Towards Practical Oblivious Join

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Preliminaries

- Oblivious RAM: A cryptographic object which can obfuscate memory access patterns with a small client memory requirement, and large memory which could be monitored: accessing encrypted data remotely while hiding access patterns.
- Memory access with “blocks” indexed by a position. Store and load operations are indistinguishable.
- ORAM is used as a black-box but Path-ORAM is specifically mentioned due to good performance and simplicity.

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- Although the data in the records isn't revealed, this is a lot of information…

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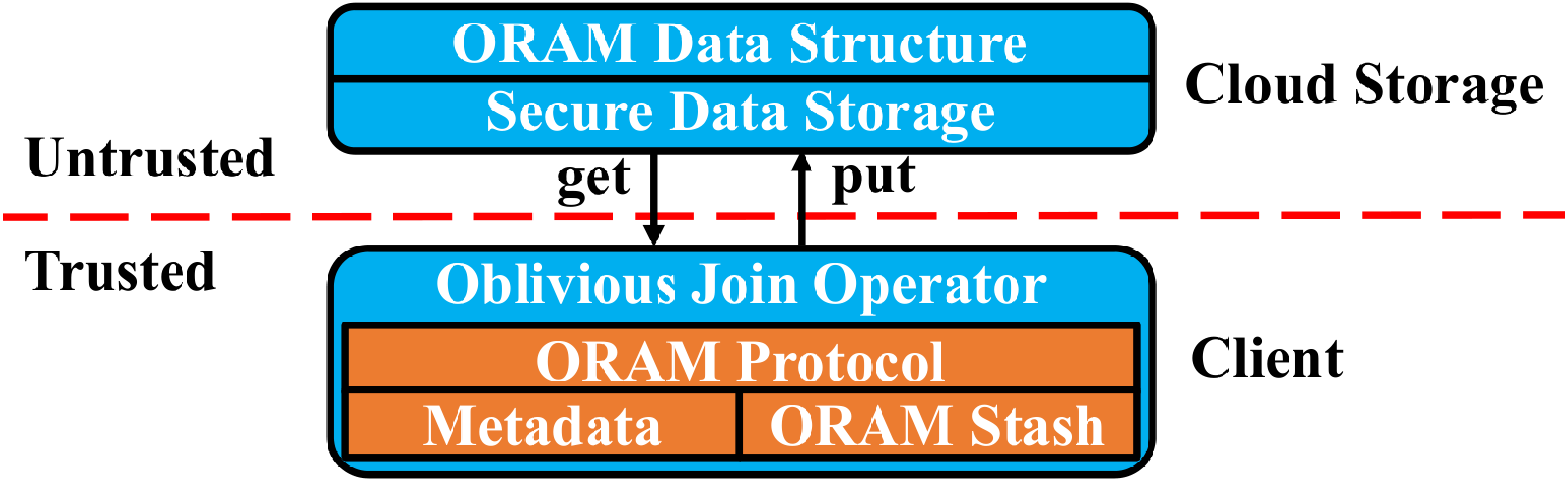

Figure 1: An overview of our oblivious join process.

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    Operators like *>, >=, <, <=* over the shared key
  - *Acyclic* multiway equi-join

    We’ll see what Acyclic means later

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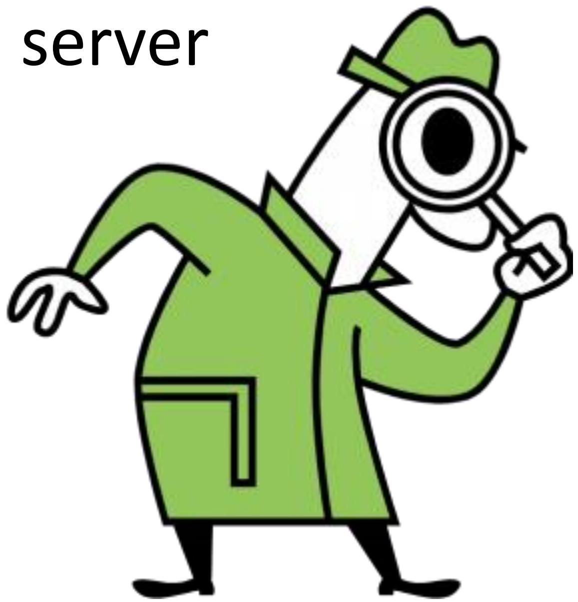
- That means that the server will always act like an honest server, but might observe our memory access patterns as well as the data.
- This is a useful security model because if the server gives malicious responses to a client which does store the database, the server provider would probably lose its reputation…



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- The cost of this can be reduced if we separate each table's data and index into separate ORAMs. Furthermore, we could even use a separate ORAM for each level of a B-tree index.
- Another approach is to integrate the B-tree information directly into the ORAM. When querying a node, we acquire the children simultaneously.

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- Finally, the dummy records are obliviously filtered out of the output table.

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  - Preferred if one of the sides of the join (N) has few rows, as the complexity is $O(N \log M)$
  - Works with operators which aren't equality
- Hash join is not relevant because hash join uses a large working memory, which is something we're trying to avoid.

A	B
1	1
2	1
2	2
3	1

Table T_1

$\bowtie$

A	C
1	1
2	1
2	2
2	3

Table T_2

A-to-A comparison

Join Comparison

T_1		T_2		res	getNext()
A	B	A	C		
1	1	1	1	$= 0$	
		2	1	< 0	$T_1 \rightarrow (2, 1)$
2	1	1	1	> 0	$T_2 \rightarrow (2, 1)$
2	1	2	1	$= 0$	
		2	2		
		2	3		
		$\perp$		< 0	$T_1 \rightarrow (2, 2)$
2	2	2	1	$= 0$	

Reached end

T_1		T_2		res	getNext()
A	B	A	C		
2	2	2	2	$= 0$	
		2	3		
		$\perp$		< 0	$T_1 \rightarrow (3, 1)$
3	1	2	1	> 0	$T_2 \rightarrow (2, 2)$
		2	2		$T_2 \rightarrow (2, 3)$
		2	3		$T_2 \rightarrow \perp$
		$\perp$		< 0	$T_1 \rightarrow \perp$
$\perp$		$\perp$		end	

Figure 3: An example of oblivious sort-merge equi-join.

The algorithm

(let’s not get too deep into it)

Match? Advance T_2 until different.
Then return to the beginning of this key in T_2 and advance T_1 once.

No match? Keep advancing whichever one is smaller, until we find a match.

Algorithm 1: Oblivious Binary Sort-Merge Equi-Join

Require: Input: two tables T_1 and T_2.
Output: join result table $T_{out} = T_1 \bowtie T_2$.

Initialize $T_{out} := \emptyset$.
Initialize $\text{tuple}[1,2] := \emptyset$.
for $i := 1$ to 2 **do**
  $\text{tuple}[i] := T_i.\text{getFirst}();$
while $\text{tuple}[1] \neq \perp$ **or** $\text{tuple}[2] \neq \perp$ **do**
  $\text{res} := \text{compare}(\text{tuple}[1], \text{tuple}[2]);$
  if $\text{res} = 0$ **then**
    $\text{begin} := \text{tuple}[2];$
    while $\text{res} = 0$ **do**
      $T_{out}.\text{put}(\text{tuple}[1] \bowtie \text{tuple}[2]);$
      $T_1.\text{getDummy}();\ \text{tuple}[2] := T_2.\text{getNext}();$
      $\text{res} := \text{compare}(\text{tuple}[1], \text{tuple}[2]);$
    $T_{out}.\text{put}(\perp);$
    $\text{tuple}[2] := \text{begin};$
    $\text{tuple}[1] := T_1.\text{getNext}();\ T_2.\text{getDummy}();$
  else
    $T_{out}.\text{put}(\perp);$
    if $\text{res} < 0$ **then**
      $\text{tuple}[1] := T_1.\text{getNext}();\ T_2.\text{getDummy}();$
    else
      $T_1.\text{getDummy}();\ \text{tuple}[2] := T_2.\text{getNext}();$
Obliviously filter out dummy records from T_{out}.
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- Otherwise, the number of accesses, as well as the accessed tables if they're in separate ORAMs, is determined by the join's size.
- This can be mitigated with padding (extra accesses): e.g. to next power of 2

Oblivious index nested-loop binary equi-join

- Similarly, the two tables are accessed alternatively, and dummy records are used. Other than that, normal index nested-loop join.

Algorithm 2: Oblivious Index Nested-Loop Binary Equi-Join

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Initialize $T_{\text{out}} := \emptyset$.
Initialize $\text{tuple}[1, 2] := \emptyset$.
for $i := 1$ to $|T_1|$ **do**
    $\text{tuple}[1] := T_1.\text{getNext}()$;
    $\text{tuple}[2] := T_2.\text{getFirst}(\text{tuple}[1].\text{key})$;
    while $\text{match}(\text{tuple}[1], \text{tuple}[2]) =$ **true do**
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This can be extended for band-join (e.g. >, >=, <, <=), retrieving tuples until they don't match

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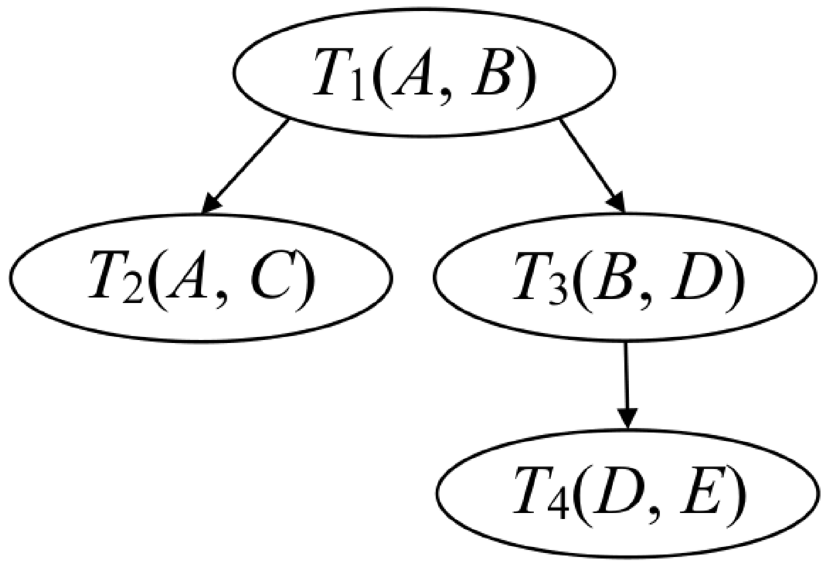

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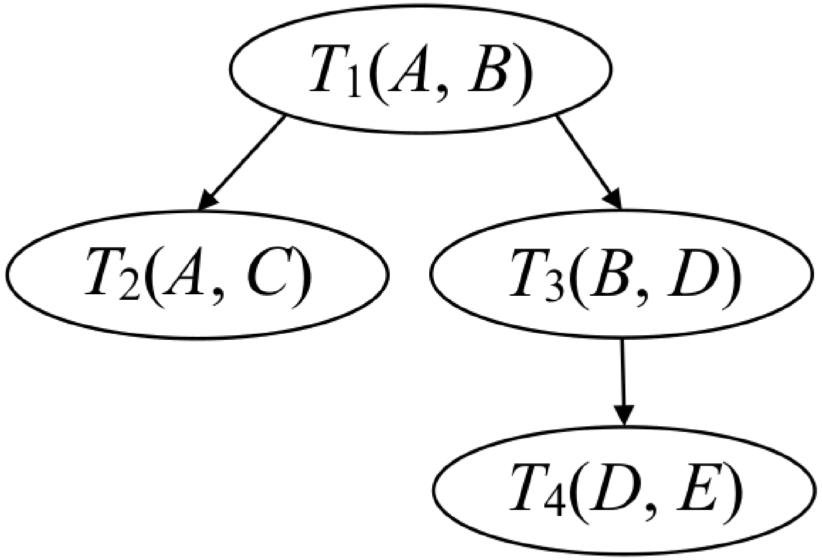

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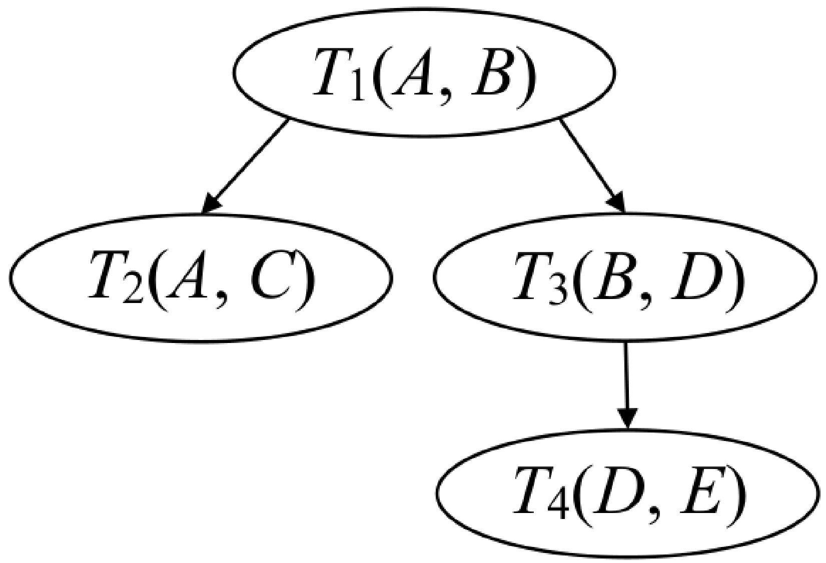

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- Additionally, the number of join steps is padded to an upper bound for obliviousness.

The join result size

$$|T_1| + 2\sum_{j=2}^{\ell} |T_j| + |R_{\text{real}}|.$$

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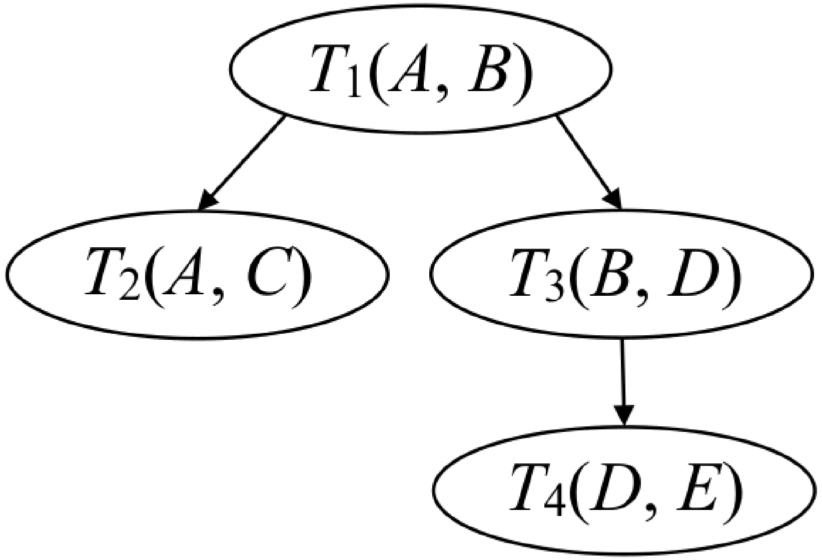

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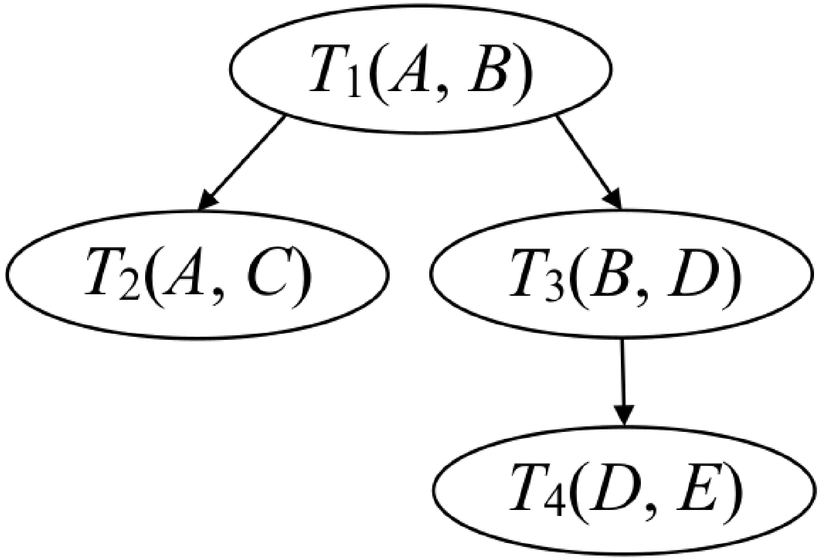

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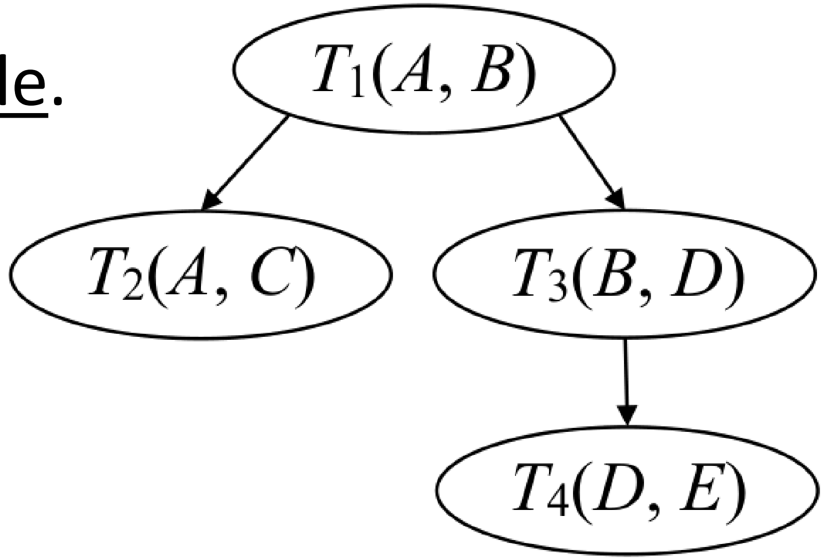

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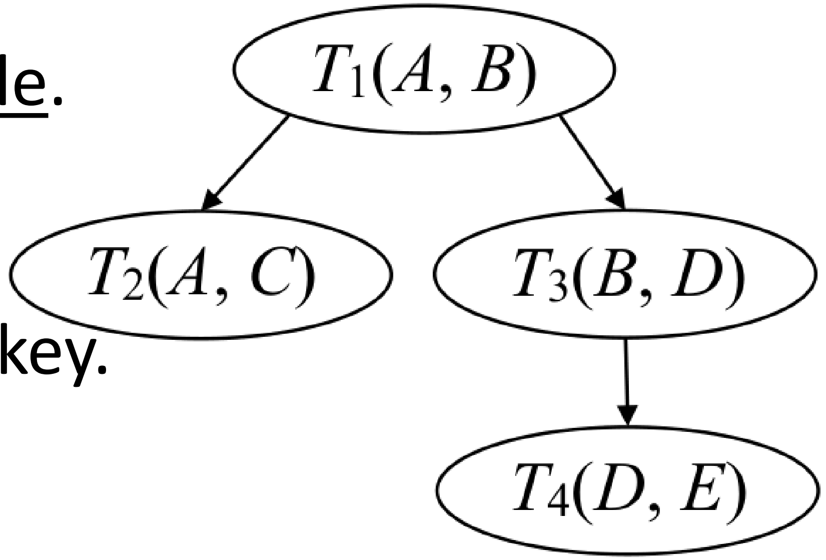
2. This can propagate upwards <u>to the parent table</u>.
3. In equi-joins if the current tuple matches, but the succeeding tuple has a different key, there will be no more matches for the parent key. This can be marked in the B-tree leaves.



Oblivious acyclic multiway equi-join

Theorem: In that way, we can achieve the following bound for the number of steps (each step accesses the ORAM in all tables):

The join result size

$$|T_1| + 2\sum_{j=2}^{\ell} |T_j| + |R_{\text{real}}|$$

- General idea: If a tuple is enabled after being processed at least once, it will be enabled all the time. And after each tuple retrieval from each table, we will output exactly one (real or dummy) join record.

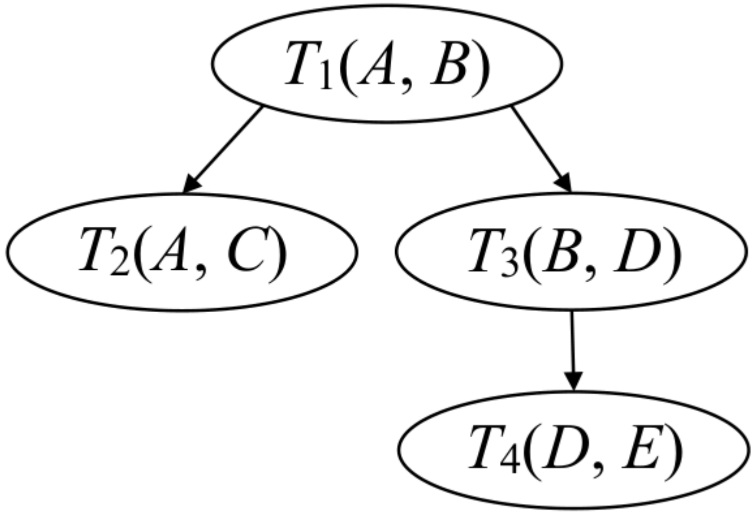


Table T_1

A	B
1	1
2	1
2	2
2	3

Table T_2

A	C
1	1
2	1
2	2
3	1

$\bowtie$

Table T_3

B	D
~~1~~	~~4~~
2	1
~~2~~	~~3~~

Table T_4

D	E
1	2
2	1
2	3

Join Comparison

T_1		T_2		T_3		T_4		match
A	B	A	C	B	D	D	E	
1	1	1	1	1	4	$\perp$		false
$\perp$		$\perp$		~~1~~	~~4~~	$\perp$		disable
2	1	2	1	2	1	$\perp$		false
2	2	2	1	2	1	1	2	true
2	2	2	1	2	3	$\perp$		false
$\perp$		$\perp$		~~2~~	~~3~~	$\perp$		disable
2	2	2	2	2	1	1	2	true
2	3	2	1	$\perp$		$\perp$		false
padding dummy operations								

Figure 6: An example of oblivious multiway equi-join.

Algorithm overview

Loop over T_1.
Join is a recursive function, and table numbers for parents are always less than for their children.

Algorithm 5: Oblivious Index Nested-Loop Multiway Equi-Join

Require: Input: ℓ tables $T_1, \cdots, T_\ell$.
Output: join result table $T_{\text{out}} = T_1 \bowtie \cdots \bowtie T_\ell$.

Initialize $T_{\text{out}} := \emptyset$.
Initialize $\text{tuple}[1 \dots \ell] := \emptyset$.
for $i := 1$ to $|T_1|$ **do**
    $\text{tuple}[1] := T_1.\text{getNext}()$;
    JOIN(2);
end for
Pad tuple retrievals and dummy output records to an upper bound.
Obliviously filter out dummy records from T_{out}.
Go over all index blocks and reset boolean tags in each entry.
return T_{out};

If there's no match for the parent's value, fail

If $j \neq$ index, then it must have failed, but I am not the parent which should get disabled. Backtrack to it…

If I am the target, disable me

Loop while there's more tuples matching the parent

Return a flag – if it is false, the parent should disable its tuple

```
function JOIN(j)
res := false;
tuple[j] := RETRIEVEFIRSTTUPLE(j, tuple[p(j)].key);
if match(tuple[p(j)], tuple[j]) = false then
    OUTPUTDUMMYRECORD(j);
else
    while true do
        if j = ℓ then
            res := true;
            OUTPUTREALJOINRECORD();
        else
            {flag, index} := JOIN(j + 1);
            if j ≠ index then
                return {flag, index};
            end if
            if flag = false then
                DISABLECURRENTTUPLE(j);
            else
                res := true;
            end if
        end if
        if HASNEXTMATCHEDTUPLE(j) = true then
            tuple[j] := RETRIEVENEXTTUPLE(j);
        else
            break;
        end if
    end while
end if
if res = false then
    return {false, p(j)};
else
    return {true, j − 1};
end if
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```
function JOIN(j)
res := false;
tuple[j] := RETRIEVEFIRSTTUPLE(j, tuple[p(j)].key);
if match(tuple[p(j)], tuple[j]) = false then
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else
   while true do
      if j = ℓ then
         res := true;
         OUTPUTREALJOINRECORD();
      else
         {flag, index} := JOIN(j + 1);
         if j ≠ index then
            return {flag, index};
         end if
         if flag = false then
            DISABLECURRENTTUPLE(j);
         else
            res := true;
         end if
      end if
      if HASNEXTMATCHEDTUPLE(j) = true then
         tuple[j] := RETRIEVENEXTTUPLE(j);
      else
         break;
      end if
   end while
end if
if res = false then
   return {false, p(j)};
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   return {true, j − 1};
end if
end function
```

If there's no match for the parent's value, fail

If $j \neq$ index, then it must have failed, but I am not the parent which should get disabled. Backtrack to it…

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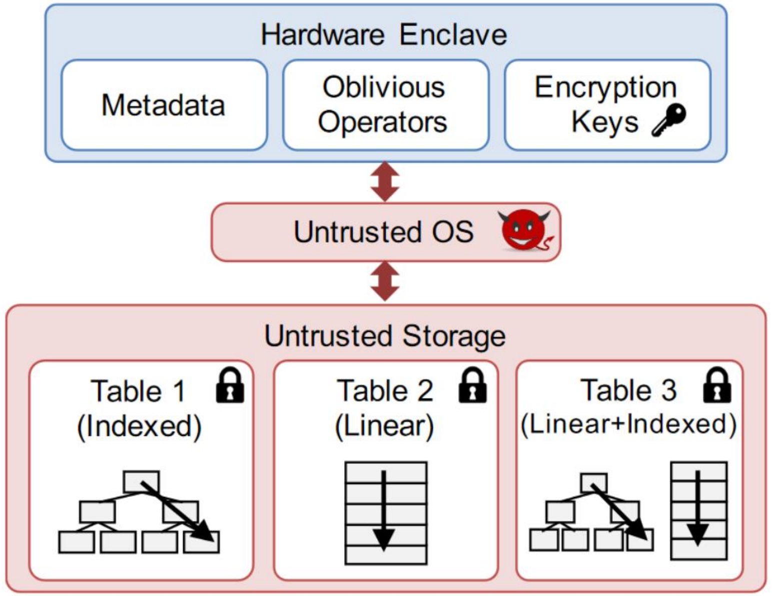

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Space	N	$\sim 4N$	$\sim 5N$
Point Read	$O(N)$	$O(\log^2 N)$	$O(\log^2 N)$
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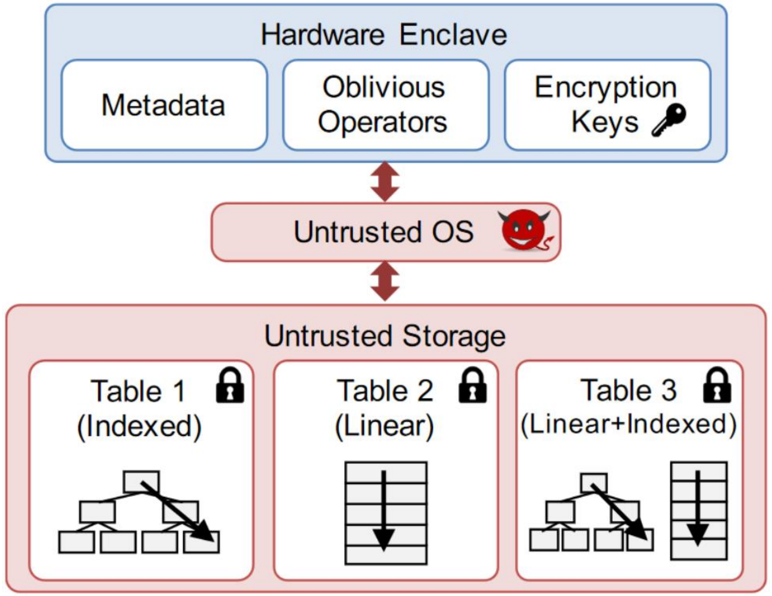

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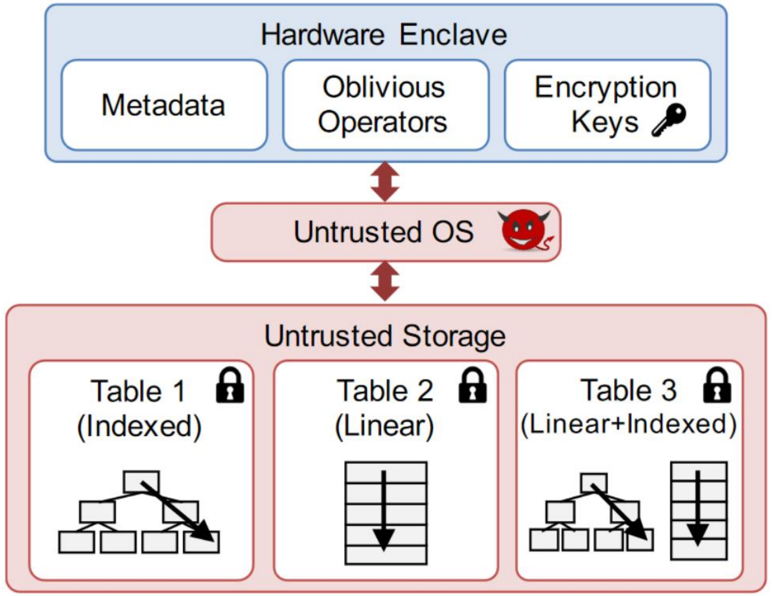

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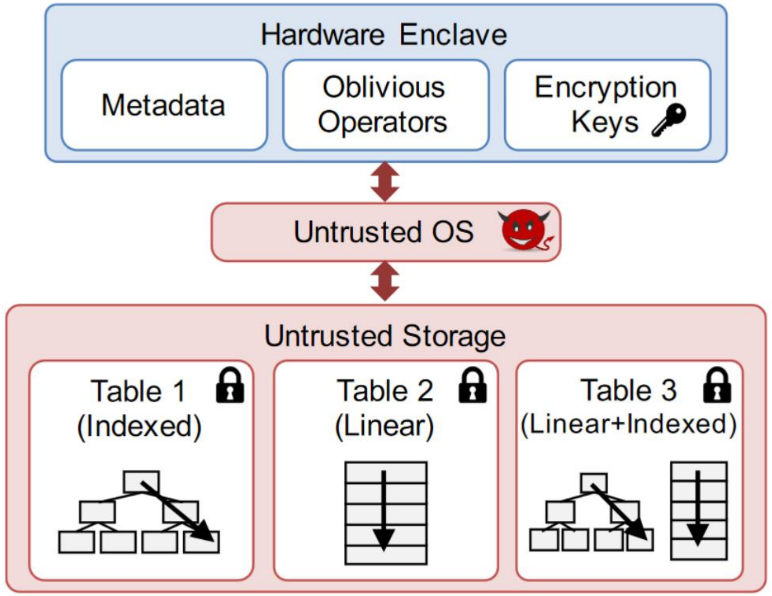

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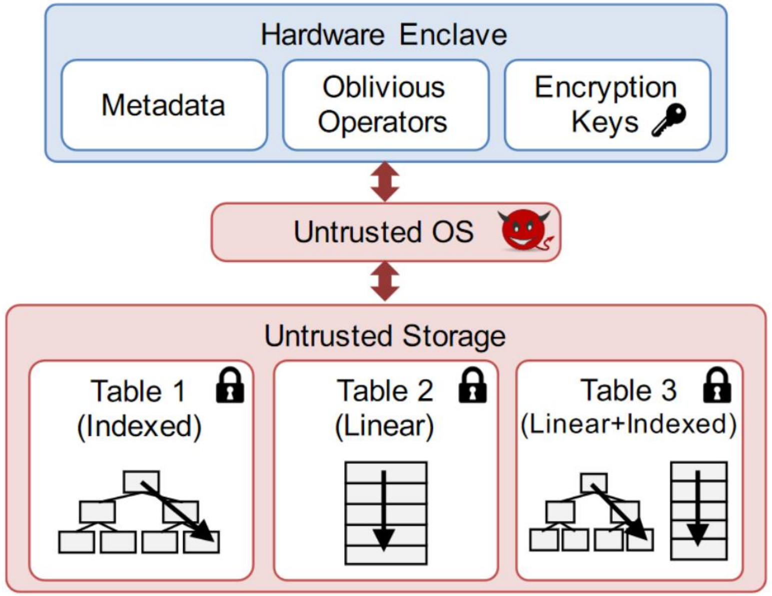

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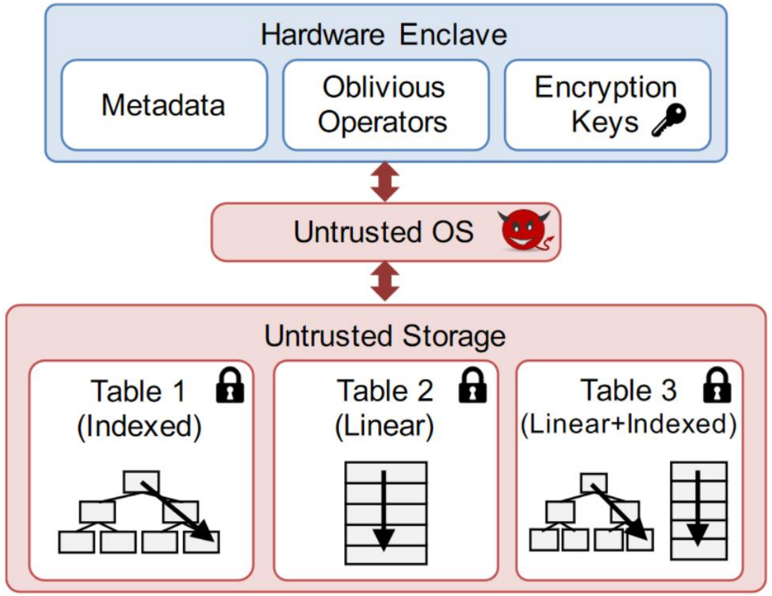
- Sort-Merge join can be implemented by appending the tables to each other and using bitonic sort ($O(n \log^2 n)$ deterministic reorders)
- Index nested loop's loop can use the flat data.
- Cool, but linear tables don't really help in multiway joins…



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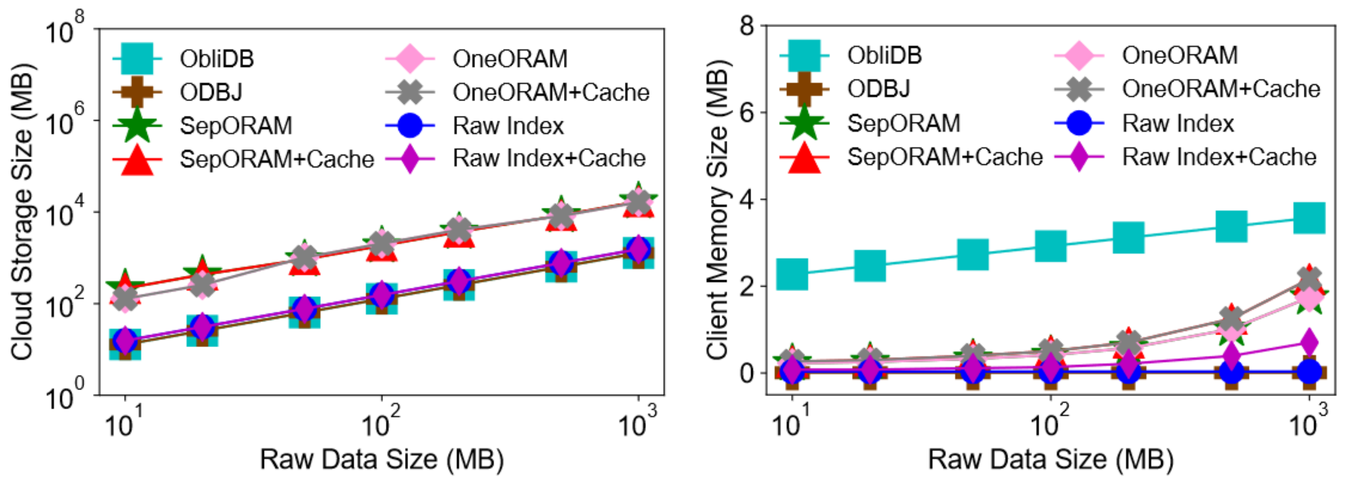
  - 4kb blocks
- All implementations are running in non-padded mode:
  - The best padding is the Cartesian Product padding which doesn’t reveal the join size at all.
  - Another option is the closest power of 2 which means up to 2x overhead.

Experimental results

- The compared implementations are:
  - Separate ORAM and One ORAM
    - SMJ (Sort Merge Join)
    - INLJ (Index Nested Loop Join)
    - INLJ+Cache (with Index Caching): the client caches all index blocks above the leaf level, and due to the large fan-out in the B-tree this is a small amount of storage.
  - Baseline: Raw SMJ, INLJ, and INLJ+Cache
    - Don’t use any encryption or ORAM protocol but the data is in a remote server.
  - Previous work:
    - ObliDB, ODBJ

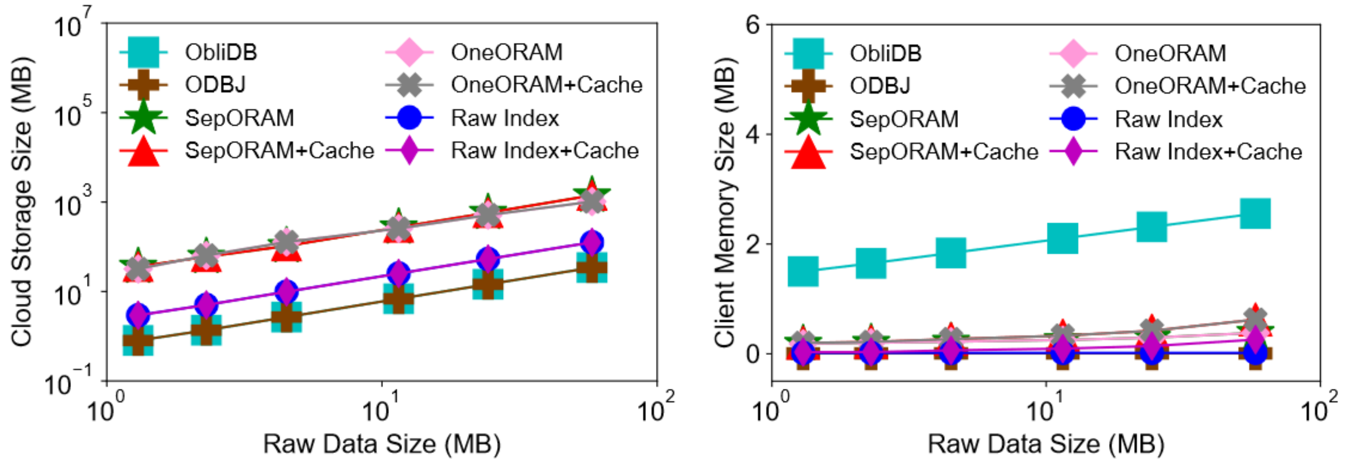
Storage and Memory

- The client memory requirement is small, and not very large even with the cache.
- The cloud storage size has noticeable (roughly 10X) overhead over a raw index, due to the use of Path-ORAM.



(a) Cloud storage size. (b) Client memory size.

Figure 7: Storage cost against raw data size on TPC-H.

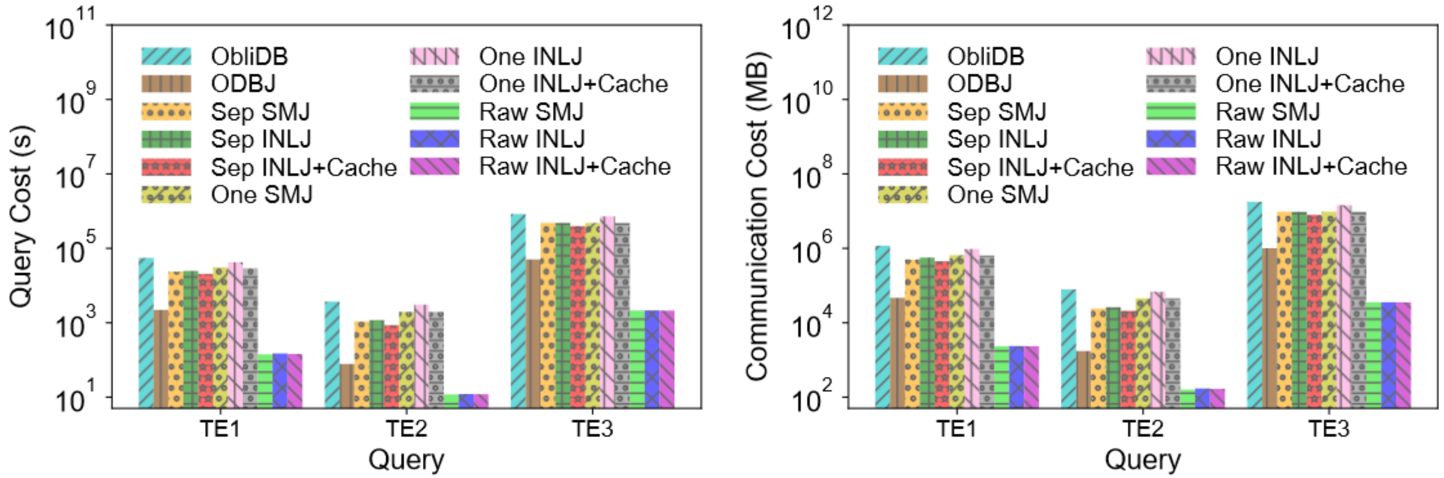


(a) Cloud storage size. (b) Client memory size.

Figure 8: Storage cost against raw data size on social graph.

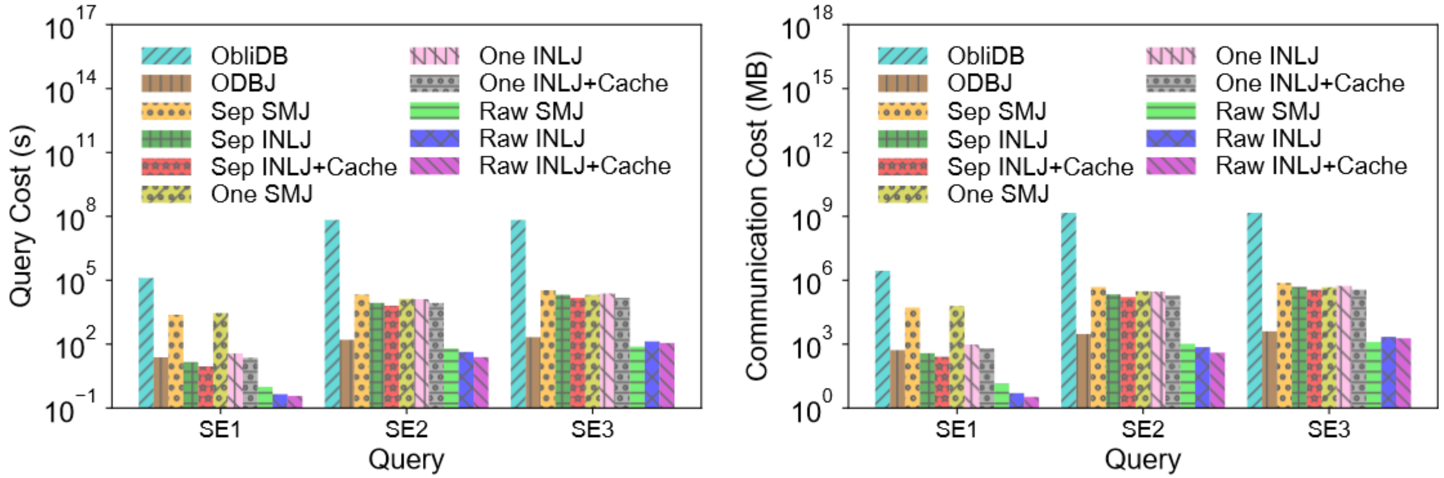
Binary Equi-Join: Performance

- Sep-INLJ is 1.2-2.6X faster than One-INLJ
- SepORAM(+Cache) is 90-450X more expensive than Raw Index(+Cache) except for SE1.
- However, the data tuples are only 100-200 bytes in TPC-H and 2 integers in social graph, and the block size of the ORAM is 4KB.



(a) Query cost. (b) Communication cost.

Figure 9: Performance of binary equi-join on TPC-H.

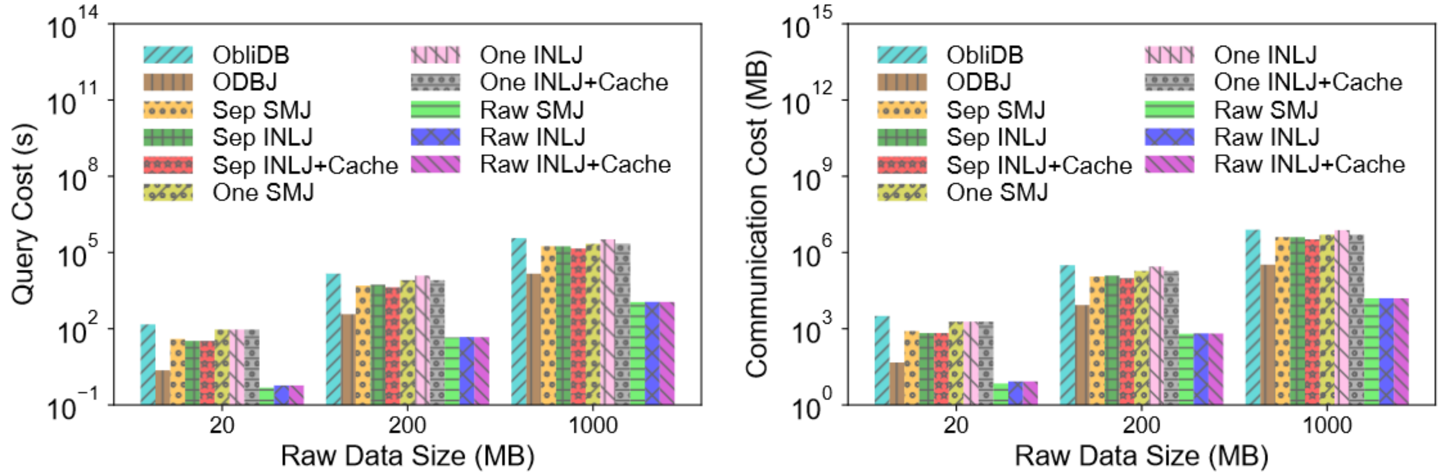


(a) Query cost. (b) Communication cost.

Figure 10: Performance of binary equi-join on social graph.

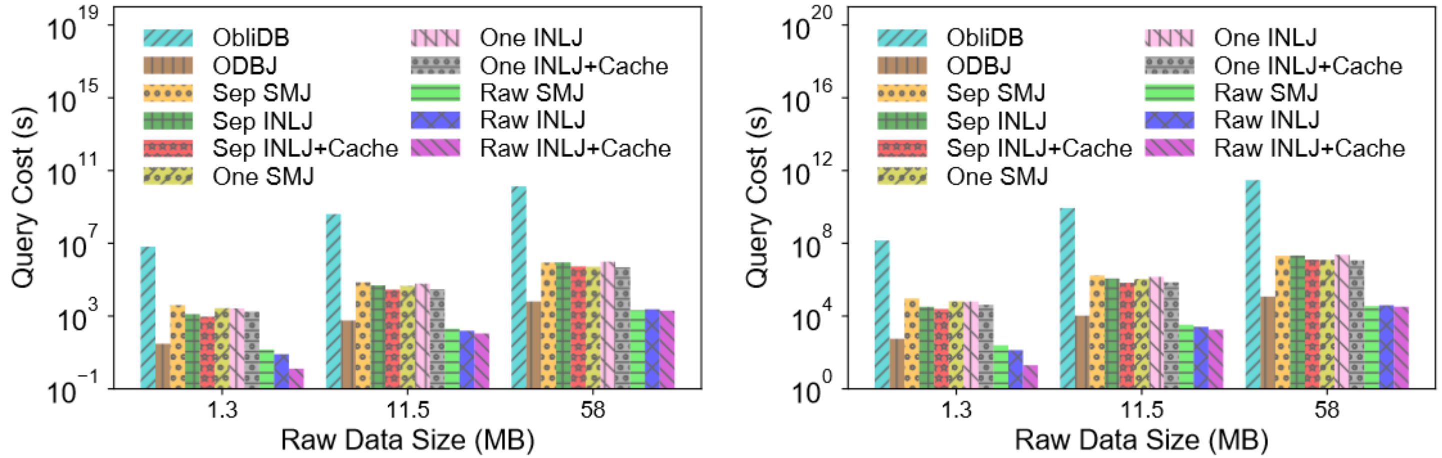
Binary Equi-Join: Scalability

- The performance difference is again because of the block size.
- The merge algorithm is scalable.



(a) Query cost. (b) Communication cost.

Figure 11: Performance of Query TE2 against raw data size.



(a) Query cost. (b) Communication cost.

Figure 12: Performance of Query SE2 against raw data size.

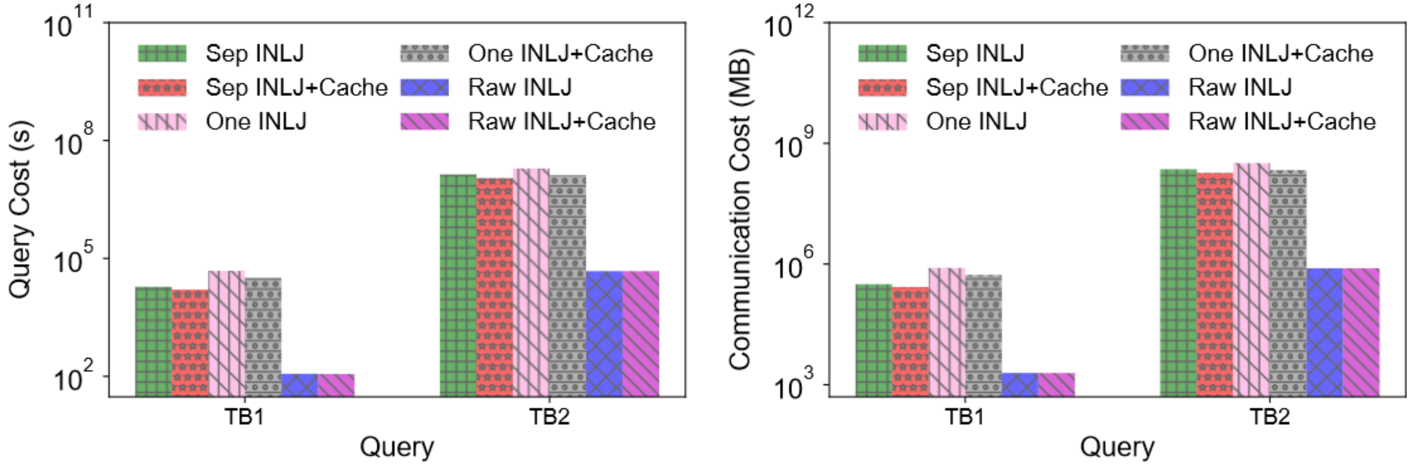
Binary Band Join: Performance

TB1 (10MB)

- Sep is 164-238X slower than Raw.
- Sep is 1.4-2.5X faster than One.
- Caching is 1.2-1.5X faster.

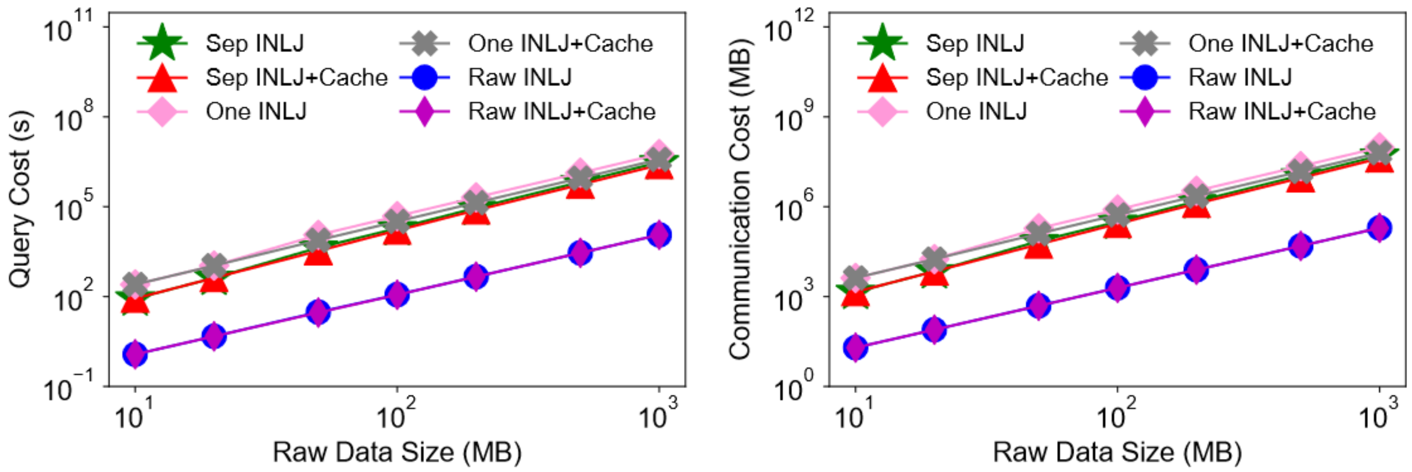
TB2 (1GB):

- Sep is 73-264X slower than Raw.
- Sep is 1.9-2.9X faster than One.
- Caching is again 1.2-1.5X faster.



(a) Query cost. (b) Communication cost.

Figure 13: Performance of band join on TPC-H.



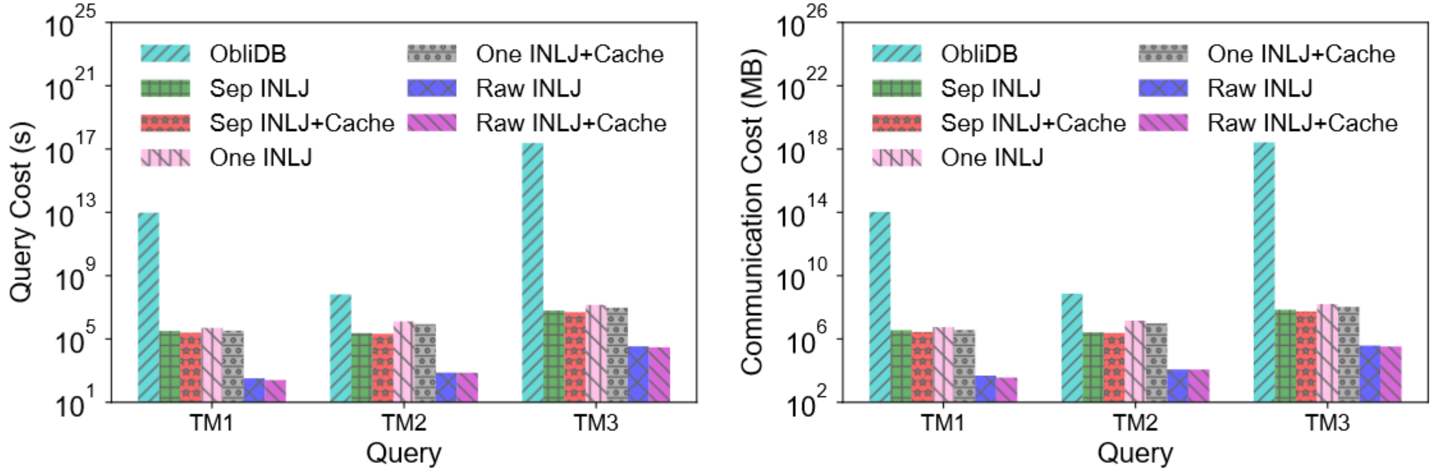
(a) Query cost. (b) Communication cost.

Figure 14: Performance of Query TB1 against raw data size.

Multiway Equi-Join: Performance

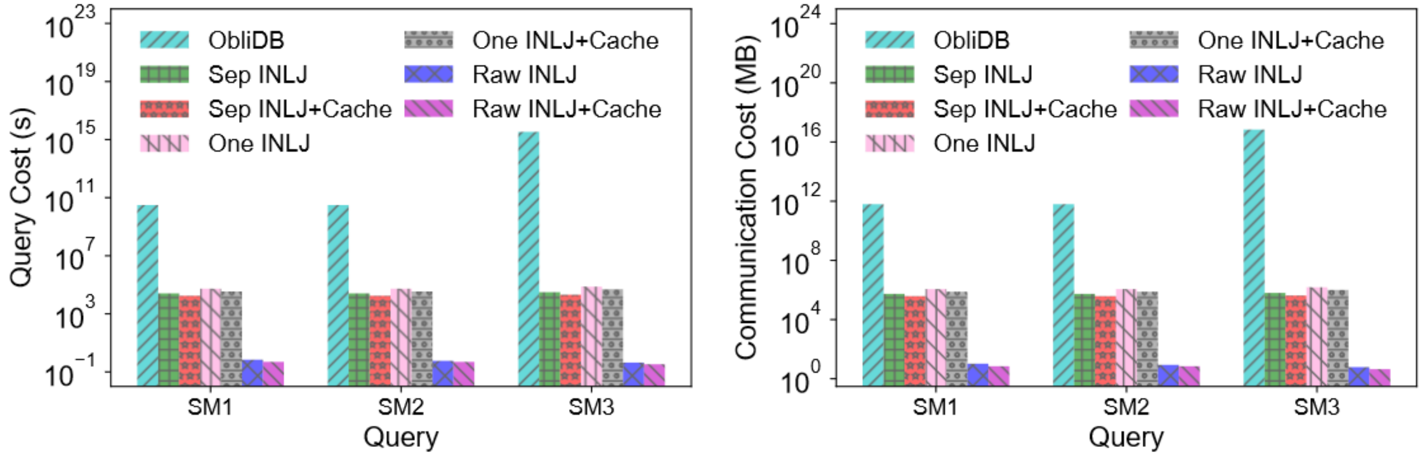
- ObliDB performs a cartesian product.
- Sep is 1.6-2.4X faster than One.
- Caching is 1.1-1.5X faster.
- Sep is <u>185-985X</u> slower than Raw in TPC-H, <u>37000-70000X</u> on social graph.
- That is because even if the join result is very small, we must pad the number of join steps to the upper bound,

$$|T_1| + 2\sum_{j=2}^{\ell} |T_j| + |R_{\mathrm{real}}|$$



(a) Query cost. (b) Communication cost.

Figure 15: Performance of multiway equi-join on TPC-H.

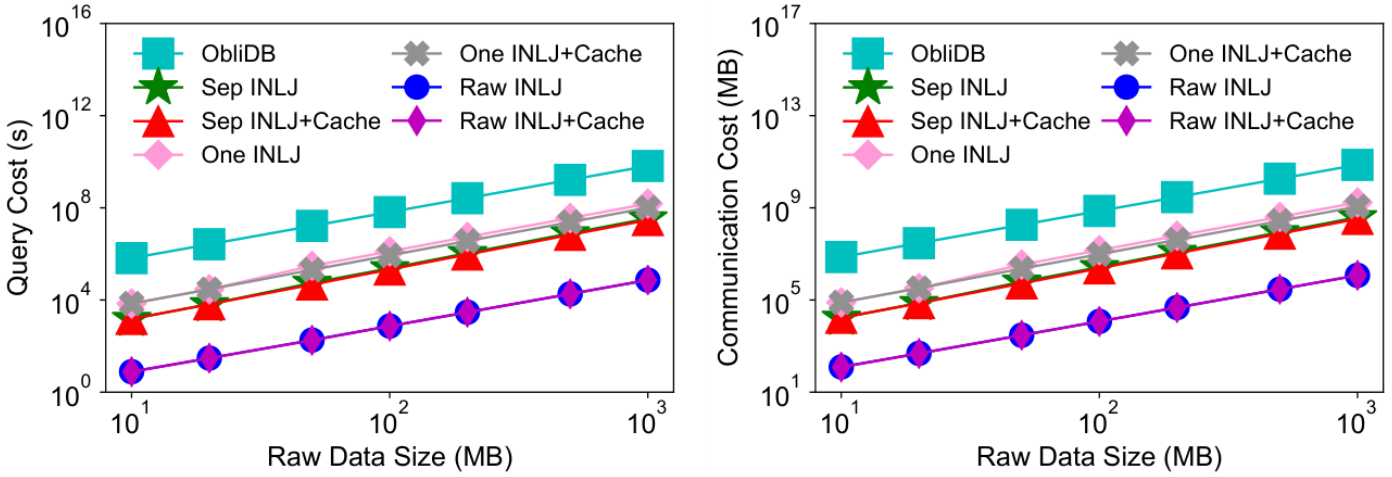


(a) Query cost. (b) Communication cost.

Figure 16: Performance of multiway equi-join on social graph.

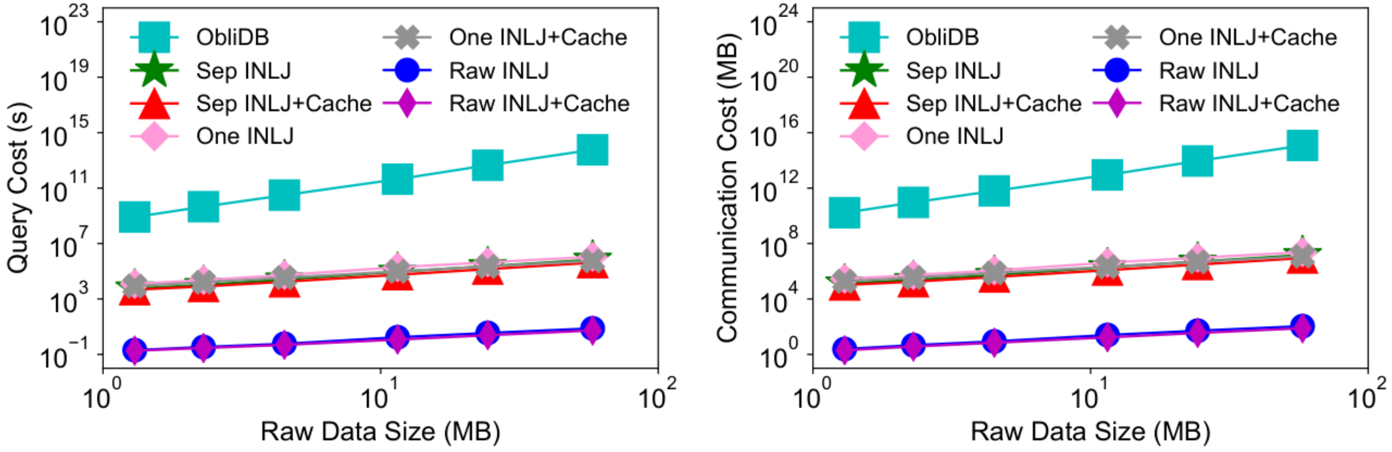
Multiway Equi-Join: Scalability

- For TM2, Sep-INLJ(+Cache) is 190-430X faster than ObliDB, and that is stable because the join result is proportional to the cartesian product.
- Sep is <u>149-469X</u> slower than raw.
- For SM2 (social graph), which has a small join result, the gap from ObliDB is $10^5 - 10^8$X.
- Sep is <u>28000-91000X</u> slower than raw.



(a) Query cost. (b) Communication cost.

Figure 17: Performance of Query TM2 against raw data size.

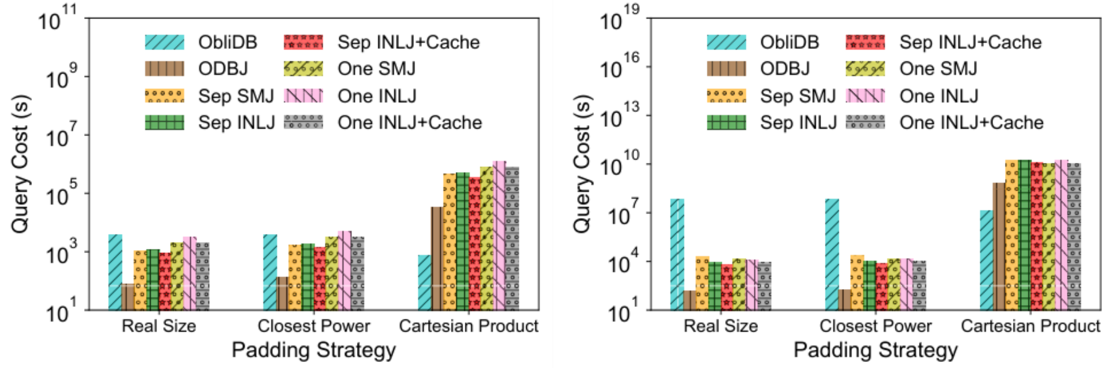


(a) Query cost. (b) Communication cost.

Figure 18: Performance of Query SM2 against raw data size.

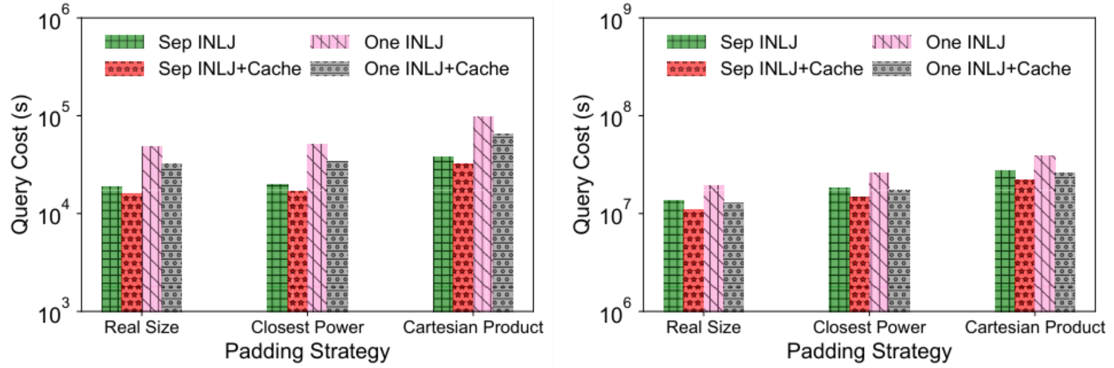
Padding Performance

- Closest power is (obviously) within 2X of Real Size.
- ObliDB is faster with Cartesian Product than it is with Real Size or Closest Product because otherwise it uses oblivious filtering.
- ObliDB is best at Cartesian Product because we have less trusted memory and use B-tree searches over ORAMs (instead of a linear database).



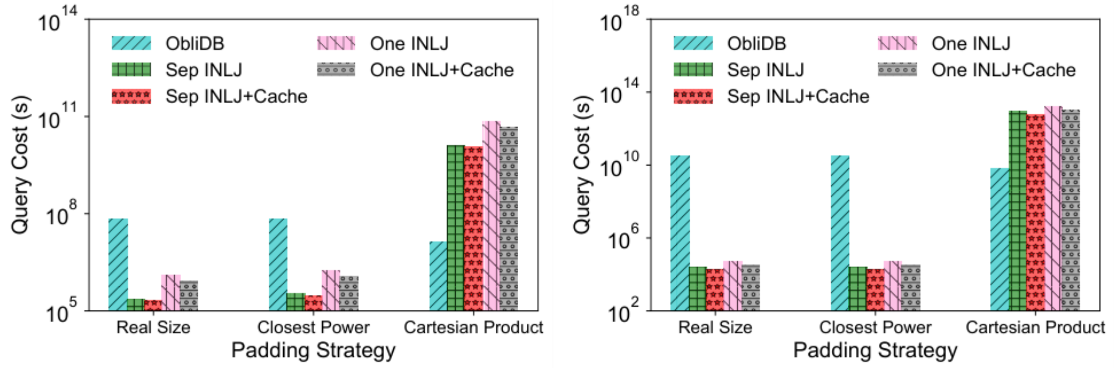
(a) Query TE2. (b) Query SE2.

Figure 19: Padded vs. non-padded mode (binary equi-join).



(a) Query TB1. (b) Query TB2.

Figure 20: Padded vs. non-padded mode (band join).



(a) Query TM2. (b) Query SM2.

Figure 21: Padded vs. non-padded mode (multiway equi-join).

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- Oblivious RAM is a nice and useful abstraction but when using it we are still responsible to make the number of accesses deterministic.
- Even by timing how long the server takes to respond, we could measure how many join results there are, which is an interesting attack vector.