A Practical Oblivious Map Data Structure with Secure Deletion and History Independence

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Goal: A remote key/value store with. . .

Strong privacy

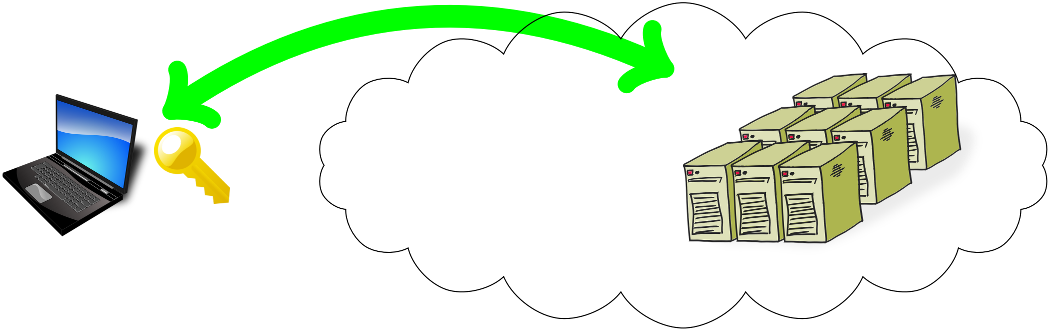
- Hidden keys, values, and access patterns (Obliviousness)
- Secure against powerful attackers (Secure Deletion and History Independence)

Practical utility

- No computation on server
- Poly-logarithmic local storage, bandwidth, computation
- Low round complexity

Oblivious RAM

Oblivious RAM (ORAM) hides access patterns as well as data.
(Goldreich & Ostrovsky JACM'96, and many more since then!)



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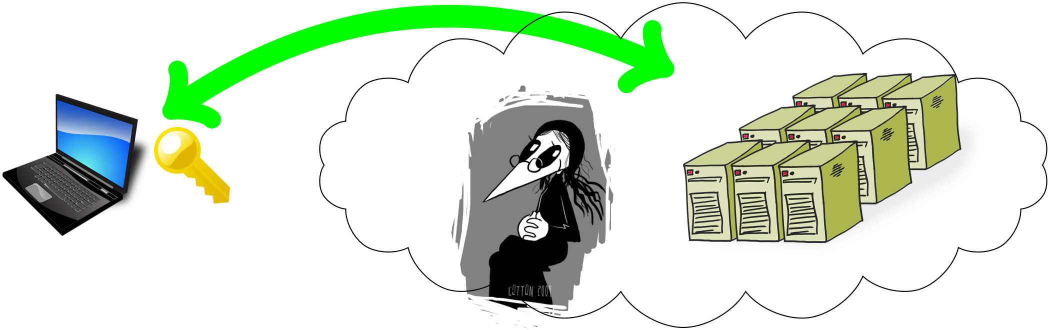

Cloud eavesdropper learns the number of operations and nothing else.

Problem 1

What if the size of data is not fixed?
ORAM reveals the number of operations, and therefore data size.

Insecure solution

Send **multiple blocks** depending on the data size

Inefficient solution

Pad all data up to the maximum size

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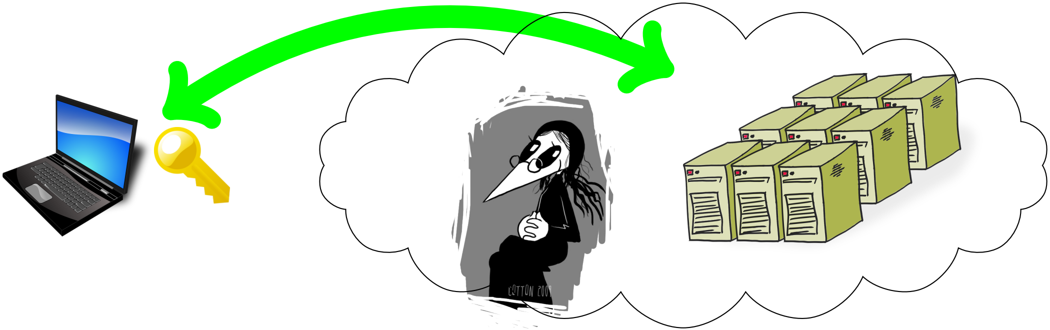
Our approach: Oblivious RAM with variable blocks (vORAM)

Hide large data in the overhead of Path ORAM,
Large data blocks are stored across multiple ORAM "buckets".

Oblivious Data Structures (ODS)

Storing a data structure in ORAM (Wang et. al, CCS’14)



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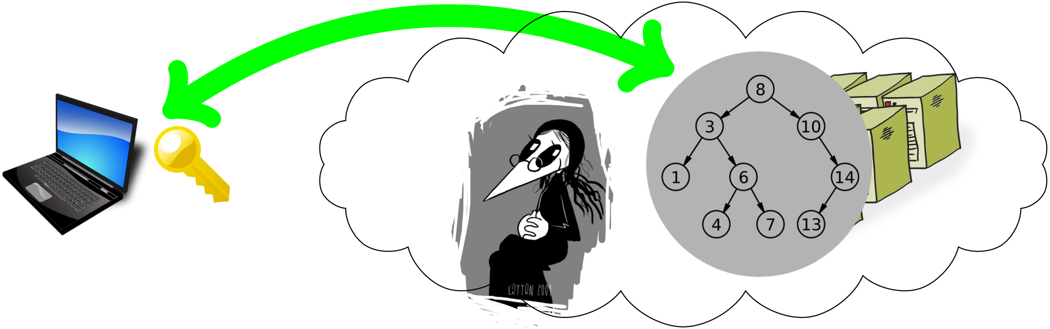

Pieces of data structure (i.e., nodes) are stored in ORAM blocks.

Problem 2

What if your data structure has varying running time?
The number of memory accesses in each operation are leaked by ORAM.

Insecure solution

Let the number of operations **vary by access**

Inefficient solution

Perform **dummy operations** up to the worst-case cost

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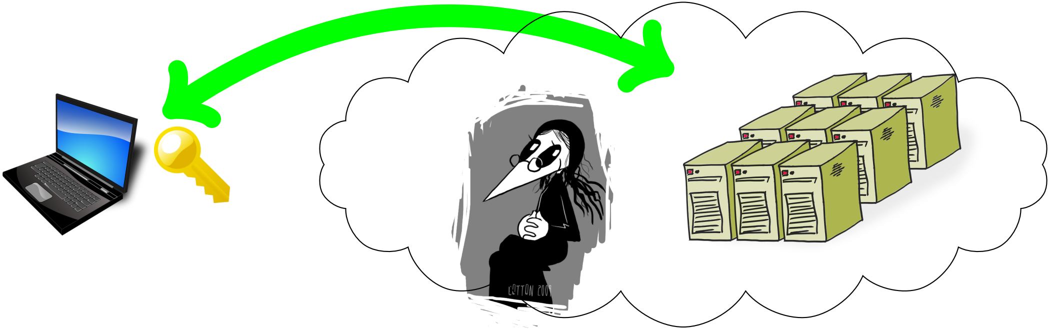
Our approach: History-Independent Randomized B Tree (HIRB)

Use a *fixed-height tree* data structure, so that no padding is necessary.

"Catastrophic" Attacks

An attacker may be able to **coerce the private key**.



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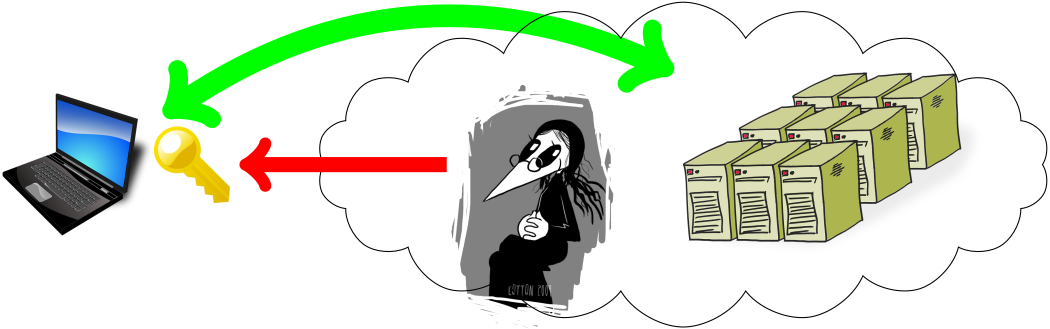

Problem 3

What if your private key is compromised?

- Some leakage is inevitable
- ORAM reveals entire history, including prior deletions
- Most data structures *also* leak history information

Inefficient solution

Re-encrypt and transfer entire data set on every access

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Our approach (vORAM+HIRB)

HIRB data structure leaks no history nor prior deletions.
vORAM leaks minimal history and no prior deletions.

Outline and Related Work

1. **Problem Statement and Goals**
2. **vORAM: Oblivious RAM with variable-sized blocks**
   - Path ORAM (Stefanov et al., CCS'13)
   - Secure deletion B-tree (Reardon et al., CCS'13)
3. **HIRB: History Independent Randomized B-Tree**
   - Oblivious Data Structures (Wang et al., CCS'14)
   - History-Independent Data Structures (Naor & Teague '01, Hartline et al. '02, Golovin '08)
4. **Experimental Results**

Path ORAM with Variable-Sized Blocks: vORAM

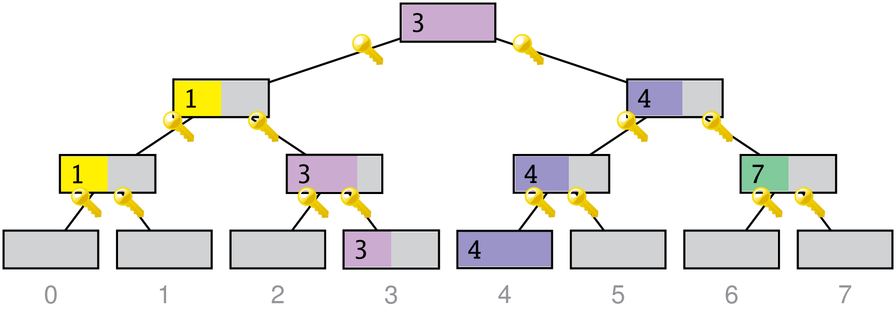
General idea: Large items are rare; distribute their bits along an ORAM path.

Terminology: Each tree node is a **bucket** stored on the server.
The user stores **blocks** of data.
Each block may be broken up into **chunks** of bytes.

Crucial restrictions:

- All chunks of the same block are on the same path
- Chunks of the same block are always in order

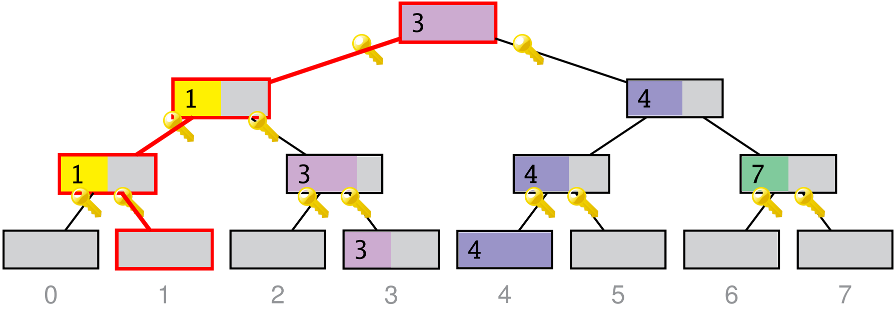
vORAM Example: Setup



Stored blocks:

Color represents data, **Width** = size, **Number** = position.

vORAM Example: Update



Stash:

UPDATE(**)**: Evict, Re-assign, Writeback

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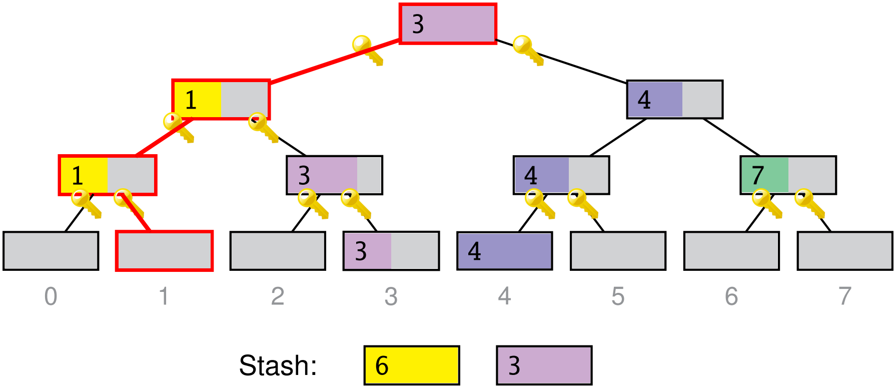

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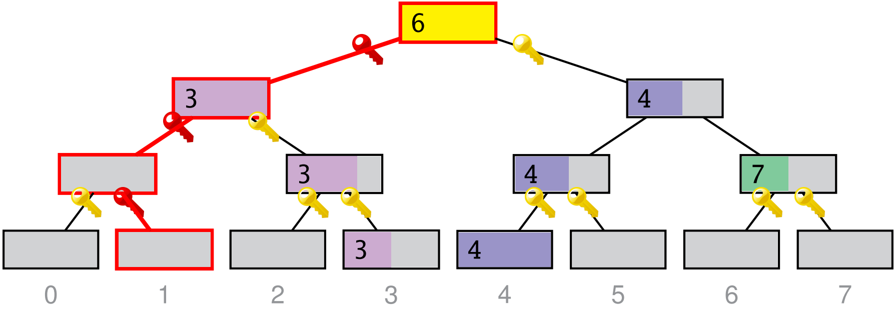

Stash:

UPDATE( ): Evict, Re-assign, Writeback

More details on vORAM

- Identifiers are chosen randomly, and the position (leaf node index) is a prefix of the identifier.
- The entire path is fetched and returned in parallel, resulting in 2 rounds per operation.
- Each node encrypted with a key stored in the parent node that is refreshed on each operation — implies secure deletion.
- No history beyond the most recent $O(n/\log n)$ operations is revealed, matching an asymptotic lower bound

How big should the buckets be?

An crucial parameter is **bucket size**: number of bytes per bucket.

As with Path ORAM, if this is too small, the root node (or stash) will “overflow”.

Theorem

The vORAM stash will overflow with only negligible probability if:

- *Block sizes are bounded by a geometric distribution*
- *Bucket size is 20 times the expected block size*

Note: In practice, the constant can be only 6, not 20.

Oblivious Data Structures

Recall the identifiers in vORAM: | 4 | 6 |

These identifiers are random; where do we store them?

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These identifiers are random; where do we store them?

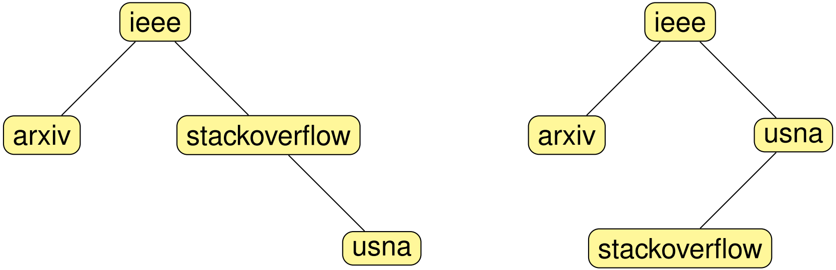
- Standard solution: Store a **position map** in recursively smaller ORAMs
- ODS (Wang et al. ’14): If you’re storing a data structure, store each node’s identifier in its parent node!

  To store a key/value map, use an AVL tree.

Example: AVL Tree Leakage

- We want to store a key/value data structure within the vORAM.
- But most data structures leak history information!

Were you browsing reddit or youtube?



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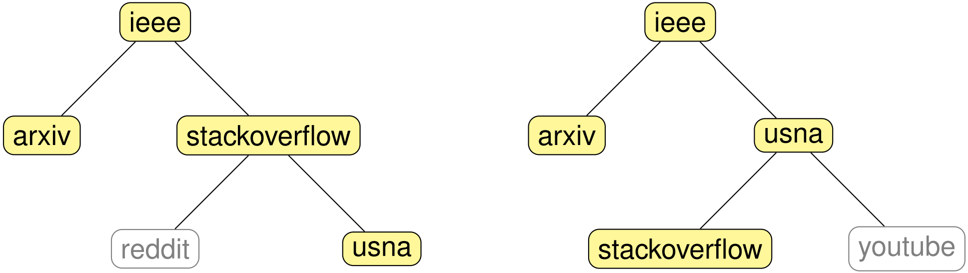


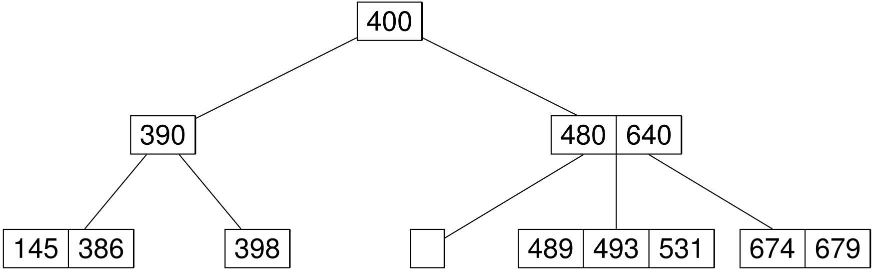
HIRB = History-Independent Randomized B-tree

Overview:

- B-tree structure, but the height of each element is uniquely determined.
- Heights determined from a **randomly-selected hash function**.
- The keys of key/value pairs are not stored, only their hashes.
- **Strong history independence** (Naor & Teague, STOC'01):
  The contents of the tree uniquely determine its structure.

HIRB Example

Over-simplification: Height = number of trailing zeros in hash



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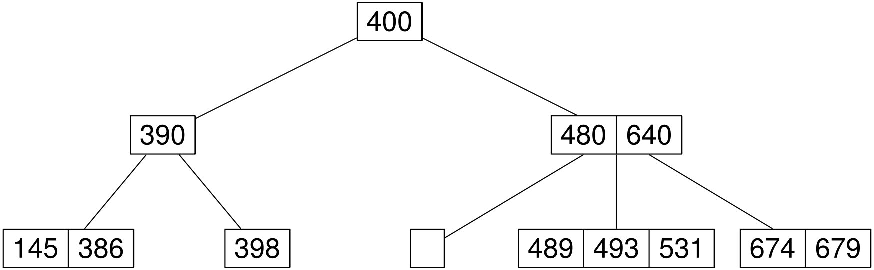
Example: Insert HELLO

hash(**HELLO**) = 510



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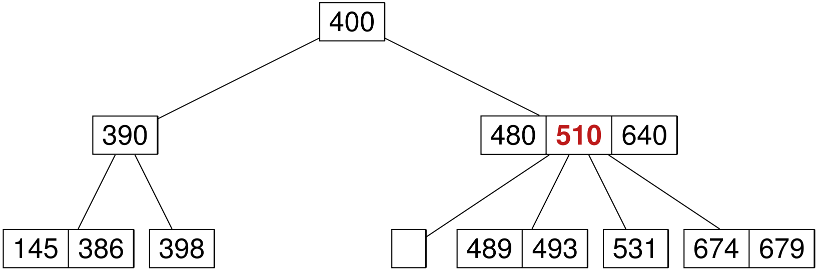


Choosing the heights

At tree creation: Choose a random hash function.

Crucial parameter: β, the expected block size

Given an element: Compute its hash, to seed a PRNG.

Sample from a geometric distribution with probability $\dfrac{\beta - 1}{\beta}$ to determine the height.

HIRB+vORAM

The HIRB is perfectly suited for vORAM:

- Node sizes follow a geometric distribution
- Identifiers can be stored in parent nodes
- Height is fixed — no padding necessary
- Combination still provides secure deletion
- HIRB leaks no operation history beyond what vORAM inevitably leaks

Comparison baselines

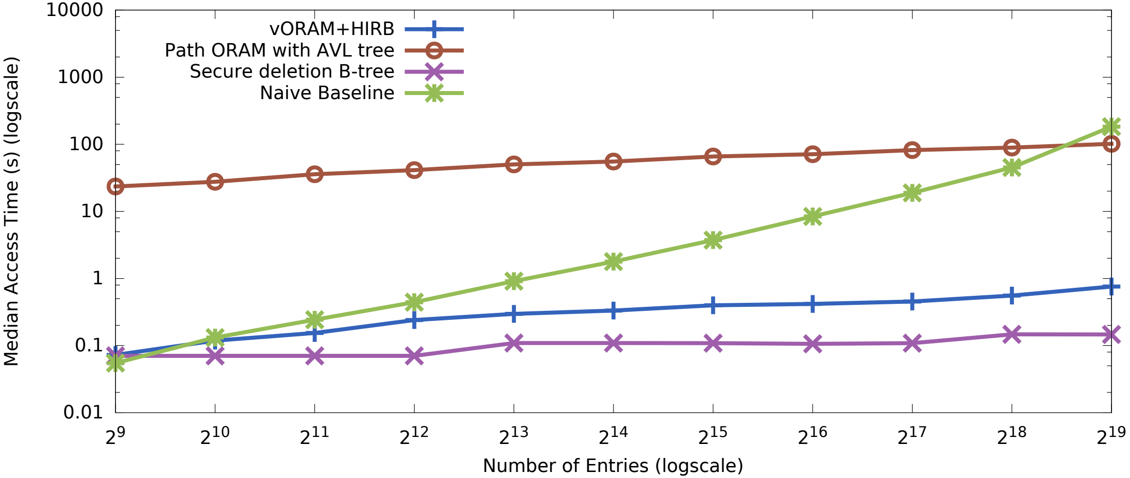
- vORAM+HIRB: Good performance, near-best security.
- Path ORAM with AVL tree: Poor performance, no secure deletion.
  Uses padding for obliviousness.
- Secure deletion B-tree: Best performance, no obliviousness.
  A normal B-tree, re-encrypting nodes on each access.
- Naïve baseline: Worst performance, best security.
  Re-encrypt and transfer the entire dataset on each access.

All implemented by us, in Python3, and tested using Amazon AWS.

Biggest Factors of Performance Improvement

- Height of HIRB compared to AVL tree
- Larger nodes in HIRB to take advantage of block size
- Efficient block packing in vORAM
- Parallel fetching of paths from vORAM
- All leads to significantly reduced round complexity

Experimental Timings



Take-Aways

- **ORAMs don't** (have to) **suck**.
  Our construction has practical utility in a real cloud setting.
- **We can get more *flexibility* and *privacy* from ORAMs**.
  We support variable-size blocks, secure deletion, and (limited) history independence.
- **Specialized data structures are needed to work well in ORAMs**
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Thank You!

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