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V-ORAM: A Versatile and Adaptive ORAM Framework with Service Transformation for Dynamic Workloads

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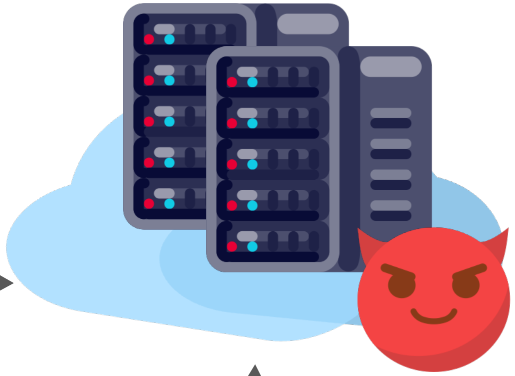
Data encryption to achieve privacy

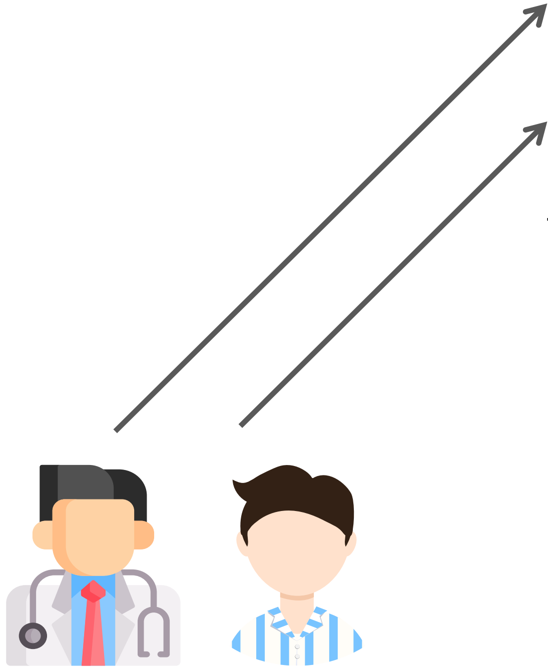
Honest-but-curious adversary



Key	Disease
1	COVID-19
2	Stroke
3	Alzheimer
4	Kidney diseases

Key	Disease
1b9	71pet11t
7fa	bjfzr0fy
cd3	vmy9cbv2
96e	ehn0xxau

Encryption alone is **NOT** enough



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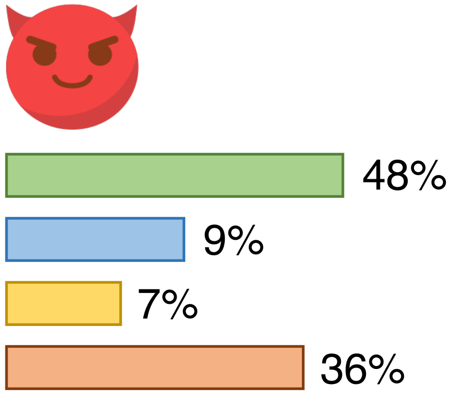

71pet11t ⟶ COVID-19

bjfzr0fy ⟶ Alzheimer

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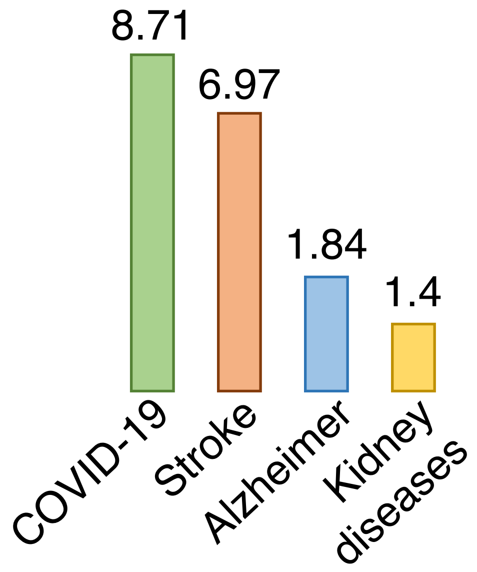
ehn0xxau ⟶ Stroke

Access Pattern Attacks

[Islam et al., NDSS'12], [Cash et al., CCS'15], [Naveed et al., CCS'15]
[Kellaris et al., CCS16], [Lacharité et al., S&P'19], [Grubbs et al., S&P'19]

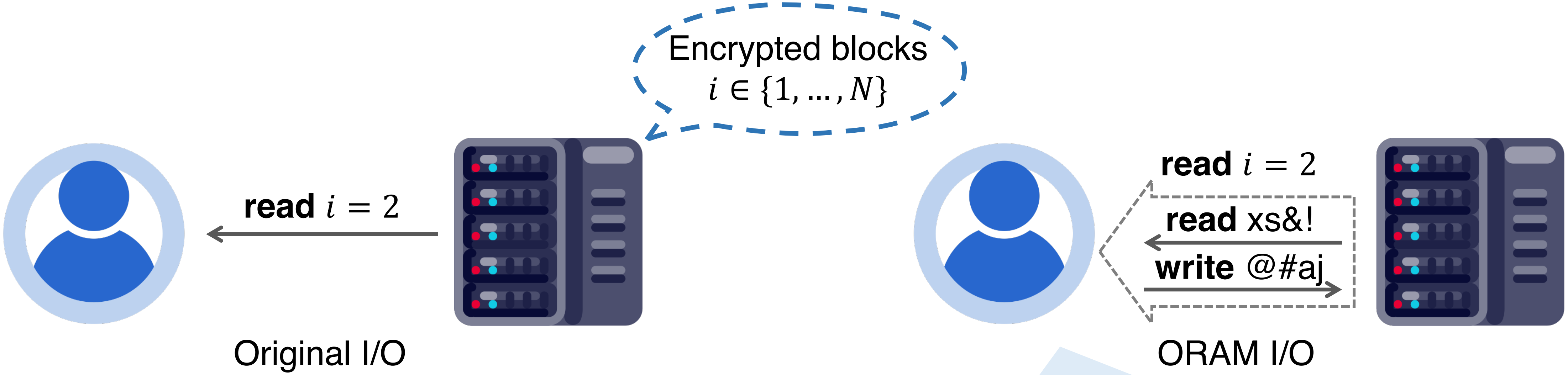
Leading causes of death worldwide in 2021 *(in millions)*[1]



[1] https://www.statista.com/statistics/1488587/leading-causes-of-death-worldwide-2021/

Oblivious RAM (ORAM) [GO, JACM'96]

- Goal: making the generated access pattern **random**



Encrypted blocks $i \in \{1, \dots, N\}$

read $i = 2$

Original I/O

read $i = 2$

read xs&!

write @#aj

ORAM I/O

Applications to various scenarios

- Parallelization: [ConcurORAM, NDSS'19], [TaoStore, S&P16]
- Secure computation: [SCORAM, CCS'14], [Circuit ORAM, CCS'16]
- Searchable encryption: [OBI, NDSS'23], [AM, EUROCRYPT'23]
- ...

Remark

- Stateful, maintains auxiliary metadata
- $\Omega(\log N)$ costs lower bound
- I/O operations need encryption key

Tailored and optimized for specific workload

How to serve for **dynamic workloads**?

- ORAM faces dynamically changing workloads in practice

Electronic medical record system

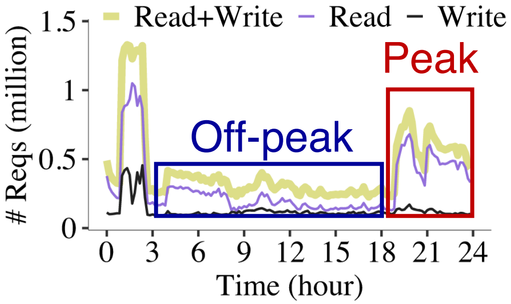
Routine usage

- No specific performance constraint
- Lower maintenance cost

Medical analysis

- Keyword search
- More complex query (join, aggerate)

Cloud storage system



Requests in a day[1]

Peak

- Higher throughput
- Lower latency

Off-peak

- Lower throughput
- Higher latency

- Or caused by system performance changes (e.g., bandwidth)

[1] Jinhong Li, Qiuping Wang, and Patrick P. C. Lee. "An In-depth Comparative Analysis of Cloud Block Storage Workloads: Findings and Implications", ACM TOS, 2023.

How to serve for **dynamic workloads**?

- Using **unmatched** ORAM scheme is not a good option
  - Sync. ORAM in async. settings → **Harm correctness**
  - Comm.-centric ORAM in low bandwidth → **Downgrade performance**
- Two strawman solutions:
  - Re-build the entire database → **$O(N)$ comm. costs**
  - Maintain multiple instances → **Heavy storage/access costs**

Can we achieve both security and efficiency?

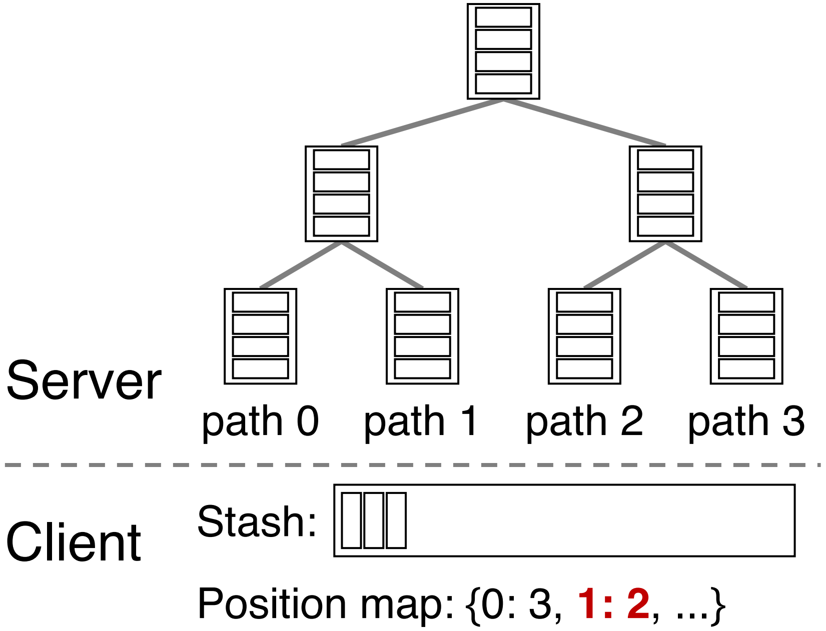
This paper & this talk

- **V-ORAM**, a versatile and adaptive ORAM framework
  - Securely transform between three tree-based ORAMs

    [Path ORAM, CCS'13], [Ring ORAM, Security'15], [ConcurORAM, NDSS'19]
  - **Constant** transformation costs
- Secure **ORAM service transformation (OST)** protocol
  - Identify **two leakages** during transformations
  - Mitigation with **constant** communication costs
- Heuristic **planner** to help choose parameters
- Implementations & Evaluations

Basic workflow of considered ORAMs

- Path ORAM, Ring ORAM, and ConcurORAM (built upon Ring ORAM)



Server

path 0 path 1 path 2 path 3

Client

Stash:

Position map: {0: 3, **1: 2**, ...}

Path ORAM

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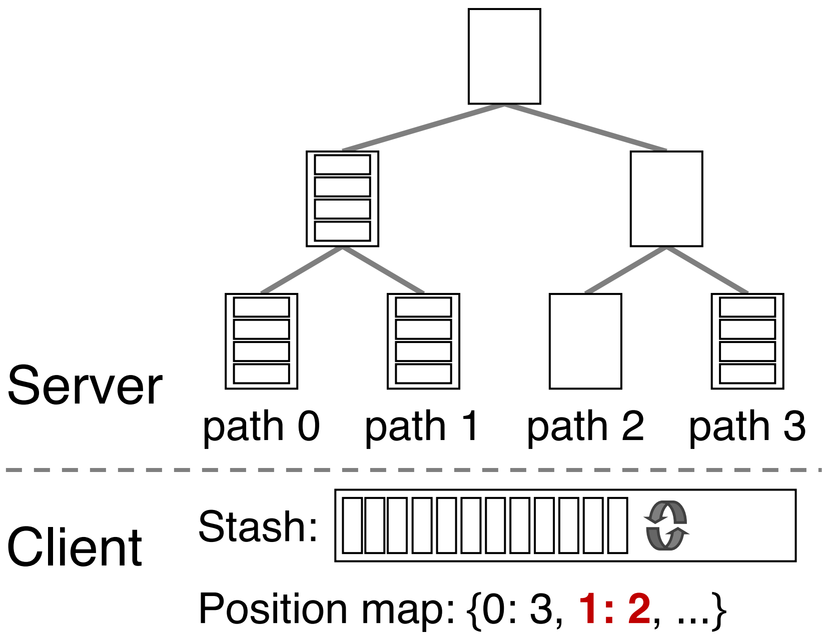

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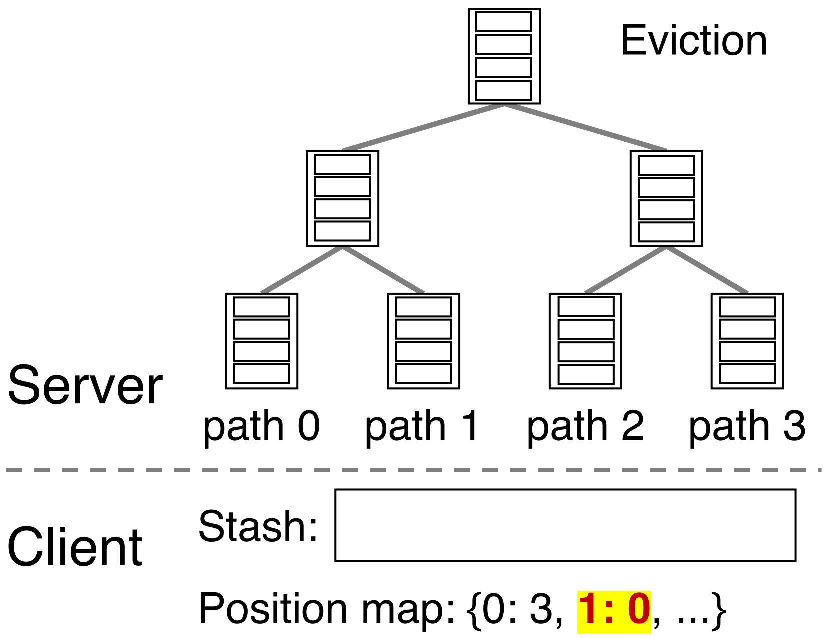


Eviction

Server

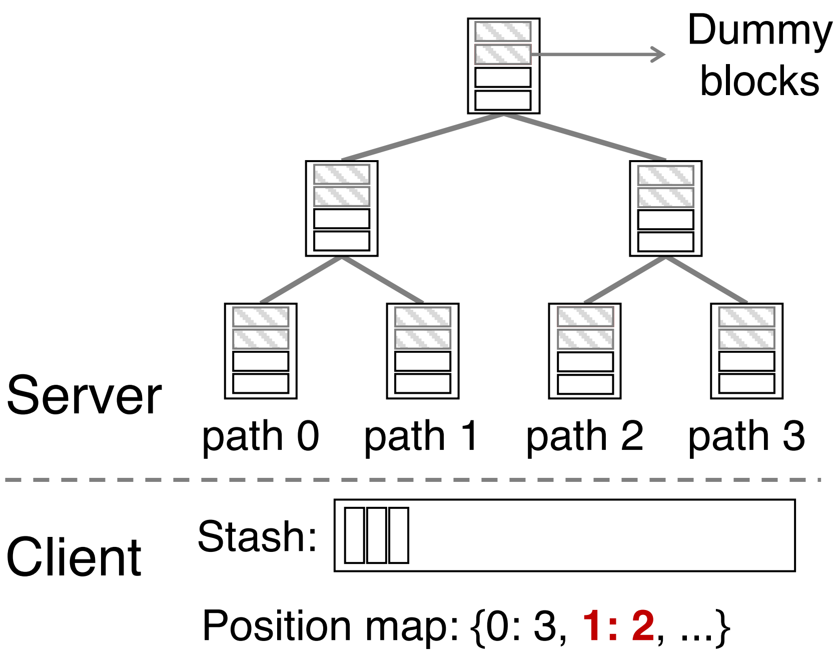
path 0 path 1 path 2 path 3

Client

Stash:

Position map: {0: 3, **1: 0**, ...}

Path ORAM



Dummy blocks

Server

path 0 path 1 path 2 path 3

Client

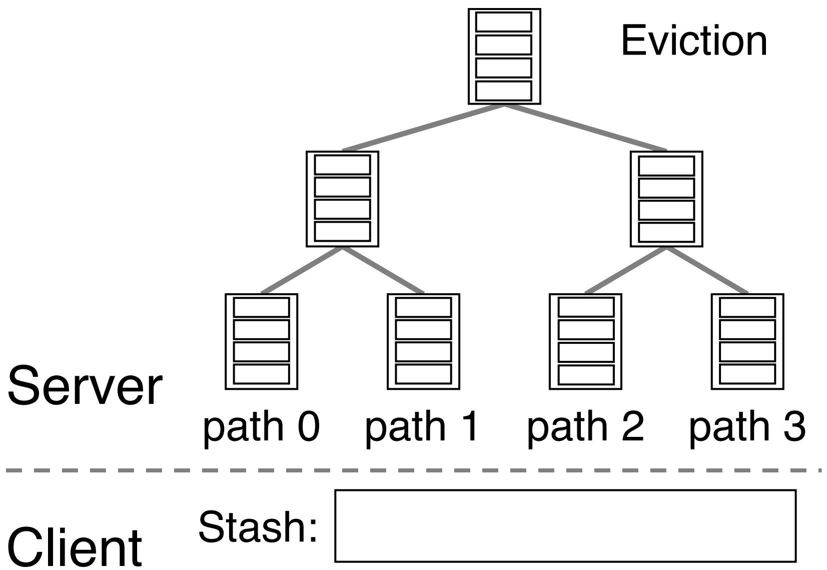
Stash:

Position map: {0: 3, **1: 2**, ...}

Ring ORAM

Basic workflow of considered ORAMs

- Path ORAM, Ring ORAM, and ConcurORAM (built upon Ring ORAM)



Eviction

Server

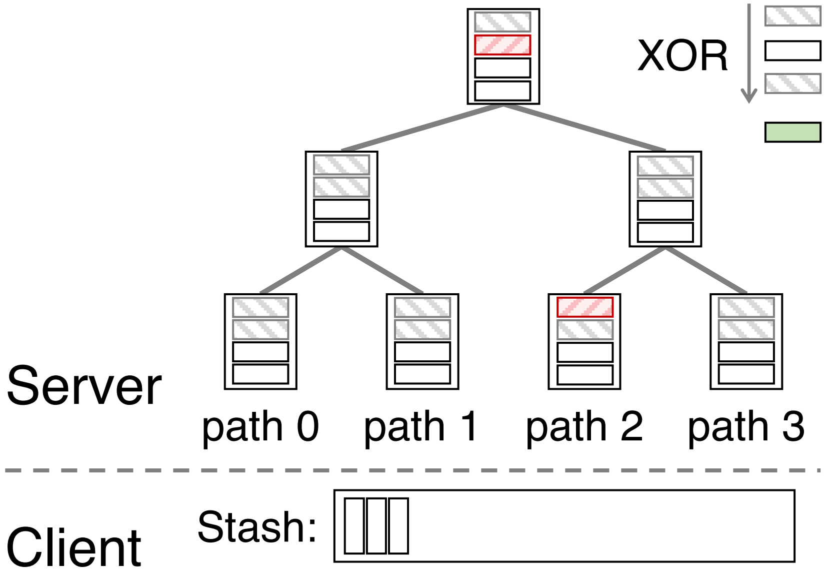
path 0 path 1 path 2 path 3

Client

Stash:

Position map: {0: 3, **1: 0**, ...}

Path ORAM



XOR

Server

path 0 path 1 path 2 path 3

Client

Stash:

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Ring ORAM

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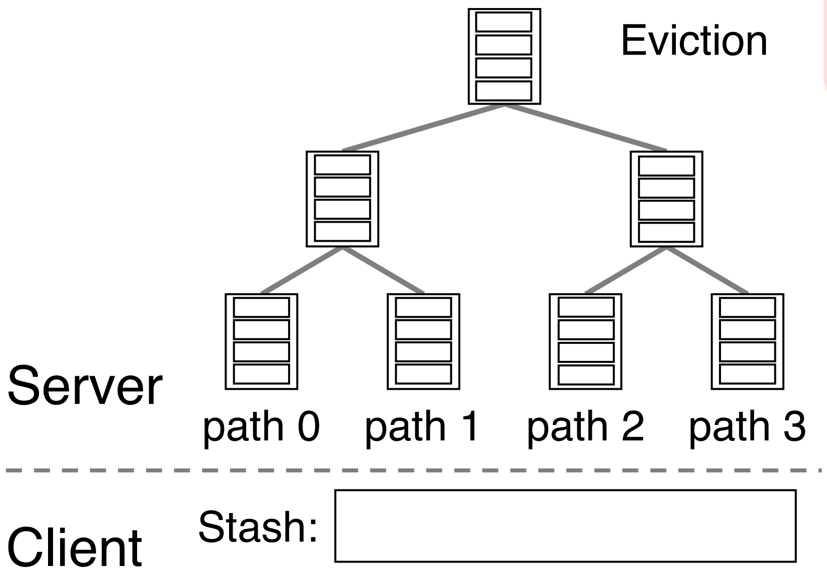


Server

Client

Stash:

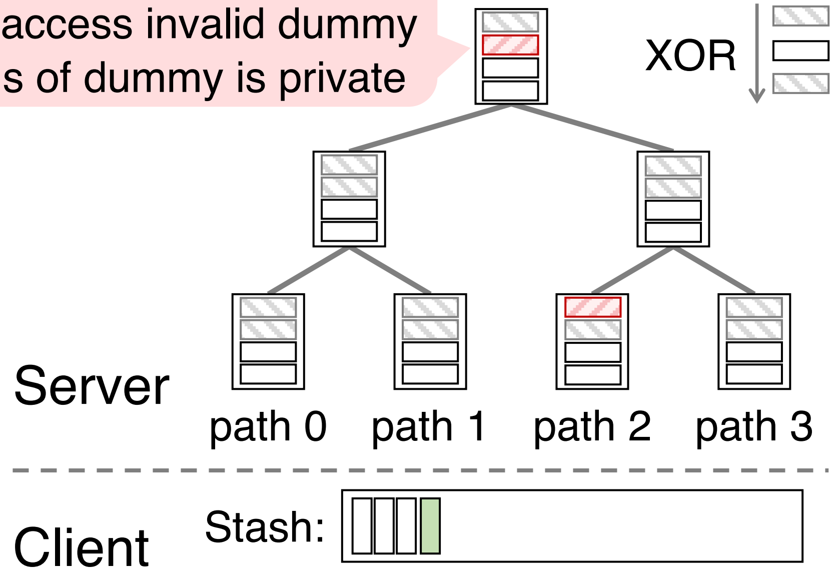
Position map: {0: 3, **1: 0**, ...}

Path ORAM

Instant eviction

Remark

- Cannot access invalid dummy
- Positions of dummy is private



Server

Client

Stash:

Position map: {0: 3, **1: 0**, ...}

Ring ORAM

Periodic eviction

EvictPath for every ***A*** queries

Why we chose these ORAMs?

- Workloads in practice
  - General storage: Path ORAM, [rORAM, NDSS19]
  - Real-time updates: Ring ORAM, ConcurORAM
  - Parallel access: [Snoopy, SOSP21], ConcurORAM, [TaoStore, S&P16]
  - Resource constrained: [FutORAMa, CCS23], [CSCL11], Path ORAM (recursive)
  - Specialized functionality: [OBI, NDSS23], [DUORAM, Security23], ConcurORAM
  - ... (see our paper for detailed taxonomy)

Why we chose these ORAMs?

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Our considered ORAMs cover the general workloads

System model & treat assumptions

- **Honest** client and **semi-honest** server

- During transformations, the adversary can learn:
  - Historical accesses
  - Access status of blocks
  - API calls of ORAMs
  - Encrypted data, metadata, and communication channel

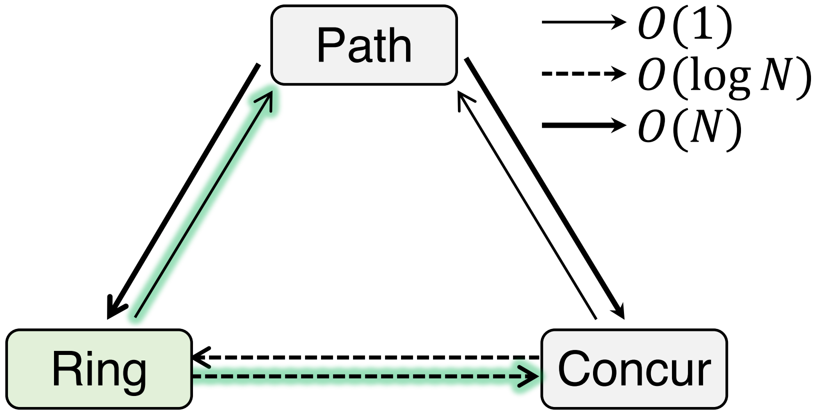
- Out-of-scope attacks
  - API calls within ORAMs are secure and correct
  - Attacks that can not be defended by original ORAM

Our design: select a base ORAM

- Transformation protocol for arbitrary ORAMs? ⟶ **$O(k^2)$ protocols**

- Find a transfer **inter-media**
  - Compatible to other schemes
  - Affordable, no heavy comp./comm.
  - Transformation-efficient, avoid massive comp./comm.

- Ring ORAM as **base ORAM** ✓
  - Compatible access protocol
  - Light-weighted XOR
  - Re-use the dummy blocks



Our design: handle the transformations

- Switch with ConcurORAM
  - **Inherit** the dummy blocks → **Potential leakage**
  - Download the server-side metadata

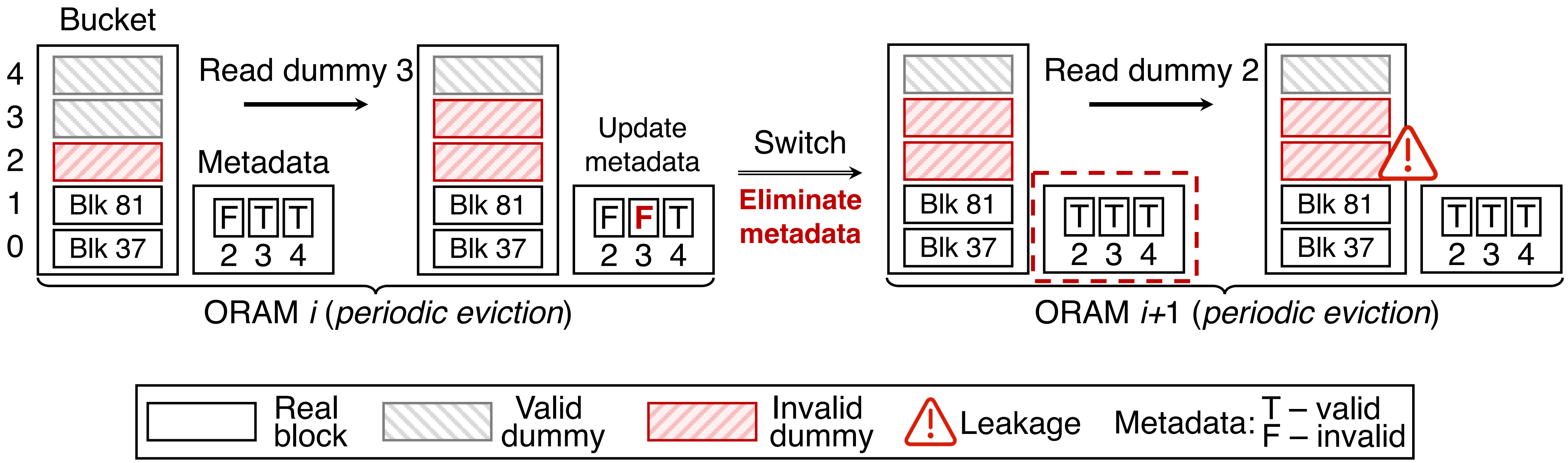
- Switch with Path ORAM
  - Directly inherit stash and position map
  - **What about the dummy blocks?**

➢ Option 1: treat dummies as real blocks ✗→ **Increase the costs**

➢ Option 2: only access real blocks → **Potential leakage**

Our design: identify the leakages

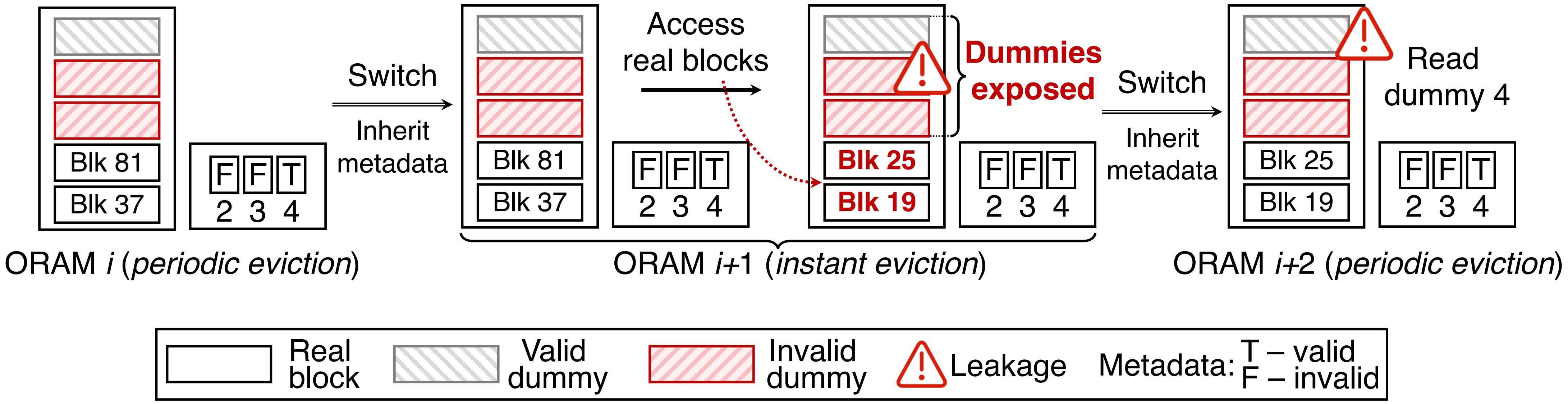
- Re-accessing invalid dummies
  - During transformation between **periodic eviction**



Our design: identify the leakages

- Re-accessing invalid dummies
  - Between ORAMs with **periodic eviction**

- Exposing dummies' position
  - Between ORAMs with **instant and periodic eviction**



Our design: mitigate the leakages

- Intuition: evict the accessed buckets before using dummies

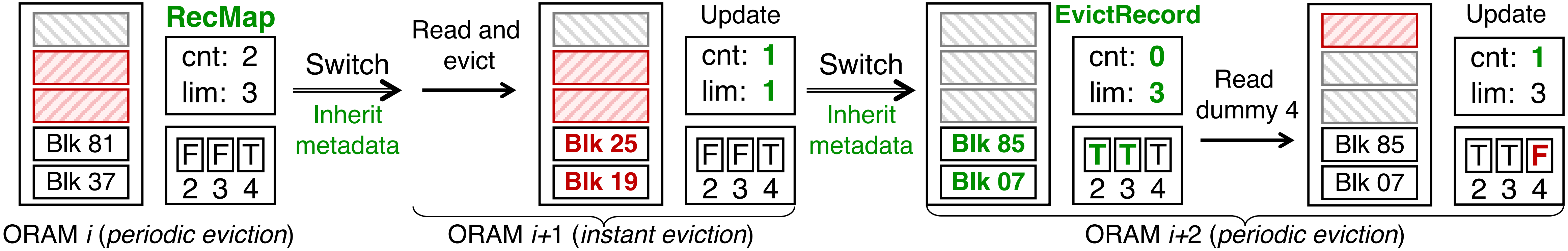
- Access limit: number of secure accesses before eviction
  - **1** for Path ORAM, ***S*** (number of dummies) for Ring ORAM
  - Evict the bucket before exceed the limit

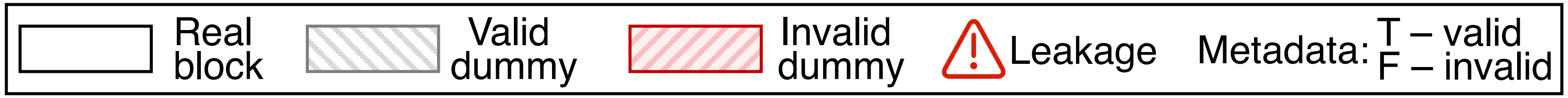
- Record map: $\{bucket\ ID \rightarrow (cnt, lim)\}$
  - cnt: access count, lim: current limit
  - lim is updated to **smaller** one

- EvictRecord: evict the bucket when $cnt = lim$

  See paper
  - Triggered **before access** and **after eviction**

Our design: mitigate the leakages





Theoretical bounds

- Costs of EvictRecord
  - For an ORAM with N blocks, bucket size of Z, and block size of B
  - Comm. and comp. costs of $\boldsymbol{O(ZB)}$, storage costs of $\boldsymbol{N \log Z}$ **bit**
- Stash size
  - The stash size of V-ORAM is bounded by $\boldsymbol{O(\log N)}$ **blocks**
- Transformation costs
  - c: batch size of Ring ORAM, MS: max stash size

	Switch to base ORAM		Switch to base ORAM	
	Comm.	Comp.	Comm.	Comp.
Path ORAM	$O(1)$	$O(1)$	$O(1)$	$O(1)$
ConcurORAM	$B(2c^2 + c + MS)$	$B(2c^2 + c + MS)$	$B(c + MS)$	$B(c + MS)$

Implementations

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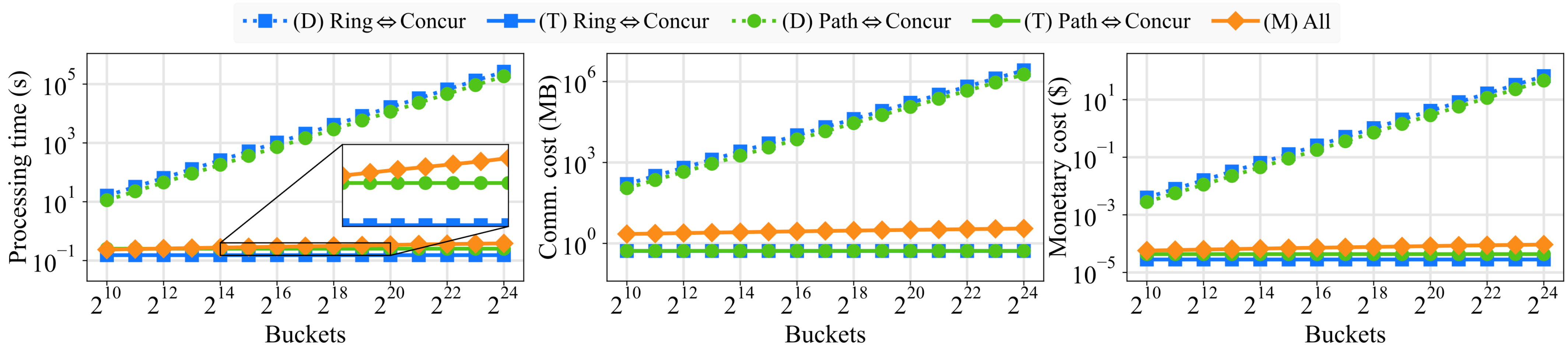
- Open-source code at github.com/BoZhangCS/V-ORAM
  - V-ORAM with Path ORAM, Ring ORAM and ConcurORAM
  - “`pycryptodemo`” for data encryption
- Experimental setup
  - Mac mini with 512GB storage and an M2 chip with 16GB RAM
- Real-world datasets
  - Microsoft Research Cambridge (MSRC)
  - Alibaba cloud trace (AliCloud)
  - Twitter workload, ChestX-ray8, COVIDx

Constant transformation costs

- (D) denotes downloading and re-building the ORAMs → **O(N)**
- (M) denotes maintaining multiple ORAMs → **O(log N)**
- (T) denotes transformation via OST protocol → **O(1)**

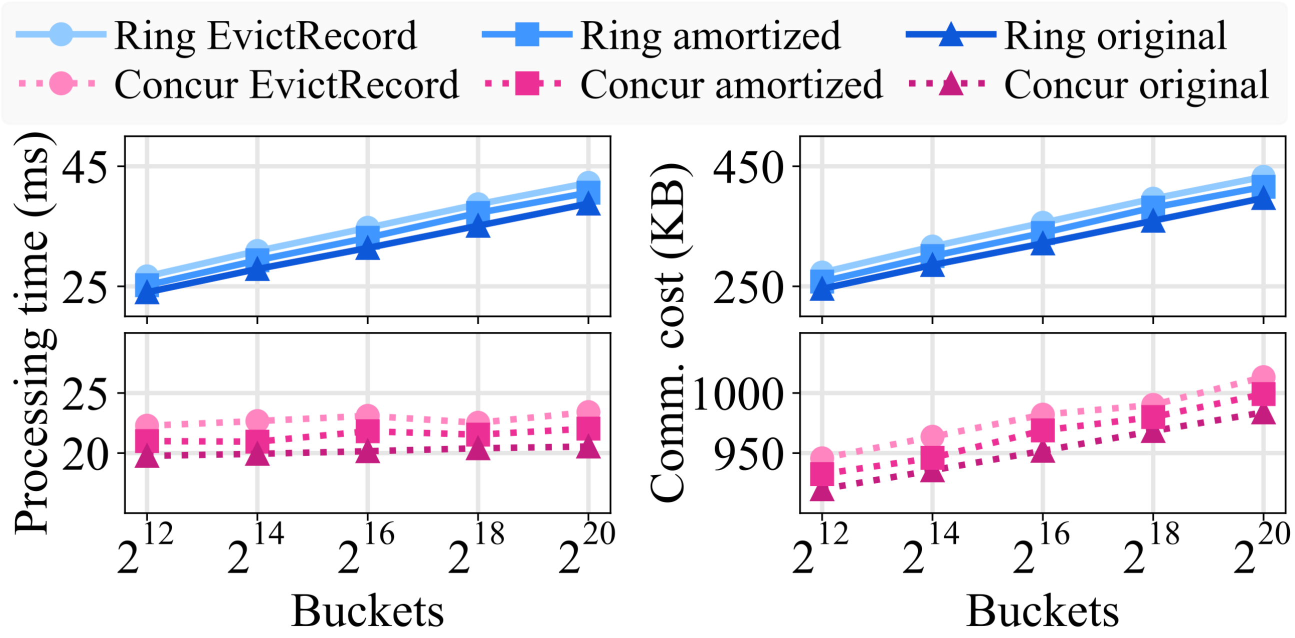


13,000x faster

The more data we store, the more benefit we gain

Constant EvictRecord costs

- Original ORAM costs
- Amortized costs in V-ORAM
- Eviction costs of each EvictRecord
- EvictRecord costs > Amortized costs > Original costs

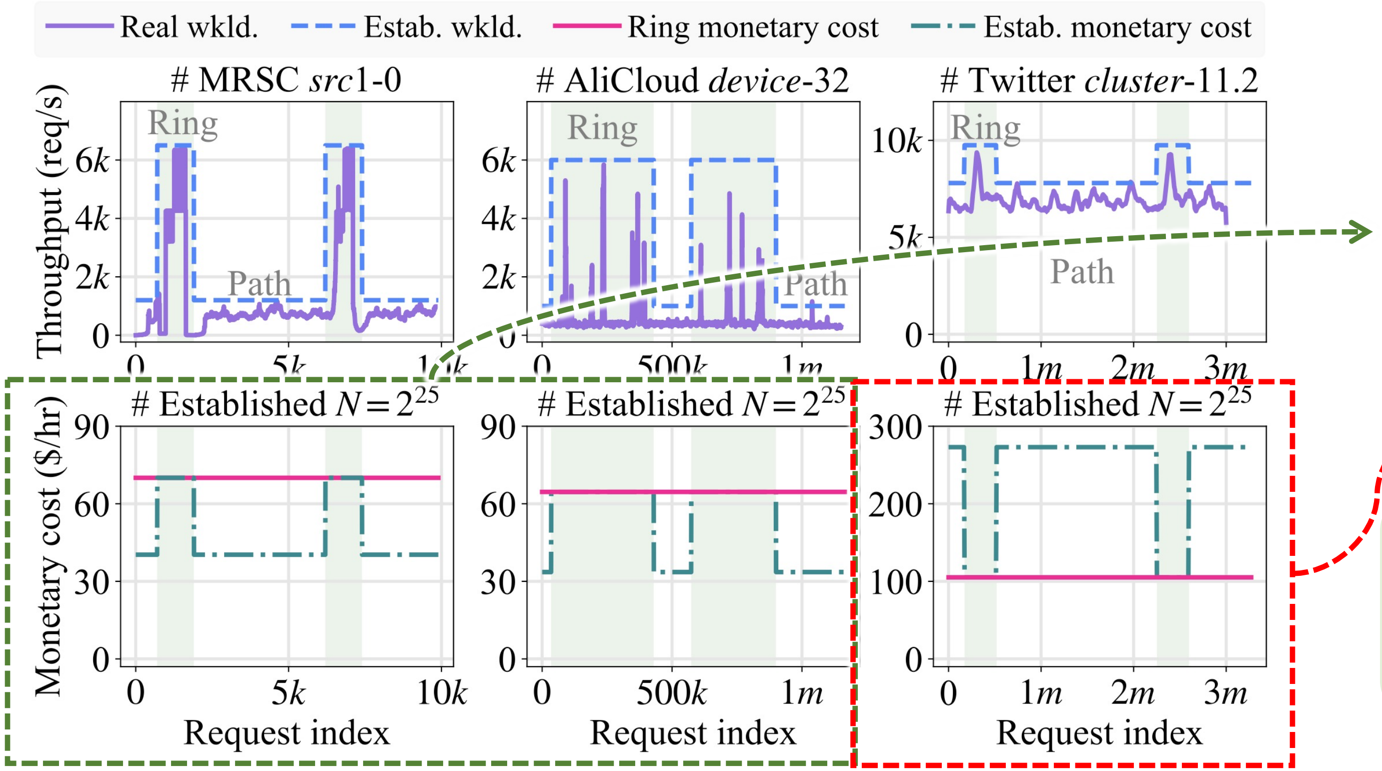


Additional processing time < 5ms

comm. costs < 50kB

Real-world case study

- Stripped workload from MRSC, AliCloud and Twitter
  - Divide workload into peaks and off-peaks
  - Ring ORAM for peaks, Path ORAM for off-peaks



Saving monetary costs of 33.1% and 24.5%

Increased costs

Suitable for workloads with higher variation

Conclusion

A versatile and adaptive ORAM framework, V-ORAM

- Secure and efficient ORAM transformation

Performs well

- 13,000x faster then strawman solutions
- Constant additional costs of < 5ms and < 50kB
- Saves up to 33.1% costs in real-world datasets

Q&A

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