Efficient Searchable Symmetric Encryption for Join Queries

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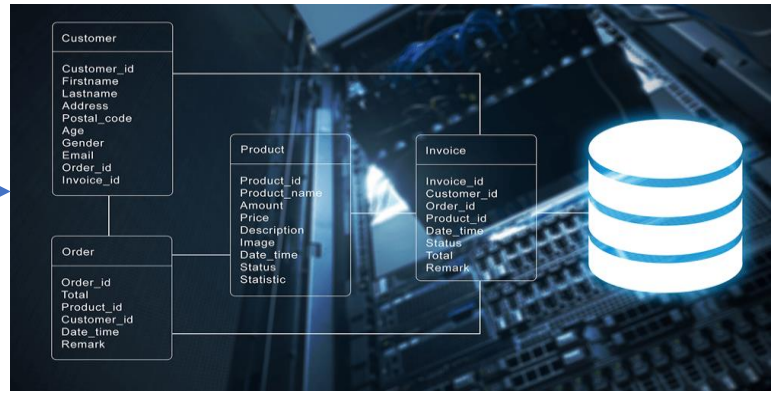
Outsourced Storage and Processing

Organization

Outsource

Database

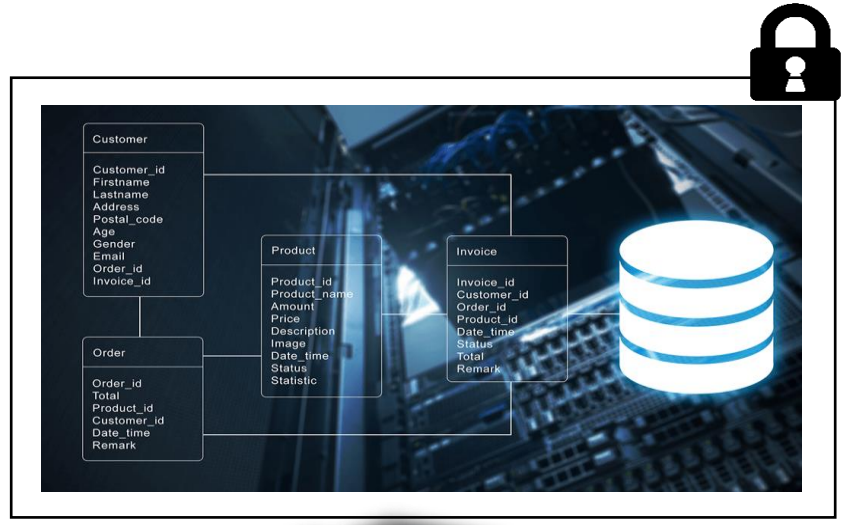


Auditor

Query Request

Result

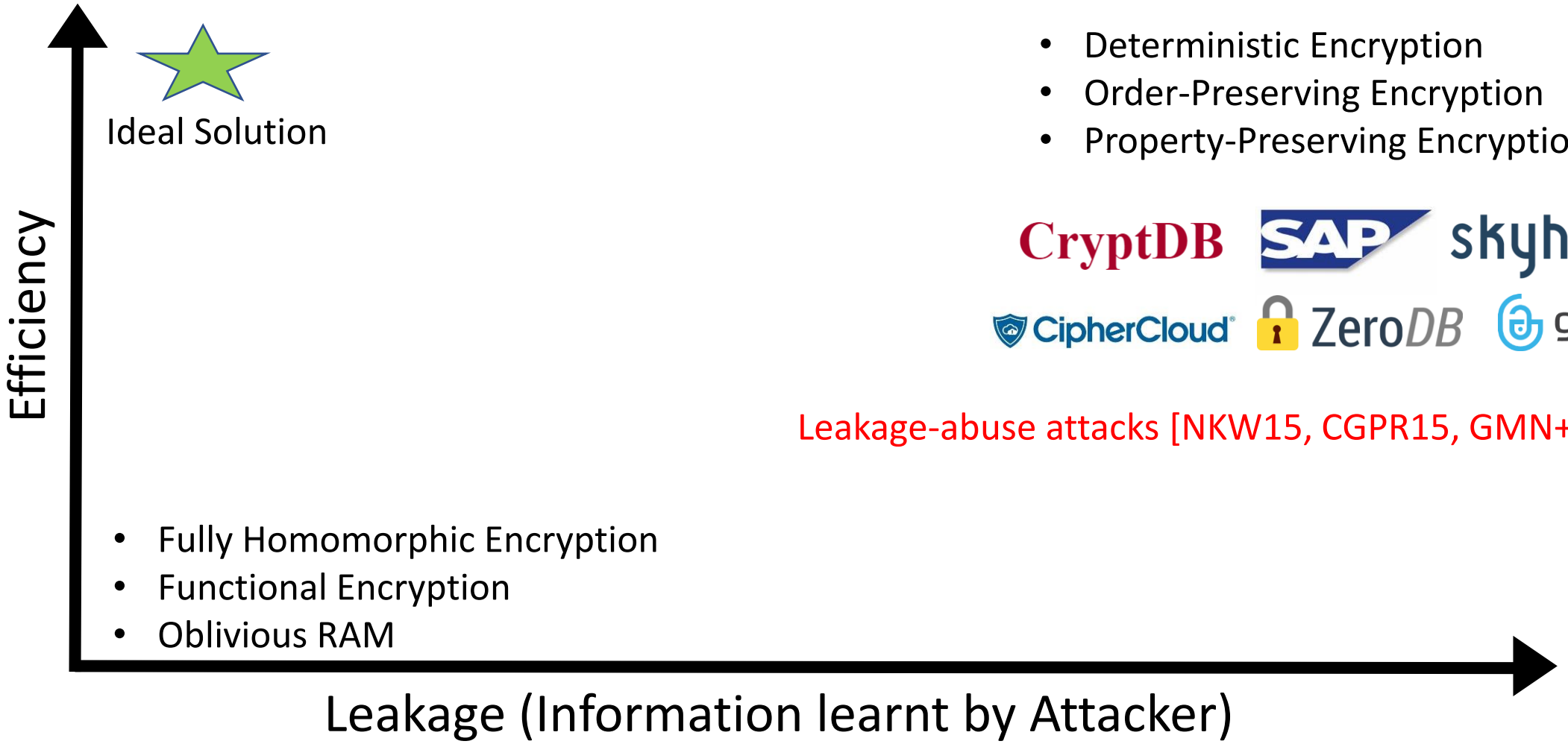
Computing on Encrypted Data



Query Request

Result

Efficiency v/s Leakage: Computing on Encrypted Data

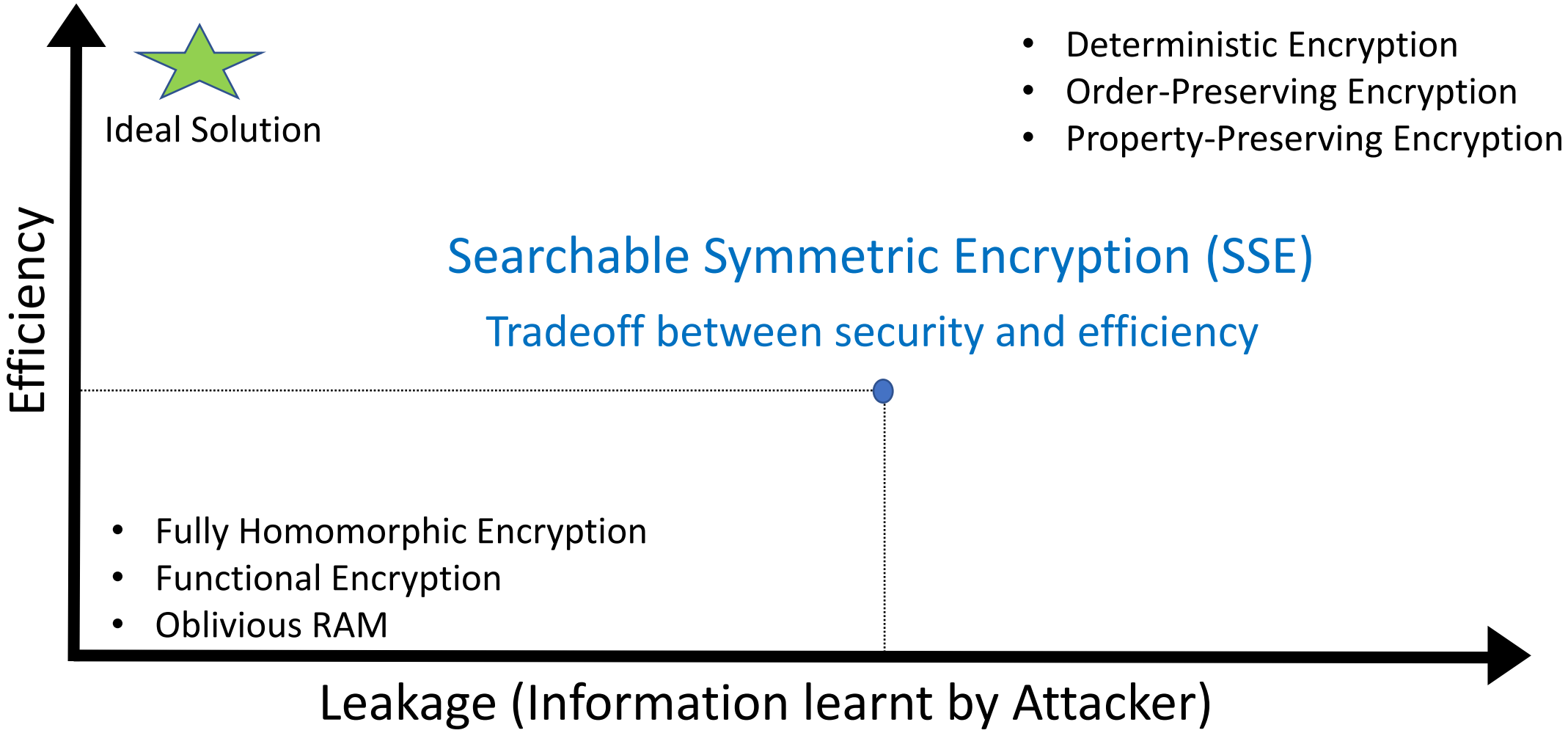


- Deterministic Encryption
- Order-Preserving Encryption
- Property-Preserving Encryption

CryptDB SAP skyhigh CipherCloud ZeroDB gitzero

Leakage-abuse attacks [NKW15, CGPR15, GMN+16,GSB+17]

Efficiency v/s Leakage: Computing on Encrypted Data



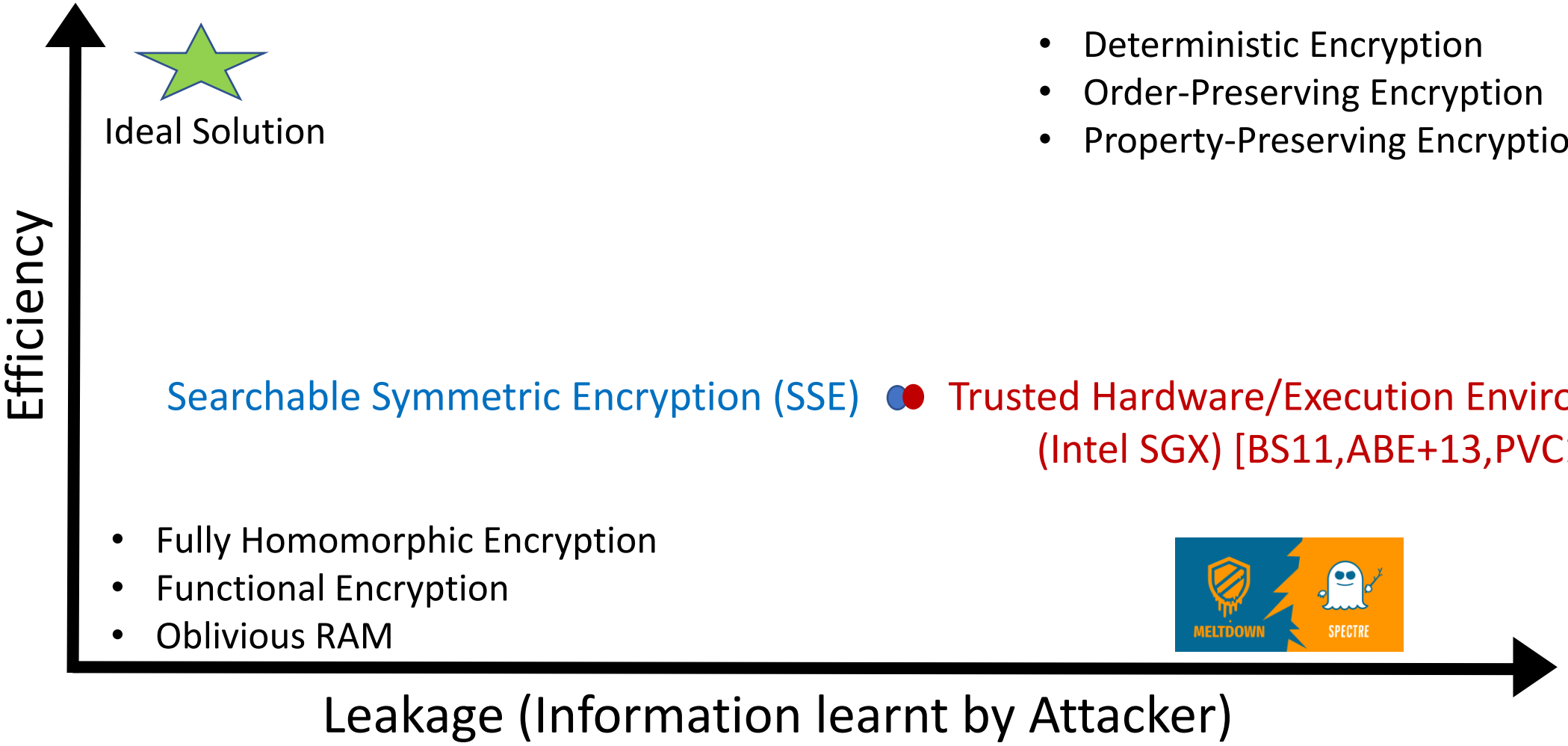
- Deterministic Encryption
- Order-Preserving Encryption
- Property-Preserving Encryption

Searchable Symmetric Encryption (SSE)

Tradeoff between security and efficiency

- Fully Homomorphic Encryption
- Functional Encryption
- Oblivious RAM

Efficiency v/s Leakage



- Deterministic Encryption
- Order-Preserving Encryption
- Property-Preserving Encryption

- Fully Homomorphic Encryption
- Functional Encryption
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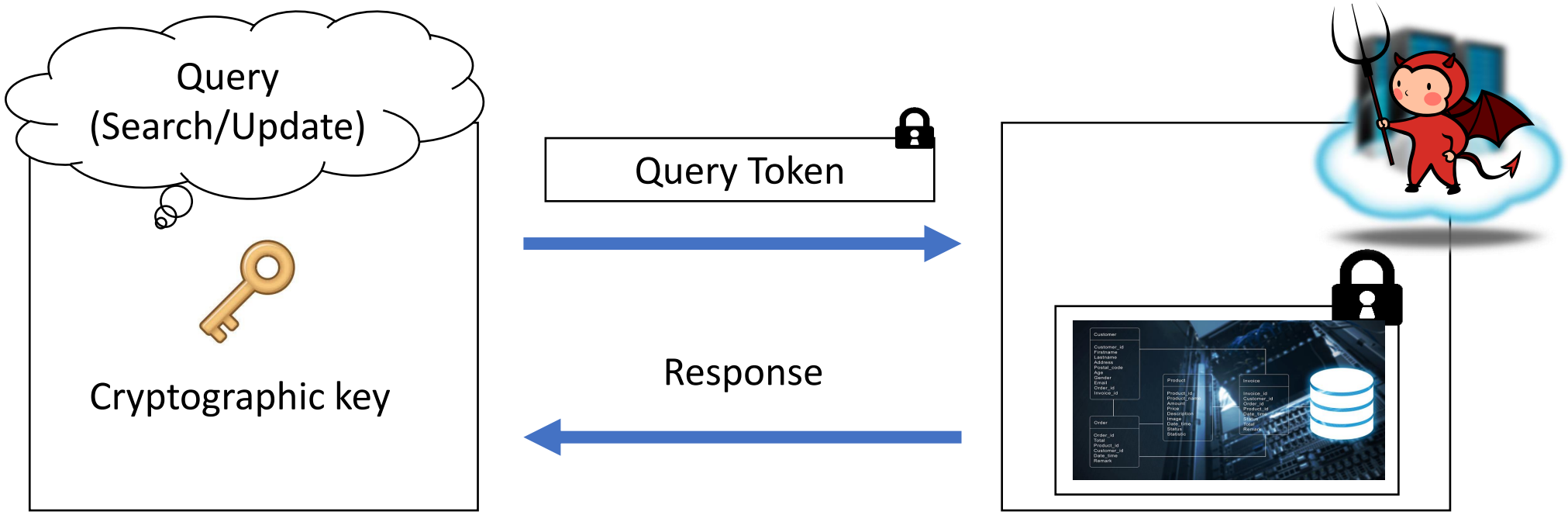
Searchable Symmetric Encryption (SSE)



Client

(Single-reader, Single-writer)

Server

(Honest but curious)

Our Contribution

Join Cross Tags (JXT)

A **practically efficient** SSE scheme for computing queries over
Equi Joins of pairs of **encrypted tables** in an **encrypted relational database**

Talk Outline

- Background: Equi Joins
- Join Cross-Tags (JXT)
- Overview of JXT
- Techniques
- Open Questions

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Example of Equi Join Query

Transactions Table

ID-1	Date (MM/YY)	Transaction ID
T1	01/2021	6F0X1
T2	05/2021	4J9T6
T3	07/2021	2C3W3
T4	01/2022	8P7A5
T5	01/2022	5S4D2

Merchants Table

ID-2	Merchant Name	Transaction ID
M1	Apple	5S4D2
M2	Exxon	9N2E8
M3	Gucci	7T8U3
M4	Apple	3L9M5
M5	Five Guys	6F0X1

Join Attribute

Example of Equi Join Query

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M1	Apple	5S4D2
M2	Exxon	9N2E8
M3	Gucci	7T8U3
M4	Apple	3L9M5
M5	Five Guys	6F0X1

SELECT ID-1, ID-2

FROM Transactions JOIN Merchants ON Transaction ID

WHERE Date = 01/2022 AND Merchant Name = Apple

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- Open Questions

Our Proposal

Join Cross Tags (JXT)

A practically efficient SSE scheme for **Equi Join** queries over pairs of encrypted tables

- **No pre-processing** of joins at setup (i.e., during encrypted database generation)
  - Tables can be encrypted and added to the encrypted database independently
  - Only require tables to have a common designated join attribute
- Storage overhead – T-fold for T designated join attributes (typically small T)
- Uses **purely symmetric-key** primitives (can be implemented entirely using AES)
- Fully compatible with OXT [CJJ+13] for (conjunctive) Boolean queries

Comparison of JXT with Prior Art

Scheme	Supported Query Types	Requires Pre-Computation of Joins
SPX [KM18]	Boolean queries + Join queries	Yes
[CNR21]	Join queries	Yes
JXT (This Work)	Boolean queries + Join queries	No

JXT is the only SSE scheme supporting join queries and flexible table updates

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Overview of JXT

No Pre-Processing of Joins

Transactions Table

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M3	Gucci	7T8U3
M4	Apple	3L9M5
M5	Five Guys	6F0X1

- Setup does not explicitly pre-process equi join of Transactions Table and Merchants Table
- Each table is processed **individually** – need not be created at the same time
- Only need each table to be configured to support join on attribute "Transaction ID"

Overview of JXT

No Pre-Processing of Joins

- At setup, each table is processed individually
- Each table has a designated set of join attributes
  - Is configured to support joins w.r.t. these attributes
- Consider a universe of 10 attributes {A1, A2, …, A10}:
  - Table T1 is configured to support joins over attributes A1, A3, A5 and A8
  - Table T2 is configured to support joins over attributes A2, A3, A7 and A9
  - JXT naturally supports queries over join of T1 and T2 on A3
  - No dedicated pre-processing of T1 and T2 w.r.t. A3 required

Overview of JXT

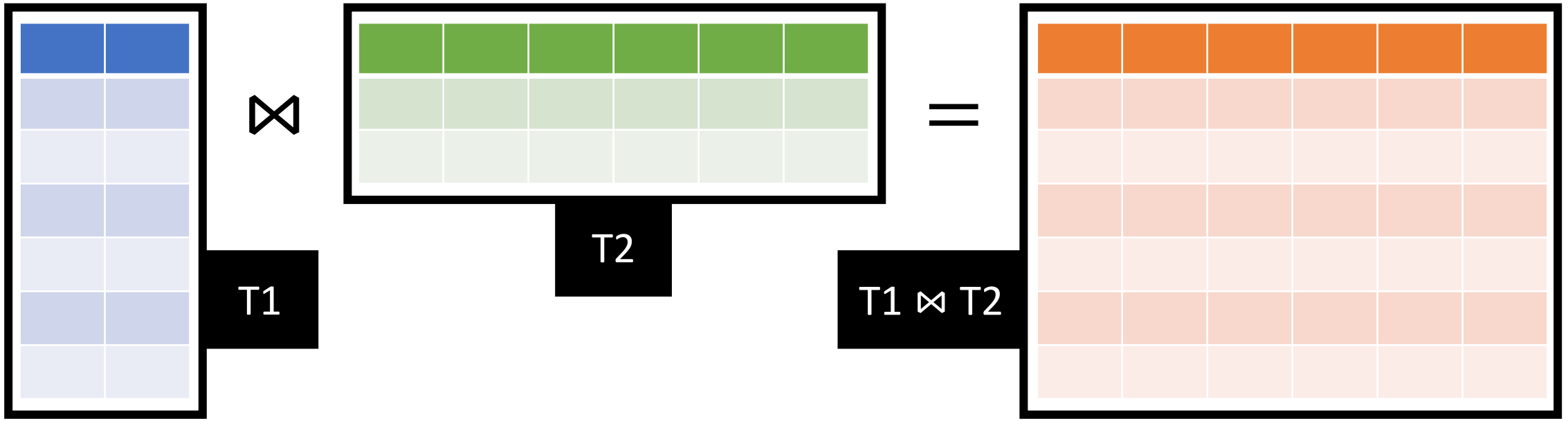
No Pre-Processing of Joins

- At setup, each table is processed individually
- Each table has a designated set of join attributes
  - Is configured to support joins w.r.t. these attributes
- In practice, number of candidate attributes for joins are small
  - Either primary/secondary key (unique value for each record)
  - Or a “high-entropy” attribute (unique values for “nearly” all records)

Overview of JXT

Comparison with Pre-Processing of Joins

- Avoids storage blow-ups due to explicit join computation:
  - Table T1 is tall and skinny (many records, few attributes)
  - Table T2 is short and wide (few records, many attributes)
  - Their equi join (for each common join attribute) maybe tall and wide



Overview of JXT

Comparison with Pre-Processing of Joins

- Avoids storage blow-ups due to explicit join computation:
  - Table T1 is tall and skinny (many records, few attributes)
  - Table T2 is short and wide (few records, many attributes)
  - Their equi join (for each common join attribute) maybe tall and wide
- Avoids re-computation of joins:
  - Suppose T1 needs to be re-setup at some point of time (updates/recovery)
  - Does not need re-computation of join with T2 (and other tables)
  - Different tables can be re-setup independently
- Avoids quadratic storage blow-up (in number of tables)

Overview of JXT

Storage and Search Overheads

- Storage Overhead:
  - Suppose a table has m rows/records and n columns/attributes
  - Suppose $\mathrm{T} \leq n$ are designated as join attributes
  - Storage: $O(mn\mathrm{T})$ i.e., $O(\mathrm{T})$-fold blowup

- Search Overhead:
  - Suppose ℓ_1 records in Transactions table matching Date = 01/2022
  - Suppose ℓ_2 records in Merchants table matching Merchant Name = Apple
  - Search cost:
    - Communication cost: $O(\ell_1 + \ell_2)$ (single round of communication)
    - Computation at client: $O(\ell_1 + \ell_2)$
    - Computation at server: $O(\ell_1 \cdot \ell_2)$

Overview of JXT

Compatibility with Oblivious Cross Tags (OXT) [CJJ+13]

- Suppose Transactions table and Merchants table had more attributes
- OXT + JXT supports more general conjunctive queries over joins of tables:

```
SELECT ID-1, ID-2

FROM Transactions JOIN Merchants ON Transaction ID

WHERE Date = 01/2022 AND Type = ACH AND Merchant Name = Apple AND City = SFO
```

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Cryptoprimitives

Transactions Table

ID-1	Date (MM/YY)	Transaction ID
T1	01/2021	6F0X1
T2	05/2021	4J9T6
T3	07/2021	2C3W3
T4	01/2022	8P7A5
T5	01/2022	5S4D2

Merchants Table

ID-2	Merchant Name	Transaction ID
M1	Apple	5S4D2
M2	Exxon	9N2E8
M3	Gucci	7T8U3
M4	Apple	3L9M5
M5	Five Guys	6F0X1

- Let F be a PRF family and let k_1, k_2, k_3 and k_4 be randomly sampled keys
- Use $f(\cdot)$ to denote $F(k_1,\cdot)$ and $g(\cdot)$ to denote $F(k_2,\cdot)$
- Use $h_0(\cdot)$ to denote $F(k_3,\cdot)$ and $h_1(\cdot)$ to denote $F(k_4,\cdot)$

Processing Transactions Table

Transactions Table

ID-1	Date (MM/YY)	Transaction ID
T1	01/2021	6F0X1
T2	05/2021	4J9T6
T3	07/2021	2C3W3
T4	01/2022	8P7A5
T5	01/2022	5S4D2

$$x_1 = f(\text{id} = \text{T1}||\text{Transaction ID})$$

$$y_1 = g(\text{Transaction ID} = \text{6F0X1})$$

$$z_1 = x_1 \oplus y_1$$

- Let F be a PRF family and let k_1, k_2, k_3 and k_4 be randomly sampled keys
- Use $f(\cdot)$ to denote $F(k_1,\cdot)$ and $g(\cdot)$ to denote $F(k_2,\cdot)$
- Use $h_0(\cdot)$ to denote $F(k_3,\cdot)$ and $h_1(\cdot)$ to denote $F(k_4,\cdot)$

Processing Merchants Table

Merchants Table

ID-2	Merchant Name	Transaction ID
M1	Apple	5S4D2
M2	Exxon	9N2E8
M3	Gucci	7T8U3
M4	Apple	3L9M5
M5	Five Guys	6F0X1

$$x'_1 = f(\text{id} = \text{M1}||\text{Transaction ID})$$

$$y'_1 = g(\text{Transaction ID} = \text{5S4D2})$$

$$z'_1 = x'_1 \oplus y'_1$$

- Let F be a PRF family and let k_1, k_2, k_3 and k_4 be randomly sampled keys
- Use $f(\cdot)$ to denote $F(k_1,\cdot)$ and $g(\cdot)$ to denote $F(k_2,\cdot)$
- Use $h_0(\cdot)$ to denote $F(k_3,\cdot)$ and $h_1(\cdot)$ to denote $F(k_4,\cdot)$

Matching Entries

Transactions Table

ID-1	Date (MM/YY)	Transaction ID
T1	01/2021	6F0X1
T2	05/2021	4J9T6
T3	07/2021	2C3W3
T4	01/2022	8P7A5
T5	01/2022	5S4D2

Merchants Table

ID-2	Merchant Name	Transaction ID
M1	Apple	5S4D2
M2	Exxon	9N2E8
M3	Gucci	7T8U3
M4	Apple	3L9M5
M5	Five Guys	6F0X1

$$x_5 = f(\text{id} = \text{T5}||\text{Transaction ID})$$

$$y_5 = g(\text{Transaction ID} = \text{5S4D2})$$

$$z_5 = x_5 \oplus y_5$$

$$x'_1 = f(\text{id} = \text{M1}||\text{Transaction ID})$$

$$y'_1 = g(\text{Transaction ID} = \text{5S4D2})$$

$$z'_1 = x'_1 \oplus y'_1$$

Non-Matching Entries

Transactions Table

ID-1	Date (MM/YY)	Transaction ID
T1	01/2021	6F0X1
T2	05/2021	4J9T6
T3	07/2021	2C3W3
T4	01/2022	8P7A5
T5	01/2022	5S4D2

Merchants Table

ID-2	Merchant Name	Transaction ID
M1	Apple	5S4D2
M2	Exxon	9N2E8
M3	Gucci	7T8U3
M4	Apple	3L9M5
M5	Five Guys	6F0X1

$$x_4 = f(\text{id} = \text{T4}||\text{Transaction ID})$$

$$y_4 = g(\text{Transaction ID} = \text{8P7A5})$$

$$z_4 = x_4 \oplus y_4$$

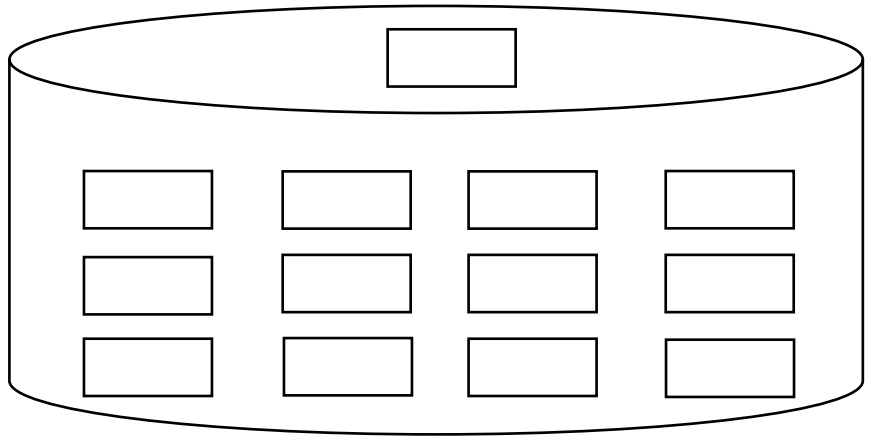
$$x'_4 = f(\text{id} = \text{M4}||\text{Transaction ID})$$

$$y'_4 = g(\text{Transaction ID} = \text{3L9M5})$$

$$z'_4 = x'_4 \oplus y'_4$$

Looking at each table in isolation

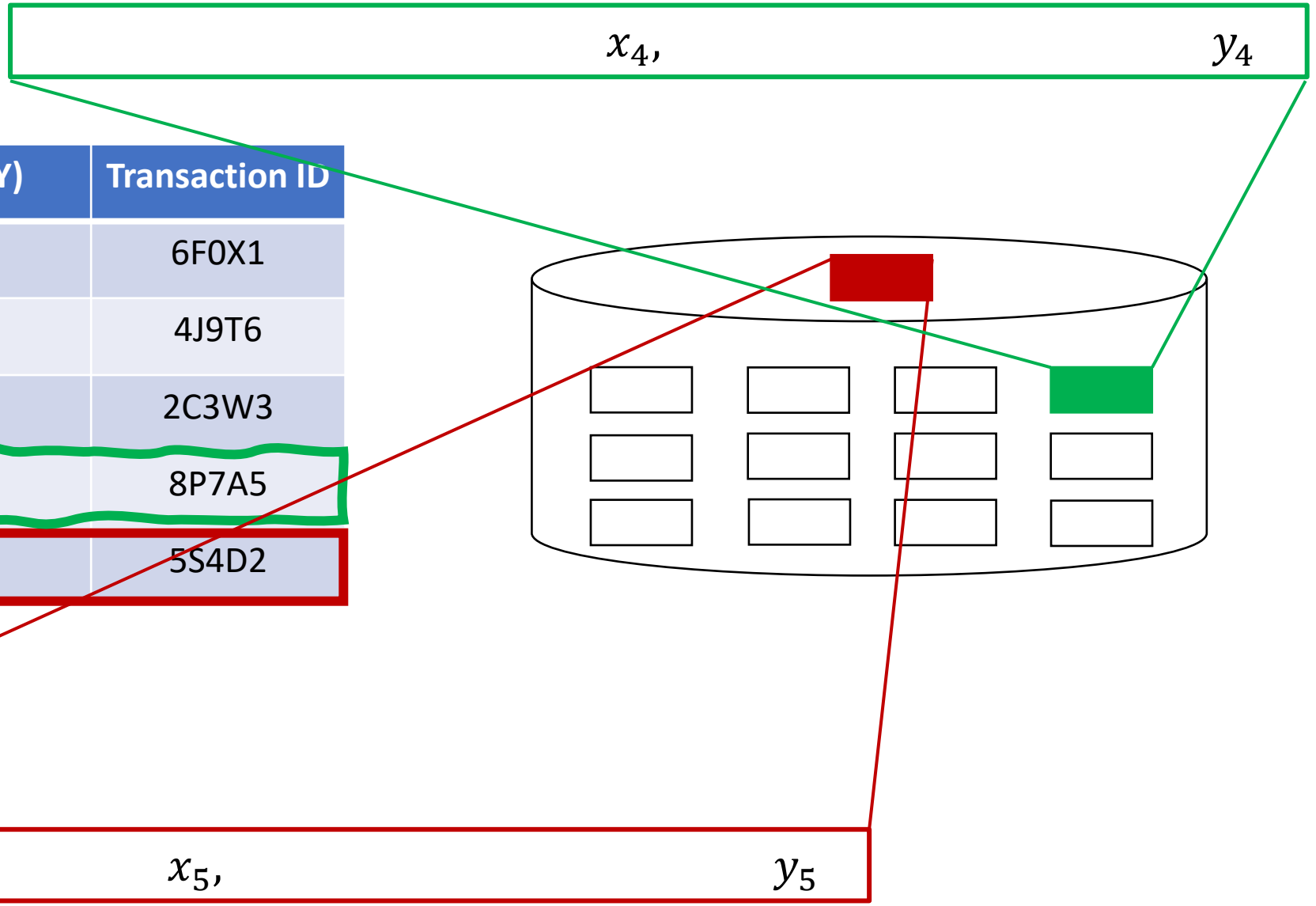
ID-1	Date (MM/YY)	Transaction ID
T1	01/2021	6F0X1
T2	05/2021	4J9T6
T3	07/2021	2C3W3
T4	01/2022	8P7A5
T5	01/2022	5S4D2



- Server stores a key-value store for each table
- Entries of the form (key, value) in random order
- Given a “valid” key, the associated value can be efficiently retrieved

Looking at each table in isolation

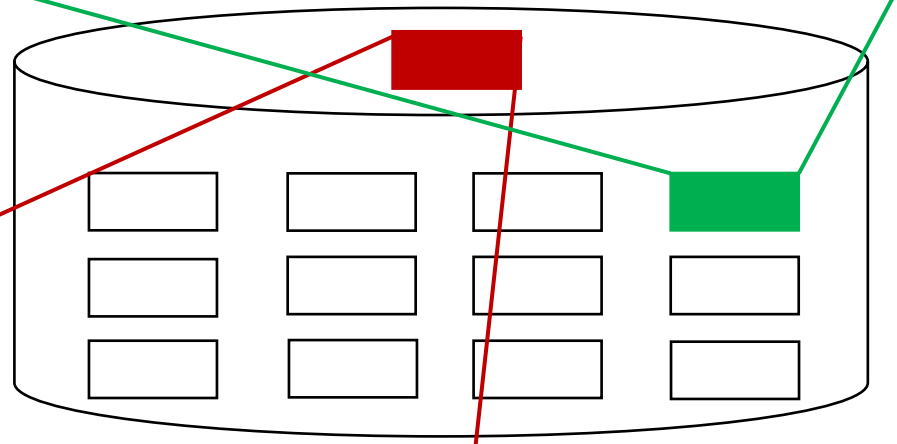
ID-1	Date (MM/YY)	Transaction ID
T1	01/2021	6F0X1
T2	05/2021	4J9T6
T3	07/2021	2C3W3
T4	01/2022	8P7A5
T5	01/2022	5S4D2



Looking at each table in isolation

$h_0(\text{Date} = 01/2022||1) \oplus x_4, h_1(\text{Date} = 01/2022||1) \oplus y_4$

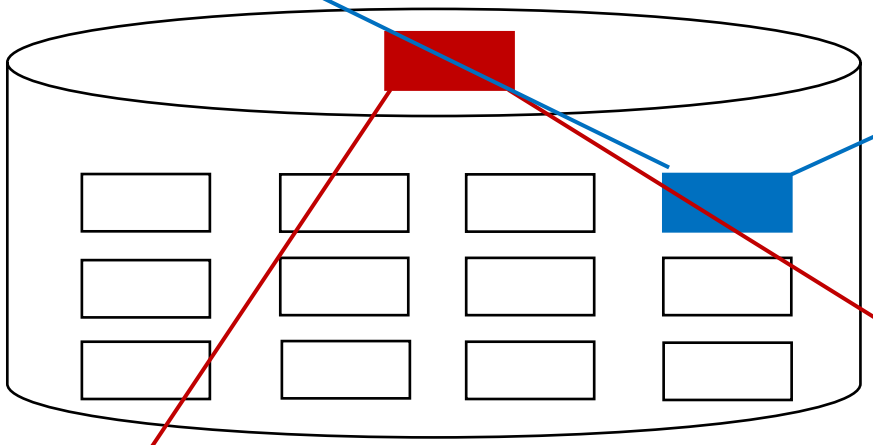
ID-1	Date (MM/YY)	Transaction ID
T1	01/2021	6F0X1
T2	05/2021	4J9T6
T3	07/2021	2C3W3
T4	01/2022	8P7A5
T5	01/2022	5S4D2



$h_0(\text{Date} = 01/2022||2) \oplus x_5, h_1(\text{Date} = 01/2022||2) \oplus y_5$

Looking at each table in isolation

$$h_0(\text{MN} = \text{Apple}||2) \oplus x'_4, h_1(\text{MN} = \text{Apple}||2) \oplus y'_4$$



ID-2	Merchant Name	Transaction ID
M1	Apple	5S4D2
M2	Exxon	9N2E8
M3	Gucci	7T8U3
M4	Apple	3L9M5
M5	Five Guys	6F0X1

$$h_0(\text{MN} = \text{Apple}||1) \oplus x'_1, h_1(\text{MN} = \text{Apple}||1) \oplus y'_1$$

Summary: What does the server store?

Transactions Table

ID-1	Date (MM/YY)	Transaction ID
T1	01/2021	6F0X1
T2	05/2021	4J9T6
T3	07/2021	2C3W3
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Merchants Table

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- Server stores masked x-values and masked y-values for each tuple of the form (record, join-attribute, attribute-value pair) in an encrypted key-value store
  - For any attribute-value pair, client should be able to generate tokens that allow the server to retrieve the relevant entries
  - Many realizations: T-Set (OXT), Encrypted Multi-Maps [KM19,PPYY19]

Summary: What does the server store?

Transactions Table

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M4	Apple	3L9M5
M5	Five Guys	6F0X1

- Server stores masked x-values and masked y-values for each tuple of the form (record, join-attribute, attribute-value pair) in an encrypted key-value store
- Server additionally stores the z-values directly in a Bloom Filter (or any data structure that allows efficient membership-testing)

Matching Entries: What server recovers from key-value store

Transactions Table

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M4	Apple	3L9M5
M5	Five Guys	6F0X1

$$h_0(\text{Date} = 01/2022||2) \oplus x_5$$

$$h_1(\text{Date} = 01/2022||2) \oplus y_5$$

$$z_5 = x_5 \oplus y_5$$

$$h_0(\text{MN} = \text{Apple}||1) \oplus x'_1$$

$$h_1(\text{MN} = \text{Apple}||1) \oplus y'_1$$

$$z'_1 = x'_1 \oplus y'_1$$

Matching Entries: What server recovers from key-value store

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M5	Five Guys	6F0X1

$$h_0(\text{Date} = 01/2022||2) \oplus x_5$$

$$h_1(\text{Date} = 01/2022||2) \oplus y'_1$$

$$z_5 = x_5 \oplus y_5$$

$$h_0(\text{MN} = \text{Apple}||1) \oplus x'_1$$

$$h_1(\text{MN} = \text{Apple}||1) \oplus y'_1$$

$$z'_1 = x'_1 \oplus y'_1$$

Matching Entries: What server checks in Bloom Filter

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Merchants Table

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M2	Exxon	9N2E8
M3	Gucci	7T8U3
M4	Apple	3L9M5
M5	Five Guys	6F0X1

$h_0(\text{Date} = 01/2022||2) \oplus x_5$

$h_1(\text{Date} = 01/2022||2) \oplus y'_1$

$z_5 = x_5 \oplus y_5$

$h_0(\text{MN} = \text{Apple}||1) \oplus x'_1$

$h_1(\text{MN} = \text{Apple}||1) \oplus y'_1$

$z'_1 = x'_1 \oplus y'_1$

Search steps: Overview

1. Client sends to server tokens to recover $h_1(\text{Date} = 01/2022||2) \oplus y'_1$ and $h_0(\text{MN} = \text{Apple}||1) \oplus x'_1$
2. Client also sends to the server $h_1(\text{Date} = 01/2022||2) \oplus h_0(\text{MN} = \text{Apple}||1)$
3. Server recovers z'_1 and checks its membership in the Bloom Filter
4. Membership test returns TRUE

$h_0(\text{Date} = 01/2022||2) \oplus x_5$

$h_1(\text{Date} = 01/2022||2) \oplus y'_1$

$z_5 = x_5 \oplus y_5$

$h_0(\text{MN} = \text{Apple}||1) \oplus x'_1$

$h_1(\text{MN} = \text{Apple}||1) \oplus y'_1$

$z'_1 = x'_1 \oplus y'_1$

Non-Matching Entries: Recap

Transactions Table

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T1	01/2021	6F0X1
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T3	07/2021	2C3W3
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Merchants Table

ID-2	Merchant Name	Transaction ID
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M3	Gucci	7T8U3
M4	Apple	3L9M5
M5	Five Guys	6F0X1

$$x_4 = f(\text{id} = \text{T4}||\text{Transaction ID})$$

$$y_4 = g(\text{Transaction ID} = \text{8P7A5})$$

$$z_4 = x_4 \oplus y_4$$

$$x'_4 = f(\text{id} = \text{M4}||\text{Transaction ID})$$

$$y'_4 = g(\text{Transaction ID} = \text{3L9M5})$$

$$z'_4 = x'_4 \oplus y'_4$$

Search steps: Overview

1. Client sends to server tokens to recover $h_1(\text{Date} = 01/2022||1) \oplus y_5$ and $h_0(\text{MN} = \text{Apple}||2) \oplus x'_4$
2. Client also sends to the server $h_1(\text{Date} = 01/2022||1) \oplus h_0(\text{MN} = \text{Apple}||2)$
3. Server recovers $(x'_4 \oplus y_5)$ and checks its membership in the Bloom Filter
4. Membership test returns FALSE

$h_0(\text{Date} = 01/2022||1) \oplus x_4$

$h_1(\text{Date} = 01/2022||1) \oplus y_5$

$z_4 = x_4 \oplus y_4$

$h_0(\text{MN} = \text{Apple}||2) \oplus x'_4$

$h_1(\text{MN} = \text{Apple}||2) \oplus y'_4$

$z'_4 = x'_4 \oplus y'_4$

Search steps: Overview

1. Client sends to server tokens to recover $h_1(\text{Date} = 01/2022||1) \oplus y_5$ and $h_0(\text{MN} = \text{Apple}||2) \oplus x'_4$
2. Client also sends to the server $h_1(\text{Date} = 01/2022||1) \oplus h_0(\text{MN} = \text{Apple}||2)$
3. Server recovers $(x'_4 \oplus y_5)$ and checks its membership in the Bloom Filter
4. Membership test returns FALSE

- Pairwise XOR of masks incurs quadratic overhead
- Additional techniques to delegate pairwise XOR computations to the server while client does linear amount of work
  - Details in the paper

Leakage of JXT: Join Attribute Distribution Pattern

- Leaks frequency distribution of values taken by Transaction ID across records matching Date = 01/2022 in Transactions Table
- Unique value for each record if join attribute is primary/secondary key
  - No non-trivial leakage in this case
- Leakage is not significant if join attribute is high-entropy
  - Unique value for nearly each record, so each value occurs only once with high probability
- Impact of leakage less clear if join attribute is low-entropy
  - Strategy: Structure query such that join-attribute is high-entropy in first table

Talk Outline

- Background: Equi Joins
- Join Cross-Tags (JXT)
- Overview of JXT
- Techniques
- Open Questions

Open Questions and Future Directions

- Extend JXT to flexibly support joins over **arbitrary** attributes
- Extend JXT to support queries over equi joins of **three (or more) tables**
- Analyze impact of leakage for **low-entropy** join attributes
- Extend JXT to support **dynamic** addition/deletion of records
- **Implementation and experimentation** over large databases

Full version: https://eprint.iacr.org/2021/1471

Thank You! Questions?