# Prime Match: A Privacy Preserving Inventory Matching System

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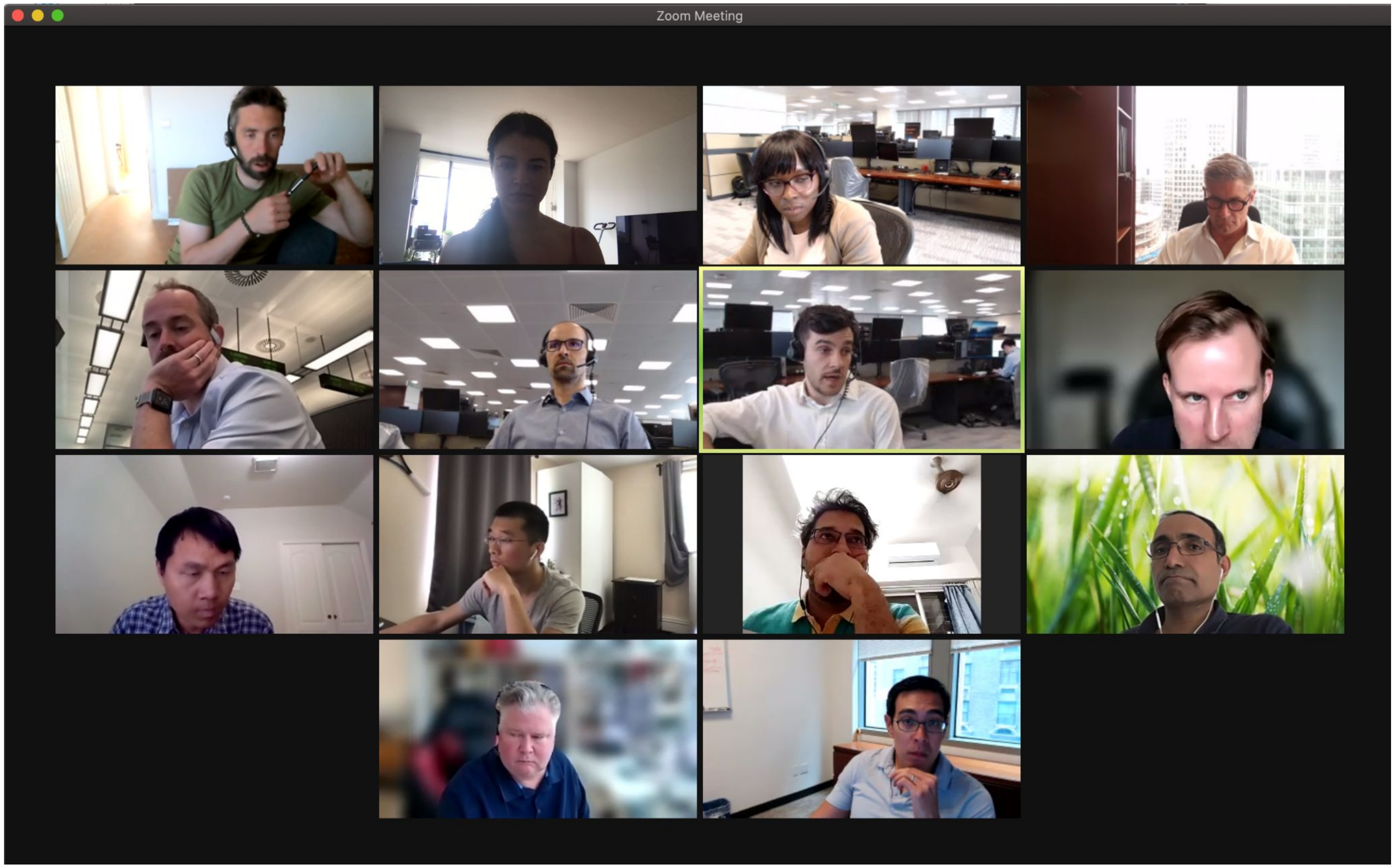
# Prime Match: Extended Team



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# Motivation

- First one-time application of MPC (electronic double auction): Sugar bit auction [Bogetof et al. 2008]
- MPC Dashboard

- Identify a real-world problem for MPC in the traditional financial world
- Academic work on privacy preserving darkpools [CSA19, B**P**V20, CSA20, MD**P**B23]
- Prime Match is the first MPC auction running live in the traditional financial world.

# Outline

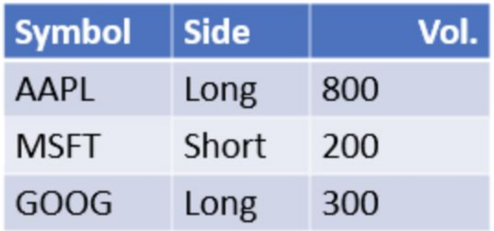
- Prime Match Problem Statement & Motivation
- Cryptographic Contributions in Prime Match
- From Proof of Concept (PoC) to Product
    - Pre-production and Production challenges
- Cryptographic Solution
- Demo

# Starting point: Inventory Matching **without** Privacy

## Inventory Matching Process:

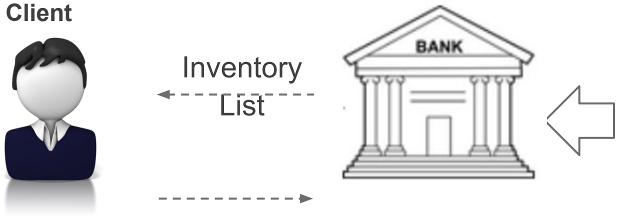
- **JPMC** Prime Brokerage desk **publishes daily** a list of inventory at a discount **to clients**
- Inventory includes a list of symbols, sides, volumes, rates for trades

Toy Inventory List Example:



| Symbol | Side | Vol. |
|---|---|---|
| AAPL | Long | 800 |
| MSFT | Short | 200 |
| GOOG | Long | 300 |

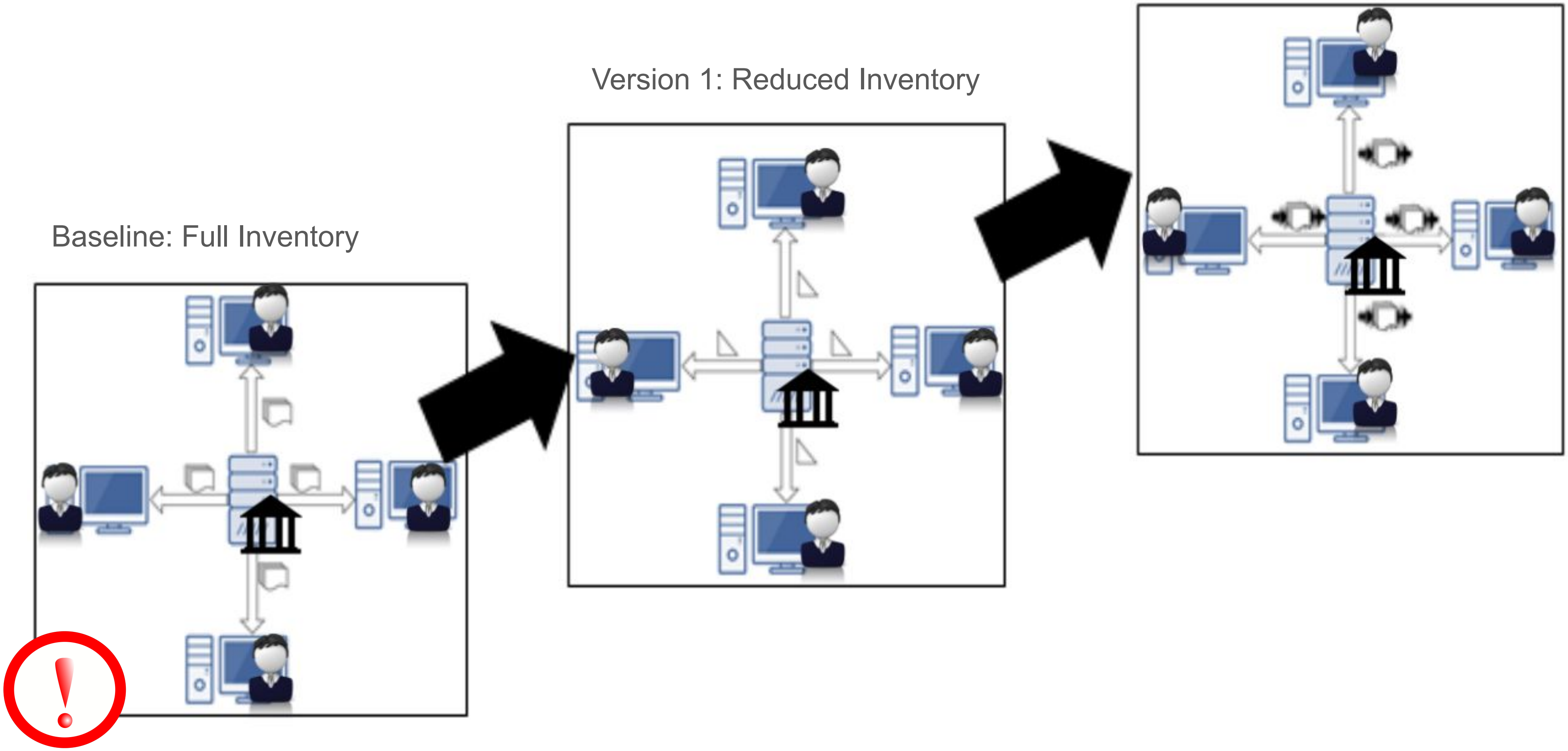
- JPMC processes **incoming trades** chosen from the list **by clients**



**Internal Data**

- JPMC inventory
- Financing rates
- Other firm / market data

# Starting point: Inventory Matching **without** Privacy



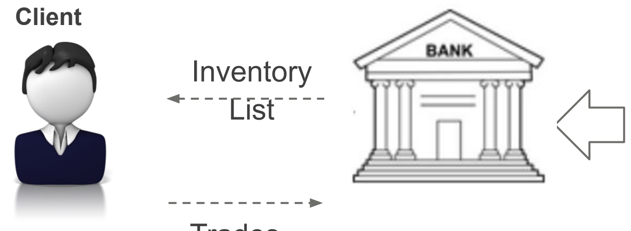
Baseline: Full Inventory

Version 1: Reduced Inventory

Version 2: Inventory with smart noise

# Starting point: Inventory Matching **without** Privacy

## Inventory Matching Process:



Client

Inventory List

Trades

BANK

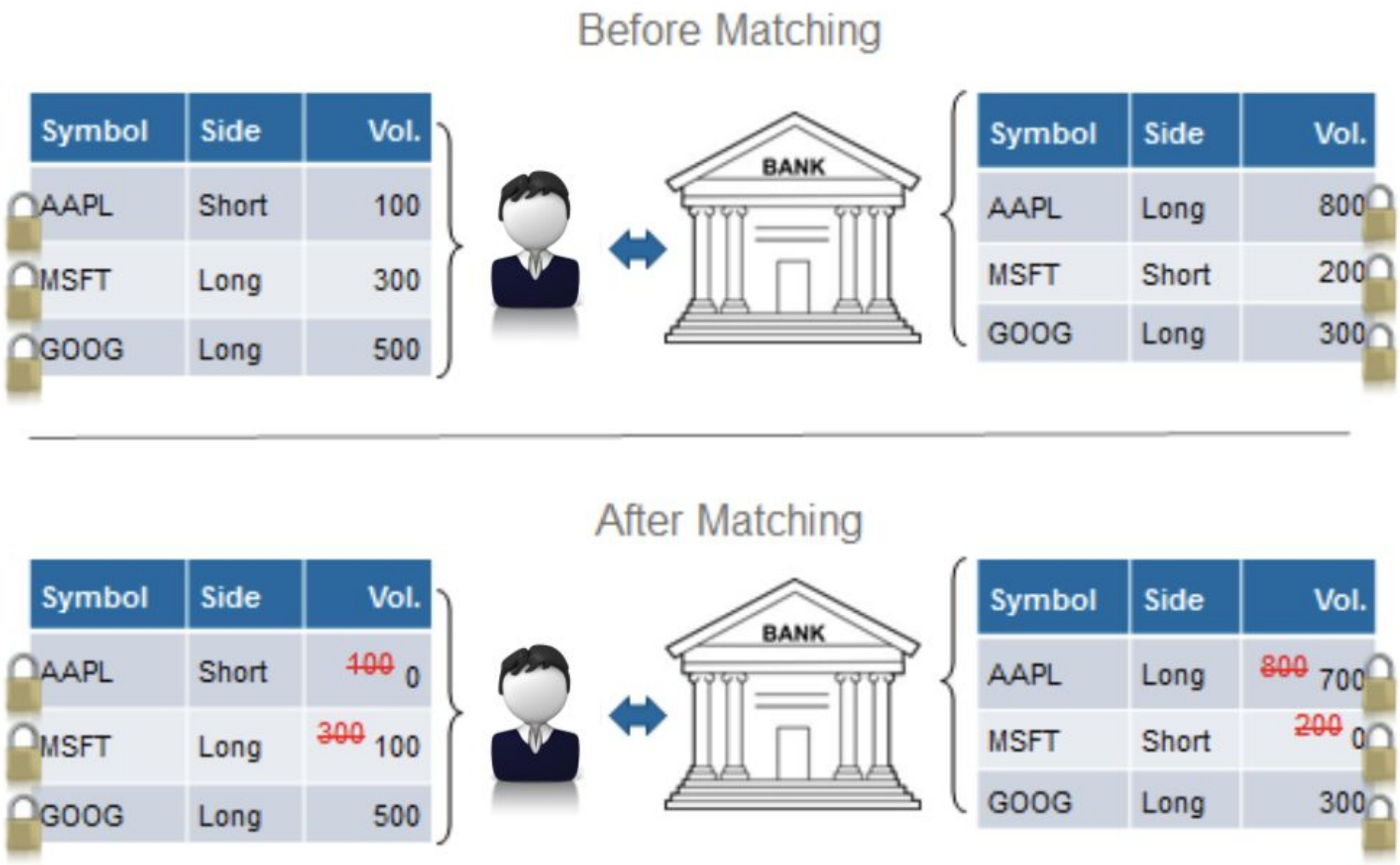
**Internal Data**

- JPMC inventory
- Financing rates
- Other firm / market data

## Problems with Inventory Matching:

- JPM reveals a large portion of its inventory list
- Clients raised concerns about potential leakage of their past trades included in the list
- Reduced inventory list available for matching
- Clients do not send to JPMC their inventory!

# Prime Match: Inventory Matching **with** Privacy



Before Matching

| Symbol | Side | Vol. |
|---|---|---|
| AAPL | Short | 100 |
| MSFT | Long | 300 |
| GOOG | Long | 500 |

| Symbol | Side | Vol. |
|---|---|---|
| AAPL | Long | 800 |
| MSFT | Short | 200 |
| GOOG | Long | 300 |

After Matching

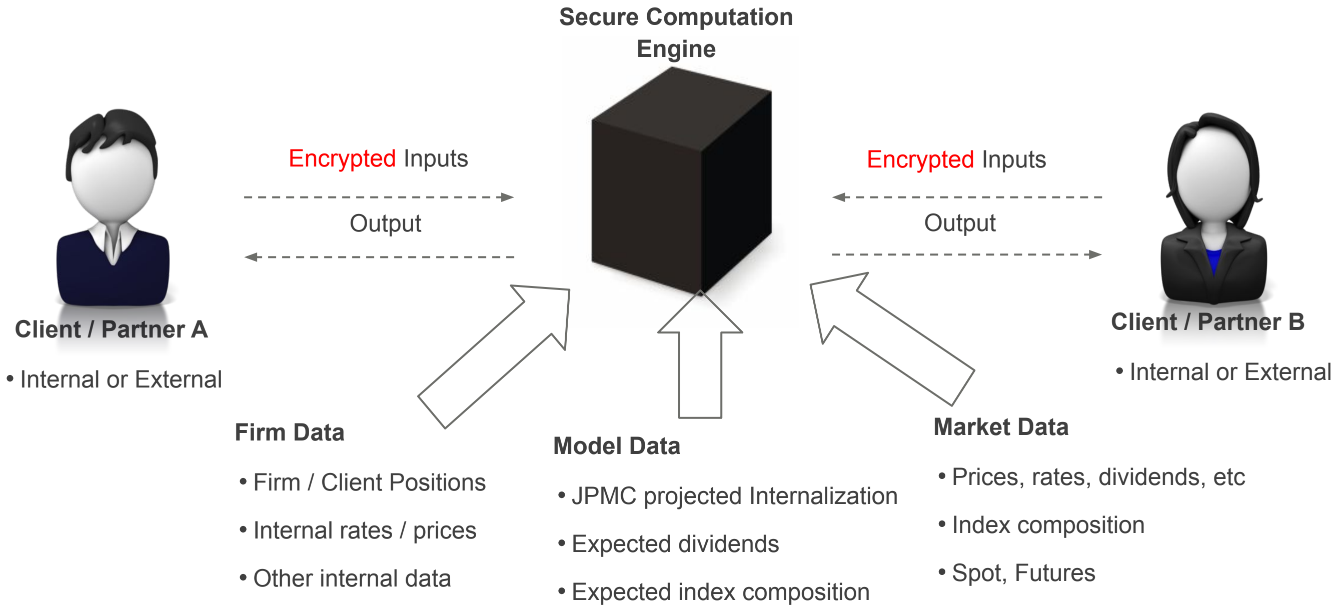
| Symbol | Side | Vol. |
|---|---|---|
| AAPL | Short | ~~100~~ 0 |
| MSFT | Long | ~~300~~ 100 |
| GOOG | Long | 500 |

| Symbol | Side | Vol. |
|---|---|---|
| AAPL | Long | ~~800~~ 700 |
| MSFT | Short | ~~200~~ 0 |
| GOOG | Long | 300 |

Solution based on Secure Multiparty Computation

# Overview of Secure Multi-Party Computation (MPC)

- Enables different organizations / parties / entities to perform a joint computation over their inputs (i.e. trade lists) while keeping it private
- Encryption ≠ Secure Multiparty Computation:
  - Encryption: Parties trust each other, but do not trust some external that might eavesdrop to the conversation
  - Secure Computation: Parties do not trust each other or cannot share their data, but still want to compute on their joint private inputs
- **Feasibility** [Yao82,GMW87,BGW88,CCD88]: every distributed computation can be computed *privately*



**Secure Computation Engine**

Encrypted Inputs

Output

Encrypted Inputs

Output

**Client / Partner A**

- Internal or External

**Client / Partner B**

- Internal or External

**Firm Data**

- Firm / Client Positions
- Internal rates / prices
- Other internal data

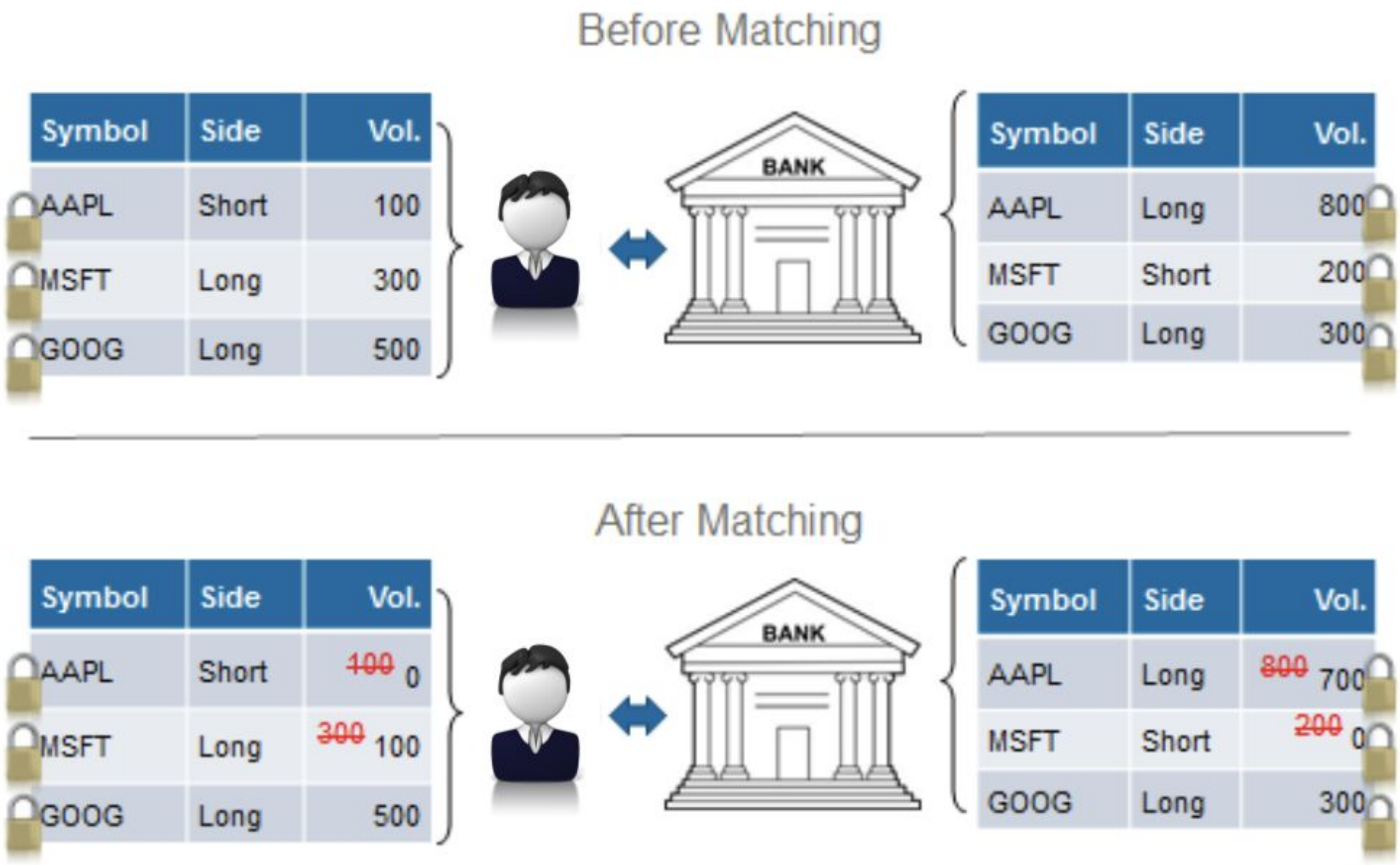
**Model Data**

- JPMC projected Internalization
- Expected dividends
- Expected index composition

**Market Data**

- Prices, rates, dividends, etc
- Index composition
- Spot, Futures

# Prime Match: Inventory Matching **with** Privacy



Before Matching

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|---|---|---|
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After Matching

| Symbol | Side | Vol. |
|---|---|---|
| AAPL | Short | ~~100~~ 0 |
| MSFT | Long | ~~300~~ 100 |
| GOOG | Long | 500 |

| Symbol | Side | Vol. |
|---|---|---|
| AAPL | Long | ~~800~~ 700 |
| MSFT | Short | ~~200~~ 0 |
| GOOG | Long | 300 |

**Main ingredient:** New secure comparison protocol for computing the minimum between two values such as min(100,800)

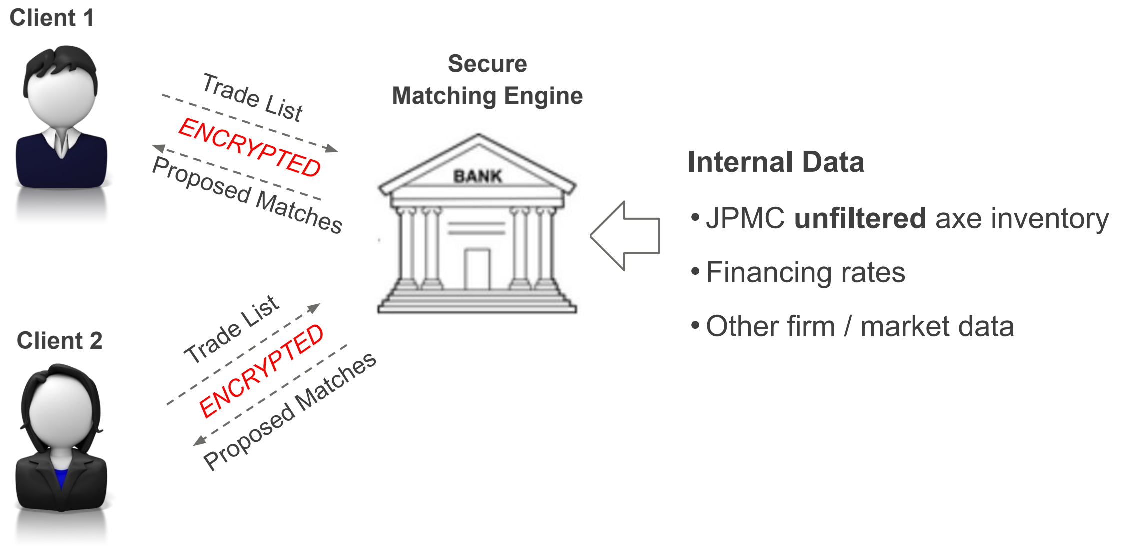
# Prime Match: Privacy-Preserving Inventory Matching with 2PC

## Proposed Service (via Secure Two-Party Computation)

- Client sends over their encrypted trade list
- Secure engine provides list of matching trades against its *full* inventory list

## Benefits:

- More tailored trades matching exact needs of clients; increased inventory availability
- JPM is not exposed to client's trade list unless there is a match; privacy is preserved:
  - No risk of information leakage to JPMC.
  - Unmatched positions are not revealed.



**Internal Data**

- JPMC **unfiltered** axe inventory
- Financing rates
- Other firm / market data

# Prime Match: Privacy-Preserving Inventory Matching with MPC

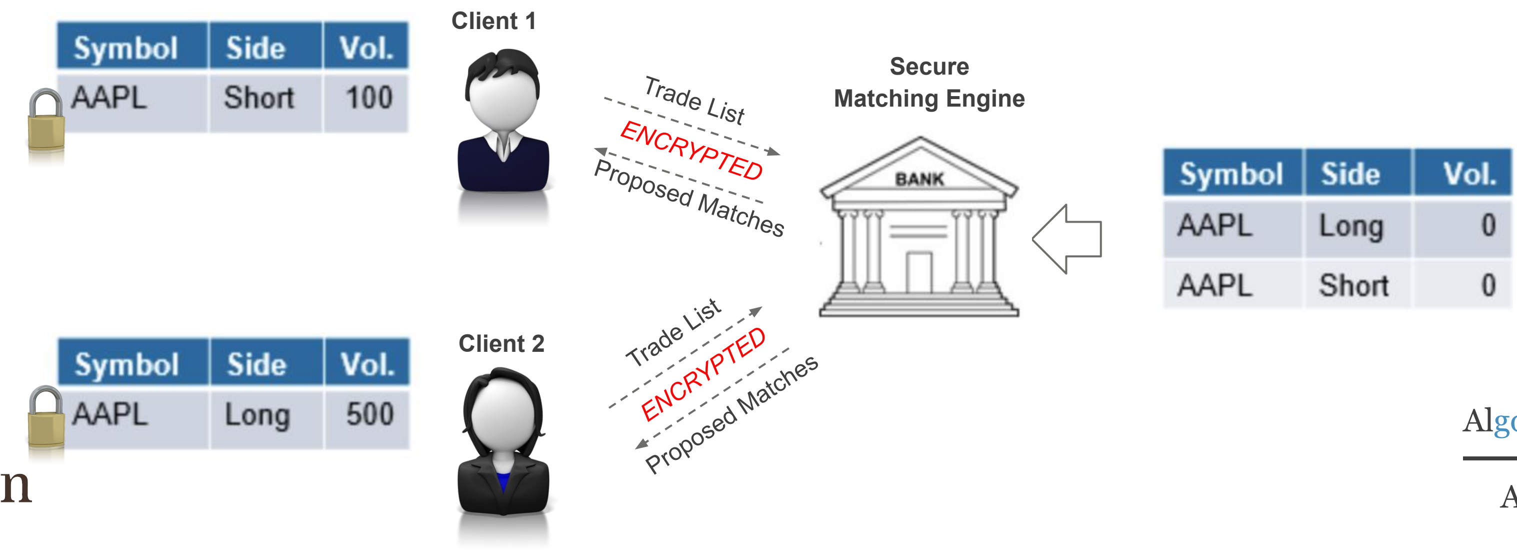
## Proposed Service (via Secure Multi-Party Computation)

- Client sends over their encrypted trade list
- Secure engine provides list of matching trades against its *full* inventory list
- Support provided to match trades **against other clients**

## Benefits:

- More tailored trades matching exact needs of clients with the ability to internalize across **multiple clients**; **significantly increased inventory** availability
- JPM is not exposed to client's trade list unless there is a match; privacy is preserved:
  - No risk of information leakage to JPMC.
  - No risk of information leakage to other clients.
  - Unmatched positions are not revealed.

Toy Example:



Client 1

| Symbol | Side | Vol. |
|---|---|---|
| AAPL | Short | 100 |

Client 2

| Symbol | Side | Vol. |
|---|---|---|
| AAPL | Long | 500 |

Secure Matching Engine

| Symbol | Side | Vol. |
|---|---|---|
| AAPL | Long | 0 |
| AAPL | Short | 0 |

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# Prime Match: Privacy-Preserving Inventory Matching with MPC

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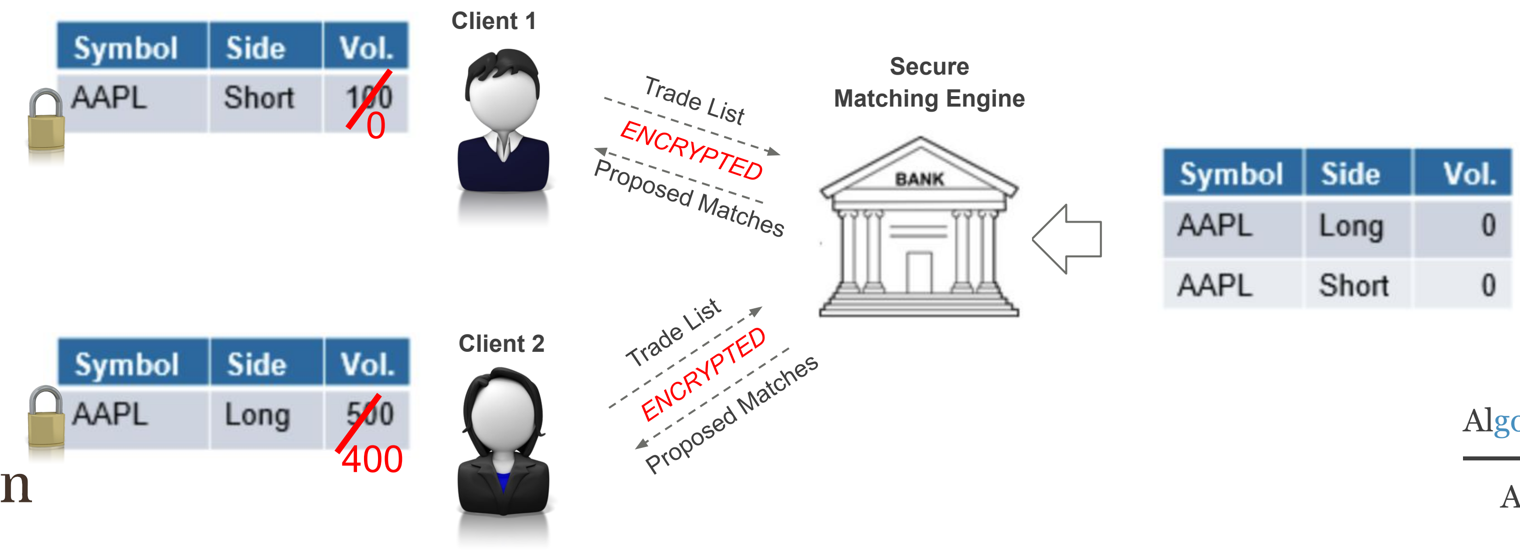
Toy Example:



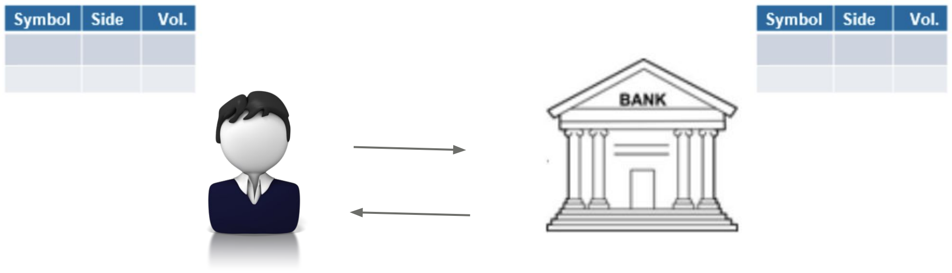
| Symbol | Side | Vol. |
|---|---|---|
| AAPL | Short | ~~100~~ 0 |

| Symbol | Side | Vol. |
|---|---|---|
| AAPL | Long | ~~500~~ 400 |

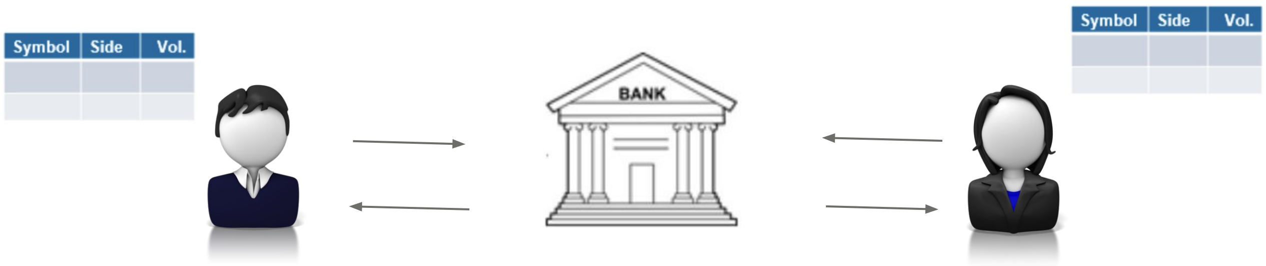
| Symbol | Side | Vol. |
|---|---|---|
| AAPL | Long | 0 |
| AAPL | Short | 0 |

# Cryptographic Contributions in Prime Match

Two-Party Secure comparison:



Three-Party Secure comparison with a third party acting as the facilitator:



New **two-round** secure **linear** comparison protocol for computing the minimum between two values with o**ne malicious corruption; no preprocessing**

Prior works: non-linear; log #round

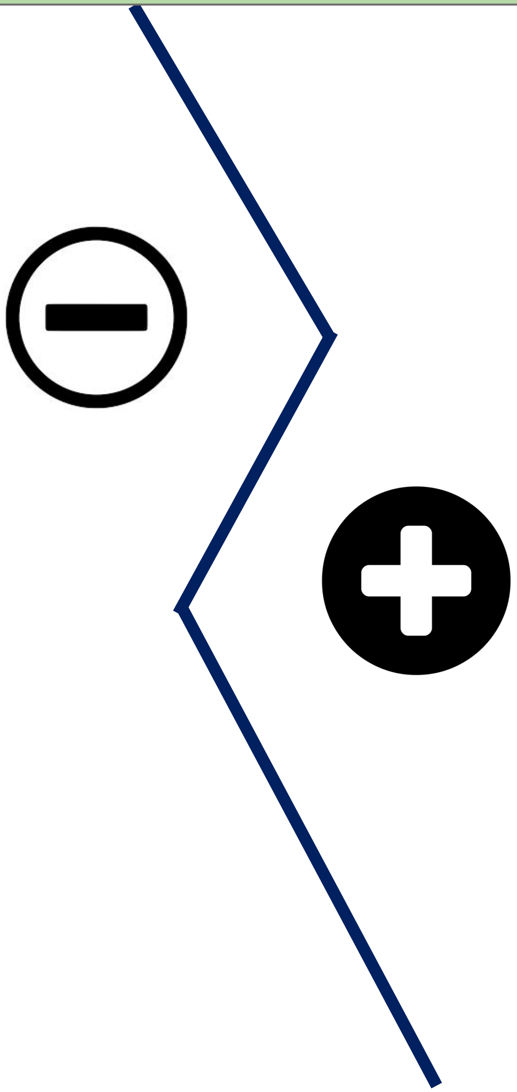
Improved version of SecureNN [WaghGuptaChandran19]

# Prime Match: Pre Production and Production challenges

# Prime Match: Pre-Production Challenges

2019

**No financial institution had taken the initiative to implement privacy preserving auctions**



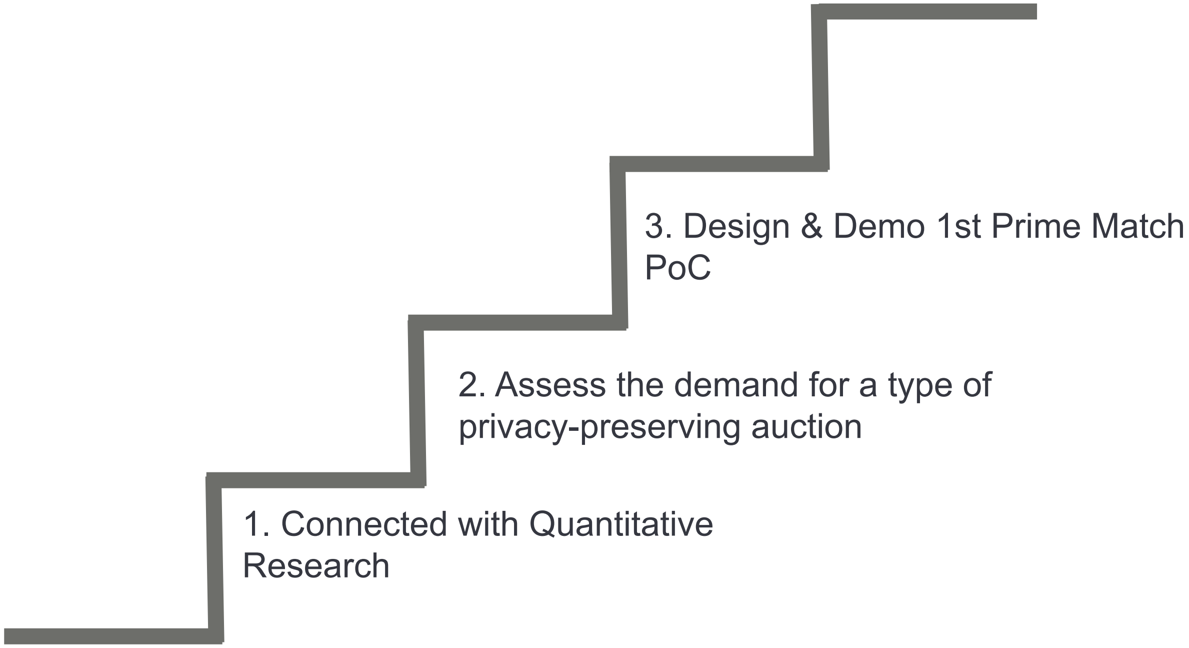
Prior to Prime Match,
**No** financial institution had
ever utilized Multi-Party
Computation (MPC)
technology.

The bank **has** long-standing clients

# Prime Match: Proof of Concept (PoC) Challenges

2019

**Internal buy-in to the product**



1. Connected with Quantitative Research

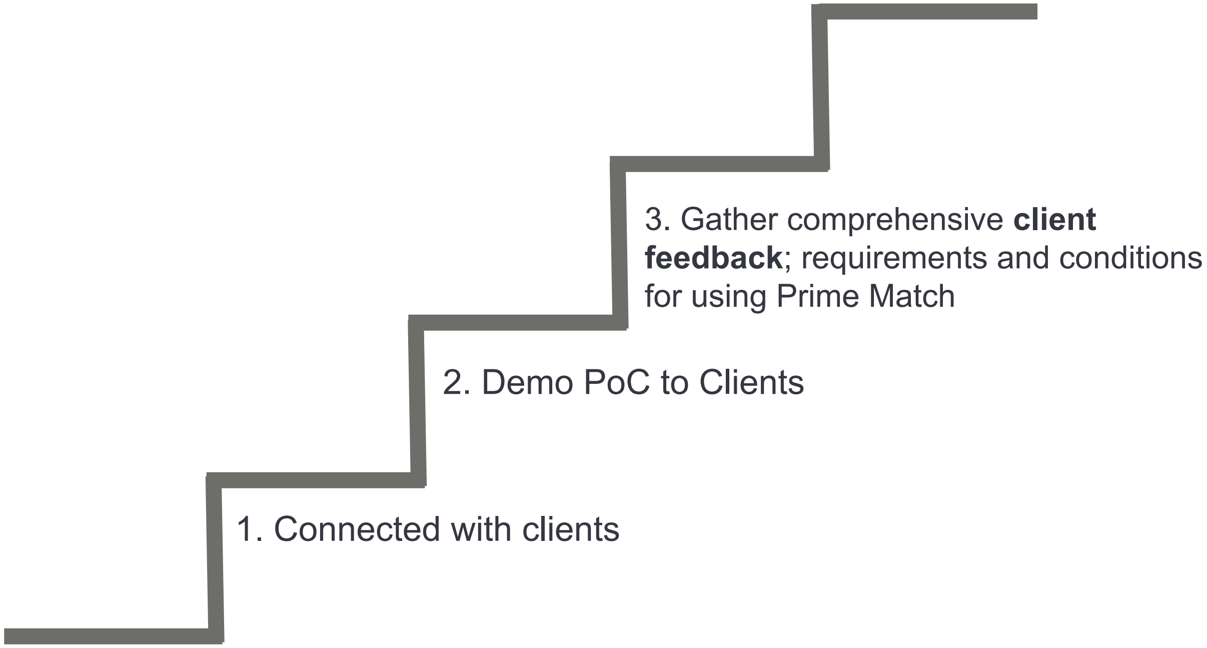
2. Assess the demand for a type of privacy-preserving auction

3. Design & Demo 1st Prime Match PoC

# Prime Match: Pre-Production Challenges

2020

**External buy-in to the product**



1. Connected with clients

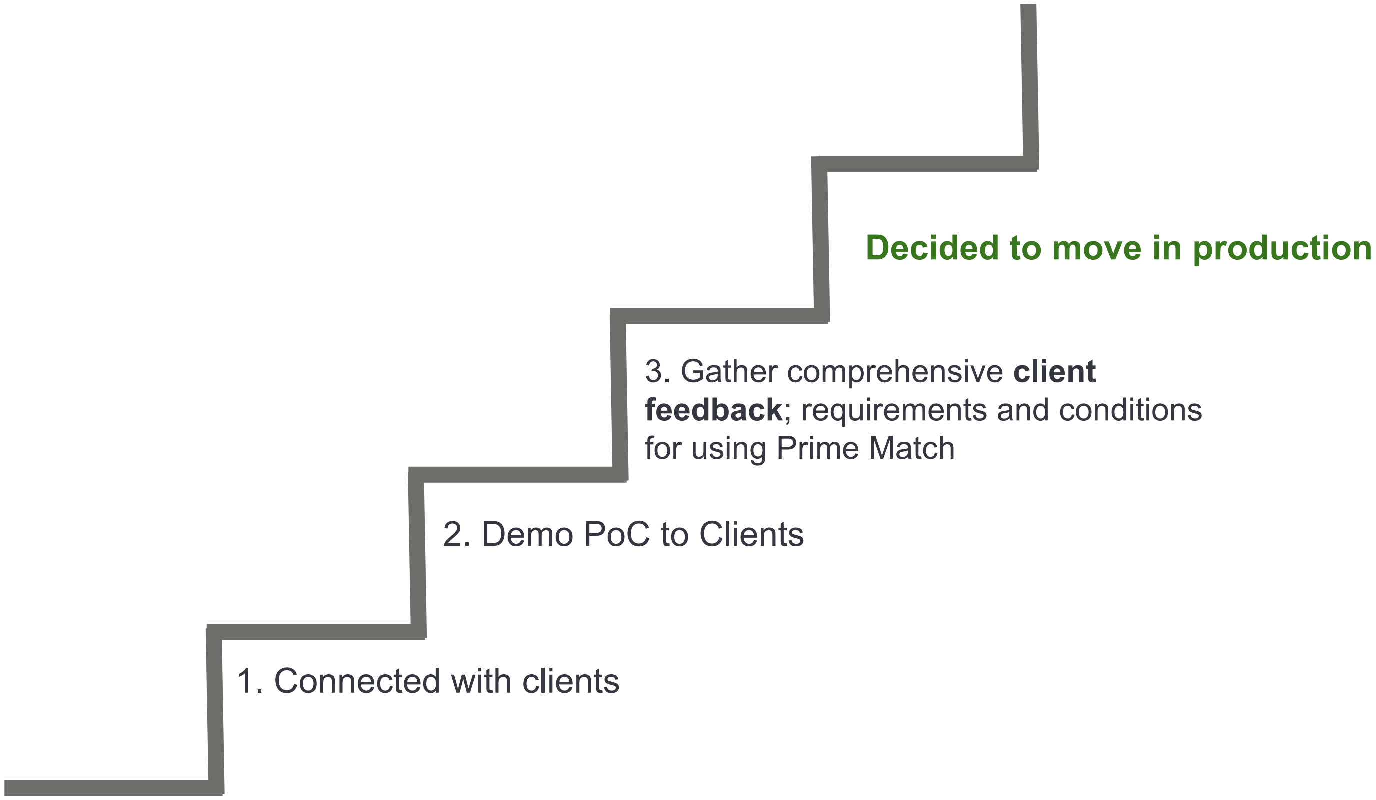
2. Demo PoC to Clients

3. Gather comprehensive **client feedback**; requirements and conditions for using Prime Match

# Prime Match: Pre-Production Challenges

2020

**Given the innovative nature of the product, the green light for production was given after a long process**



1. Connected with clients

2. Demo PoC to Clients

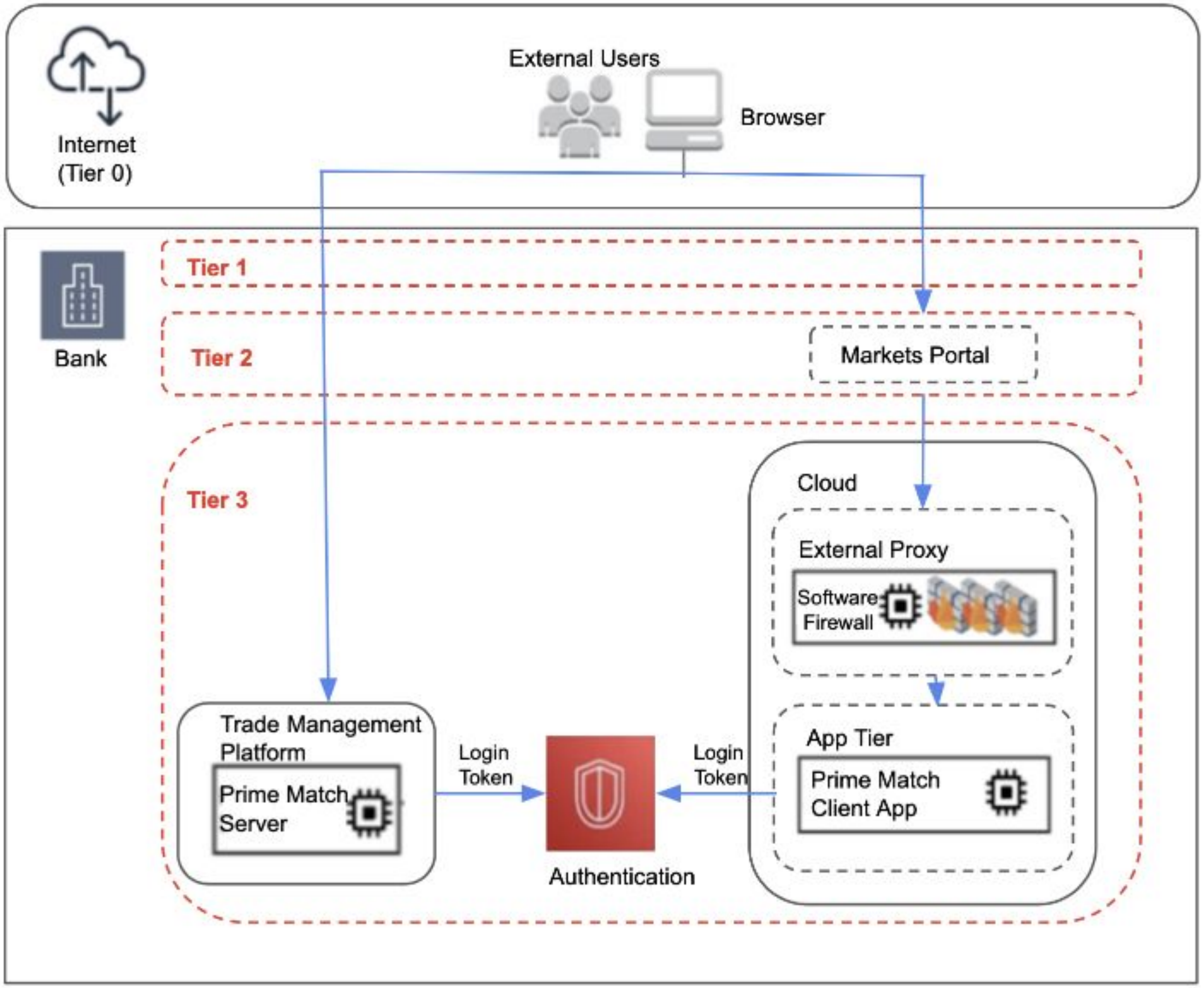
3. Gather comprehensive **client feedback**; requirements and conditions for using Prime Match

**Decided to move in production**

# Prime Match: Client Requirements

- **No communication with other clients**, only communication with the bank
- **No heavy installation of code** on client's machines - a web-based application was required
- Client computation should be **minimal**
- **No resources** for preprocessing data
- **Stronger security guarantees** than semi-honest security
- **Peer review** of the solution
- **Frequent** auctions

# Prime Match: Tech Challenges - Architecture



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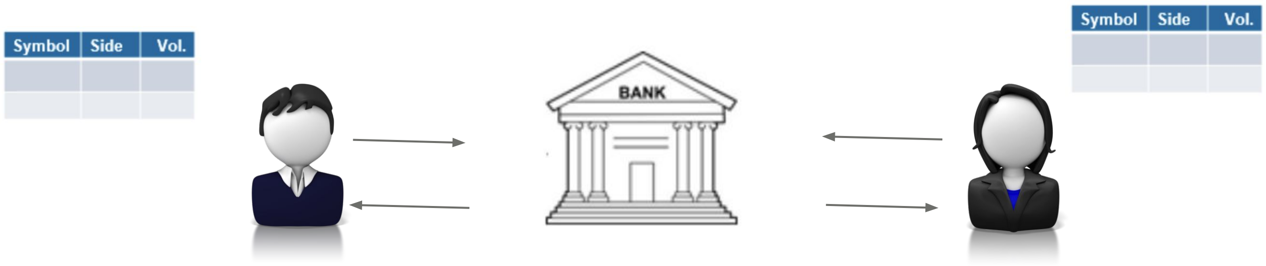
# Prime Match: Cryptographic Solution

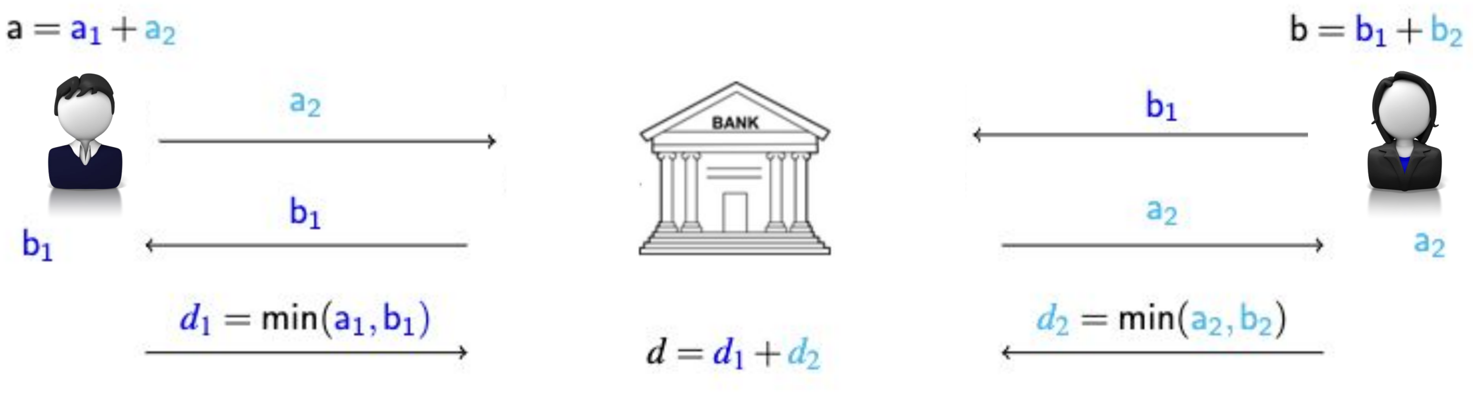
# Cryptographic Contributions in Prime Match

Three-Party Secure comparison with a third party acting as the facilitator:



Three parallel executions

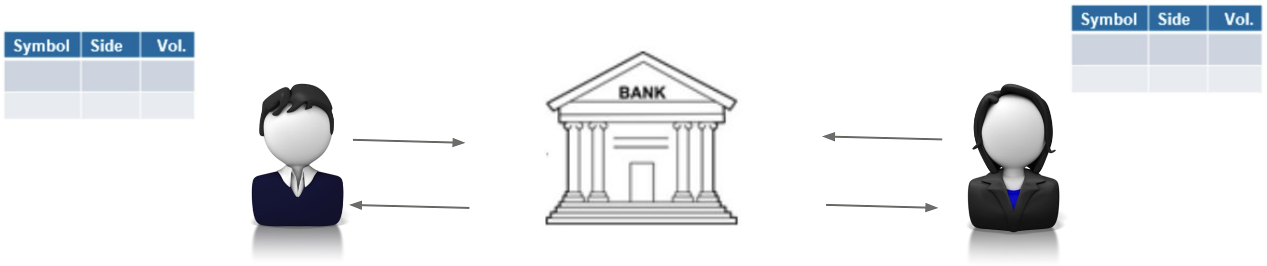
Secret Shared Inputs



New **two-round** secure **linear** comparison protocol

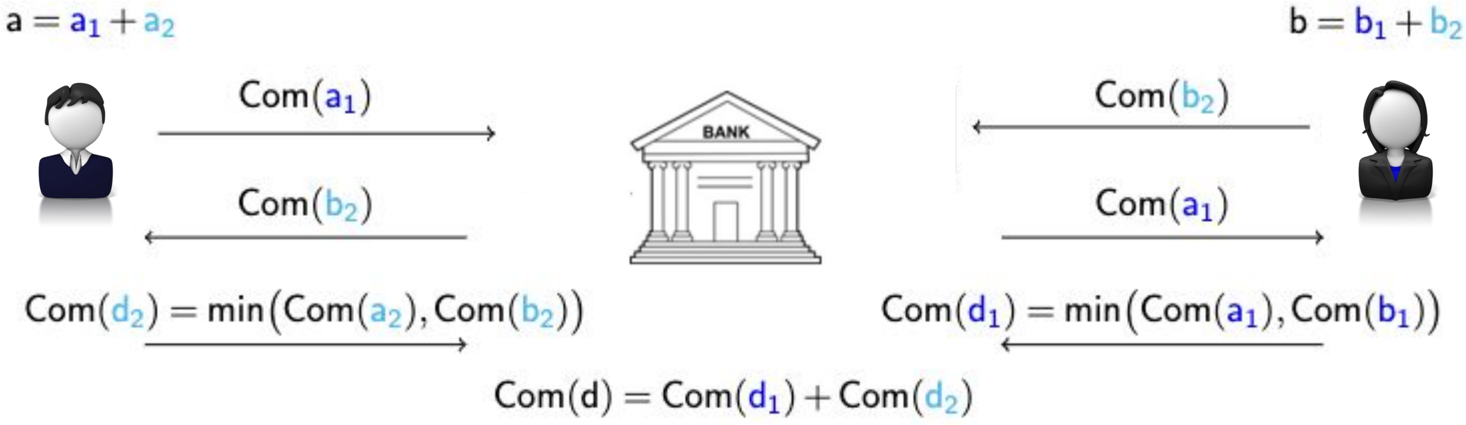
# Cryptographic Contributions in Prime Match

Three-Party Secure comparison with a third party acting as the facilitator:



Three parallel executions

Committed Secret Shares



$a = a_1 + a_2$

$b = b_1 + b_2$

$\mathsf{Com}(a_1)$

$\mathsf{Com}(b_2)$

$\mathsf{Com}(b_2)$

$\mathsf{Com}(a_1)$

$\mathsf{Com}(d_2) = \min(\mathsf{Com}(a_2), \mathsf{Com}(b_2))$

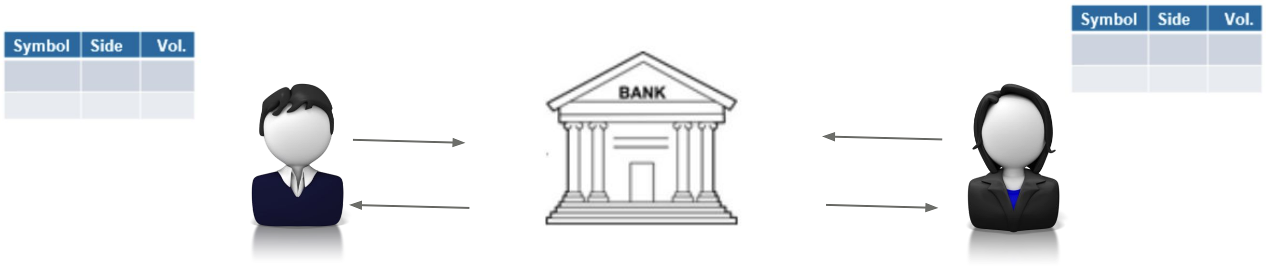
$\mathsf{Com}(d_1) = \min(\mathsf{Com}(a_1), \mathsf{Com}(b_1))$

$\mathsf{Com}(d) = \mathsf{Com}(d_1) + \mathsf{Com}(d_2)$

New **two-round** secure **linear** comparison protocol

# Cryptographic Contributions in Prime Match

## Three-Party Secure comparison with a third party acting as the facilitator:



Registration phase +
Three parallel executions

Openings of Committed Shares

New **two-round** secure **linear** comparison protocol

# Prime Match: High Level Solution

Registration Phase: Need for committed computation

Matching Phase: web based support → low round complexity and communication

Improved version of SecureNN [WaghGuptaChandran19]

**High level of Comparison (min) circuit: (output 1 if any di=0)**

❑ $P_0$, $P_1$ compute shares of:

$$\mathbf{c_i = 1 - a_i + b_i + \Sigma_{j>i}\, r_j\, (a_j - b_j)}$$

❑ $P_0$, $P_1$ send to bank shares of $s_i * c_i$

❑ Bank reconstructs $d_i = s_i * c_i$ and outputs 1 (a>b) if **any** $s_i * c_i = 0$

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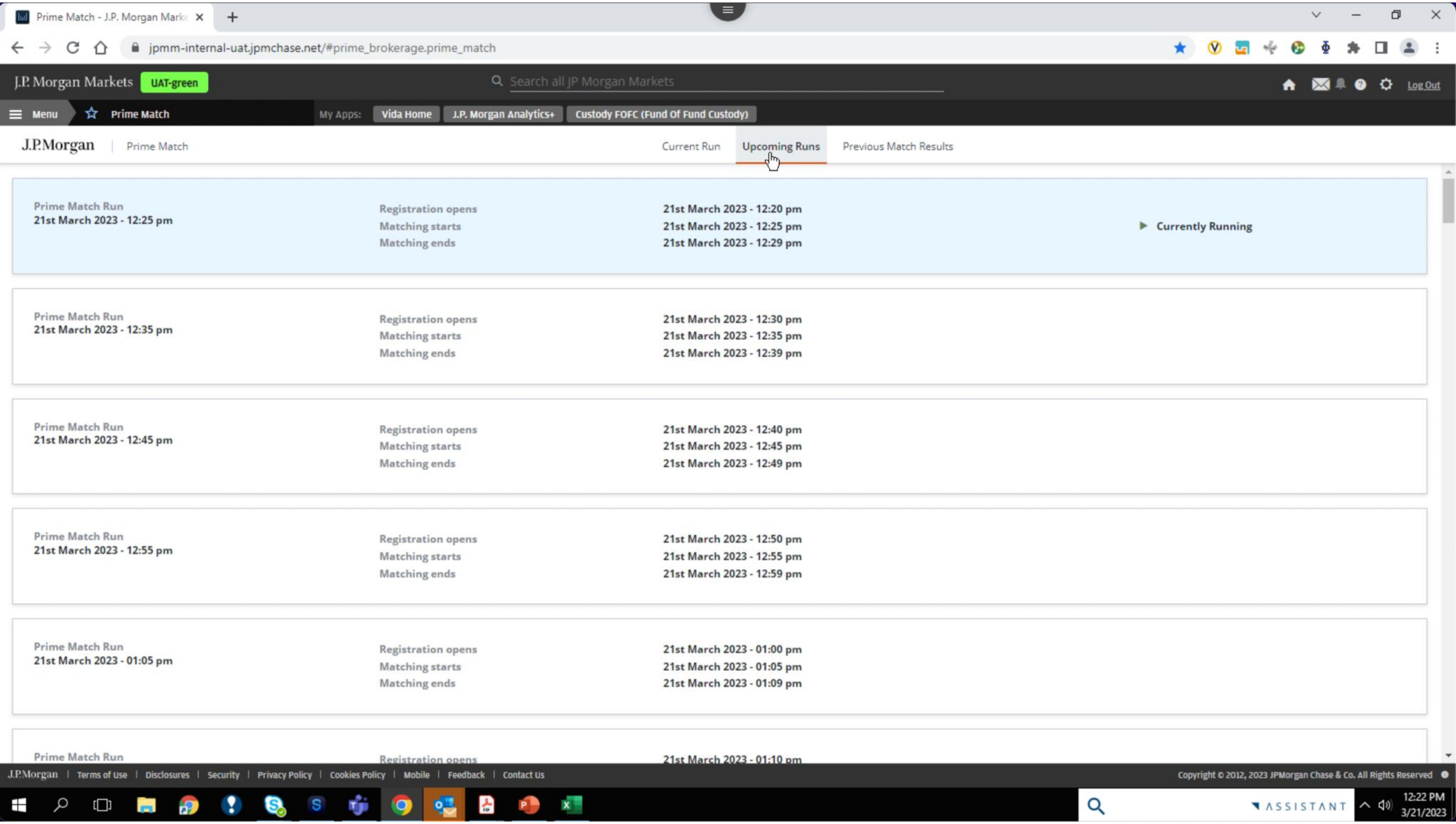
# Prime Match: Tech Challenges - Architecture

Demo

# Prime Match Demo: Auction Runs



Prime Match Run
21st March 2023 - 12:25 pm
Registration opens 21st March 2023 - 12:20 pm
Matching starts 21st March 2023 - 12:25 pm
Matching ends 21st March 2023 - 12:29 pm
▶ Currently Running

Prime Match Run
21st March 2023 - 12:35 pm
Registration opens 21st March 2023 - 12:30 pm
Matching starts 21st March 2023 - 12:35 pm
Matching ends 21st March 2023 - 12:39 pm

Prime Match Run
21st March 2023 - 12:45 pm
Registration opens 21st March 2023 - 12:40 pm
Matching starts 21st March 2023 - 12:45 pm
Matching ends 21st March 2023 - 12:49 pm

Prime Match Run
21st March 2023 - 12:55 pm
Registration opens 21st March 2023 - 12:50 pm
Matching starts 21st March 2023 - 12:55 pm
Matching ends 21st March 2023 - 12:59 pm

Prime Match Run
21st March 2023 - 01:05 pm
Registration opens 21st March 2023 - 01:00 pm
Matching starts 21st March 2023 - 01:05 pm
Matching ends 21st March 2023 - 01:09 pm

Prime Match Run
Registration opens 21st March 2023 - 01:10 pm

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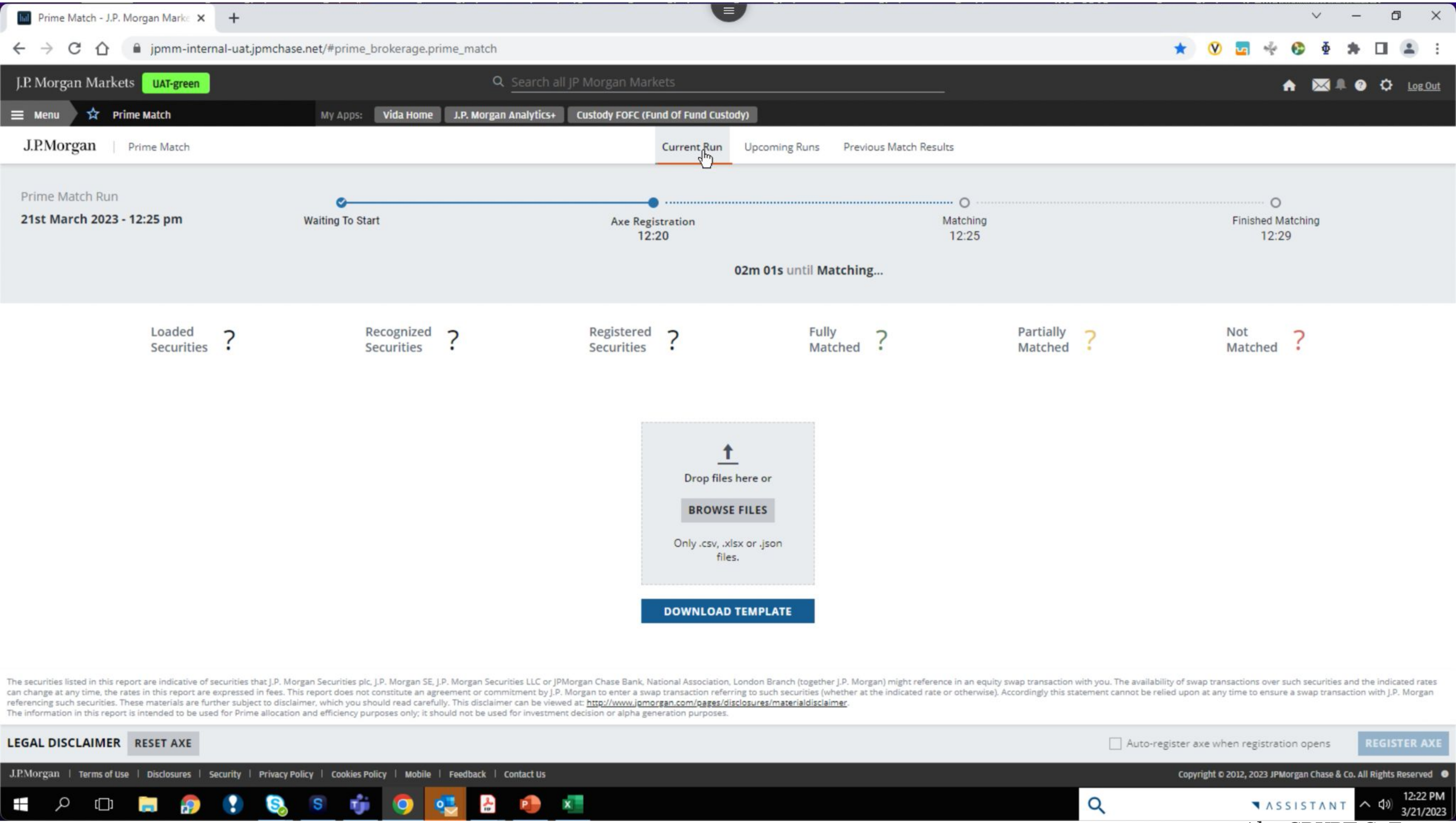
# Prime Match Demo: Registration Phase



Prime Match Run
**21st March 2023 - 12:25 pm**

| Waiting To Start | Axe Registration | Matching | Finished Matching |
|---|---|---|---|
| | 12:20 | 12:25 | 12:29 |

**02m 01s** until **Matching...**

| Loaded Securities | Recognized Securities | Registered Securities | Fully Matched | Partially Matched | Not Matched |
|---|---|---|---|---|---|
| ? | ? | ? | ? | ? | ? |

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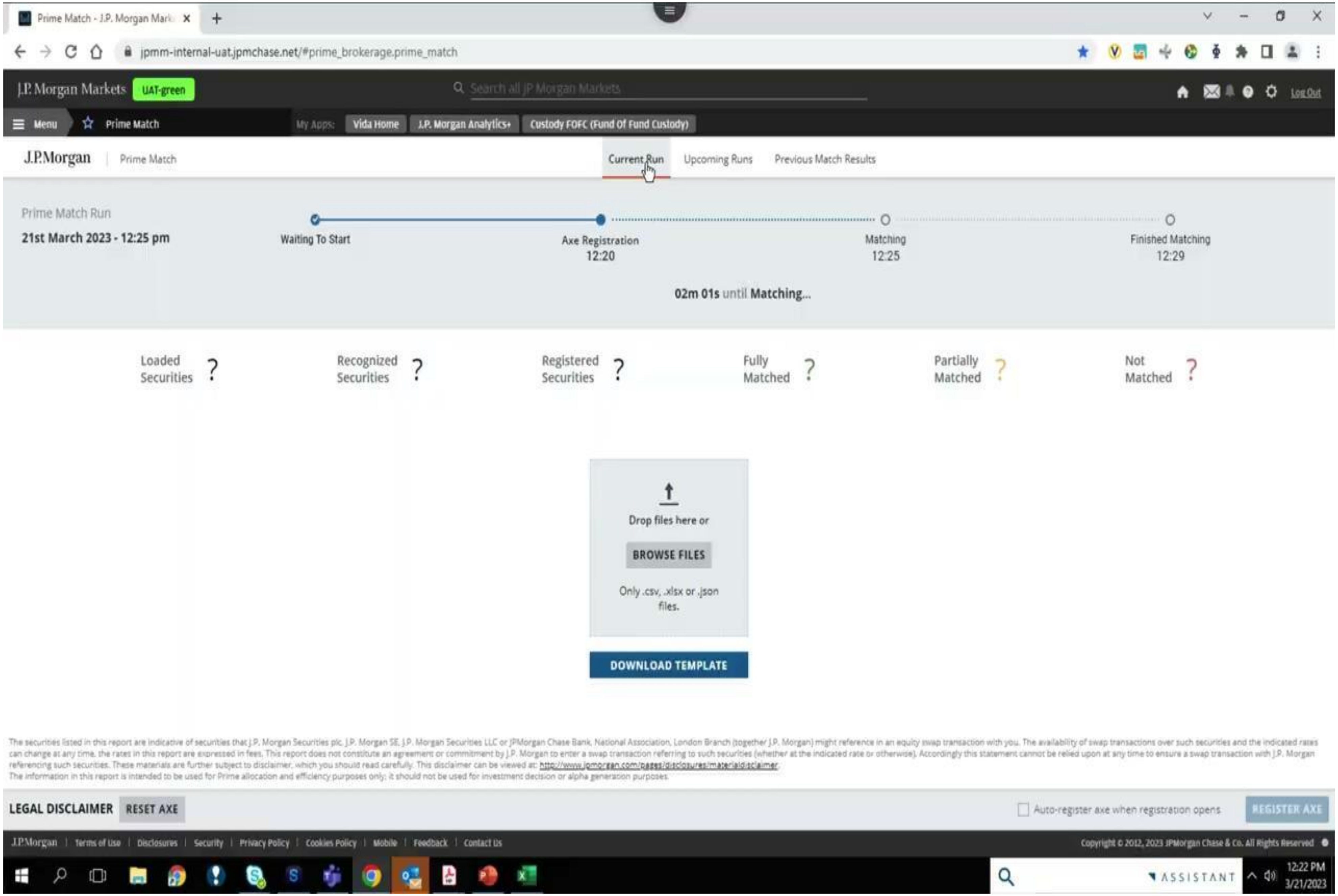
# Prime Match Demo: Registration Phase



Prime Match Run

**21st March 2023 - 12:25 pm**

**02m 01s** until **Matching...**

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|---|---|---|---|---|---|
| ? | ? | ? | ? | ? | ? |

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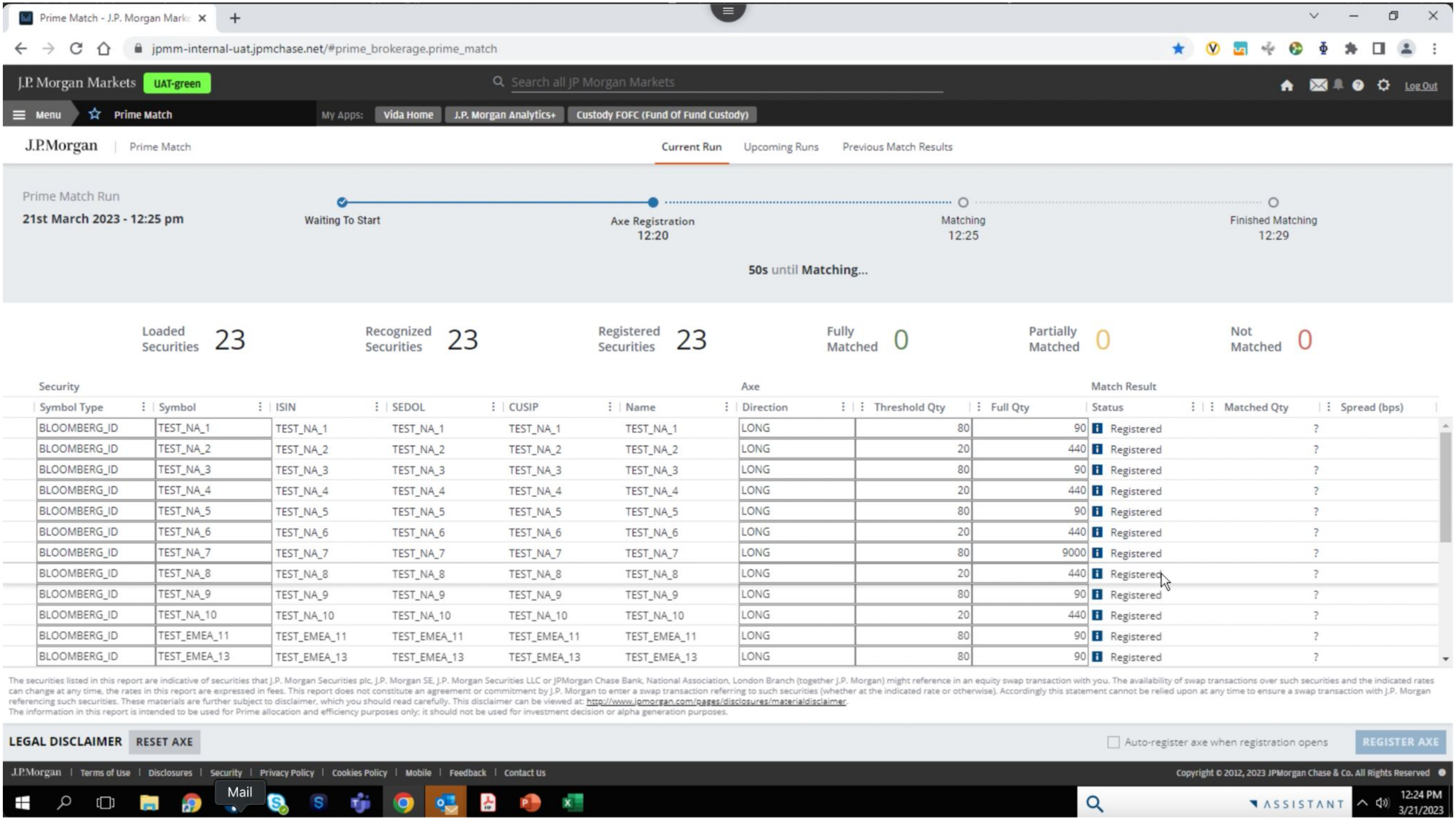
# Prime Match Demo: Registration Phase

[redacted]

# Prime Match Demo: Registration Phase



Prime Match Run
**21st March 2023 - 12:25 pm**

| Waiting To Start | Axe Registration | Matching | Finished Matching |
|---|---|---|---|
| | 12:20 | 12:25 | 12:29 |

**50s** until **Matching...**

| Loaded Securities | Recognized Securities | Registered Securities | Fully Matched | Partially Matched | Not Matched |
|---|---|---|---|---|---|
| 23 | 23 | 23 | 0 | 0 | 0 |

| Security | | | | | | Axe | | | Match Result | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Symbol Type | Symbol | ISIN | SEDOL | CUSIP | Name | Direction | Threshold Qty | Full Qty | Status | Matched Qty | Spread (bps) |
| BLOOMBERG_ID | TEST_NA_1 | TEST_NA_1 | TEST_NA_1 | TEST_NA_1 | TEST_NA_1 | LONG | 80 | 90 | Registered | ? | |
| BLOOMBERG_ID | TEST_NA_2 | TEST_NA_2 | TEST_NA_2 | TEST_NA_2 | TEST_NA_2 | LONG | 20 | 440 | Registered | ? | |
| BLOOMBERG_ID | TEST_NA_3 | TEST_NA_3 | TEST_NA_3 | TEST_NA_3 | TEST_NA_3 | LONG | 80 | 90 | Registered | ? | |
| BLOOMBERG_ID | TEST_NA_4 | TEST_NA_4 | TEST_NA_4 | TEST_NA_4 | TEST_NA_4 | LONG | 20 | 440 | Registered | ? | |
| BLOOMBERG_ID | TEST_NA_5 | TEST_NA_5 | TEST_NA_5 | TEST_NA_5 | TEST_NA_5 | LONG | 80 | 90 | Registered | ? | |
| BLOOMBERG_ID | TEST_NA_6 | TEST_NA_6 | TEST_NA_6 | TEST_NA_6 | TEST_NA_6 | LONG | 20 | 440 | Registered | ? | |
| BLOOMBERG_ID | TEST_NA_7 | TEST_NA_7 | TEST_NA_7 | TEST_NA_7 | TEST_NA_7 | LONG | 80 | 9000 | Registered | ? | |
| BLOOMBERG_ID | TEST_NA_8 | TEST_NA_8 | TEST_NA_8 | TEST_NA_8 | TEST_NA_8 | LONG | 20 | 440 | Registered | ? | |
| BLOOMBERG_ID | TEST_NA_9 | TEST_NA_9 | TEST_NA_9 | TEST_NA_9 | TEST_NA_9 | LONG | 80 | 90 | Registered | ? | |
| BLOOMBERG_ID | TEST_NA_10 | TEST_NA_10 | TEST_NA_10 | TEST_NA_10 | TEST_NA_10 | LONG | 20 | 440 | Registered | ? | |
| BLOOMBERG_ID | TEST_EMEA_11 | TEST_EMEA_11 | TEST_EMEA_11 | TEST_EMEA_11 | TEST_EMEA_11 | LONG | 80 | 90 | Registered | ? | |
| BLOOMBERG_ID | TEST_EMEA_13 | TEST_EMEA_13 | TEST_EMEA_13 | TEST_EMEA_13 | TEST_EMEA_13 | LONG | 80 | 90 | Registered | ? | |

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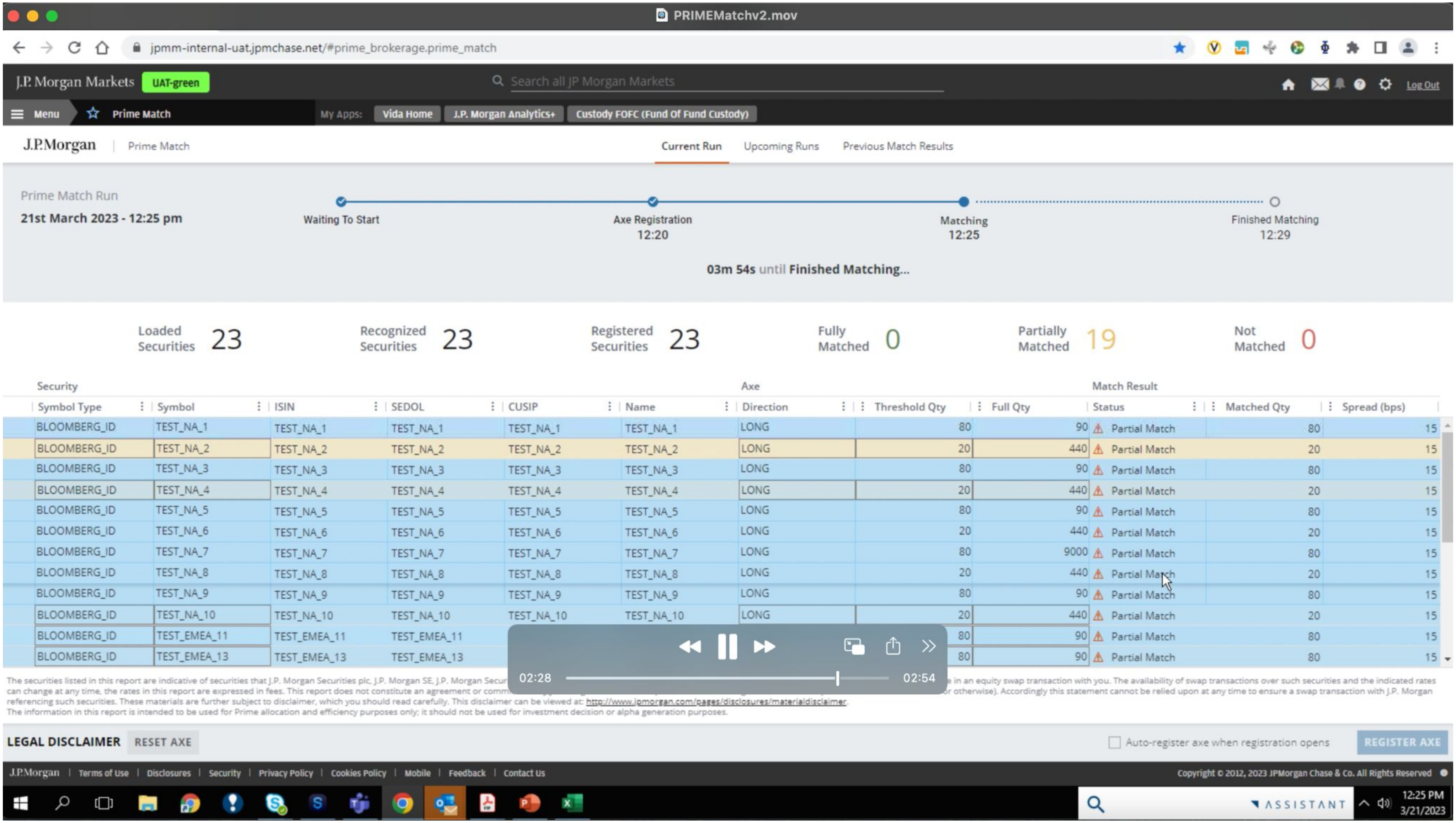
# Prime Match Demo: Matching Phase

# Prime Match Demo: Matching Phase

# Prime Match Demo: Matching Phase



Prime Match Run
**21st March 2023 - 12:25 pm**

**03m 54s** until **Finished Matching...**

| Loaded Securities | Recognized Securities | Registered Securities | Fully Matched | Partially Matched | Not Matched |
|---|---|---|---|---|---|
| 23 | 23 | 23 | 0 | 19 | 0 |

| Security | | | | | | Axe | | | Match Result | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Symbol Type | Symbol | ISIN | SEDOL | CUSIP | Name | Direction | Threshold Qty | Full Qty | Status | Matched Qty | Spread (bps) |
| BLOOMBERG_ID | TEST_NA_1 | TEST_NA_1 | TEST_NA_1 | TEST_NA_1 | TEST_NA_1 | LONG | 80 | 90 | ⚠ Partial Match | 80 | 15 |
| BLOOMBERG_ID | TEST_NA_2 | TEST_NA_2 | TEST_NA_2 | TEST_NA_2 | TEST_NA_2 | LONG | 20 | 440 | ⚠ Partial Match | 20 | 15 |
| BLOOMBERG_ID | TEST_NA_3 | TEST_NA_3 | TEST_NA_3 | TEST_NA_3 | TEST_NA_3 | LONG | 80 | 90 | ⚠ Partial Match | 80 | 15 |
| BLOOMBERG_ID | TEST_NA_4 | TEST_NA_4 | TEST_NA_4 | TEST_NA_4 | TEST_NA_4 | LONG | 20 | 440 | ⚠ Partial Match | 20 | 15 |
| BLOOMBERG_ID | TEST_NA_5 | TEST_NA_5 | TEST_NA_5 | TEST_NA_5 | TEST_NA_5 | LONG | 80 | 90 | ⚠ Partial Match | 80 | 15 |
| BLOOMBERG_ID | TEST_NA_6 | TEST_NA_6 | TEST_NA_6 | TEST_NA_6 | TEST_NA_6 | LONG | 20 | 440 | ⚠ Partial Match | 20 | 15 |
| BLOOMBERG_ID | TEST_NA_7 | TEST_NA_7 | TEST_NA_7 | TEST_NA_7 | TEST_NA_7 | LONG | 80 | 9000 | ⚠ Partial Match | 80 | 15 |
| BLOOMBERG_ID | TEST_NA_8 | TEST_NA_8 | TEST_NA_8 | TEST_NA_8 | TEST_NA_8 | LONG | 20 | 440 | ⚠ Partial Match | 20 | 15 |
| BLOOMBERG_ID | TEST_NA_9 | TEST_NA_9 | TEST_NA_9 | TEST_NA_9 | TEST_NA_9 | LONG | 80 | 90 | ⚠ Partial Match | 80 | 15 |
| BLOOMBERG_ID | TEST_NA_10 | TEST_NA_10 | TEST_NA_10 | TEST_NA_10 | TEST_NA_10 | LONG | 20 | 440 | ⚠ Partial Match | 20 | 15 |
| BLOOMBERG_ID | TEST_EMEA_11 | TEST_EMEA_11 | TEST_EMEA_11 | | | | 80 | 90 | ⚠ Partial Match | 80 | 15 |
| BLOOMBERG_ID | TEST_EMEA_13 | TEST_EMEA_13 | TEST_EMEA_13 | | | | 80 | 90 | ⚠ Partial Match | 80 | 15 |

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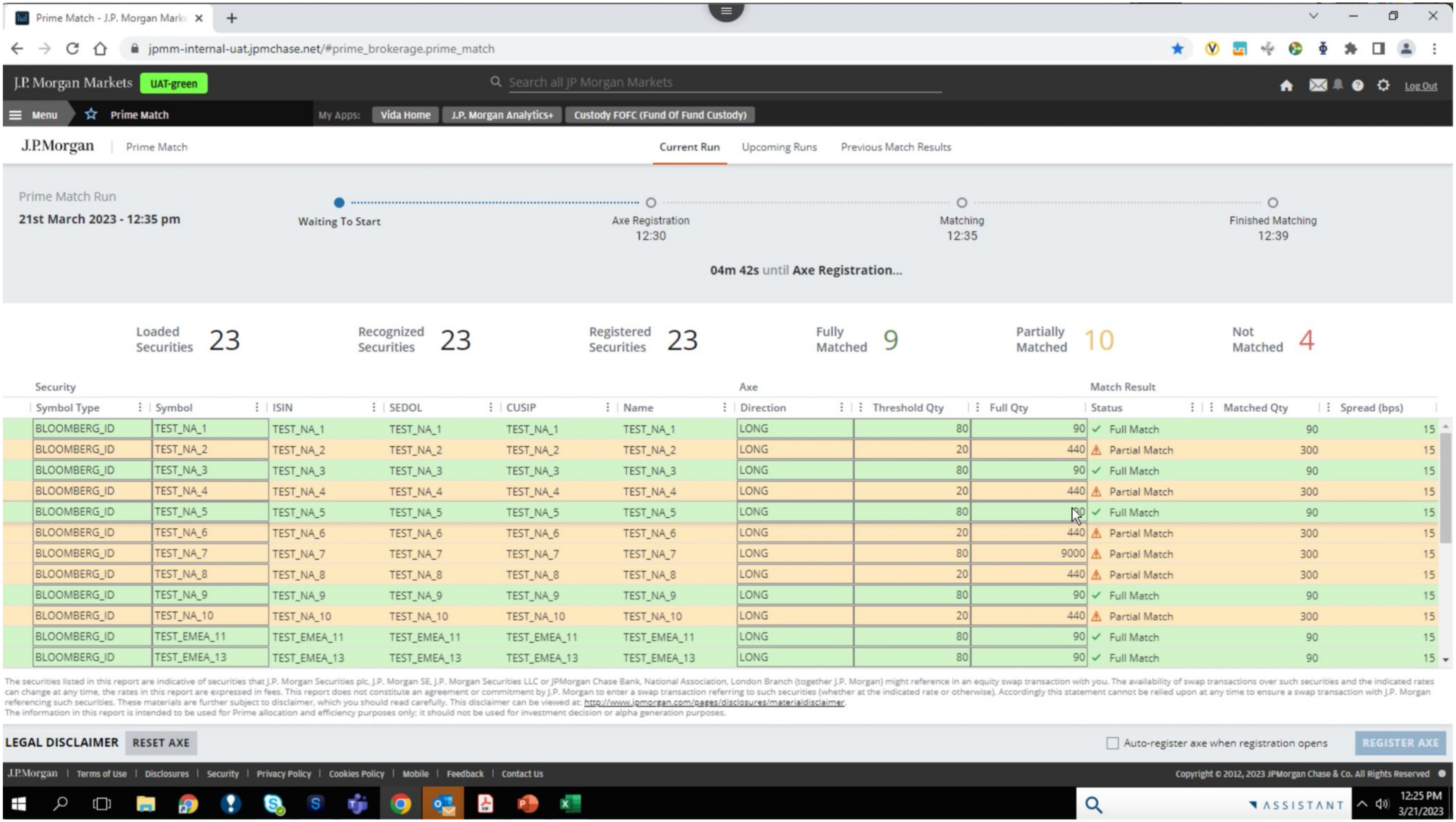
# Prime Match Demo: Matching Phase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Previous Match Results

Prime Match Run
**21st March 2023 - 12:35 pm**

Waiting To Start — Axe Registration 12:30 — Matching 12:35 — Finished Matching 12:39

**04m 42s** until **Axe Registration...**

| Loaded Securities | Recognized Securities | Registered Securities | Fully Matched | Partially Matched | Not Matched |
|---|---|---|---|---|---|
| 23 | 23 | 23 | 9 | 10 | 4 |

| Security | | | | | | Axe | | | Match Result | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Symbol Type | Symbol | ISIN | SEDOL | CUSIP | Name | Direction | Threshold Qty | Full Qty | Status | Matched Qty | Spread (bps) |
| BLOOMBERG_ID | TEST_NA_1 | TEST_NA_1 | TEST_NA_1 | TEST_NA_1 | TEST_NA_1 | LONG | 80 | 90 | ✓ Full Match | 90 | 15 |
| BLOOMBERG_ID | TEST_NA_2 | TEST_NA_2 | TEST_NA_2 | TEST_NA_2 | TEST_NA_2 | LONG | 20 | 440 | ⚠ Partial Match | 300 | 15 |
| BLOOMBERG_ID | TEST_NA_3 | TEST_NA_3 | TEST_NA_3 | TEST_NA_3 | TEST_NA_3 | LONG | 80 | 90 | ✓ Full Match | 90 | 15 |
| BLOOMBERG_ID | TEST_NA_4 | TEST_NA_4 | TEST_NA_4 | TEST_NA_4 | TEST_NA_4 | LONG | 20 | 440 | ⚠ Partial Match | 300 | 15 |
| BLOOMBERG_ID | TEST_NA_5 | TEST_NA_5 | TEST_NA_5 | TEST_NA_5 | TEST_NA_5 | LONG | 80 | 90 | ✓ Full Match | 90 | 15 |
| BLOOMBERG_ID | TEST_NA_6 | TEST_NA_6 | TEST_NA_6 | TEST_NA_6 | TEST_NA_6 | LONG | 20 | 440 | ⚠ Partial Match | 300 | 15 |
| BLOOMBERG_ID | TEST_NA_7 | TEST_NA_7 | TEST_NA_7 | TEST_NA_7 | TEST_NA_7 | LONG | 80 | 9000 | ⚠ Partial Match | 300 | 15 |
| BLOOMBERG_ID | TEST_NA_8 | TEST_NA_8 | TEST_NA_8 | TEST_NA_8 | TEST_NA_8 | LONG | 20 | 440 | ⚠ Partial Match | 300 | 15 |
| BLOOMBERG_ID | TEST_NA_9 | TEST_NA_9 | TEST_NA_9 | TEST_NA_9 | TEST_NA_9 | LONG | 80 | 90 | ✓ Full Match | 90 | 15 |
| BLOOMBERG_ID | TEST_NA_10 | TEST_NA_10 | TEST_NA_10 | TEST_NA_10 | TEST_NA_10 | LONG | 20 | 440 | ⚠ Partial Match | 300 | 15 |
| BLOOMBERG_ID | TEST_EMEA_11 | TEST_EMEA_11 | TEST_EMEA_11 | TEST_EMEA_11 | TEST_EMEA_11 | LONG | 80 | 90 | ✓ Full Match | 90 | 15 |
| BLOOMBERG_ID | TEST_EMEA_13 | TEST_EMEA_13 | TEST_EMEA_13 | TEST_EMEA_13 | TEST_EMEA_13 | LONG | 80 | 90 | ✓ Full Match | 90 | 15 |

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# Conclusion

- **Identified a real-world problem for MPC** in which the privacy of the previous inventory matching procedure can be significantly enhanced
- Prime Match protocols—bank-to-client inventory matching and client-to-client inventory matching—completely replace the current method which not only leaks information but also fails to identify potential matches
  - **Our protocols are novel and customized** to the particular use case being addressed (privacy preserving auctions)
- At the core of our matching engine lies a new **two-round comparison** protocol that minimizes interaction and requires **only linear operations**.
- Prime Match protocols are implemented and **run live for the first time, in production**, by a major bank in the US – J.P. Morgan.

# Conclusion and Future Work

Future work:

1. **Fair matching t**hat ensures no single client can monopolize the majority of the inventory.
2. Extend MPC for:
   1. Privacy preserving **darkpools**
   2. Privacy preserving **portfolio optimization**

# Prime Match: A Privacy Preserving Inventory Matching System

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Thank you!

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