EnigMap: External-Memory Oblivious Map for Secure Enclaves

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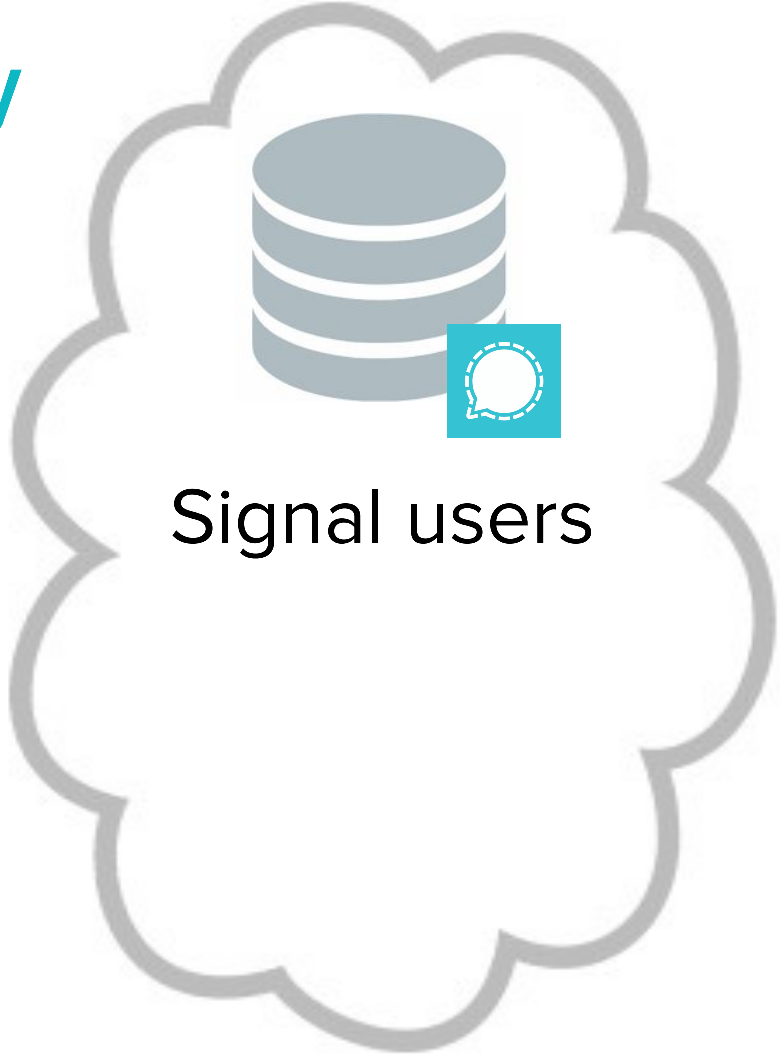
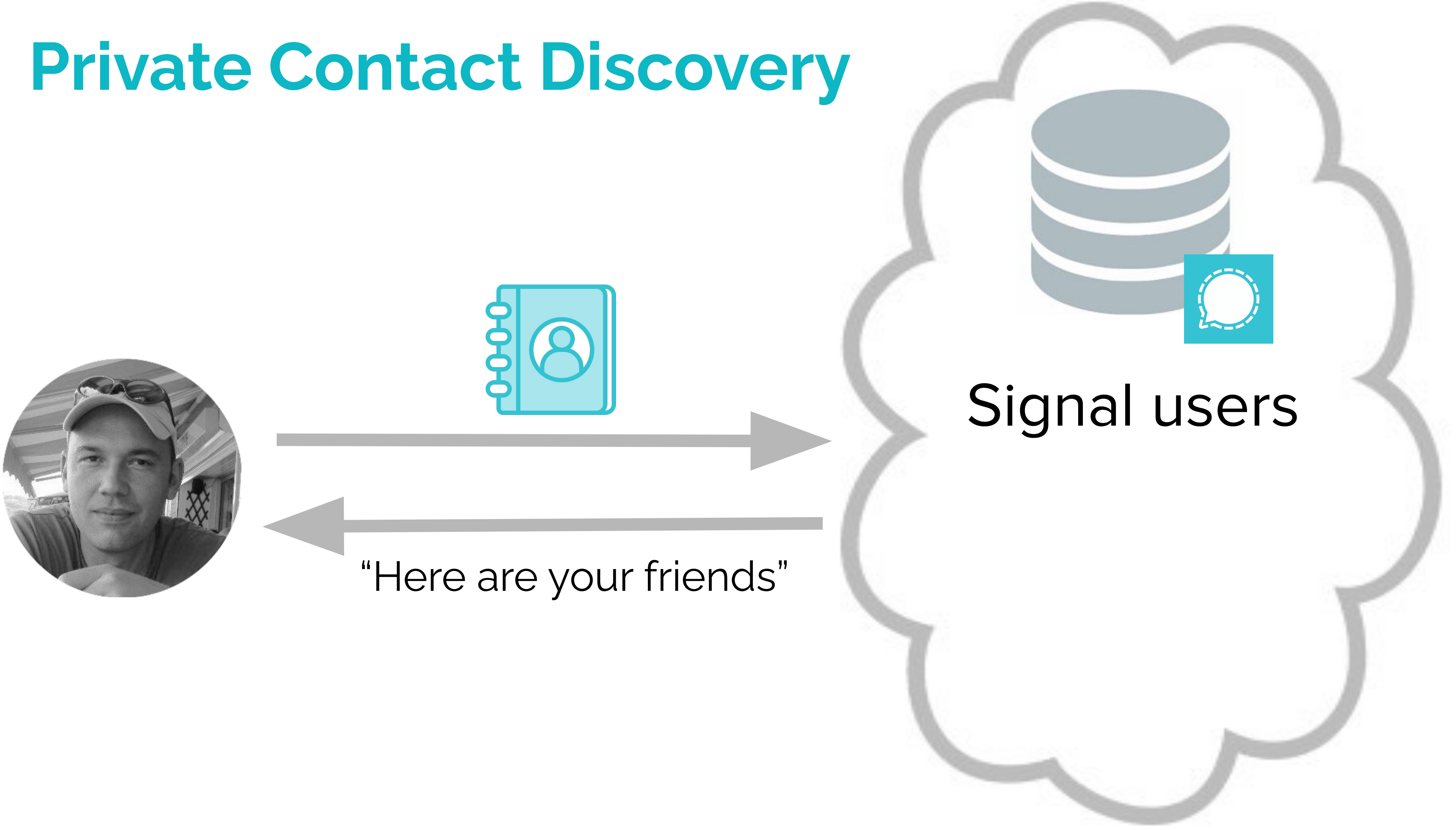
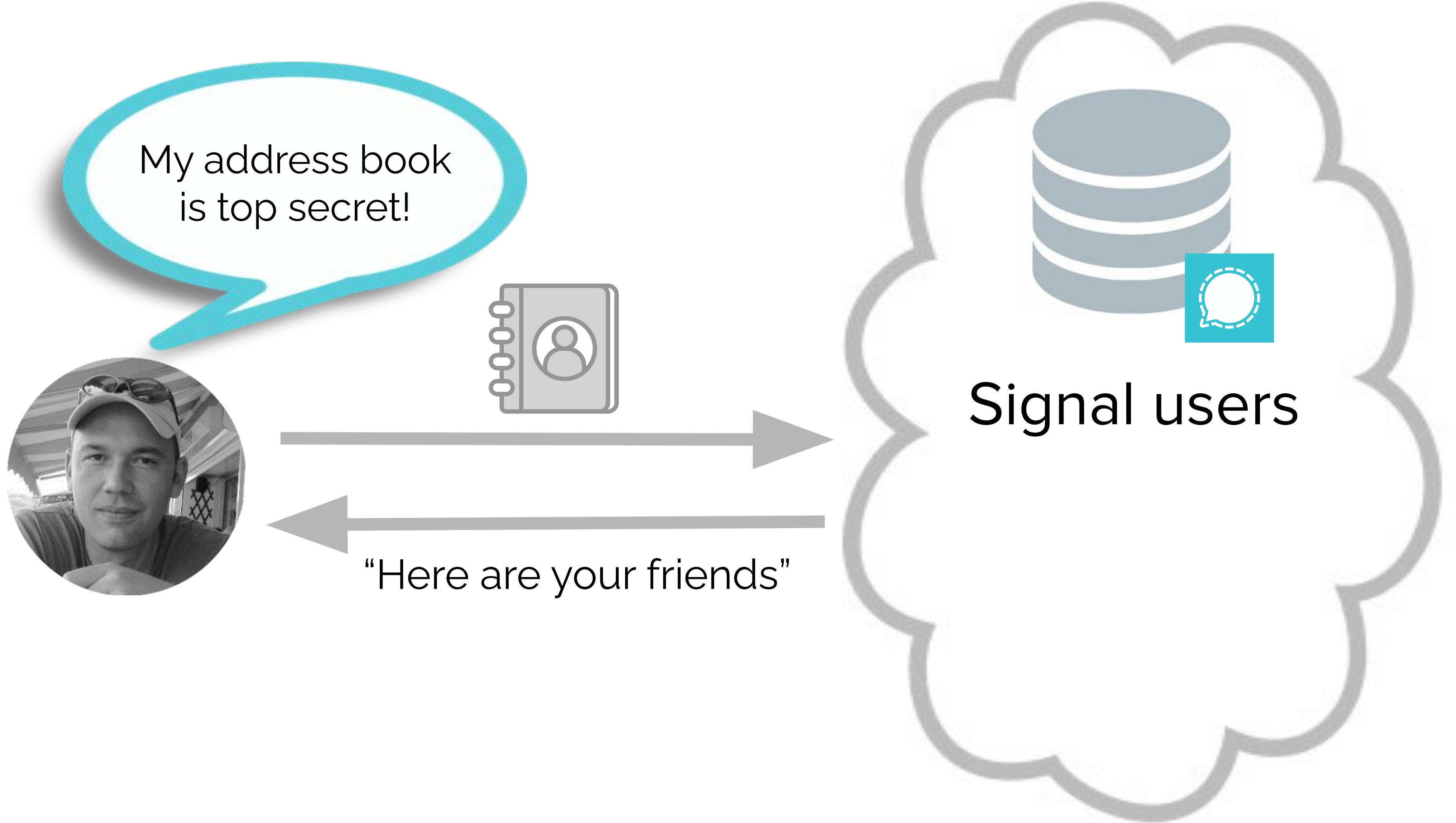
Private Contact Discovery

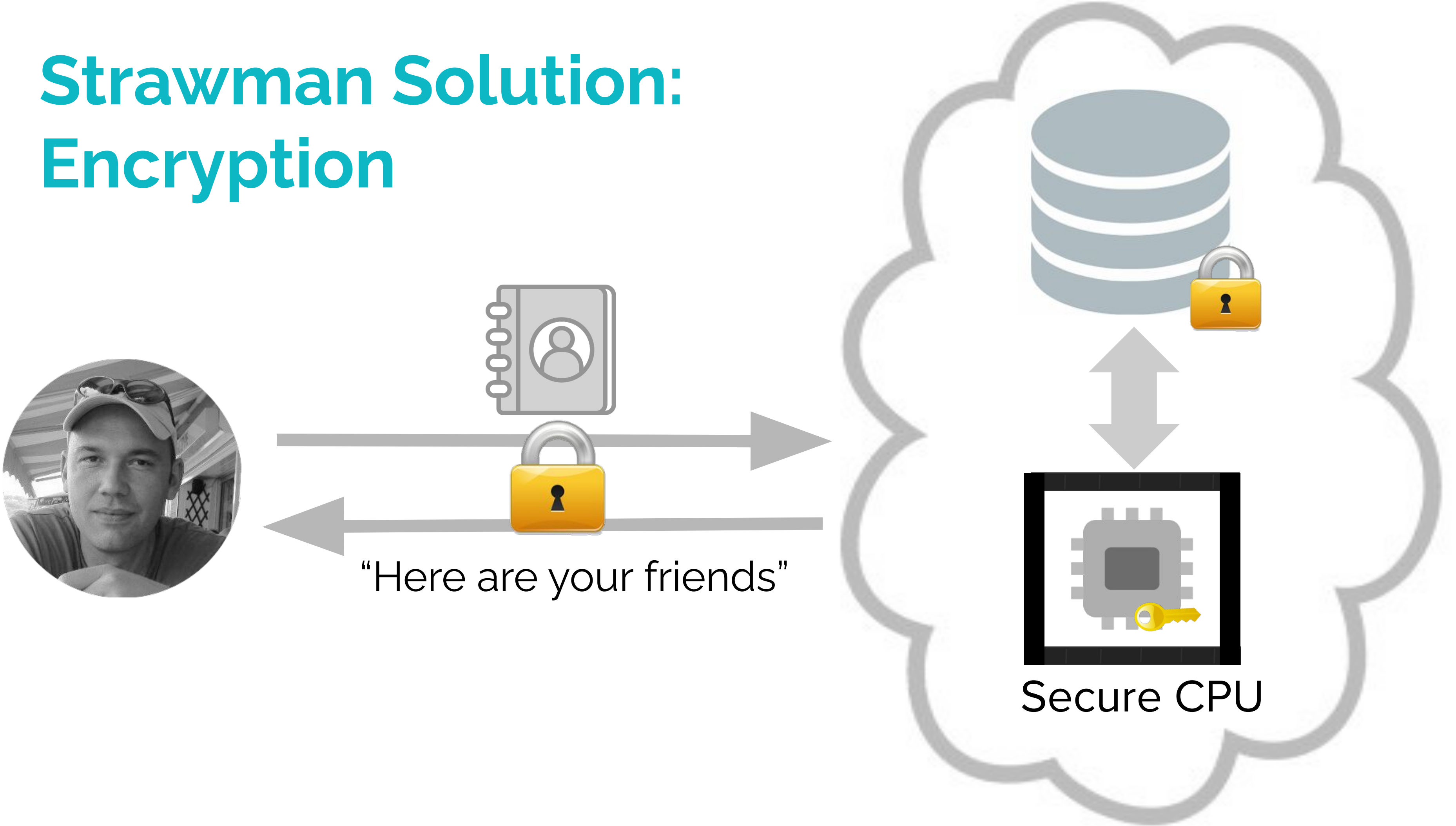


Private Contact Discovery

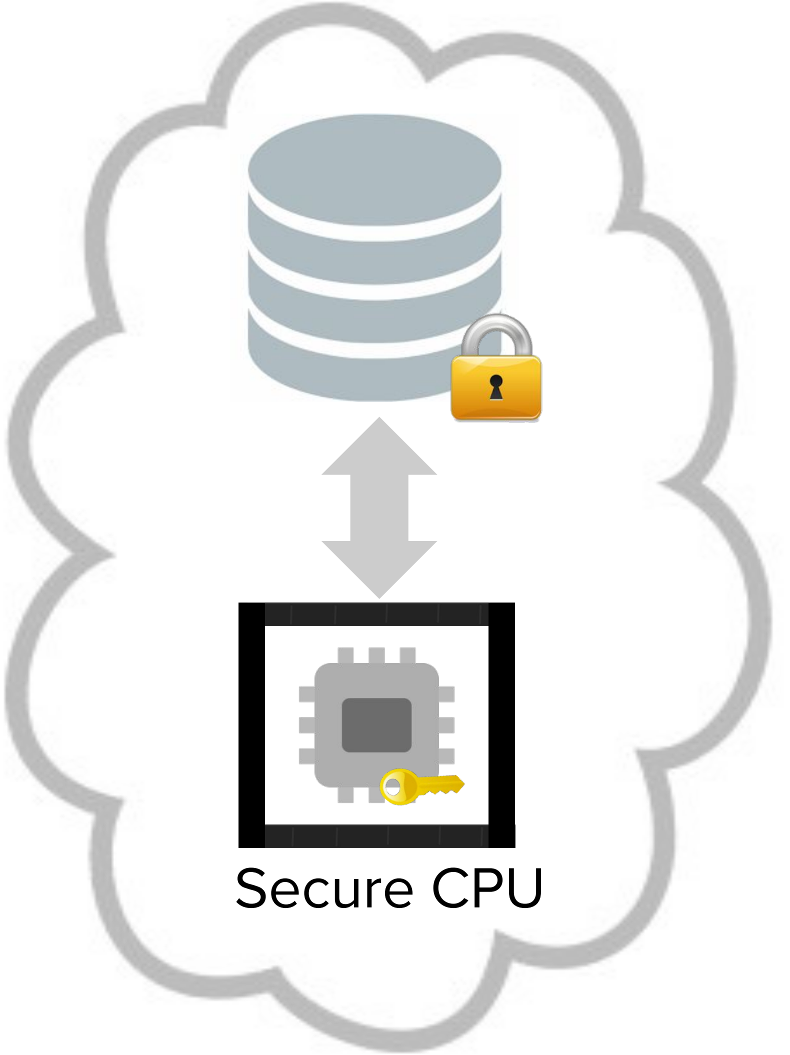



My address book
is top secret!
Signal users
"Here are your friends"

Strawman Solution: Encryption



Access patterns to even encrypted data leak sensitive information.



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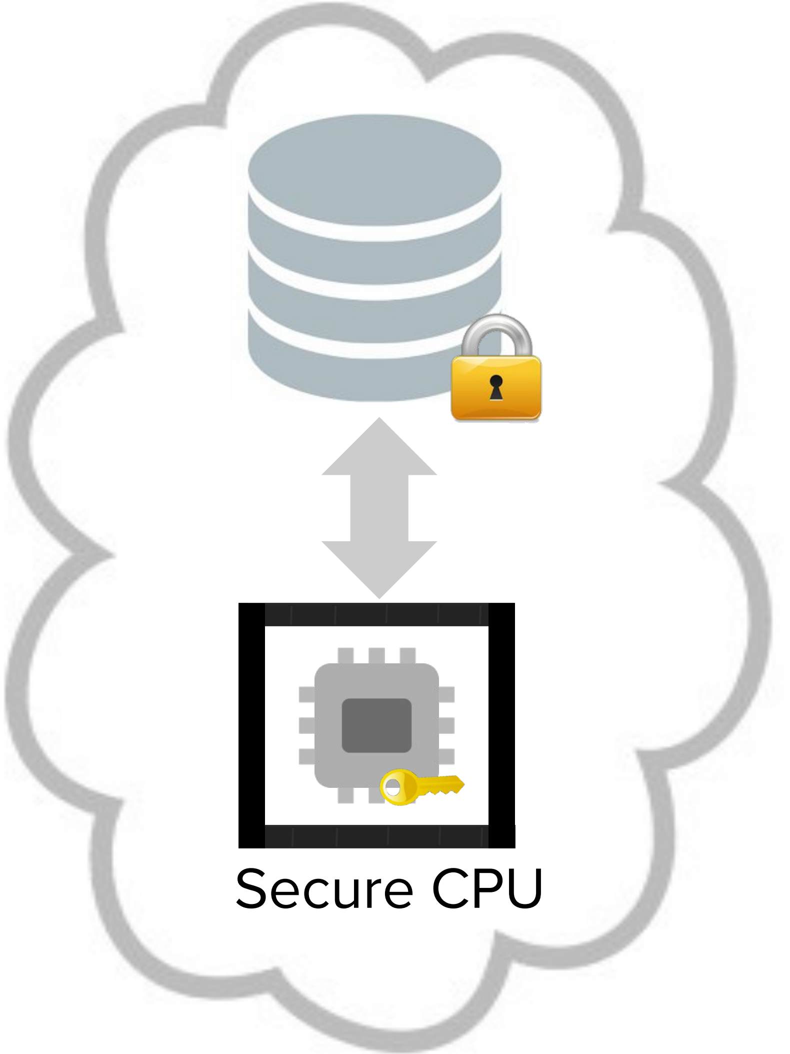


Simply permuting the data doesn't solve the problem

⇒

Need Oblivious Algorithms

Signal 2017: batched linear scan

$O(n/\beta)$ overhead
500 servers

n: total # memory blocks
β: batch size

Signal 2022: Path ORAM

[SDS+13]

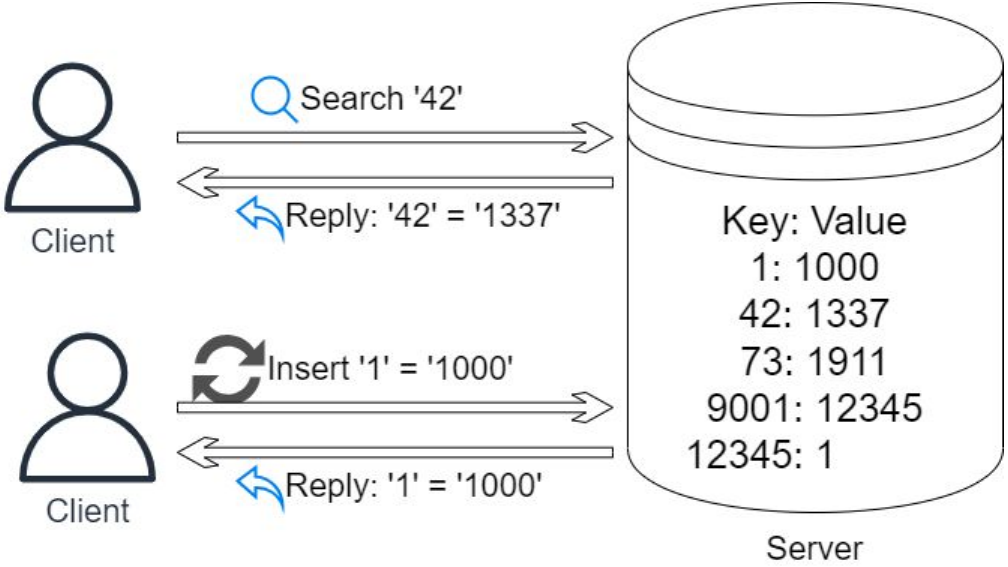
$O(\log^2 n)$ overhead
6 servers

Trusted hardware needs oblivious algorithms!

- Secret Network, Oasis Network, Flashbots

Oblivious Map: Key-Value Store

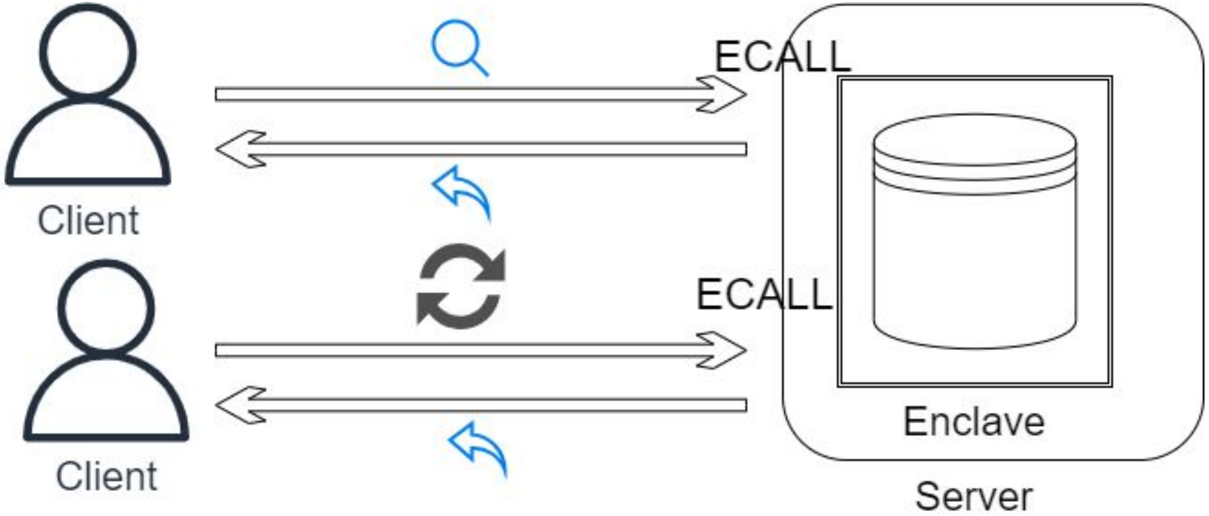
- Query Privacy client doesn’t leak which keys it is querying
- Database Privacy database is kept private



SGX & Oblivious Algorithms

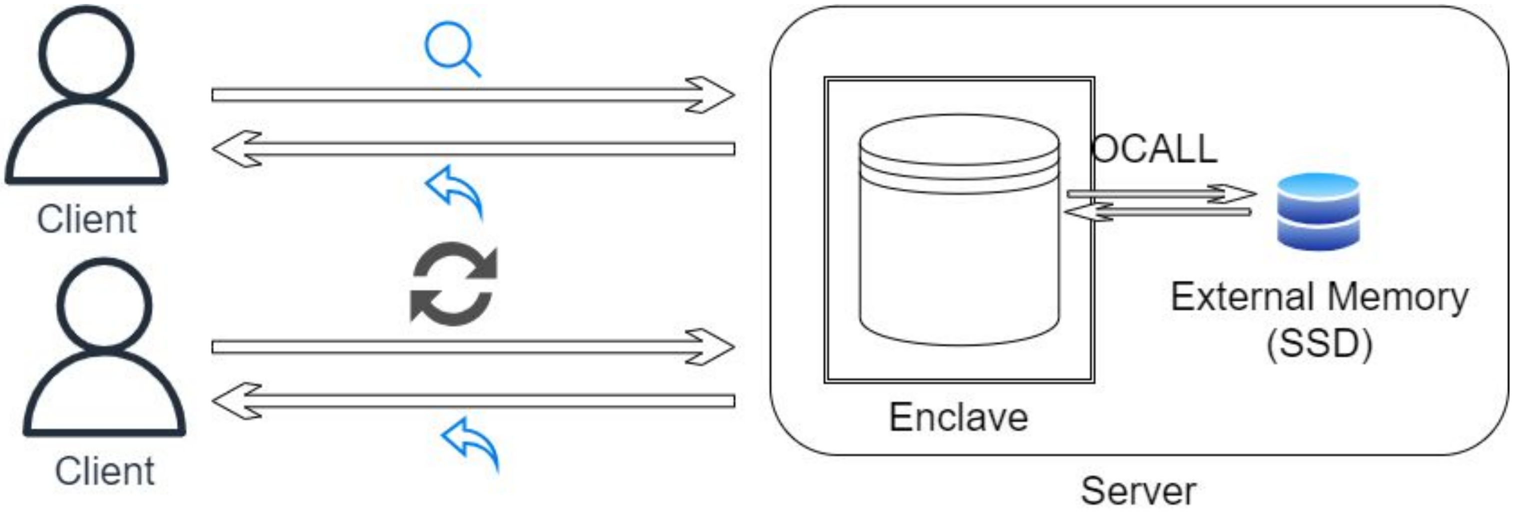
- Oblivious map inside of SGX Enclave
- Instruction and memory trace should not leak information about private data □ use x86's CMOVcc

SGX-Step



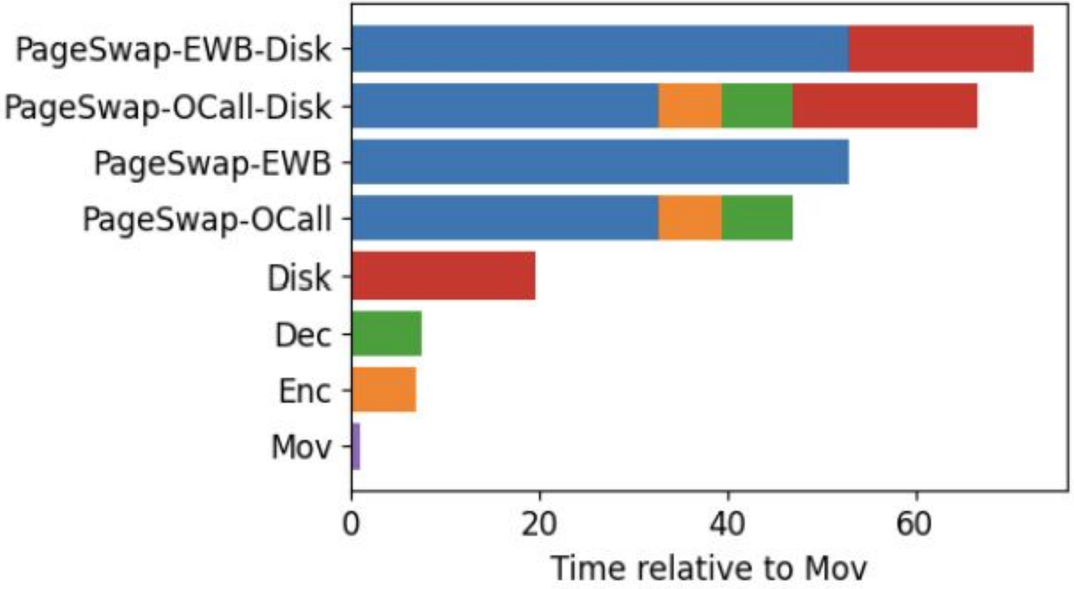
SGX & External-Memory

- Limited EPC memory
- Larger External-Memory via EWB or OCALL



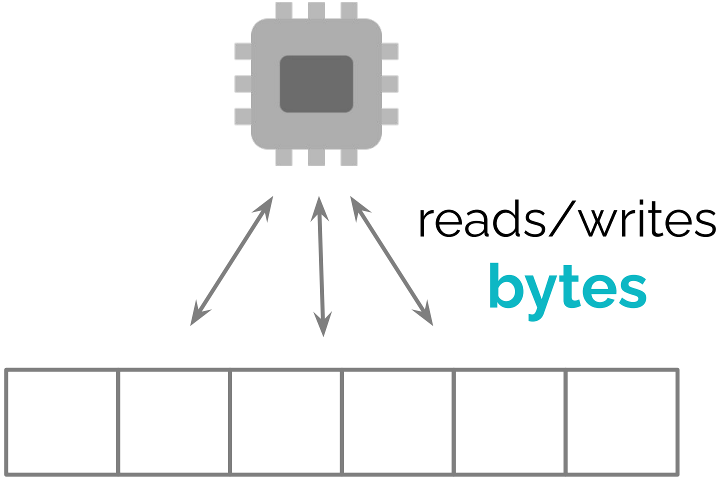
SGX & External-Memory - Microbenchmarks

- OCALL 46x to 66x more expensive than MOV

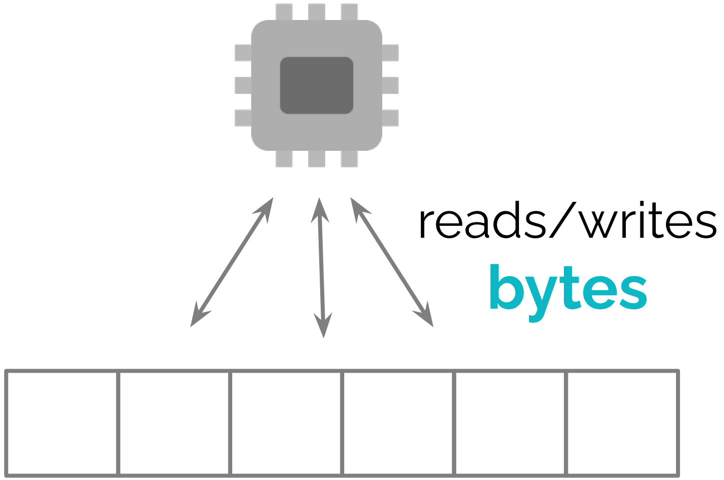


 External-Memory page swaps is an important metric for SGX’s algorithms

ORAM/algorithms literature: **word RAM**



ORAM/algorithms literature: **word RAM**

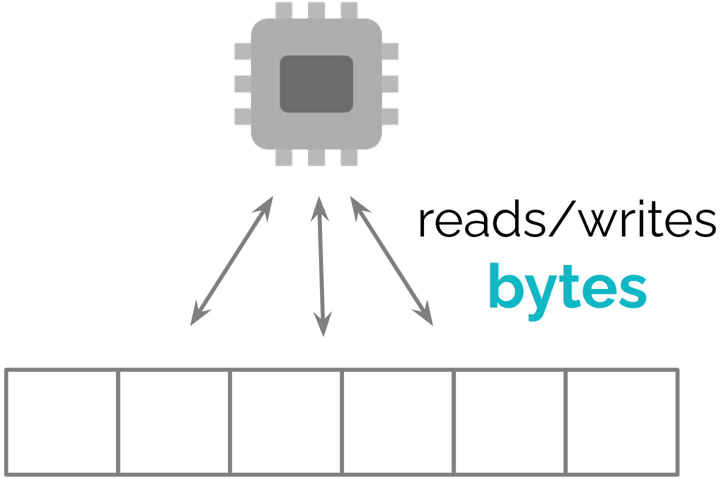


Compute overhead

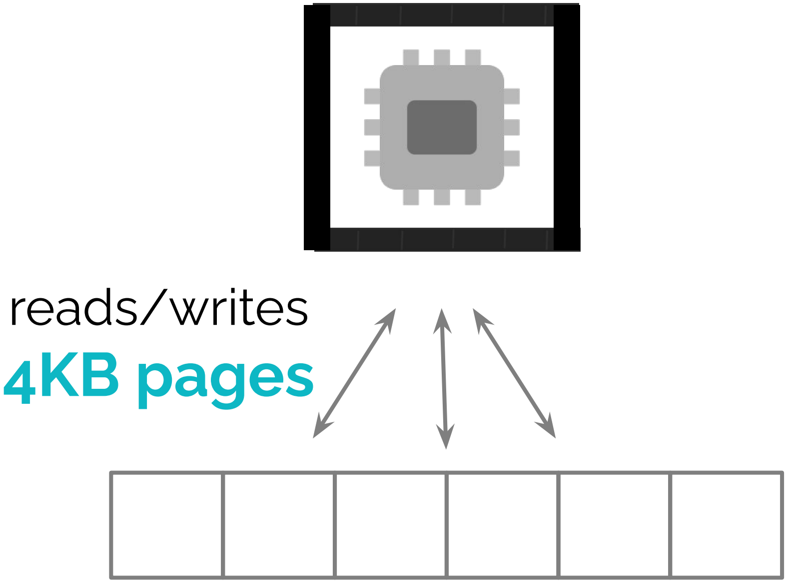
||

Memory overhead

ORAM/algorithms literature: **word RAM**

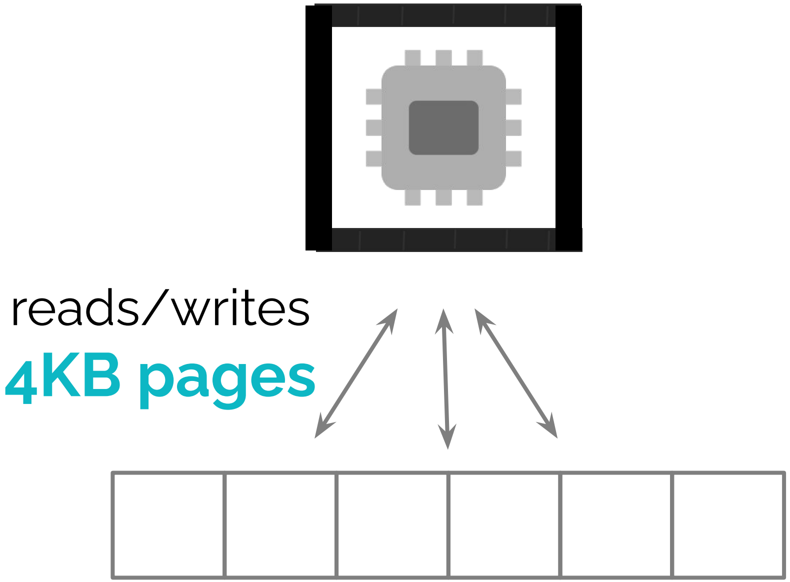


Secure enclaves: **external-memory**



Secure enclaves: **external-memory**

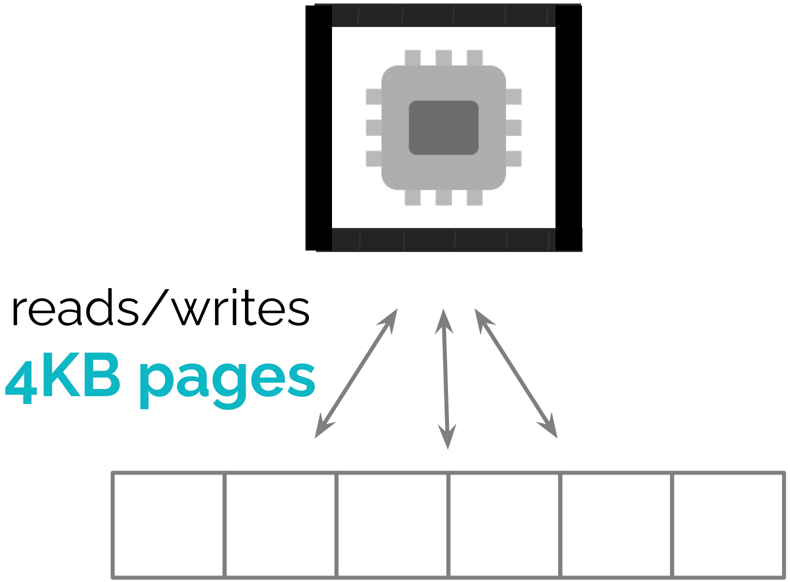
Enclave needs to fetch encrypted data stored in unprotected memory/disk



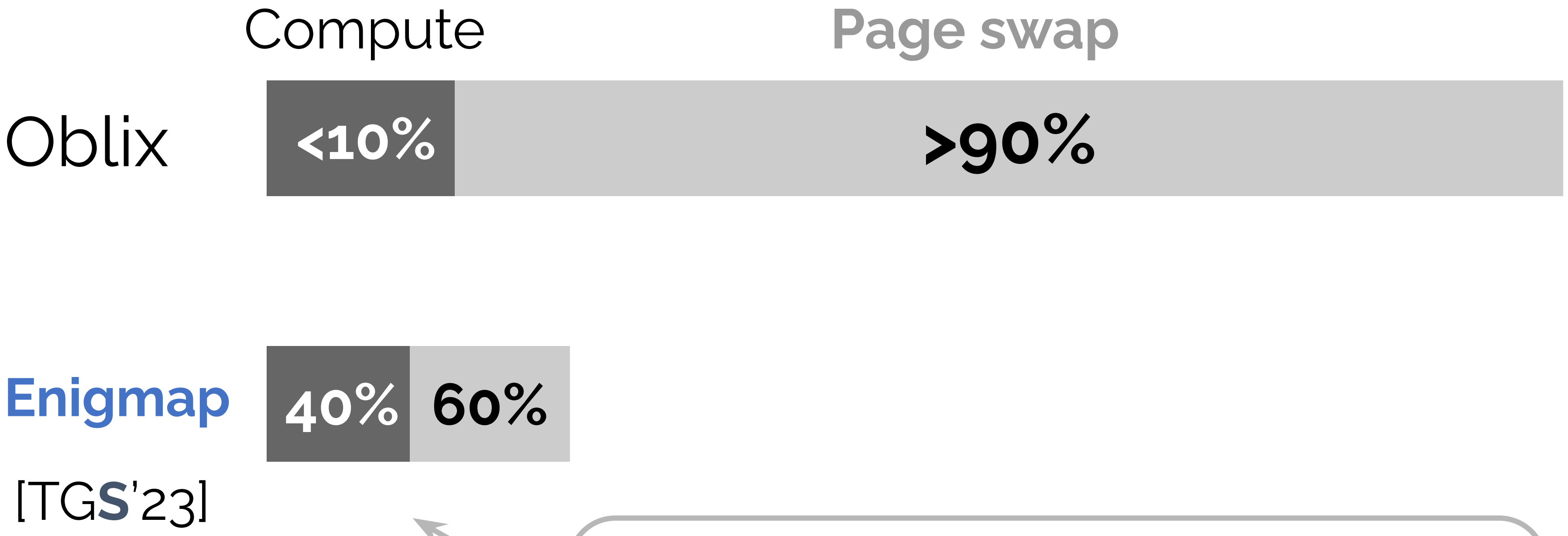
Secure enclaves: **external-memory**

Page swap dominates

- System call
- Enc/Dec
- Possible disk swap




Compute
Page swap
Oblix
<10%
>90%



- Uses **external-memory** algo
- **10-100X** faster than Oblix

Our Contributions

- Design and implement EnigMap - an oblivious map
- Instruction and Memory Trace Oblivious
- Both External-Memory and Instruction asymptotically more efficient than previous implementations (Oblix [MPCCP18])
- Concretely 13-53x faster than previous work
- Improved Initialization Algorithm

ARTIFACT EVALUATED usenix ASSOCIATION AVAILABLE

ARTIFACT EVALUATED usenix ASSOCIATION FUNCTIONAL

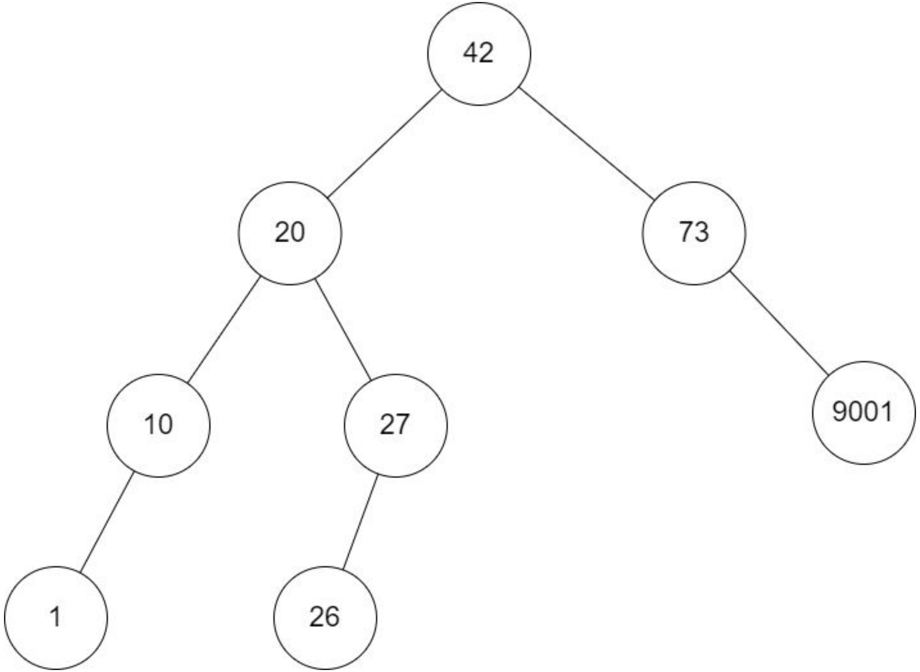
ARTIFACT EVALUATED usenix ASSOCIATION REPRODUCED

Our Solution

- Oblivious AVL Tree [WNLC**S**SH14]
- PathORAM storage [SD**S**CFRYD12]
- Optimized for the External-Memory model [EnigMap]

AVL Tree

- Binary Search Tree
- Each node corresponds to a key
- For an AVL tree with N nodes:
  - 1.44 log(N) maximum depth
  - Search/Insert/Delete start from root

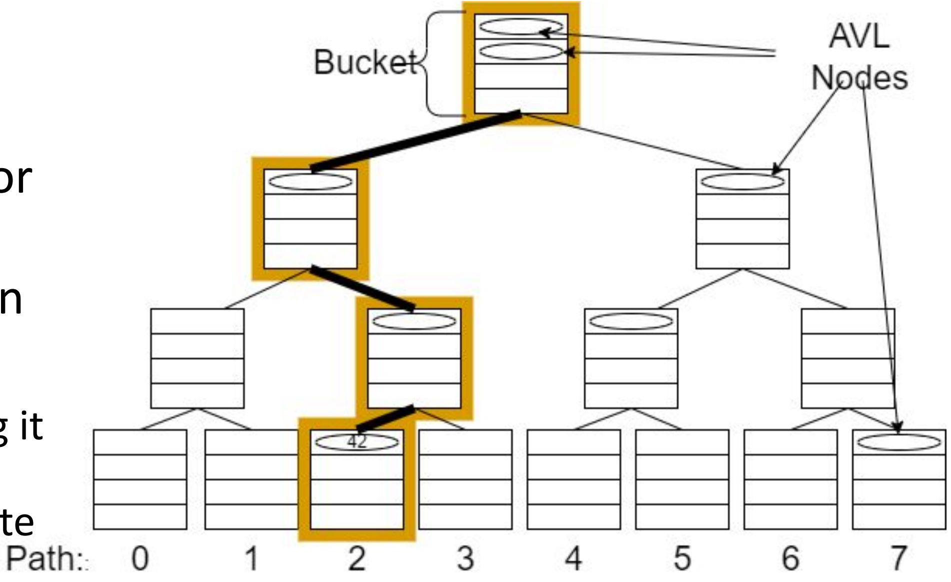


Oblivious AVL Tree

- Recall: “Instruction and **memory trace** should not leak information about private data”
- Oblivious Data Structures [WNLC**S**SH14] Store nodes in ORAM

PathORAM

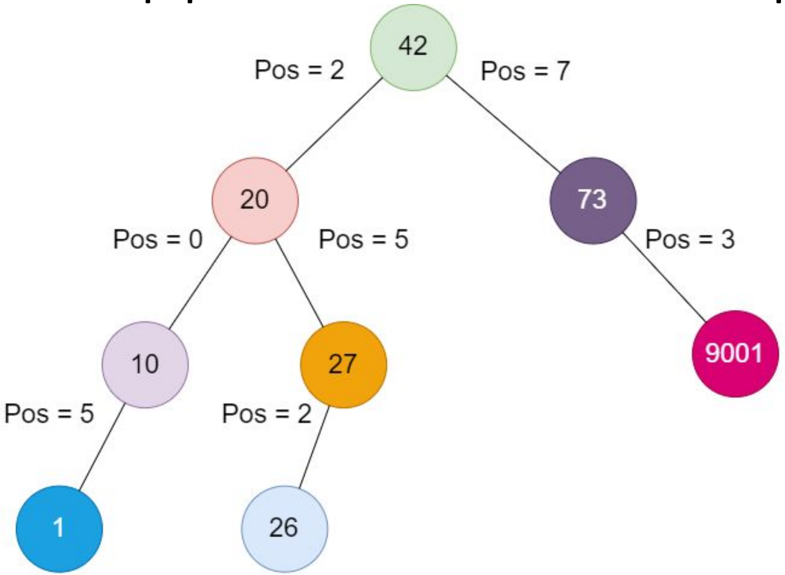
- Full binary tree with N leafs
- Each bucket has Z=4 blocks
- Blocks can have data (an AVL node) or be fillers
- Each AVL node has a random position
- Access(key, position):
  - Returns node with a given key knowing it is on path position
  - Cost: Each access call will read and write that path
  - Node with key gets assigned a new random position after access



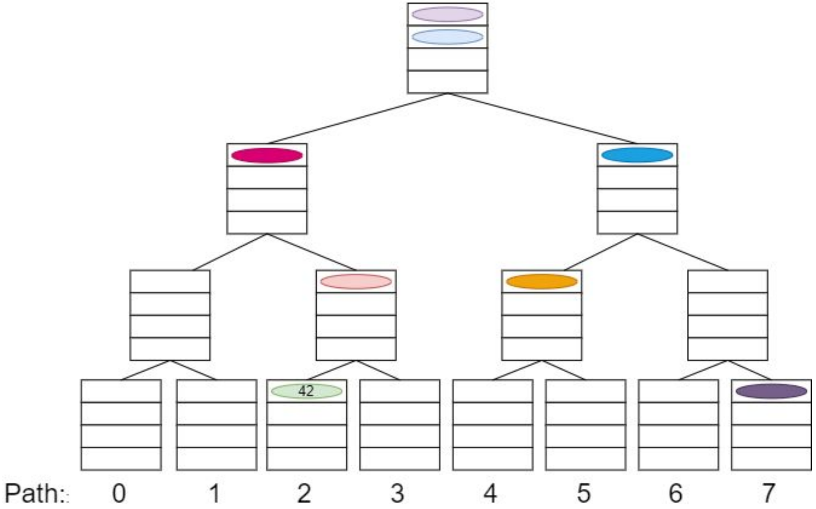
Oblivious AVL Tree

- Oblivious Data Structures [WNLC**S**SH14] □ Store nodes in ORAM

→ keep position of child nodes as part of parent nodes metadata



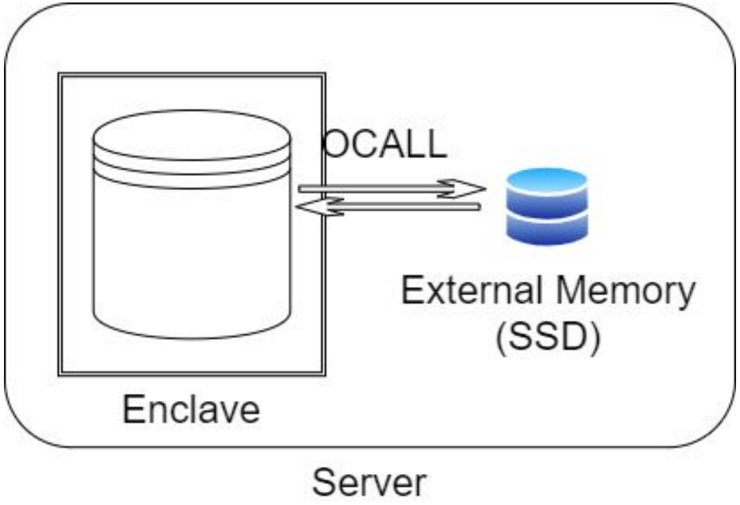
AVL (Logical) Tree



ORAM Tree

External memory

Not all buckets can be cached in EPC



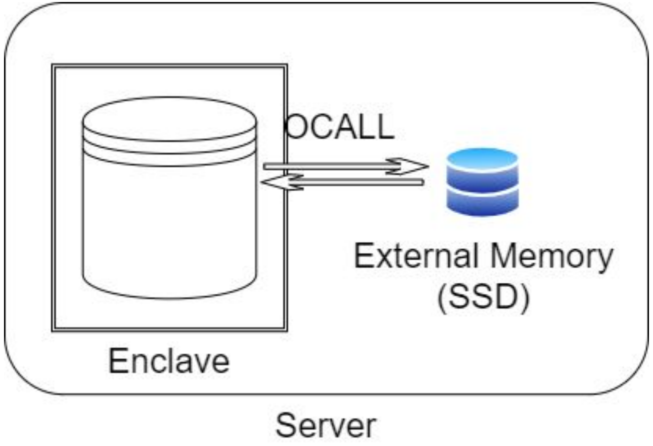
Our key optimizations

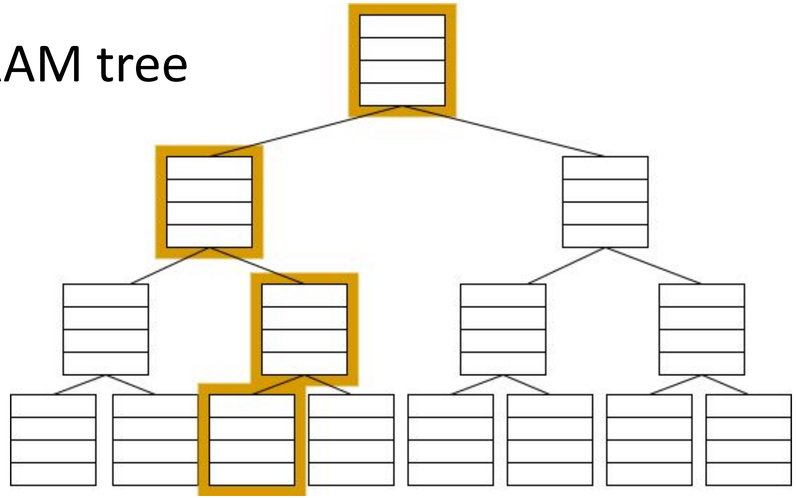
- Locality friendly layout
- Initialization algorithm

Scheme	Cost per batch of operations		Cost of initialization	
	page swaps	compute	page swaps	compute
Signal [4]	$O(N/B)$	$O(\beta^2 + N)$	$O(N/B)$	$O(N)$
Oblix [2]	$O(\beta \log^2 N)$	$O(\beta \log^3 N)$	$O(\frac{N}{B} \log^2 N)$	$O(N \log^3 N)$
ENIGMAP	$O(\beta \log_B N \cdot \log N)$	$\widetilde{O}(\beta \log^2 N)$	$O(\frac{N}{B} \log_{\frac{M}{B}} \frac{N}{B})$	$\widetilde{O}(N \log N)$

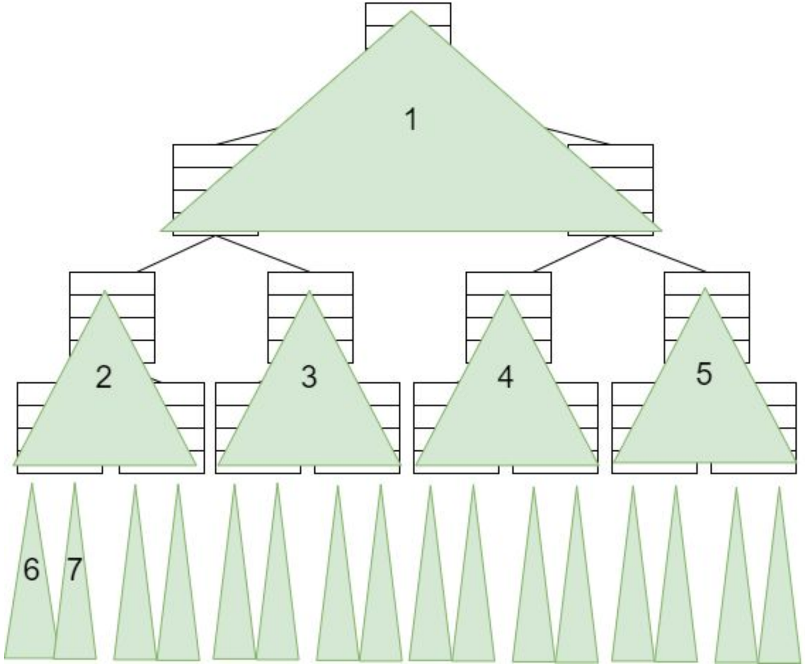
Locality Friendly layout

- PathORAM reads paths on the ORAM tree
- Disk pages store several buckets
- Our layout:
  - Store subtrees in the same page

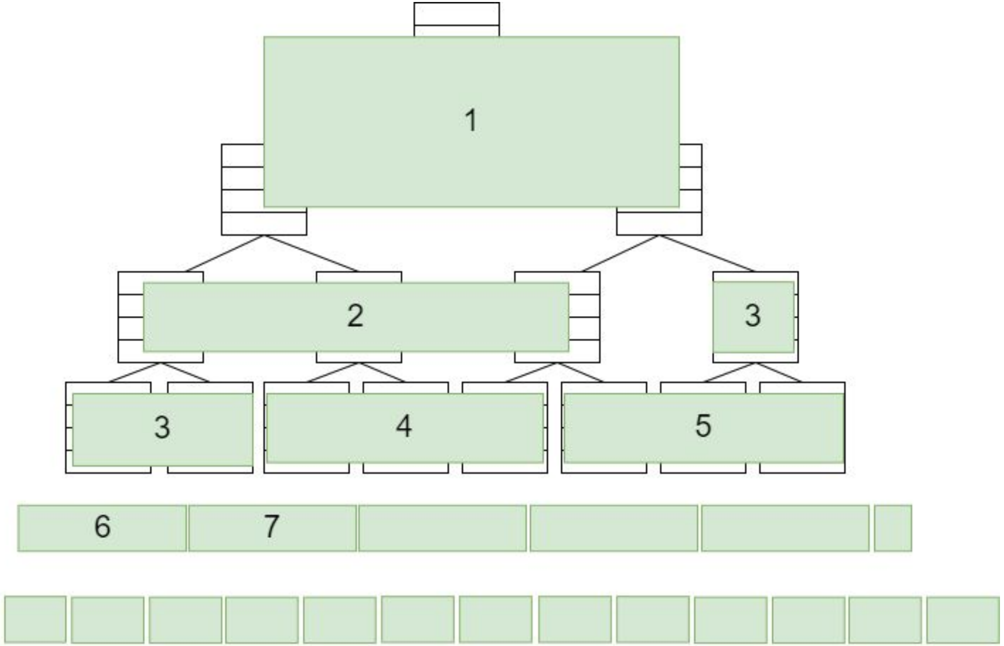




Locality Friendly layout

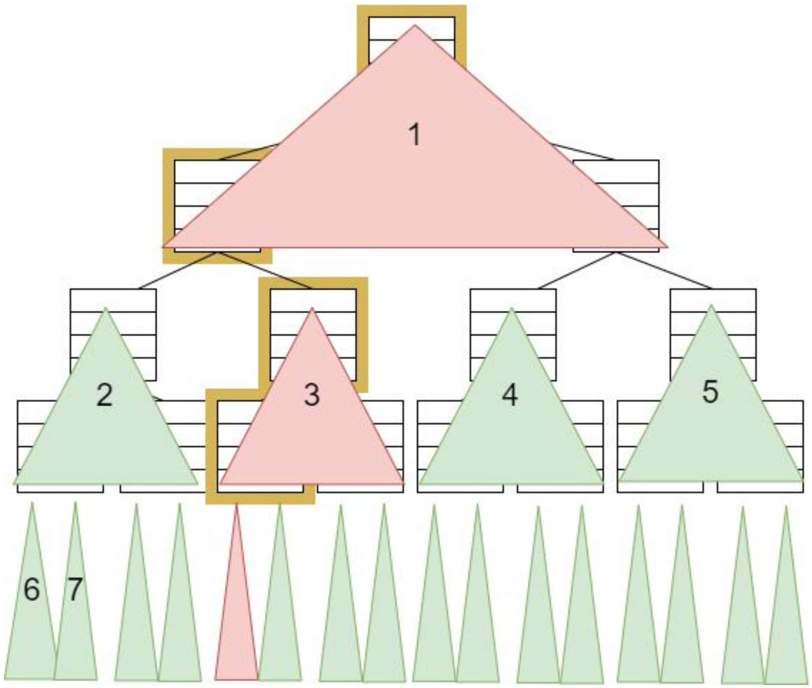


Our layout



Heap layout

Locality Friendly layout – $\log_B N$ pages



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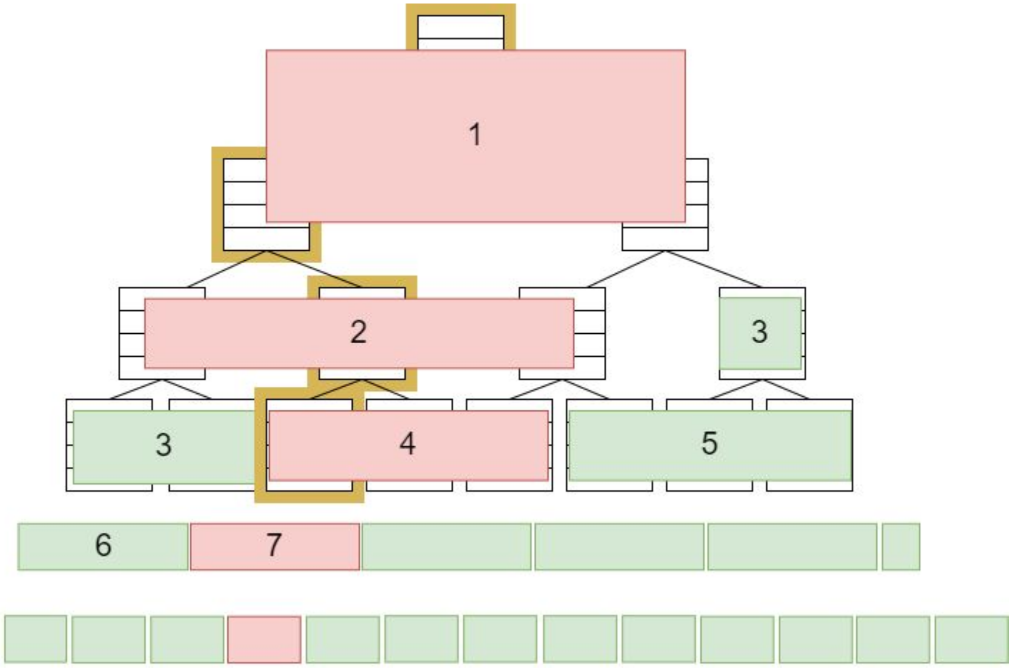
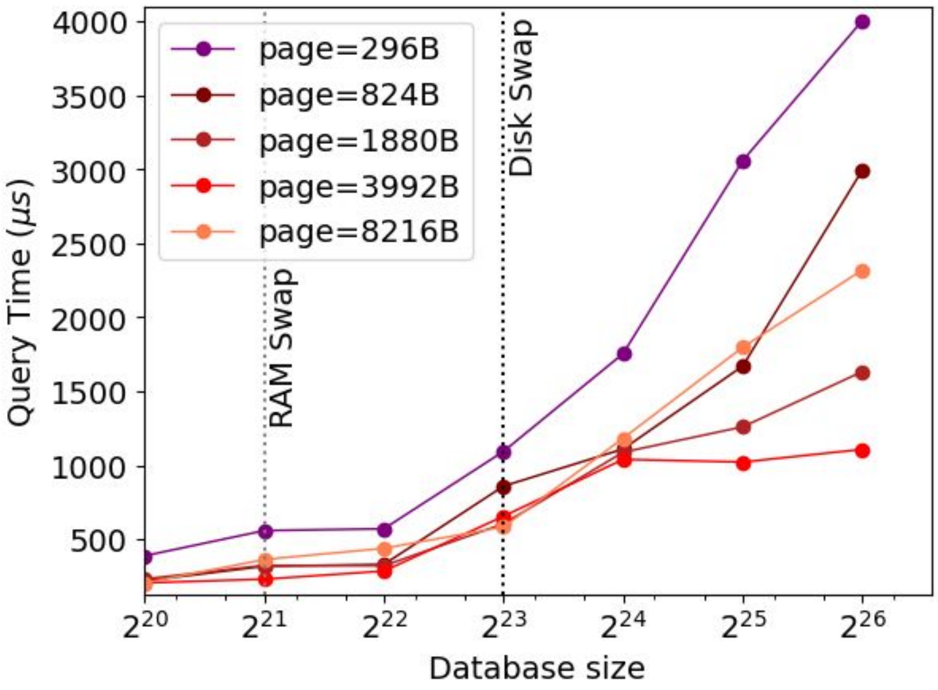


Heap layout

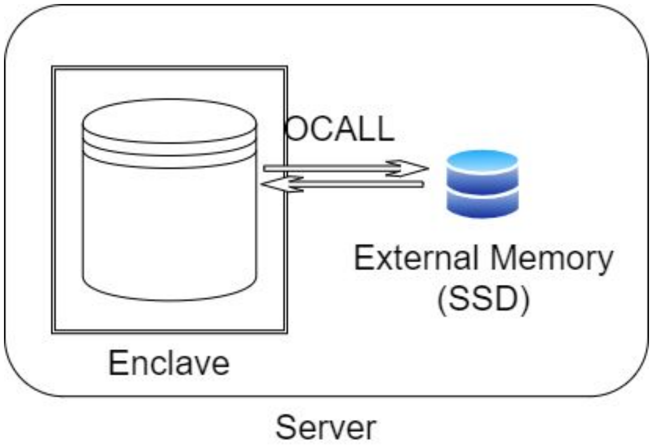
Locality Friendly layout - $\log_B N$ pages

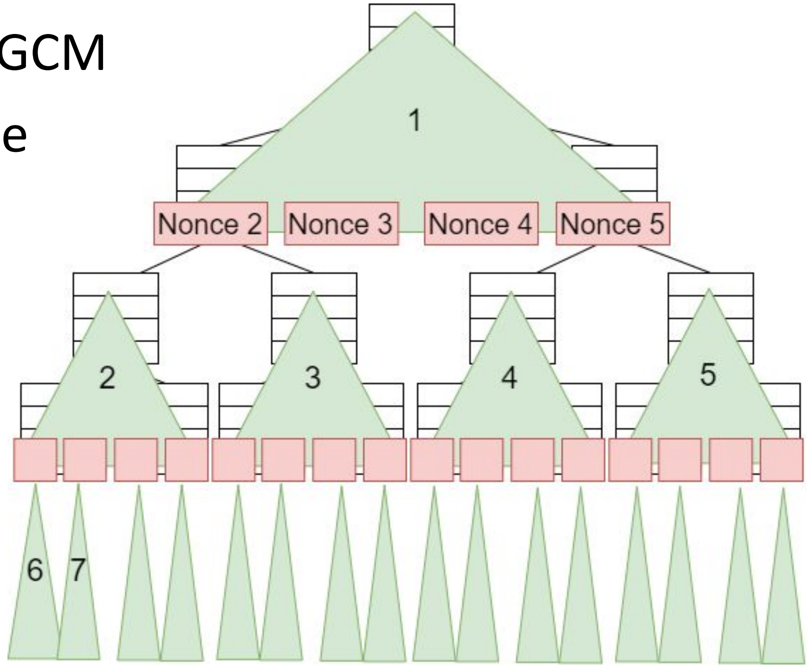
- Experimental optimization
- Optimize pagesize (B)
- Pages with 4 levels (15 Buckets)



Integrity and freshness for free

- Encrypt each disk page with AES-GCM
- Keep nonce stored on parent page
- Implicit merkle tree
- Smaller EPC – no Version Array





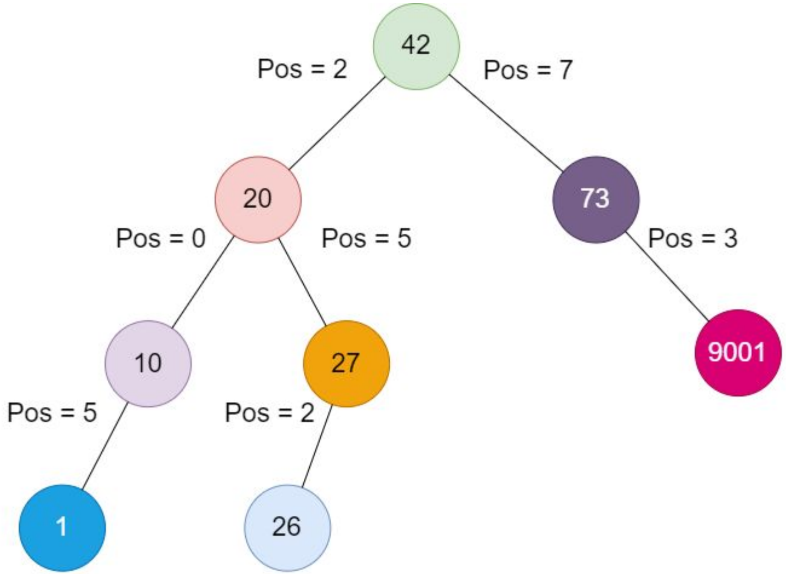
Initialization Algorithm

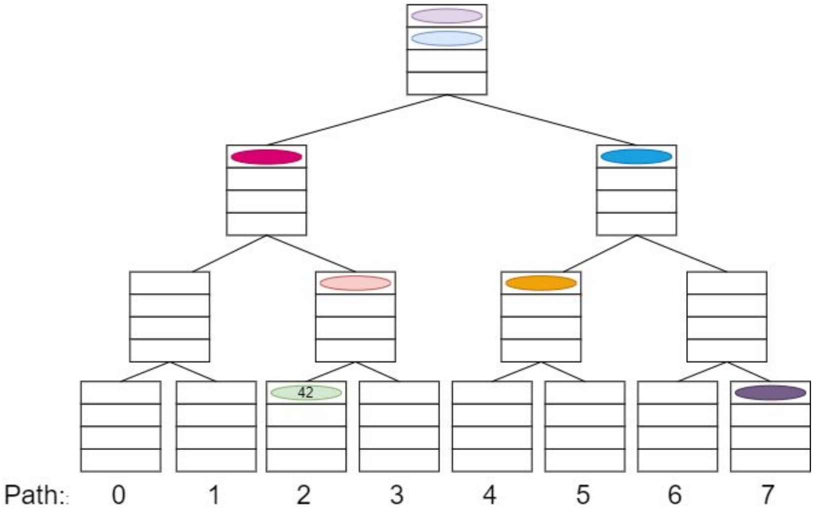
- How to initialize a database if we have N key-value pairs in plaintext
- Naïve Initialization:
  - Do N insertions
  - $O(N \log_B N \ \log N)$ page swaps
  - $\tilde{O}\ (N \log^2 N)$ computation
- We can do better! →Read our paper for full details

Initialization Algorithm

- We receive a list of N keys – Key[N]
- Need to build both AVL tree and ORAM with correct positions

Key							
1	91	26	42	10	27	73	20





Initialization Algorithm – Asymptotic Results

- $O\left(\frac{N}{B}\log_{\frac{M}{B}}\frac{N}{B}\right)$ page swaps
- $O(N \log N)$ computation

$\rightarrow$ Read paper for details

Other concrete optimizations

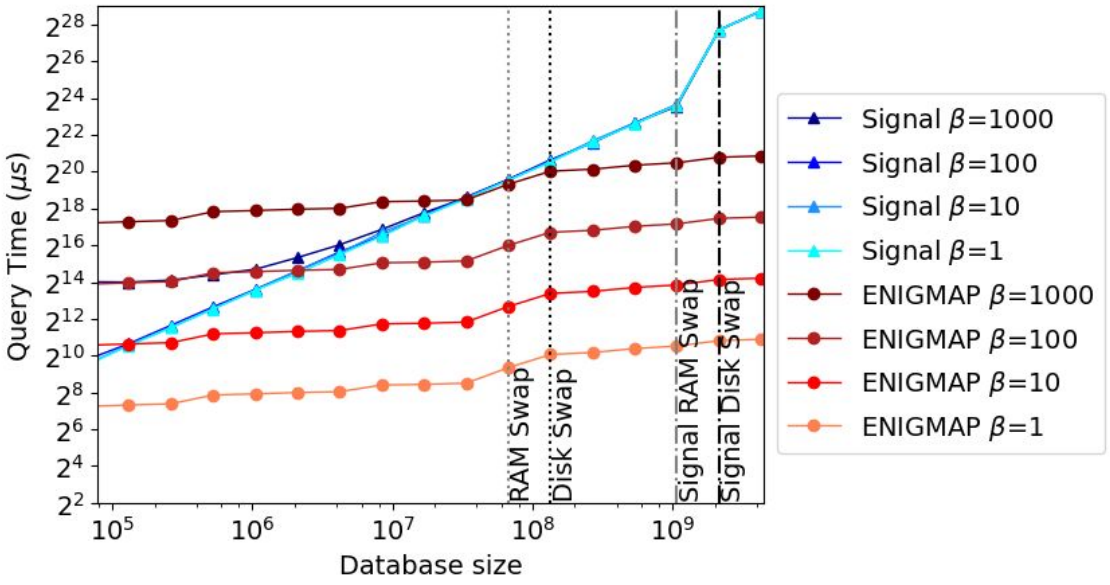
- **Cache blocks during insertions** ½ ORAM operations for insert
- **ORAM treetop caching** less external memory reads per ORAM operation
- **Single pass AVL insertion** ½ instructions for insertion
- **Optimize page size for OCALL** improve concrete external memory performance
- **Store values in separate ORAM** increasing the size of values doesn’t affect AVL performance

Experimental Results

- Private Contact Discovery – search
- Initialization

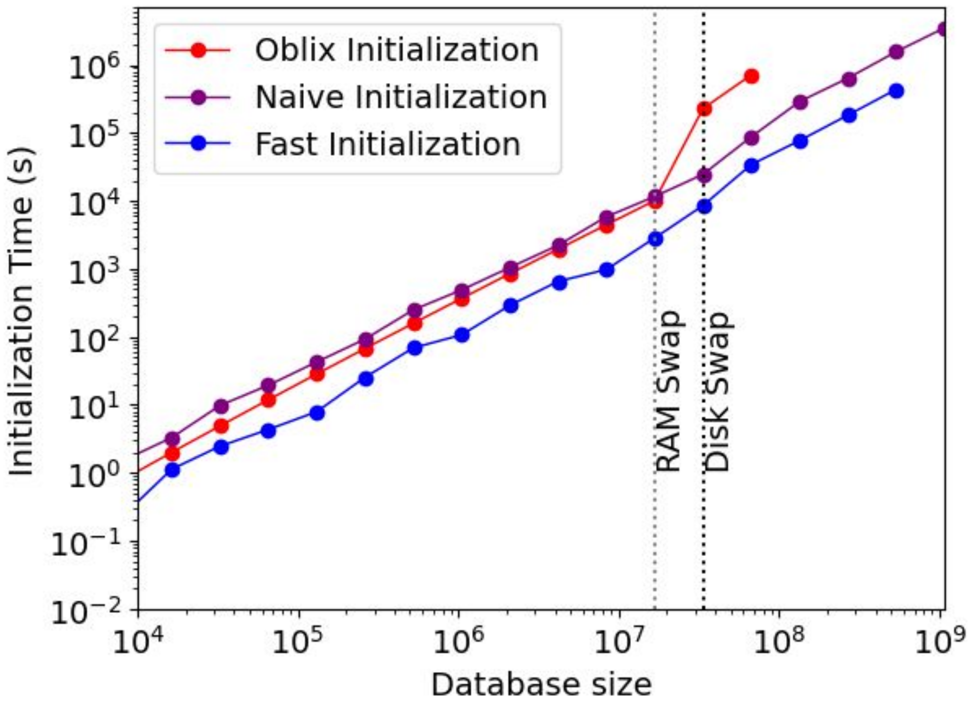
Private Contact Discovery

- Query β contacts
- Vary database size (N)
- Speedup Signal β=1000:
  - $N=2^{28}$ → 15x
  - $N=2^{32}$ → 132x
- Comparison Oblix (SOTA)
  - $N=2^{24}$ → 13x
  - $N=2^{28}$ → 53x
- Comparison new signal:
  - 2-4x speedup



Initialization

- Vary database size (N)
- Compare with:
  - Oblix – SOTA
  - Naïve Initialization – N insertions
- Results:
  - 2-8x speedup



Oblivious Data Structure Library

- Open source oblivious algorithm library
- Memory and instruction trace oblivious
- External-Memory efficient

https://github.com/odslib/odsl

Conclusions

- Takeaways:
  - Efficient trace oblivious algorithms are possible and crucial for enclave security
  - External Memory is an important model for enclave algorithms
  - By focusing on external memory we achieved 13-53x query speedup compared to previous SOTA

- Resources:
  - Oblivious Data Structure Library □ https://github.com/odslib/odsl
  - Extended Version □ https://eprint.iacr.org/2022/1083
  - Artifacts □ https://github.com/odslib/EnigMap/tree/usenix-artifacts-final

Questions?

Oblivious Data Structure Library □ https://github.com/odslib/odsl