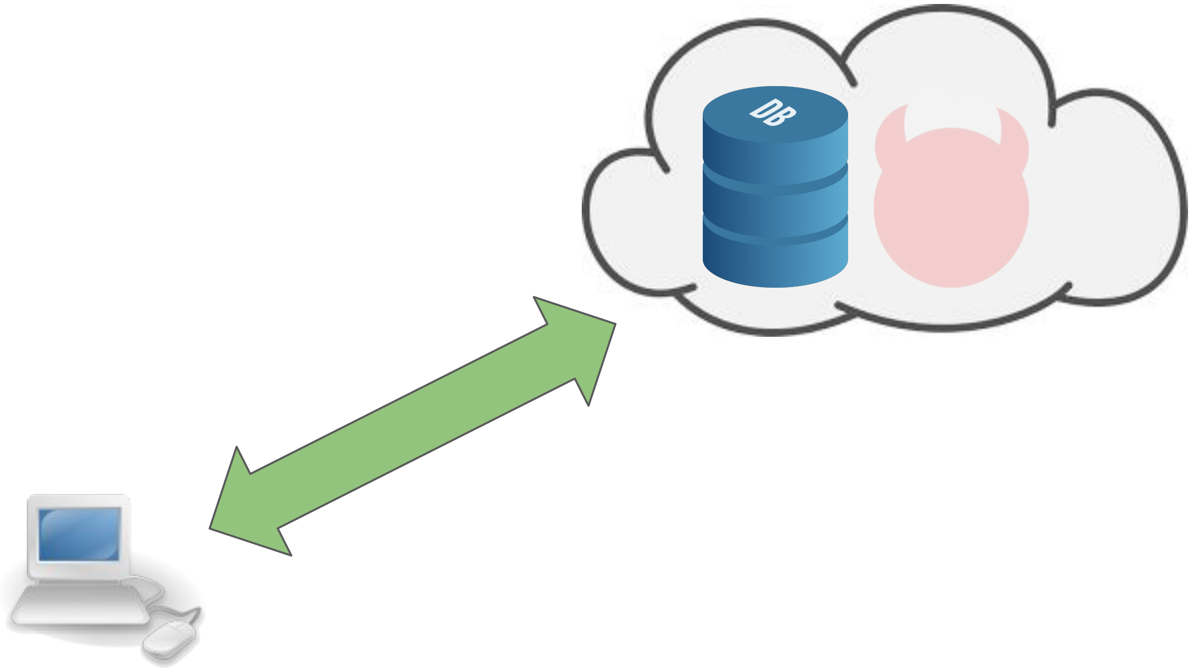
ObliDB: Oblivious Query Processing using Hardware Enclaves

Saba Eskandarian Matei Zaharia

Private Data in the Cloud



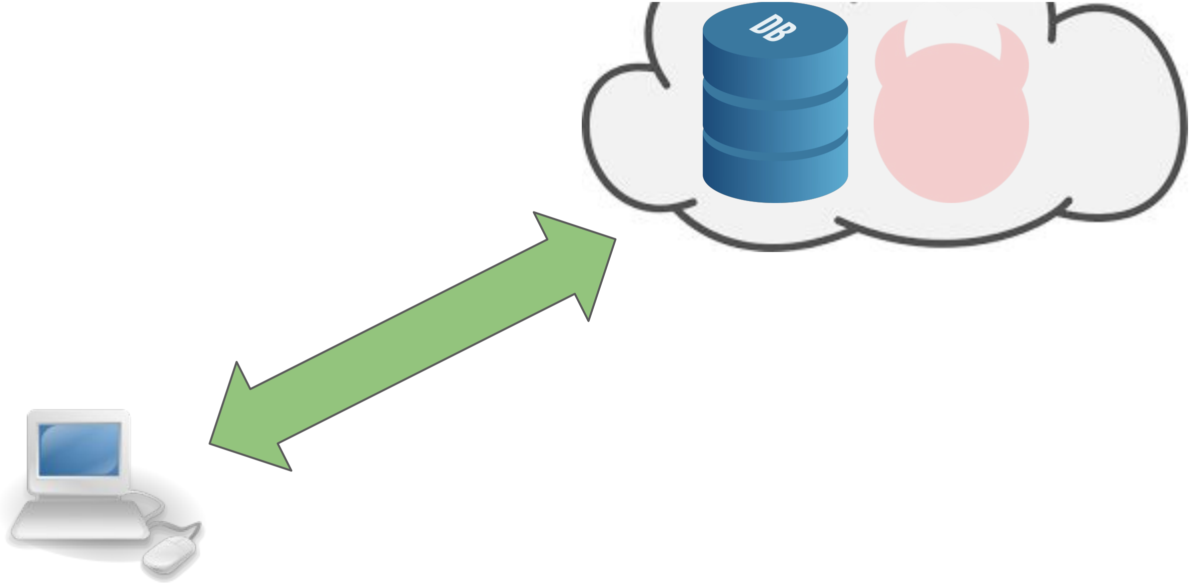
Compromised cloud can:

Read data
Read queries
Alter data

Private Data in the Cloud

NSA spying fiasco sending customers overseas

NSA spy program cold lead to loss of business for some hosting vendors, experts say



Read queries
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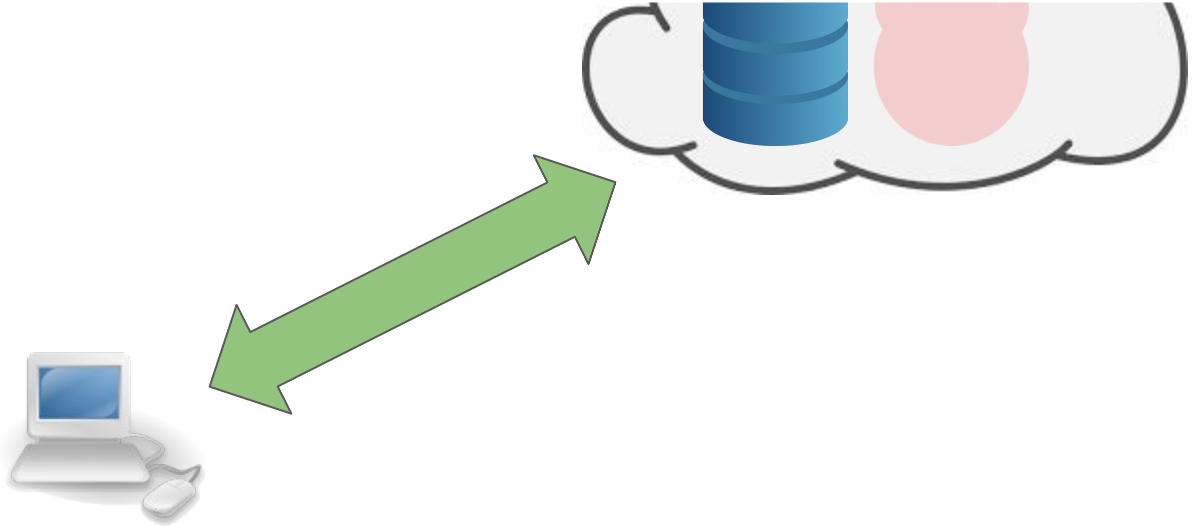
Private Data in the Cloud

Uber will pay $20,000 fine in settlement over 'God View' tracking

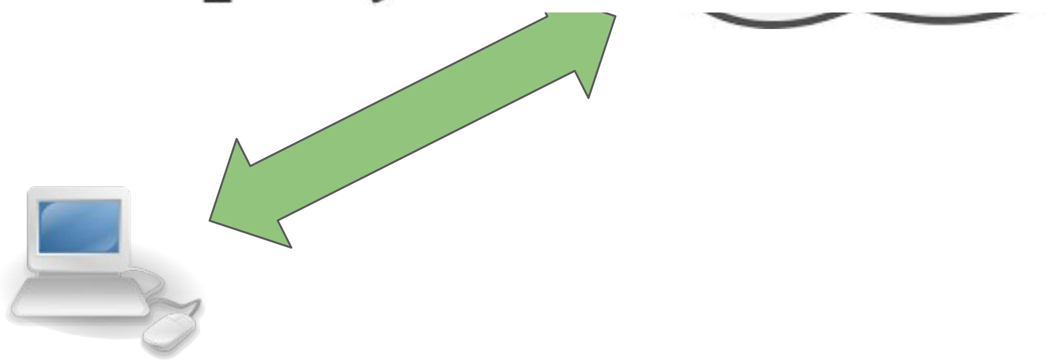


Alter data

Private Data in the Cloud

EXCLUSIVE

Lyft Investigates Allegation That Employees Abused Customer Data



Private Data in the Cloud

NSA spying fiasco sending customers overseas

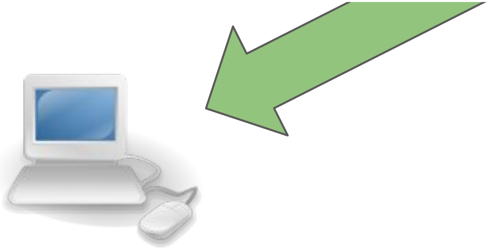
Uber will pay $20,000 fine in settlement over 'God

EXCLUSIVE

CNN tech BUSINESS CULTURE GADGETS FUTURE STARTUPS

Cyber-Safe

Every single Yahoo account was hacked - 3 billion in all



Private Data in the Cloud

EXCLUSIVE

CNN tech BUSINESS CULTURE GADGETS FUTURE STARTUPS

Cyber-Safe

Atos, IT provider for Winter Olympics, hacked months before Opening Ceremony cyberattack

(Purely) Cryptographic Solutions

Huge body of work on how to protect databases with cryptography

Various tradeoffs between functionality, performance, and security, but relatively little industry adoption thus far.

Fuller et al., SoK: Cryptographically Protected Database Search, 2017.

(Purely) Cryptographic Solutions

Huge body of work on how to protect databases with cryptography

Various tradeoffs between functionality, performance, and security, but relatively little industry adoption thus far.

Minimum Requirements:

- Broad support for common workloads
- Acceptable performance
- Strong security guarantees

Fuller et al., SoK: Cryptographically Protected Database Search, 2017.

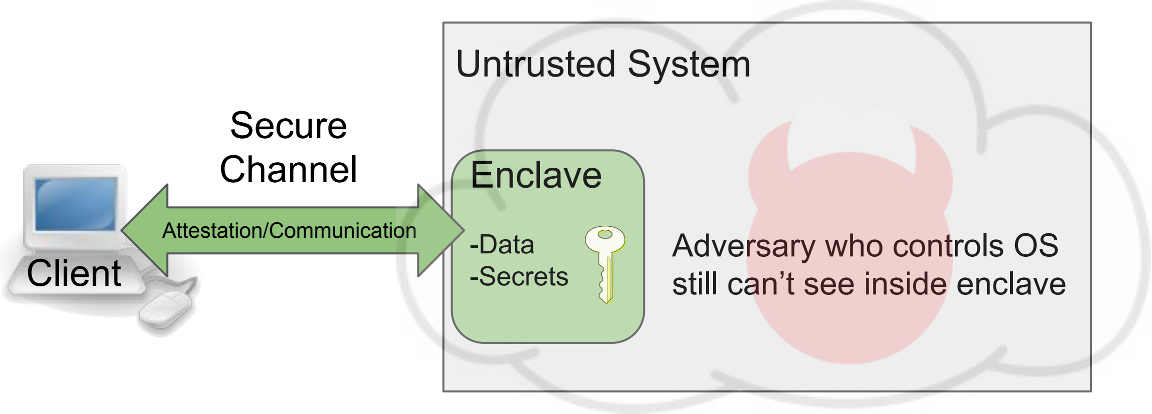
Outline

- Intro: Protecting Cloud Data
- **Hardware Enclaves and Obliviousness**
- ObliDB Design
  - Threat Model and Security Guarantees
  - SELECT Algorithms
  - Oblivious Indexes
- ObliDB Performance Evaluation

Hardware Enclaves

A trusted component in an untrusted system

- Uses protected memory to isolate enclave execution from compromised OS
- Proves that it is an authentic enclave running the desired code with *attestation*
- Enclaves in our implementation use Intel SGX



Azure Confidential Computing Heralds the Next Generation of Encryption in the Cloud

BY ERICA PORTNOY | SEPTEMBER 18, 2017

For years, EFF has commended companies who make cloud applications that encrypt data in transit. But soon, the new gold standard for cloud application encryption will be the cloud provider never having access to the user's data—not even while performing computations on it.

Microsoft has become the first major cloud provider to offer developers the ability to build their applications on top of Intel's Software Guard Extensions (SGX) technology, making Azure "the first SGX-capable servers in the public cloud." Azure customers in Microsoft's Early Access program can now begin to develop applications with the "confidential computing" technology.

Google Cloud Platform Blog

Product updates, customer stories, and tips and tricks on Google Cloud Platform

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Introducing Asylo: an open-source framework for confidential computing

Thursday, May 3, 2018

“We are exploring future backends based on AMD Secure Encryption Virtualization (SEV) technology, Intel® Software Guard Extensions (Intel® SGX)”

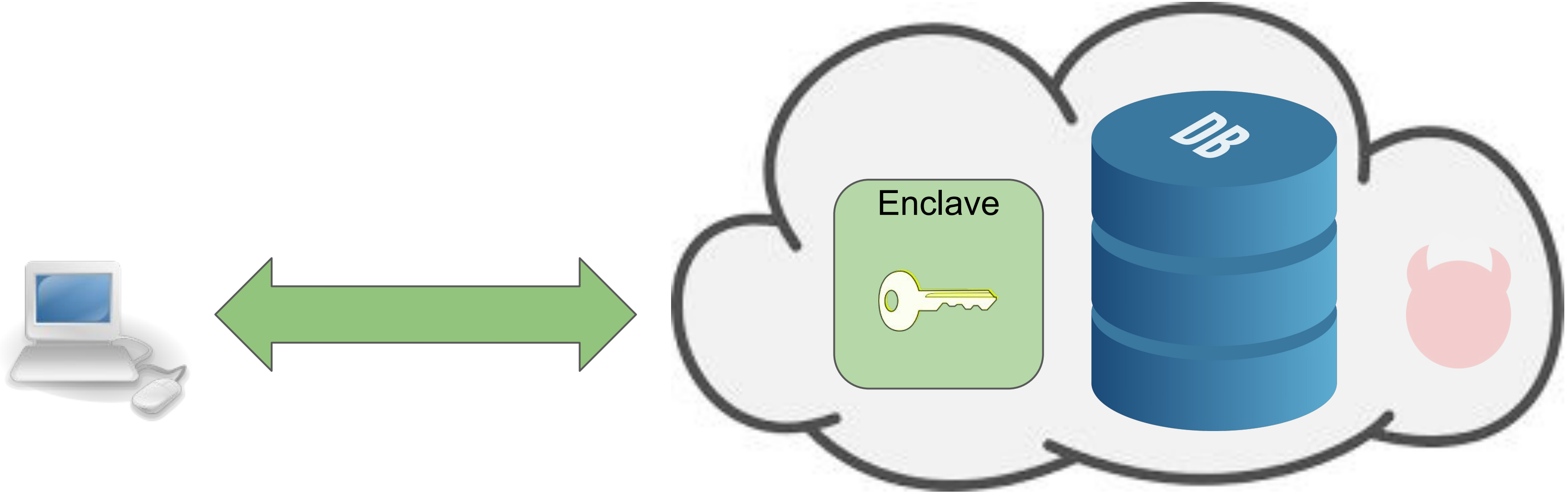
ANJUNA
Securing Data In Use

Fortanix®

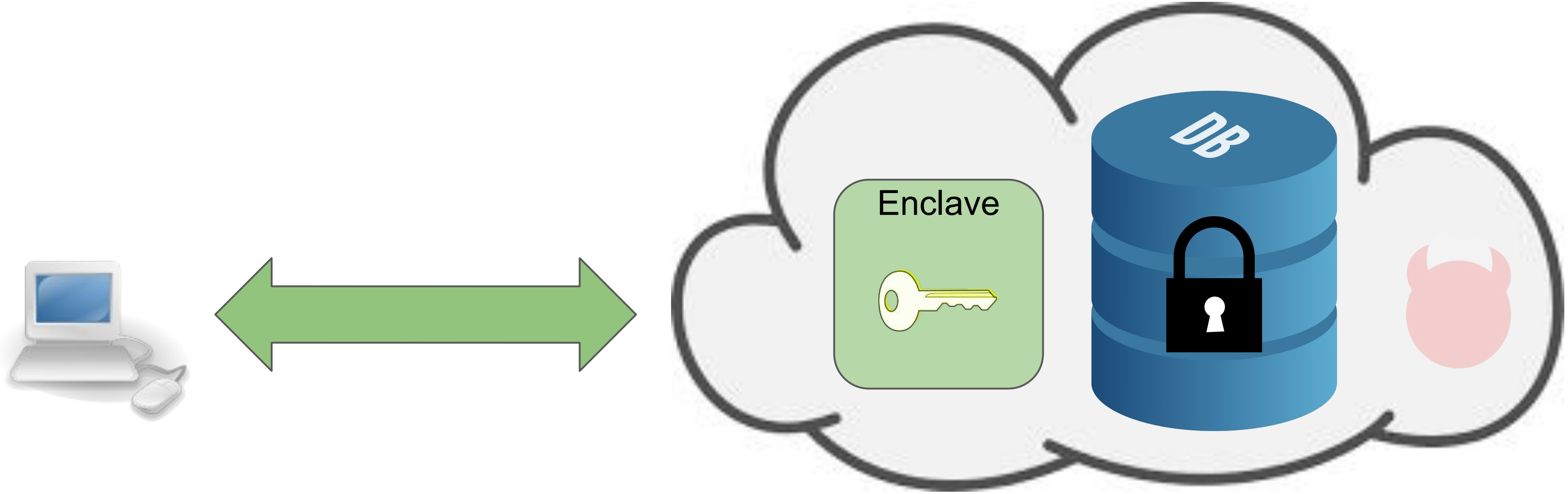
Kalepso
Data protection, trust-free

Enclaves in the Cloud

Enclave space is limited, but data is big!

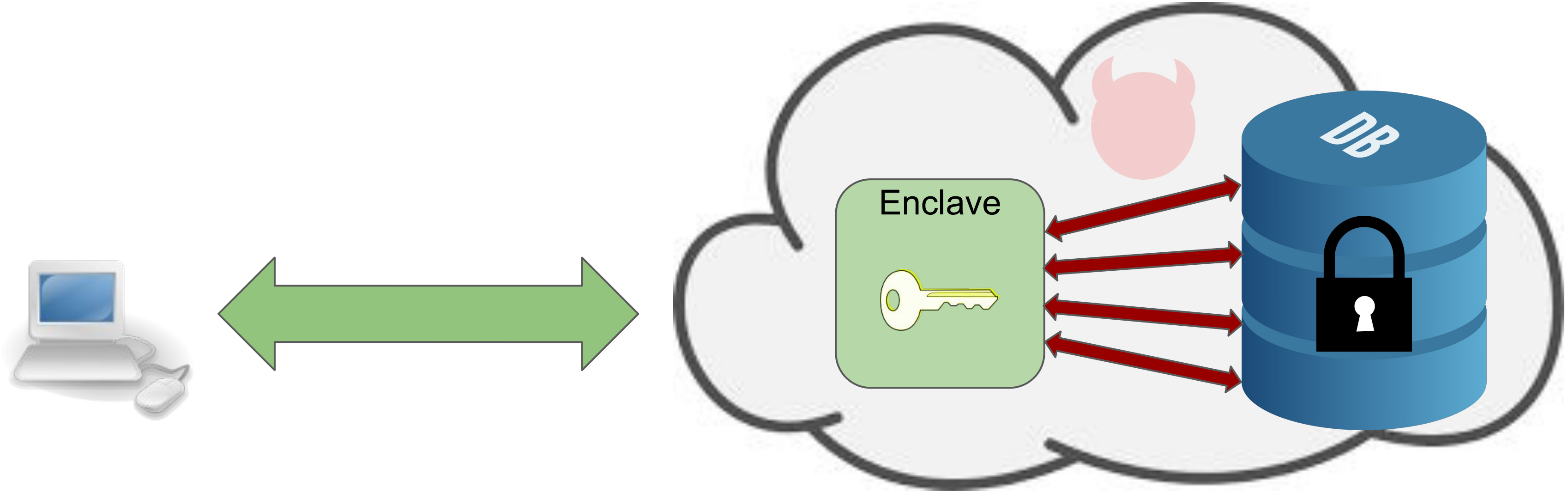


Enclaves in the Cloud



Enclaves in the Cloud

Malicious attacker can observe access patterns to encrypted data!



Enclaves in the Cloud

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Access Pattern disclosure on Searchable Encryption: Ramification, Attack and Mitigation

Mohammad Saiful Islam, Mehmet Kuzu, Murat Kantarcioglu
Jonsson School of Engineering
and Computer Science
The University of Texas at Dallas
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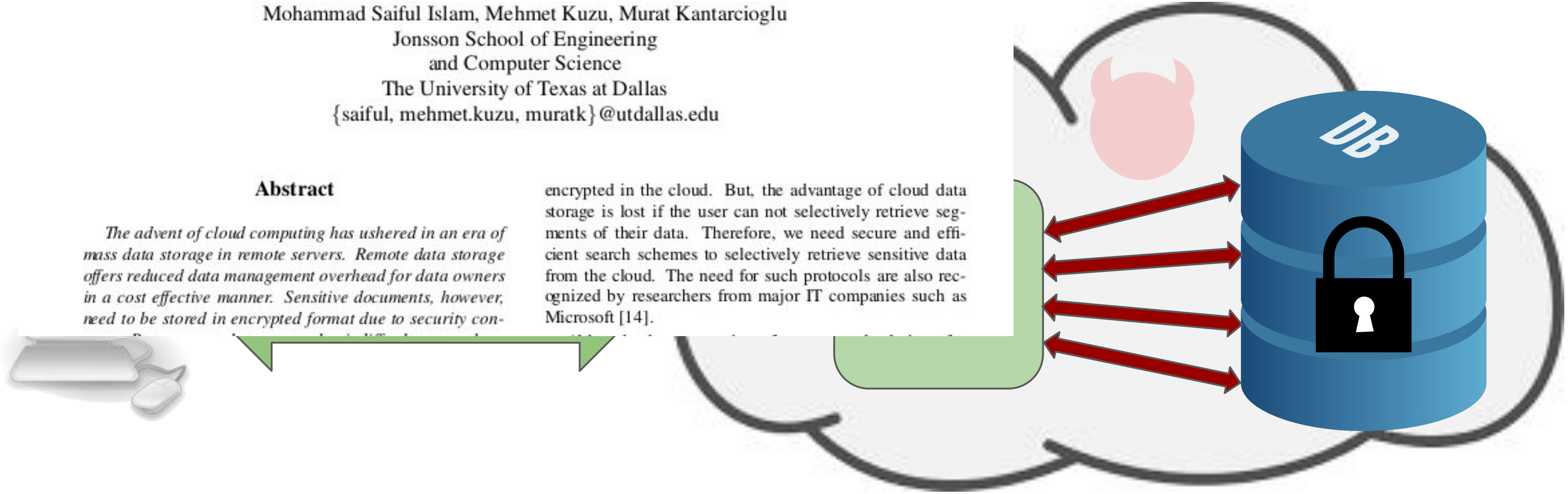
Abstract

The advent of cloud computing has ushered in an era of mass data storage in remote servers. Remote data storage offers reduced data management overhead for data owners in a cost effective manner. Sensitive documents, however, need to be stored in encrypted format due to security con-

encrypted in the cloud. But, the advantage of cloud data storage is lost if the user can not selectively retrieve segments of their data. Therefore, we need secure and efficient search schemes to selectively retrieve sensitive data from the cloud. The need for such protocols are also recognized by researchers from major IT companies such as Microsoft [14].



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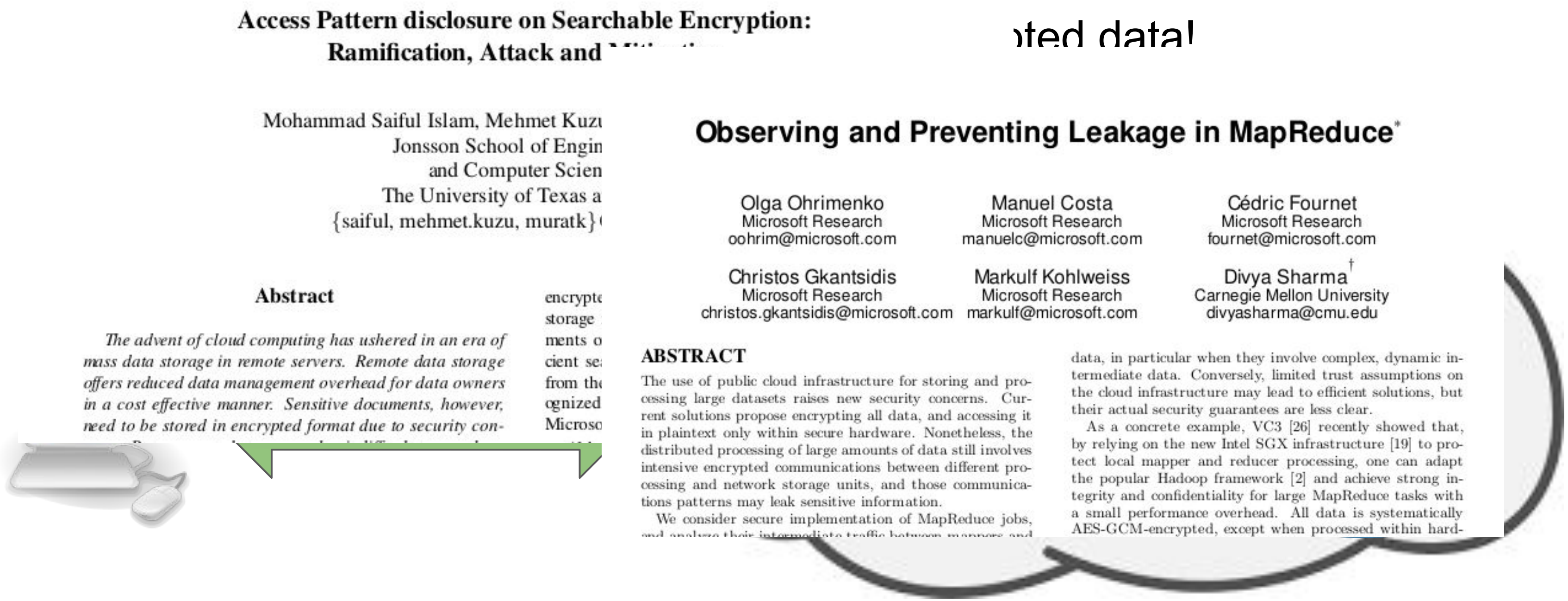
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Observing and Preventing Leakage in MapReduce[*]

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ABSTRACT

The use of public cloud infrastructure for storing and processing large datasets raises new security concerns. Current solutions propose encrypting all data, and accessing it in plaintext only within secure hardware. Nonetheless, the distributed processing of large amounts of data still involves intensive encrypted communications between different processing and network storage units, and those communications patterns may leak sensitive information.

We consider secure implementation of MapReduce jobs,

data, in particular when they involve complex, dynamic intermediate data. Conversely, limited trust assumptions on the cloud infrastructure may lead to efficient solutions, but their actual security guarantees are less clear.

As a concrete example, VC3 [26] recently showed that, by relying on the new Intel SGX infrastructure [19] to protect local mapper and reducer processing, one can adapt the popular Hadoop framework [2] and achieve strong integrity and confidentiality for large MapReduce tasks with a small performance overhead. All data is systematically AES-GCM-encrypted, except when processed within hard-

Enclaves in the Cloud

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Observing and Preventing Leakage in MapReduce*

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> "A persistent passive attacker can extract even more information by observing an application's access patterns … In our case study applications, this reveals users' medical conditions, genomes, and contents of shopping carts"

Breaking Web Applications Built On Top of Encrypted Data

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ABSTRACT

We develop a systematic approach for analyzing client-server applications that aim to hide sensitive user data from untrusted servers. We then apply it to Mylar, a framework that uses multi-key searchable encryption (MKSE) to build Web applications on top of encrypted data.

We demonstrate that (1) the Popa-Zeldovich model for MKSE does not imply security against either passive or active attacks; (2) Mylar-based Web applications reveal users'

activity on the server but not interfering with its operations), and active attacks involving arbitrary malicious behavior. We then work backwards from these adversarial capabilities to models. This approach uncovers significant challenges and security-critical decisions faced by the designers of BoPETs: how to partition functionality between the clients and the server, which data to encrypt, which access patterns can leak sensitive information, and more.

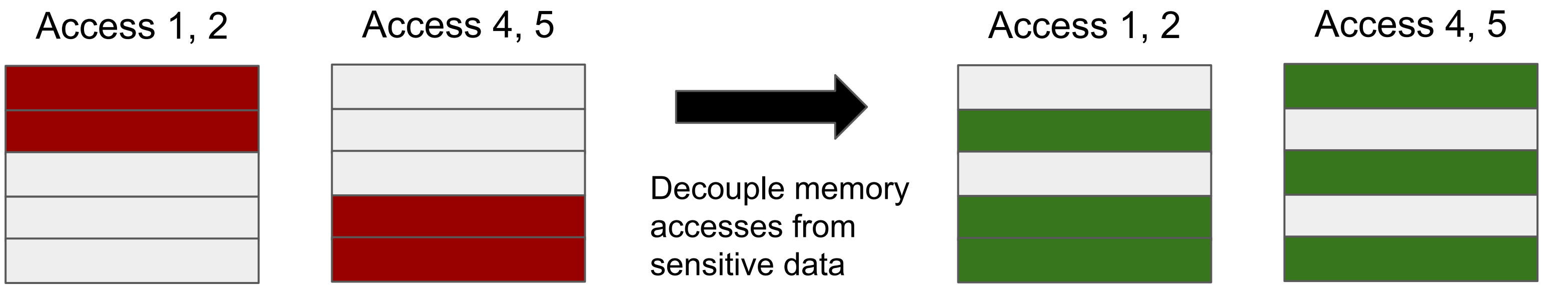
We then apply our methodology to a recent BoPET called

Goal: Obliviousness

Leakage attacks observe *access patterns* to protected memory

Problem: Leakage of access patterns completely compromises security

Solution: design enclave operation to be oblivious of input data



Introducing ObliDB

Functionality:

Oblivious query processing algorithms *for both transactional and analytic queries*

Supports most SQL operations (SELECT, GROUP BY, JOIN, various aggregates)

Security:

Protects against powerful attacker with full control of the OS

Performance:

Point queries 7-22x faster than (non-enclave) prior work (Sophos, HIRB)

Analytic queries 20-330x faster than naive, 1-19x faster than prior work (Opaque)

Threat Model

ObliDB <u>protects against an attacker with full control of the OS</u> who can:

- Read *and tamper with* all of untrusted memory
- Pause and resume enclave execution
- Observe access patterns to untrusted memory
- Monitor network communications
- Know auxiliary information about data stored

Threat Model

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- Monitor network communications
- Know auxiliary information about data stored
- **Assumption:** limited oblivious memory pool (same as Opaque)

Security Guarantees

ObliDB protects data and query parameters:

- Detects any malicious attempt to tamper with data
- Leaks only query selectivity, table sizes (including intermediate tables), and query plan
- Optional padding mode available to hide table sizes and query selectivity

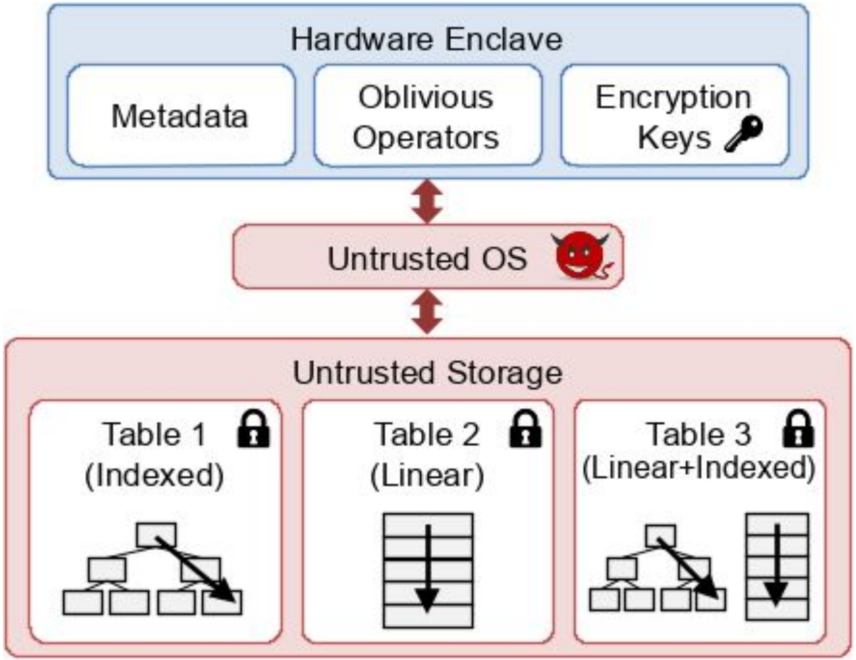
ObliDB Overview

Oblivious database engine with support for both transactional and analytic queries

Tables stored encrypted in untrusted memory but access patterns hidden

Two storage methods: linear tables and oblivious indexes

Enclave used to store keys/metadata and as working space for sensitive operations



SELECT Algorithms

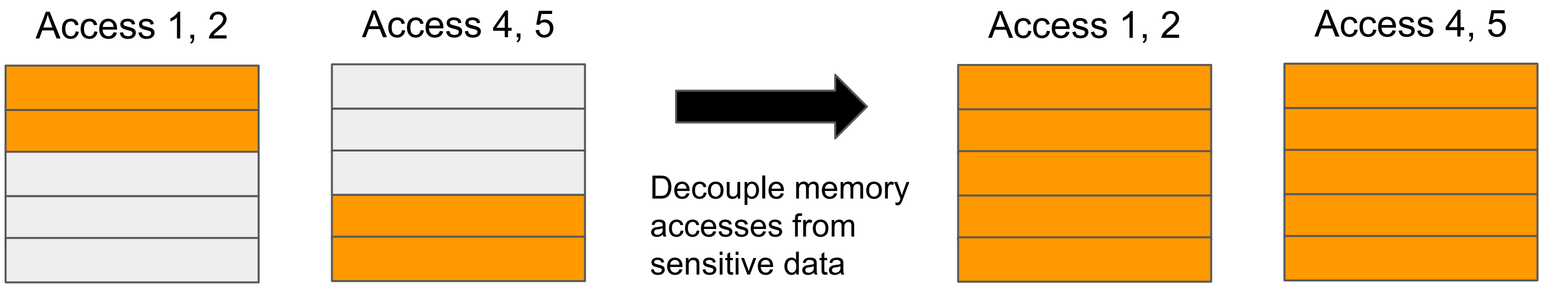
Storage Methods: Linear

Access every block every time!

Good when accessing most blocks anyway

Used when we only need oblivious analytics

Point Read: O(N)
Large Read: O(N)
Insertion: O(1)
Deletion: O(N)



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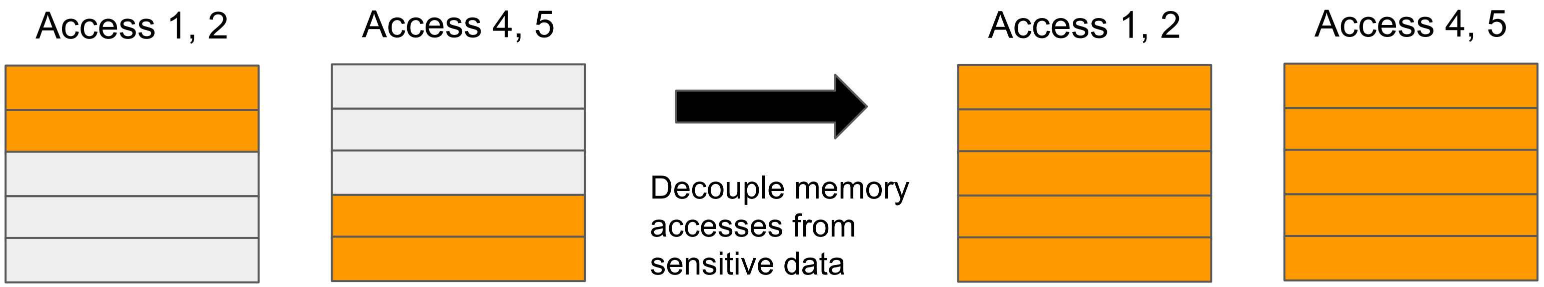
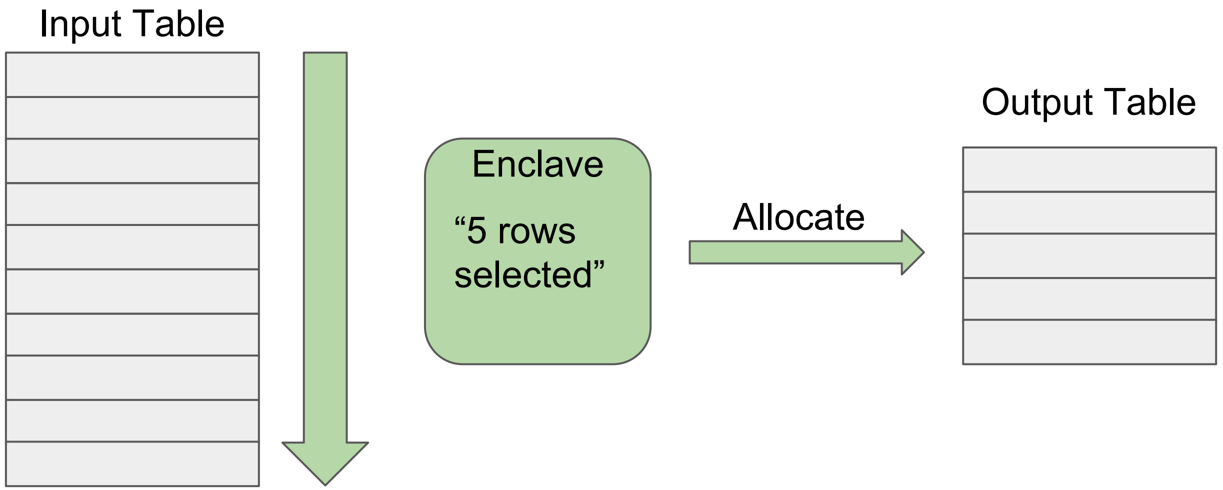


Oblivious SELECT

First pass over data: determine size of output table, pick strategy to satisfy query

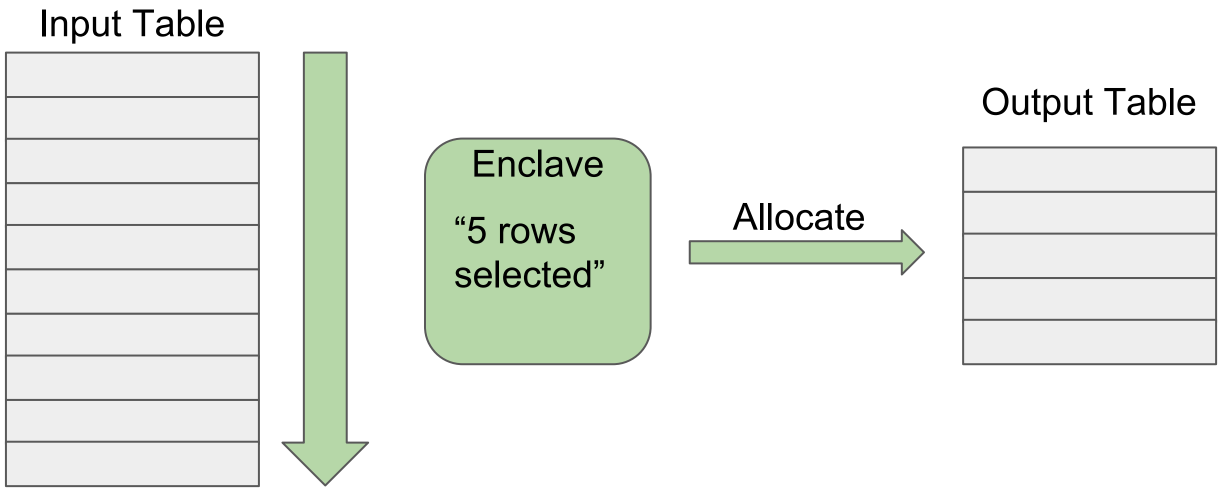


4 Strategies

Continuous
Large
Small
Hash

Oblivious SELECT

First pass over data: determine size of output table, pick strategy to satisfy query



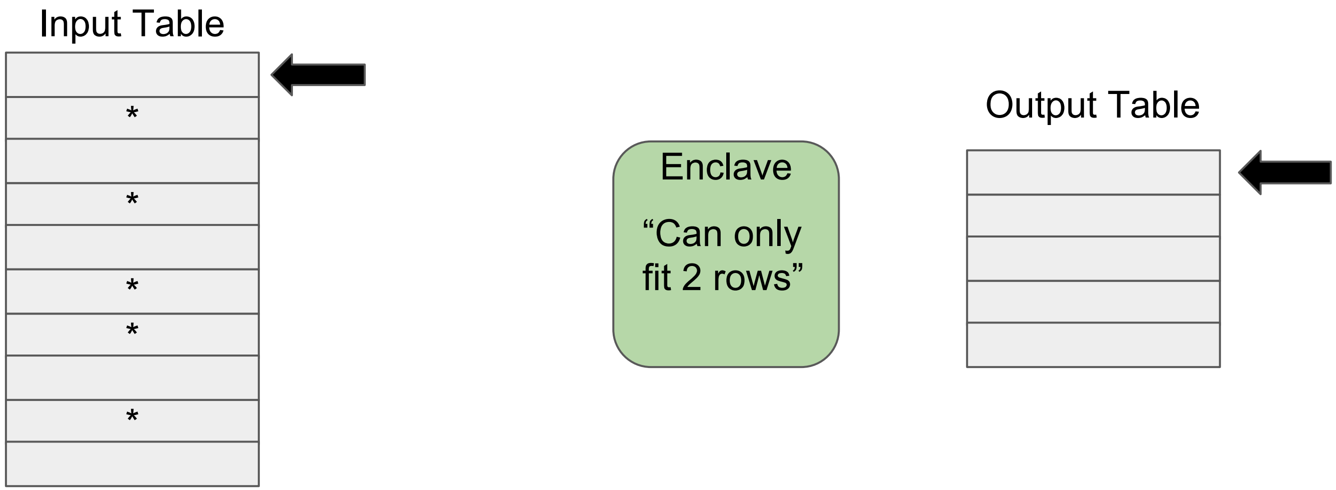
4 Strategies

Small
Continuous
Large
Hash

Q: Why not just select at the same time as the first pass?
A: Naive SELECT is not oblivious!

Oblivious SELECT

Naive SELECT is not oblivious!



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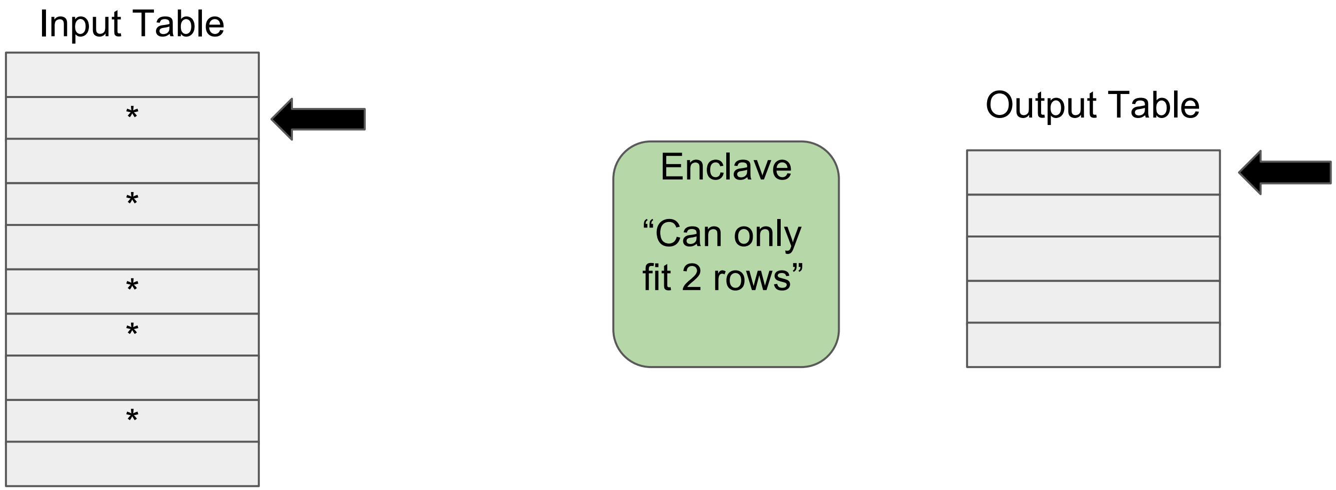

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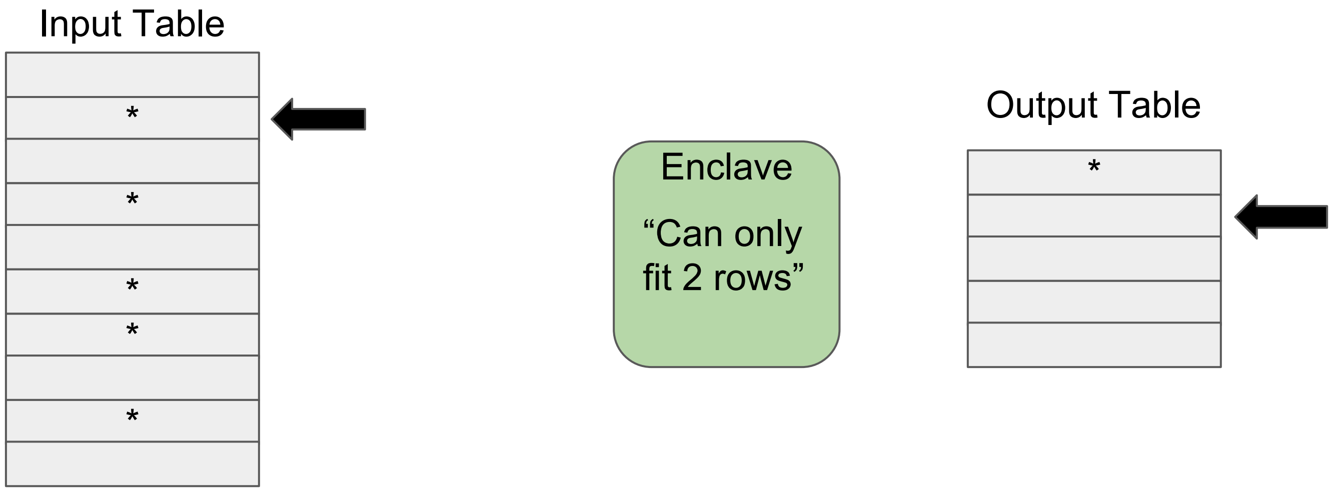

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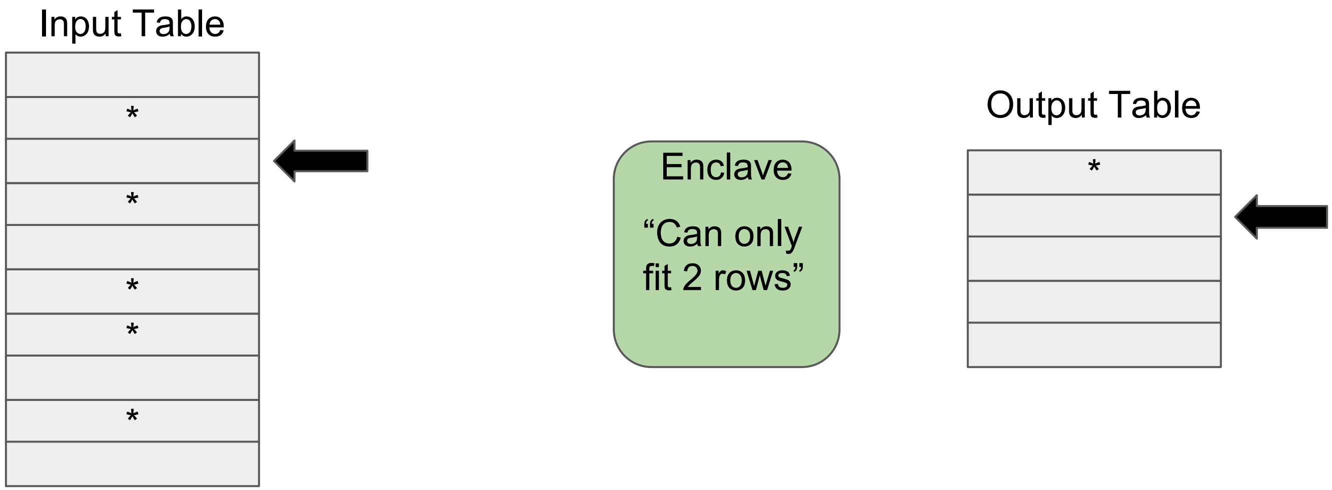

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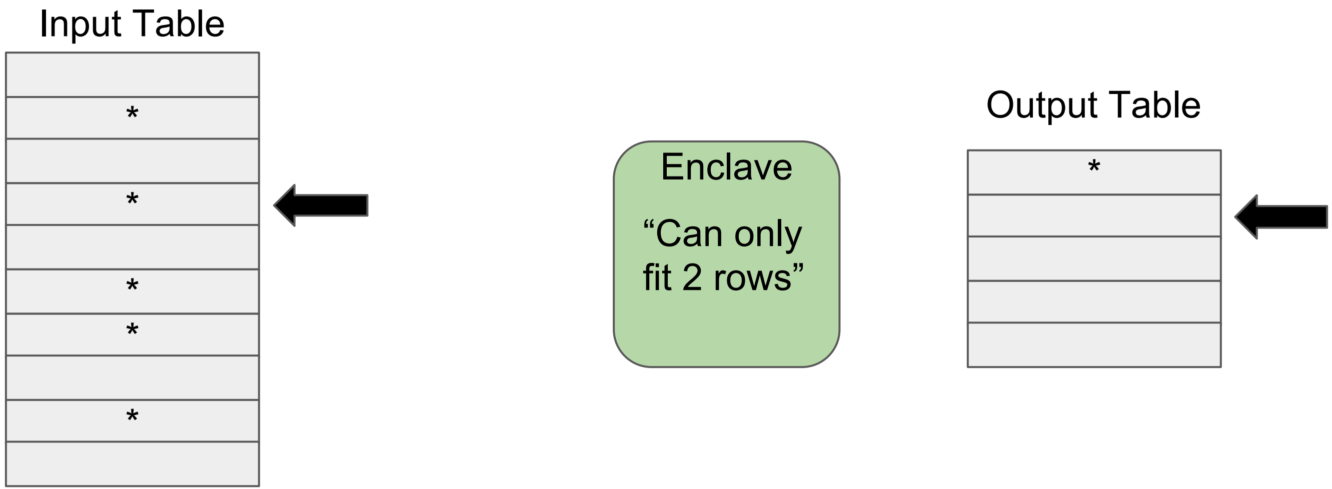

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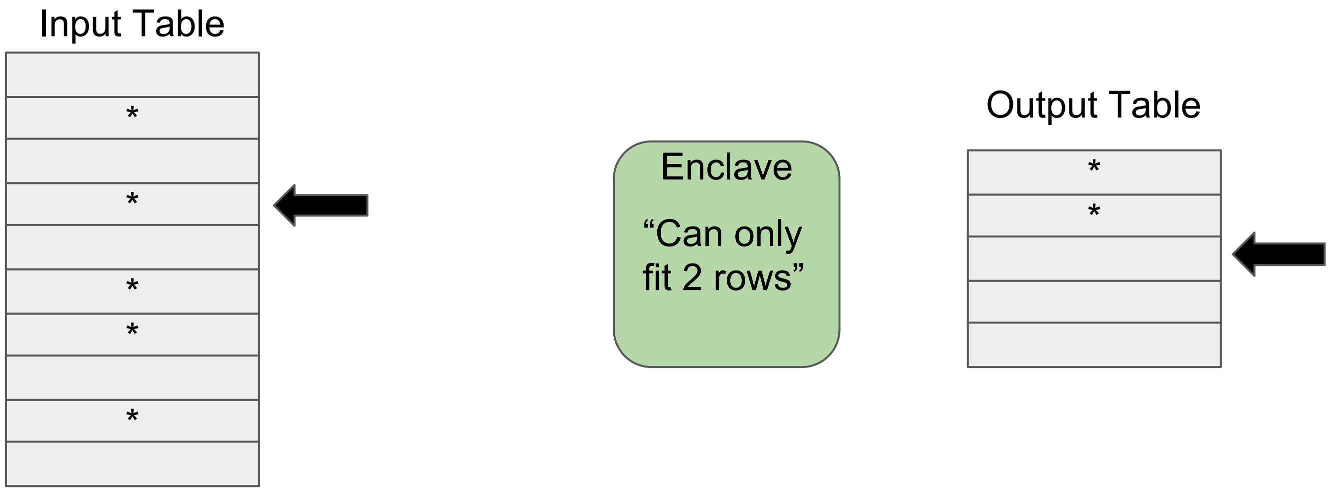

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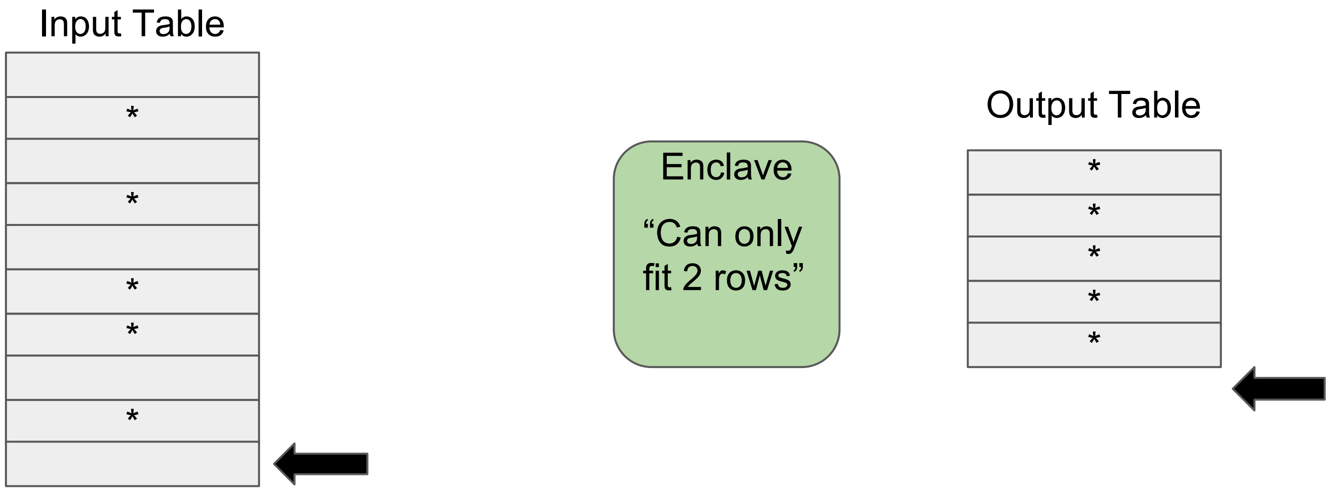

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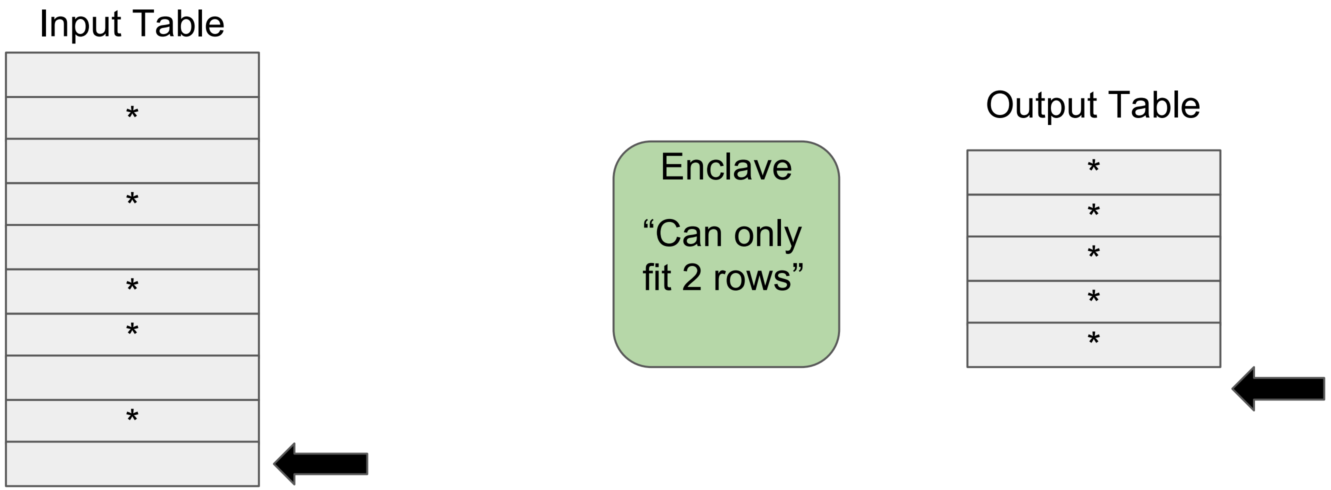
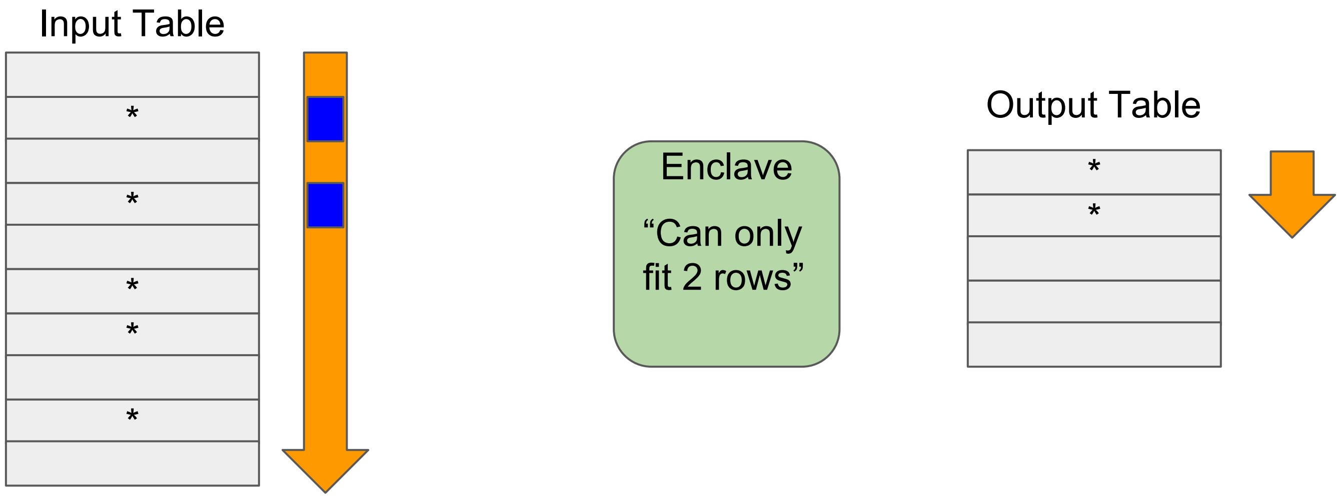


Watching when we write to the output table reveals exactly which rows of the input table we select!

Oblivious SELECT

“Small” SELECT algorithm



Oblivious SELECT

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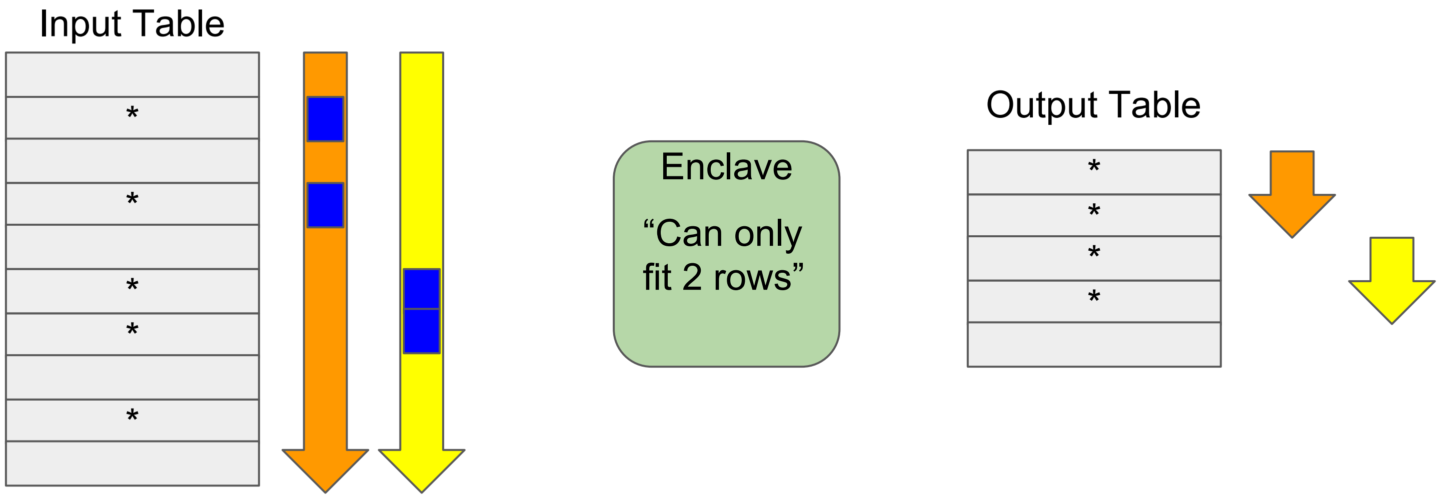

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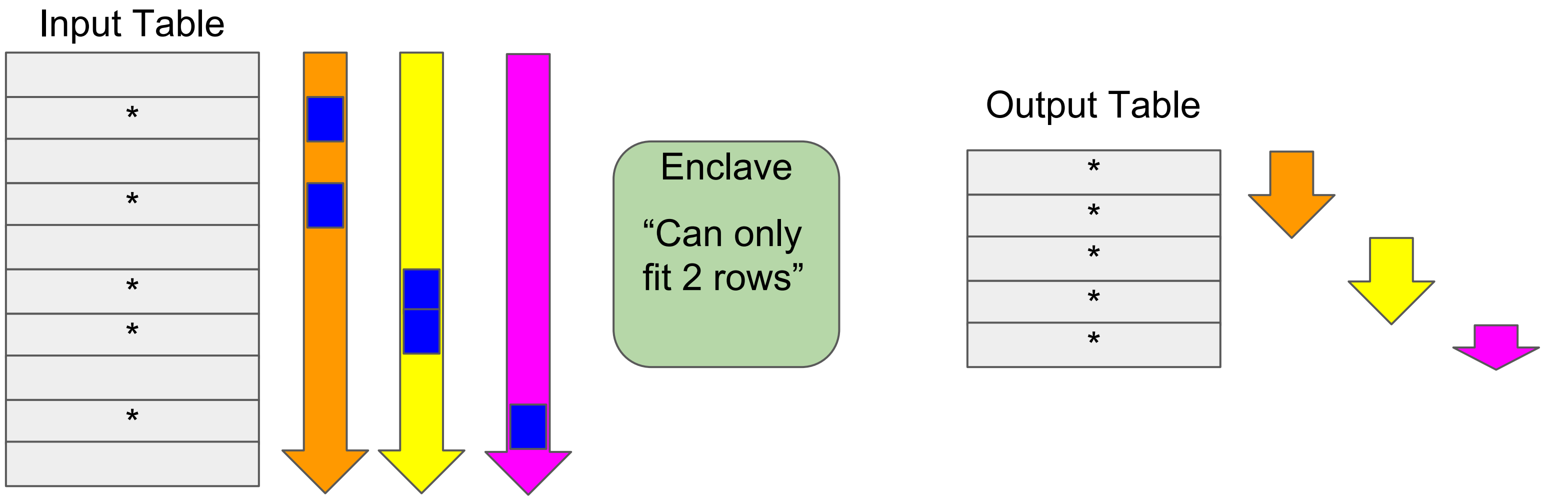
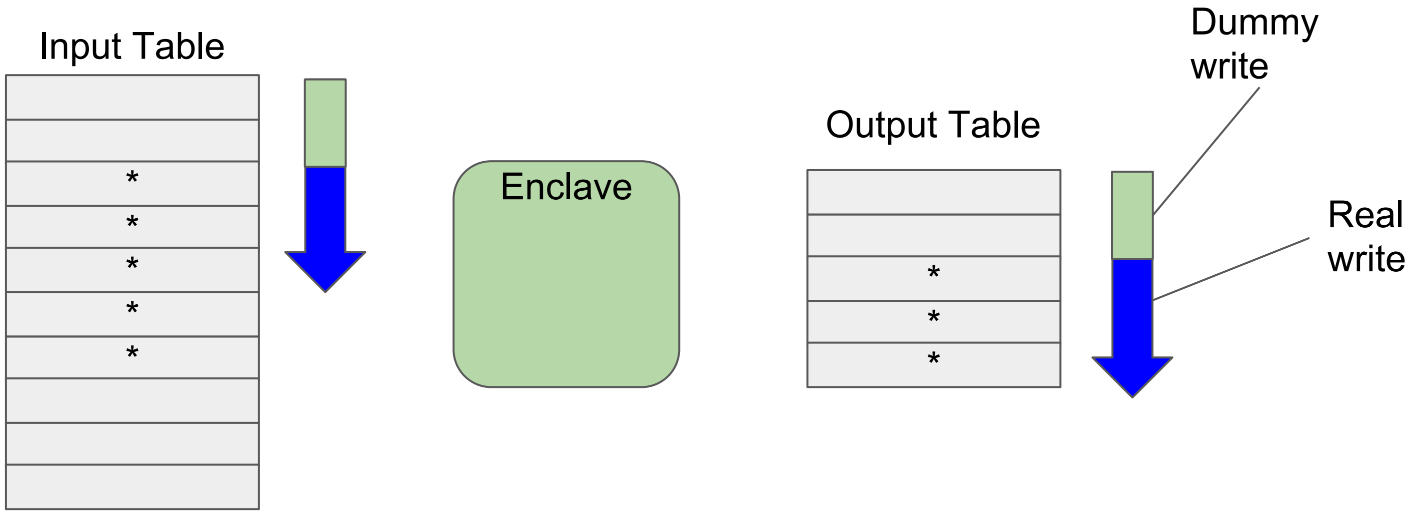


Oblivious SELECT

"Continuous" SELECT algorithm



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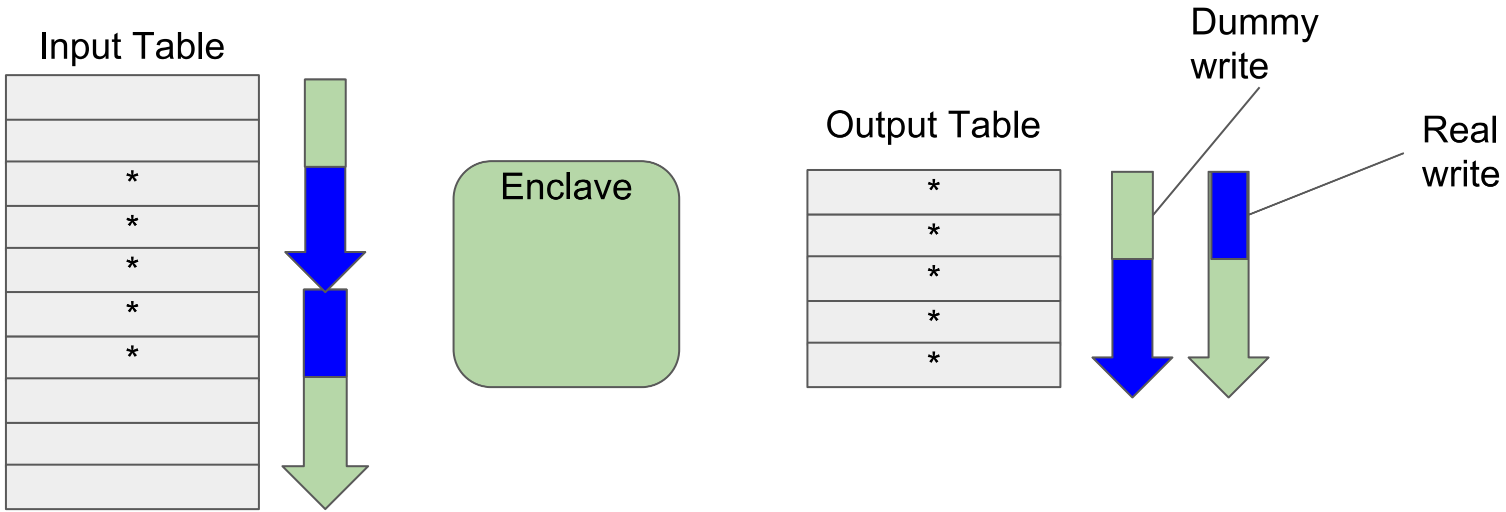
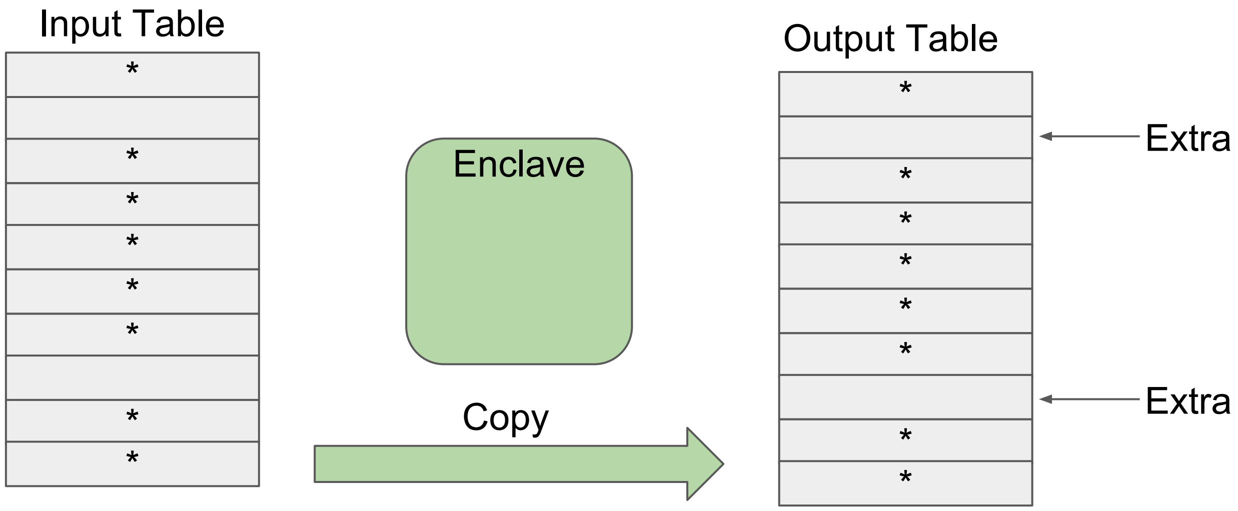


Oblivious SELECT

“Large” SELECT Algorithm



Oblivious SELECT

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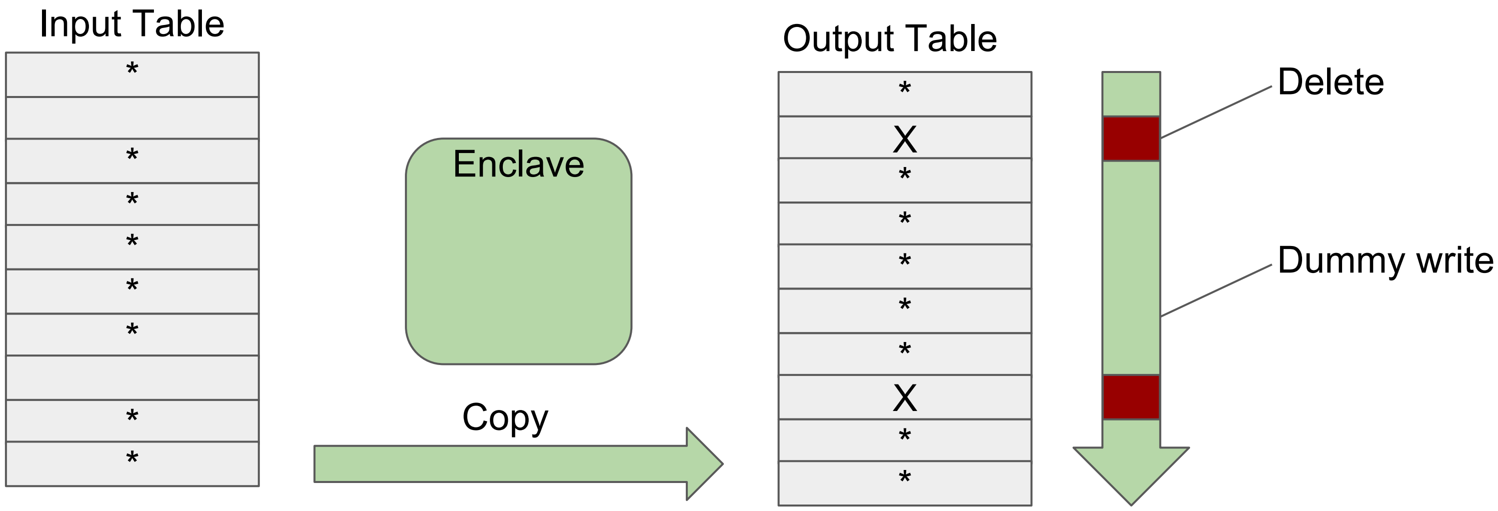

Oblivious Indexes

Tool: ORAM

Crypto primitive to generically hide access patterns to data

Security guarantee: two memory traces of **the same length** are indistinguishable

Important: does <u>not</u> automatically give obliviousness

Key question: how can we use ORAM to make indexes oblivious?

Goldreich and Ostrovsky, Software Protection and Simulation on Oblivious RAMs, 1993.
Shi et al, PATH ORAM: An Extremely Simple Oblivious RAM Protocol, 2012.

Oblivious Indexes: Considerations

- Naive composition of ORAM + Index NOT oblivious
- Generic solution: pad everything to maximum number of possible accesses
- How to do this without destroying performance?
  - Choice of index data structure (T tree, B tree, B+ tree, other?)
  - Make the worst case less bad (optimize for enclave/ORAM setting)
  - Small average-case improvements can be big worst-case improvements

Oblivious Indexes

Naive composition of ORAM and B+ Tree is not oblivious!

All data in leaves → ORAM ensures oblivious access ✓

Insert/Delete → number of operations depends on data ✗

First solution: pad all inserts/deletes to *worst-case* number of ORAM accesses,

but this is too slow.

Oblivious Indexes

Optimizations:

1. Cache nodes accessed during insertion/deletion inside enclave until certain they will not be accessed again
2. Remove parent pointers
3. Pad operation to worst-case number of operations, *knowing* we have made optimizations (1) and (2)

Point Read: $O(\log^2 N)$
Large Read: $O(N)$
Insertion: $O(\log^2 N)$
Deletion: $O(\log^2 N)$

Oblivious Indexes

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Point Read: $O(\log^2 N)$
Large Read: O(N)
Insertion: $O(\log^2 N)$
Deletion: $O(\log^2 N)$

Why not O(NlogN)?

Can do linear scan over ORAM data structure without using ORAM algorithm

Enables analytics on frequently updated table!

Performance

Design Validation

Choice of Storage Method

Effectiveness of Optimizer

Design Validation

Choice of Storage Method

Workload Type	Best Storage Method
90% Insert, 5% Point/Large read	Combined
90% Small read, 9% Insert, 1% Delete	Index
50% Large read, 50% Point read	Combined
45% Point/Large read, 5% Insert/Delete	Combined
90% Large read, 5% Insert/Delete	Linear

Queries over 100k row table

Effectiveness of Optimizer

Query Selectivity	Alg. Choice
5% of table, continuous	Small
5% of table, non-continuous	Small
95% of table, continuous	Continuous
95% of table, non-continuous	Large

Takeaway: Variety of storage methods and operator algorithms helpful for diverse workloads!

Comparison to Baseline

Performance vs baseline based on naive use of index/operators with ORAM

Query Type	Speedup
Range Selection (Linear)	29.2x
Group By Aggregate (Linear)	185x
Range Selection (Index)	1.4x
Point Selection (Index)	1.5x
Insert (Index)	64x
Delete (Index)	15x

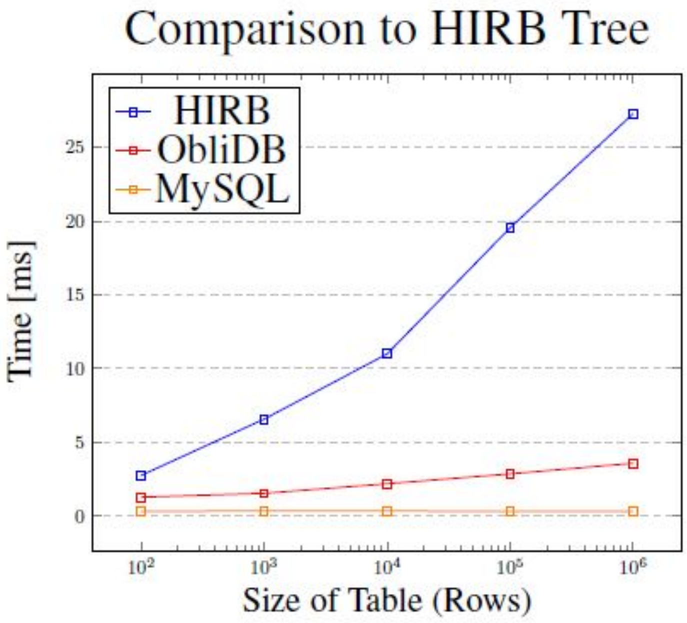
Queries over Consumer Financial Protection Bureau dataset: ~107k rows

Comparison to HIRB + vORAM

7.6x faster for point query on 1M row table

HIRB Tree does not support range queries

Difference: enclave security guarantees

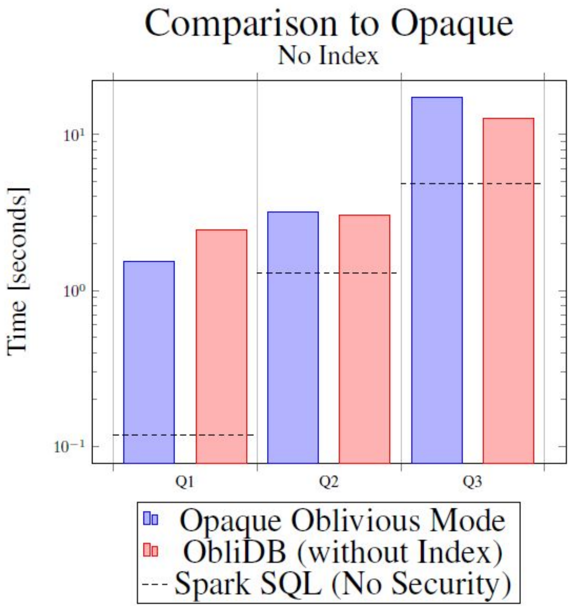


Roche et al, A Practical Oblivious Map Data Structure with Secure Deletion and History Independence, 2016.

Comparison to Opaque

Linear storage method:

comparable



Queries from Big Data Benchmark

Zheng et al, Opaque: An Oblivious and Encrypted Distributed Analytics Platform, 2017.

Comparison to Opaque

Linear storage method:

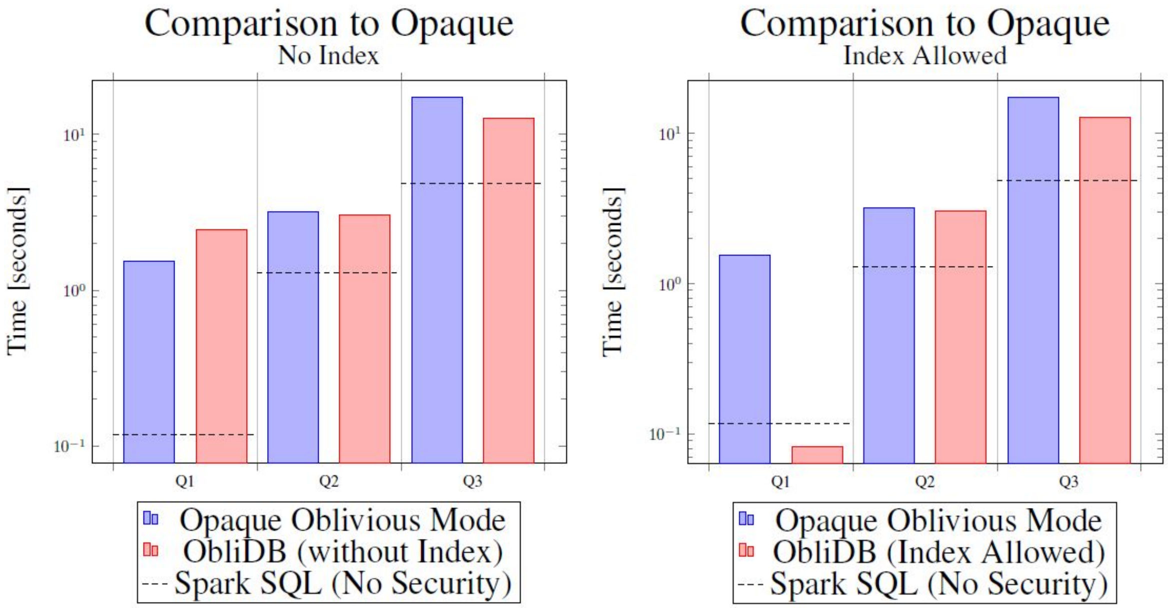
comparable

Combined storage method:

comparable - 19x speedup

Analytics within 2.6x of

Spark SQL



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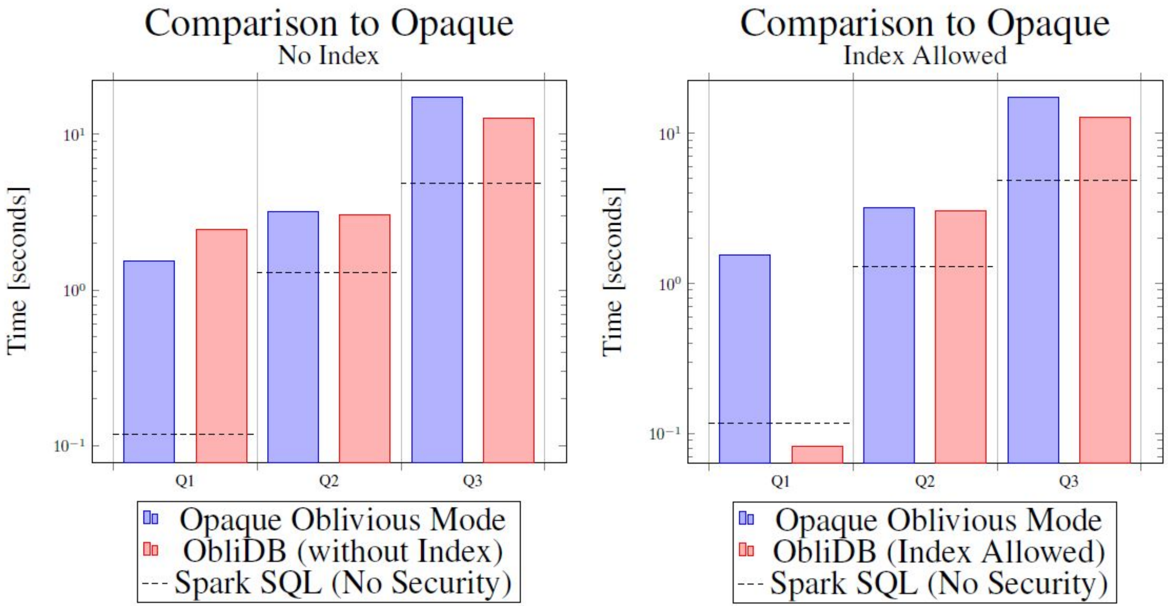
Oblivious Index only:

<2x slowdown vs combined



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Summary

ObliDB: Secure hardware enclave

+ new oblivious operator algorithms

+ multiple storage methods

= <u>fast oblivious performance on analytic AND transactional queries</u>

See paper at https://arxiv.org/pdf/1710.00458.pdf

Source code available at https://github.com/SabaEskandarian/ObliDB

Extra Slides

Prior/Concurrent Oblivious Systems over SGX

Opaque [ZDBPGS17] (Prior): oblivious analytics, no support for indexes

Oblix [MPCCP18], **POSUP** [HOJY18]: oblivious indexes, but no operators over them

StealthDB [GVG17]: SGX database, no integrity or access pattern protection for index

EnclaveDB [PVC18]: SGX database, no access pattern protection (not oblivious)

VeritasDB [SC18]: integrity for key-value store over SGX

ZeroTrace [SGF17] (Prior): ORAM for oblivious key-value store over SGX

ObliDB: Obliviousness, Integrity, support for queries regardless of selectivity

Oblivious SELECT

“Hash” SELECT Algorithm

Goal: only one additional scan over data, regardless of query selectivity

Idea: Hash each input row to an output row

Obliviousness considerations:

- Hash based on row number, not contents
- Oblivious collision handling: average case → worst case

Asymptotically best strategy, but often outperformed by special cases

Tool: B+ Tree

Often used for indexes in databases

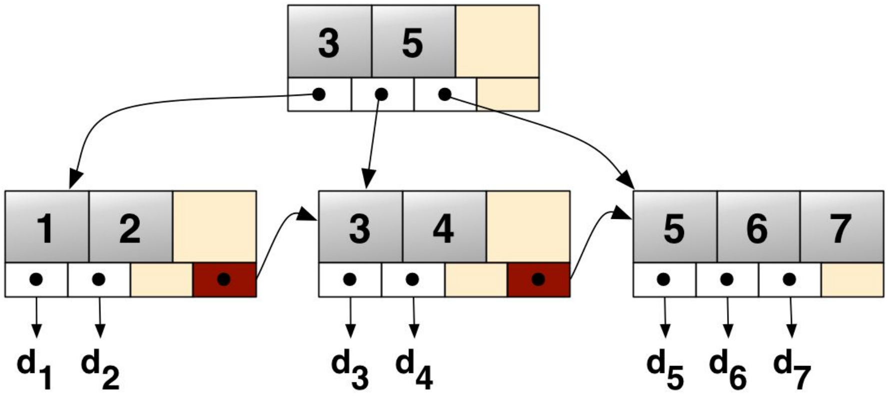
Generalization of binary search tree

All data in the leaves

Average-case insert/delete very fast

Worst-case insert/delete modifies tree at every level

Good for minimizing pointer traversals



Source: Wikimedia Commons
https://commons.wikimedia.org/wiki/File:Bplustree.png

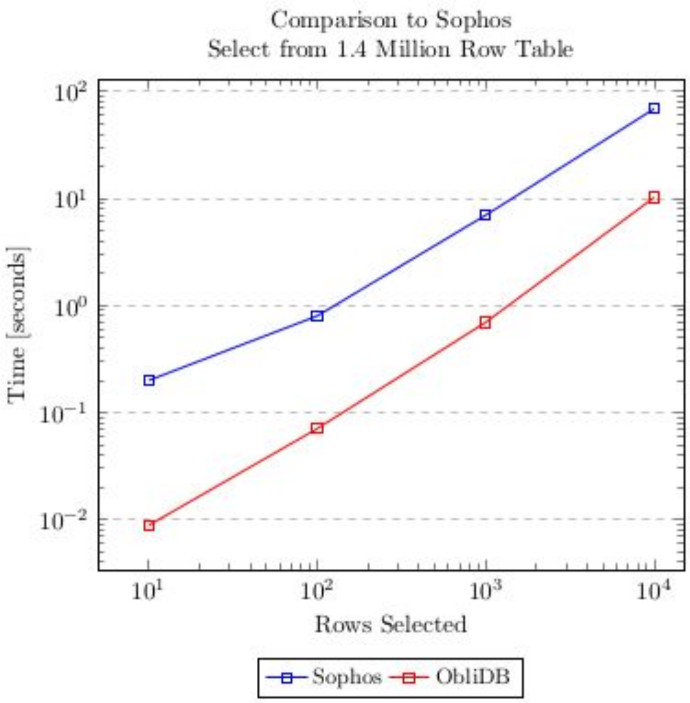
Performance: Comparison to Sophos

Searchable symmetric encryption scheme without obliviousness

Supports only keyword lookups

Does not use hardware enclaves

22x speedup or more



Bost, Sophos - Forward Secure Searchable Encryption, 2016.