Resequencing) — Out-of-Sequence Orders (After Resequencing)

Highcharts.com

Portfolio Values	Stock Prices

Portfolio Values

Evolution of each trader's portfolio value over time.

Legend: A1 balance, A2 balance, A3 balance, A4 balance, C1 balance, C2 balance, C3 balance, C4 balance, C5 balance, C6 balance

Highcharts.com
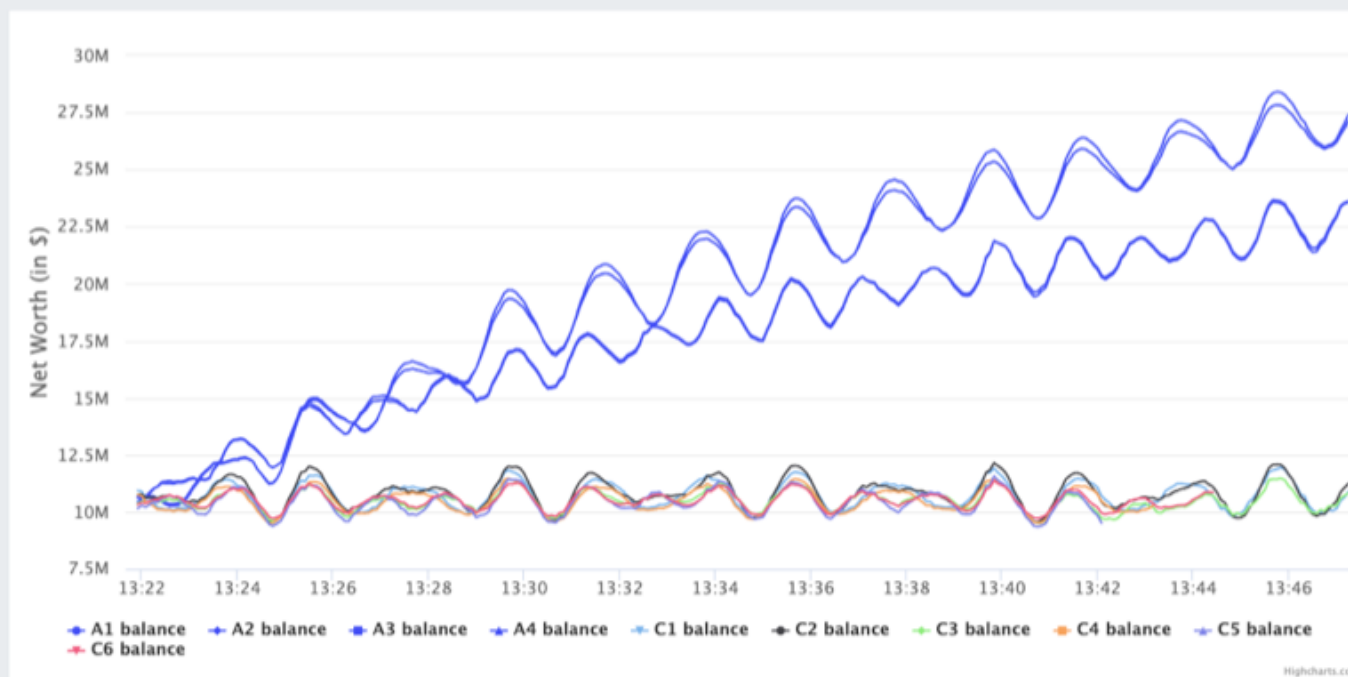
CloudEx in Numbers
(Not a STAC benchmark)

- **Performance**
  - **Throughput**
    - 1 ME Shard: Throughput ~ 30K/second
    - 2 ME Shards: Throughput ~ 63K/second
    - ~30µs processing latency for each order per shard
  - **Latency:** Inbound (order placement, 2 Hops)
    - Trader to Gateway: 164**µs**
    - Gateway to Matching Engine 156µs
  - **Latency:** Outbound (market data, 2 Hops)
    - Matching Engine to Gateway: 217µs
    - Gateway to Trader: 199µs

- **Work In-Progress**
  - Working with VM timestamps currently: 100s nanosecs accuracy, large stack latencies
  → NIC timestamps + using SR-IOV will lower latencies

  - Replace network communication library (ZMQ) with high-performance bypass framework (e.g., DPDK)
  → Significantly decrease latency

  - Currently have verification overhead (Portfolio Matrix); may move verification out of trading path
  → Significantly increase throughput