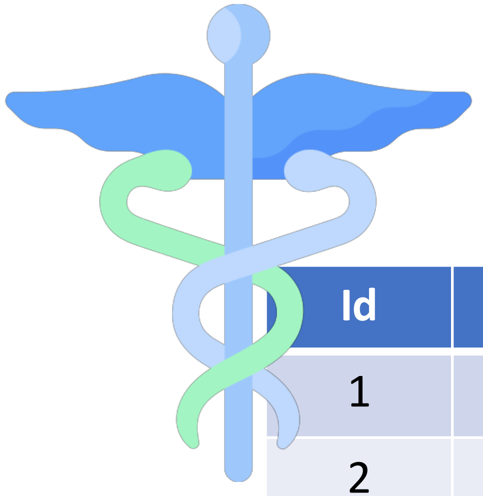
CS848
Oblivious RAM

Sujaya Maiyya

Slides partially acquired from Prof. Amr El Abbadi and Sajin Sasy

Data encryption to achieve privacy?



Id	Medicine
1	Humira
2	Januvia
3	Tivicay
4	Herceptin

Honest-but-curious adversary

Id	Medicine
X12	S6C…23
2SD	1NW…SJ
D45	3G8…SO
F4A	DJW…O8

Encryption is **not** sufficient for data privacy

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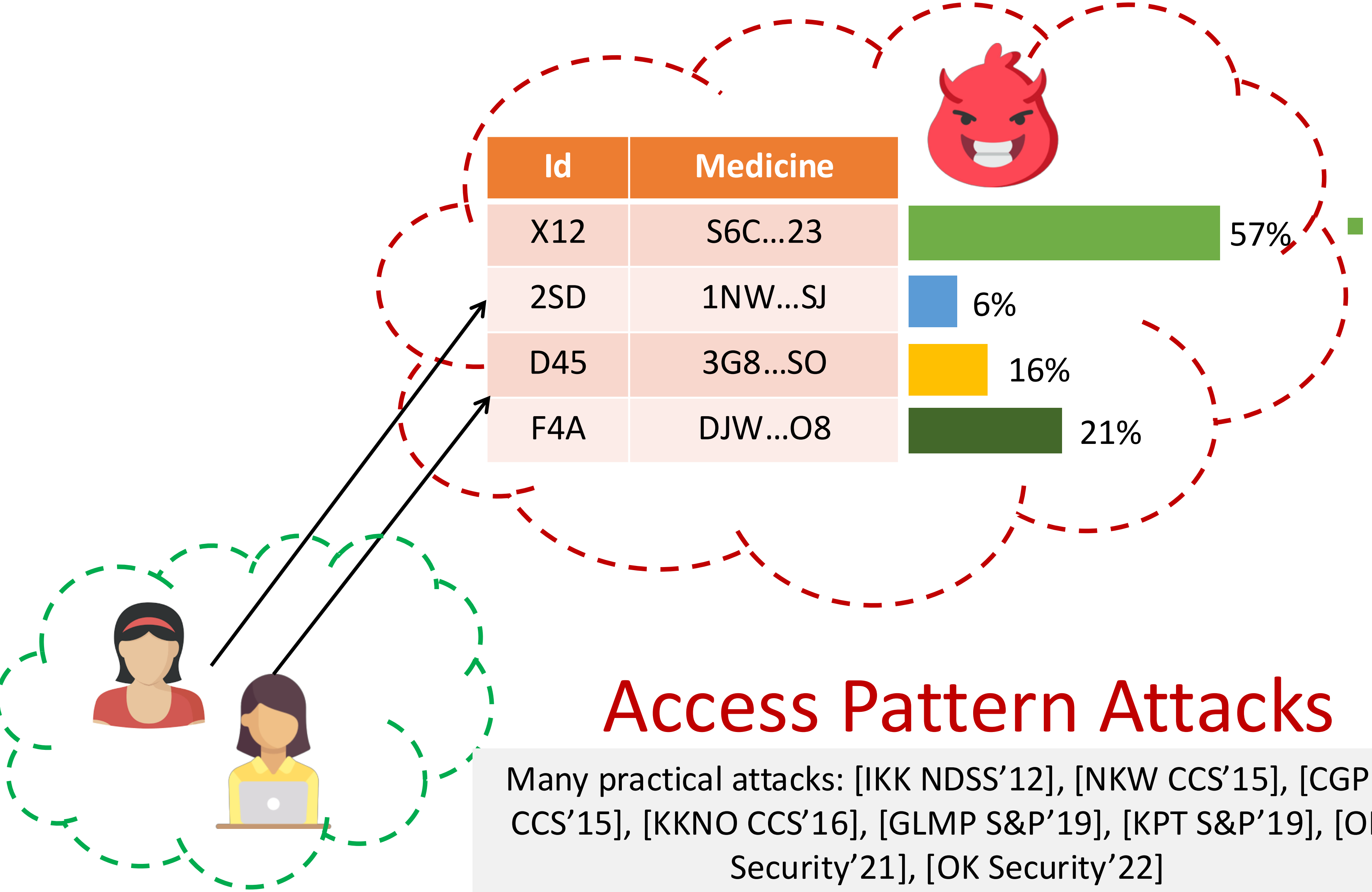
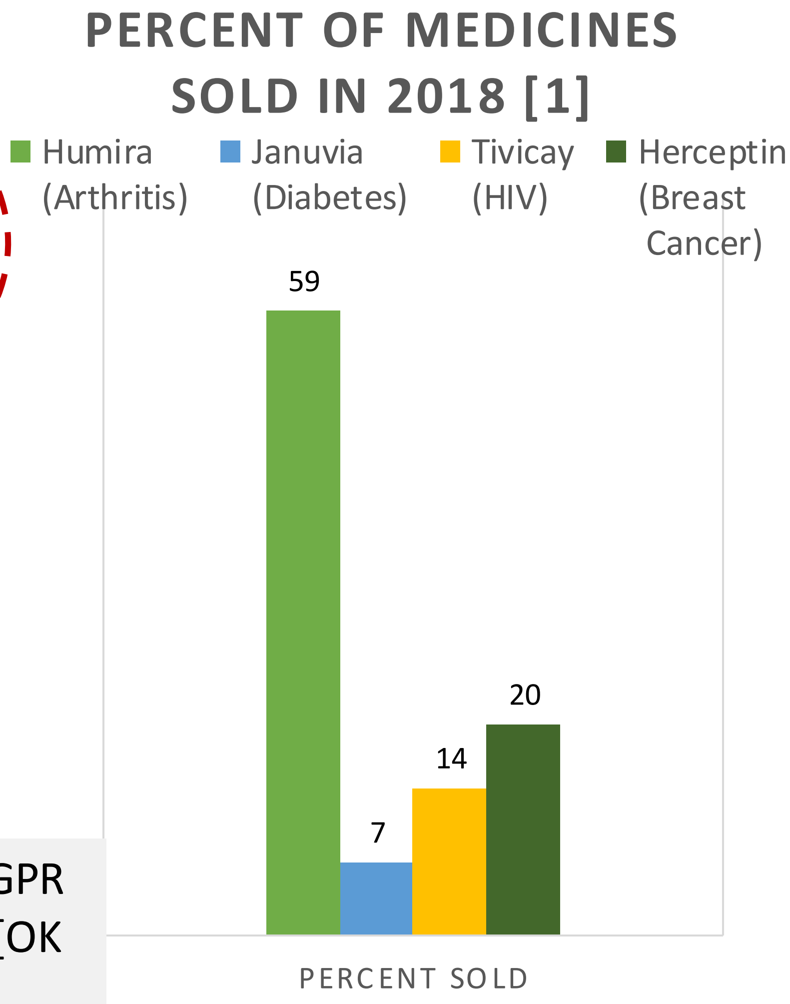




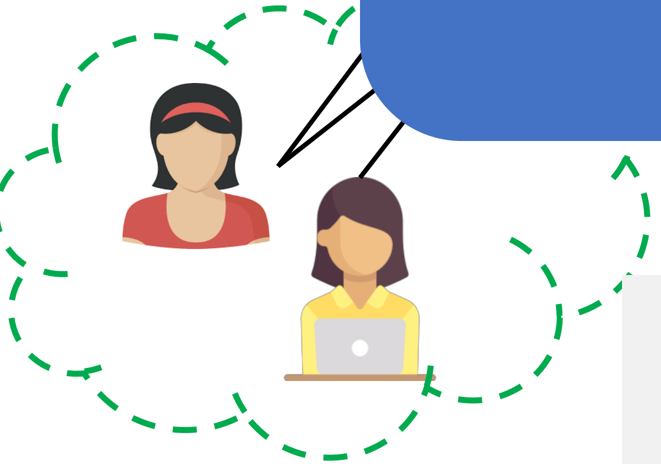
Access Pattern Attacks

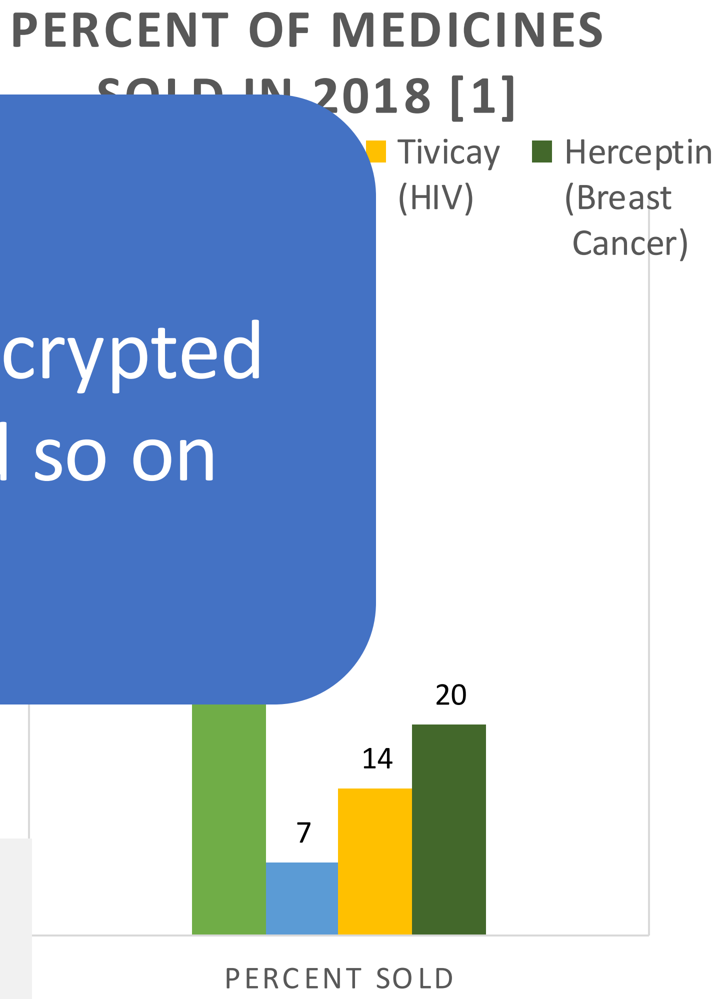
Many practical attacks: [IKK NDSS’12], [NKW CCS’15], [CGPR CCS’15], [KKNO CCS’16], [GLMP S&P’19], [KPT S&P’19], [OK Security’21], [OK Security’22]

[1] https://truecostofhealthcare.org/pharmas-50-best-sellers/

Encryption is **not** sufficient for data privacy

Attacks on electronic health records, encrypted emails, news articles, movie plots, and so on





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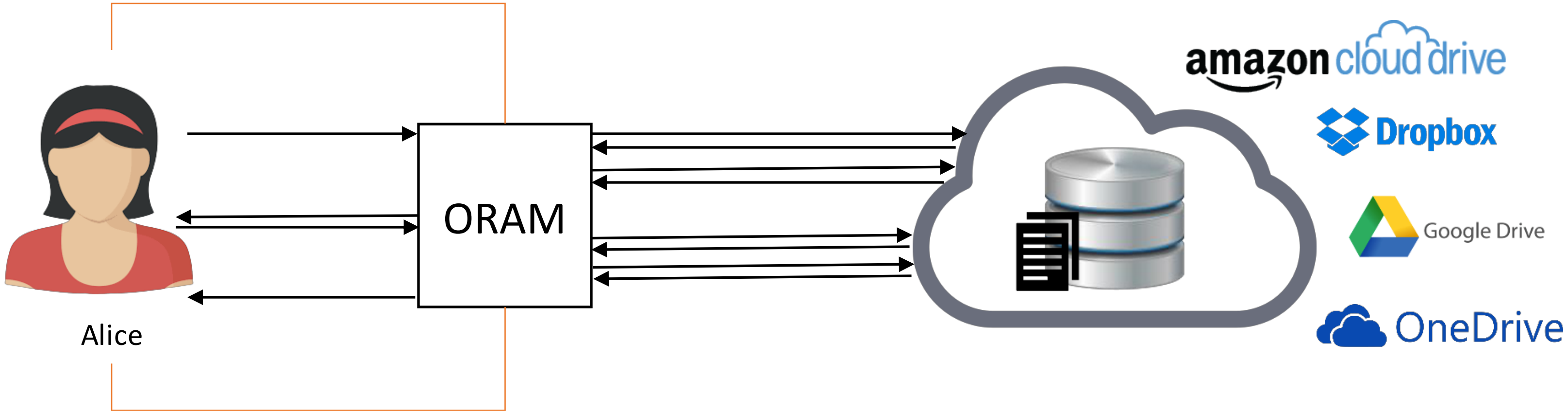
Workload independence

to protect against these attacks by hiding…

- which data is being accessed
- how old it is (when it was last accessed)
- whether the same data is being accessed
- access pattern (skewed vs. uniform)
- whether the access is a read or a write

Random accesses ensures workload independence



Goal: Oblivious Access

Translate each logical access
to a sequence of random-looking accesses

OBLIVIOUS RAM (ORAM)

Initially proposed by [Goldreich and Ostrovsky, JACM'96]

ORAM provides workload independence

- Clients wish to outsource data to an untrusted cloud storage
- Honest-But-Curious cloud can control & observe network & cloud storage
- Keep the **data** and **access pattern** private

Client 1

Client 2

A =

0	0	0	0

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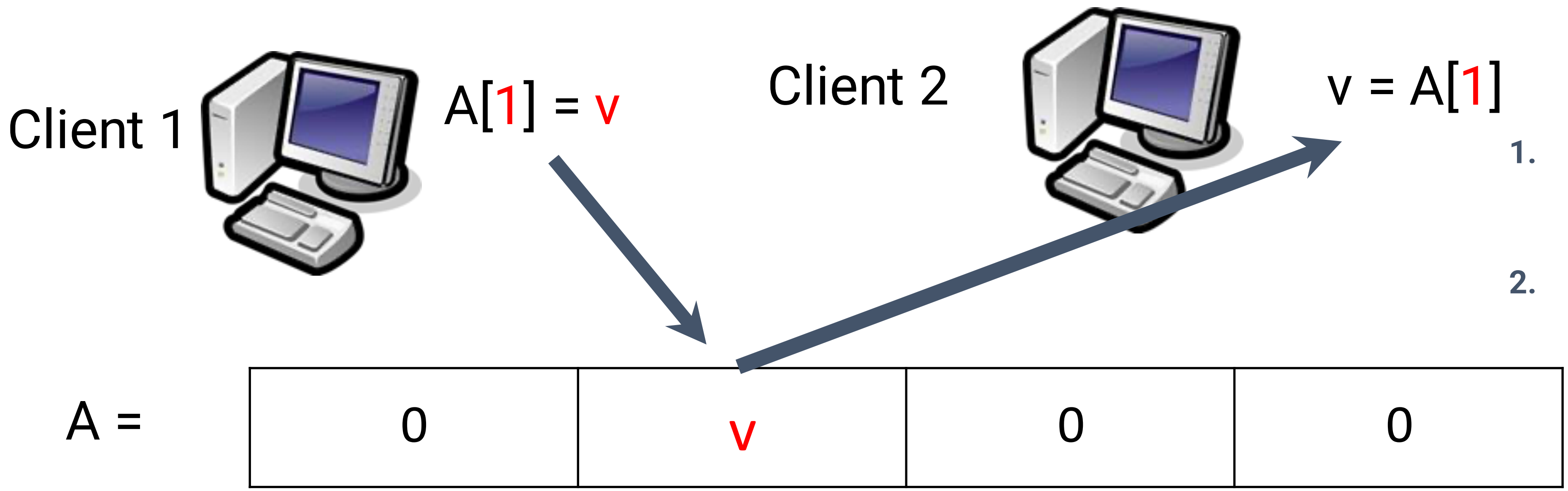
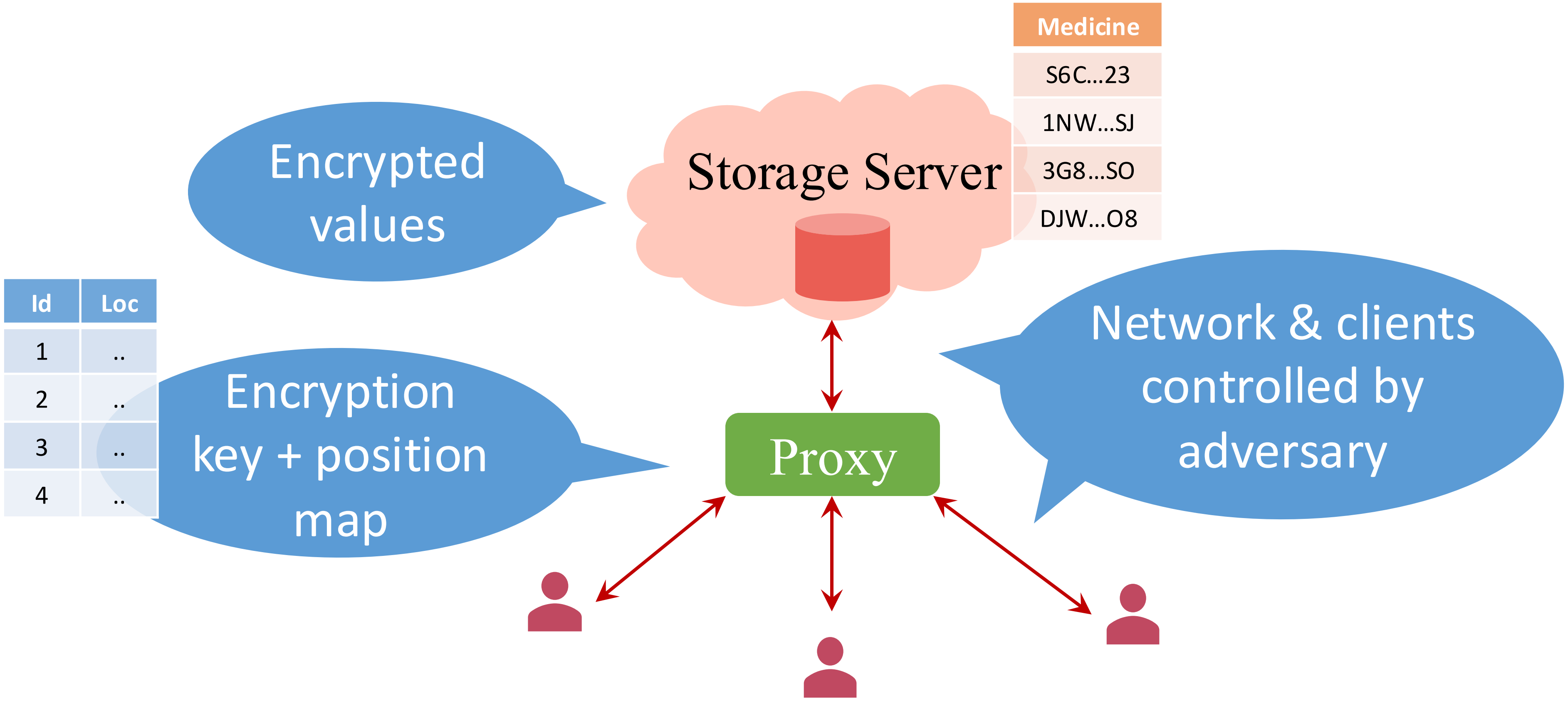
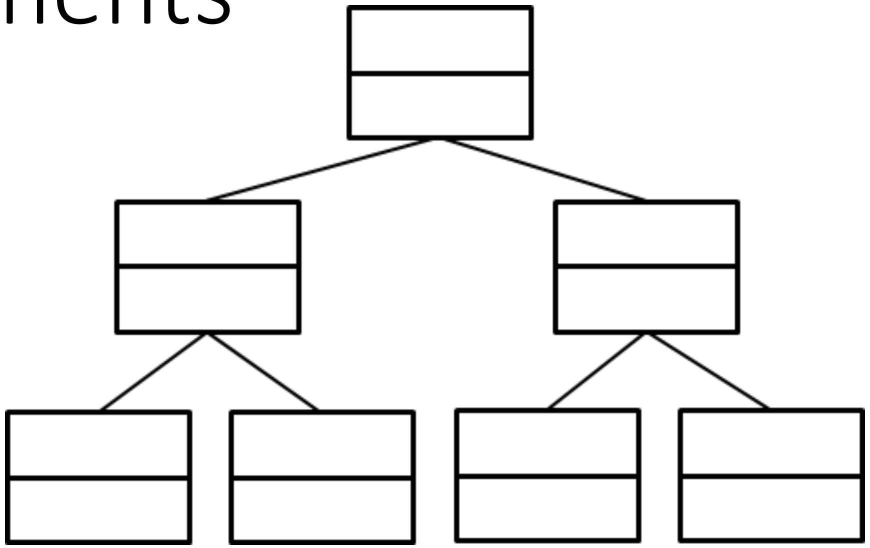


1. The cloud never learns about **v**
2. The cloud never learns that clients accessed **index 1**

Typical (but not all) ORAM architecture



Tree-based ORAM Developments

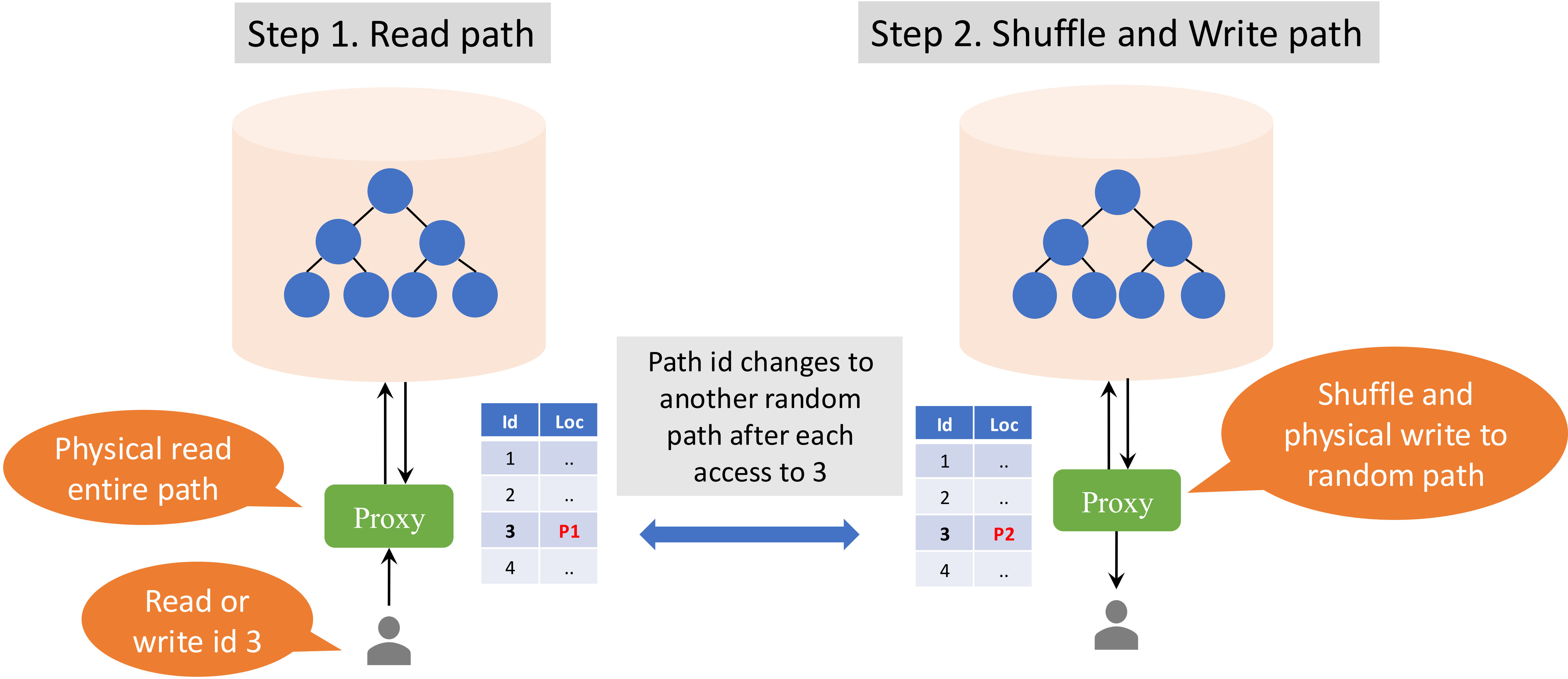


- While other forms ORAM constructions exist, most are theoretical in nature

A practical and popular solution

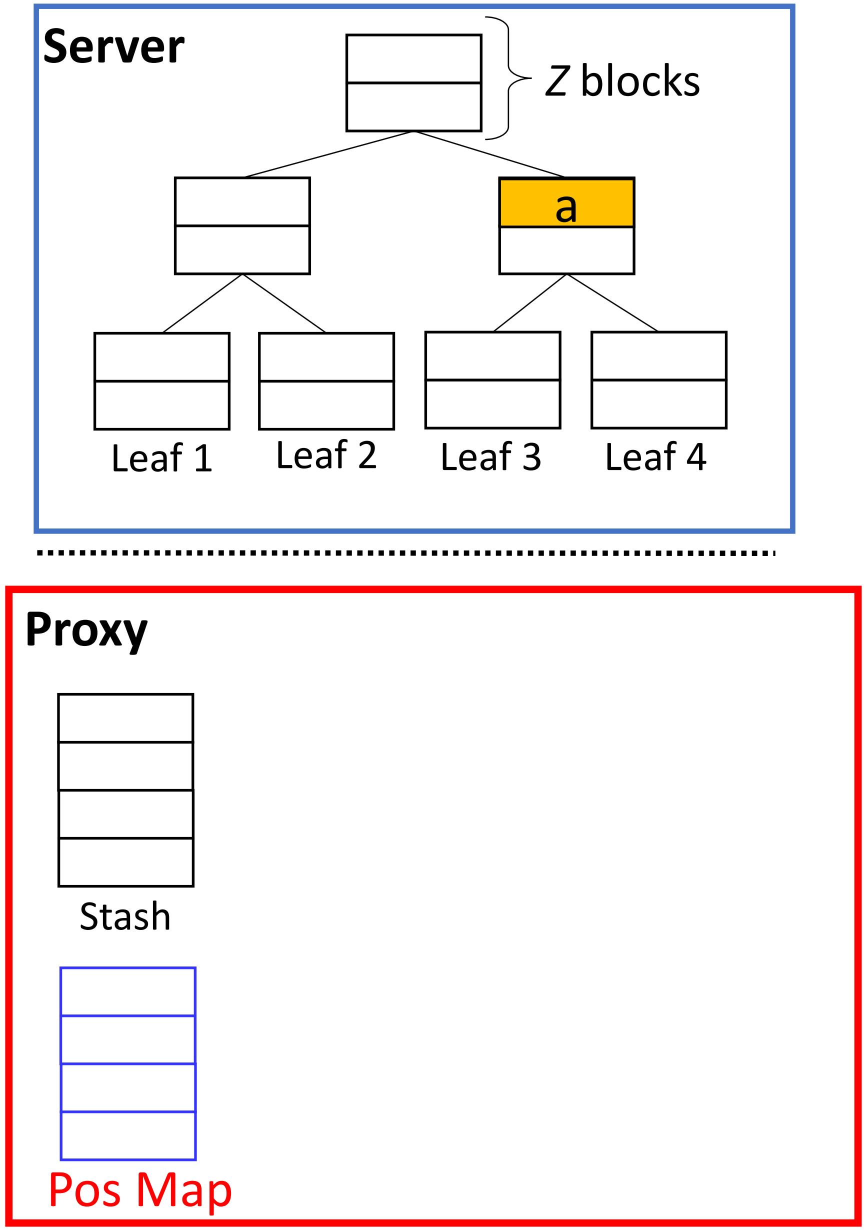
- Path ORAM: an extremely simple oblivious RAM protocol [Stefanov et al. CCS'13]

1000 ft overview of ORAM (PathORAM[1])



[1] E. Stefanov, et al. "Path ORAM: an extremely simple oblivious RAM protocol." *Proceedings of the 2013 ACM SIGSAC*. 2013.

Path ORAM [Stefanov et al. CCS'13]

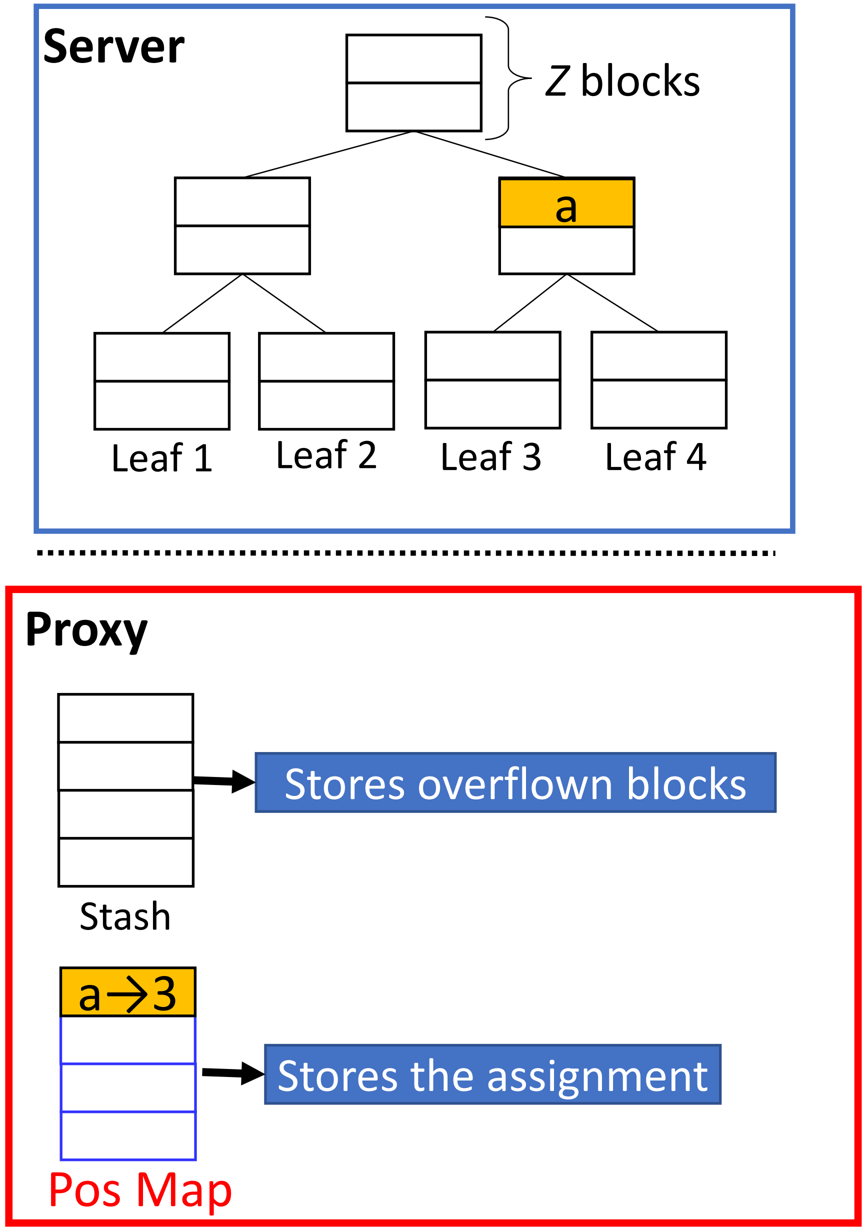


Storage is organized as a binary tree

Every access to a random path

Items randomly re-assigned after every access

Path ORAM [Stefanov et al. CCS'13]



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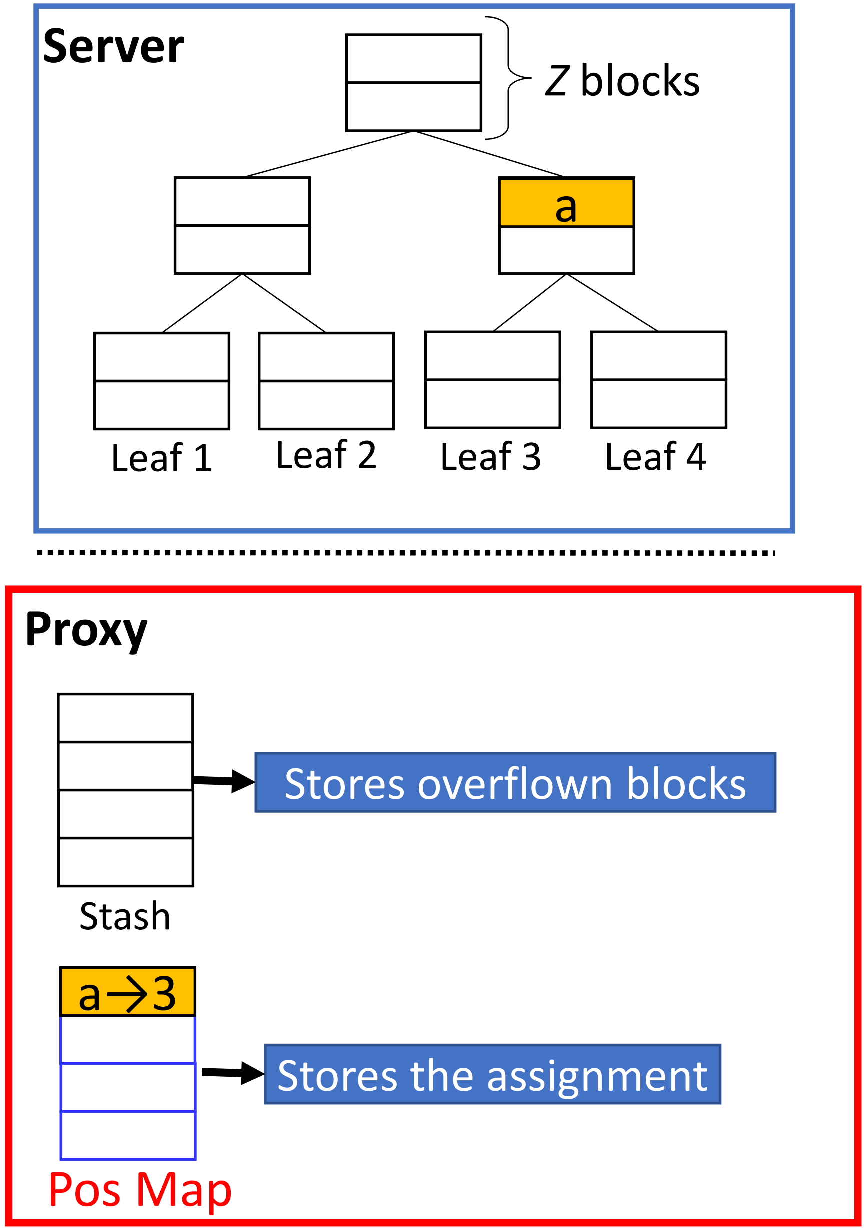

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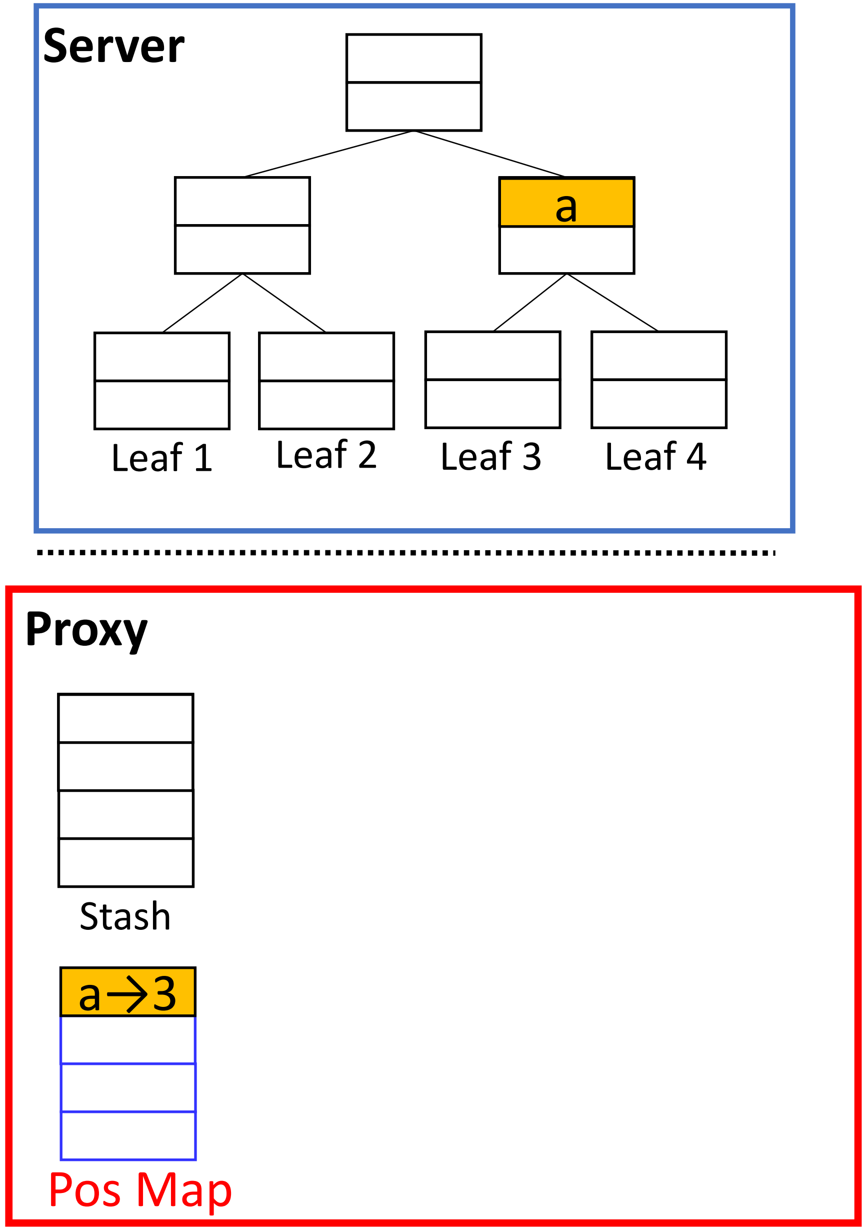
Every access to a random path

Items randomly re-assigned after every access

Possible to outsource position map recursively

But need many rounds of communication

Path ORAM



Read/Write block a

1) Read path

- Fetch associated path
- Read/Modify block
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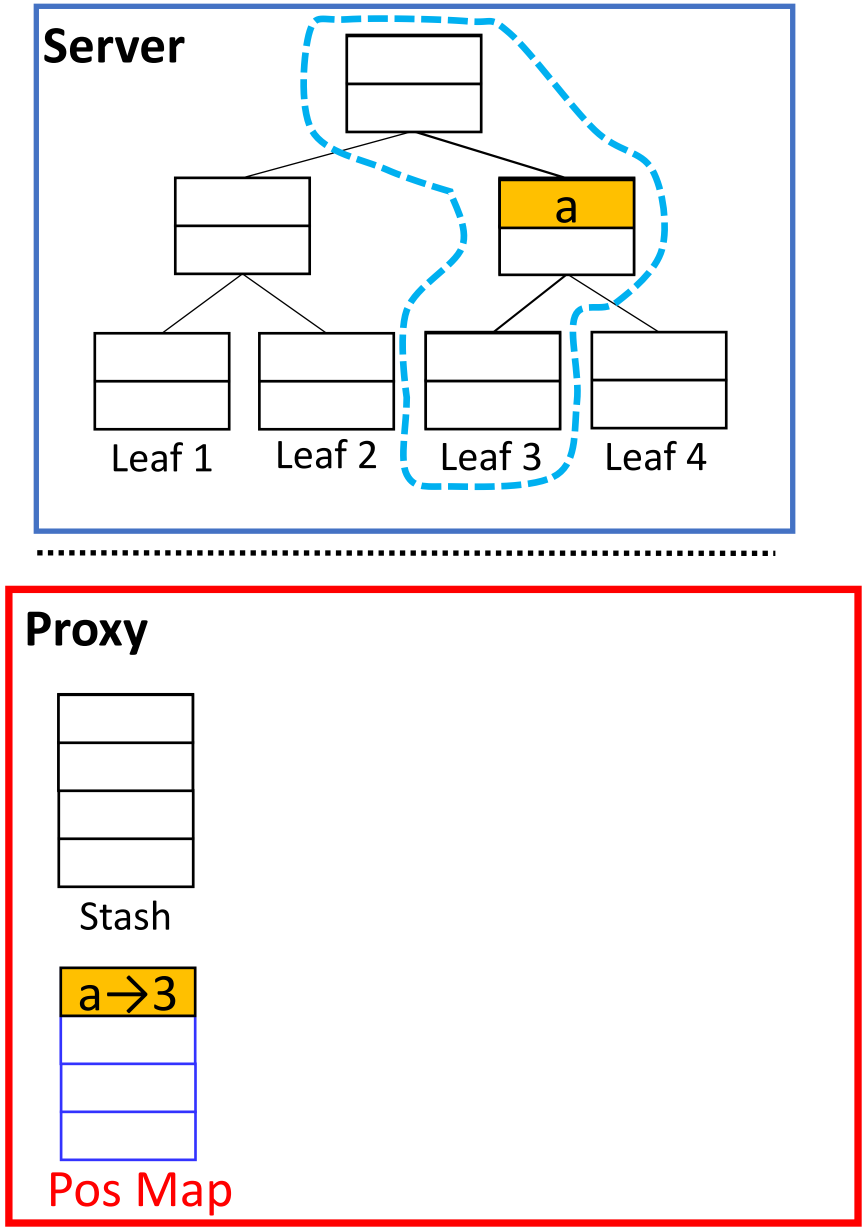
- Move all read blocks to *stash*

Path ORAM



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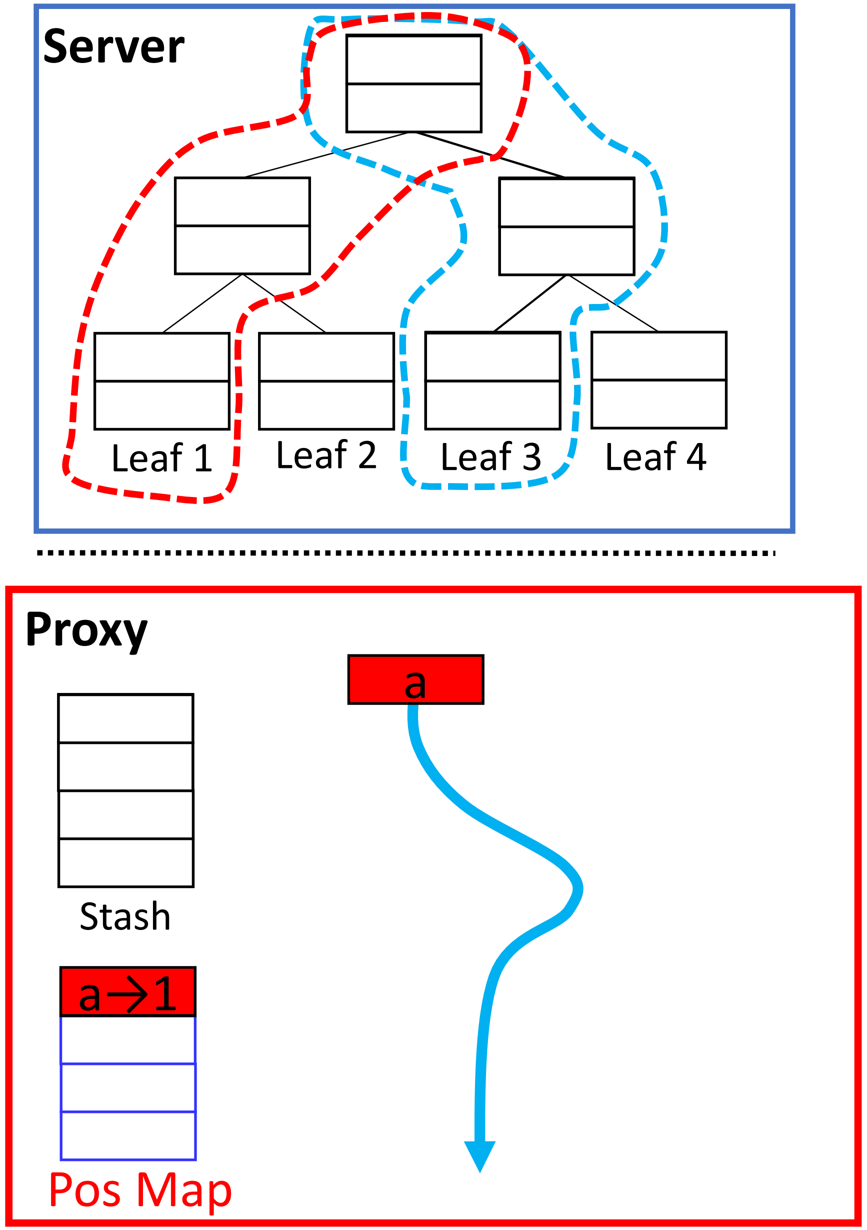

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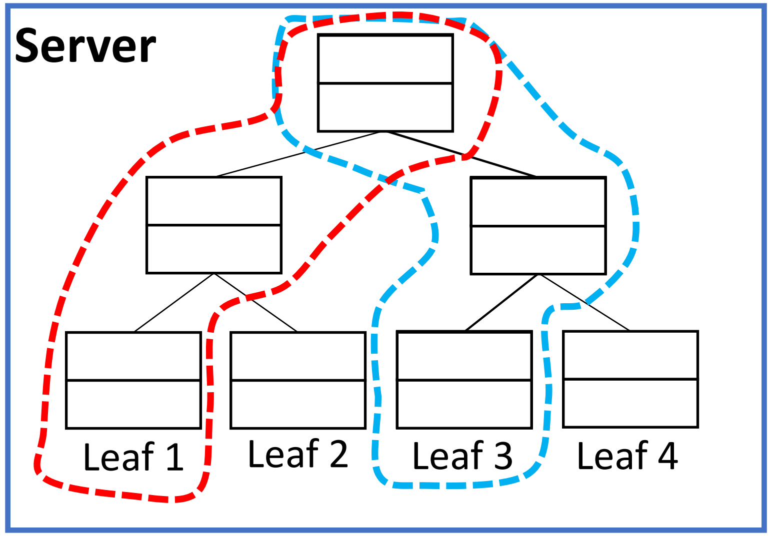
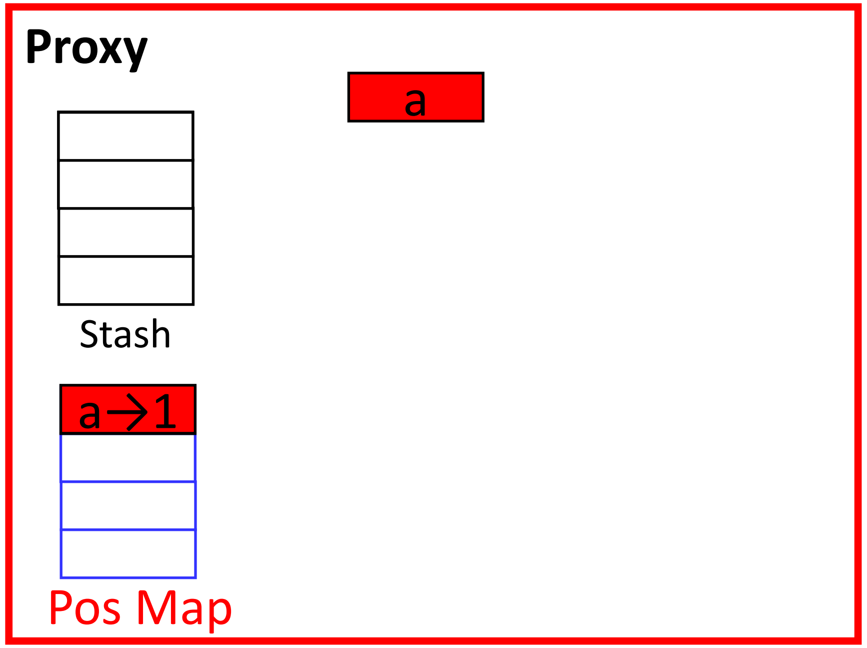
Path ORAM





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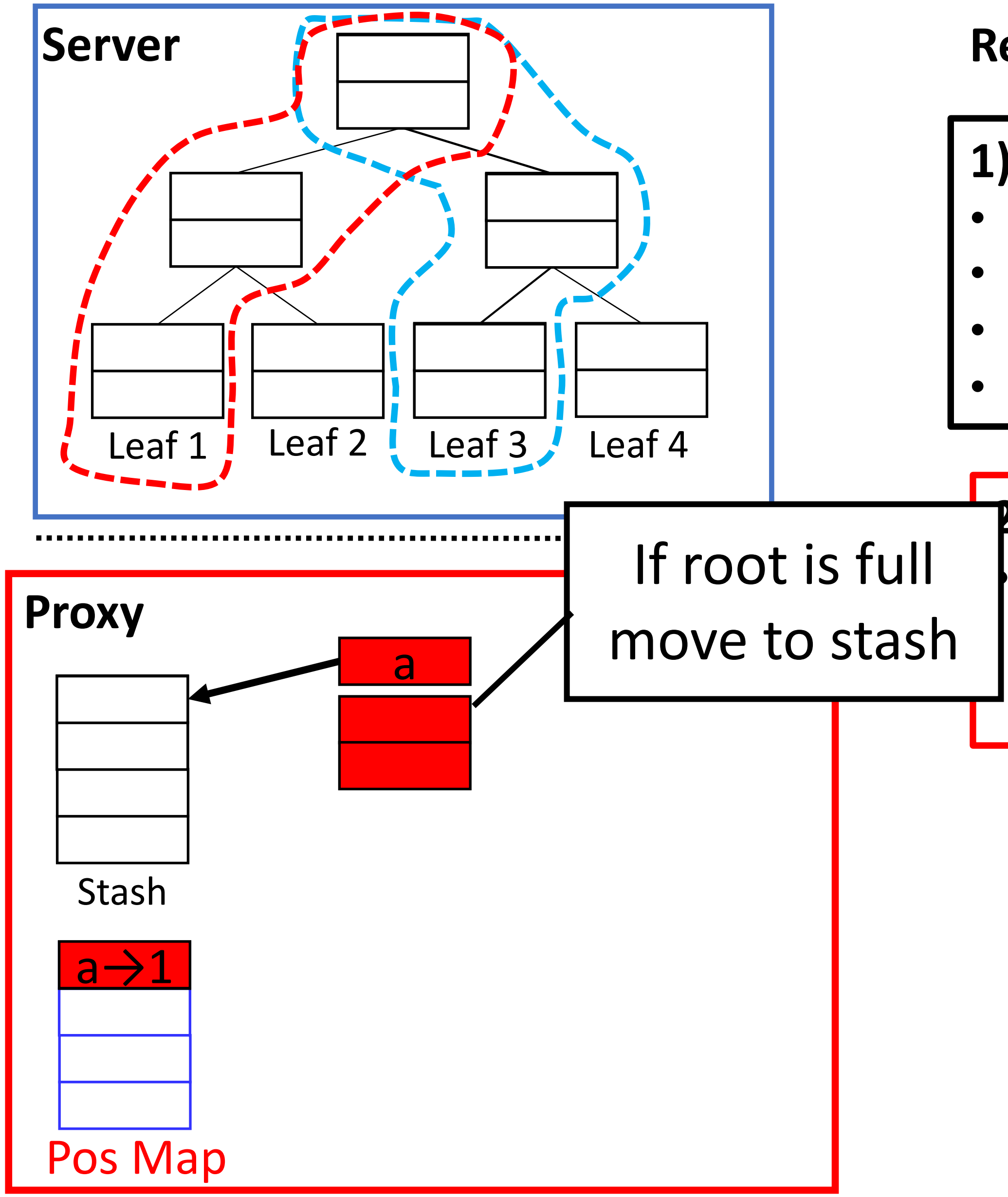

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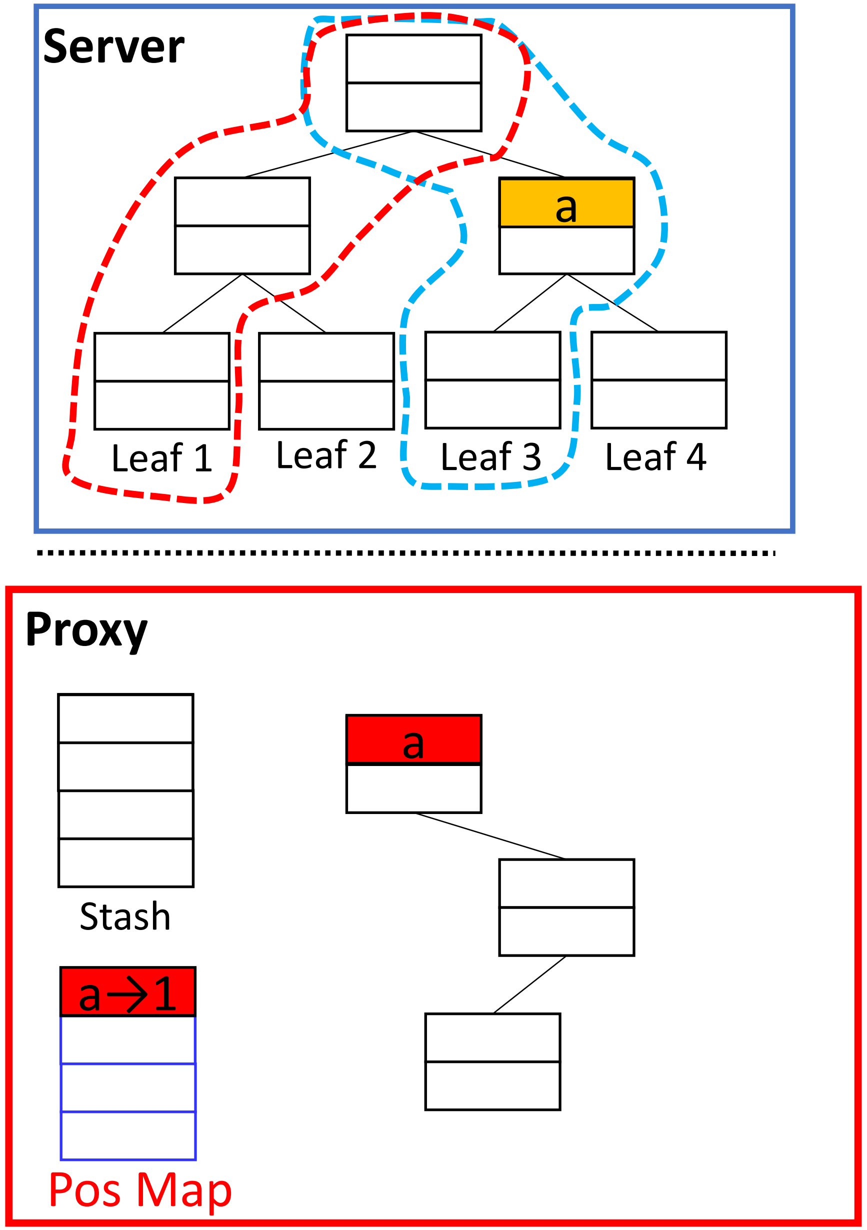

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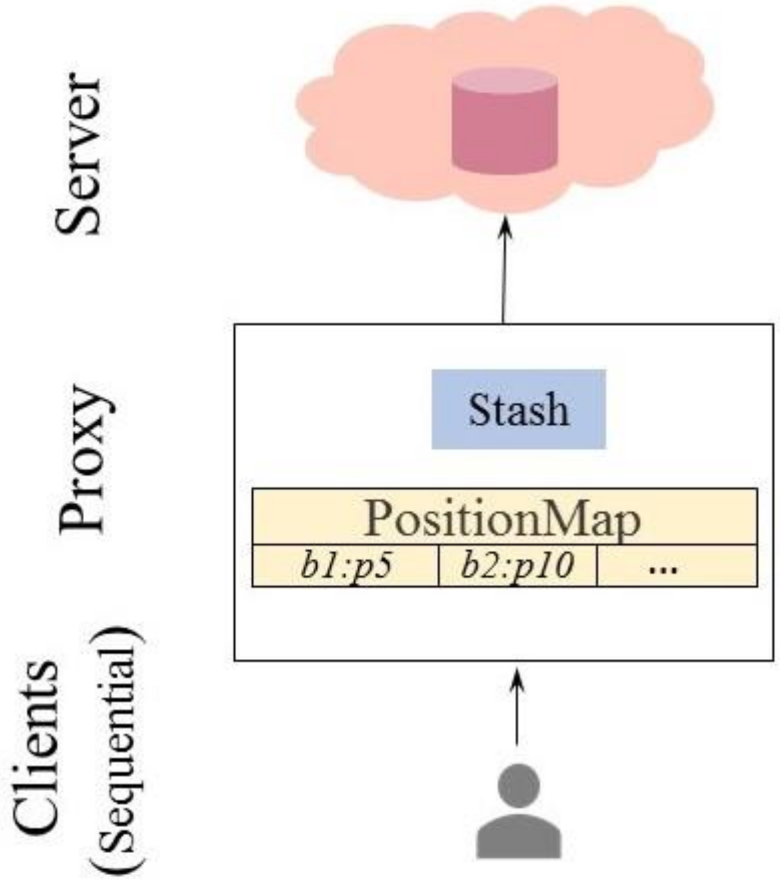
3) Write-back
- Re-encrypt w/ fresh randomness

PathORAM

- Steps to access block *B*:
  1. Fetch path *P* containing block *B* from Server
  2. Update requested block *B* (if write)
  3. Answer Client Request
  4. Assign block *B* to random path
  5. Flush path *P*
  6. Writeback to server



Does PathORAM provide workload independence (informal)?

Say a client requested block *b* stored in path *p*. From an adversary's perspective

- Which data is accessed? → One of the Z**logN* objects accessed
- When was *b* last accessed? → Only knows when *p* was last accessed, not when *b* was last accessed
- Did 2 subsequent requests access *b*? → Only knows two random paths *p* and *p'* being accessed in subsequent requests
- Access pattern (uniform or skewed)? → Observes accesses to random paths
- Is *b* read or written? → Each path is read and then written with fresh encryption

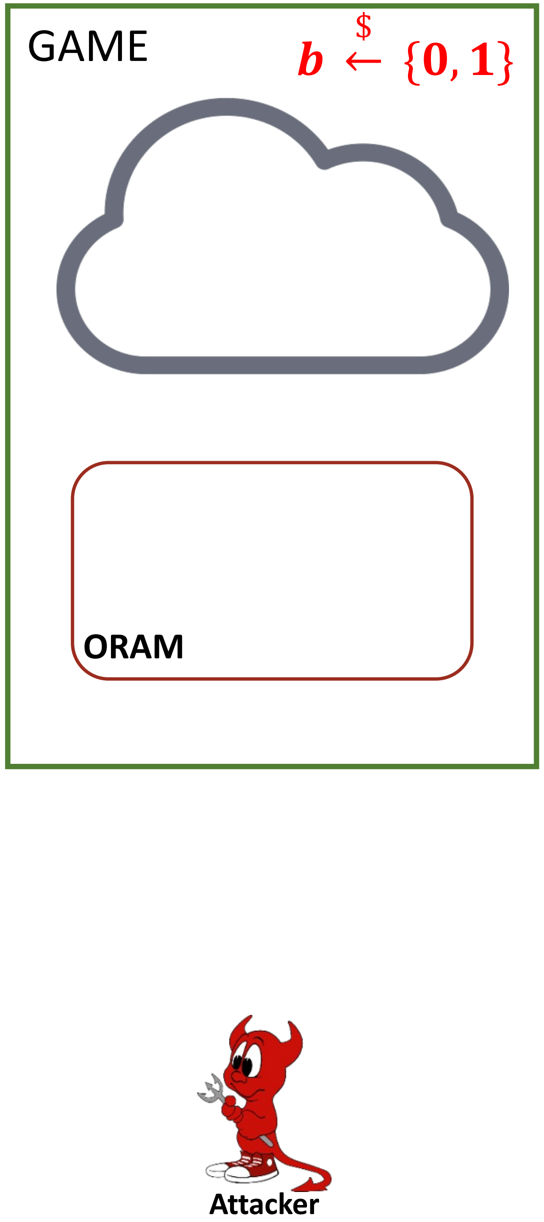
Yes! PathORAM provides workload independence!

ORAM – Security (formal)

- Let $\mathrm{A} = \{(\mathrm{op}_1, \mathrm{bid}_1, \mathrm{val}_1),\ \ldots (\mathrm{opm}, \mathrm{bidm}, \mathrm{valm})\}$ represent a sequence of *m* accesses $op_i \ \in \{read, write\}$, *bid*$_i$ is the block identifier, and *val*$_i$ is either updated value writes or null for reads

- An ORAM scheme is secure if given two such sequences A_0 *and* A_1 and the system executed A_i, the adversary cannot guess which sequence was executed with probability >> 1/2

ORAM - Security



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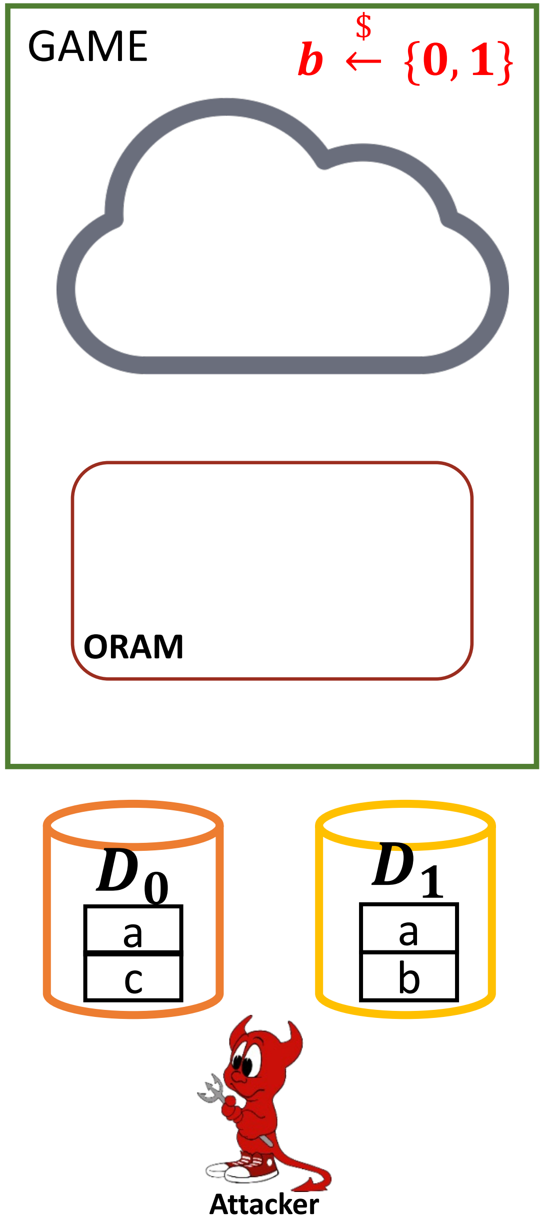

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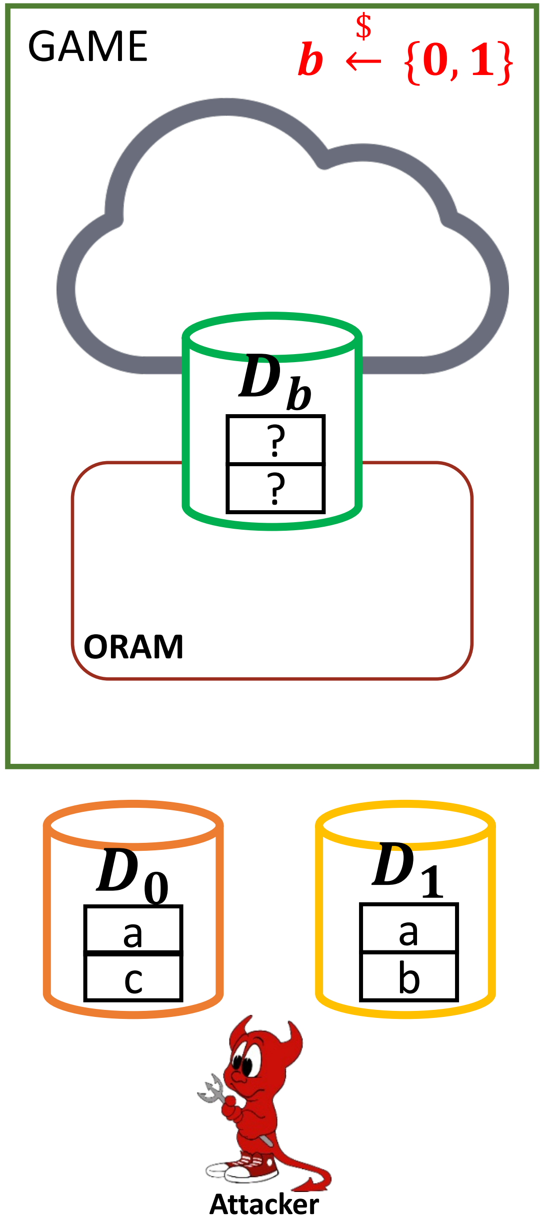

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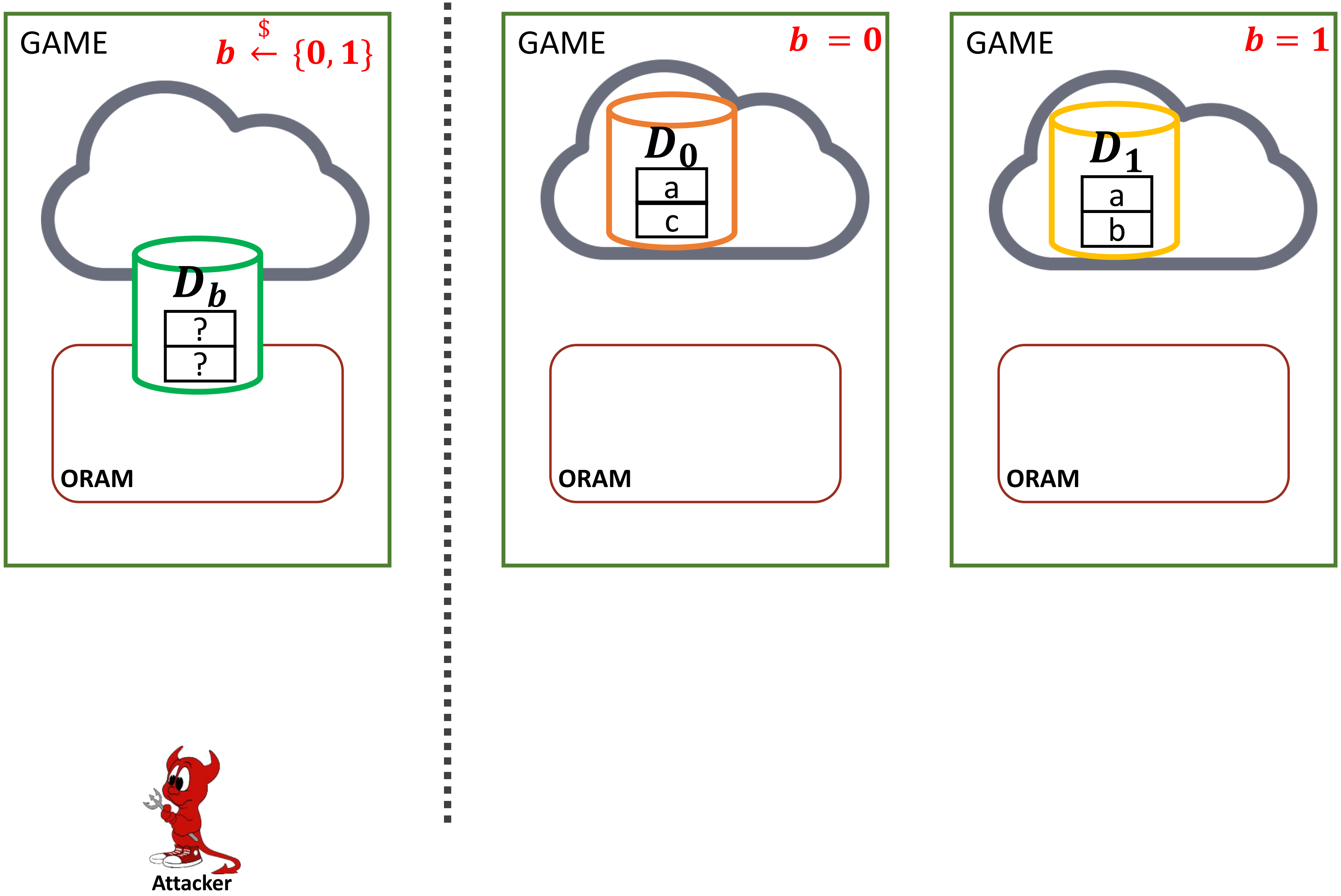

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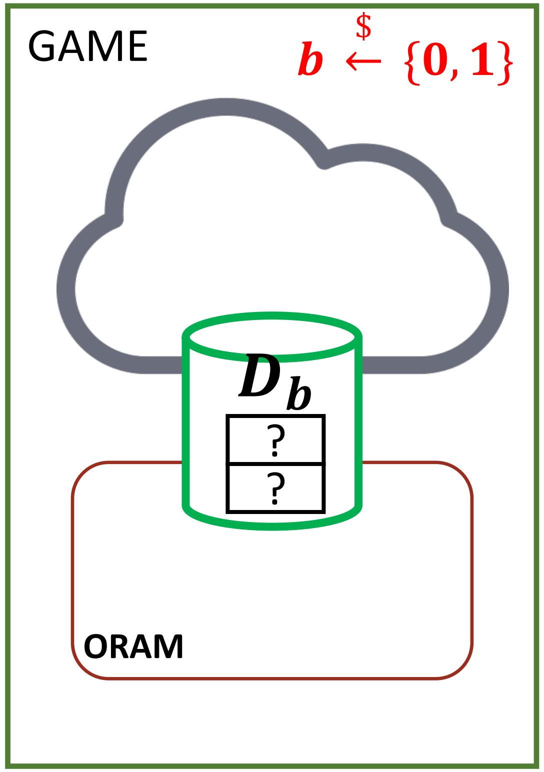
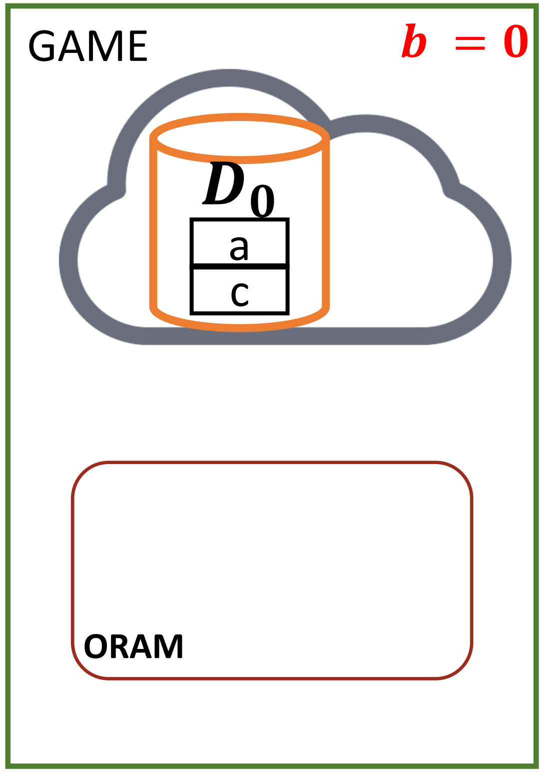
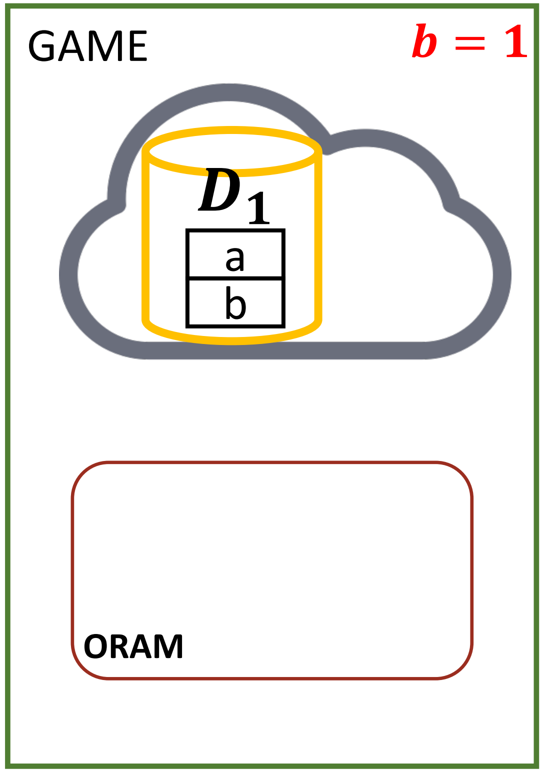


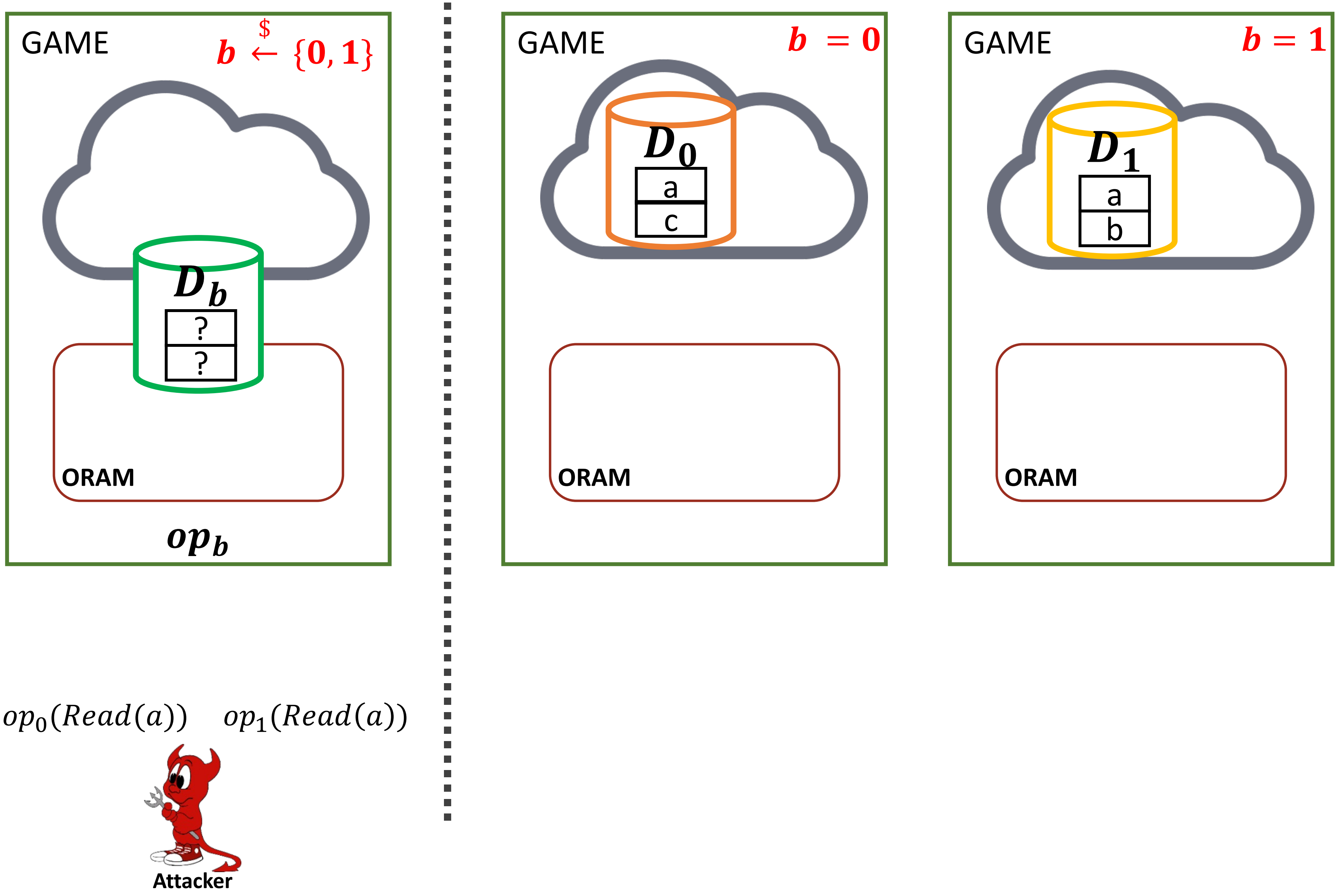




$op_0(Read(a))$ $op_1(Read(a))$


Attacker

ORAM - Security



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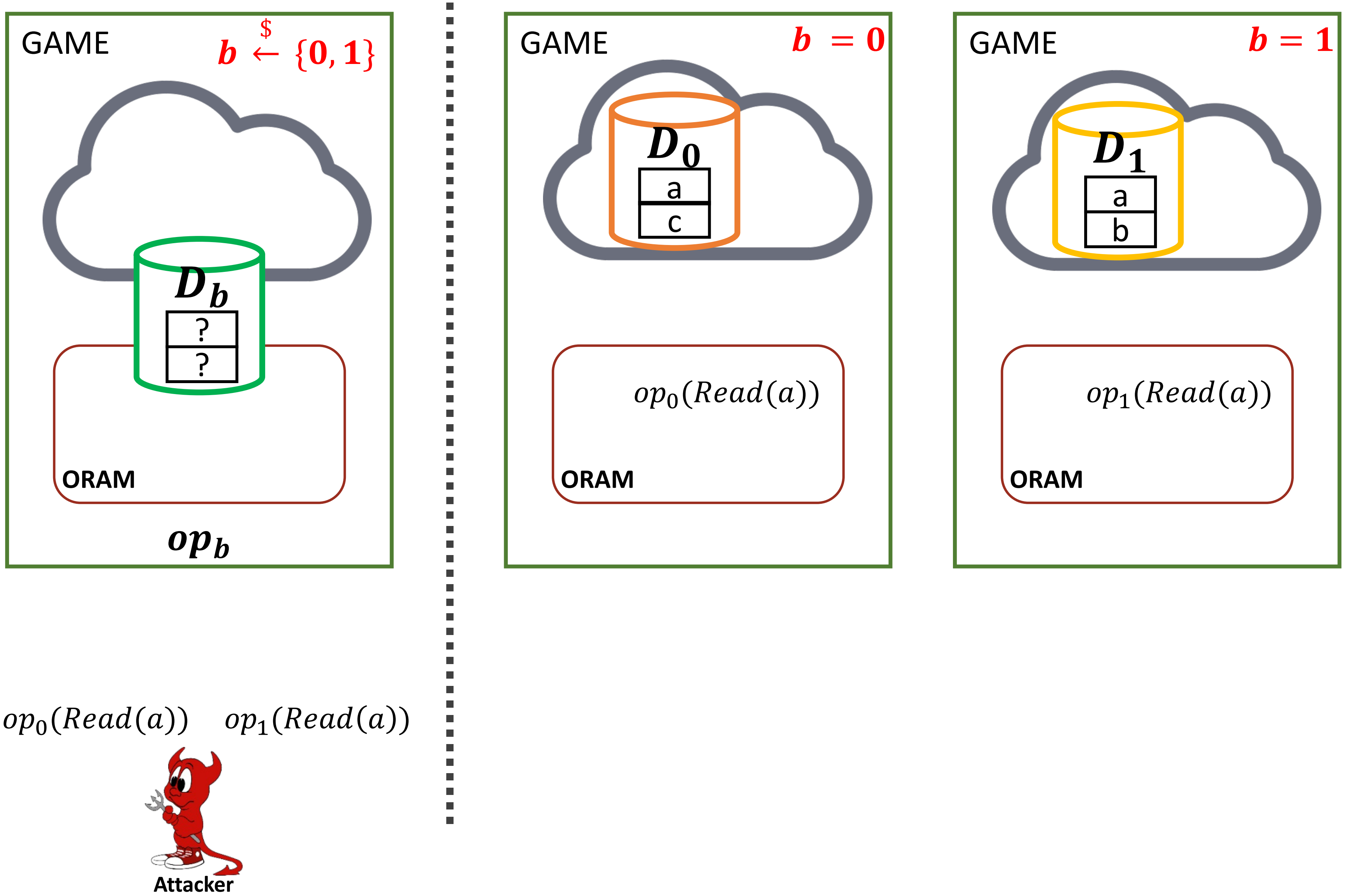

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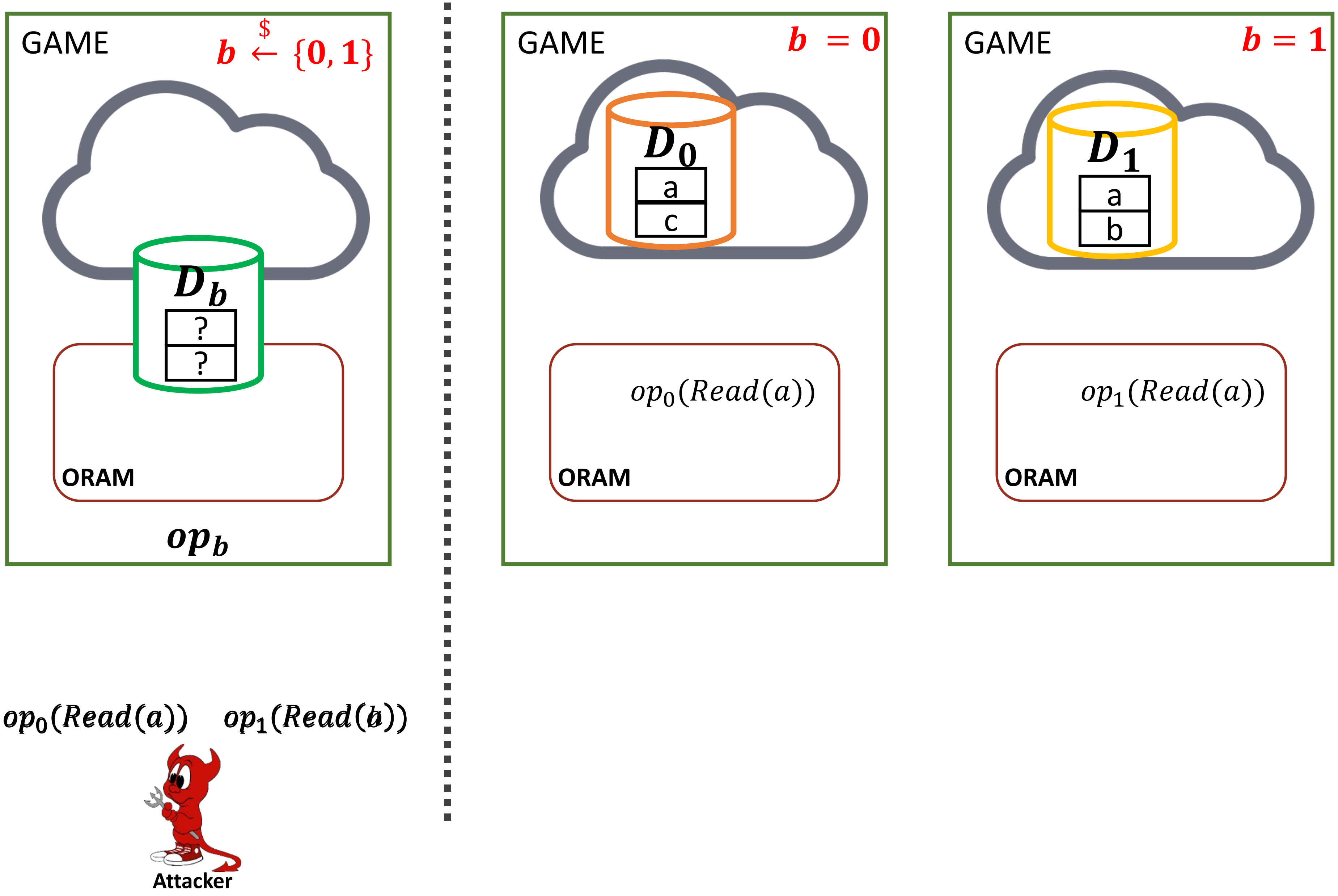

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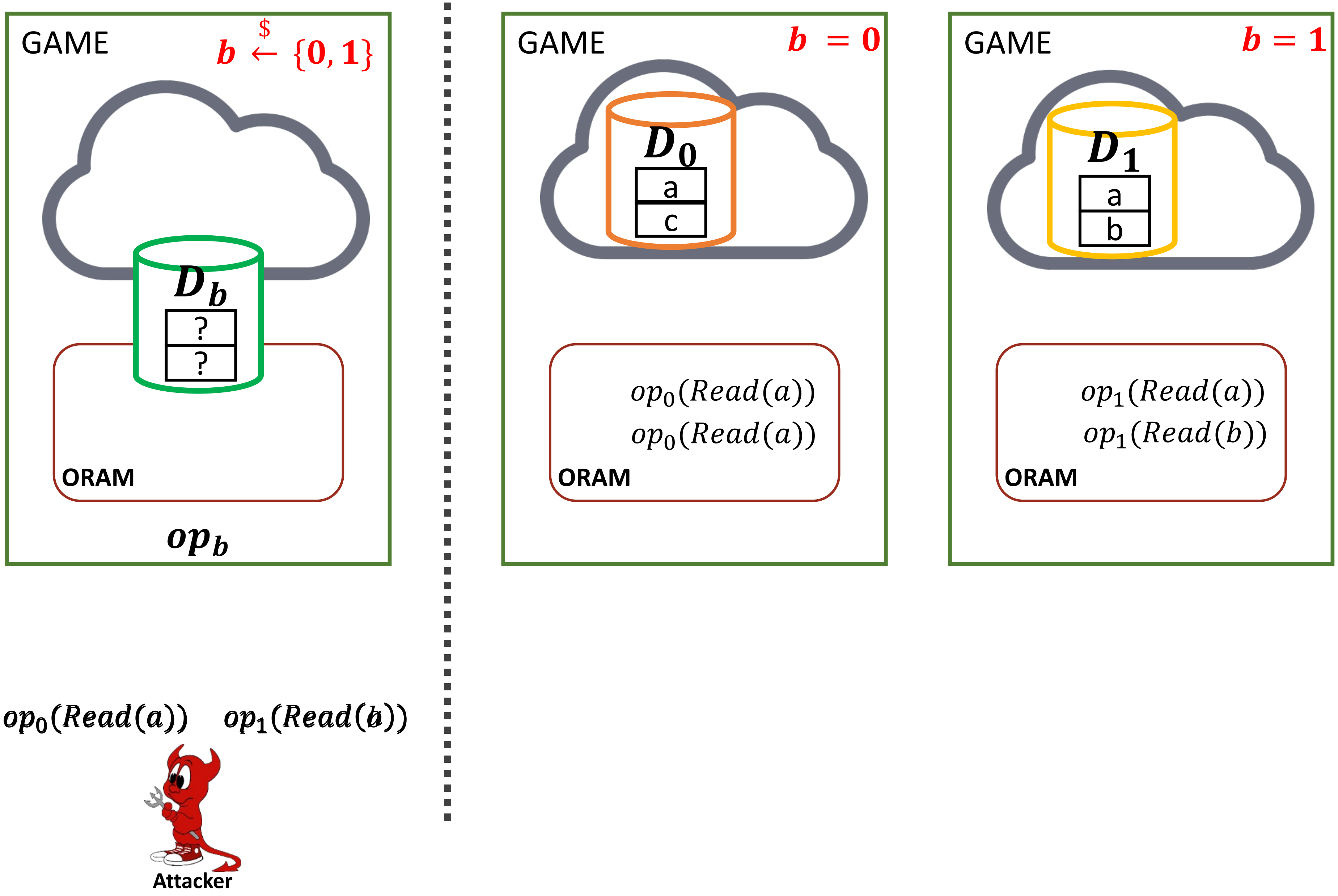

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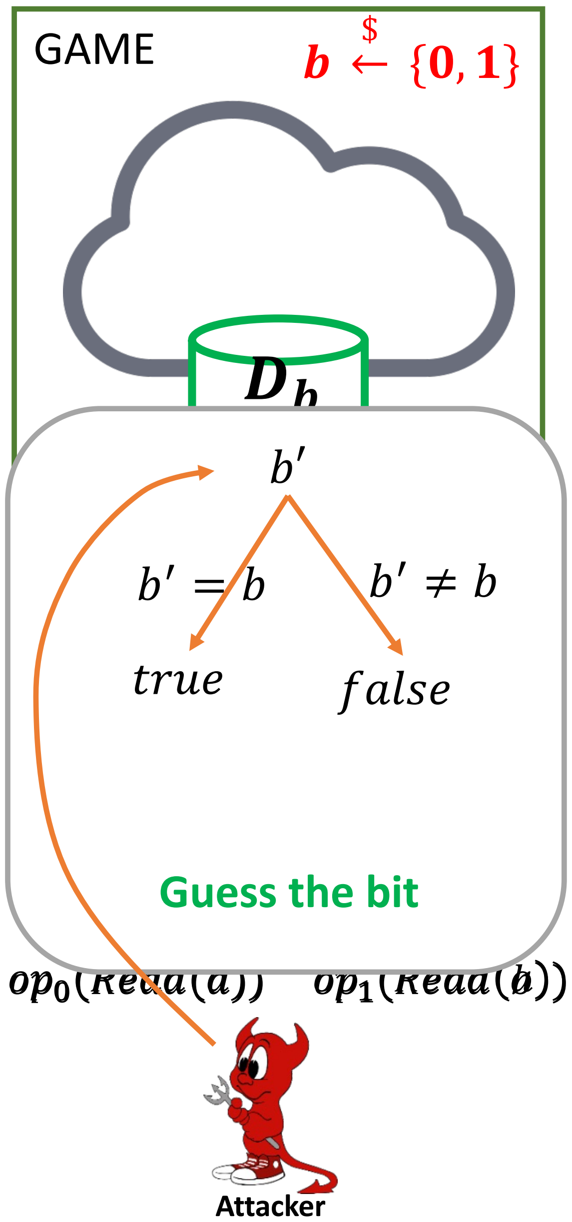
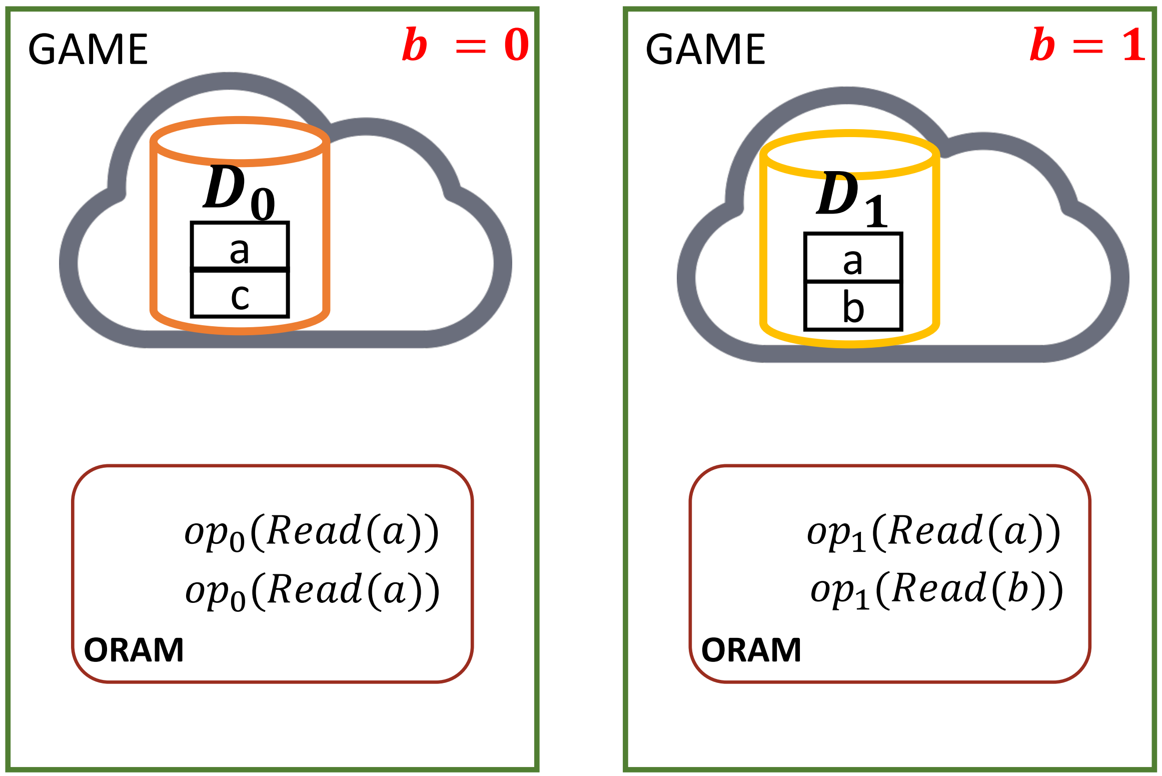




A secure ORAM has

$$\Pr(A \diamond G \rightarrow true) = \frac{1}{2} + negl$$

i.e., adversary has negligible advantage is guessing bit b

Two observations on PathORAM

- Bandwidth overhead: ***2*Z*logN*** → Depends on *Z*
- The *online* rounds of communication b/w client and server: **2 rounds**
  - Even for read reqs, need an online write step
- Can these two limitations be improved?

RingORAM [Ren et al. Usenix Security'15]

Goals:

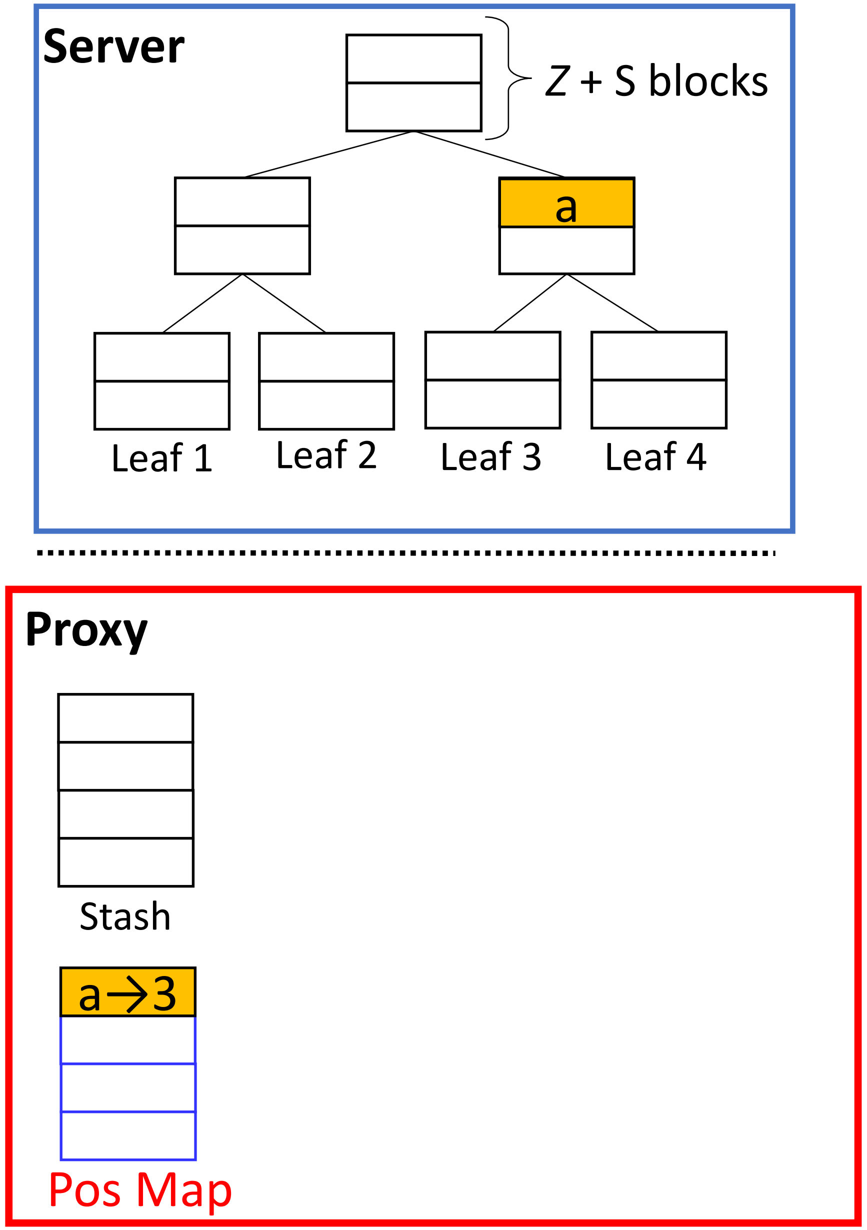
1. Eliminate the ORAM bandwidth's dependence on Z

How?
Read exactly one block per bucket along the path

2. Reduce online communication rounds to 1

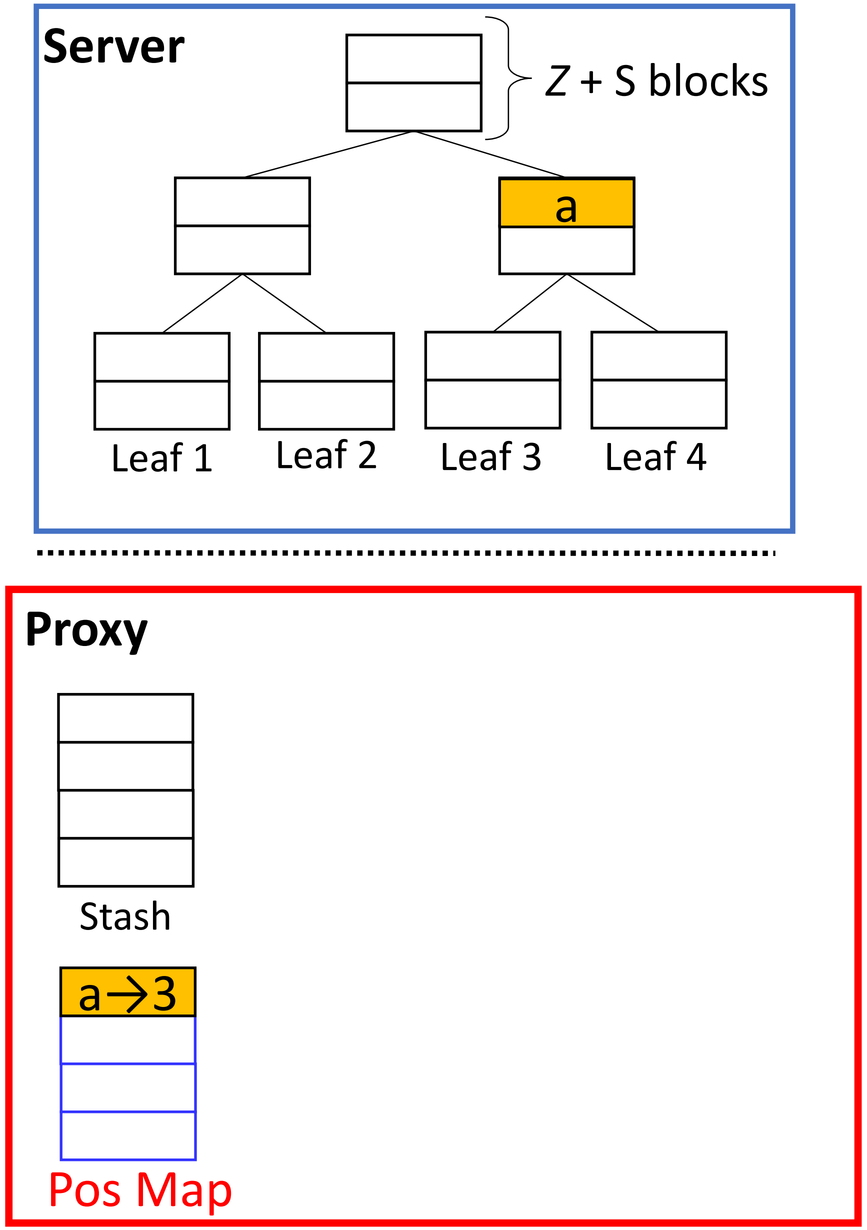
How?
Only read path for each client request, buffer writes, and write path back in an offline step

Ring ORAM



Each bucket stores at most *Z* real blocks and at least *S* dummy blocks

Ring ORAM



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Every access to a random path reads only one block per bucket

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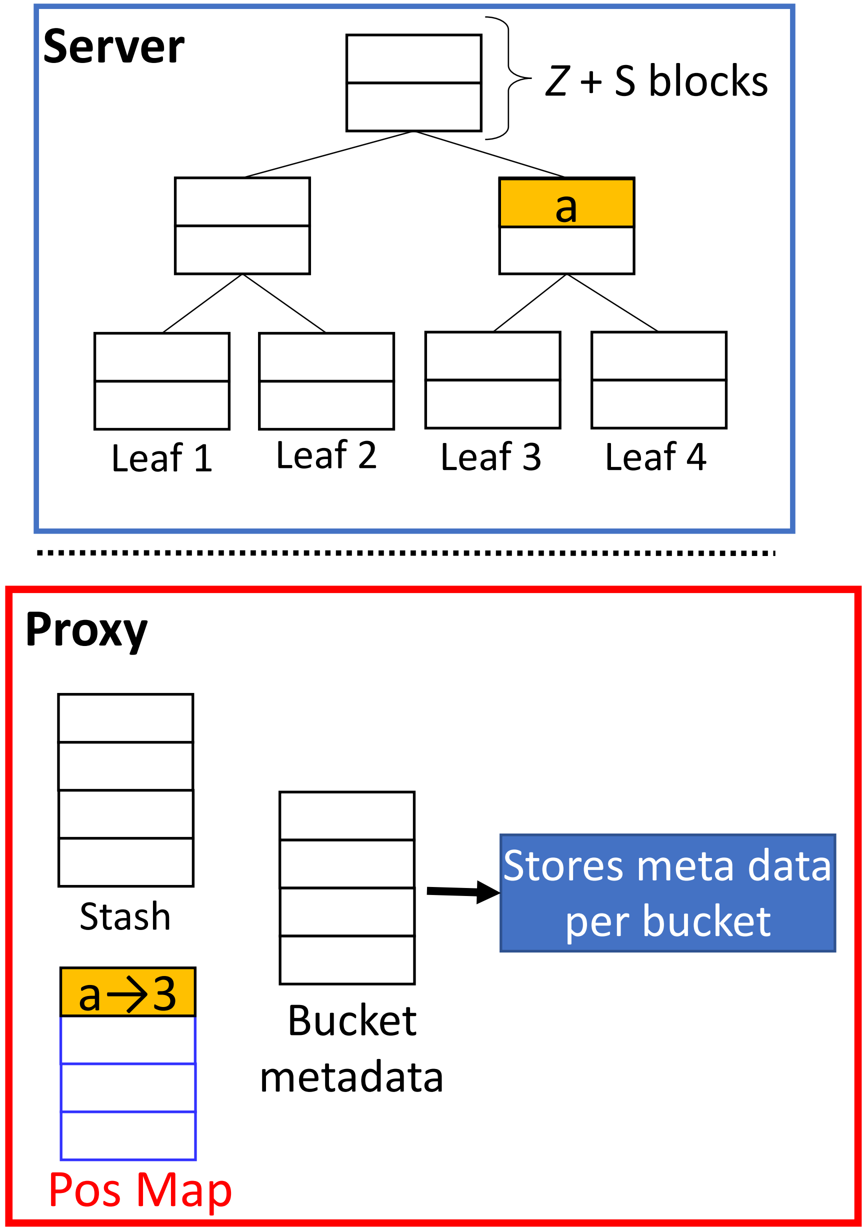

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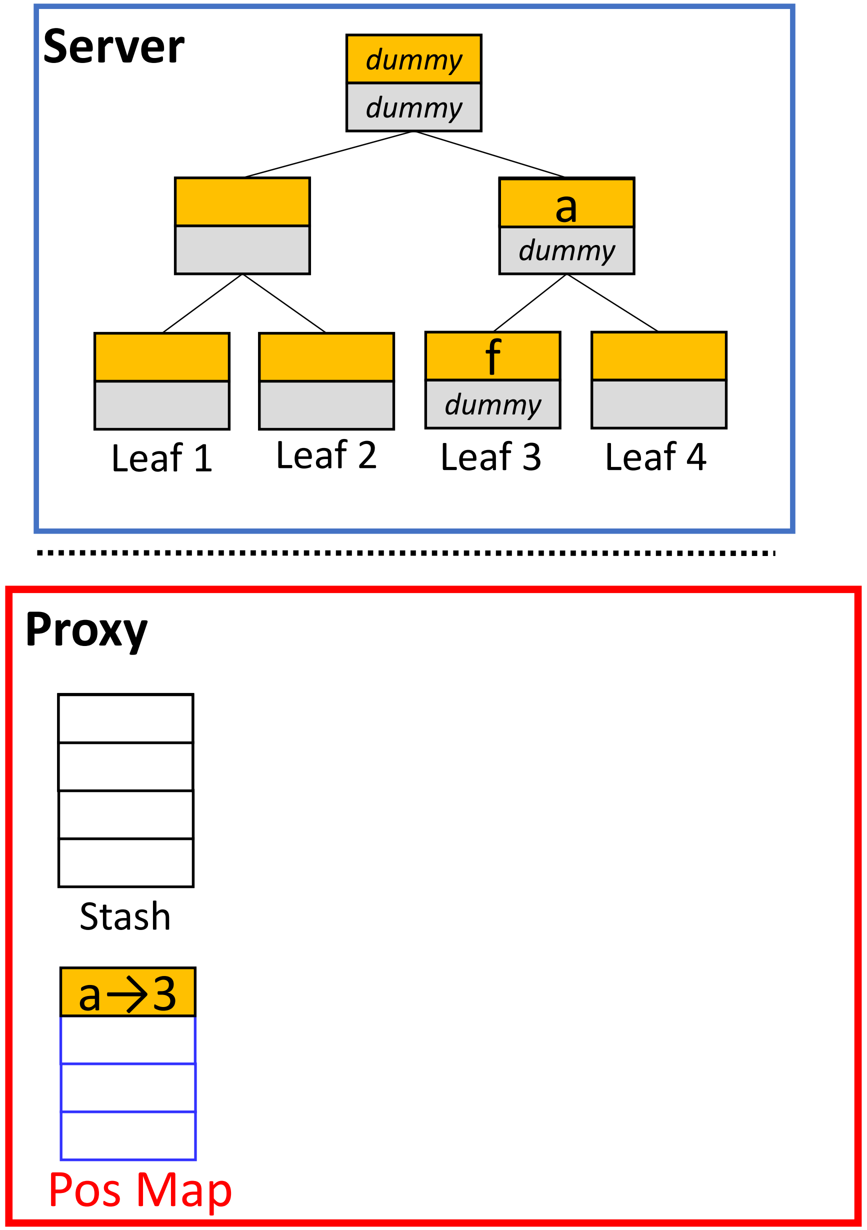
Bucket metadata stores info on

1. *count:* how many times is this bucket accessed
2. *valid:* which of the *Z+S* blocks are not yet accessed
3. *addr:* ids of real blocks in a bucket

Note: Bucket metadata actually stored at server

Ring ORAM



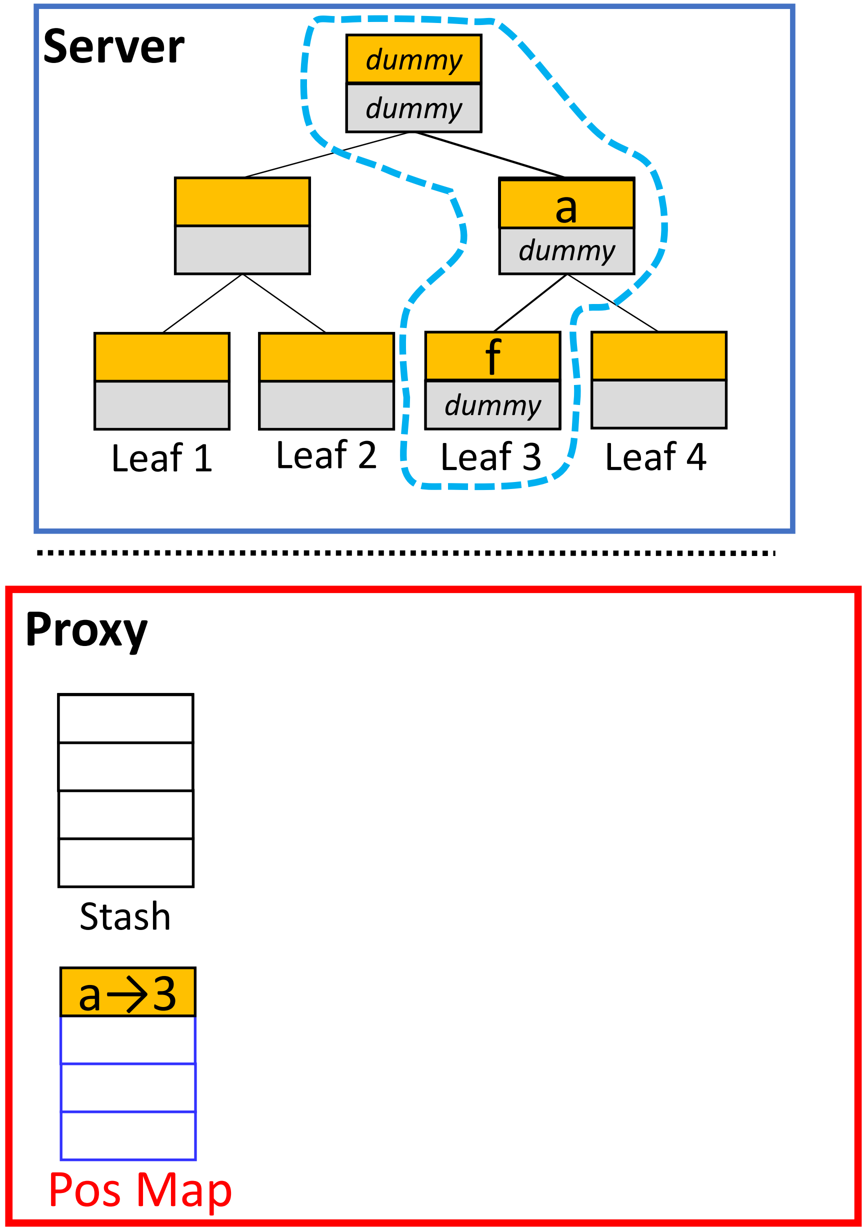
1) Read path

For each bucket in path

- From *valid* and *addr*, either read real block or a valid dummy block
- Invalidate the read block in *valid*
- Increment *count*

Assign block to a new random path in position map

Ring ORAM



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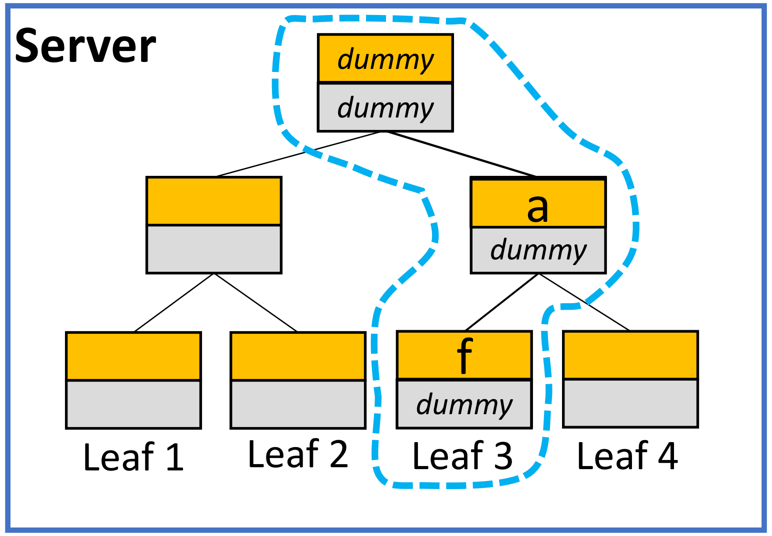

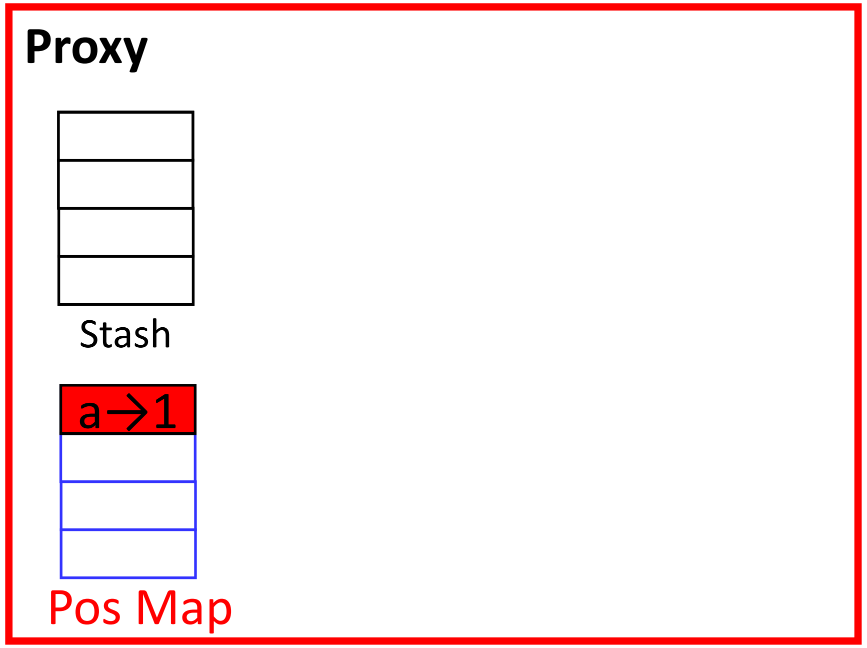

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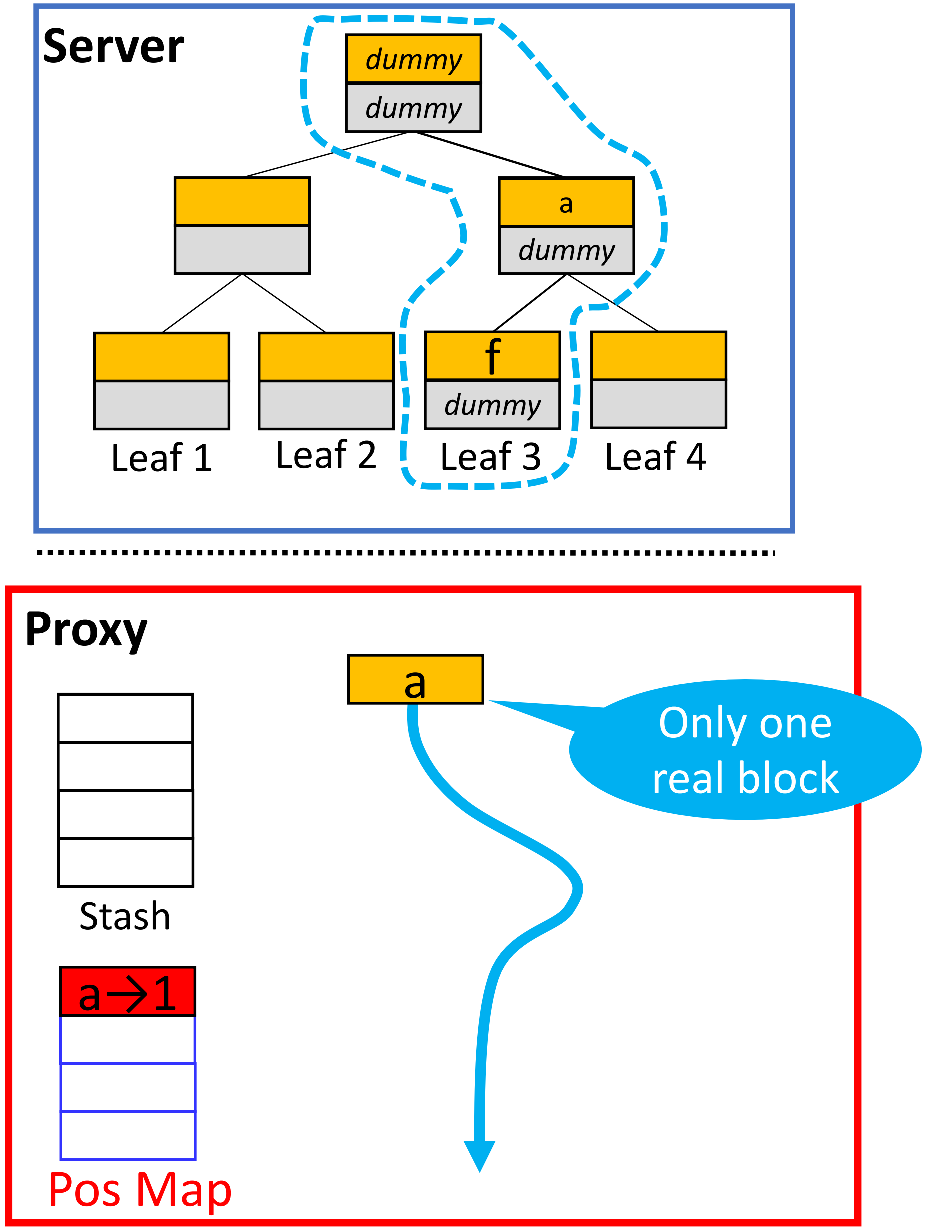

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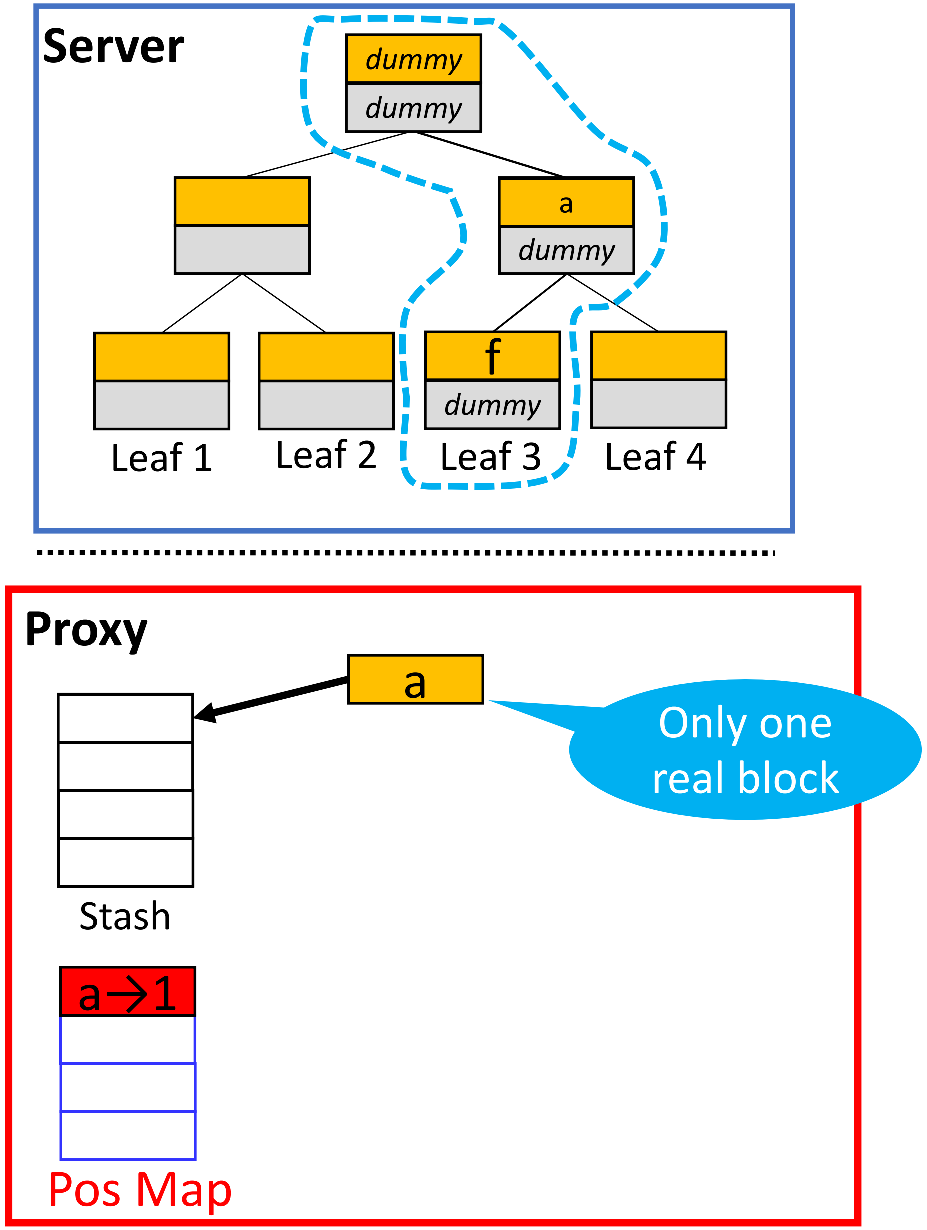

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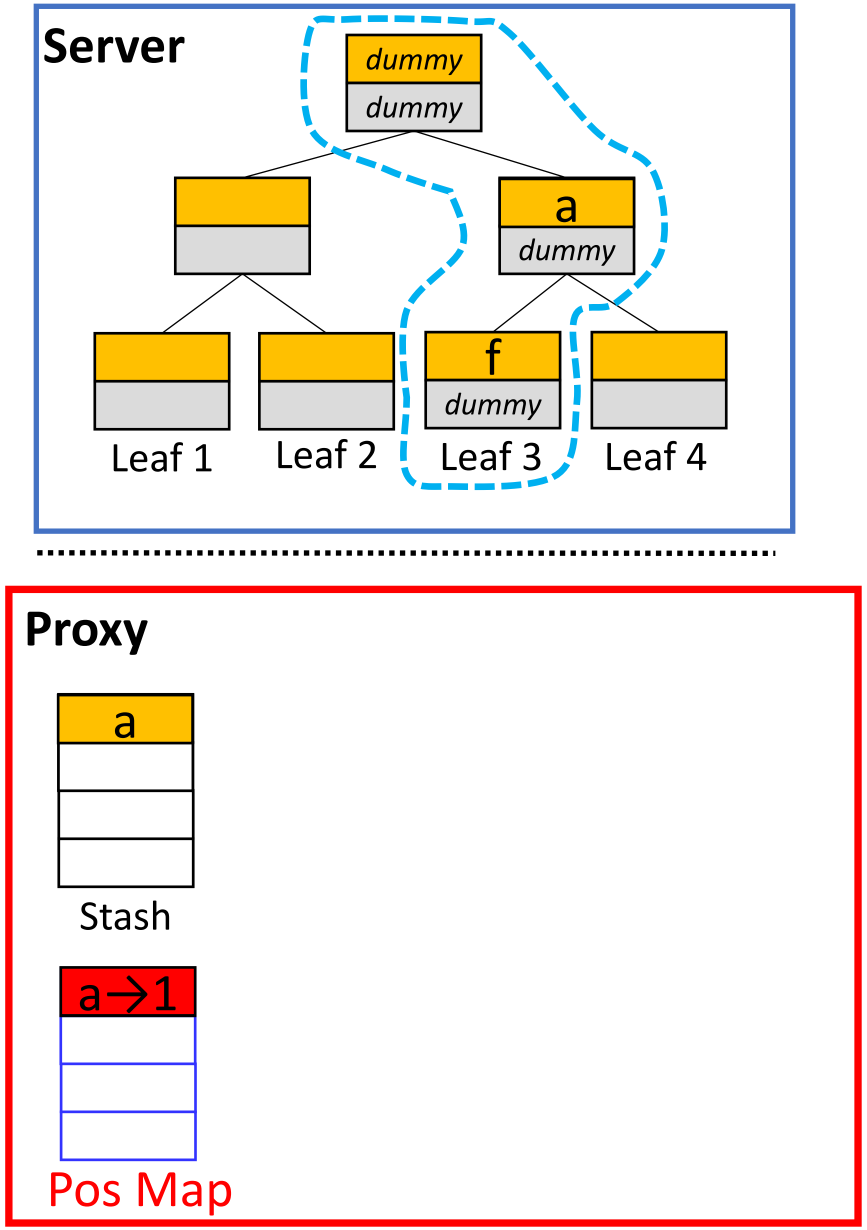

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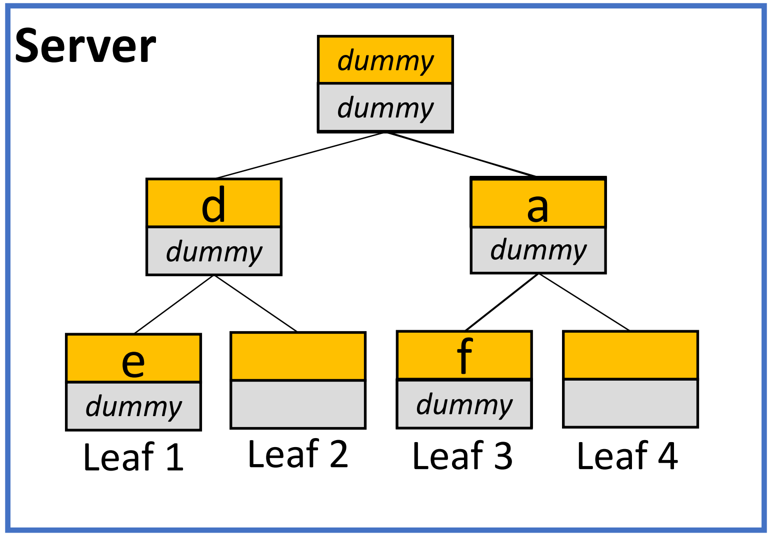

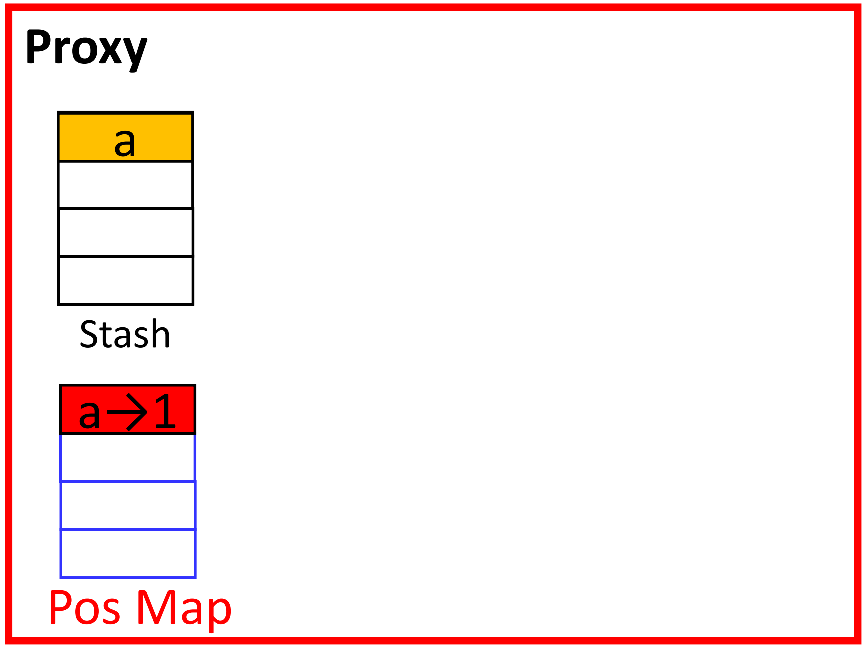

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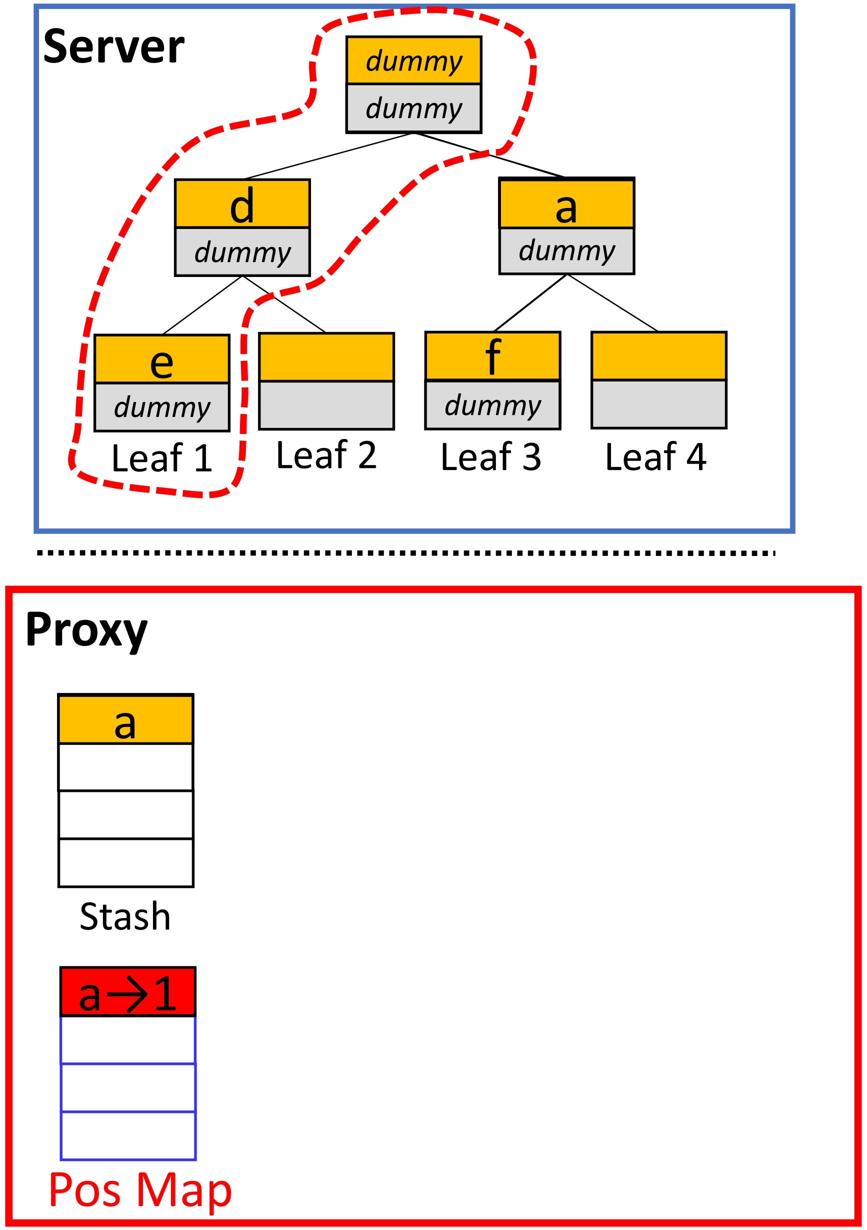

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- After *A* read paths, in a deterministic order pick the next path to evict
- For each bucket, read all remaining valid real blocks (if < Z, read dummy) to *stash*
- Write each bucket from *stash* and reset all metadata

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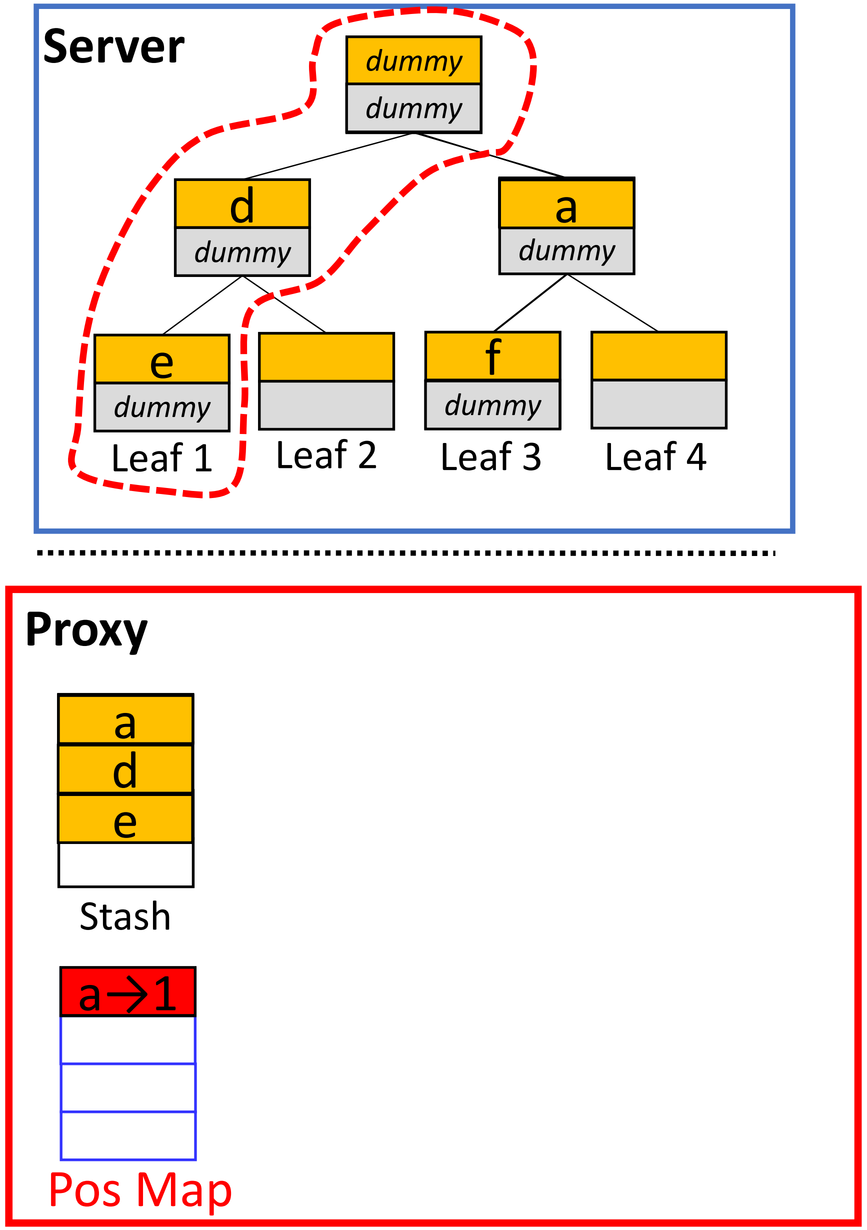

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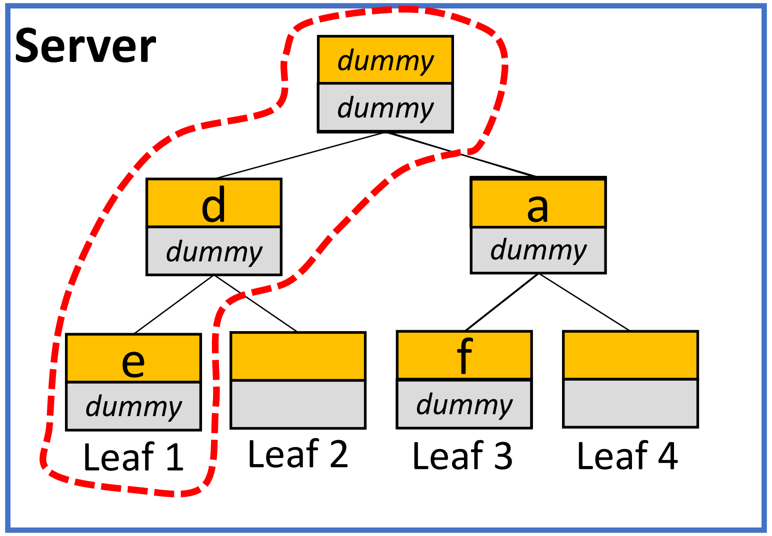
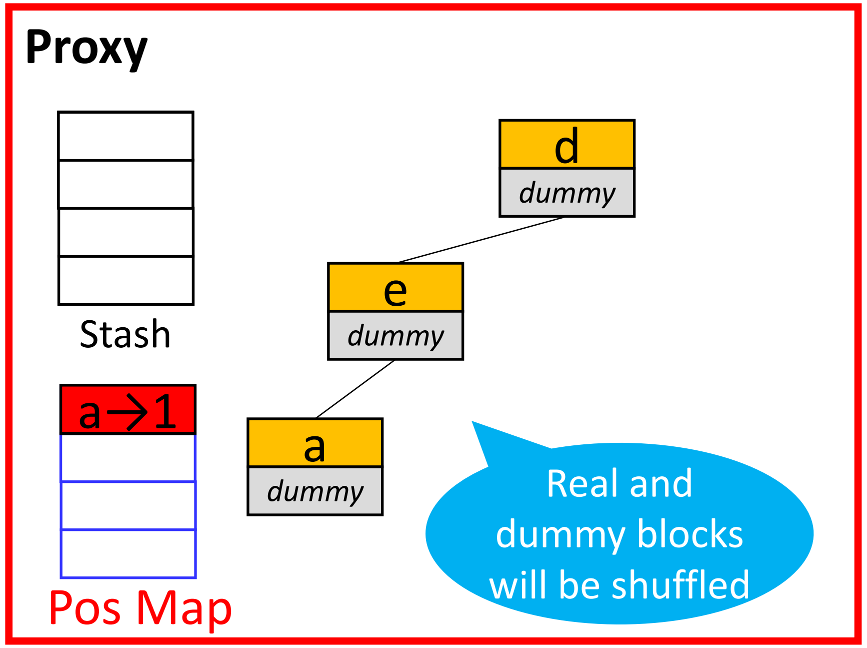




1) Read path

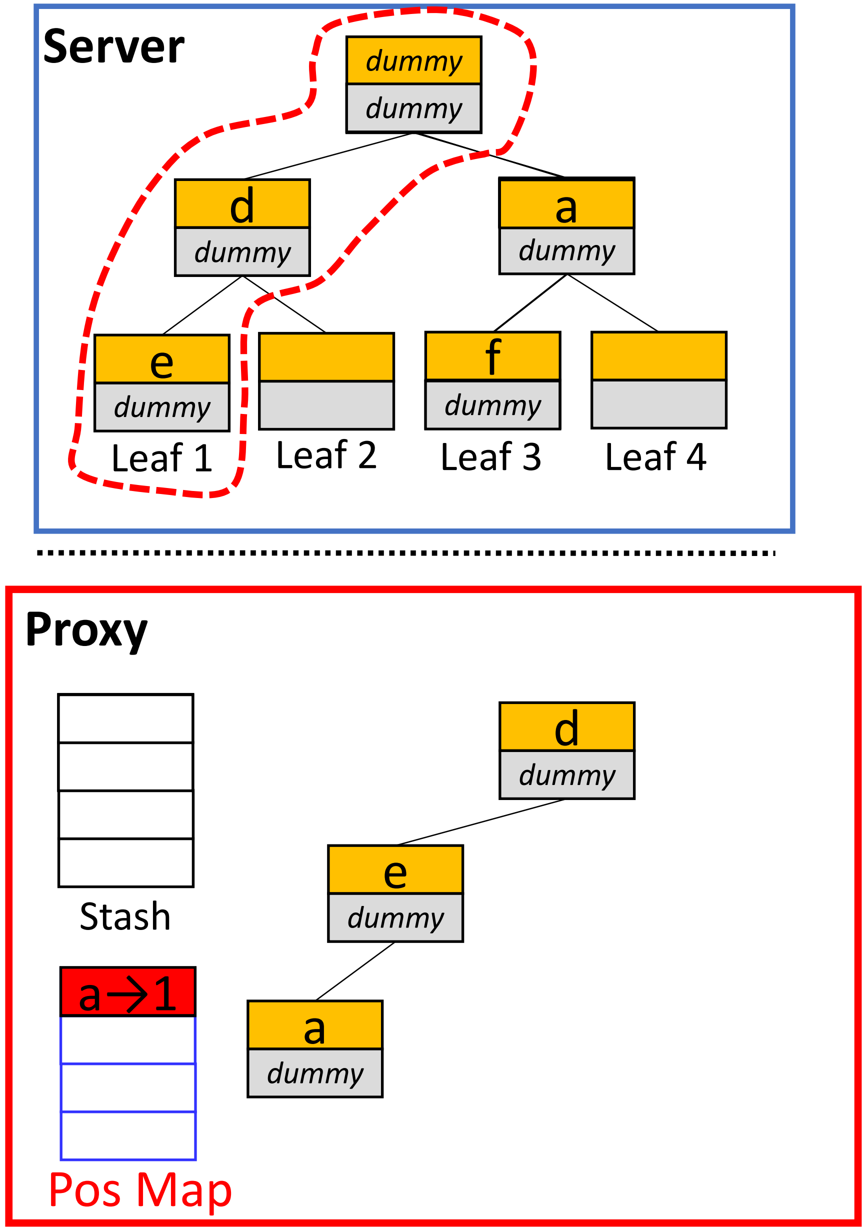
For each bucket in path

- From *valid* and *addr*, either read real block or a valid dummy block
- Invalidate the read block in *valid*
- Increment *count*
- Assign block to a new random path in position map

2) Evict

- After *A* read paths, in a deterministic order pick the next path to evict
- For each bucket, read all remaining valid real blocks (if < Z, read dummy) to *stash*
- Write each bucket from *stash* and reset all metadata

Ring ORAM



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- Write each bucket from *stash* and reset all metadata

3) Early reshuffle

- If a bucket is accessed *s* times, read all valid real blocks, permute, and write back
- Reset metadata for the bucket

Security arguments for Ring ORAM

1. Read path leaks no information
   - For each access, a random path is read
   - For each bucket, a random offset is read

2. Evict path leaks no information
   - Every *A* accesses, a deterministically chosen path is read
   - Each bucket reads *Z* blocks
   - Path written back

3. Early shuffle leaks no information
   - After *S* accesses to a bucket, *Z* blocks are read
   - Bucket is written back

Limitations of Path and Ring ORAM

- Both are sequential
  - Treebeard by Setayesh et al. USENIX Security’25 [Oct 1st]
  - Obladi by Crooks et al. OSDI’18 [Oct 1st]
- They both require a proxy to be practical
  - ConcurORAM by Chakraborti et al. NDSS’19 (not reading)
  - Snoopy by Dauterman et al. SOSP’21 [Oct 29th]
- They do not support transactions or complex queries
  - Obladi by Crooks et al. OSDI’18 [Oct 1st]
  - SEAL by Demertzis et al. USENIX Security’20 [Oct 22nd]
  - OasisDB by Ahmed et al. VLDB’25 [Oct 22nd]
- Neither is fault tolerant
  - QuORAM by Maiyya et al. Usenix Security’22 (not reading)
  - Treebeard by Setayesh et al. USENIX Security’25 [Oct 1st]
- Neither is scalable
  - ObliviStore by Stefanova et al. S&P’13 (not reading)
  - Treebeard by Setayesh et al. USENIX Security’25 [Oct 1st]
  - Snoopy by Dauterman et al. SOSP’21 [Oct 29th]

ORAM Conclusion

- Access patterns leak information
- Need workload independence
- Databases using ORAM ensure workload independence
- PathORAM: a highly efficient tree-based ORAM
  - Simple abstraction & easy to implement
- RingORAM: optimizes PathORAM by reducing online bandwidth cost

Trusted Execution Environments (TEEs)

Trusted Execution Environments – Intel SGX

- A secure enclave is an **isolated unit of data and code execution** that cannot be accessed even by privileged code (e.g., the operating system or hypervisor)
- *Memory encryption:* only enclave process can access a program’s memory
- *Remote attestation:* proof that the code running in the enclave is the one intended, and that it is running on a genuine TEE platform
- *Sealing:* encrypt and authentical the enclave’s data to allow stopping and restarting an enclave process w/o losing state
- Developers must partition code as sensitive and non-sensitive. Sensitive code run in the enclave, non-sensitive in host space
- Learn more here

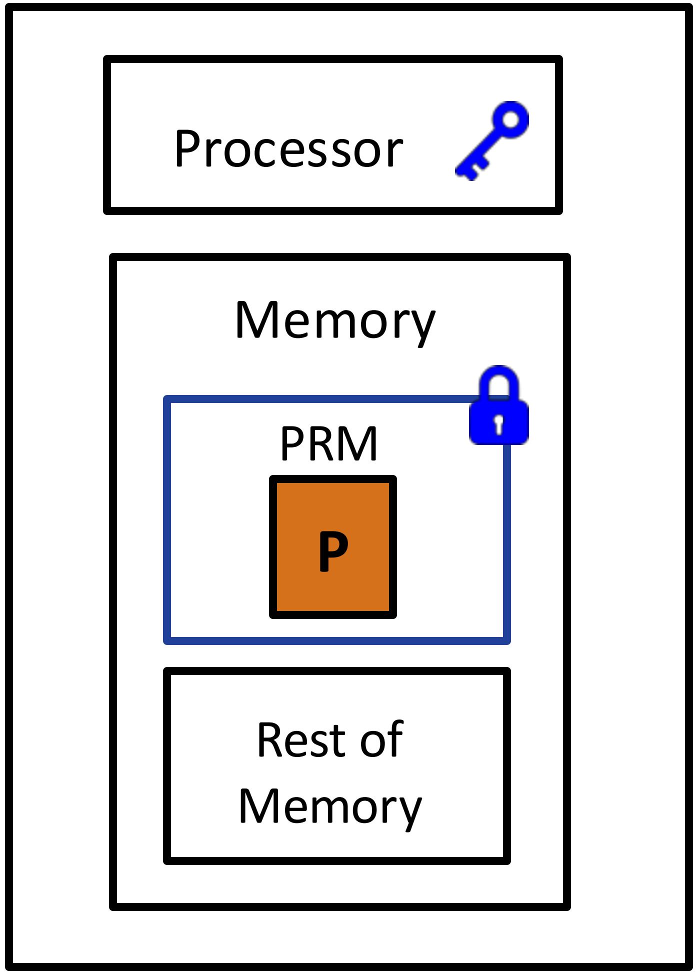
Trusted Execution Environments (TEEs)

- Processor fused with secret keys at manufacture time

- Enables the processor to set aside Processor Reserved Memory (**PRM**) at boot time

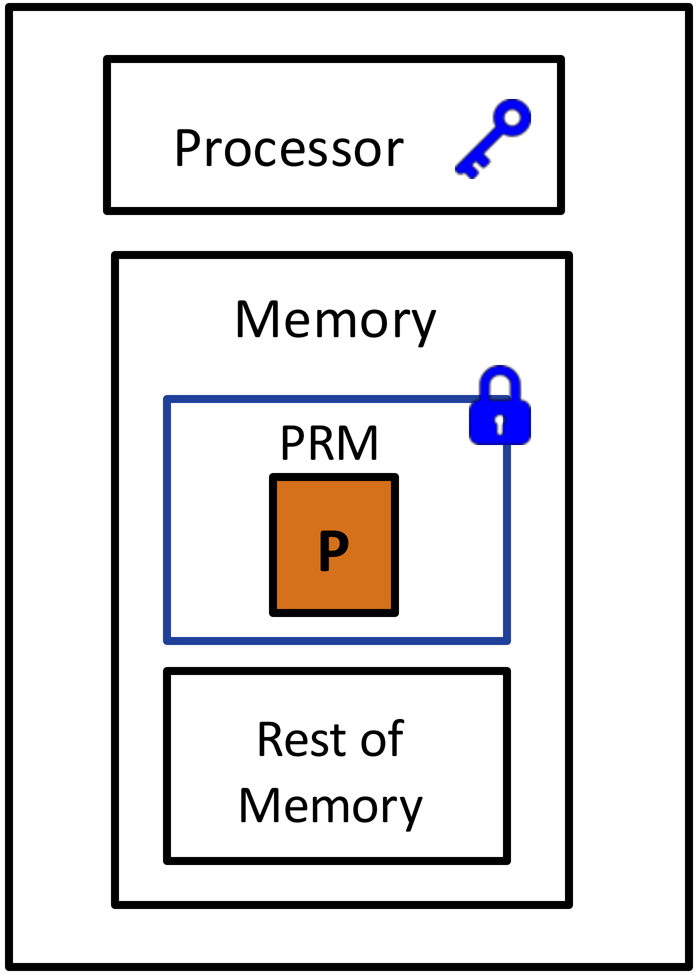
- Able to instantiate secure virtual containers called **enclaves**

- Enclaves can load programs with confidentiality, integrity and freshness guarantees



Trusted Execution Environments (TEEs)

- All data within PRM remain encrypted at all times



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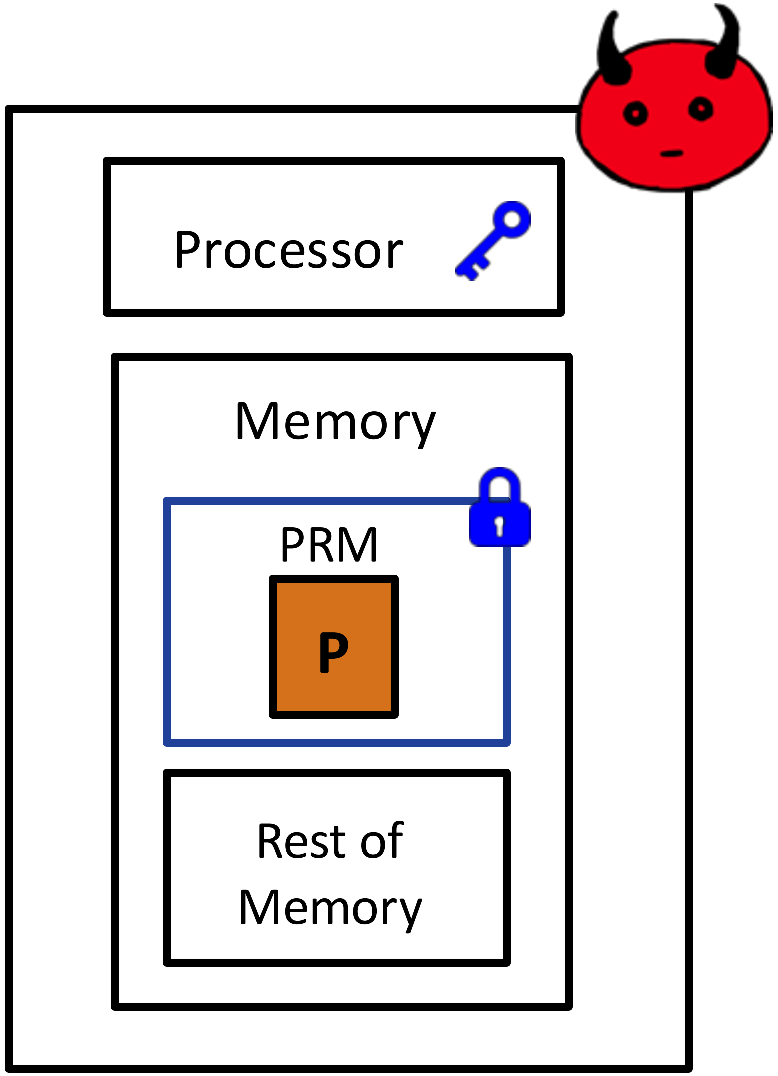
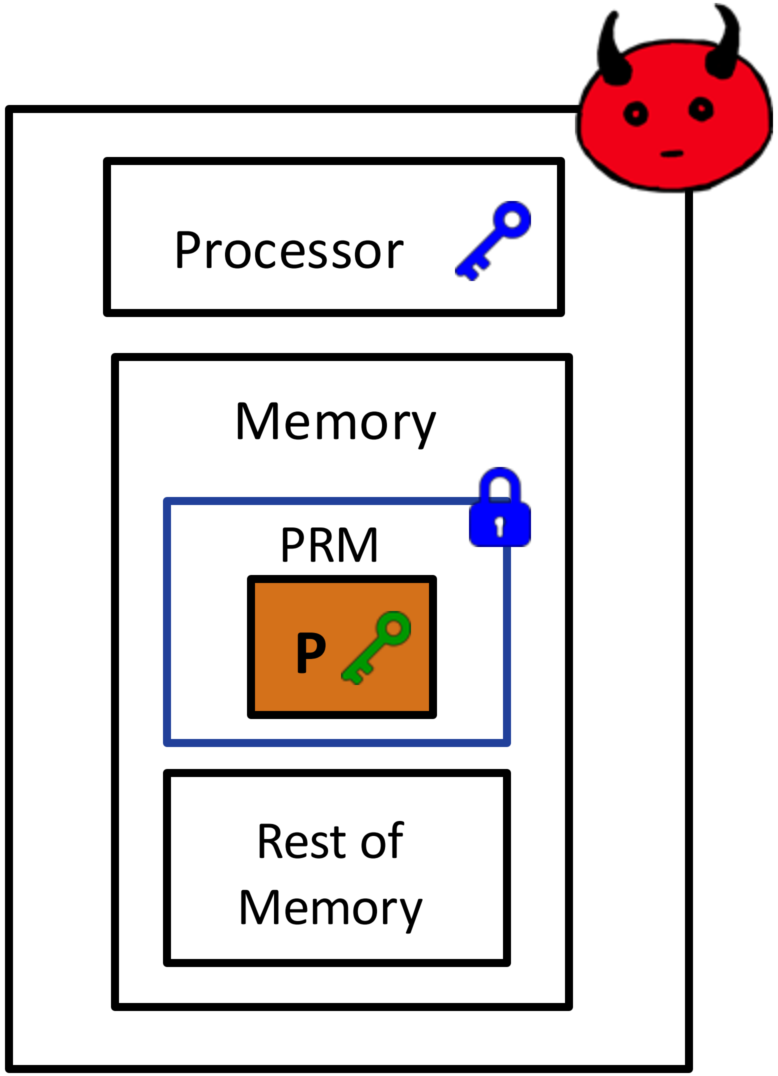


Trusted Execution Environments (TEEs)

- All data within PRM remain encrypted at all times
- P can have its own key pair enabling users to send private data to P, that only P can decrypt.



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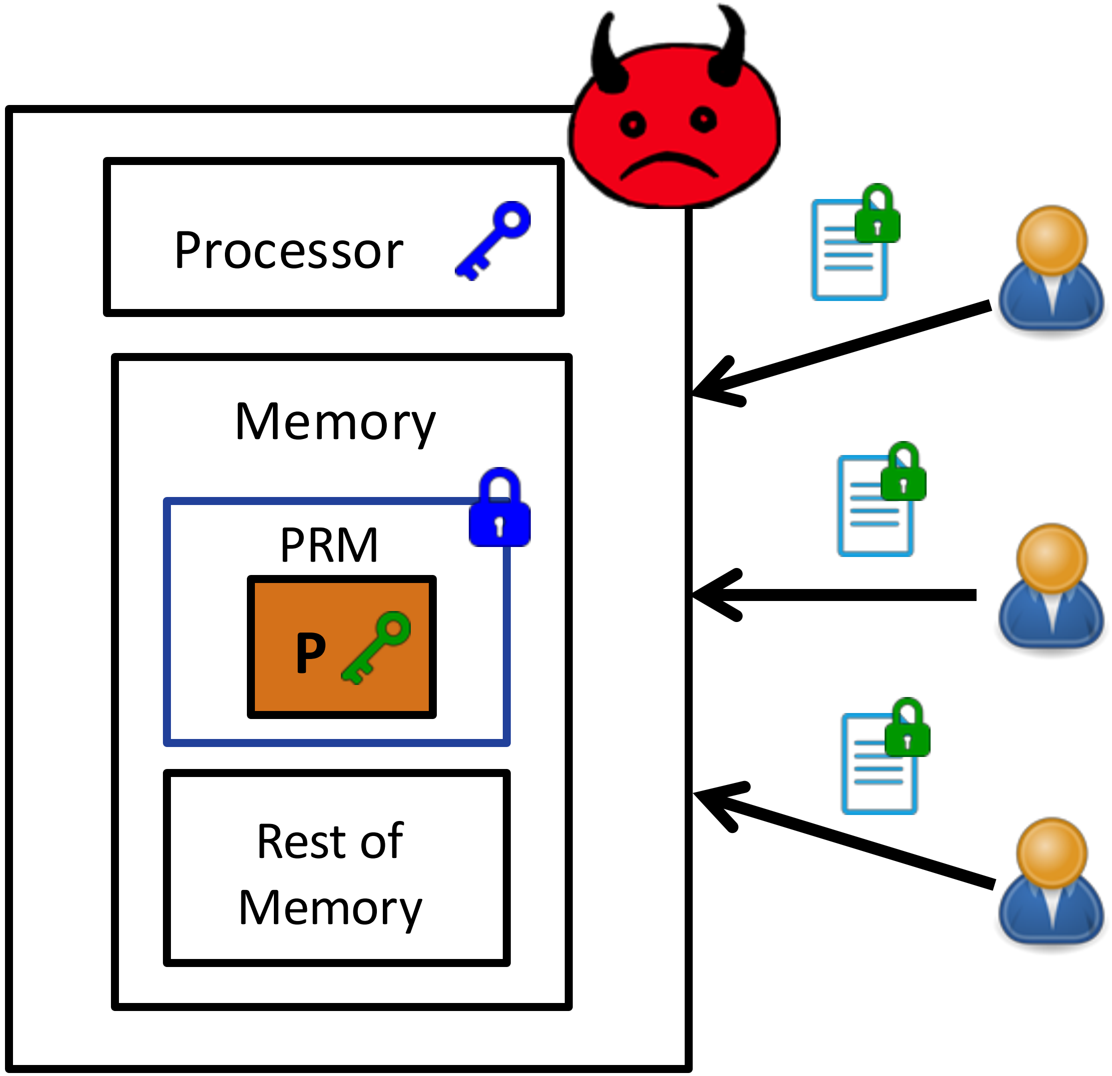
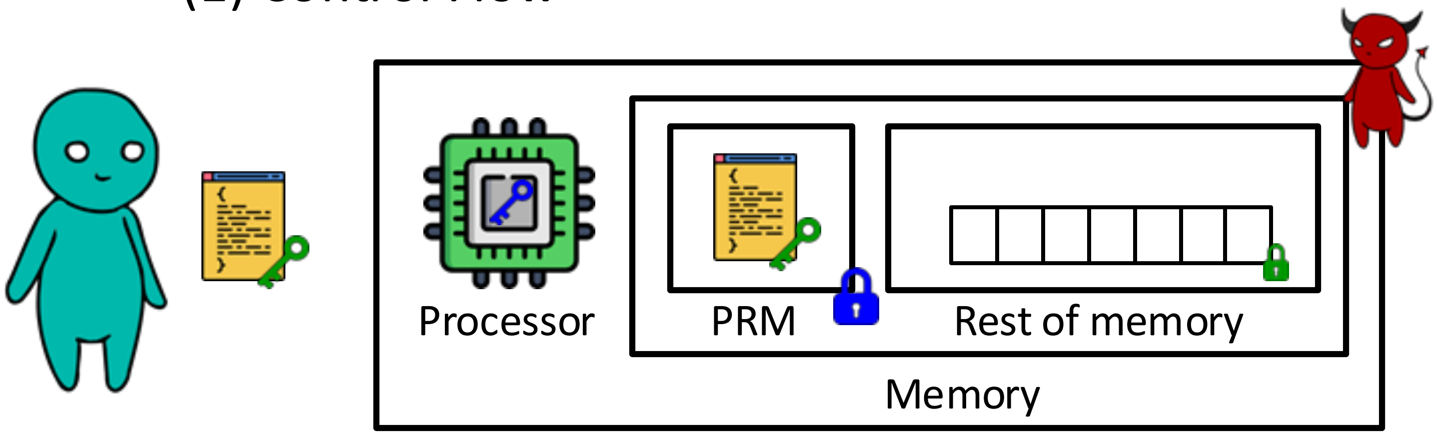


SGX is vulnerable to side channel attacks

```
if (secret==1):
        Branch A
else:
        Branch B
```

Software
Side-channels

(1) Control Flow



SGX is vulnerable to side channel attacks

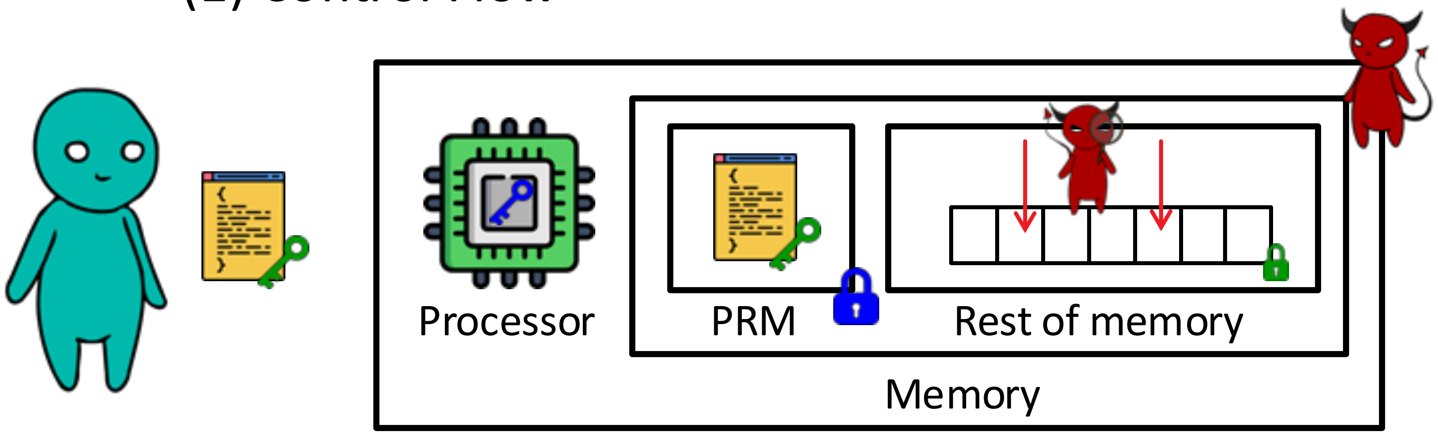
```
if (secret==1):
        Branch A
else:
        Branch B
```

Software
Side-channels

Attacks exploit input dependent access behavior on CPU caches, registers, and page faults to uncover plaintext data

Learn more about attacks: link

(1) Control Flow

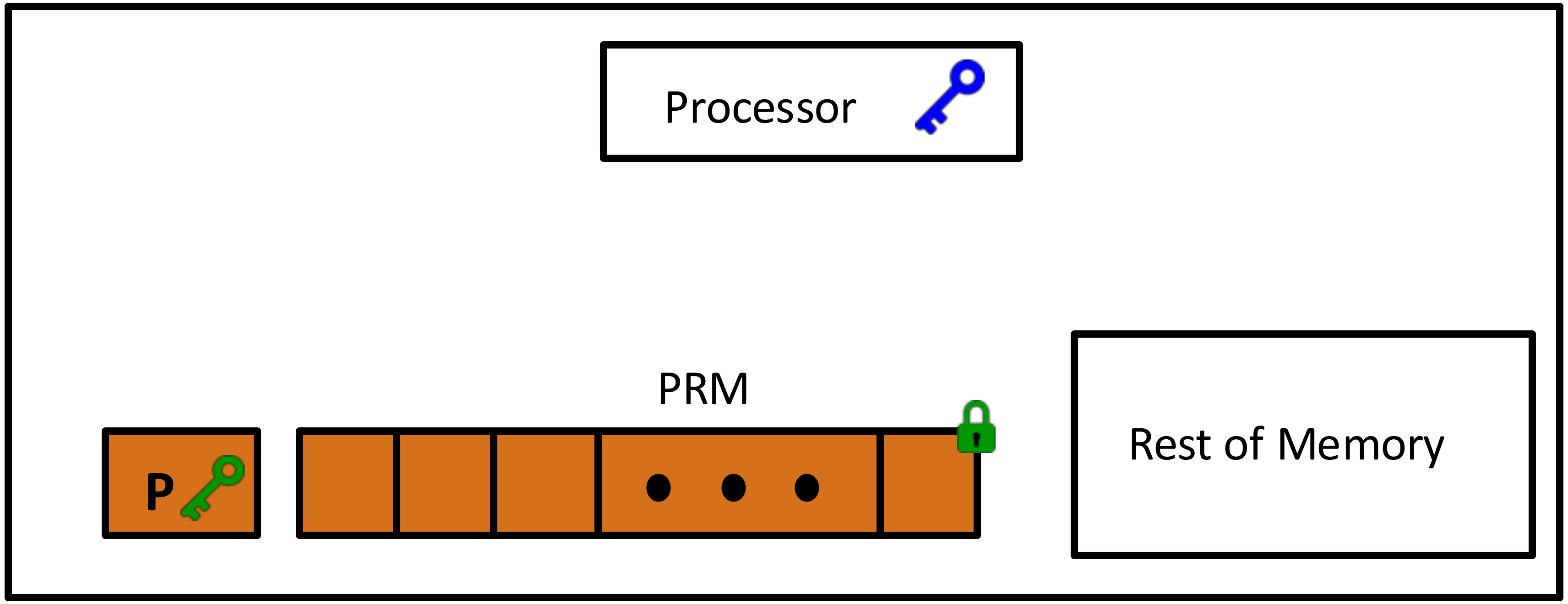


(2) Memory Access Patterns

```
X = A[secret]
```

We need ***obliviousness***

Levels of Obliviousness



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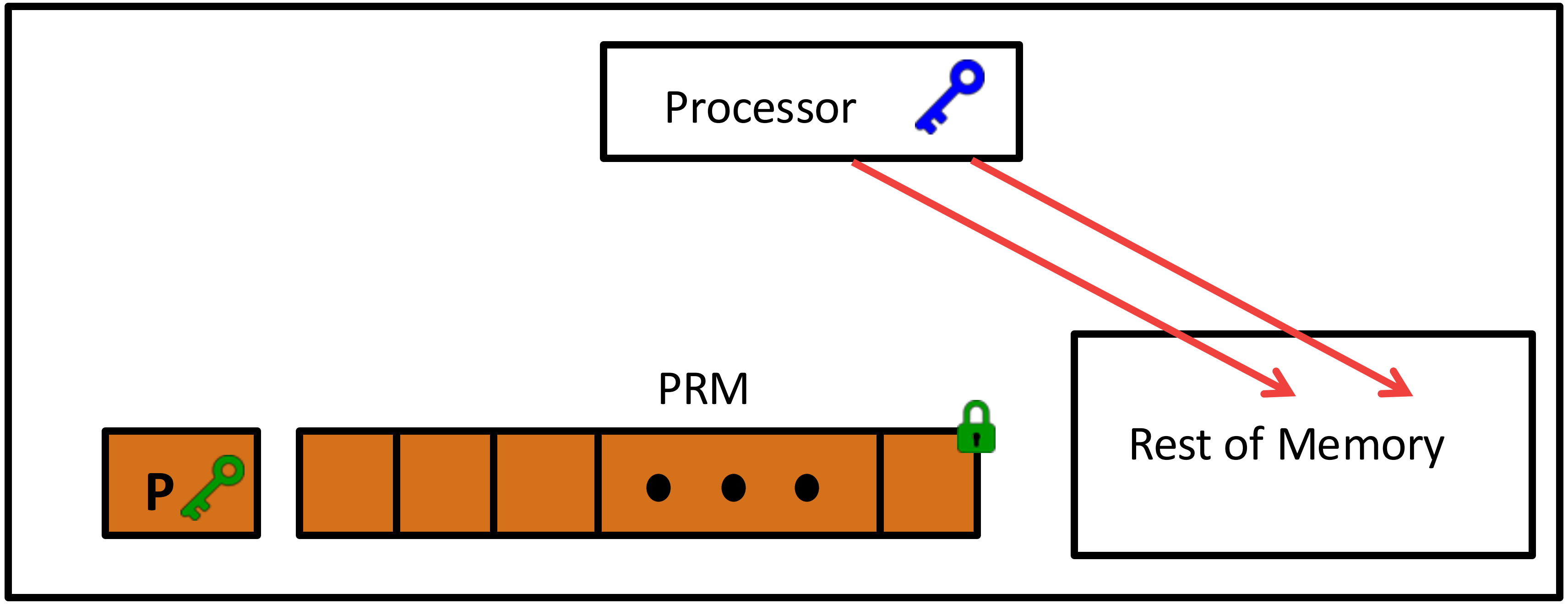

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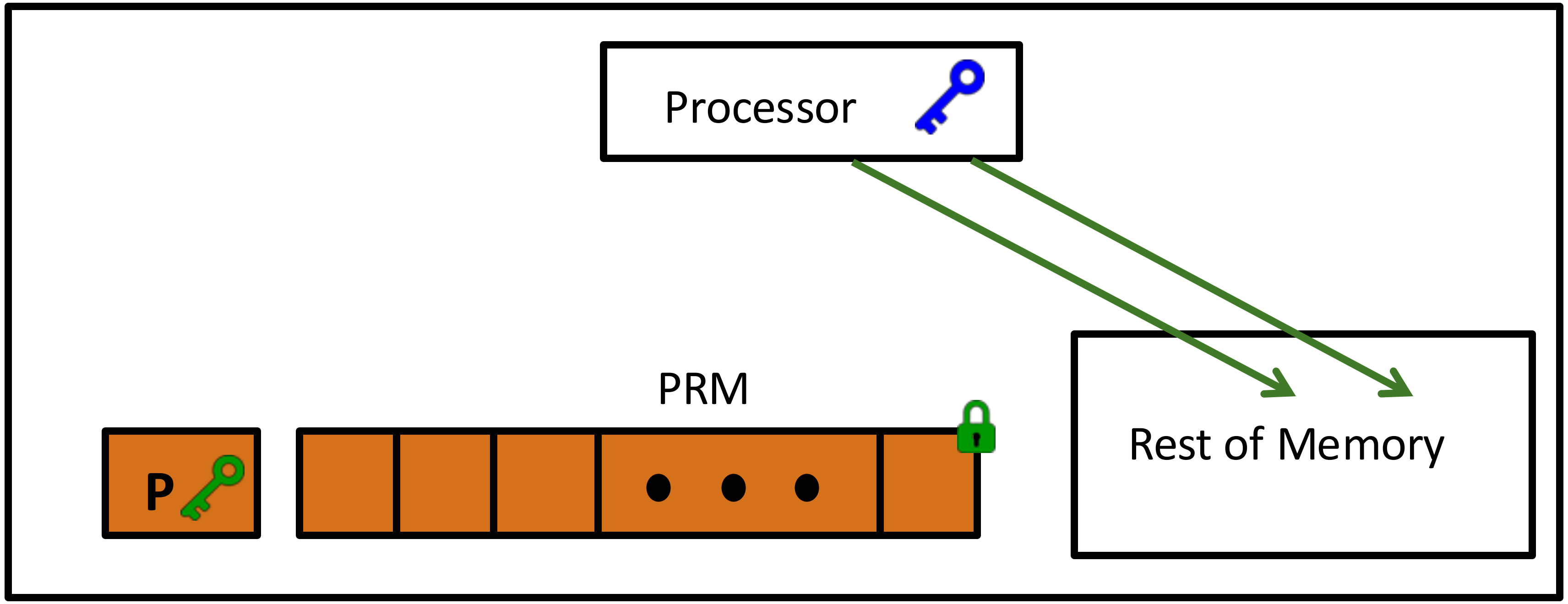
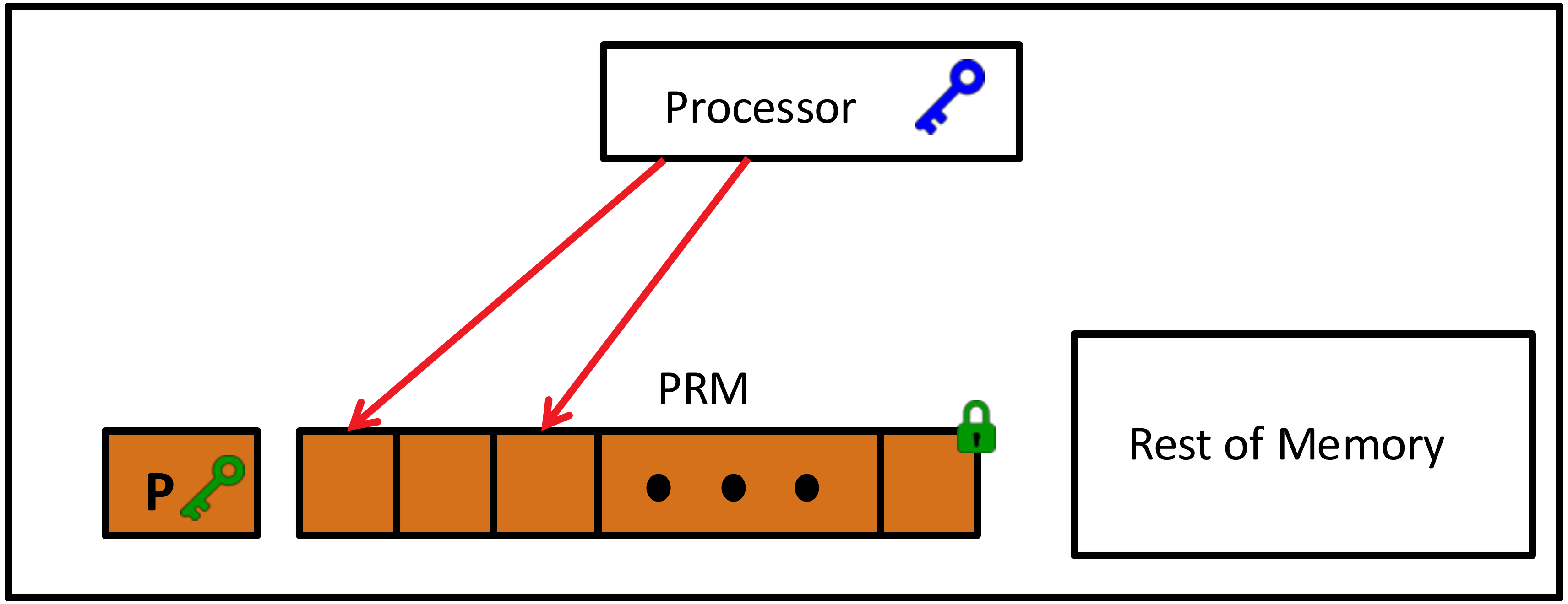


1) External-Memory

External-Memory Oblivious: Access to data outside of the PRM are independent of any secret data.

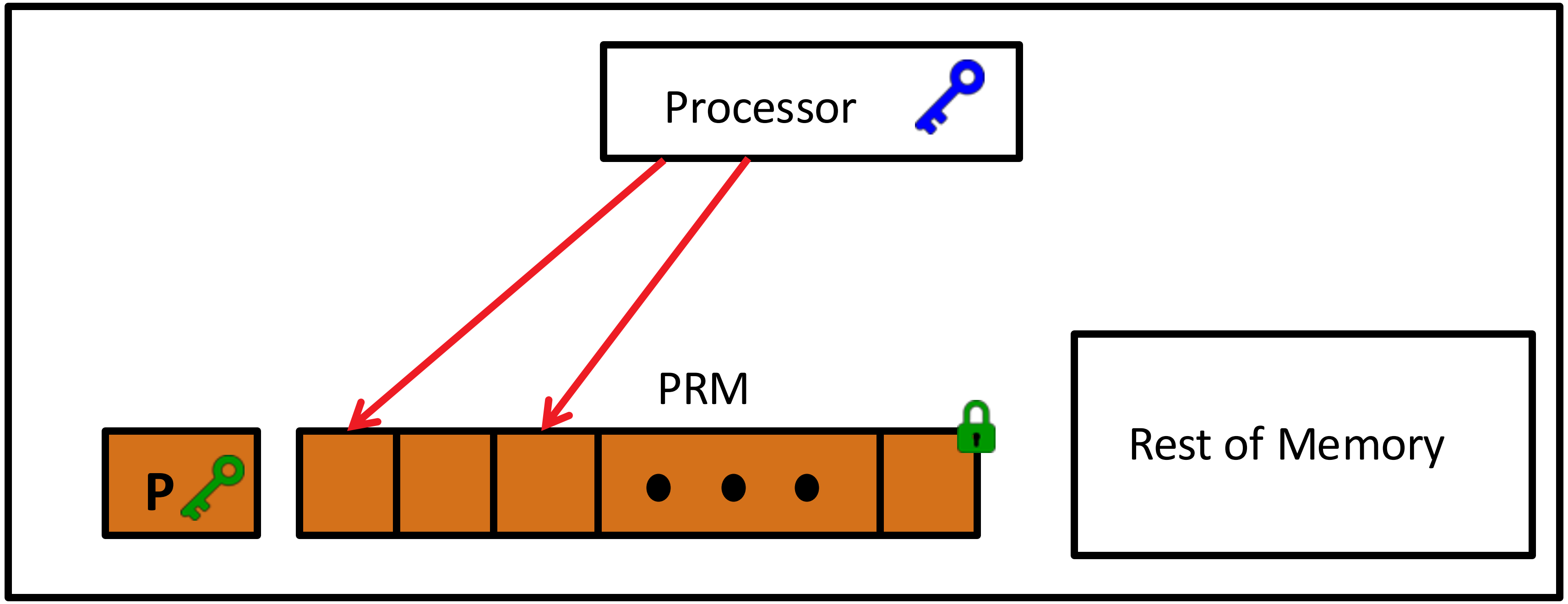
Levels of Obliviousness

1) External-Memory



Protected-Memory Oblivious: Access to data within the PRM are independent of any secret data.

Levels of Obliviousness

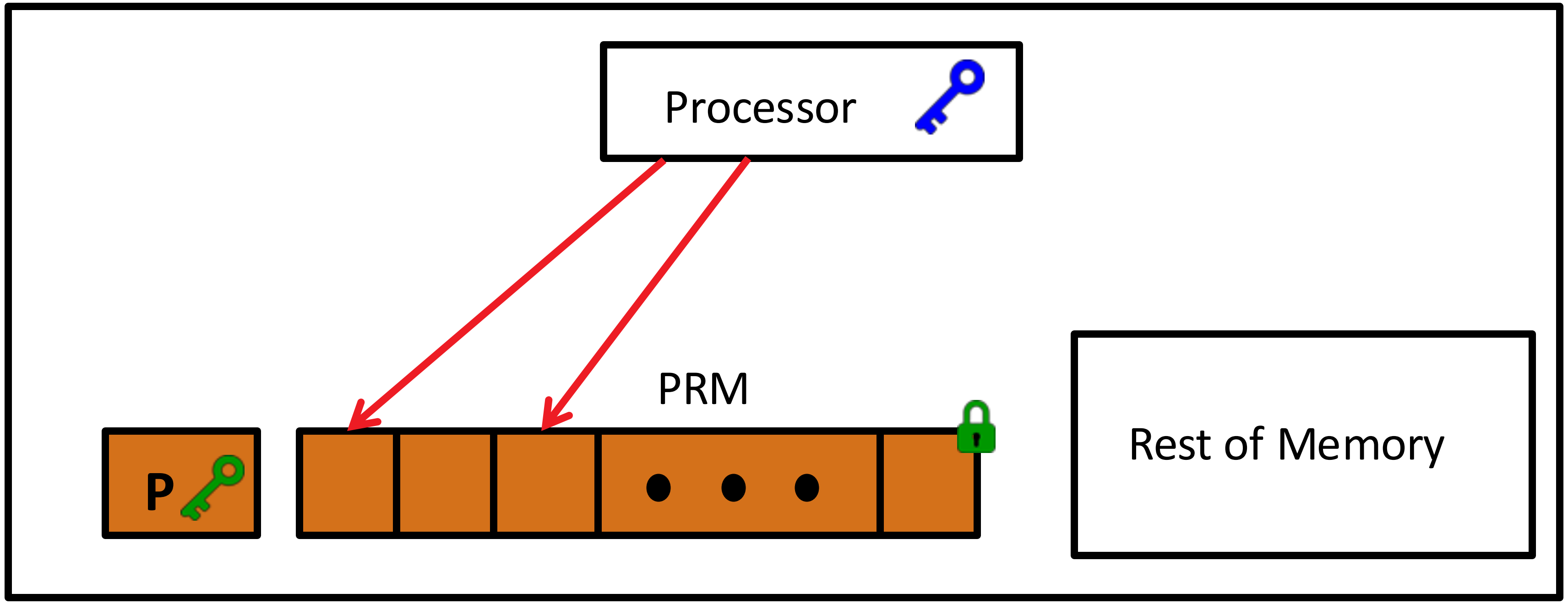


1) External-Memory

2) Protected-Memory

Protected-Memory Oblivious: Access to data within the PRM are independent of any secret data.

Levels of Obliviousness



1) External-Memory

2) Protected-Memory

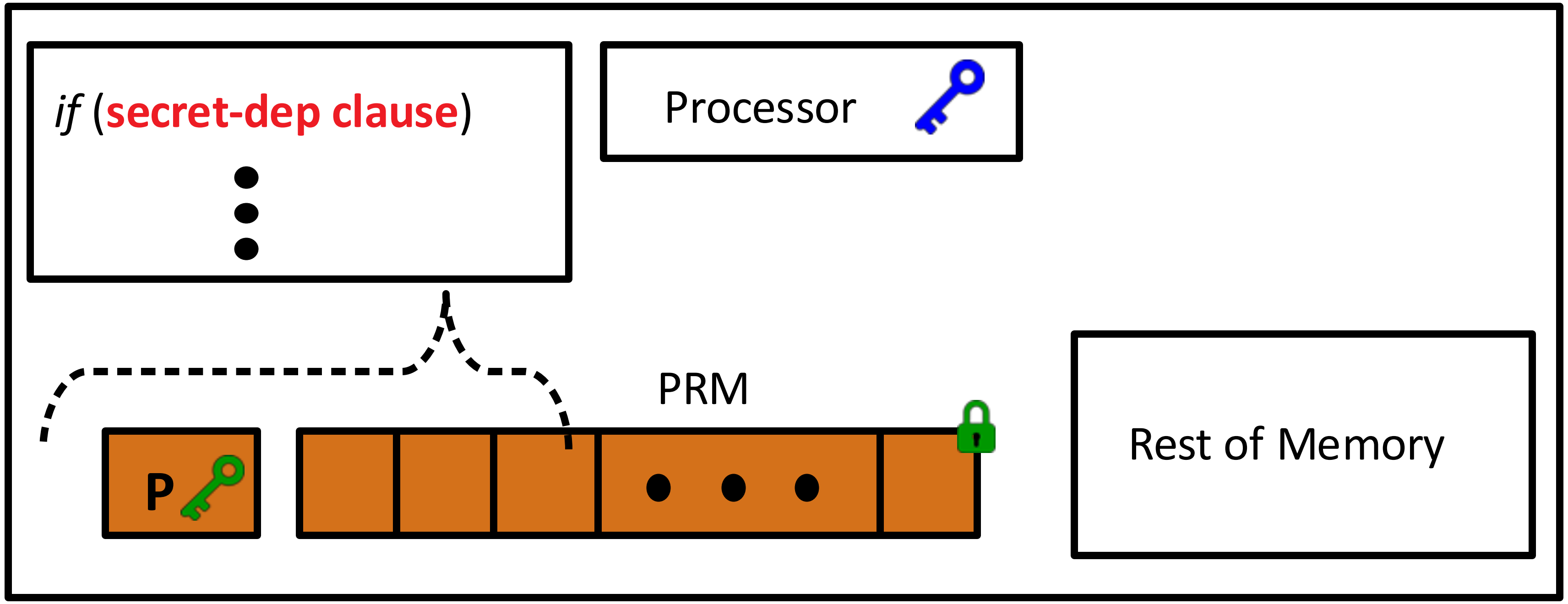
i. Page

ii. Caches

OS is responsible for page table management; Page-granular attacks induce page faults to extract memory locations accessed by the program.

Adversary can observe timing info on caches in the Processor to also launch attacks

Levels of Obliviousness

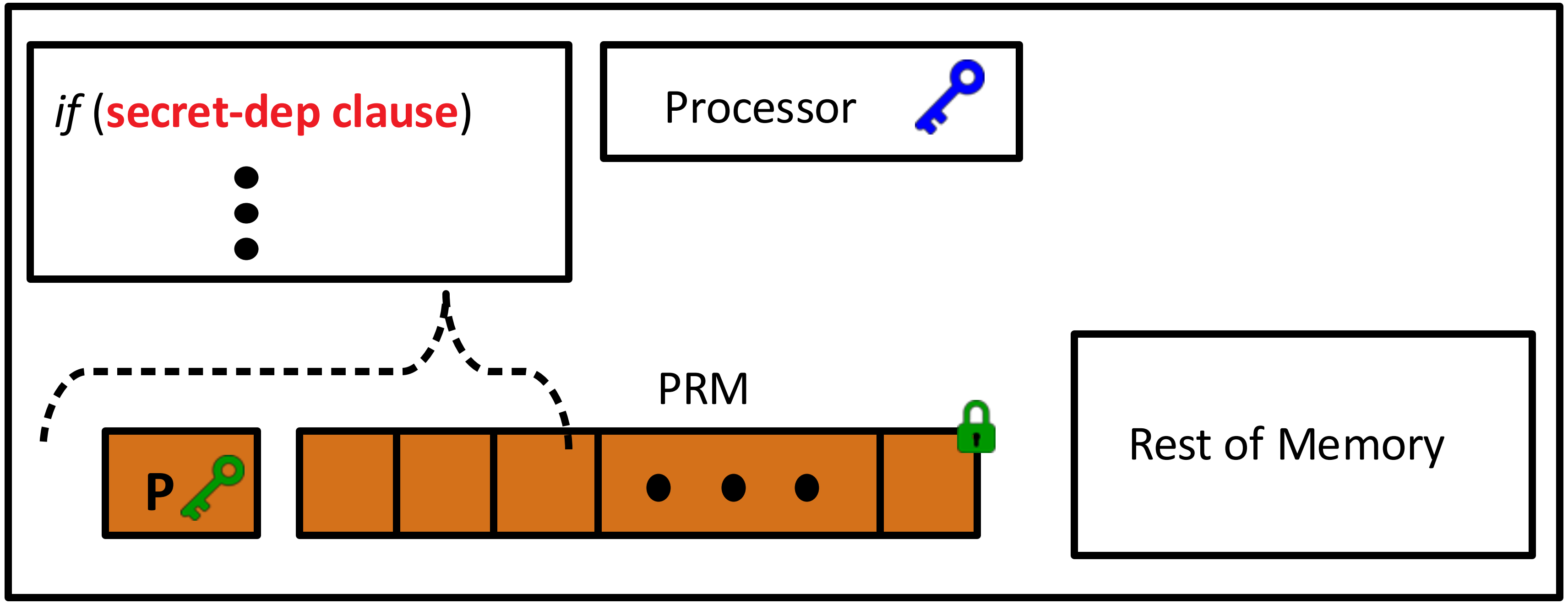


1) External-Memory

2) Protected-Memory
i. Page
ii. Caches

Control-Flow oblivious: Secret-dependent control flow branches leak information about the underlying secret; ensure that the program has no secret-dependent control-flow branches.

Levels of Obliviousness



1) External-Memory

2) Protected-Memory
i. Page
ii. Caches

3) Control flow

Fully Oblivious: A program is fully oblivious if it satisfies all above definitions of obliviousness

Responsibility of the app developer to design oblivious code

Levels of Obliviousness

1) **External-Memory** → **Single obliviousness** (e.g., achieved by PathORAM)

2) **Protected-Memory**

i. Page

ii. Caches

3) **Control flow**

Levels of Obliviousness

1) External-Memory

2) Protected-Memory
i. Page
ii. Caches

3) Control flow

} Doubly or fully obliviousness

Doubly or Fully Oblivious: A program is fully oblivious if it satisfies all above definitions of obliviousness

Responsibility of the app developer to design oblivious code

TEEs: Protected memory vs protected VM

A **protected VM TEE** runs an entire vm with encrypted and integrity-protected memory, isolating it from the host OS and hypervisor while enabling remote attestation.

Feature	Protected-Memory TEE (e.g., SGX, TrustZone)	Protected-VM TEE (e.g., SEV-SNP, TDX)
Granularity of Isolation	Protects only specific application memory regions (enclaves)	Protects the entire VM's memory and CPU state (guest OS + apps)
Deployment Model	Requires rewriting or partitioning applications into enclaves	Runs unmodified OSs and apps inside a protected VM
Trust Boundary	Enclave isolated, but still relies on host OS/hypervisor for scheduling	Hardware isolates whole VM from host OS and hypervisor
Compatibility & Workload Size	Limited enclave size and special APIs	Larger workloads with standard VM interfaces, minimal code changes

TEEs conclusion

- Gives confidentiality and integrity guarantees
- Allows an application verify the attestation to check if the correct code is running
- But enclave code should ensure *obliviousness* both to external and internal memory
- Requires enclave code developers to write doubly oblivious code