Buliding a Structurally-Encrypted Relational Database

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Outsourcing Data to the Cloud

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- Outsourced infrastructure; Uptime, computation and storage on-demand.
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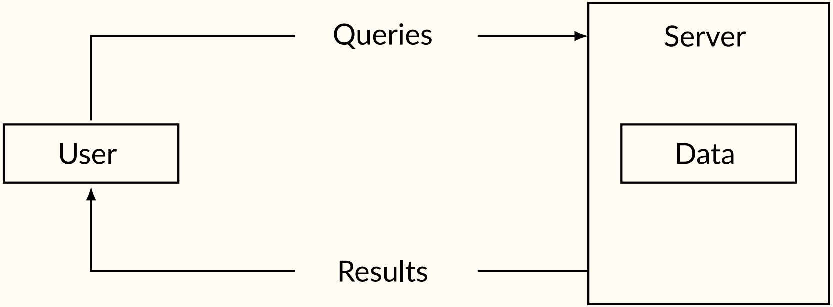
- Outsourced infrastructure; Uptime, computation and storage on-demand.
- By 2020, 80% small & medium businesses in US will use cloud services [Col15].
- Privacy issues
  - Data breaches: unlawful disclosure or access to sensitive data [GDPR16]
  - Service provider can get subpoenaed to reveal encryption key [Gre14]

Outsourcing Data to the Cloud



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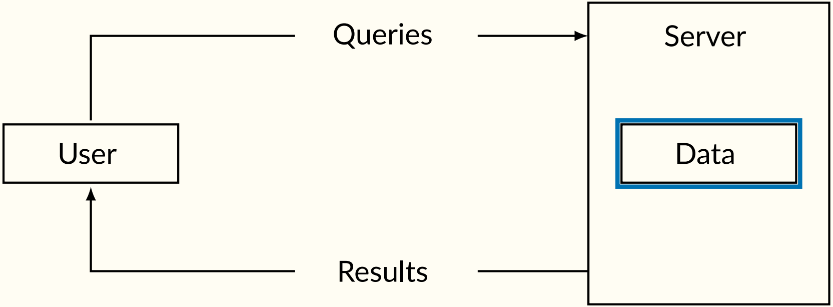

Snapshot attack

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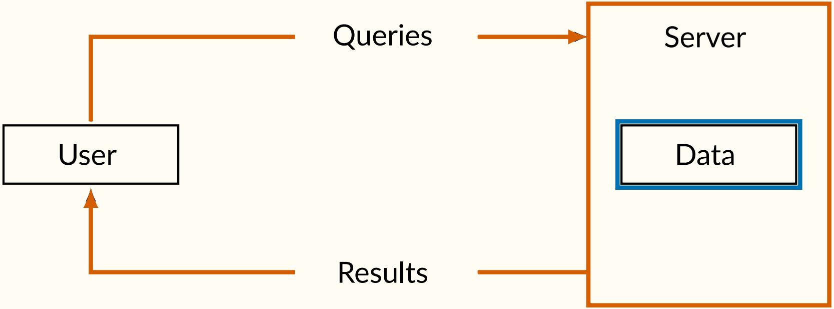

Persistent attack

Snapshot attack

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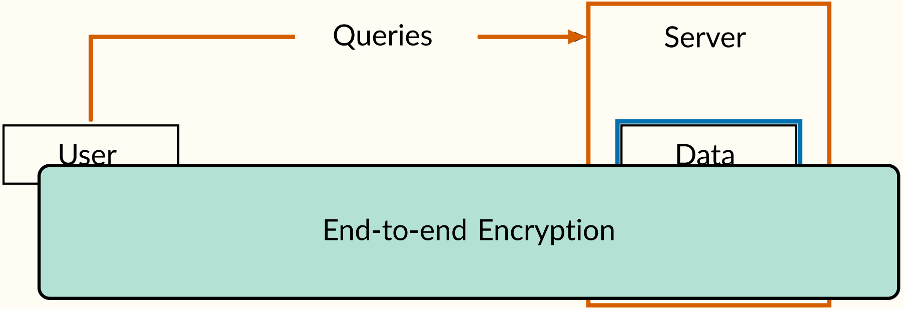

Persistent attack

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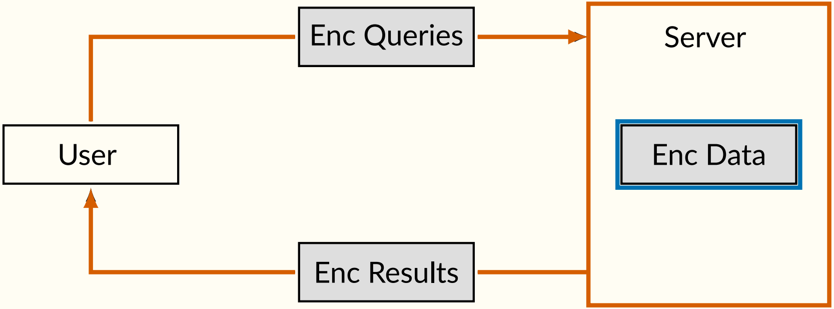

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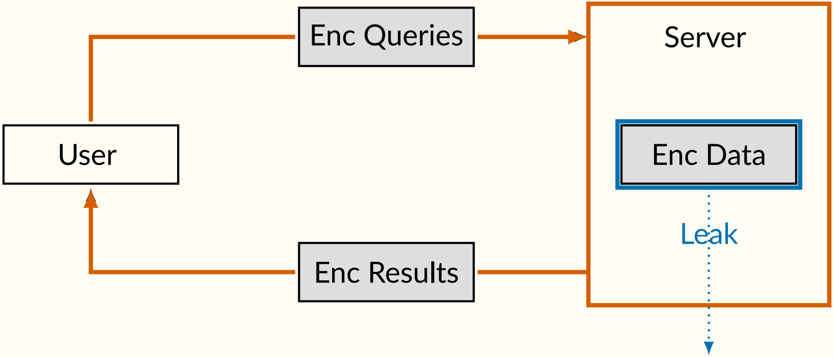


Enc Queries

Server

User

Enc Data

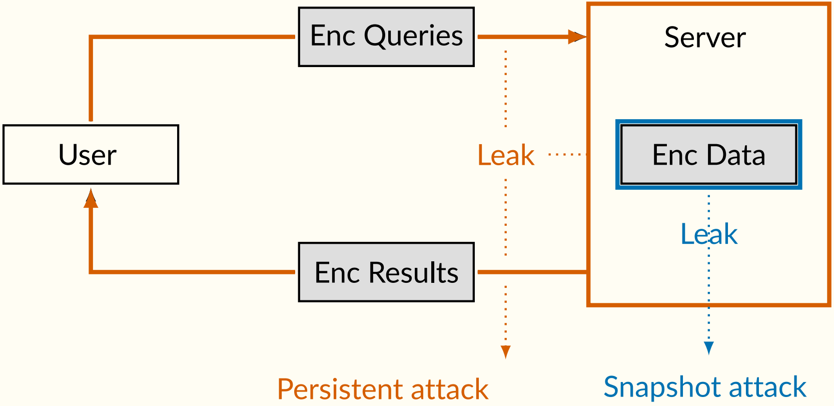
Leak

Enc Results

Persistent attack

Snapshot attack

Outsourcing Data to the Cloud



Outsourcing Data to the Cloud

New Schemes and System

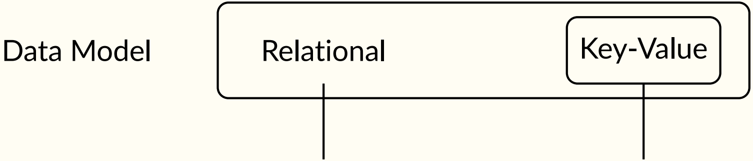
- Efficiency
- Small Leakage
- Expressivity: SQL / Relational Model
- Query Optimization
- Legacy Compatibility

Background

Background

Data Model	Relational	Key-Value

Background



Data Model

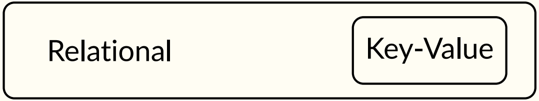
Relational

Key-Value

- SQL: Turing Complete
- Linear in DB length

- Boolean Algebra
- Linear in Result length

Background



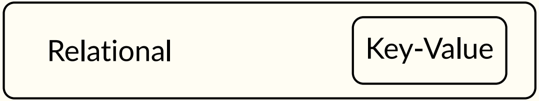
Relational

Key-Value

Trusted HW

- SCPA: TrustedDB [BS11]
- FPGA: Cipherbase [ABE+13]
- SGX: StealthDB [GVG19], Bunker [AKM19]
- Memory / Workload Limit
- Intrusive SW changes

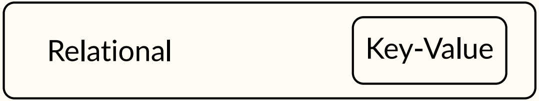
Background



Generic

- FHE [Gen09]: hides result length
- ORAM [GO96]: hides access pattern
- Smallest leakage but inefficient

Background

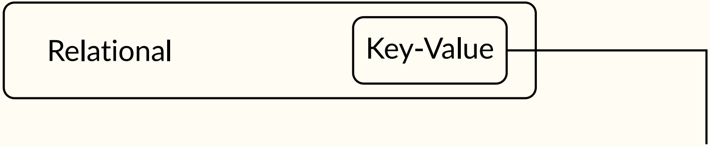


Relational

Key-Value

Trade leakage for higher efficiency

Background



Relational

Key-Value

SSE [SWP00,CGKO06]

- Optimal in KV
- Small Leakage
- Systems
  - BlindSeer [PKV+14]
  - ESPADA [CJJ+14]

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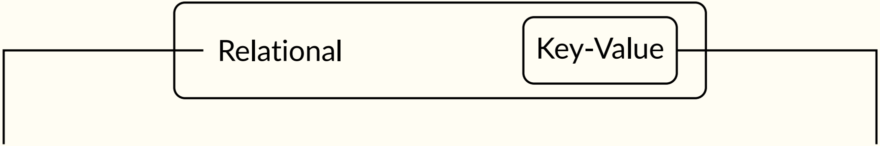

Relational

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PPE [BCLO09]

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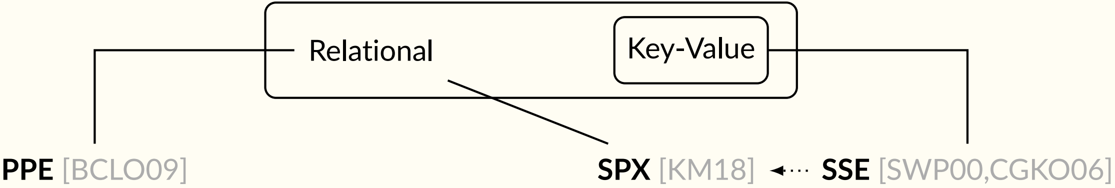

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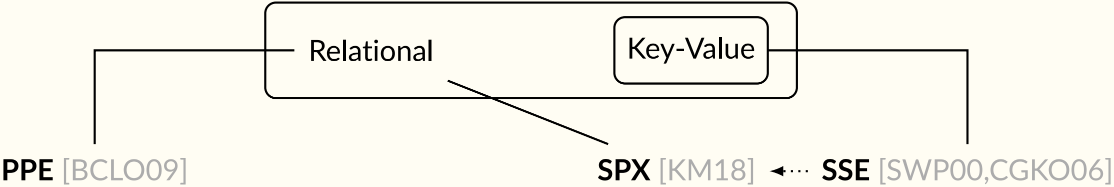
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SPX [KM18] ◂⋯ **SSE** [SWP00,CGKO06]

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TPC-H showed

- 1000× query overhead
- 252× space overhead

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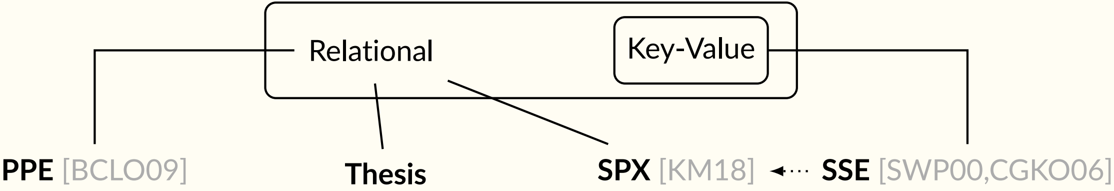

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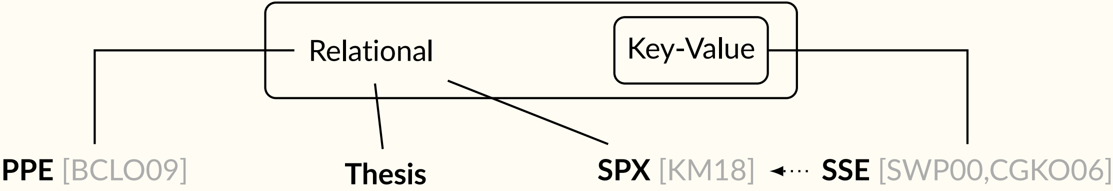

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Thesis

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4× overhead

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Tables and Operators: Select σ, Project π, Join $\bowtie$ (Conjunctive Queries).

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Customer

Name	Pay	Nation
Alice	VISA	US
Bob	PayPal	US
Bob	VISA	MEX

Supplier

Name	Nation
Intel	US
IBM	US
Intel	MEX
Arca	MEX

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Name	Nation
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Select Customer.Name, Supplier.Name
From Customer **Join** Supplier **On** Nation
Where Pay = VISA **And** Nation = US

Security

Security of Encrypted Relational Database

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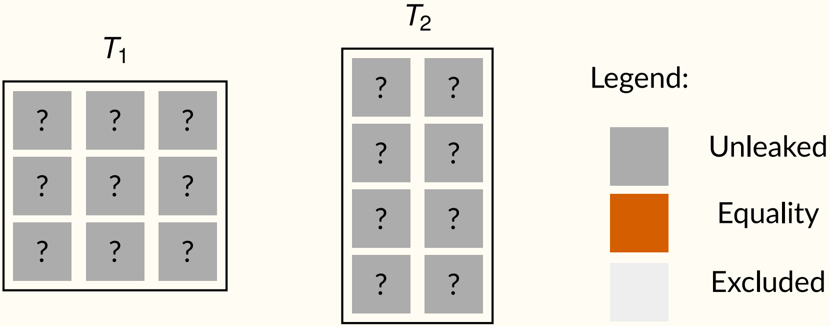

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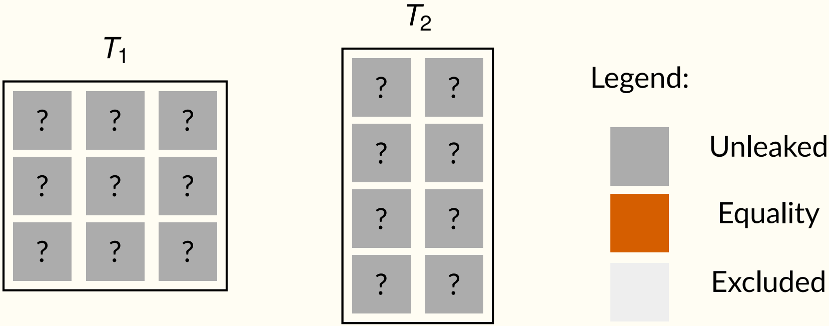

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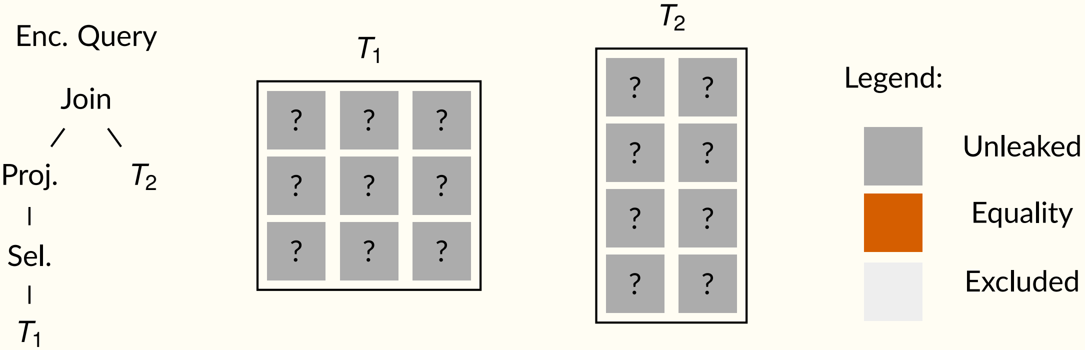

T_1

?	?	?
?	?	?
?	?	?

T_2

?	?
?	?
?	?
?	?

Legend:

▨	Unleaked
🟧	Equality
□	Excluded

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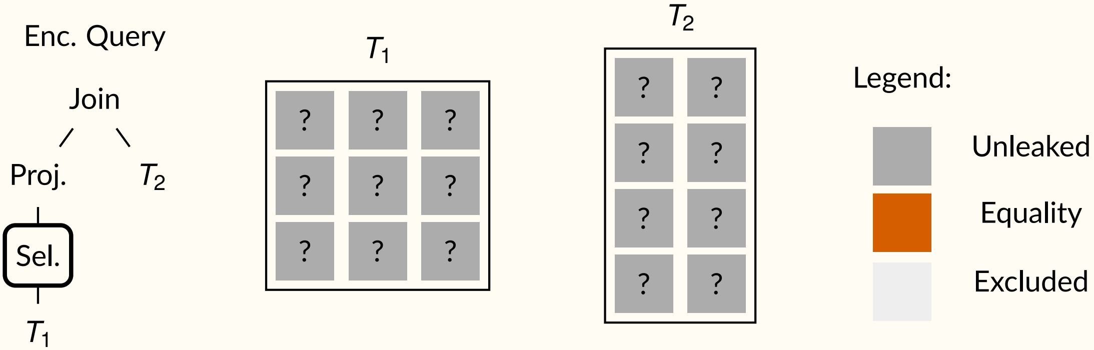

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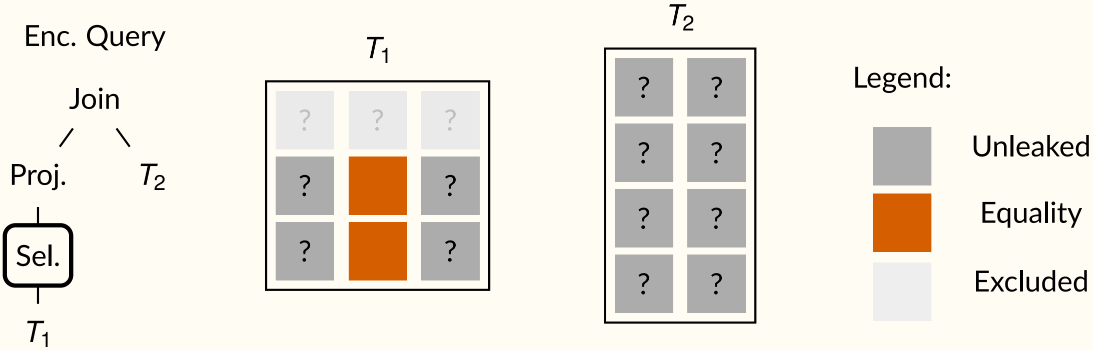

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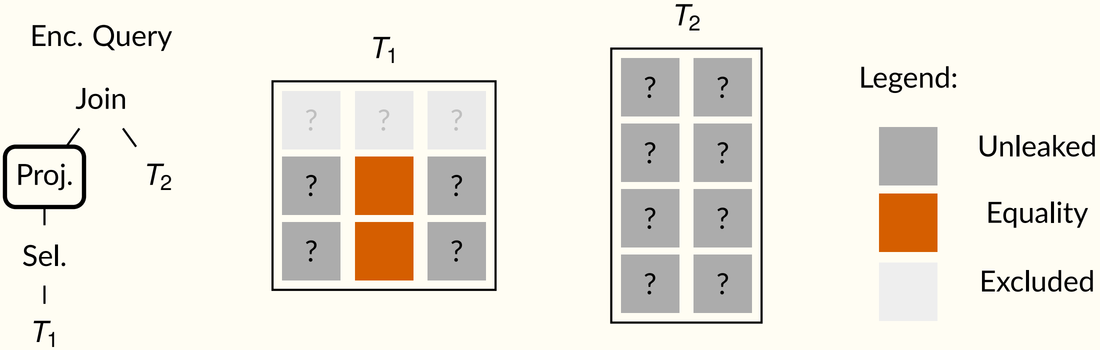

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?	?	?
?	🟧	?
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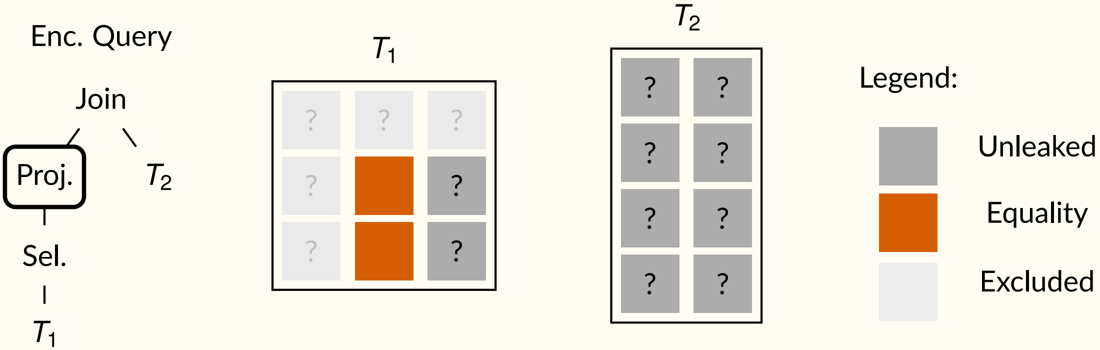

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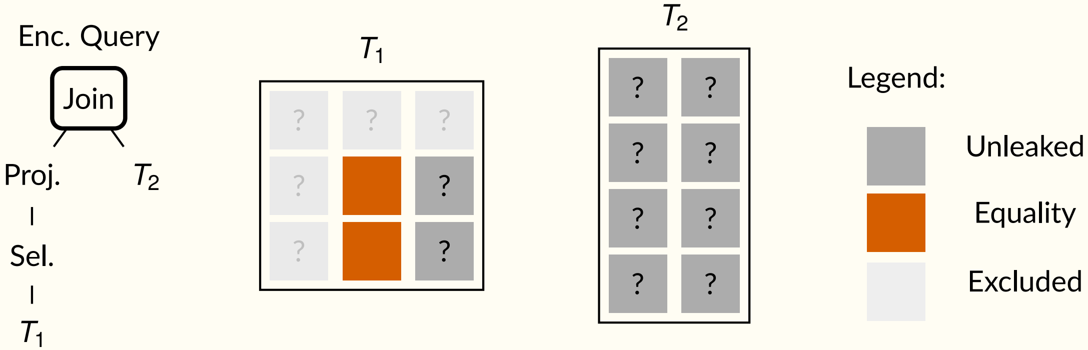

Enc. Query

Join

Proj.

T_2

Sel.

T_1

T_1

?	?	?
?	🟧	?
?	🟧	?

T_2

?	?
?	?
?	?
?	?

Legend:

⬛ Unleaked

🟧 Equality

⬜ Excluded

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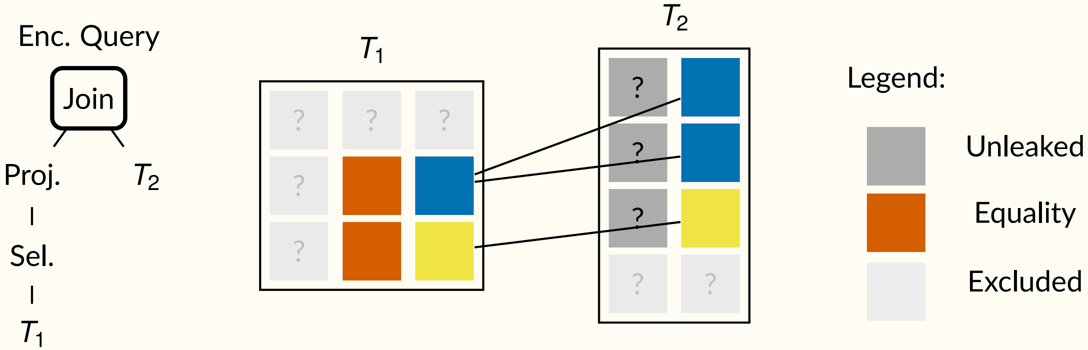

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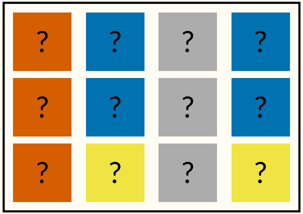

🟧 ?	🟦 ?	⬜ ?	🟦 ?
🟧 ?	🟦 ?	⬜ ?	🟦 ?
🟧 ?	🟨 ?	⬜ ?	🟨 ?

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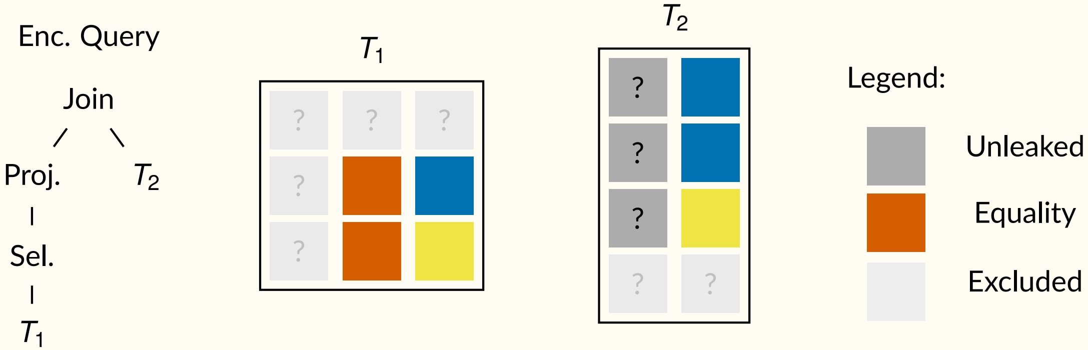

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Existing Approaches

PPE-based schemes[1]

- Deterministic Encryption [BBO07]: ciphertexts reveal equality pattern
- Order-preserving Encryption [AKSX04]: ciphertexts reveal ordering pattern

[1] Quantization [HILM02], CryptDB [PRZB11], Monomi [TKMZ13]

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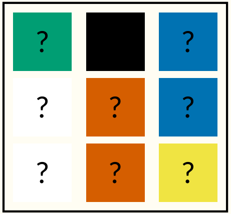

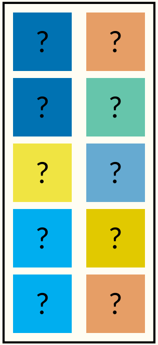

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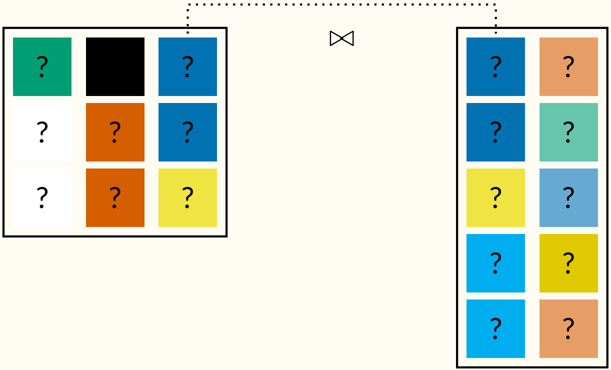

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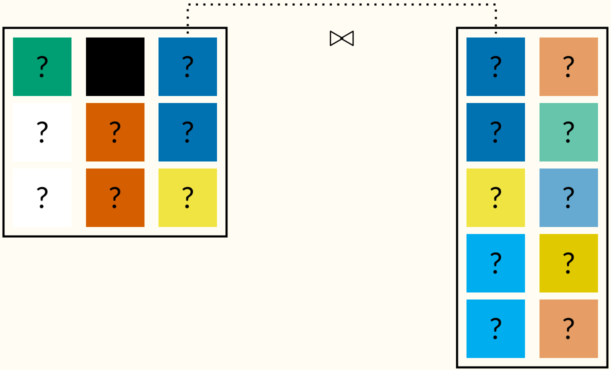

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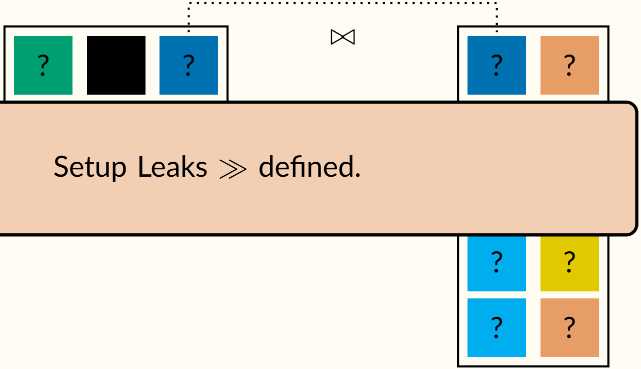

Setup Leaks $\gg$ defined.

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Structured Encryption (STE) [CK10]

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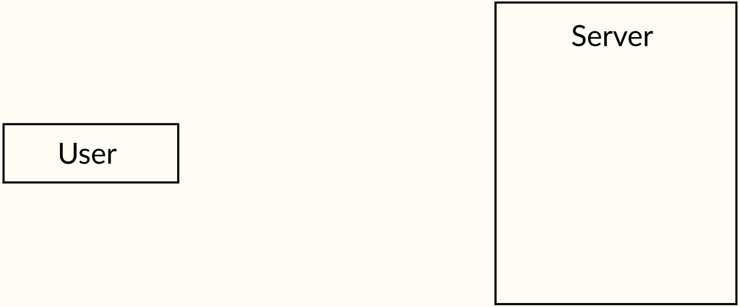

User

Server

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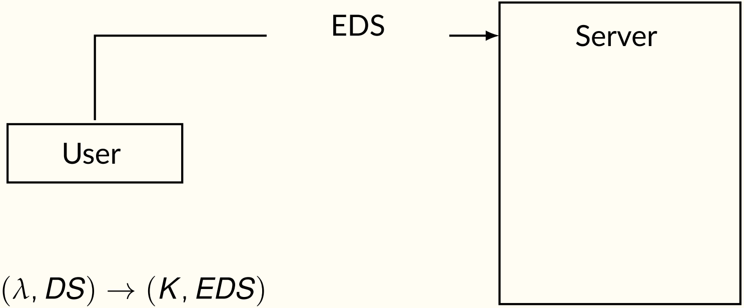

$Setup(\lambda, DS) \rightarrow (K, EDS)$

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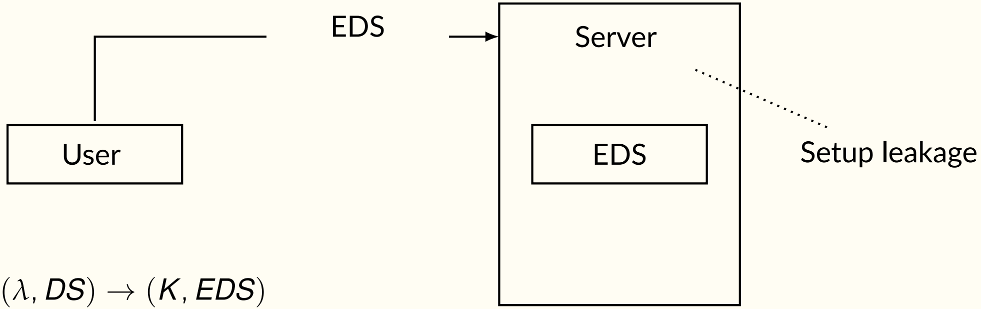

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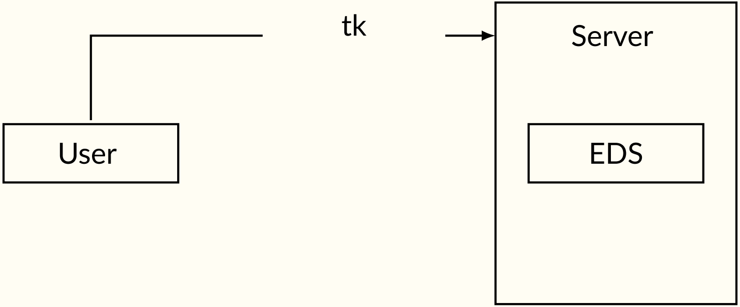

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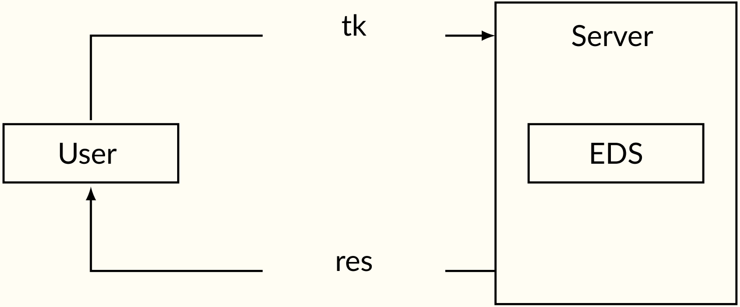

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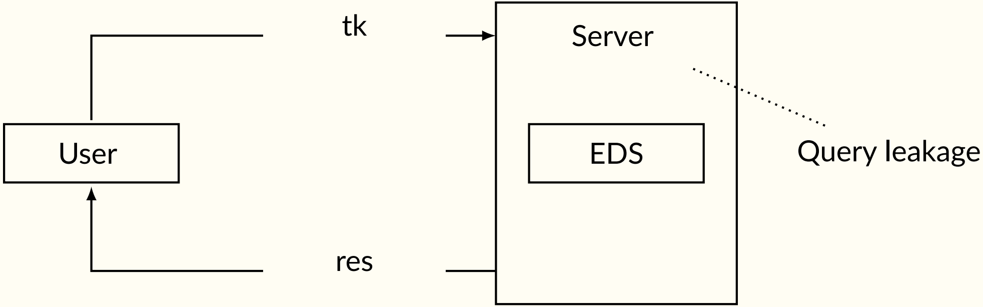

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Encrypted Multimaps[2]

- Multimap associates a label with a tuple of values.

[2] [CGKO06],[CK10],[KPR12],[KP13],[CJJ+14],[Bost16],[BMO17],[AKM19]

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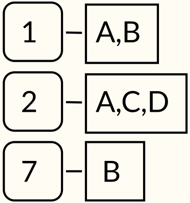
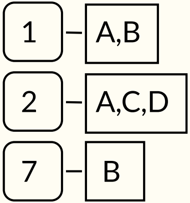


1	A,B
2	A,C,D
7	B

[2] [CGKO06],[CK10],[KPR12],[KP13],[CJJ+14],[Bost16],[BMO17],[AKM19]

Encrypted Multimaps[2]

- Multimap associates a label with a tuple of values.
-
    - $Get(2)$ returns (A, C, D).



1 – A,B

2 – A,C,D

7 – B

[2] [CGKO06],[CK10],[KPR12],[KP13],[CJJ+14],[Bost16],[BMO17],[AKM19]

Encrypted Multimaps[2]

- Multimap associates a label with a tuple of values.
-
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- STE schemes for multimap
  - $\mathit{Setup}(\lambda, \mathit{MM}) \rightarrow (K, \mathit{EMM})$
  - $\mathit{Token}(K, 2) \rightarrow \mathit{tk}$
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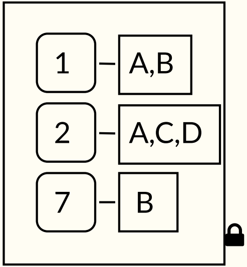

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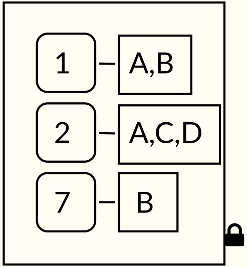

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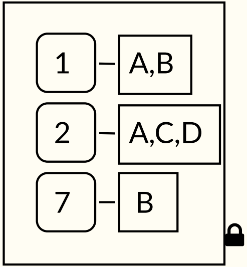
- E.g. Zero-leakage constructions[KMO18,KM19].



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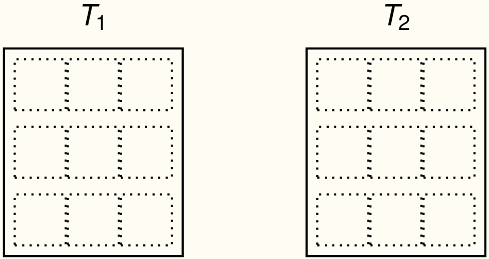
Encrypted Multimap-based Construction, SPX [KM18]

Represent tables and operators as multimaps. Example: Join



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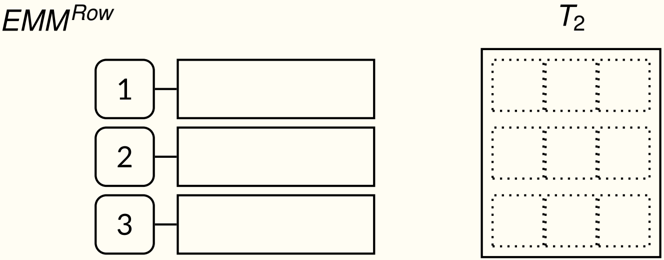

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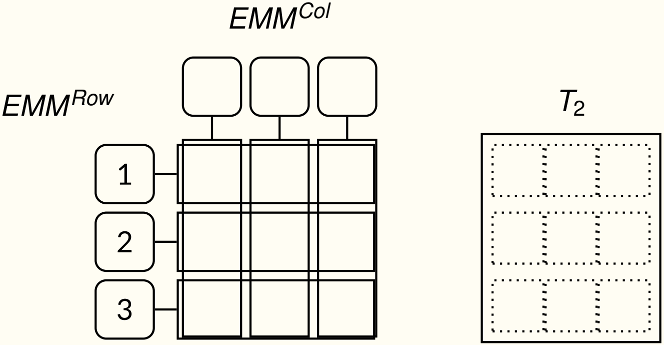

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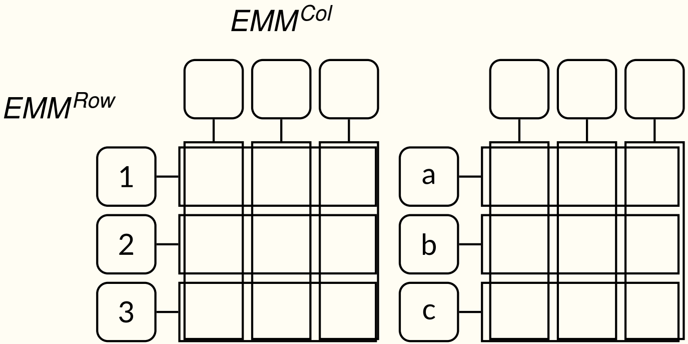

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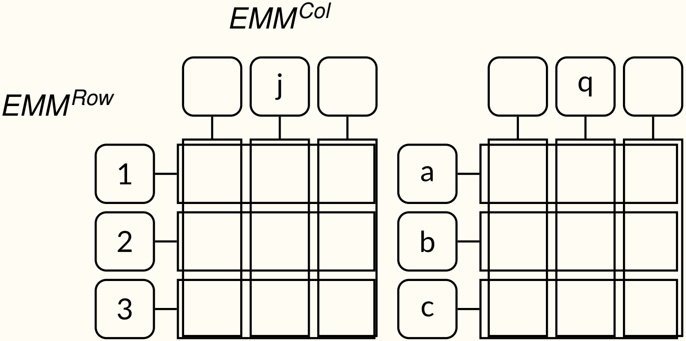

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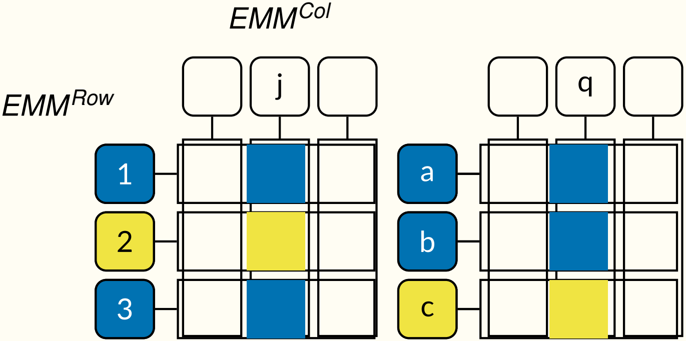

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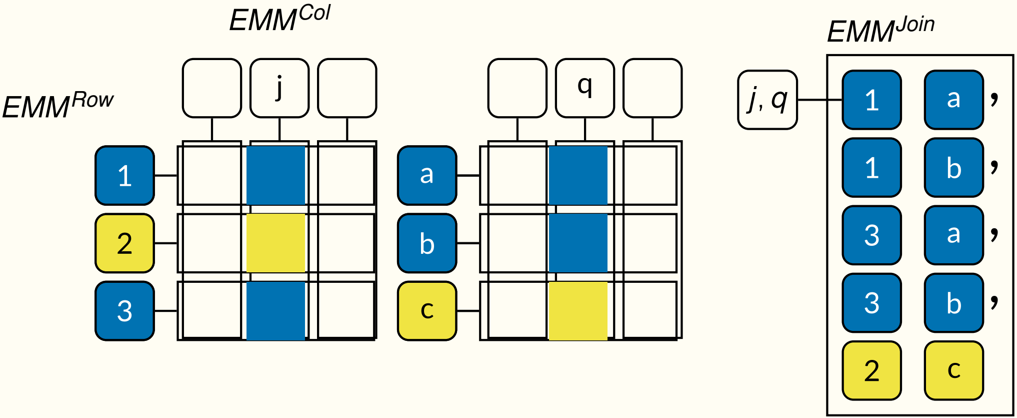

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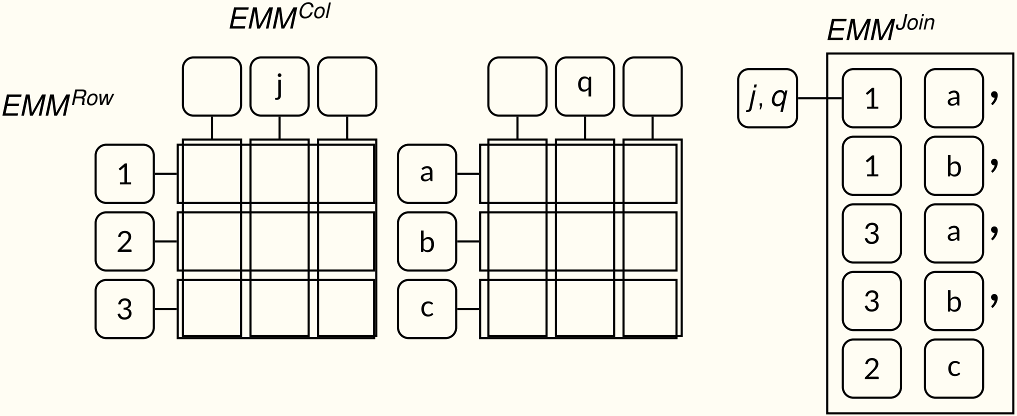

Encrypted as EMMs

Encrypted Multimap-based Construction, SPX [KM18]

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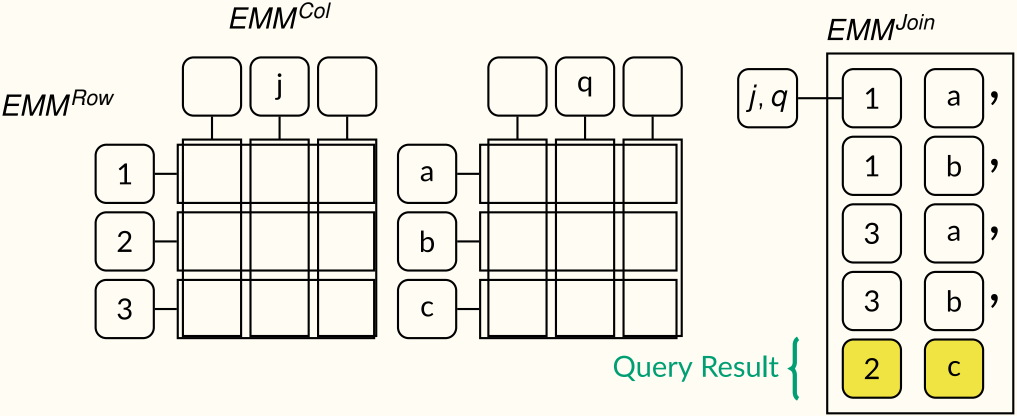

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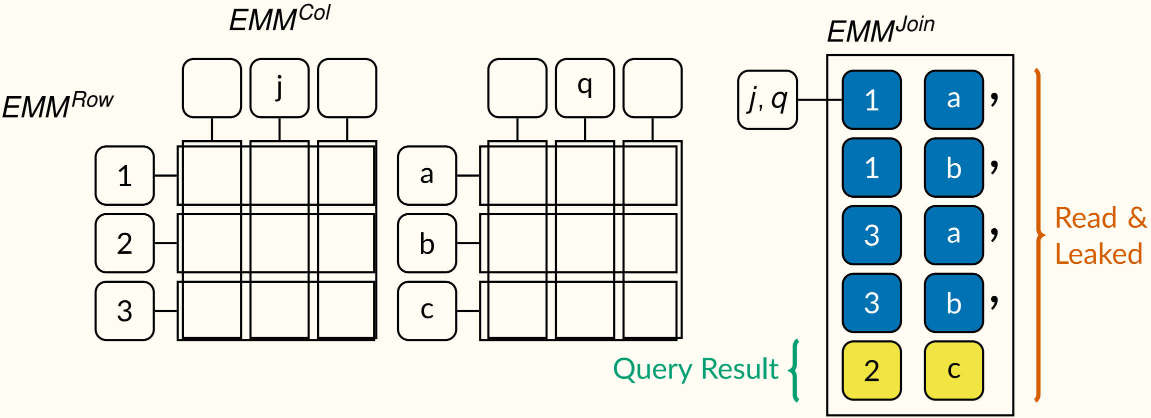

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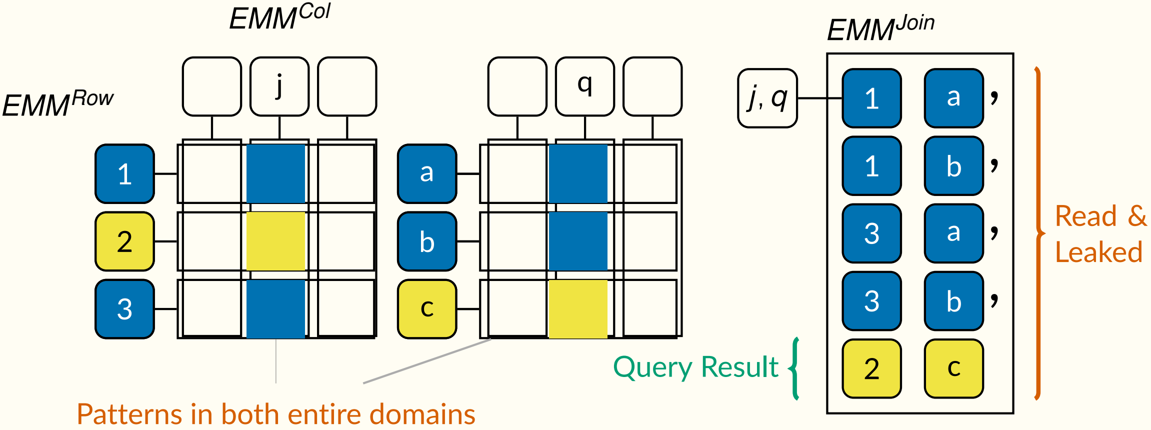

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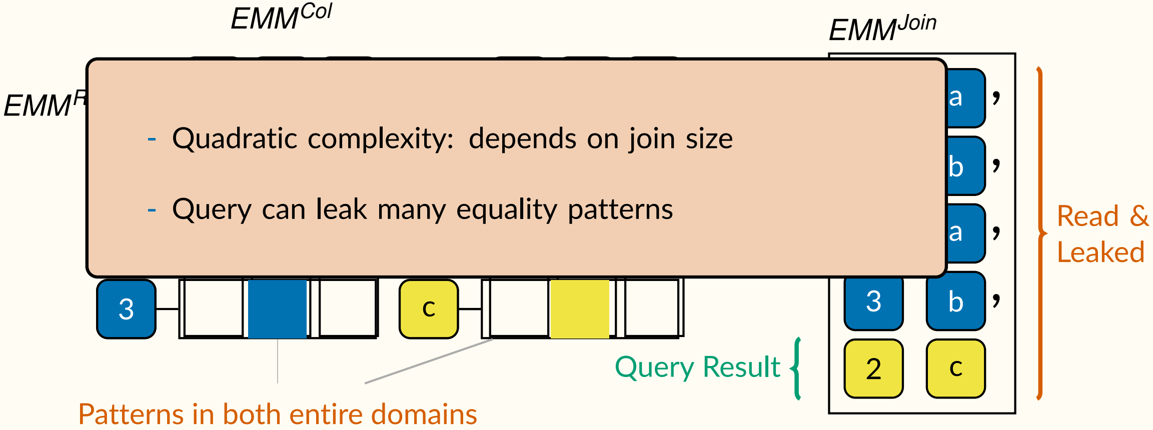

- Quadratic complexity: depends on join size
- Query can leak many equality patterns

Thesis

Outline[3]

- OPX: encrypted query optimization, quadratic
- PKFK: (1) optimal scheme in relational setting; (2) improved locality; (3) reduced leakage
- KafeDB: legacy compatible encrypted SQL database

[3] Joint work with Tarik Moataz at Aroki Systems, Seny Kamara and Stan Zdonik at Brown University. Works include OPX [KMZZ20], KafeDB [ZKMZ21], PKFK [In submission].

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Overview of PKFK Scheme

- Optimal encrypted Join: matches plaintext Join in complexity [BTAO15]

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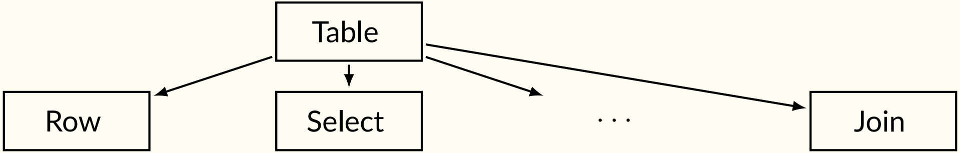
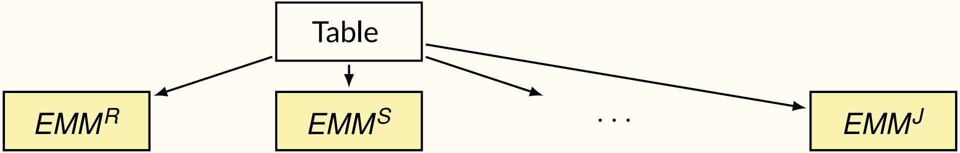
Overview of PKFK Scheme

- Optimal encrypted Join: matches plaintext Join in complexity [BTAO15]
- Improved leakage
- General techniques for STE:
- (1) Emulation: make STE legacy friendly
- (2) Colocation: increase STE locality

Overview of PKFK Scheme



Overview of PKFK Scheme



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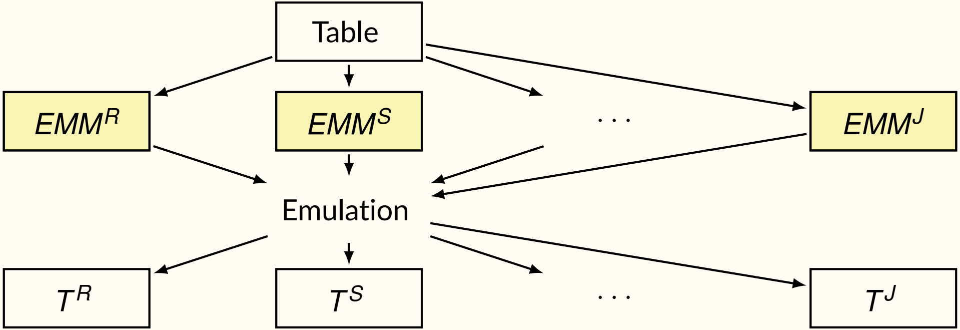

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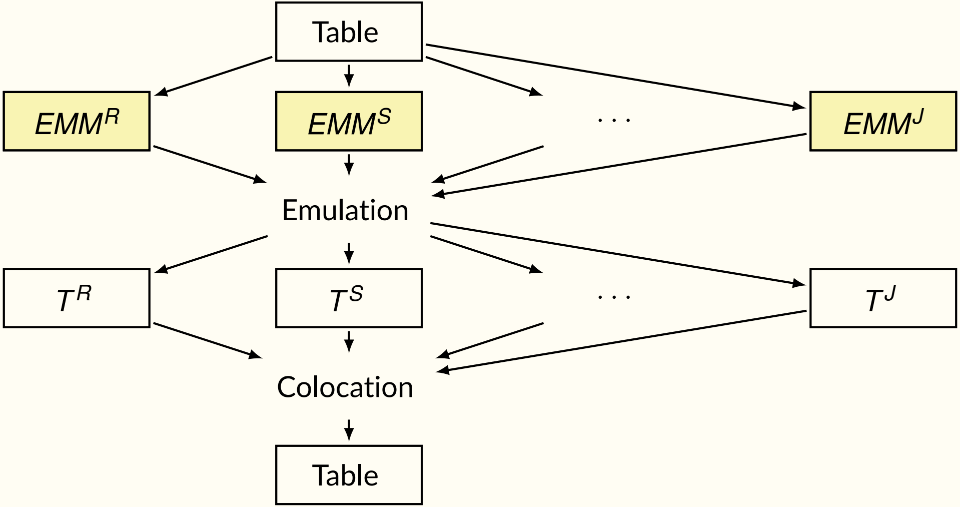


Table

EMM^R

EMM^S

. . .

EMM^J

Emulation

T^R

T^S

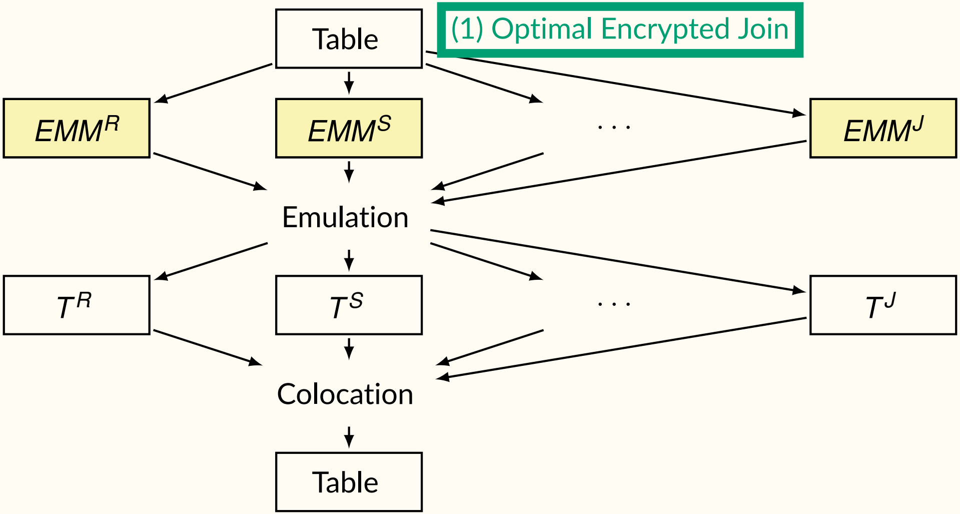
. . .

T^J

Colocation

Table

Overview of PKFK Scheme



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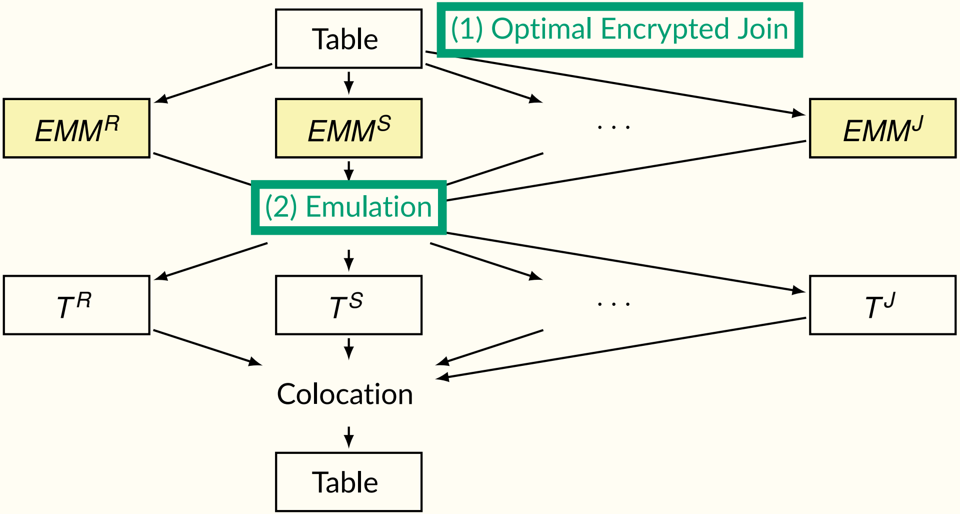

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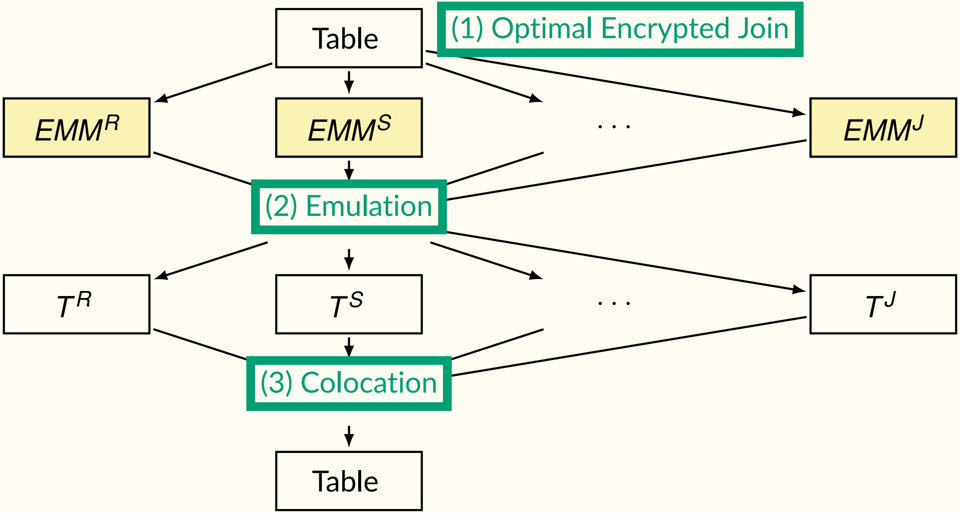


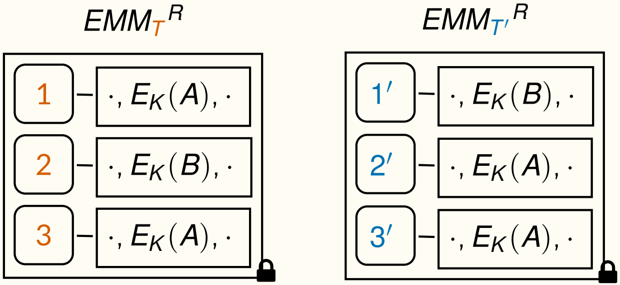
Optimal Encrypted Join

Optimal Encrypted Join

T		Col j	
1		A	
2		B	
3		A	

T'		Col q	
$1'$		B	
$2'$		A	
$3'$		A	

Optimal Encrypted Join



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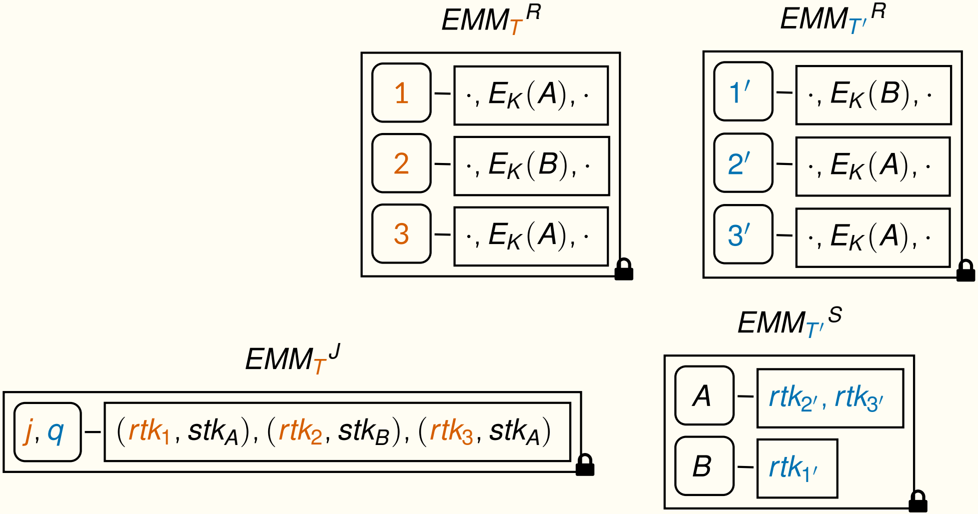


$EMM_T{}^R$

1	$\cdot, E_K(A), \cdot$
2	$\cdot, E_K(B), \cdot$
3	$\cdot, E_K(A), \cdot$

$EMM_{T'}{}^R$

$1'$	$\cdot, E_K(B), \cdot$
$2'$	$\cdot, E_K(A), \cdot$
$3'$	$\cdot, E_K(A), \cdot$

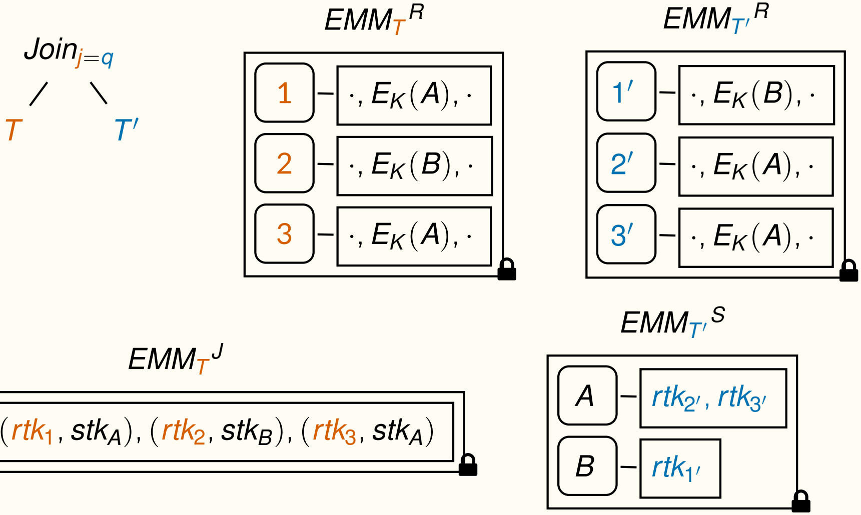
$EMM_T{}^J$

j, q	$(rtk_1, stk_A), (rtk_2, stk_B), (rtk_3, stk_A)$

$EMM_{T'}{}^S$

A	$rtk_{2'}, rtk_{3'}$
B	$rtk_{1'}$

Optimal Encrypted Join



$\mathit{Join}_{j=q}$

T $\quad$ T'

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2	$\cdot, E_K(B), \cdot$
3	$\cdot, E_K(A), \cdot$

$EMM_{T'}{}^R$

$1'$	$\cdot, E_K(B), \cdot$
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j, q	$(rtk_1, stk_A), (rtk_2, stk_B), (rtk_3, stk_A)$

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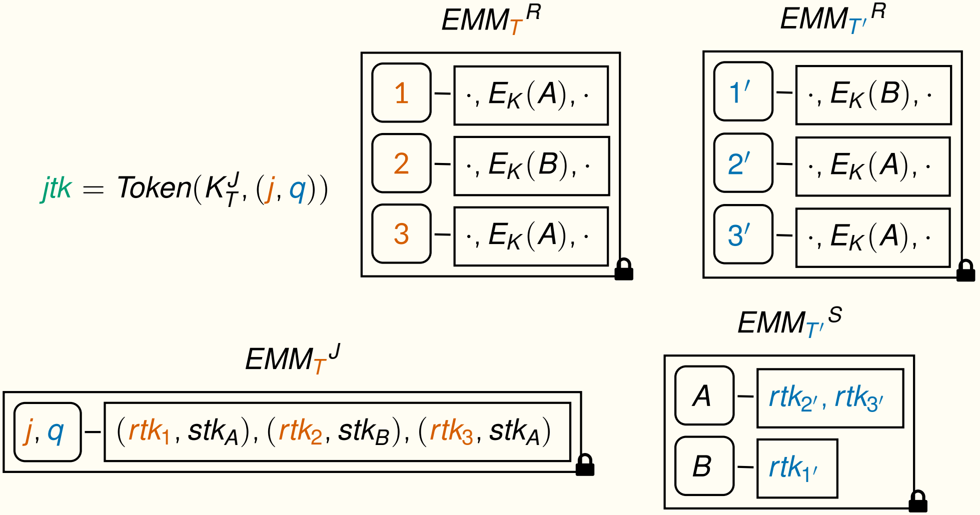

$jtk = Token(K_T^J, (j, q))$

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$EMM_{T'}{}^R$

$1'$ — $\cdot, E_K(B), \cdot$

$2'$ — $\cdot, E_K(A), \cdot$

$3'$ — $\cdot, E_K(A), \cdot$

$EMM_T{}^J$

j, q — $(rtk_1, stk_A), (rtk_2, stk_B), (rtk_3, stk_A)$

$EMM_{T'}{}^S$

A — $rtk_{2'}, rtk_{3'}$

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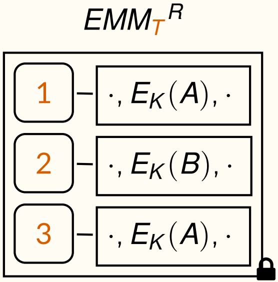
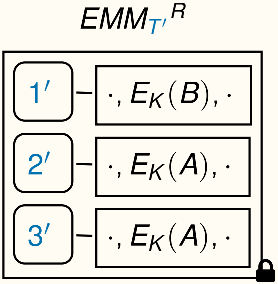
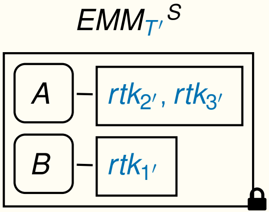
Optimal Encrypted Join

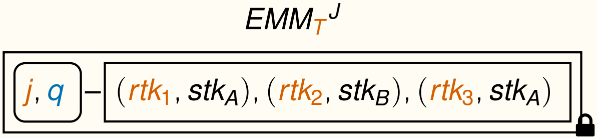
$Query(EDB, jtk)$

```
For $(rtk, stk)$ in $Query(EMM_T{}^J, jtk)$
    $r \leftarrow Query(EMM_T{}^R, rtk)$
    For $rtk'$ in $Query(EMM_{T'}{}^S, stk)$
        $R' \leftarrow R' \cup Query(EMM_{T'}{}^R, rtk')$
    Output $(r, R')$
```









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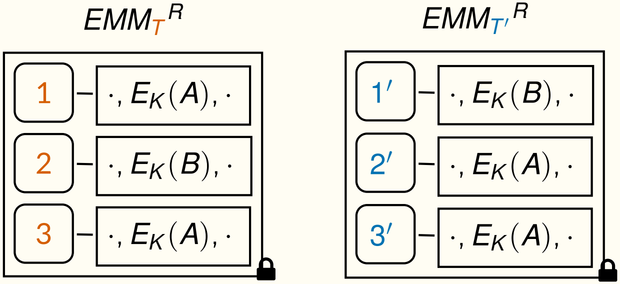

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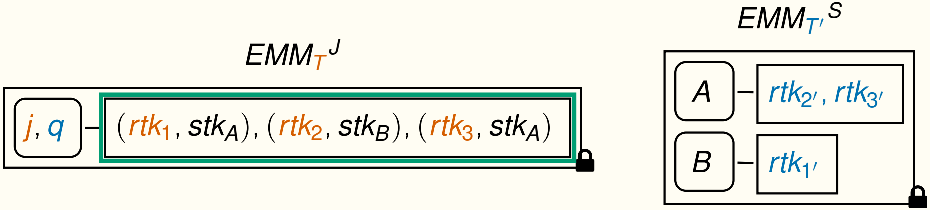

$EMM_T{}^J$

j, q	$(rtk_1, stk_A), (rtk_2, stk_B), (rtk_3, stk_A)$

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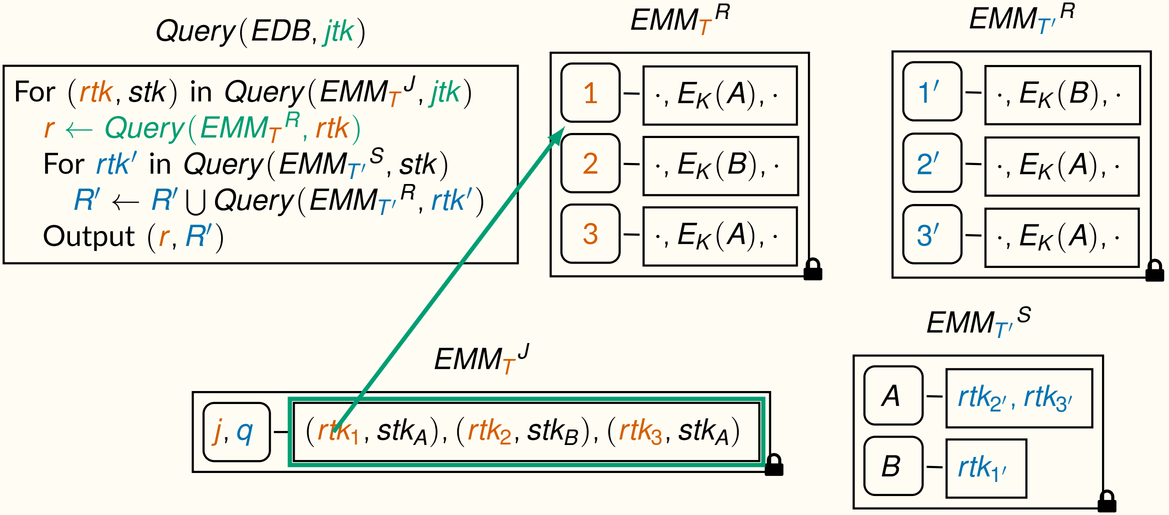
Optimal Encrypted Join



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Optimal Encrypted Join

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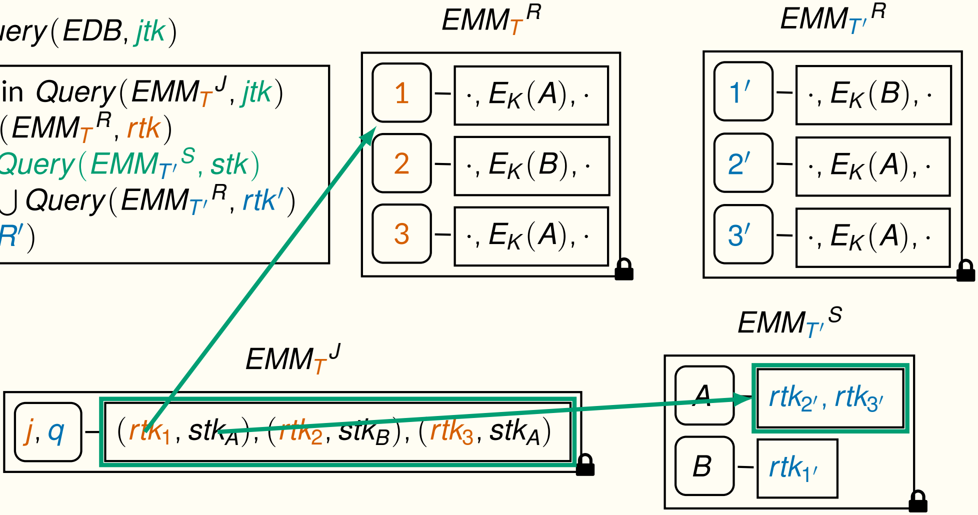
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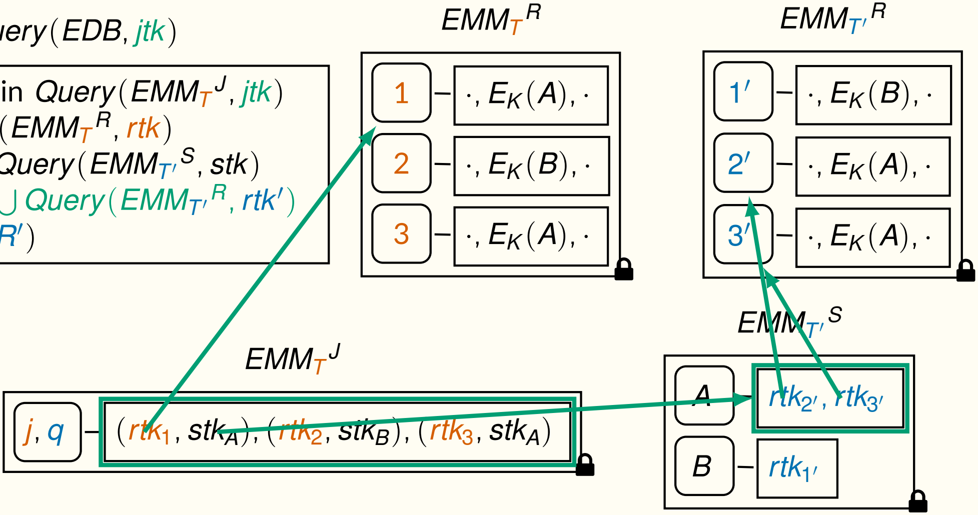

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$2'$ — $\cdot, E_K(A), \cdot$

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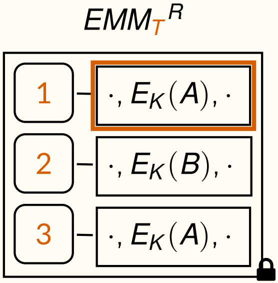
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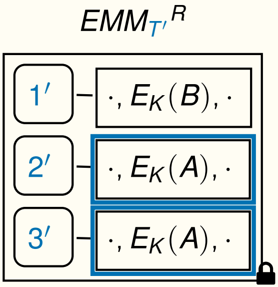
$EMM_{T'}{}^R$
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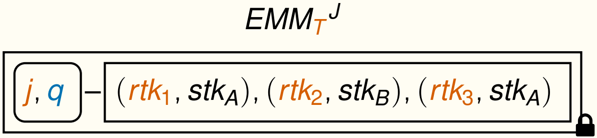
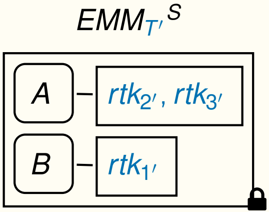
$2'$ — $\cdot, E_K(A), \cdot$
$3'$ — $\cdot, E_K(A), \cdot$

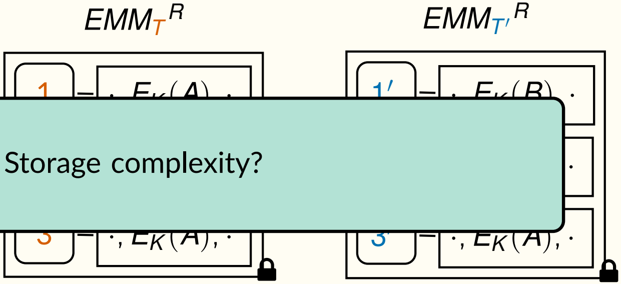




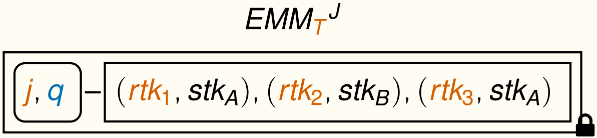
Optimal Encrypted Join

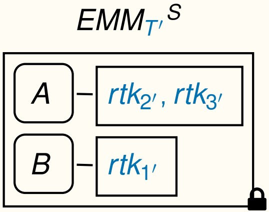
$Query(EDB, jtk)$

```
For $(rtk, stk)$ in $Query(EMM_T{}^J, jtk)$
    $r \leftarrow Query(EM$
    For $rtk'$ in $Quer$
        $R' \leftarrow R' \cup Qu$
    Output $(r, R')$
```



Storage complexity?



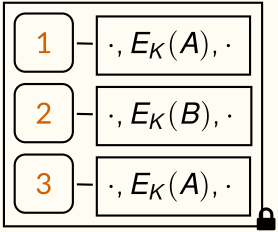


Optimal Encrypted Join

$Query(EDB, jtk)$

```
For $(rtk, stk)$ in $Query(EMM_T{}^J, jtk)$
    $r \leftarrow Query(EMM_T{}^R, rtk)$
    For $rtk'$ in $Query(EMM_{T'}{}^S, stk)$
        $R' \leftarrow R' \cup Query(EMM_{T'}{}^R, rtk')$
    Output $(r, R')$
```

$EMM_T{}^R$

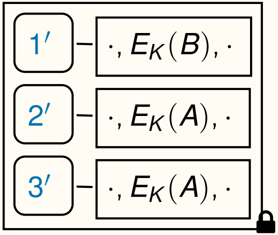


1 – $\cdot, E_K(A), \cdot$

2 – $\cdot, E_K(B), \cdot$

3 – $\cdot, E_K(A), \cdot$

$EMM_{T'}{}^R$

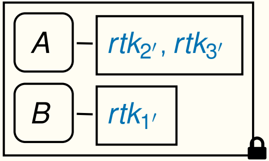


$1'$ – $\cdot, E_K(B), \cdot$

$2'$ – $\cdot, E_K(A), \cdot$

$3'$ – $\cdot, E_K(A), \cdot$

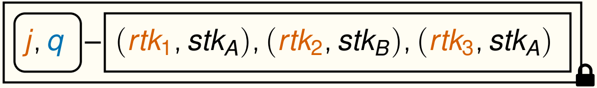
$EMM_{T'}{}^S$



A – $rtk_{2'}, rtk_{3'}$

B – $rtk_{1'}$

$EMM_T{}^J$

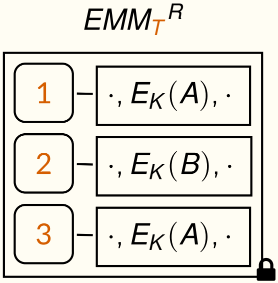


j, q – $(rtk_1, stk_A), (rtk_2, stk_B), (rtk_3, stk_A)$

Optimal Encrypted Join

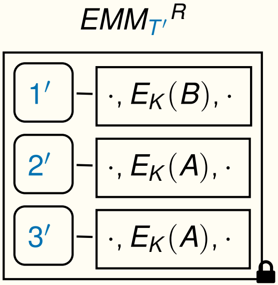
$Query(EDB, jtk)$

```
For $(rtk, stk)$ in $Query(EMM_T{}^J, jtk)$
    $r \leftarrow Query(EMM_T{}^R, rtk)$
    For $rtk'$ in $Query(EMM_{T'}{}^S, stk)$
        $R' \leftarrow R' \cup Query(EMM_{T'}{}^R, rtk')$
    Output $(r, R')$
```



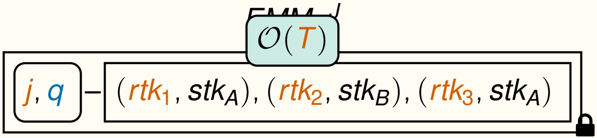
$EMM_T{}^R$

1	$\cdot, E_K(A), \cdot$
2	$\cdot, E_K(B), \cdot$
3	$\cdot, E_K(A), \cdot$



$EMM_{T'}{}^R$

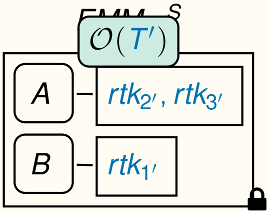
$1'$	$\cdot, E_K(B), \cdot$
$2'$	$\cdot, E_K(A), \cdot$
$3'$	$\cdot, E_K(A), \cdot$



EMM^J

$\mathcal{O}(T)$

j, q	$(rtk_1, stk_A), (rtk_2, stk_B), (rtk_3, stk_A)$



EMM^S

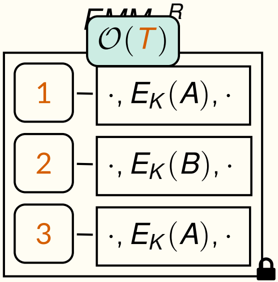
$\mathcal{O}(T')$

A	$rtk_{2'}, rtk_{3'}$
B	$rtk_{1'}$

Optimal Encrypted Join

$Query(EDB, jtk)$

```
For $(rtk, stk)$ in $Query(EMM_T{}^J, jtk)$
    $r \leftarrow Query(EMM_T{}^R, rtk)$
    For $rtk'$ in $Query(EMM_{T'}{}^S, stk)$
        $R' \leftarrow R' \cup Query(EMM_{T'}{}^R, rtk')$
    Output $(r, R')$
```



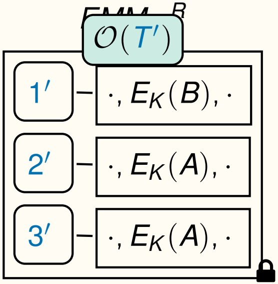
$EMM_T{}^R$

$\mathcal{O}(T)$

1 — $\cdot, E_K(A), \cdot$

2 — $\cdot, E_K(B), \cdot$

3 — $\cdot, E_K(A), \cdot$



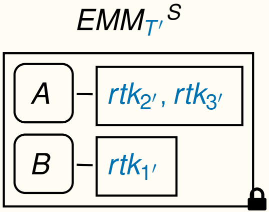
$EMM_{T'}{}^R$

$\mathcal{O}(T')$

$1'$ — $\cdot, E_K(B), \cdot$

$2'$ — $\cdot, E_K(A), \cdot$

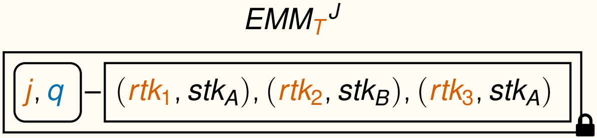
$3'$ — $\cdot, E_K(A), \cdot$



$EMM_{T'}{}^S$

A — $rtk_{2'}, rtk_{3'}$

B — $rtk_{1'}$



$EMM_T{}^J$

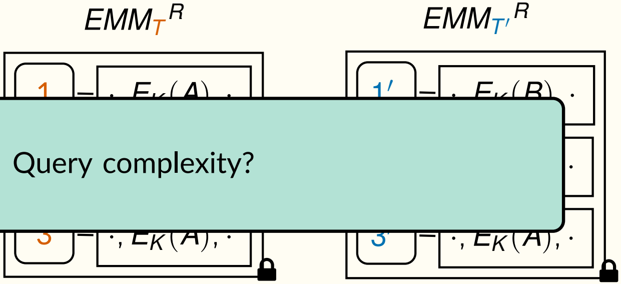
j, q — $(rtk_1, stk_A), (rtk_2, stk_B), (rtk_3, stk_A)$

Optimal Encrypted Join

$Query(EDB, jtk)$

```
For $(rtk, stk)$ in $Query(EMM_T{}^J, jtk)$
    $r \leftarrow Query(EM$
    For $rtk'$ in $Quer$
        $R' \leftarrow R' \bigcup Qu$
    Output $(r, R')$
```

Query complexity?



$EMM_T{}^R$

1 — $\cdot, E_K(A), \cdot$

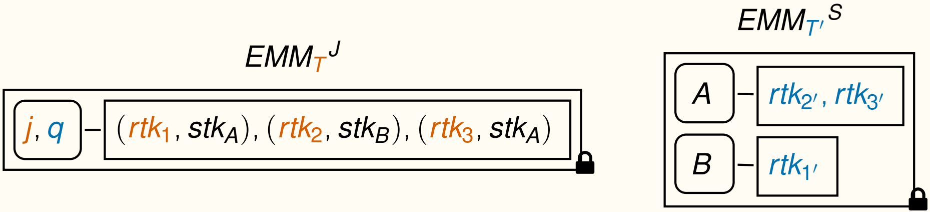
3 — $\cdot, E_K(A), \cdot$

$EMM_{T'}{}^R$

$1'$ — $\cdot, E_K(B), \cdot$

$\cdot$

$3'$ — $\cdot, E_K(A), \cdot$



$EMM_T{}^J$

j, q — $(rtk_1, stk_A), (rtk_2, stk_B), (rtk_3, stk_A)$

$EMM_{T'}{}^S$

A — $rtk_{2'}, rtk_{3'}$

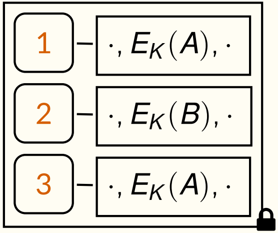
B — $rtk_{1'}$

Optimal Encrypted Join

$\mathit{Query}(\mathit{EDB}, \mathit{jtk})$

```
For $(rtk, stk)$ in $Query(EMM_T{}^J, jtk)$
    $r \leftarrow Query(EMM_T{}^R, rtk)$
    For $rtk'$ in $Query(EMM_{T'}{}^S, stk)$
        $R' \leftarrow R' \cup Query(EMM_{T'}{}^R, rtk')$
    Output $(r, R')$
```

$EMM_T{}^R$

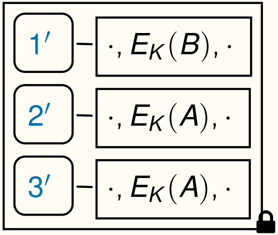


1 — $\cdot, E_K(A), \cdot$

2 — $\cdot, E_K(B), \cdot$

3 — $\cdot, E_K(A), \cdot$

$EMM_{T'}{}^R$

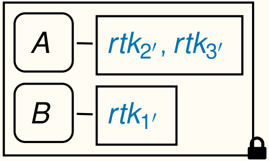


$1'$ — $\cdot, E_K(B), \cdot$

$2'$ — $\cdot, E_K(A), \cdot$

$3'$ — $\cdot, E_K(A), \cdot$

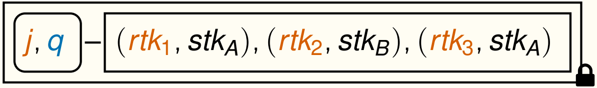
$EMM_{T'}{}^S$



A — $rtk_{2'}, rtk_{3'}$

B — $rtk_{1'}$

$EMM_T{}^J$



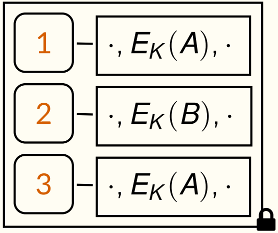
j, q — $(rtk_1, stk_A), (rtk_2, stk_B), (rtk_3, stk_A)$

Optimal Encrypted Join

$Query(EDB, jtk)$

```
For $(rtk, stk)$ in $Query(EMM_T{}^J, jtk)$
    $r \leftarrow Query(EMM_T{}^R, rtk)$
    For $rtk'$ in $Query(EMM_{T'}{}^S, stk)$
        $R' \leftarrow R' \cup Query(EMM_{T'}{}^R, rtk')$
    Output $(r, R')$
```

$EMM_T{}^R$

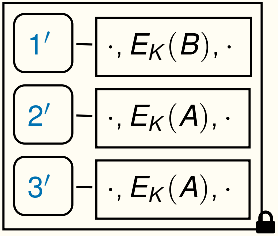


1 — $\cdot, E_K(A), \cdot$

2 — $\cdot, E_K(B), \cdot$

3 — $\cdot, E_K(A), \cdot$

$EMM_{T'}{}^R$

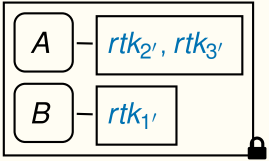


$1'$ — $\cdot, E_K(B), \cdot$

$2'$ — $\cdot, E_K(A), \cdot$

$3'$ — $\cdot, E_K(A), \cdot$

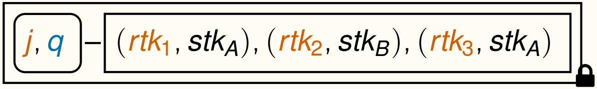
$EMM_{T'}{}^S$



A — $rtk_{2'}, rtk_{3'}$

B — $rtk_{1'}$

$EMM_T{}^J$

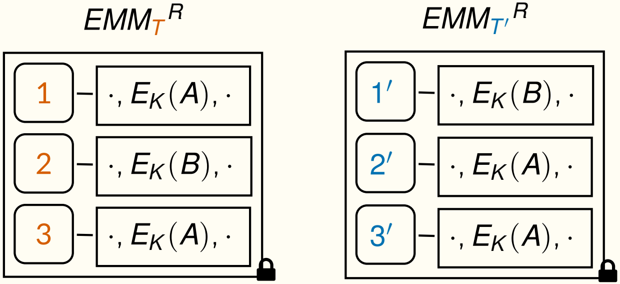


j, q — $(rtk_1, stk_A), (rtk_2, stk_B), (rtk_3, stk_A)$

Optimal Encrypted Join

$Query(EDB, jtk)$ $\mathcal{O}(T)$

```
For $(rtk, stk)$ in $Query(EMM_T{}^J, jtk)$
    $r \leftarrow Query(EMM_T{}^R, rtk)$
    For $rtk'$ in $Query(EMM_{T'}{}^S, stk)$
        $R' \leftarrow R' \cup Query(EMM_{T'}{}^R, rtk')$
    Output $(r, R')$
```

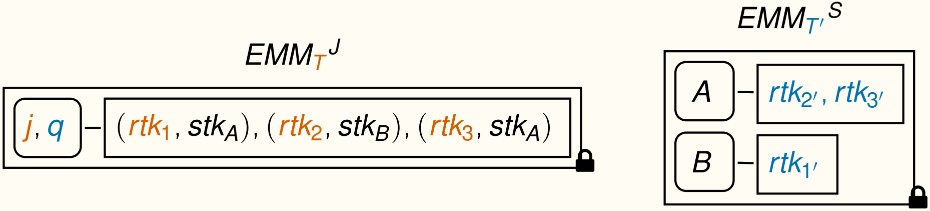


$EMM_T{}^R$

1	$\cdot, E_K(A), \cdot$
2	$\cdot, E_K(B), \cdot$
3	$\cdot, E_K(A), \cdot$

$EMM_{T'}{}^R$

$1'$	$\cdot, E_K(B), \cdot$
$2'$	$\cdot, E_K(A), \cdot$
$3'$	$\cdot, E_K(A), \cdot$



$EMM_T{}^J$

j, q	$(rtk_1, stk_A), (rtk_2, stk_B), (rtk_3, stk_A)$

$EMM_{T'}{}^S$

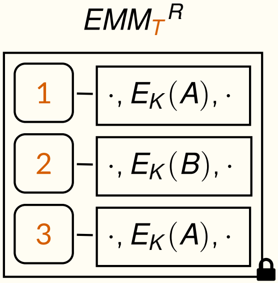
A	$rtk_{2'}, rtk_{3'}$
B	$rtk_{1'}$

Optimal Encrypted Join

$Query(EDB, jtk)$

$\mathcal{O}(T)$

```
For $(rtk, stk)$ in $Query({EMM_T}^J, jtk)$
    $r \leftarrow Query({EMM_T}^R, rtk)$
    For $rtk'$ in $Query({EMM_{T'}}^S, stk)$
        $R' \leftarrow R' \bigcup Query({EMM_{T'}}^R, rtk')$
    Output $(r, R')$
```

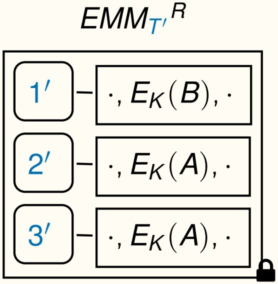


${EMM_T}^R$

1 — $\cdot, E_K(A), \cdot$

2 — $\cdot, E_K(B), \cdot$

3 — $\cdot, E_K(A), \cdot$

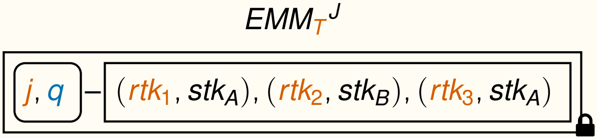


${EMM_{T'}}^R$

$1'$ — $\cdot, E_K(B), \cdot$

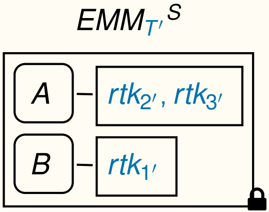
$2'$ — $\cdot, E_K(A), \cdot$

$3'$ — $\cdot, E_K(A), \cdot$



${EMM_T}^J$

j, q — $(rtk_1, stk_A), (rtk_2, stk_B), (rtk_3, stk_A)$



${EMM_{T'}}^S$

A — $rtk_{2'}, rtk_{3'}$

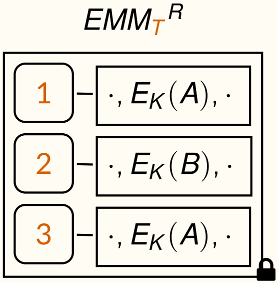
B — $rtk_{1'}$

Optimal Encrypted Join

$Query(EDB, jtk)$

$\mathcal{O}(T)$

```
For $(rtk, stk)$ in $Query(EMM_T{}^J, jtk)$
    $r \leftarrow Query(EMM_T{}^R, rtk)$
    For $rtk'$ in $Query(EMM_{T'}{}^S, stk)$
        $R' \leftarrow R' \cup Query(EMM_{T'}{}^R, rtk')$
    Output $(r, R')$
```

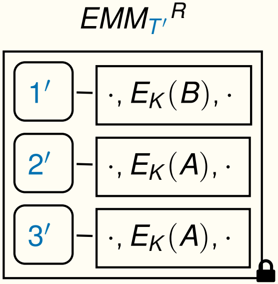


$EMM_T{}^R$

1 – $\cdot, E_K(A), \cdot$

2 – $\cdot, E_K(B), \cdot$

3 – $\cdot, E_K(A), \cdot$

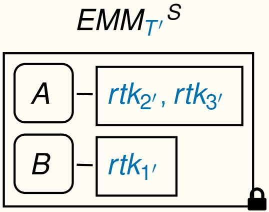


$EMM_{T'}{}^R$

$1'$ – $\cdot, E_K(B), \cdot$

$2'$ – $\cdot, E_K(A), \cdot$

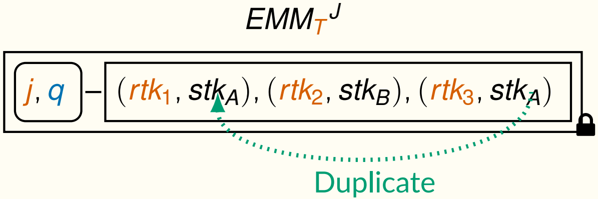
$3'$ – $\cdot, E_K(A), \cdot$



$EMM_{T'}{}^S$

A – $rtk_{2'}, rtk_{3'}$

B – $rtk_{1'}$



$EMM_T{}^J$

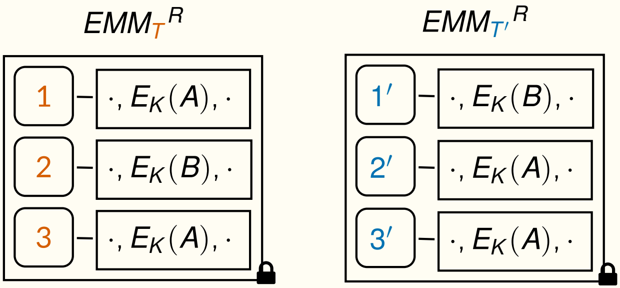
j, q – $(rtk_1, stk_A), (rtk_2, stk_B), (rtk_3, stk_A)$

Duplicate

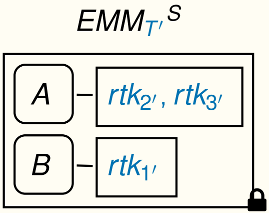
Optimal Encrypted Join

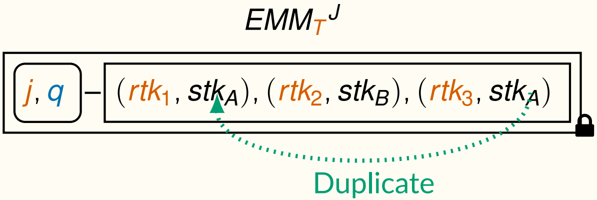
$Query(EDB, jtk)$

```
For $(rtk, stk)$ in $Query(EMM_T{}^J, jtk)$    $\mathcal{O}(T)$
    $r \leftarrow Query(EMM_T{}^R, rtk)$
    // Memoise for same $stk$
    For $rtk'$ in $Query(EMM_{T'}{}^S, stk)$
        $R' \leftarrow R' \cup Query(EMM_{T'}{}^R, rtk')$
    Output $(r, R')$
```



$EMM_T{}^R$
1 — $\cdot, E_K(A), \cdot$
2 — $\cdot, E_K(B), \cdot$
3 — $\cdot, E_K(A), \cdot$
$EMM_{T'}{}^R$
$1'$ — $\cdot, E_K(B), \cdot$
$2'$ — $\cdot, E_K(A), \cdot$
$3'$ — $\cdot, E_K(A), \cdot$

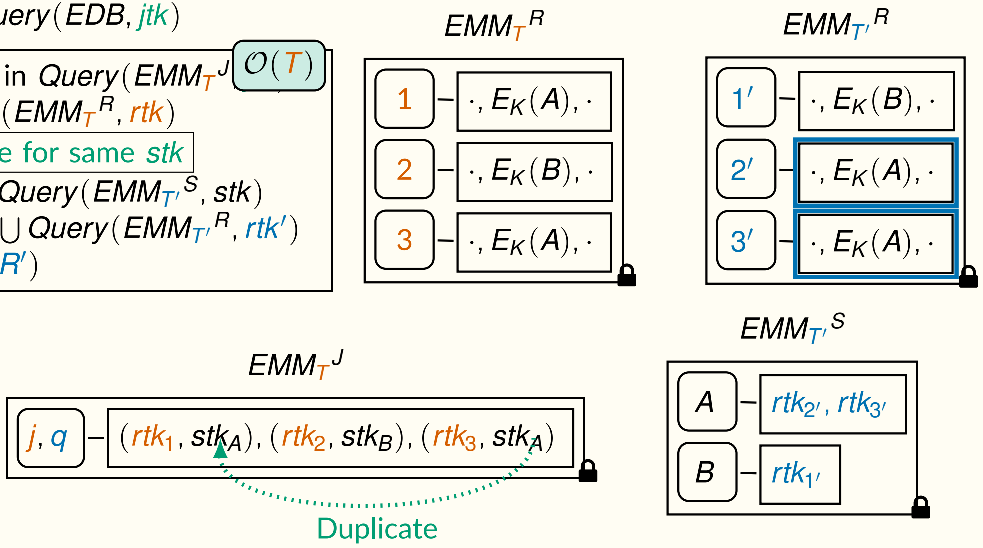




Optimal Encrypted Join

$Query(EDB, jtk)$

```
For $(rtk, stk)$ in $Query(EMM_T{}^J$   $\mathcal{O}(T)$
    $r \leftarrow Query(EMM_T{}^R, rtk)$
    // Memoise for same $stk$
    For $rtk'$ in $Query(EMM_{T'}{}^S, stk)$
        $R' \leftarrow R' \cup Query(EMM_{T'}{}^R, rtk')$
    Output $(r, R')$
```



$EMM_T{}^R$

1	$\cdot, E_K(A), \cdot$
2	$\cdot, E_K(B), \cdot$
3	$\cdot, E_K(A), \cdot$

$EMM_{T'}{}^R$

$1'$	$\cdot, E_K(B), \cdot$
$2'$	$\cdot, E_K(A), \cdot$
$3'$	$\cdot, E_K(A), \cdot$

$EMM_T{}^J$

j, q	$(rtk_1, stk_A), (rtk_2, stk_B), (rtk_3, stk_A)$

Duplicate

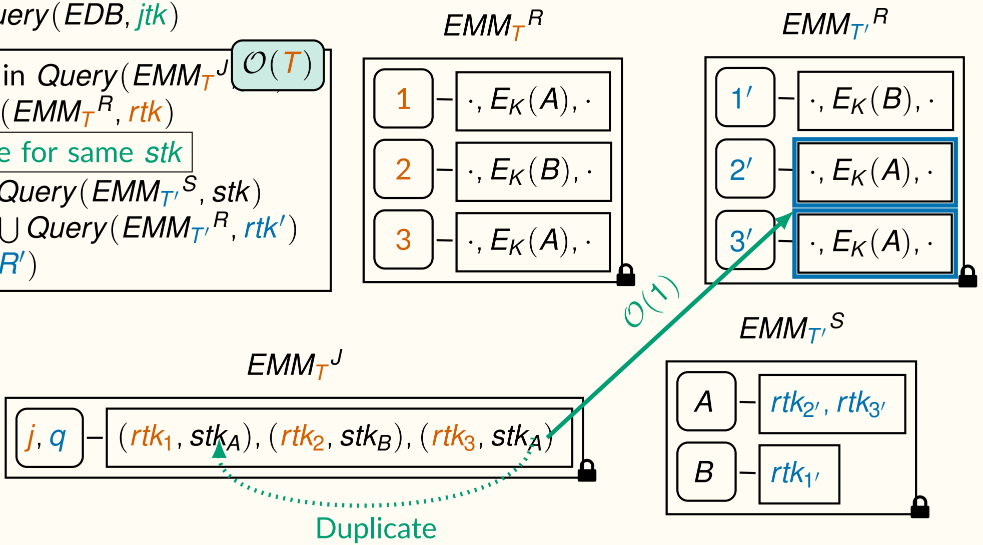
$EMM_{T'}{}^S$

A	$rtk_{2'}, rtk_{3'}$
B	$rtk_{1'}$

Optimal Encrypted Join

$Query(EDB, jtk)$

```
For $(rtk, stk)$ in $Query(EMM_T{}^J$ $\mathcal{O}(T)$
    $r \leftarrow Query(EMM_T{}^R, rtk)$
    // Memoise for same $stk$
    For $rtk'$ in $Query(EMM_{T'}{}^S, stk)$
        $R' \leftarrow R' \cup Query(EMM_{T'}{}^R, rtk')$
    Output $(r, R')$
```



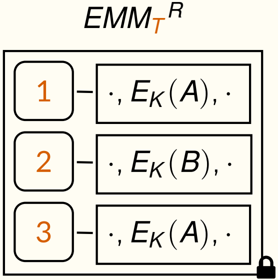
$EMM_T{}^R$
1 — $\cdot, E_K(A), \cdot$
2 — $\cdot, E_K(B), \cdot$
3 — $\cdot, E_K(A), \cdot$
$EMM_{T'}{}^R$
$1'$ — $\cdot, E_K(B), \cdot$
$2'$ — $\cdot, E_K(A), \cdot$
$3'$ — $\cdot, E_K(A), \cdot$
$\mathcal{O}(1)$
$EMM_{T'}{}^S$
A — $rtk_{2'}, rtk_{3'}$
B — $rtk_{1'}$
$EMM_T{}^J$
j, q — $(rtk_1, stk_A), (rtk_2, stk_B), (rtk_3, stk_A)$
Duplicate

Optimal Encrypted Join

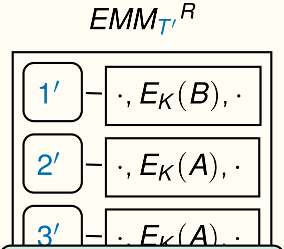
$\mathit{Query}(\mathit{EDB}, \mathit{jtk})$

```
For $(rtk, stk)$ in $\mathit{Query}(\mathit{EMM}_T{}^J$
    $r \leftarrow \mathit{Query}(\mathit{EMM}_T{}^R, rtk)$
    // Memoise for same $stk$
    For $rtk'$ in $\mathit{Query}(\mathit{EMM}_{T'}{}^S, stk)$
        $R' \leftarrow R' \cup \mathit{Query}(\mathit{EMM}_{T'}{}^R, rtk')$
    Output $(r, R')$
```

$\mathcal{O}(T)$

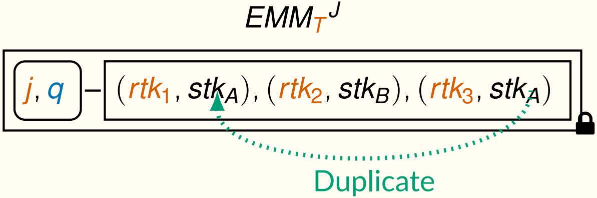


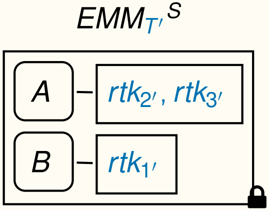
$\mathit{EMM}_T{}^R$
1 — $\cdot, E_K(A), \cdot$
2 — $\cdot, E_K(B), \cdot$
3 — $\cdot, E_K(A), \cdot$



$\mathit{EMM}_{T'}{}^R$
$1'$ — $\cdot, E_K(B), \cdot$
$2'$ — $\cdot, E_K(A), \cdot$
$3'$ — $\cdot, E_K(A), \cdot$

$\mathcal{O}(T')$ total accesses



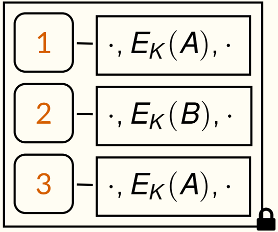


Optimal Encrypted Join

$Query(EDB, jtk)$ $\boxed{\mathcal{O}(T + T')}$

```
For $(rtk, stk)$ in $Query(EMM_T{}^J, jtk)$
    $r \leftarrow Query(EMM_T{}^R, rtk)$
    // Memoise for same $stk$
    For $rtk'$ in $Query(EMM_{T'}{}^S, stk)$
        $R' \leftarrow R' \cup Query(EMM_{T'}{}^R, rtk')$
    Output $(r, R')$
```

$EMM_T{}^R$

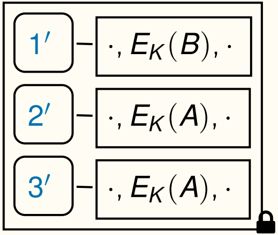


1 — $\cdot, E_K(A), \cdot$

2 — $\cdot, E_K(B), \cdot$

3 — $\cdot, E_K(A), \cdot$

$EMM_{T'}{}^R$

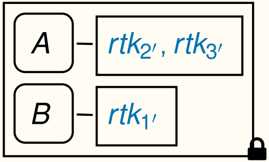


$1'$ — $\cdot, E_K(B), \cdot$

$2'$ — $\cdot, E_K(A), \cdot$

$3'$ — $\cdot, E_K(A), \cdot$

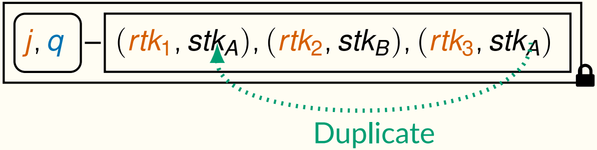
$EMM_{T'}{}^S$



A — $rtk_{2'}, rtk_{3'}$

B — $rtk_{1'}$

$EMM_T{}^J$



j, q — $(rtk_1, stk_A), (rtk_2, stk_B), (rtk_3, stk_A)$

Duplicate

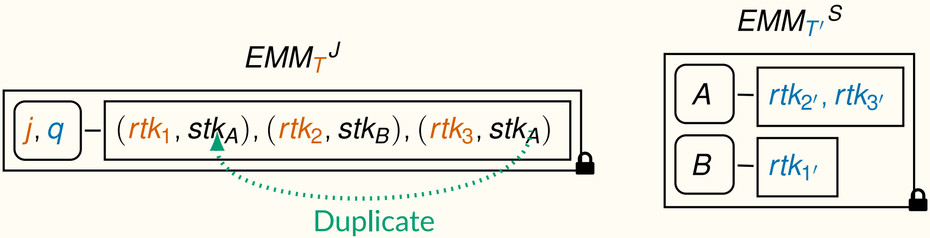
Optimal Encrypted Join

$Query(EDB, jtk$ $\mathcal{O}(T + T')$

```
For $(rtk, stk)$ in $Q$
  $r \leftarrow Query(EM$
  // Memoise for
  For $rtk'$ in $Quer$
    $R' \leftarrow R' \cup Qu$
  Output $(r, R')$
```

$EMM_{T}{}^{R}$ $EMM_{T'}{}^{R}$

- Matches plaintext join asymtotic complexity.
- Improved leakage for conjunctive queries (deferred).



Emulation

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- Common belief: STE requires re-architecting existing storage system

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Emulation

- Common belief: STE requires re-architecting existing storage system
- Emulation: New technique to make STE legacy friendly
- Express the data structure and language in STE using Relation Model
- Does not change security and complexity

Emulation

- Two components: structure reshape and query reform

Emulation

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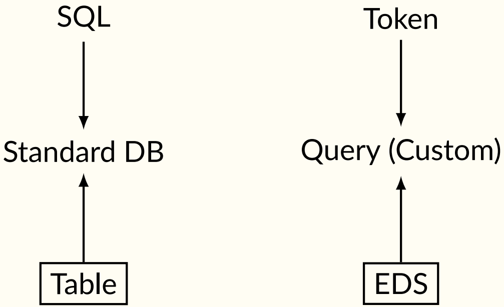


SQL

Standard DB

Table

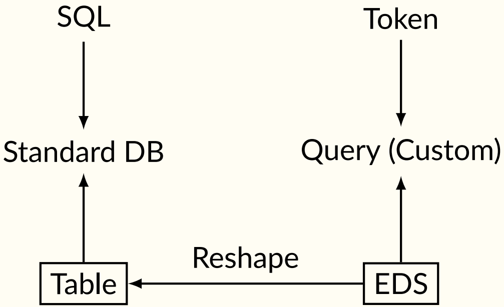
Token

Query (Custom)

EDS

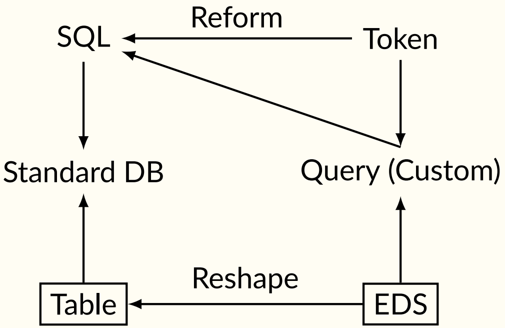
Emulation

- Two components: structure reshape and query reform



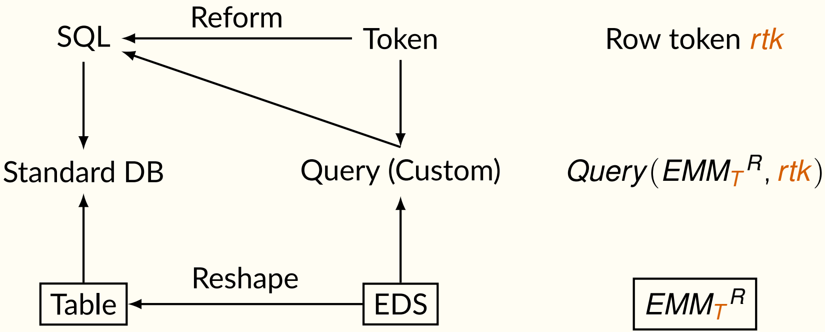
Emulation

- Two components: structure reshape and query reform



Emulation

- Two components: structure reshape and query reform



Reform

SQL

Token

Row token *rtk*

Standard DB

Query (Custom)

$Query(EMM_{T}{}^{R}, rtk)$

Reshape

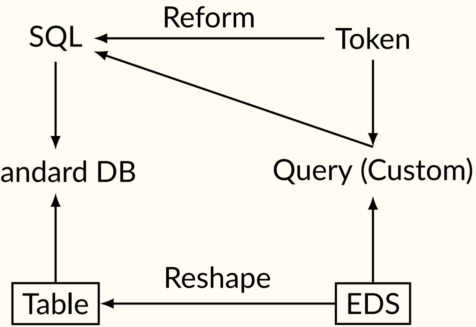
Table

EDS

$EMM_{T}{}^{R}$

Emulation

- Two components: structure reshape and query reform



SQL

Reform

Token

Standard DB

Query (Custom)

Table

Reshape

EDS

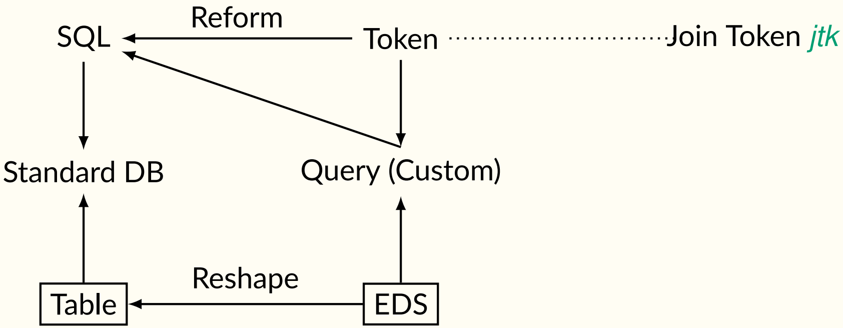
Row token *rtk*

$Query(EMM_T{}^R, rtk)$

$\boxed{EMM_T{}^R}$ — Pibas[CJJ+14]

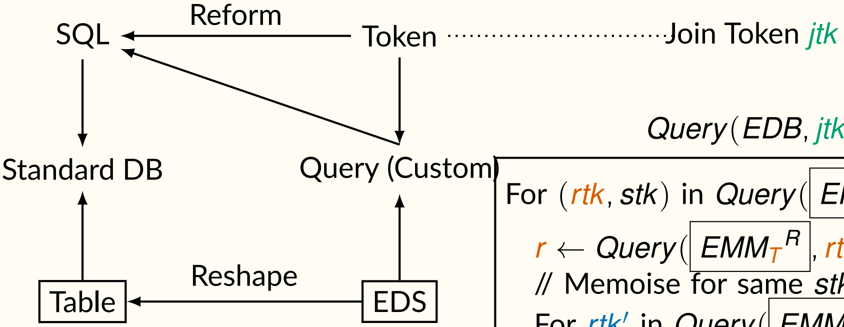
Emulation

- Two components: structure reshape and query reform



Emulation

- Two components: structure reshape and query reform



$Query(EDB, jtk)$

```
For $(rtk, stk)$ in $Query(\boxed{EMM_T{}^J}, jtk)$
    $r \leftarrow Query(\boxed{EMM_T{}^R}, rtk)$
    // Memoise for same $stk$
    For $rtk'$ in $Query(\boxed{EMM_{T'}{}^S}, stk)$
        $R' \leftarrow R' \cup Query(\boxed{EMM_{T'}{}^R}, rtk')$
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```

Emulation of PKFK Scheme

- PKFK supports conjunctive queries (multiple filters and joins) in SQL

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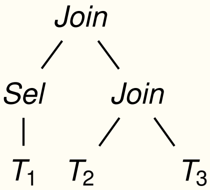

Emulation of PKFK Scheme

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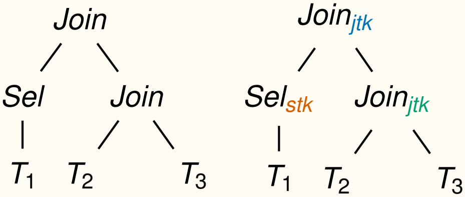

Emulation of PKFK Scheme

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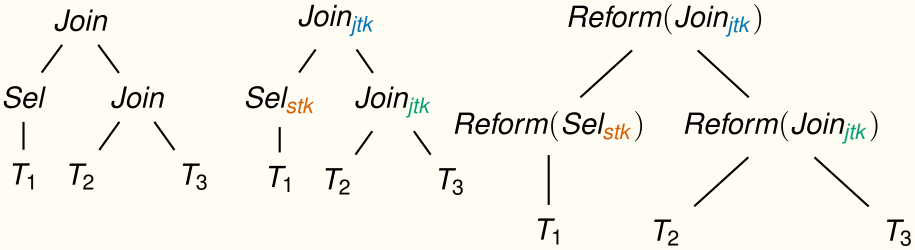

Colocation

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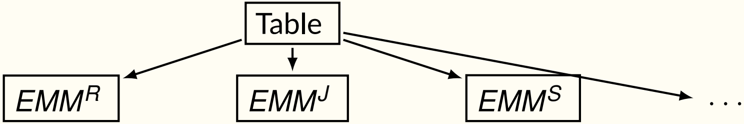
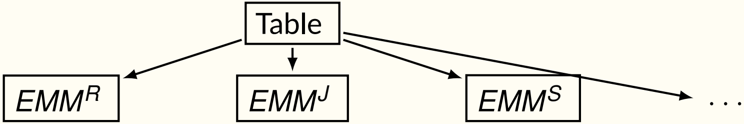


Colocation

- Data locality is important to achieve high efficiency in database
- The representations of EMMs reduces data locality
- Colocation: New technique to increase data locality



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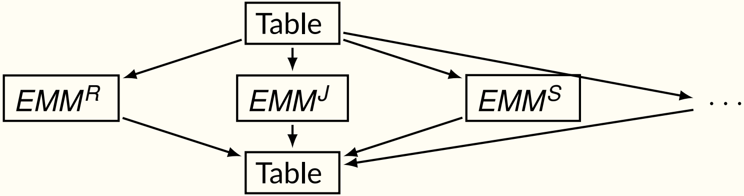
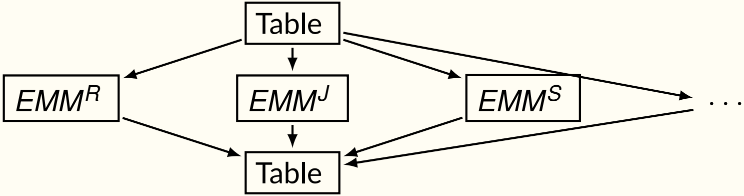
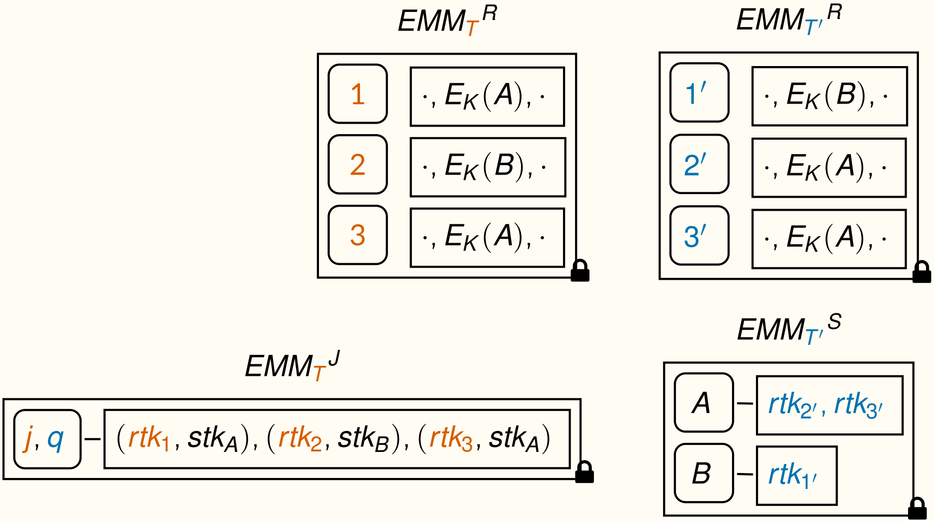


Colocation

- Data locality is important to achieve high efficiency in database
- The representations of EMMs reduces data locality
- Colocation: New technique to increase data locality
- Does not change security



Colocation Example for Join



$EMM_T{}^R$

1	$\cdot, E_K(A), \cdot$
2	$\cdot, E_K(B), \cdot$
3	$\cdot, E_K(A), \cdot$

$EMM_{T'}{}^R$

$1'$	$\cdot, E_K(B), \cdot$
$2'$	$\cdot, E_K(A), \cdot$
$3'$	$\cdot, E_K(A), \cdot$

$EMM_T{}^J$

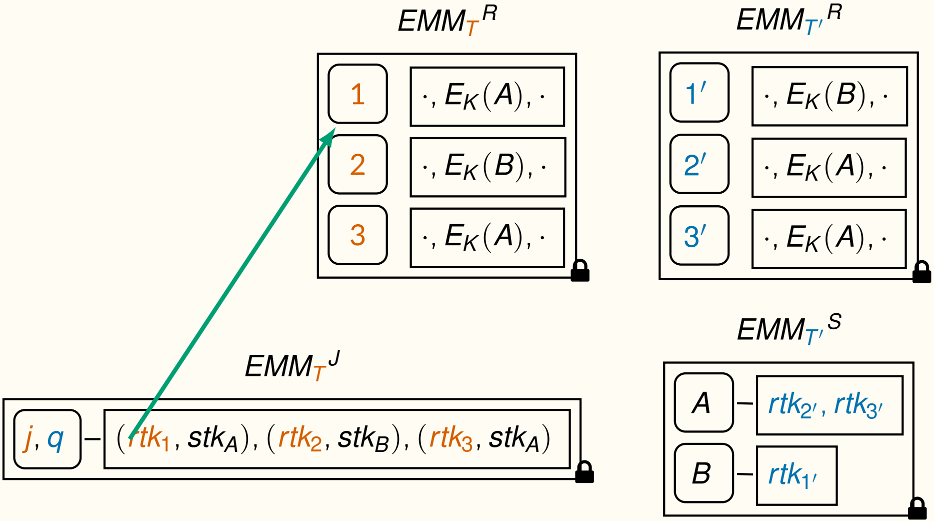
j, q – $(rtk_1, stk_A), (rtk_2, stk_B), (rtk_3, stk_A)$

$EMM_{T'}{}^S$

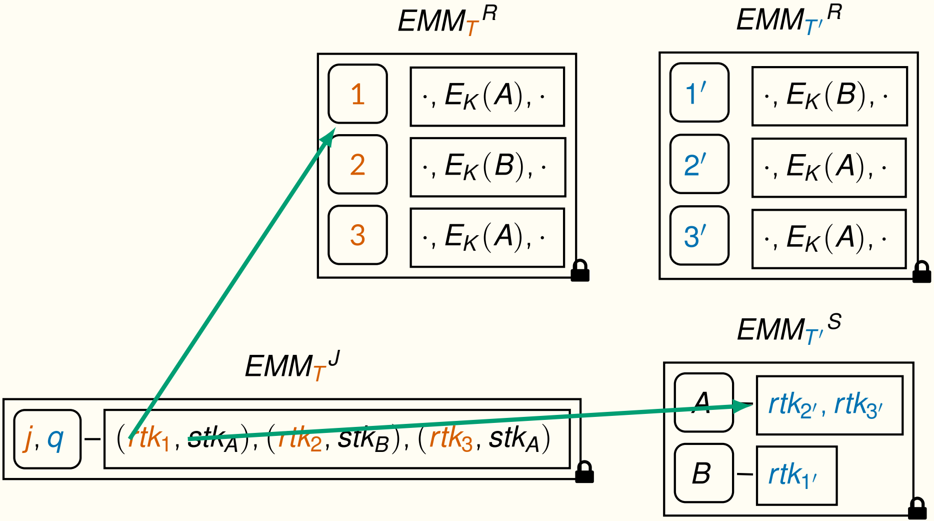
A – $rtk_{2'}, rtk_{3'}$

B – $rtk_{1'}$

Colocation Example for Join



Colocation Example for Join



$EMM_T{}^R$

1 — $\cdot, E_K(A), \cdot$

2 — $\cdot, E_K(B), \cdot$

3 — $\cdot, E_K(A), \cdot$

$EMM_{T'}{}^R$

$1'$ — $\cdot, E_K(B), \cdot$

$2'$ — $\cdot, E_K(A), \cdot$

$3'$ — $\cdot, E_K(A), \cdot$

$EMM_T{}^J$

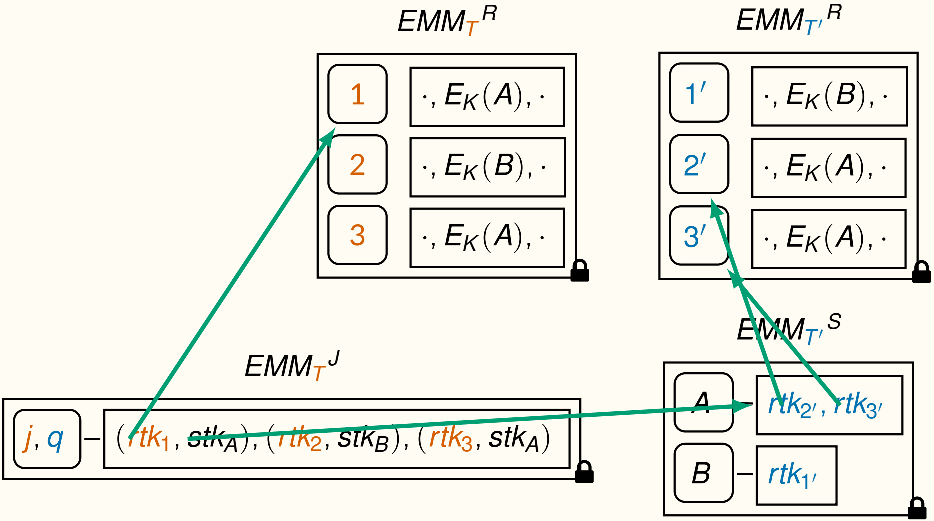
j, q — $(rtk_1, stk_A), (rtk_2, stk_B), (rtk_3, stk_A)$

$EMM_{T'}{}^S$

A — $rtk_{2'}, rtk_{3'}$

B — $rtk_{1'}$

Colocation Example for Join



${EMM_T}^R$

1 — $\cdot, E_K(A), \cdot$

2 — $\cdot, E_K(B), \cdot$

3 — $\cdot, E_K(A), \cdot$

${EMM_{T'}}^R$

$1'$ — $\cdot, E_K(B), \cdot$

$2'$ — $\cdot, E_K(A), \cdot$

$3'$ — $\cdot, E_K(A), \cdot$

${EMM_T}^J$

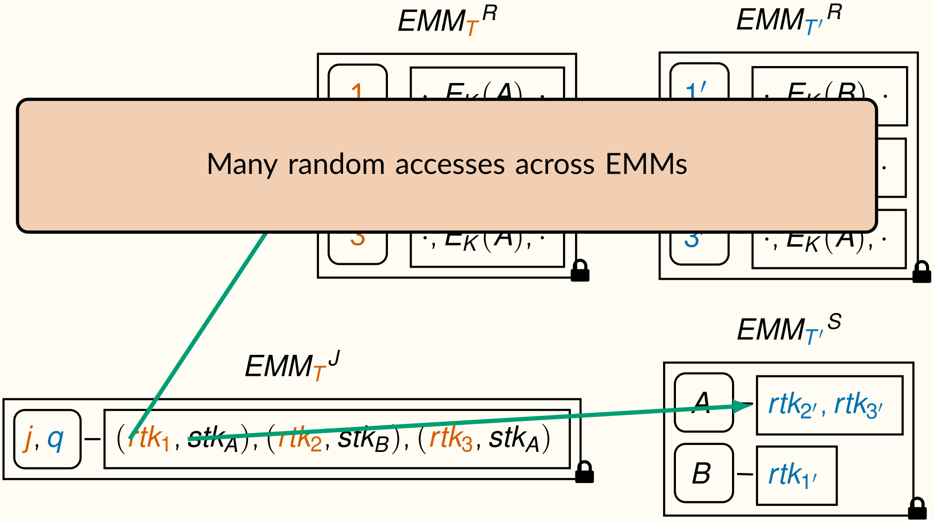
j, q — $(rtk_1, stk_A), (rtk_2, stk_B), (rtk_3, stk_A)$

${EMM_{T'}}^S$

A — $rtk_{2'}, rtk_{3'}$

B — $rtk_{1'}$

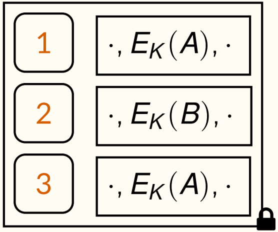
Colocation Example for Join



Many random accesses across EMMs

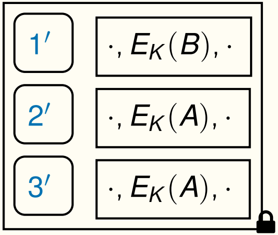
Colocation Example for Join

$EMM_{T}{}^{R}$



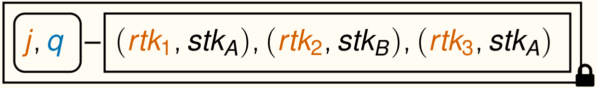
1	$\cdot, E_K(A), \cdot$
2	$\cdot, E_K(B), \cdot$
3	$\cdot, E_K(A), \cdot$

$EMM_{T'}{}^{R}$



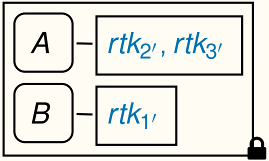
$1'$	$\cdot, E_K(B), \cdot$
$2'$	$\cdot, E_K(A), \cdot$
$3'$	$\cdot, E_K(A), \cdot$

$EMM_{T}{}^{J}$



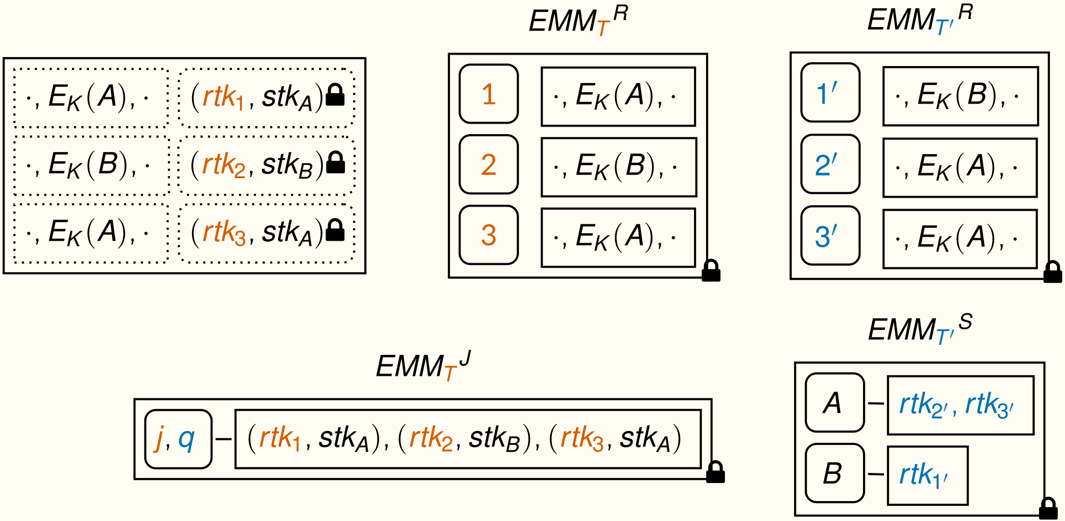
j, q	$(rtk_1, stk_A), (rtk_2, stk_B), (rtk_3, stk_A)$

$EMM_{T'}{}^{S}$



A	$rtk_{2'}, rtk_{3'}$
B	$rtk_{1'}$

Colocation Example for Join



$\cdot, E_K(A), \cdot$ | (rtk_1, stk_A)

$\cdot, E_K(B), \cdot$ | (rtk_2, stk_B)

$\cdot, E_K(A), \cdot$ | (rtk_3, stk_A)

$EMM_T{}^R$

1 | $\cdot, E_K(A), \cdot$

2 | $\cdot, E_K(B), \cdot$

3 | $\cdot, E_K(A), \cdot$

$EMM_{T'}{}^R$

$1'$ | $\cdot, E_K(B), \cdot$

$2'$ | $\cdot, E_K(A), \cdot$

$3'$ | $\cdot, E_K(A), \cdot$

$EMM_T{}^J$

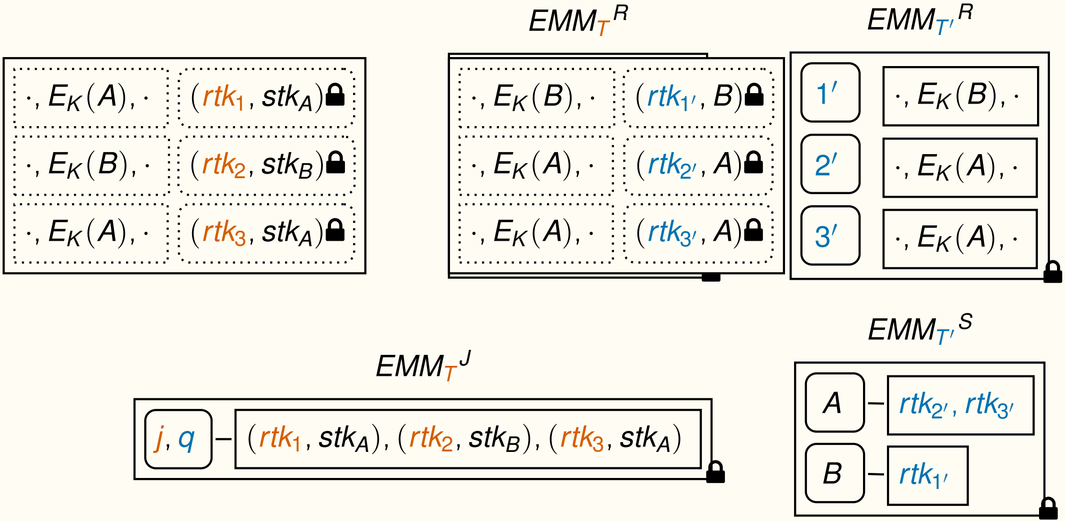
j, q – $(rtk_1, stk_A), (rtk_2, stk_B), (rtk_3, stk_A)$

$EMM_{T'}{}^S$

A – $rtk_{2'}, rtk_{3'}$

B – $rtk_{1'}$

Colocation Example for Join



$\cdot, E_K(A), \cdot$	(rtk_1, stk_A)🔒
$\cdot, E_K(B), \cdot$	(rtk_2, stk_B)🔒
$\cdot, E_K(A), \cdot$	(rtk_3, stk_A)🔒

$EMM_T{}^R$

$\cdot, E_K(B), \cdot$	$(rtk_{1'}, B)$🔒
$\cdot, E_K(A), \cdot$	$(rtk_{2'}, A)$🔒
$\cdot, E_K(A), \cdot$	$(rtk_{3'}, A)$🔒

$EMM_{T'}{}^R$

$1'$	$\cdot, E_K(B), \cdot$
$2'$	$\cdot, E_K(A), \cdot$
$3'$	$\cdot, E_K(A), \cdot$

$EMM_T{}^J$

j, q	$(rtk_1, stk_A), (rtk_2, stk_B), (rtk_3, stk_A)$

$EMM_{T'}{}^S$

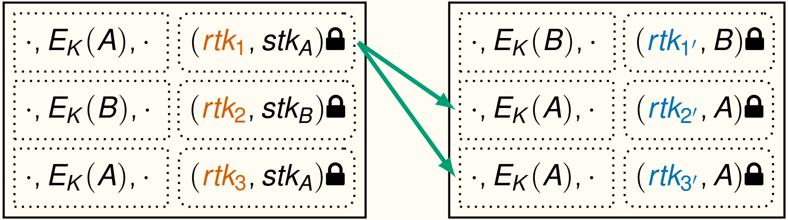
A	$rtk_{2'}, rtk_{3'}$
B	$rtk_{1'}$

Colocation Example for Join

$\cdot, E_K(A), \cdot$	(rtk_1, stk_A)🔒
$\cdot, E_K(B), \cdot$	(rtk_2, stk_B)🔒
$\cdot, E_K(A), \cdot$	(rtk_3, stk_A)🔒

$\cdot, E_K(B), \cdot$	$(rtk_{1'}, B)$🔒
$\cdot, E_K(A), \cdot$	$(rtk_{2'}, A)$🔒
$\cdot, E_K(A), \cdot$	$(rtk_{3'}, A)$🔒

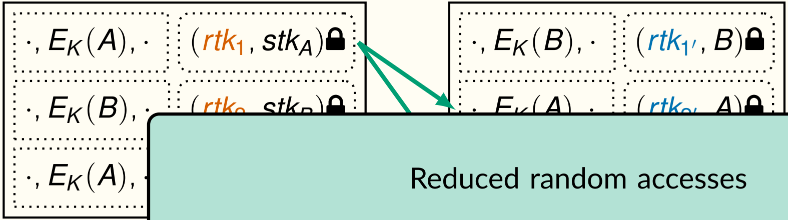
Colocation Example for Join



$\cdot, E_K(A), \cdot$	(rtk_1, stk_A)🔒
$\cdot, E_K(B), \cdot$	(rtk_2, stk_B)🔒
$\cdot, E_K(A), \cdot$	(rtk_3, stk_A)🔒

$\cdot, E_K(B), \cdot$	$(rtk_{1'}, B)$🔒
$\cdot, E_K(A), \cdot$	$(rtk_{2'}, A)$🔒
$\cdot, E_K(A), \cdot$	$(rtk_{3'}, A)$🔒

Colocation Example for Join



Reduced random accesses

The KafeDB System

Legacy-Compatible Architecture, KafeDB

Legacy-Compatible Architecture, KafeDB

- Any SQL database backend

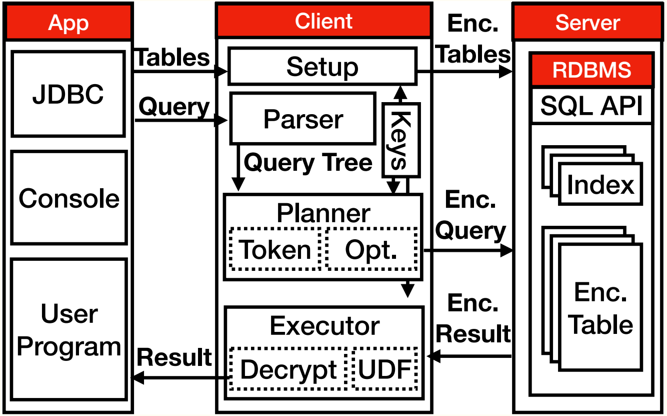
Legacy-Compatible Architecture, KafeDB

- Any SQL database backend
- Applications same API

Legacy-Compatible Architecture, KafeDB

- Any SQL database backend
- Applications same API
- Leverage DB optimizations

Legacy-Compatible Architecture, KafeDB



- Any SQL database backend
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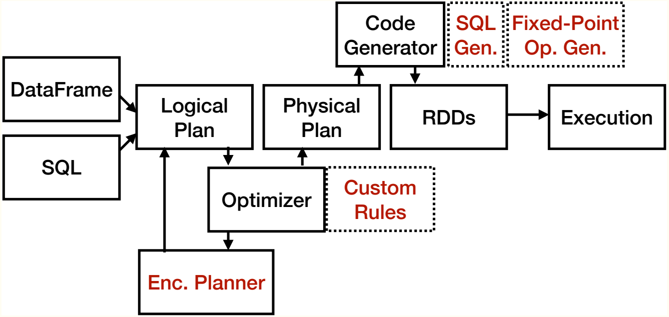
- Leverage DB optimizations

SparkSQL[5]-based Implementation



- PostgreSQL 9.6.2, libcrypto, AES CBC/pkcs7, SHA256.
- BouncyCastle 1.64 on JDK 1.5+
- Apache Spark, Scala, 1000+ lines of code
-

[5] Apache SparkSQL [AXL+15]

Query Optimization Rules

- Important to support query optimization to build upon mature DB research.

Query Optimization Rules

- Important to support query optimization to build upon mature DB research.
- Based on Rules

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- Based on Rules

Rules	TPC-H[a]

Query Optimization Rules

- Important to support query optimization to build upon mature DB research.
- Based on Rules
    - Standard Rules: Operator Reorder

Rules	TPC-H[a]

[a] Scale factor 10.

Query Optimization Rules

- Important to support query optimization to build upon mature DB research.
- Based on Rules
  - Standard Rules: Operator Reorder

Rules	TPC-H[a]
Sel/Proj Pushdown	19.8×
Join/Sel Reorder	22.8×

[a] Scale factor 10.

Query Optimization Rules

- Important to support query optimization to build upon mature DB research.
- Based on Rules
  - Standard Rules: Operator Reorder
  - New Rules

Rules	TPC-H[a]
Sel/Proj Pushdown	19.8 ×
Join/Sel Reorder	22.8 ×

[a] Scale factor 10.

Query Optimization Rules

- Important to support query optimization to build upon mature DB research.
- Based on Rules
  - Standard Rules: Operator Reorder
  - New Rules

Rules	TPC-H[a]
Sel/Proj Pushdown	19.8×
Join/Sel Reorder	22.8×
Data Parallel Rewrite[b]	2.7×
Join Direction Reorder	12.6×

[a] Scale factor 10.

Query Optimization Rules

- Important to support query optimization to build upon mature DB research.
- Based on Rules
  - Standard Rules: Operator Reorder
  - New Rules

Rules	TPC-H[a]
Sel/Proj Pushdown	19.8×
Join/Sel Reorder	22.8×
Data Parallel Rewrite[b]	2.7×
Join Direction Reorder	12.6×

[a] Scale factor 10.

[b] 6 cores.

Benchmark

TPC-H Benchmark [TPC-Council'08]

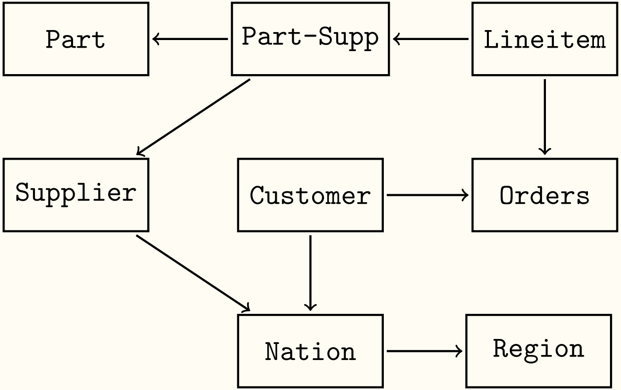
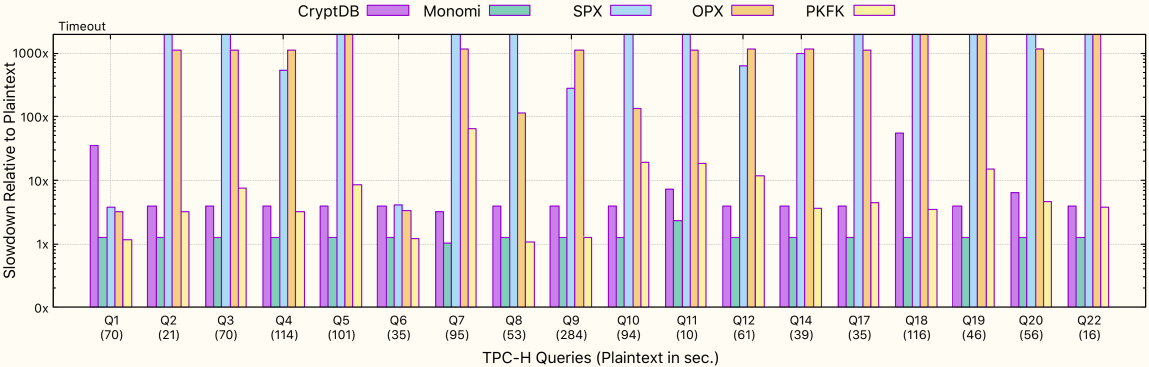


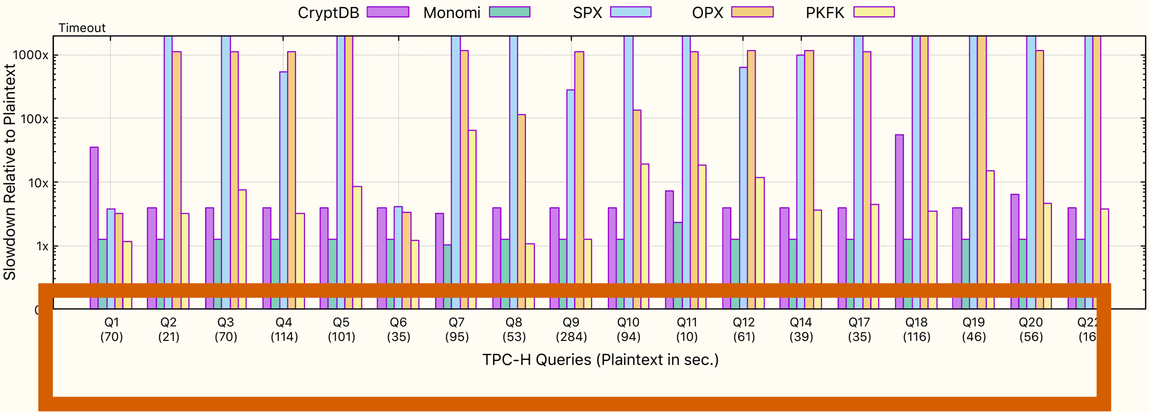
Table	Attrs.	Rows
Part	9	2×10^6
Supplier	7	100×10^3
Part-Supp	7	8×10^6
Customer	8	1.5×10^6
Nation	4	250
Region	3	50
Lineitem	17	60×10^6
Orders	9	15×10^6

- Models data warehouse analyic workload.
- Scale factor 10 (17GB).
- 32GB RAM, 8 CPUs, 5.2TB EBS for SPX and OPX; 1.2TB EBS for PKFK.

Query Overhead



Query Overhead

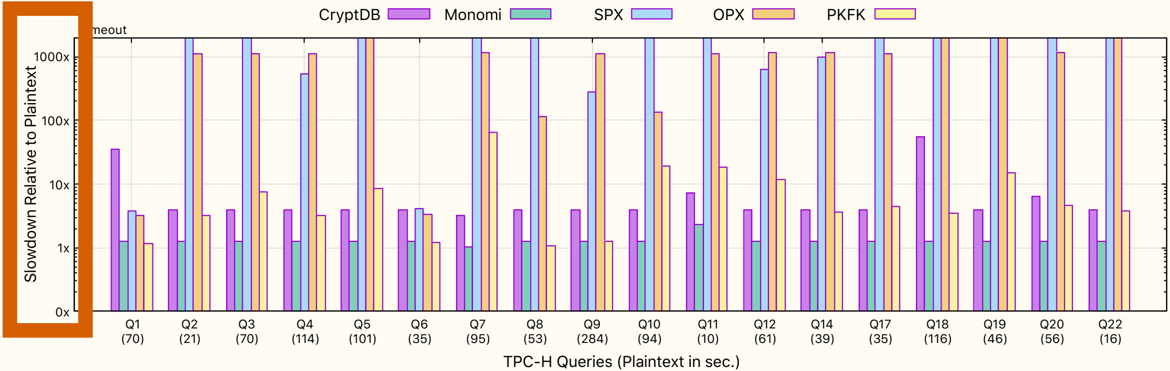


Queries

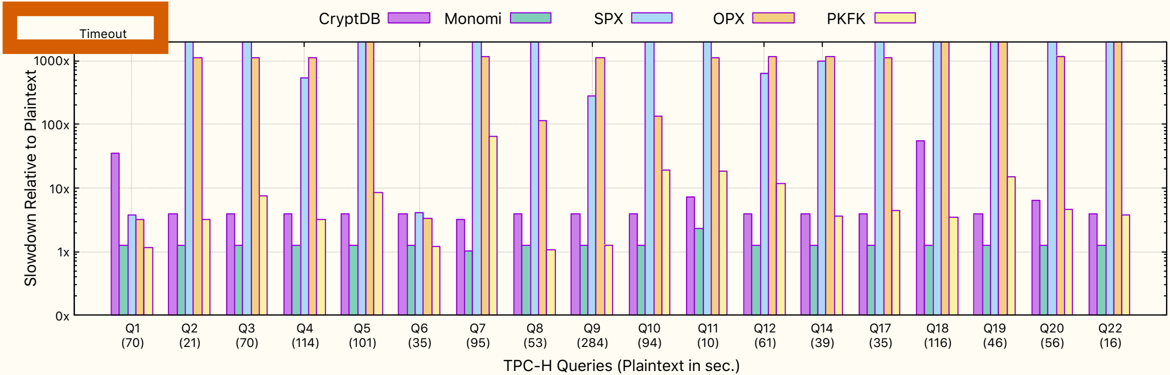
Query Overhead

Overhead

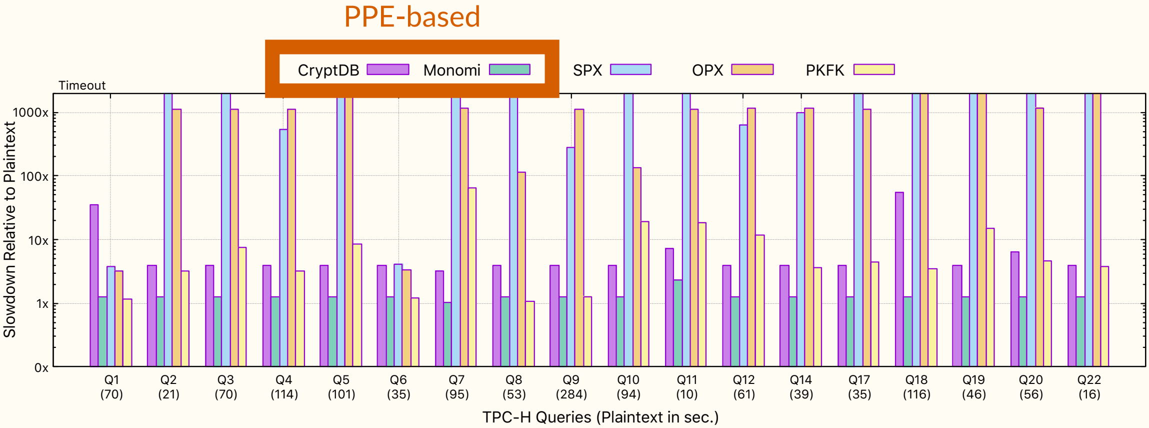
Log Scale



Query Overhead

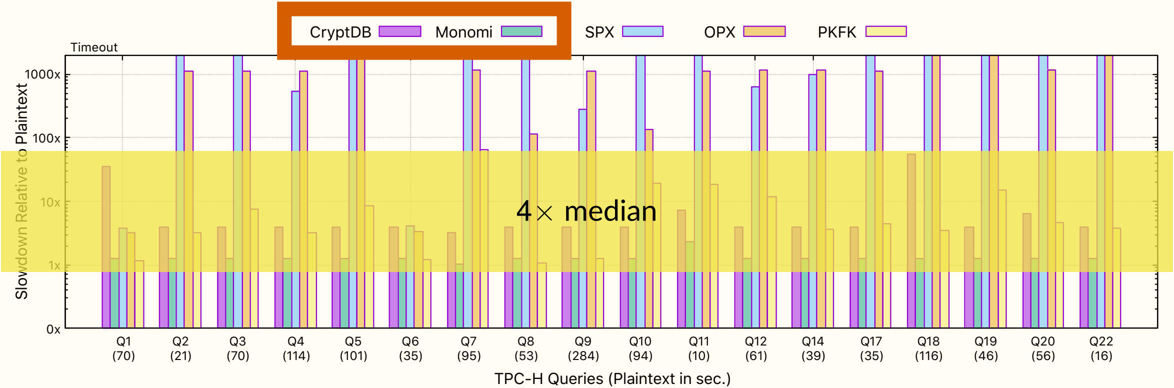


Query Overhead



Query Overhead

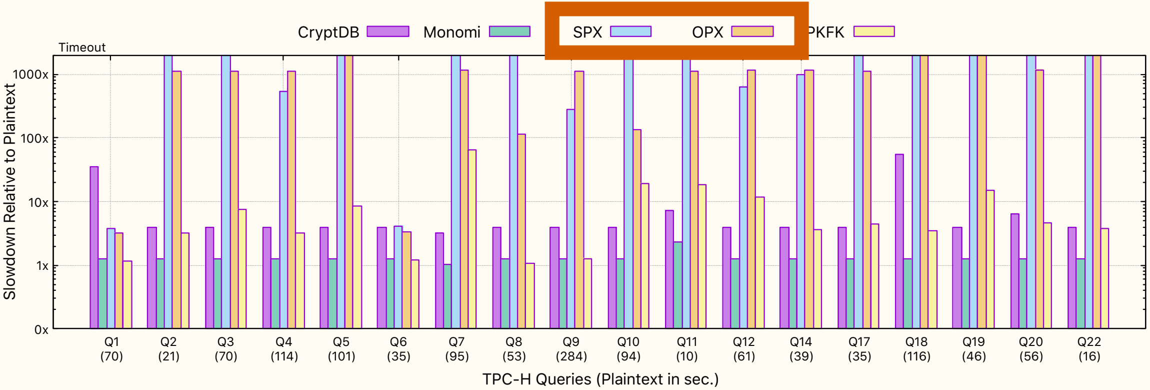
PPE-based



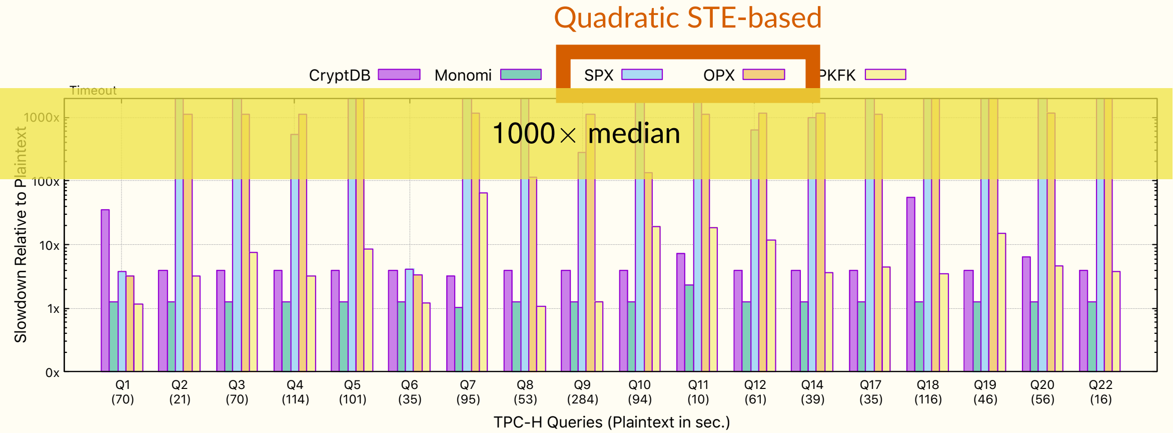
4 × median

Query Overhead

Quadratic STE-based

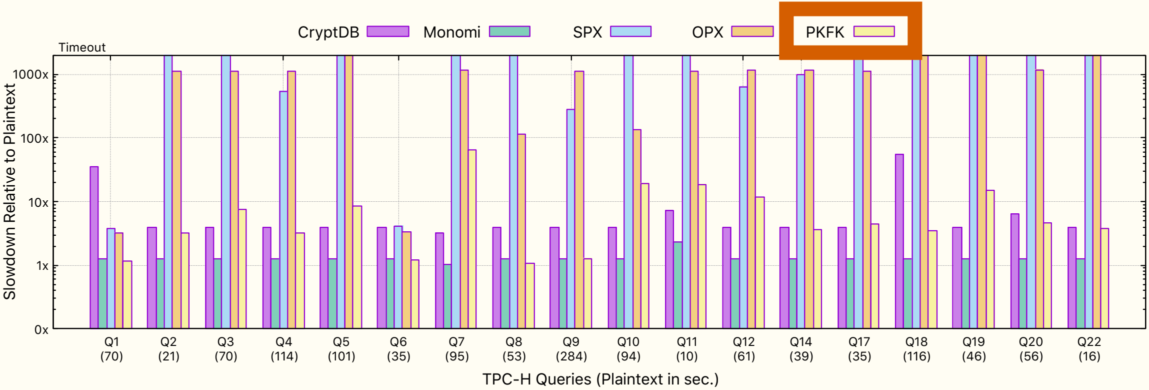


Query Overhead



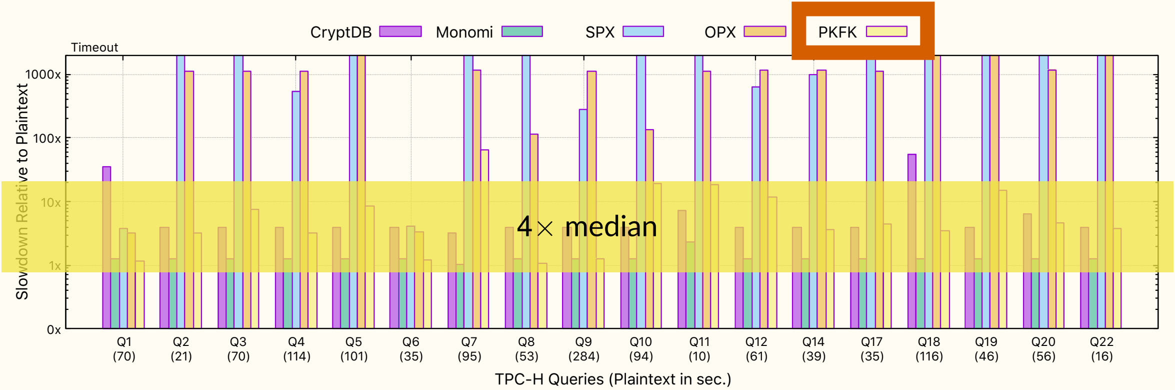
Query Overhead

Optimal STE-based



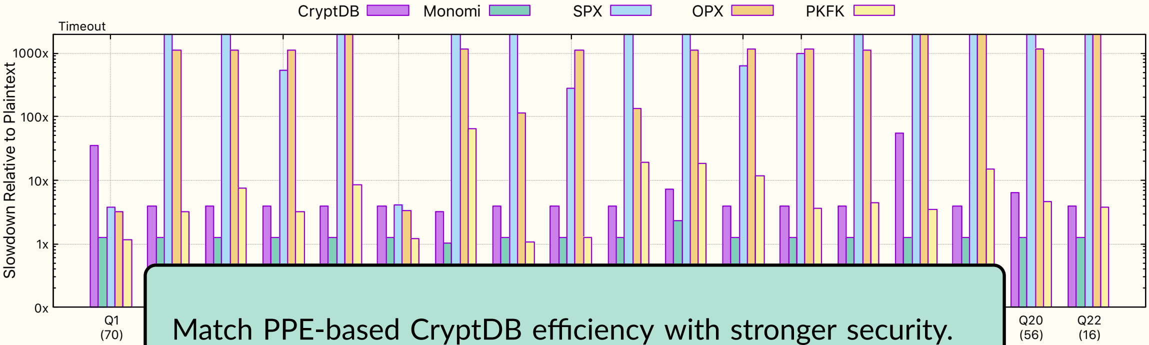
Query Overhead

Optimal STE-based



4 × median

Query Overhead



Match PPE-based CryptDB efficiency with stronger security.

Storage Overhead

System	Size

Storage Overhead

System	Size
Plaintext	17.1GB

Storage Overhead

System	Size
Plaintext	17.1GB
CryptDB	4.2×
Monomi	1.7×

Storage Overhead

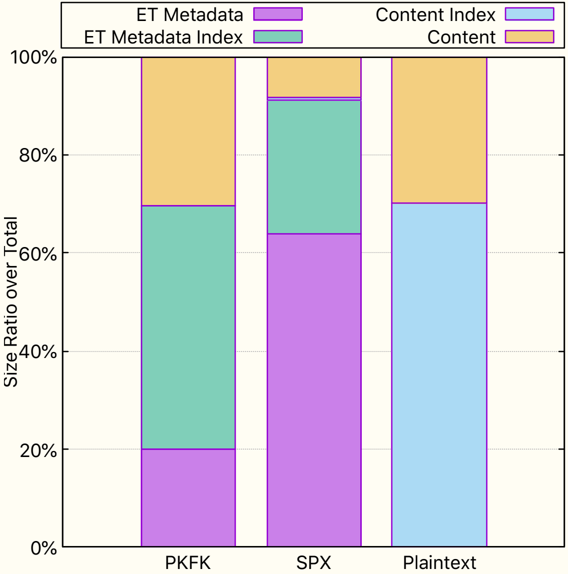
System	Size
Plaintext	17.1GB
CryptDB	4.2×
Monomi	1.7×
SPX	252.2×
OPX	265.4×

Storage Overhead

System	Size
Plaintext	17.1GB
CryptDB	4.2×
Monomi	1.7×
SPX	252.2×
OPX	265.4×
PKFK	3.6×

Storage Overhead

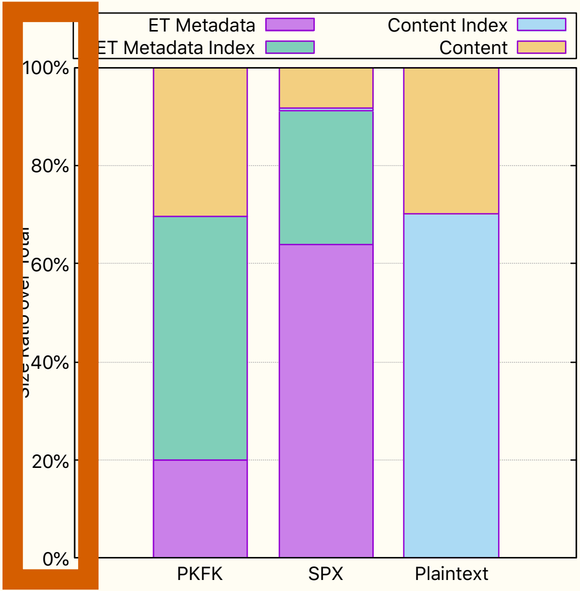
System	Size
Plaintext	17.1GB
CryptDB	4.2×
Monomi	1.7×
SPX	252.2×
OPX	265.4×
PKFK	3.6×



Storage Overhead

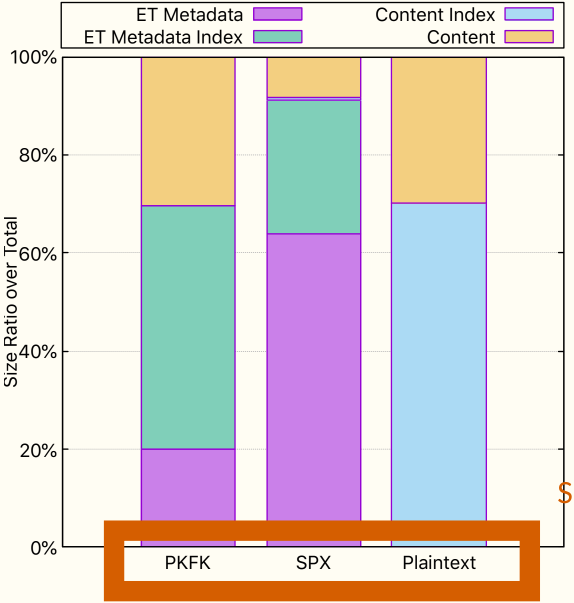
System	Size
Plaintext	17.1GB
CryptDB	4.2×
Monomi	1.7×
SPX	252.2×
OPX	265.4×
PKFK	3.6×

Breakdown Ratio



Storage Overhead

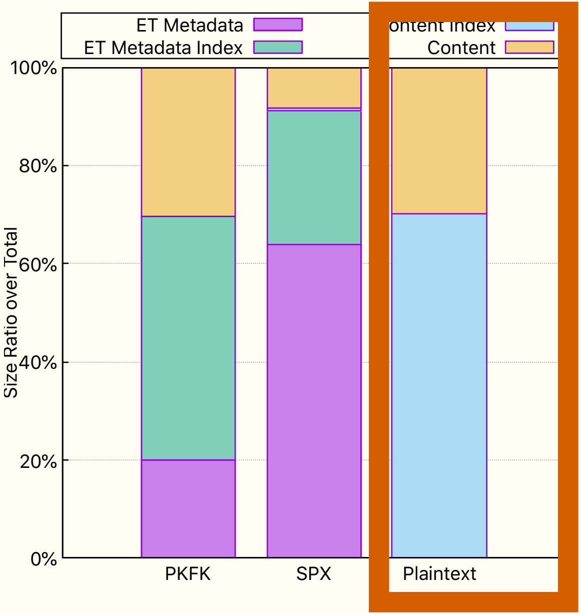
System	Size
Plaintext	17.1GB
CryptDB	4.2×
Monomi	1.7×
SPX	252.2×
OPX	265.4×
PKFK	3.6×



Schemes

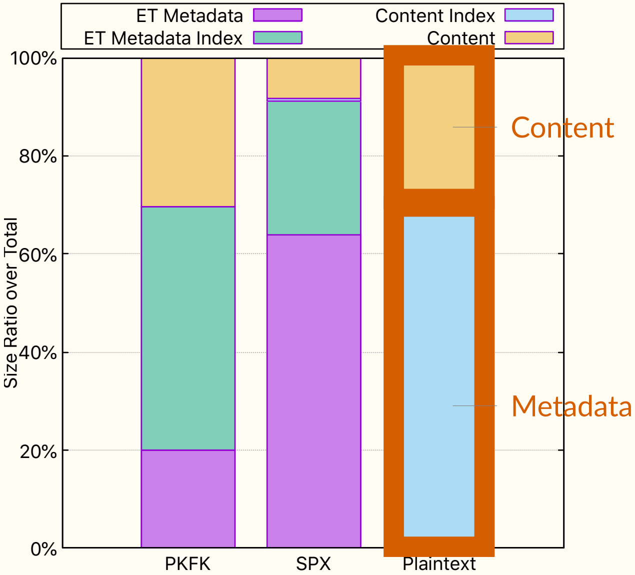
Storage Overhead

System	Size
Plaintext	17.1GB
CryptDB	4.2×
Monomi	1.7×
SPX	252.2×
OPX	265.4×
PKFK	3.6×



Storage Overhead

System	Size
Plaintext	17.1GB
CryptDB	4.2×
Monomi	1.7×
SPX	252.2×
OPX	265.4×
PKFK	3.6×

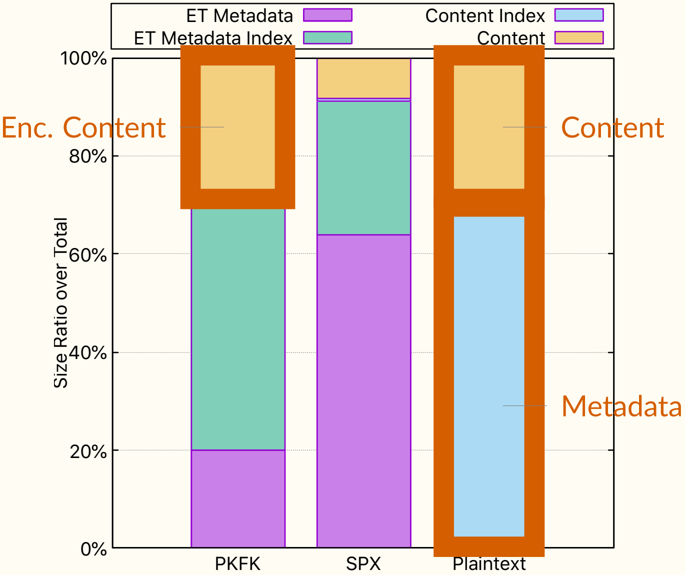


Content

Metadata

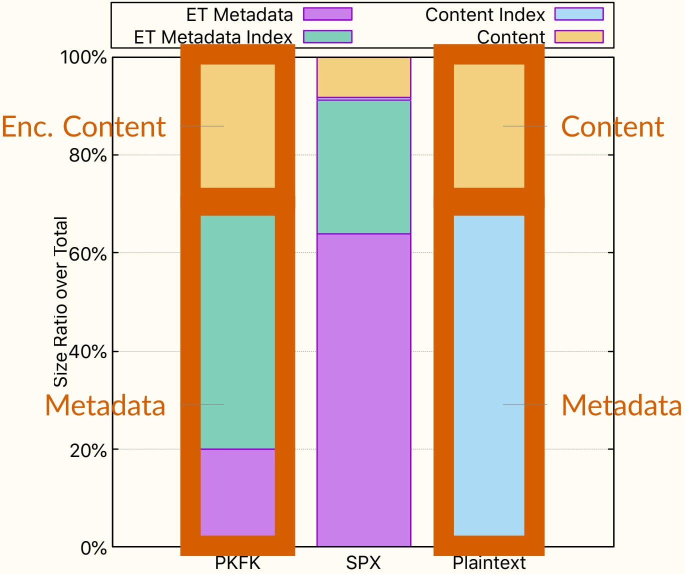
Storage Overhead

System	Size
Plaintext	17.1GB
CryptDB	4.2×
Monomi	1.7×
SPX	252.2×
OPX	265.4×
PKFK	3.6×



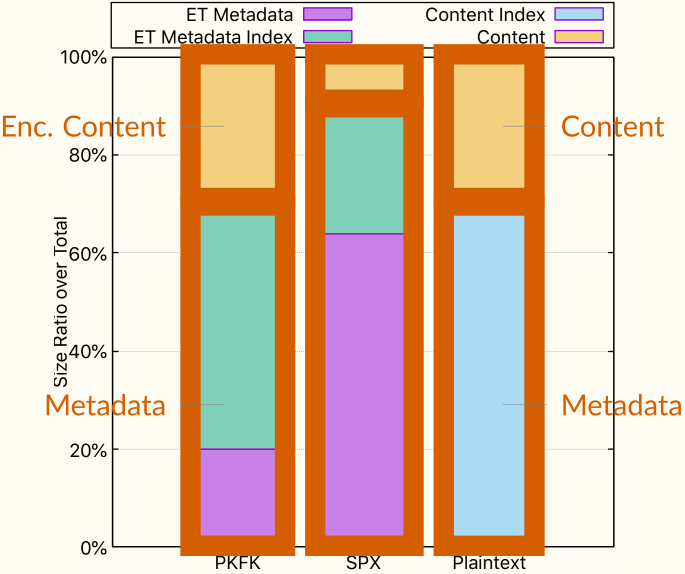
Storage Overhead

System	Size
Plaintext	17.1GB
CryptDB	4.2×
Monomi	1.7×
SPX	252.2×
OPX	265.4×
PKFK	3.6×



Storage Overhead

System	Size
Plaintext	17.1GB
CryptDB	4.2×
Monomi	1.7×
SPX	252.2×
OPX	265.4×
PKFK	3.6×



Enc. Content

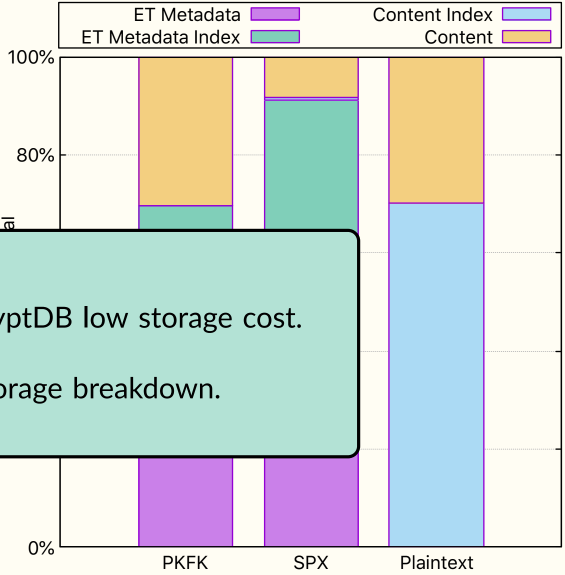
Metadata

Content

Metadata

Storage Overhead

System	Size
Plaintext	17.1GB
CryptDB	4.2×
Monomi	1.7×
SPX	252.2×
OPX	265.4×
PK	



- Match PPE-based CryptDB low storage cost.
- Match Plaintext in storage breakdown.

Summary

- Outsource data securely to the untrusted party such as the cloud.
- STE-based relational scheme: optimal join complexity, expressiveness, improved leakage.
- New techniques: Emulation for legacy. Collocation for locality.
- System based on SparkSQL and interace with any SQL DB.
- Efficiency comparable to PPE-based CryptDB but with stronger security.
- Support for effective query optimization.
- Open source: *https://github.com/zheguang/encrypted-spark*

Appendix

Table vs. Multimap

Data Structure	Table	Multimap
Model	Relational (SQL)	Key-Value (NoSQL)
Language	Relational Algebra	Retrieval by Key
Optimality	$\mathcal{O}(T)$	$\mathcal{O}(Q)$
Basis for EDB	PKFK	SPX,OPX

Encrypted Selection

Name	Pay	Nation
Alice	VISA	US
Bob	AMEX	US
Bob	VISA	CAN

Encrypted Selection

Name	Pay	Nation
Alice$_1$	VISA$_1$	US$_1$
Bob$_1$	AMEX$_1$	US$_2$
Bob$_2$	VISA$_2$	CAN$_1$

Subscripted rep counter

Encrypted Selection

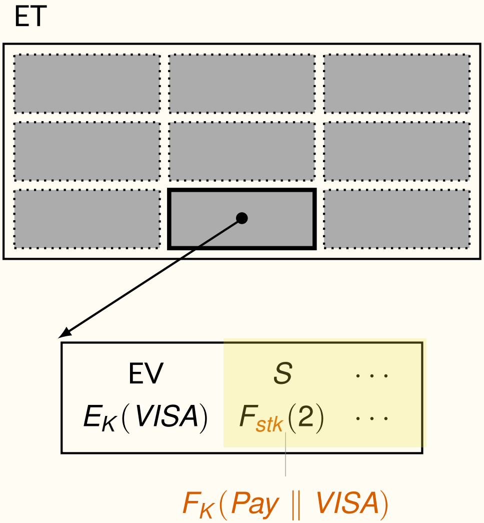
Name	Pay	Nation
Alice_1	VISA_1	US_1
Bob_1	AMEX_1	US_2
Bob_2	VISA_2	CAN_1

ET

▨	▨	▨
▨	▨	▨
▨	▨	▨

Encrypted Selection

Name	Pay	Nation
Alice_1	VISA_1	US_1
Bob_1	AMEX_1	US_2
Bob_2	$\boxed{\text{VISA}_2}$	CAN_1

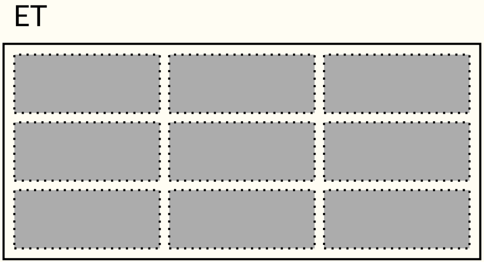


EV	S	$\cdots$
$E_K(VISA)$	$F_{stk}(2)$	$\cdots$

$F_K(Pay \parallel VISA)$

Encrypted Selection

Name	Pay	Nation
Alice$_1$	VISA$_1$	US$_1$
Bob$_1$	AMEX$_1$	US$_2$
Bob$_2$	VISA$_2$	CAN$_1$

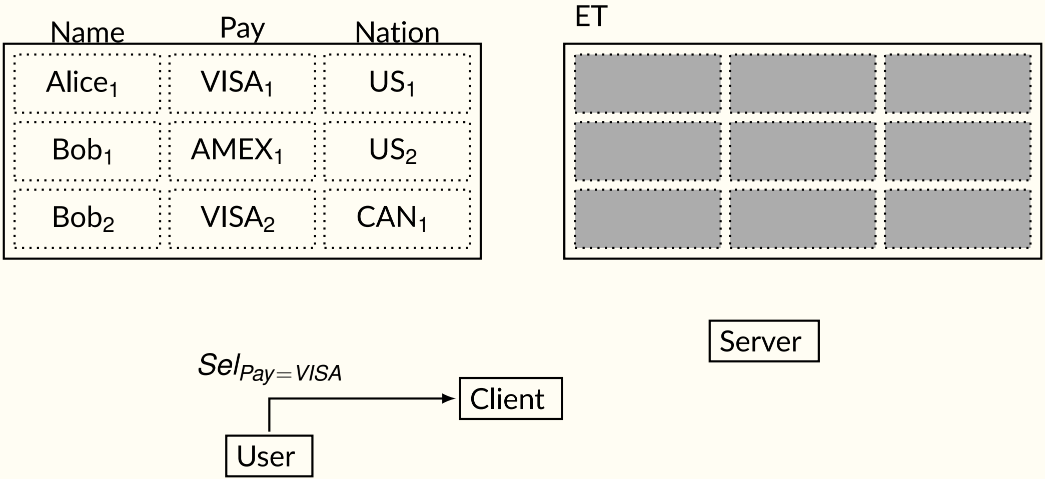


Server

Client

User

Encrypted Selection



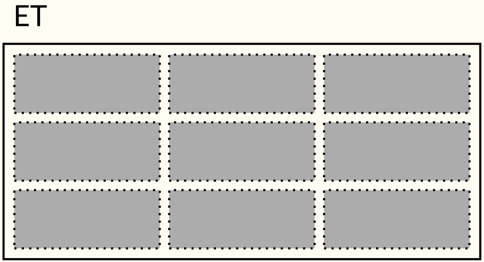
Name	Pay	Nation
Alice_1	VISA_1	US_1
Bob_1	AMEX_1	US_2
Bob_2	VISA_2	CAN_1

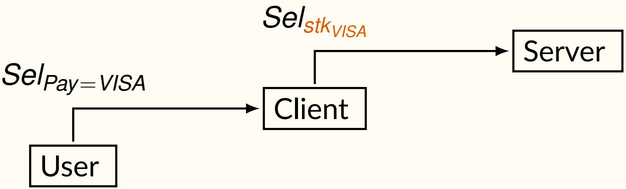
ET

$Sel_{Pay=VISA}$

Encrypted Selection

Name	Pay	Nation
$Alice_1$	$VISA_1$	US_1
Bob_1	$AMEX_1$	US_2
Bob_2	$VISA_2$	CAN_1

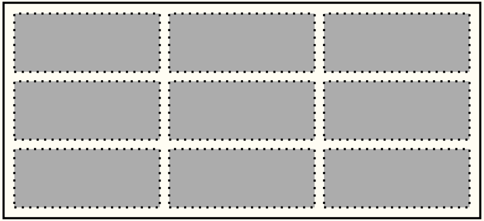


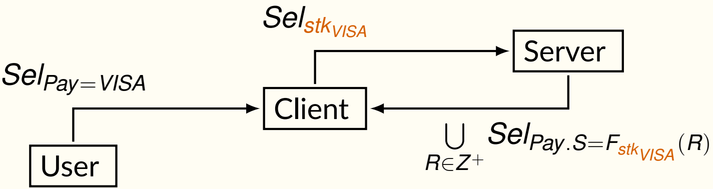


Encrypted Selection

Name	Pay	Nation
Alice_1	VISA_1	US_1
Bob_1	AMEX_1	US_2
Bob_2	VISA_2	CAN_1

ET



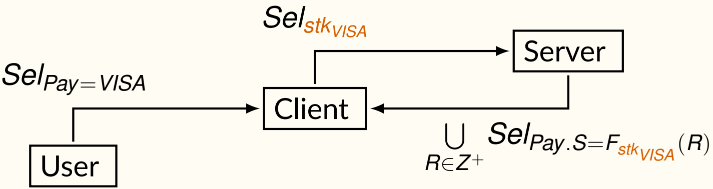


Encrypted Selection

Name	Pay	Nation
$Alice_1$	$VISA_1$	US_1
Bob_1	$AMEX_1$	US_2
Bob_2	$VISA_2$	CAN_1

ET

▨	S	▨
▨	S	▨
▨	S	▨



$Sel_{stk_{VISA}}$

Server

$Sel_{Pay=VISA}$

Client

$\bigcup_{R \in Z^+} Sel_{Pay.S=F_{stk_{VISA}}(R)}$

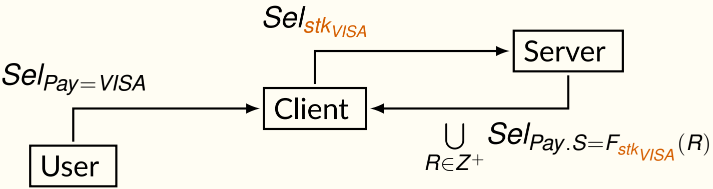
User

Encrypted Selection

Name	Pay	Nation
$Alice_1$	$VISA_1$	US_1
Bob_1	$AMEX_1$	US_2
Bob_2	$VISA_2$	CAN_1

ET

▨	$F_{stk_{VISA}}(1)$	▨
▨	$F_{stk_{AMEX}}(1)$	▨
▨	$F_{stk_{VISA}}(2)$	▨



$Sel_{stk_{VISA}}$

Server

$Sel_{Pay=VISA}$

Client

User

$\bigcup_{R\in Z^+} Sel_{Pay.S=F_{stk_{VISA}}(R)}$

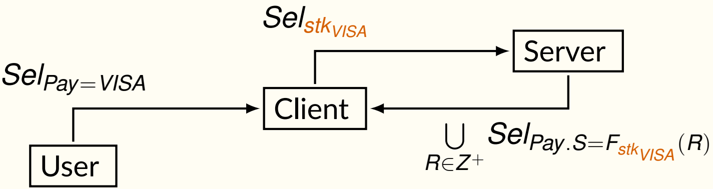
Encrypted Selection

Name	Pay	Nation
Alice_1	VISA_1	US_1
Bob_1	AMEX_1	US_2
Bob_2	VISA_2	CAN_1

ET

Run: $\sigma_{Pay.S=F_{stk_{VISA}}}(1)$

▨	$F_{stk_{VISA}}(1)$	▨
▨	$F_{stk_{AMEX}}(1)$	▨
▨	$F_{stk_{VISA}}(2)$	▨



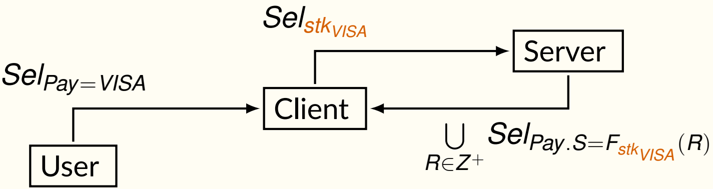
Encrypted Selection

Name	Pay	Nation
Alice_1	VISA_1	US_1
Bob_1	AMEX_1	US_2
Bob_2	VISA_2	CAN_1

ET

Run: $\sigma_{Pay.S=F_{stk_{VISA}}(1)}$

▨	🟩	▨
▨	$F_{stk_{AMEX}}(1)$	▨
▨	$F_{stk_{VISA}}(2)$	▨



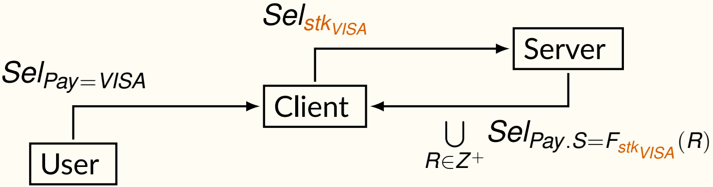
Encrypted Selection

Name	Pay	Nation
Alice_1	$\boxed{\text{VISA}_1}$	US_1
Bob_1	AMEX_1	US_2
Bob_2	VISA_2	CAN_1

ET

Run: $\sigma_{Pay.S=F_{stk_{VISA}}}(2)$

▨	🟩	▨
▨	$F_{stk_{AMEX}}(1)$	▨
▨	$F_{stk_{VISA}}(2)$	▨

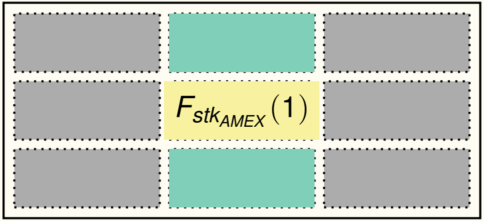


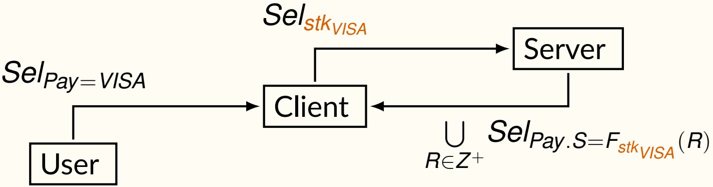
Encrypted Selection

Name	Pay	Nation
Alice$_1$	VISA$_1$	US$_1$
Bob$_1$	AMEX$_1$	US$_2$
Bob$_2$	VISA$_2$	CAN$_1$

ET

Run: $\sigma_{Pay.S=F_{stk_{VISA}}}(2)$





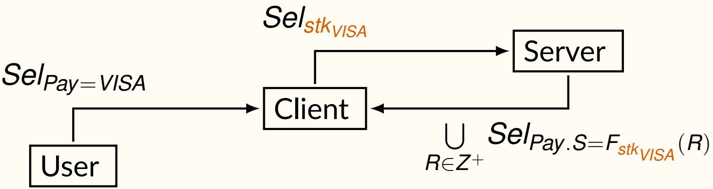
Encrypted Selection

Name	Pay	Nation
Alice_1	VISA_1	US_1
Bob_1	AMEX_1	US_2
Bob_2	VISA_2	CAN_1

ET

Run: $\sigma_{Pay.S=F_{stk_{VISA}}}(3)$

▨	🟩	▨
▨	$F_{stk_{AMEX}}(1)$	▨
▨	🟩	▨

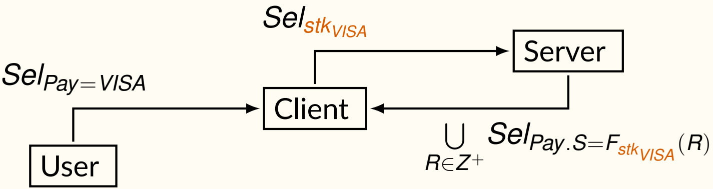


Encrypted Selection

Name	Pay	Nation
Alice$_1$	VISA$_1$	US$_1$
Bob$_1$	AMEX$_1$	US$_2$
Bob$_2$	VISA$_2$	CAN$_1$

ET

	Done	
▨	🟩	▨
▨	$F_{stk_{AMEX}}(1)$	▨
▨	🟩	▨

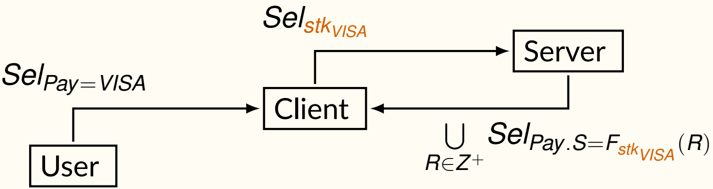


Encrypted Selection

Name	Pay	Nation
$Alice_1$	$VISA_1$	US_1
Bob_1	$AMEX_1$	US_2
Bob_2	$VISA_2$	CAN_1

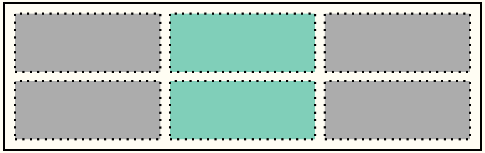
ET

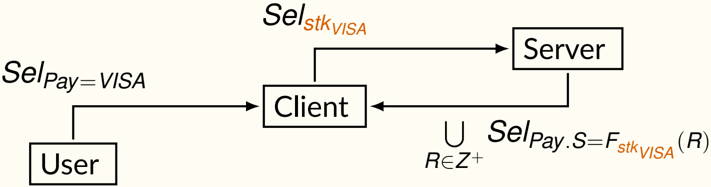
▨	🟩	▨
□	□	□
▨	🟩	▨



Encrypted Selection

Result ET





$Sel_{stk_{VISA}}$

Server

$Sel_{Pay=VISA}$

Client

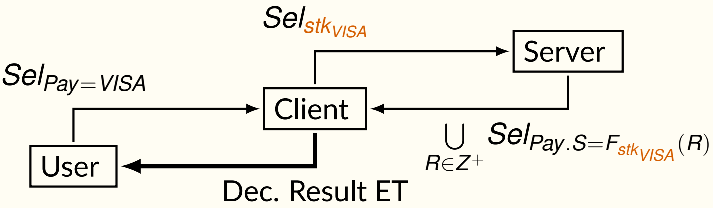
User

$\bigcup_{R \in Z^+} Sel_{Pay.S=F_{stk_{VISA}}(R)}$

Encrypted Selection

Result ET

$D_K(EV)$	$D_K(EV)$	$D_K(EV)$
$D_K(EV)$	$D_K(EV)$	$D_K(EV)$



$Sel_{stk_{VISA}}$

Server

$Sel_{Pay=VISA}$

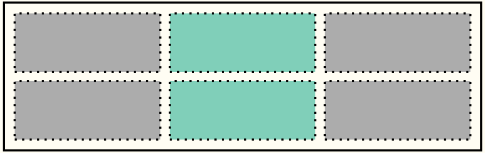
Client

$\bigcup_{R \in Z^+} Sel_{Pay.S=F_{stk_{VISA}}(R)}$

User

Dec. Result ET

Encrypted Selection

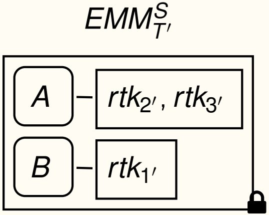


Result ET

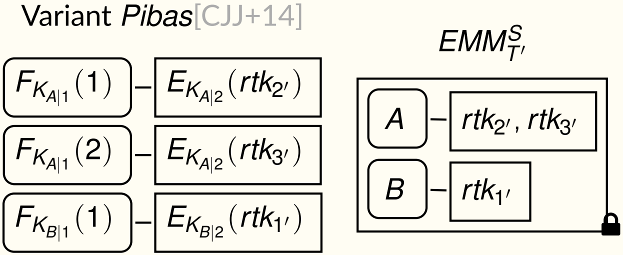
Encrypted Selection

- Leakage: equality pattern in result, etc.
- Sublinear cost.
- Locality.

Emulation of Pibas EMM [CJJ+14]



Emulation of Pibas EMM [CJJ+14]



Variant *Pibas*[CJJ+14]

$F_{K_{A|1}}(1)$ – $E_{K_{A|2}}(rtk_{2'})$

$F_{K_{A|1}}(2)$ – $E_{K_{A|2}}(rtk_{3'})$

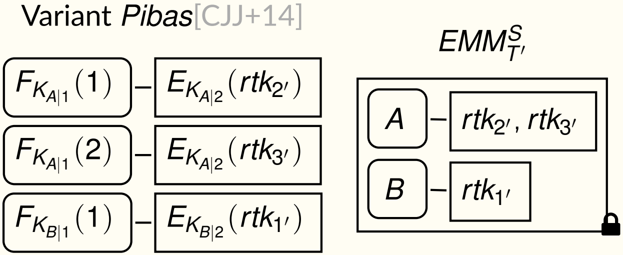
$F_{K_{B|1}}(1)$ – $E_{K_{B|2}}(rtk_{1'})$

$EMM^{S}_{T'}$

A – $rtk_{2'}, rtk_{3'}$

B – $rtk_{1'}$

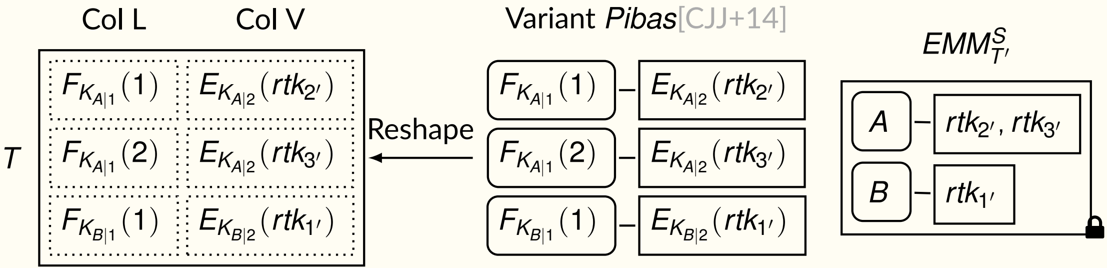
Emulation of Pibas EMM [CJJ+14]


Variant *Pibas*[CJJ+14]
$EMM^S_{T'}$
$F_{K_{A|1}}(1)$ – $E_{K_{A|2}}(rtk_{2'})$
$F_{K_{A|1}}(2)$ – $E_{K_{A|2}}(rtk_{3'})$
$F_{K_{B|1}}(1)$ – $E_{K_{B|2}}(rtk_{1'})$
A – $rtk_{2'}, rtk_{3'}$
B – $rtk_{1'}$

$Query(stk_A)$

```
$K_{A|1} = F_{stk_A}(1)$
$K_{A|2} = F_{stk_A}(2)$
For $R = 1, 2, \cdots$
    $v = Get(F_{K_{A|1}}(R))$
    Output $D_{K_{A|2}}(v)$
```

Emulation of Pibas EMM [CJJ+14]



T

Col L	Col V
$F_{K_{A\|1}}(1)$	$E_{K_{A\|2}}(rtk_{2'})$
$F_{K_{A\|1}}(2)$	$E_{K_{A\|2}}(rtk_{3'})$
$F_{K_{B\|1}}(1)$	$E_{K_{B\|2}}(rtk_{1'})$

Reshape

Variant *Pibas*[CJJ+14]

$F_{K_{A\|1}}(1)$	$E_{K_{A\|2}}(rtk_{2'})$
$F_{K_{A\|1}}(2)$	$E_{K_{A\|2}}(rtk_{3'})$
$F_{K_{B\|1}}(1)$	$E_{K_{B\|2}}(rtk_{1'})$

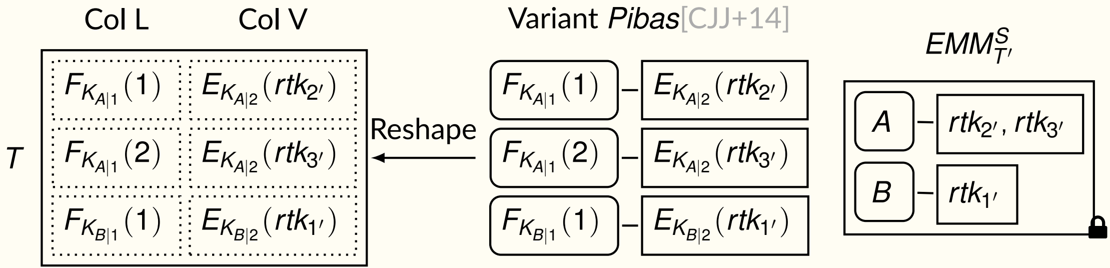
$EMM^{S}_{T'}$

A	$rtk_{2'}, rtk_{3'}$
B	$rtk_{1'}$

$Query(stk_A)$

```
$K_{A|1} = F_{stk_A}(1)$
$K_{A|2} = F_{stk_A}(2)$
For $R = 1, 2, \cdots$
    $v = Get(F_{K_{A|1}}(R))$
    Output $D_{K_{A|2}}(v)$
```

Emulation of Pibas EMM [CJJ+14]



	Col L	Col V
T	$F_{K_{A\|1}}(1)$	$E_{K_{A\|2}}(rtk_{2'})$
	$F_{K_{A\|1}}(2)$	$E_{K_{A\|2}}(rtk_{3'})$
	$F_{K_{B\|1}}(1)$	$E_{K_{B\|2}}(rtk_{1'})$

Reshape

Variant *Pibas*[CJJ+14]

$F_{K_{A|1}}(1)$ — $E_{K_{A|2}}(rtk_{2'})$

$F_{K_{A|1}}(2)$ — $E_{K_{A|2}}(rtk_{3'})$

$F_{K_{B|1}}(1)$ — $E_{K_{B|2}}(rtk_{1'})$

$EMM^S_{T'}$

A — $rtk_{2'}, rtk_{3'}$

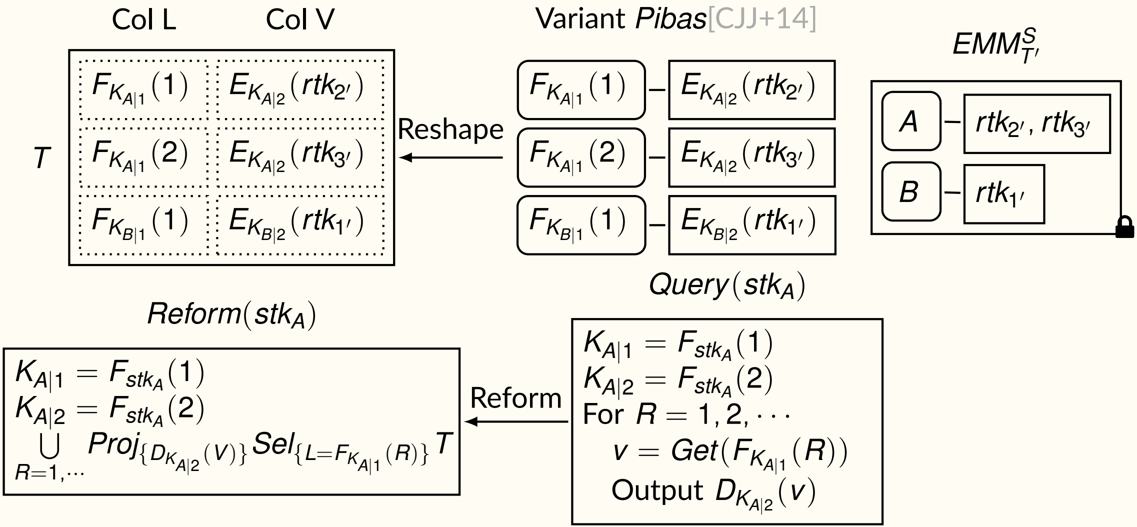
B — $rtk_{1'}$

$Query(stk_A)$

```
$K_{A|1} = F_{stk_A}(1)$
$K_{A|2} = F_{stk_A}(2)$
For $R = 1, 2, \cdots$
    $v = Get(F_{K_{A|1}}(R))$
    Output $D_{K_{A|2}}(v)$
```

- Recursive Common Table Expression in PostgreSQL
- New optimization rule (deferred)

Emulation of Pibas EMM [CJJ+14]



	Col L	Col V
T	$F_{K_{A\|1}}(1)$	$E_{K_{A\|2}}(rtk_{2'})$
	$F_{K_{A\|1}}(2)$	$E_{K_{A\|2}}(rtk_{3'})$
	$F_{K_{B\|1}}(1)$	$E_{K_{B\|2}}(rtk_{1'})$

Reshape

Variant *Pibas*[CJJ+14]

$F_{K_{A\|1}}(1)$	$E_{K_{A\|2}}(rtk_{2'})$
$F_{K_{A\|1}}(2)$	$E_{K_{A\|2}}(rtk_{3'})$
$F_{K_{B\|1}}(1)$	$E_{K_{B\|2}}(rtk_{1'})$

$EMM^{S}_{T'}$

A	$rtk_{2'}, rtk_{3'}$
B	$rtk_{1'}$

$Query(stk_A)$

```
$K_{A|1} = F_{stk_A}(1)$
$K_{A|2} = F_{stk_A}(2)$
For $R = 1, 2, \cdots$
    $v = Get(F_{K_{A|1}}(R))$
    Output $D_{K_{A|2}}(v)$
```

Reform

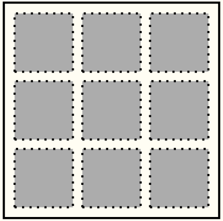
$Reform(stk_A)$

$$K_{A|1} = F_{stk_A}(1)$$
$$K_{A|2} = F_{stk_A}(2)$$
$$\bigcup_{R=1,\cdots} Proj_{\{D_{K_{A|2}}(V)\}} Sel_{\{L=F_{K_{A|1}}(R)\}}\, T$$

Encrypted Conjunction

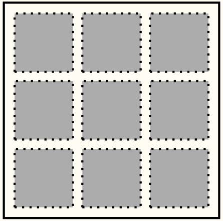
Encrypted Conjunction

Name	Pay	Nation
Alice_1	VISA_1	US_1
Bob_1	PayPal_1	US_2
Bob_2	VISA_2	CAN_1



Encrypted Conjunction

Name	Pay	Nation
Alice$_1$	VISA$_1$	US$_1$
Bob$_1$	PayPal$_1$	US$_2$
Bob$_2$	VISA$_2$	CAN$_1$

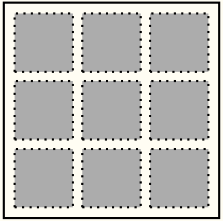


Conjunction

$\sigma_{Play=VISA \wedge Name=Bob}$

Encrypted Conjunction

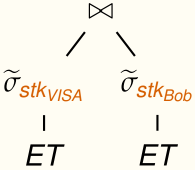
Name	Pay	Nation
Alice_1	VISA_1	US_1
Bob_1	PayPal_1	US_2
Bob_2	VISA_2	CAN_1



Conjunction

$$\sigma_{Play=VISA \wedge Name=Bob}$$

Approach 1



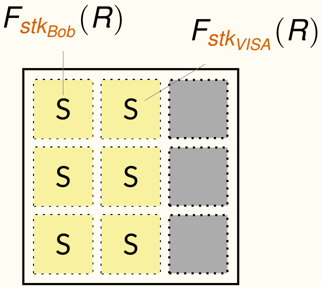
$$\bowtie$$

$\widetilde{\sigma}_{stk_{VISA}}$ $\widetilde{\sigma}_{stk_{Bob}}$

ET ET

Encrypted Conjunction

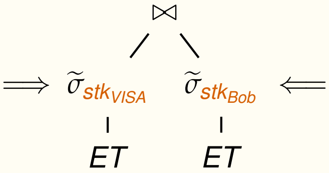
Name	Pay	Nation
Alice_1	VISA_1	US_1
Bob_1	PayPal_1	US_2
Bob_2	VISA_2	CAN_1



Conjunction

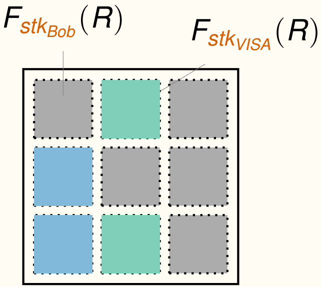
$\sigma_{Play=VISA \wedge Name=Bob}$

Approach 1


$\bowtie$
$\Longrightarrow$
$\widetilde{\sigma}_{stk_{VISA}}$
$\widetilde{\sigma}_{stk_{Bob}}$
$\Longleftarrow$
ET
ET

Encrypted Conjunction

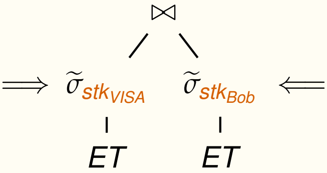
Name	Pay	Nation
Alice_1	VISA_1	US_1
Bob_1	PayPal_1	US_2
Bob_2	VISA_2	CAN_1



Conjunction

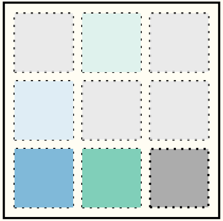
$\sigma_{Play=VISA \wedge Name=Bob}$

Approach 1


$\bowtie$
$\Longrightarrow$
$\widetilde{\sigma}_{stk_{VISA}}$
$\widetilde{\sigma}_{stk_{Bob}}$
$\Longleftarrow$
ET
ET

Encrypted Conjunction

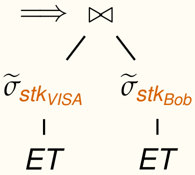
Name	Pay	Nation
Alice_1	VISA_1	US_1
Bob_1	PayPal_1	US_2
Bob_2	VISA_2	CAN_1



Conjunction

$\sigma_{Play=VISA \wedge Name=Bob}$

Approach 1



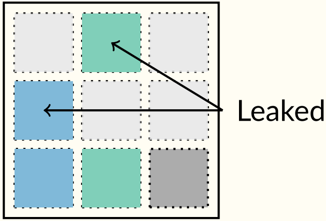
⟹ ⋈
$\widetilde{\sigma}_{stk_{VISA}}$
$\widetilde{\sigma}_{stk_{Bob}}$
ET
ET

Encrypted Conjunction

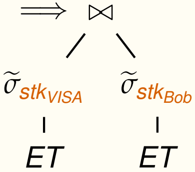
Name	Pay	Nation
Alice$_1$	VISA$_1$	US$_1$
Bob$_1$	PayPal$_1$	US$_2$
Bob$_2$	VISA$_2$	CAN$_1$

Conjunction

$$\sigma_{Play=VISA \wedge Name=Bob}$$

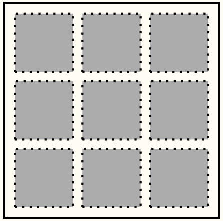


Approach 1

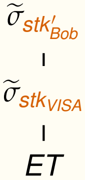

$\Longrightarrow$
$\bowtie$
$\widetilde{\sigma}_{stk_{VISA}}$
$\widetilde{\sigma}_{stk_{Bob}}$
ET
ET

Encrypted Conjunction

Name	Pay	Nation
Alice$_1$	VISA$_1$	US$_1$
Bob$_1$	PayPal$_1$	US$_2$
Bob$_2$	VISA$_2$	CAN$_1$



Approach 2



$\widetilde{\sigma}_{stk'_{Bob}}$

$\widetilde{\sigma}_{stk_{VISA}}$

ET

Encrypted Conjunction

Name	Pay	Nation
Alice_1	VISA_1	US_1
Bob_1	PayPal_1	US_2
Bob_2	VISA_2	CAN_1

▨	S	▨
▨	S	▨
▨	S	▨

Approach 2

$$\widetilde{\sigma}_{stk'_{Bob}}$$

$$|$$

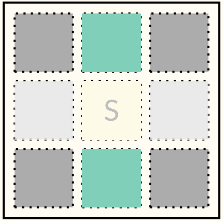
$$\Longrightarrow \widetilde{\sigma}_{stk_{VISA}}$$

$$|$$

$$ET$$

Encrypted Conjunction

Name	Pay	Nation
Alice_1	VISA_1	US_1
Bob_1	PayPal_1	US_2
Bob_2	VISA_2	CAN_1



Approach 2

$\widetilde{\sigma}_{stk'_{Bob}}$

|

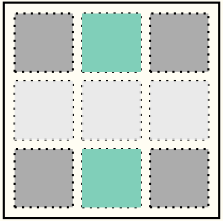
$\Longrightarrow \widetilde{\sigma}_{stk_{VISA}}$

|

ET

Encrypted Conjunction

Name	Pay	Nation
Alice_1	VISA_1	US_1
Bob_1	PayPal_1	US_2
Bob_2	VISA_2	CAN_1



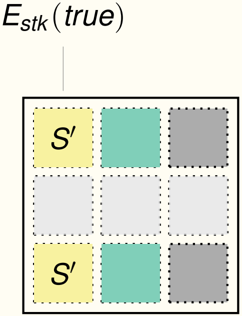
Approach 2

$$\Longrightarrow \widetilde{\sigma}_{stk'_{Bob}} \text{ —— } F_K(Name \,\|\, \boxed{\text{Bob}} \,\|\, Pay \,\|\, \boxed{\text{VISA}})$$

$$\begin{tikzcd} \widetilde{\sigma}_{stk'_{Bob}} \arrow[d, dash] \\ \widetilde{\sigma}_{stk_{VISA}} \arrow[d, dash] \\ ET \end{tikzcd}$$

Encrypted Conjunction

Name	Pay	Nation
$Alice_1$	$VISA_1$	US_1
Bob_1	$PayPal_1$	US_2
Bob_2	$VISA_2$	CAN_1



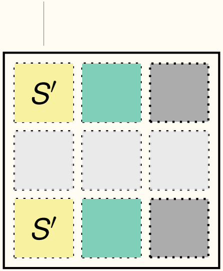
Approach 2

$$\Longrightarrow \begin{tikzcd}
\widetilde{\sigma}_{stk'_{Bob}} \arrow[r, dash] \arrow[d, dash] & F_K(Name \,\|\, \boxed{Bob} \,\|\, Pay \,\|\, \boxed{VISA}) \\
\widetilde{\sigma}_{stk_{VISA}} \arrow[d, dash] & \\
ET &
\end{tikzcd}$$

Encrypted Conjunction

$D_{stk'_{Bob}}(S') = true?$

Name	Pay	Nation
Alice$_1$	VISA$_1$	US$_1$
Bob$_1$	PayPal$_1$	US$_2$
Bob$_2$	VISA$_2$	CAN$_1$



Approach 2

$$\Longrightarrow \widetilde{\sigma}_{stk'_{Bob}} \;—\; F_K(Name \,\|\, \boxed{Bob} \,\|\, Pay \,\|\, \boxed{VISA})$$

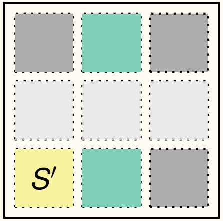
$$\widetilde{\sigma}_{stk_{VISA}}$$

$$ET$$

Encrypted Conjunction

Name	Pay	Nation
Alice$_1$	VISA$_1$	US$_1$
Bob$_1$	PayPal$_1$	US$_2$
$\boxed{\text{Bob}_2}$	$\boxed{\text{VISA}_2}$	CAN$_1$

$$D_{stk'_{Bob}}(S') = true?$$



Approach 2

$$\Longrightarrow \widetilde{\sigma}_{stk'_{Bob}} \text{ — } F_K(Name \| \boxed{\text{Bob}} \| Pay \| \boxed{\text{VISA}})$$

$$|$$

$$\widetilde{\sigma}_{stk_{VISA}}$$

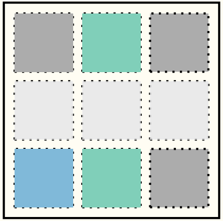
$$|$$

$$ET$$

Encrypted Conjunction

Name	Pay	Nation
Alice$_1$	VISA$_1$	US$_1$
Bob$_1$	PayPal$_1$	US$_2$
Bob$_2$	VISA$_2$	CAN$_1$

$$D_{stk'_{Bob}}(S') = true?$$



Approach 2

$$\Longrightarrow \widetilde{\sigma}_{stk'_{Bob}} \text{ --- } F_K(Name \,\|\, \boxed{Bob} \,\|\, Pay \,\|\, \boxed{VISA})$$

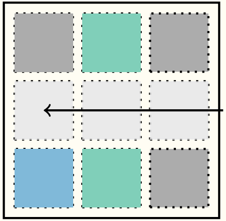
$$\widetilde{\sigma}_{stk_{VISA}}$$

$$ET$$

Encrypted Conjunction

$D_{stk'_{Bob}}(S') = true?$

Name	Pay	Nation
Alice$_1$	VISA$_1$	US$_1$
Bob$_1$	PayPal$_1$	US$_2$
Bob$_2$	VISA$_2$	CAN$_1$



Not leaked

Approach 2

$$\Longrightarrow \widetilde{\sigma}_{stk'_{Bob}} \text{ --- } F_K(Name \parallel \boxed{Bob} \parallel Pay \parallel \boxed{VISA})$$

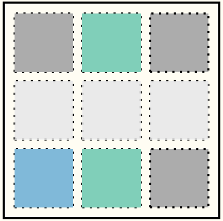
$$\widetilde{\sigma}_{stk_{VISA}}$$

$$ET$$

Encrypted Conjunction

Name	Pay	Nation
Alice_1	VISA_1	US_1
Bob_1	PayPal_1	US_2
Bob_2	VISA_2	CAN_1

Only check on smaller ET



Approach 2

$$\Longrightarrow \widetilde{\sigma}_{stk'_{Bob}} \text{ — } F_K(Name \parallel \boxed{Bob} \parallel Pay \parallel \boxed{VISA})$$

$$|$$

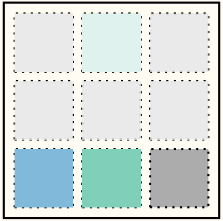
$$\widetilde{\sigma}_{stk_{VISA}}$$

$$|$$

$$ET$$

Encrypted Conjunction

Name	Pay	Nation
Alice_1	VISA_1	US_1
Bob_1	PayPal_1	US_2
Bob_2	VISA_2	CAN_1



Approach 2

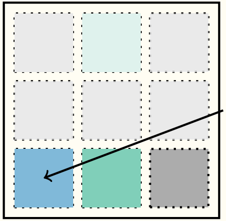
$$\Longrightarrow \widetilde{\sigma}_{stk'_{Bob}} \text{ — } F_K(Name \,\|\, \boxed{\text{Bob}} \,\|\, Pay \,\|\, \boxed{\text{VISA}})$$

$$\widetilde{\sigma}_{stk_{VISA}}$$

$$ET$$

Encrypted Conjunction

Name	Pay	Nation
Alice_1	VISA_1	US_1
Bob_1	PayPal_1	US_2
Bob_2	VISA_2	CAN_1



Leaked only $\bigcap$

Approach 2

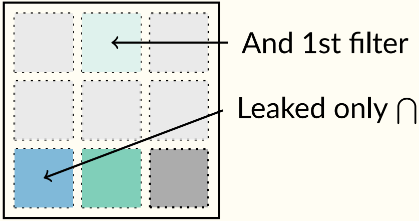
$$\Longrightarrow \widetilde{\sigma}_{stk'_{Bob}} \text{ —— } F_K(Name \,\|\, \boxed{Bob} \,\|\, Pay \,\|\, \boxed{VISA})$$

$$\widetilde{\sigma}_{stk_{VISA}}$$

$$ET$$

Encrypted Conjunction

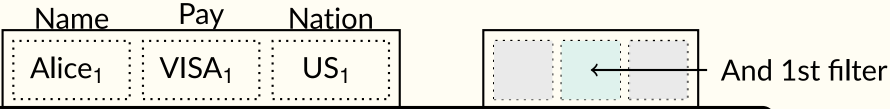
Name	Pay	Nation
Alice_1	VISA_1	US_1
Bob_1	PayPal_1	US_2
Bob_2	VISA_2	CAN_1



Approach 2

$$\begin{tikzcd} \Longrightarrow \widetilde{\sigma}_{stk'_{Bob}} \arrow[r, dash] \arrow[d, dash] & F_K(Name \parallel \boxed{Bob} \parallel Pay \parallel \boxed{VISA}) \\ \widetilde{\sigma}_{stk_{VISA}} \arrow[d, dash] & \\ ET & \end{tikzcd}$$

Encrypted Conjunction



ed only $\bigcap$

- Composition $\Longrightarrow$ leak less
- Ordering $\Longrightarrow$ smaller intermediate ETs $\Longrightarrow$ faster

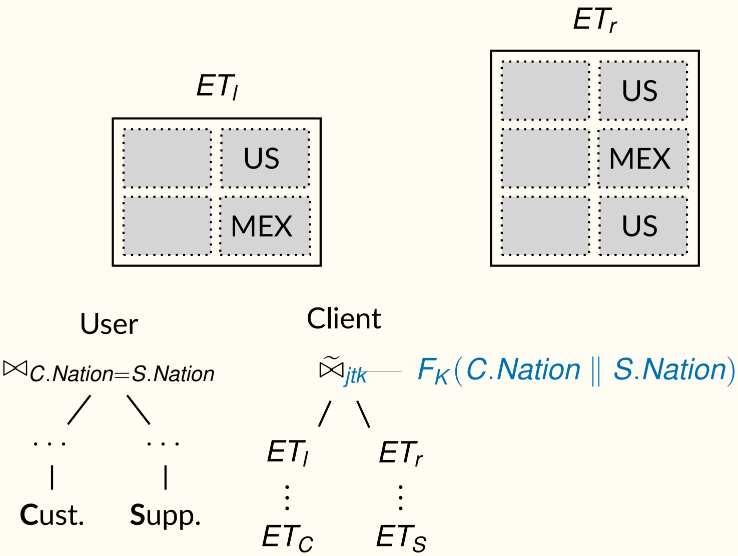
$$\Longrightarrow \widetilde{\sigma}_{stk'_{Bob}} \text{ — } F_K(Name \,\|\, \boxed{\text{Bob}} \,\|\, Pay \,\|\, \boxed{\text{VISA}})$$

$\widetilde{\sigma}_{stk_{VISA}}$

ET

Reducing Leakage

Reducing Leakage



ET_r

	US
	MEX
	US

ET_l

	US
	MEX

User

$\bowtie_{C.Nation=S.Nation}$

Cust. Supp.

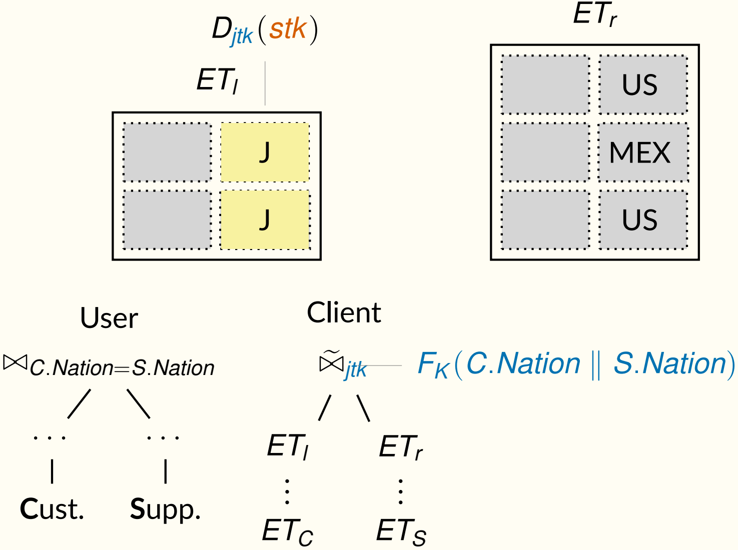
Client

$\widetilde{\bowtie}_{jtk}$ — $F_K(C.Nation \,\|\, S.Nation)$

ET_l ET_r

ET_C ET_S

Reducing Leakage



$D_{jtk}(stk)$

ET_l

	J
	J

ET_r

	US
	MEX
	US

User

$\bowtie_{C.Nation=S.Nation}$

$\cdots$ $\cdots$

Cust. Supp.

Client

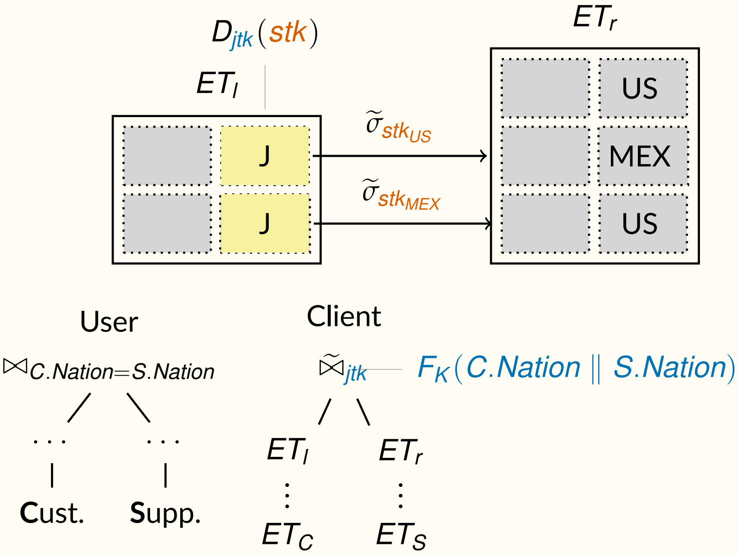
$\widetilde{\bowtie}_{jtk}$ $F_K(C.Nation \parallel S.Nation)$

ET_l ET_r

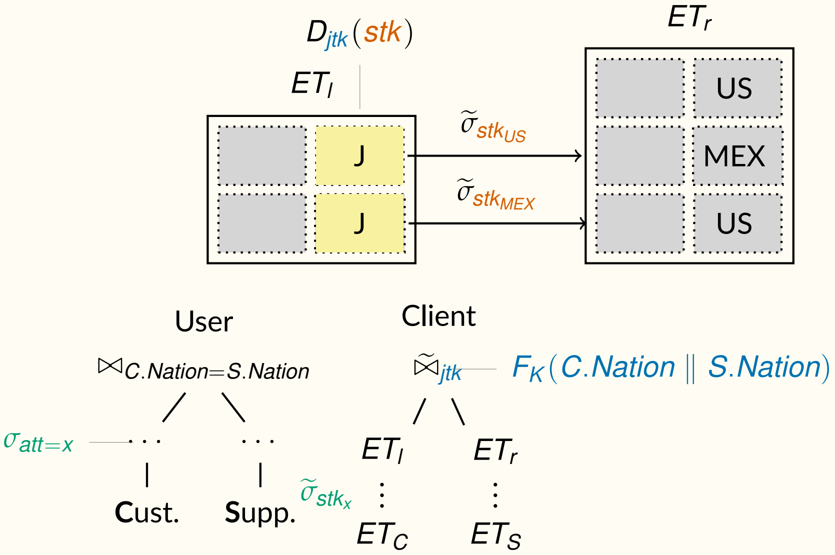
$\vdots$ $\vdots$

ET_C ET_S

Reducing Leakage


$D_{jtk}(stk)$
ET_l
J
J
$\widetilde{\sigma}_{stk_{US}}$
$\widetilde{\sigma}_{stk_{MEX}}$
ET_r
US
MEX
US
User
$\bowtie_{C.Nation=S.Nation}$
. . .
. . .
Cust.
Supp.
Client
$\widetilde{\bowtie}_{jtk}$
$F_K(C.Nation \parallel S.Nation)$
ET_l
ET_r
ET_C
ET_S

Reducing Leakage



$D_{jtk}(stk)$

ET_l

J

J

$\widetilde{\sigma}_{stk_{US}}$

$\widetilde{\sigma}_{stk_{MEX}}$

ET_r

US

MEX

US

User

$\bowtie_{C.Nation=S.Nation}$

$\sigma_{att=x}$ $\cdots$ $\cdots$

Cust. Supp.

Client

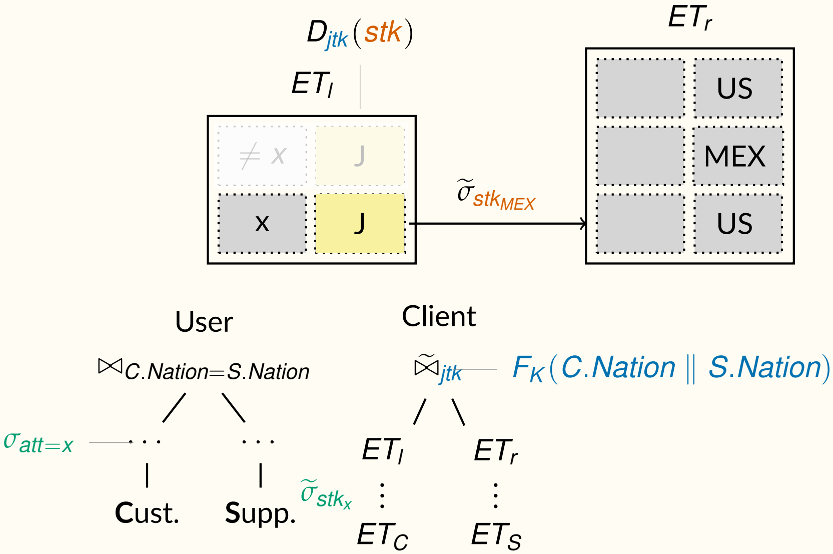
$\widetilde{\bowtie}_{jtk}$ $F_K(C.Nation \parallel S.Nation)$

ET_l ET_r

$\widetilde{\sigma}_{stk_x}$ $\vdots$ $\vdots$

ET_C ET_S

Reducing Leakage



$D_{jtk}(stk)$

ET_l

$\neq x$ | J

x | J

$\widetilde{\sigma}_{stk_{MEX}}$

ET_r

US

MEX

US

User

$\bowtie_{C.Nation=S.Nation}$

$\sigma_{att=x}$

Cust.

Supp.

Client

$\widetilde{\bowtie}_{jtk}$

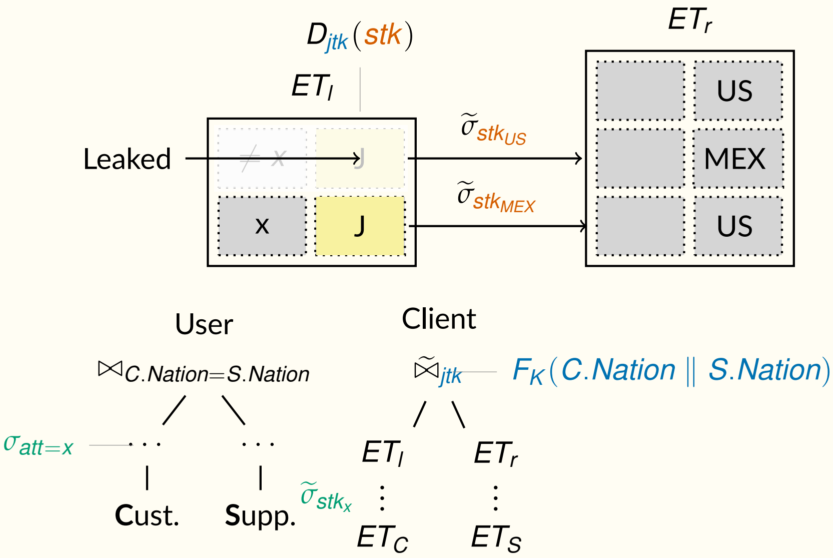
$F_K(C.Nation \parallel S.Nation)$

ET_l ET_r

$\widetilde{\sigma}_{stk_x}$

ET_C ET_S

Reducing Leakage



$D_{jtk}(stk)$

ET_l

ET_r

Leaked

$\neq x$ J

x J

$\widetilde{\sigma}_{stk_{US}}$

$\widetilde{\sigma}_{stk_{MEX}}$

US

MEX

US

User

Client

$\bowtie_{C.Nation=S.Nation}$

$\sigma_{att=x}$ $\cdots$ $\cdots$

Cust. Supp.

$\widetilde{\bowtie}_{jtk}$ $F_K(C.Nation \parallel S.Nation)$

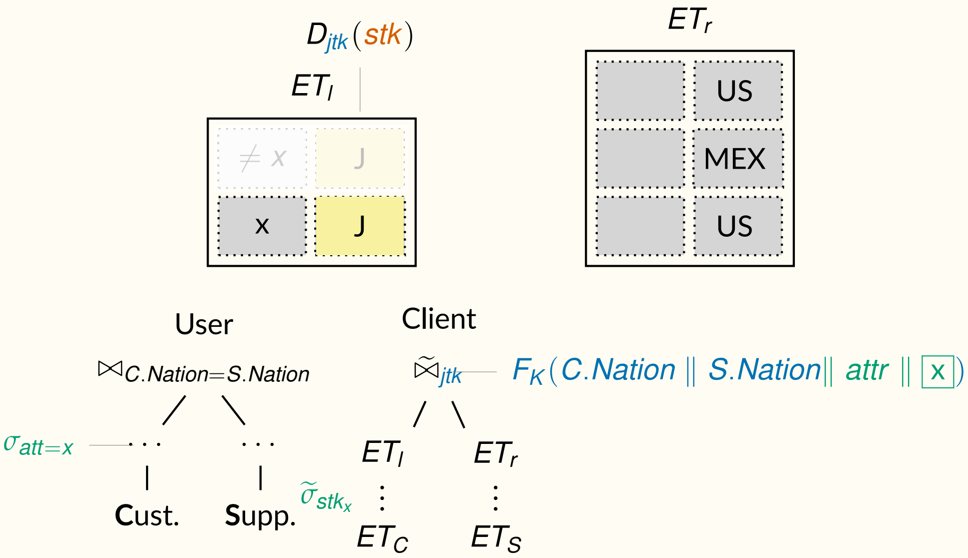
$\widetilde{\sigma}_{stk_x}$

ET_l ET_r

$\vdots$ $\vdots$

ET_C ET_S

Reducing Leakage



$D_{jtk}(stk)$

ET_l

$\neq x$	J
x	J

ET_r

	US
	MEX
	US

User

$\bowtie_{C.Nation=S.Nation}$

$\sigma_{att=x}$

Cust.

Supp.

Client

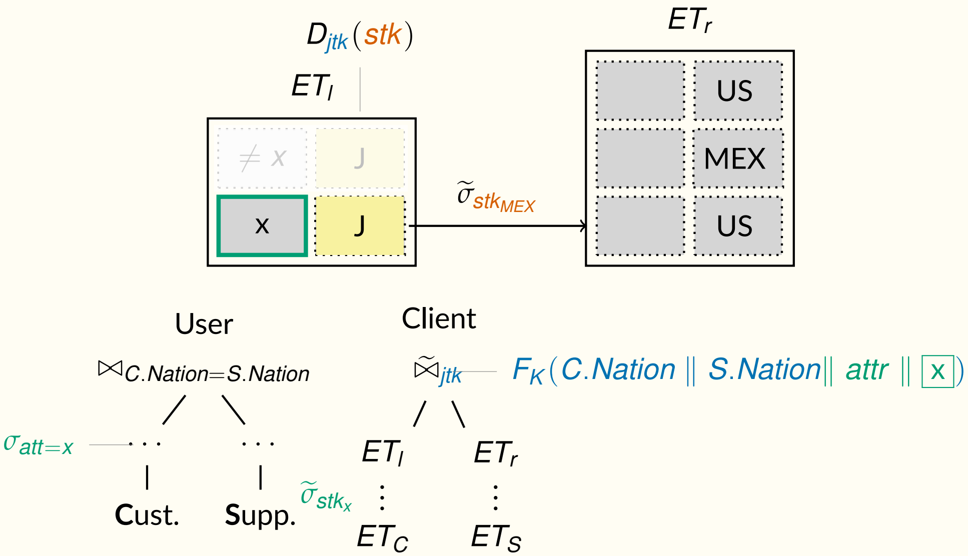
$\widetilde{\bowtie}_{jtk}$ $F_K(C.Nation \,\|\, S.Nation \| \; attr \,\|\, \boxed{x})$

$\widetilde{\sigma}_{stk_x}$

ET_l ET_r

ET_C ET_S

Reducing Leakage



$D_{jtk}(stk)$

ET_l

$\neq x$ | J

x | J

$\widetilde{\sigma}_{stk_{MEX}}$

ET_r

US

MEX

US

User

$\bowtie_{C.Nation=S.Nation}$

$\sigma_{att=x}$ . . .

. . .

Cust.

Supp.

Client

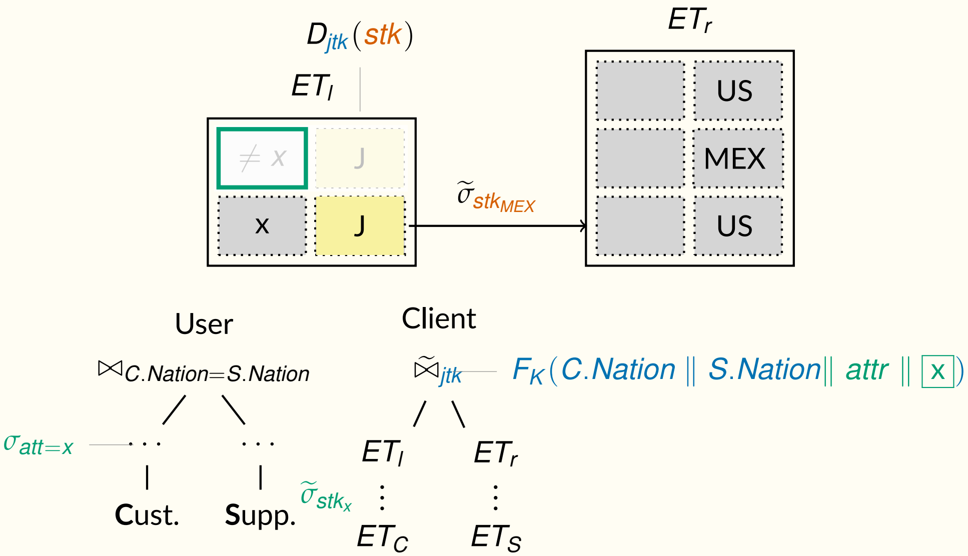
$\widetilde{\bowtie}_{jtk}$ $F_K(C.Nation \parallel S.Nation \parallel attr \parallel \boxed{x})$

$\widetilde{\sigma}_{stk_x}$

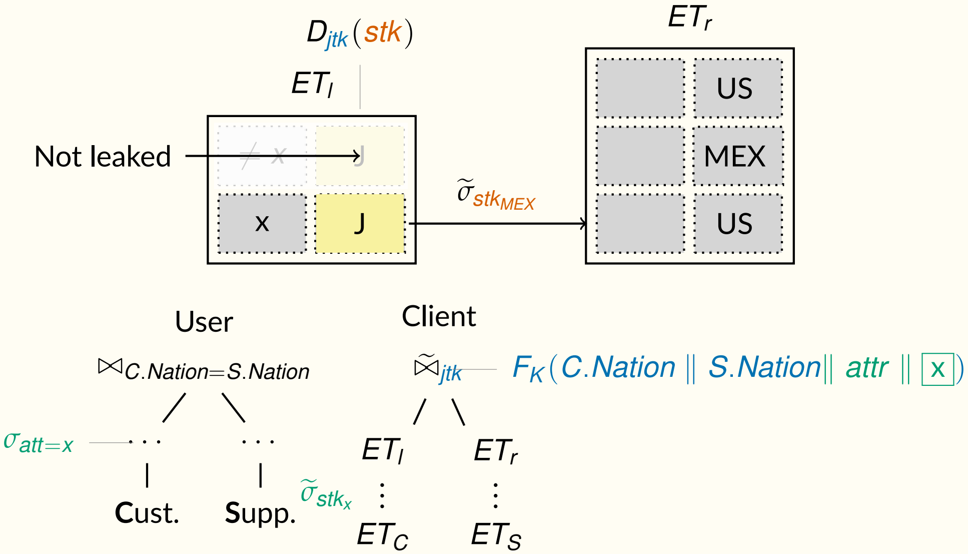
ET_l ET_r

ET_C ET_S

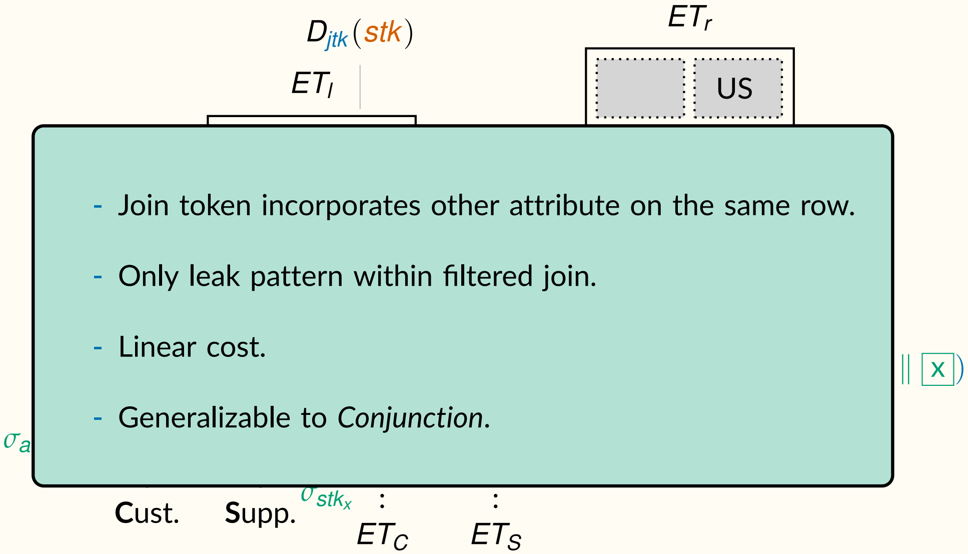
Reducing Leakage


$D_{jtk}(stk)$
ET_l
$\neq x$
J
x
J
$\widetilde{\sigma}_{stk_{MEX}}$
ET_r
US
MEX
US
User
$\bowtie_{C.Nation=S.Nation}$
$\sigma_{att=x}$
Cust.
Supp.
Client
$\widetilde{\bowtie}_{jtk}$
$F_K(C.Nation \parallel S.Nation \parallel attr \parallel \boxed{x})$
ET_l
ET_r
$\widetilde{\sigma}_{stk_x}$
ET_C
ET_S

Reducing Leakage


$D_{jtk}(stk)$
ET_l
ET_r
Not leaked
$\neq x$
J
x
J
$\widetilde{\sigma}_{stk_{MEX}}$
US
MEX
US
User
Client
$\bowtie_{C.Nation=S.Nation}$
$\sigma_{att=x}$
Cust.
Supp.
$\widetilde{\bowtie}_{jtk}$
$F_K(C.Nation \parallel S.Nation \parallel attr \parallel \boxed{x})$
$\widetilde{\sigma}_{stk_x}$
ET_l
ET_r
ET_C
ET_S

Reducing Leakage

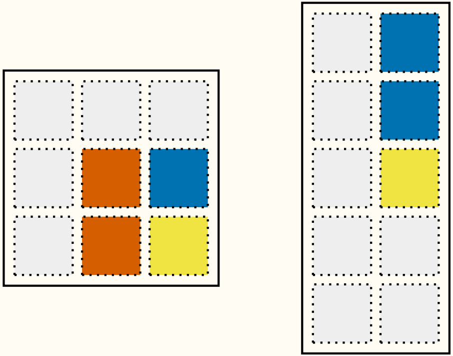


- Join token incorporates other attribute on the same row.
- Only leak pattern within filtered join.
- Linear cost.
- Generalizable to *Conjunction*.

Security

Simulation

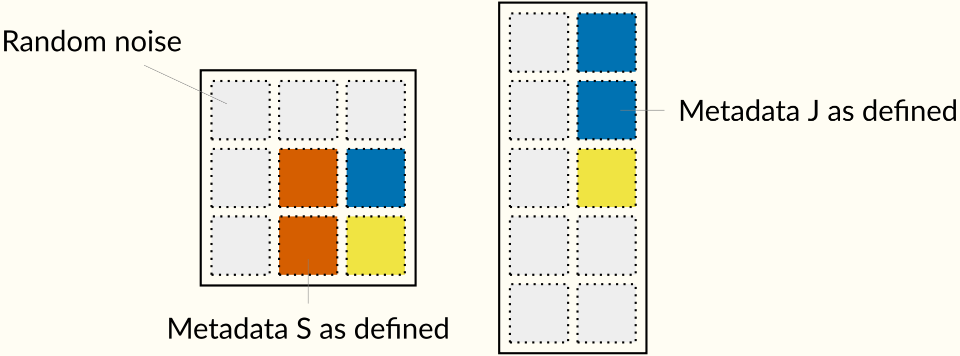
Show: leaks patterns in query result and nothing else.



Simulation

Show: leaks patterns in query result and nothing else.

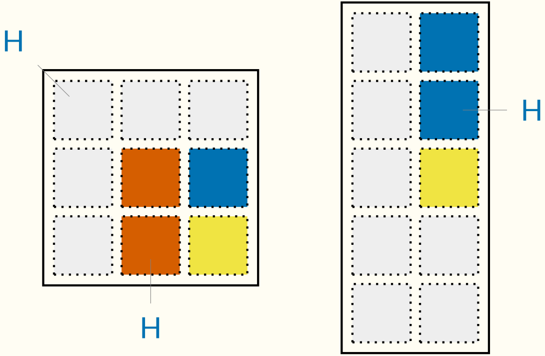
- Non-adaptive security: swap non-queried cells with random noise



Simulation

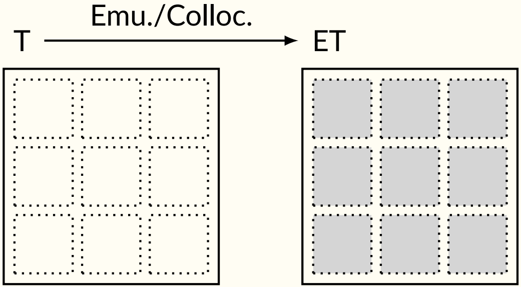
Show: leaks patterns in query result and nothing else.

- Adaptive security in ROM: $F_K(x) \doteq H(K \parallel x)$, $E_K(m) \doteq (r, H(K \parallel r) \oplus m)$ for random K, r.

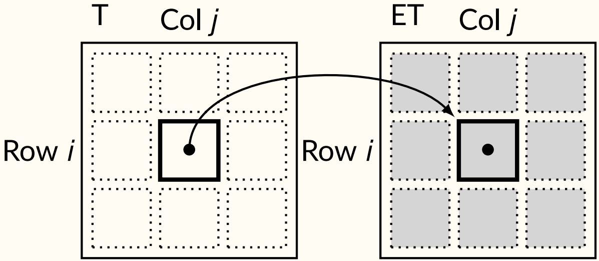


Encrypted Table

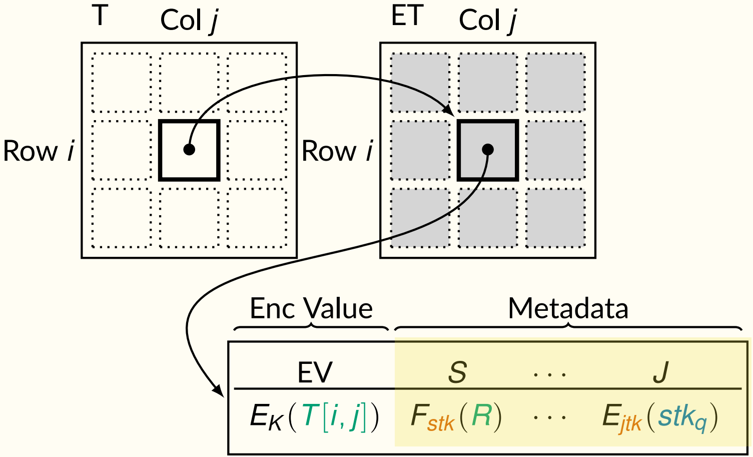
Encrypted Table



Encrypted Table



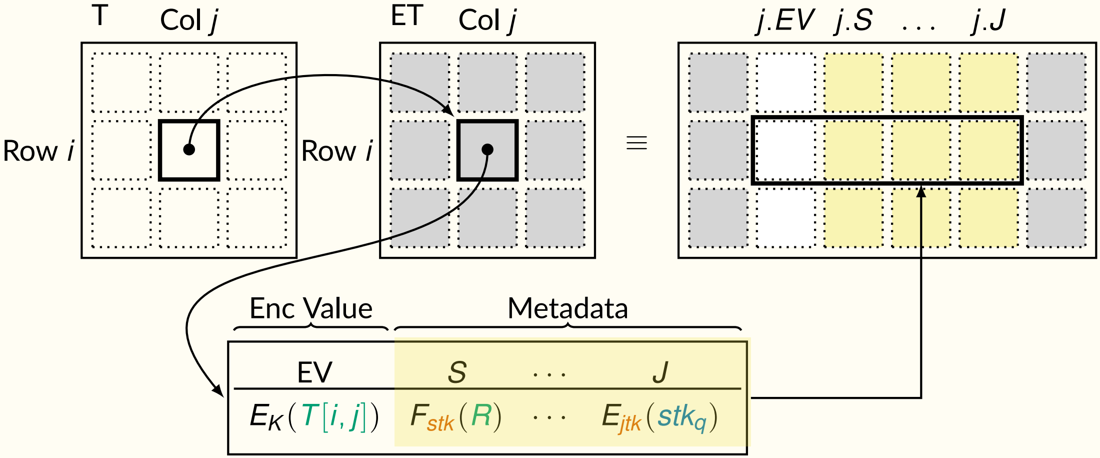
Encrypted Table



EV	S	$\cdots$	J
$E_K(T[i,j])$	$F_{stk}(R)$	$\cdots$	$E_{jtk}(stk_q)$

Collocated from $EMM^R, EMM^S, EMM^J, \cdots$

Encrypted Table



Collocated from $EMM^R, EMM^S, EMM^J, \cdots$

Encrypted Join

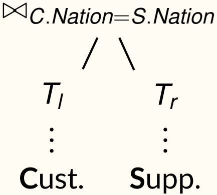
T_l

	US
	MEX

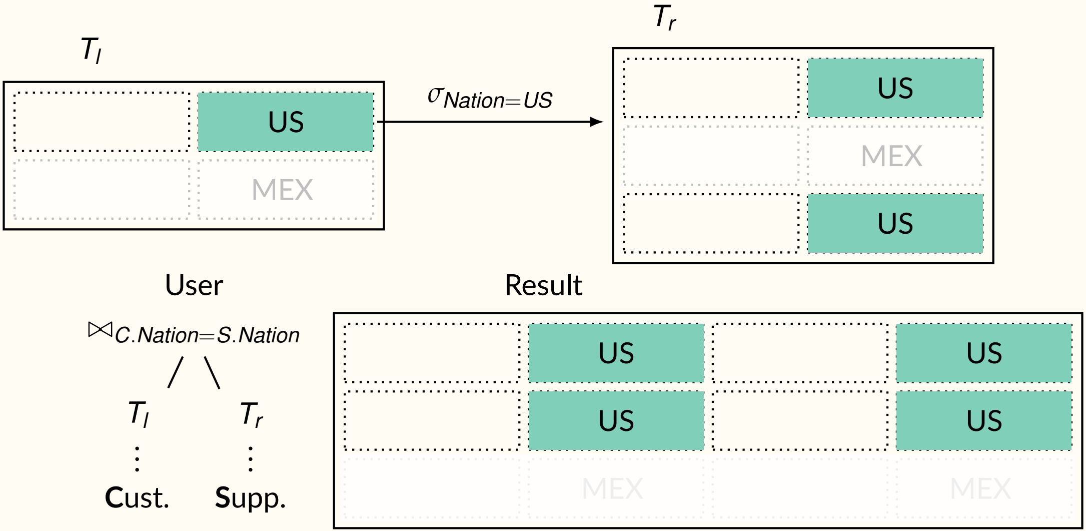
T_r

	US
	MEX
	US

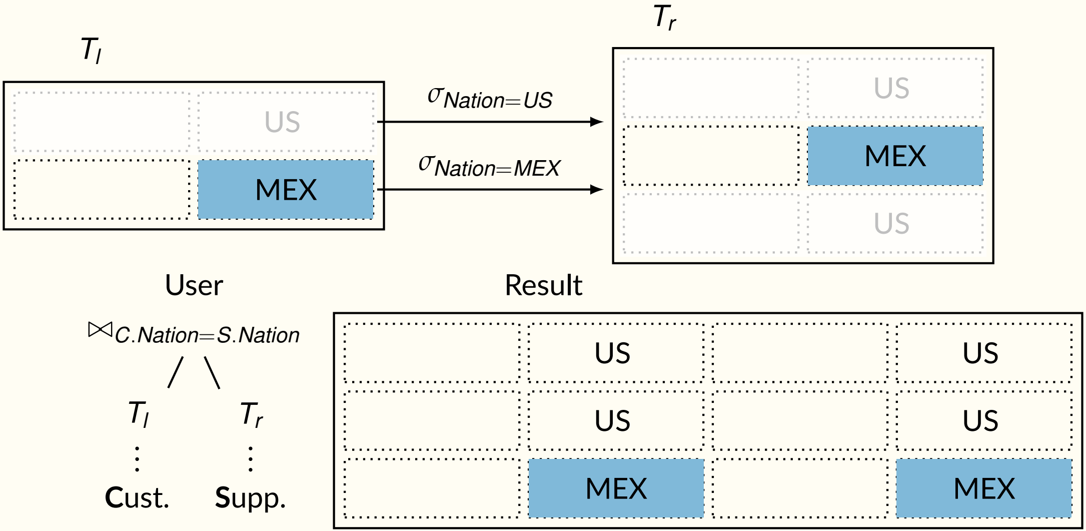
User



Encrypted Join



Encrypted Join



T_l

	US
	MEX

$\sigma_{Nation=US}$

$\sigma_{Nation=MEX}$

T_r

	US
	MEX
	US

User

$\bowtie_{C.Nation=S.Nation}$

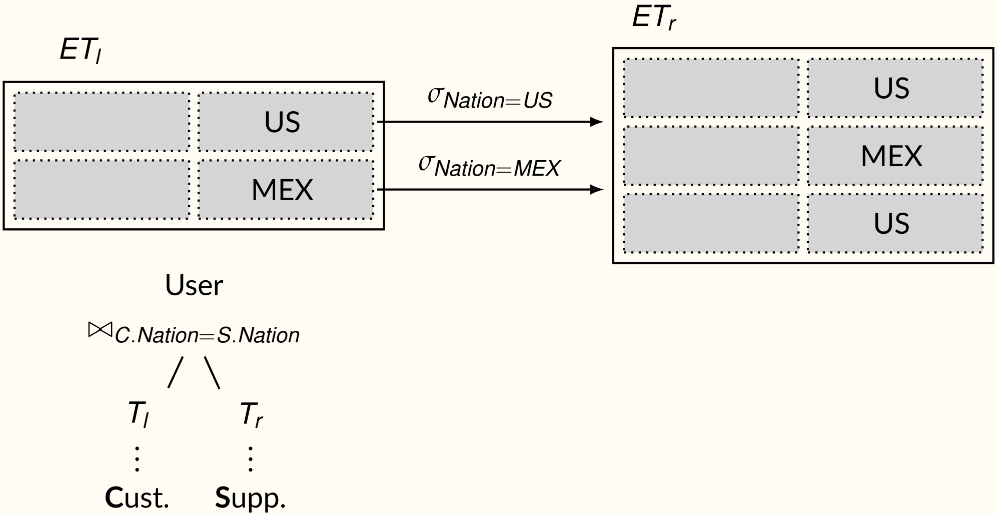
T_l T_r

Cust. Supp.

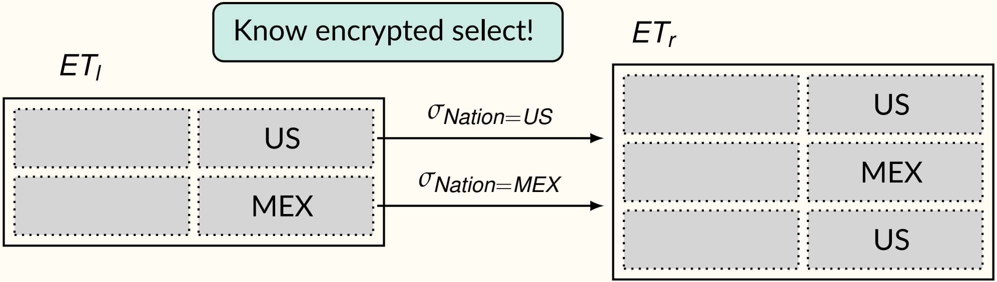
Result

	US		US
	US		US
	MEX		MEX

Encrypted Join



Encrypted Join



Know encrypted select!

ET_l

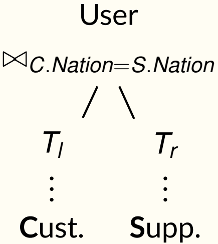
	US
	MEX

$\sigma_{Nation=US}$

$\sigma_{Nation=MEX}$

ET_r

	US
	MEX
	US



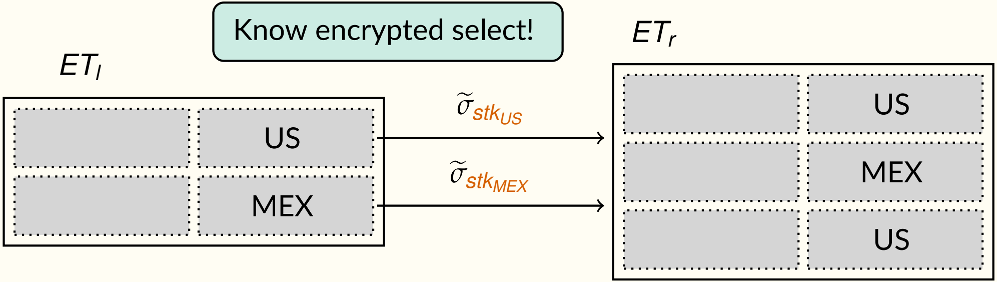
User

$\bowtie_{C.Nation=S.Nation}$

T_l T_r

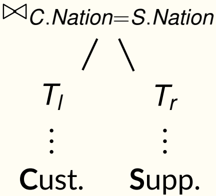
Cust. **Supp.**

Encrypted Join

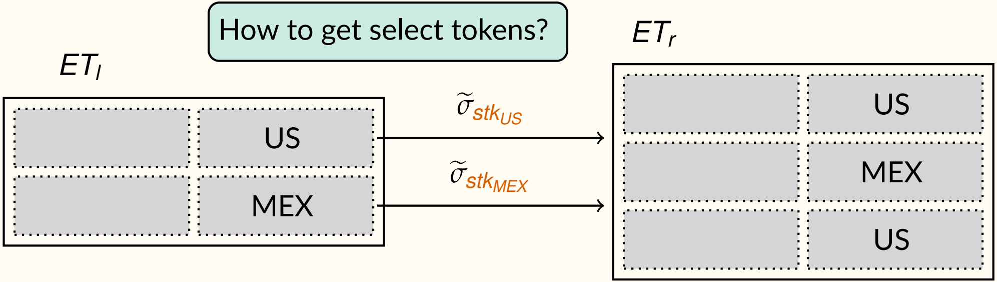

Know encrypted select!

ET_l
US
MEX
$\widetilde{\sigma}_{stk_{US}}$
$\widetilde{\sigma}_{stk_{MEX}}$
ET_r
US
MEX
US

User



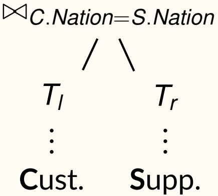
Encrypted Join



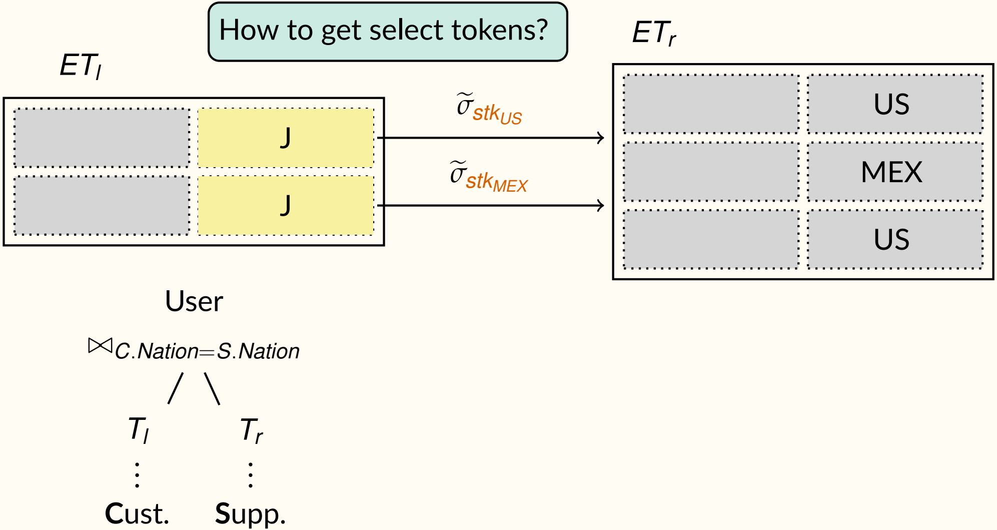
How to get select tokens?

ET_l
US
MEX
$\widetilde{\sigma}_{stk_{US}}$
$\widetilde{\sigma}_{stk_{MEX}}$
ET_r
US
MEX
US

User



Encrypted Join



How to get select tokens?

ET_l

J

J

$\widetilde{\sigma}_{stk_{US}}$

$\widetilde{\sigma}_{stk_{MEX}}$

ET_r

US

MEX

US

User

$\bowtie_{C.Nation=S.Nation}$

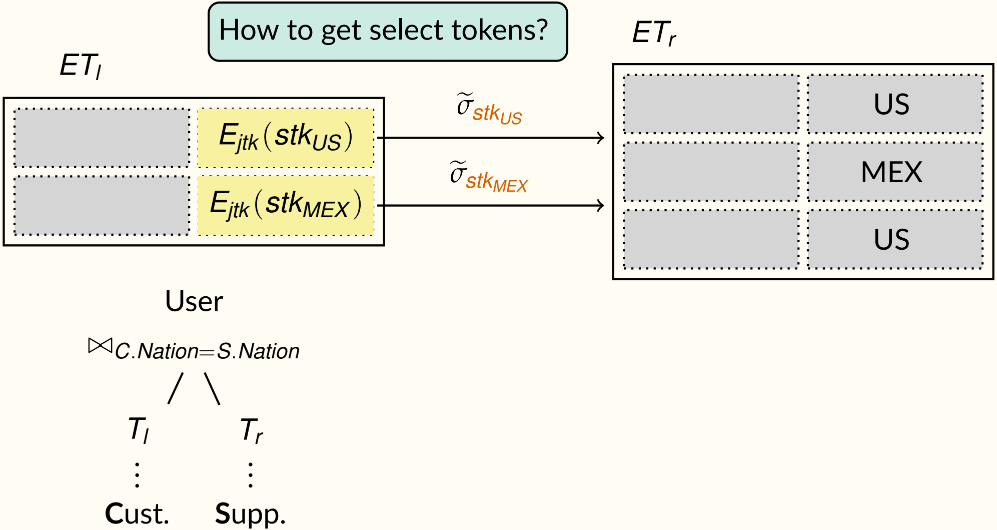
T_l

T_r

Cust.

Supp.

Encrypted Join

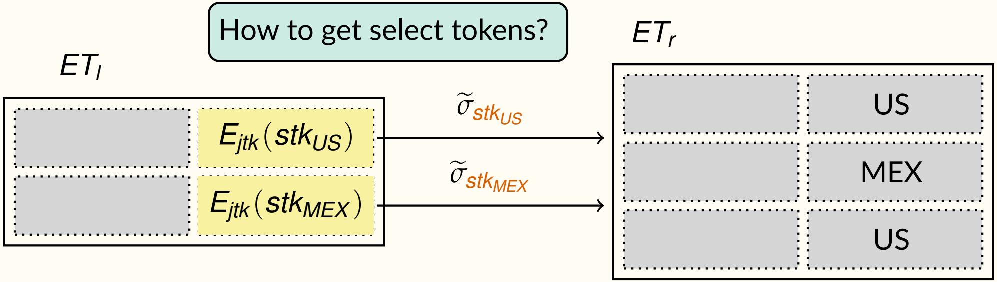


How to get select tokens?

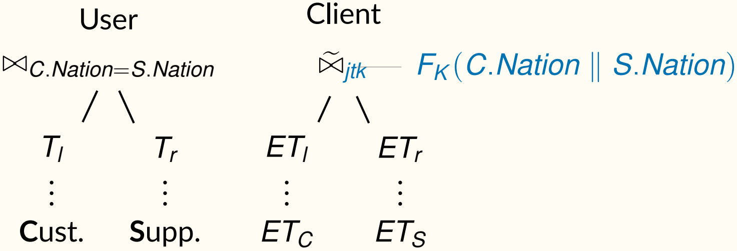
ET_l
$E_{jtk}(stk_{US})$
$E_{jtk}(stk_{MEX})$
$\widetilde{\sigma}_{stk_{US}}$
$\widetilde{\sigma}_{stk_{MEX}}$
ET_r
US
MEX
US
User
$\bowtie_{C.Nation=S.Nation}$
T_l
T_r
Cust.
Supp.

Encrypted Join

How to get select tokens?



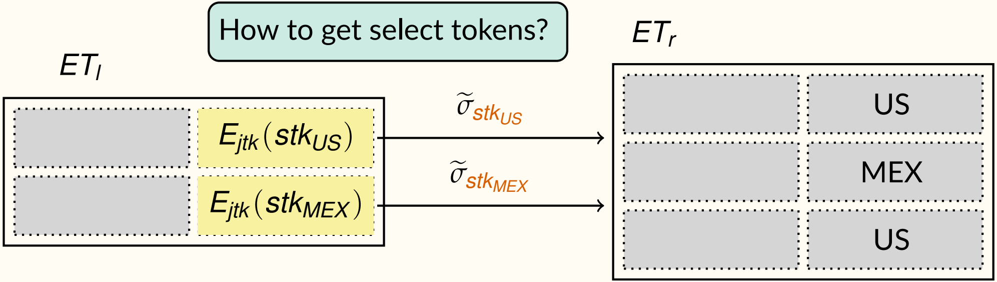
ET_l
$E_{jtk}(stk_{US})$
$E_{jtk}(stk_{MEX})$
$\widetilde{\sigma}_{stk_{US}}$
$\widetilde{\sigma}_{stk_{MEX}}$
ET_r
US
MEX
US

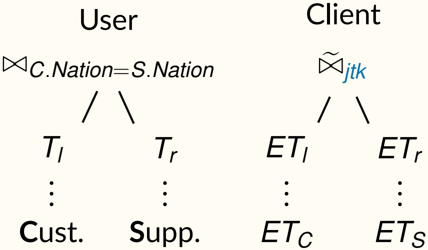


User
$\bowtie_{C.Nation=S.Nation}$
T_l
T_r
Cust.
Supp.
Client
$\widetilde{\bowtie}_{jtk}$
$F_K(C.Nation \parallel S.Nation)$
ET_l
ET_r
ET_C
ET_S

Encrypted Join

How to get select tokens?

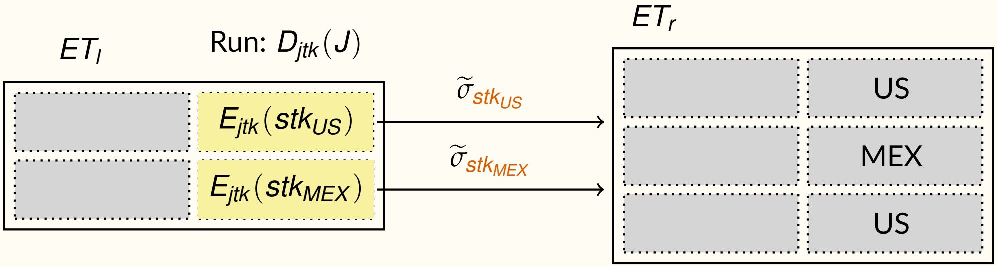

ET_l
$E_{jtk}(stk_{US})$
$E_{jtk}(stk_{MEX})$
$\widetilde{\sigma}_{stk_{US}}$
$\widetilde{\sigma}_{stk_{MEX}}$
ET_r
US
MEX
US

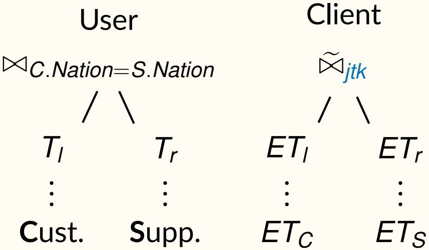


Server

```
For i-th row $\in ET_l$:
    Let $stk_i \leftarrow D_{jtk}(J_i)$,
    Output $ET_l[i,\cdot] \times \widetilde{\sigma}_{stk_i}(ET_r)$
```

Encrypted Join

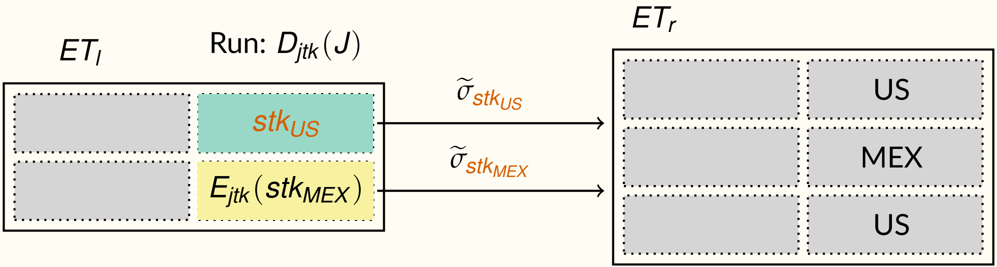


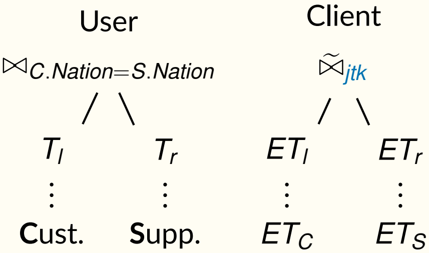


Server

```
For i-th row $\in ET_l$:
    Let $stk_i \leftarrow D_{jtk}(J_i)$,
    Output $ET_l[i,\cdot] \times \tilde{\sigma}_{stk_i}(ET_r)$
```

Encrypted Join

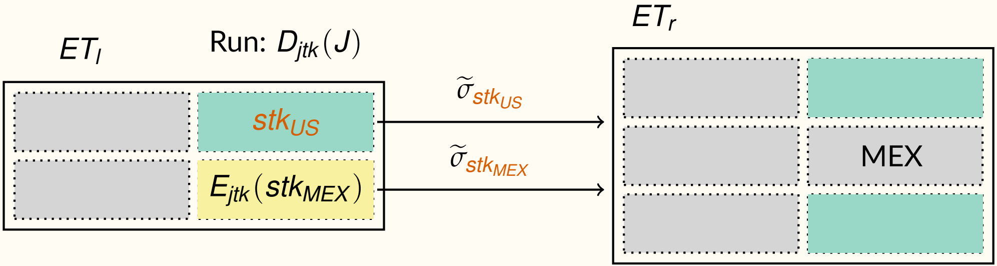


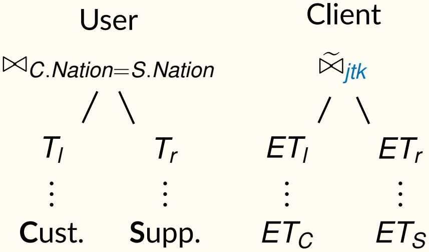


Server

```
For i-th row $\in ET_l$:
    Let $stk_i \leftarrow D_{jtk}(J_i)$,
    Output $ET_l[i,\cdot] \times \tilde{\sigma}_{stk_i}(ET_r)$
```

Encrypted Join

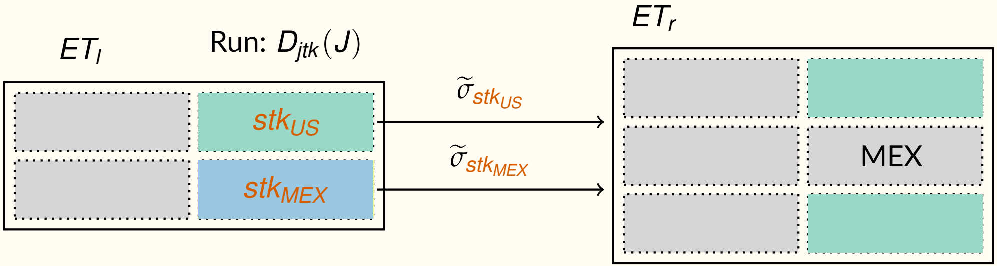

ET_l
Run: $D_{jtk}(J)$
stk_{US}
$E_{jtk}(stk_{MEX})$
$\widetilde{\sigma}_{stk_{US}}$
$\widetilde{\sigma}_{stk_{MEX}}$
ET_r
MEX



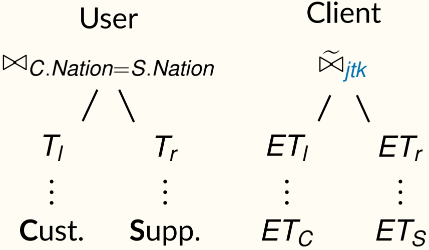
Server

```
For i-th row $\in ET_l$:
    Let $stk_i \leftarrow D_{jtk}(J_i)$,
    Output $ET_l[i, \cdot] \times \widetilde{\sigma}_{stk_i}(ET_r)$
```

Encrypted Join



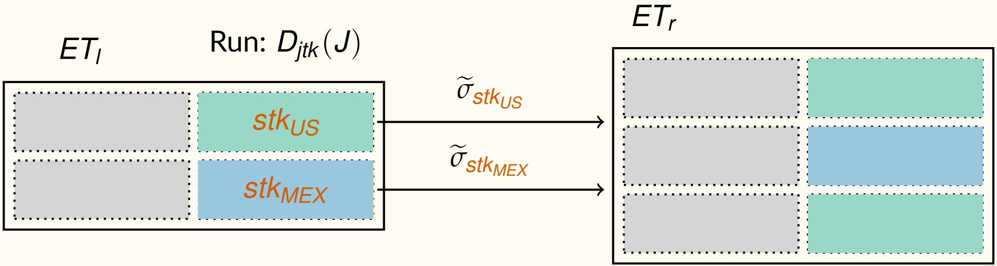
ET_l
Run: $D_{jtk}(J)$
stk_{US}
stk_{MEX}
$\widetilde{\sigma}_{stk_{US}}$
$\widetilde{\sigma}_{stk_{MEX}}$
ET_r
MEX



Server

```
For i-th row $\in ET_l$:
    Let $stk_i \leftarrow D_{jtk}(J_i)$,
    Output $ET_l[i, \cdot] \times \widetilde{\sigma}_{stk_i}(ET_r)$
```

Encrypted Join



ET_l

Run: $D_{jtk}(J)$

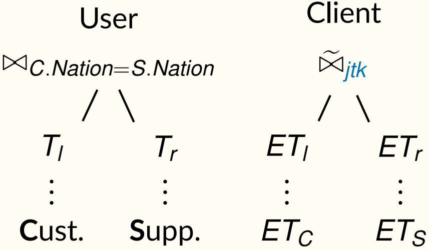
stk_{US}

stk_{MEX}

$\widetilde{\sigma}_{stk_{US}}$

$\widetilde{\sigma}_{stk_{MEX}}$

ET_r



User

$\bowtie_{C.Nation=S.Nation}$

T_l T_r

Cust. Supp.

Client

$\widetilde{\bowtie}_{jtk}$

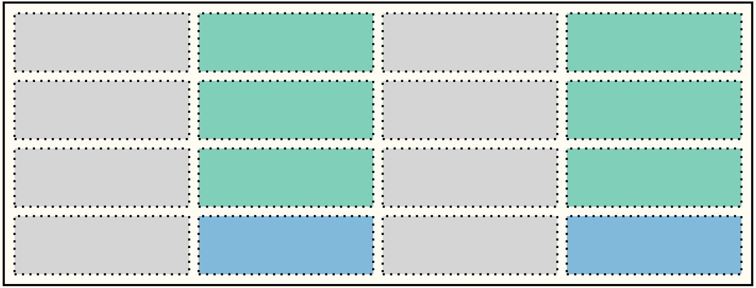
ET_l ET_r

ET_C ET_S

Server

```
For i-th row $\in ET_l$:
    Let $stk_i \leftarrow D_{jtk}(J_i)$,
    Output $ET_l[i,\cdot] \times \widetilde{\sigma}_{stk_i}(ET_r)$
```

Encrypted Join



Encrypted Join

- Linear cost.
- Extension for leakage redunction for filtered joins at linear cost.

Fixed-Point Operator

- For recursion: common in Encryted Selection and Encrypted Join

$$\bigcup_{R \in Z^+} \sigma_{S = F_{stk}(R)} ET$$

Fixed-Point Operator

- For recursion: common in Encryted Selection and Encrypted Join

$$\bigcup_{R \in Z^{+}} \sigma_{S=F_{stk}(R)} ET$$

- Extension beyond relational algebra
  - Not in all database systems: SparkSQL
  - Postgres 8+/MySQL 8+/SQL Server 2005+: Recursive Common Table Expression
  - Oracle 11g Release 2: Recursive Subquery Factoring / CONNECT BY

Fixed-Point Operator

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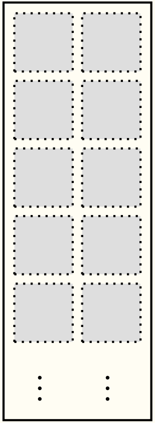
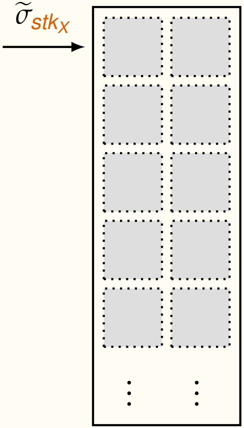
- Extension beyond relational algebra
  - Not in all database systems: SparkSQL
  - Postgres 8+/MySQL 8+/SQL Server 2005+: Recursive Common Table Expression
  - Oracle 11g Release 2: Recursive Subquery Factoring / CONNECT BY
- Important to optimize for efficiency
  - Data Paralllel Rewrite
  - Join Direction Reorder
  - Hash Join Reuse

Fixed-Point Operator

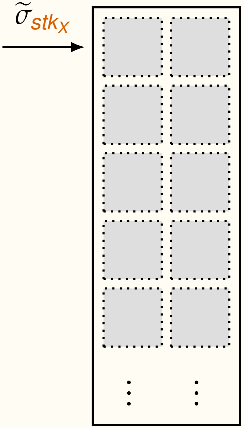


Fixed-Point Operator



Fixed-Point Operator

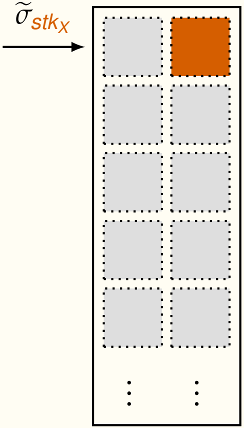
Run: $\bigcup_{R \in Z^+} \sigma_{S=F_{stk}(R)}$

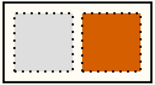


Fixed-Point Operator

Run: $\bigcup_{R \in Z^+} \sigma_{S=F_{stk}(R)}$

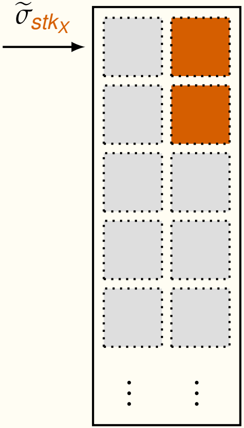
For $R = 1$



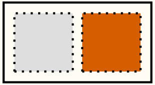


Fixed-Point Operator

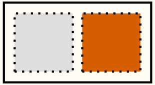
Run: $\bigcup_{R \in Z^+} \sigma_{S=F_{stk}(R)}$



For $R = 1$



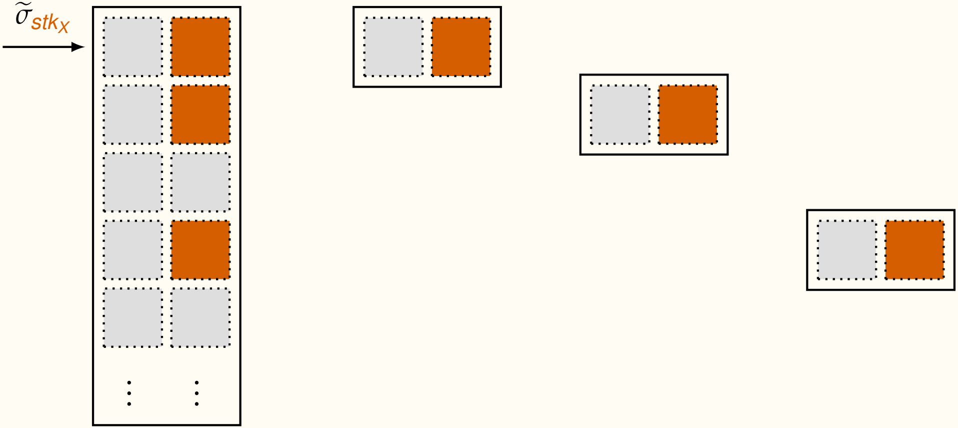
For $R = 2$



Fixed-Point Operator

Run: $\bigcup_{R\in Z^+} \sigma_{S=F_{stk}(R)}$

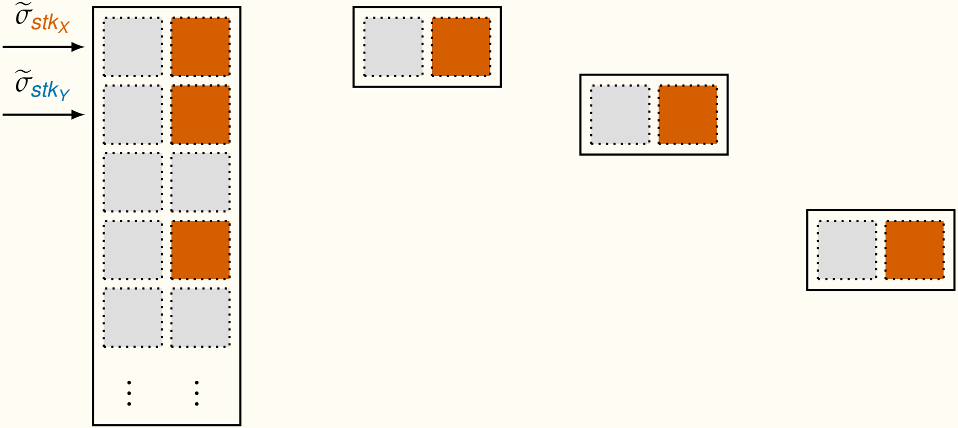
For $R = 1$ For $R = 2$ For $R = 3$



Fixed-Point Operator

Run: $\bigcup_{R\in Z^+} \sigma_{S=F_{stk}(R)}$

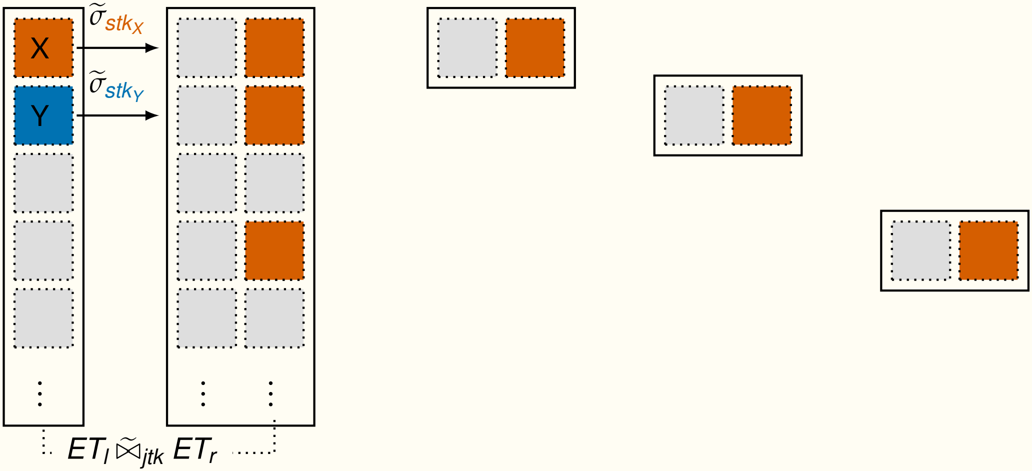
For $R = 1$ For $R = 2$ For $R = 3$



Fixed-Point Operator

Run: $\bigcup_{R \in Z^+} \sigma_{S=F_{stk}(R)}$

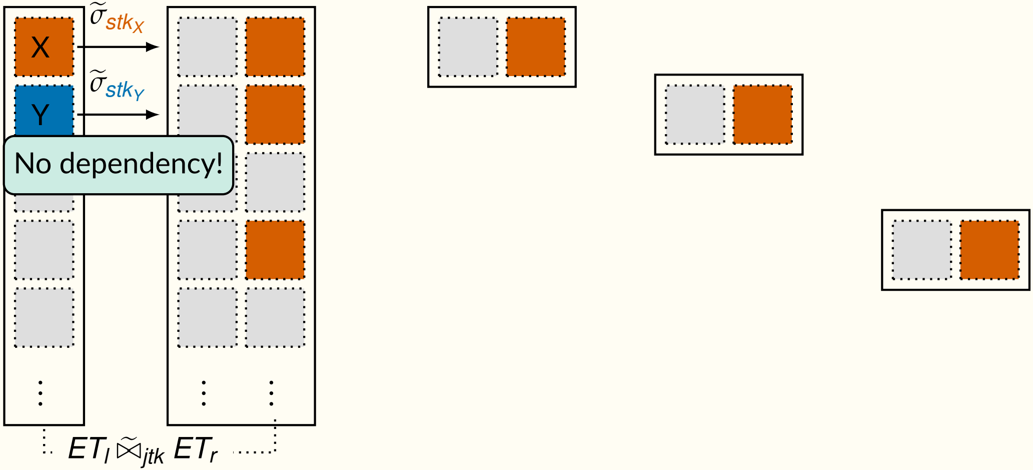
For $R = 1$ For $R = 2$ For $R = 3$


X
Y
$\widetilde{\sigma}_{stk_X}$
$\widetilde{\sigma}_{stk_Y}$
$ET_l \,\widetilde{\bowtie}_{jtk}\, ET_r$

Fixed-Point Operator

Run: $\bigcup_{R\in Z^{+}} \sigma_{S=F_{stk}(R)}$

For $R = 1$ For $R = 2$ For $R = 3$

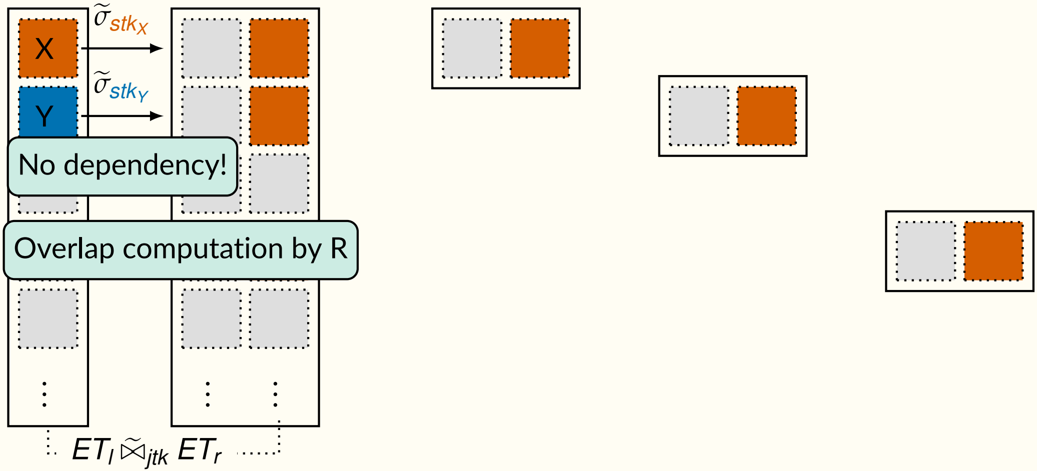

X
Y
$\widetilde{\sigma}_{stk_X}$
$\widetilde{\sigma}_{stk_Y}$
$\vdots$
$ET_l \mathbin{\widetilde{\bowtie}_{jtk}} ET_r$

No dependency!

Fixed-Point Operator

Run: $\bigcup_{R \in Z^{+}} \sigma_{S=F_{stk}(R)}$

For $R = 1$ For $R = 2$ For $R = 3$



X
Y
$\widetilde{\sigma}_{stk_X}$
$\widetilde{\sigma}_{stk_Y}$
$ET_l \widetilde{\bowtie}_{jtk} ET_r$

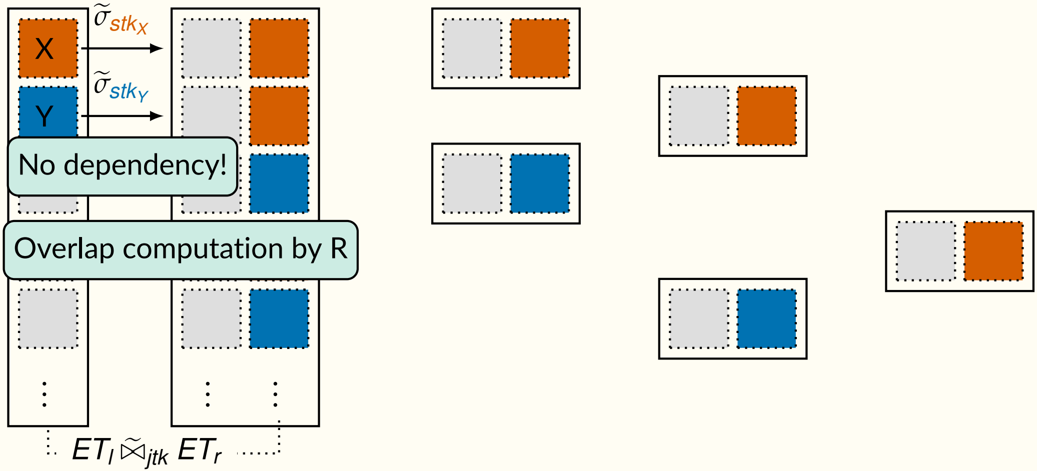
No dependency!

Overlap computation by R

Fixed-Point Operator

Run: $\bigcup_{R \in Z^+} \sigma_{S=F_{stk}(R)}$

For $R = 1$ For $R = 2$ For $R = 3$


X
Y
$\widetilde{\sigma}_{stk_X}$
$\widetilde{\sigma}_{stk_Y}$
$ET_l \,\widetilde{\bowtie}_{jtk}\, ET_r$

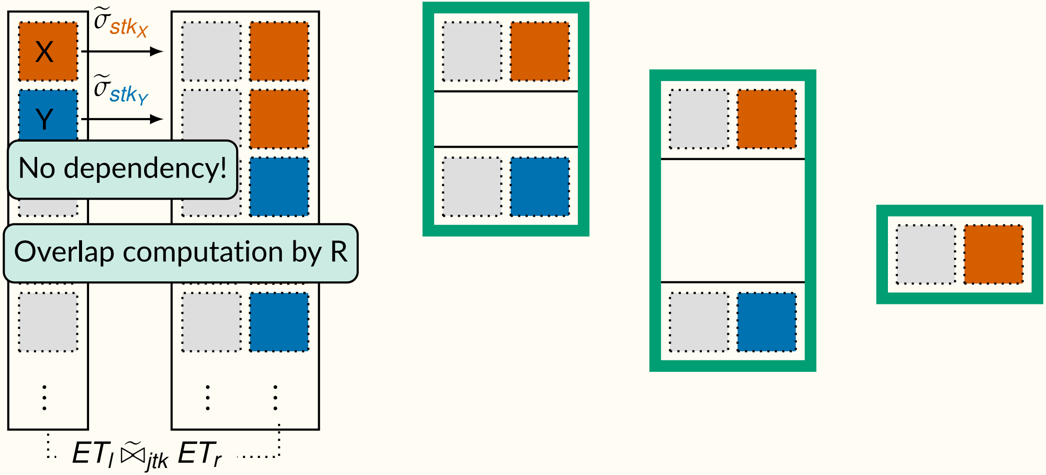
No dependency!

Overlap computation by R

Fixed-Point Operator

Run: $\bigcup_{R\in Z^+} \sigma_{S=F_{stk}(R)}$

SIMD (Single Instruction Multiple Data)

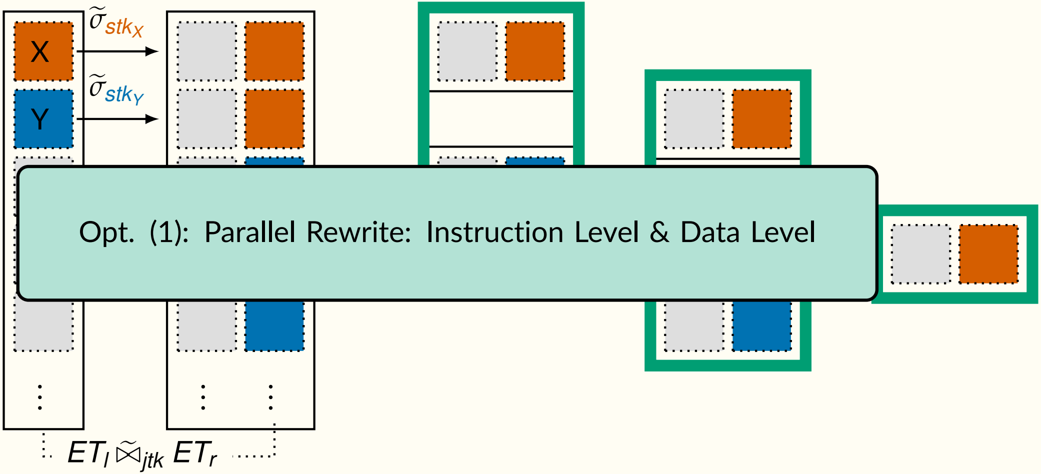

X
Y
$\widetilde{\sigma}_{stk_X}$
$\widetilde{\sigma}_{stk_Y}$
$ET_l \widetilde{\bowtie}_{jtk} ET_r$

No dependency!

Overlap computation by R

Fixed-Point Operator

Run: $\bigcup_{R\in Z^+} \sigma_{S=F_{stk}(R)}$

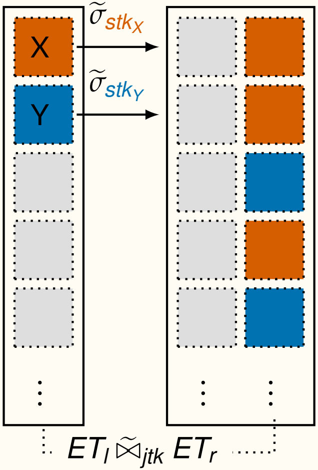

For $R = 1$
For $R = 2$
For $R = 3$
X
Y
$\widetilde{\sigma}_{stk_X}$
$\widetilde{\sigma}_{stk_Y}$
$ET_l \,\widetilde{\bowtie}_{jtk}\, ET_r$

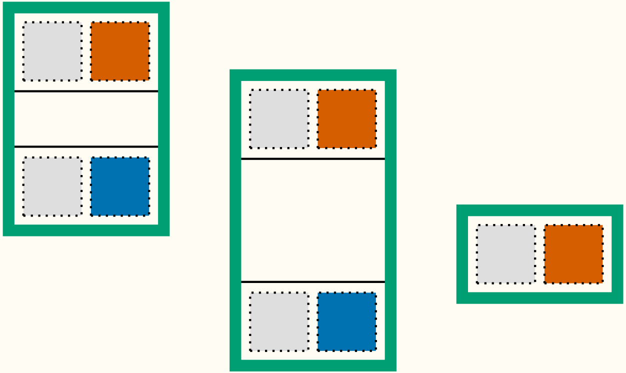
Opt. (1): Parallel Rewrite: Instruction Level & Data Level

Fixed-Point Operator

Run: $\bigcup_{R \in Z^+} \sigma_{S=F_{stk}(R)}$

Data Skew ⇒ Load Inbalance

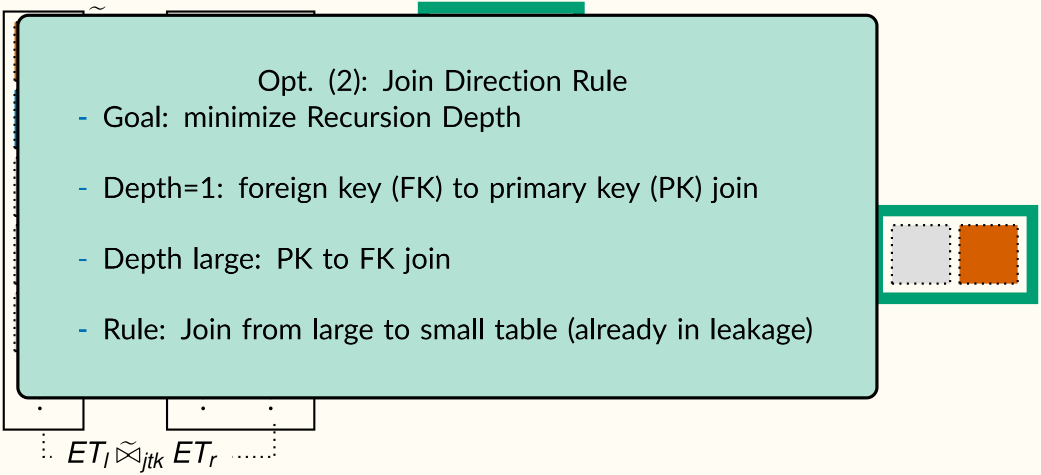

X
Y
$\widetilde{\sigma}_{stk_X}$
$\widetilde{\sigma}_{stk_Y}$
$ET_l \,\widetilde{\bowtie}_{jtk}\, ET_r$



Fixed-Point Operator

Run: $\bigcup_{R\in Z^+} \sigma_{S=F_{stk}(R)}$

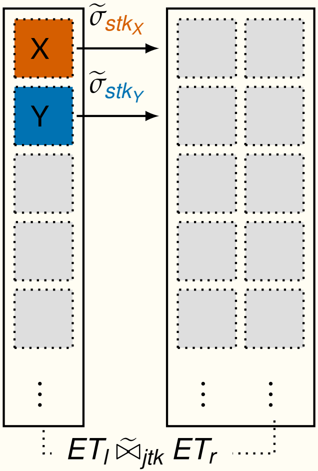
Data Skew ⇒ Load Inbalance



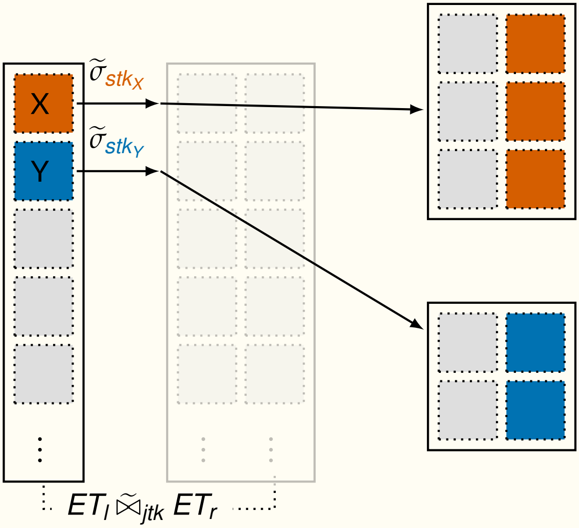
Opt. (2): Join Direction Rule

- Goal: minimize Recursion Depth
- Depth=1: foreign key (FK) to primary key (PK) join
- Depth large: PK to FK join
- Rule: Join from large to small table (already in leakage)

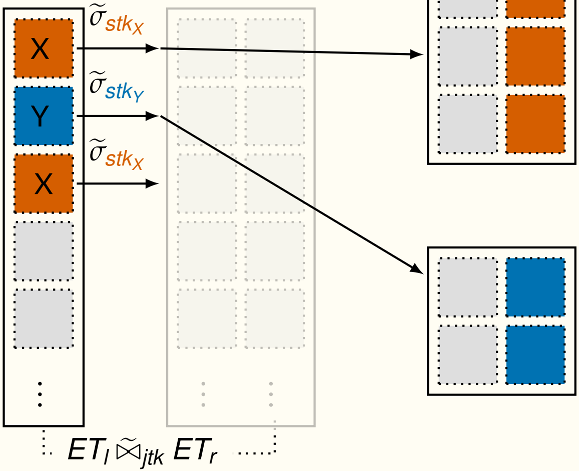
Fixed-Point Operator


X
Y
$\widetilde{\sigma}_{stk_X}$
$\widetilde{\sigma}_{stk_Y}$
$ET_l \,\widetilde{\bowtie}_{jtk}\, ET_r$

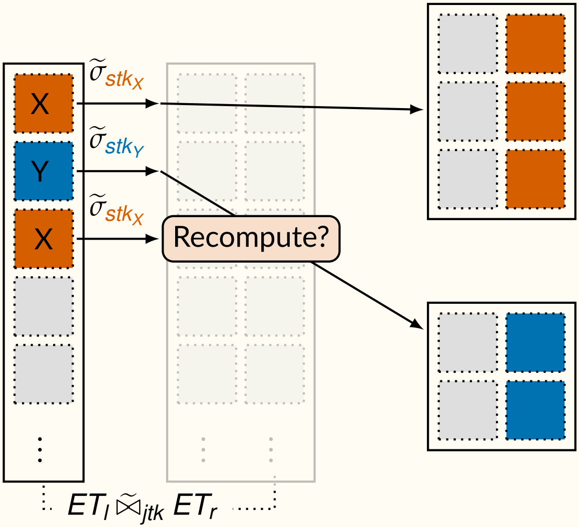
Fixed-Point Operator


X
Y
$\widetilde{\sigma}_{stk_X}$
$\widetilde{\sigma}_{stk_Y}$
$ET_l \widetilde{\bowtie}_{jtk} ET_r$

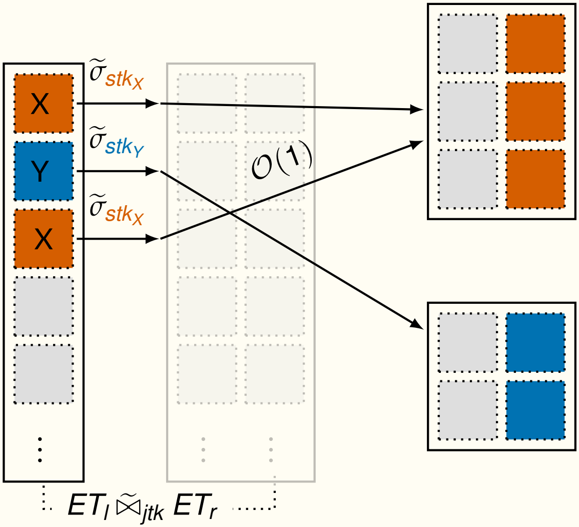
Fixed-Point Operator


X
Y
X
$\widetilde{\sigma}_{stk_X}$
$\widetilde{\sigma}_{stk_Y}$
$\widetilde{\sigma}_{stk_X}$
$ET_l \,\widetilde{\bowtie}_{jtk}\, ET_r$

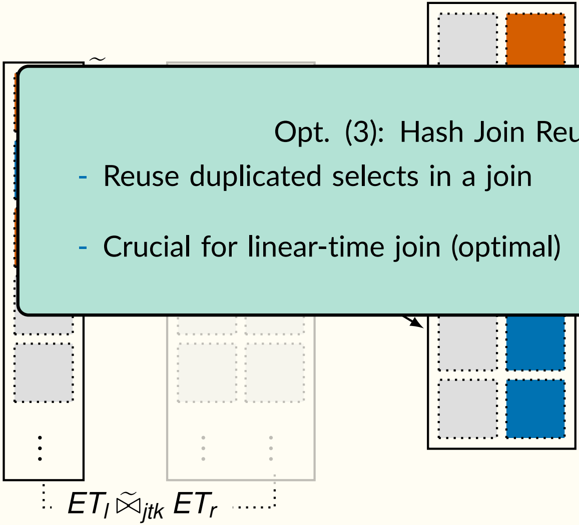
Fixed-Point Operator


X
Y
X
⋮
$\widetilde{\sigma}_{stk_X}$
$\widetilde{\sigma}_{stk_Y}$
$\widetilde{\sigma}_{stk_X}$
Recompute?
$ET_l \widetilde{\bowtie}_{jtk} ET_r$

Fixed-Point Operator


X
Y
X
$\widetilde{\sigma}_{stk_X}$
$\widetilde{\sigma}_{stk_Y}$
$\widetilde{\sigma}_{stk_X}$
$\mathcal{O}(1)$
$ET_l \,\widetilde{\bowtie}_{jtk}\, ET_r$

Fixed-Point Operator



Opt. (3): Hash Join Reuse

- Reuse duplicated selects in a join

- Crucial for linear-time join (optimal)