MacORAMa:

Optimal Oblivious RAM with Integrity

To appear at CRYPTO 2023

Surya Mathialagan

MIT

Neekon Vafa

MIT

Remote RAM Computation

Remote RAM Computation

- User wants to perform RAM computation, but doesn’t have enough local space.

Remote RAM Computation

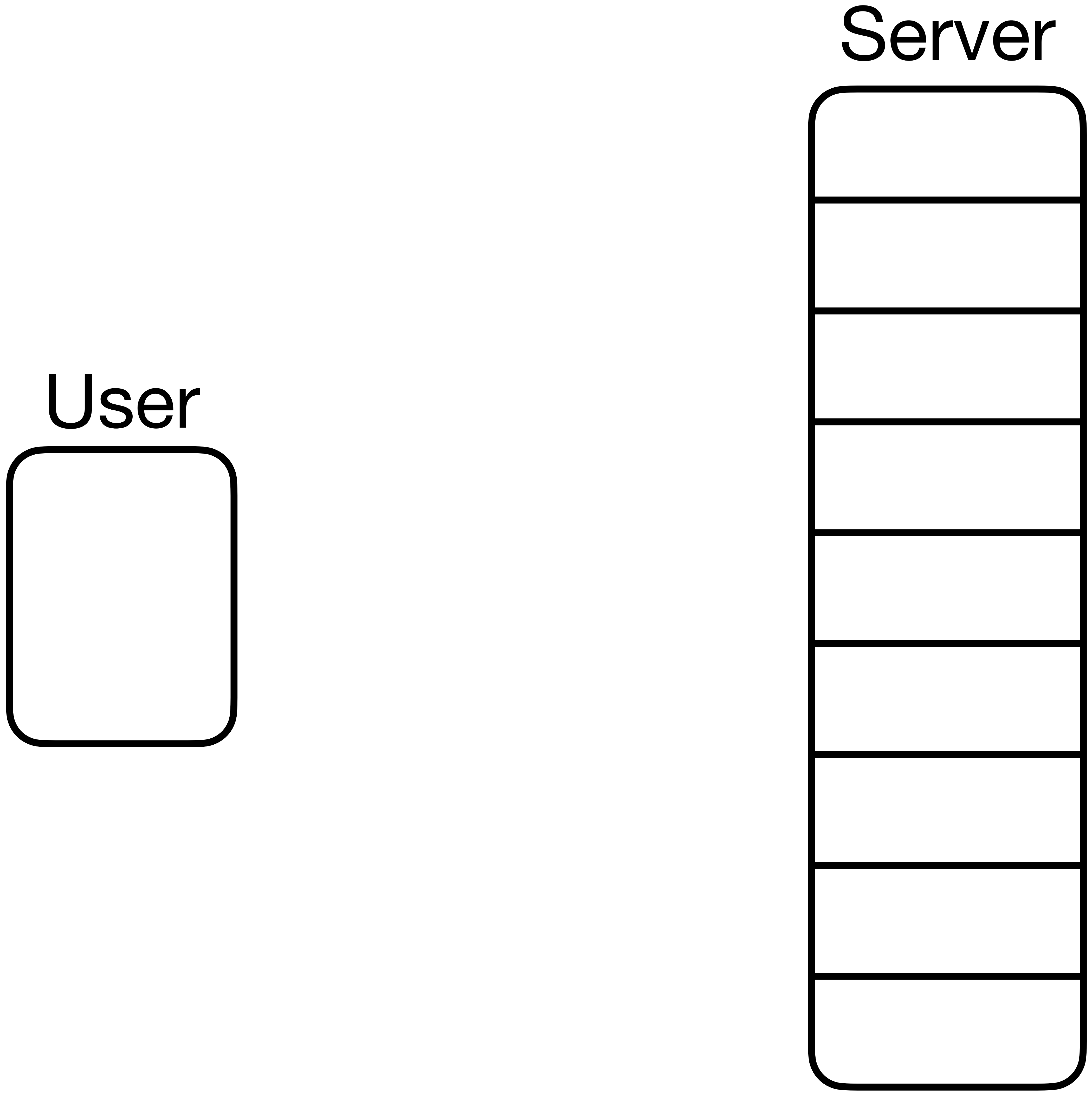
- User wants to perform RAM computation, but doesn’t have enough local space.

- Solution: Use remote RAM server.

Remote RAM Computation

- User wants to perform RAM computation, but doesn't have enough local space.

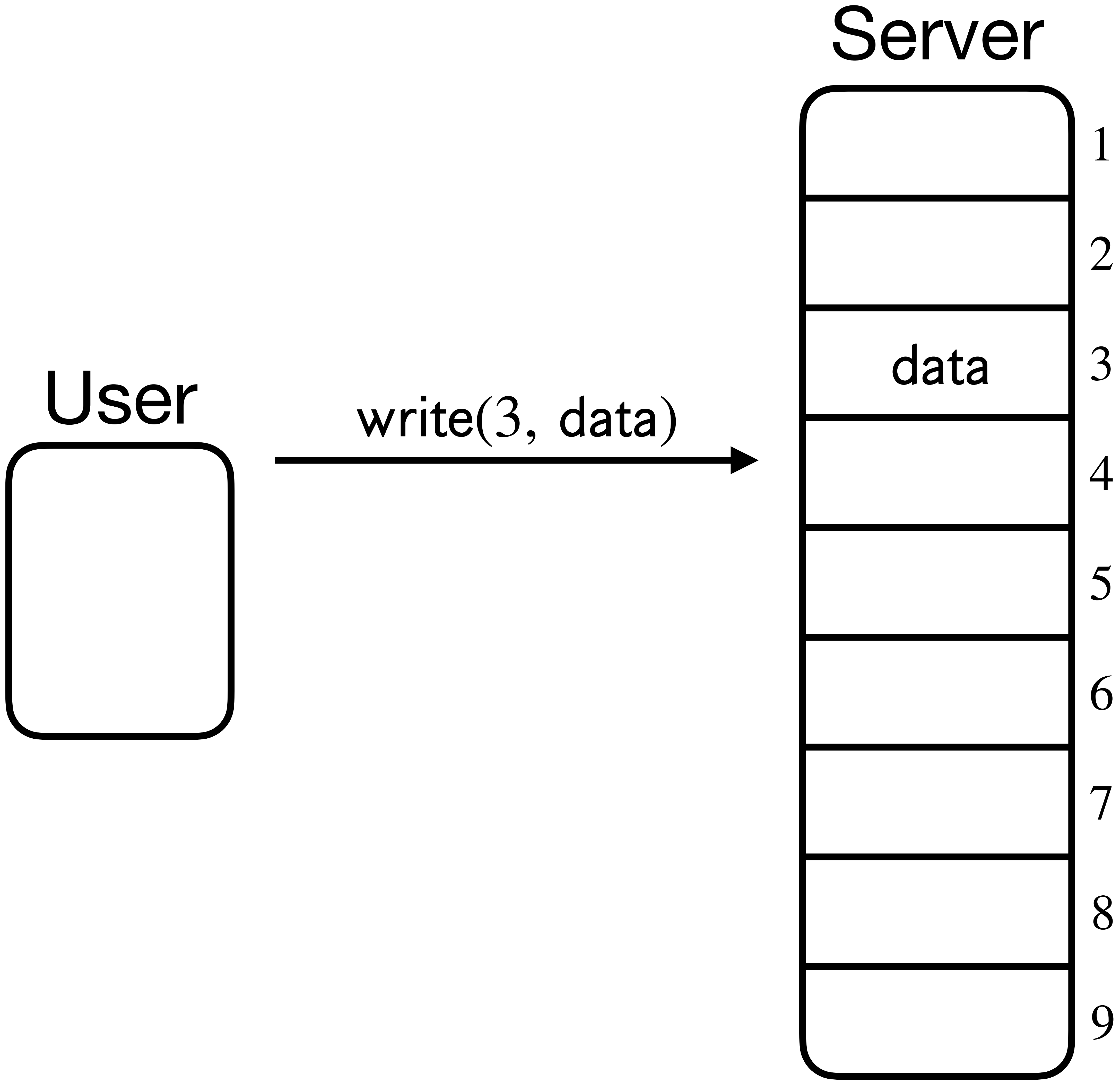
- Solution: Use remote RAM server.



Remote RAM Computation

- User wants to perform RAM computation, but doesn't have enough local space.

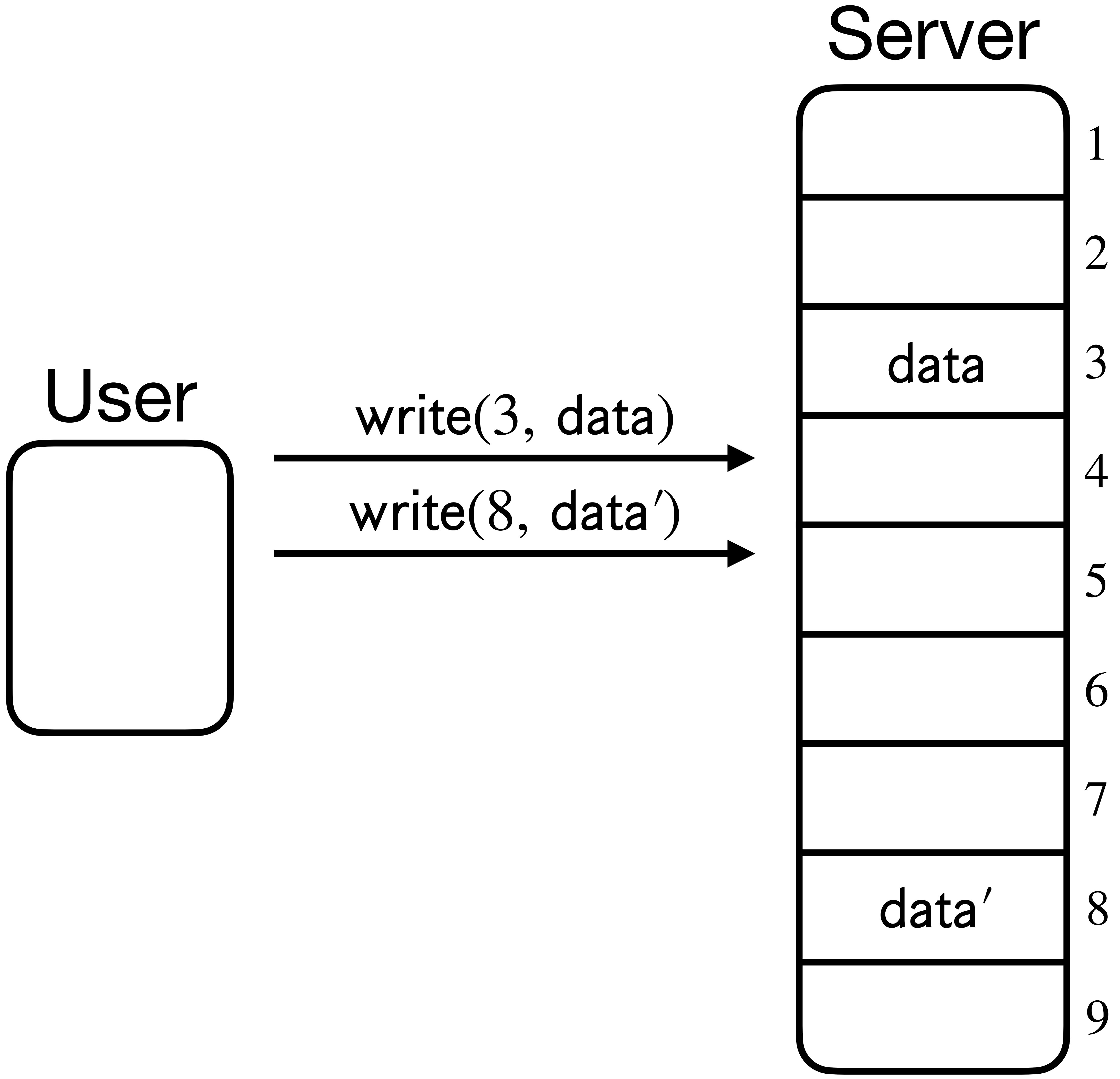
- Solution: Use remote RAM server.



Remote RAM Computation

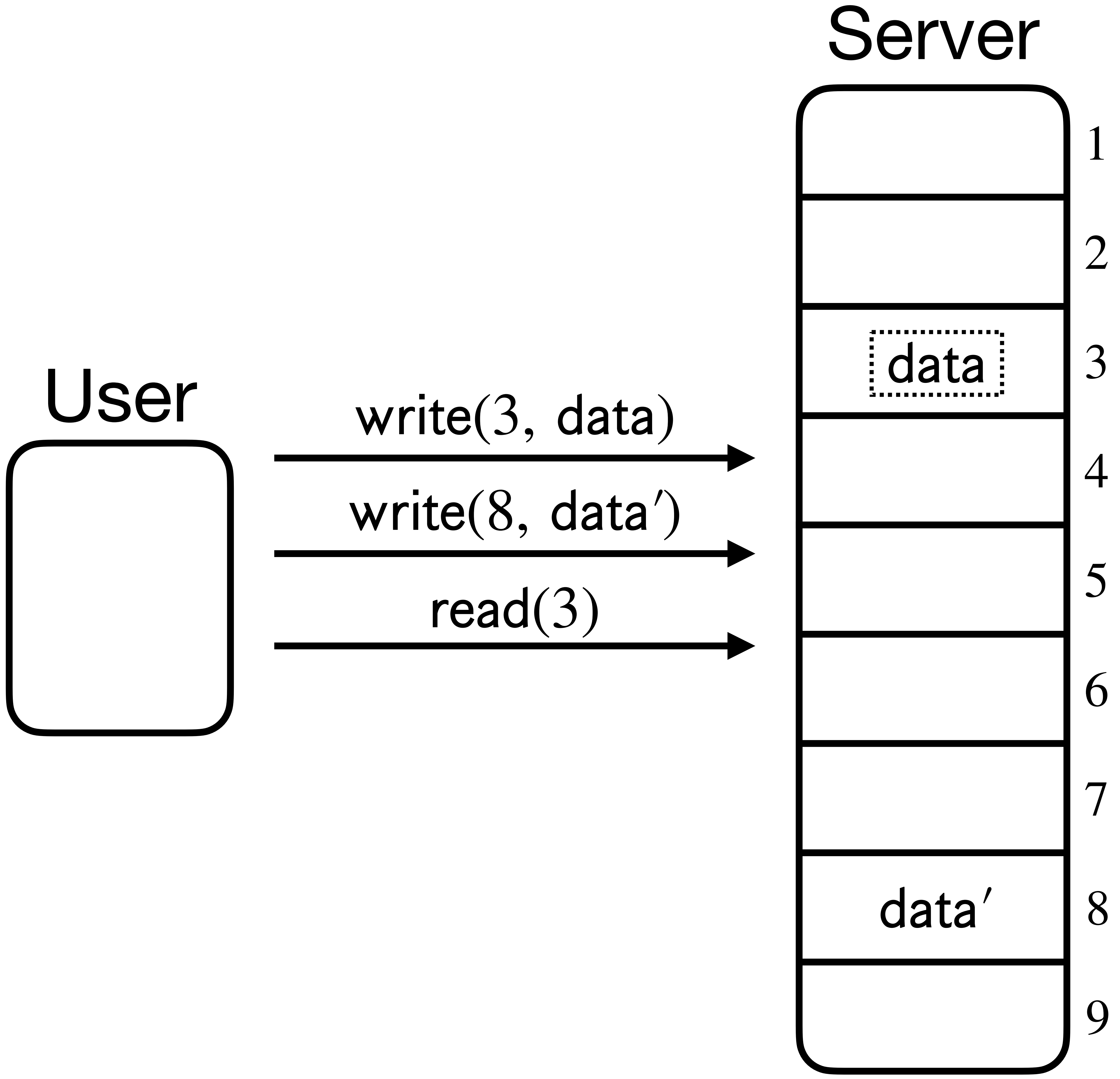
- User wants to perform RAM computation, but doesn't have enough local space.

- Solution: Use remote RAM server.



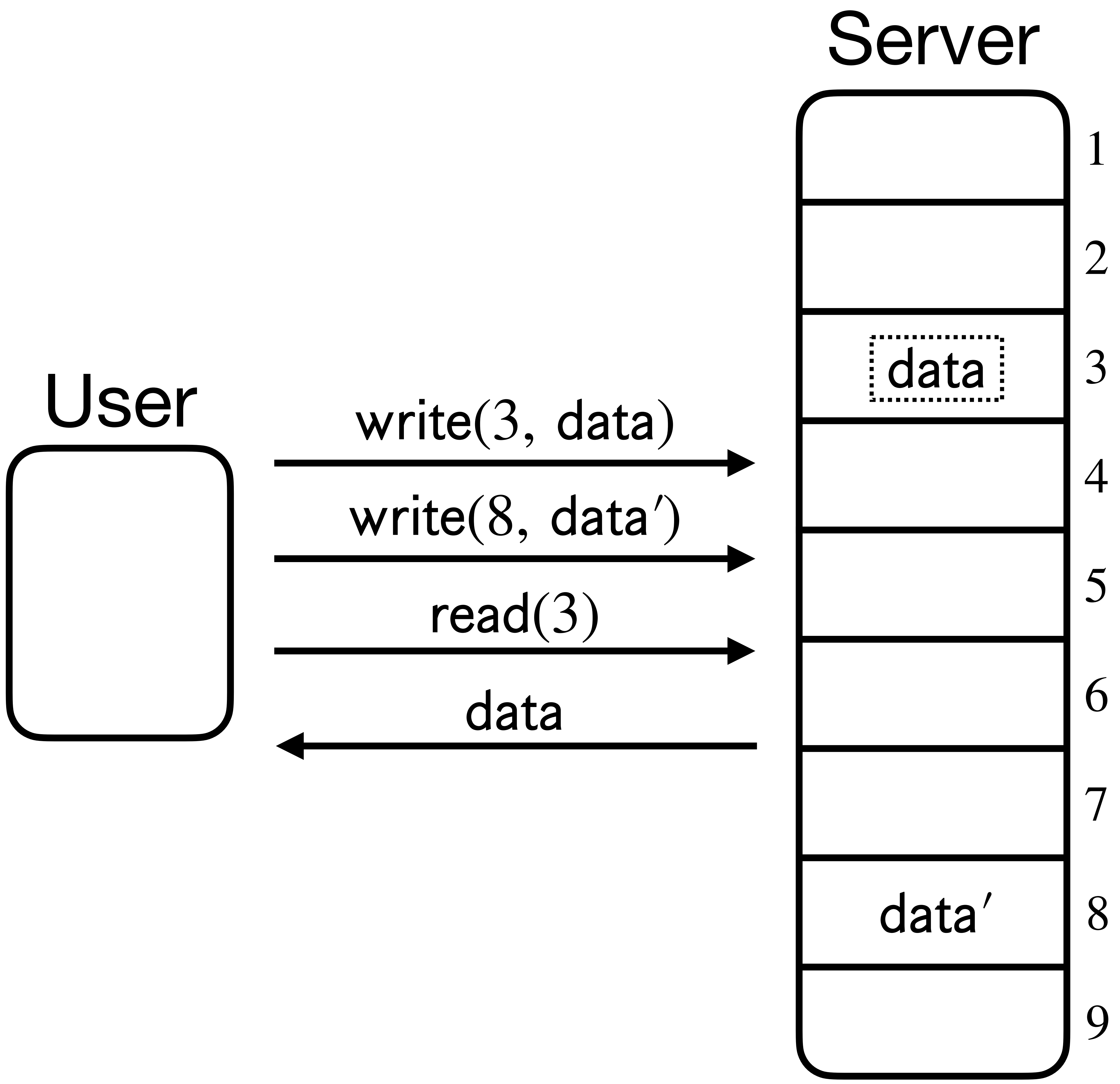
Remote RAM Computation

- User wants to perform RAM computation, but doesn't have enough local space.
- Solution: Use remote RAM server.



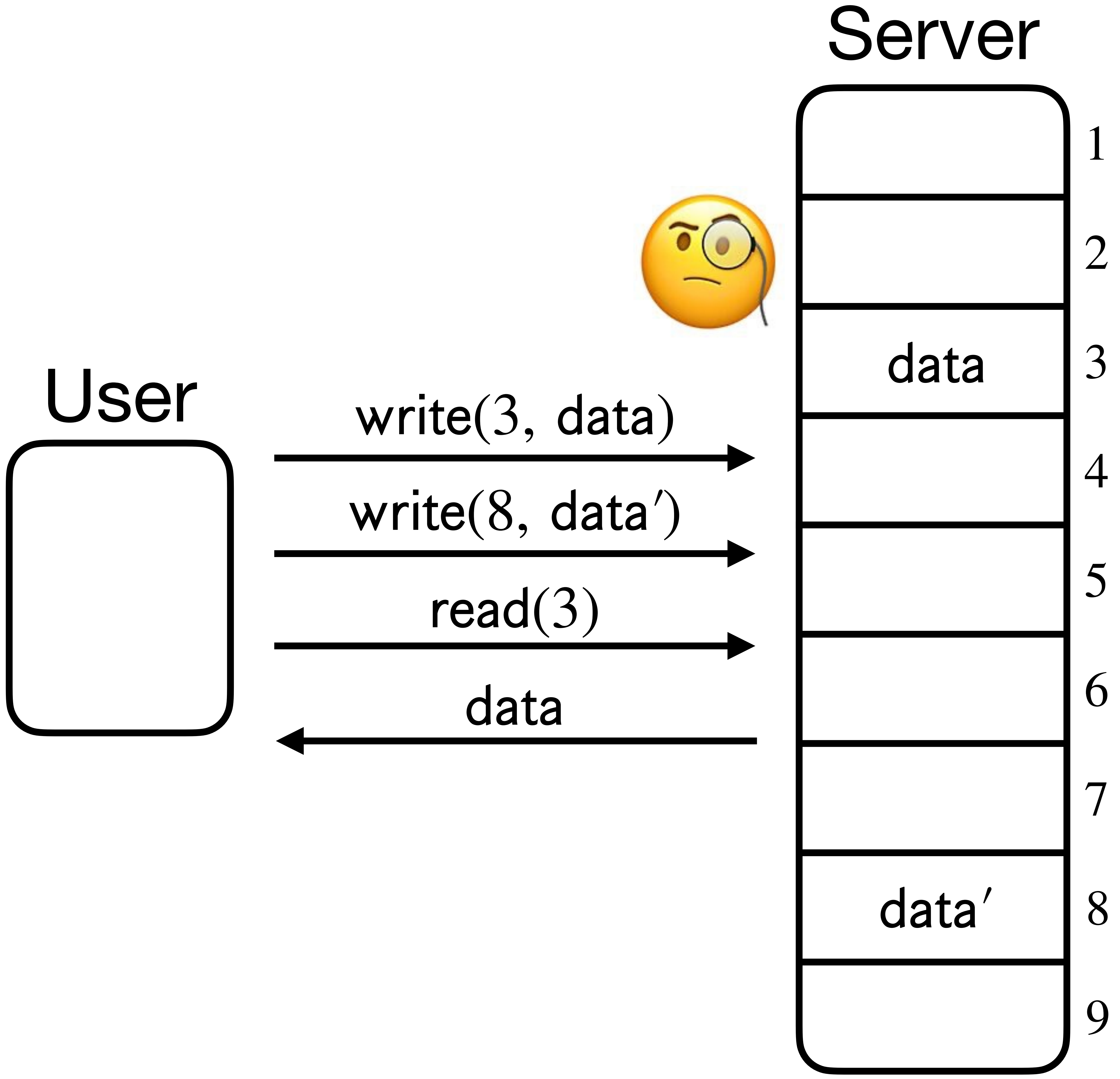
Remote RAM Computation

- User wants to perform RAM computation, but doesn't have enough local space.
- Solution: Use remote RAM server.



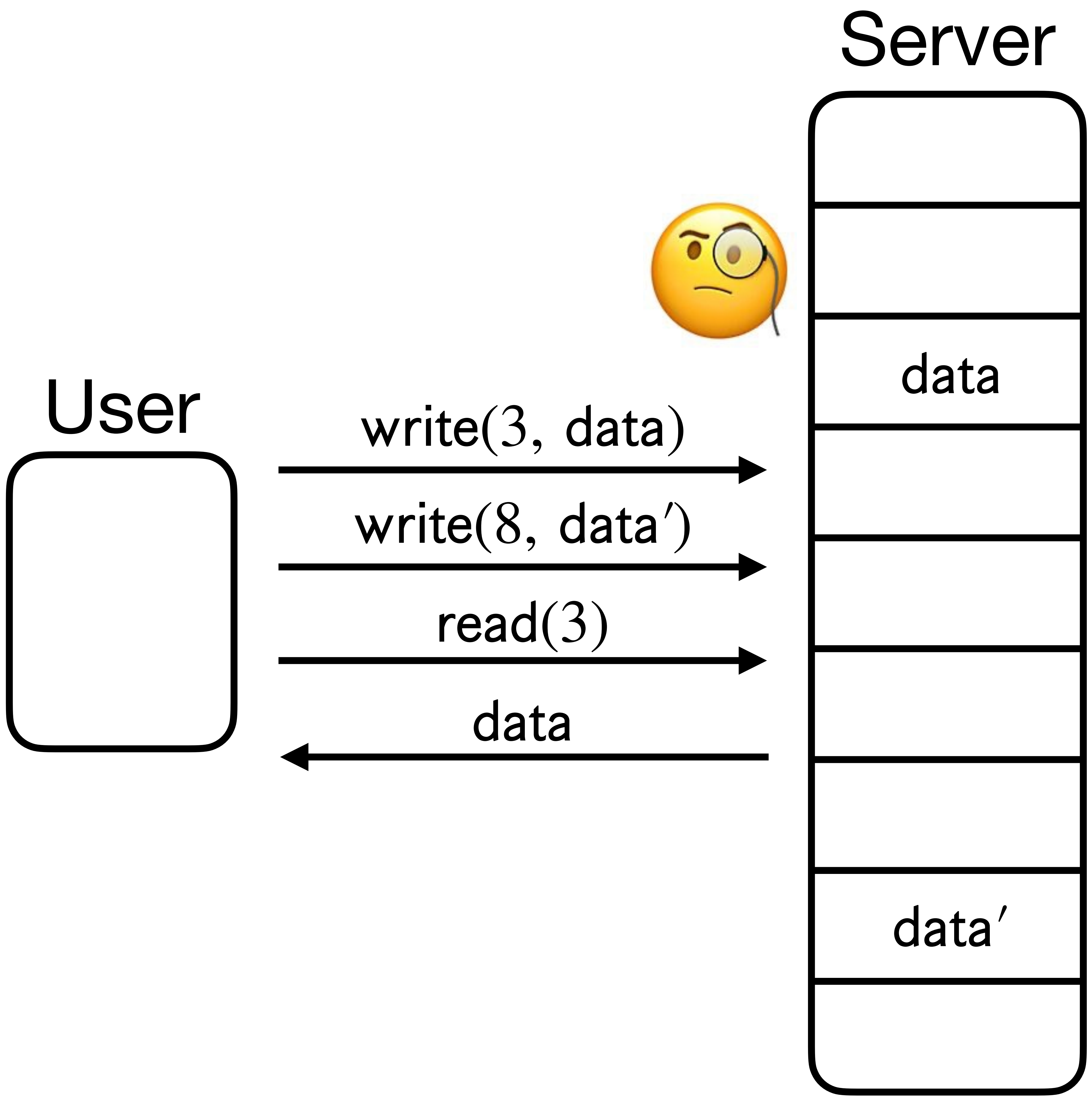
Remote RAM Computation

- User wants to perform RAM computation, but doesn't have enough local space.
- Solution: Use remote RAM server.
- How can the user ensure privacy of its computation against a curious server?



Remote RAM Computation

- One idea to ensure privacy: Encrypt the data (private key)



Server

User

$\mathsf{write}(3,\ \mathsf{data})$

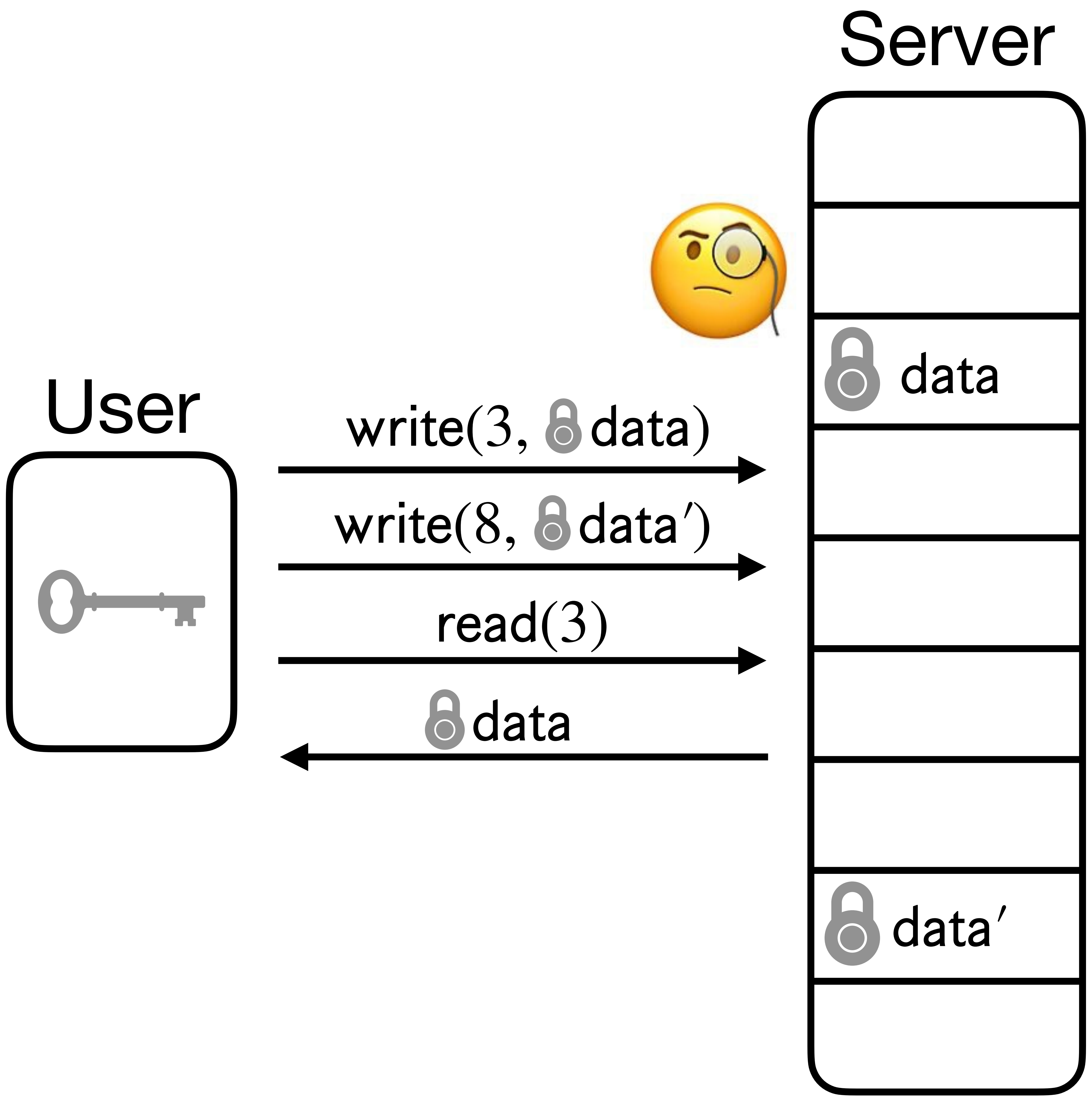
$\mathsf{write}(8,\ \mathsf{data}')$

$\mathsf{read}(3)$

data

Remote RAM Computation

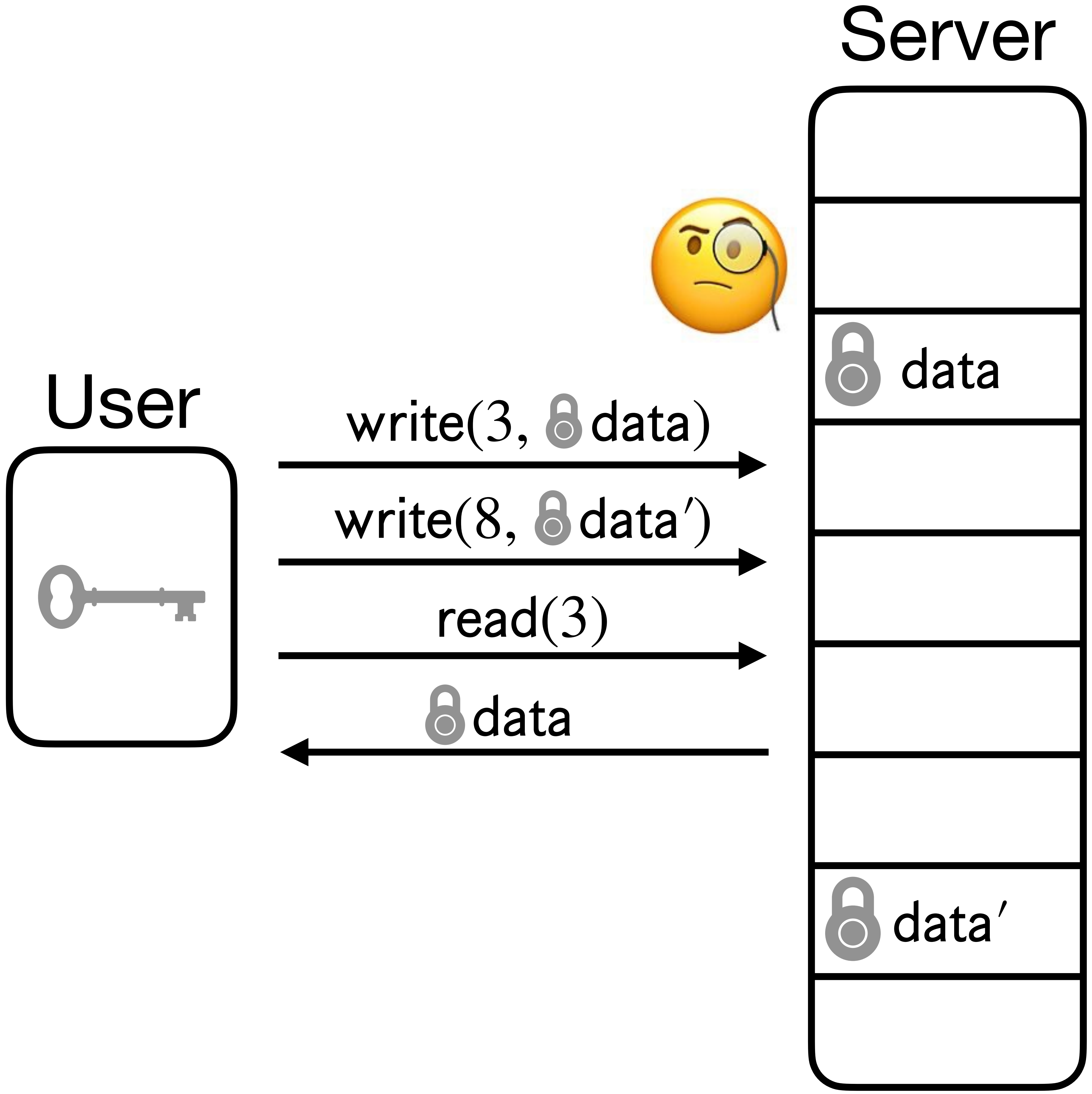
- One idea to ensure privacy:
  Encrypt the data (private key)



Remote RAM Computation

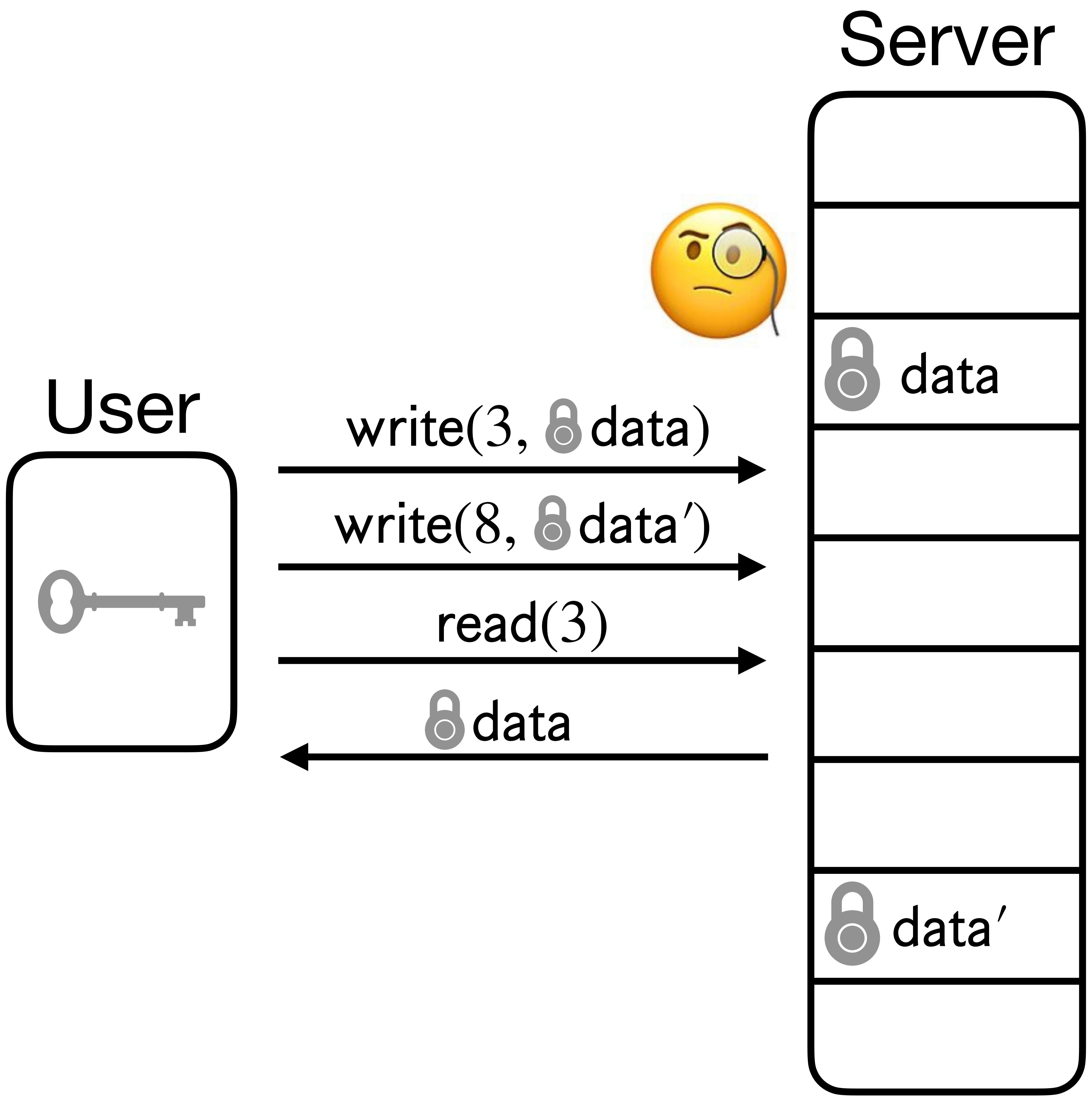
- One idea to ensure privacy: Encrypt the data (private key)

- Problem: Encryption is insufficient (access patterns reveal private information!)



Remote RAM Computation

- One idea to ensure privacy: Encrypt the data (private key)
- Problem: Encryption is insufficient (access patterns reveal private information!)
- Example: Medical study



Server

User

write(3, 🔒data)

write(8, 🔒data′)

read(3)

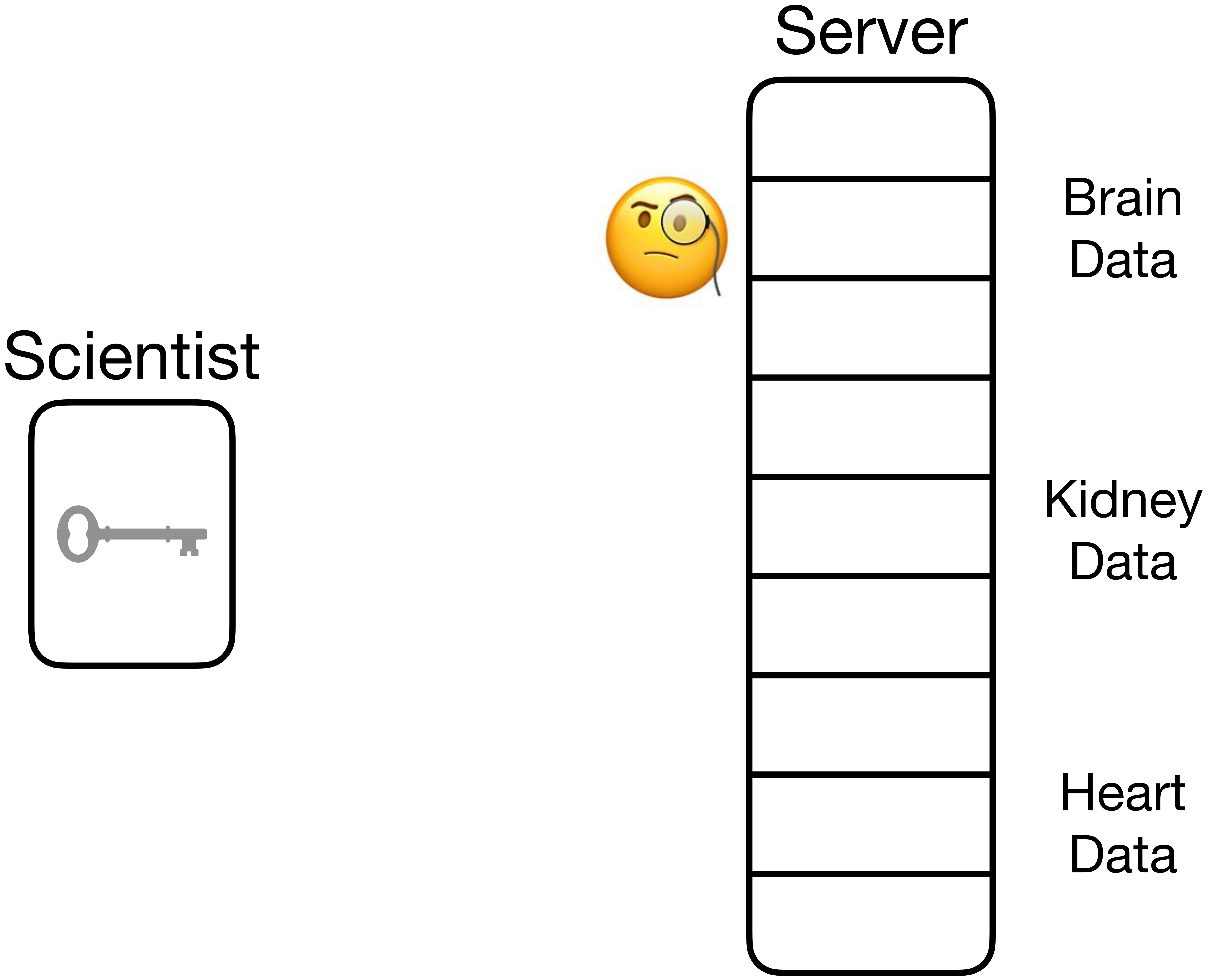
🔒data

🔒 data

🔒 data′

Remote RAM Computation

- One idea to ensure privacy: Encrypt the data (private key)
- Problem: Encryption is insufficient (access patterns reveal private information!)
- Example: Medical study



Scientist

Server

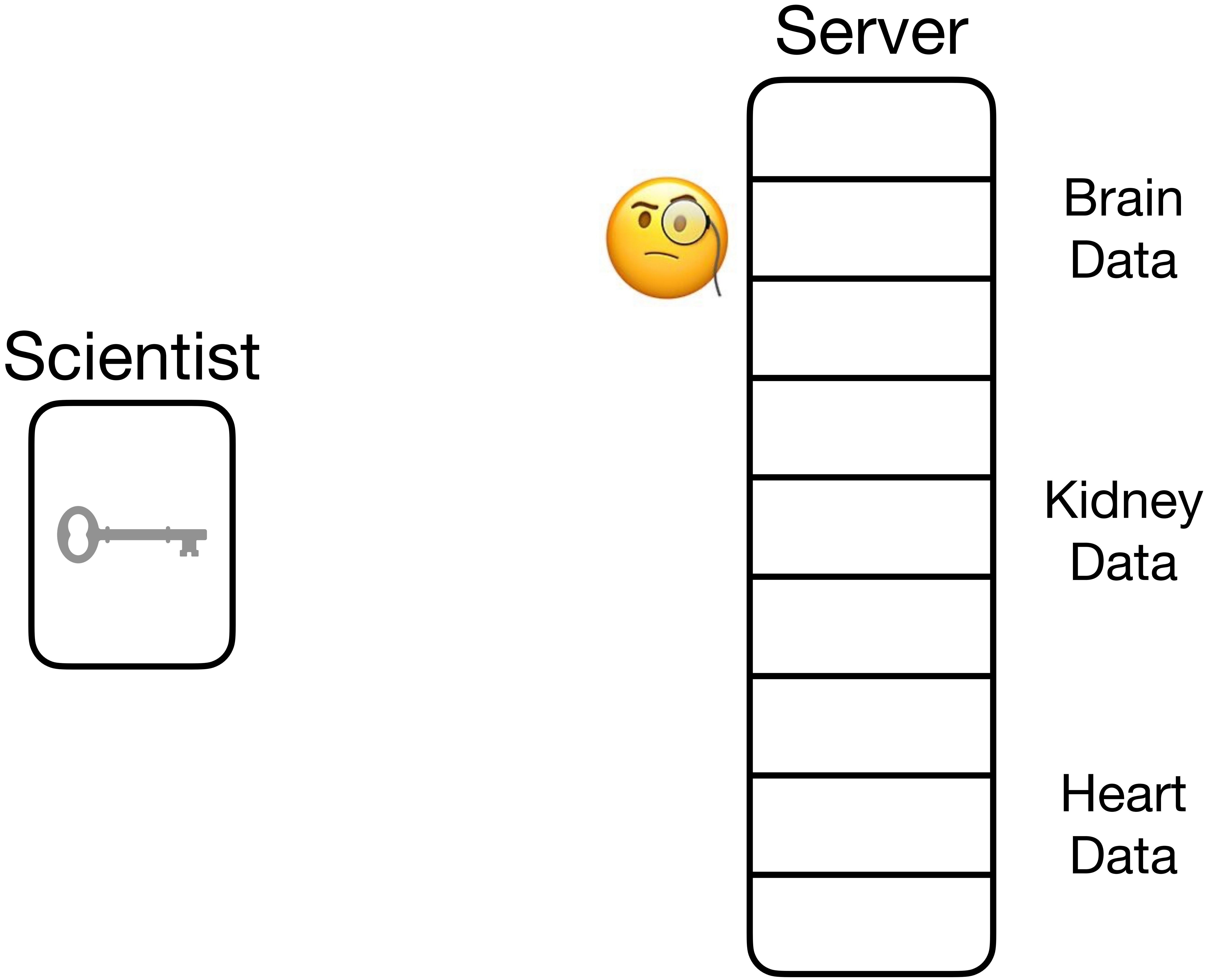
Brain Data

Kidney Data

Heart Data

Remote RAM Computation

- One idea to ensure privacy: Encrypt the data (private key)
- Problem: Encryption is insufficient (access patterns reveal private information!)
- Example: Medical study
- RAM addresses in accesses can reveal private information!



Server

Scientist

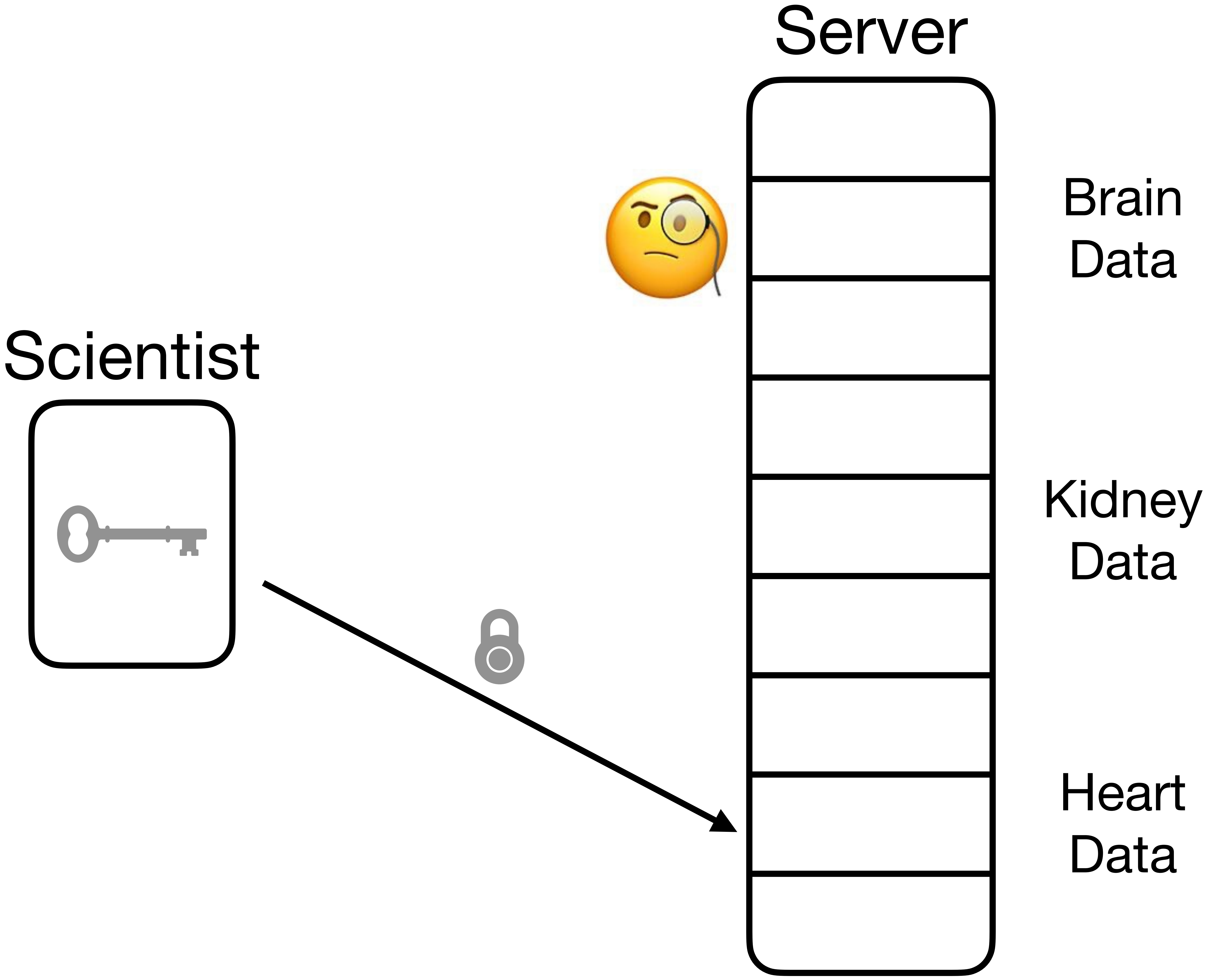
Brain Data

Kidney Data

Heart Data

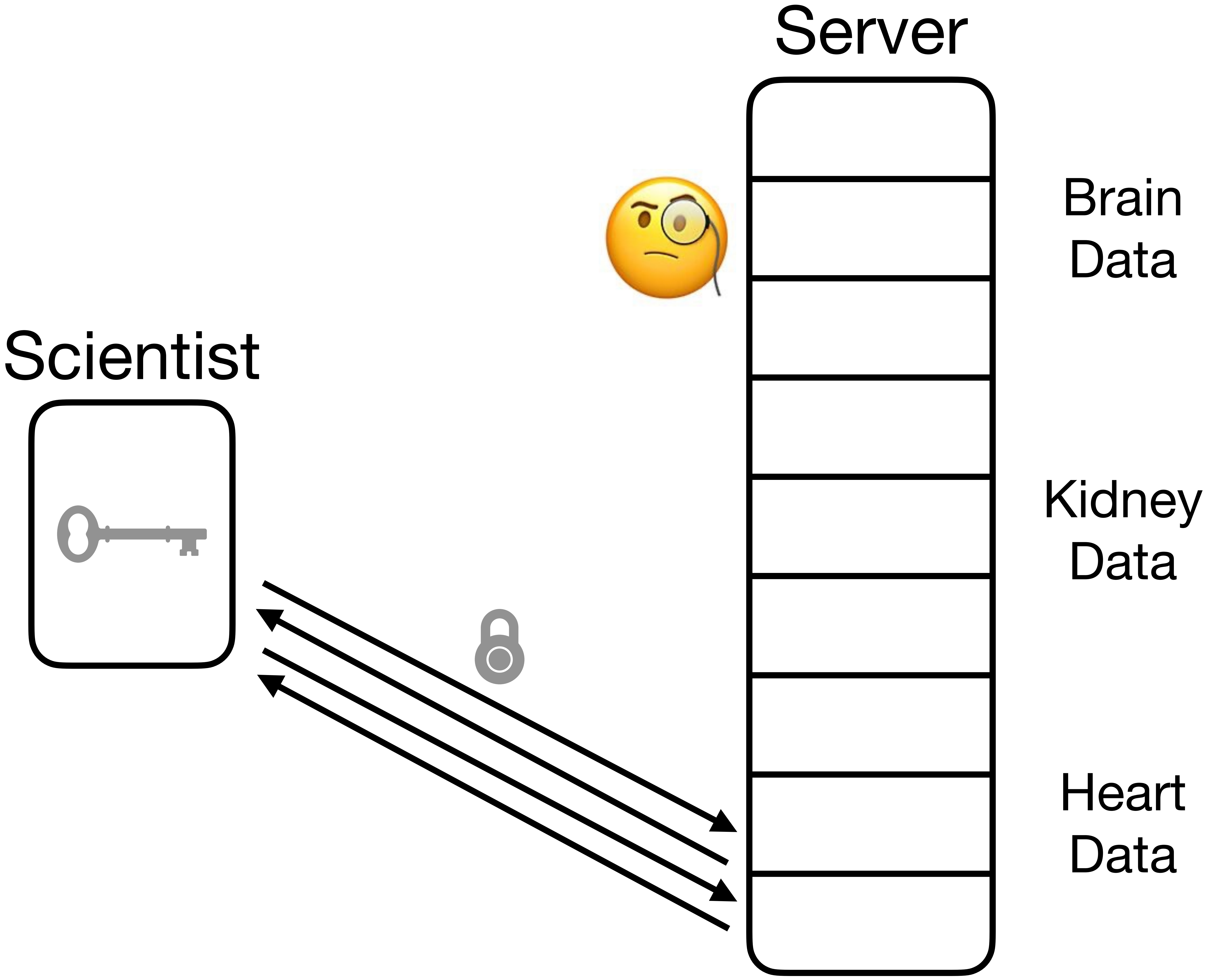
Remote RAM Computation

- One idea to ensure privacy: Encrypt the data (private key)
- Problem: Encryption is insufficient (access patterns reveal private information!)
- Example: Medical study
- RAM addresses in accesses can reveal private information!



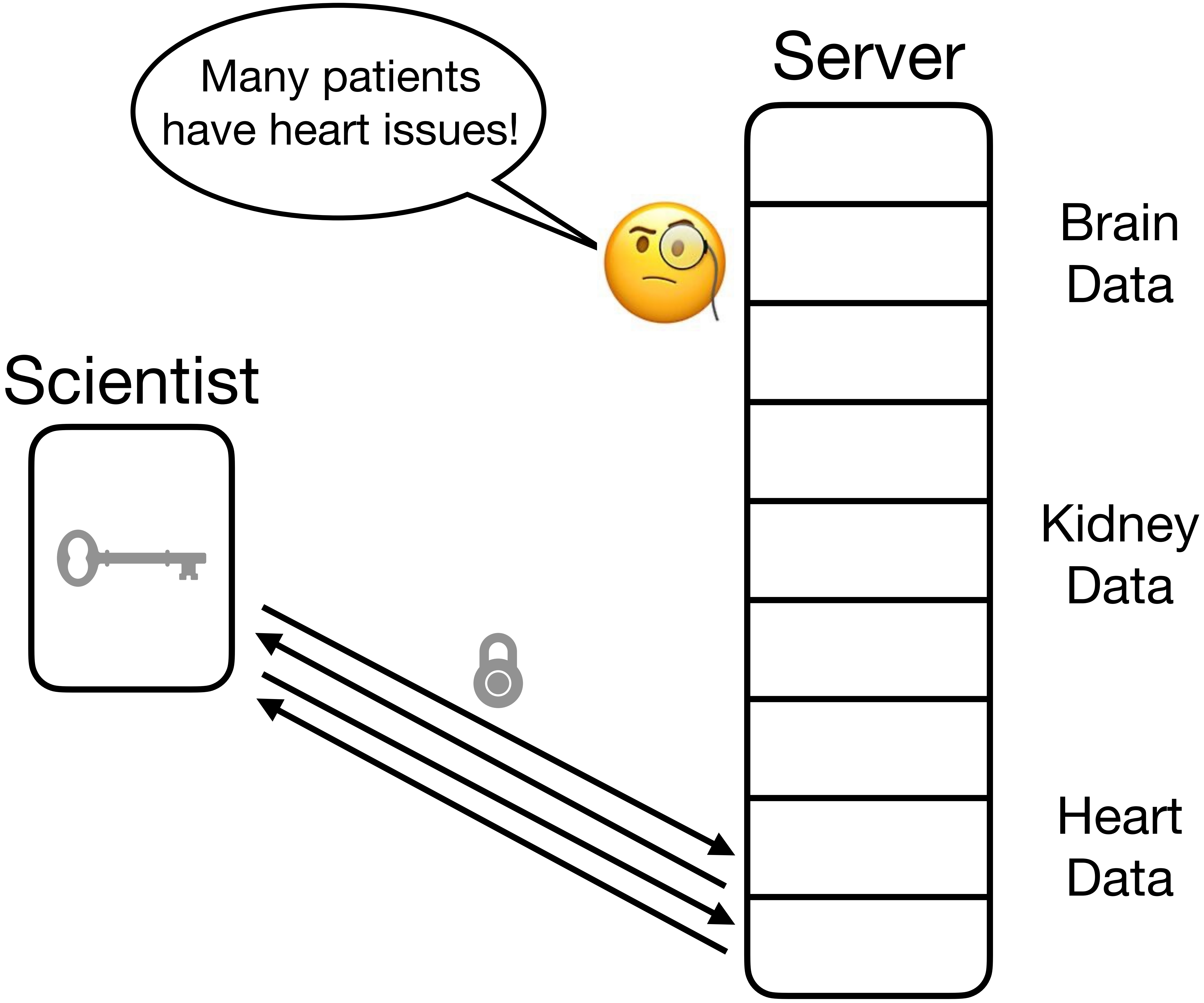
Remote RAM Computation

- One idea to ensure privacy: Encrypt the data (private key)
- Problem: Encryption is insufficient (access patterns reveal private information!)
- Example: Medical study
- RAM addresses in accesses can reveal private information!



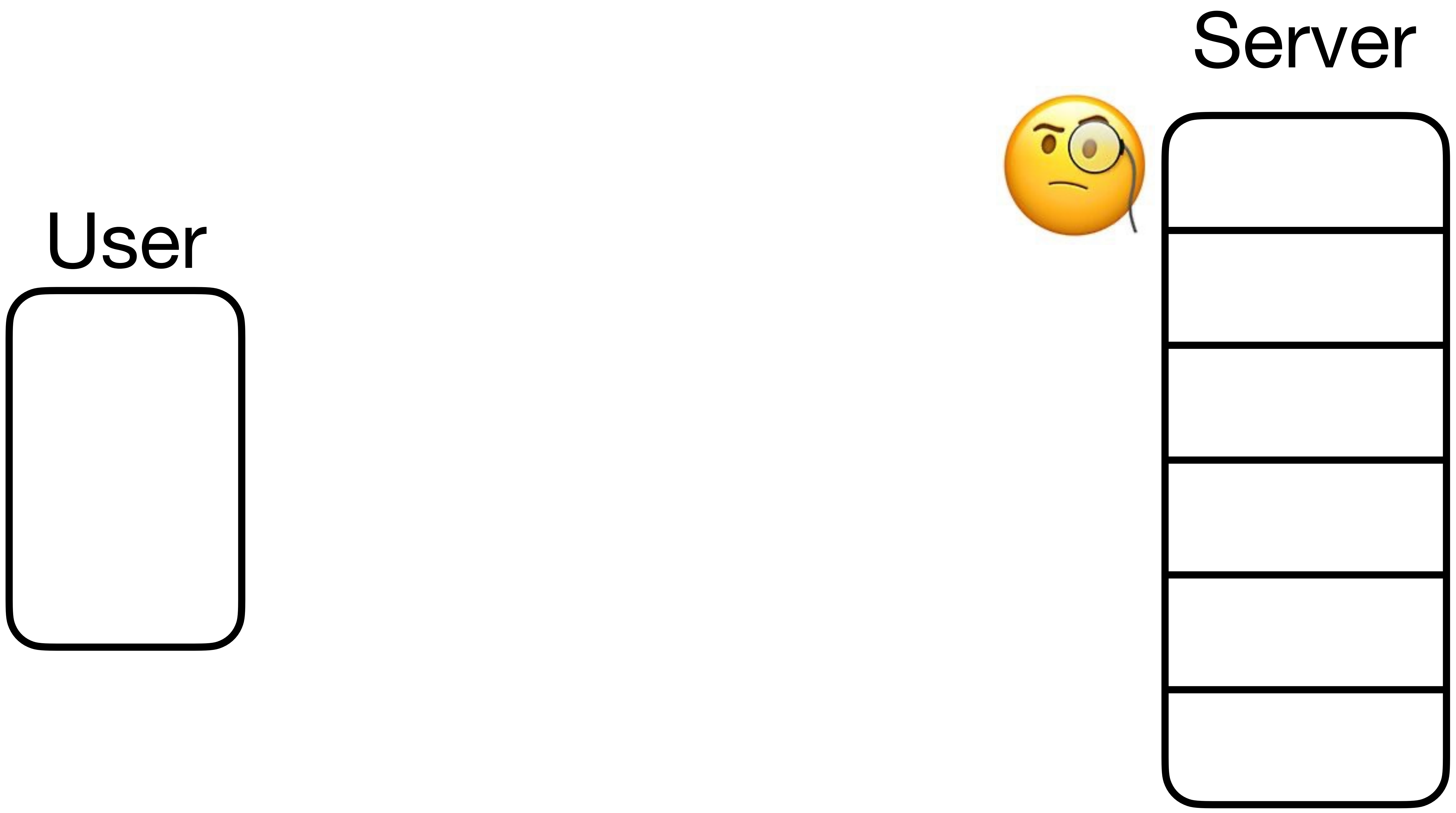
Remote RAM Computation

- One idea to ensure privacy: Encrypt the data (private key)
- Problem: Encryption is insufficient (access patterns reveal private information!)
- Example: Medical study
- RAM addresses in accesses can reveal private information!



Oblivious RAM (ORAM)

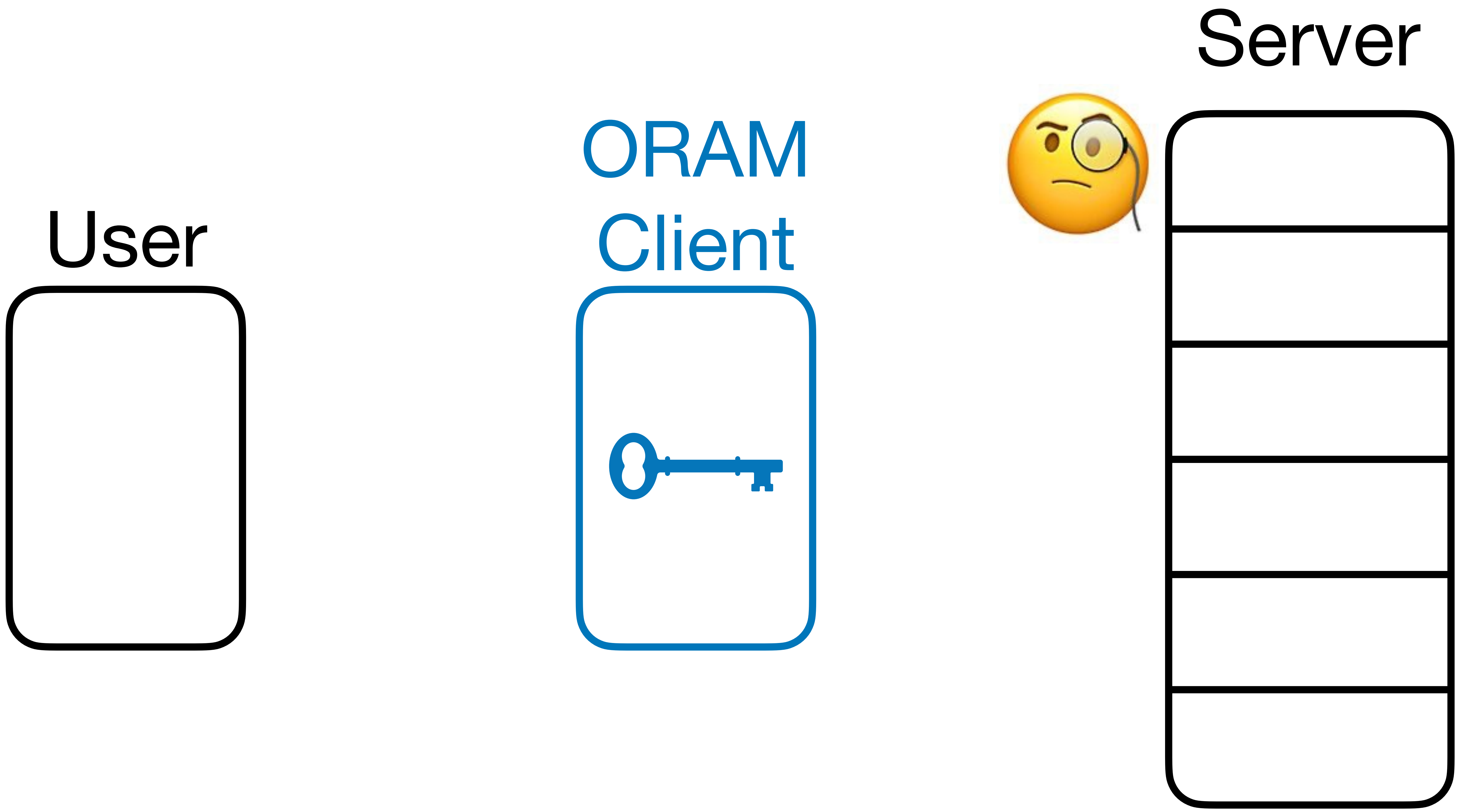
[Goldreich ’87,
Ostrovsky ’90,
Goldreich-
Ostrovsky ‘96]


Server

User

Oblivious RAM (ORAM)

[Goldreich ’87,
Ostrovsky ’90,
Goldreich-
Ostrovsky ‘96]



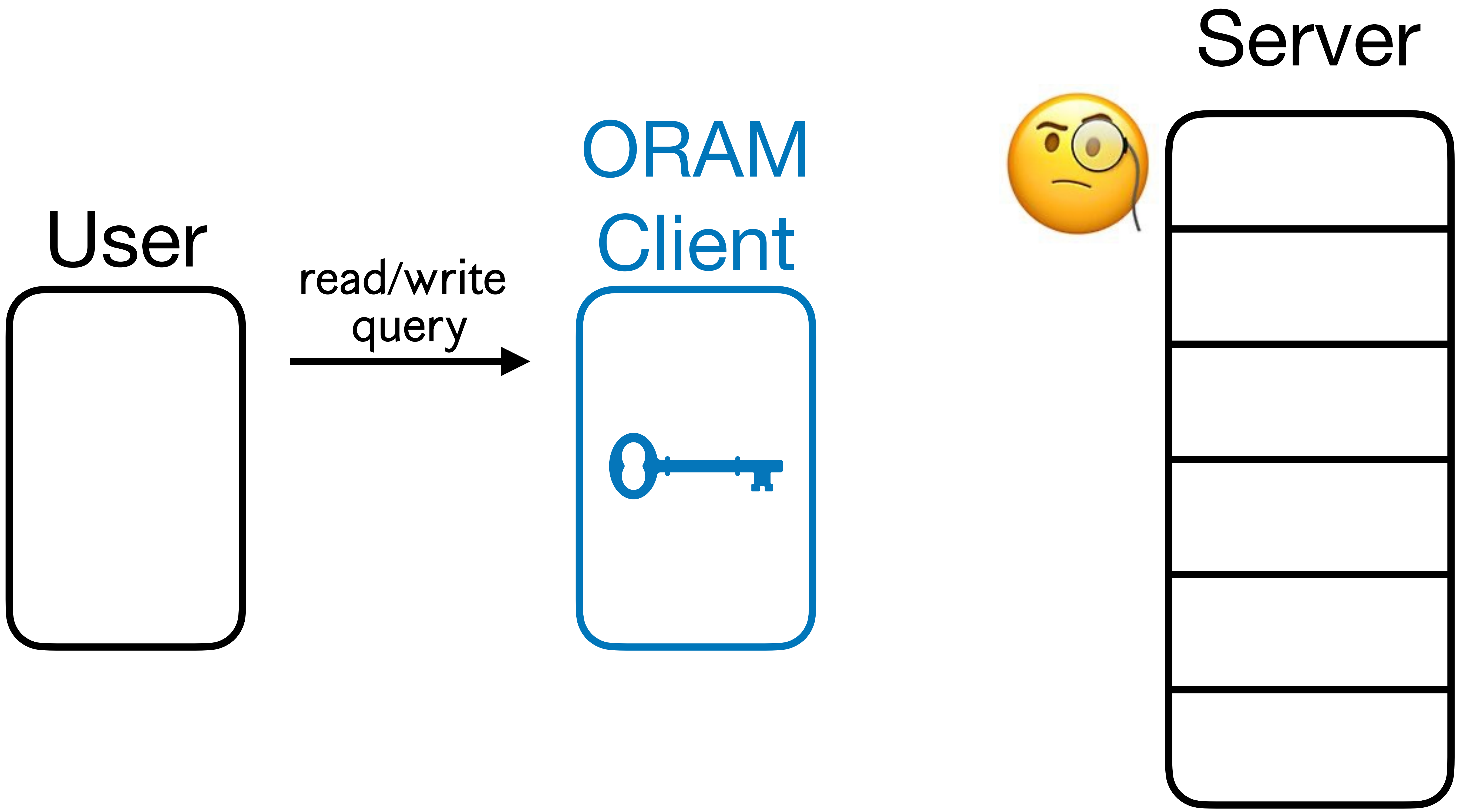
User

ORAM
Client

Server

Oblivious RAM (ORAM)

[Goldreich ’87,
Ostrovsky ’90,
Goldreich-
Ostrovsky ‘96]



Server

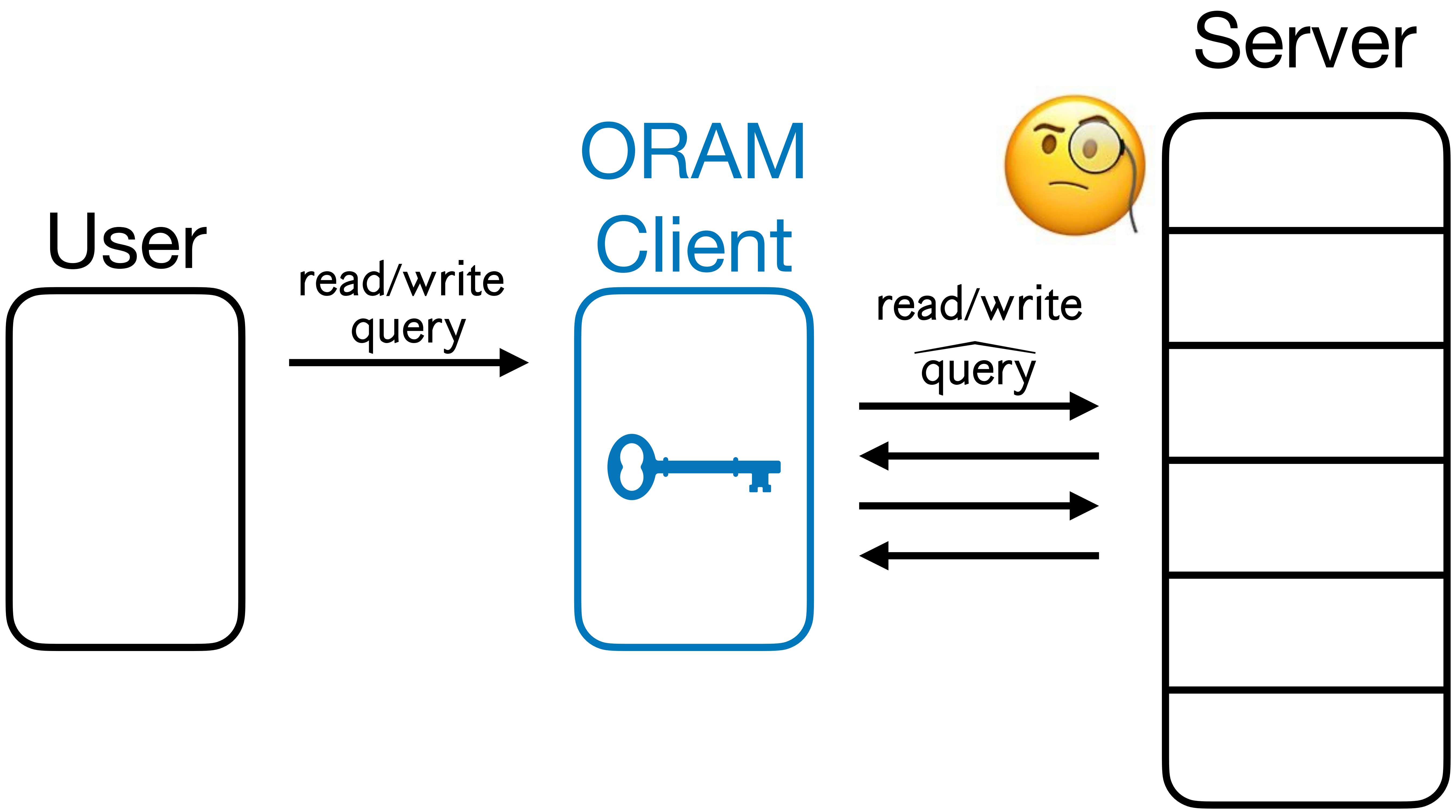
User

read/write
query

ORAM
Client

Oblivious RAM (ORAM)

[Goldreich ’87,
Ostrovsky ’90,
Goldreich-
Ostrovsky ‘96]



Server

ORAM
Client

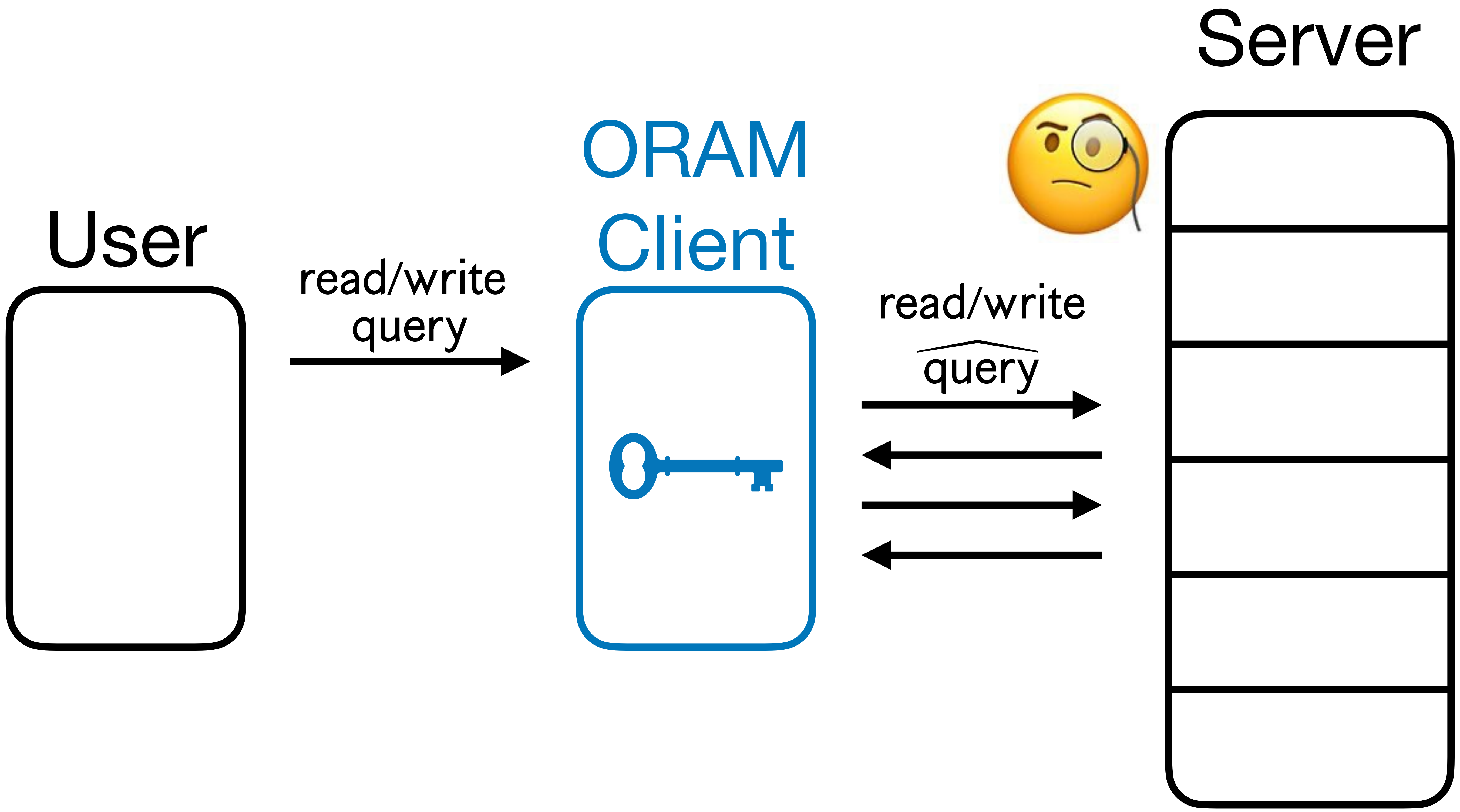
User

read/write
query

read/write
$\widehat{\text{query}}$

Oblivious RAM (ORAM)

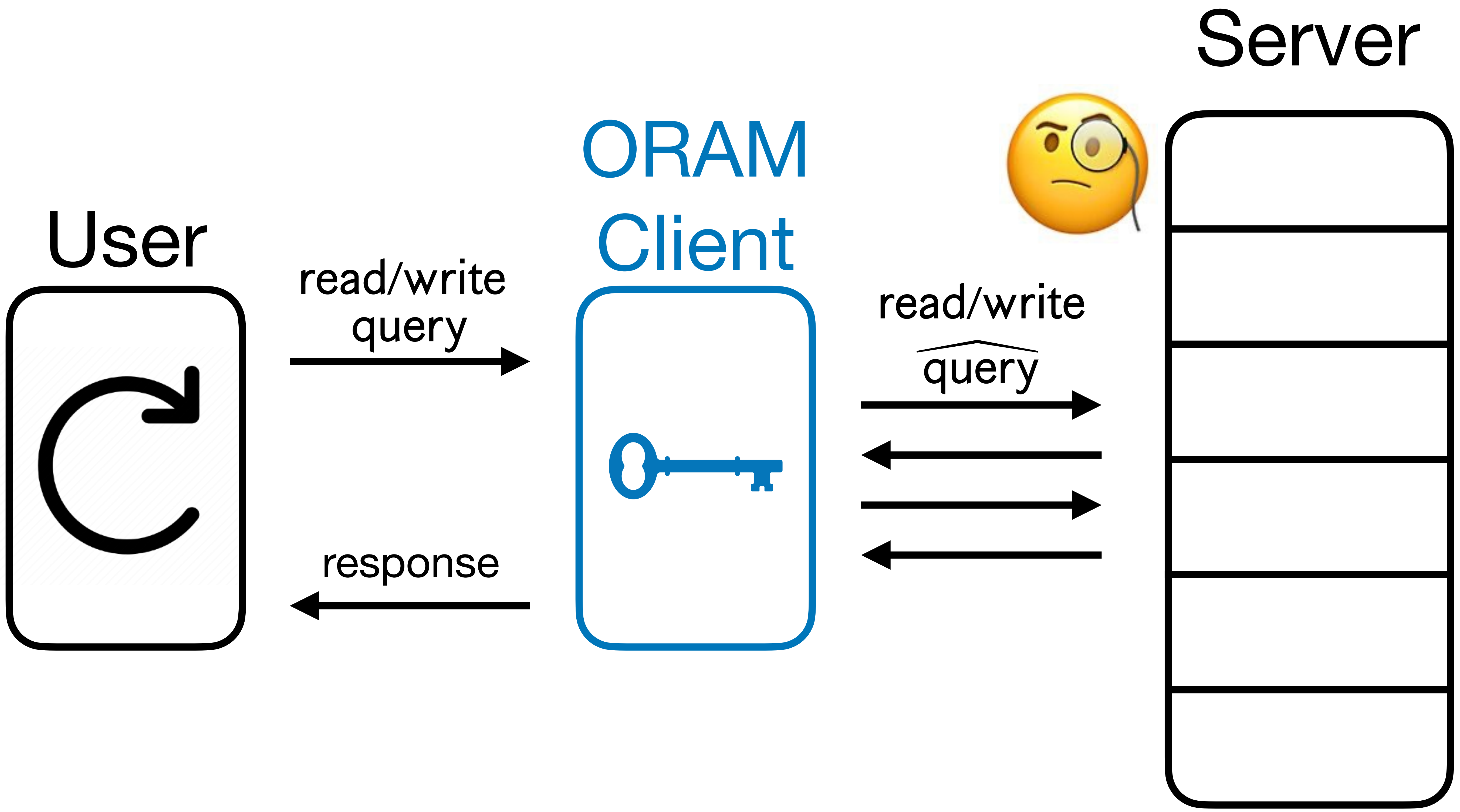
[Goldreich '87,
Ostrovsky '90,
Goldreich-
Ostrovsky '96]



Server is a *passive storage* which does no **additional** work.

Oblivious RAM (ORAM)

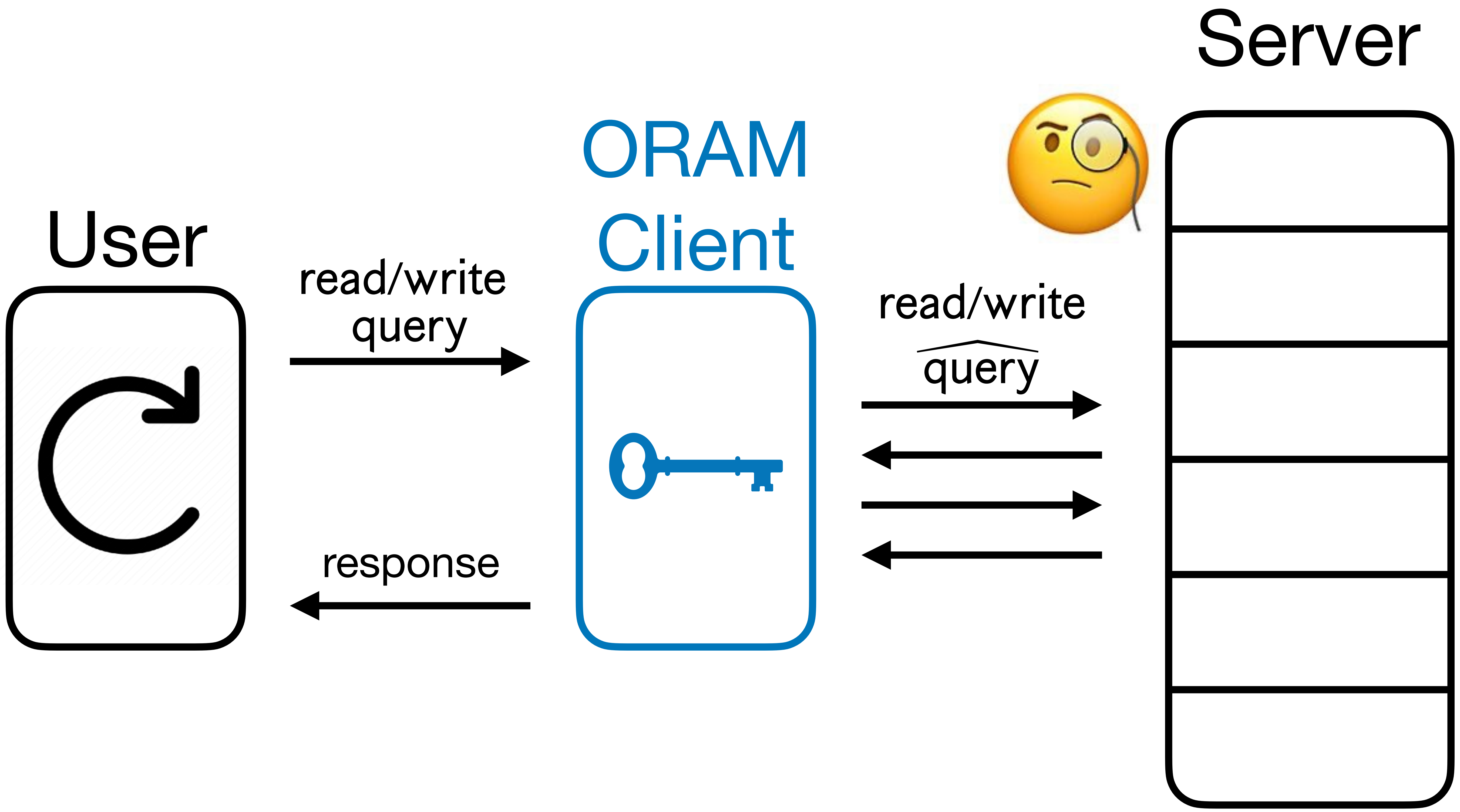
[Goldreich '87, Ostrovsky '90, Goldreich-Ostrovsky '96]



Server is a *passive storage* which does no **additional** work.

Oblivious RAM (ORAM)

[Goldreich ’87,
Ostrovsky ’90,
Goldreich-
Ostrovsky ‘96]



Server

ORAM
Client

User

read/write
query

response

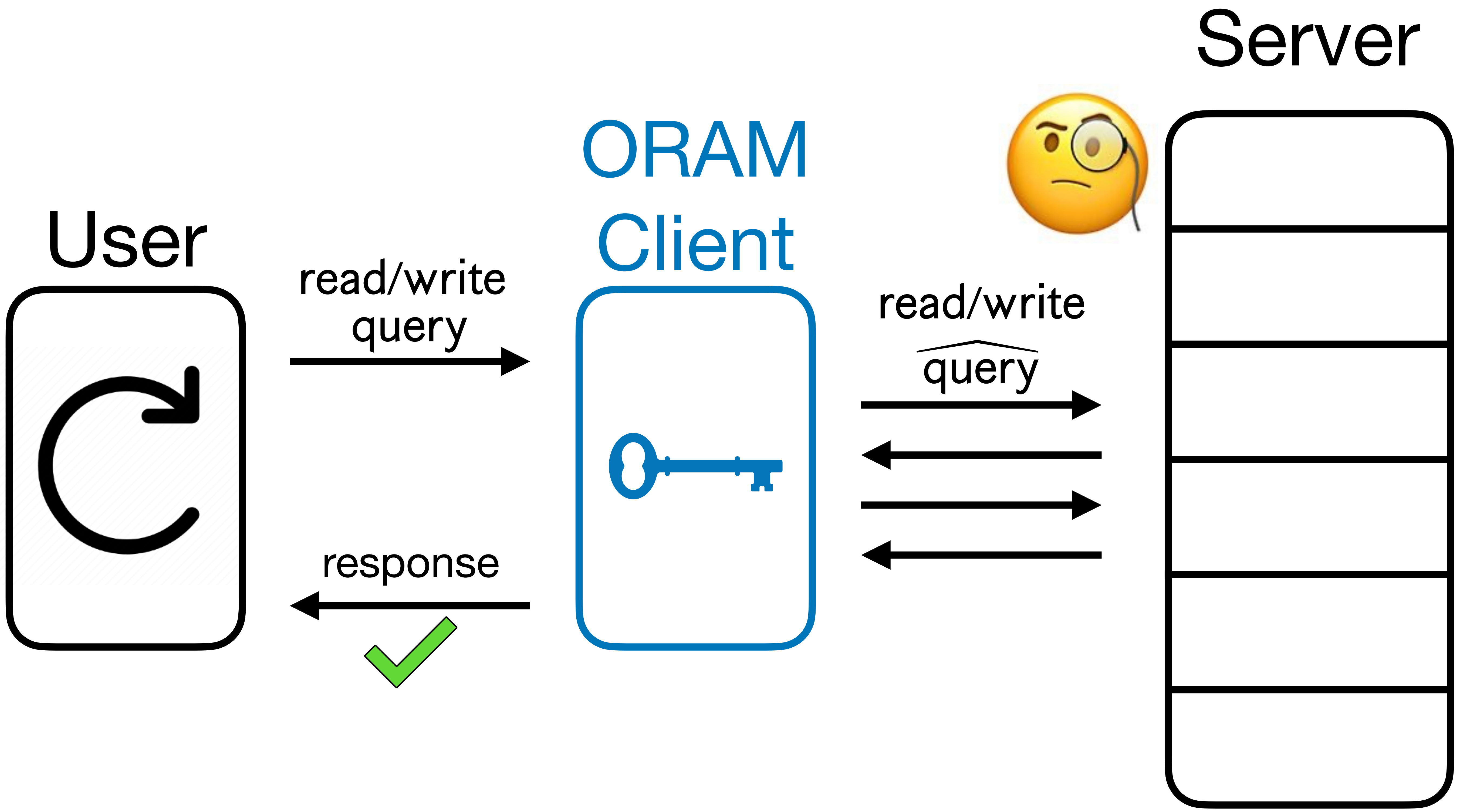
read/write
$\widehat{\text{query}}$

Server is a *passive storage* which does no **additional** work.

- **Correctness:** For any user queries, the ORAM responses to the user are correct.

Oblivious RAM (ORAM)

[Goldreich '87,
Ostrovsky '90,
Goldreich-
Ostrovsky '96]

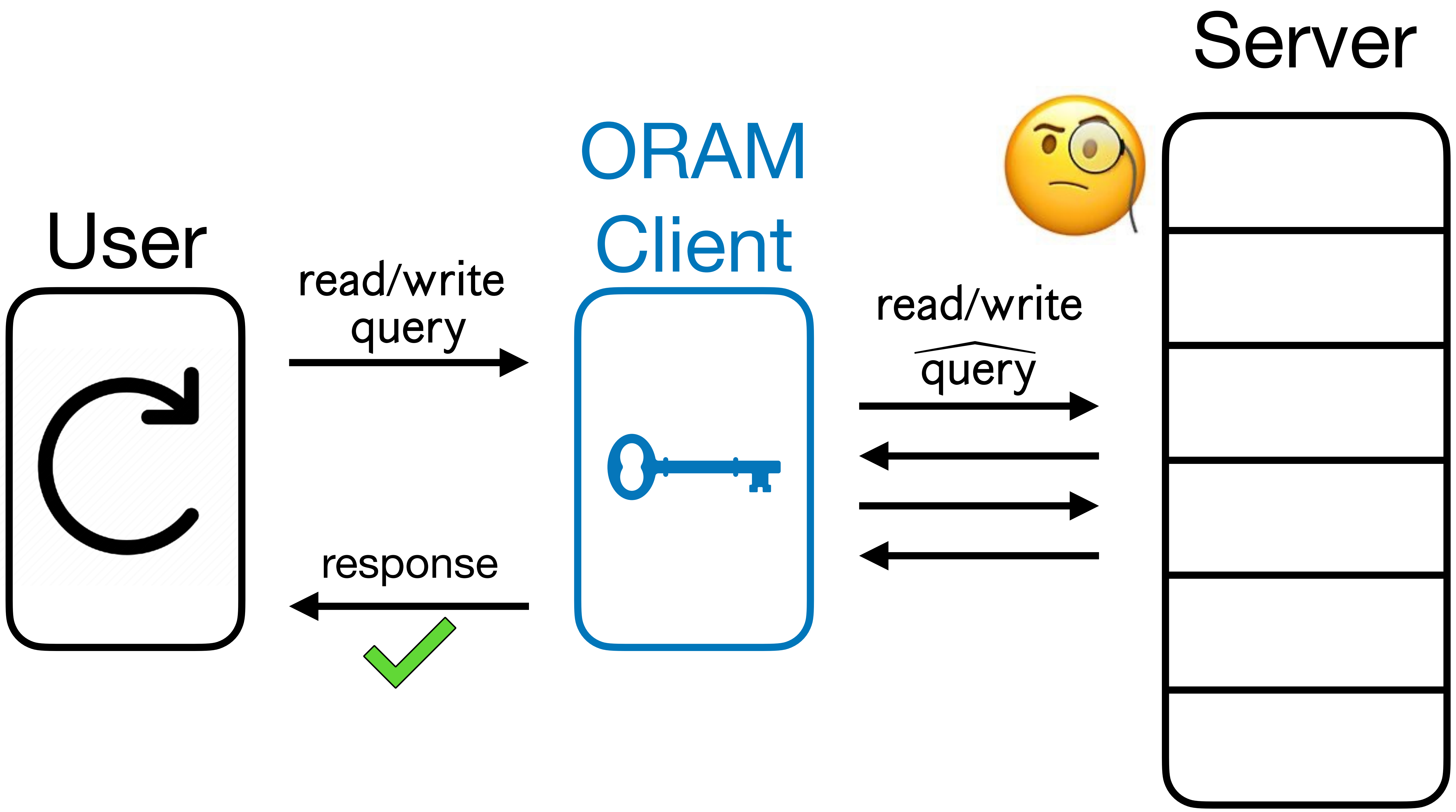


Server is a *passive storage* which does no **additional** work.

- **Correctness:** For any user queries, the ORAM responses to the user are correct.

Oblivious RAM (ORAM)

[Goldreich ’87, Ostrovsky ’90, Goldreich-Ostrovsky ‘96]



Server

ORAM Client

User

read/write query

response

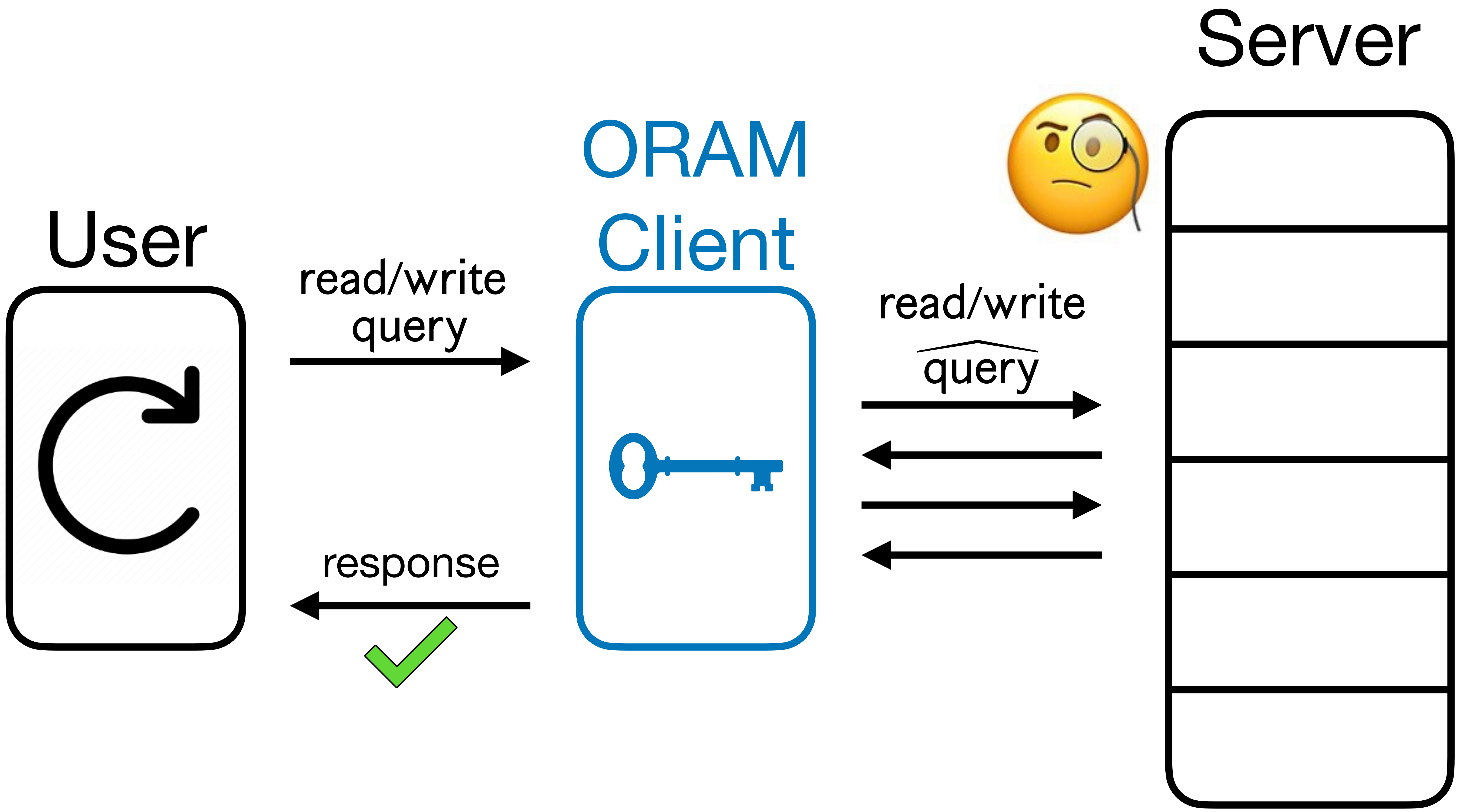
read/write $\widehat{\text{query}}$

Server is a *passive storage* which does no **additional** work.

- **Correctness**: For any user queries, the ORAM responses to the user are correct.
- **Obliviousness**: Compiled queries leak *nothing* about the user queries (except for the number of queries):

Oblivious RAM (ORAM)

[Goldreich ’87, Ostrovsky ’90, Goldreich-Ostrovsky ‘96]



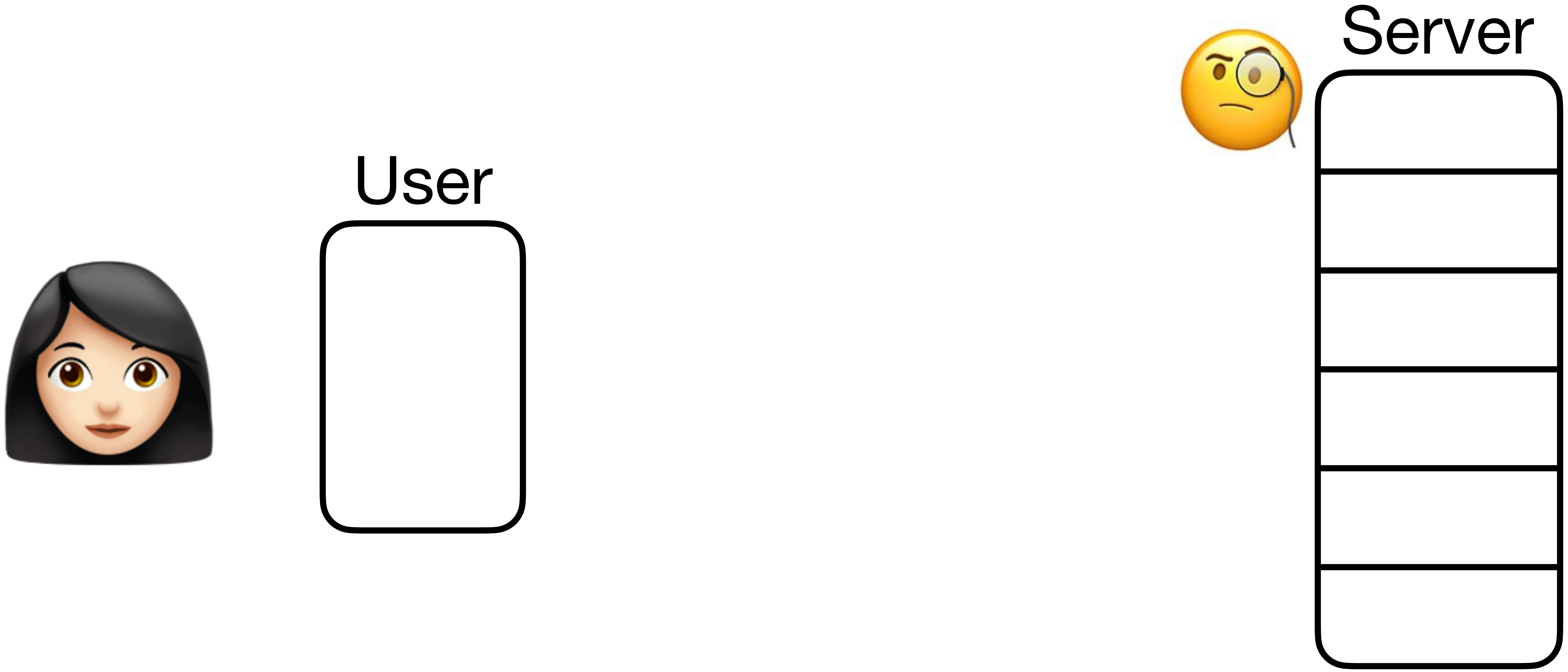
Server is a *passive storage* which does no **additional** work.

- **Correctness**: For any user queries, the ORAM responses to the user are correct.

- **Obliviousness**: Compiled queries leak *nothing* about the user queries (except for the number of queries):

$$“\{\widehat{\text{query}}\} \approx_{\text{comp}} \text{Sim}\left(1^{|\overrightarrow{\text{query}}|}\right)”$$

Application: File Storage Platforms

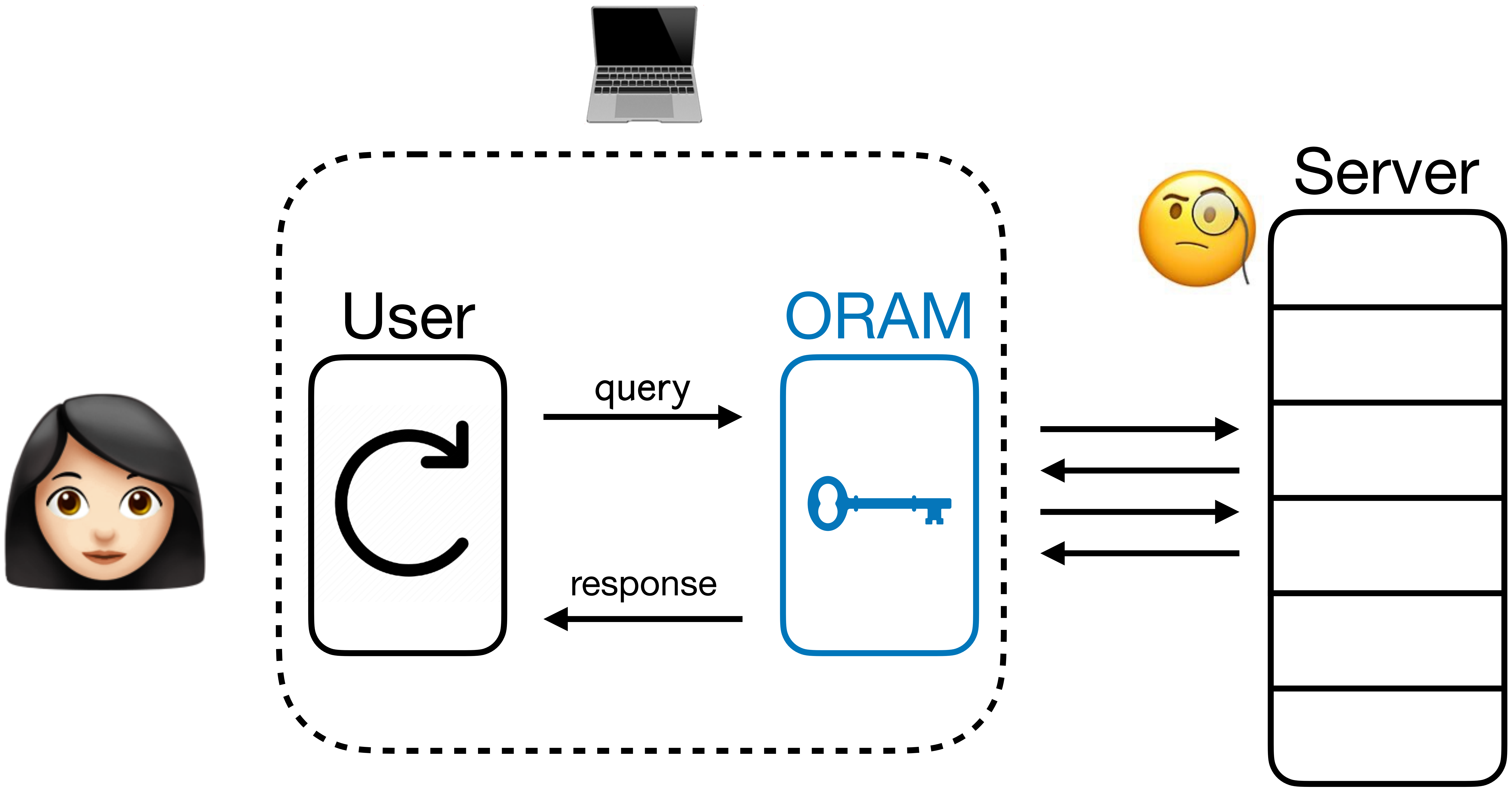


Dropbox

Google Drive

OneDrive

Application: File Storage Platforms



User

query

response

ORAM

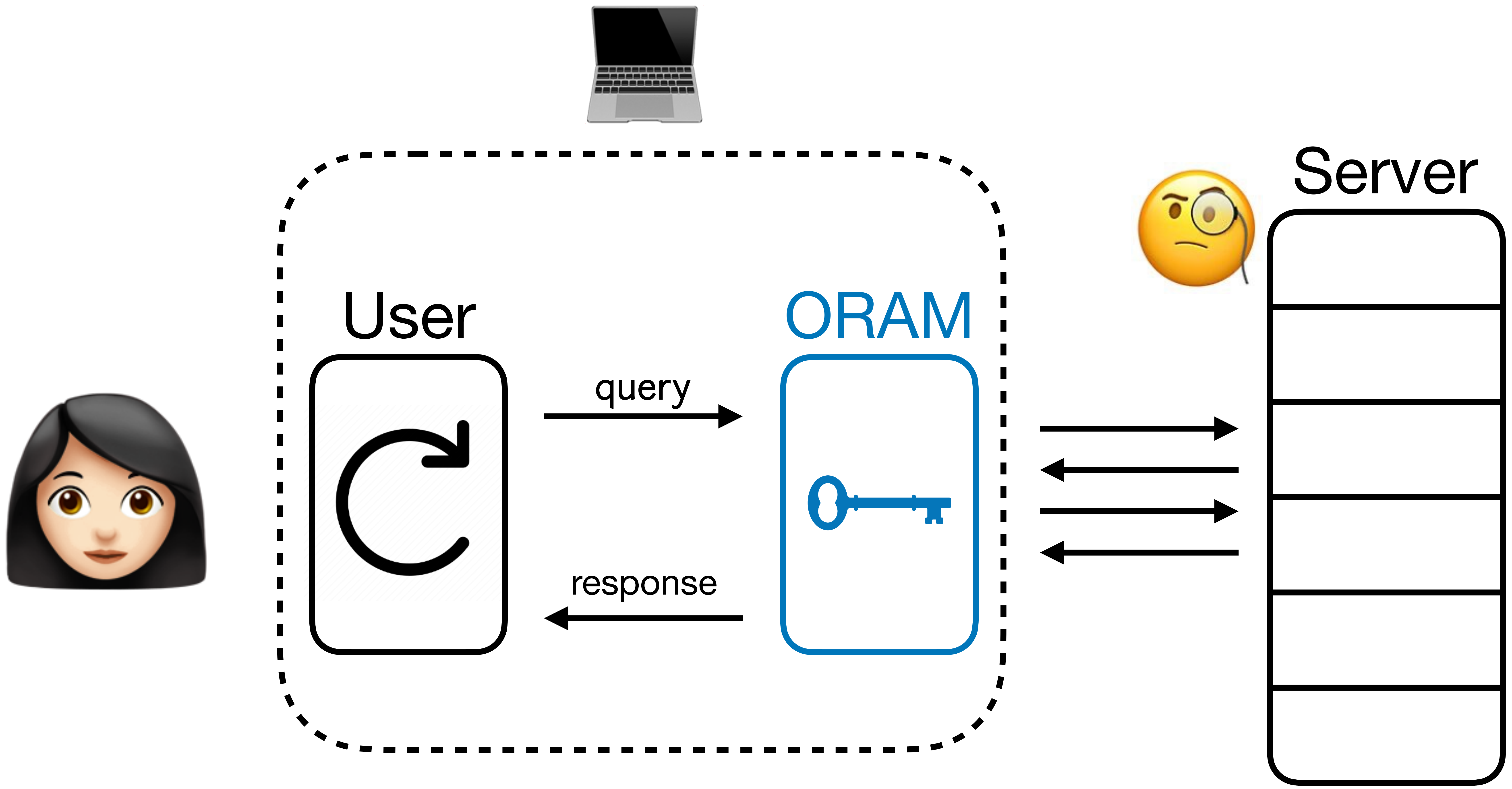
Server

Dropbox

Google Drive

OneDrive

Application: File Storage Platforms



User

query

response

ORAM

Server

Dropbox

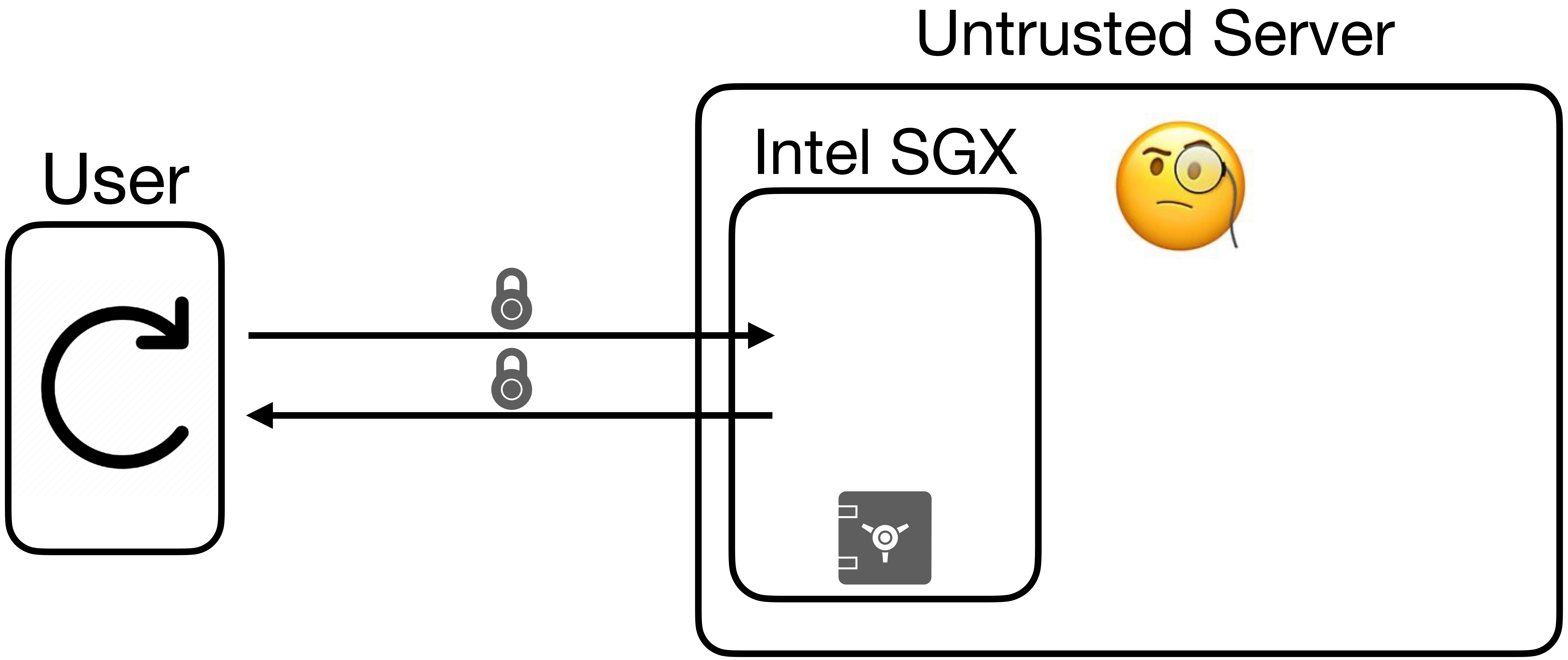
Google Drive

OneDrive

With ORAM, storage platform can’t learn anything.

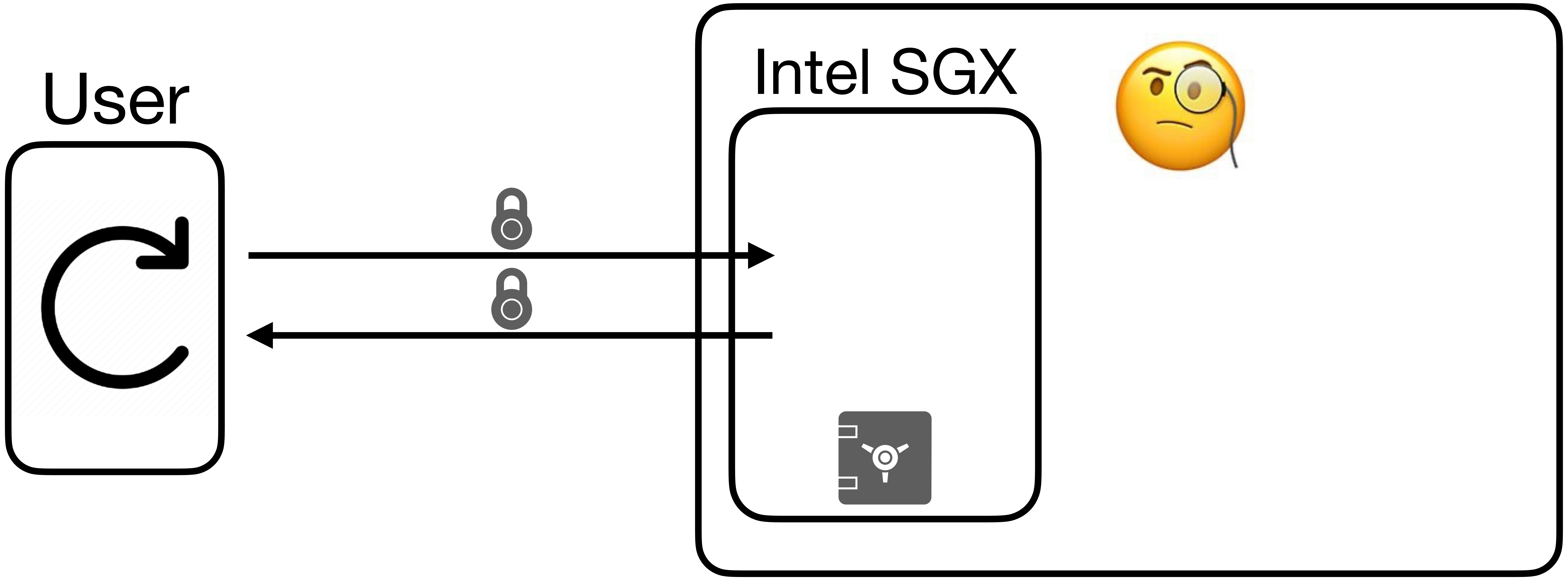
Application: Secure Hardware Enclaves

- **Secure Hardware Enclaves** (e.g., Intel SGX) allow users to execute programs securely on untrusted remote servers.



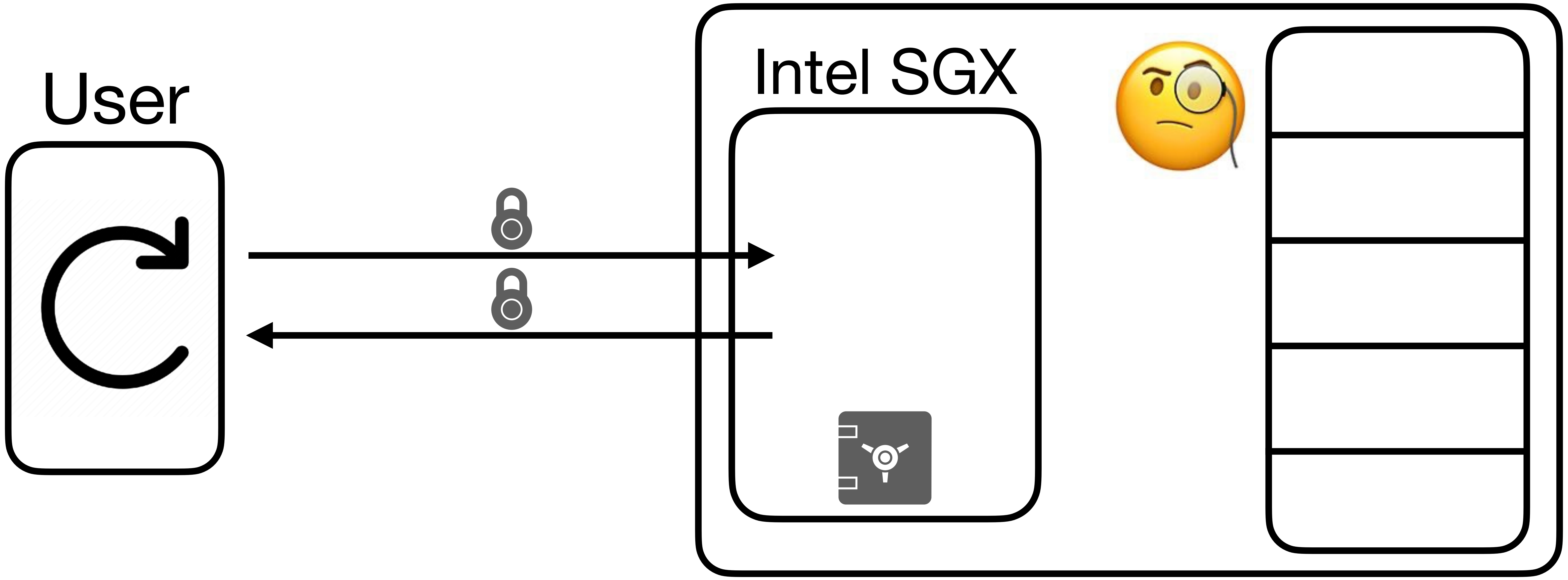
Application: Secure Hardware Enclaves

- **Secure Hardware Enclaves** (e.g., Intel SGX) allow users to execute programs securely on untrusted remote servers.
- Some enclaves have tiny internal space. Use untrusted memory within the server!



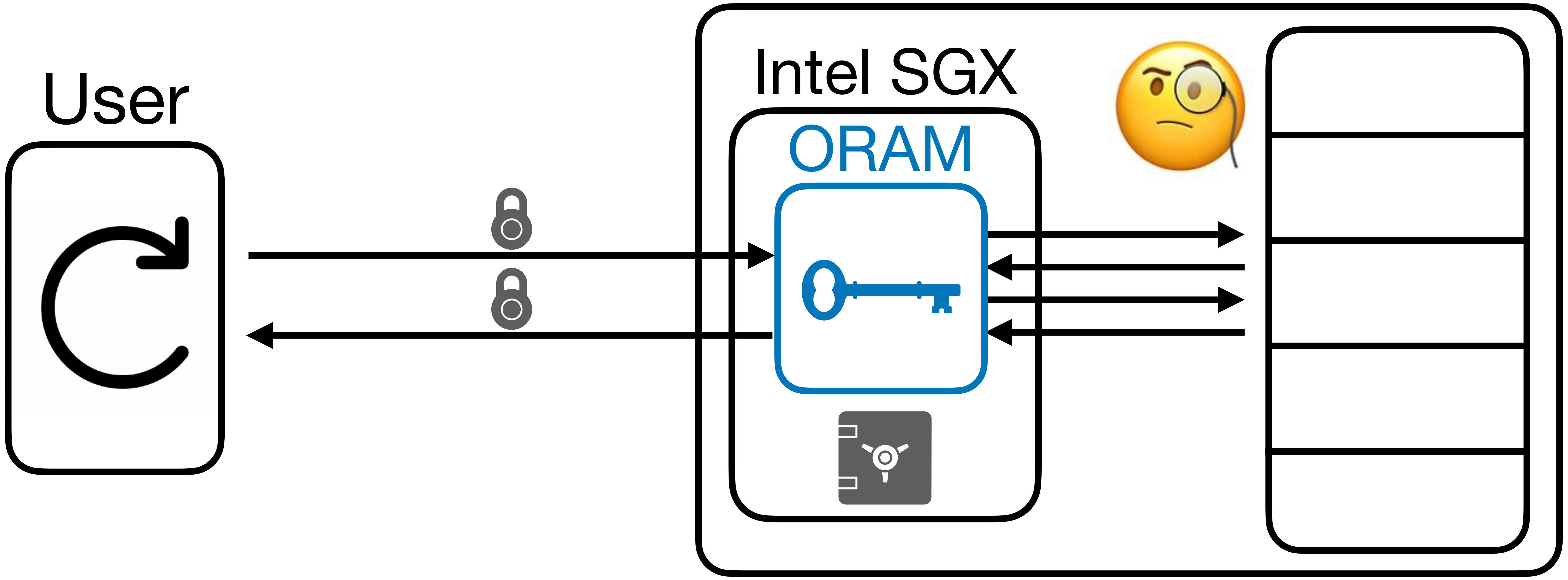
Application: Secure Hardware Enclaves

- **Secure Hardware Enclaves** (e.g., Intel SGX) allow users to execute programs securely on untrusted remote servers.
- Some enclaves have tiny internal space. Use untrusted memory within the server!



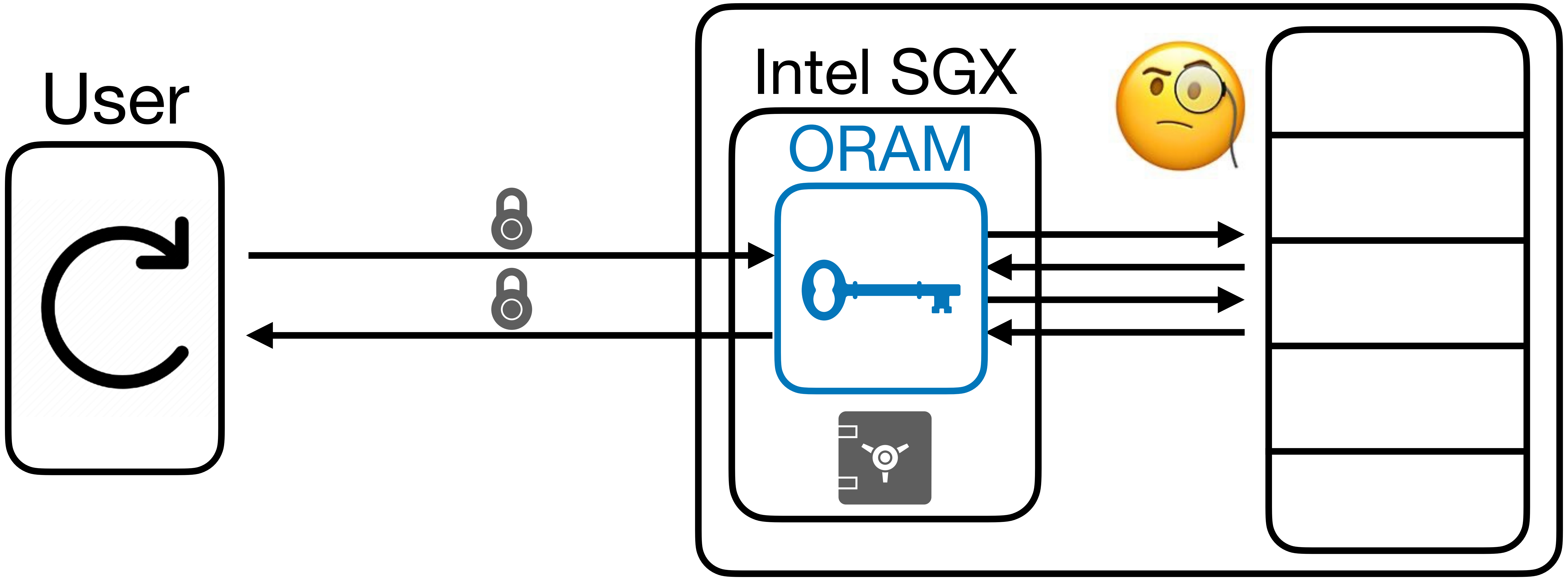
Application: Secure Hardware Enclaves

- **Secure Hardware Enclaves** (e.g., Intel SGX) allow users to execute programs securely on untrusted remote servers.
- Some enclaves have tiny internal space. Use untrusted memory within the server!



Application: Secure Hardware Enclaves

- **Secure Hardware Enclaves** (e.g., Intel SGX) allow users to execute programs securely on untrusted remote servers.
- Some enclaves have tiny internal space. Use untrusted memory within the server!



- **Real World**: Signal very recently implemented ORAM for private contact discovery!

Signal

ORAM vs. PIR

ORAM vs. PIR

- Private Information Retrieval (PIR) is similar to ORAM but has crucial differences:

ORAM vs. PIR

- Private Information Retrieval (PIR) is similar to ORAM but has crucial differences:
    - In PIR, the database is typically **public**.

ORAM vs. PIR

- Private Information Retrieval (PIR) is similar to ORAM but has crucial differences:
  - In PIR, the database is typically **public**.
  - Unlike ORAM, PIR allows **many clients** to access database.

ORAM vs. PIR

- Private Information Retrieval (PIR) is similar to ORAM but has crucial differences:

  - In PIR, the database is typically **public**.

  - Unlike ORAM, PIR allows **many clients** to access database.

  - PIR (usually) not stateful, and is typically **read-only** (not updatable).

ORAM Efficiency

ORAM Efficiency

Two main complexity measures for ORAMs:

ORAM Efficiency

Two main complexity measures for ORAMs:

1. **Local Space**: Amount of space the ORAM can store locally (trusted & private).

ORAM Efficiency

Two main complexity measures for ORAMs:

1. **Local Space**: Amount of space the ORAM can store locally (trusted & private).
    - For a RAM with N entries, space N is trivial (can store the full RAM itself).

ORAM Efficiency

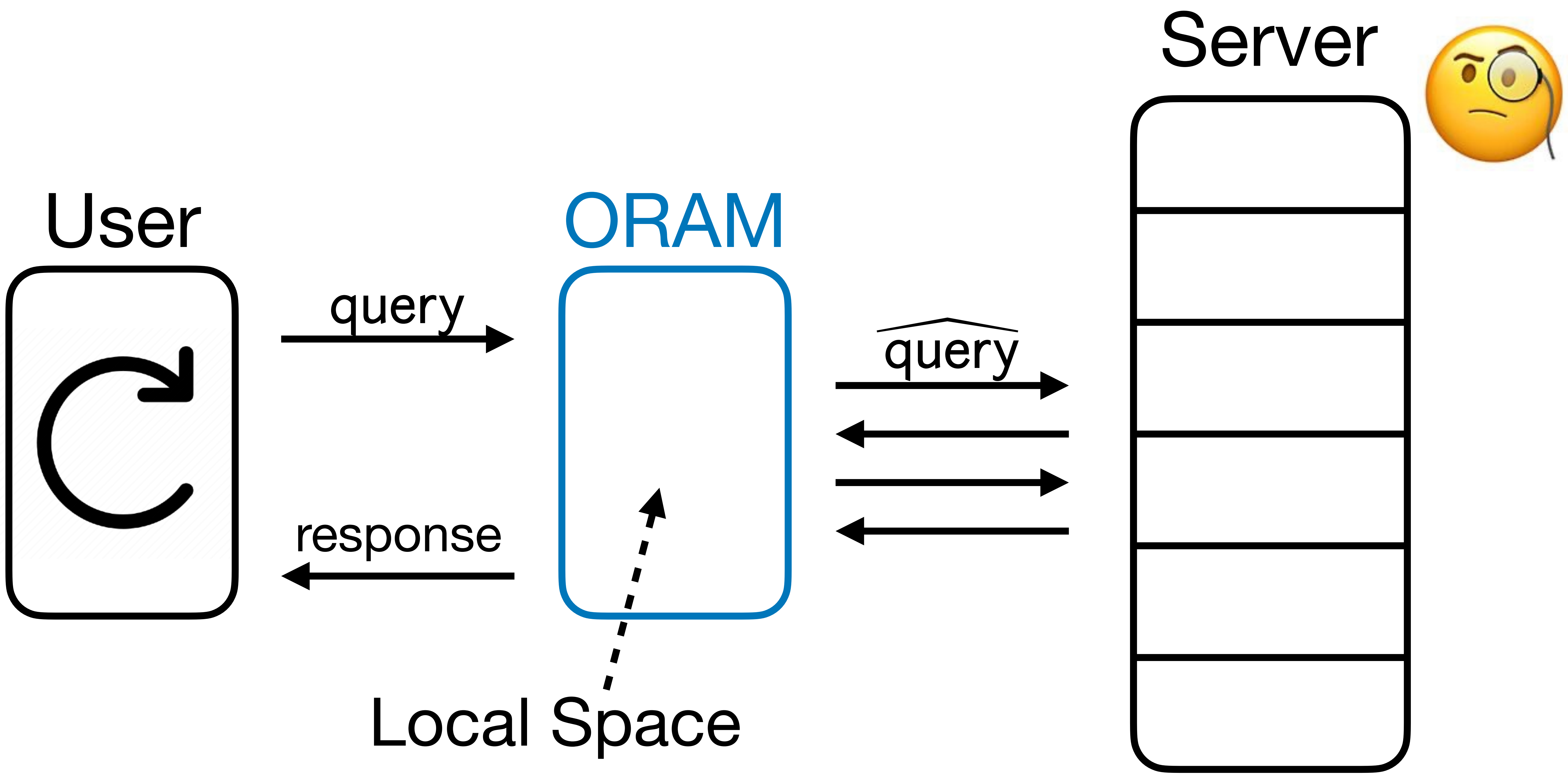
Two main complexity measures for ORAMs:

1. **Local Space**: Amount of space the ORAM can store locally (trusted & private).

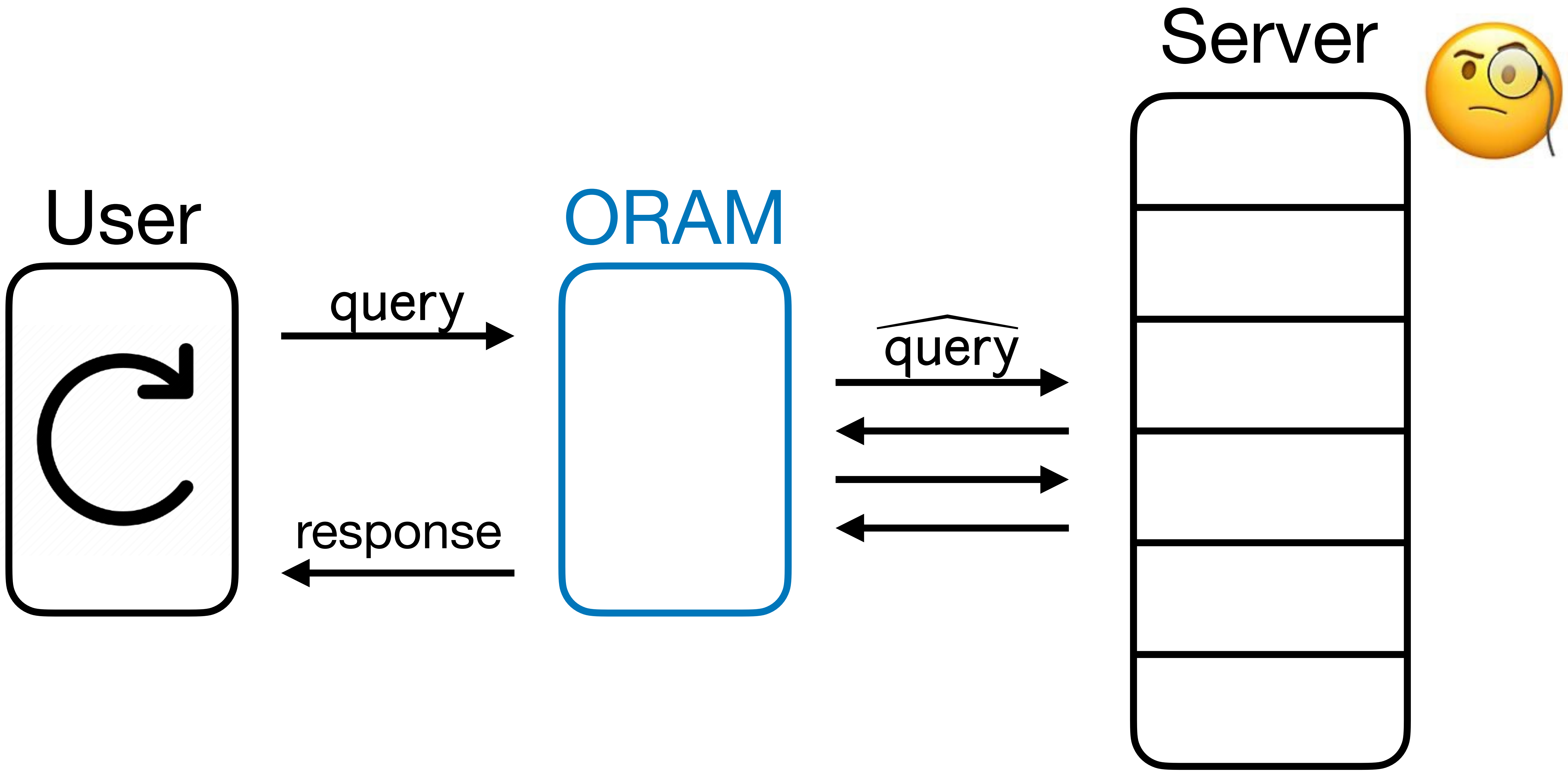
    - For a RAM with N entries, space N is trivial (can store the full RAM itself).

    - For the rest of the talk, think space $O(1)$ words (of size $\approx \log(N)$).

ORAM Efficiency

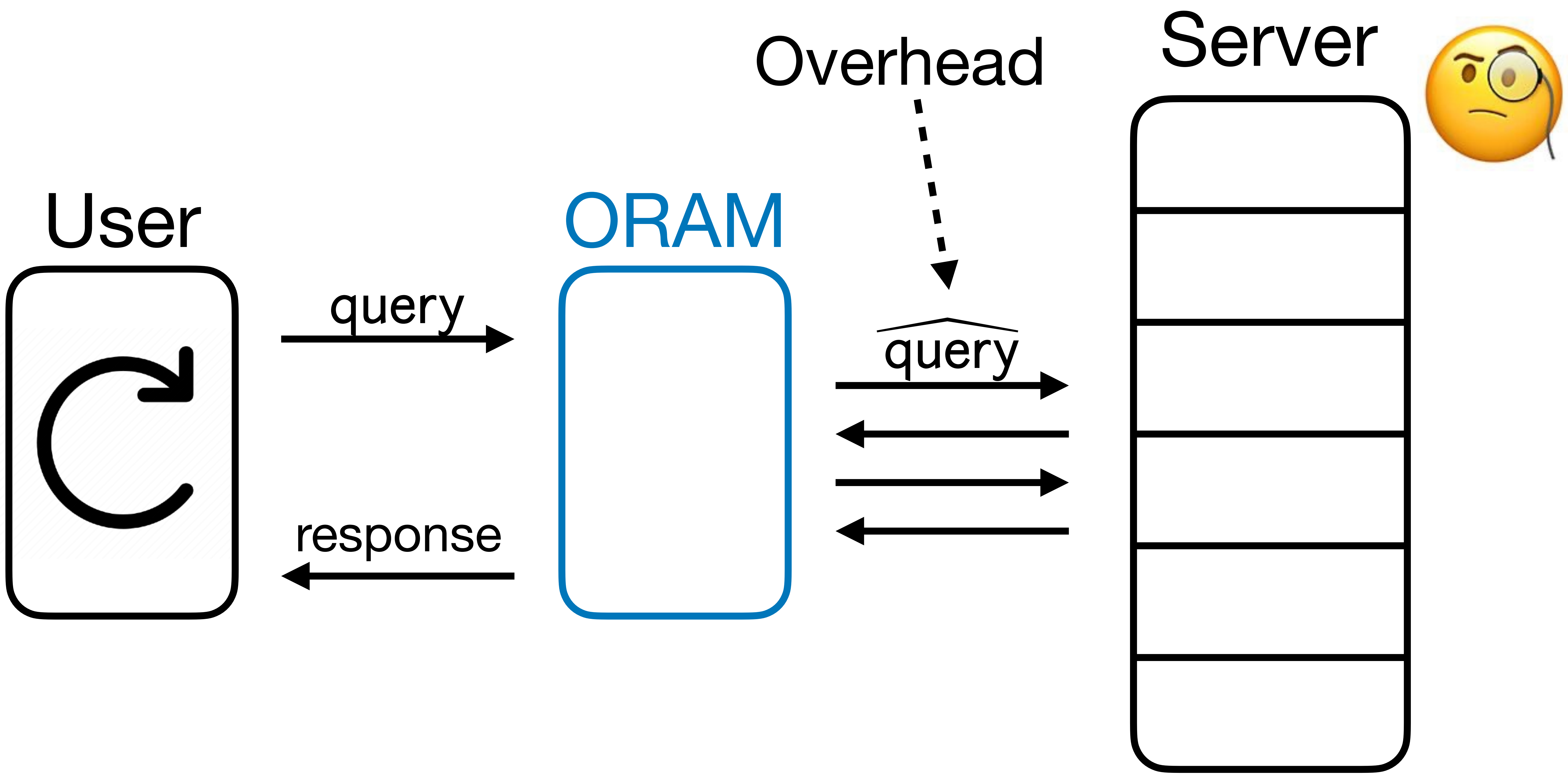


ORAM Efficiency



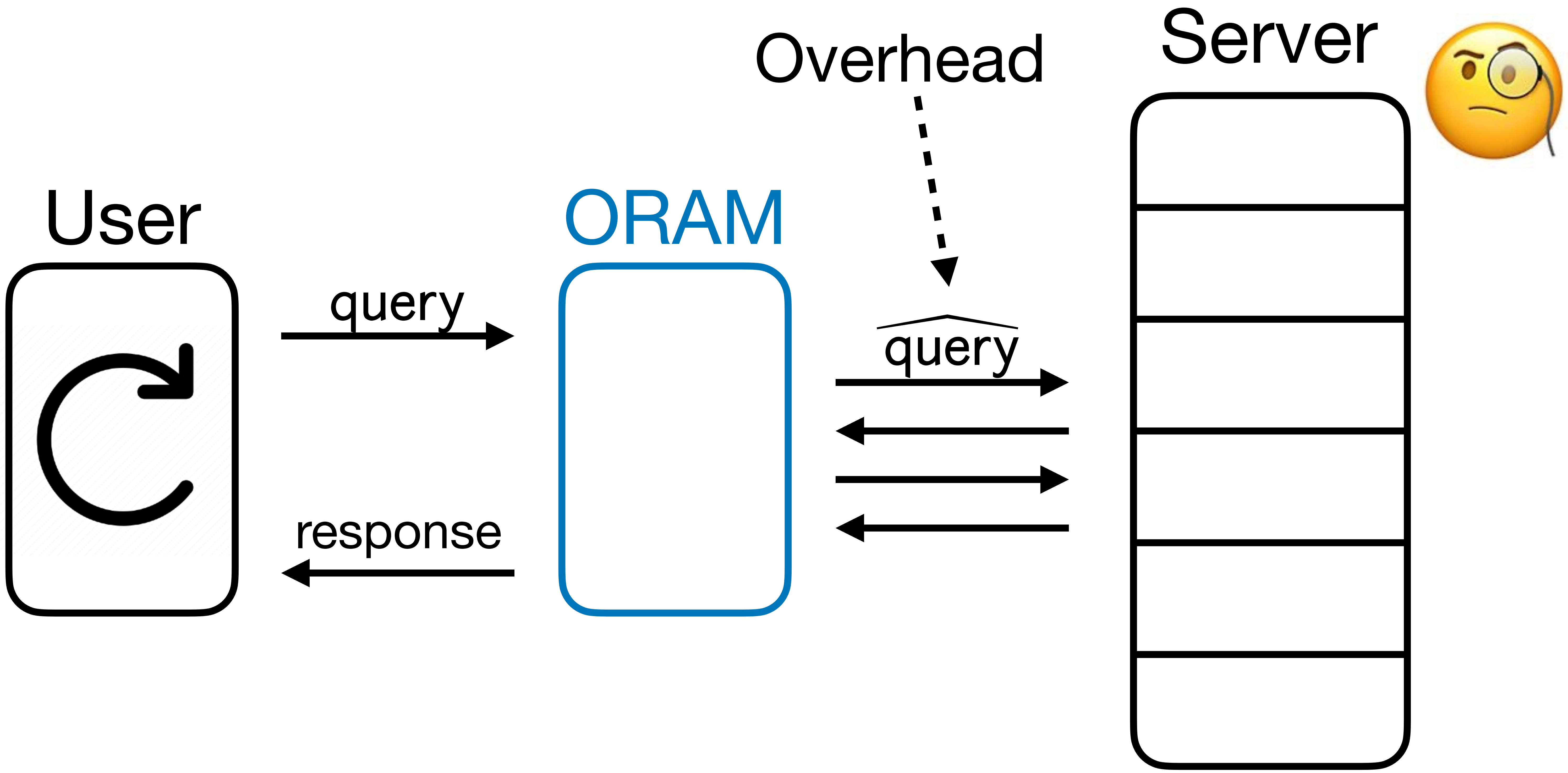
2. **Overhead:** Number of queries made to the server per user query.

ORAM Efficiency



2. **Overhead:** Number of queries made to the server per user query.

ORAM Efficiency



2. **Overhead:** Number of queries made to the server per user query.

- For a RAM with N entries, overhead N is trivial (always do a linear scan).

ORAM History

RAM of size N, word size $\Theta(\log N)$, local space size $O(1)$

Work	**Overhead**

ORAM History

RAM of size N, word size $\Theta(\log N)$, local space size $O(1)$

Work	**Overhead**
[Goldreich ’87]	$\sqrt{N} \log N$

ORAM History

RAM of size N, word size $\Theta(\log N)$, local space size $O(1)$

Work	**Overhead**
[Goldreich ’87]	$\sqrt{N} \log N$
[Ostrovsky ’90, Goldreich-Ostrovsky ’96]	$\log^3 N$

ORAM History

RAM of size N, word size $\Theta(\log N)$, local space size $O(1)$

Work	**Overhead**
[Goldreich ’87]	$\sqrt{N}\log N$
[Ostrovsky ’90, Goldreich-Ostrovsky ’96]	$\log^3 N$
Path ORAM [SvDSCFRYD ’12]	$\log^2 N$

ORAM History

RAM of size N, word size $\Theta(\log N)$, local space size $O(1)$

Work	**Overhead**
[Goldreich ’87]	$\sqrt{N} \log N$
[Ostrovsky ’90, Goldreich-Ostrovsky ’96]	$\log^3 N$
Path ORAM [SvDSCFRYD ’12]	$\log^2 N$
PanORAMa [Patel-Persiano-Raykova-Yeo ’18]	$\log N \log \log N$

ORAM History

RAM of size N, word size $\Theta(\log N)$, local space size $O(1)$

Work	**Overhead**
[Goldreich ’87]	$\sqrt{N} \log N$
[Ostrovsky ’90, Goldreich-Ostrovsky ’96]	$\log^3 N$
Path ORAM [SvDSCFRYD ’12]	$\log^2 N$
PanORAMa [Patel-Persiano-Raykova-Yeo ’18]	$\log N \log \log N$
OptORAMa [AKLNPS ‘20, AKLS ’21]	$\log N$

ORAM History

RAM of size N, word size $\Theta(\log N)$, local space size $O(1)$

Work	**Overhead**
[Goldreich ’87]	$\sqrt{N} \log N$
[Ostrovsky ’90, Goldreich-Ostrovsky ’96]	$\log^3 N$
Path ORAM [SvDSCFRYD ’12]	$\log^2 N$
PanORAMa [Patel-Persiano-Raykova-Yeo ’18]	$\log N \log \log N$
OptORAMa [AKLNPS ‘20, AKLS ’21]	$\log N$

Lower Bound: [Goldreich ’87, Larsen-Nielsen ’18, Komargodski-Lin ’21]	$\Omega\left(\log N\right)$

ORAM History

RAM of size N, word size $\Theta(\log N)$, local space size $O(1)$

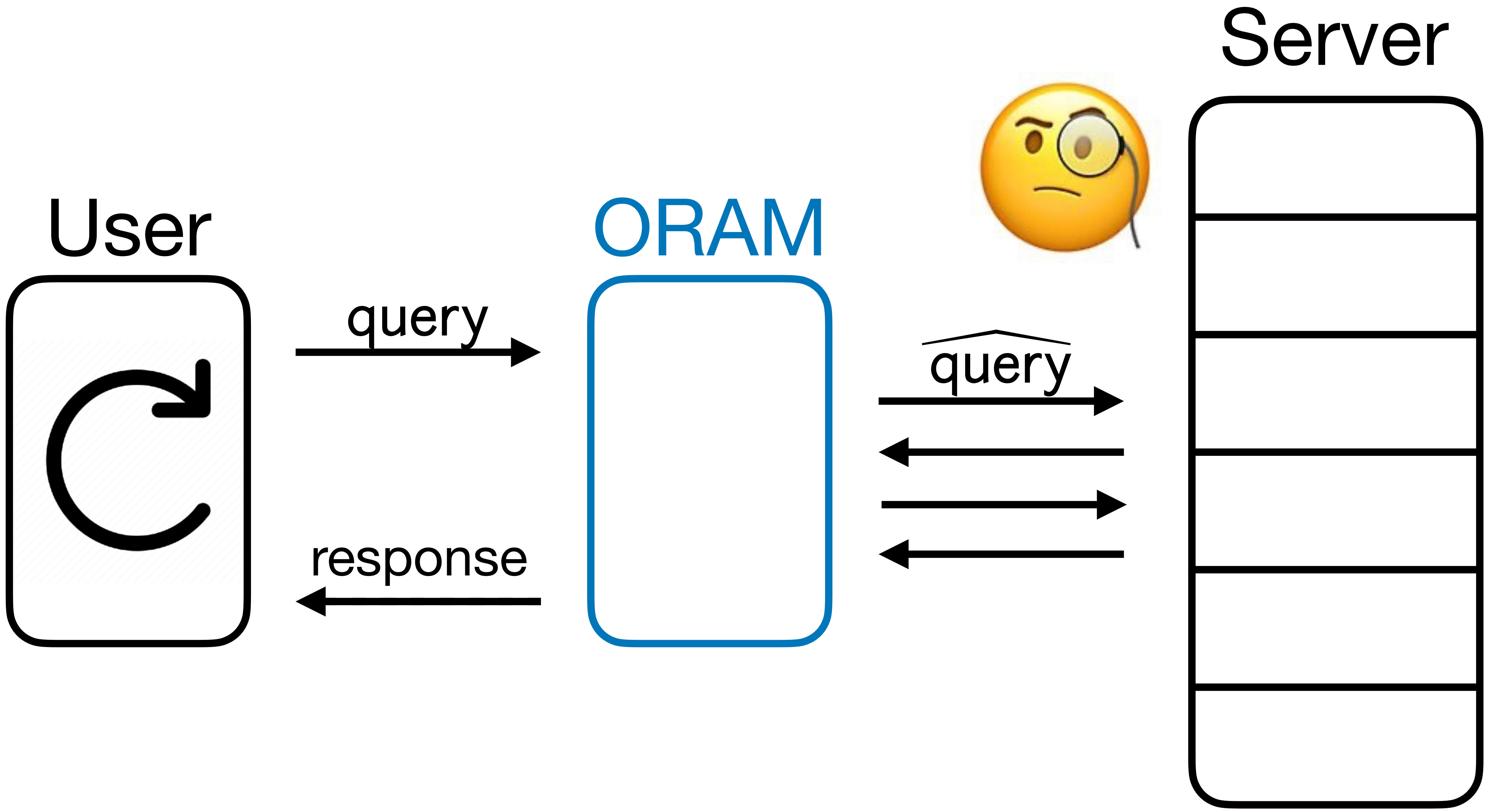
Work	**Overhead**
[Goldreich ’87]	$\sqrt{N} \log N$
[Ostrovsky ’90, Goldreich-Ostrovsky ’96]	$\log^3 N$
Path ORAM [SvDSCFRYD ’12]	$\log^2 N$
PanORAMa [Patel-Persiano-Raykova-Yeo ’18]	$\log N \log \log N$
OptORAMa [AKLNPS ‘20, AKLS ’21]	$\log N$

Optimal!

Lower Bound: [Goldreich ’87, Larsen-Nielsen ’18, Komargodski-Lin ’21]	$\Omega\left(\log N\right)$

Power of the Adversary

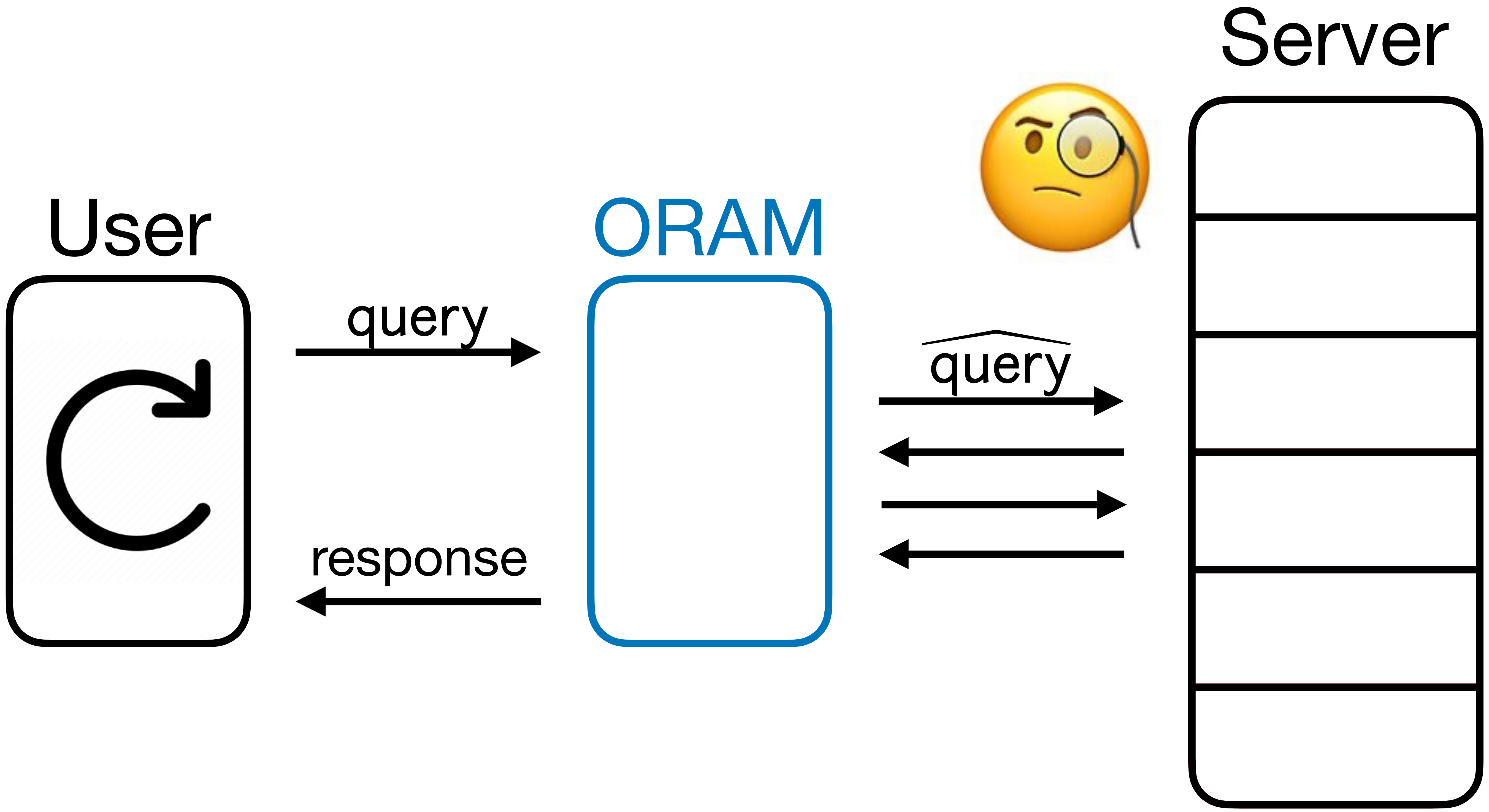
- But up until now, we have assumed a **passive**, **honest-but-curious** RAM server that can try to learn something about the queries.



Power of the Adversary

- But up until now, we have assumed a **passive**, **honest-but-curious** RAM server that can try to learn something about the queries.

- In reality, ***an adversary can do more***! What about an **active, malicious** adversary that can **modify** the contents in the RAM?



Server

User

ORAM

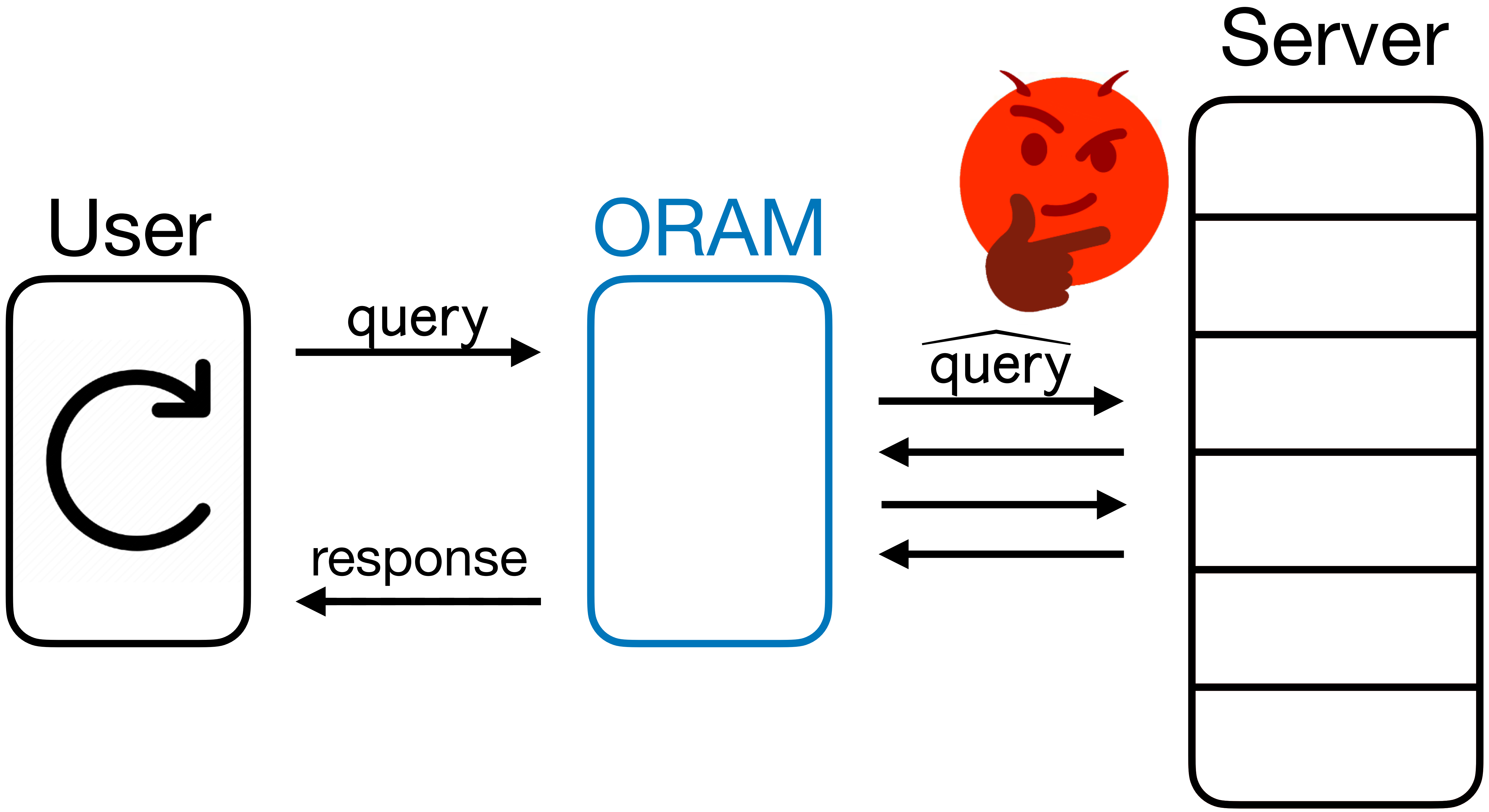
query

$\widehat{\text{query}}$

response

Power of the Adversary

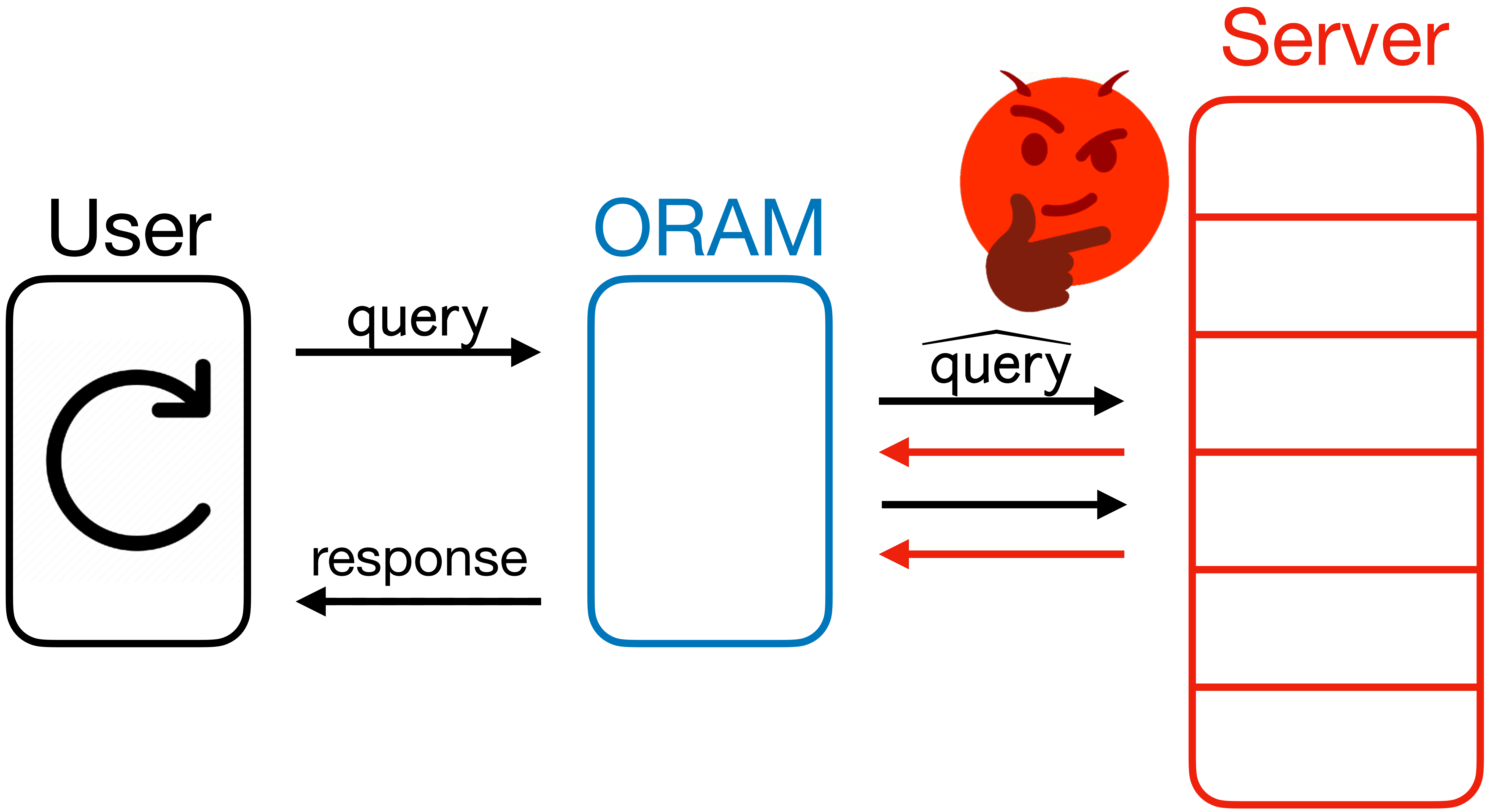
- But up until now, we have assumed a **passive**, **honest-but-curious** RAM server that can try to learn something about the queries.
- In reality, ***an adversary can do more***! What about an **active, malicious** adversary that can **modify** the contents in the RAM?



Power of the Adversary

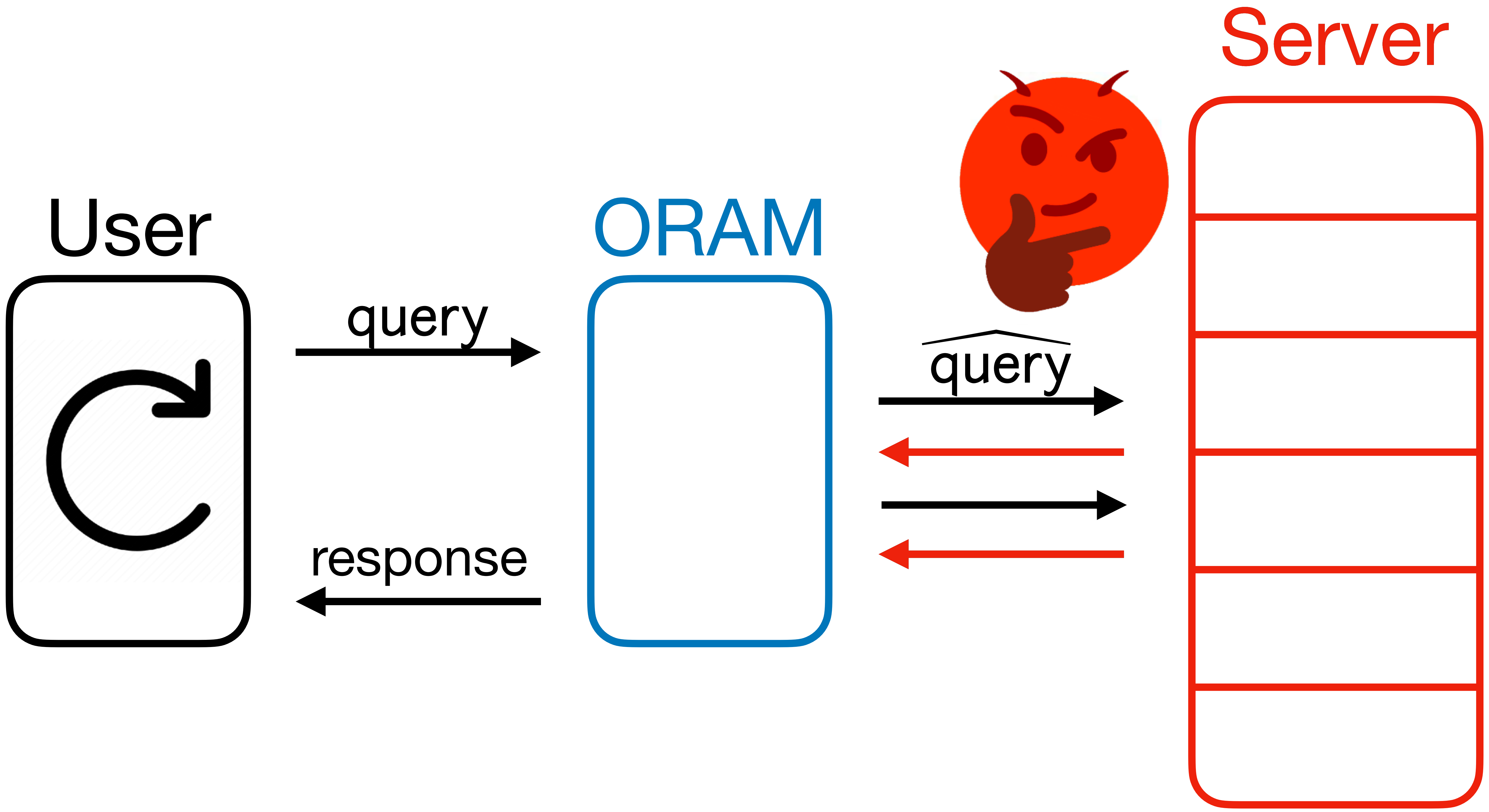
- But up until now, we have assumed a **passive**, **honest-but-curious** RAM server that can try to learn something about the queries.

- In reality, ***an adversary can do more***! What about an **active, malicious** adversary that can **modify** the contents in the RAM?



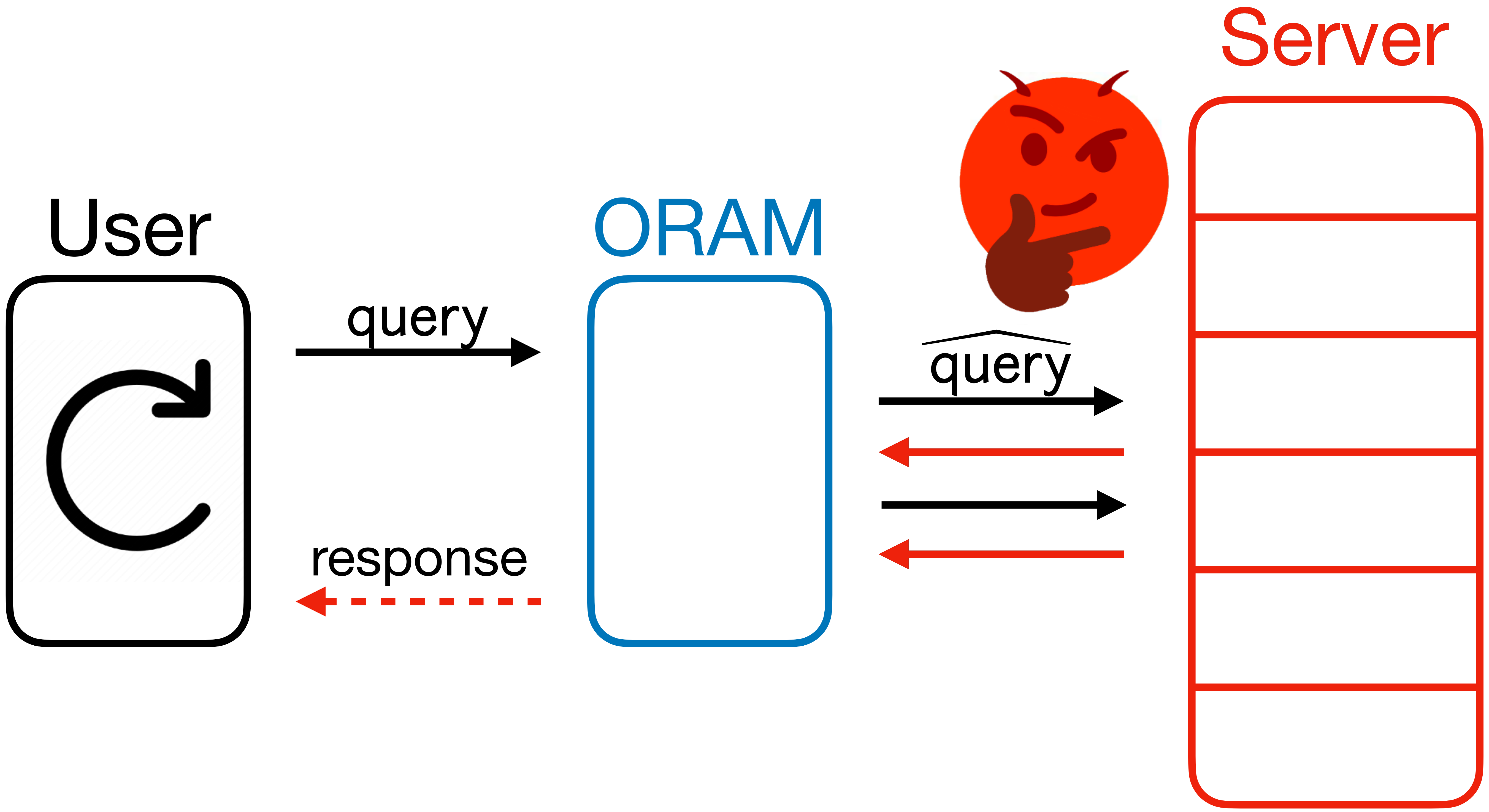
Malicious Security

- A malicious server breaks correctness



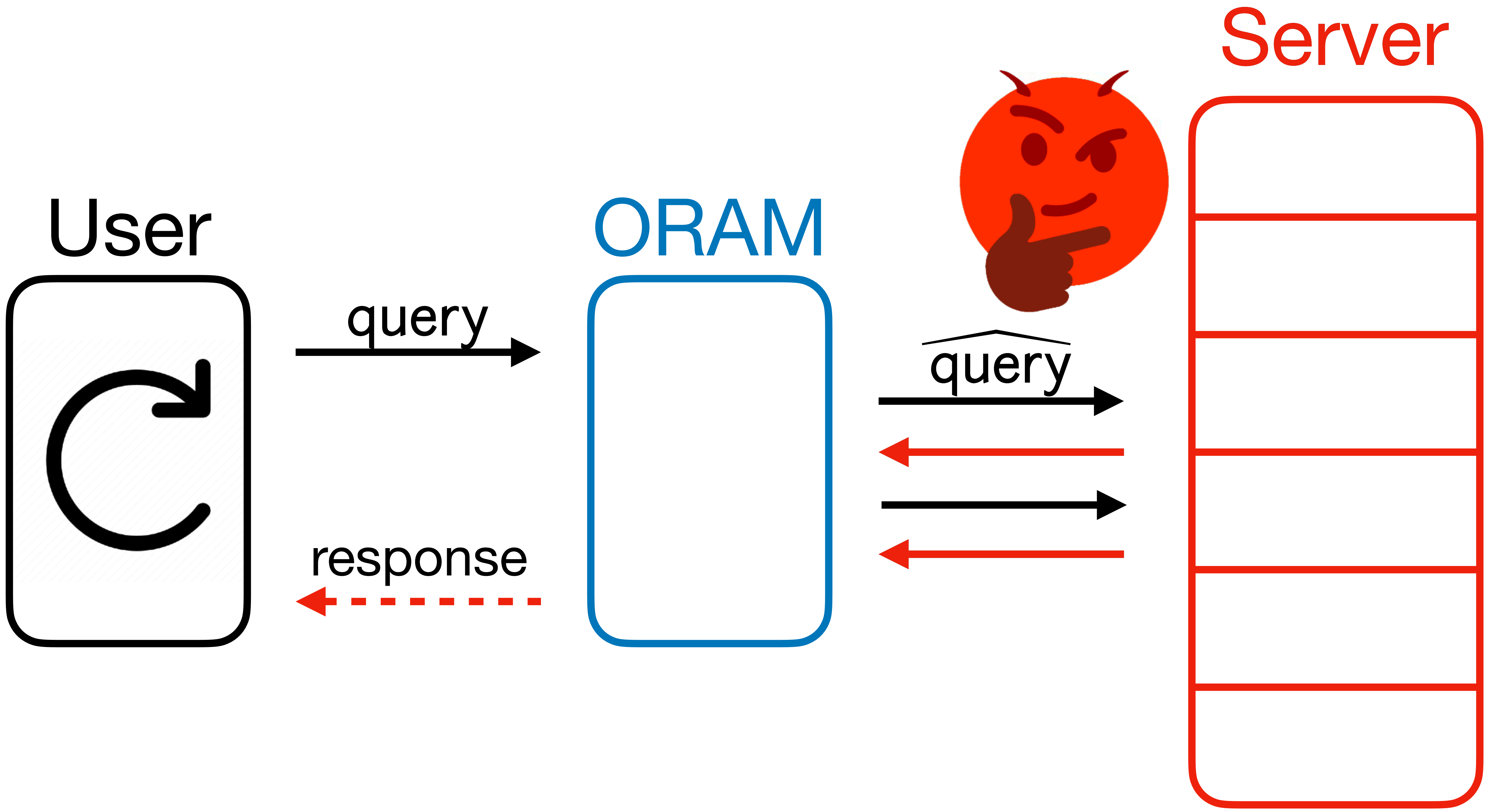
Malicious Security

- A malicious server breaks correctness



Malicious Security

- A malicious server breaks correctness *and also obliviousness*.



Server

User

ORAM

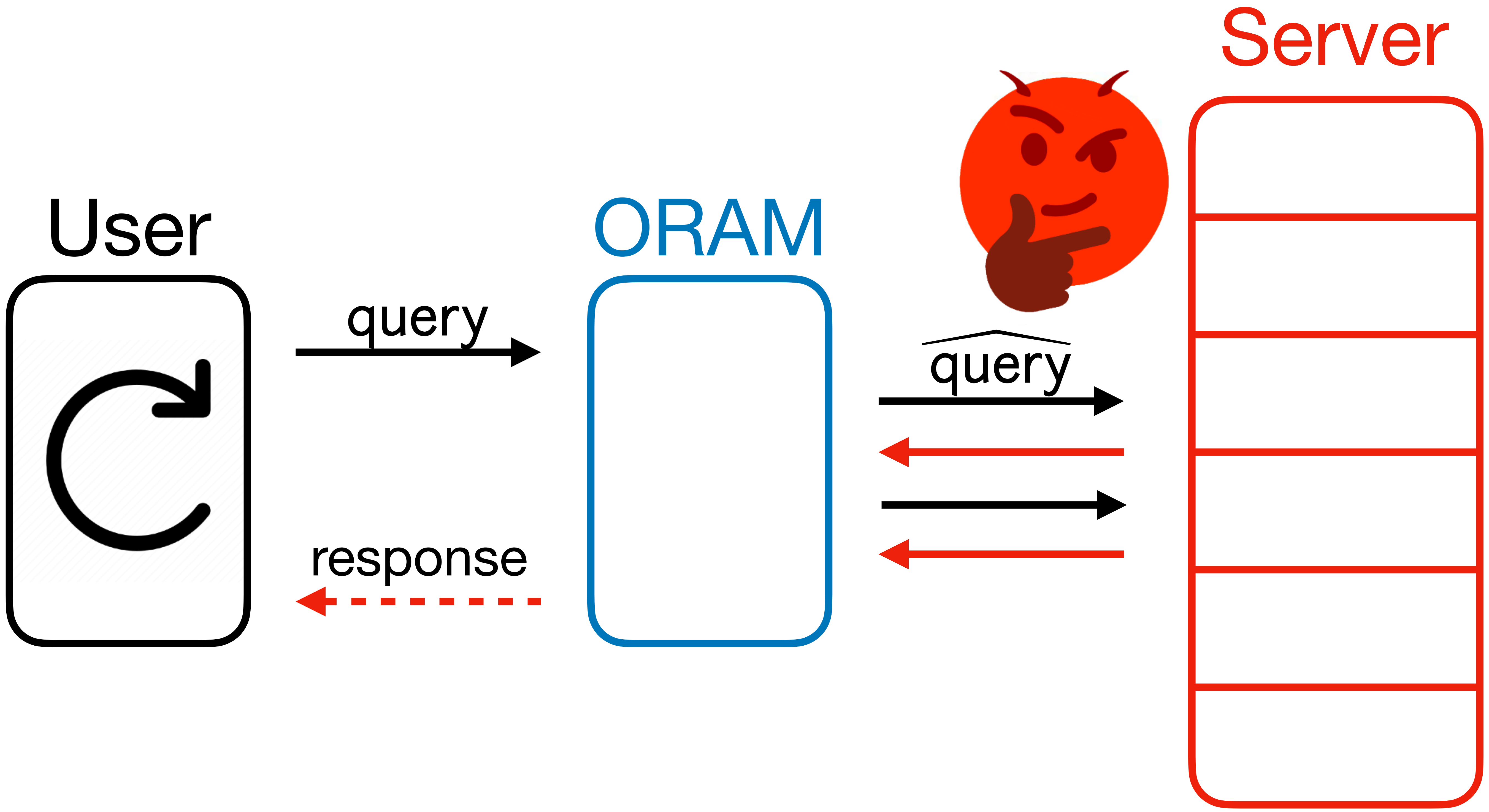
query

$\widehat{\text{query}}$

response

Malicious Security

- A malicious server breaks correctness *and also obliviousness*.
  - Why? After a corrupted server response, a standard ORAM has no obliviousness guarantee anymore. (This will be a big issue!)



Server

User

ORAM

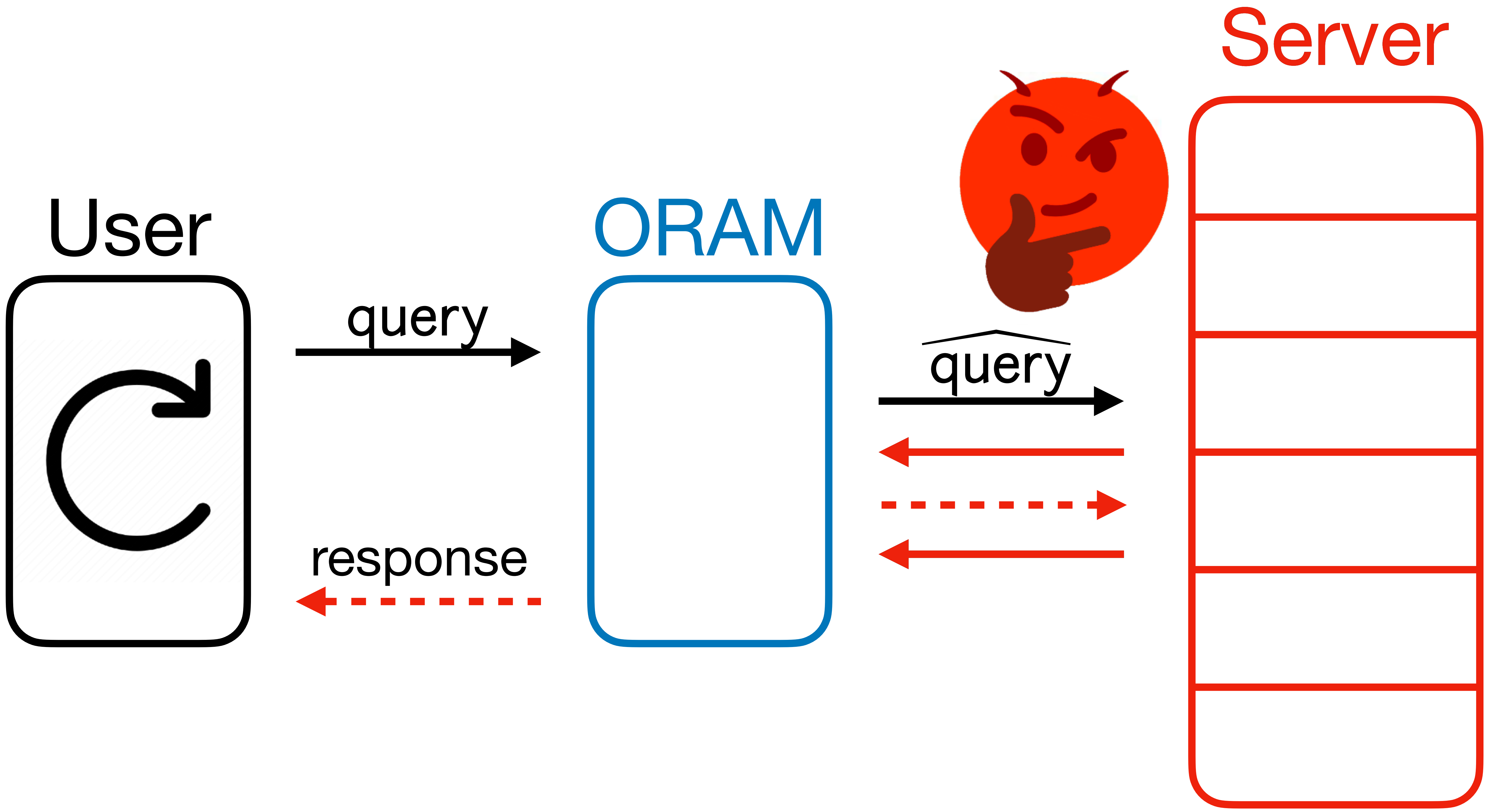
query

$\widehat{\text{query}}$

response

Malicious Security

- A malicious server breaks correctness *and also obliviousness*.
    - Why? After a corrupted server response, a standard ORAM has no obliviousness guarantee anymore. (This will be a big issue!)



Applications of Malicious Attacks

Applications of Malicious Attacks

- For file storage platforms (e.g., Dropbox, Google Drive), what if adversary breaks in and tampers database?

Applications of Malicious Attacks

- For file storage platforms (e.g., Dropbox, Google Drive), what if adversary breaks in and tampers database?
  - **No more privacy guarantees!**

Applications of Malicious Attacks

- For file storage platforms (e.g., Dropbox, Google Drive), what if adversary breaks in and tampers database?
    - **No more privacy guarantees!**
- What if adversary tampers with untrusted memory outside the secure enclave?

Applications of Malicious Attacks

- For file storage platforms (e.g., Dropbox, Google Drive), what if adversary breaks in and tampers database?
  - **No more privacy guarantees!**
- What if adversary tampers with untrusted memory outside the secure enclave?
  - **No more privacy guarantees!**

ORAM History (Malicious)

RAM of size N, word size $\omega(\log N)$, local space $O(1)$, assuming OWF

Work	**Overhead**	**Malicious?**
[Goldreich ’87]		
[Ostrovsky ’90, Goldreich-Ostrovsky ’96]		
Path ORAM [SvDSCFRYD ’12]		
PanORAMa [Patel-Persiano-Raykova-Yeo ’18]		
OptORAMa [AKLNPS ‘20, AKLS ’21]		

ORAM History (Malicious)

RAM of size N, word size $\omega(\log N)$, local space $O(1)$, assuming OWF

Work	Overhead	Malicious?
[Goldreich '87]	$\sqrt{N} \log N$	
[Ostrovsky '90, Goldreich-Ostrovsky '96]	$\log^3 N$	
Path ORAM [SvDSCFRYD '12]	$\log^2 N$	
PanORAMa [Patel-Persiano-Raykova-Yeo '18]	$\log N \log \log N$	
OptORAMa [AKLNPS '20, AKLS '21]	$\log N$	

Lower Bound: [Goldreich '87, LN '18, KL '21]	$\Omega\left(\log N\right)$	

ORAM History (Malicious)

RAM of size N, word size $\omega(\log N)$, local space $O(1)$, assuming OWF

Work	Overhead	Malicious?
[Goldreich '87]	$\sqrt{N}\log N$	Yes
[Ostrovsky '90, Goldreich-Ostrovsky '96]	$\log^3 N$	Yes
Path ORAM [SvDSCFRYD '12]	$\log^2 N$	Yes
PanORAMa [Patel-Persiano-Raykova-Yeo '18]	$\log N \log\log N$	
OptORAMa [AKLNPS '20, AKLS '21]	$\log N$	

Lower Bound: [Goldreich '87, LN '18, KL '21]	$\Omega\left(\log N\right)$	

ORAM History (Malicious)

RAM of size N, word size $\omega(\log N)$, local space $O(1)$, assuming OWF

Work	Overhead	Malicious?
[Goldreich '87]	$\sqrt{N} \log N$	Yes
[Ostrovsky '90, Goldreich-Ostrovsky '96]	$\log^3 N$	Yes
Path ORAM [SvDSCFRYD '12]	$\log^2 N$	Yes
PanORAMa [Patel-Persiano-Raykova-Yeo '18]	$\log N \log \log N$	No
OptORAMa [AKLNPS '20, AKLS '21]	$\log N$	No

Lower Bound: [Goldreich '87, LN '18, KL '21]	$\Omega\left(\log N\right)$	

ORAM History (Malicious)

RAM of size N, word size $\omega(\log N)$, local space $O(1)$, assuming OWF

Work	**Overhead**	**Malicious?**
[Goldreich '87]	$\sqrt{N} \log N$	Yes
[Ostrovsky '90, Goldreich-Ostrovsky '96]	$\log^3 N$	Yes
Path ORAM [SvDSCFRYD '12]	$\log^2 N$	Yes
PanORAMa [Patel-Persiano-Raykova-Yeo '18]	$\log N \log \log N$	No
OptORAMa [AKLNPS '20, AKLS '21]	$\log N$	No

Attacks!

Lower Bound: [Goldreich '87, LN '18, KL '21]	$\Omega\left(\log N\right)$	

ORAM History (Malicious)

RAM of size N, word size $\omega(\log N)$, local space $O(1)$, assuming OWF

Work	**Overhead**	**Malicious?**
[Goldreich ’87]	$\sqrt{N} \log N$	Yes
[Ostrovsky ’90, Goldreich-Ostrovsky ’96]	$\log^3 N$	Yes
Path ORAM [SvDSCFRYD ’12]	$\log^2 N$	Yes
PanORAMa [Patel-Persiano-Raykova-Yeo ’18]	$\log N \log \log N$	No
OptORAMa [AKLNPS ‘20, AKLS ’21]	$\log N$	No

Attacks!

Lower Bound: [Goldreich ’87, LN ’18, KL ’21]	$\Omega\left(\log N\right)$	Any stronger?

Optimal Maliciously Secure ORAM

Optimal Maliciously Secure ORAM

Question:

Is there a maliciously secure ORAM with $O(\log N)$ overhead?

Optimal Maliciously Secure ORAM

Question:

Is there a maliciously secure ORAM with $O(\log N)$ overhead?

Theorem [M.-Vafa '23]: Yes!

Optimal Maliciously Secure ORAM

Question:

Is there a maliciously secure ORAM with $O(\log N)$ overhead?

Theorem [M.-Vafa '23]: Yes!

Assuming one-way functions, we construct **MacORAMa**, a maliciously secure ORAM with $O(\log N)$ overhead and $O(1)$ local space*.

Optimal Maliciously Secure ORAM?

Theorem [M.-Vafa ’23]: Assuming one-way functions, there is a maliciously secure ORAM with $O(\log N)$ overhead and $O(1)$ word local space*.

- As before, $O(\log N)$ overhead is optimal – malicious security for free!

Optimal Maliciously Secure ORAM?

Theorem [M.-Vafa '23]: Assuming one-way functions, there is a maliciously secure ORAM with $O(\log N)$ overhead and $O(1)$ word local space*.

- As before, $O(\log N)$ overhead is optimal – malicious security for free!
- Maliciously secure ORAM still in passive storage model! No **extra work** for honest server.

Optimal Maliciously Secure ORAM?

Theorem [M.-Vafa '23]: Assuming one-way functions, there is a maliciously secure ORAM with $O(\log N)$ overhead and $O(1)$ word local space*.

- As before, $O(\log N)$ overhead is optimal – malicious security for free!
- Maliciously secure ORAM still in passive storage model! No **extra work** for honest server.
- OWFs are also *necessary* for maliciously secure ORAM. [Naor, Rothblum '05]

Optimal Maliciously Secure ORAM?

Theorem [M.-Vafa '23]: Assuming one-way functions, there is a maliciously secure ORAM with $O(\log N)$ overhead and $O(1)$ word local space*.

- As before, $O(\log N)$ overhead is optimal – malicious security for free!
- Maliciously secure ORAM still in passive storage model! No **extra work** for honest server.
- OWFs are also *necessary* for maliciously secure ORAM. [Naor, Rothblum '05]
- In private random oracle model, we get *statistical* malicious security against *unbounded adversaries*.

ORAM History (Malicious)

RAM of size N, word size $\omega(\log N)$, local space $O(1)$

Work	**Overhead**	**Malicious?**
[Goldreich '87]	$\sqrt{N} \log N$	Yes
[Ostrovsky '90, Goldreich-Ostrovsky '96]	$\log^3 N$	Yes
Path ORAM [SvDSCFRYD '12]	$\log^2 N$	Yes
PanORAMa [Patel-Persiano-Raykova-Yeo '18]	$\log N \log \log N$	No
OptORAMa [AKLNPS '20, AKLS '21]	$\log N$	No

Lower Bound: [Goldreich '87, LN '18, KL '21]	$\Omega\left(\log N\right)$	Any stronger?

ORAM History (Malicious)

RAM of size N, word size $\omega(\log N)$, local space $O(1)$

Work	**Overhead**	**Malicious?**
[Goldreich '87]	$\sqrt{N} \log N$	Yes
[Ostrovsky '90, Goldreich-Ostrovsky '96]	$\log^3 N$	Yes
Path ORAM [SvDSCFRYD '12]	$\log^2 N$	Yes
PanORAMa [Patel-Persiano-Raykova-Yeo '18]	$\log N \log \log N$	No
OptORAMa [AKLNPS '20, AKLS '21]	$\log N$	No
MacORAMa [M.-Vafa '22]	$\log N$	**Yes**
Lower Bound: [Goldreich '87, LN '18, KL '21]	$\Omega\left(\log N\right)$	$\Omega\left(\log N\right)$

Starting Point

We start with **OptORAMa** [Asharov, Komargodski, Lin, Nayak, Peserico, Shi] - a **honest-but-curious** ORAM with **optimal** $O(\log N)$ overhead.

Background: Hierarchical ORAM

Background: Hierarchical ORAM

- Many ORAM constructions, starting with [Ostrovsky ’90, Goldreich-Ostrovsky ’96] and including **OptORAMa** [AKLNPS ’21], follow the **hierarchical paradigm.**

Background: Hierarchical ORAM

- Many ORAM constructions, starting with [Ostrovsky ’90, Goldreich-Ostrovsky ’96] and including **OptORAMa** [AKLNPS ’21], follow the **hierarchical paradigm**.

- For each $i \in [\log_2(N)]$, there’s an *oblivious* hash table H_i of size 2^i.

Background: Hierarchical ORAM

- Many ORAM constructions, starting with [Ostrovsky ’90, Goldreich-Ostrovsky ’96] and including **OptORAMa** [AKLNPS ’21], follow the **hierarchical paradigm**.

- For each $i \in [\log_2(N)]$, there’s an *oblivious* hash table H_i of size 2^i.

  - **Lookup Phase**: Given a query to addr, lookup addr in $\mathsf{H}_1, \mathsf{H}_2, \ldots$ until found. Lookup dummy elements for the subsequent tables, and write updated addr back to H_1.

Background: Hierarchical ORAM

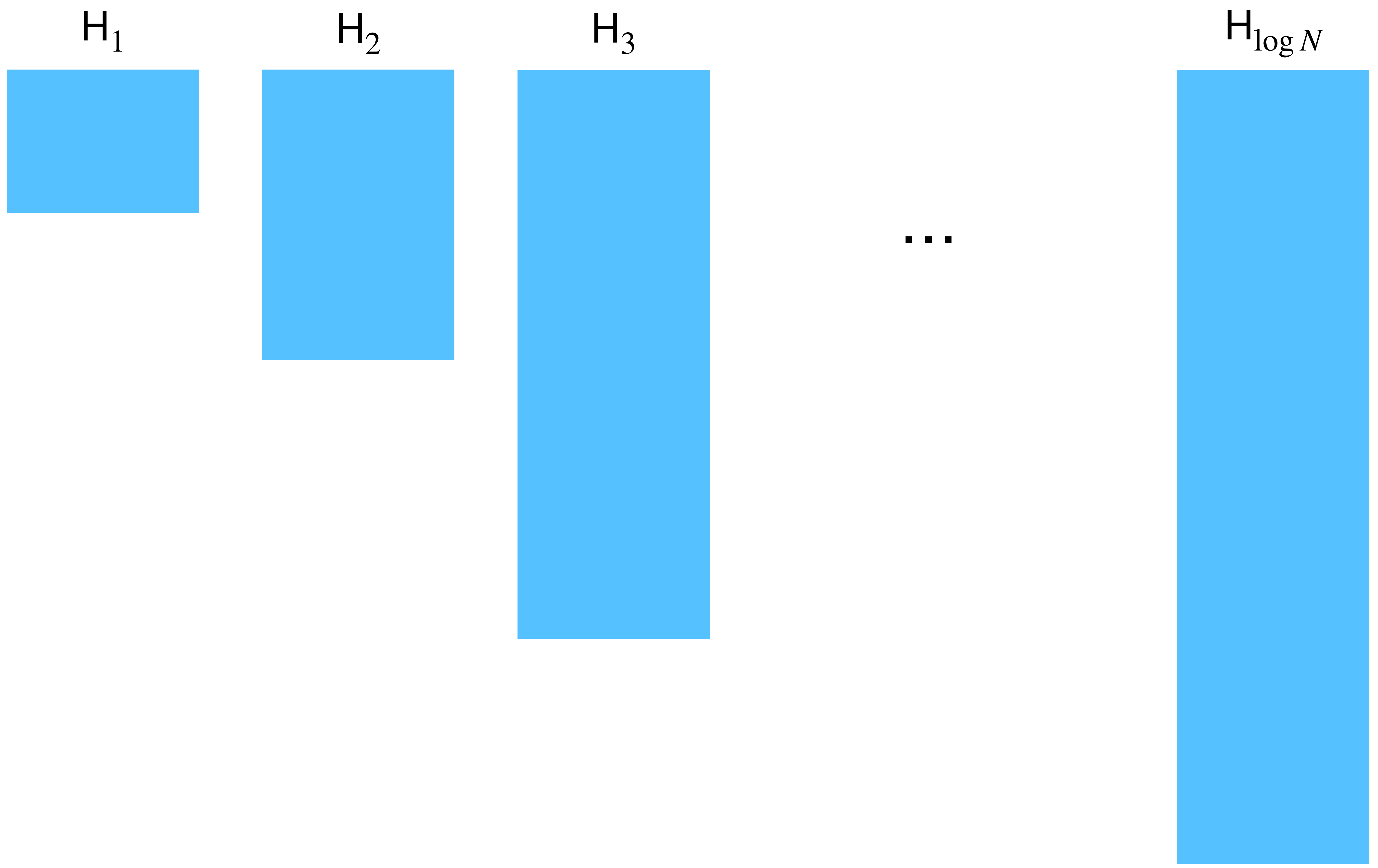
- Many ORAM constructions, starting with [Ostrovsky ’90, Goldreich-Ostrovsky ’96] and including **OptORAMa** [AKLNPS ’21], follow the **hierarchical paradigm**.

- For each $i \in [\log_2(N)]$, there’s an *oblivious* hash table H_i of size 2^i.

  - **Lookup Phase**: Given a query to addr, lookup addr in $\mathsf{H}_1, \mathsf{H}_2, \ldots$ until found. Lookup dummy elements for the subsequent tables, and write updated addr back to H_1.

  - **Rebuild Phase**: Every 2^i queries, obliviously merge $\mathsf{H}_1 \to \mathsf{H}_2 \to \cdots \to \mathsf{H}_{i+1}$ into new H_{i+1}, removing duplicate addresses by keeping the version from the smaller H_j.

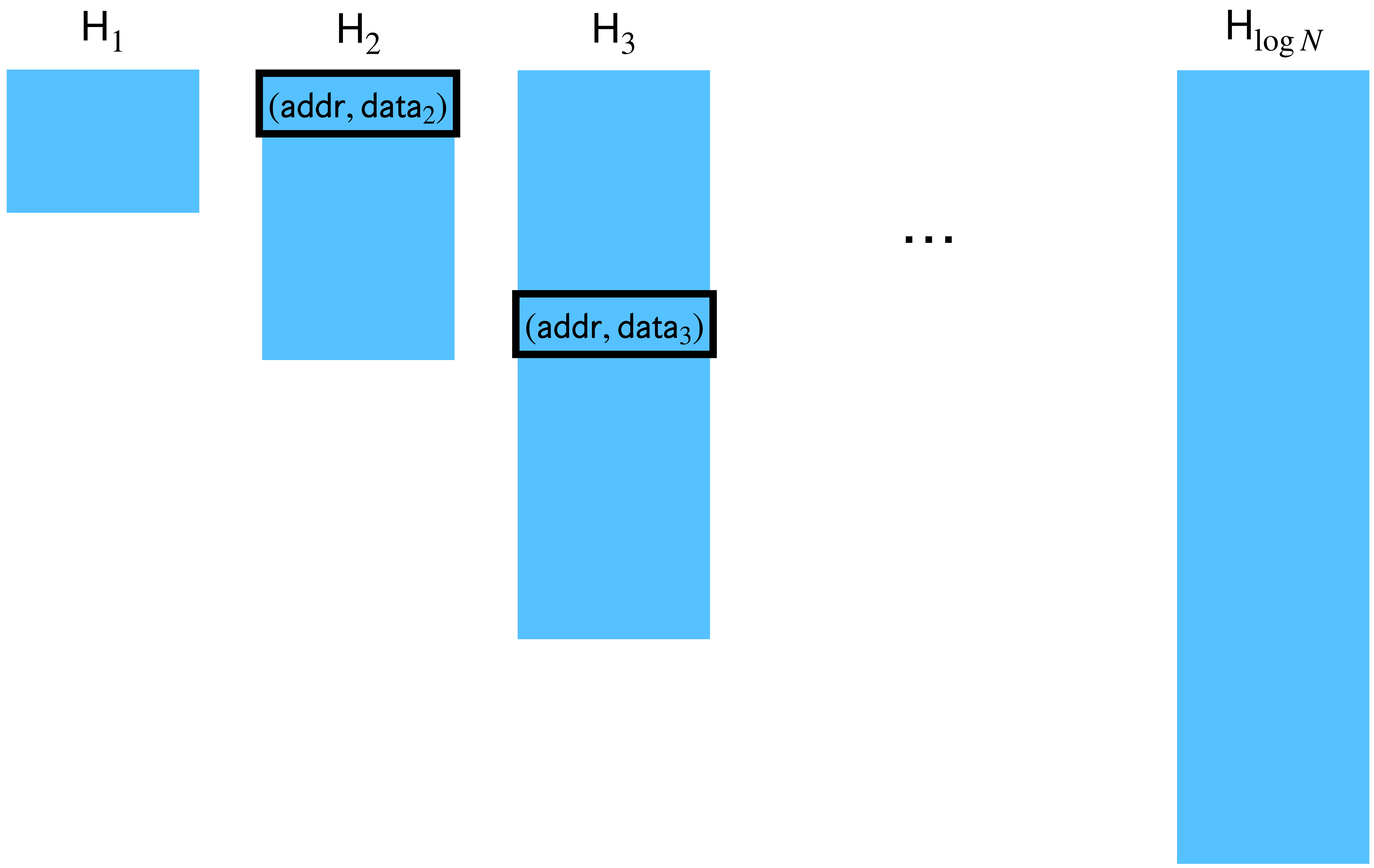
Hierarchical Construction: Lookup



Lookup Phase

Hierarchical Construction: Lookup

Query to addr:



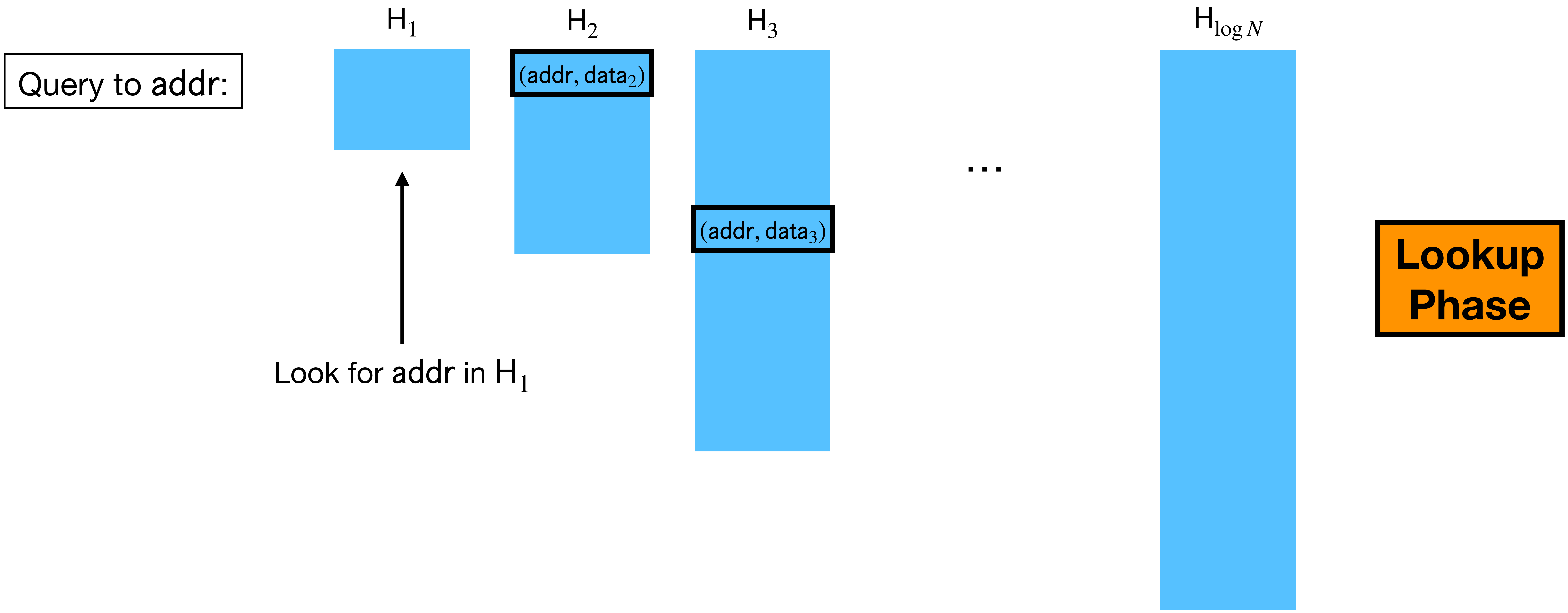
H_1 H_2 H_3 … $H_{\log N}$

$(\text{addr}, \text{data}_2)$

$(\text{addr}, \text{data}_3)$

Lookup Phase

Hierarchical Construction: Lookup



Query to addr:

H_1 H_2 H_3 … $H_{\log N}$

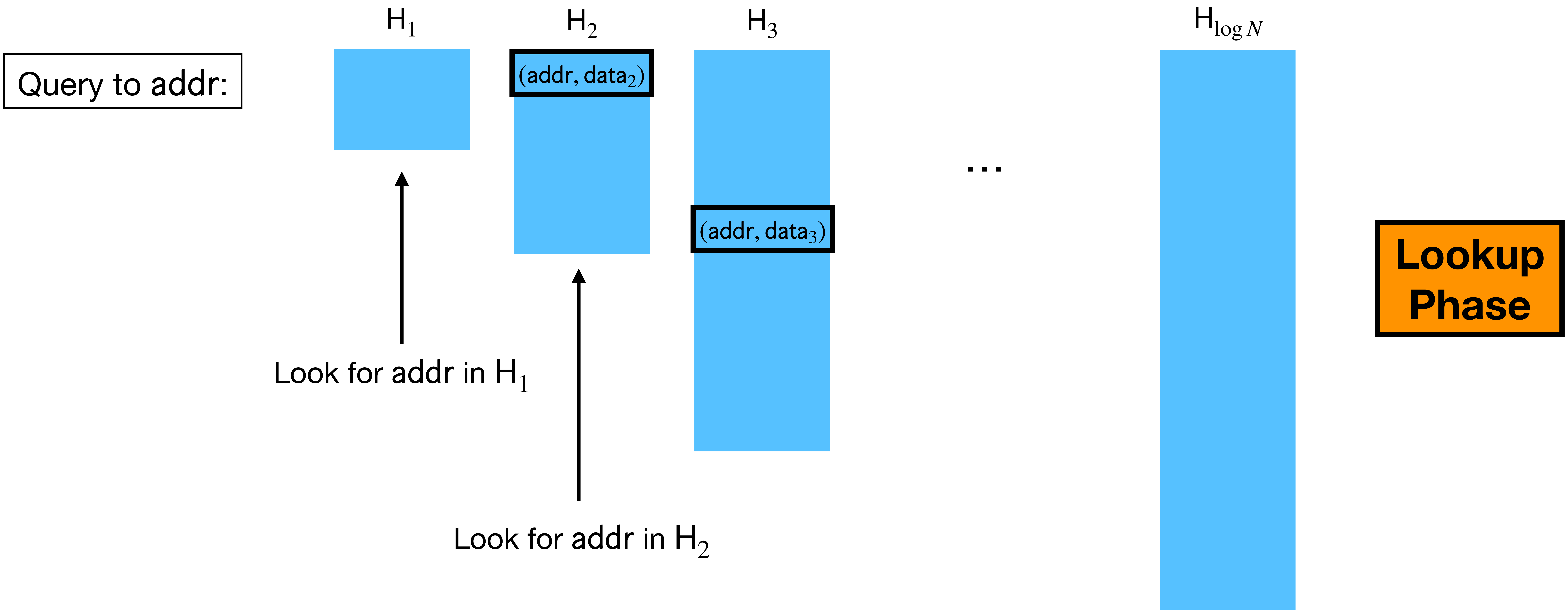
$(\text{addr}, \text{data}_2)$

$(\text{addr}, \text{data}_3)$

Look for addr in H_1

Lookup Phase

Hierarchical Construction: Lookup



Query to addr:

H_1 H_2 H_3 … $H_{\log N}$

(addr, $data_2$)

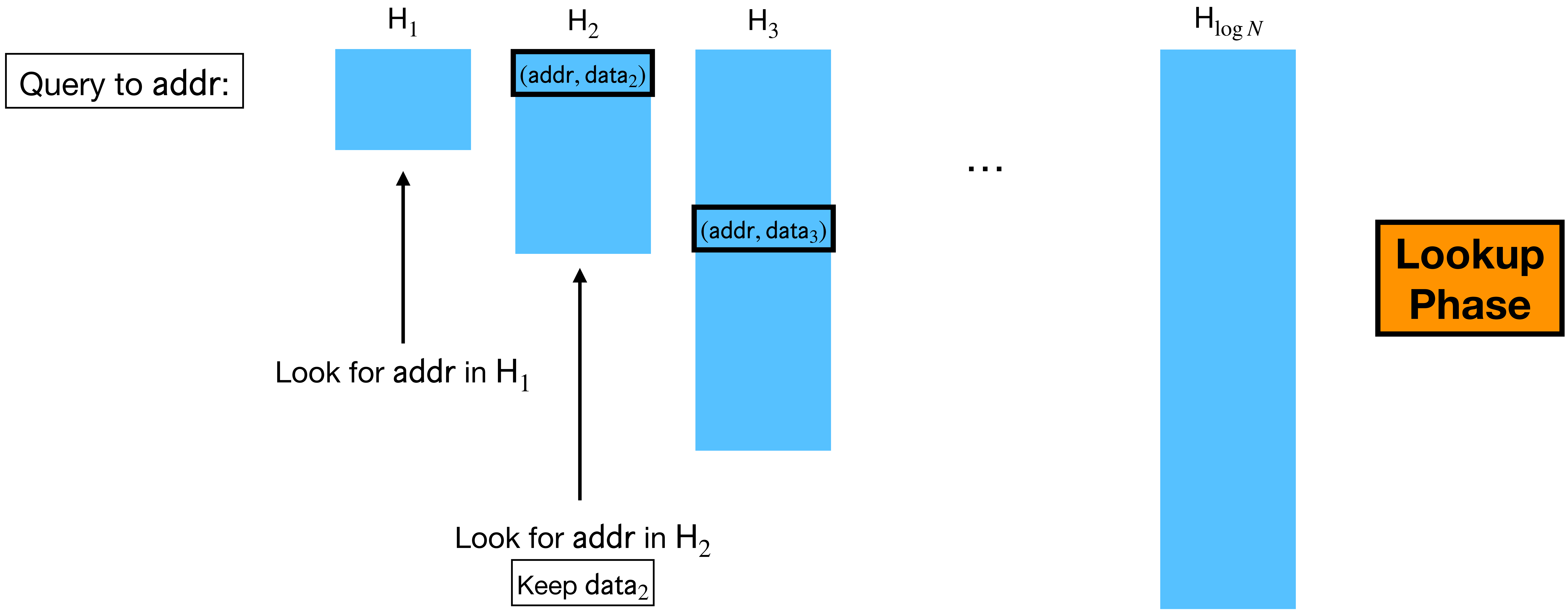
(addr, $data_3$)

Look for addr in H_1

Look for addr in H_2

Lookup Phase

Hierarchical Construction: Lookup



Query to addr:

H_1 H_2 H_3 … $H_{\log N}$

(addr, $data_2$)

(addr, $data_3$)

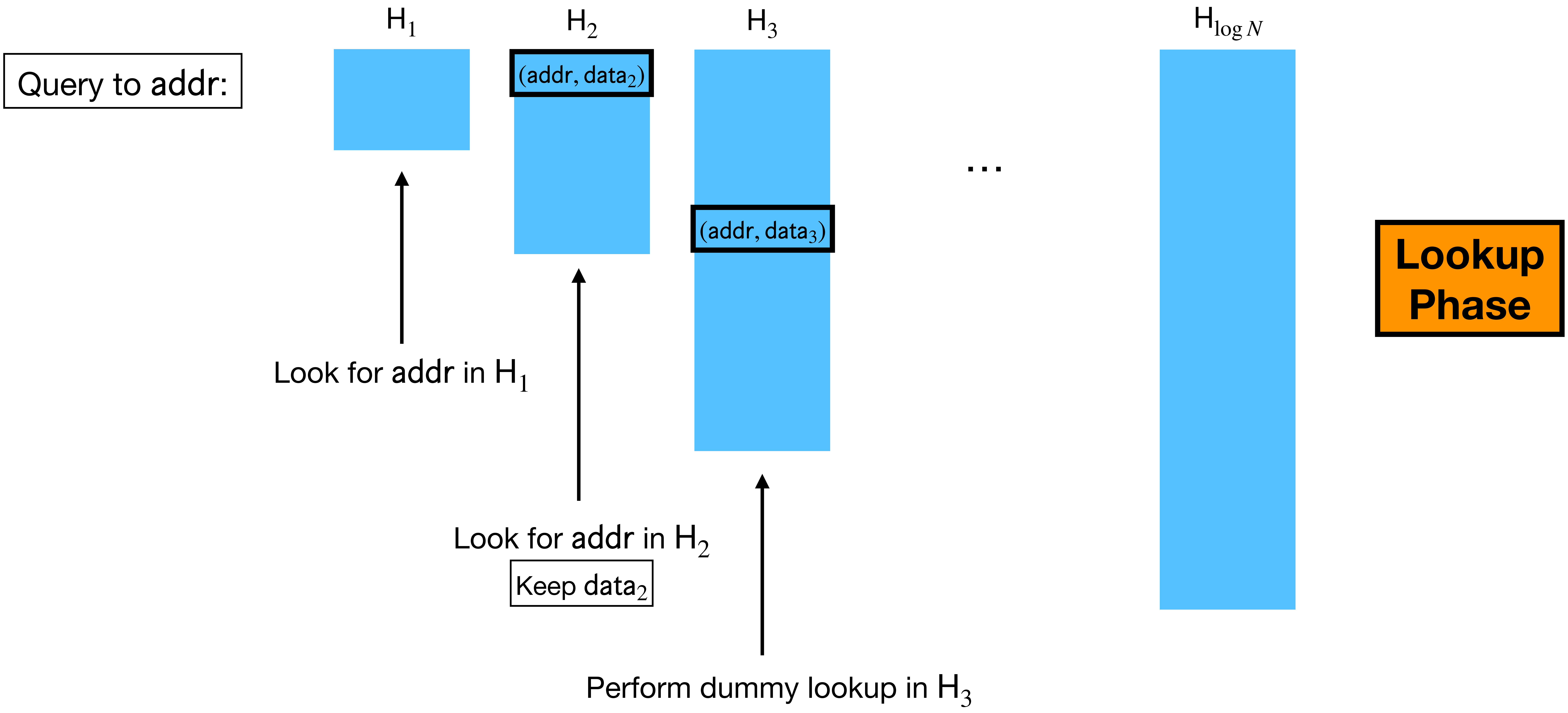
Look for addr in H_1

Look for addr in H_2

Keep $data_2$

Lookup Phase

Hierarchical Construction: Lookup



Query to addr:

H_1

H_2

H_3

…

$H_{\log N}$

(addr, data$_2$)

(addr, data$_3$)

Look for addr in H_1

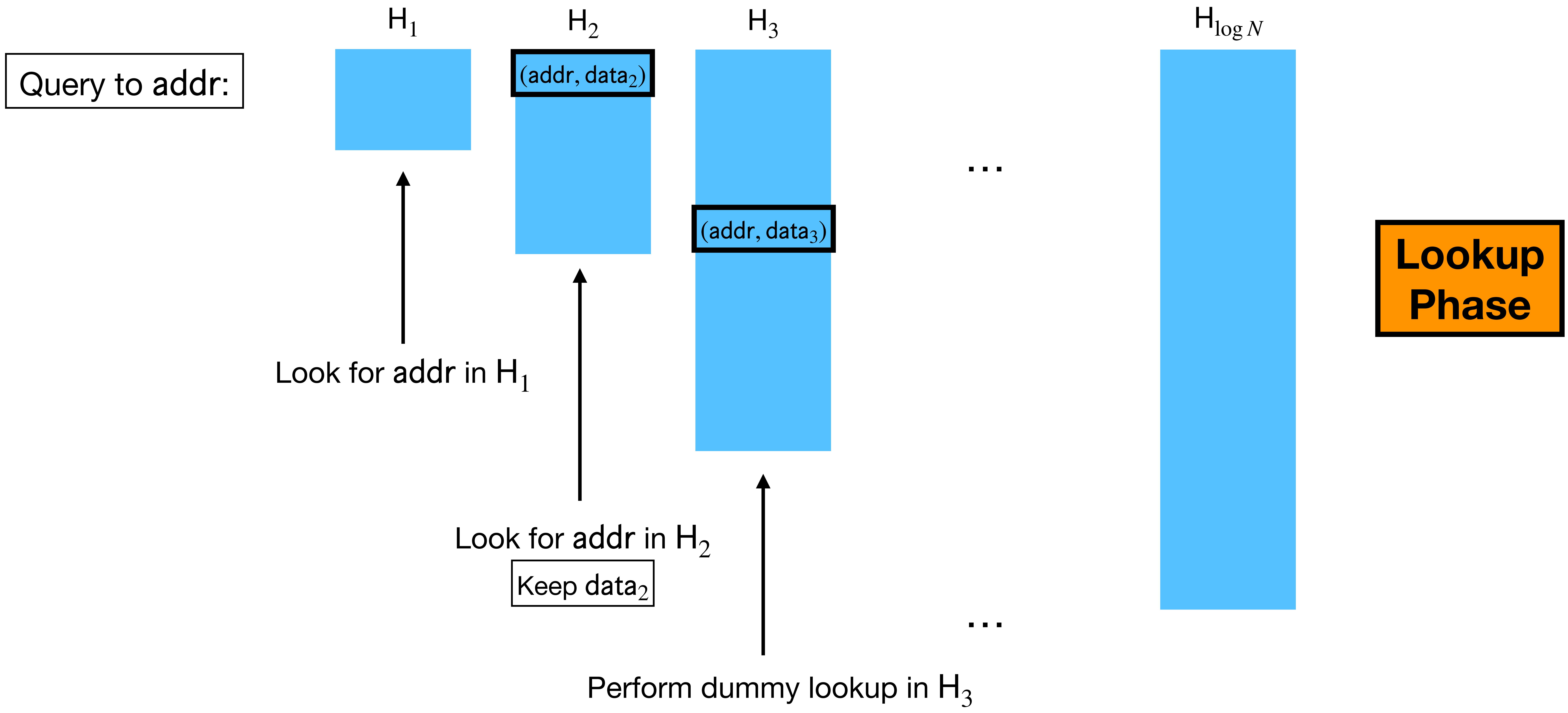
Look for addr in H_2

Keep data$_2$

Perform dummy lookup in H_3

Lookup Phase

Hierarchical Construction: Lookup



Query to addr:

H_1 H_2 H_3 … $\mathsf{H}_{\log N}$

$(\mathsf{addr}, \mathsf{data}_2)$

$(\mathsf{addr}, \mathsf{data}_3)$

Look for addr in H_1

Look for addr in H_2

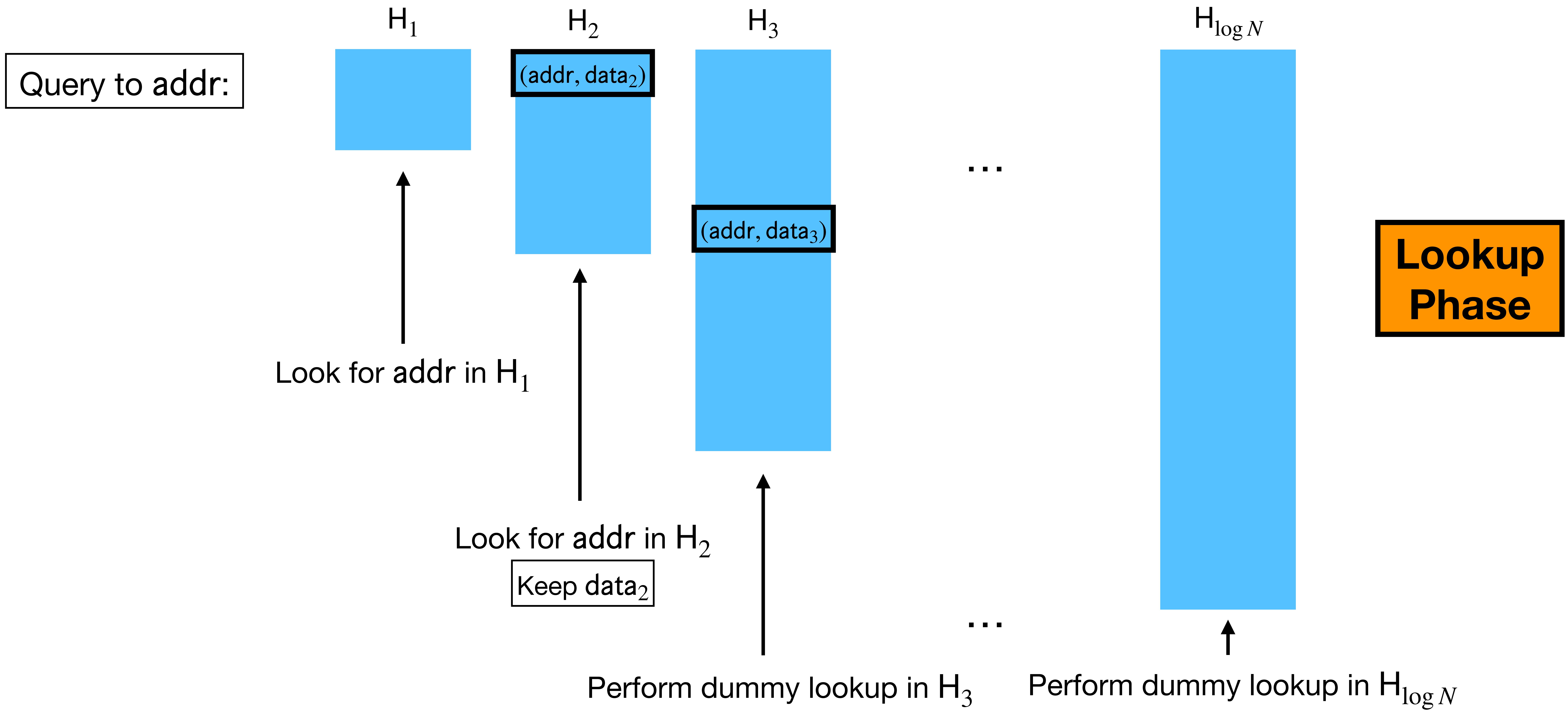
Keep data_2

…

Perform dummy lookup in H_3

Lookup Phase

Hierarchical Construction: Lookup



Query to addr:

H_1 H_2 H_3 … $H_{\log N}$

(addr, data_2)

(addr, data_3)

Lookup Phase

Look for addr in H_1

Look for addr in H_2

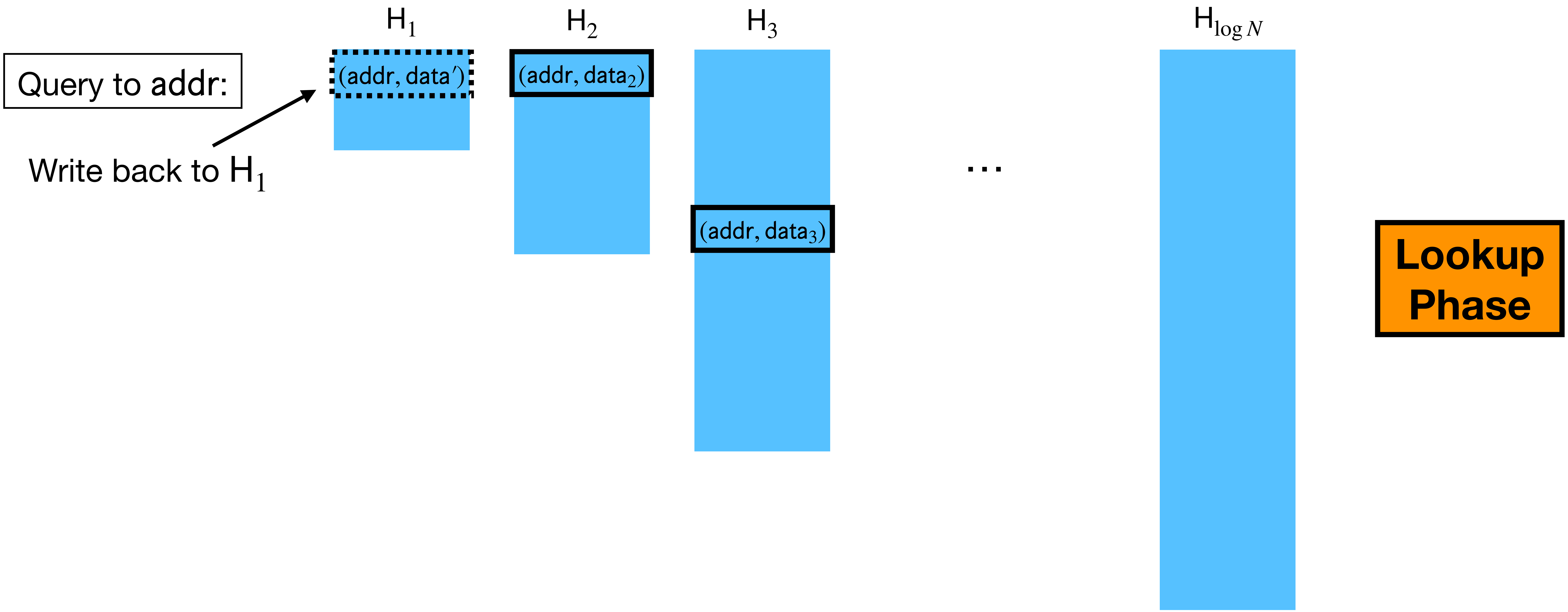
Keep data_2

Perform dummy lookup in H_3

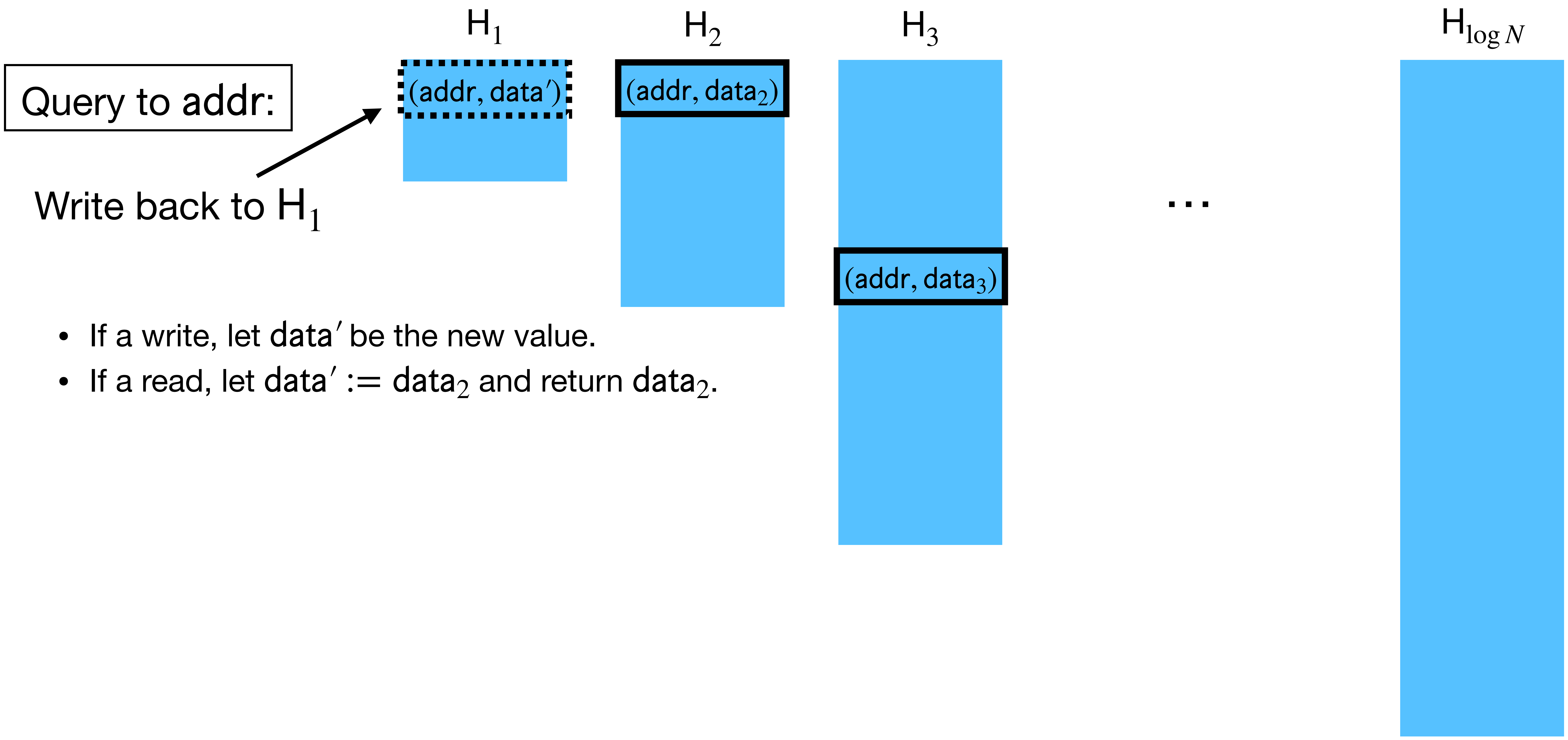
…

Perform dummy lookup in $H_{\log N}$

Hierarchical Construction: Lookup



Hierarchical Construction: Lookup



Query to addr:

Write back to H_1

H_1 H_2 H_3 … $\mathsf{H}_{\log N}$

$(\mathsf{addr}, \mathsf{data}')$

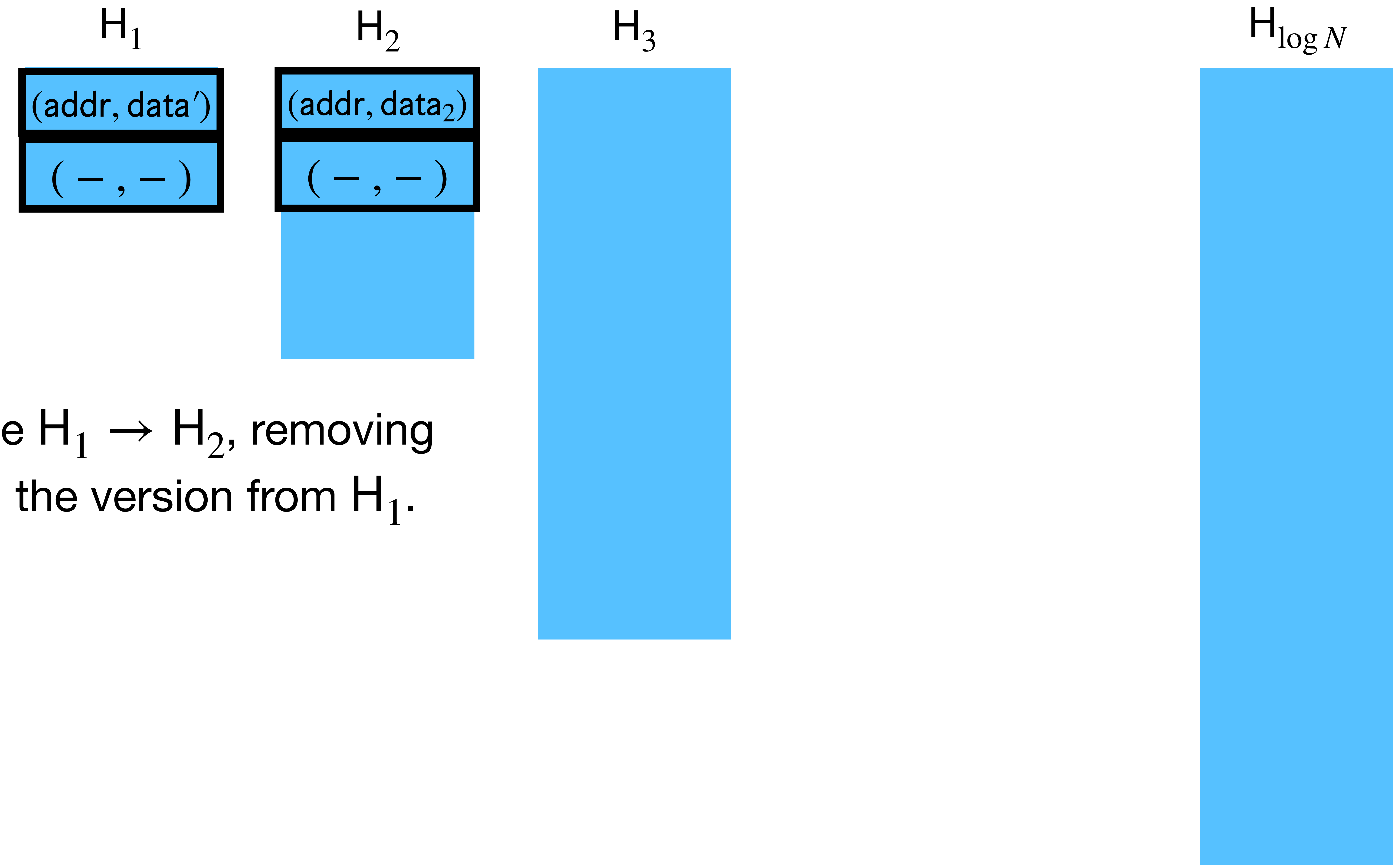
$(\mathsf{addr}, \mathsf{data}_2)$

$(\mathsf{addr}, \mathsf{data}_3)$

- If a write, let data' be the new value.
- If a read, let $\mathsf{data}' := \mathsf{data}_2$ and return data_2.

Lookup Phase

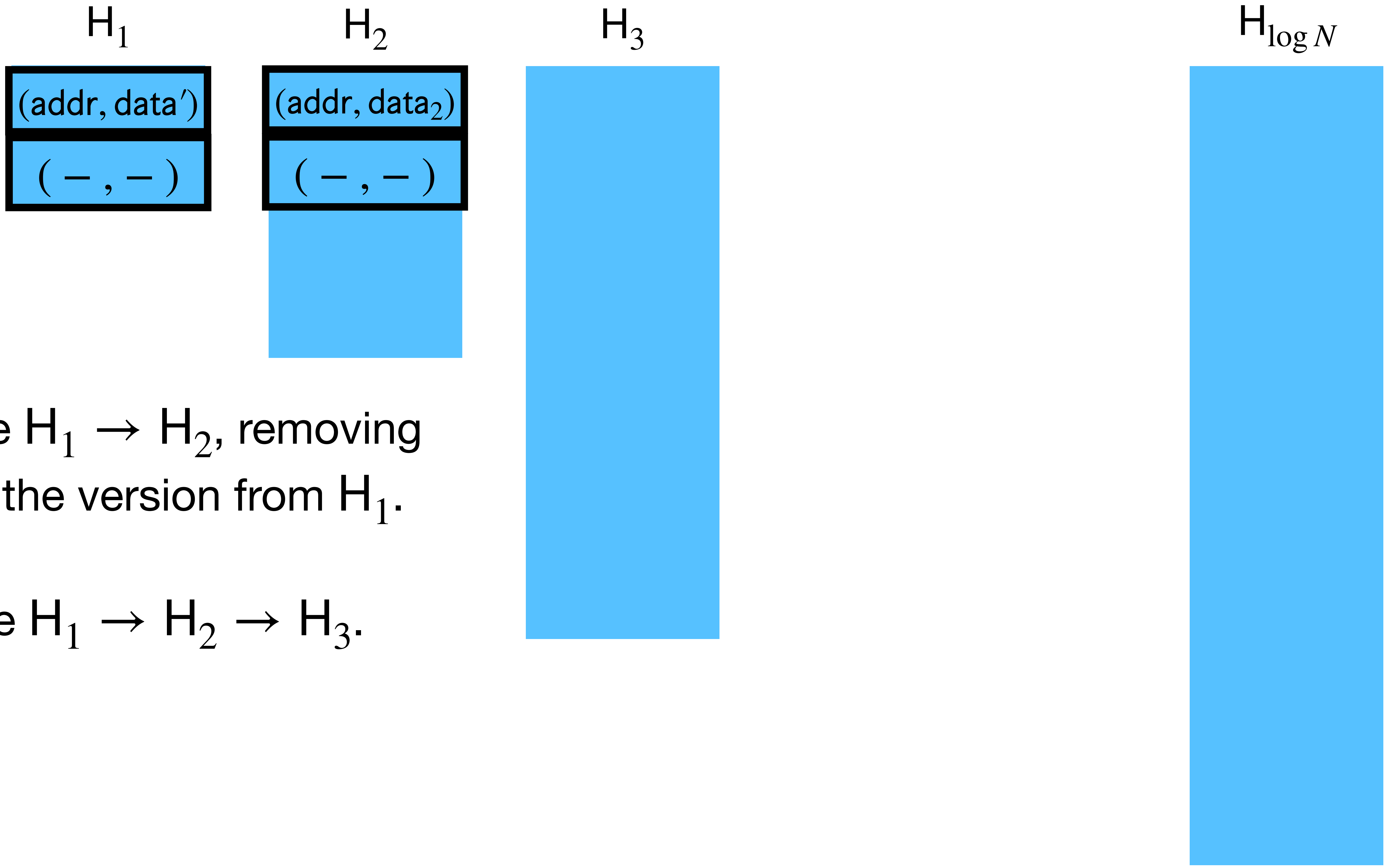
Hierarchical Construction: Rebuild



Rebuild Phase

- Every 2 queries, merge $H_1 \rightarrow H_2$, removing duplicates by keeping the version from H_1.

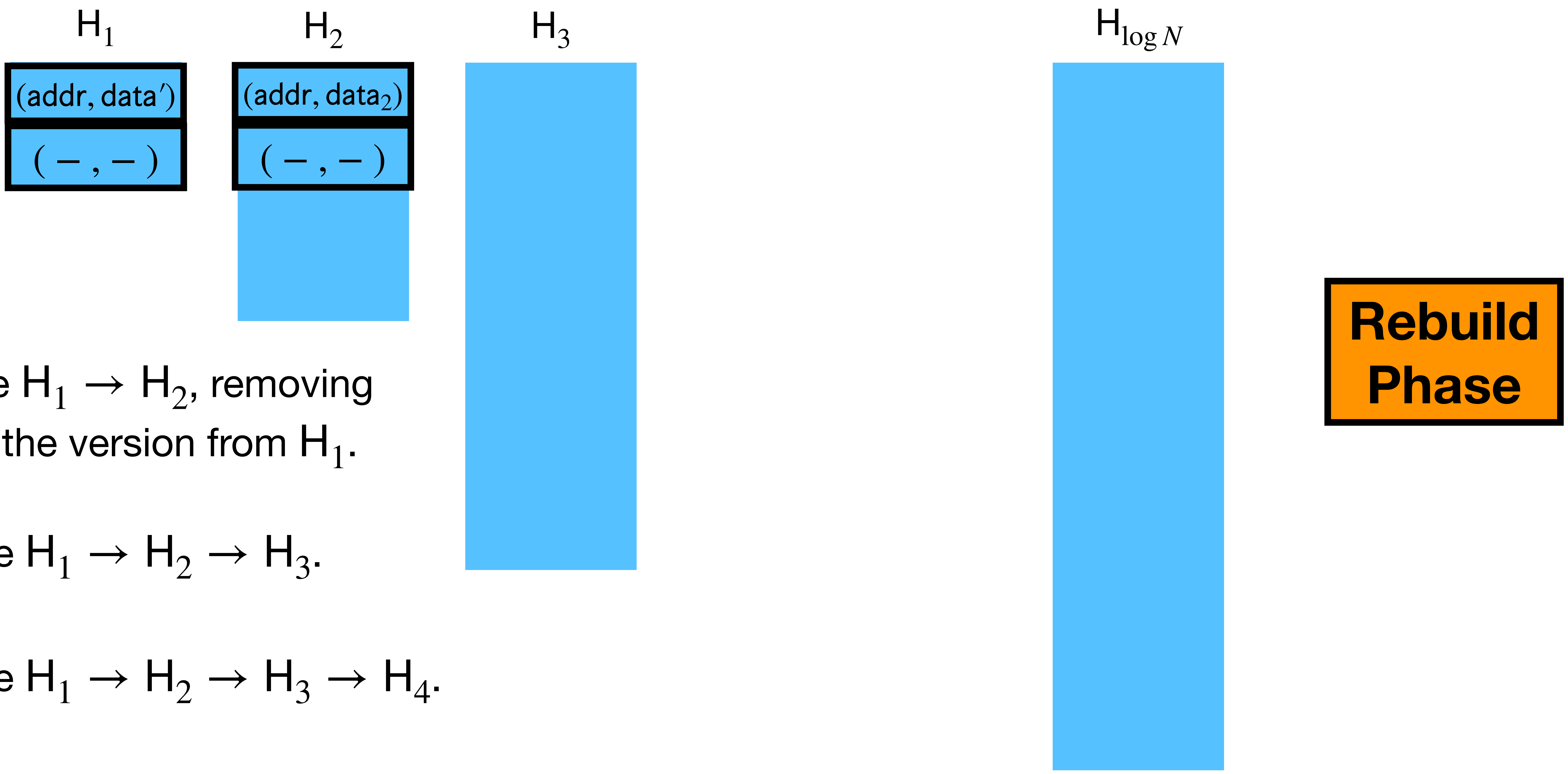
Hierarchical Construction: Rebuild



Rebuild Phase

- Every 2 queries, merge $\mathsf{H}_1 \to \mathsf{H}_2$, removing duplicates by keeping the version from H_1.
- Every 4 queries, merge $\mathsf{H}_1 \to \mathsf{H}_2 \to \mathsf{H}_3$.

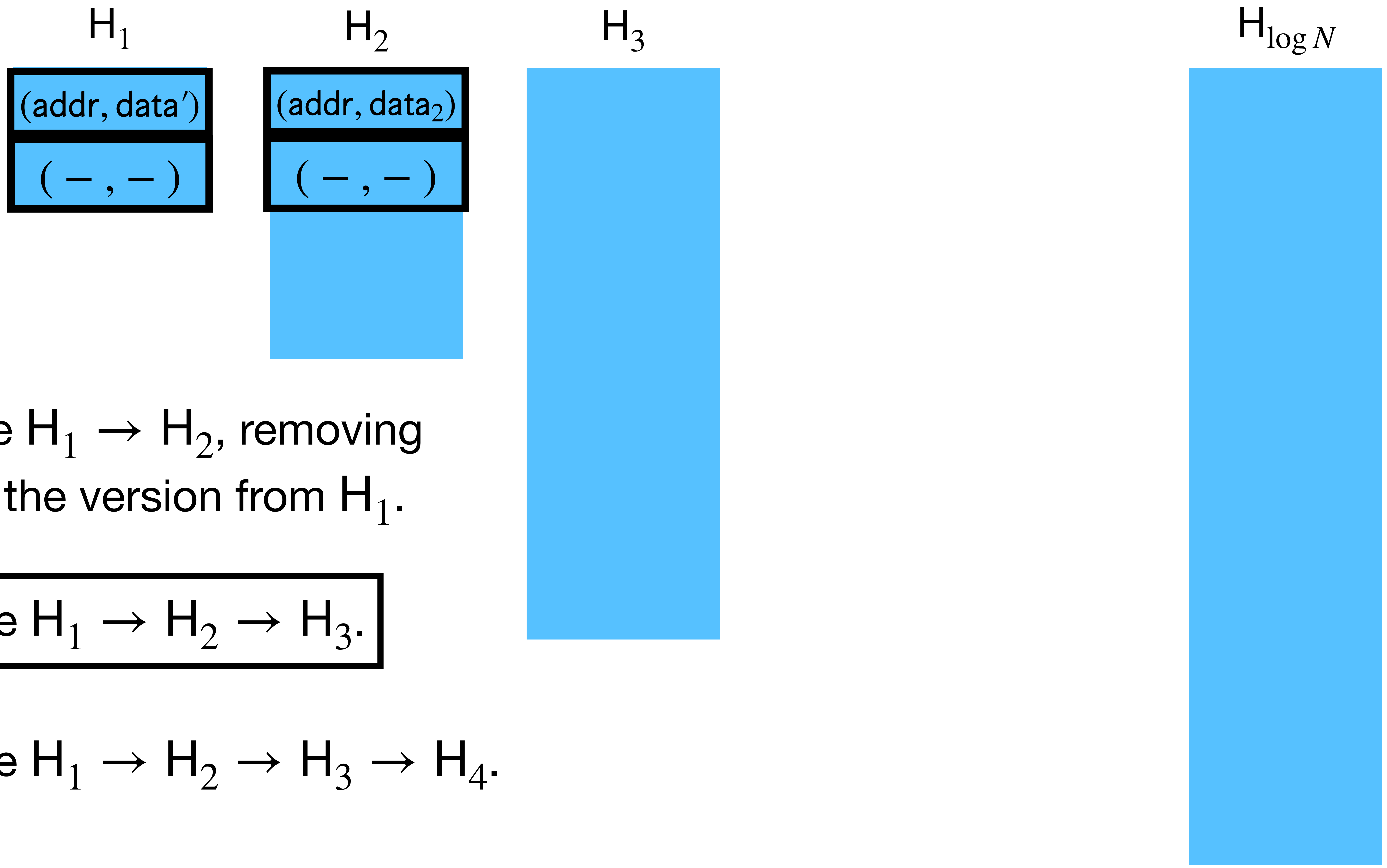
Hierarchical Construction: Rebuild



Rebuild Phase

- Every 2 queries, merge $H_1 \to H_2$, removing duplicates by keeping the version from H_1.
- Every 4 queries, merge $H_1 \to H_2 \to H_3$.
- Every 8 queries, merge $H_1 \to H_2 \to H_3 \to H_4$.
- …

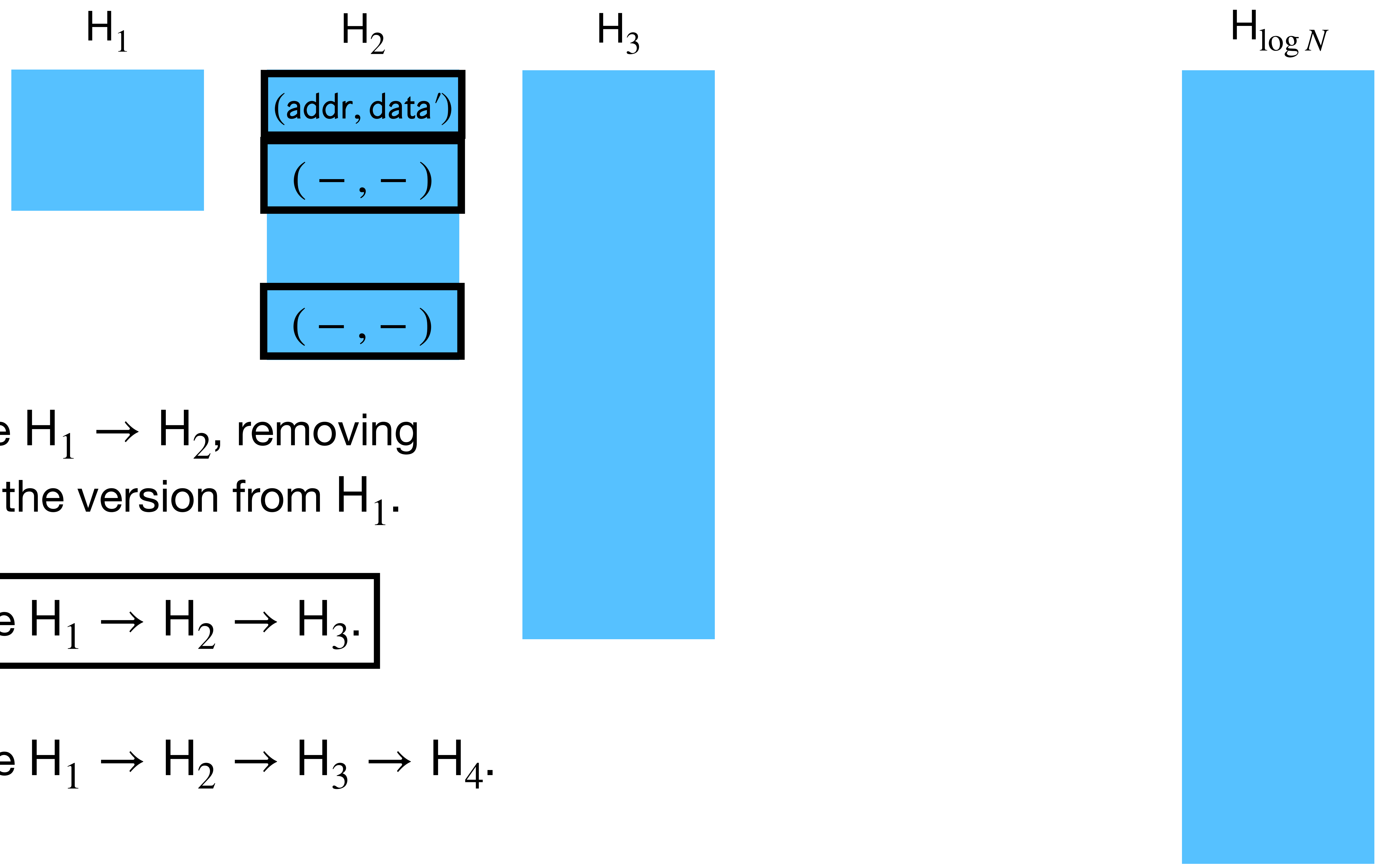
Hierarchical Construction: Rebuild



Rebuild Phase

- Every 2 queries, merge $H_1 \to H_2$, removing duplicates by keeping the version from H_1.
- Every 4 queries, merge $H_1 \to H_2 \to H_3$.
- Every 8 queries, merge $H_1 \to H_2 \to H_3 \to H_4$.
- …

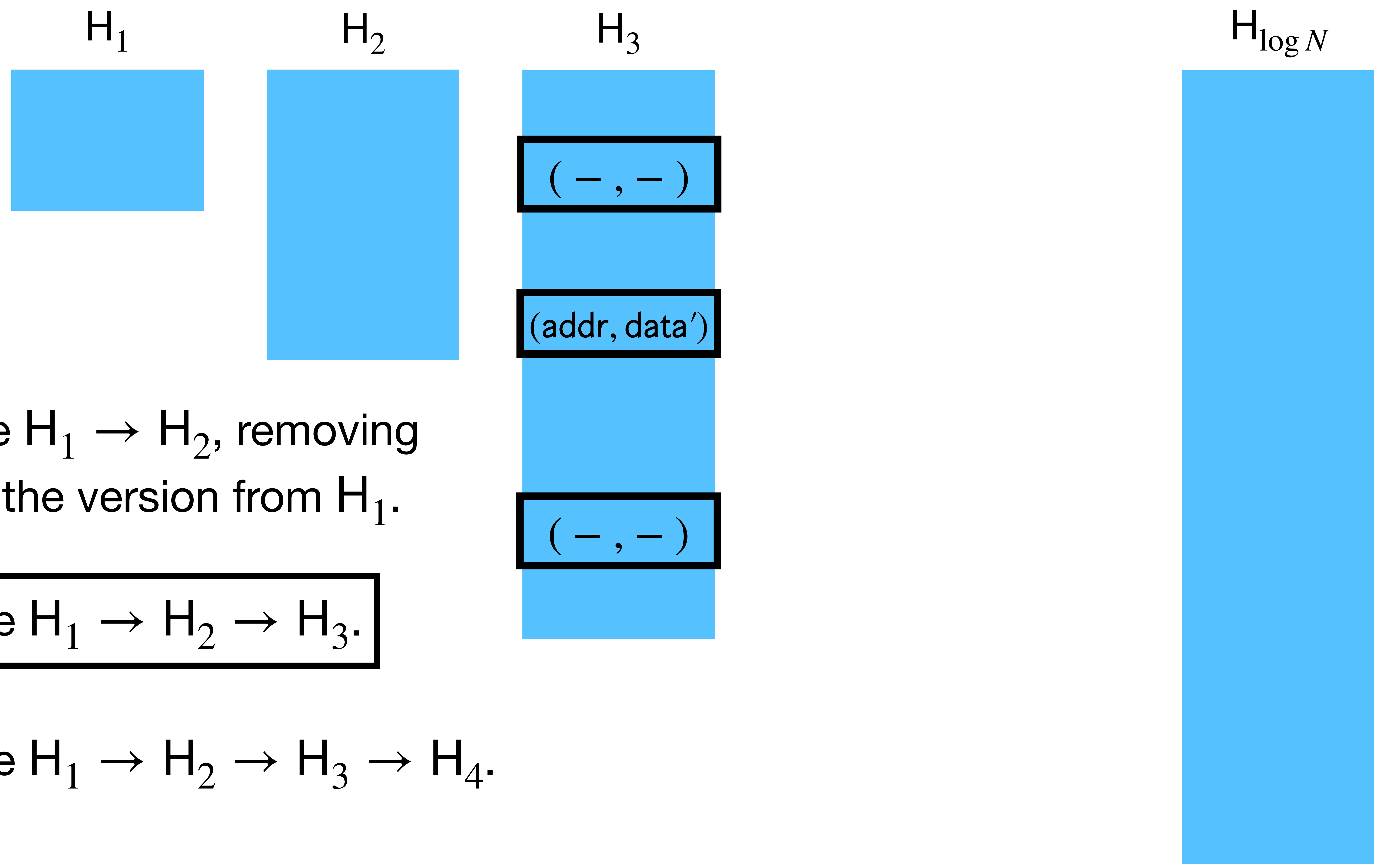
Hierarchical Construction: Rebuild



Rebuild Phase

- Every 2 queries, merge $H_1 \to H_2$, removing duplicates by keeping the version from H_1.
- Every 4 queries, merge $H_1 \to H_2 \to H_3$.
- Every 8 queries, merge $H_1 \to H_2 \to H_3 \to H_4$.
- …

Hierarchical Construction: Rebuild



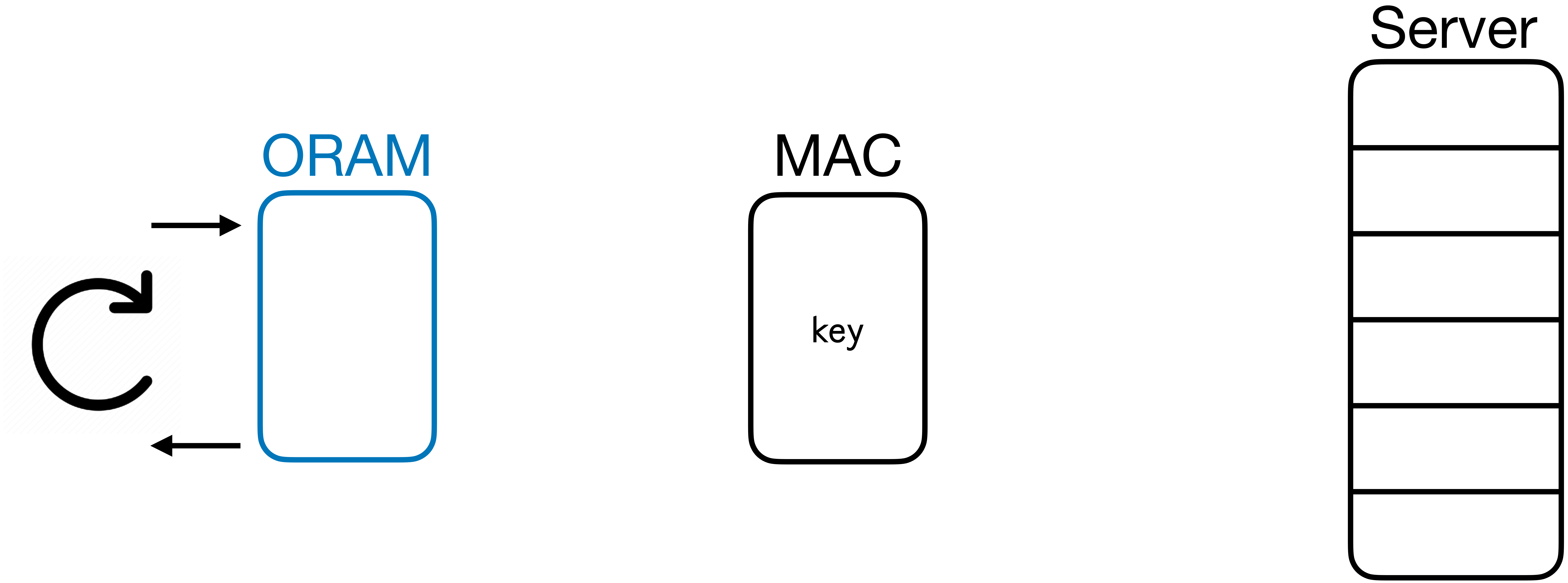
Rebuild Phase

- Every 2 queries, merge $\mathsf{H}_1 \rightarrow \mathsf{H}_2$, removing duplicates by keeping the version from H_1.
- Every 4 queries, merge $\mathsf{H}_1 \rightarrow \mathsf{H}_2 \rightarrow \mathsf{H}_3$.
- Every 8 queries, merge $\mathsf{H}_1 \rightarrow \mathsf{H}_2 \rightarrow \mathsf{H}_3 \rightarrow \mathsf{H}_4$.
- …

Overview of our techniques

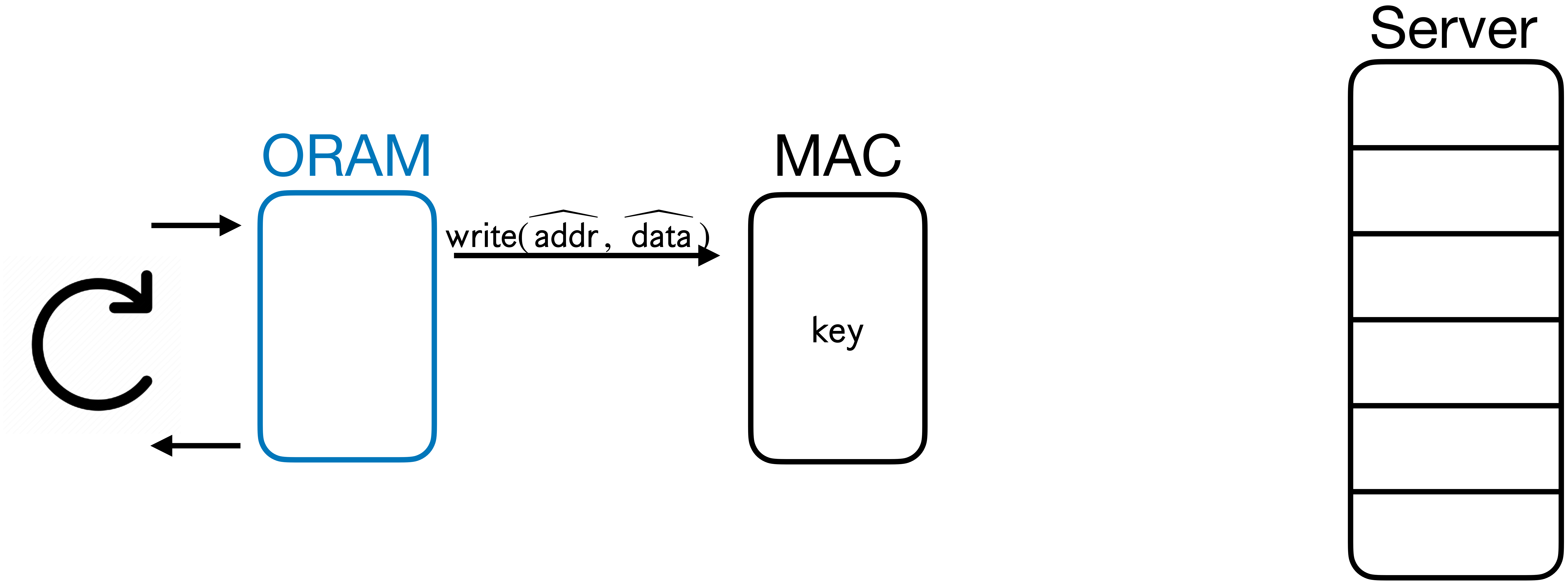
Technique #1: MACs

- What about Message Authentication Codes (MACs)?



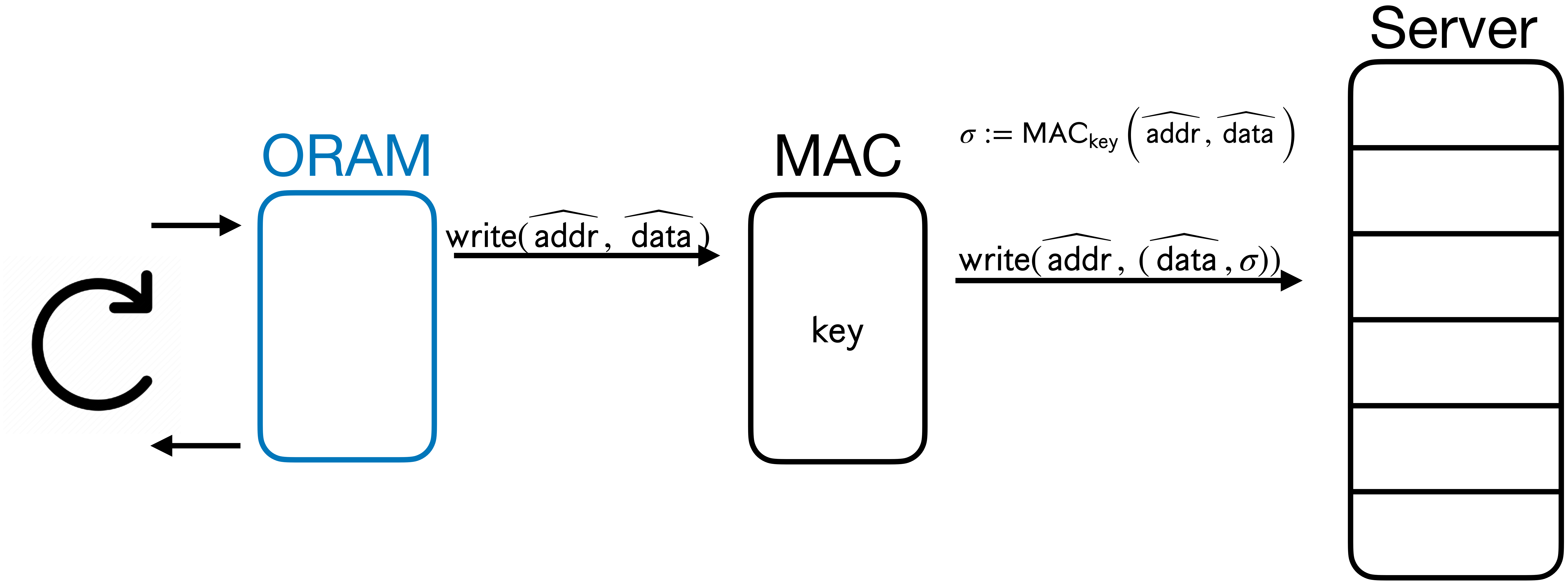
Technique #1: MACs

- What about Message Authentication Codes (MACs)?



Technique #1: MACs

- What about Message Authentication Codes (MACs)?



ORAM

MAC

key

Server

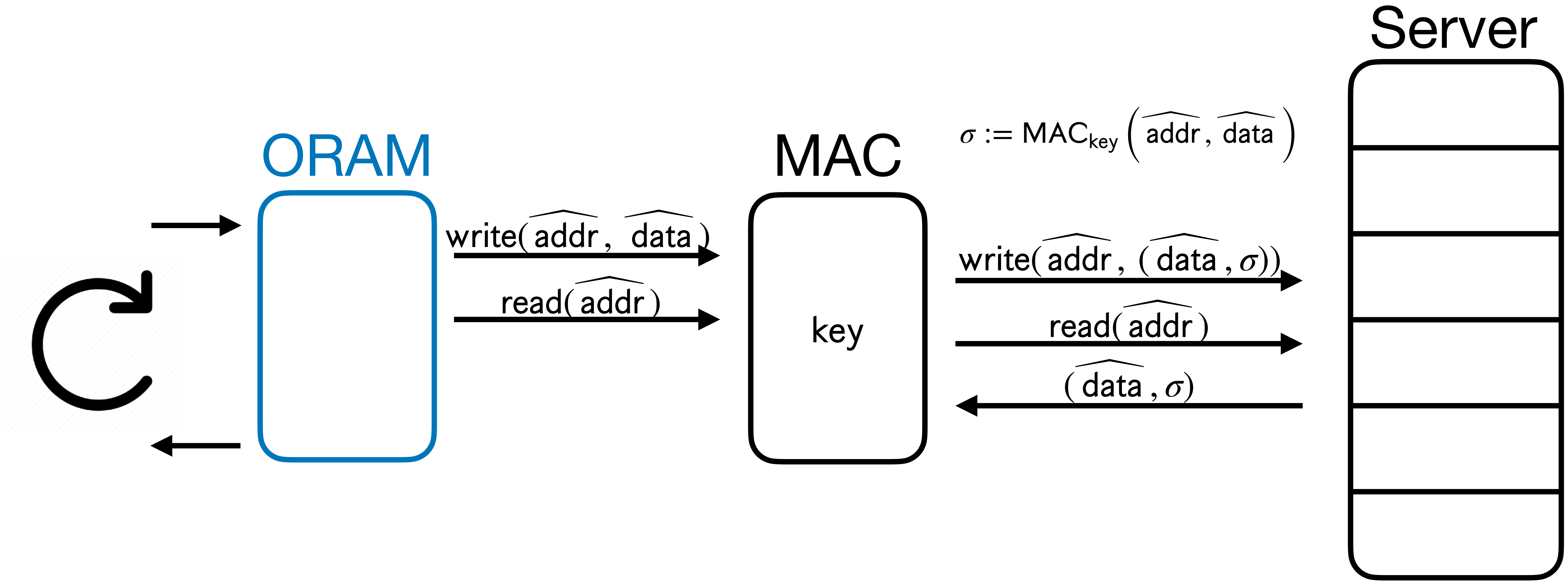
$\mathrm{write}(\widehat{\mathrm{addr}}, \widehat{\mathrm{data}})$

$\sigma := \mathrm{MAC}_{\mathrm{key}}\left(\widehat{\mathrm{addr}}, \widehat{\mathrm{data}}\right)$

$\mathrm{write}(\widehat{\mathrm{addr}}, (\widehat{\mathrm{data}}, \sigma))$

Technique #1: MACs

- What about Message Authentication Codes (MACs)?



Server

ORAM

MAC

$\sigma := \text{MAC}_{\text{key}}\left(\widehat{\text{addr}}, \widehat{\text{data}}\right)$

$\text{write}(\widehat{\text{addr}}, \widehat{\text{data}})$

$\text{read}(\widehat{\text{addr}})$

key

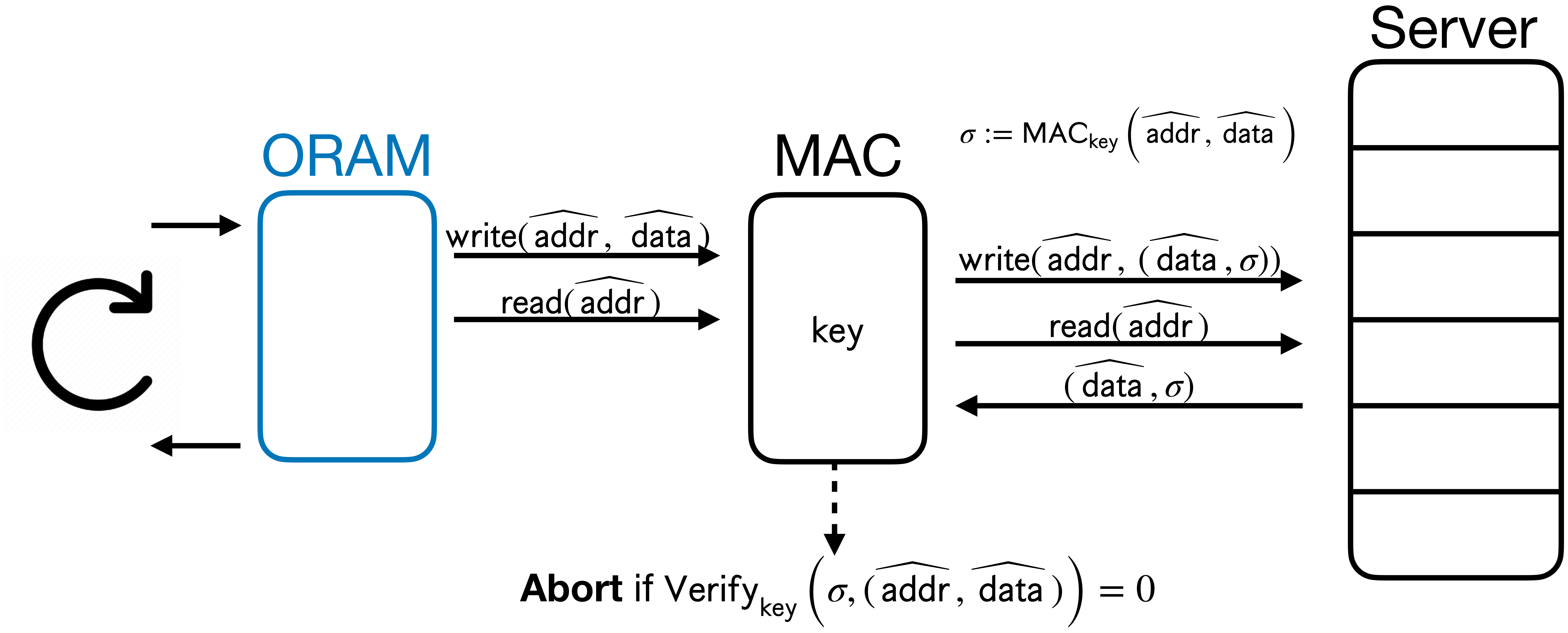
$\text{write}(\widehat{\text{addr}}, (\widehat{\text{data}}, \sigma))$

$\text{read}(\widehat{\text{addr}})$

$(\widehat{\text{data}}, \sigma)$

Technique #1: MACs

- What about Message Authentication Codes (MACs)?



Server

ORAM

MAC

key

$\sigma := \mathrm{MAC}_{\mathrm{key}}\left(\widehat{\mathrm{addr}}, \widehat{\mathrm{data}}\right)$

$\mathrm{write}(\widehat{\mathrm{addr}}, \widehat{\mathrm{data}})$

$\mathrm{read}(\widehat{\mathrm{addr}})$

$\mathrm{write}(\widehat{\mathrm{addr}}, (\widehat{\mathrm{data}}, \sigma))$

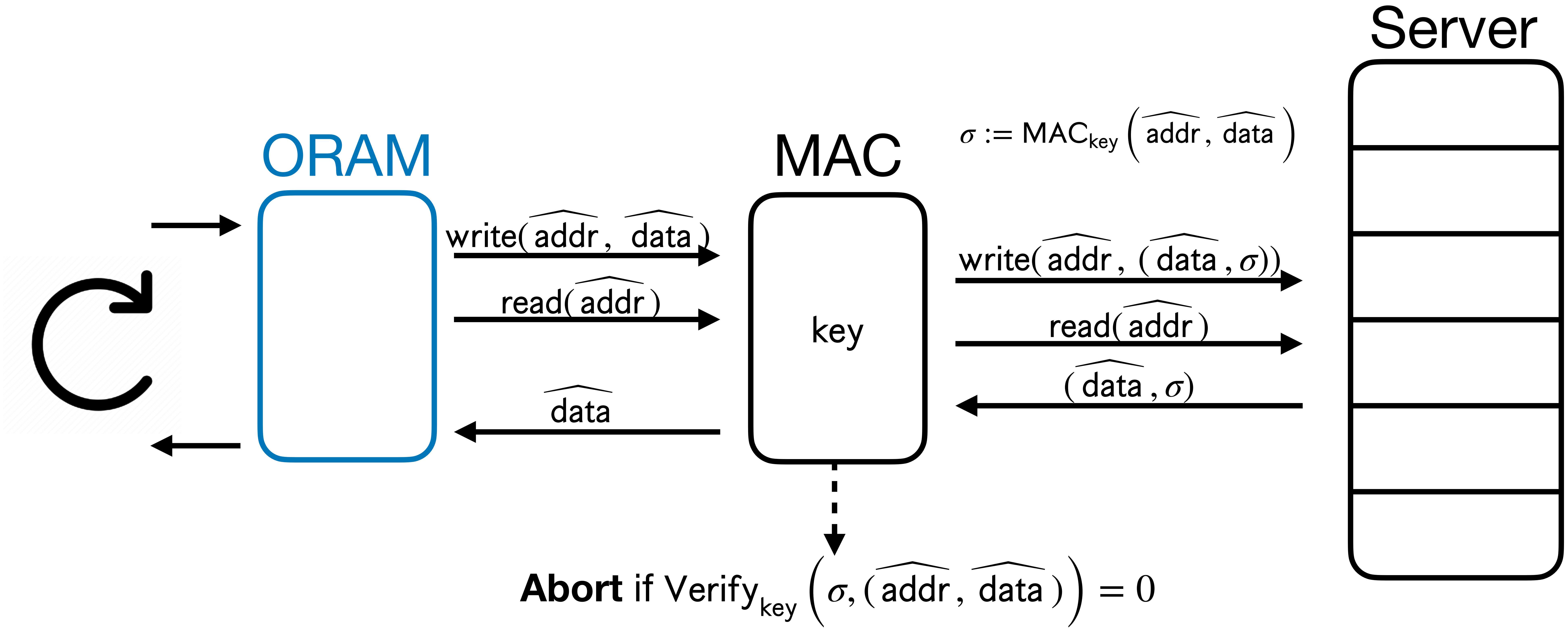
$\mathrm{read}(\widehat{\mathrm{addr}})$

$(\widehat{\mathrm{data}}, \sigma)$

Abort if $\mathrm{Verify}_{\mathrm{key}}\left(\sigma, (\widehat{\mathrm{addr}}, \widehat{\mathrm{data}})\right) = 0$

Technique #1: MACs

- What about Message Authentication Codes (MACs)?



ORAM

write($\widehat{\text{addr}}$, $\widehat{\text{data}}$)

read($\widehat{\text{addr}}$)

$\widehat{\text{data}}$

MAC

key

$\sigma := \text{MAC}_{\text{key}}\left(\widehat{\text{addr}}, \widehat{\text{data}}\right)$

write($\widehat{\text{addr}}$, ($\widehat{\text{data}}$, σ))

read($\widehat{\text{addr}}$)

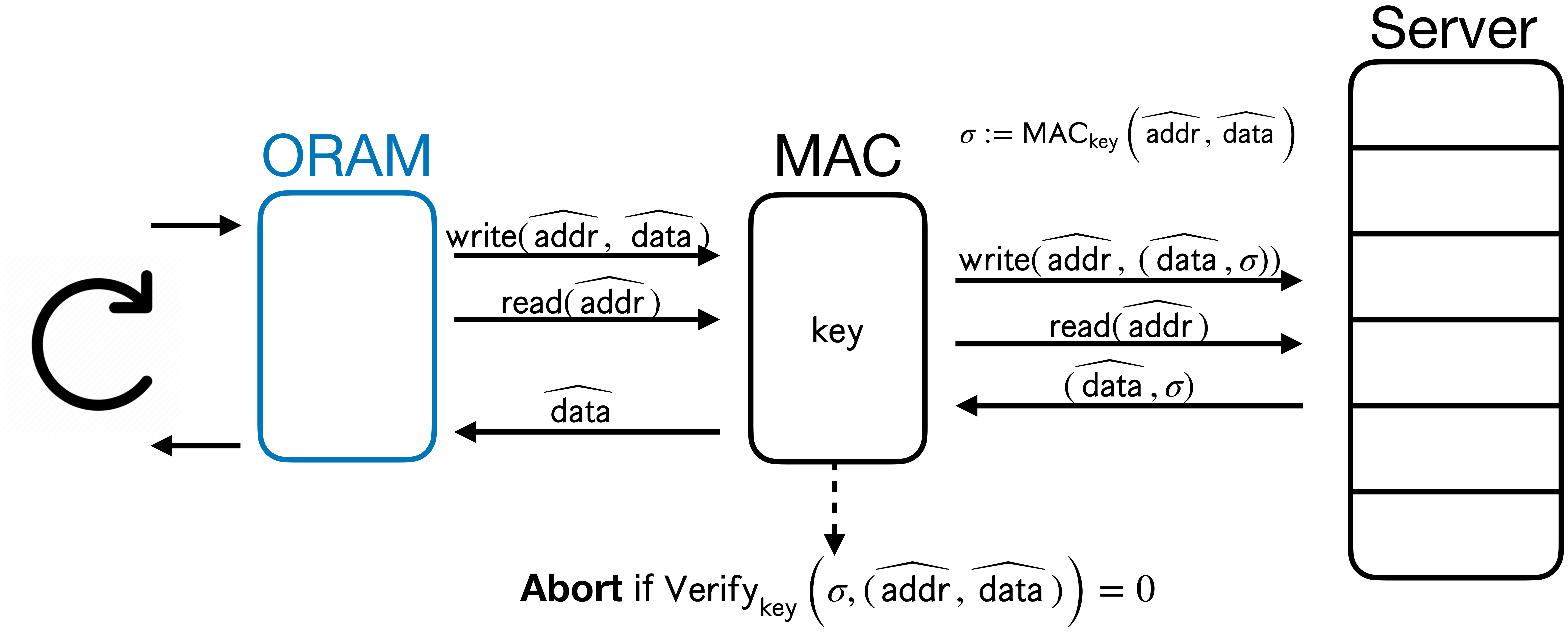
($\widehat{\text{data}}$, σ)

Server

Abort if $\text{Verify}_{\text{key}}\left(\sigma, (\widehat{\text{addr}}, \widehat{\text{data}})\right) = 0$

Technique #1: MACs

- What about Message Authentication Codes (MACs)?
- MACs force the server to only send back values it has already seen.



Server

ORAM

MAC

$\sigma := \text{MAC}_{\text{key}}\left(\widehat{\text{addr}}, \widehat{\text{data}}\right)$

write($\widehat{\text{addr}}$, $\widehat{\text{data}}$)

read($\widehat{\text{addr}}$)

$\widehat{\text{data}}$

key

write($\widehat{\text{addr}}$, ($\widehat{\text{data}}$, σ))

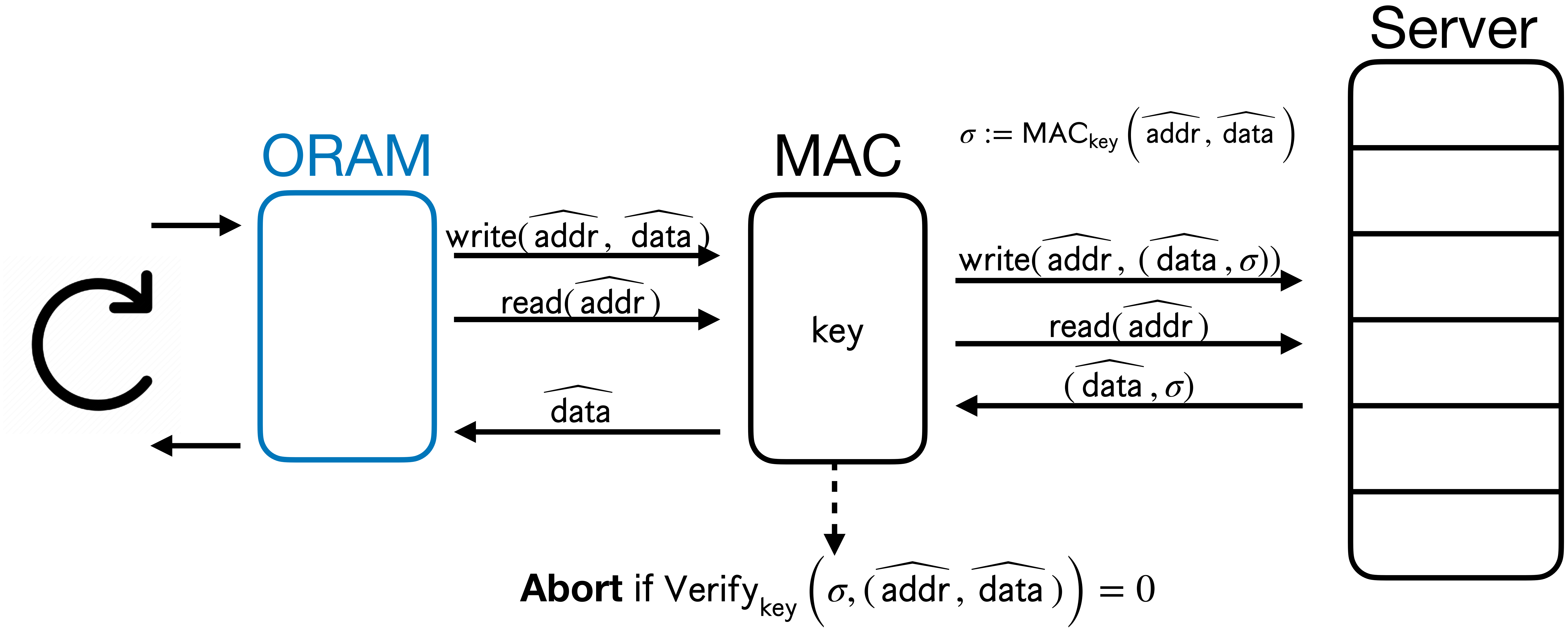
read($\widehat{\text{addr}}$)

($\widehat{\text{data}}$, σ)

Abort if $\text{Verify}_{\text{key}}\left(\sigma, (\widehat{\text{addr}}, \widehat{\text{data}})\right) = 0$

Technique #1: MACs

- MACs are **insufficient** because the server can do *replay attacks*.



ORAM

$\mathrm{write}(\widehat{\mathrm{addr}}, \widehat{\mathrm{data}})$

$\mathrm{read}(\widehat{\mathrm{addr}})$

$\widehat{\mathrm{data}}$

MAC

key

$\sigma := \mathrm{MAC}_{\mathrm{key}}\left(\widehat{\mathrm{addr}}, \widehat{\mathrm{data}}\right)$

$\mathrm{write}(\widehat{\mathrm{addr}}, (\widehat{\mathrm{data}}, \sigma))$

$\mathrm{read}(\widehat{\mathrm{addr}})$

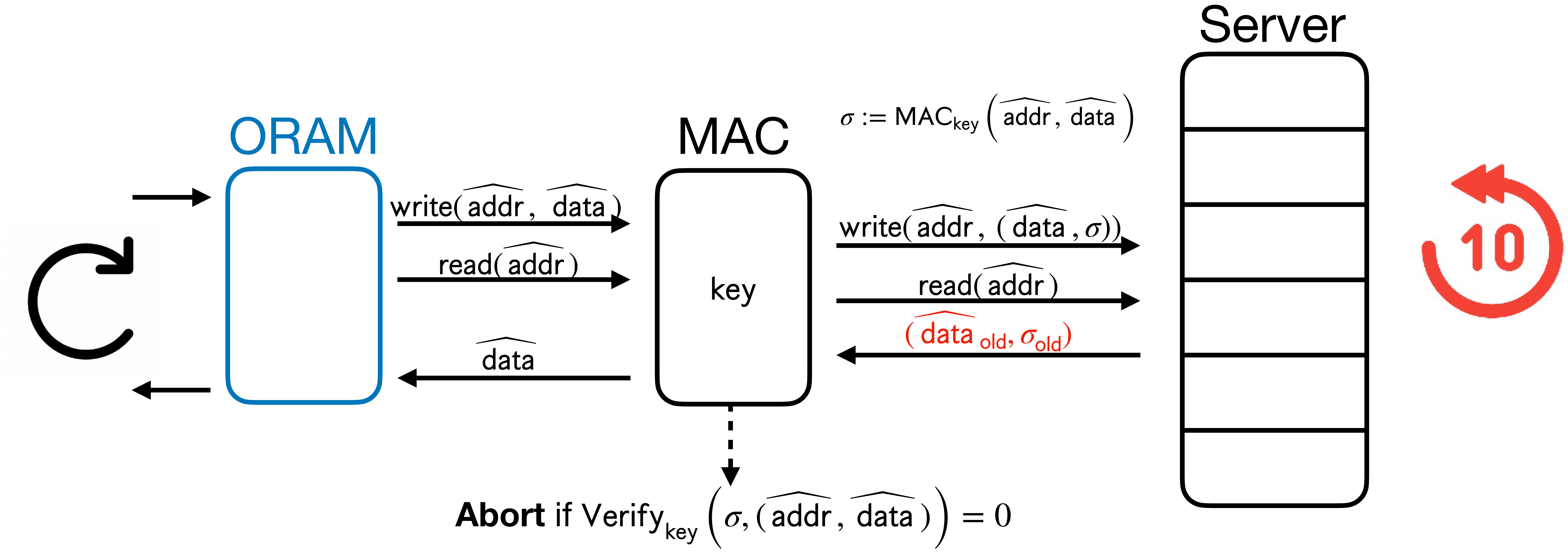
$(\widehat{\mathrm{data}}, \sigma)$

Server

Abort if $\mathrm{Verify}_{\mathrm{key}}\left(\sigma, (\widehat{\mathrm{addr}}, \widehat{\mathrm{data}})\right) = 0$

Technique #1: MACs

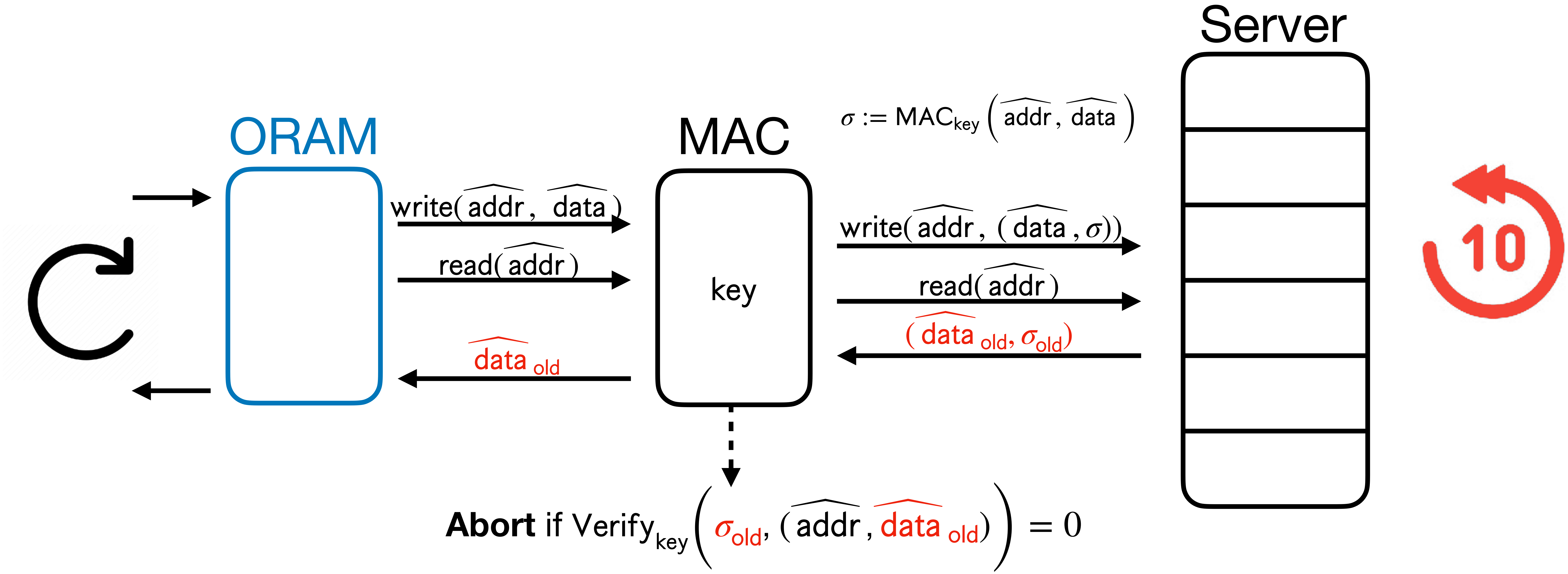
- MACs are **insufficient** because the server can do *replay attacks*.



Abort if $\text{Verify}_{\text{key}}\left(\sigma, (\widehat{\text{addr}}, \widehat{\text{data}})\right) = 0$

Technique #1: MACs

- MACs are **insufficient** because the server can do *replay attacks*.



ORAM

MAC

Server

$\sigma := \text{MAC}_{\text{key}}\left(\widehat{\text{addr}}, \widehat{\text{data}}\right)$

write($\widehat{\text{addr}}$, $\widehat{\text{data}}$)

read($\widehat{\text{addr}}$)

$\widehat{\text{data}}_{\text{old}}$

key

write($\widehat{\text{addr}}$, ($\widehat{\text{data}}$, σ))

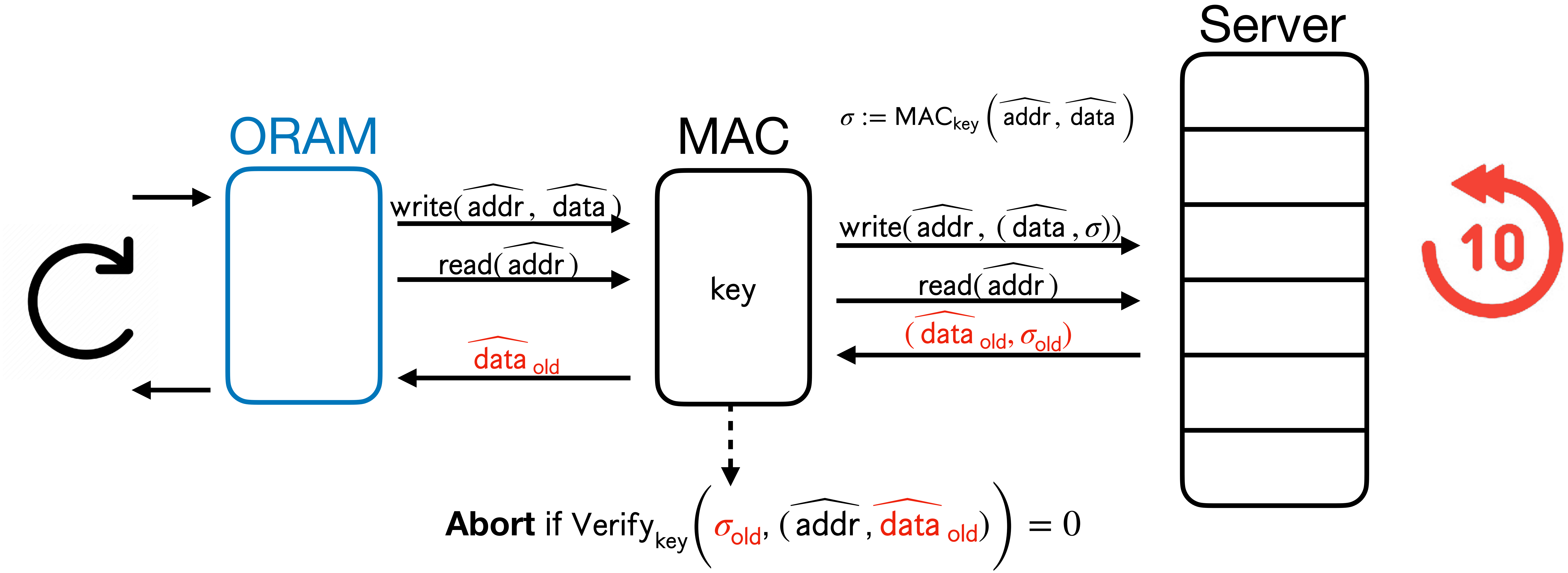
read($\widehat{\text{addr}}$)

$\widehat{(\text{data}}_{\text{old}}, \sigma_{\text{old}})$

Abort if $\text{Verify}_{\text{key}}\left(\sigma_{\text{old}}, (\widehat{\text{addr}}, \widehat{\text{data}}_{\text{old}})\right) = 0$

Technique #1: MACs

- MACs are **insufficient** because the server can do *replay attacks*.
- Affects correctness *and obliviousness*!



ORAM

MAC

key

Server

$\sigma := \mathrm{MAC}_{\mathrm{key}}\left(\widehat{\mathrm{addr}}, \widehat{\mathrm{data}}\right)$

$\mathrm{write}(\widehat{\mathrm{addr}}, \widehat{\mathrm{data}})$

$\mathrm{read}(\widehat{\mathrm{addr}})$

$\widehat{\mathrm{data}}_{\mathrm{old}}$

$\mathrm{write}(\widehat{\mathrm{addr}}, (\widehat{\mathrm{data}}, \sigma))$

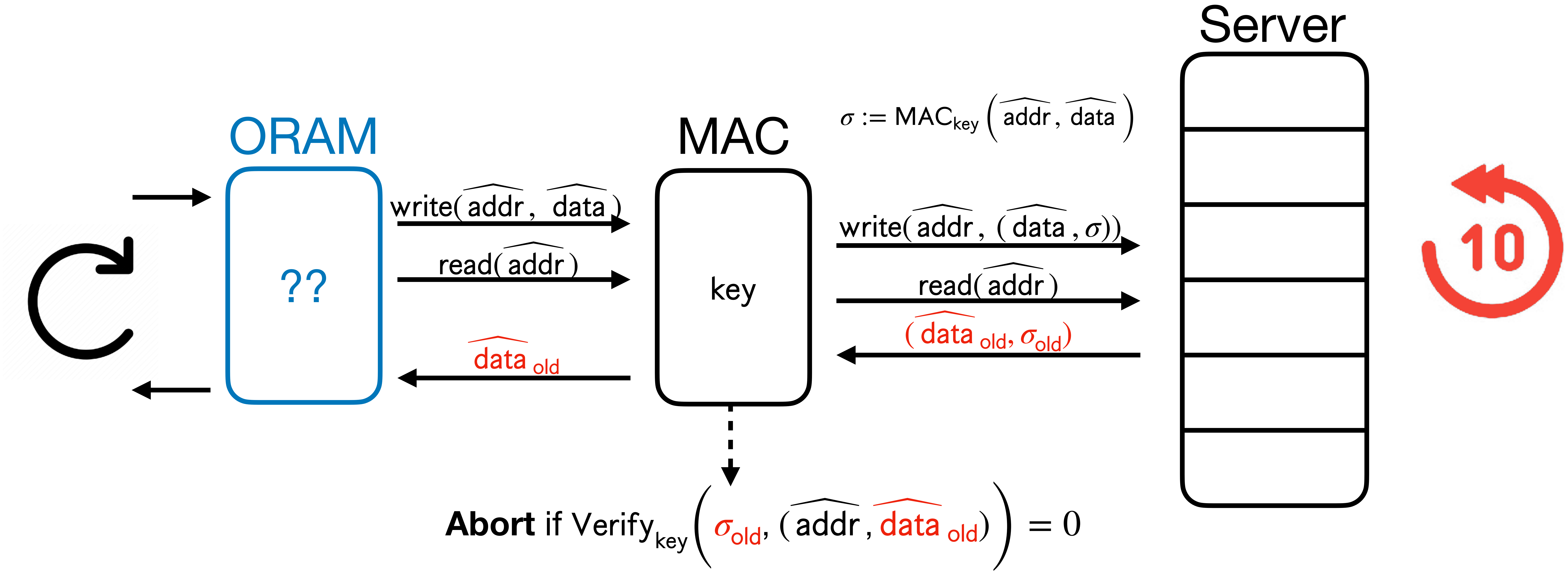
$\mathrm{read}(\widehat{\mathrm{addr}})$

$(\widehat{\mathrm{data}}_{\mathrm{old}}, \sigma_{\mathrm{old}})$

Abort if $\mathrm{Verify}_{\mathrm{key}}\left(\sigma_{\mathrm{old}}, (\widehat{\mathrm{addr}}, \widehat{\mathrm{data}}_{\mathrm{old}})\right) = 0$

Technique #1: MACs

- MACs are **insufficient** because the server can do *replay attacks*.
- Affects correctness *and obliviousness*!



Server

ORAM

??

MAC

key

$\sigma := \mathrm{MAC}_{\mathrm{key}}\left(\widehat{\mathrm{addr}}, \widehat{\mathrm{data}}\right)$

$\mathrm{write}(\widehat{\mathrm{addr}}, \widehat{\mathrm{data}})$

$\mathrm{read}(\widehat{\mathrm{addr}})$

$\widehat{\mathrm{data}}_{\mathrm{old}}$

$\mathrm{write}(\widehat{\mathrm{addr}}, (\widehat{\mathrm{data}}, \sigma))$

$\mathrm{read}(\widehat{\mathrm{addr}})$

$(\widehat{\mathrm{data}}_{\mathrm{old}}, \sigma_{\mathrm{old}})$

Abort if $\mathrm{Verify}_{\mathrm{key}}\left(\sigma_{\mathrm{old}}, (\widehat{\mathrm{addr}}, \widehat{\mathrm{data}}_{\mathrm{old}})\right) = 0$

Replay Attack for Hierarchical Framework

Replay Attack for Hierarchical Framework

- **Key fact**: Oblivious hash tables are oblivious only if lookups are *non-recurrent*.

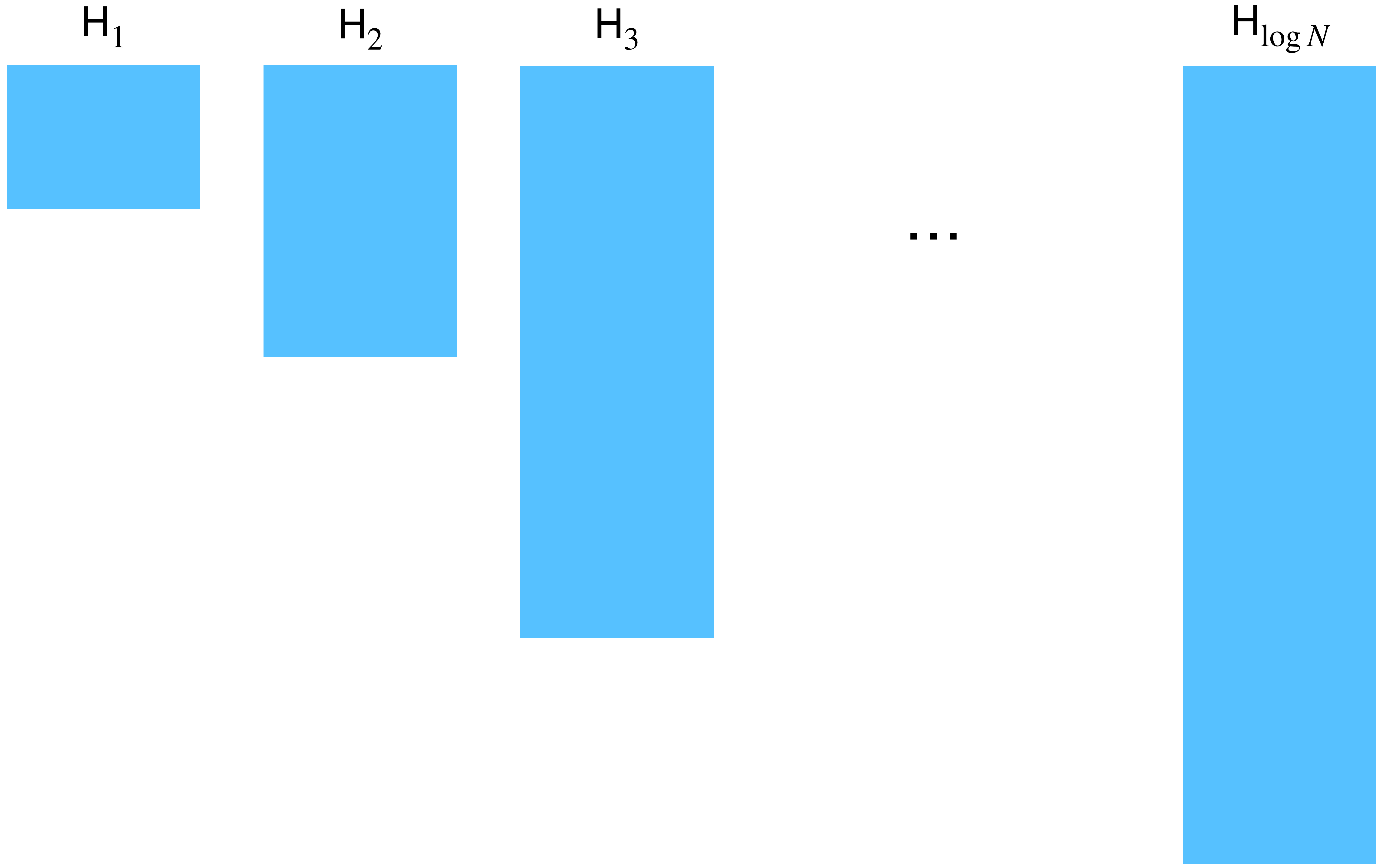
Replay Attack for Hierarchical Framework

- **Key fact**: Oblivious hash tables are oblivious only if lookups are *non-recurrent*.
    - If you look up the same addr twice in some H_i without rebuilding in between, **access pattern to** H_i **will be identical – not oblivious***.*

Replay Attack for Hierarchical Framework

- **Key fact**: Oblivious hash tables are oblivious only if lookups are *non-recurrent*.
  - If you look up the same addr twice in some H_i without rebuilding in between, **access pattern to H_i will be identical – not oblivious***.*
  - In honest-but-curious setting, looking up **dummies** and rebuilding hash tables ensures reads will be non-recurrent.

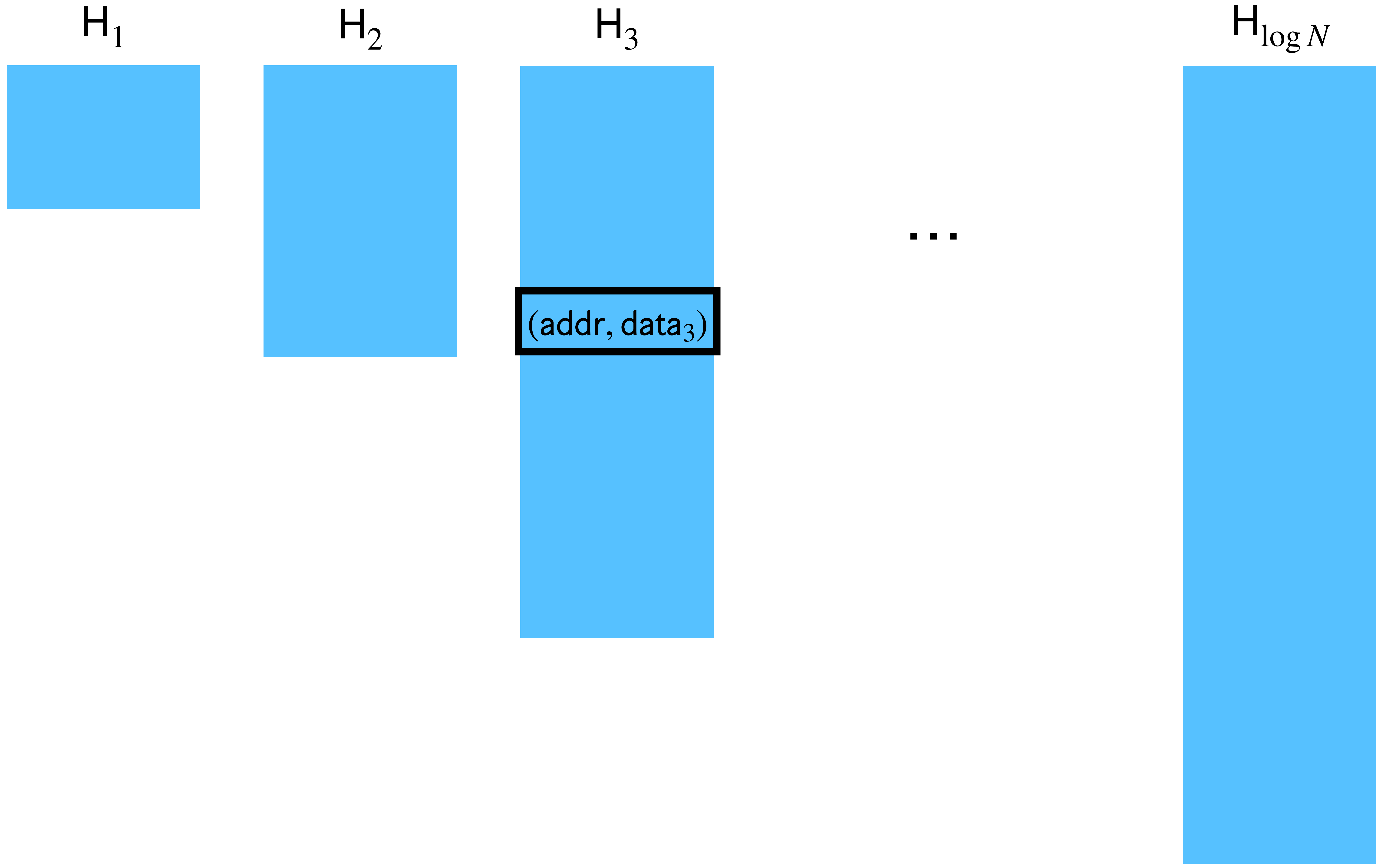
Replay Attack



Lookup Phase

Replay Attack

Read addr:



H_1

H_2

H_3

$H_{\log N}$

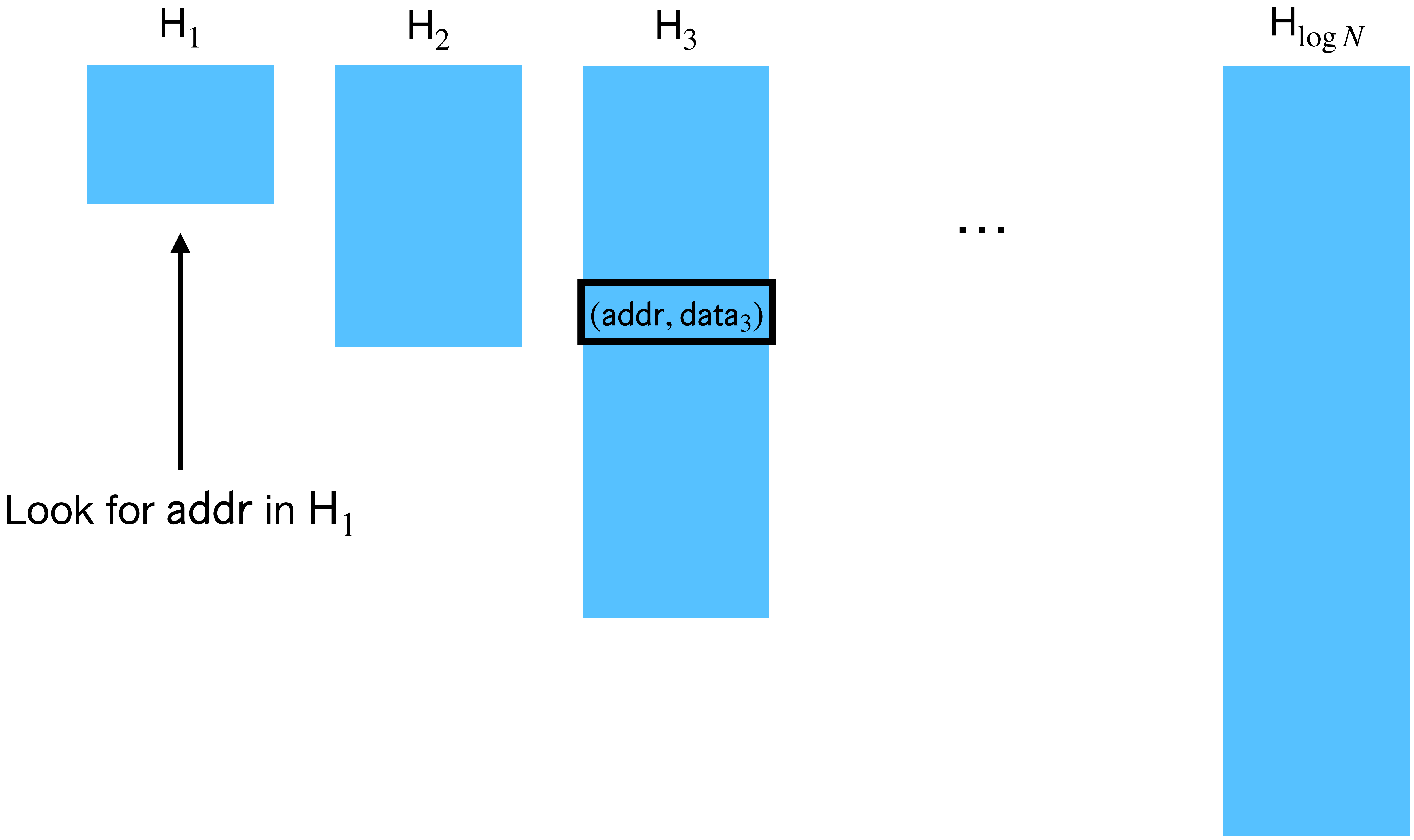
$(\text{addr}, \text{data}_3)$

…

Lookup Phase

Replay Attack

Read addr:



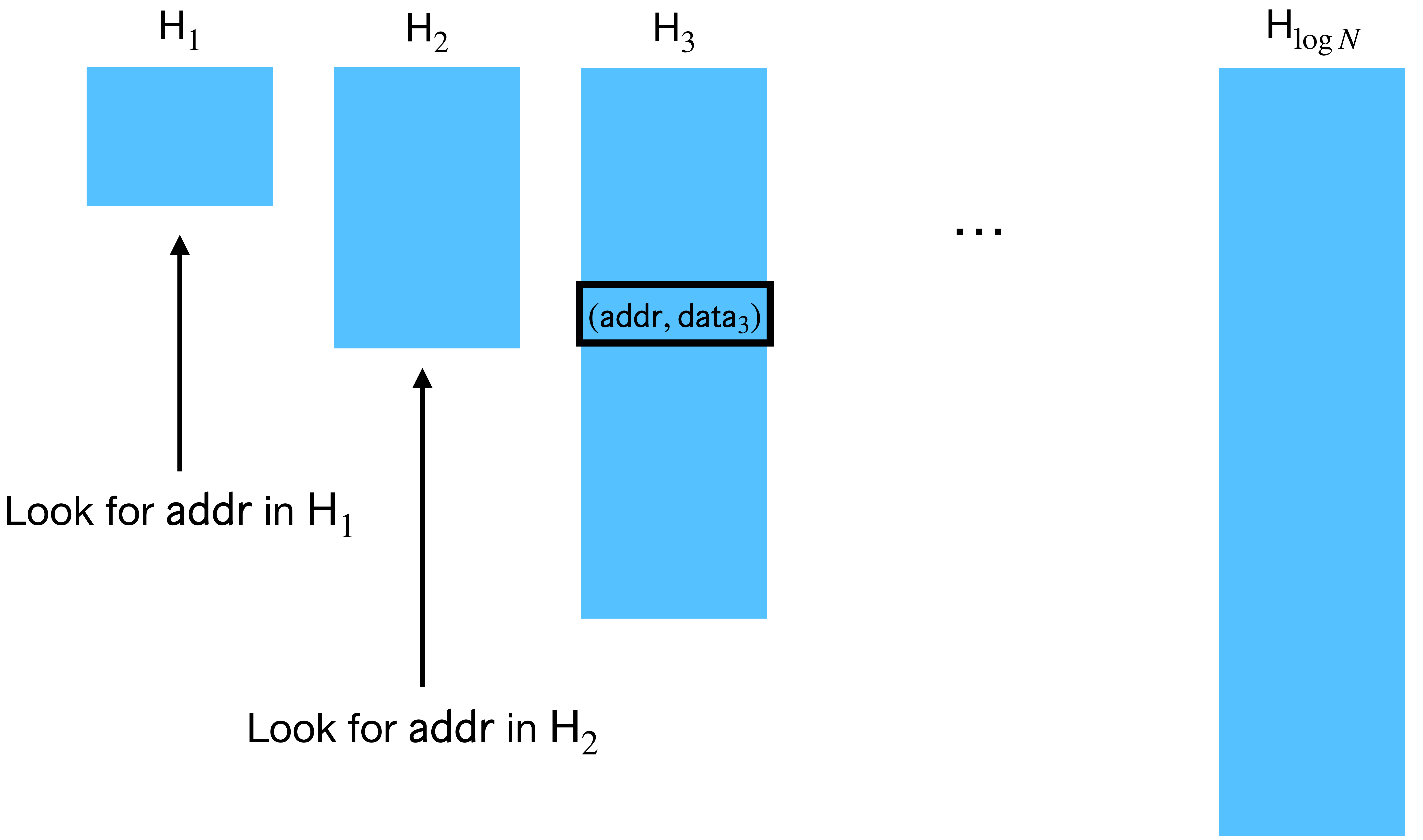
H_1 H_2 H_3 … $H_{\log N}$

(addr, data_3)

Look for addr in H_1

Lookup Phase

Replay Attack



Read addr:

H_1 H_2 H_3 … $H_{\log N}$

$(\mathrm{addr}, \mathrm{data}_3)$

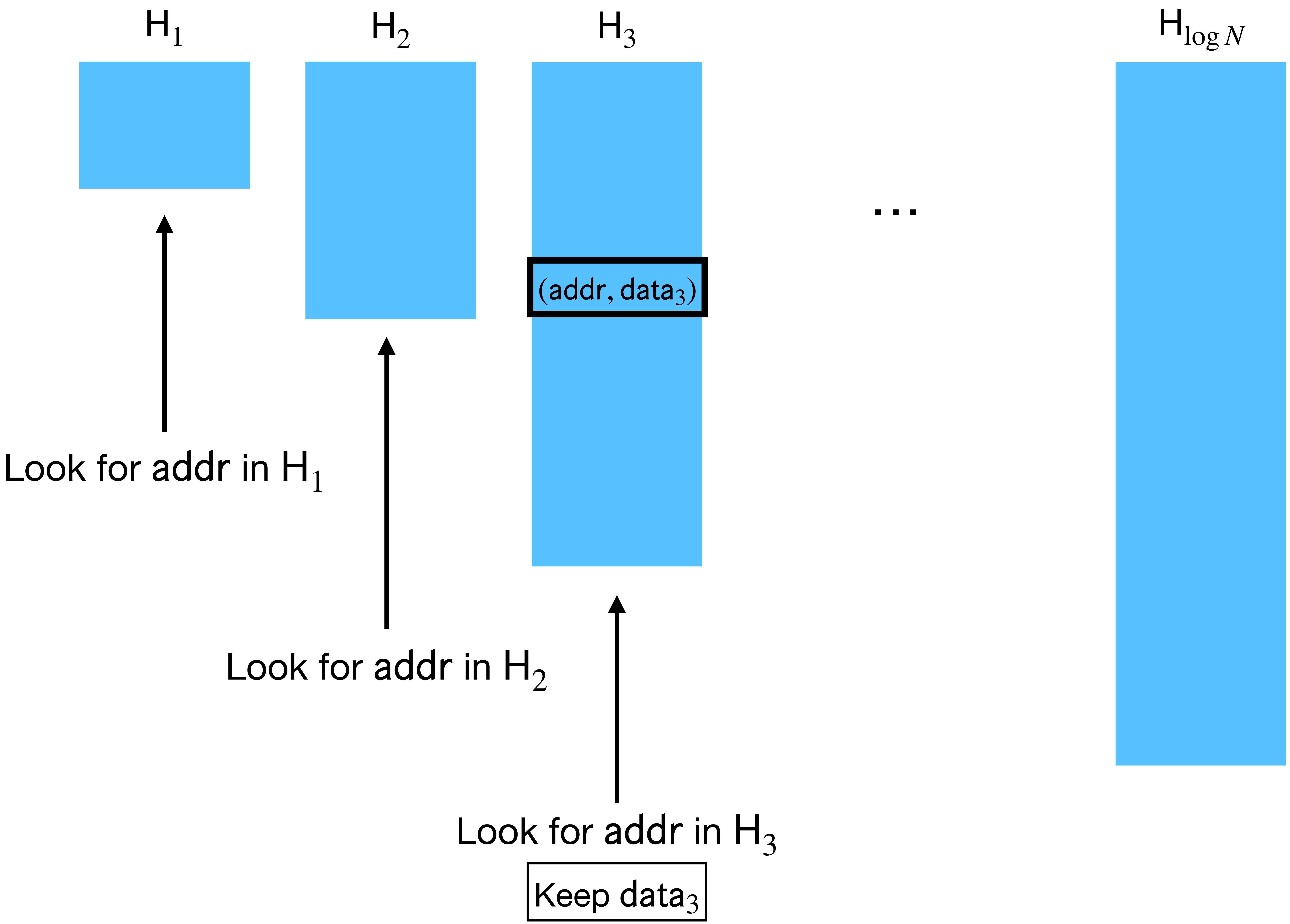
Look for addr in H_1

Look for addr in H_2

Lookup Phase

Replay Attack

Read addr:



H_1 H_2 H_3 … $H_{\log N}$

$(\mathrm{addr}, \mathrm{data}_3)$

Look for addr in H_1

Look for addr in H_2

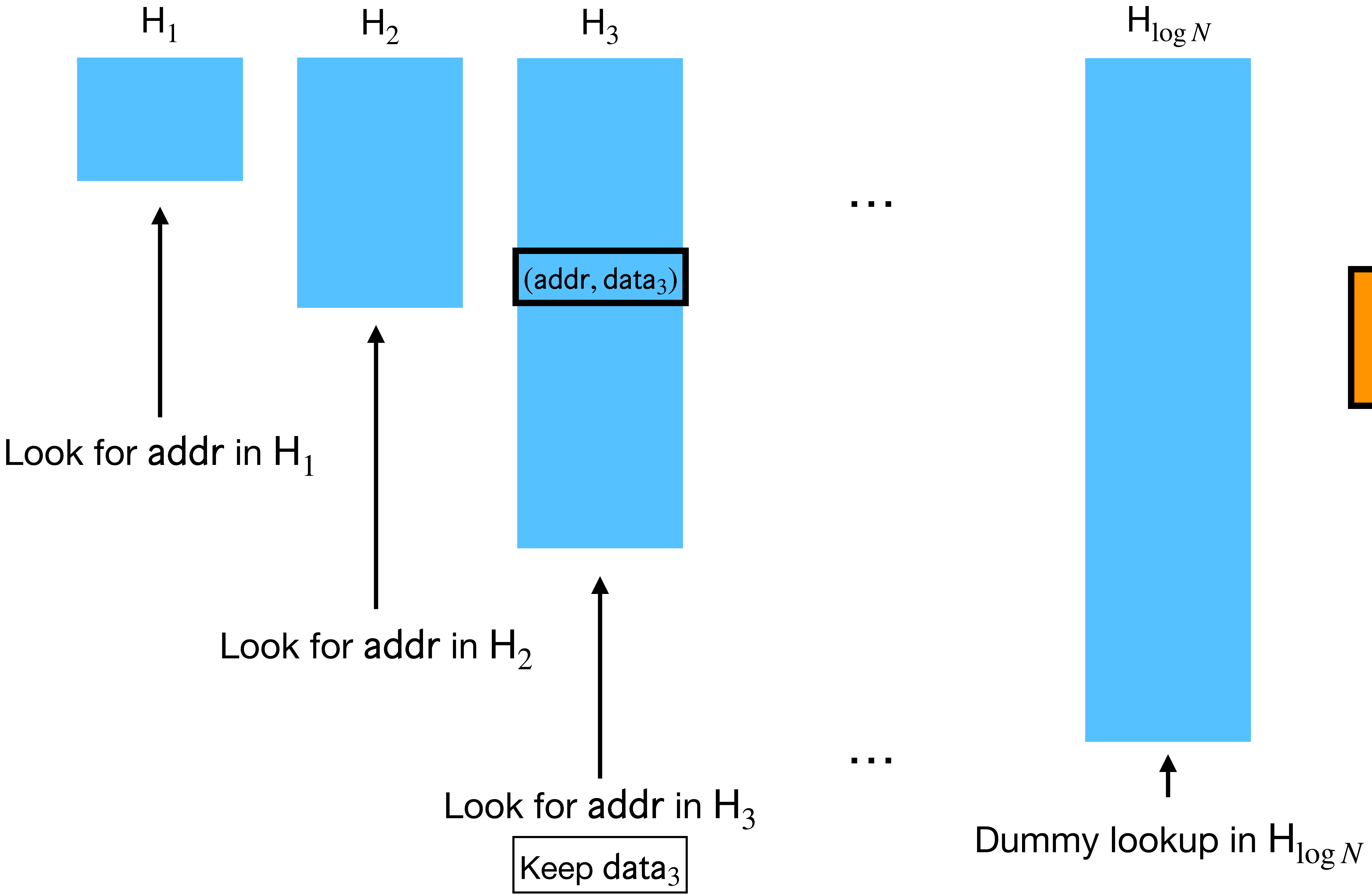
Look for addr in H_3

Keep data_3

Lookup Phase

Replay Attack

Read addr:



H_1

H_2

H_3

…

$H_{\log N}$

(addr, $data_3$)

Look for addr in H_1

Look for addr in H_2

Look for addr in H_3

Keep $data_3$

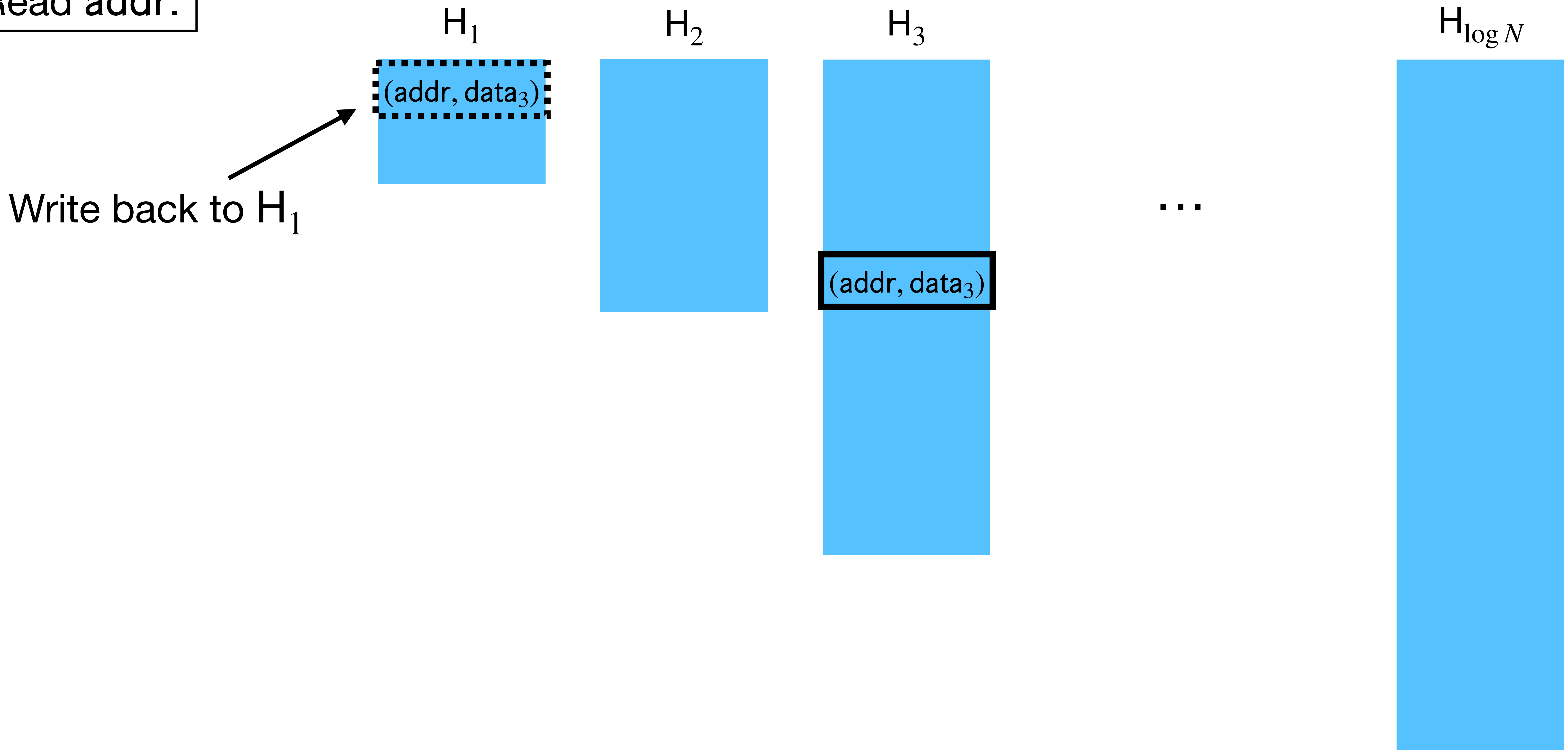
…

Dummy lookup in $H_{\log N}$

Lookup Phase

Replay Attack

Read addr:

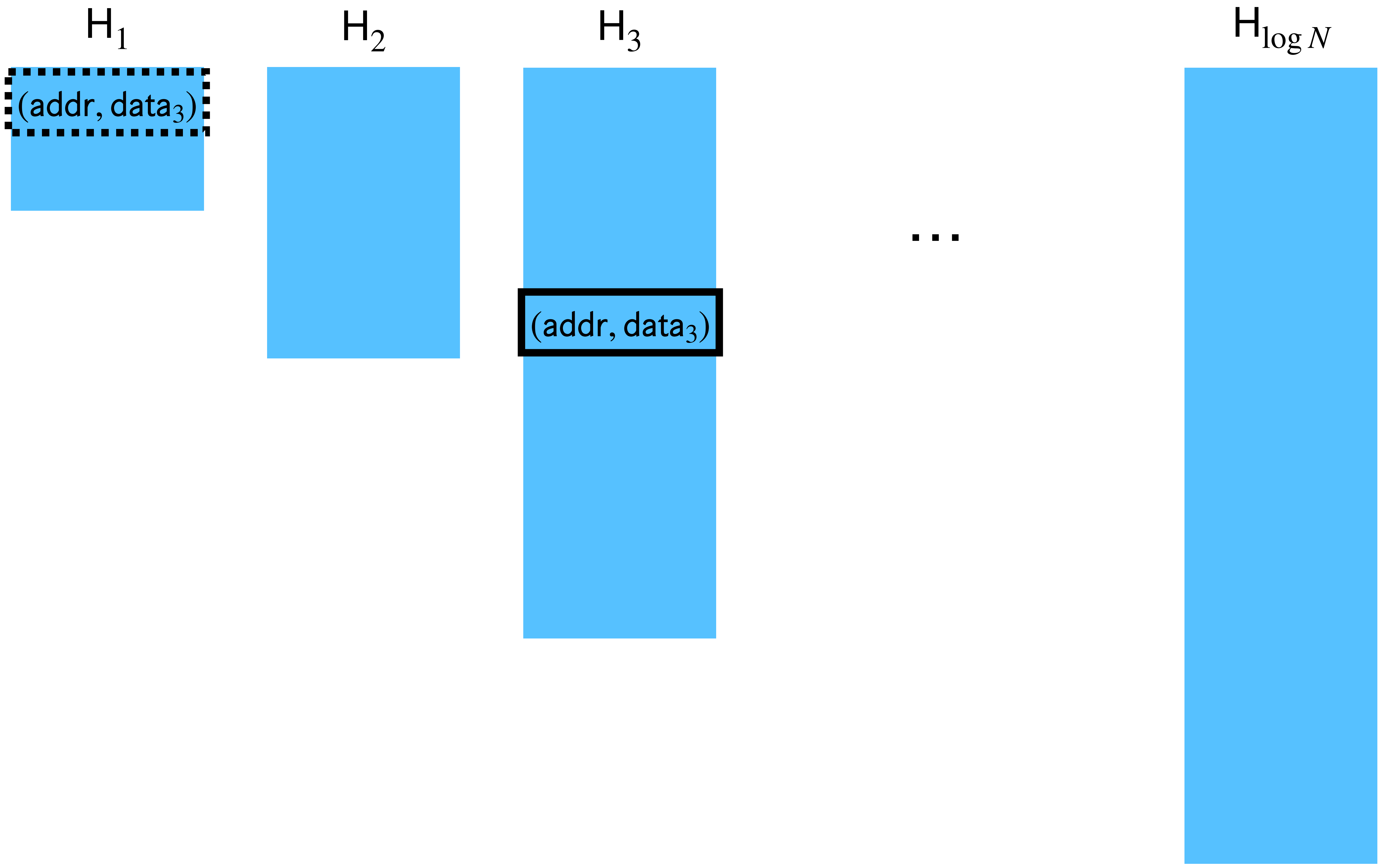


Lookup Phase

Replay Attack

Read addr:

Write to addr:



H_1 H_2 H_3 … $H_{\log N}$

(addr, data_3)

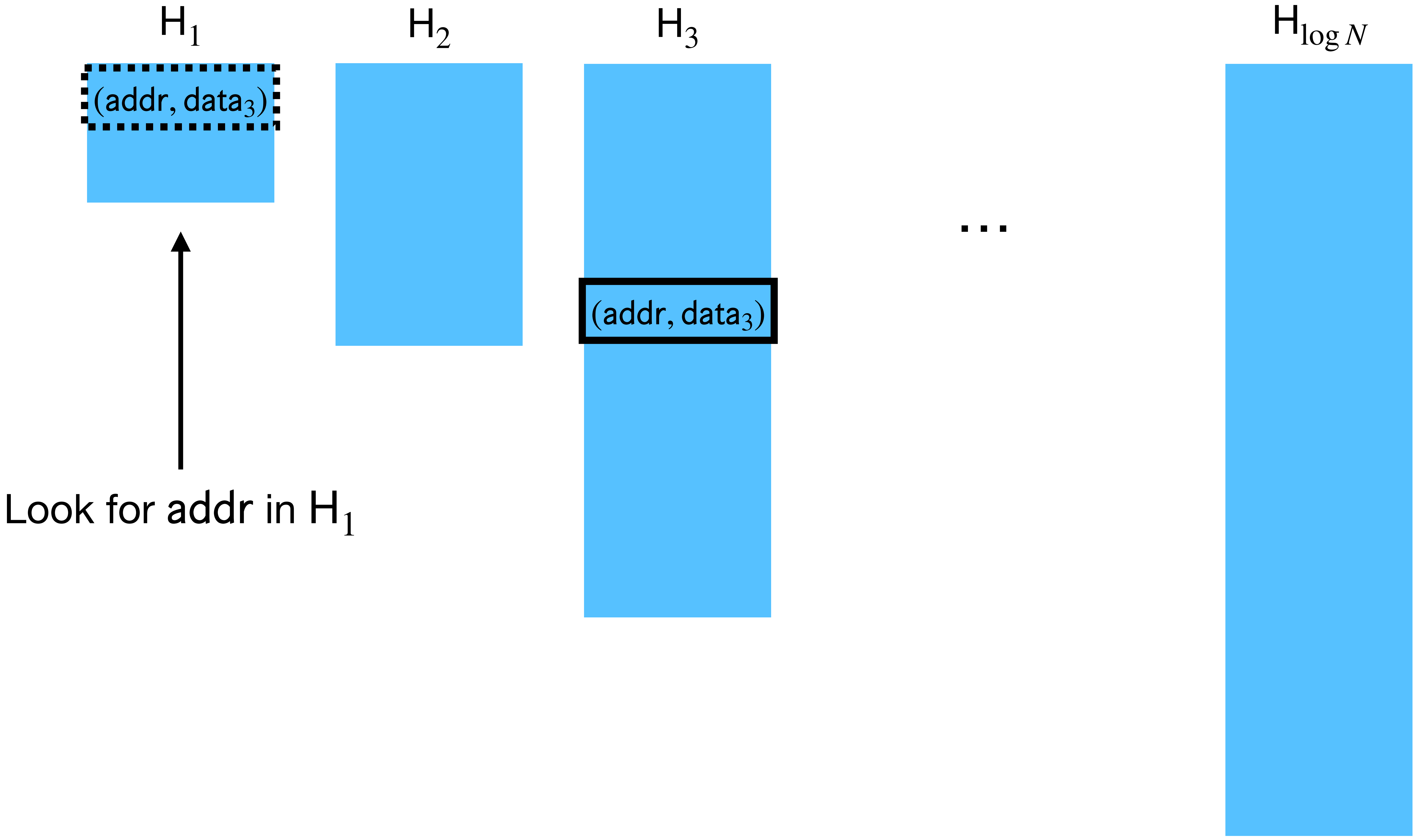
(addr, data_3)

Lookup Phase

Replay Attack

Read addr:

Write to addr:



H_1

$(\text{addr}, \text{data}_3)$

Look for addr in H_1

H_2

H_3

$(\text{addr}, \text{data}_3)$

…

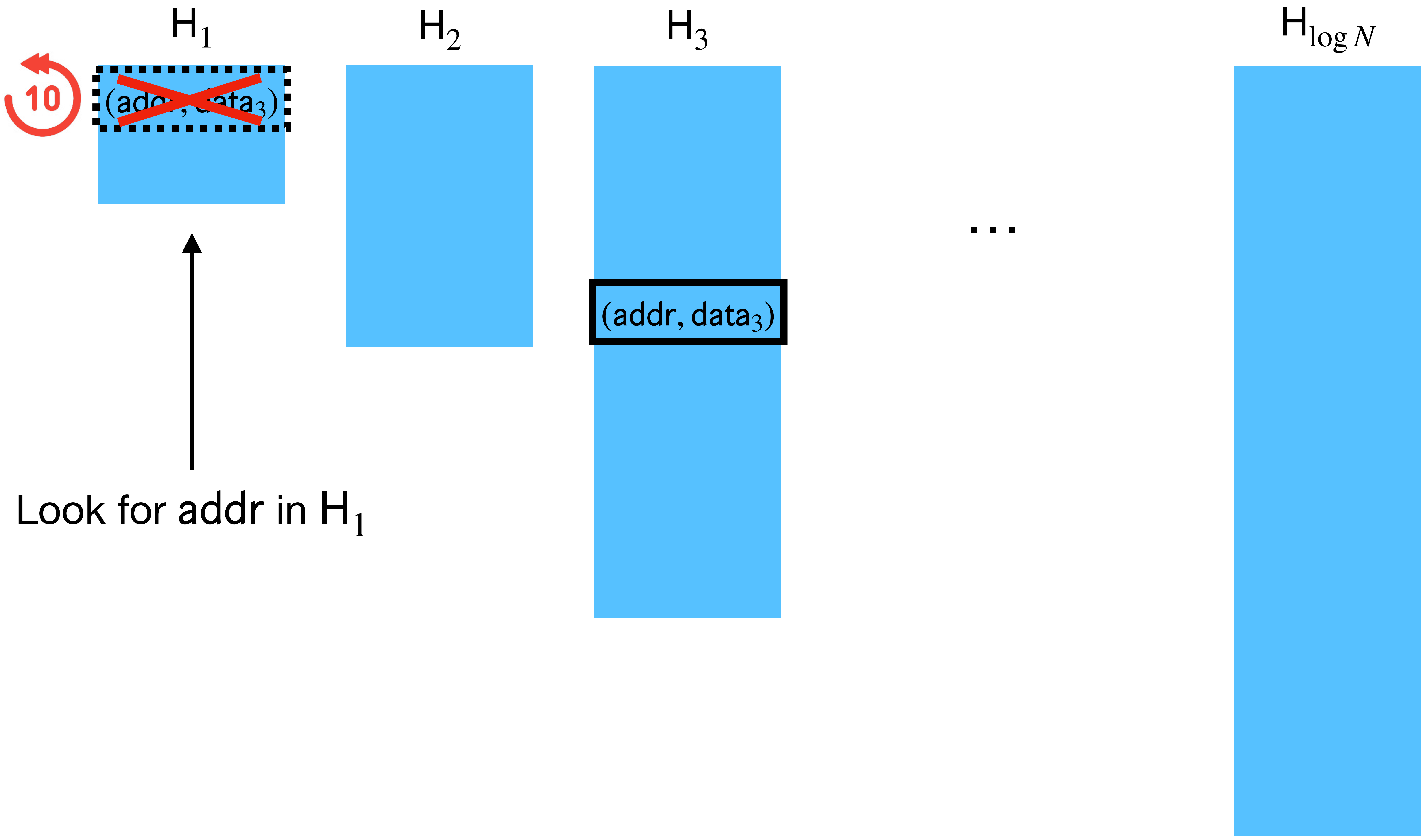
$H_{\log N}$

Lookup Phase

Replay Attack

Read addr:

Write to addr:



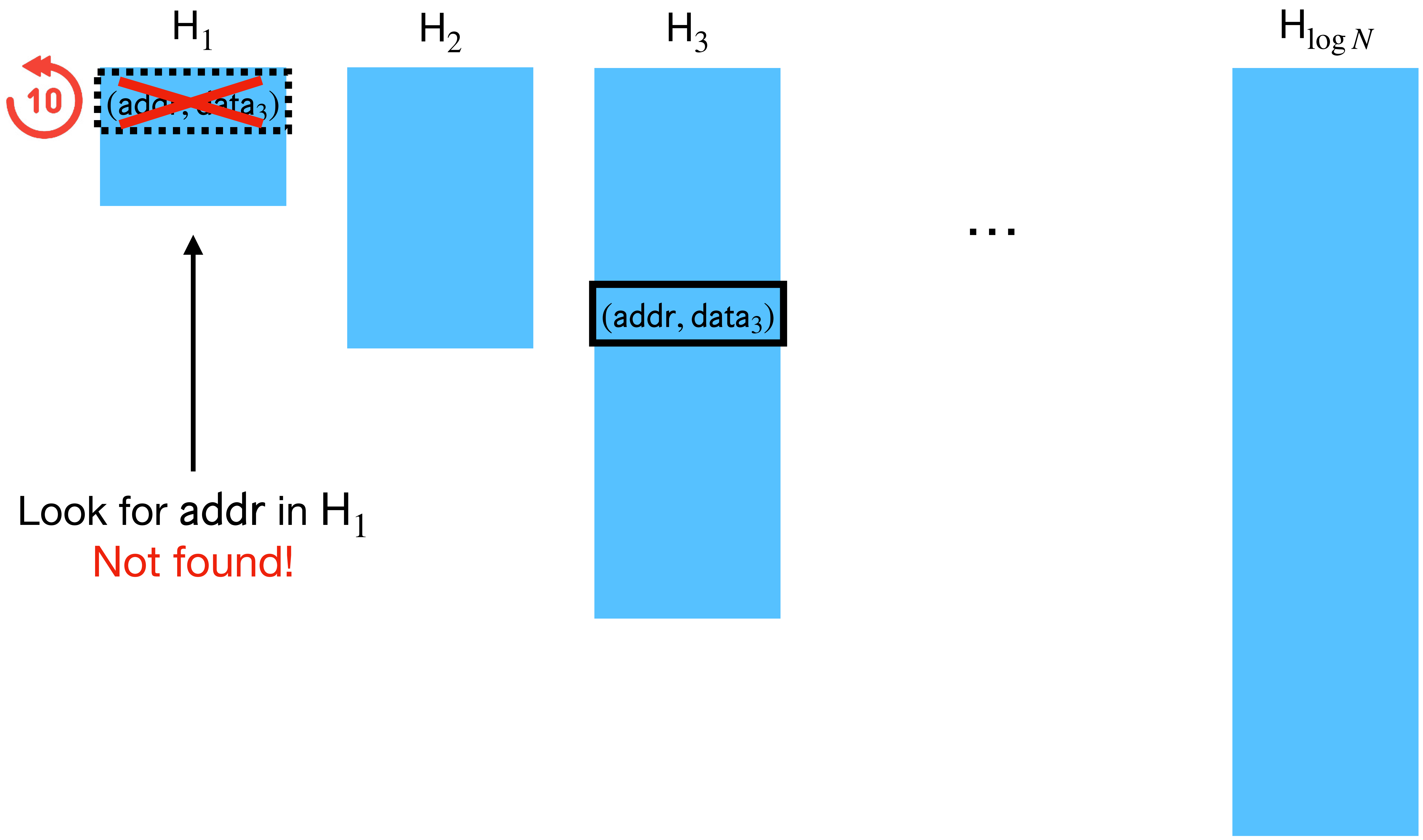
Look for addr in H_1

Lookup Phase

Replay Attack

Read addr:

Write to addr:



Look for addr in H_1

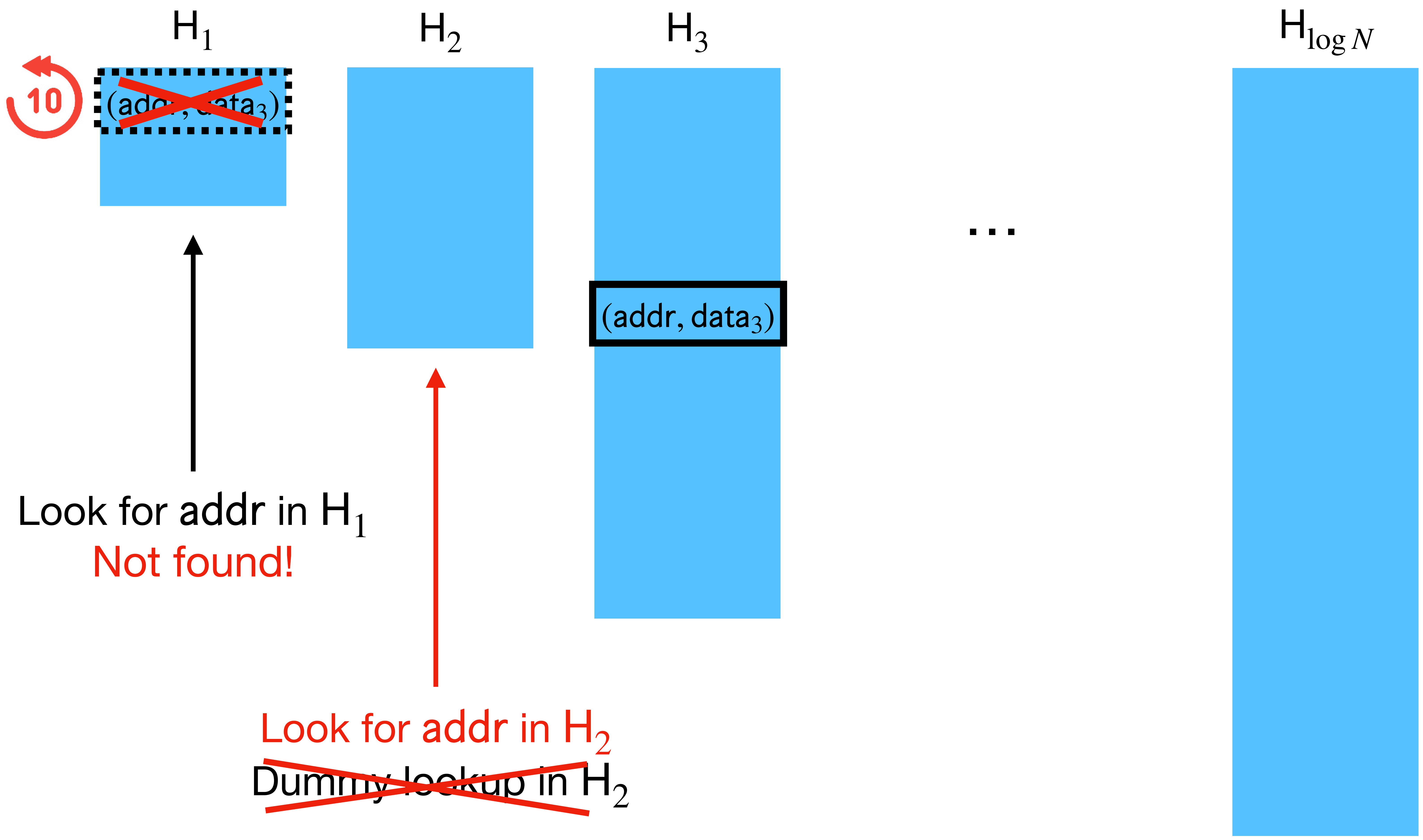
Not found!

Lookup Phase

Replay Attack

Read addr:

Write to addr:



H_1 H_2 H_3 … $H_{\log N}$

10 ~~$(\text{addr}, \text{data}_3)$~~

$(\text{addr}, \text{data}_3)$

Look for addr in H_1

Not found!

Look for addr in H_2

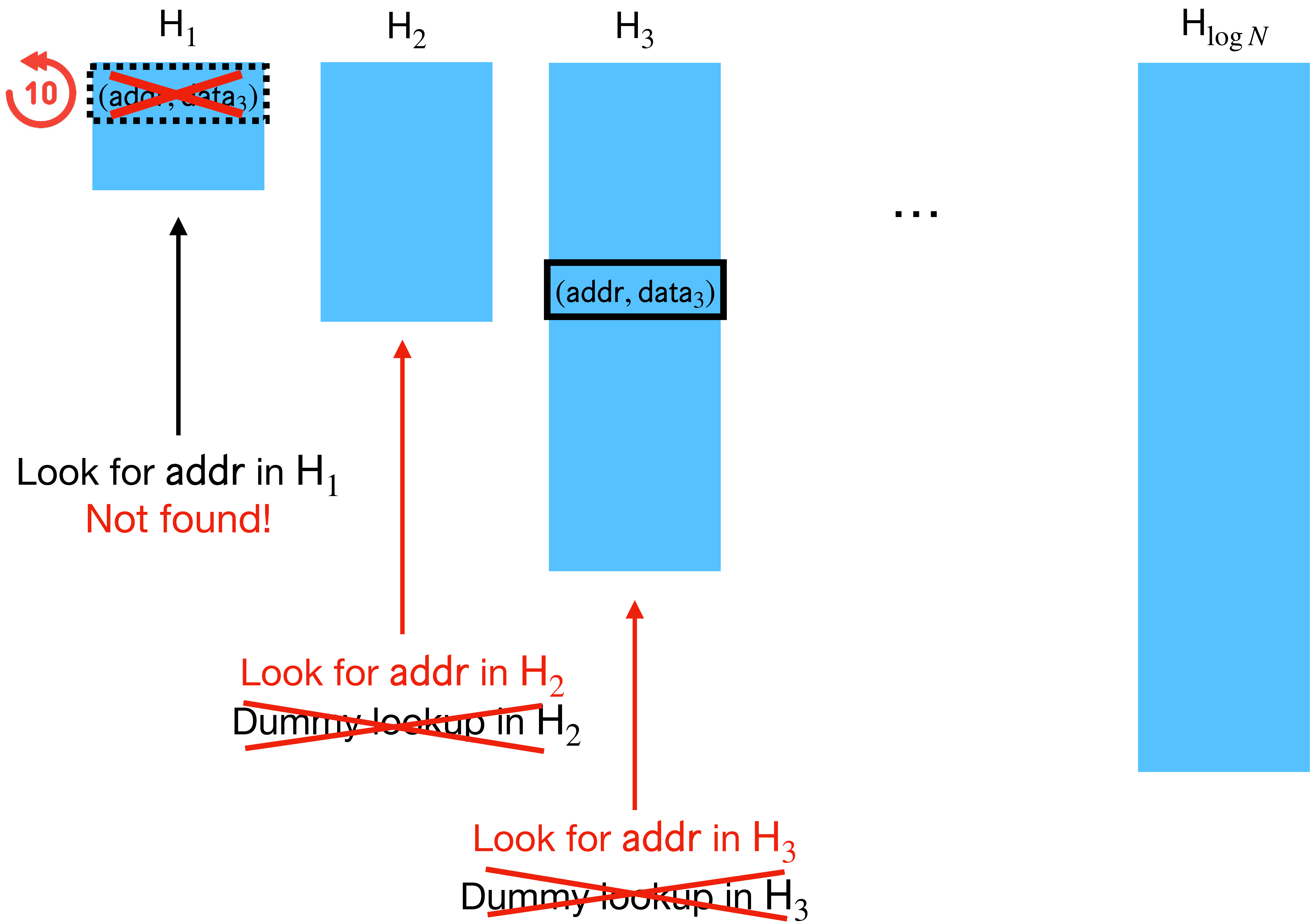
~~Dummy lookup in H_2~~

Lookup Phase

Replay Attack

Read addr:

Write to addr:



Look for addr in H$_1$

Not found!

Look for addr in H$_2$

~~Dummy lookup in H$_2$~~

Look for addr in H$_3$

~~Dummy lookup in H$_3$~~

Lookup Phase

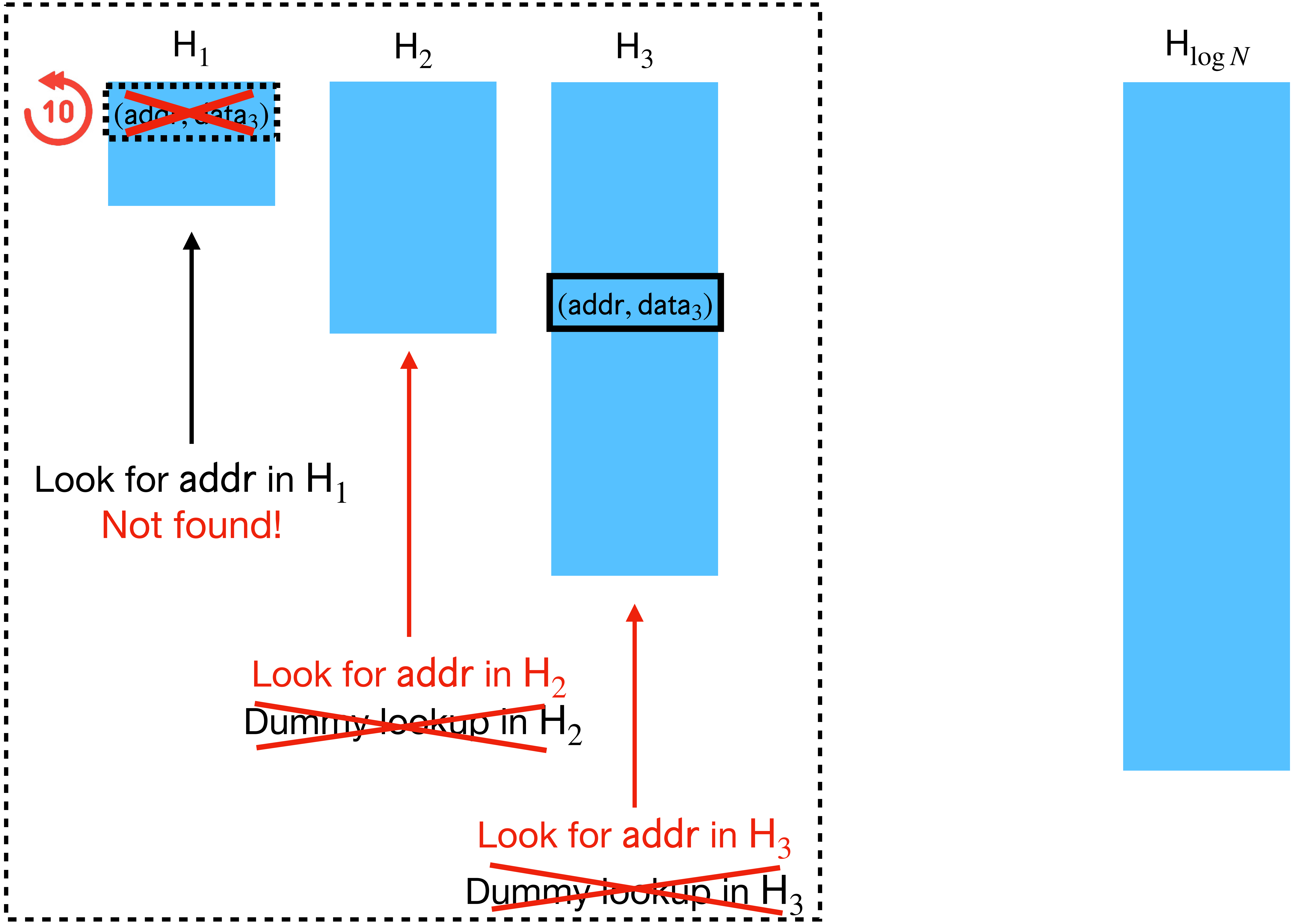
Replay Attack

Read addr:

Write to addr:

Exact same access pattern as first query!

Leaks repeated address.



Look for addr in H_1
Not found!

Look for addr in H_2
~~Dummy lookup in H_2~~

Look for addr in H_3
~~Dummy lookup in H_3~~

Lookup Phase

Replay Attack

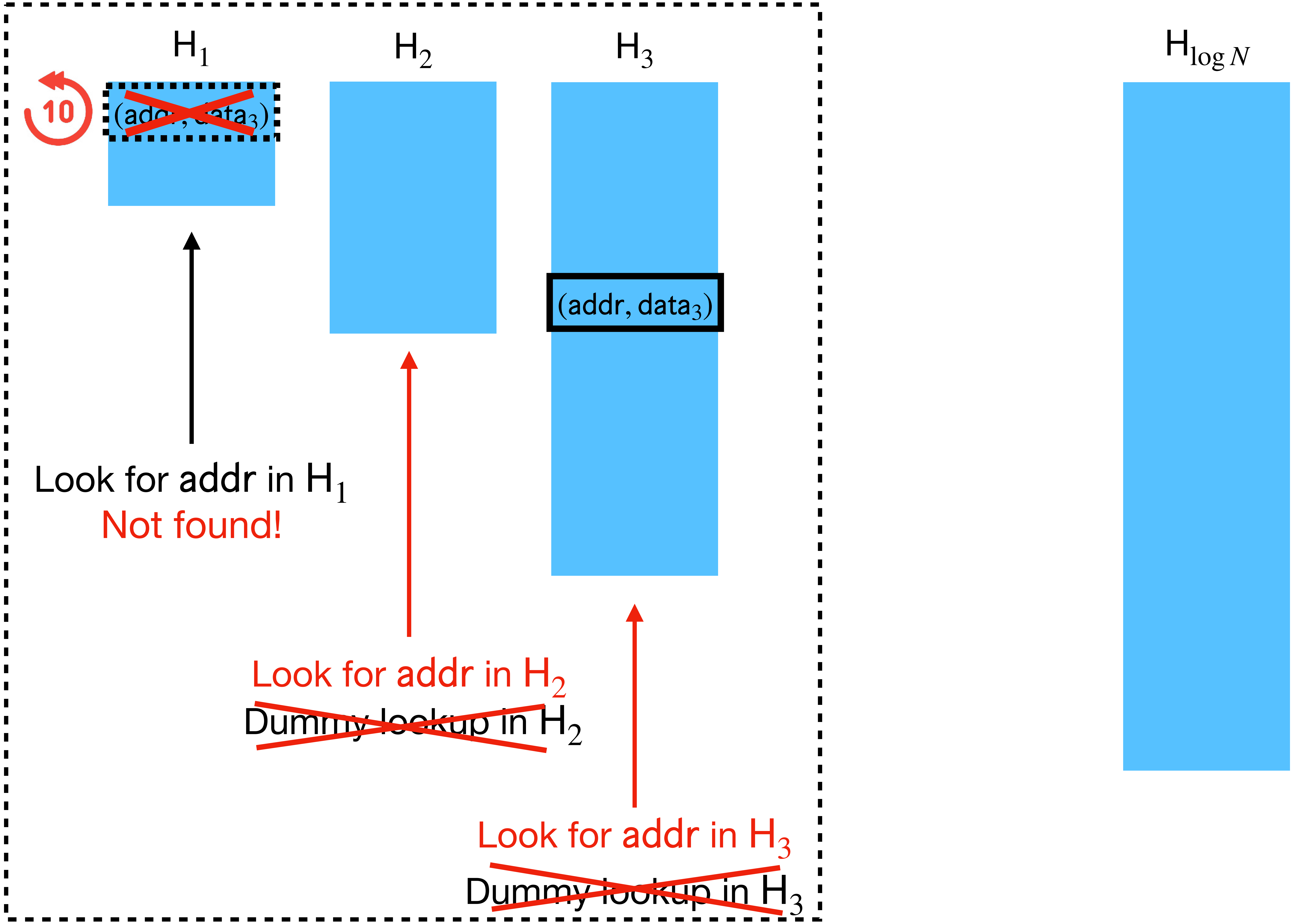
Read addr:

Write to addr:

Exact same access pattern as first query!

Leaks repeated address.

Obliviousness of H_i lookups depends on **correctness** of $H_{<i}$ lookups!



Look for addr in H_1
Not found!

Look for addr in H_2
~~Dummy lookup in H_2~~

Look for addr in H_3
~~Dummy lookup in H_3~~

Lookup Phase

Replay Attack for Hierarchical

- As is, the hierarchical paradigm with MACs is susceptible to replay attacks, so it’s still maliciously insecure.

Replay Attack for Hierarchical

- As is, the hierarchical paradigm with MACs is susceptible to replay attacks, so it’s still maliciously insecure.
- Is there a fix?

General Fix For Replay Attacks: Time-Stamping

- [Ostrovsky ’90, Goldreich-Ostrovsky ’96] noticed that *time-stamping* is sufficient to prevent replay attacks with MACs (in their $O(\log^3 N)$ ORAM).

General Fix For Replay Attacks: Time-Stamping

- [Ostrovsky '90, Goldreich-Ostrovsky '96] noticed that *time-stamping* is sufficient to prevent replay attacks with MACs (in their $O(\log^3 N)$ ORAM).
- **Time-stamping**:

General Fix For Replay Attacks: Time-Stamping

- [Ostrovsky ’90, Goldreich-Ostrovsky ’96] noticed that *time-stamping* is sufficient to prevent replay attacks with MACs (in their $O(\log^3 N)$ ORAM).
- **Time-stamping**:
  - Keep track of global counter ctr, counting the number of $\widehat{\mathsf{query}}$’s so far.

General Fix For Replay Attacks: Time-Stamping

- [Ostrovsky ’90, Goldreich-Ostrovsky ’96] noticed that *time-stamping* is sufficient to prevent replay attacks with MACs (in their $O(\log^3 N)$ ORAM).
- **Time-stamping**:
  - Keep track of global counter ctr, counting the number of $\widehat{\mathsf{query}}$’s so far.

$$\boxed{\mathsf{PrevTime}\left(\mathsf{ctr}, \widehat{\mathsf{addr}}\right) := \begin{array}{c}\text{most recent time (up until } \mathsf{ctr}\text{)} \\ \text{when } \widehat{\mathsf{addr}} \text{ has been written to.}\end{array}}$$

General Fix For Replay Attacks: Time-Stamping

- [Ostrovsky '90, Goldreich-Ostrovsky '96] noticed that *time-stamping* is sufficient to prevent replay attacks with MACs (in their $O(\log^3 N)$ ORAM).
- **Time-stamping**:
  - Keep track of global counter ctr, counting the number of $\widehat{\mathsf{query}}$'s so far.

$$\boxed{\mathsf{PrevTime}\left(\mathsf{ctr}, \widehat{\mathsf{addr}}\right) := \begin{array}{c}\text{most recent time (up until ctr)}\\ \text{when } \widehat{\mathsf{addr}} \text{ has been written to.}\end{array}}$$

- **Theorem** [GO '96]: If ORAM has **local, low-space** computable $\mathsf{PrevTime}$, then MACs + time-stamping converts honest-but-curious ORAM to maliciously secure ORAM with the same asymptotic overhead.

Time-Stamping

🧐

$\widehat{\text{addr}_1}$	$\widehat{\text{addr}_2}$	$\widehat{\text{addr}_3}$	$\widehat{\text{addr}_4}$	$\widehat{\text{addr}_5}$	$\widehat{\text{addr}_6}$	$\widehat{\text{addr}_7}$
$\text{data}_1, \text{ctr}_1$	$\text{data}_2, \text{ctr}_2$	$\text{data}_3, \text{ctr}_3$	$\text{data}_4, \text{ctr}_4$	$\text{data}_5, \text{ctr}_5$	$\text{data}_6, \text{ctr}_6$	$\text{data}_7, \text{ctr}_7$

$$\boxed{\text{PrevTime}\left(\text{ctr}, \widehat{\text{addr}}\right) := \begin{array}{c}\text{most recent time (up until ctr)} \\ \text{when } \widehat{\text{addr}} \text{ has been written to.}\end{array}}$$

Time-Stamping

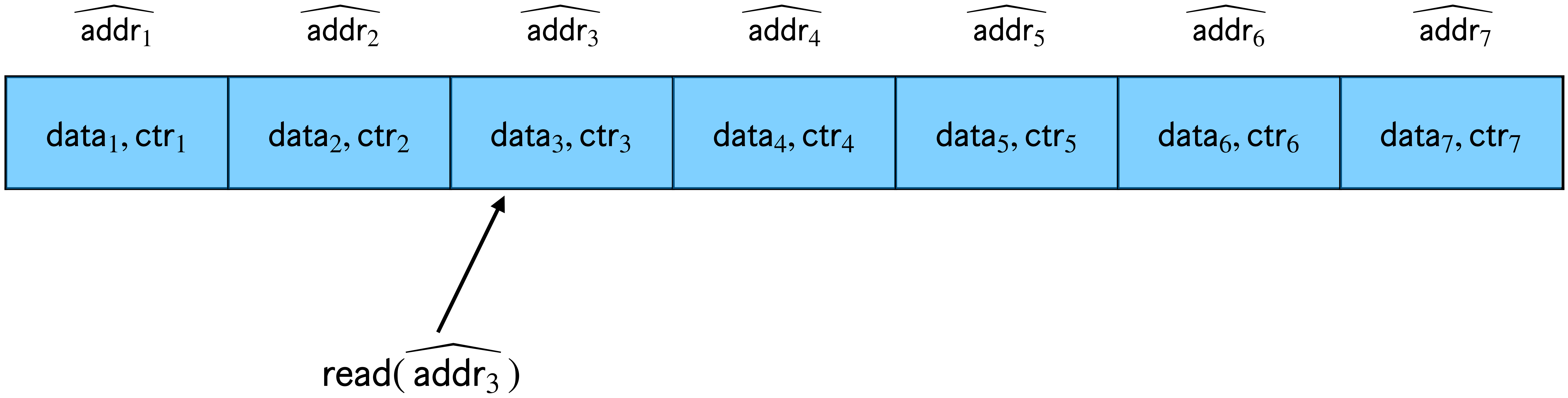
All entries are MAC'ed
Current time: ctr

$\widehat{\text{addr}}_1$	$\widehat{\text{addr}}_2$	$\widehat{\text{addr}}_3$	$\widehat{\text{addr}}_4$	$\widehat{\text{addr}}_5$	$\widehat{\text{addr}}_6$	$\widehat{\text{addr}}_7$
$\text{data}_1, \text{ctr}_1$	$\text{data}_2, \text{ctr}_2$	$\text{data}_3, \text{ctr}_3$	$\text{data}_4, \text{ctr}_4$	$\text{data}_5, \text{ctr}_5$	$\text{data}_6, \text{ctr}_6$	$\text{data}_7, \text{ctr}_7$

$\text{PrevTime}\left(\text{ctr}, \widehat{\text{addr}}\right) :=$ most recent time (up until ctr) when $\widehat{\text{addr}}$ has been written to.

Time-Stamping

All entries are MAC'ed
Current time: ctr



$\widehat{\mathrm{addr}_1}$ $\widehat{\mathrm{addr}_2}$ $\widehat{\mathrm{addr}_3}$ $\widehat{\mathrm{addr}_4}$ $\widehat{\mathrm{addr}_5}$ $\widehat{\mathrm{addr}_6}$ $\widehat{\mathrm{addr}_7}$

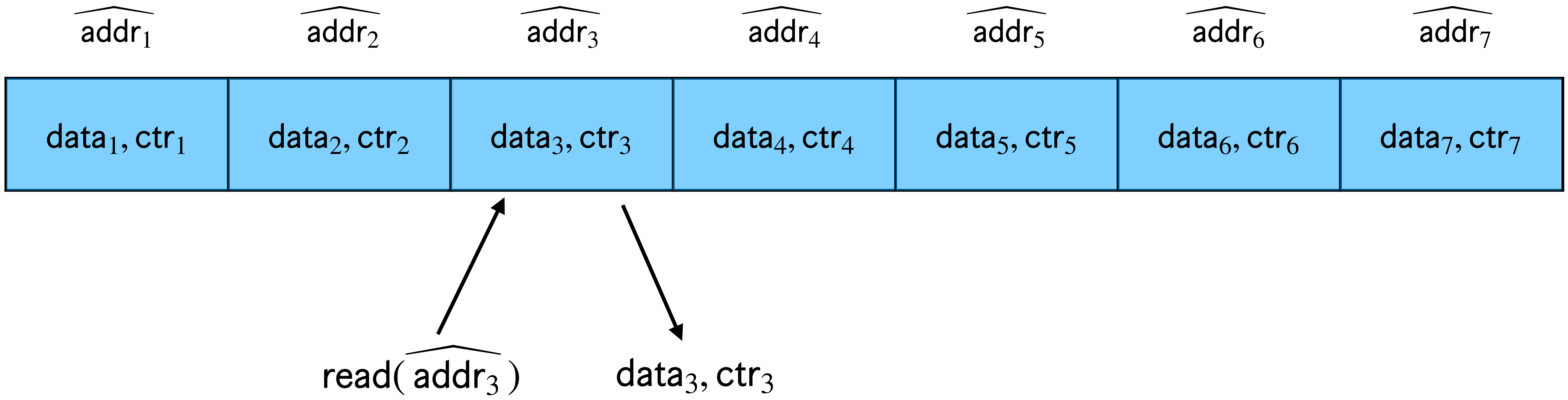
$\mathrm{data}_1, \mathrm{ctr}_1$	$\mathrm{data}_2, \mathrm{ctr}_2$	$\mathrm{data}_3, \mathrm{ctr}_3$	$\mathrm{data}_4, \mathrm{ctr}_4$	$\mathrm{data}_5, \mathrm{ctr}_5$	$\mathrm{data}_6, \mathrm{ctr}_6$	$\mathrm{data}_7, \mathrm{ctr}_7$

$\mathrm{read}(\,\widehat{\mathrm{addr}_3}\,)$

$\mathrm{PrevTime}\left(\mathrm{ctr}, \widehat{\mathrm{addr}}\right) :=$ most recent time (up until ctr) when $\widehat{\mathrm{addr}}$ has been written to.

Time-Stamping

All entries are MAC'ed
Current time: ctr


$\widehat{\text{addr}}_1$ $\widehat{\text{addr}}_2$ $\widehat{\text{addr}}_3$ $\widehat{\text{addr}}_4$ $\widehat{\text{addr}}_5$ $\widehat{\text{addr}}_6$ $\widehat{\text{addr}}_7$

$\text{data}_1, \text{ctr}_1$ $\text{data}_2, \text{ctr}_2$ $\text{data}_3, \text{ctr}_3$ $\text{data}_4, \text{ctr}_4$ $\text{data}_5, \text{ctr}_5$ $\text{data}_6, \text{ctr}_6$ $\text{data}_7, \text{ctr}_7$

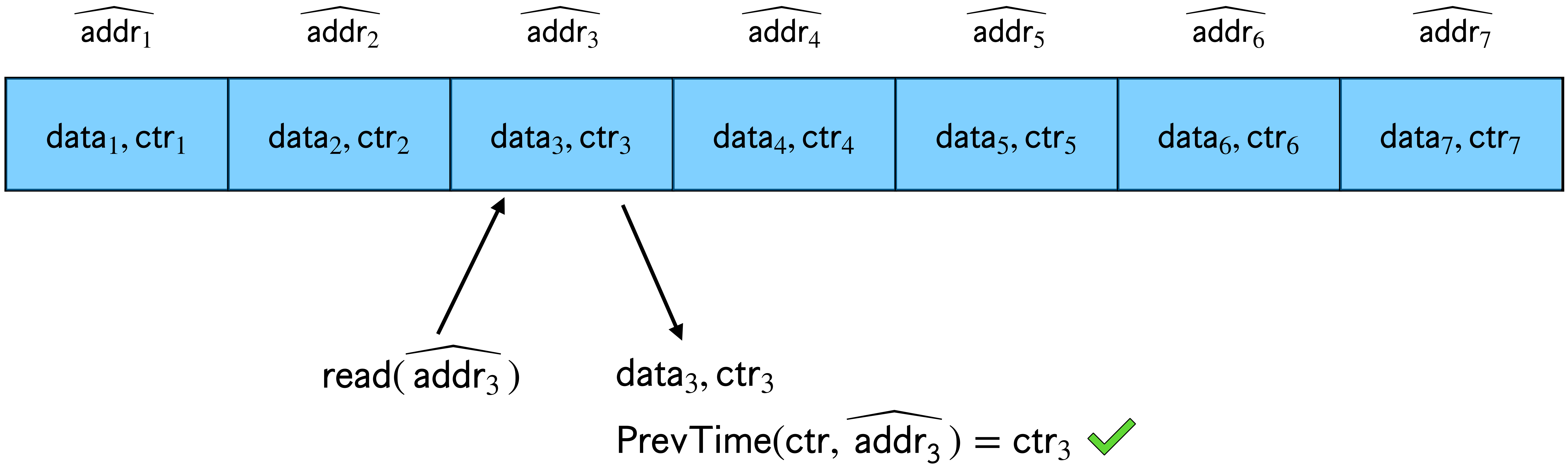
$\text{read}(\widehat{\text{addr}}_3)$

$\text{data}_3, \text{ctr}_3$

$\text{PrevTime}\left(\text{ctr}, \widehat{\text{addr}}\right) :=$ most recent time (up until ctr) when $\widehat{\text{addr}}$ has been written to.

Time-Stamping

All entries are MAC'ed
Current time: ctr



$\widehat{\text{addr}_1}$ $\widehat{\text{addr}_2}$ $\widehat{\text{addr}_3}$ $\widehat{\text{addr}_4}$ $\widehat{\text{addr}_5}$ $\widehat{\text{addr}_6}$ $\widehat{\text{addr}_7}$

$\text{data}_1, \text{ctr}_1$	$\text{data}_2, \text{ctr}_2$	$\text{data}_3, \text{ctr}_3$	$\text{data}_4, \text{ctr}_4$	$\text{data}_5, \text{ctr}_5$	$\text{data}_6, \text{ctr}_6$	$\text{data}_7, \text{ctr}_7$

$\text{read}(\widehat{\text{addr}_3})$

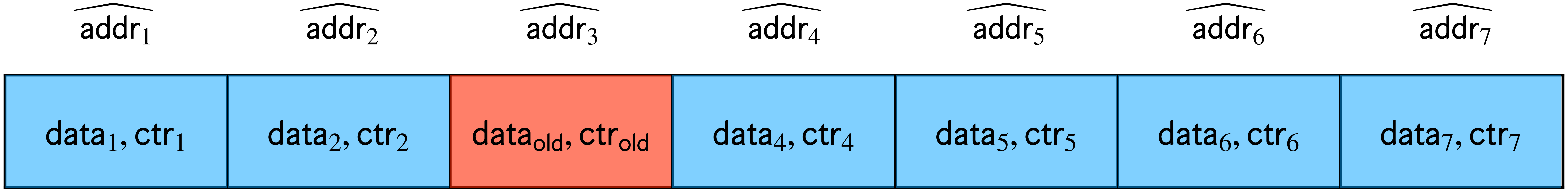
$\text{data}_3, \text{ctr}_3$

$\text{PrevTime}(\text{ctr}, \widehat{\text{addr}_3}) = \text{ctr}_3$ ✓

$\text{PrevTime}\left(\text{ctr}, \widehat{\text{addr}}\right) :=$ most recent time (up until ctr) when $\widehat{\text{addr}}$ has been written to.

Time-Stamping

All entries are MAC'ed
Current time: ctr

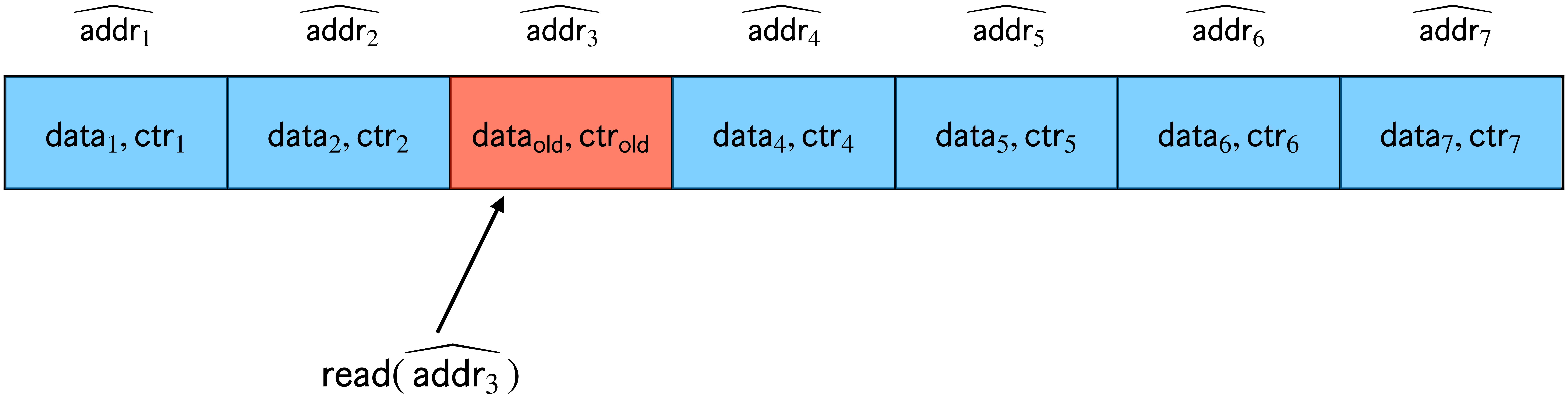


$\widehat{\text{addr}_1}$	$\widehat{\text{addr}_2}$	$\widehat{\text{addr}_3}$	$\widehat{\text{addr}_4}$	$\widehat{\text{addr}_5}$	$\widehat{\text{addr}_6}$	$\widehat{\text{addr}_7}$
$\text{data}_1, \text{ctr}_1$	$\text{data}_2, \text{ctr}_2$	$\text{data}_{\text{old}}, \text{ctr}_{\text{old}}$	$\text{data}_4, \text{ctr}_4$	$\text{data}_5, \text{ctr}_5$	$\text{data}_6, \text{ctr}_6$	$\text{data}_7, \text{ctr}_7$

$\text{PrevTime}\left(\text{ctr}, \widehat{\text{addr}}\right) :=$ most recent time (up until ctr) when $\widehat{\text{addr}}$ has been written to.

Time-Stamping

All entries are MAC’ed
Current time: ctr



$\widehat{\text{addr}}_1$ $\widehat{\text{addr}}_2$ $\widehat{\text{addr}}_3$ $\widehat{\text{addr}}_4$ $\widehat{\text{addr}}_5$ $\widehat{\text{addr}}_6$ $\widehat{\text{addr}}_7$

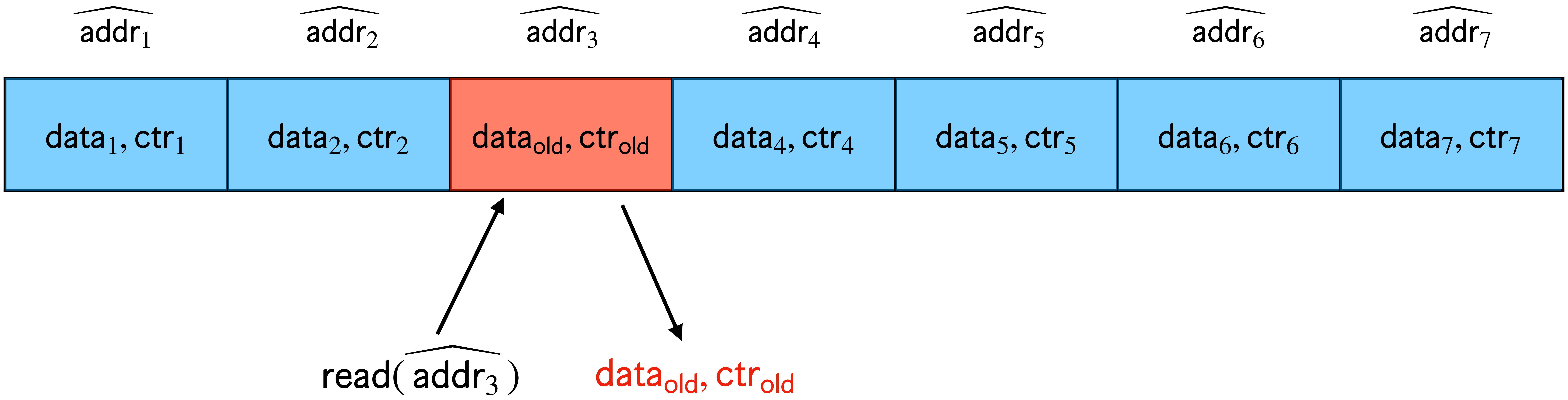
$\text{data}_1, \text{ctr}_1$	$\text{data}_2, \text{ctr}_2$	$\text{data}_{\text{old}}, \text{ctr}_{\text{old}}$	$\text{data}_4, \text{ctr}_4$	$\text{data}_5, \text{ctr}_5$	$\text{data}_6, \text{ctr}_6$	$\text{data}_7, \text{ctr}_7$

$\text{read}(\widehat{\text{addr}}_3)$

$\text{PrevTime}\left(\text{ctr}, \widehat{\text{addr}}\right) :=$ most recent time (up until ctr) when $\widehat{\text{addr}}$ has been written to.

Time-Stamping

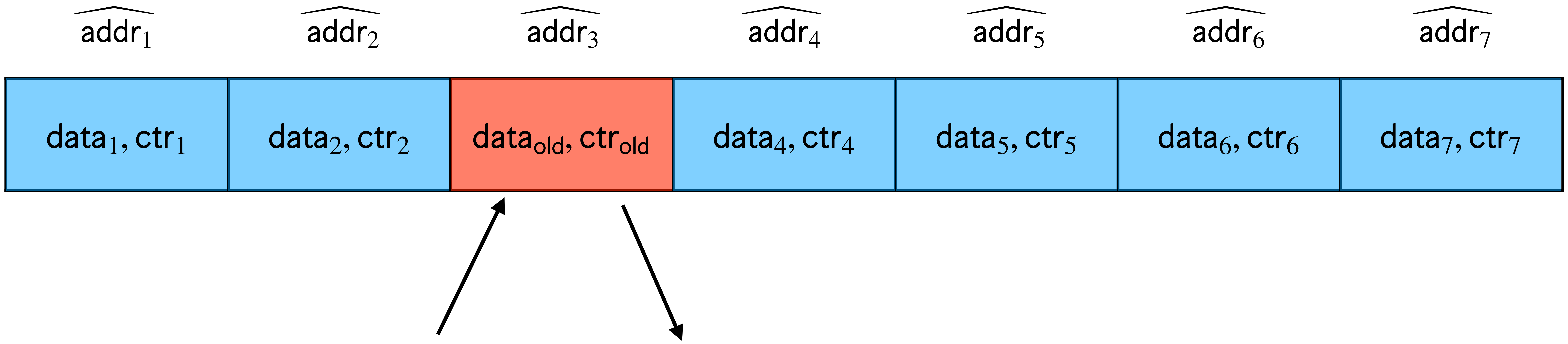
All entries are MAC'ed
Current time: ctr



$\text{PrevTime}\left(\text{ctr}, \widehat{\text{addr}}\right) :=$ most recent time (up until ctr) when $\widehat{\text{addr}}$ has been written to.

Time-Stamping

All entries are MAC'ed
Current time: ctr



$\widehat{\text{addr}_1}$	$\widehat{\text{addr}_2}$	$\widehat{\text{addr}_3}$	$\widehat{\text{addr}_4}$	$\widehat{\text{addr}_5}$	$\widehat{\text{addr}_6}$	$\widehat{\text{addr}_7}$
$\text{data}_1, \text{ctr}_1$	$\text{data}_2, \text{ctr}_2$	$\text{data}_{\text{old}}, \text{ctr}_{\text{old}}$	$\text{data}_4, \text{ctr}_4$	$\text{data}_5, \text{ctr}_5$	$\text{data}_6, \text{ctr}_6$	$\text{data}_7, \text{ctr}_7$

read($\widehat{\text{addr}_3}$)

$\text{data}_{\text{old}}, \text{ctr}_{\text{old}}$

Since $\text{ctr}_{\text{old}} < \text{ctr}_3 = \text{PrevTime}(\text{ctr}, \widehat{\text{addr}_3})$,
replay attack detected!

$$\text{PrevTime}\left(\text{ctr}, \widehat{\text{addr}}\right) := \begin{array}{c}\text{most recent time (up until ctr)} \\ \text{when } \widehat{\text{addr}} \text{ has been written to.}\end{array}$$

Time-Stamping is Hard

Time-Stamping is Hard

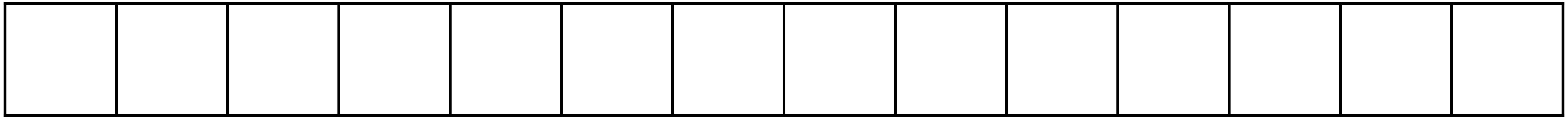
- Unfortunately, **the recent hierarchical ORAM constructions cannot be time-stamped**

Time-Stamping is Hard

- Unfortunately, **the recent hierarchical ORAM constructions cannot be time-stamped**
- **Unconditionally** requires $\Omega(N)$ bits of local space to time-stamp **OptORAMa**.

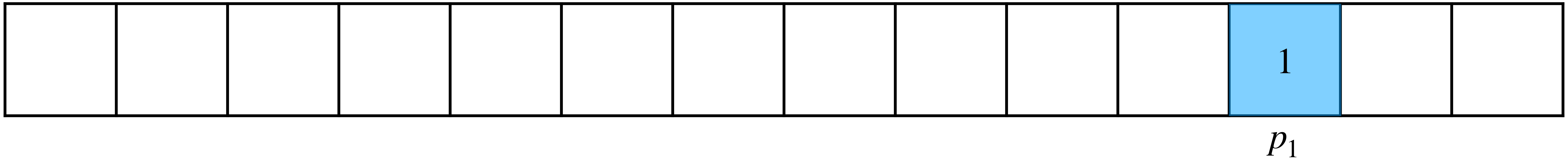
Time-Stamping is Hard

- Unfortunately, **the recent hierarchical ORAM constructions cannot be time-stamped**
- **Unconditionally** requires $\Omega(N)$ bits of local space to time-stamp **OptORAMa**.
- Example: **Marking** (appears in oblivious hash tables in **PanORAMa** and **OptORAMa**)



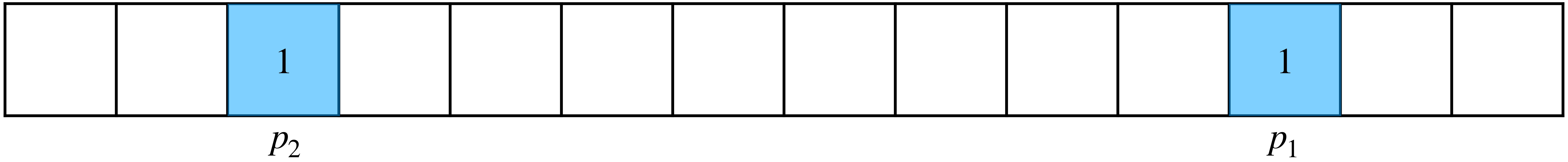
Time-Stamping is Hard

- Unfortunately, **the recent hierarchical ORAM constructions cannot be time-stamped**
- **Unconditionally** requires $\Omega(N)$ bits of local space to time-stamp **OptORAMa**.
- Example: **Marking** (appears in oblivious hash tables in **PanORAMa** and **OptORAMa**)



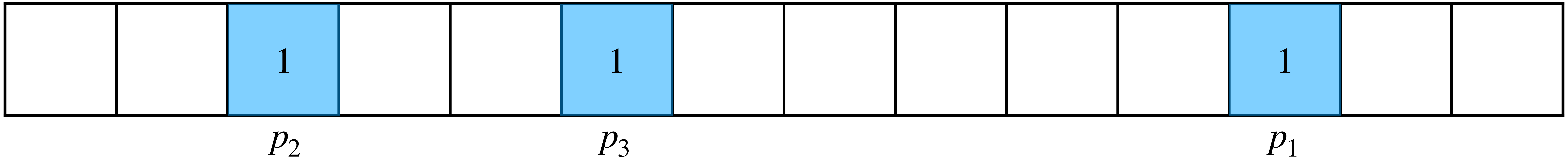
Time-Stamping is Hard

- Unfortunately, **the recent hierarchical ORAM constructions cannot be time-stamped**
- **Unconditionally** requires $\Omega(N)$ bits of local space to time-stamp **OptORAMa**.
- Example: **Marking** (appears in oblivious hash tables in **PanORAMa** and **OptORAMa**)



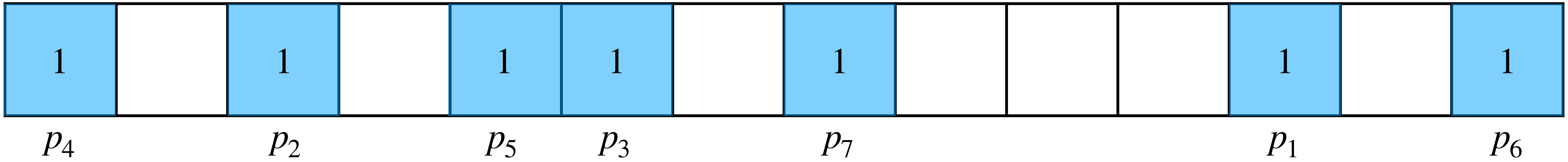
Time-Stamping is Hard

- Unfortunately, **the recent hierarchical ORAM constructions cannot be time-stamped**
- **Unconditionally** requires $\Omega(N)$ bits of local space to time-stamp **OptORAMa**.
- Example: **Marking** (appears in oblivious hash tables in **PanORAMa** and **OptORAMa**)



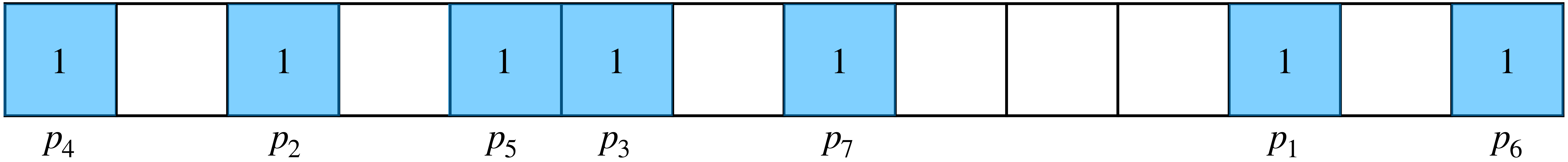
Time-Stamping is Hard

- Unfortunately, **the recent hierarchical ORAM constructions cannot be time-stamped**
- **Unconditionally** requires $\Omega(N)$ bits of local space to time-stamp **OptORAMa**.
- Example: **Marking** (appears in oblivious hash tables in **PanORAMa** and **OptORAMa**)



Time-Stamping is Hard

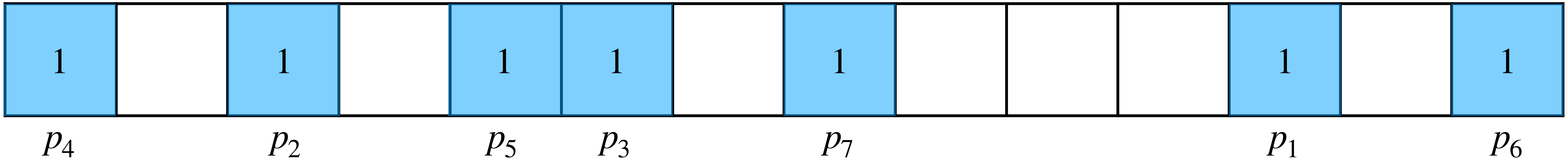
- Unfortunately, **the recent hierarchical ORAM constructions cannot be time-stamped**
- **Unconditionally** requires $\Omega(N)$ bits of local space to time-stamp **OptORAMa**.
- Example: **Marking** (appears in oblivious hash tables in **PanORAMa** and **OptORAMa**)
  - Setup: Mark positions $p_i \in [N]$ as *visited* when given online way for $1 \leq i \leq N/2$.



1		1		1	1		1				1		1
p_4		p_2		p_5	p_3		p_7				p_1		p_6

Time-Stamping is Hard

- Unfortunately, **the recent hierarchical ORAM constructions cannot be time-stamped**
- **Unconditionally** requires $\Omega(N)$ bits of local space to time-stamp **OptORAMa**.
- Example: **Marking** (appears in oblivious hash tables in **PanORAMa** and **OptORAMa**)
  - Setup: Mark positions $p_i \in [N]$ as *visited* when given online way for $1 \leq i \leq N/2$.

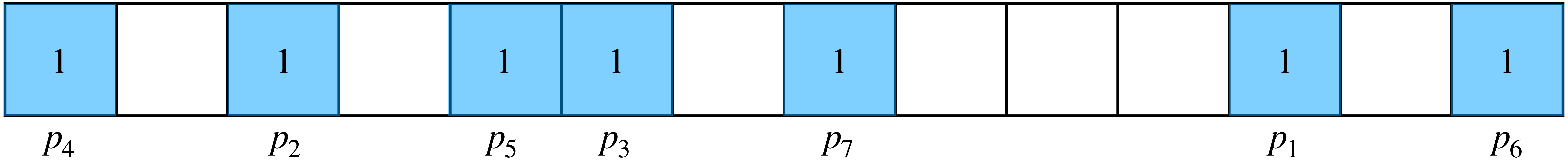


1		1		1	1		1				1		1
p_4		p_2		p_5	p_3		p_7				p_1		p_6

  - If you can time-stamp this access pattern, you can recover all p_i.

Time-Stamping is Hard

- Unfortunately, **the recent hierarchical ORAM constructions cannot be time-stamped**
- **Unconditionally** requires $\Omega(N)$ bits of local space to time-stamp **OptORAMa**.
- Example: **Marking** (appears in oblivious hash tables in **PanORAMa** and **OptORAMa**)
  - Setup: Mark positions $p_i \in [N]$ as *visited* when given online way for $1 \leq i \leq N/2$.



1		1		1	1		1				1		1
p_4		p_2		p_5	p_3		p_7				p_1		p_6

  - If you can time-stamp this access pattern, you can recover all p_i.
  - Random sequence of p_i has entropy $\Theta(N \log N)$, so no way to time-stamp with even $O(N)$ bits of space, let alone $O(\log N)$ bits.

Summary of Technique #1: MACs

Summary of Technique #1: MACs

- With MACs, hierarchical ORAM is susceptible to replay attacks.

Summary of Technique #1: MACs

- With MACs, hierarchical ORAM is susceptible to replay attacks.
- *Time-stamping* can prevent replay attacks.

Summary of Technique #1: MACs

- With MACs, hierarchical ORAM is susceptible to replay attacks.
- *Time-stamping* can prevent replay attacks.
    - Time-stamping is possible for [Goldreich-Ostrovsky ’96] **but not OptORAMa** (or **PanORAMa**).

Summary of Technique #1: MACs

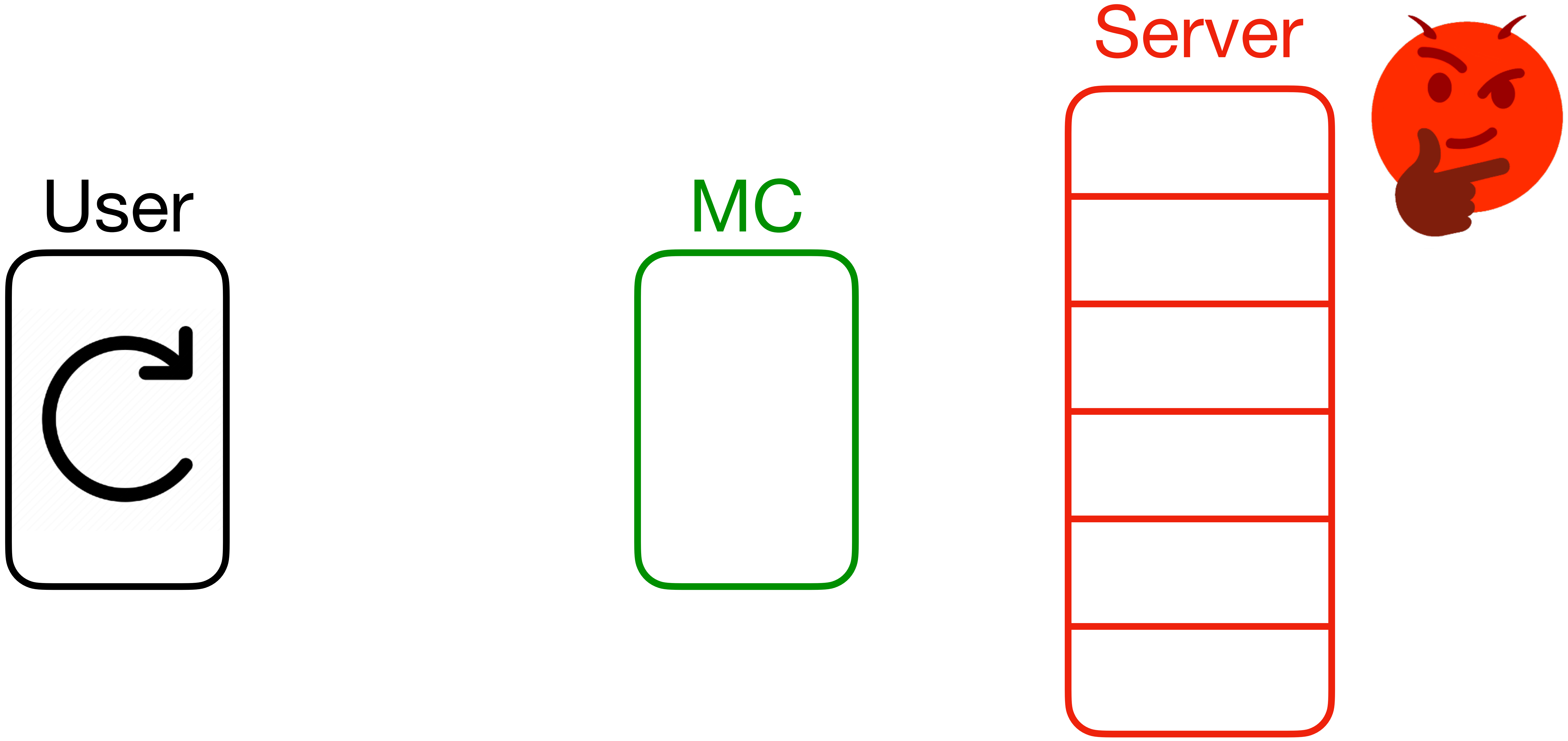
- With MACs, hierarchical ORAM is susceptible to replay attacks.
- *Time-stamping* can prevent replay attacks.
  - Time-stamping is possible for [Goldreich-Ostrovsky ’96] **but not OptORAMa** (or **PanORAMa**).
- We need another technique for malicious security!

Technique #2: Memory Checking

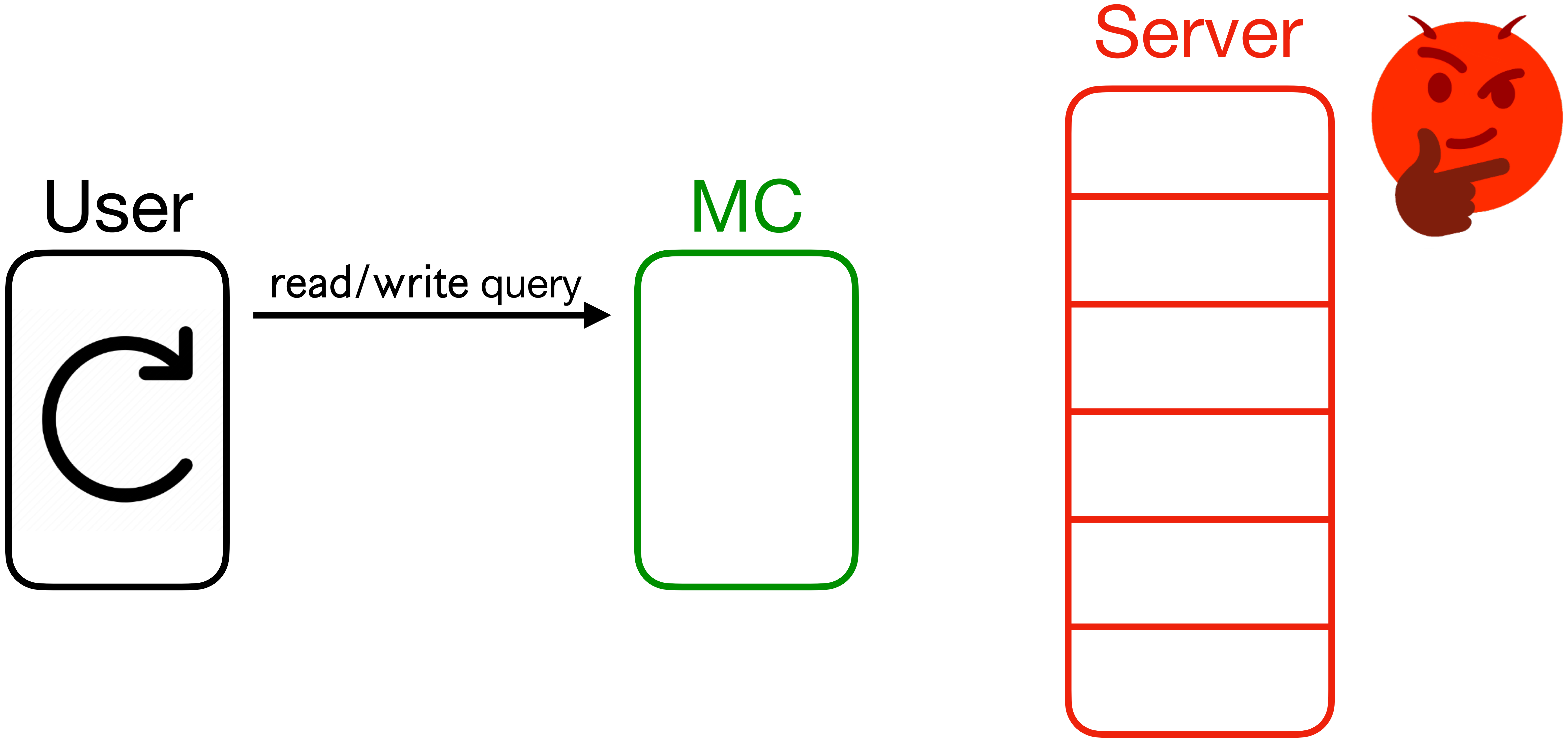
Technique #2: Memory Checking

- A **Memory Checker** (MC) is a protocol that detects whether a malicious server tampered with RAM. [Blum, Evans, Gemmell, Kannan, Naor ’94]

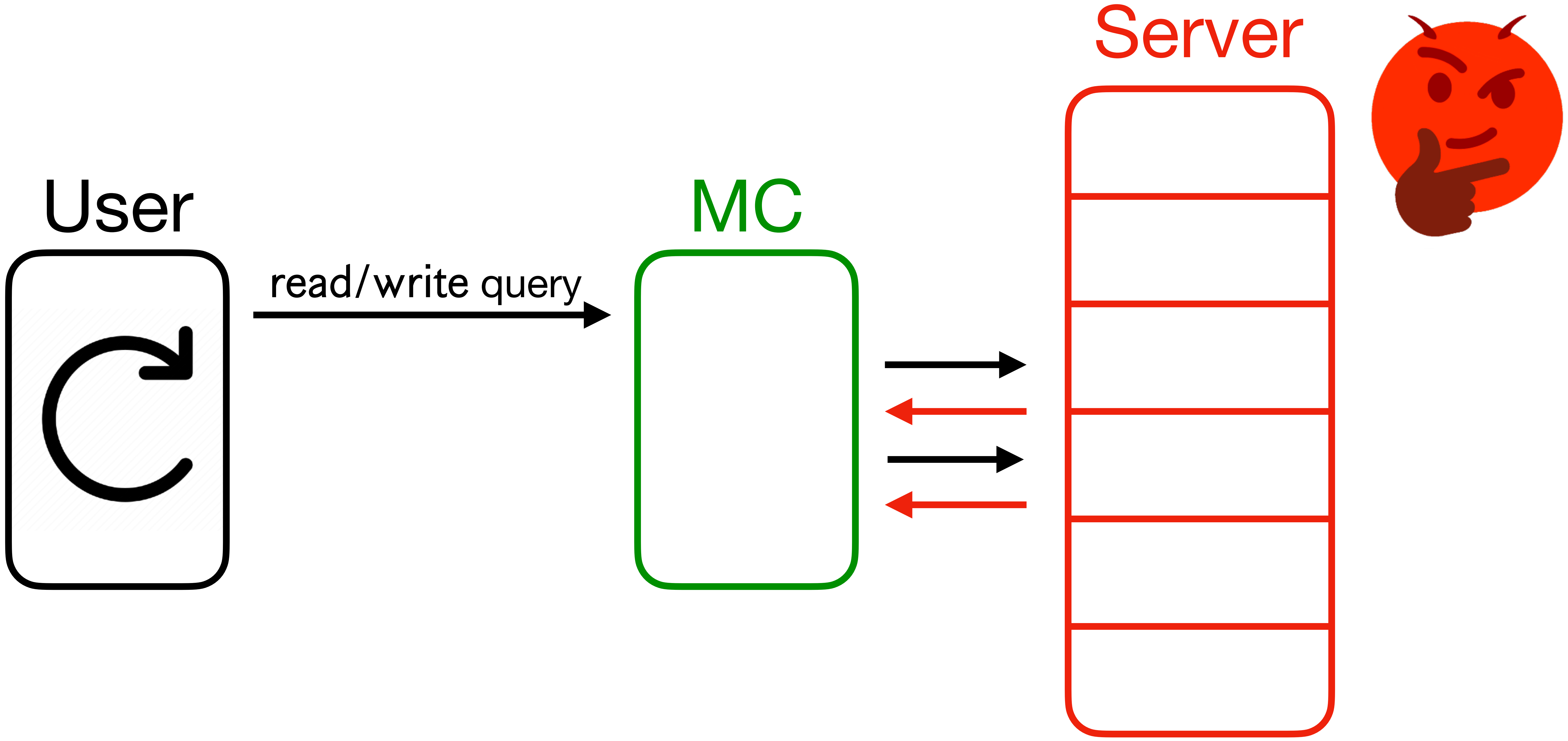
Technique #2: Memory Checking



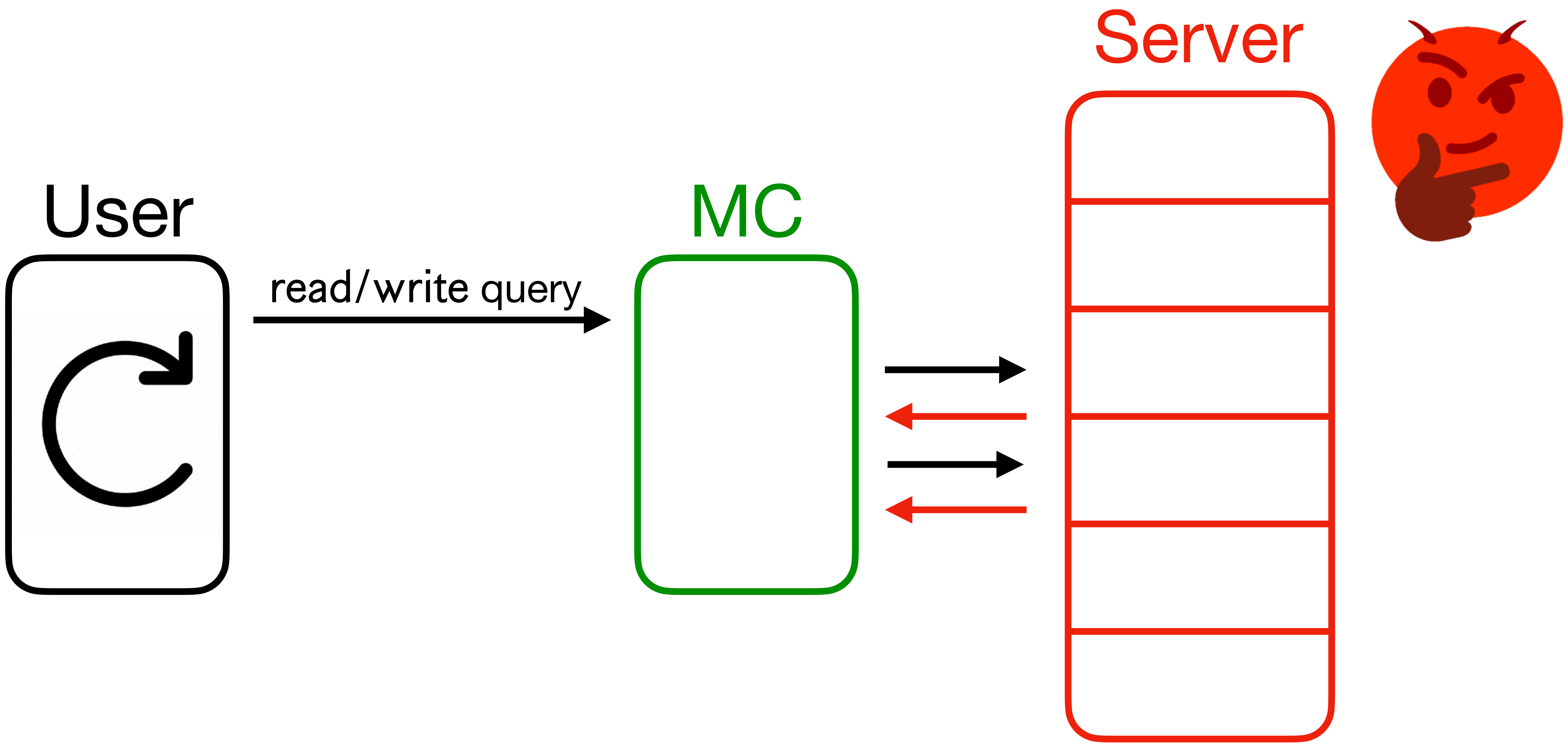
Technique #2: Memory Checking



Technique #2: Memory Checking

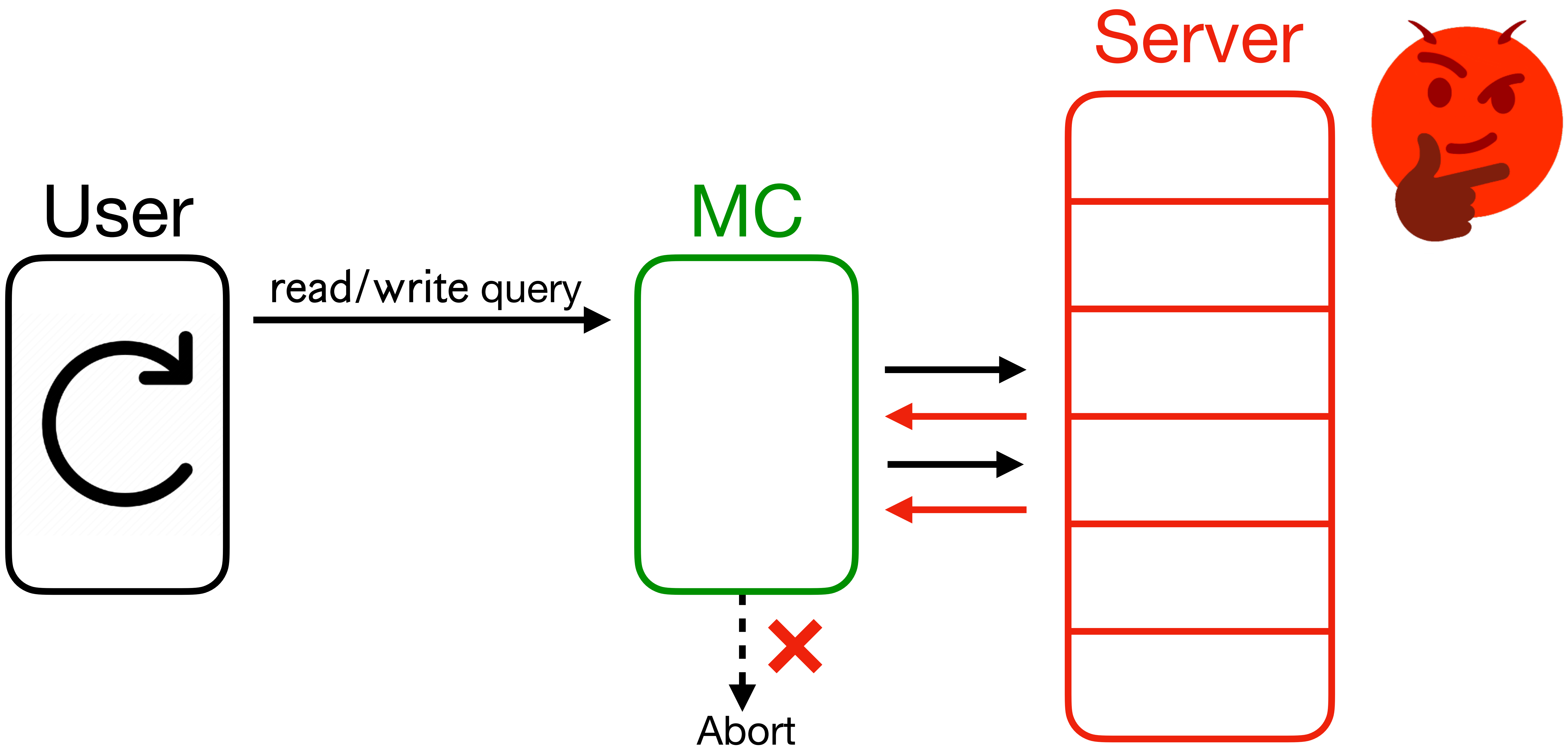


Technique #2: Memory Checking



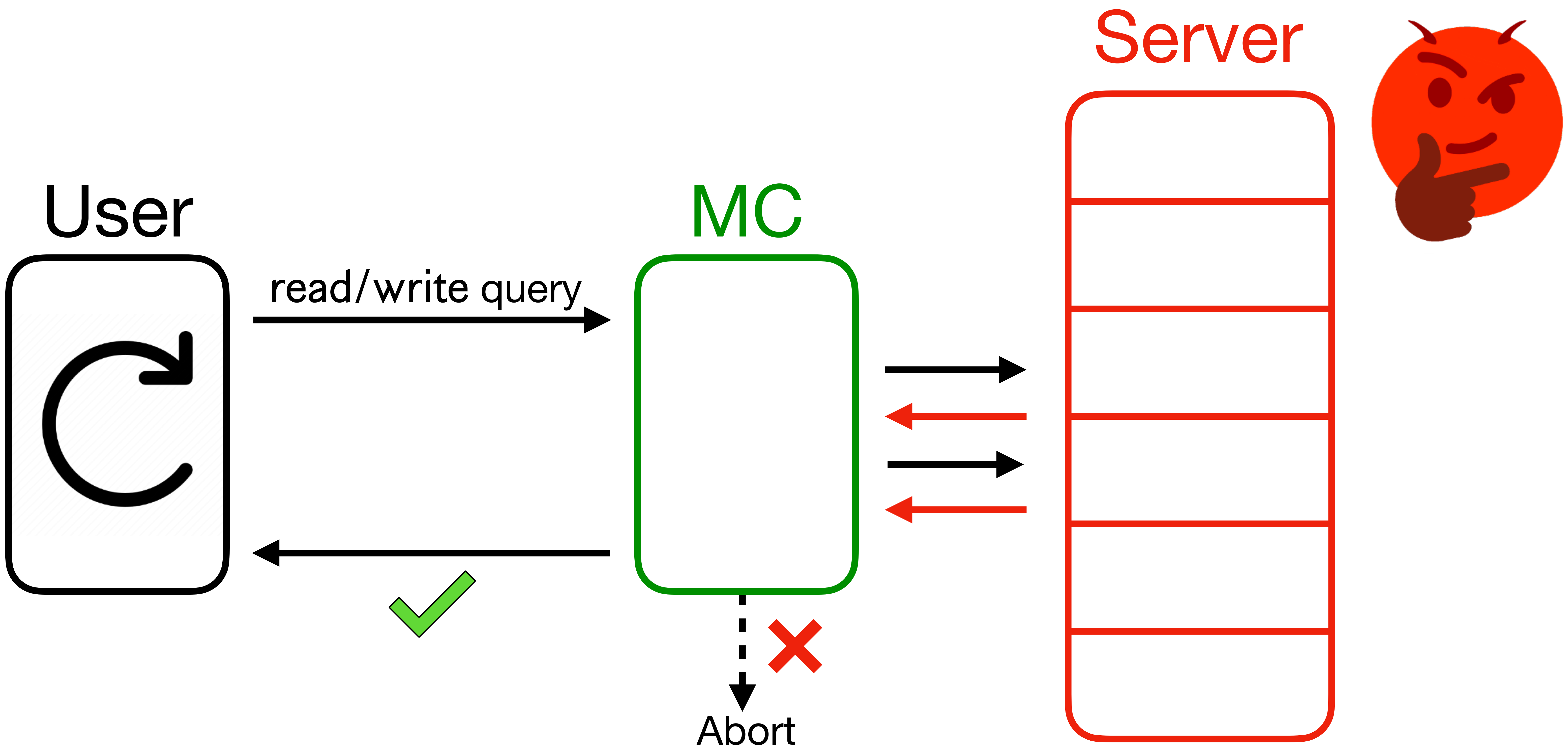
- **Correctness**: For any PPT malicious server, MC either **aborts** or gives correct responses.

Technique #2: Memory Checking



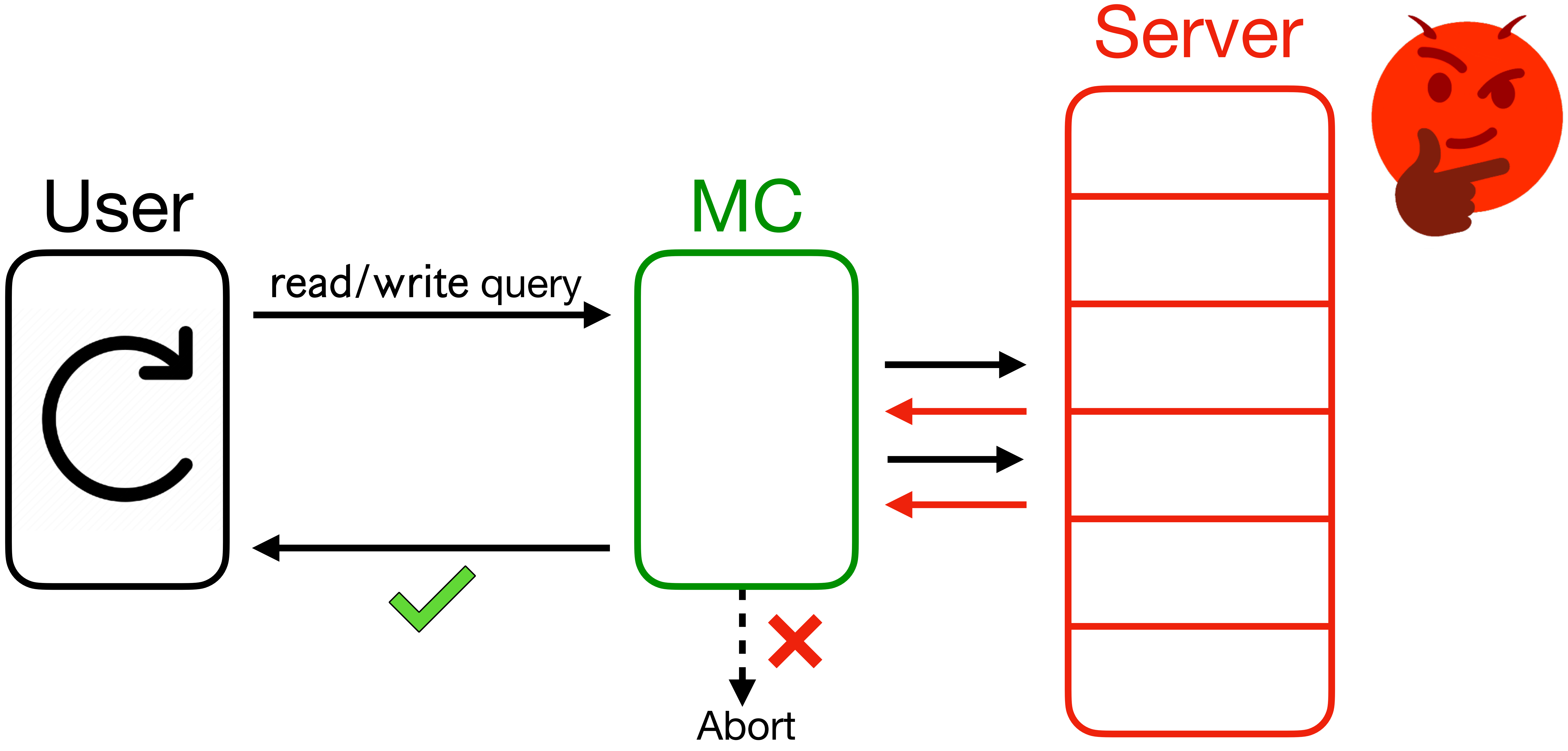
- **Correctness**: For any PPT malicious server, MC either **aborts** or gives correct responses.

Technique #2: Memory Checking



- **Correctness**: For any PPT malicious server, MC either **aborts** or gives correct responses.

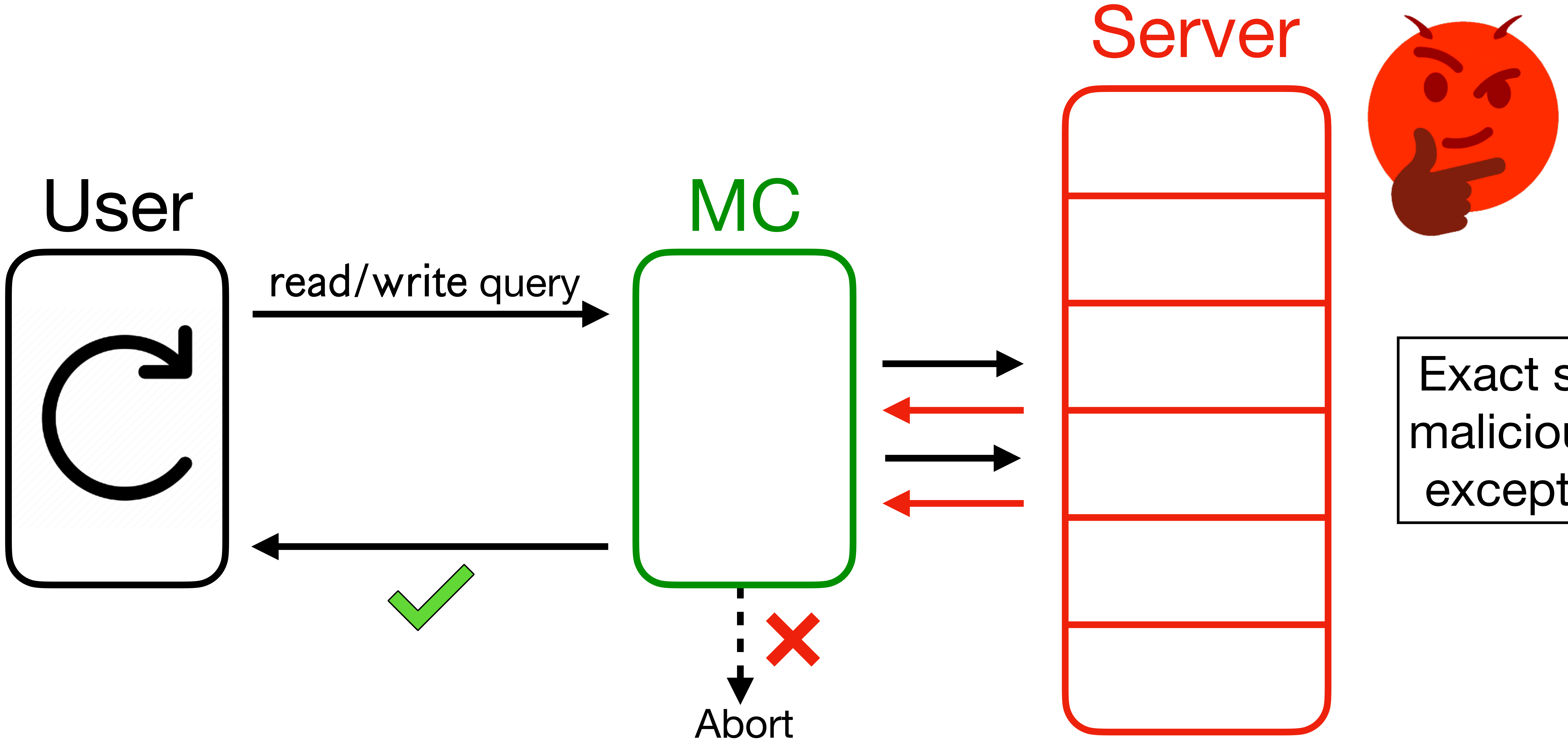
Technique #2: Memory Checking



- **Correctness**: For any PPT malicious server, MC either **aborts** or gives correct responses.

- **Completeness**: If the server behaved honestly, MC doesn't abort.

Technique #2: Memory Checking



Exact same properties as maliciously secure ORAM, except no obliviousness.

- **Correctness**: For any PPT malicious server, MC either **aborts** or gives correct responses.

- **Completeness**: If the server behaved honestly, MC doesn't abort.

Memory Checking Efficiency

Memory Checking Efficiency

- Just like ORAM, **local space** and **overhead** are two main efficiency metrics (local space N trivial). For $O(1)$ local space:

Memory Checking Efficiency

- Just like ORAM, **local space** and **overhead** are two main efficiency metrics (local space N trivial). For $O(1)$ local space:
    - Memory checking with $o(N)$ overhead implies OWF. [Naor-Rothblum ’05]

Memory Checking Efficiency

- Just like ORAM, **local space** and **overhead** are two main efficiency metrics (local space N trivial). For $O(1)$ local space:
  - Memory checking with $o(N)$ overhead implies OWF. [Naor-Rothblum ’05]
  - Best known constructions have $O(\log N)$ overhead.* [Blum et al. ’94]

*More accurately, bandwidth (in terms of bits), not overhead (in case word sizes differ).

Memory Checking Efficiency

- Just like ORAM, **local space** and **overhead** are two main efficiency metrics (local space N trivial). For $O(1)$ local space:
  - Memory checking with $o(N)$ overhead implies OWF. [Naor-Rothblum '05]
  - Best known constructions have $O(\log N)$ overhead.* [Blum et al. '94]
    - E.g., Merkle trees. Store Merkle root and access paths in binary tree.

*More accurately, bandwidth (in terms of bits), not overhead (in case word sizes differ).

Memory Checking Efficiency

- Just like ORAM, **local space** and **overhead** are two main efficiency metrics (local space N trivial). For $O(1)$ local space:
  - Memory checking with $o(N)$ overhead implies OWF. [Naor-Rothblum ’05]
  - Best known constructions have $O(\log N)$ overhead.* [Blum et al. ’94]
    - E.g., Merkle trees. Store Merkle root and access paths in binary tree.
  - **Lower bound** of $\Omega(\log N / \log \log N)$ overhead for deterministic, non-adaptive memory checkers (which the existing constructions are).

[Dwork-Naor-Rothblum-Vaikuntanathan ’09]

*More accurately, bandwidth (in terms of bits), not overhead (in case word sizes differ).

Technique #2: Memory Checking

Technique #2: Memory Checking

- Intuitively, memory checking seems to solve the issue of a tampering adversary.

Technique #2: Memory Checking

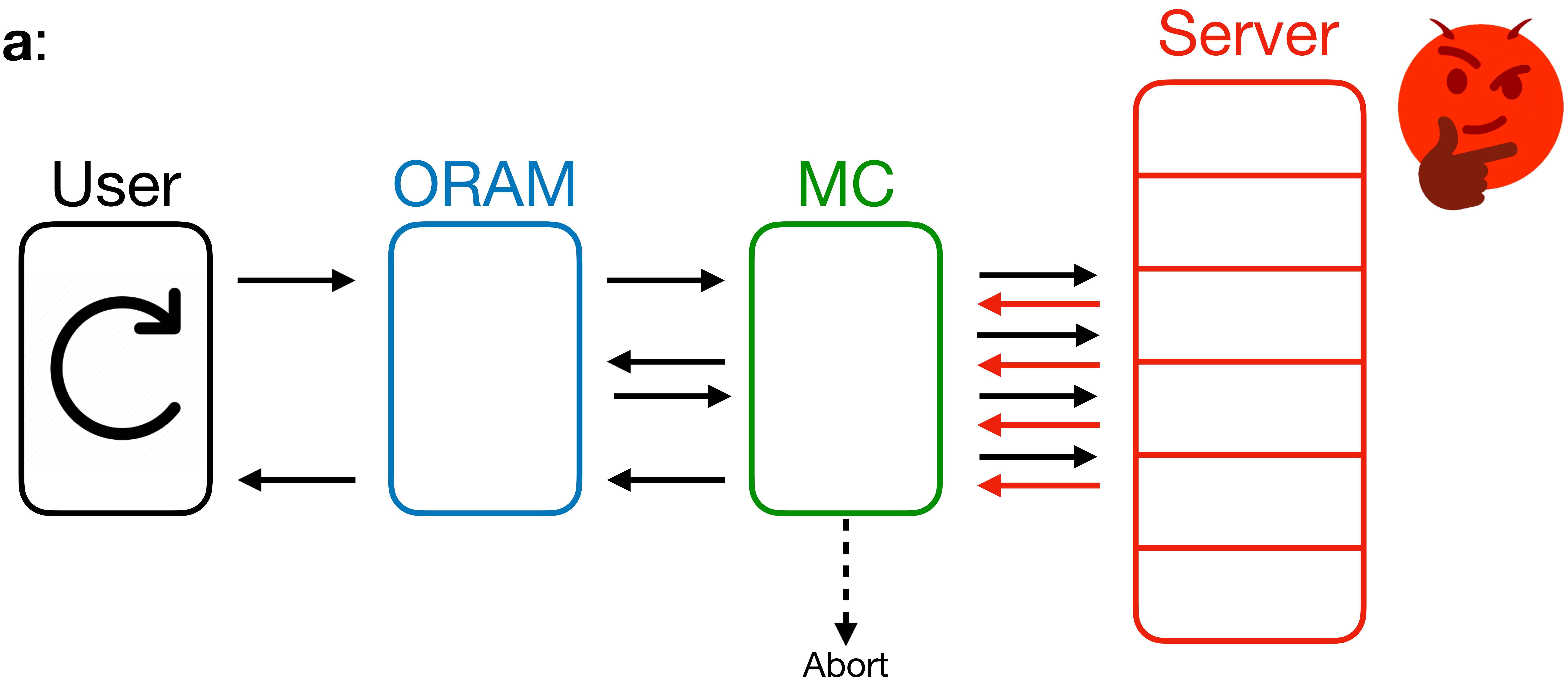
- Intuitively, memory checking seems to solve the issue of a tampering adversary.
- **Theorem**: Honest-but-curious ORAM + MC = maliciously secure ORAM.

Technique #2: Memory Checking

- Intuitively, memory checking seems to solve the issue of a tampering adversary.
- **Theorem**: Honest-but-curious ORAM + MC = maliciously secure ORAM.
- **Idea**:

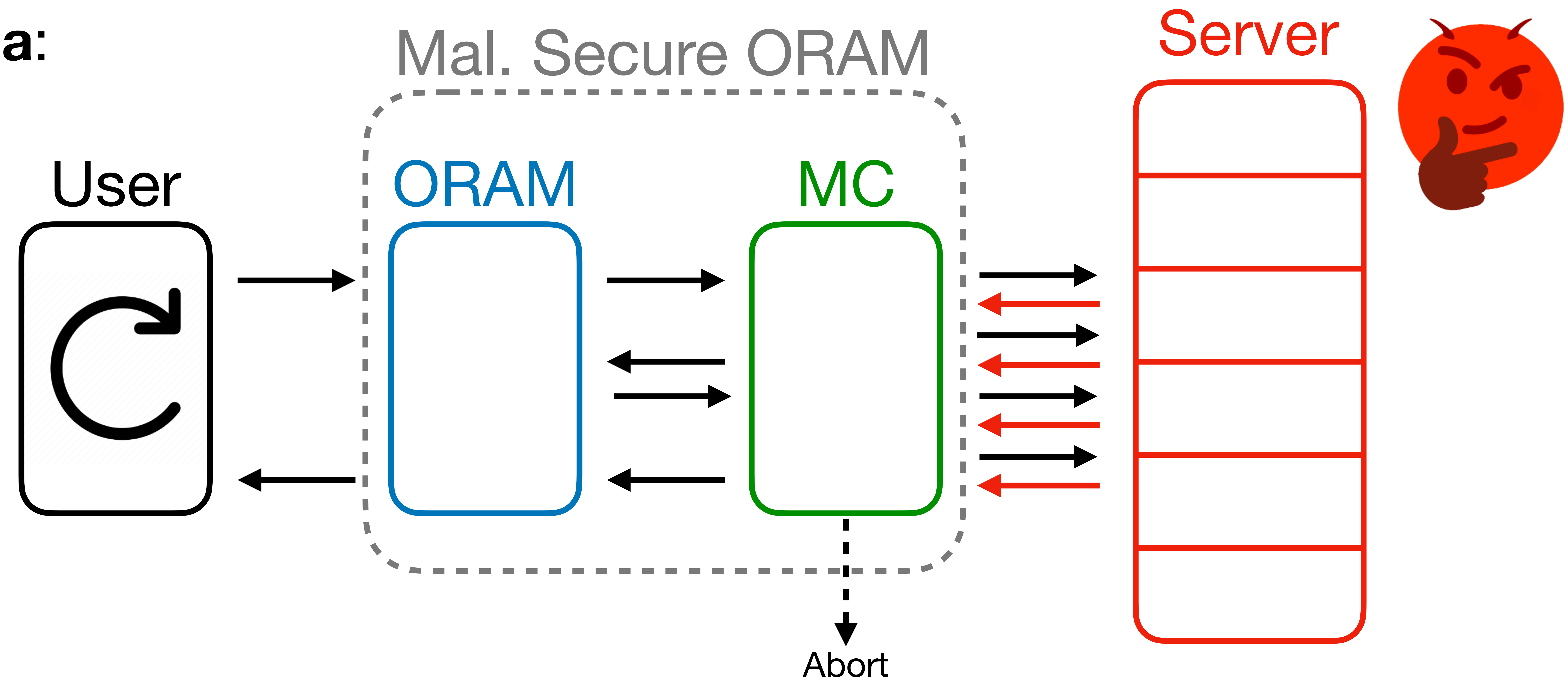
Technique #2: Memory Checking

- Intuitively, memory checking seems to solve the issue of a tampering adversary.
- **Theorem**: Honest-but-curious ORAM + MC = maliciously secure ORAM.
- **Idea**:



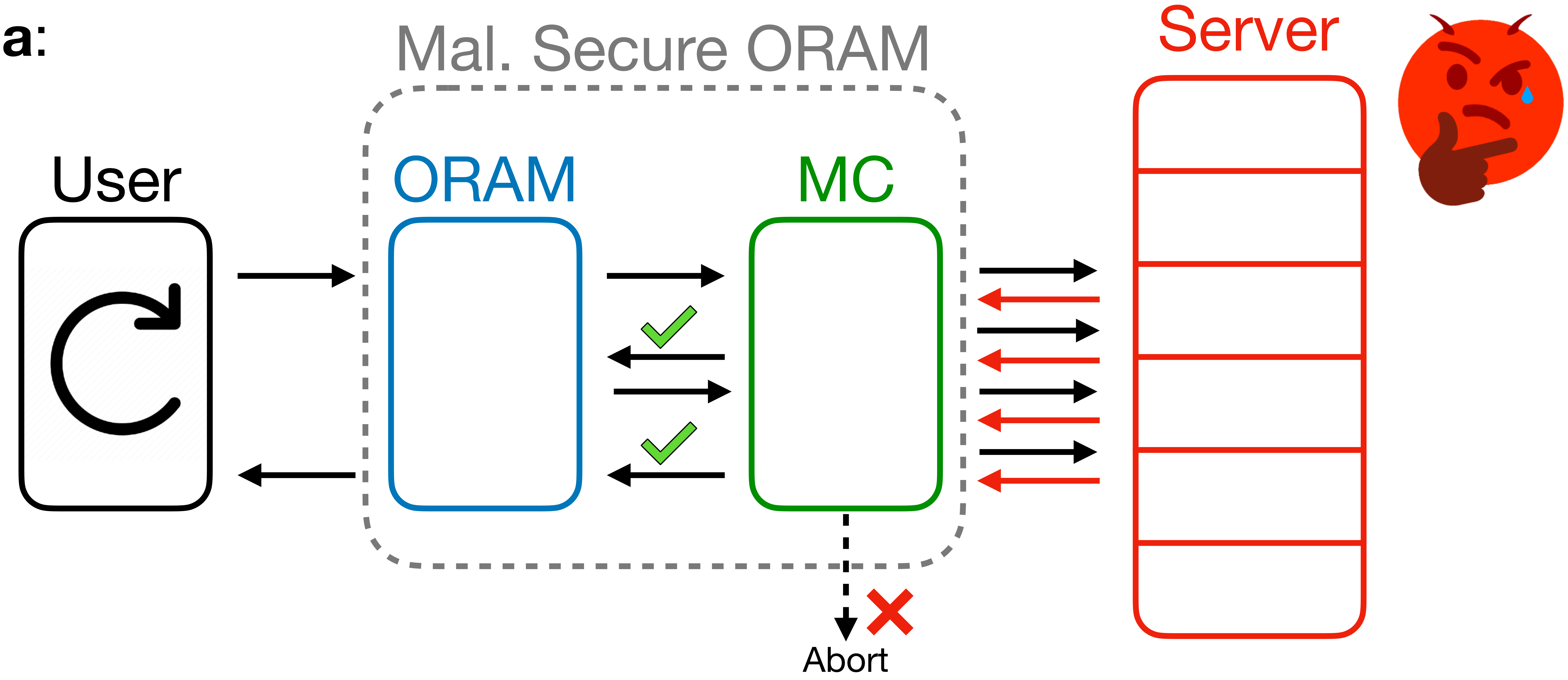
Technique #2: Memory Checking

- Intuitively, memory checking seems to solve the issue of a tampering adversary.
- **Theorem**: Honest-but-curious ORAM + MC = maliciously secure ORAM.
- **Idea**:



Technique #2: Memory Checking

- Intuitively, memory checking seems to solve the issue of a tampering adversary.
- **Theorem**: Honest-but-curious ORAM + MC = maliciously secure ORAM.
- **Idea**:



Technique #2: Memory Checking

- Great! But this isn’t efficient enough.

Technique #2: Memory Checking

- Great! But this isn’t efficient enough.

Technique #2: Memory Checking

- Great! But this isn't efficient enough.

$$\text{Overhead}(\text{ORAM}_{\text{Mal}}) = \text{Overhead}(\text{ORAM}_{\text{HBC}}) \cdot \text{Overhead}(\text{MC})$$

Technique #2: Memory Checking

- Great! But this isn't efficient enough.

$$\text{Overhead}(\text{ORAM}_{\text{Mal}}) = \underset{\substack{\uparrow \\ \log N}}{\text{Overhead}(\text{ORAM}_{\text{HBC}})} \cdot \text{Overhead}(\text{MC})$$

Technique #2: Memory Checking

- Great! But this isn't efficient enough.

$$\mathrm{Overhead}(\mathrm{ORAM}_{\mathrm{Mal}}) = \underset{\overset{\uparrow}{\log N}}{\mathrm{Overhead}(\mathrm{ORAM}_{\mathrm{HBC}})} \cdot \underset{\overset{\uparrow}{\log N}}{\mathrm{Overhead}(\mathrm{MC})}$$

Technique #2: Memory Checking

- Great! But this isn't efficient enough.

$$\underset{\substack{\Big\uparrow \\ \log^2(N)}}{\text{Overhead}(\text{ORAM}_{\text{Mal}})} = \underset{\substack{\Big\uparrow \\ \log N}}{\text{Overhead}(\text{ORAM}_{\text{HBC}})} \cdot \underset{\substack{\Big\uparrow \\ \log N}}{\text{Overhead}(\text{MC})}$$

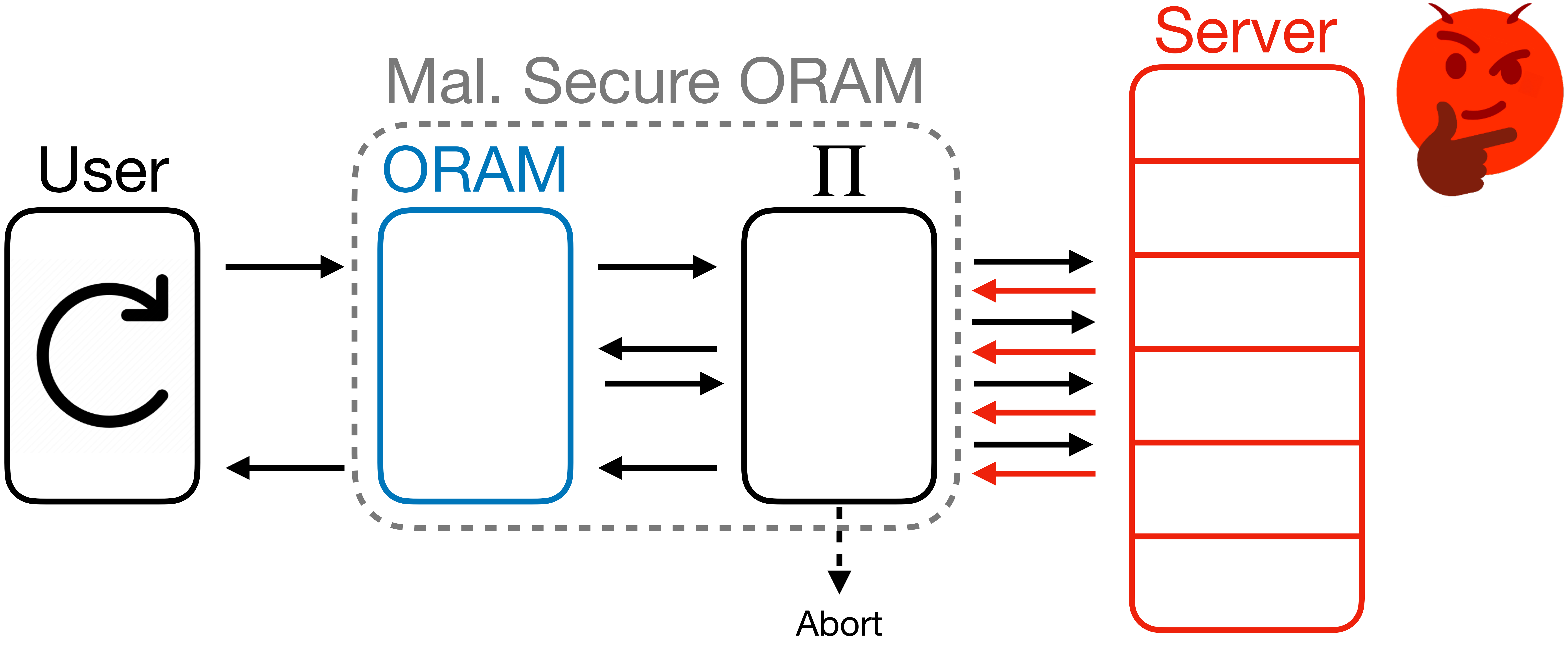
Technique #2: Memory Checking

- Great! But this isn't efficient enough.

$$\underset{\substack{\uparrow \\ \log^2(N)}}{\mathrm{Overhead}(\mathrm{ORAM}_{\mathrm{Mal}})} = \underset{\substack{\uparrow \\ \log N}}{\mathrm{Overhead}(\mathrm{ORAM}_{\mathrm{HBC}})} \cdot \underset{\substack{\uparrow \\ \log N}}{\mathrm{Overhead}(\mathrm{MC})}$$

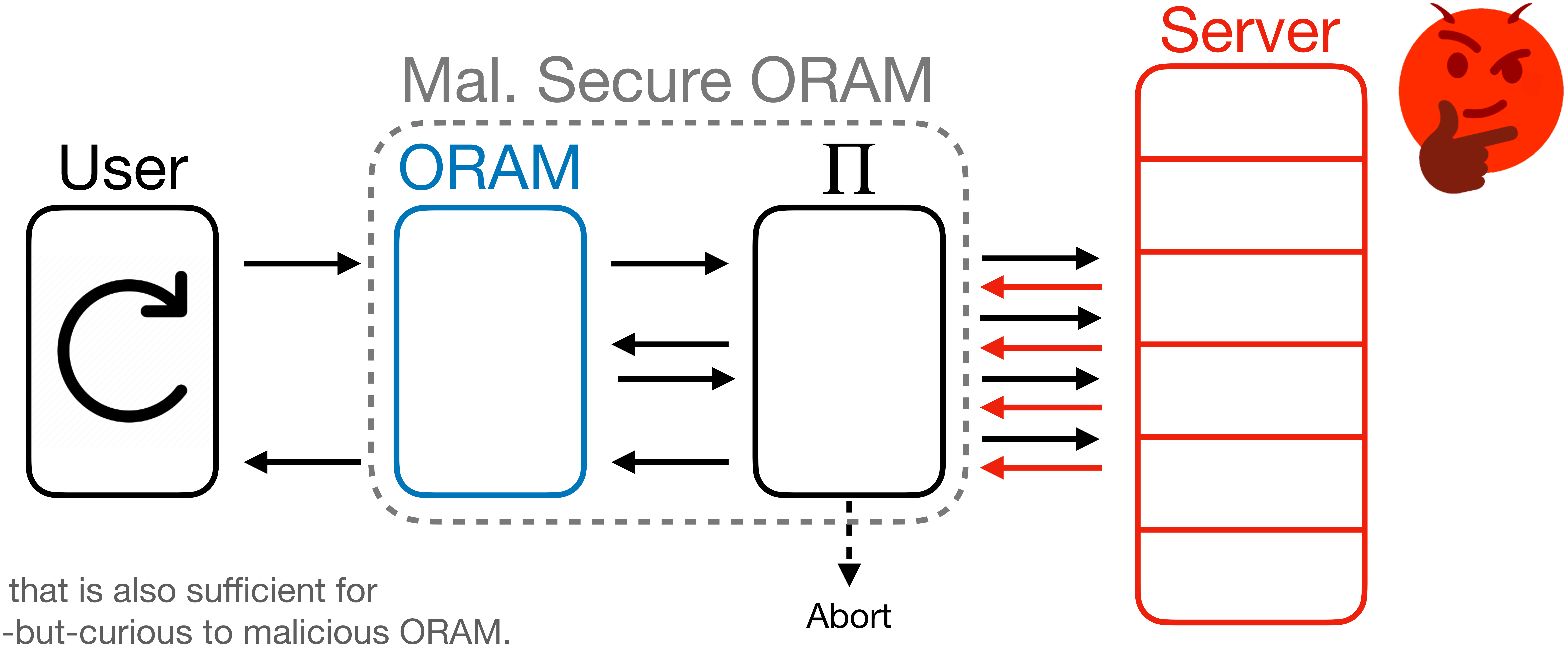
- Do we really need a memory checker? Does a weaker compiler suffice?

Technique #2: Memory Checking



Technique #2: Memory Checking

Theorem [M.-Vafa '23]: If Π compiles any honest-but-curious ORAM into a maliciously secure ORAM with overhead blowup ℓ in this way, then Π is a memory checker* with overhead ℓ.

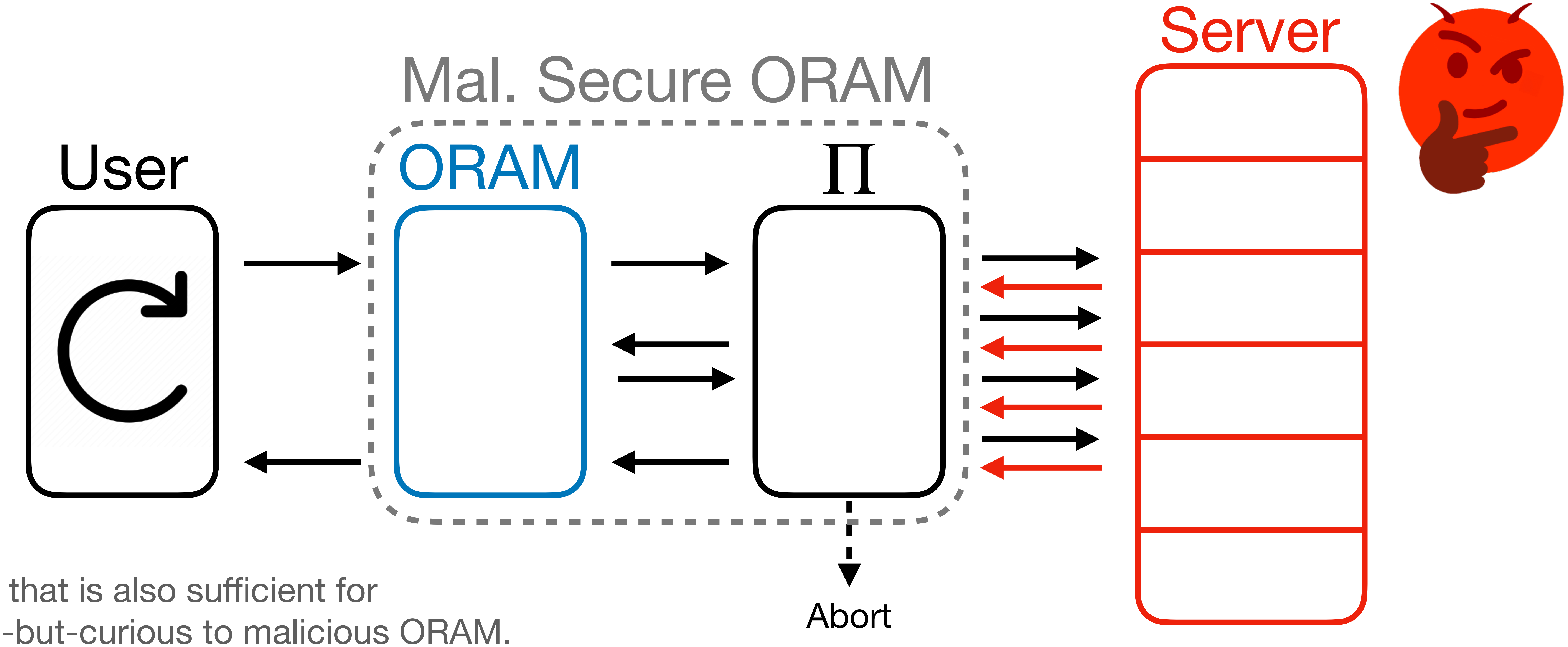


*Slight weakening that is also sufficient for converting honest-but-curious to malicious ORAM.

Technique #2: Memory Checking

Theorem [M.-Vafa '23]: If Π compiles any honest-but-curious ORAM into a maliciously secure ORAM with overhead blowup ℓ in this way, then Π is a memory checker* with overhead ℓ.

Proof: If Π *not* memory checker, construct ORAM to force a mistake from Π.

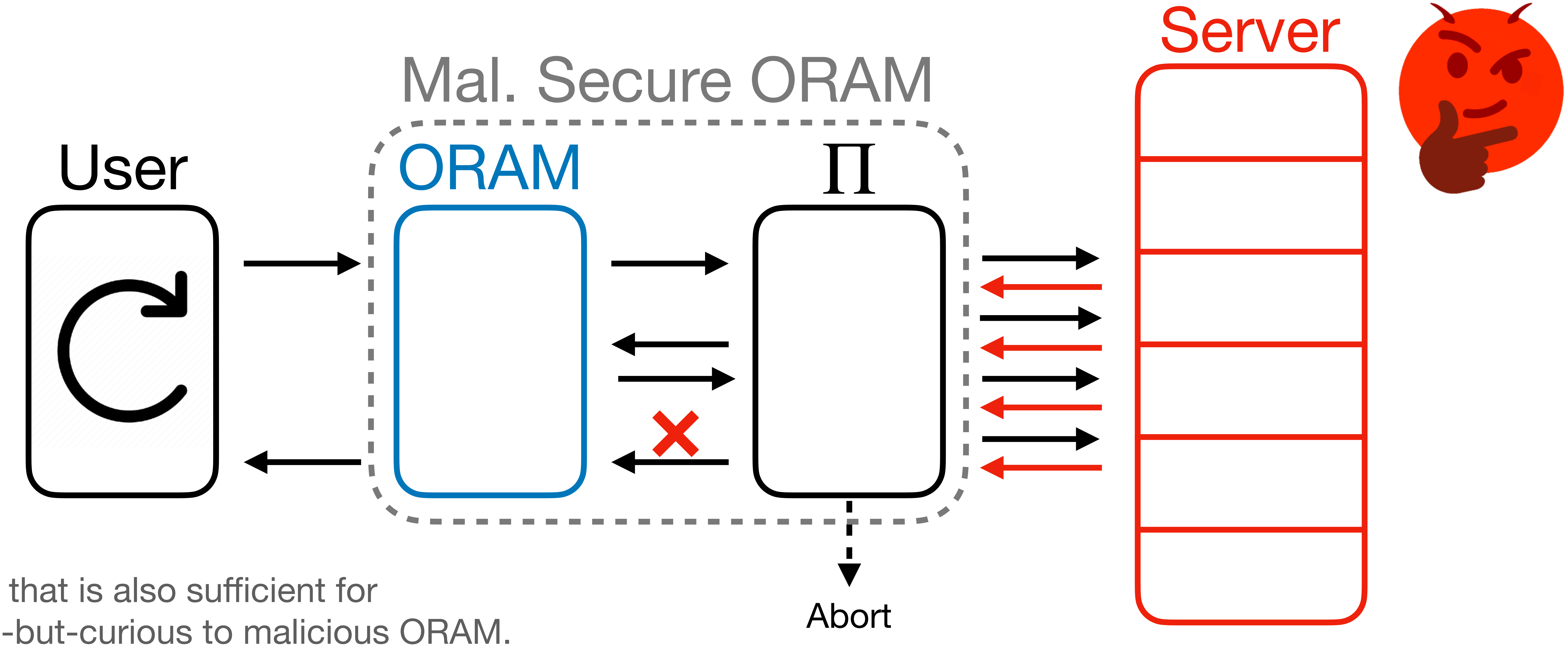


*Slight weakening that is also sufficient for converting honest-but-curious to malicious ORAM.

Technique #2: Memory Checking

Theorem [M.-Vafa '23]: If Π compiles any honest-but-curious ORAM into a maliciously secure ORAM with overhead blowup ℓ in this way, then Π is a memory checker* with overhead ℓ.

Proof: If Π *not* memory checker, construct ORAM to force a mistake from Π.

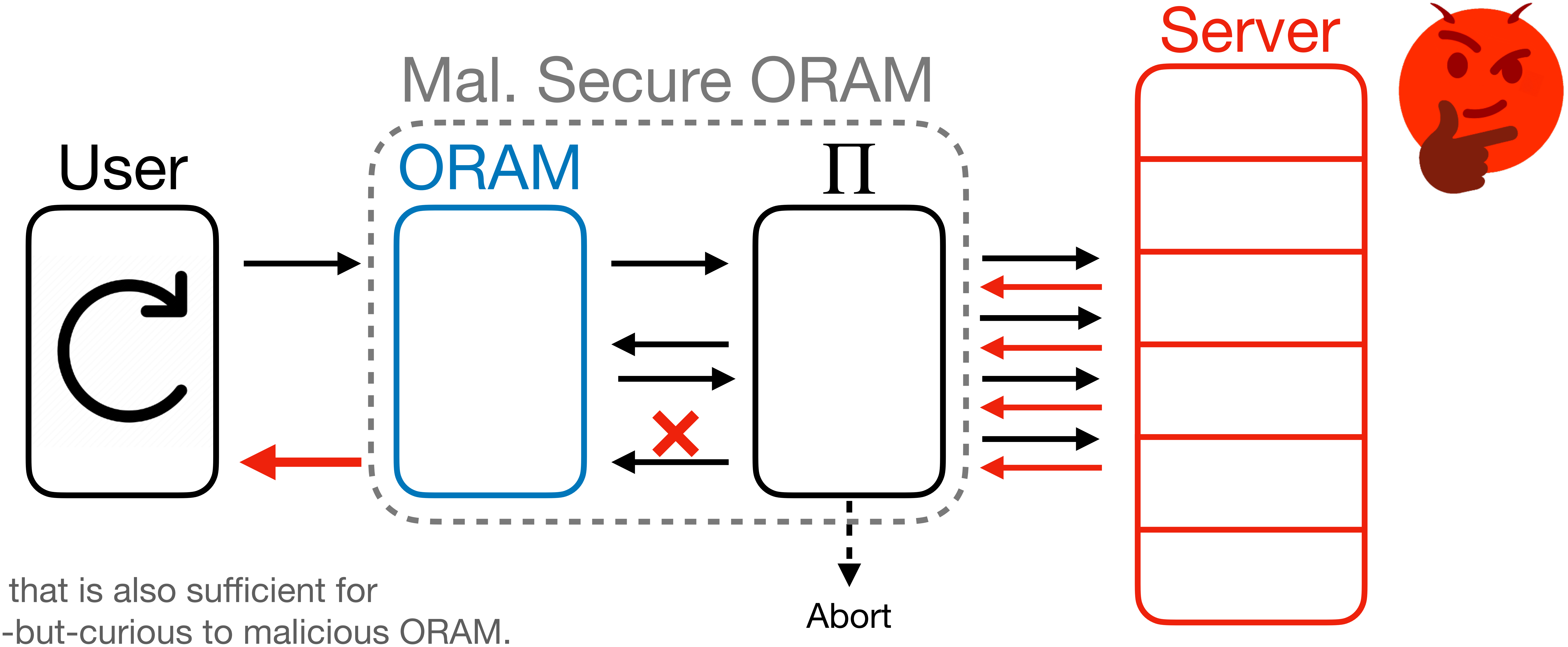


*Slight weakening that is also sufficient for converting honest-but-curious to malicious ORAM.

Technique #2: Memory Checking

<u>Theorem [M.-Vafa '23]</u>: If Π compiles any honest-but-curious ORAM into a maliciously secure ORAM with overhead blowup ℓ in this way, then Π is a memory checker* with overhead ℓ.

Proof: If Π *not* memory checker, construct ORAM to force a mistake from Π.

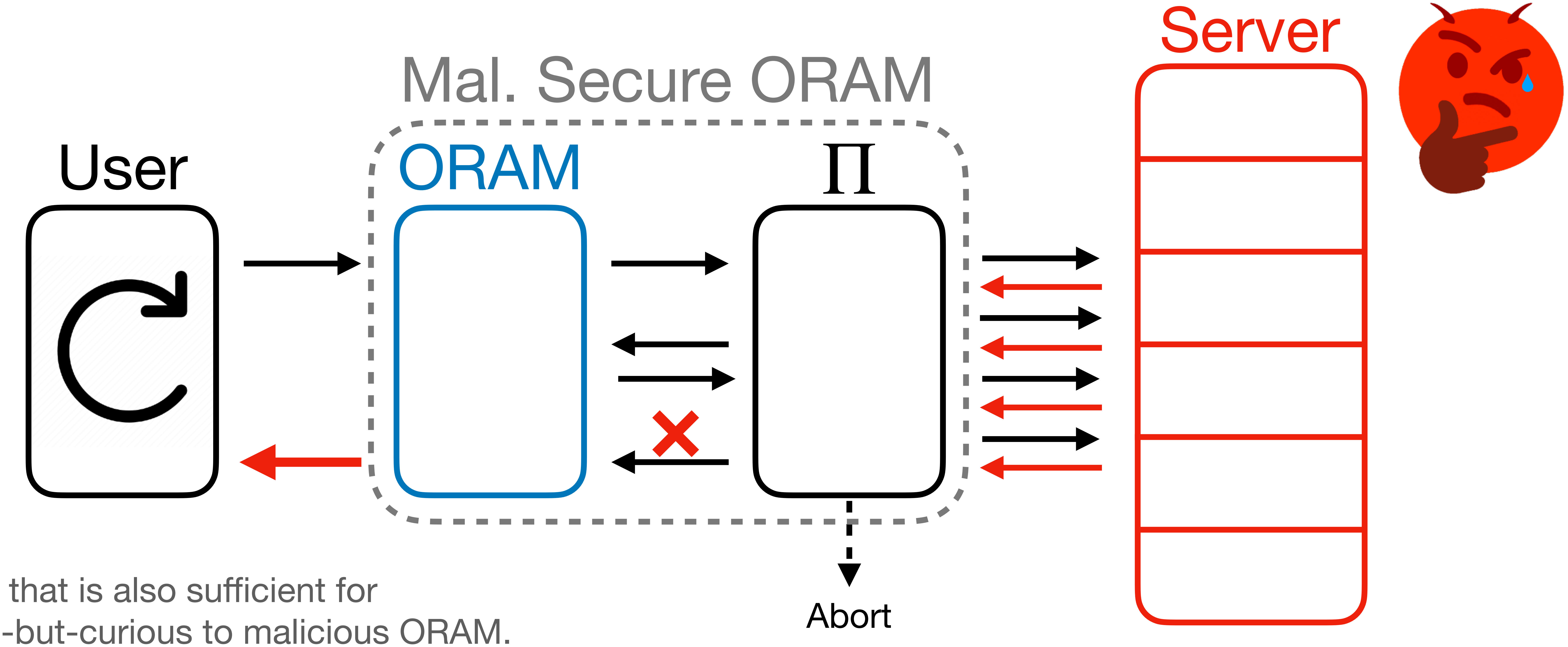


*Slight weakening that is also sufficient for converting honest-but-curious to malicious ORAM.

Technique #2: Memory Checking

Theorem [M.-Vafa '23]: If Π compiles any honest-but-curious ORAM into a maliciously secure ORAM with overhead blowup ℓ in this way, then Π is a memory checker* with overhead ℓ.

Proof: If Π *not* memory checker, construct ORAM to force a mistake from Π.



*Slight weakening that is also sufficient for converting honest-but-curious to malicious ORAM.

Summary of Barriers

Summary of Barriers

1. **Message Authentication Codes (MACs)**

Summary of Barriers

1. **Message Authentication Codes (MACs)**
    - Replay attack in hierarchical setting breaks obliviousness.

Summary of Barriers

1. **Message Authentication Codes (MACs)**
   - Replay attack in hierarchical setting breaks obliviousness.
   - **Time-stamping** prevents replay attack, but unlike older ORAM constructions, **OptORAMa can't** be time-stamped to prevent replay attacks.

Summary of Barriers

1. **Message Authentication Codes (MACs)**
    - Replay attack in hierarchical setting breaks obliviousness.
    - **Time-stamping** prevents replay attack, but unlike older ORAM constructions, **OptORAMa can't** be time-stamped to prevent replay attacks.
2. **Memory Checking (MC)**

Summary of Barriers

1. **Message Authentication Codes (MACs)**
    - Replay attack in hierarchical setting breaks obliviousness.
    - **Time-stamping** prevents replay attack, but unlike older ORAM constructions, **OptORAMa can't** be time-stamped to prevent replay attacks.
2. **Memory Checking (MC)**
    - $O(1)$-blowup post-compiler is **equivalent** to an $O(1)$-overhead memory checker.

Summary of Barriers

1. **Message Authentication Codes (MACs)**
    - Replay attack in hierarchical setting breaks obliviousness.
    - **Time-stamping** prevents replay attack, but unlike older ORAM constructions, **OptORAMa can't** be time-stamped to prevent replay attacks.
2. **Memory Checking (MC)**
    - $O(1)$-blowup post-compiler is **equivalent** to an $O(1)$-overhead memory checker.
    - Best memory checkers have $O(\log N)$ overhead, so seems unlikely.

Summary of Barriers

1. **Message Authentication Codes (MACs)**
    - Replay attack in hierarchical setting breaks obliviousness.
    - **Time-stamping** prevents replay attack, but unlike older ORAM constructions, **OptORAMa can't** be time-stamped to prevent replay attacks.

How can we proceed?

2. **Memory Checking (MC)**
    - $O(1)$-blowup post-compiler is **equivalent** to an $O(1)$-overhead memory checker.
    - Best memory checkers have $O(\log N)$ overhead, so seems unlikely.

Summary of Barriers

1. **Message Authentication Codes (MACs)**
   - Replay attack in hierarchical setting breaks obliviousness.
   - **Time-stamping** prevents replay attack, but unlike older ORAM constructions, **OptORAMa can't** be time-stamped to prevent replay attacks.

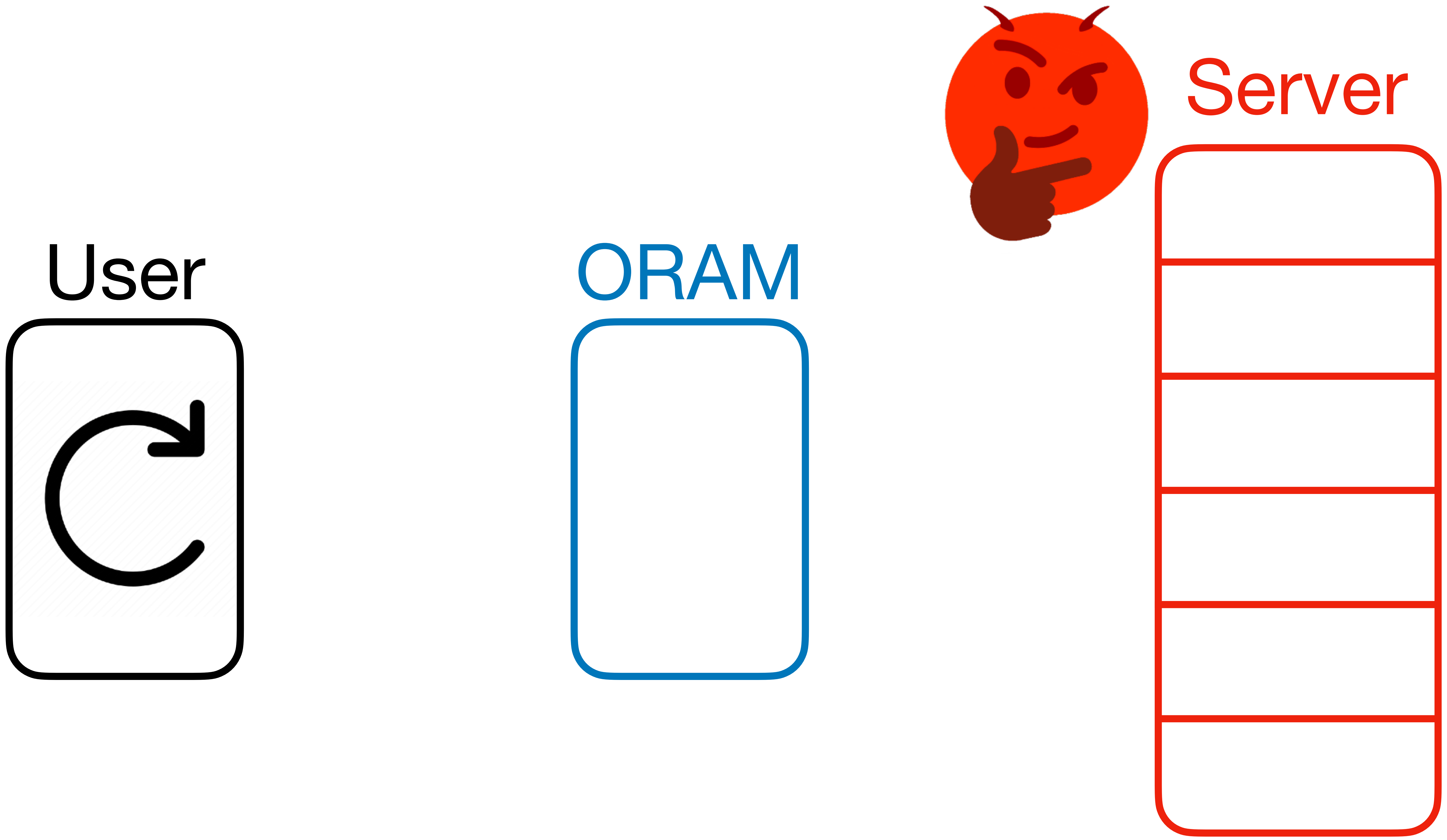
How can we proceed?

2. **Memory Checking (MC)**

We have to handle OptORAMa in a white-box way!

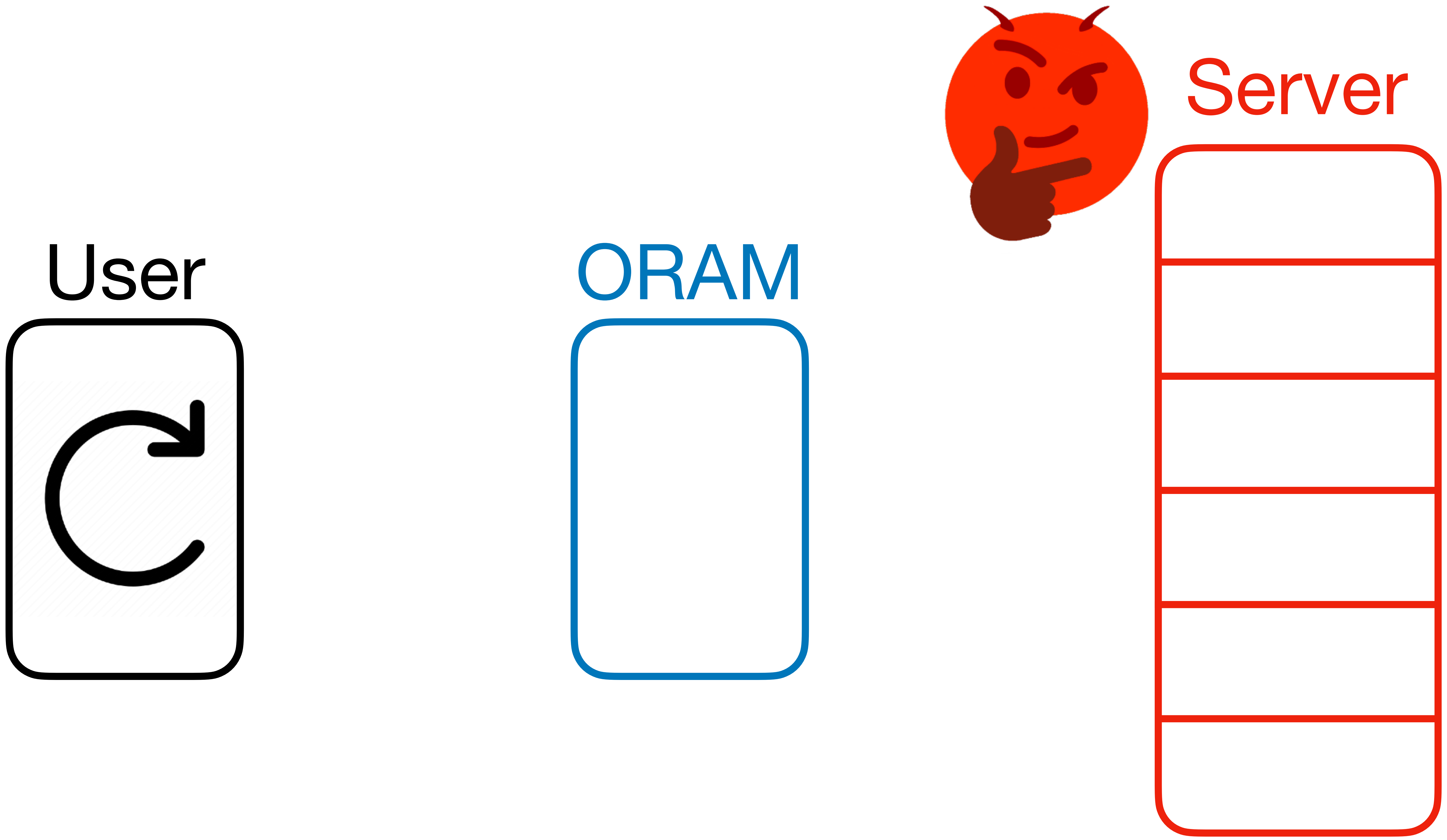
   - $O(1)$-blowup post-compiler is **equivalent** to an $O(1)$-overhead memory checker.
   - Best memory checkers have $O(\log N)$ overhead, so seems unlikely.

Does OptORAMa really need memory checking?



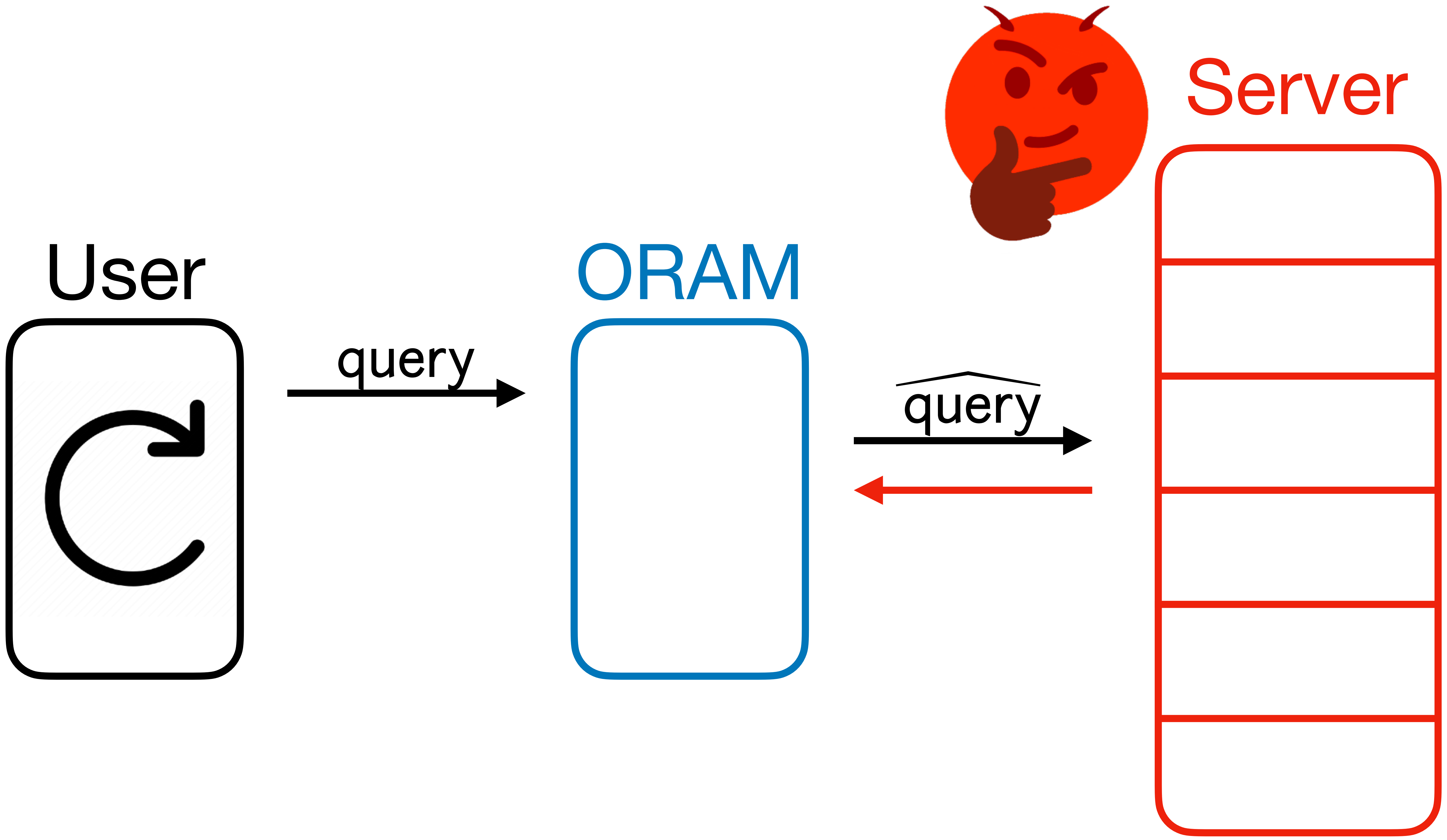
Does OptORAMa really need memory checking?

- What if **OptORAMa** can tolerate *some* lies from the server?



Does OptORAMa really need memory checking?

- What if **OptORAMa** can tolerate *some* lies from the server?



User

query

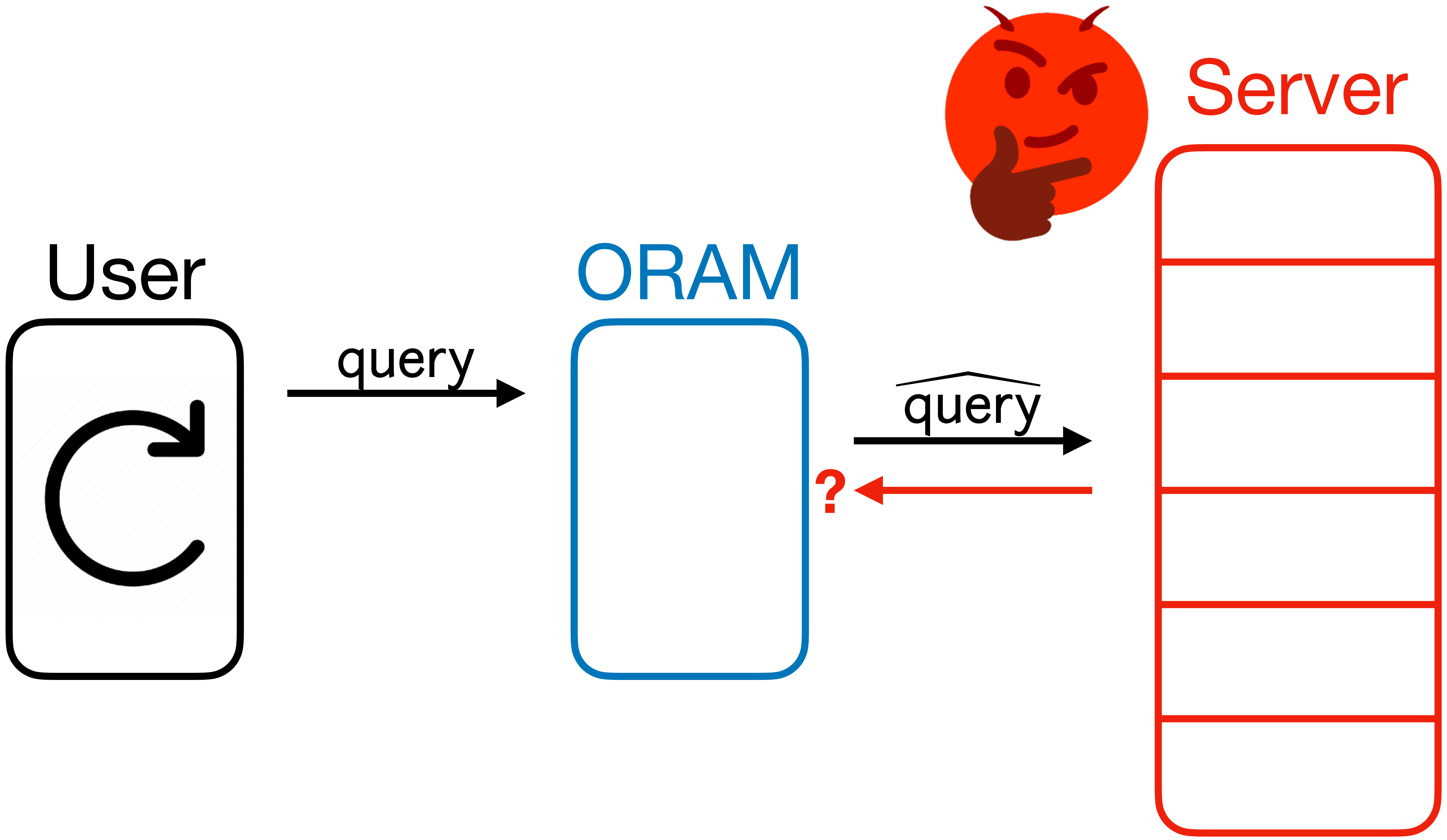
ORAM

$\widehat{\text{query}}$

Server

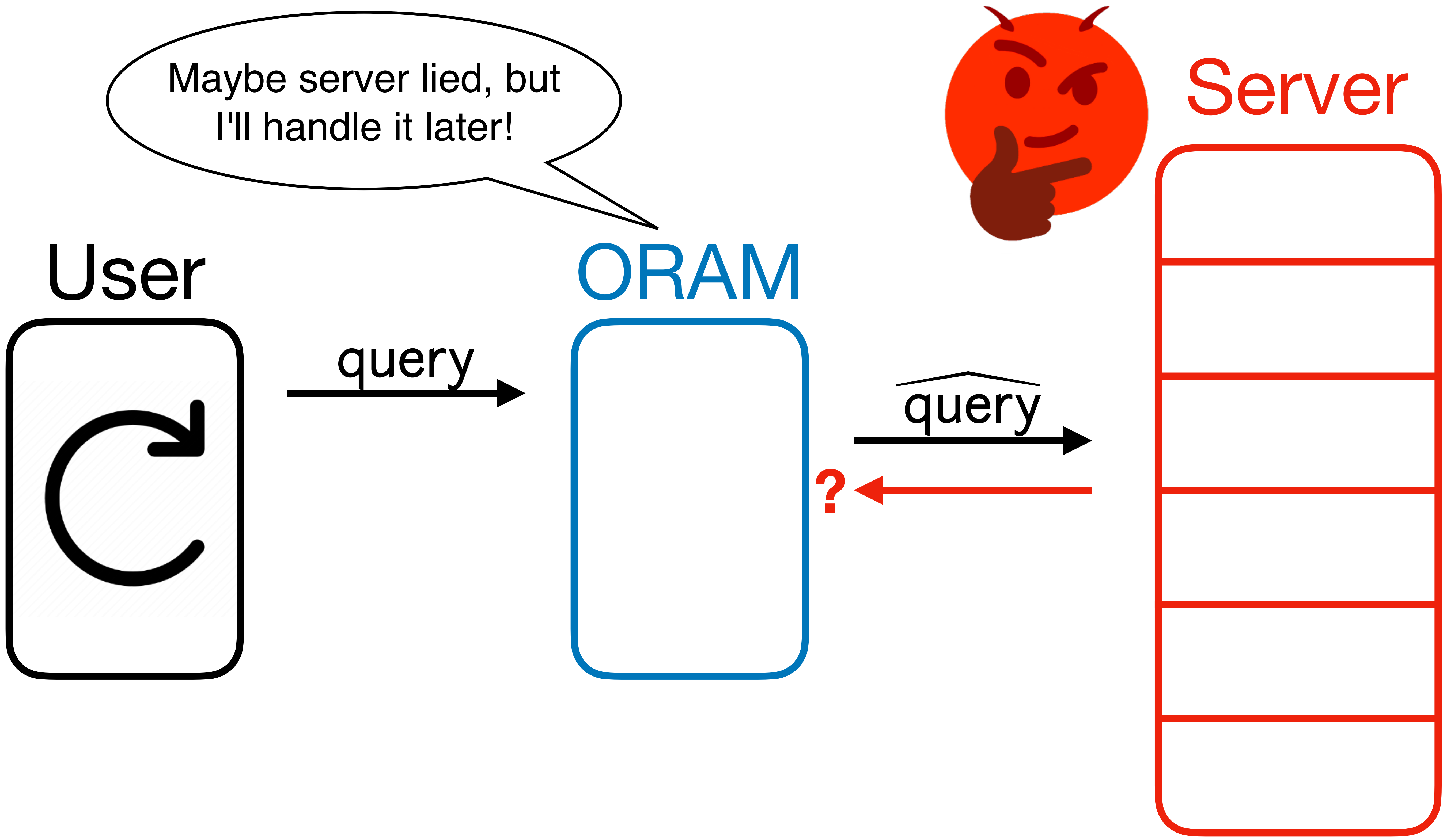
Does OptORAMa really need memory checking?

- What if **OptORAMa** can tolerate *some* lies from the server?



Does OptORAMa really need memory checking?

- What if **OptORAMa** can tolerate *some* lies from the server?



Maybe server lied, but I'll handle it later!

Server

User

ORAM

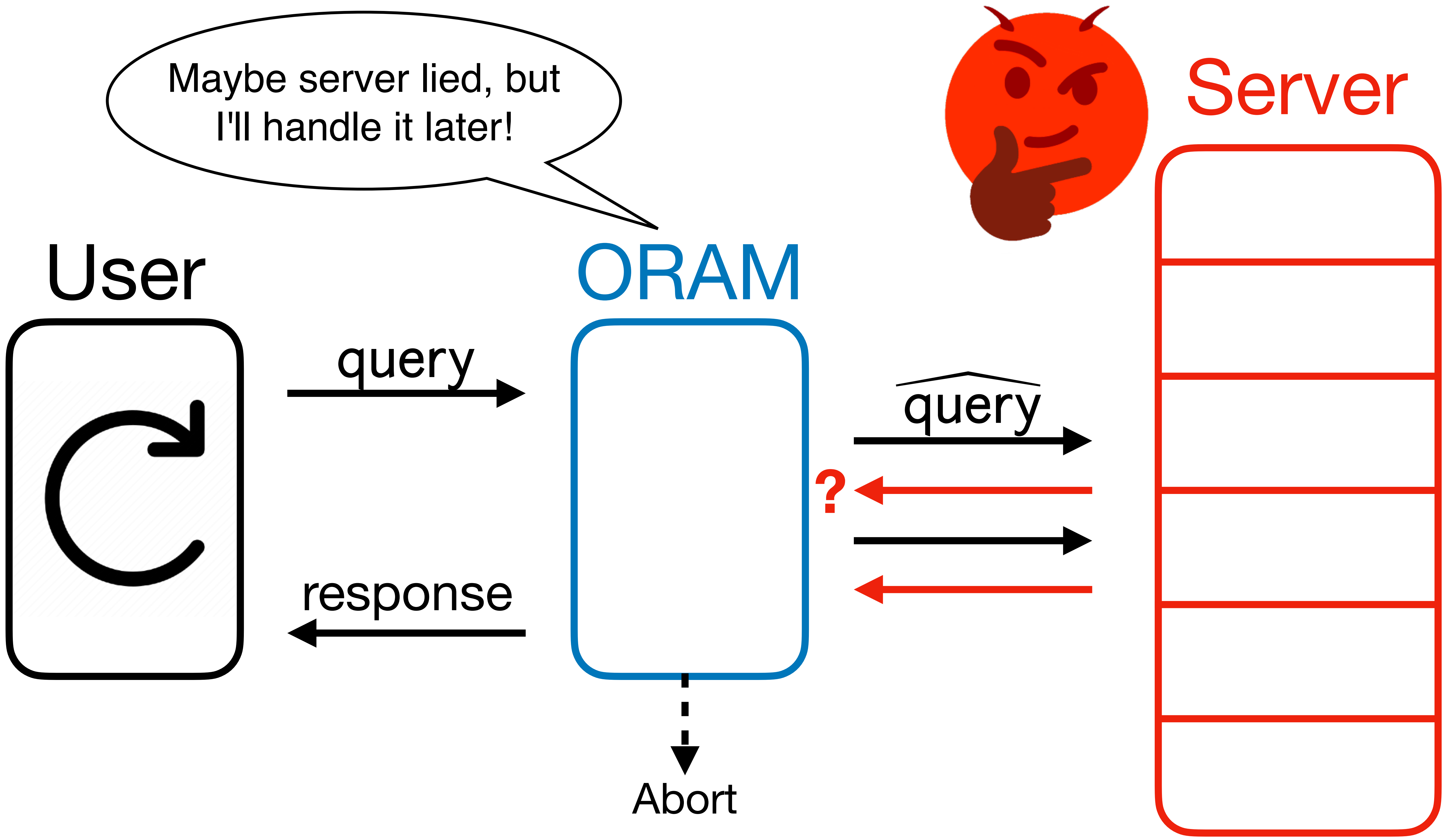
query

$\widehat{\text{query}}$

?

Does OptORAMa really need memory checking?

- What if **OptORAMa** can tolerate *some* lies from the server?



Maybe server lied, but I'll handle it later!

User

ORAM

Server

query

response

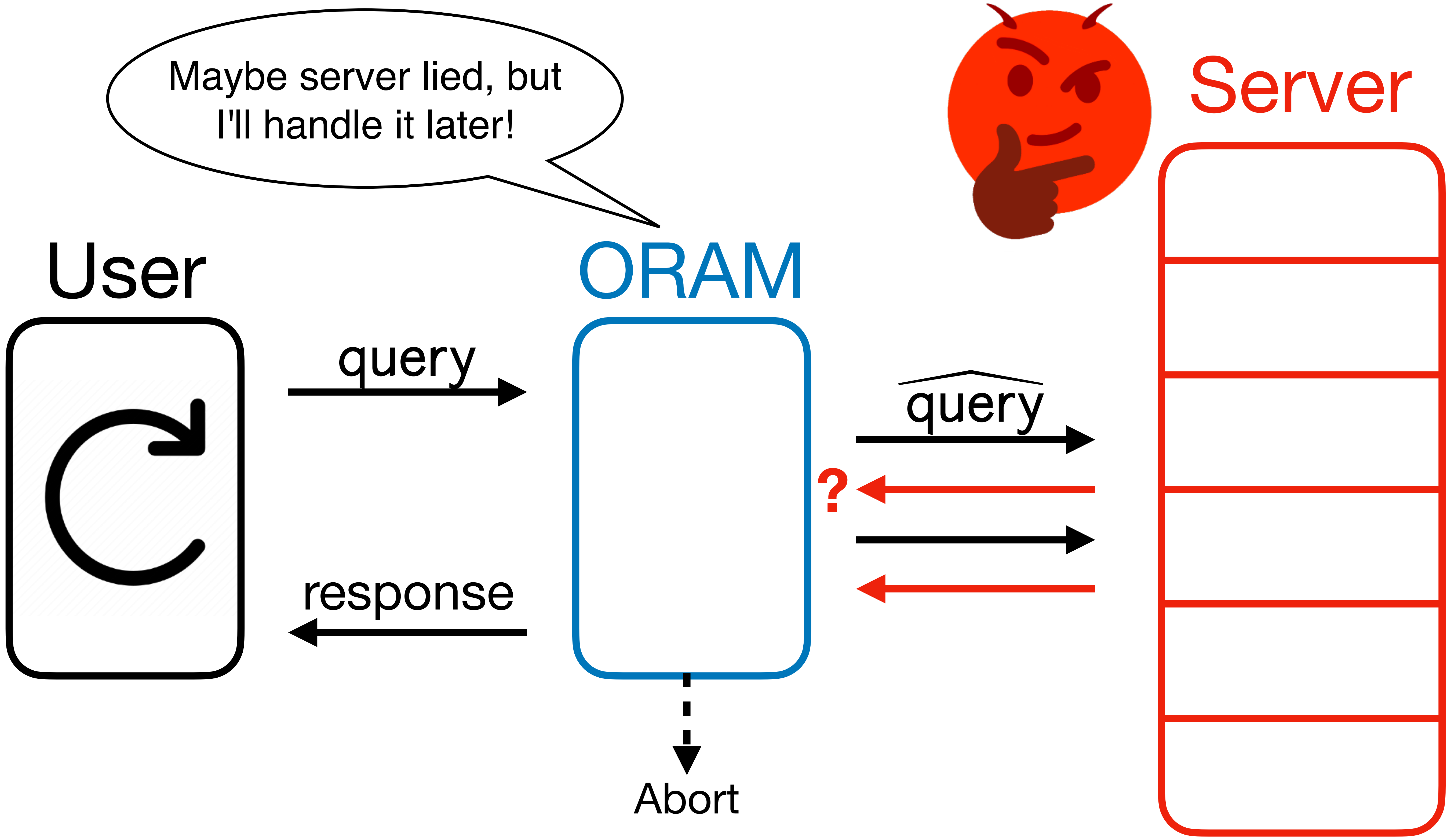
$\widehat{\text{query}}$

?

Abort

Does OptORAMa really need memory checking?

- What if **OptORAMa** can tolerate *some* lies from the server?
- **Our Idea**: Use weaker, more efficient notion of memory checking to capitalize on this!



Offline Memory Checking

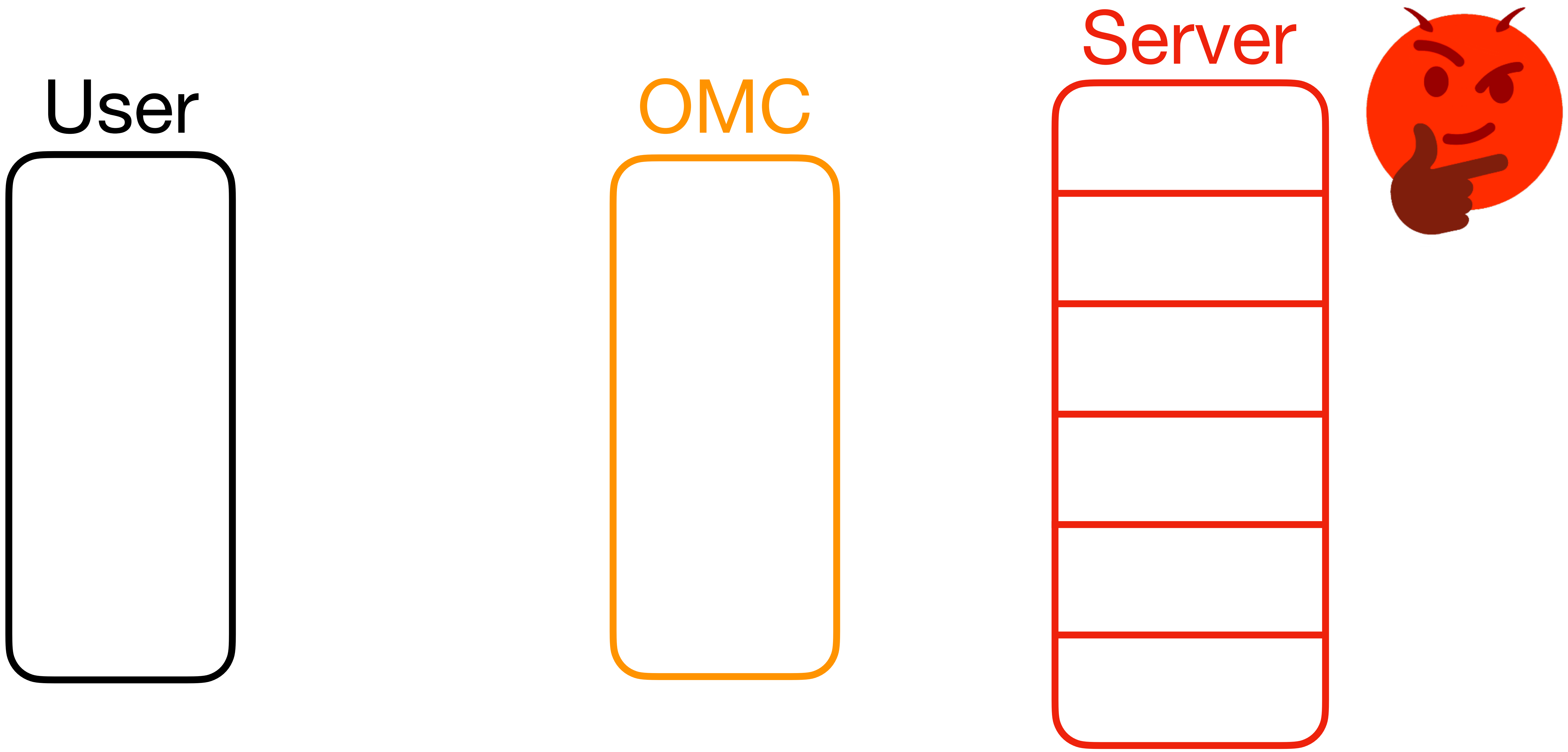
Offline Memory Checking

- An **Offline Memory Checker** (OMC) is a memory checker with a weaker correctness condition:

[Blum et al. ’94]

Offline Memory Checking

- An **Offline Memory Checker** (OMC) is a memory checker with a weaker correctness condition: [Blum et al. ’94]

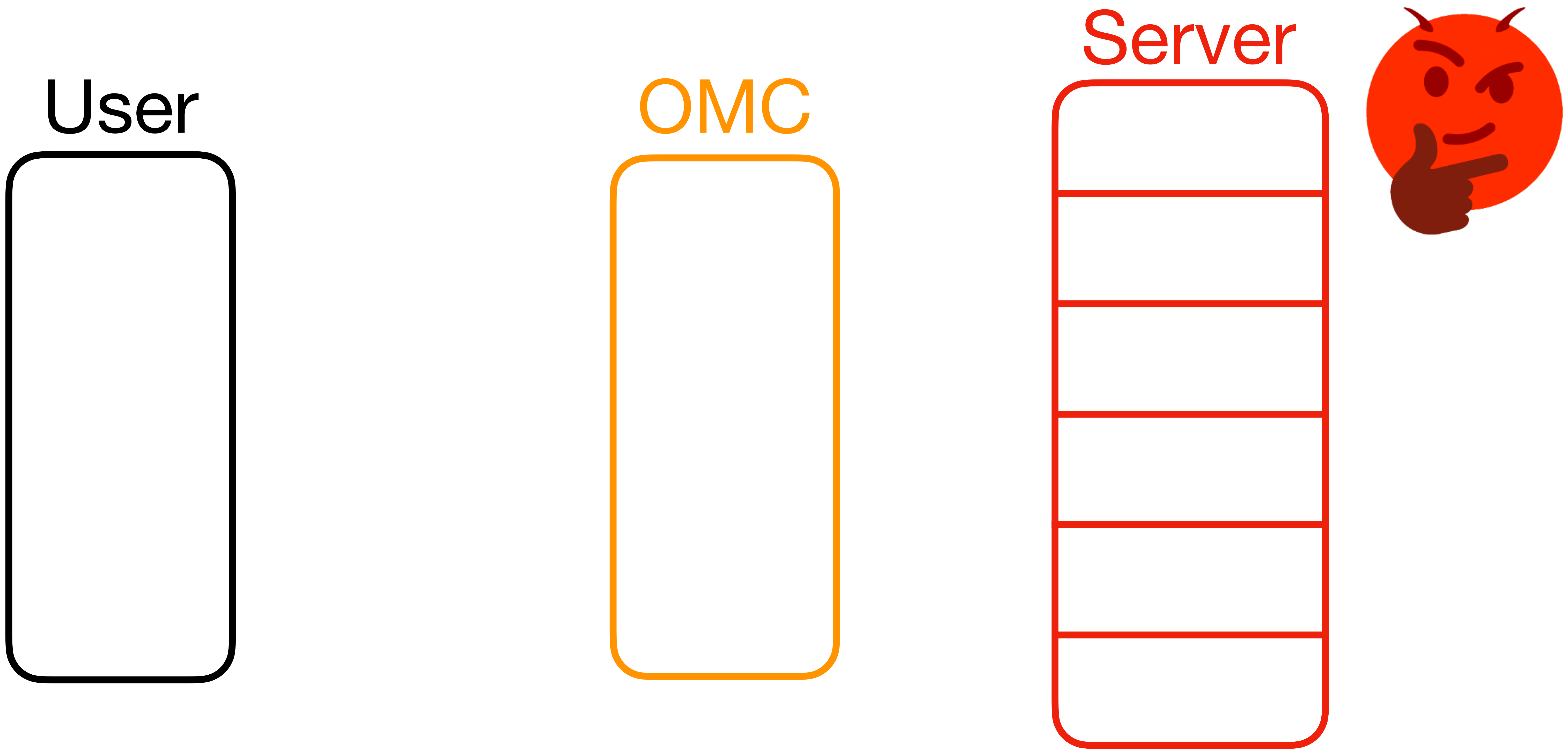


Offline Memory Checking

- An **Offline Memory Checker** (OMC) is a memory checker with a weaker correctness condition:

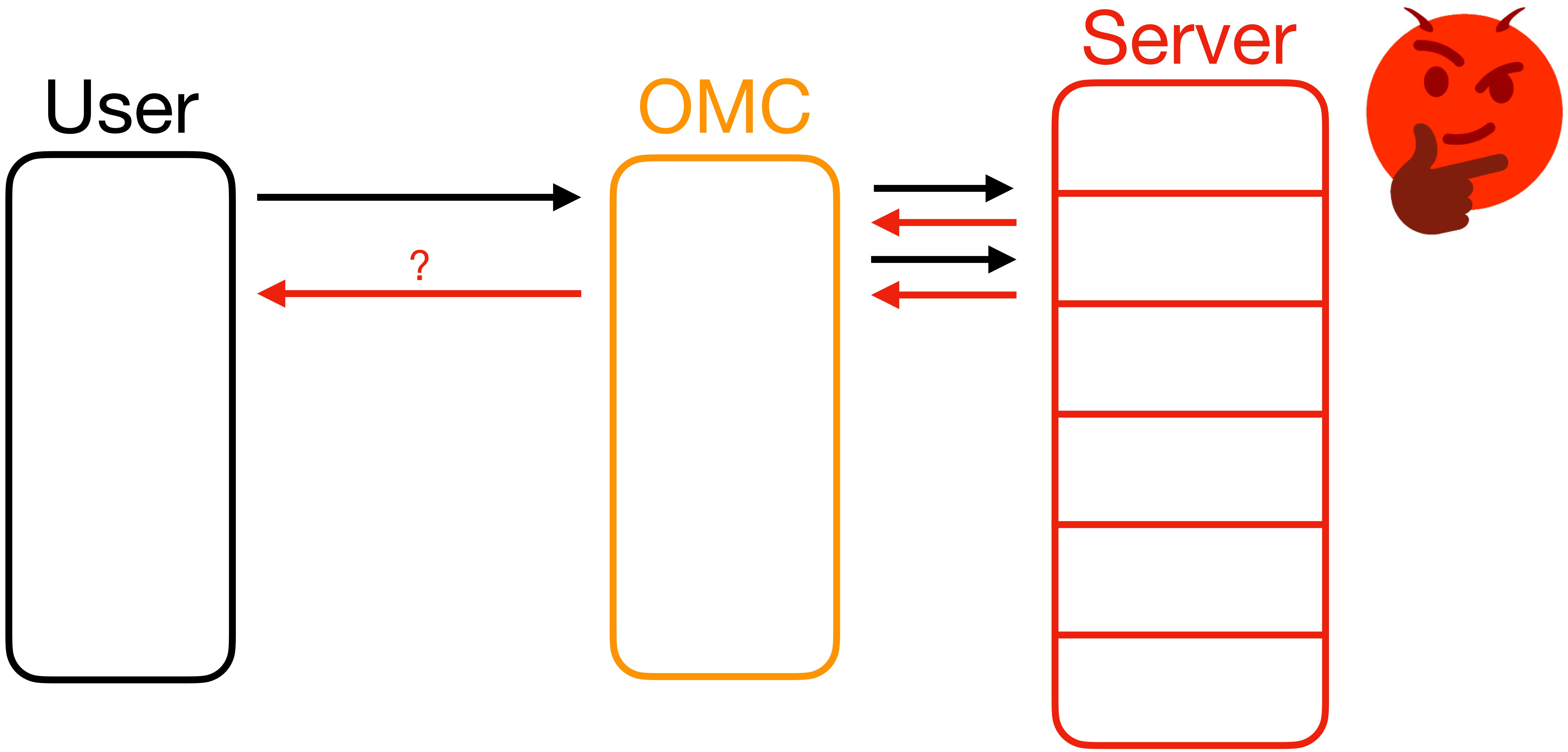
[Blum et al. '94]

- Just needs to abort **by the end** – intermediate responses from the OMC may be incorrect! (Think "batching" a regular memory checker.)



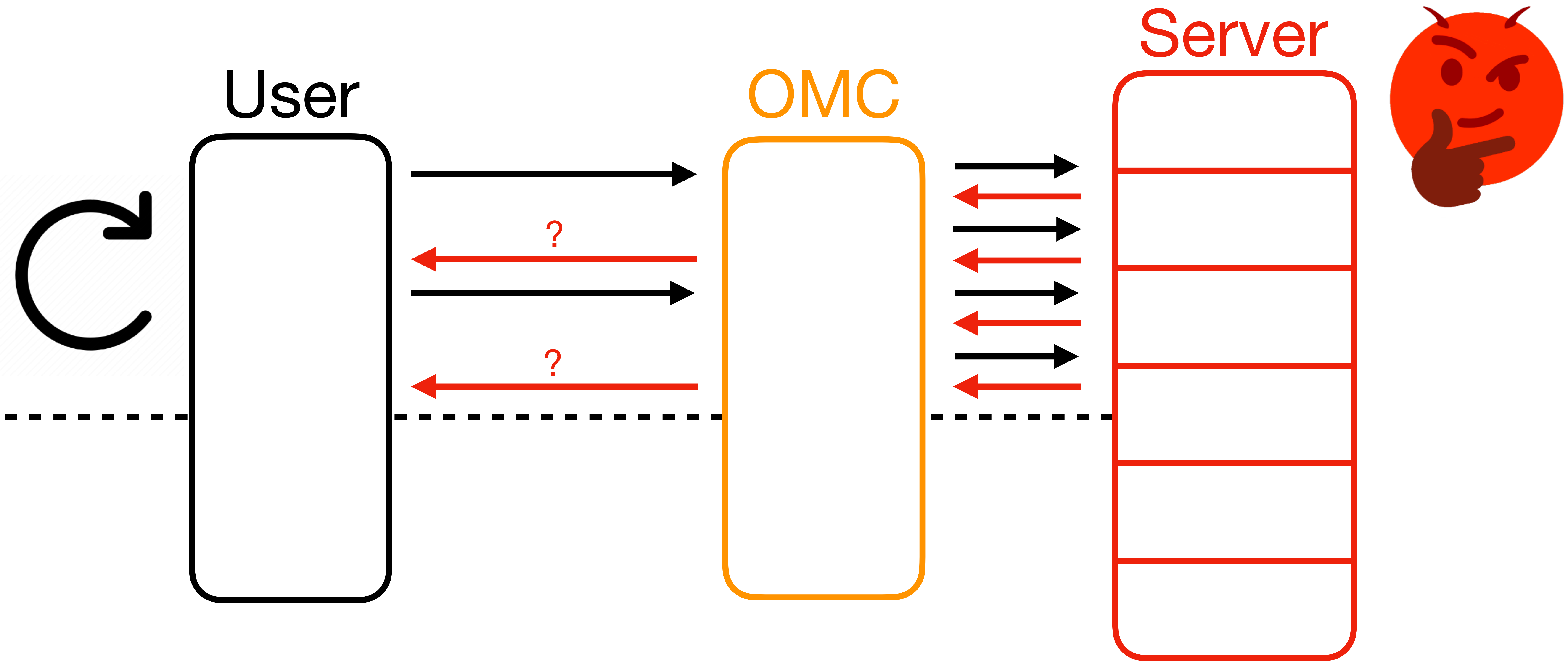
Offline Memory Checking

- An **Offline Memory Checker** (OMC) is a memory checker with a weaker correctness condition: [Blum et al. ’94]
- Just needs to abort **by the end** – intermediate responses from the OMC may be incorrect! (Think “batching” a regular memory checker.)



Offline Memory Checking

- An **Offline Memory Checker** (OMC) is a memory checker with a weaker correctness condition: [Blum et al. '94]
- Just needs to abort **by the end** – intermediate responses from the OMC may be incorrect! (Think "batching" a regular memory checker.)

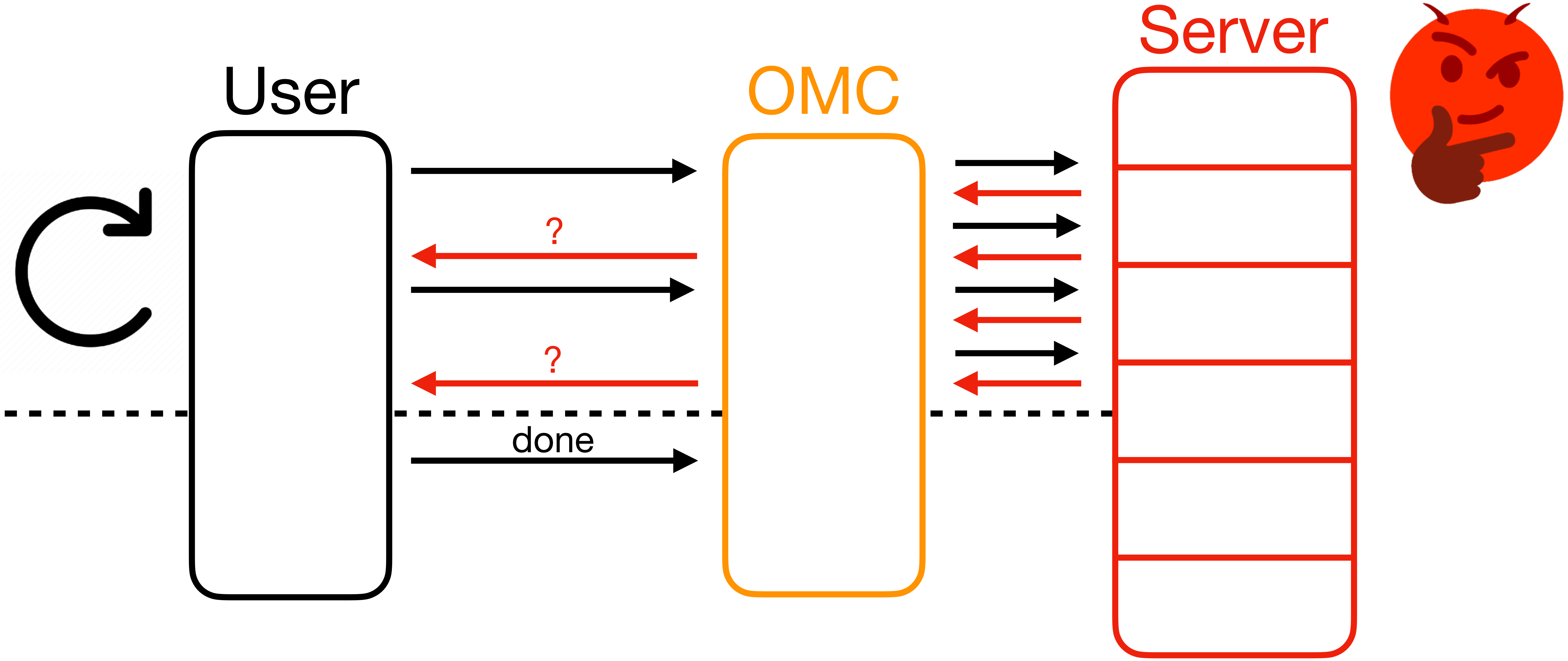


Offline Memory Checking

- An **Offline Memory Checker** (OMC) is a memory checker with a weaker correctness condition:

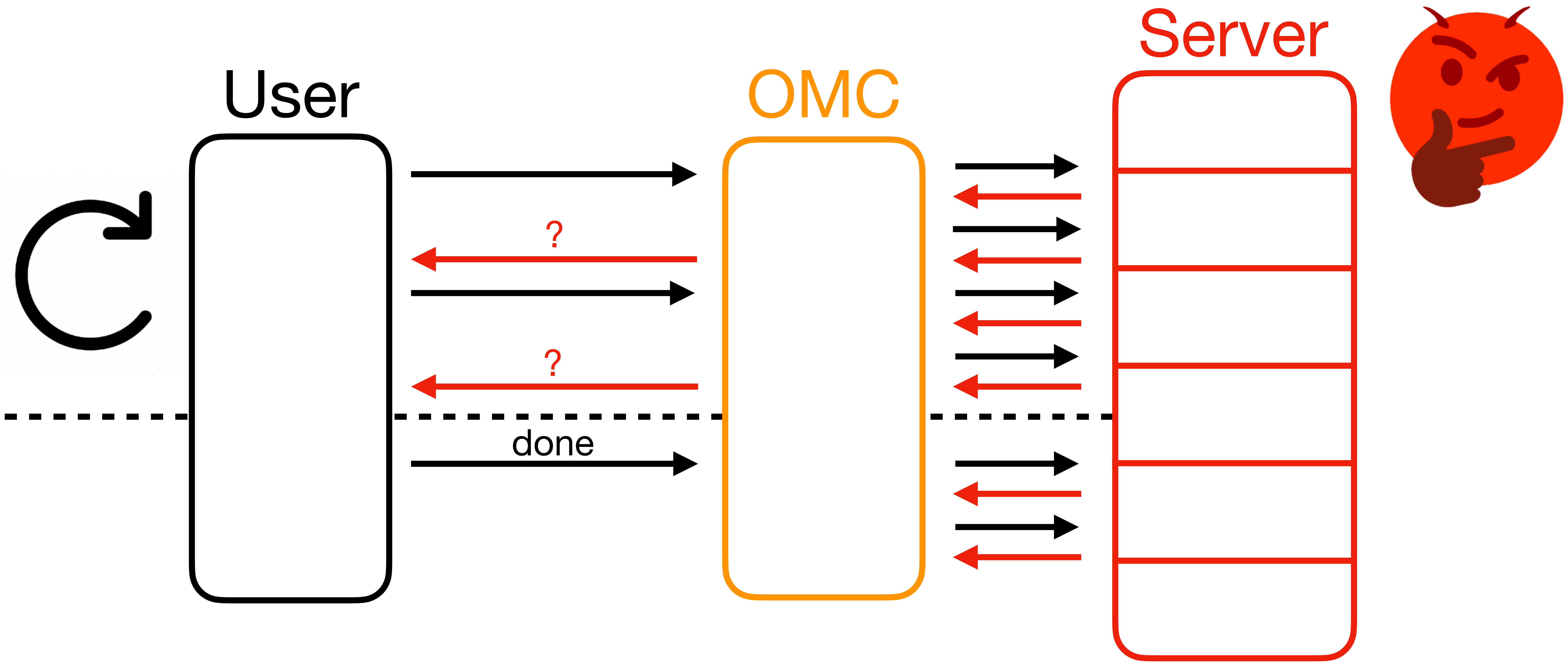
[Blum et al. ’94]

- Just needs to abort **by the end** – intermediate responses from the OMC may be incorrect! (Think “batching” a regular memory checker.)



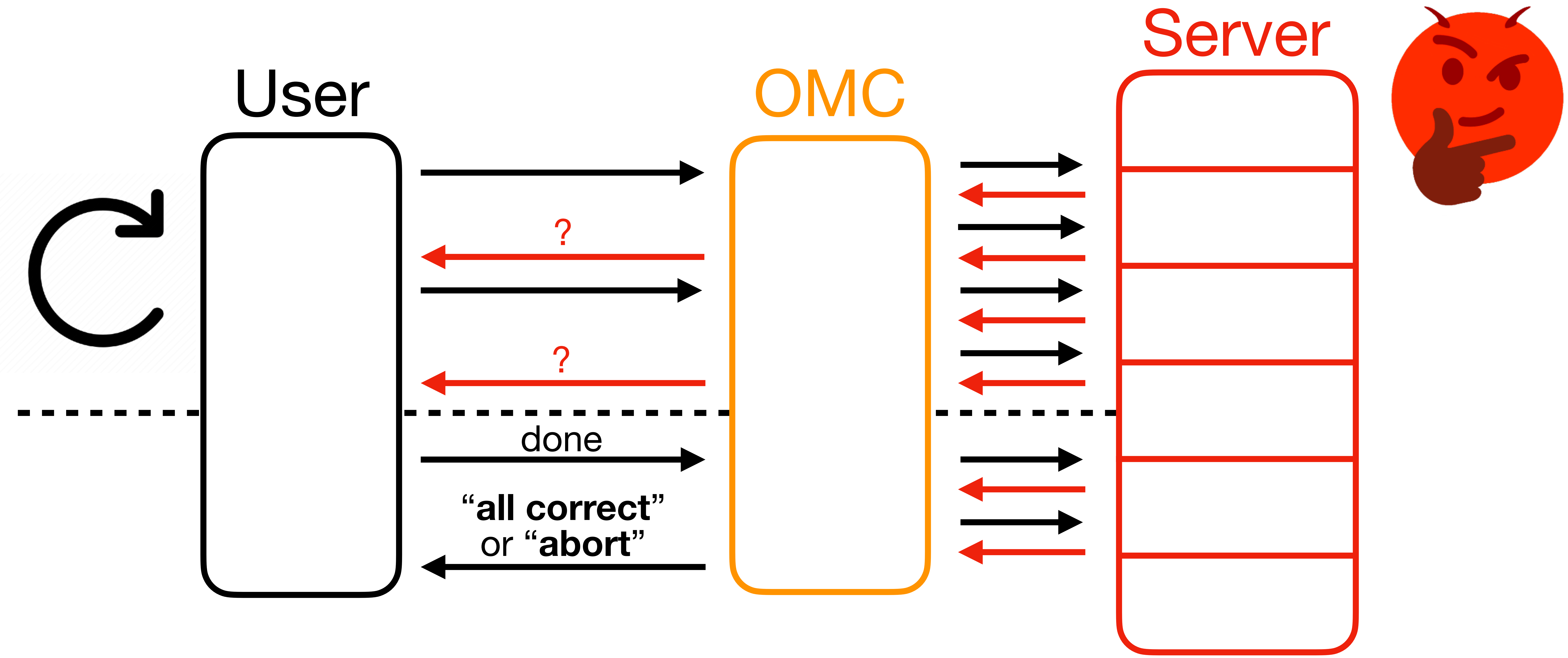
Offline Memory Checking

- An **Offline Memory Checker** (OMC) is a memory checker with a weaker correctness condition: [Blum et al. ’94]
- Just needs to abort **by the end** – intermediate responses from the OMC may be incorrect! (Think “batching” a regular memory checker.)



Offline Memory Checking

- An **Offline Memory Checker** (OMC) is a memory checker with a weaker correctness condition: [Blum et al. '94]
- Just needs to abort **by the end** – intermediate responses from the OMC may be incorrect! (Think "batching" a regular memory checker.)



Offline Memory Checking

- Benefit of offline memory checking: **constructions with** (amortized) $O(1)$ **overhead!**

[Blum et al. '94]
[Dwork et al. '09]

Offline Memory Checking

- Benefit of offline memory checking: **constructions with** (amortized) $O(1)$ **overhead!**
- Con of offline memory checking: **insufficient**! **Insecure for OptORAMa.**

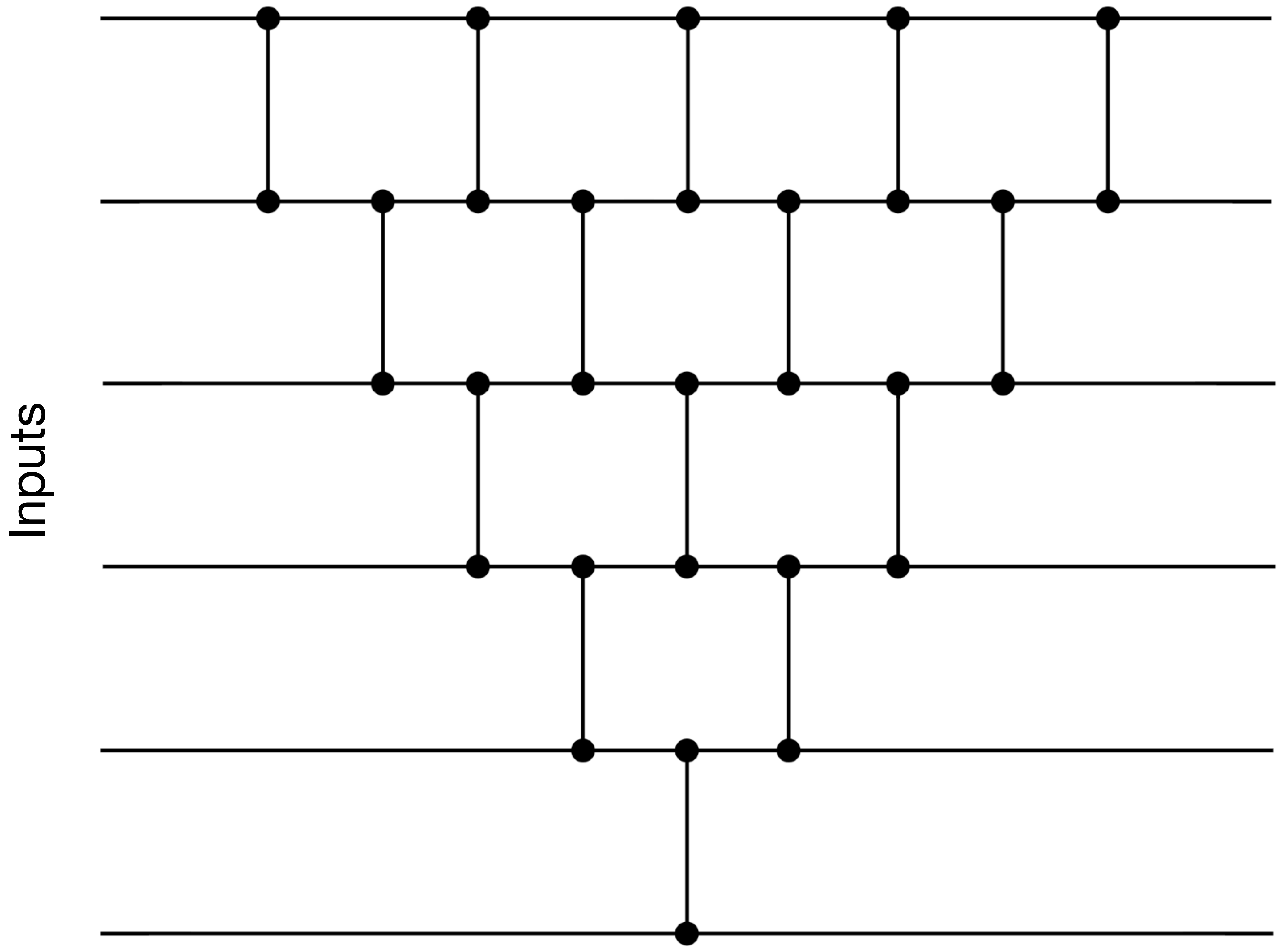
Offline Memory Checking

- Benefit of offline memory checking: **constructions with** (amortized) $O(1)$ **overhead!**
- Con of offline memory checking: **insufficient**! **Insecure for OptORAMa**.
  - Replay attack (with MACs and offline memory checking) **still applies.**

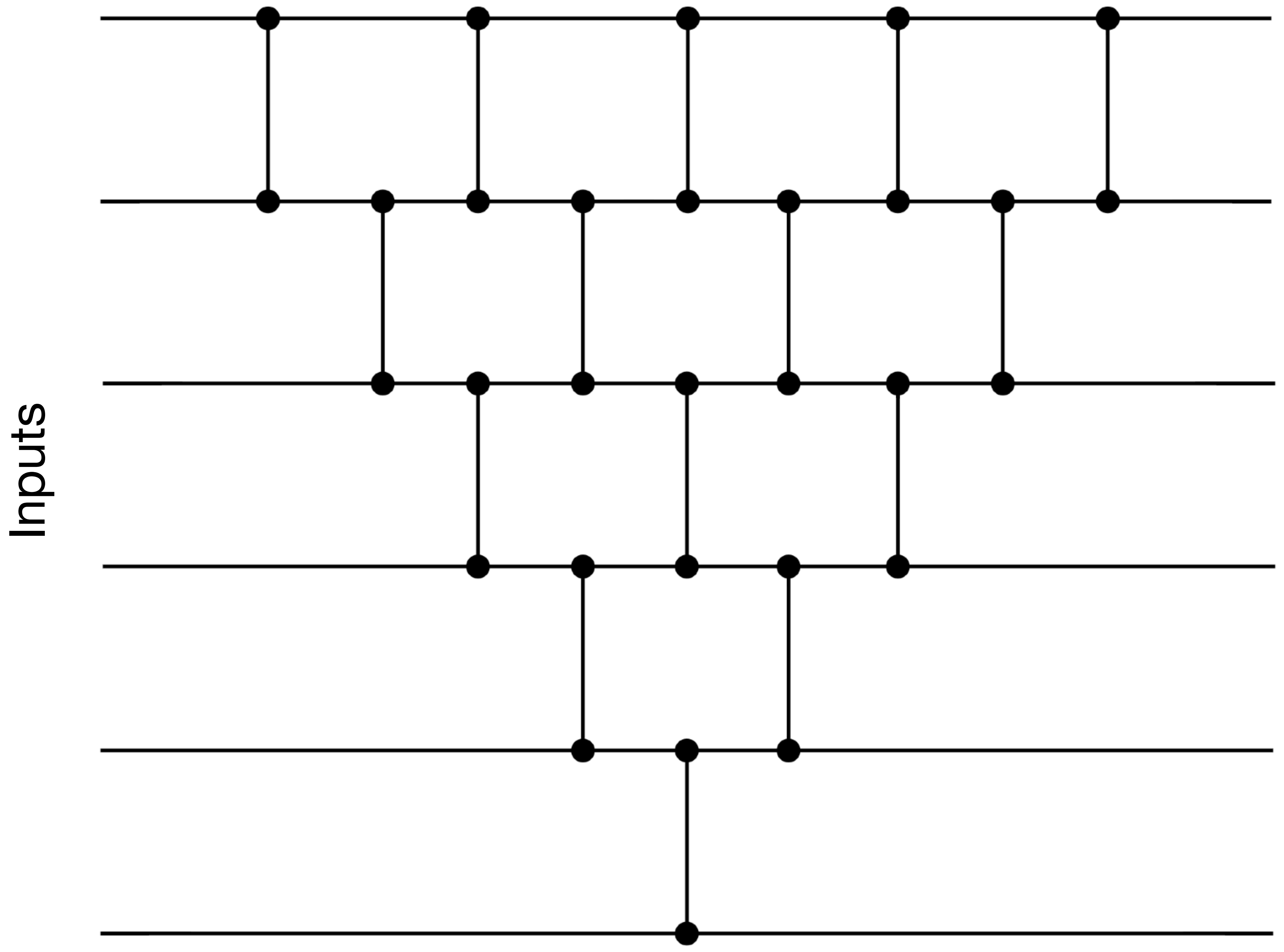
Offline Memory Checking

- Benefit of offline memory checking: **constructions with** (amortized) $O(1)$ **overhead!**
- Con of offline memory checking: **insufficient**! **Insecure for OptORAMa**.
  - Replay attack (with MACs and offline memory checking) **still applies.**
- So when is offline checking safe?

When is Offline Checking Safe?

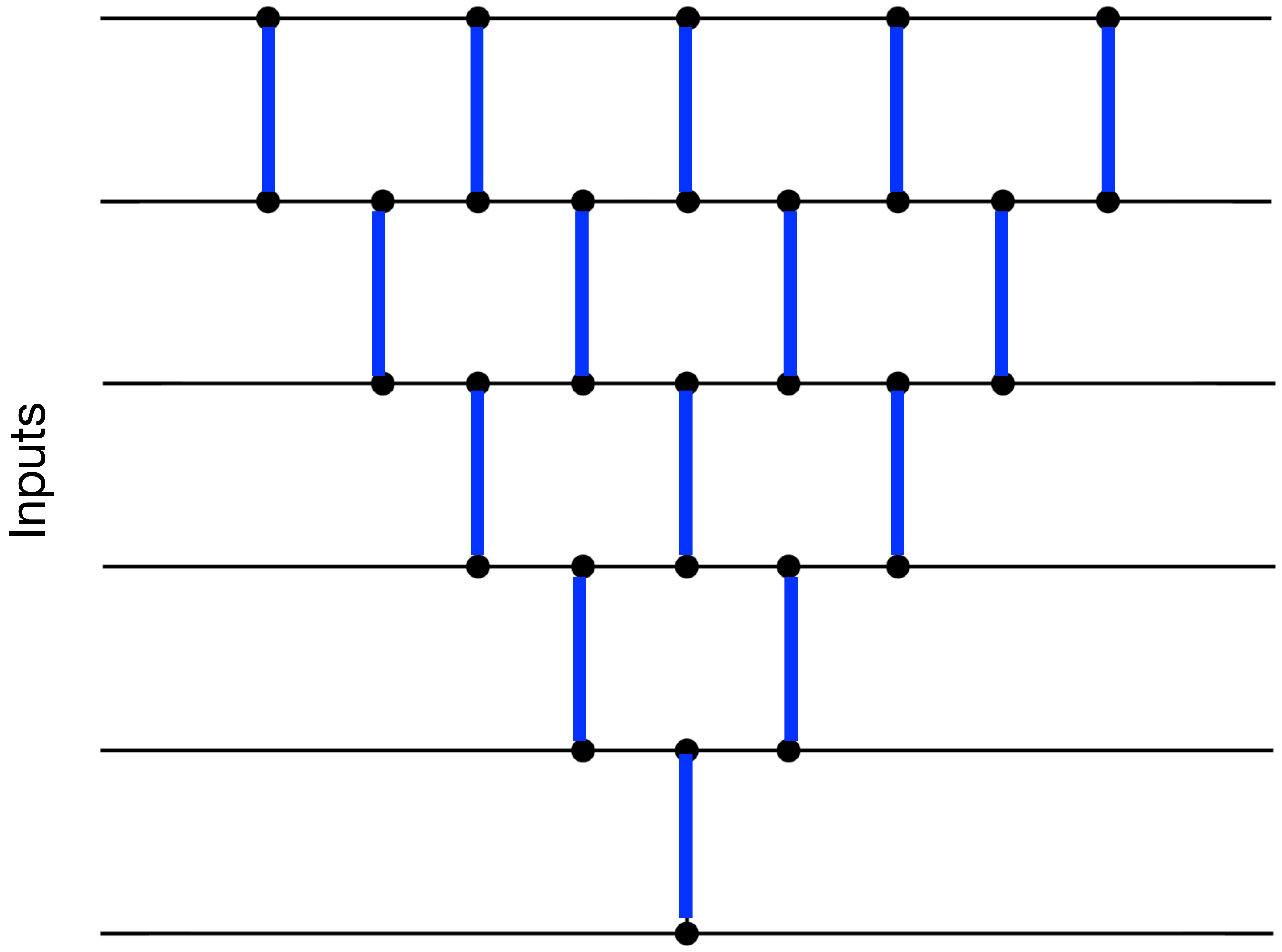


When is Offline Checking Safe?



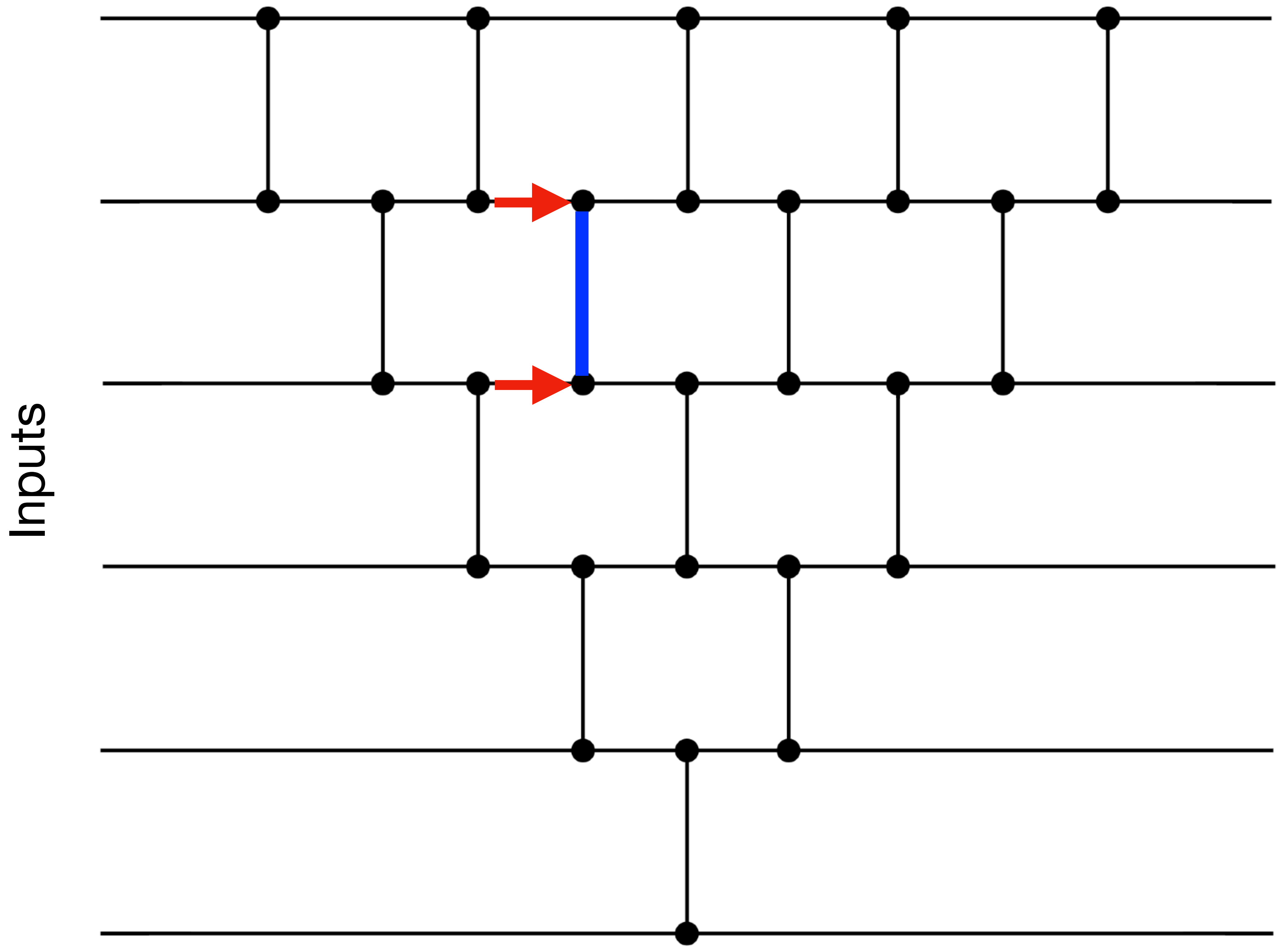
- Eg. Simple sorting networks (e.g. Batcher's)

When is Offline Checking Safe?



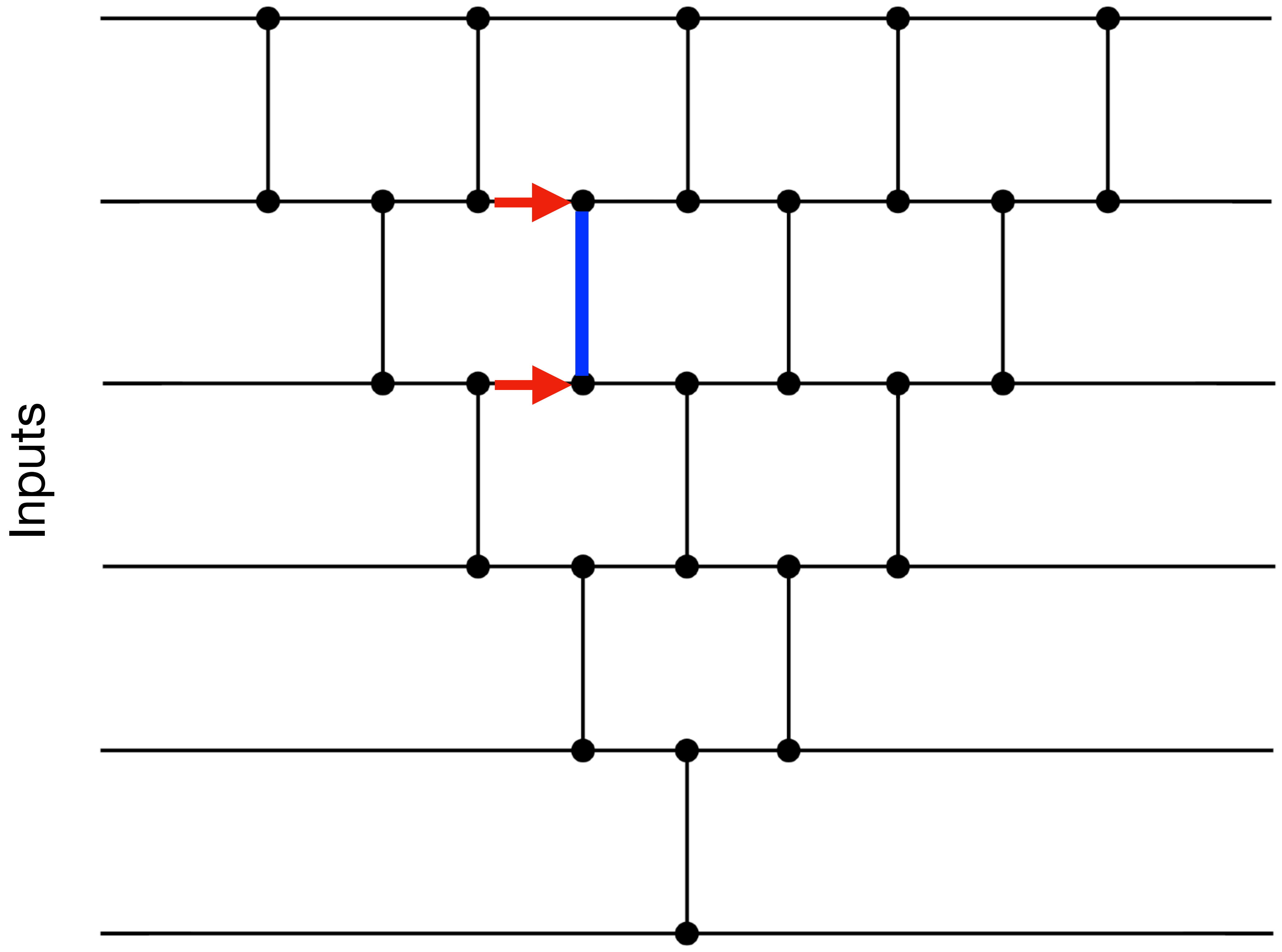
- Eg. Simple sorting networks (e.g. Batcher’s)
- Can locally compute all comparisons to be made.

When is Offline Checking Safe?



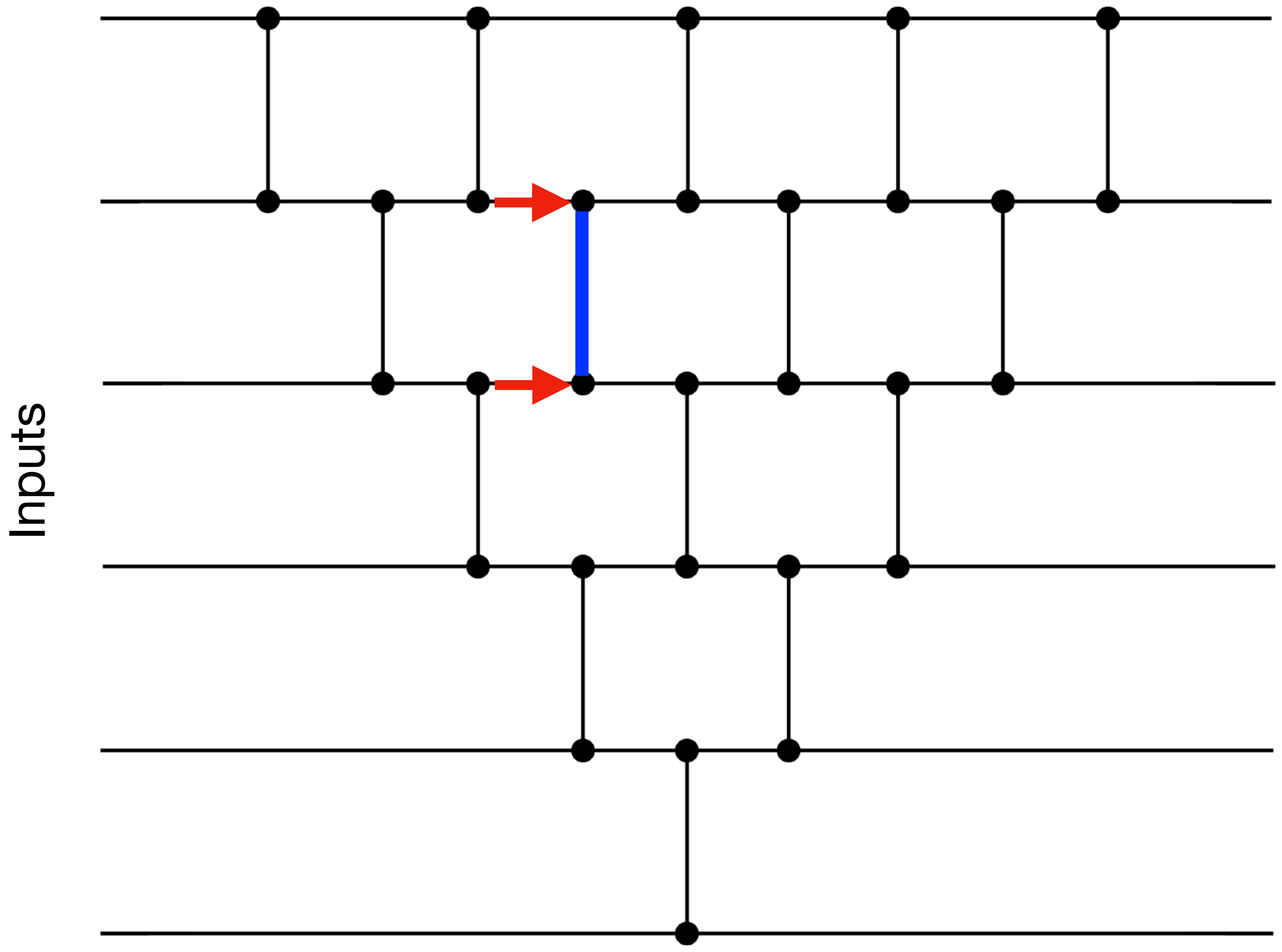
- Eg. Simple sorting networks (e.g. Batcher’s)
- Can locally compute all comparisons to be made.
- Incorrect wire values do not affect the comparisons made, so access pattern is **not affected.**

When is Offline Checking Safe?



- Eg. Simple sorting networks (e.g. Batcher's)
- Can locally compute all comparisons to be made.
- Incorrect wire values do not affect the comparisons made, so access pattern is **not affected.**
- Safe to offline-check!

When is Offline Checking Safe?



- Eg. Simple sorting networks (e.g. Batcher’s)
- Can locally compute all comparisons to be made.
- Incorrect wire values do not affect the comparisons made, so access pattern is **not affected.**
- Safe to offline-check!
- In our work, we generalise this further to capture more classes of algorithms.

Making OptORAMa Maliciously Secure

Making OptORAMa Maliciously Secure

- In an ideal world:

Making OptORAMa Maliciously Secure

- In an ideal world:
    - **Time-stamp** whatever you can using MACs (with no overhead).

Making OptORAMa Maliciously Secure

- In an ideal world:
    - **Time-stamp** whatever you can using MACs (with no overhead).
    - Hope that everything else in **OptORAMa** is **offline-safe**.

Making OptORAMa Maliciously Secure

- In an ideal world:
    - **Time-stamp** whatever you can using MACs (with no overhead).
    - Hope that everything else in **OptORAMa** is **offline-safe**.
- Unfortunately, this isn’t true.

Making OptORAMa Maliciously Secure

- In an ideal world:
  - **Time-stamp** whatever you can using MACs (with no overhead).
  - Hope that everything else in **OptORAMa** is **offline-safe**.
- Unfortunately, this isn't true.
  - Oblivious hash table of **OptORAMa** is **not time-stampable** or **offline-safe**.

Our Construction

Our Construction

- How do we get around this?

Our Construction

- How do we get around this?
- We combine time-stamping and offline checking **within algorithms**!

Balls-in-Bins Hashing

Balls-in-Bins Hashing

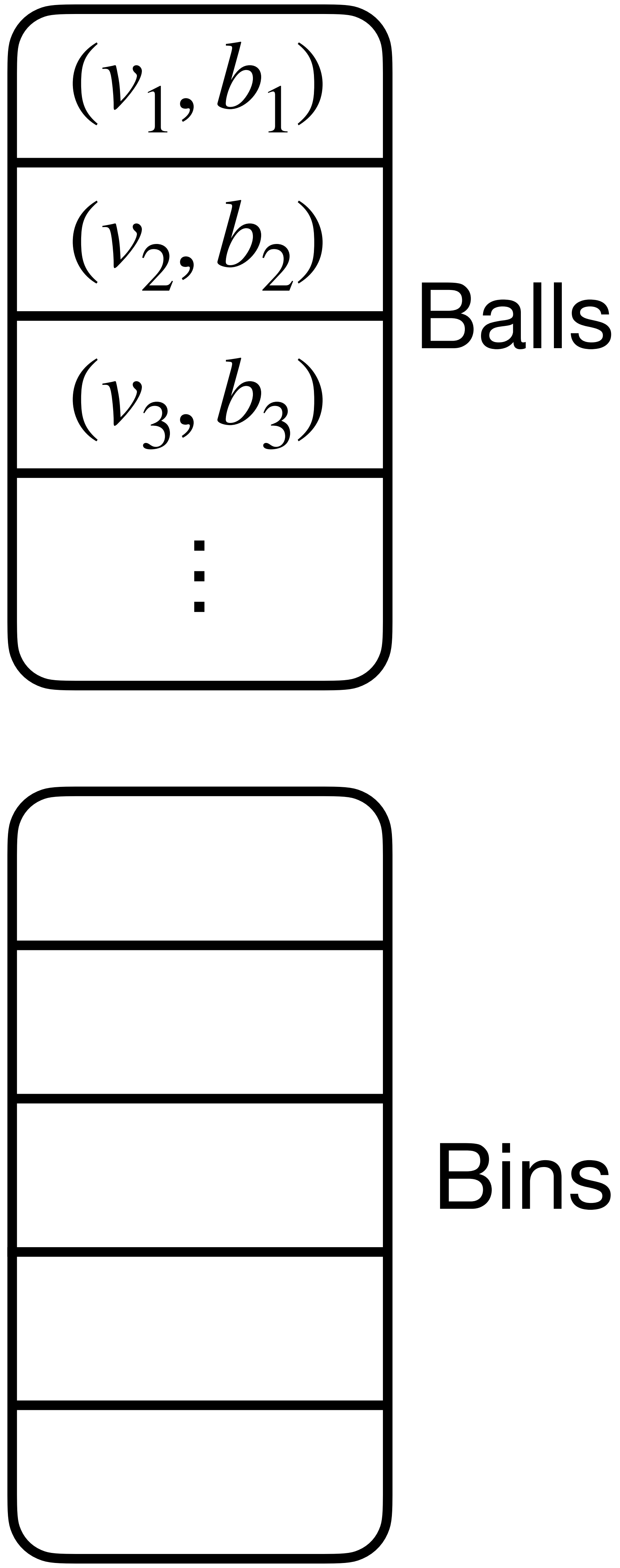
- **Example**: Hashing balls (values v_i) into bins (b_i).

Balls-in-Bins Hashing

- **Example**: Hashing balls (values v_i) into bins (b_i).
  - Used in building **OptORAMa** oblivious hash tables.

Balls-in-Bins Hashing

- **Example**: Hashing balls (values v_i) into bins (b_i).
  - Used in building **OptORAMa** oblivious hash tables.



(v_1, b_1)

(v_2, b_2)

(v_3, b_3)

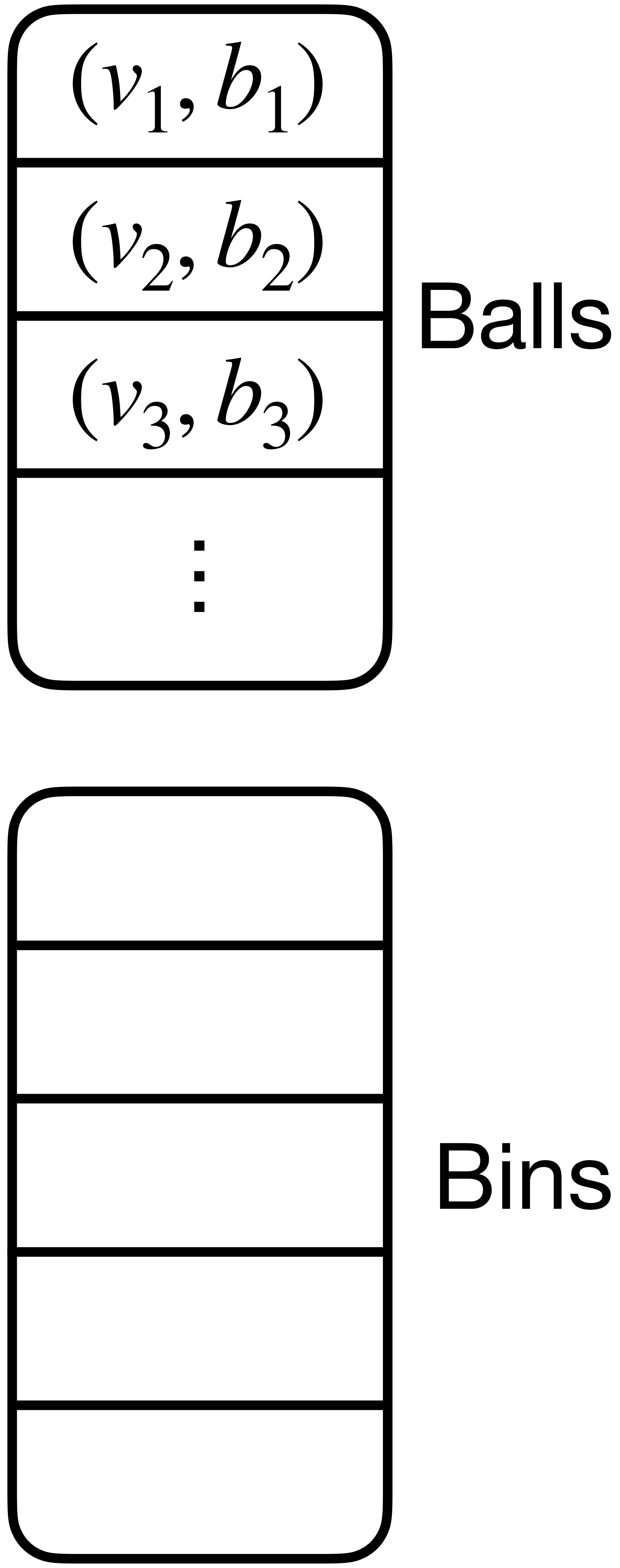
$\vdots$

Balls

Bins

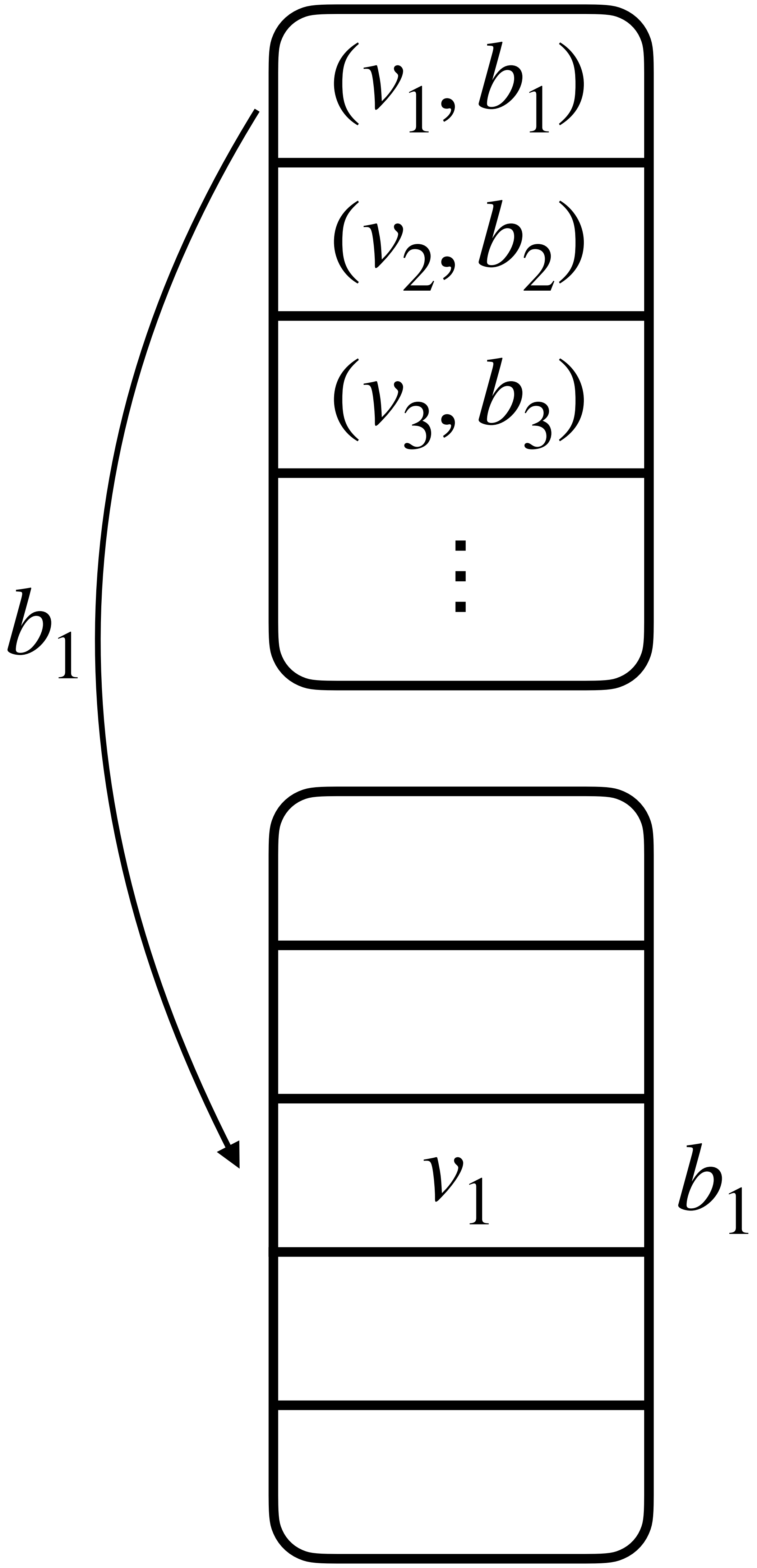
Balls-in-Bins Hashing

- **Example**: Hashing balls (values v_i) into bins (b_i).
    - Used in building **OptORAMa** oblivious hash tables.
- If b_i is safe to leak, access pattern is determined by $\{(v_i, b_i)\}$ array. Only b_i leaked.



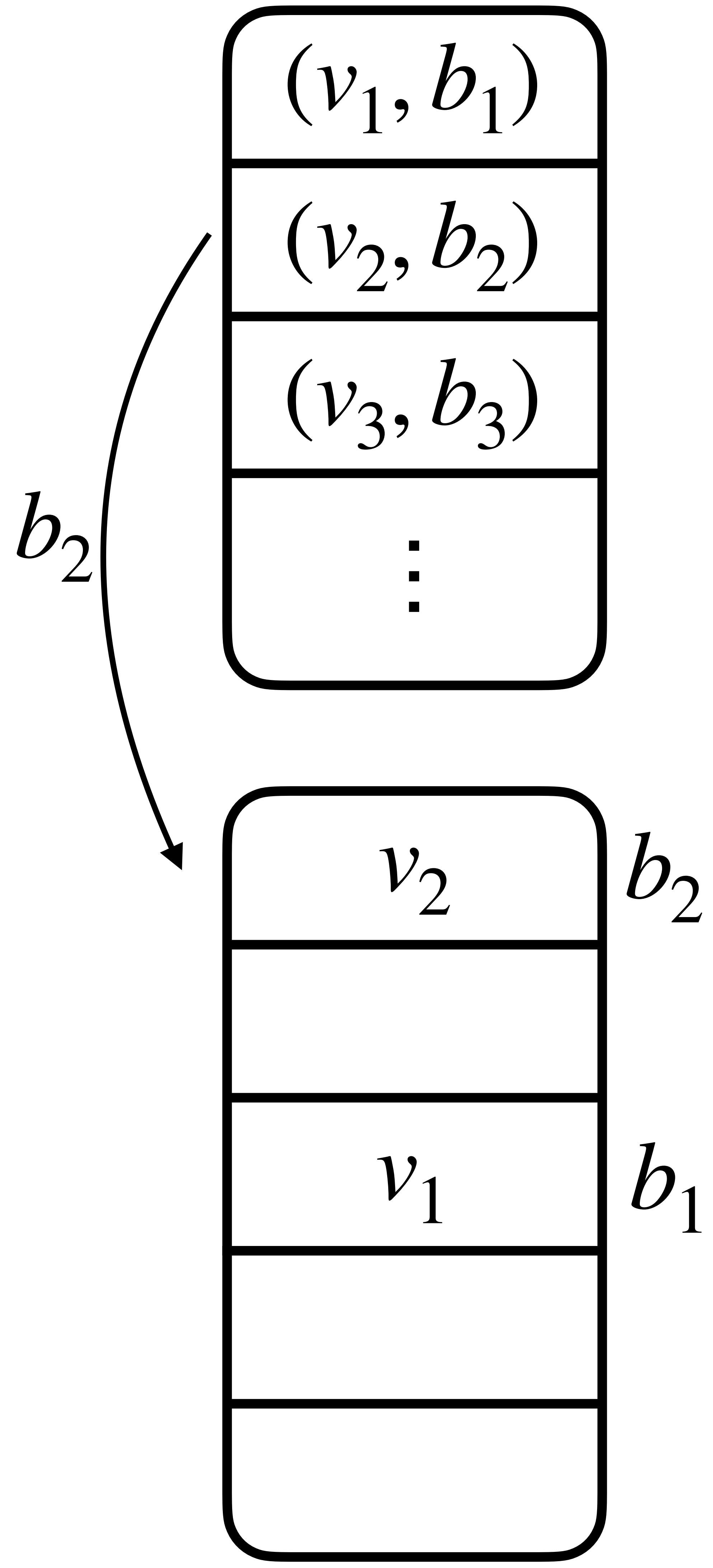
Balls-in-Bins Hashing

- **Example**: Hashing balls (values v_i) into bins (b_i).
    - Used in building **OptORAMa** oblivious hash tables.
- If b_i is safe to leak, access pattern is determined by $\{(v_i, b_i)\}$ array. Only b_i leaked.



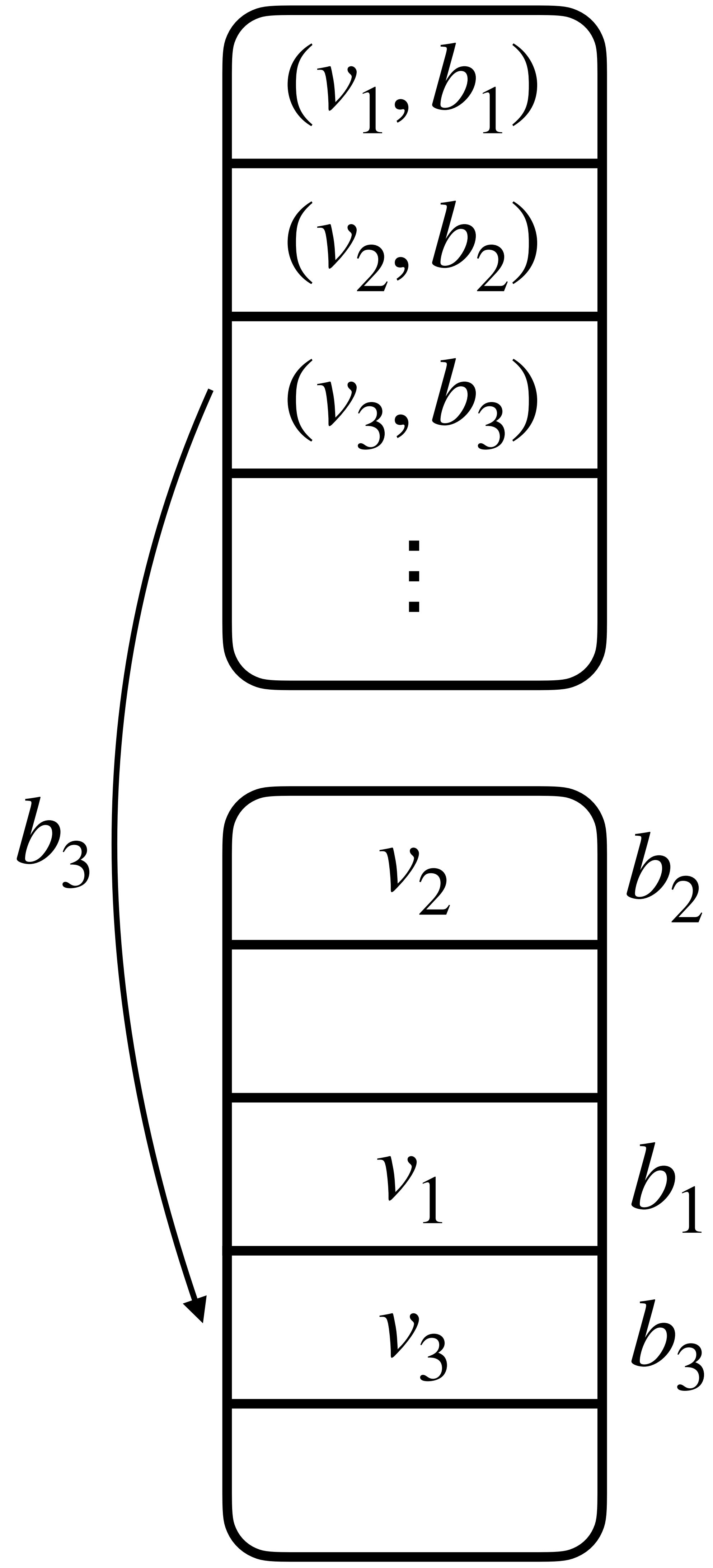
Balls-in-Bins Hashing

- **Example**: Hashing balls (values v_i) into bins (b_i).
  - Used in building **OptORAMa** oblivious hash tables.
- If b_i is safe to leak, access pattern is determined by $\{(v_i, b_i)\}$ array. Only b_i leaked.



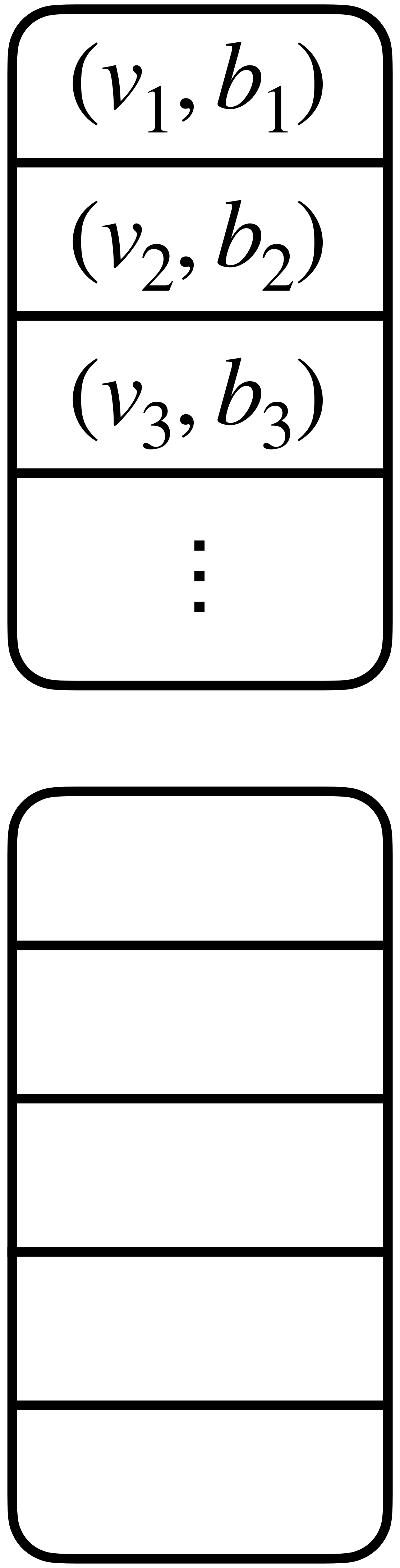
Balls-in-Bins Hashing

- **Example**: Hashing balls (values v_i) into bins (b_i).
  - Used in building **OptORAMa** oblivious hash tables.
- If b_i is safe to leak, access pattern is determined by $\{(v_i, b_i)\}$ array. Only b_i leaked.



Balls-in-Bins Hashing

- **Example**: Hashing balls (values v_i) into bins (b_i).
    - Used in building **OptORAMa** oblivious hash tables.
- If b_i is safe to leak, access pattern is determined by $\{(v_i, b_i)\}$ array. Only b_i leaked.
- If $\{(v_i, b_i)\}$ array is tampered to include ciphertext of **private** x_i**,** then access pattern leaks x_i! Not offline-safe!



(v_1, b_1)

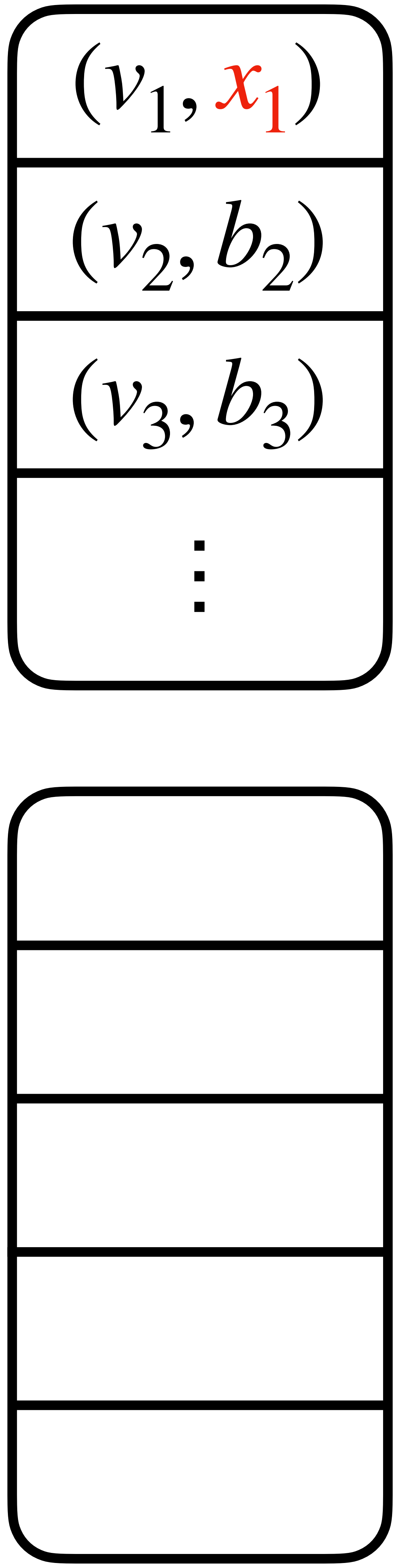
(v_2, b_2)

(v_3, b_3)

$\vdots$

Balls-in-Bins Hashing

- **Example**: Hashing balls (values v_i) into bins (b_i).
  - Used in building **OptORAMa** oblivious hash tables.
- If b_i is safe to leak, access pattern is determined by $\{(v_i, b_i)\}$ array. Only b_i leaked.
- If $\{(v_i, b_i)\}$ array is tampered to include ciphertext of **private x_i,** then access pattern leaks x_i! Not offline-safe!



(v_1, x_1)

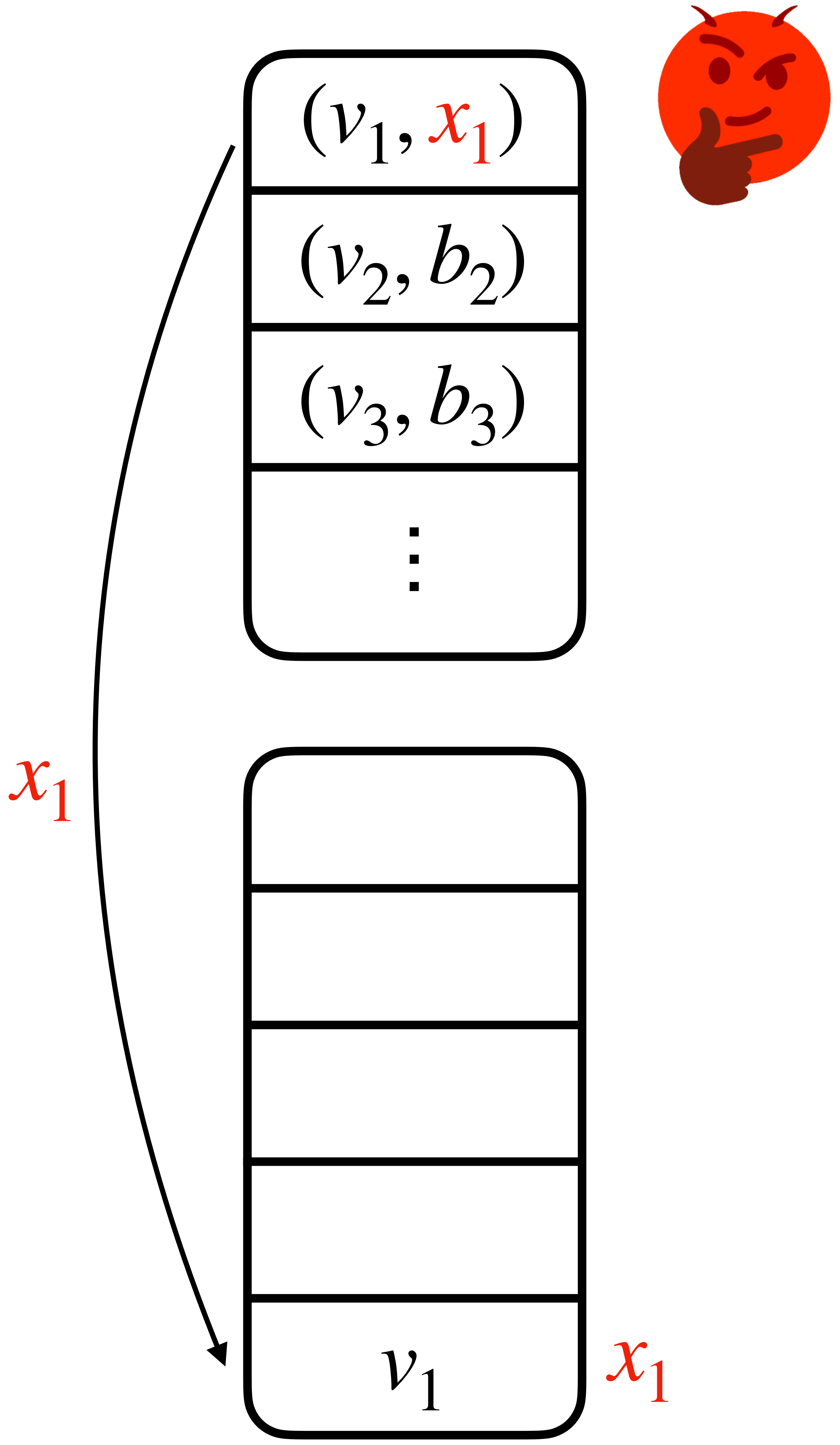
(v_2, b_2)

(v_3, b_3)

$\vdots$

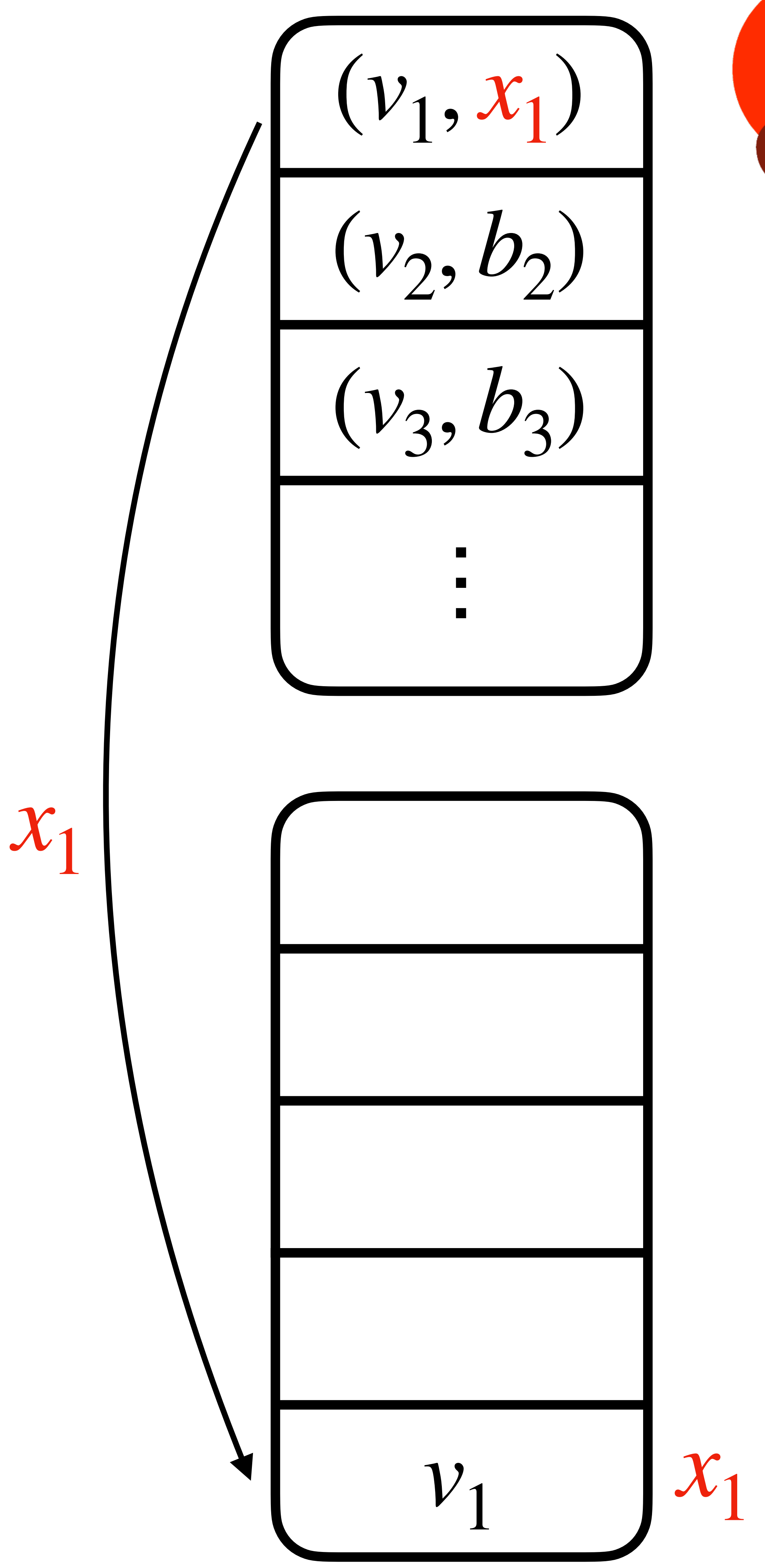
Balls-in-Bins Hashing

- **Example**: Hashing balls (values v_i) into bins (b_i).
  - Used in building **OptORAMa** oblivious hash tables.
- If b_i is safe to leak, access pattern is determined by $\{(v_i, b_i)\}$ array. Only b_i leaked.
- If $\{(v_i, b_i)\}$ array is tampered to include ciphertext of **private** x_i**,** then access pattern leaks x_i! Not offline-safe!

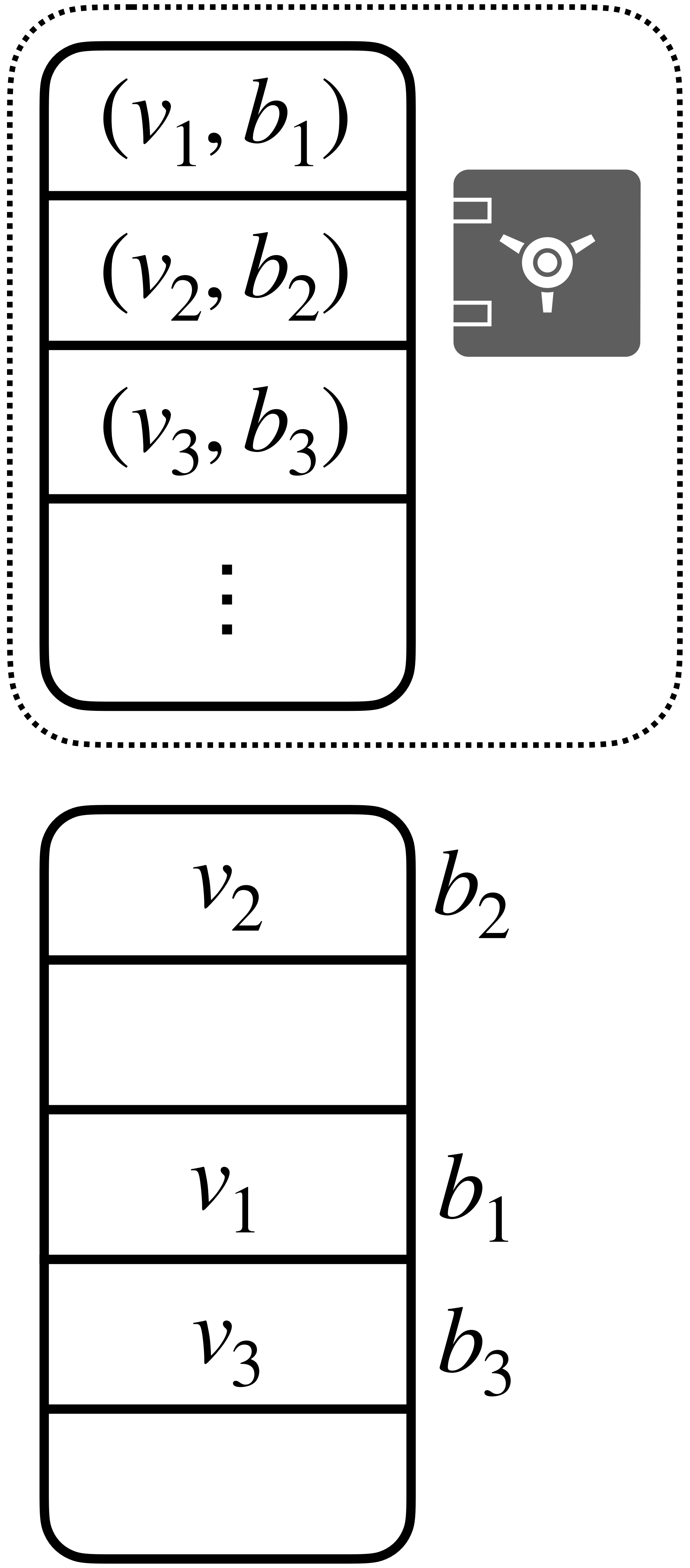


Balls-in-Bins Hashing

- **Example**: Hashing balls (values v_i) into bins (b_i).
  - Used in building **OptORAMa** oblivious hash tables.
- If b_i is safe to leak, access pattern is determined by $\{(v_i, b_i)\}$ array. Only b_i leaked.
- If $\{(v_i, b_i)\}$ array is tampered to include ciphertext of **private** x_i**,** then access pattern leaks x_i! Not offline-safe!
- But offline-safe if $\{(v_i, b_i)\}$ is not tampered with.

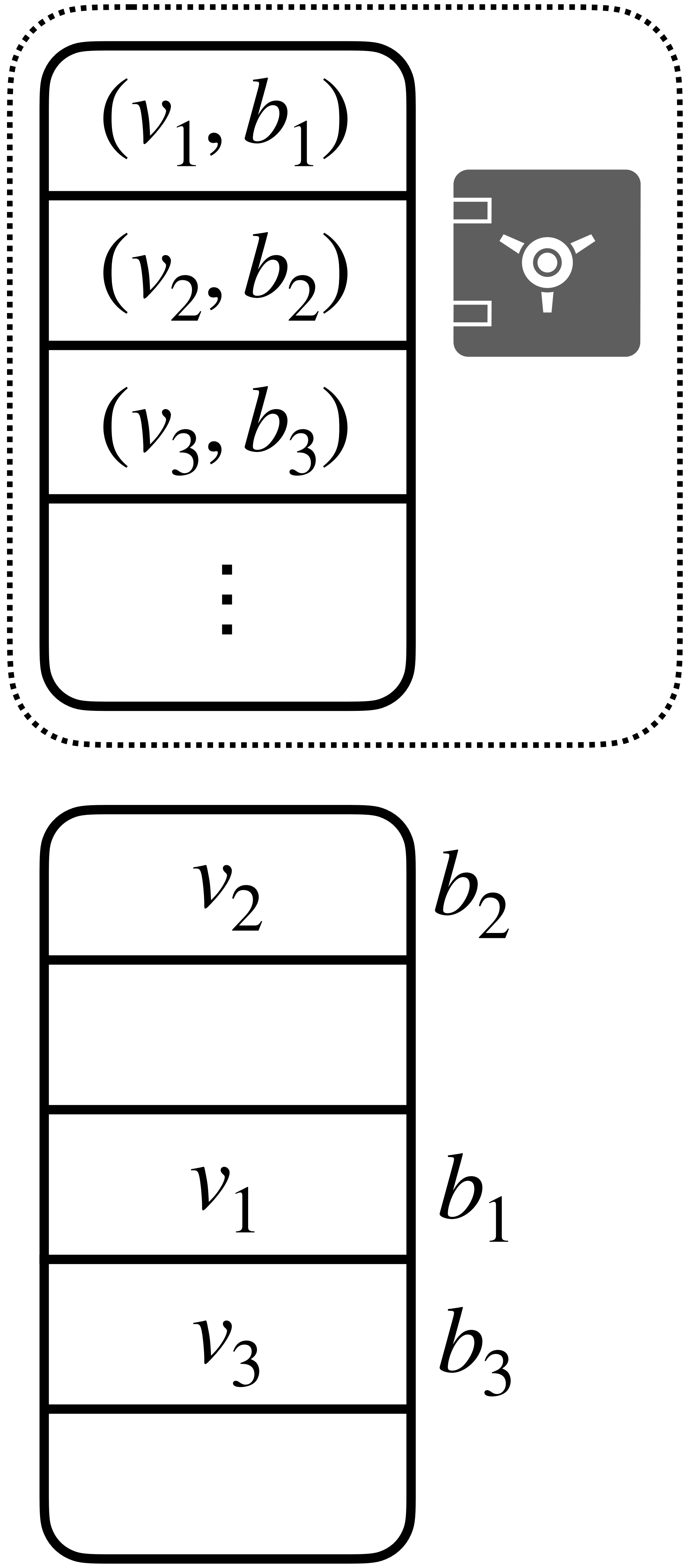


Combining Time-Stamping + Offline Checking



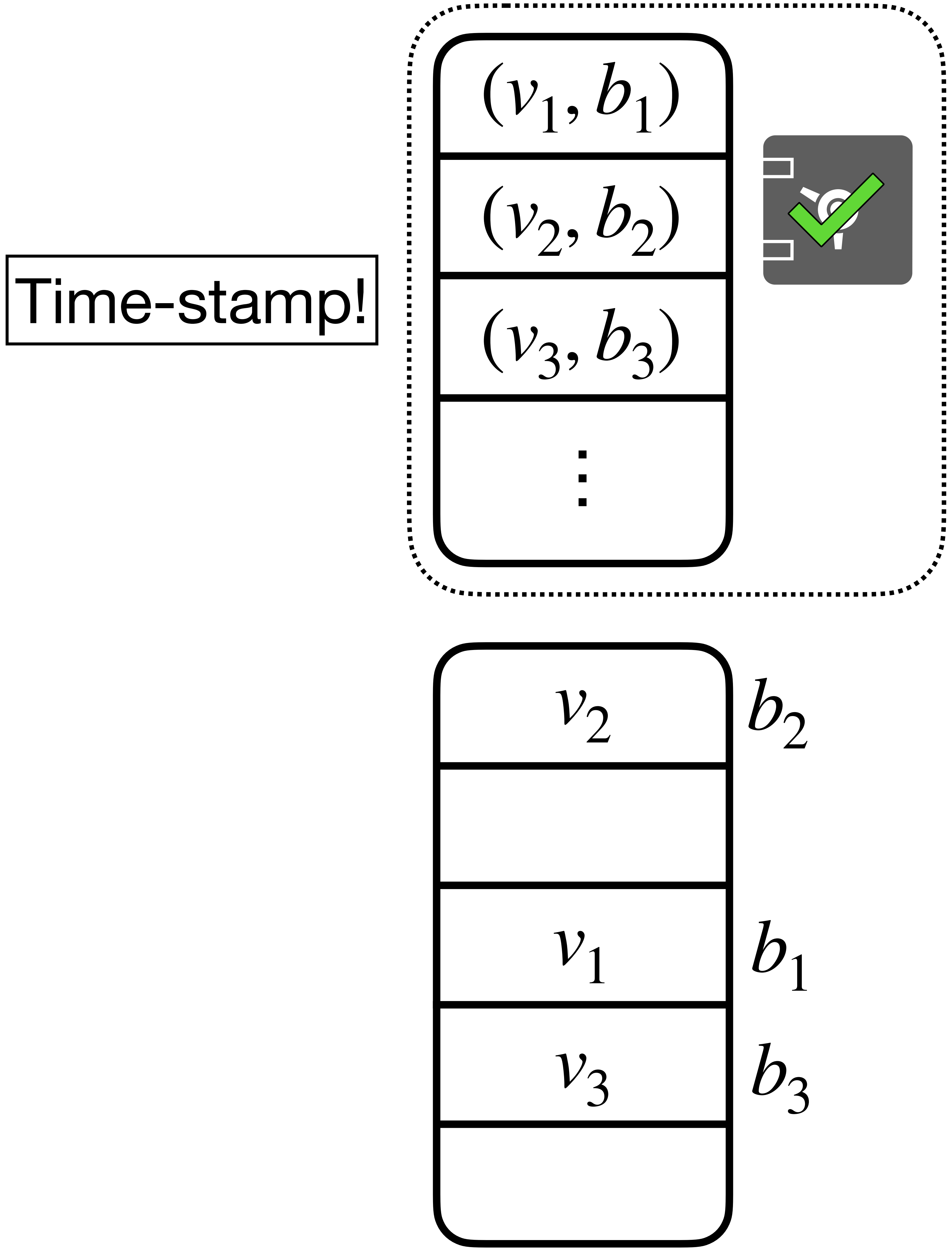
Combining Time-Stamping + Offline Checking

- **Key point**: If we can time-stamp $\{(v_i, b_i)\}$ array, the adversary can no longer tamper with it!



Combining Time-Stamping + Offline Checking

- **Key point**: If we can time-stamp $\{(v_i, b_i)\}$ array, the adversary can no longer tamper with it!



Time-stamp!

(v_1, b_1)

(v_2, b_2)

(v_3, b_3)

$\vdots$

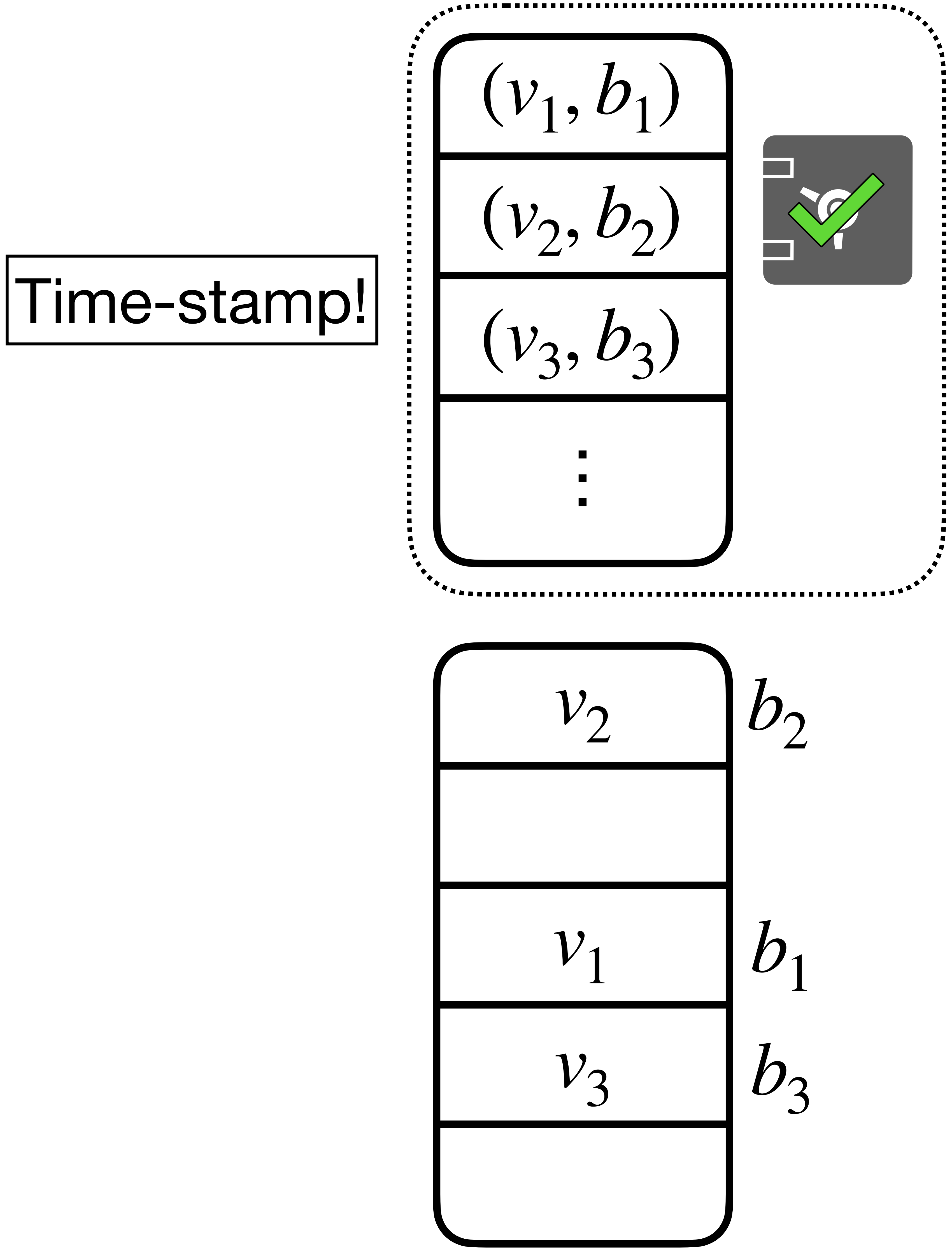
v_2 b_2

v_1 b_1

v_3 b_3

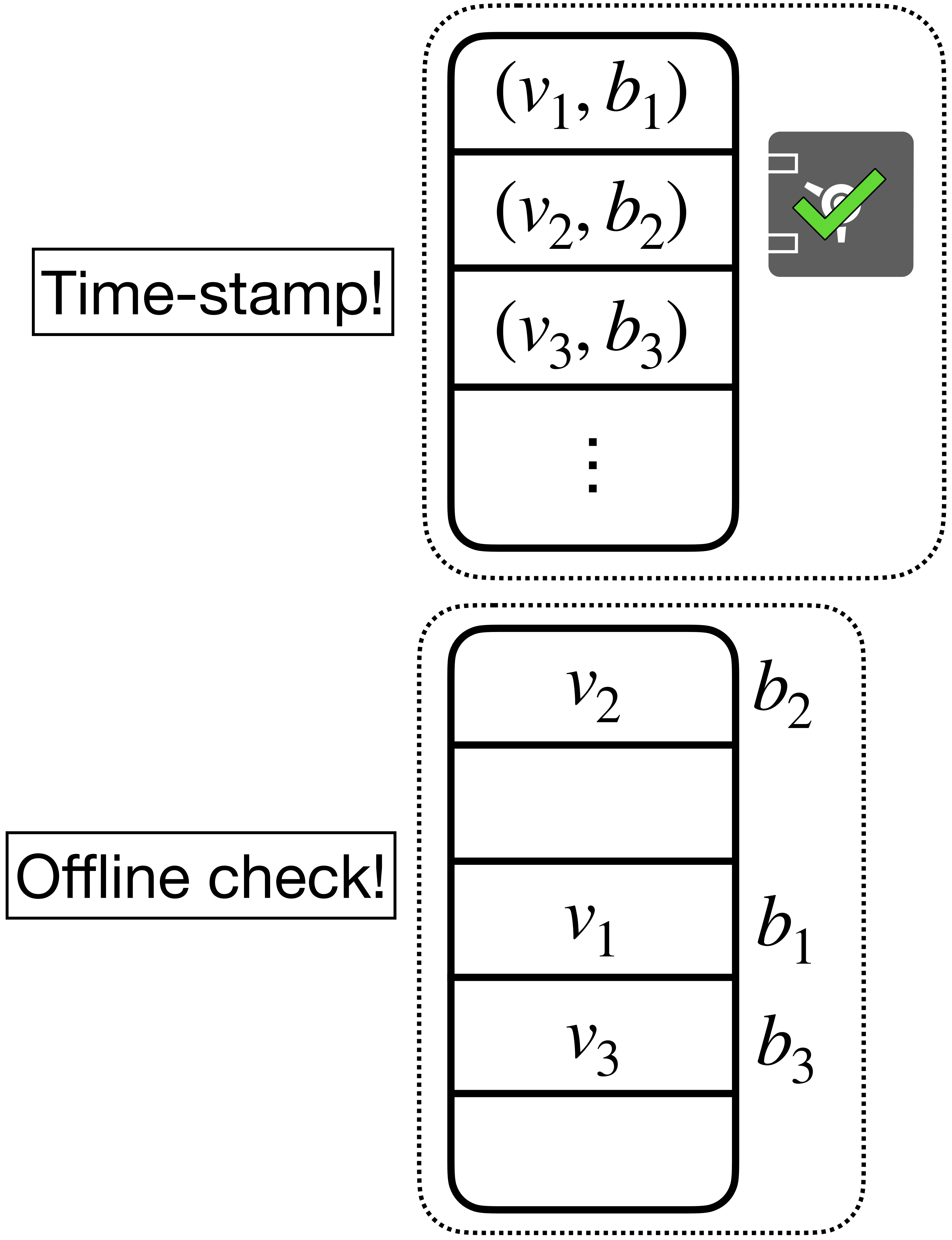
Combining Time-Stamping + Offline Checking

- **Key point**: If we can time-stamp $\{(v_i, b_i)\}$ array, the adversary can no longer tamper with it!
- Now, the hashing algorithm is offline-safe.



Combining Time-Stamping + Offline Checking

- **Key point**: If we can time-stamp $\{(v_i, b_i)\}$ array, the adversary can no longer tamper with it!
- Now, the hashing algorithm is offline-safe.



Time-stamp!

(v_1, b_1)

(v_2, b_2)

(v_3, b_3)

$\vdots$

Offline check!

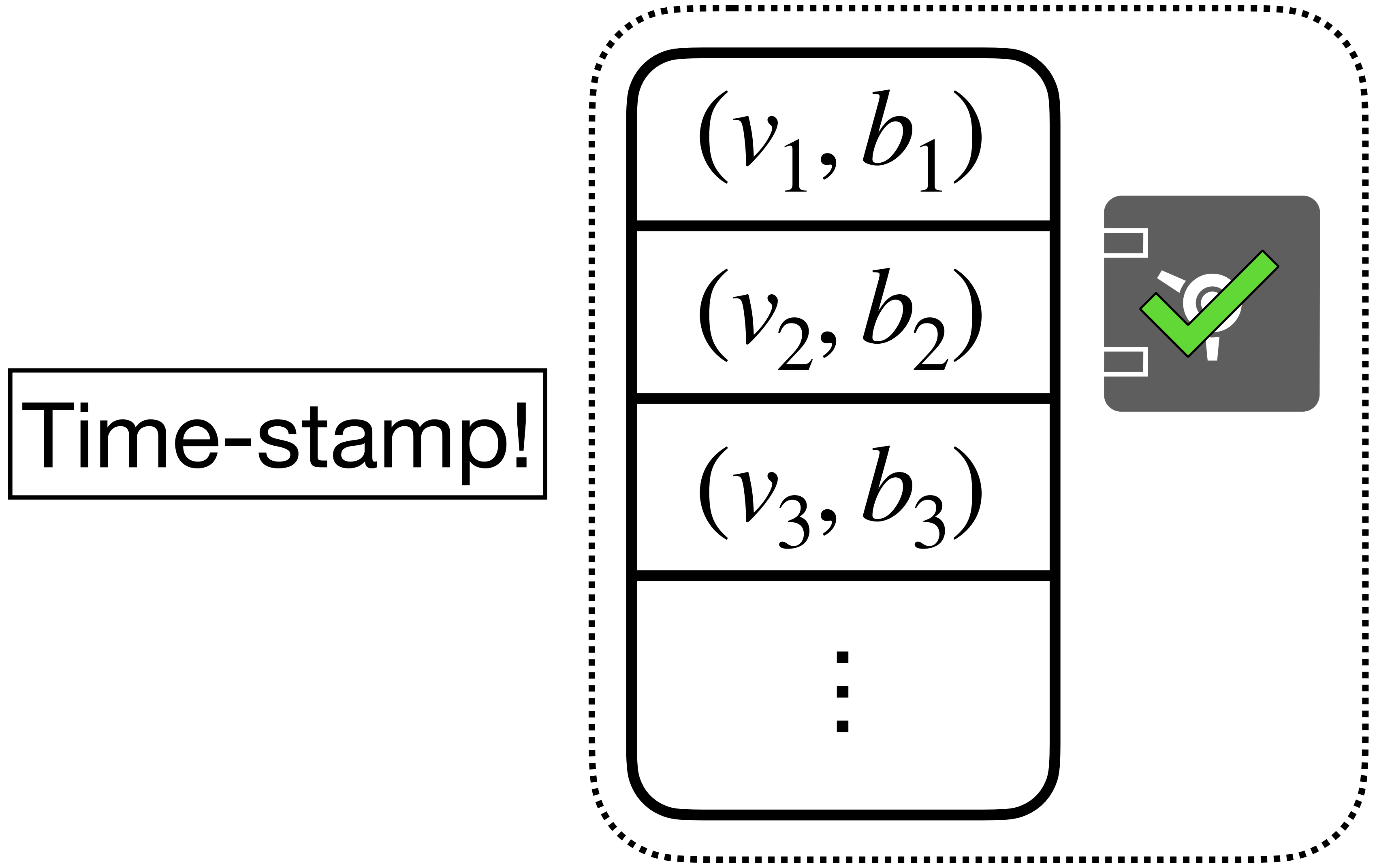
v_2 b_2

v_1 b_1

v_3 b_3

Combining Time-Stamping + Offline Checking

- **Key point**: If we can time-stamp $\{(v_i, b_i)\}$ array, the adversary can no longer tamper with it!
- Now, the hashing algorithm is offline-safe.
- **Summary**:



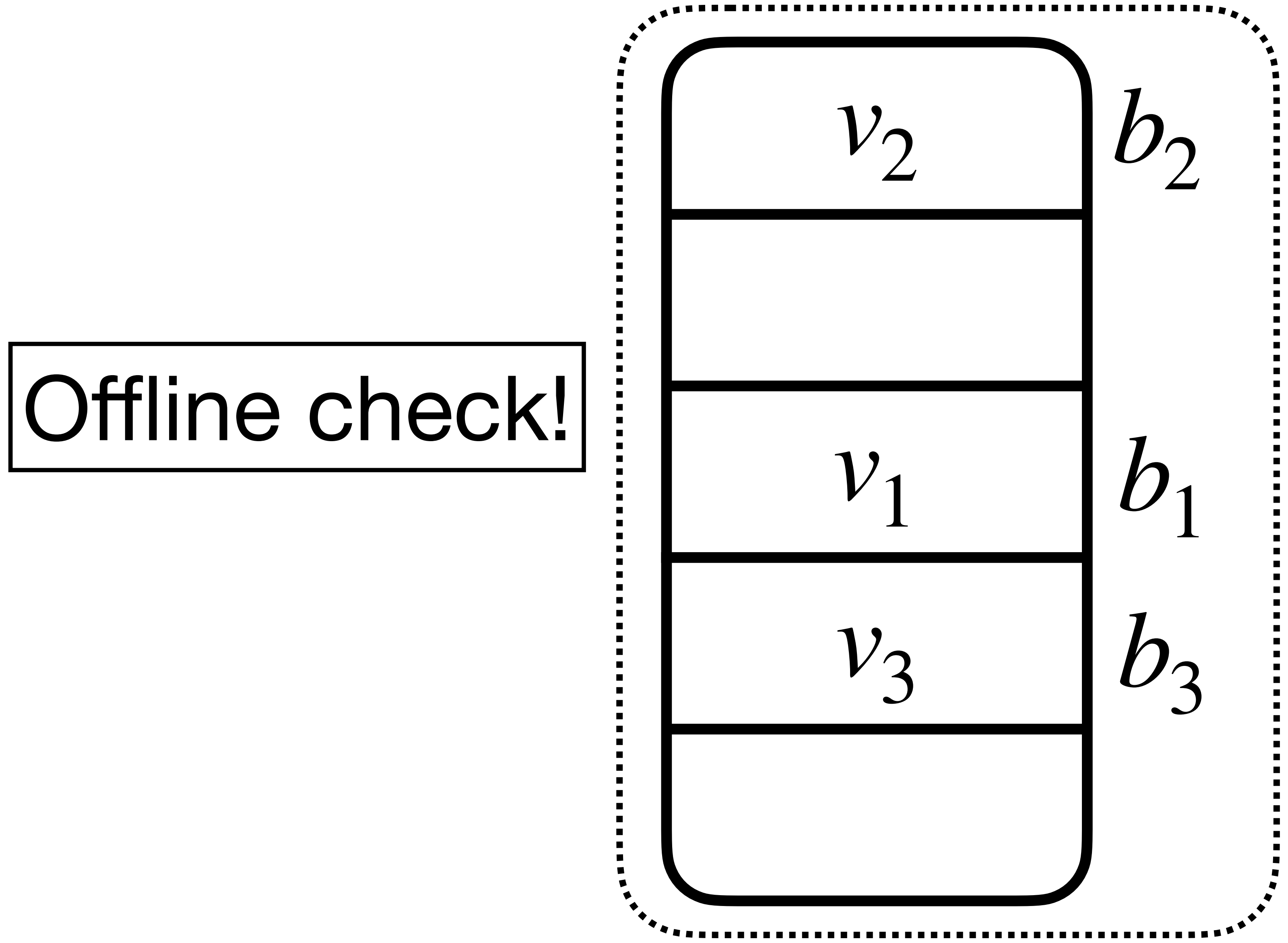
Time-stamp!

(v_1, b_1)

(v_2, b_2)

(v_3, b_3)

$\vdots$



Offline check!

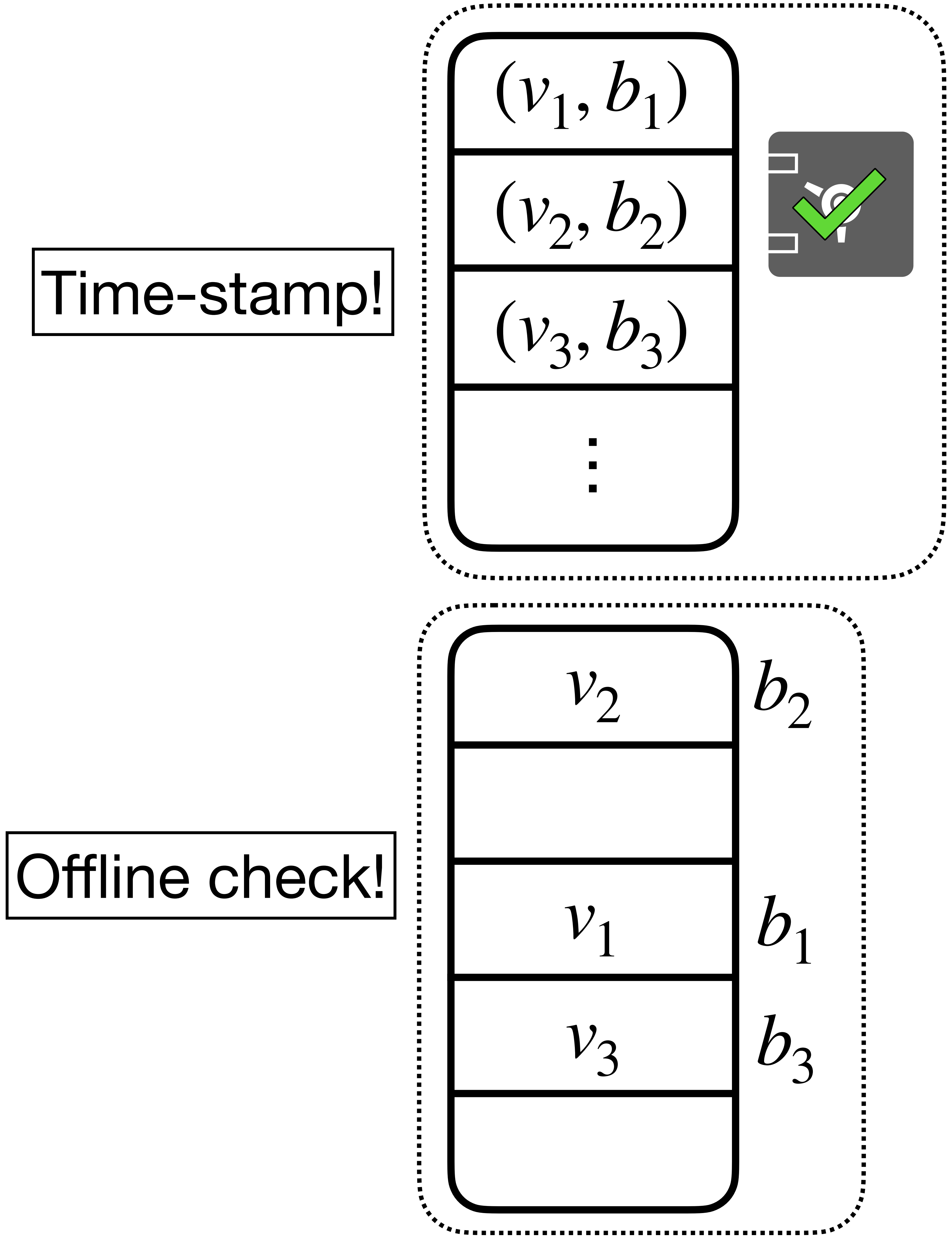
v_2 b_2

v_1 b_1

v_3 b_3

Combining Time-Stamping + Offline Checking

- **Key point**: If we can time-stamp $\{(v_i, b_i)\}$ array, the adversary can no longer tamper with it!
- Now, the hashing algorithm is offline-safe.
- **Summary**:
    - **Time-stamp** the part that needs to be tamper-proof (e.g., $\{(v_i, b_i)\}$ array).



Time-stamp!

(v_1, b_1)

(v_2, b_2)

(v_3, b_3)

$\vdots$

Offline check!

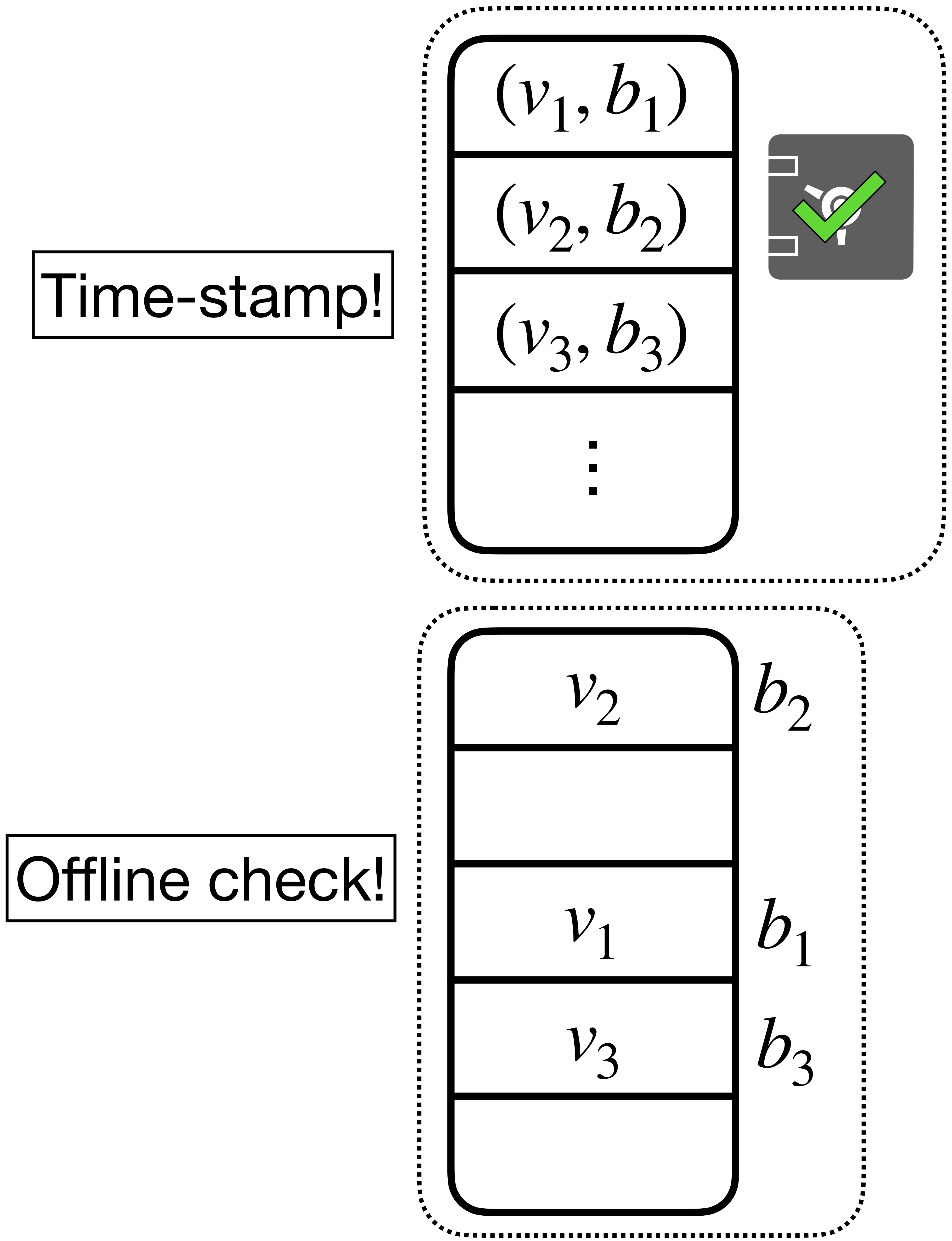
v_2 b_2

v_1 b_1

v_3 b_3

Combining Time-Stamping + Offline Checking

- **Key point**: If we can time-stamp $\{(v_i, b_i)\}$ array, the adversary can no longer tamper with it!
- Now, the hashing algorithm is offline-safe.
- **Summary**:
    - **Time-stamp** the part that needs to be tamper-proof (e.g., $\{(v_i, b_i)\}$ array).
    - **Offline check** the rest.



Time-stamp!

(v_1, b_1)

(v_2, b_2)

(v_3, b_3)

$\vdots$

Offline check!

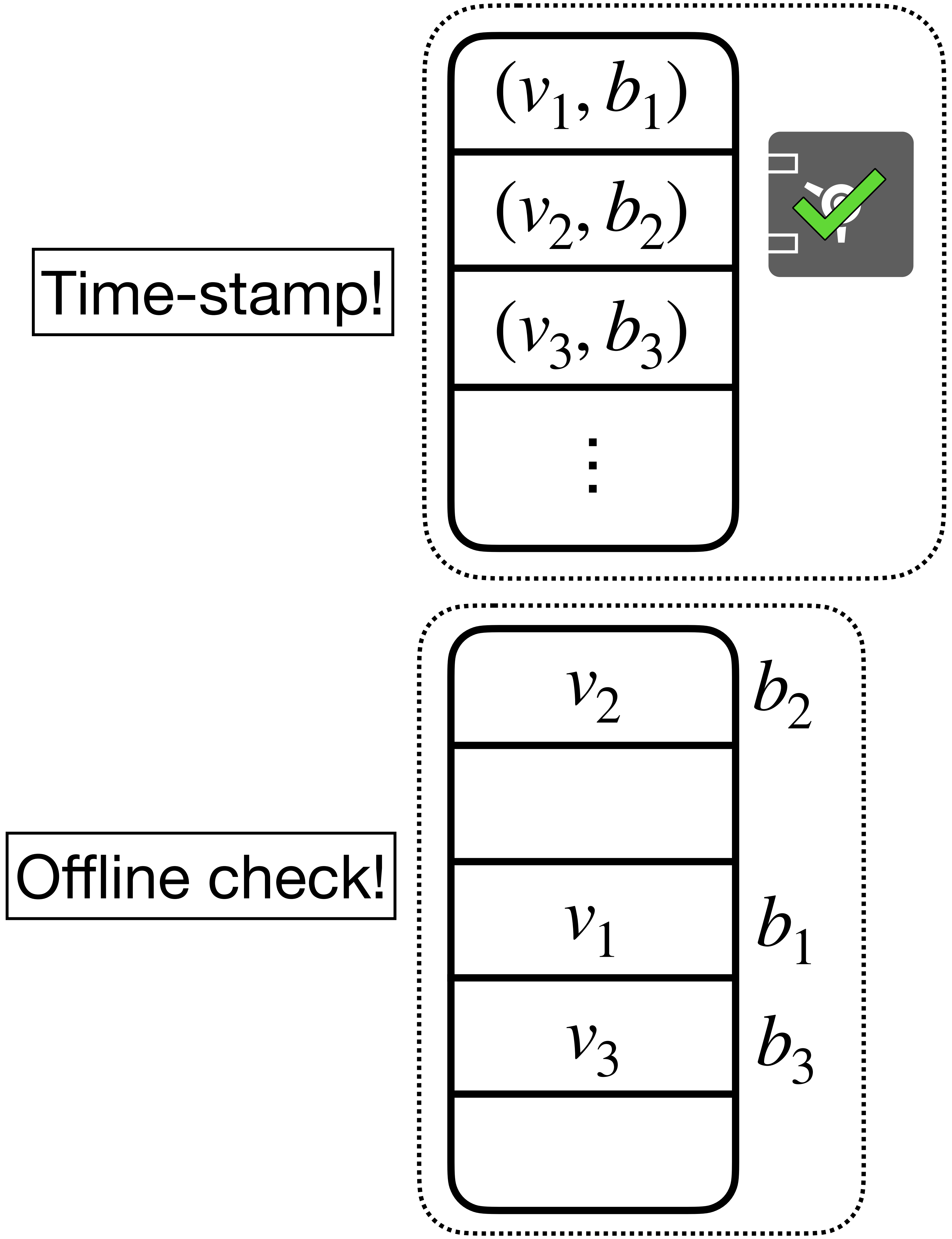
v_2 b_2

v_1 b_1

v_3 b_3

Combining Time-Stamping + Offline Checking

- **Key point**: If we can time-stamp $\{(v_i, b_i)\}$ array, the adversary can no longer tamper with it!
- Now, the hashing algorithm is offline-safe.
- **Summary**:
    - **Time-stamp** the part that needs to be tamper-proof (e.g., $\{(v_i, b_i)\}$ array).
    - **Offline check** the rest.
    - Converts **honest-but-curious** to **malicious** security!



Time-stamp!

(v_1, b_1)

(v_2, b_2)

(v_3, b_3)

$\vdots$

Offline check!

v_2 b_2

v_1 b_1

v_3 b_3

Summary & Conclusion

Summary & Conclusion

- We construct **MacORAMa**, a **maliciously** secure ORAM with **optimal** $O(\log N)$ overhead and $O(1)$ local space.

Summary & Conclusion

- We construct **MacORAMa**, a **maliciously** secure ORAM with **optimal** $O(\log N)$ overhead and $O(1)$ local space.
  - **Another interpretation**: First *oblivious* memory checker with $O(\log N)$ overhead, matching best *non-oblivious* memory checker overhead.

Summary & Conclusion

- We construct **MacORAMa**, a **maliciously** secure ORAM with **optimal** $O(\log N)$ overhead and $O(1)$ local space.
  - **Another interpretation**: First *oblivious* memory checker with $O(\log N)$ overhead, matching best *non-oblivious* memory checker overhead.
  - Assumptions are **provably minimal** (OWF necessary and sufficient).

Summary & Conclusion

- We construct **MacORAMa**, a **maliciously** secure ORAM with **optimal** $O(\log N)$ overhead and $O(1)$ local space.
  - **Another interpretation**: First *oblivious* memory checker with $O(\log N)$ overhead, matching best *non-oblivious* memory checker overhead.
  - Assumptions are **provably minimal** (OWF necessary and sufficient).
- An overhead-preserving compiler from honest-but-curious to malicious security has a barrier.

Summary & Conclusion

- We construct **MacORAMa**, a **maliciously** secure ORAM with **optimal** $O(\log N)$ overhead and $O(1)$ local space.
  - **Another interpretation**: First *oblivious* memory checker with $O(\log N)$ overhead, matching best *non-oblivious* memory checker overhead.
  - Assumptions are **provably minimal** (OWF necessary and sufficient).
- An overhead-preserving compiler from honest-but-curious to malicious security has a barrier.
- Instead, we develop **memory checking** techniques in the ORAM setting that should generalize to future constructions.

Open Questions

Open Questions

- Any maliciously secure ORAM with $O(\log N)$ overhead with better constant factors? **OptORAMa** has large constant factors.

Open Questions

- Any maliciously secure ORAM with $O(\log N)$ overhead with better constant factors? **OptORAMa** has large constant factors.
- Any memory checker with $O(1)$ overhead? Any lower bounds? (Best constructions have $O(\log N)$ overhead.)

Thank you!

Bonus Slides

Ideal Malicious Security

Ideal Malicious Security

- What guarantee do we want?

Ideal Malicious Security

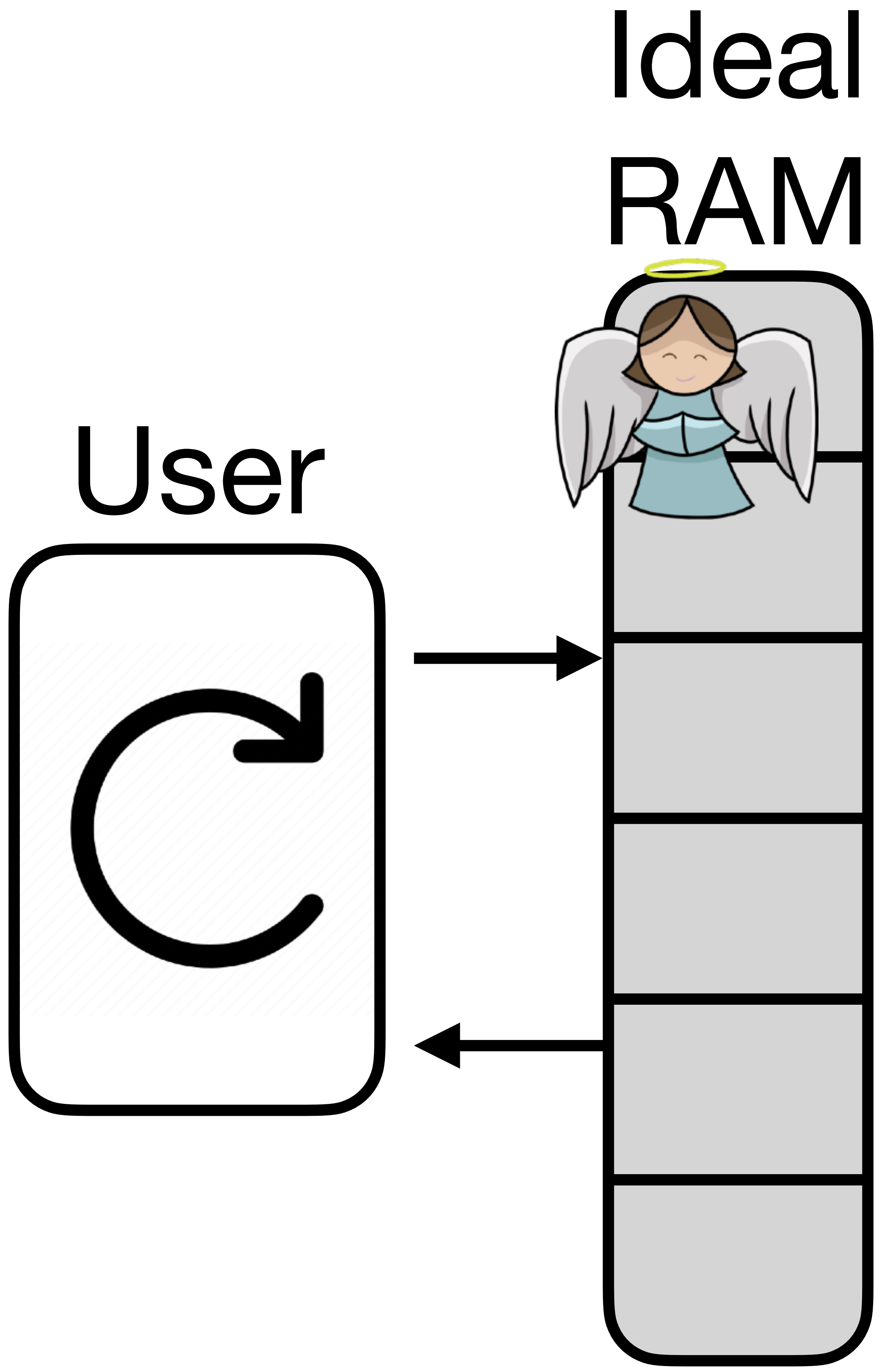
- What guarantee do we want?

  1. **Correctness**: If no abort, user should never get incorrect responses from ORAM, even if server tampers.

Ideal Malicious Security

- What guarantee do we want?

  1. **Correctness**: If no abort, user should never get incorrect responses from ORAM, even if server tampers.

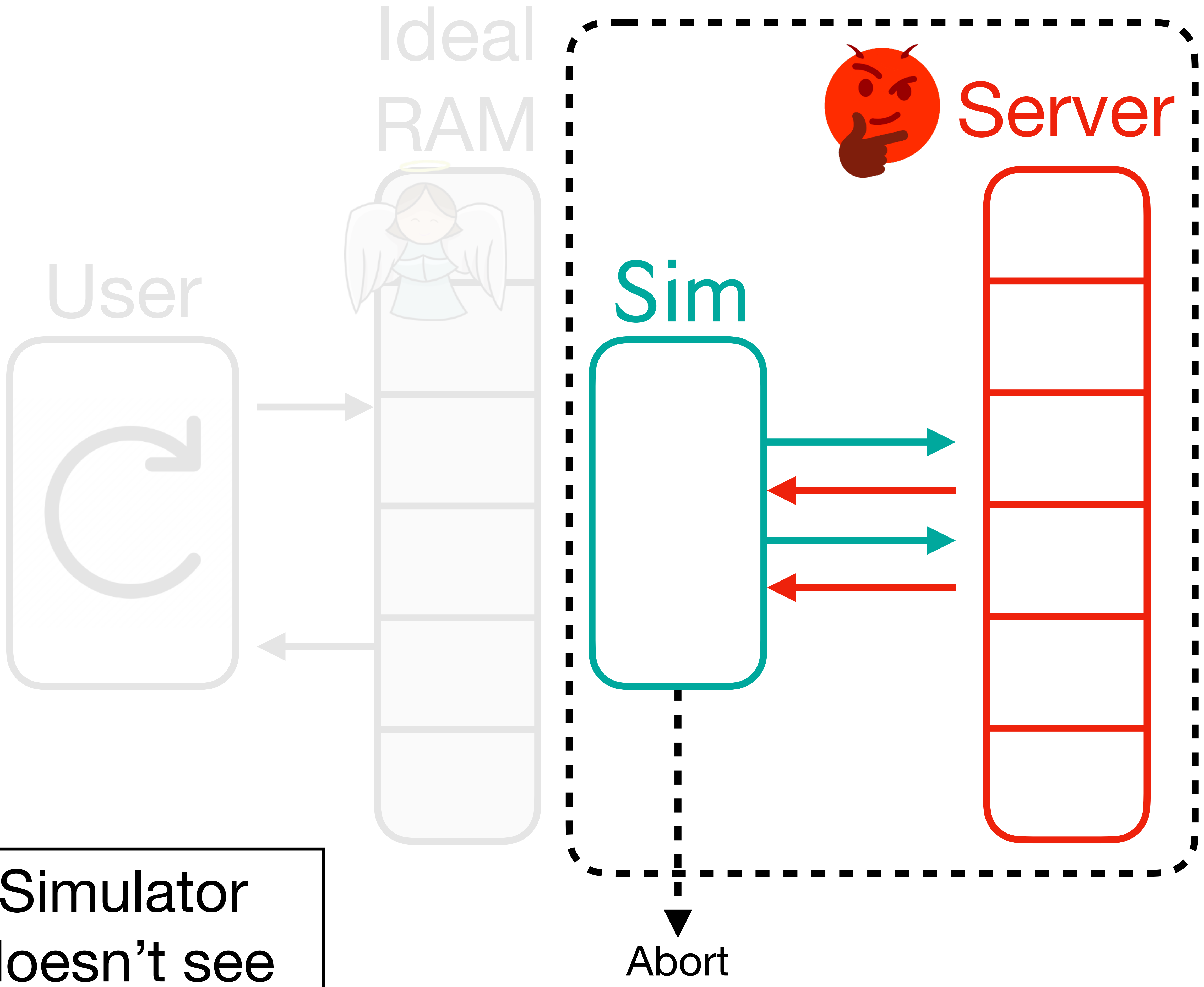


Ideal Malicious Security

- What guarantee do we want?

  1. **Correctness**: If no abort, user should never get incorrect responses from ORAM, even if server tampers.

  2. **Obliviousness**: Server shouldn't be able to learn ***anything, even by tampering***. Server should **only** be able to:



Simulator doesn't see user queries!

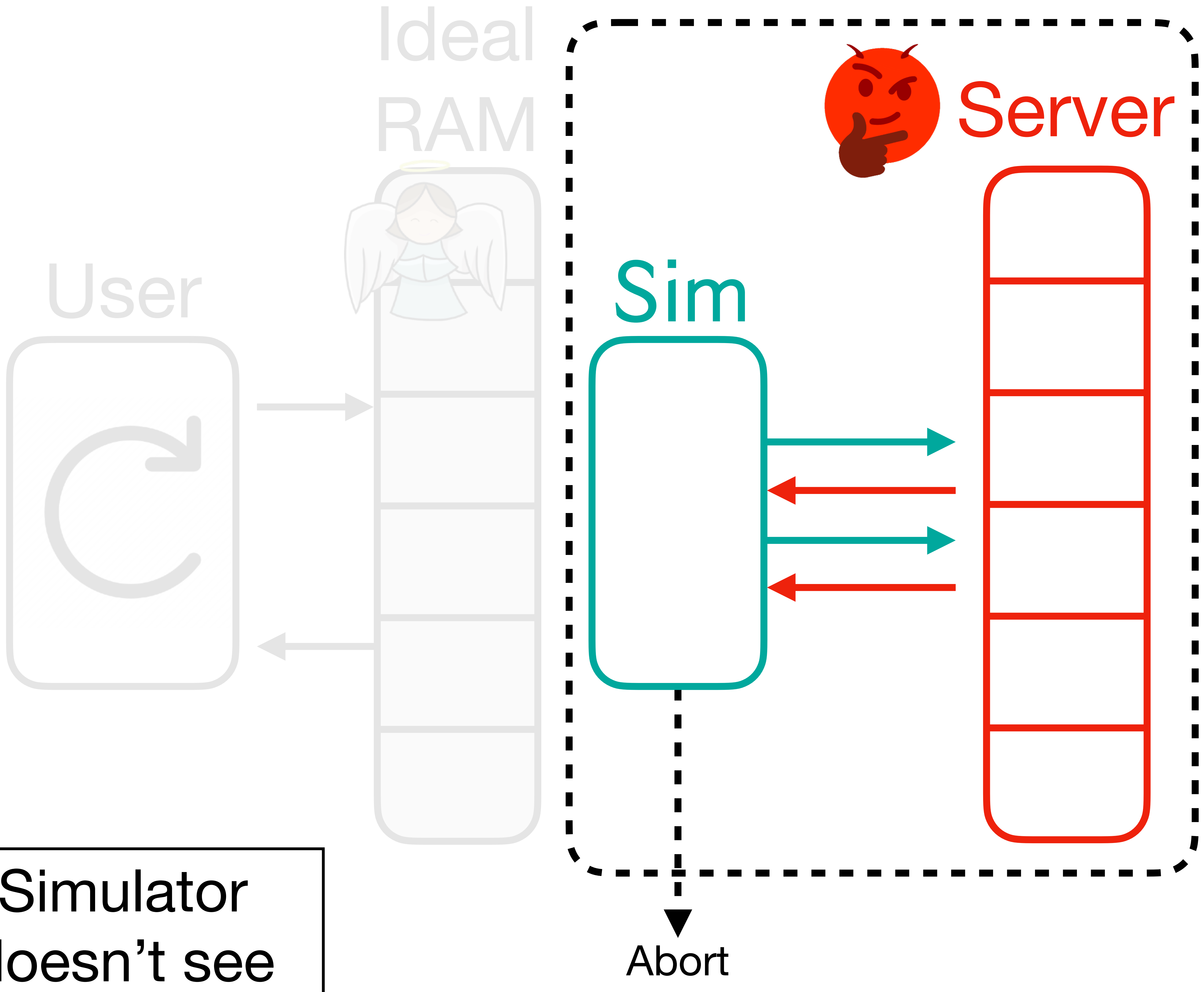
Ideal Malicious Security

- What guarantee do we want?

  1. **Correctness**: If no abort, user should never get incorrect responses from ORAM, even if server tampers.

  2. **Obliviousness**: Server shouldn't be able to learn ***anything, even by tampering***. Server should **only** be able to:

     A. Learn number of queries.



Simulator doesn't see user queries!

Ideal Malicious Security

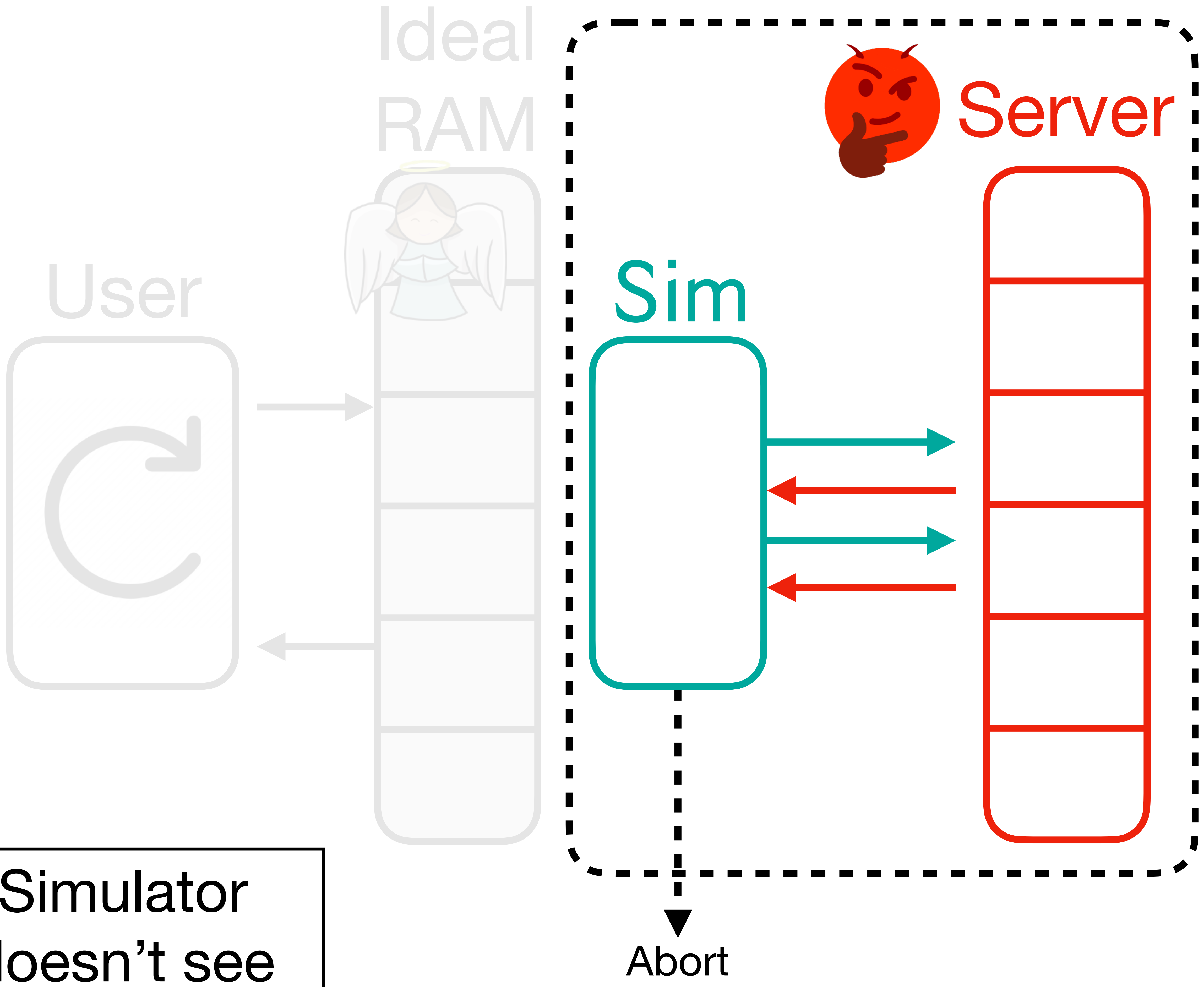
- What guarantee do we want?

1. **Correctness**: If no abort, user should never get incorrect responses from ORAM, even if server tampers.

2. **Obliviousness**: Server shouldn't be able to learn ***anything, even by tampering***. Server should **only** be able to:

    A. Learn number of queries.

    B. Decide whether to abort.



Simulator doesn't see user queries!

Ideal Malicious Security

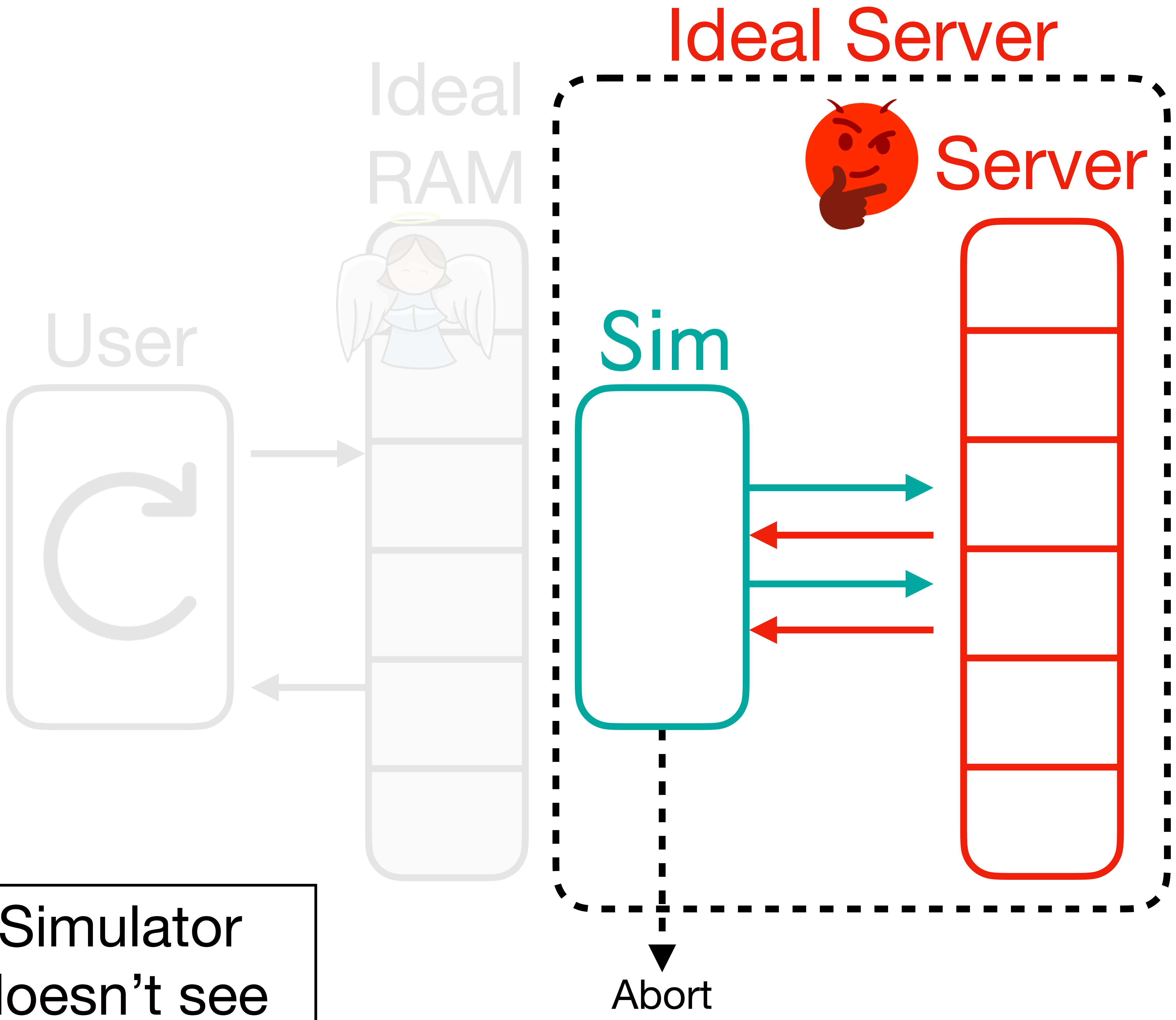
- What guarantee do we want?

  1. **Correctness**: If no abort, user should never get incorrect responses from ORAM, even if server tampers.

  2. **Obliviousness**: Server shouldn't be able to learn ***anything, even by tampering***. Server should **only** be able to:

     A. Learn number of queries.

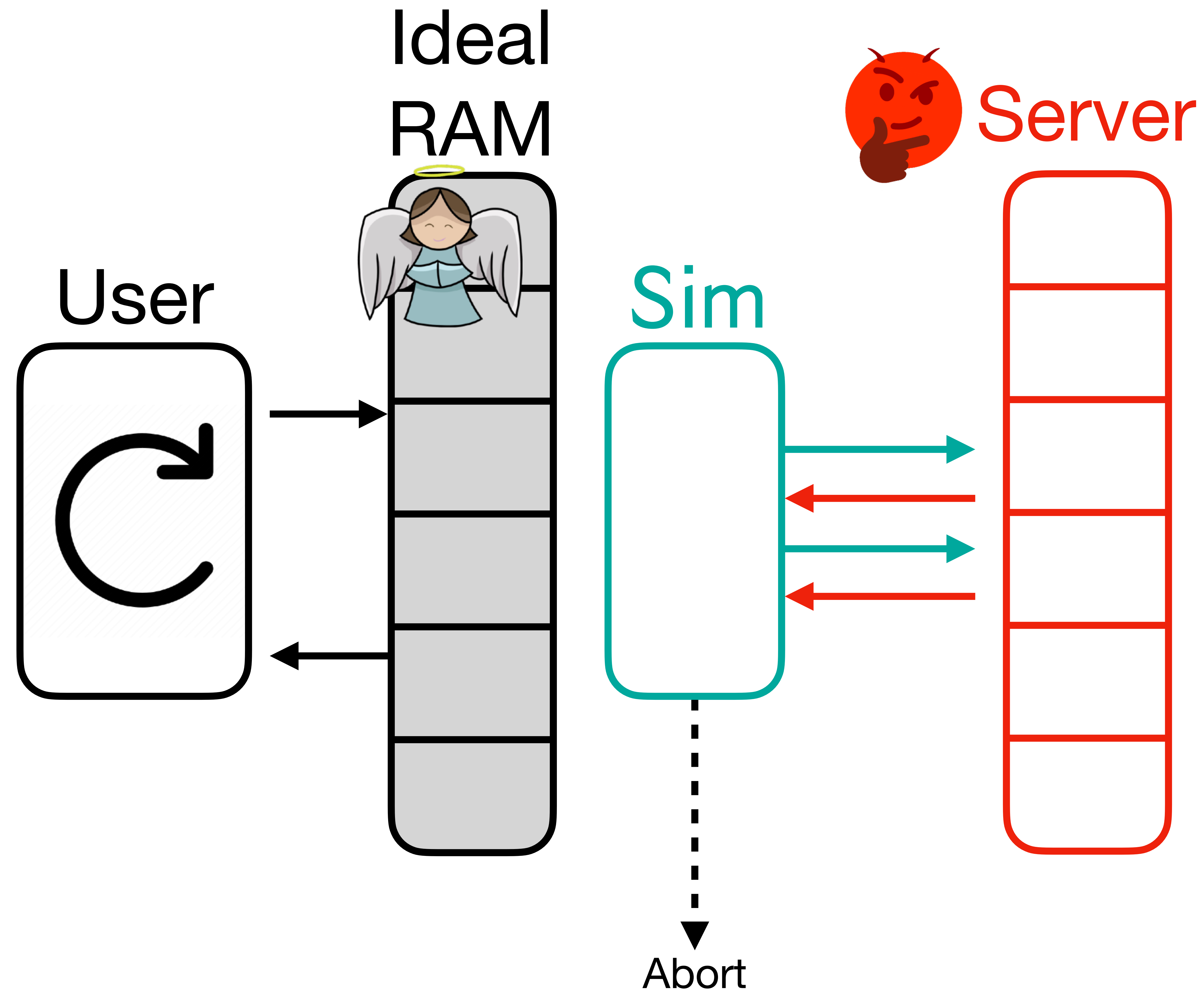
     B. Decide whether to abort.



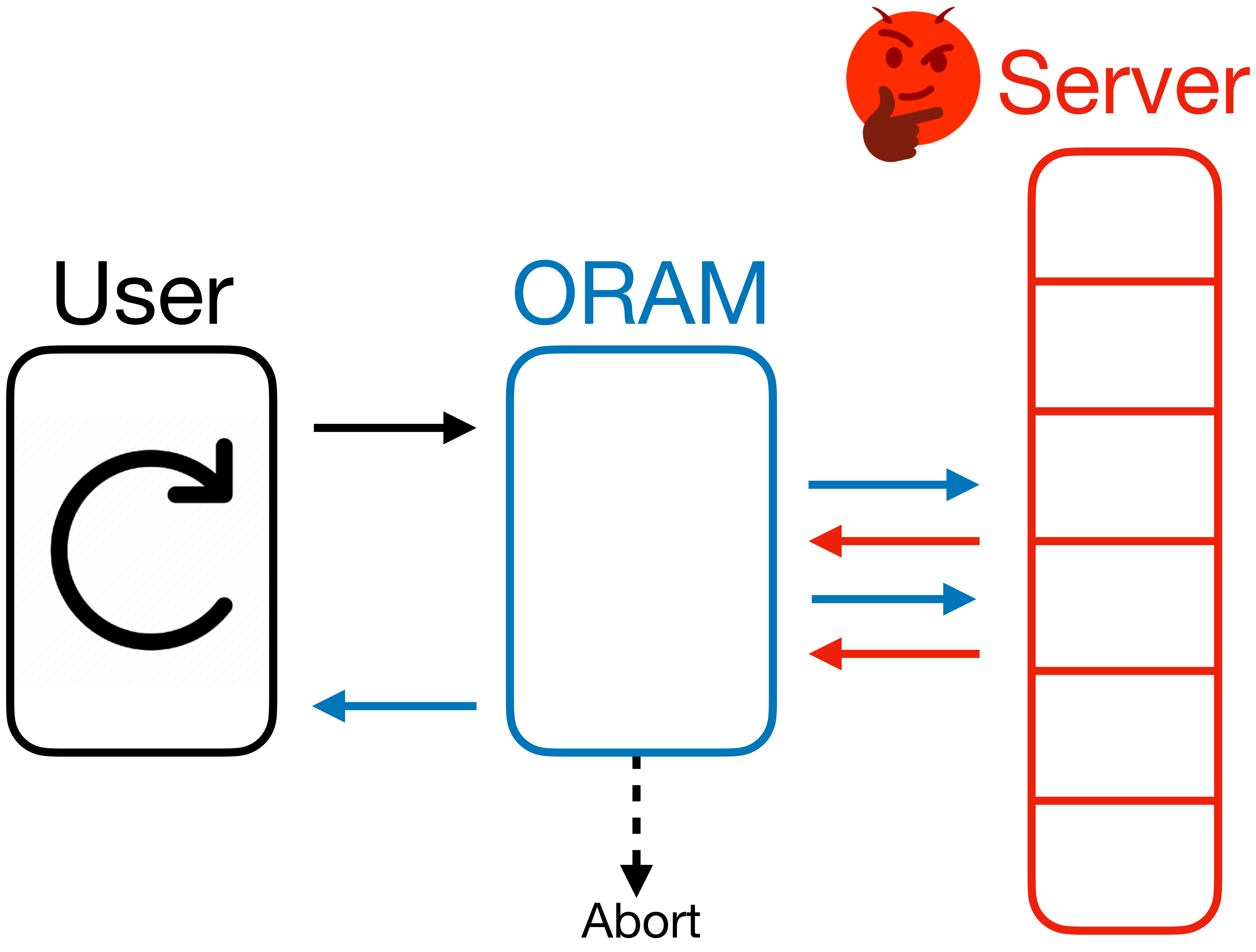
Simulator doesn't see user queries!

Real

Ideal



Real



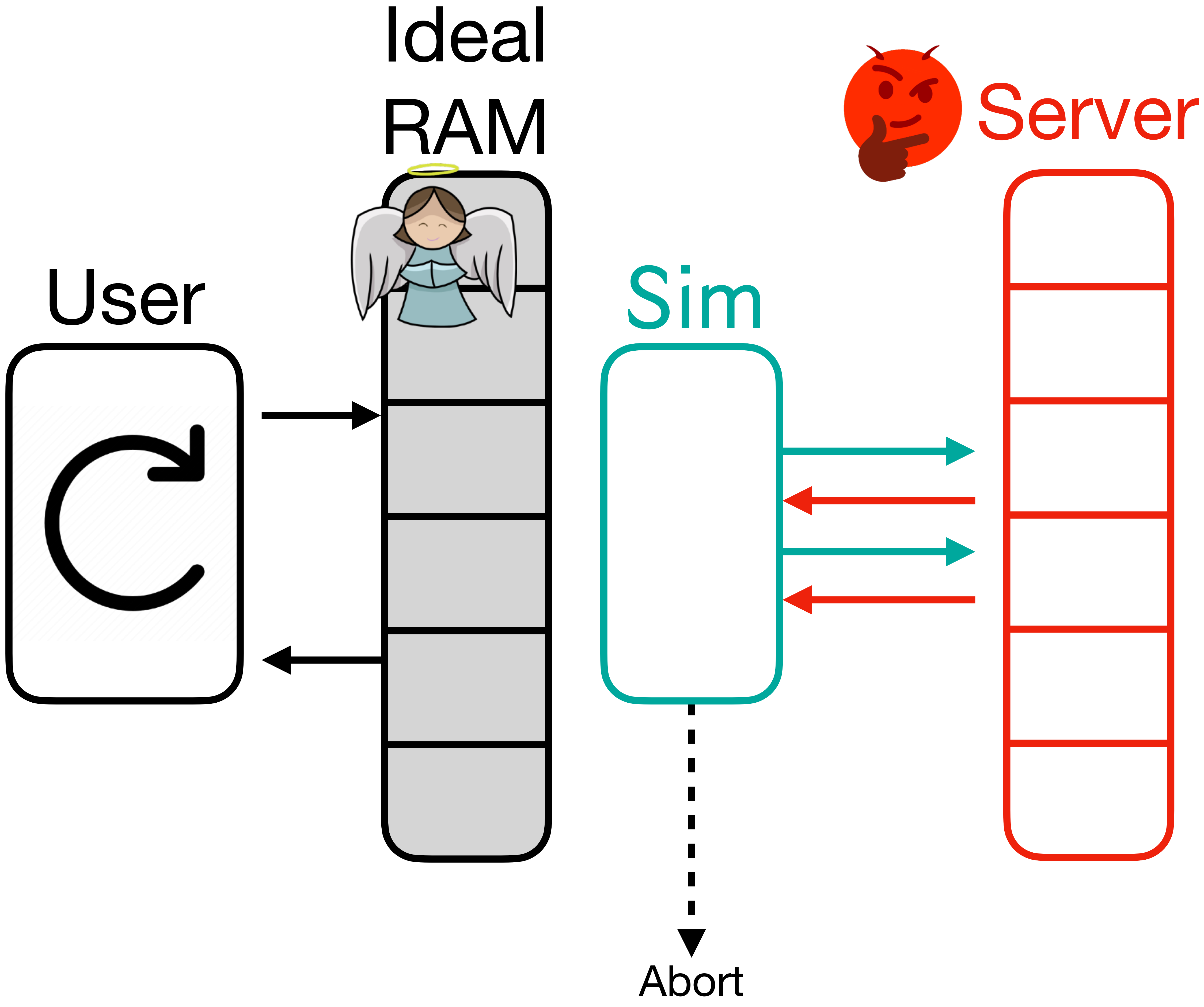
Server

User

ORAM

Abort

Ideal



Ideal RAM

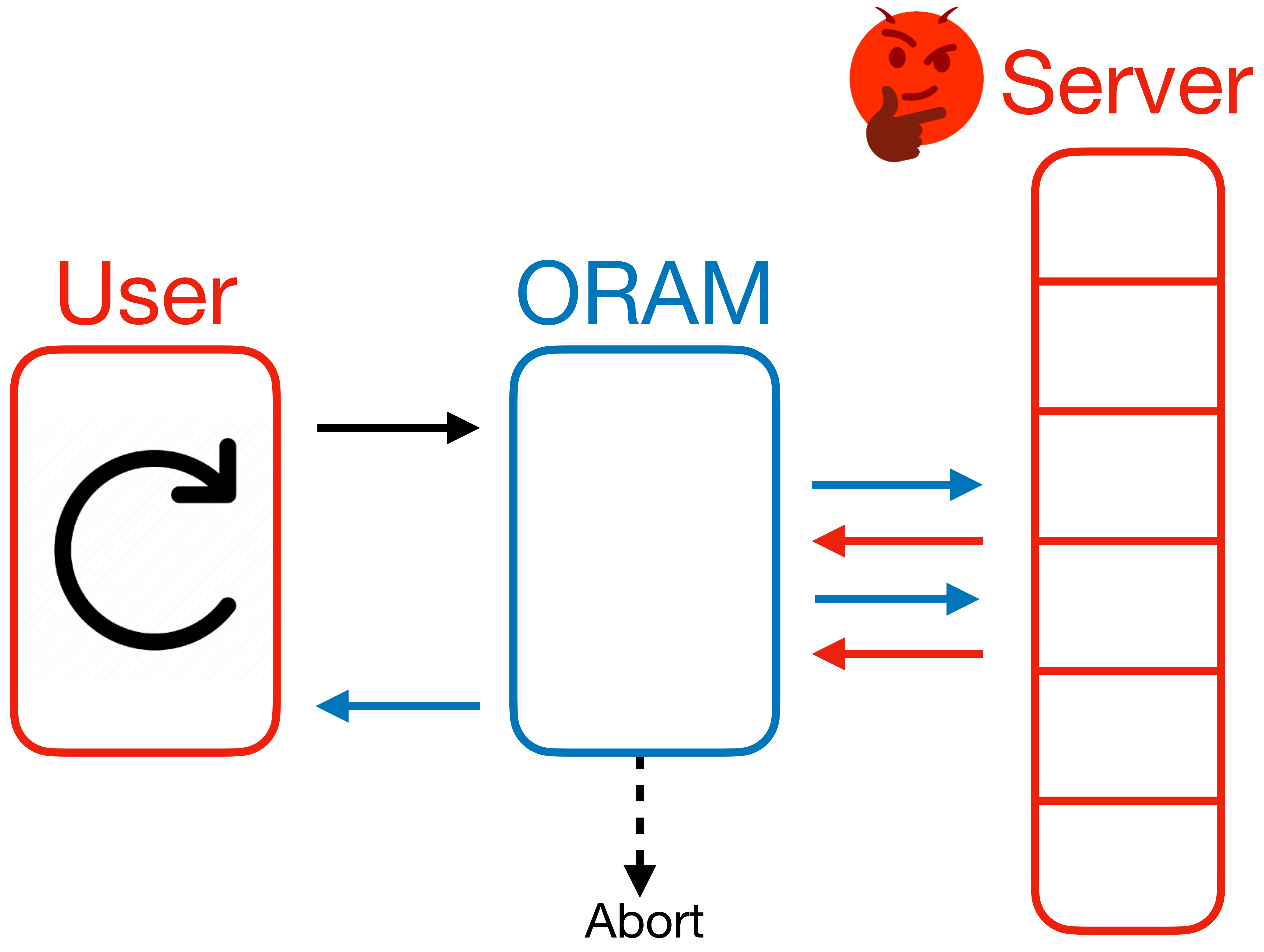
Server

User

Sim

Abort

Real



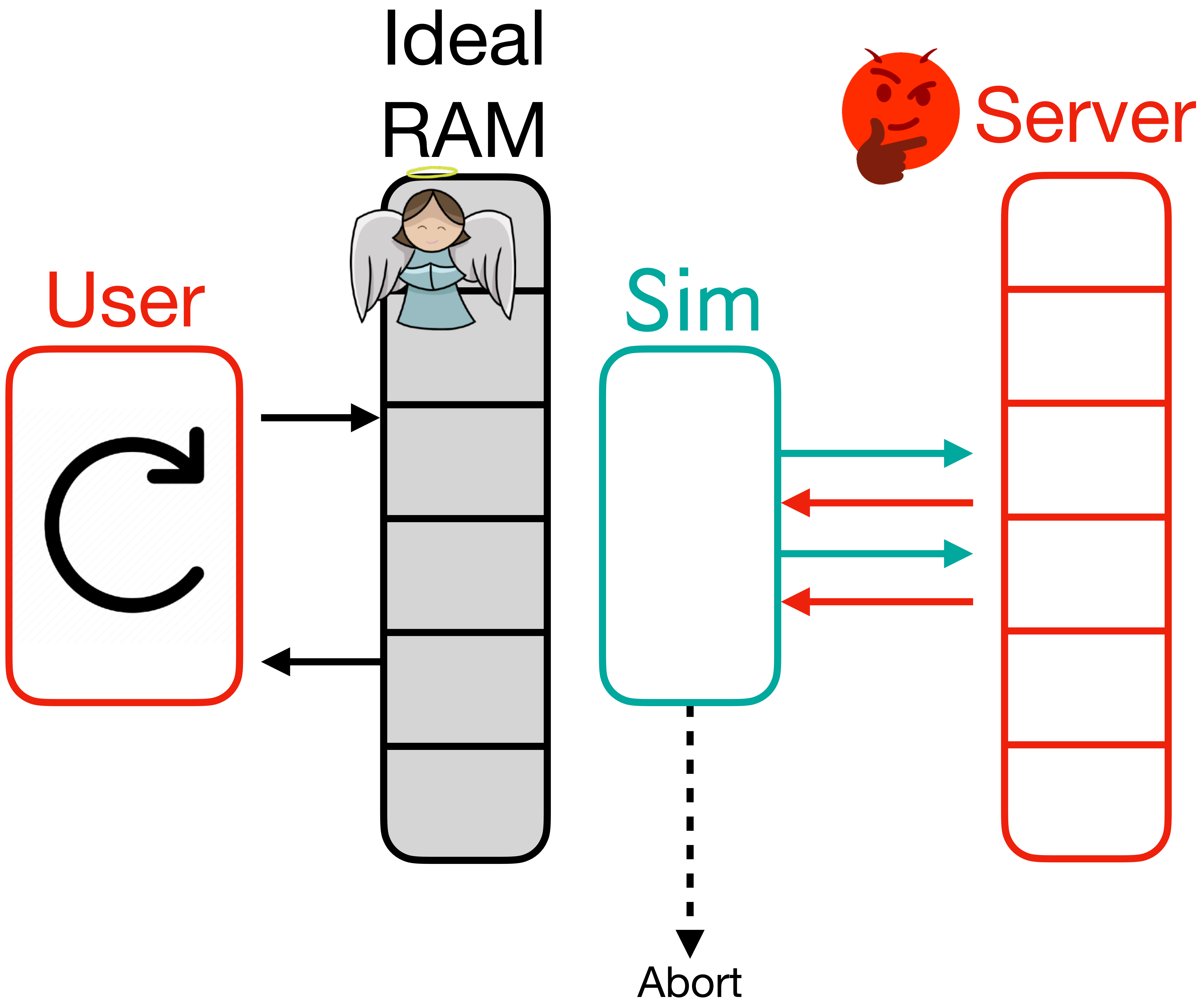
Server

User

ORAM

Abort

Ideal



Ideal RAM

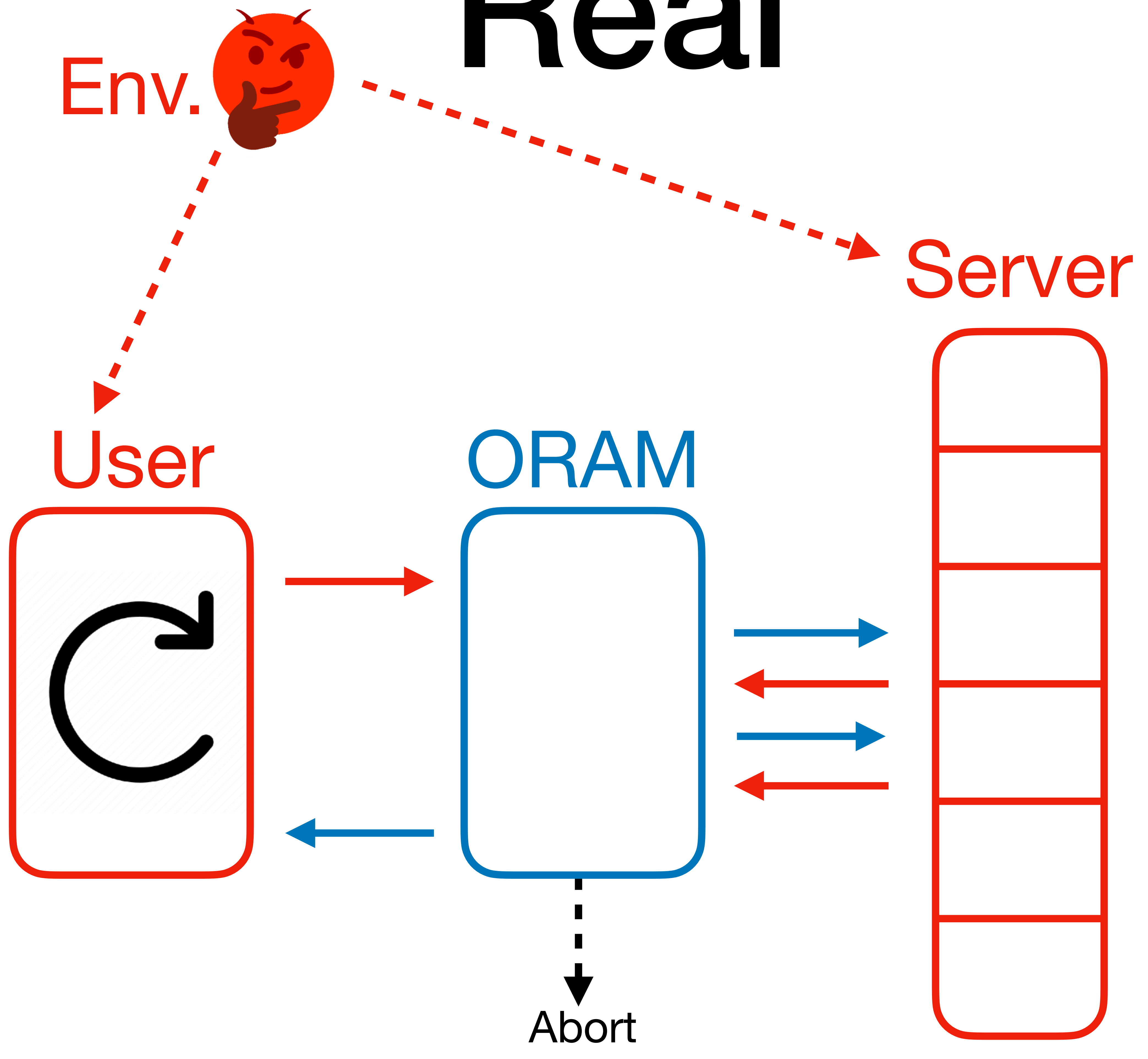
Server

User

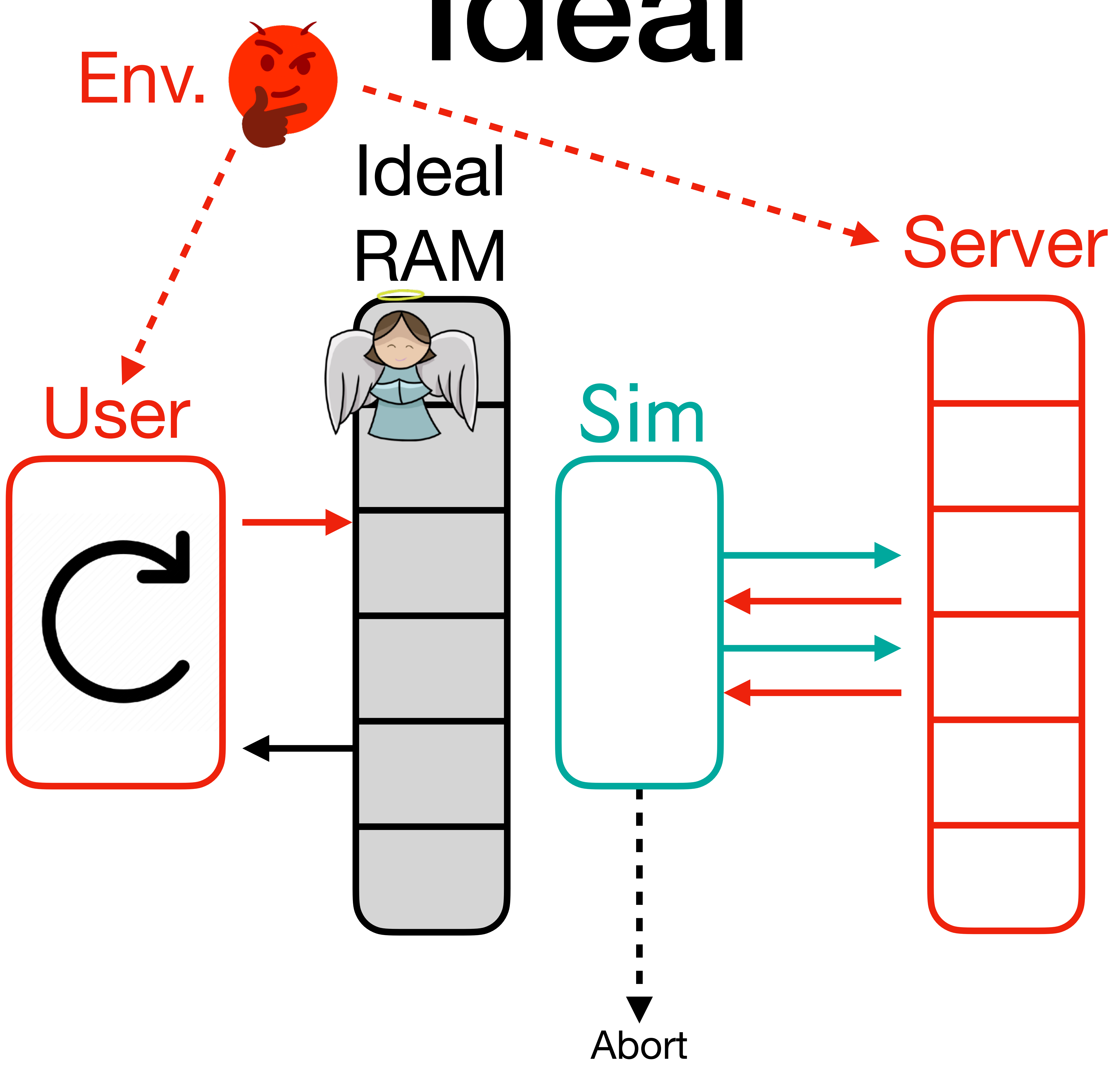
Sim

Abort

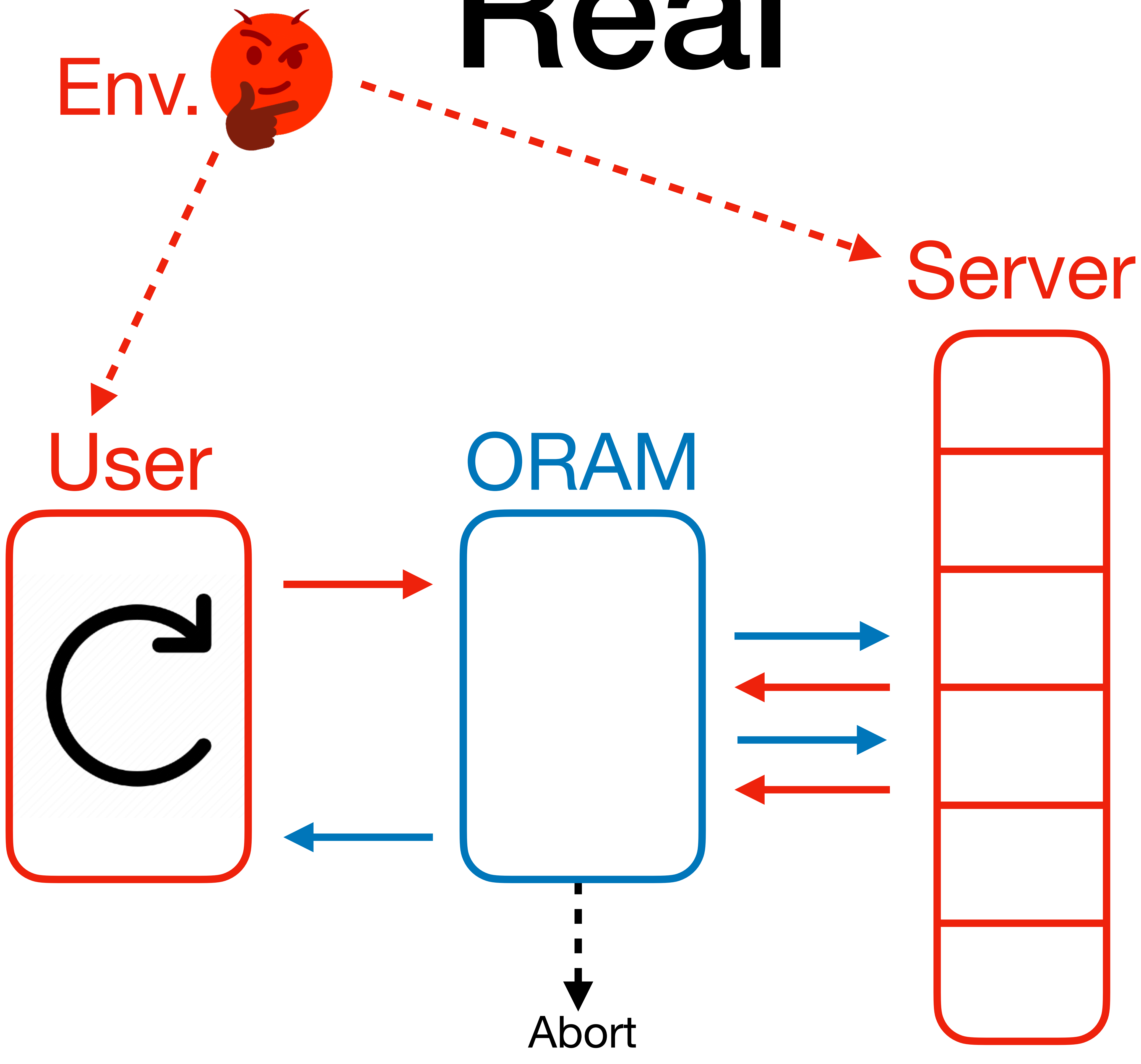
Real


Env.
Server
User
ORAM
Abort

Ideal


Env.
Ideal
RAM
Server
User
Sim
Abort

Real



Env.

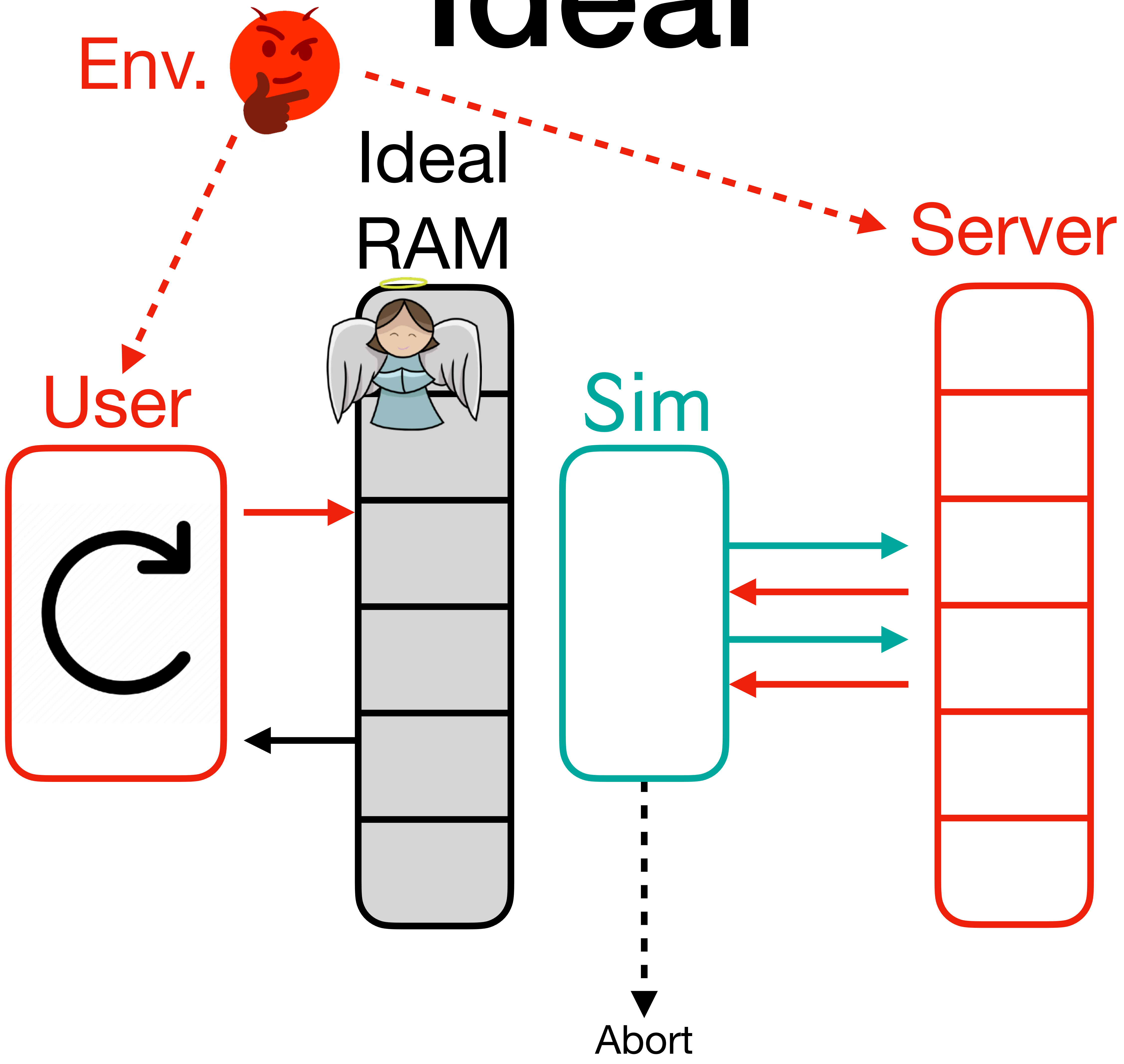
Server

User

ORAM

Abort

Ideal



Env.

Ideal RAM

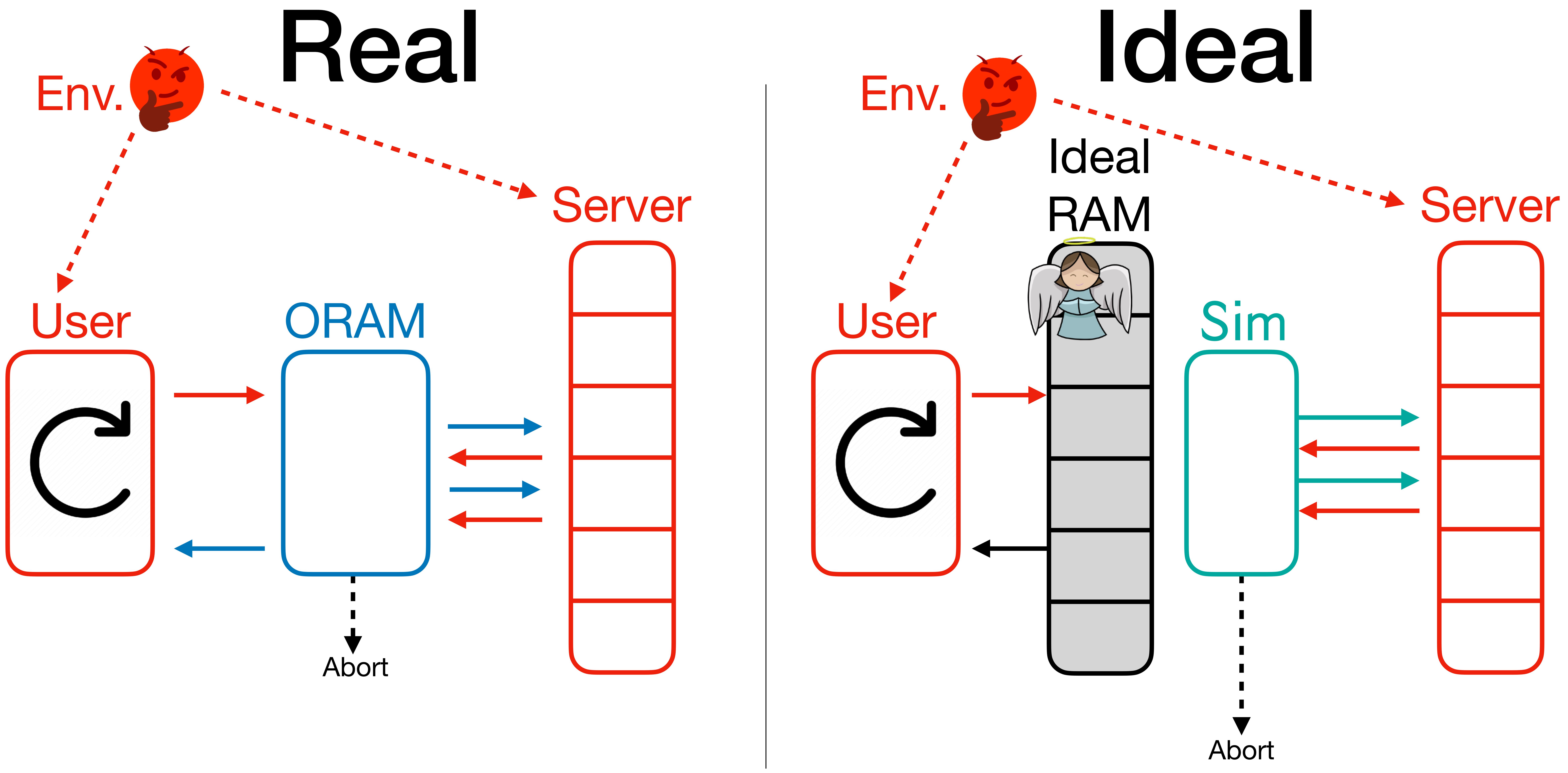
Server

User

Sim

Abort

Our Definition: ORAM is *maliciously secure* if ∃Sim such that for all 🤔, Real $\approx_{\text{comp}}$ Ideal



Real

Env.

User

ORAM

Server

Abort

Ideal

Env.

Ideal RAM

User

Sim

Server

Abort

Our Definition: ORAM is *maliciously secure* if $\exists$Sim such that for all 🤔, Real $\approx_{\text{comp}}$ Ideal (and ORAM doesn't abort against an honest server).

Hierarchical Efficiency

Hierarchical Efficiency

- Each H_i lookup takes $O(1)$ $\widehat{\text{query}}$'s using oblivious cuckoo hashing.*

[Goodrich-Mitzenmacher '11]

*Ignoring cuckoo hash-table stashes.

Hierarchical Efficiency

- Each H_i lookup takes $O(1)$ $\widehat{\mathsf{query}}$'s using oblivious cuckoo hashing.*
  - Iterating over $i \in [\log N]$, the Lookup Phase takes $O(\log N)$ $\widehat{\mathsf{query}}$'s.

Hierarchical Efficiency

- Each H_i lookup takes $O(1)$ $\widehat{\mathsf{query}}$'s using oblivious cuckoo hashing.*
    - Iterating over $i \in [\log N]$, the Lookup Phase takes $O(\log N)$ $\widehat{\mathsf{query}}$'s.
- Suppose the Rebuild Phase happening every 2^i steps takes $T\left(2^i\right)$ $\widehat{\mathsf{query}}$'s.

Hierarchical Efficiency

- Each H_i lookup takes $O(1)$ $\widehat{\text{query}}$'s using oblivious cuckoo hashing.*
  - Iterating over $i \in [\log N]$, the Lookup Phase takes $O(\log N)$ $\widehat{\text{query}}$'s.
- Suppose the Rebuild Phase happening every 2^i steps takes $T\left(2^i\right)$ $\widehat{\text{query}}$'s.
- Amortized ORAM overhead over $\geq N$ queries:

$$O\left(\log N\right) + \sum_{i \in [\log N]} \frac{1}{2^i} \cdot T\left(2^i\right)$$

Hierarchical Efficiency

- Each H_i lookup takes $O(1)$ $\widehat{\text{query}}$'s using oblivious cuckoo hashing.*
  - Iterating over $i \in [\log N]$, the Lookup Phase takes $O(\log N)$ $\widehat{\text{query}}$'s.
- Suppose the Rebuild Phase happening every 2^i steps takes $T\left(2^i\right)$ $\widehat{\text{query}}$'s.
- Amortized ORAM overhead over $\geq N$ queries:

$$O\left(\underset{\substack{\uparrow \\ \text{Lookup}}}{\log N}\right) + \sum_{i \in [\log N]} \frac{1}{2^i} \cdot T\left(2^i\right)$$

Hierarchical Efficiency

- Each H_i lookup takes $O(1)$ $\widehat{\text{query}}$'s using oblivious cuckoo hashing.*
  - Iterating over $i \in [\log N]$, the Lookup Phase takes $O(\log N)$ $\widehat{\text{query}}$'s.
- Suppose the Rebuild Phase happening every 2^i steps takes $T\left(2^i\right)$ $\widehat{\text{query}}$'s.
- Amortized ORAM overhead over $\geq N$ queries:

$$O\left(\log N\right) + \sum_{i \in [\log N]} \frac{1}{2^i} \cdot T\left(2^i\right)$$

Lookup

Rebuild

Hierarchical Efficiency

- Each H_i lookup takes $O(1)$ $\widehat{\mathsf{query}}$'s using oblivious cuckoo hashing.*
  - Iterating over $i \in [\log N]$, the Lookup Phase takes $O(\log N)$ $\widehat{\mathsf{query}}$'s.
- Suppose the Rebuild Phase happening every 2^i steps takes $T\left(2^i\right)$ $\widehat{\mathsf{query}}$'s.
- Amortized ORAM overhead over $\geq N$ queries:

$$O\left(\log N\right) + \sum_{i \in [\log N]} \frac{1}{2^i} \cdot T\left(2^i\right)$$

- If $T\left(2^i\right) = O\left(2^i\right)$, then this becomes $O(\log N)$! [**OptORAMa**, AKLNPS '20]

Hierarchical Efficiency

- Each H$_i$ lookup takes $\boxed{O(1)}$ $\widehat{\text{query}}$'s using oblivious cuckoo hashing.*
  - Iterating over $i \in [\log N]$, the Lookup Phase takes $O(\log N)$ $\widehat{\text{query}}$'s.
- Suppose the Rebuild Phase happening every 2^i steps takes $T\left(2^i\right)$ $\widehat{\text{query}}$'s.
- Amortized ORAM overhead over $\geq N$ queries:

$$O\left(\log N\right) + \sum_{i \in [\log N]} \frac{1}{2^i} \cdot T\left(2^i\right)$$

- If $T\left(2^i\right) = \boxed{O\left(2^i\right)}$, then this becomes $O(\log N)$! [**OptORAMa**, AKLNPS '20]

Quite difficult! Long line of work to get this efficiency.

Replay Attack for Hierarchical

- As is, the hierarchical paradigm with MACs is susceptible to replay attacks, so it’s still maliciously insecure.

Replay Attack for Hierarchical

- As is, the hierarchical paradigm with MACs is susceptible to replay attacks, so it’s still maliciously insecure.
- Is there a fix?

When is Offline Checking Safe?

Access-Deterministic

When is Offline Checking Safe?

Access-Deterministic

- **Definition**: A subroutine is **access-deterministic** if $\{\widehat{\mathsf{addr}}_i\}$ is deterministic and *perfectly independent* of the input **when interacting with an honest server**.

When is Offline Checking Safe?

Access-Deterministic

- **Definition**: A subroutine is **access-deterministic** if $\{\widehat{\mathsf{addr}}_i\}$ is deterministic and *perfectly independent* of the input **when interacting with an honest server**.
- In general, access-deterministic subroutines **may not be offline-safe** against **adversarial** servers. Nonetheless:

When is Offline Checking Safe?

Access-Deterministic

- **Definition**: A subroutine is **access-deterministic** if $\{\widehat{\mathsf{addr}}_i\}$ is deterministic and *perfectly independent* of the input **when interacting with an honest server**.
- In general, access-deterministic subroutines **may not be offline-safe** against **adversarial** servers. Nonetheless:

Theorem [**M**V '23]: If a subroutine is *access-deterministic*, then it can be made *maliciously secure* with the **same asymptotic overhead.**

When is Offline Checking Safe?

Access-Deterministic

- **Definition**: A subroutine is **access-deterministic** if $\{\widehat{\mathsf{addr}}_i\}$ is deterministic and *perfectly independent* of the input **when interacting with an honest server**.
- In general, access-deterministic subroutines **may not be offline-safe** against **adversarial** servers. Nonetheless:

Theorem [**M**V '23]: If a subroutine is *access-deterministic*, then it can be made *maliciously secure* with the **same asymptotic overhead.**

- **Idea:** Use *offline-checking* to pre-process a $\mathsf{PrevTime}$ data-structure for the algorithm, and use this to **time-stamp** the algorithm.

When is Offline Checking Safe?

Access-Deterministic

- **Definition**: A subroutine is **access-deterministic** if $\{\widehat{\mathsf{addr}}_i\}$ is deterministic and *perfectly independent* of the input **when interacting with an honest server**.
- In general, access-deterministic subroutines **may not be offline-safe** against **adversarial** servers. Nonetheless:

Theorem [**M**V '23]: If a subroutine is *access-deterministic*, then it can be made *maliciously secure* with the **same asymptotic overhead.**

- **Idea:** Use *offline-checking* to pre-process a $\mathsf{PrevTime}$ data-structure for the algorithm, and use this to **time-stamp** the algorithm.
- Can be viewed as a strengthening of Goldreich-Ostrovsky's time-stamping theorem!

Why Access-Deterministic Algorithms May Not Be Offline-Safe

- Consider the following implementation of an AKS sort.

  1. Use server space to compute and store a bipartite expander $G = (V, E)$.

  2. Iterate over edge set E, and make comparisons according to E.

- If the contents of E are **replaced with secret data**, the secret data will be leaked!

Offline Memory Checking

$\widehat{\mathsf{addr}_1}$	$\widehat{\mathsf{addr}_2}$	$\widehat{\mathsf{addr}_3}$	$\widehat{\mathsf{addr}_4}$	$\widehat{\mathsf{addr}_5}$	$\widehat{\mathsf{addr}_6}$	$\widehat{\mathsf{addr}_7}$
$\mathsf{data}_1, \mathsf{ctr}_1$	$\mathsf{data}_2, \mathsf{ctr}_2$	$\mathsf{data}_3, \mathsf{ctr}_3$	$\mathsf{data}_4, \mathsf{ctr}_4$	$\mathsf{data}_5, \mathsf{ctr}_5$	$\mathsf{data}_6, \mathsf{ctr}_6$	$\mathsf{data}_7, \mathsf{ctr}_7$

Offline Memory Checking

All entries are MAC'ed
Current time: ctr

$\widehat{\text{addr}_1}$	$\widehat{\text{addr}_2}$	$\widehat{\text{addr}_3}$	$\widehat{\text{addr}_4}$	$\widehat{\text{addr}_5}$	$\widehat{\text{addr}_6}$	$\widehat{\text{addr}_7}$
$\text{data}_1, \text{ctr}_1$	$\text{data}_2, \text{ctr}_2$	$\text{data}_3, \text{ctr}_3$	$\text{data}_4, \text{ctr}_4$	$\text{data}_5, \text{ctr}_5$	$\text{data}_6, \text{ctr}_6$	$\text{data}_7, \text{ctr}_7$

Offline Memory Checking

All entries are MAC'ed
Current time: ctr

$\widehat{\mathsf{addr}_1}$	$\widehat{\mathsf{addr}_2}$	$\widehat{\mathsf{addr}_3}$	$\widehat{\mathsf{addr}_4}$	$\widehat{\mathsf{addr}_5}$	$\widehat{\mathsf{addr}_6}$	$\widehat{\mathsf{addr}_7}$
$\mathsf{data}_1, \mathsf{ctr}_1$	$\mathsf{data}_2, \mathsf{ctr}_2$	$\mathsf{data}_3, \mathsf{ctr}_3$	$\mathsf{data}_4, \mathsf{ctr}_4$	$\mathsf{data}_5, \mathsf{ctr}_5$	$\mathsf{data}_6, \mathsf{ctr}_6$	$\mathsf{data}_7, \mathsf{ctr}_7$

- Initialize the array so that all $\mathsf{ctr}_i = 0$, and initialize a local counter T.

Offline Memory Checking

All entries are MAC’ed
Current time: ctr

$\widehat{\text{addr}_1}$	$\widehat{\text{addr}_2}$	$\widehat{\text{addr}_3}$	$\widehat{\text{addr}_4}$	$\widehat{\text{addr}_5}$	$\widehat{\text{addr}_6}$	$\widehat{\text{addr}_7}$
$\text{data}_1, \text{ctr}_1$	$\text{data}_2, \text{ctr}_2$	$\text{data}_3, \text{ctr}_3$	$\text{data}_4, \text{ctr}_4$	$\text{data}_5, \text{ctr}_5$	$\text{data}_6, \text{ctr}_6$	$\text{data}_7, \text{ctr}_7$

- Initialize the array so that all $\text{ctr}_i = 0$, and initialize a local counter T.
- Every time an index i is accessed, increment ctr_i (on the remote server), and increment local counter T.

Offline Memory Checking

All entries are MAC'ed
Current time: ctr

$\widehat{\mathsf{addr}_1}$	$\widehat{\mathsf{addr}_2}$	$\widehat{\mathsf{addr}_3}$	$\widehat{\mathsf{addr}_4}$	$\widehat{\mathsf{addr}_5}$	$\widehat{\mathsf{addr}_6}$	$\widehat{\mathsf{addr}_7}$
$\mathsf{data}_1, \mathsf{ctr}_1$	$\mathsf{data}_2, \mathsf{ctr}_2$	$\mathsf{data}_3, \mathsf{ctr}_3$	$\mathsf{data}_4, \mathsf{ctr}_4$	$\mathsf{data}_5, \mathsf{ctr}_5$	$\mathsf{data}_6, \mathsf{ctr}_6$	$\mathsf{data}_7, \mathsf{ctr}_7$

- Initialize the array so that all $\mathsf{ctr}_i = 0$, and initialize a local counter T.
- Every time an index i is accessed, increment ctr_i (on the remote server), and increment local counter T.
- At the end of the execution, iterate over the array and accept if and only if $\sum_i \mathsf{ctr}_i = T$.