MacORAMa:
Optimal Oblivious RAM with Integrity

Crypto 2023

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MIT

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MIT

Remote RAM Computation

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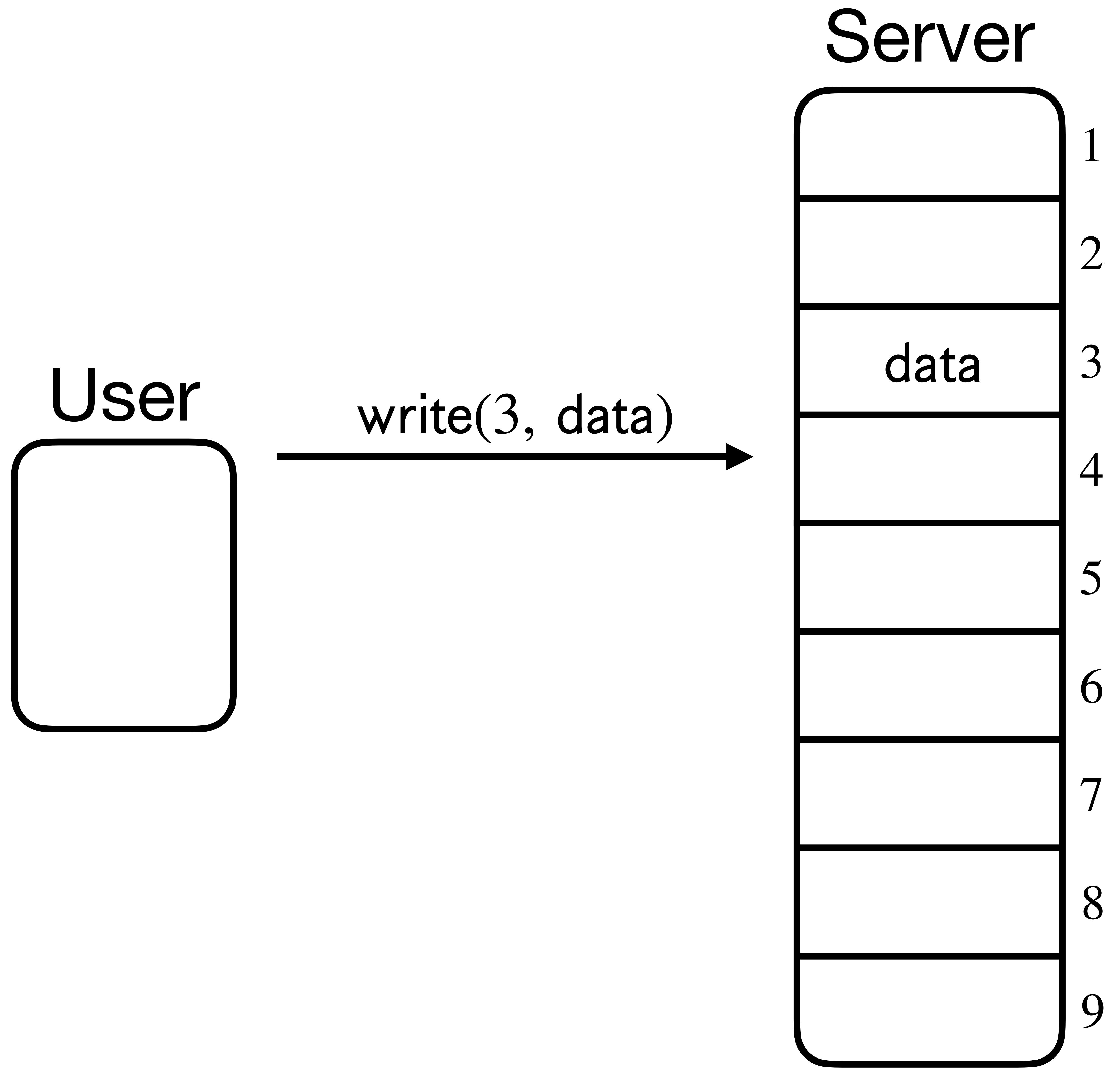

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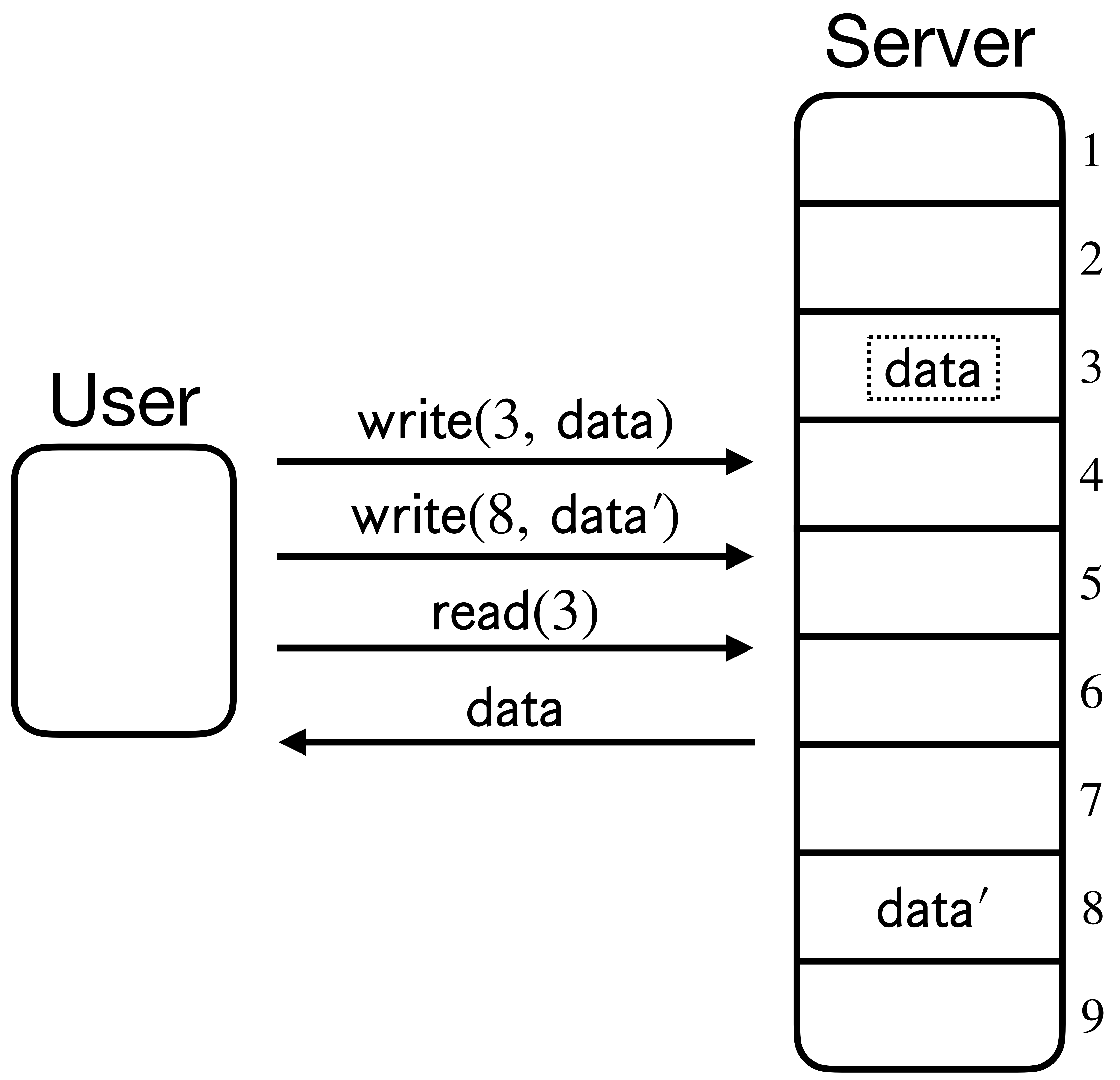

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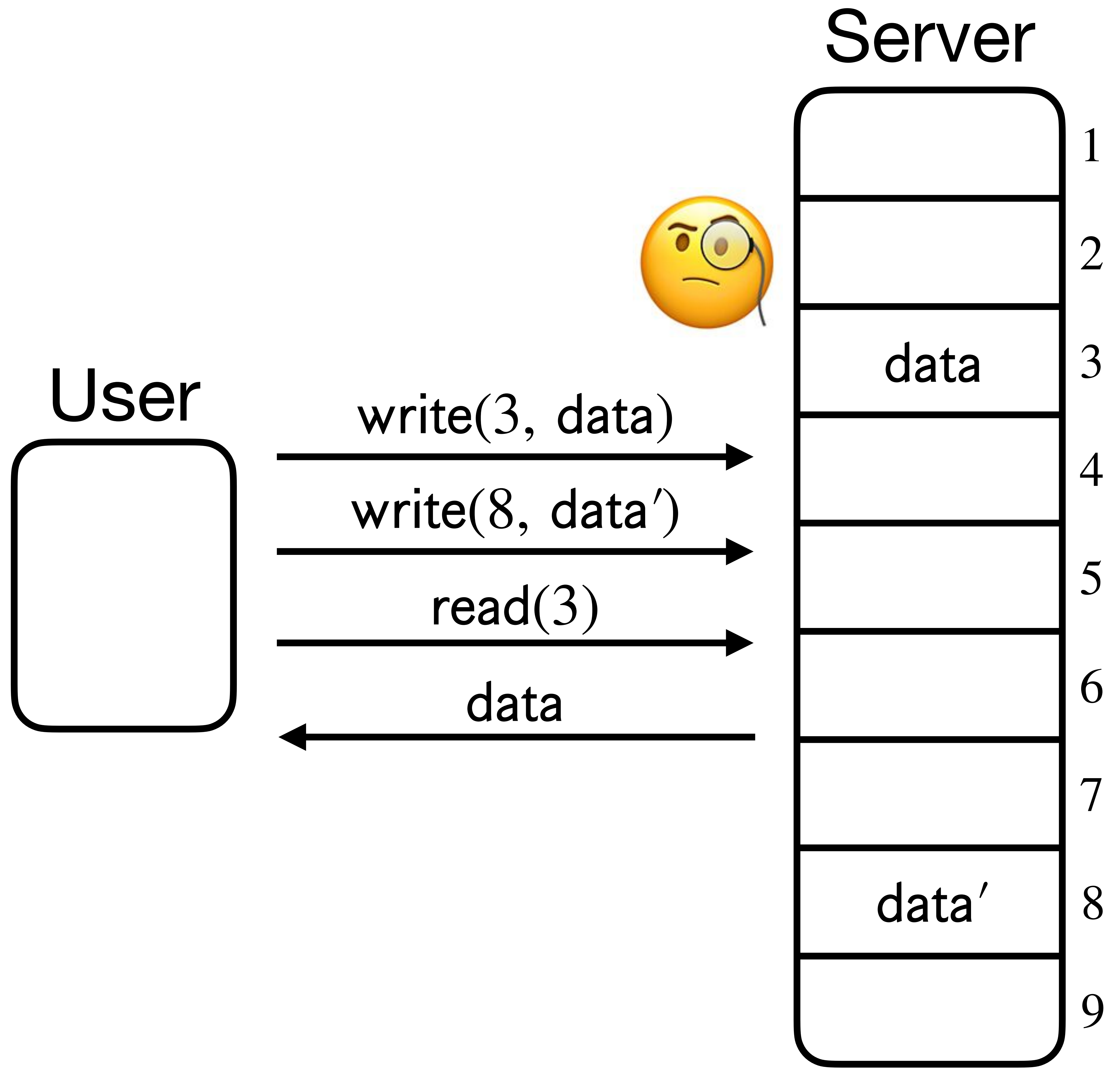
- How can the user ensure privacy of its computation against a curious server?



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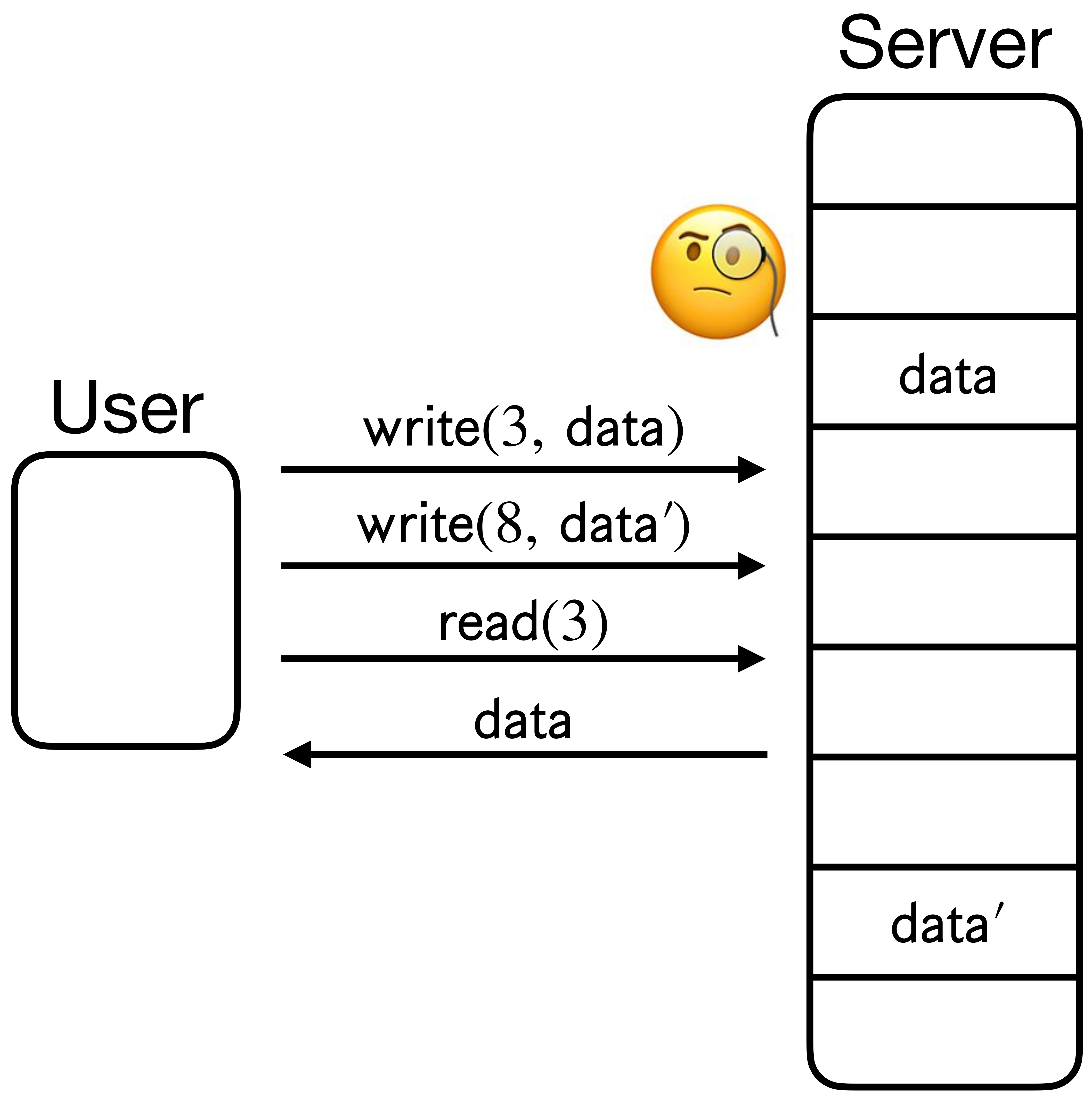

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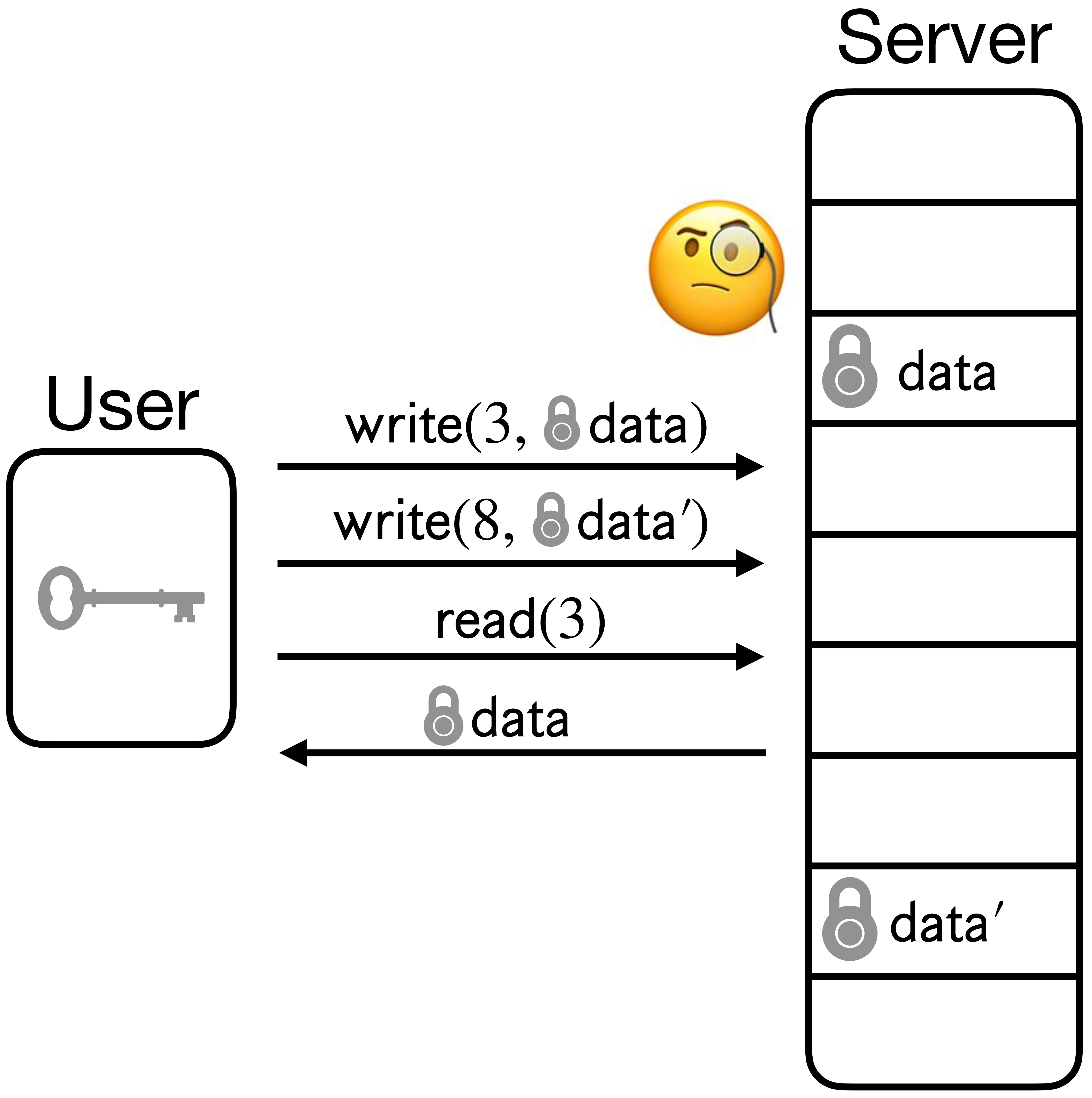

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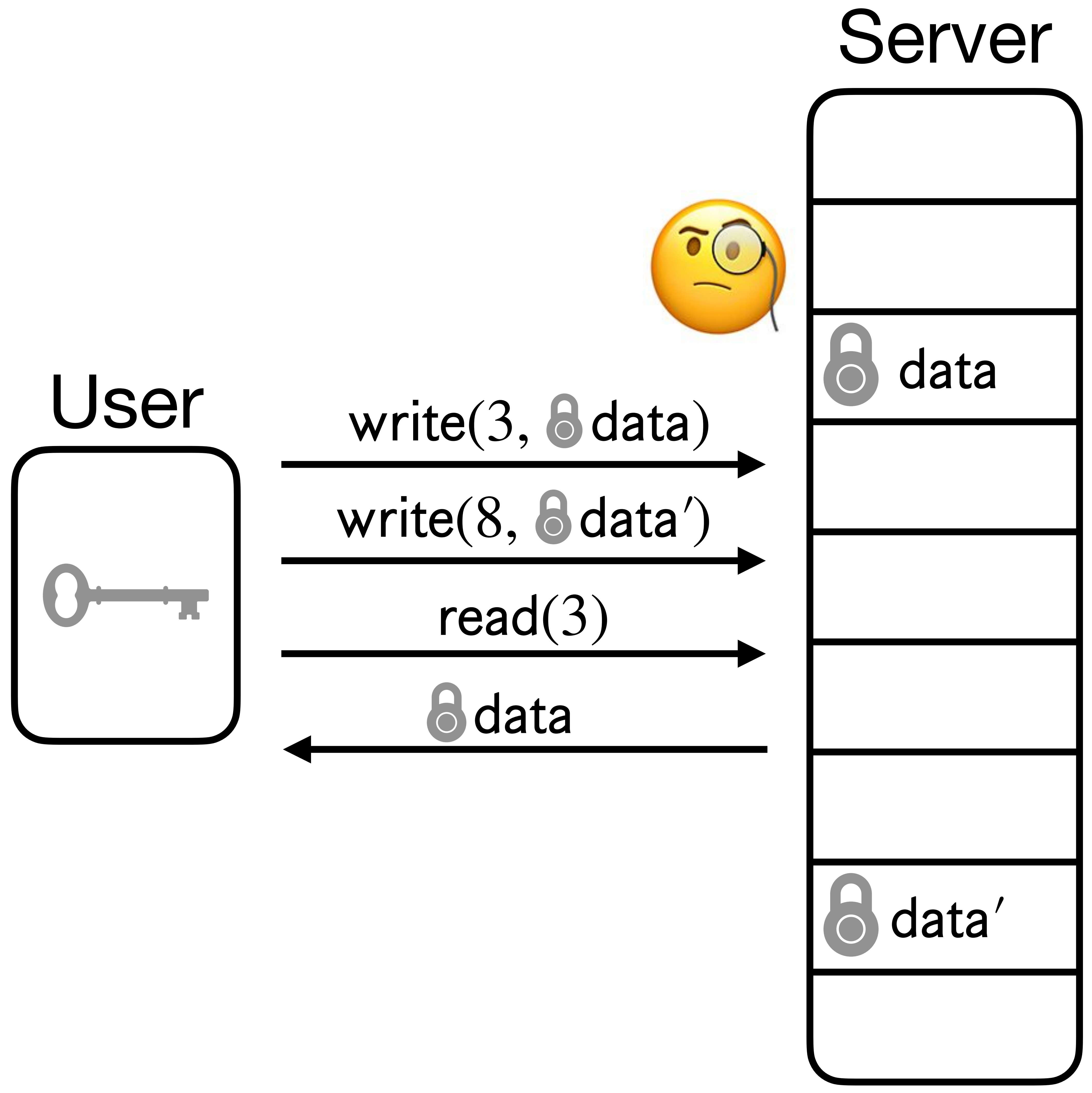

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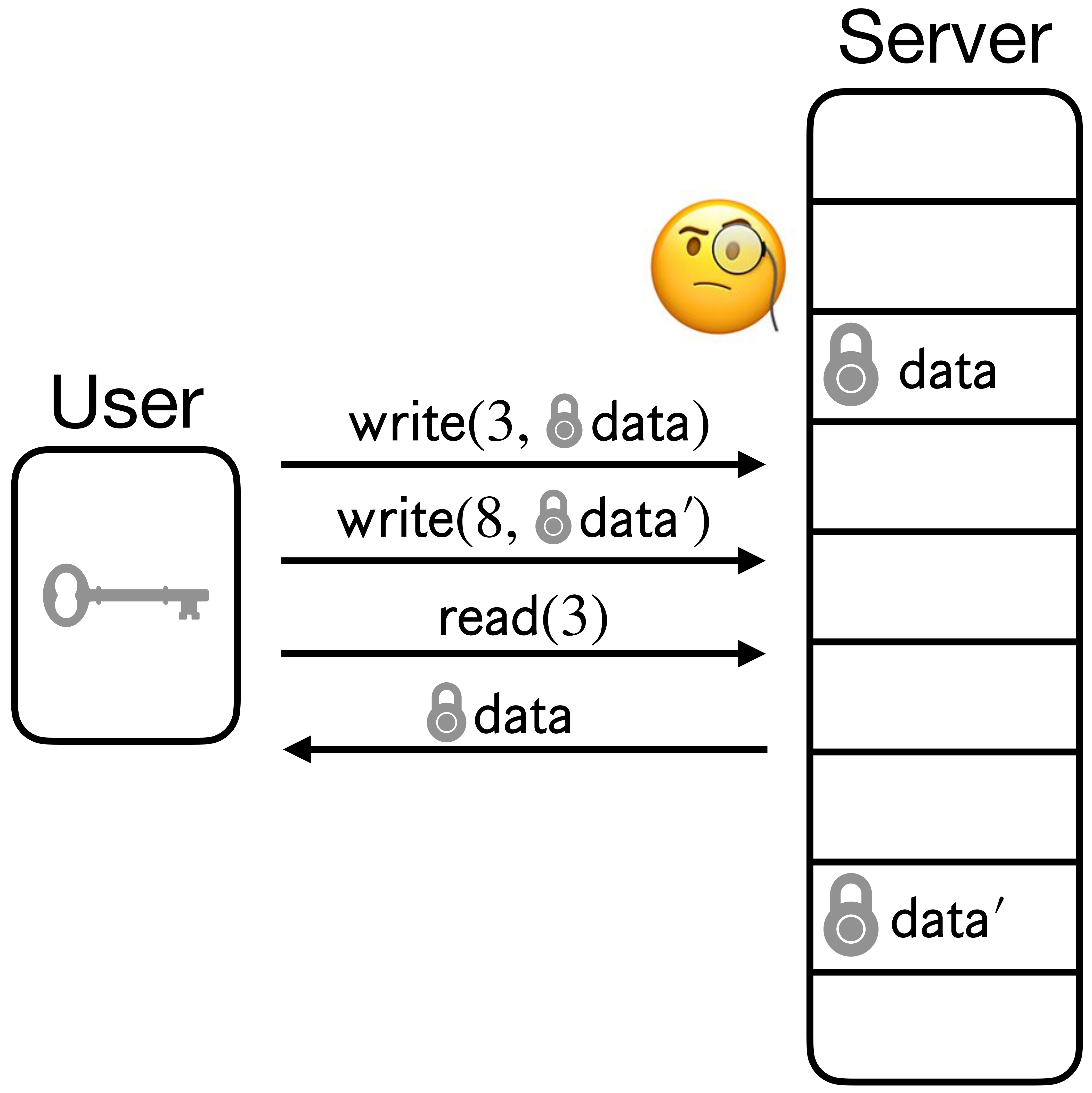

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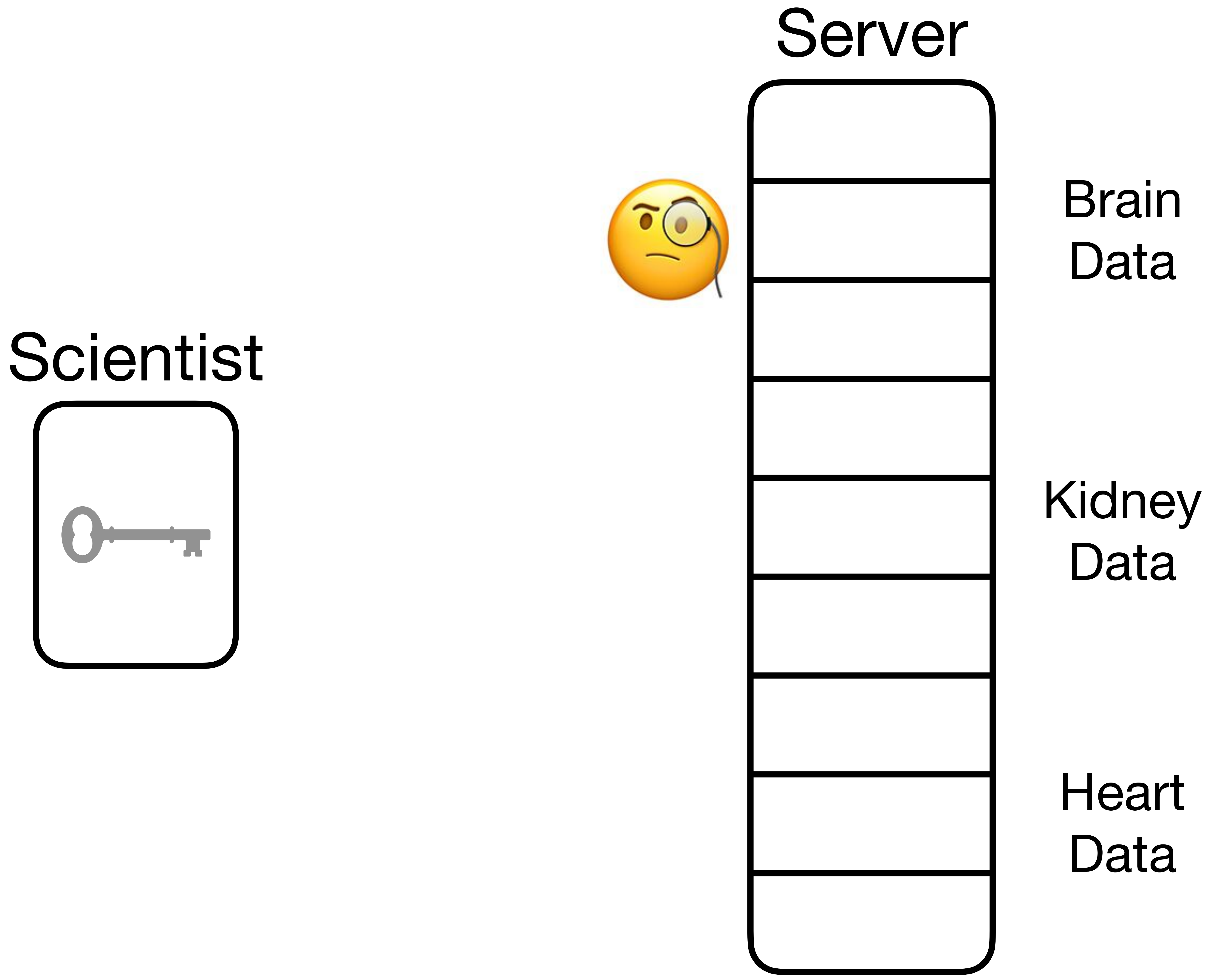

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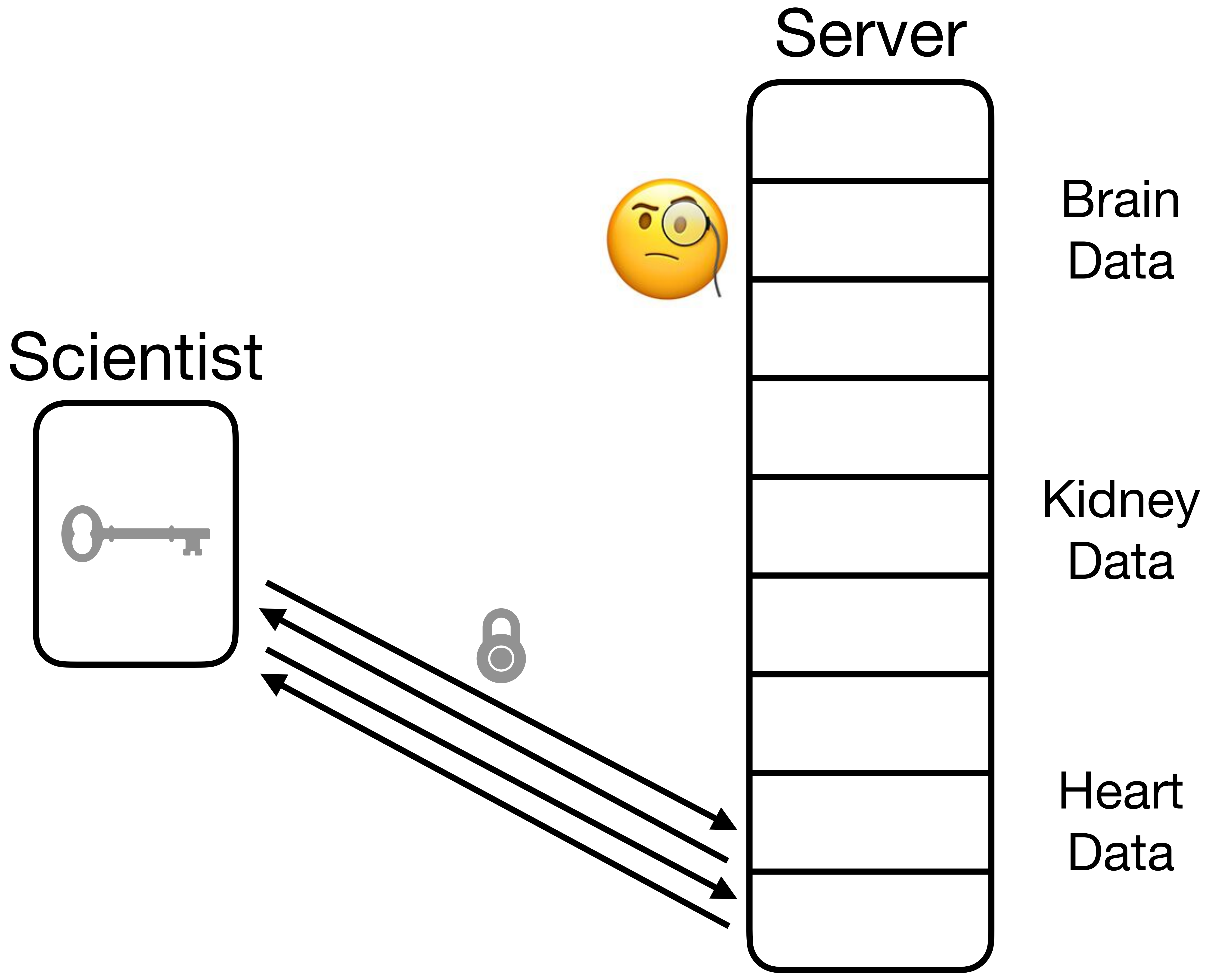

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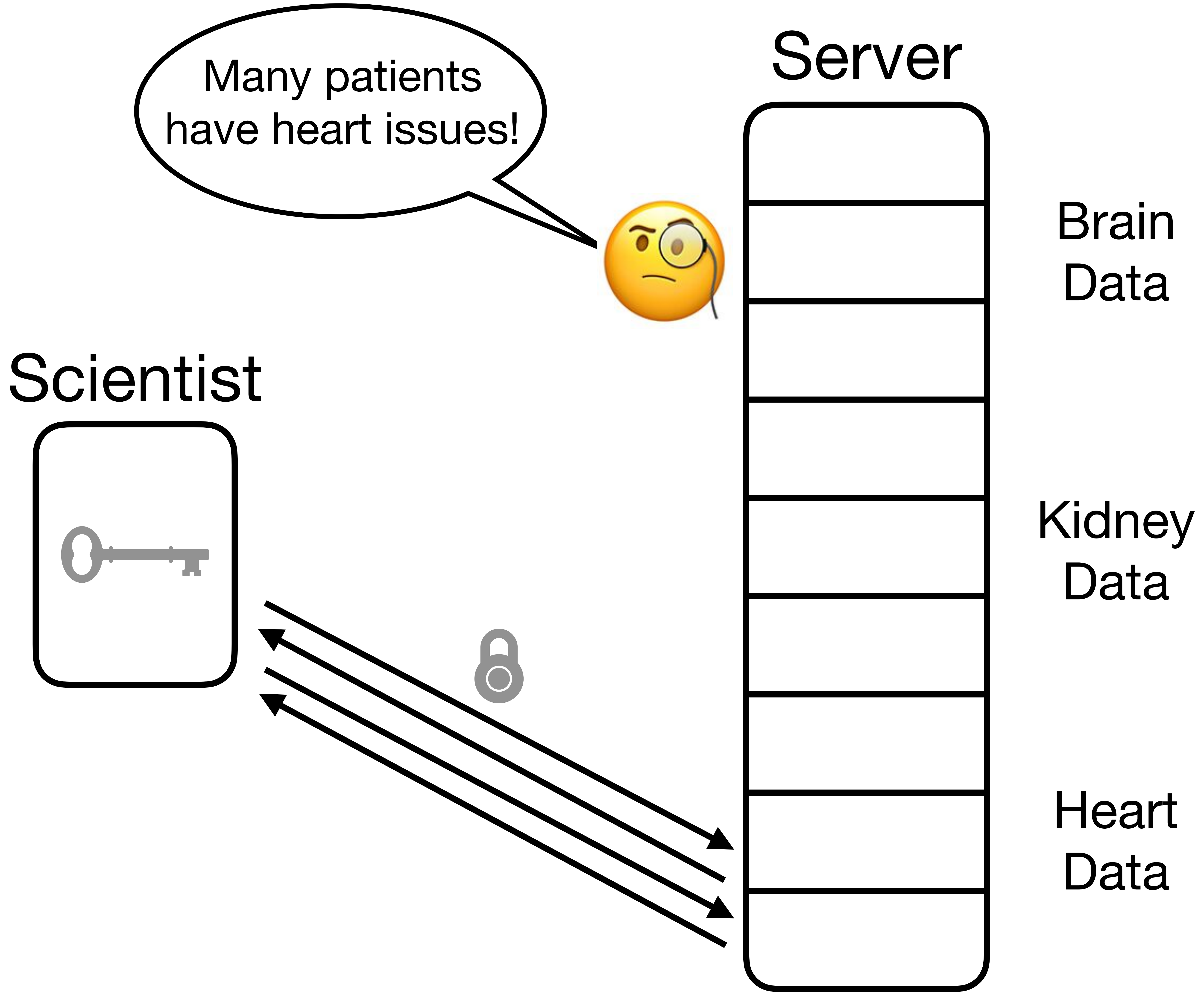

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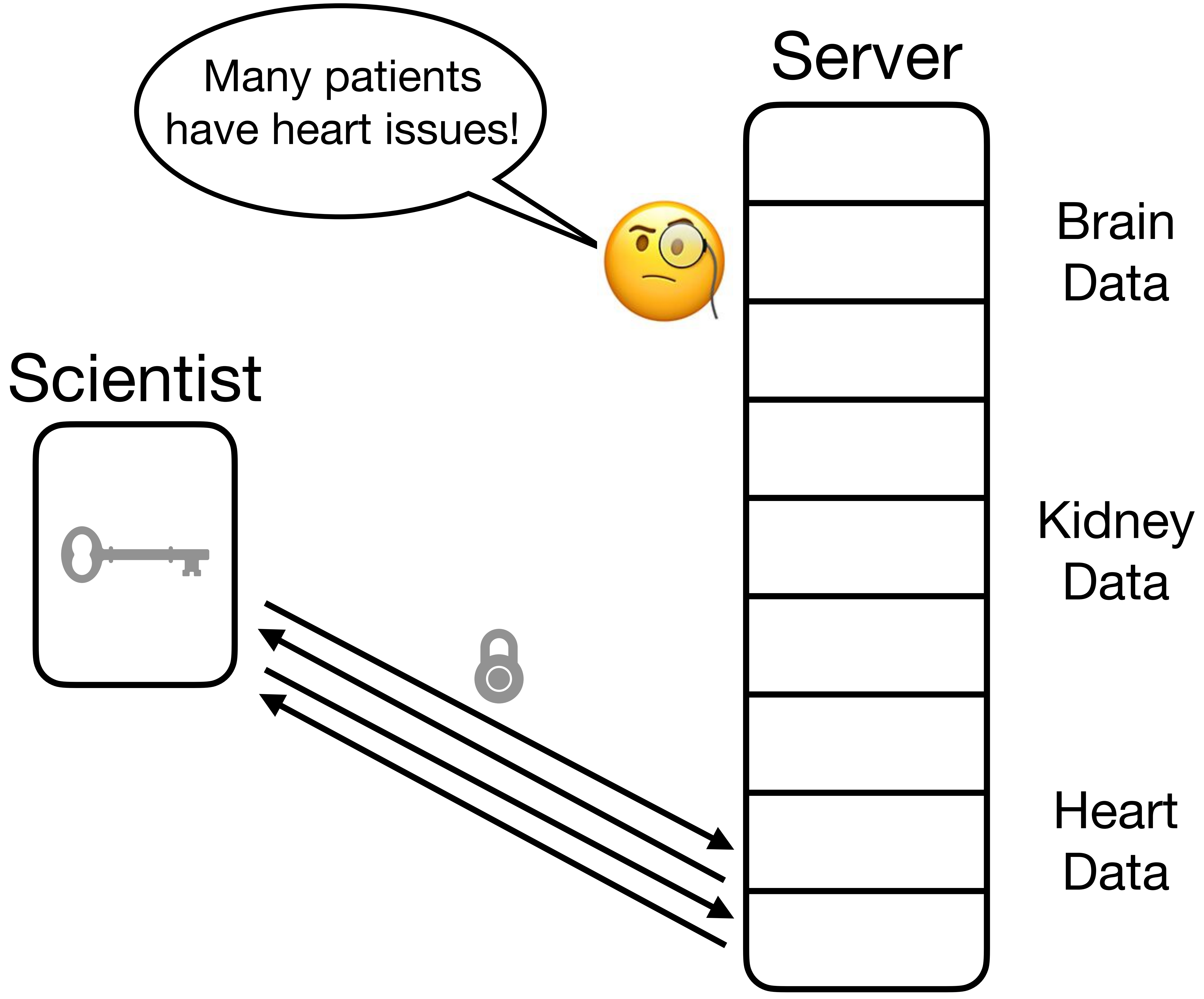
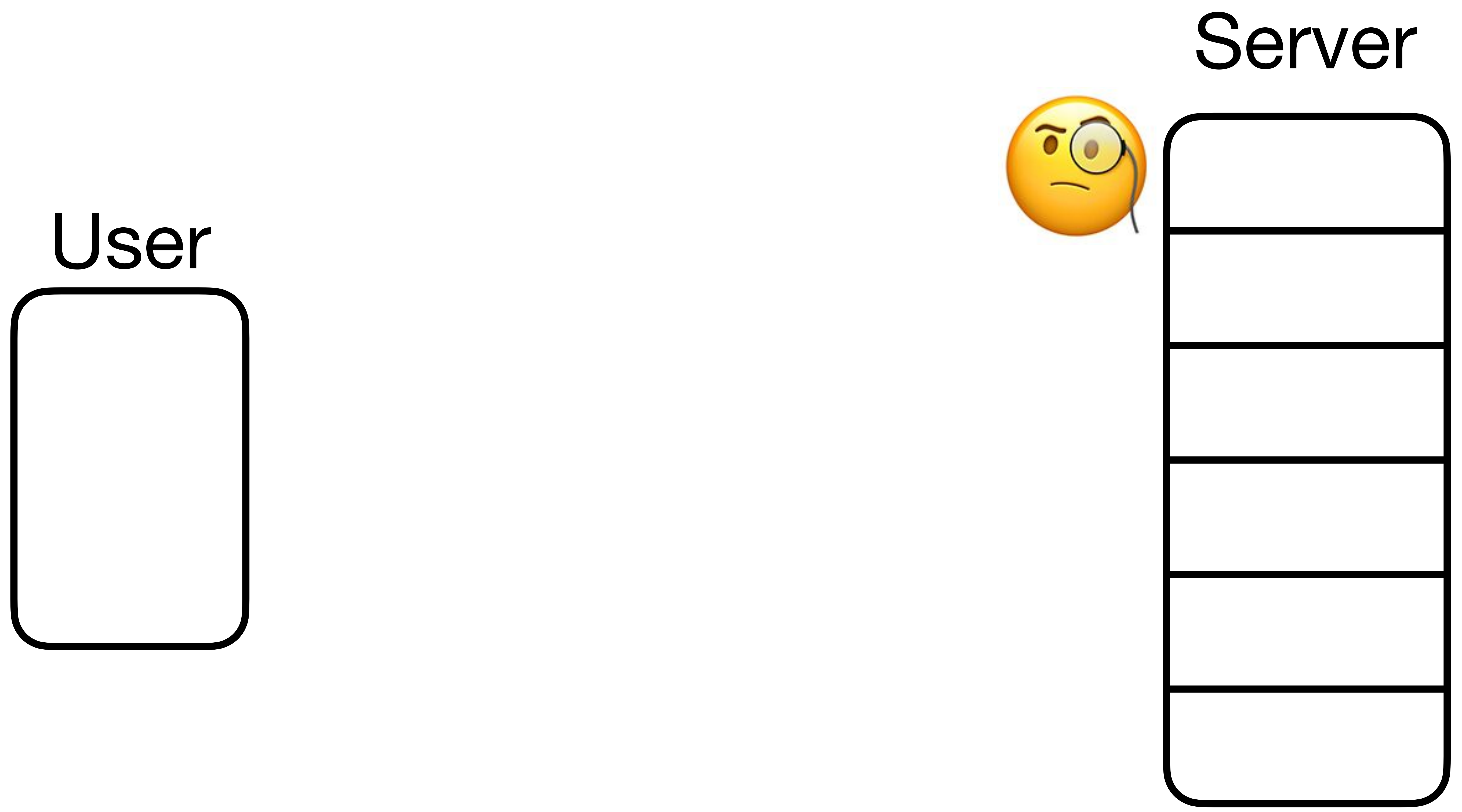
- RAM addresses in accesses can reveal private information!



Oblivious RAM (ORAM)

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



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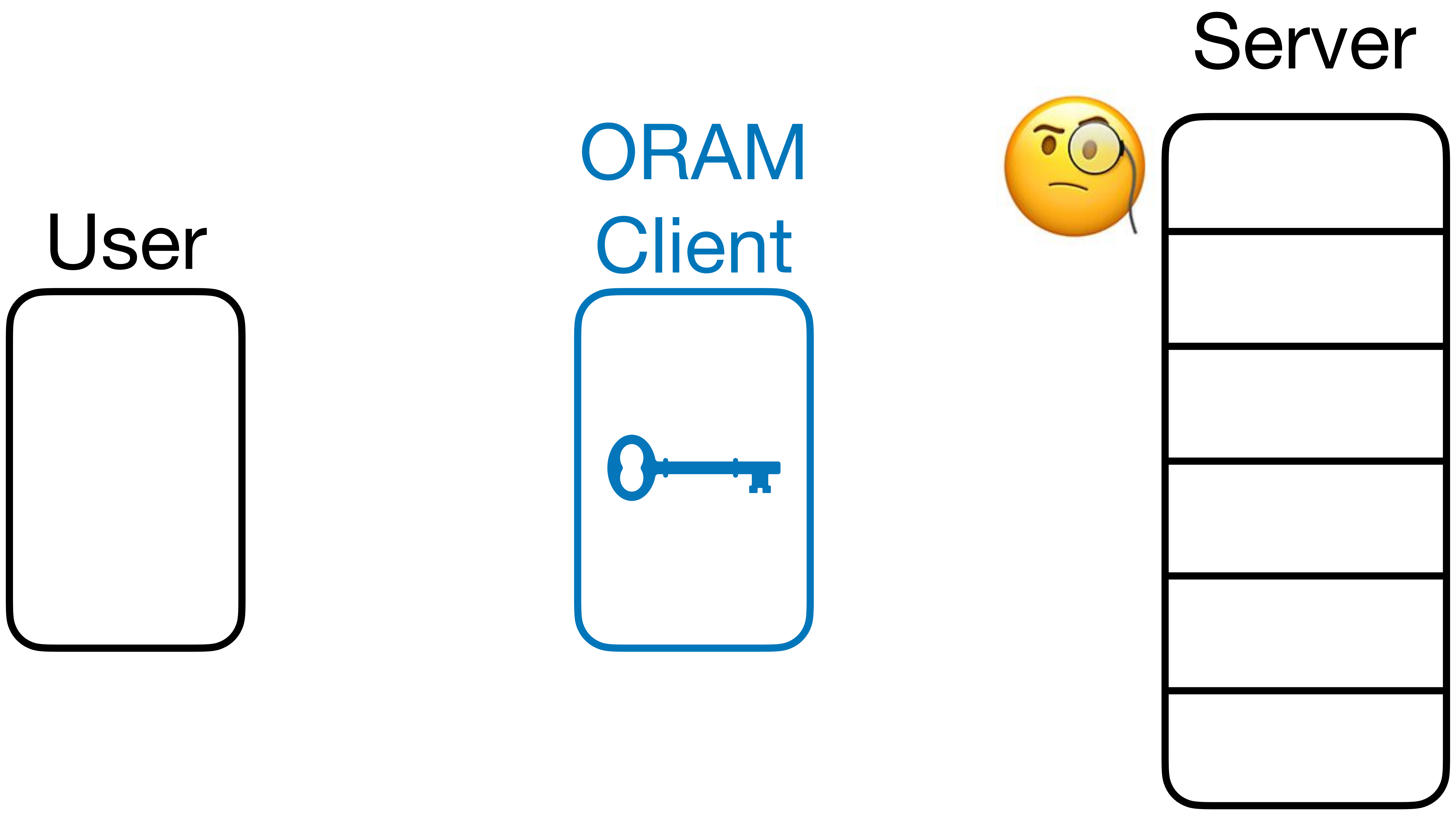

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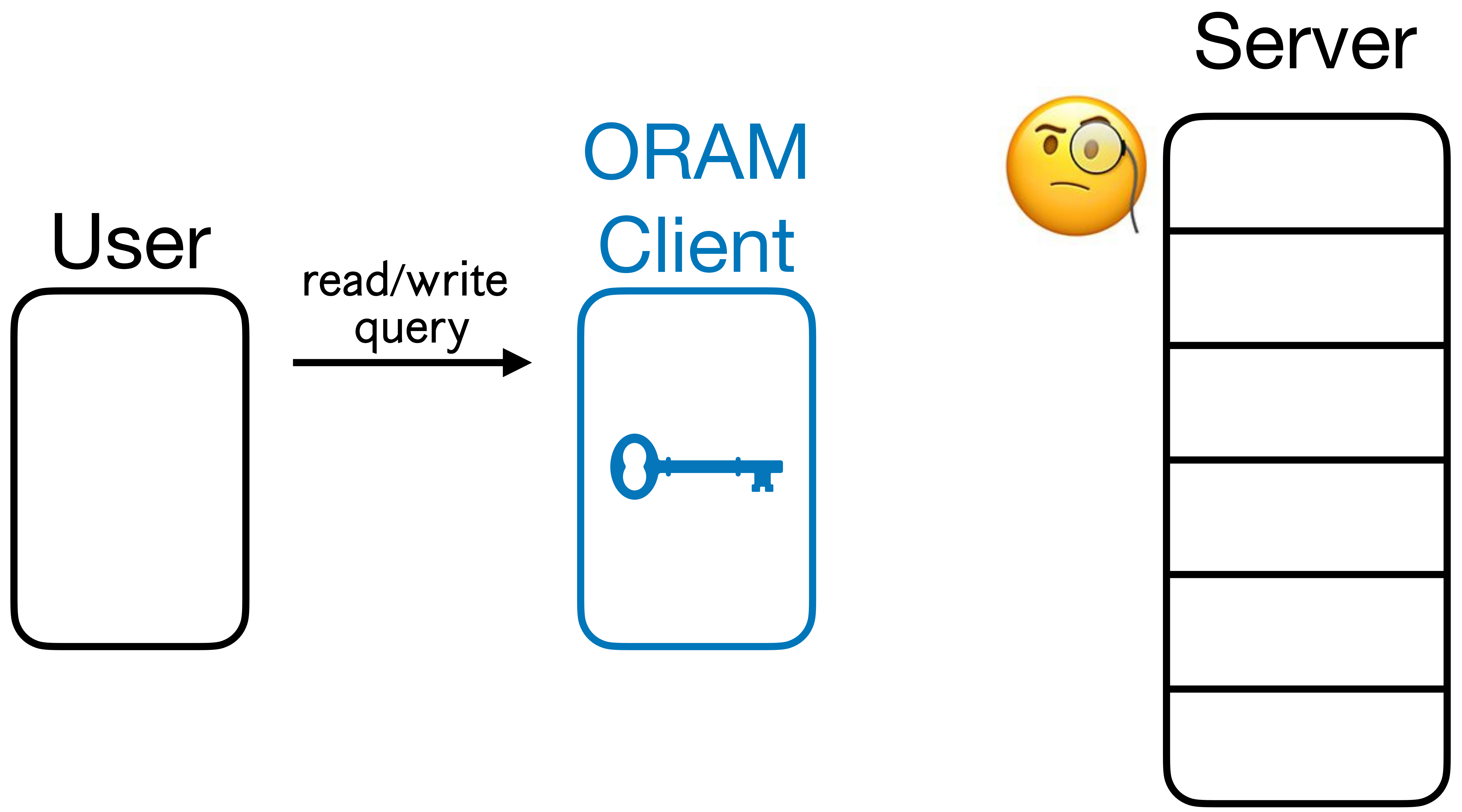

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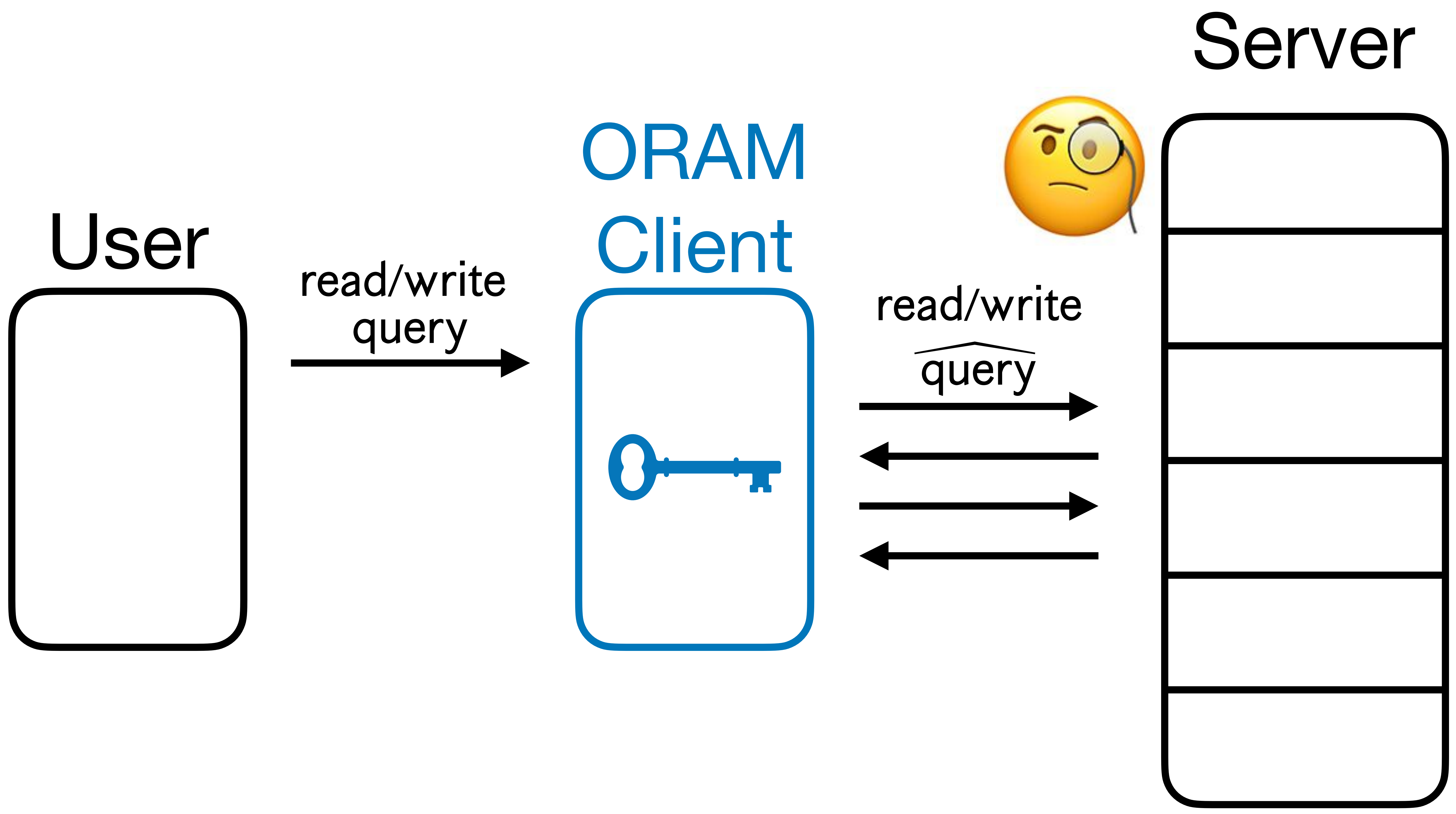

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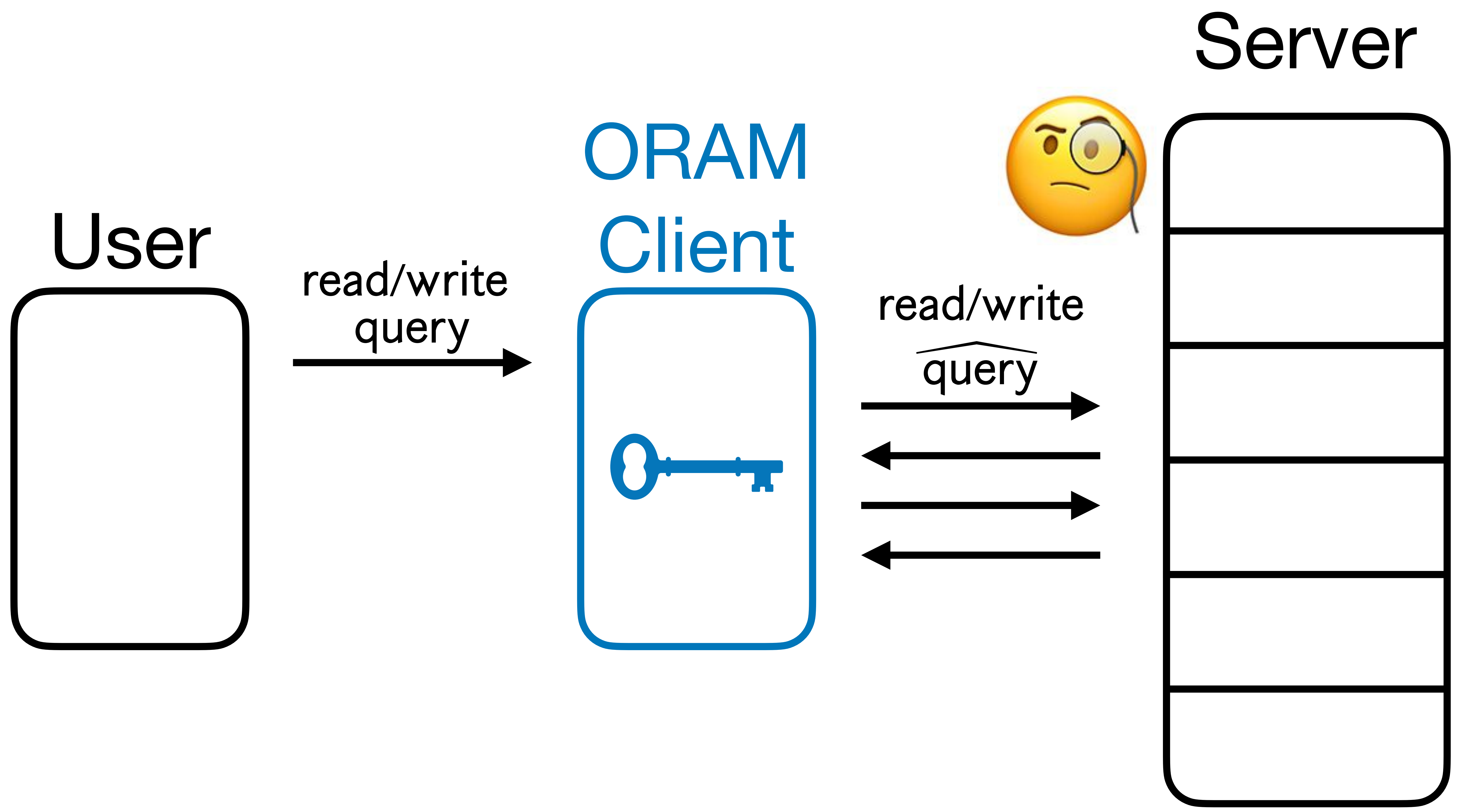

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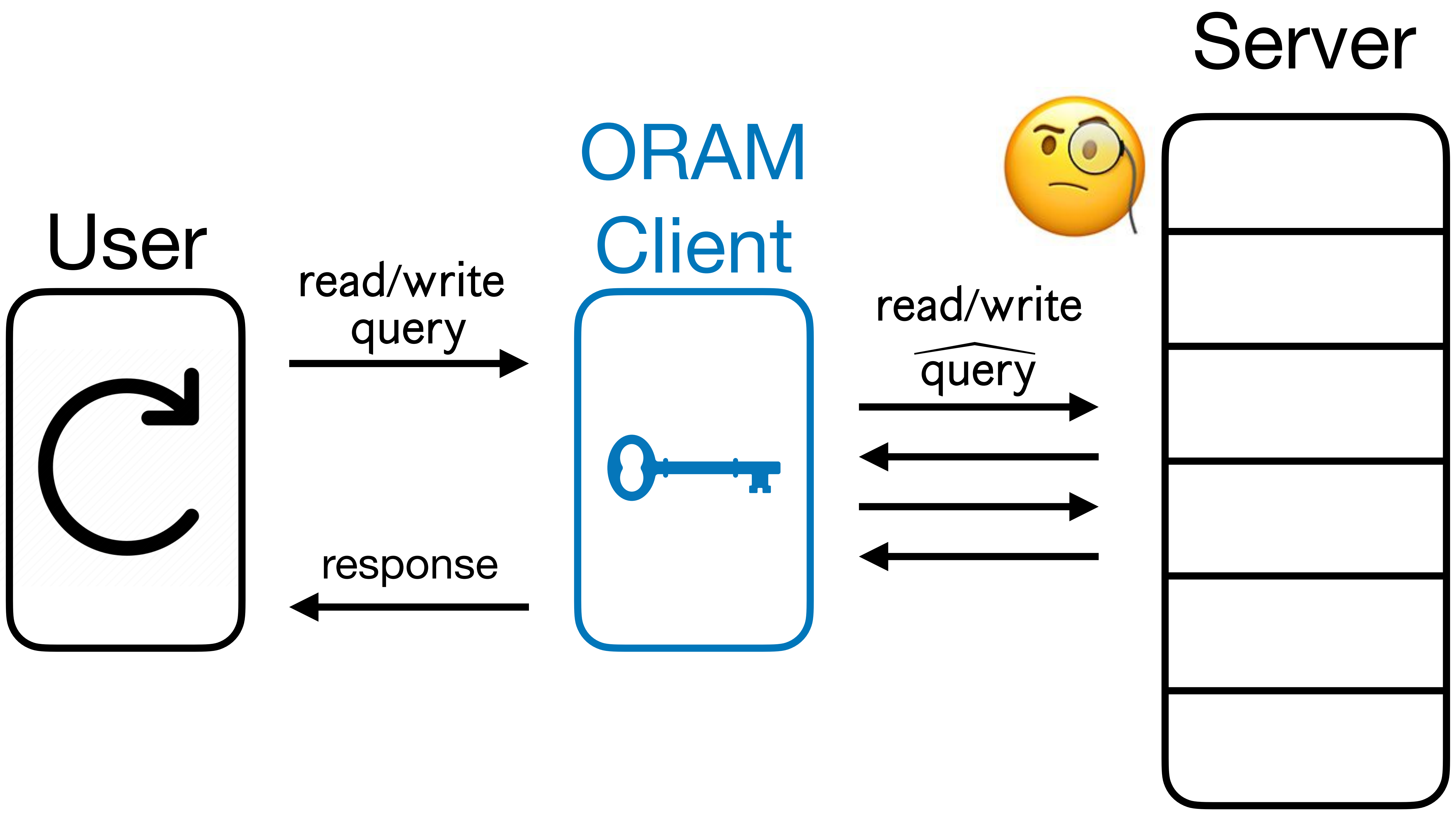

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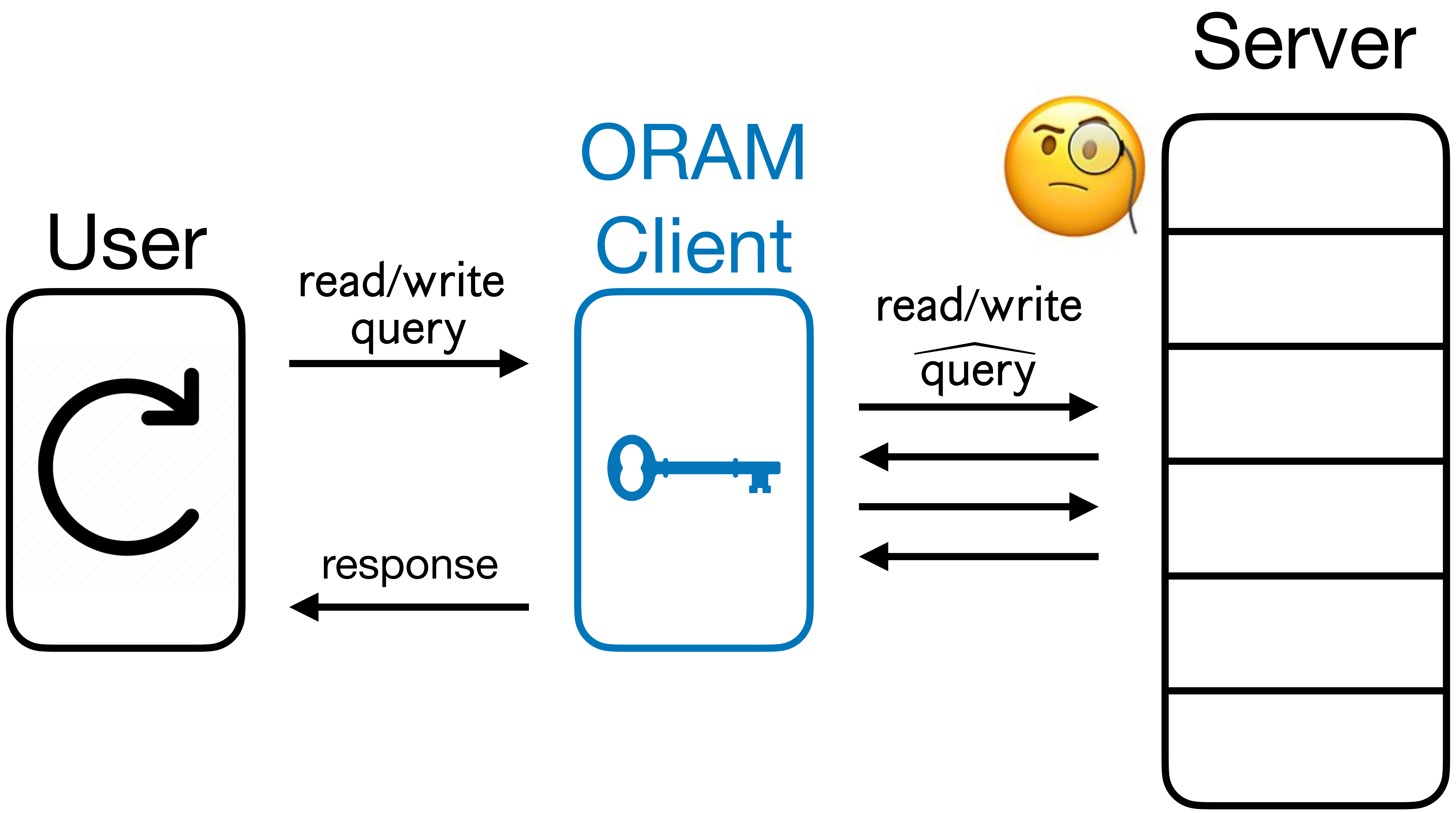

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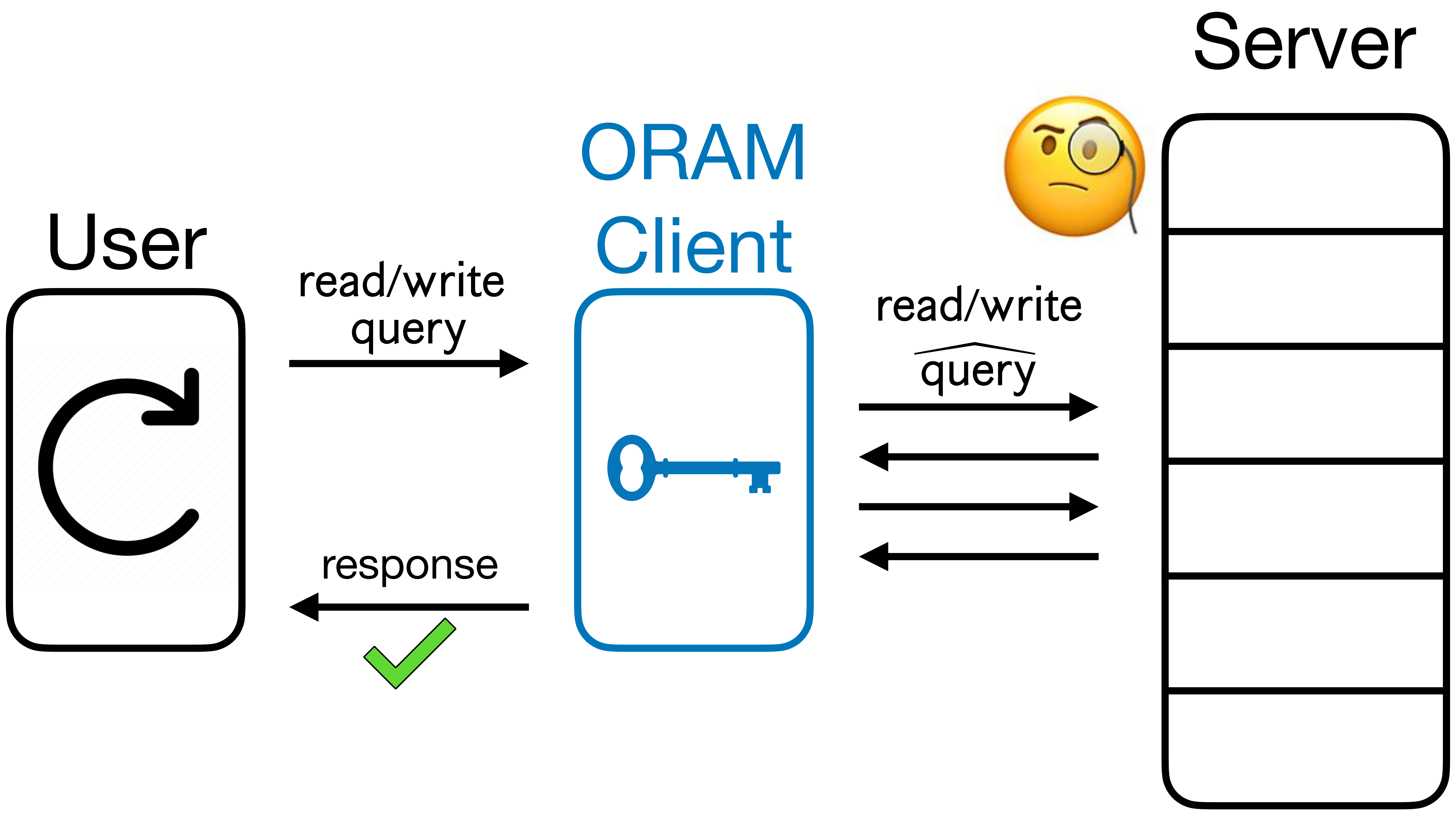

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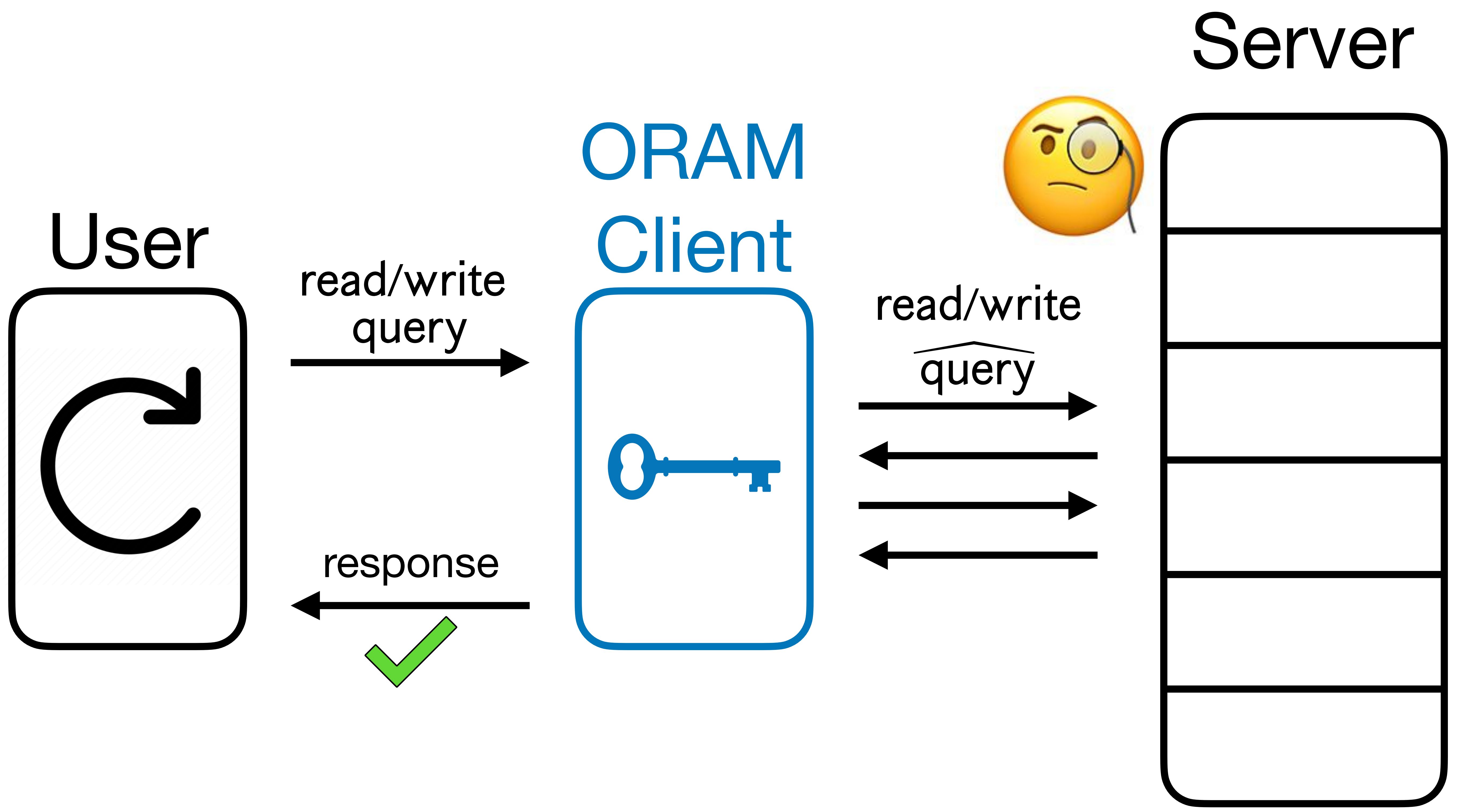

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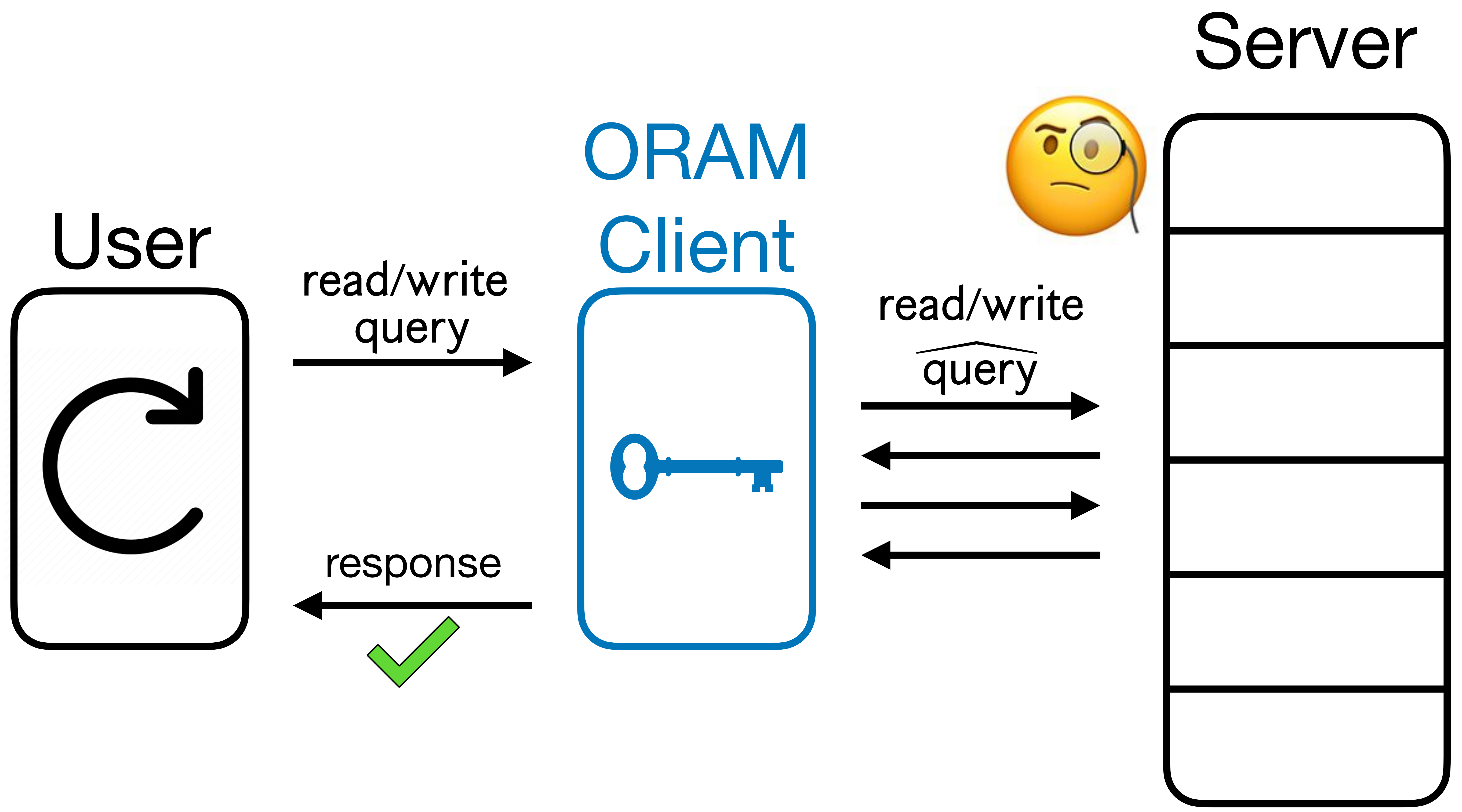

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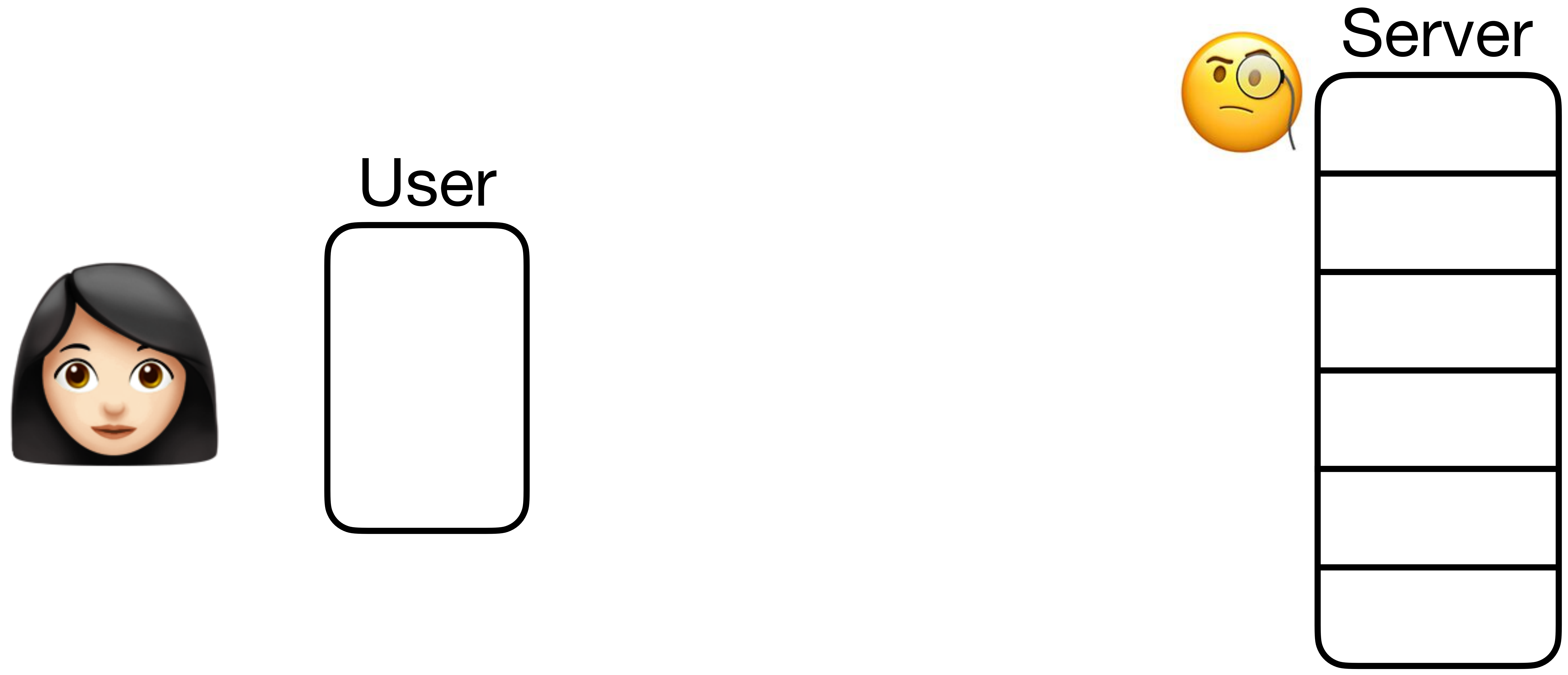

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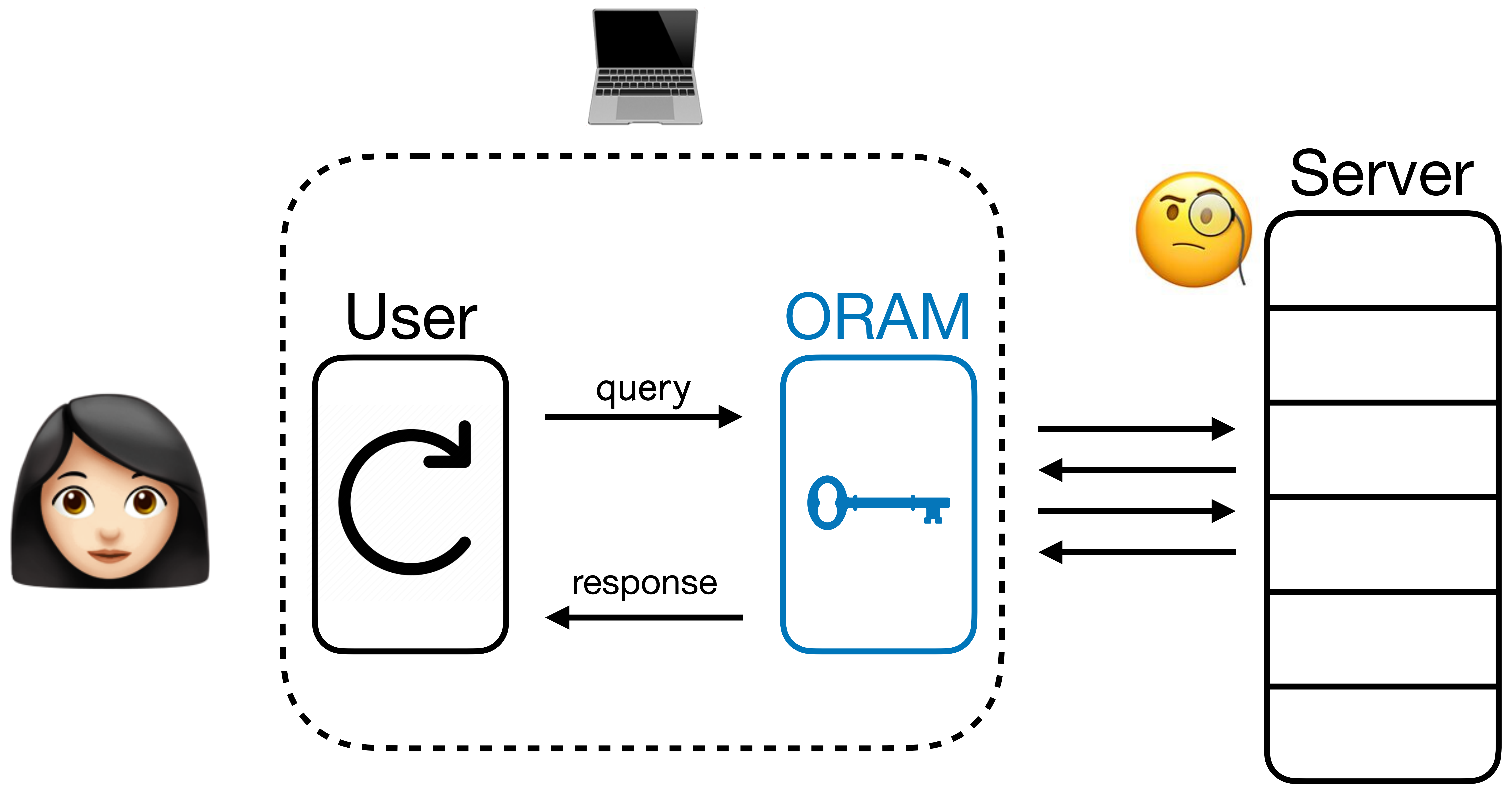

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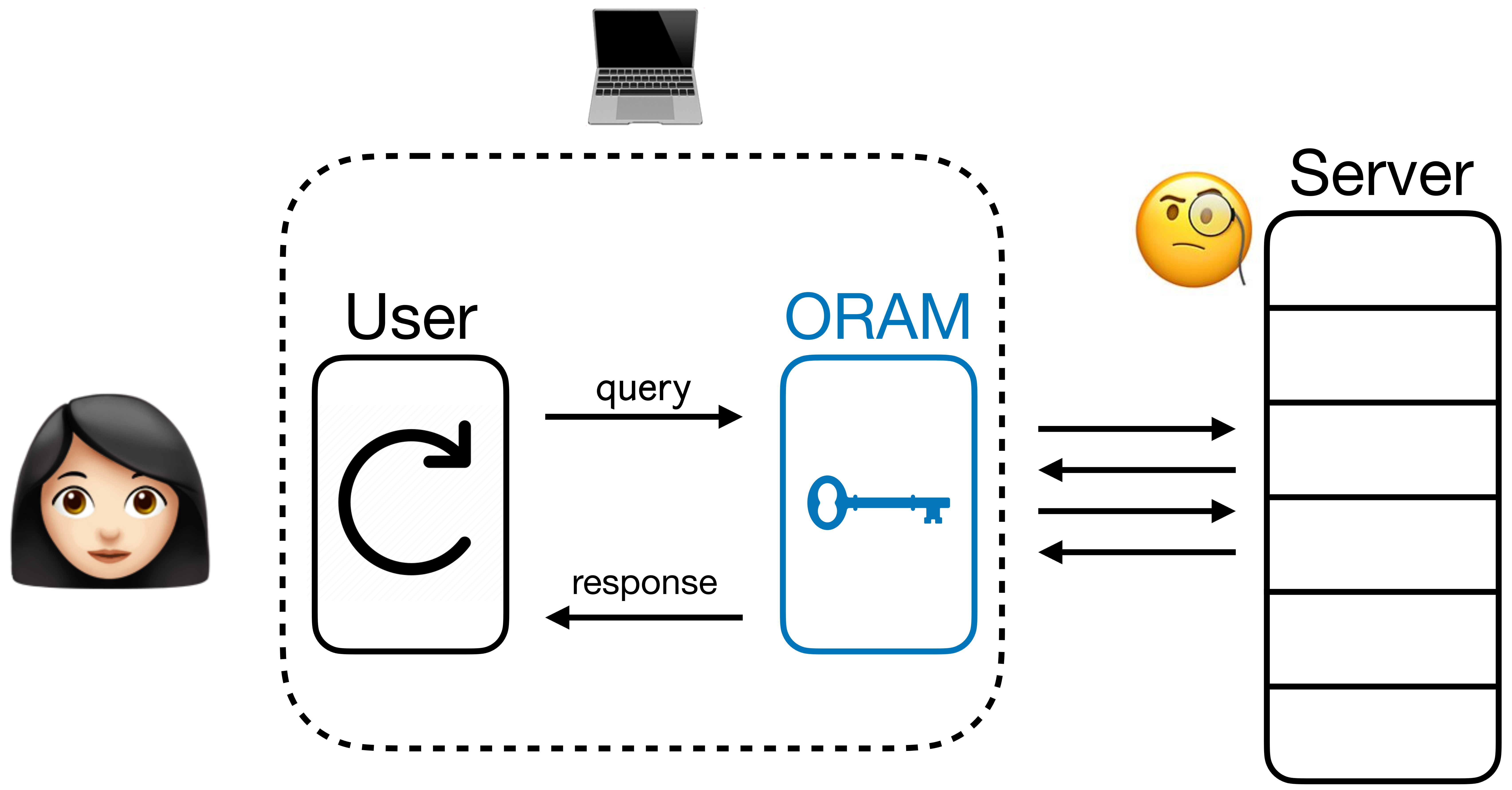

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With ORAM, storage platform can't learn anything.

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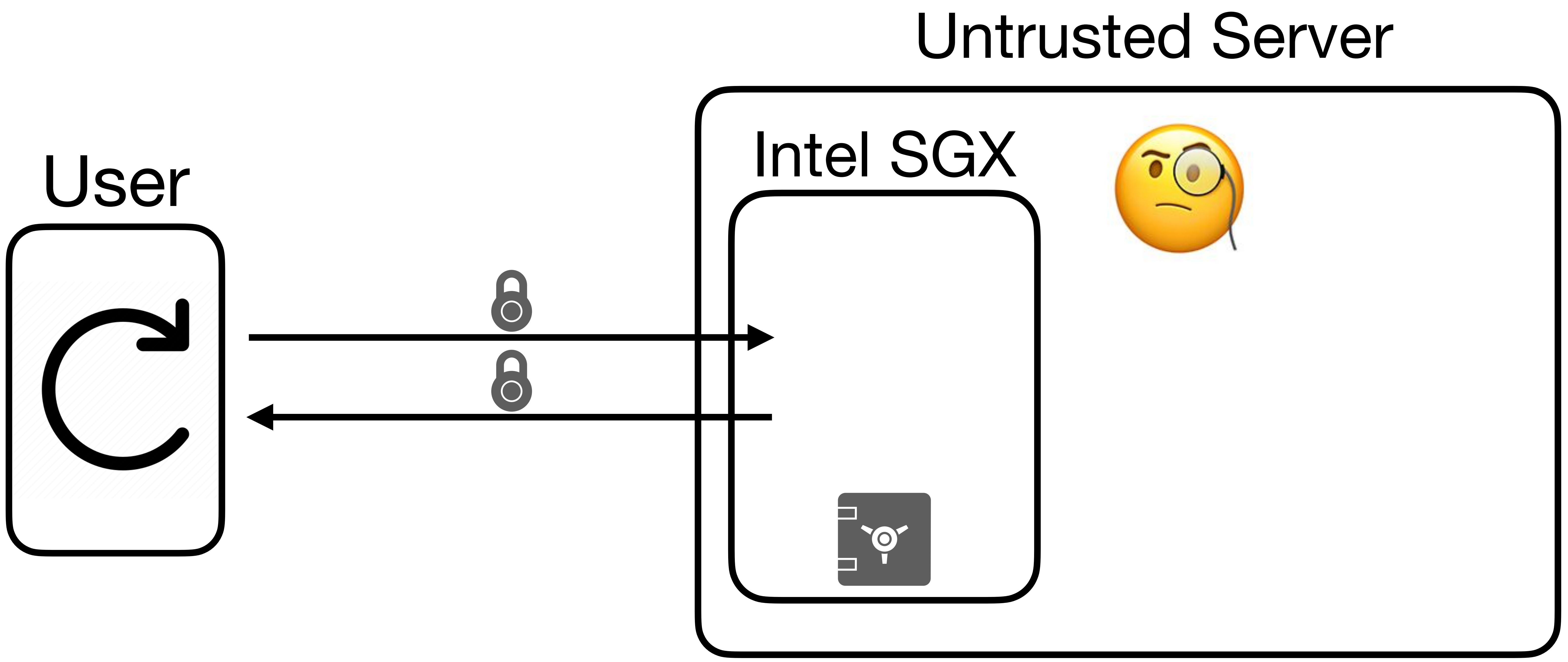

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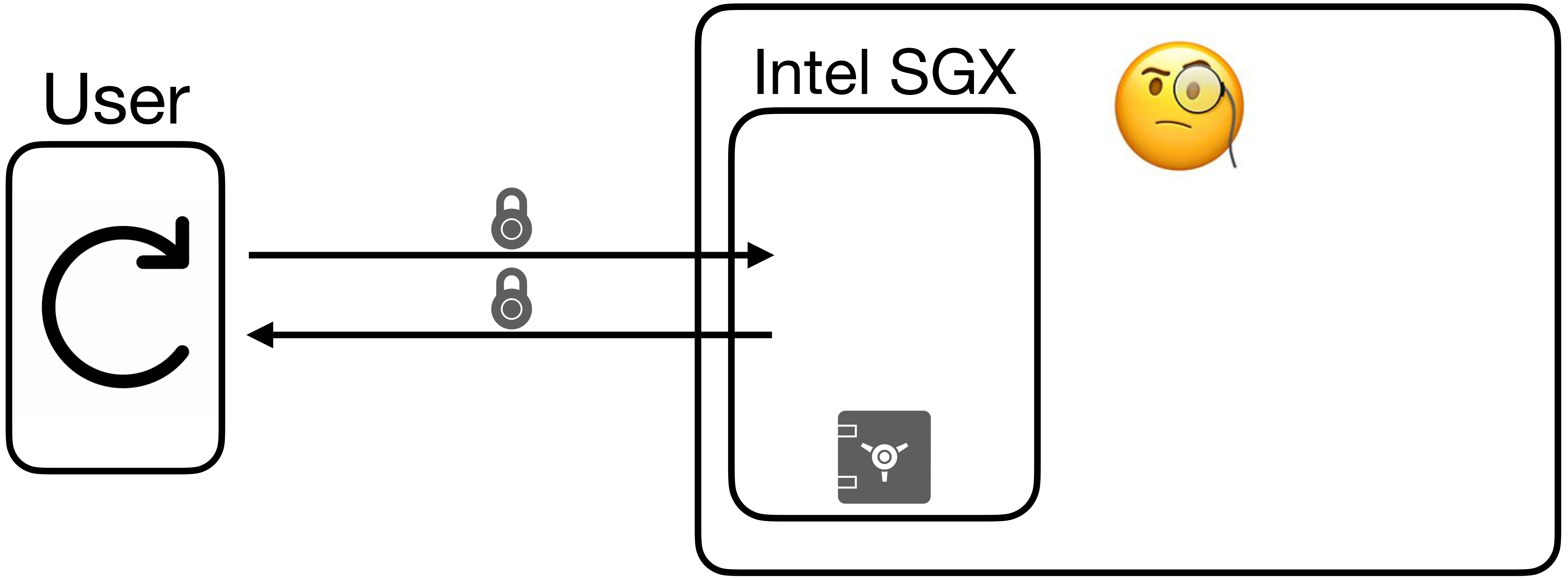

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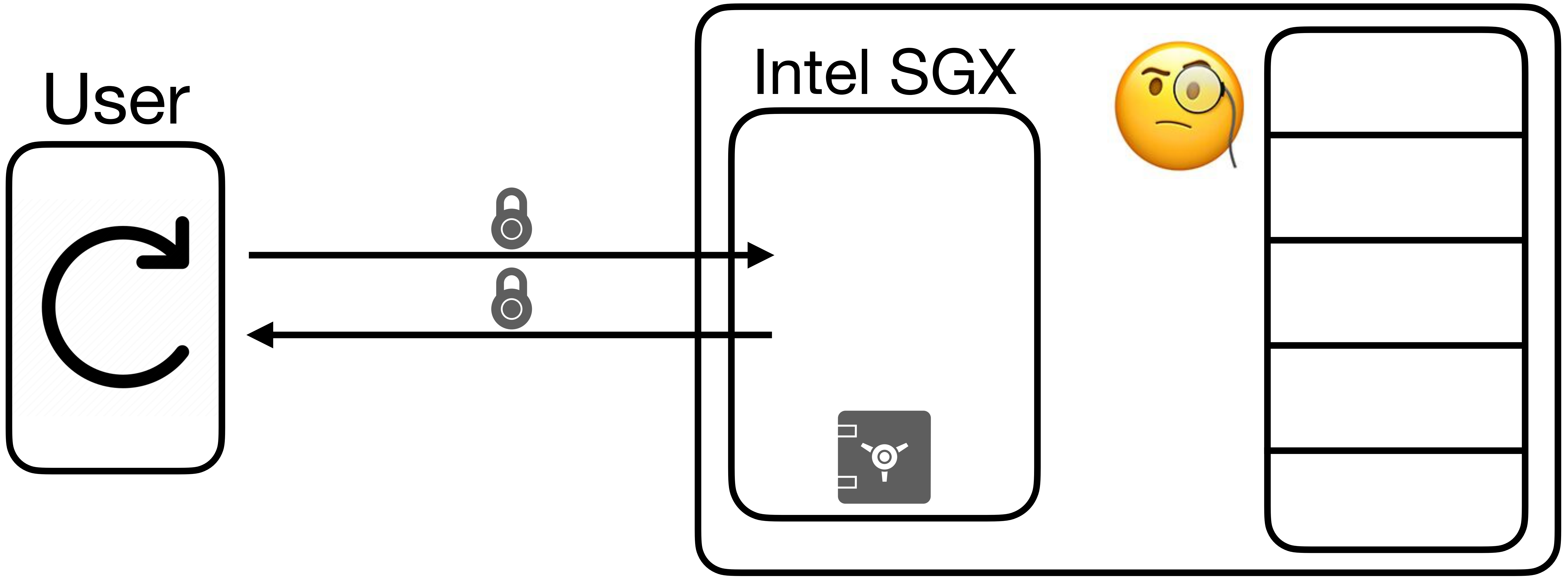

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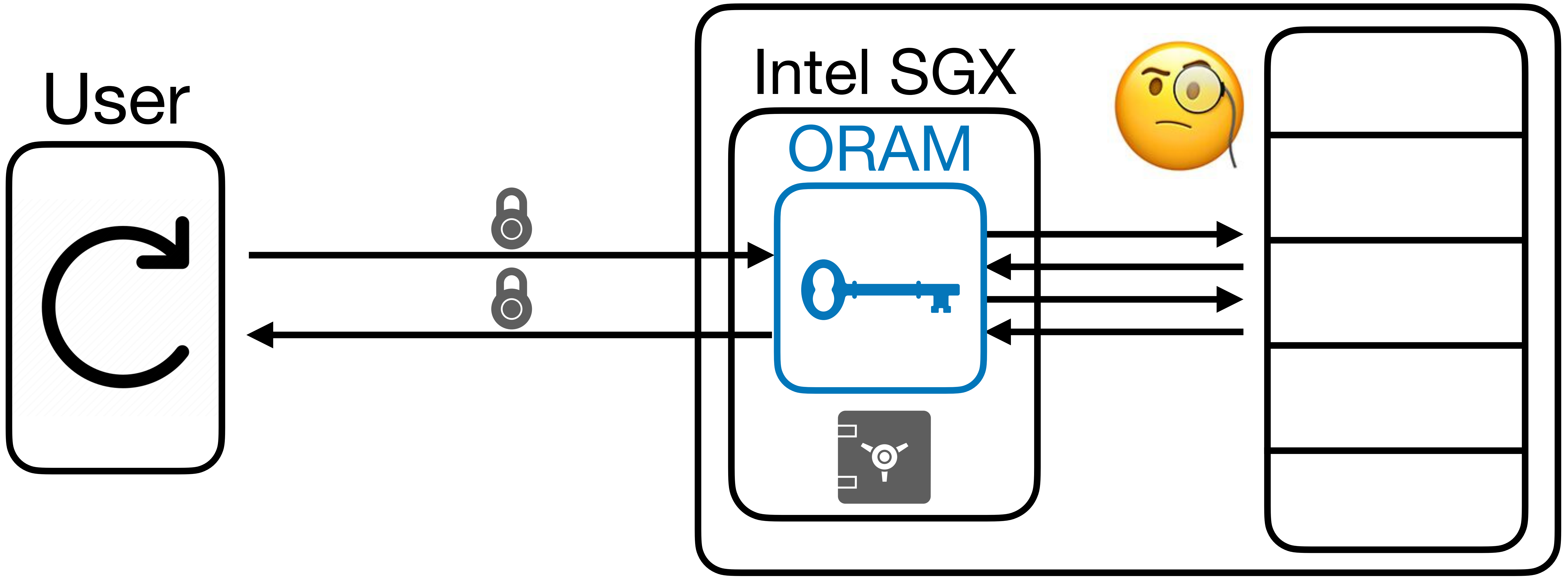

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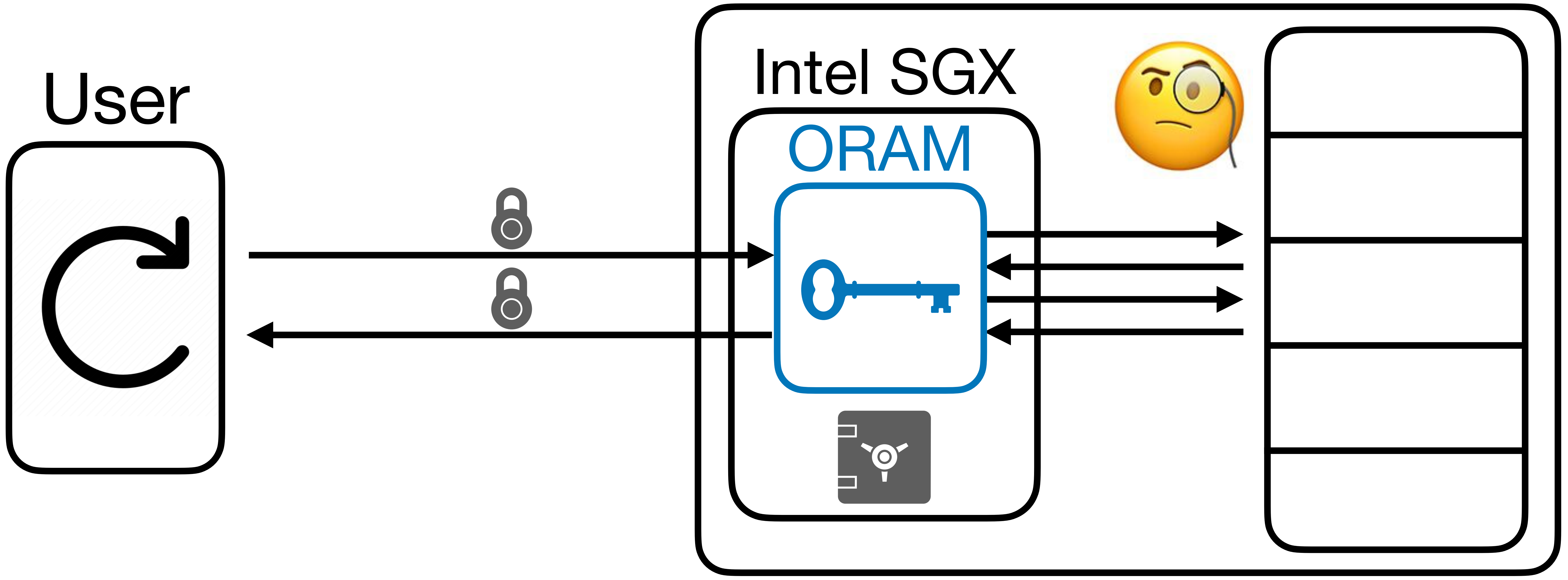
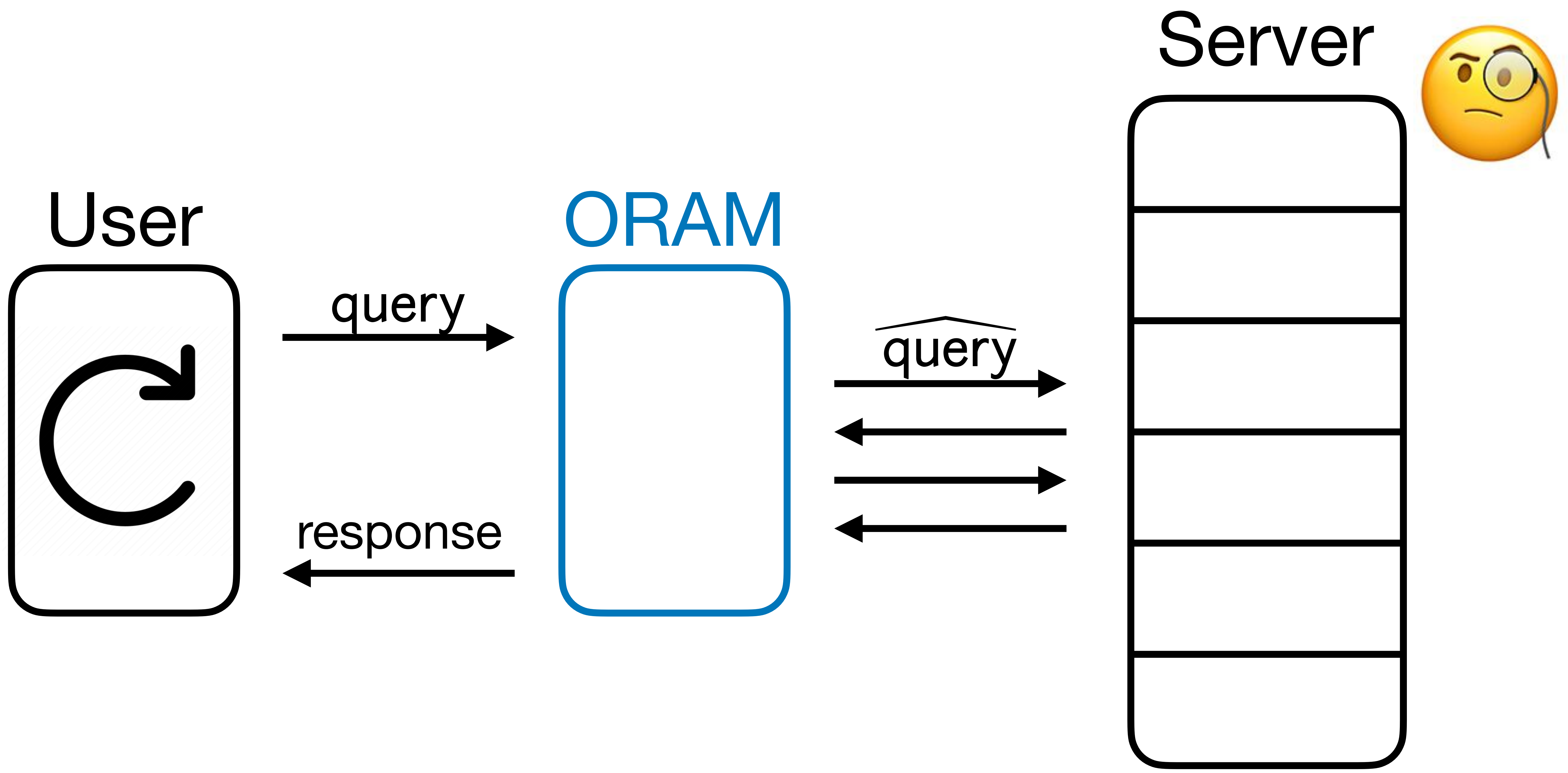


- **Real World**: Signal very recently implemented ORAM for private contact discovery!

Signal

ORAM Efficiency



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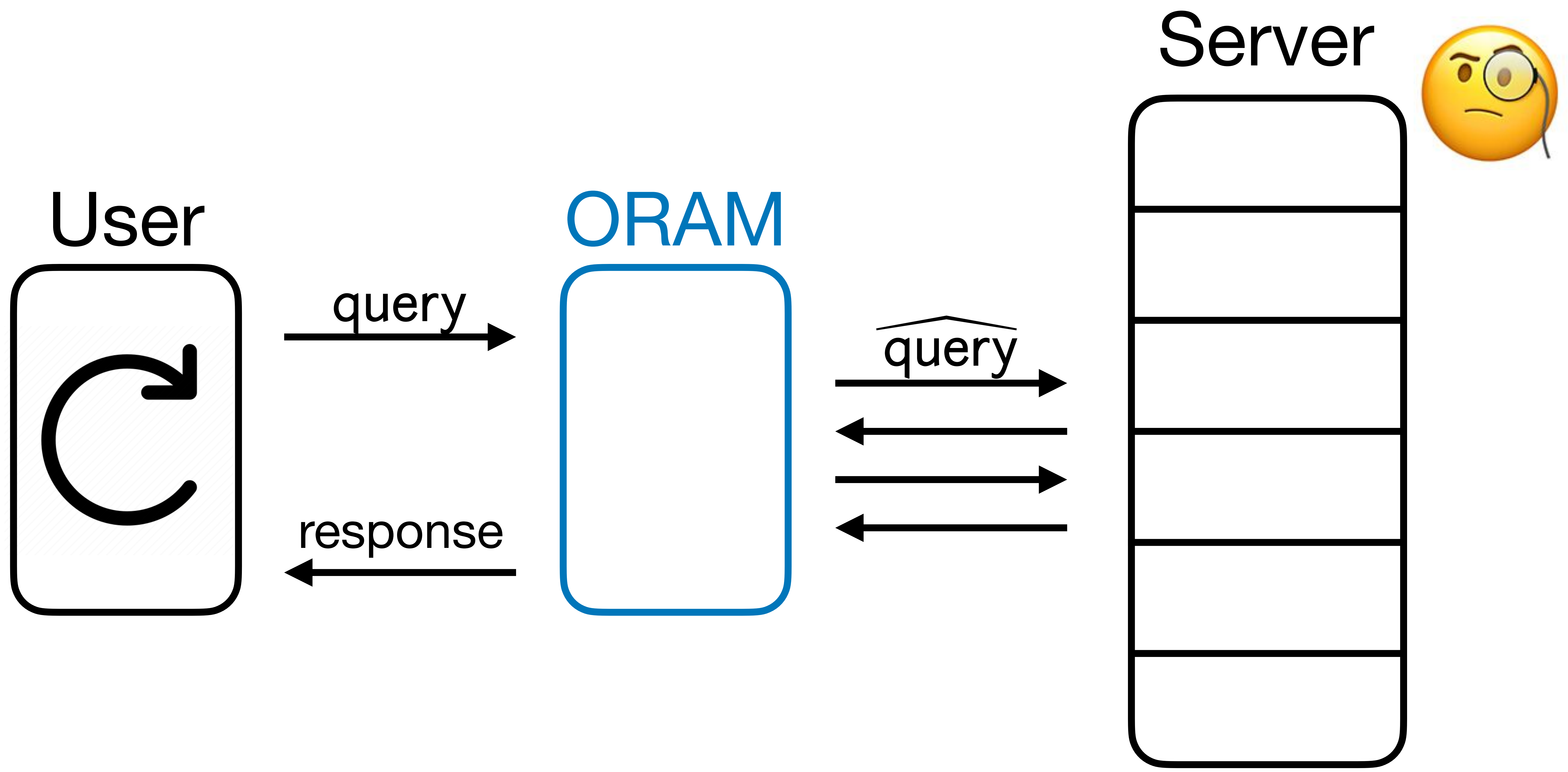

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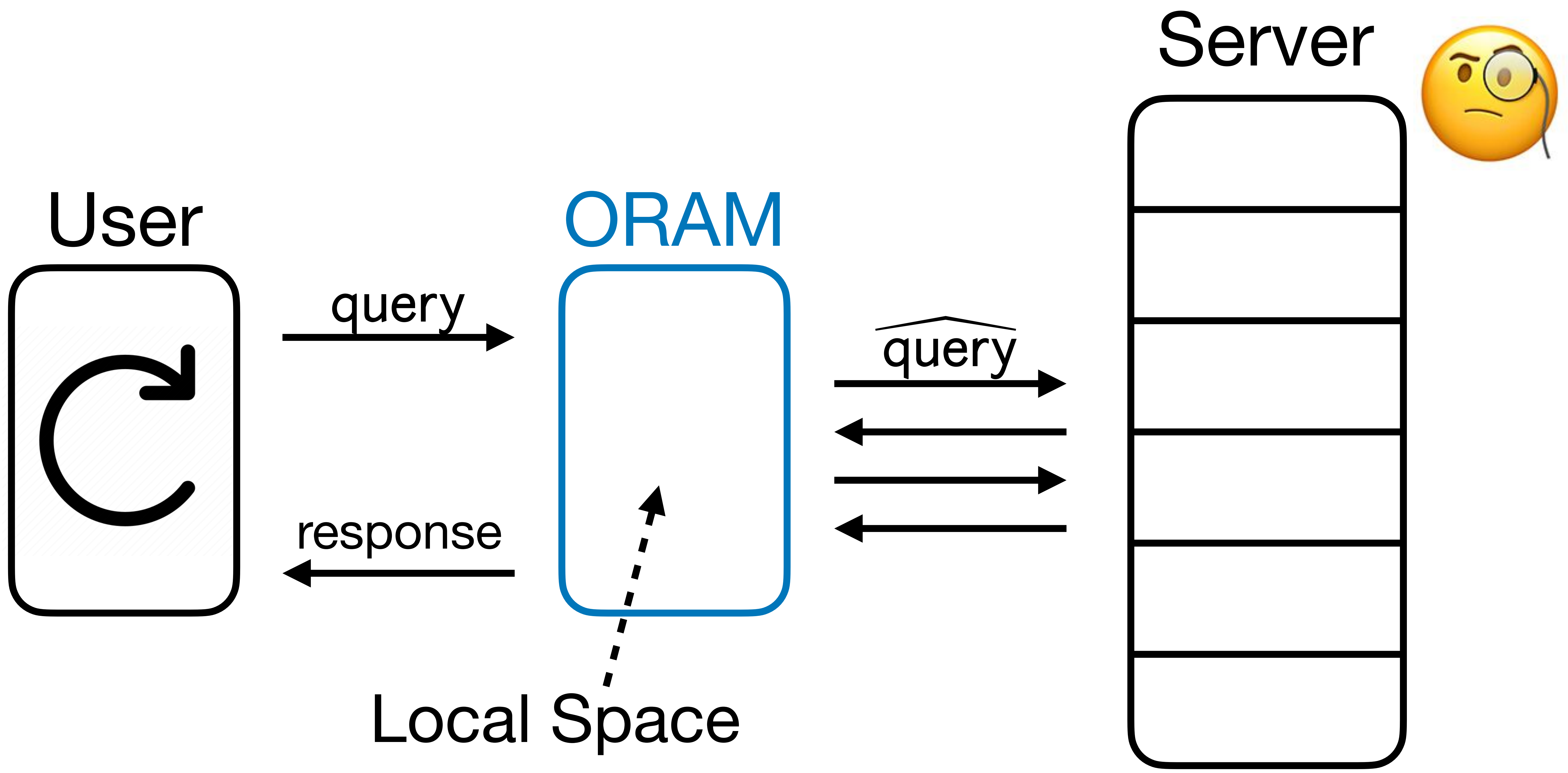

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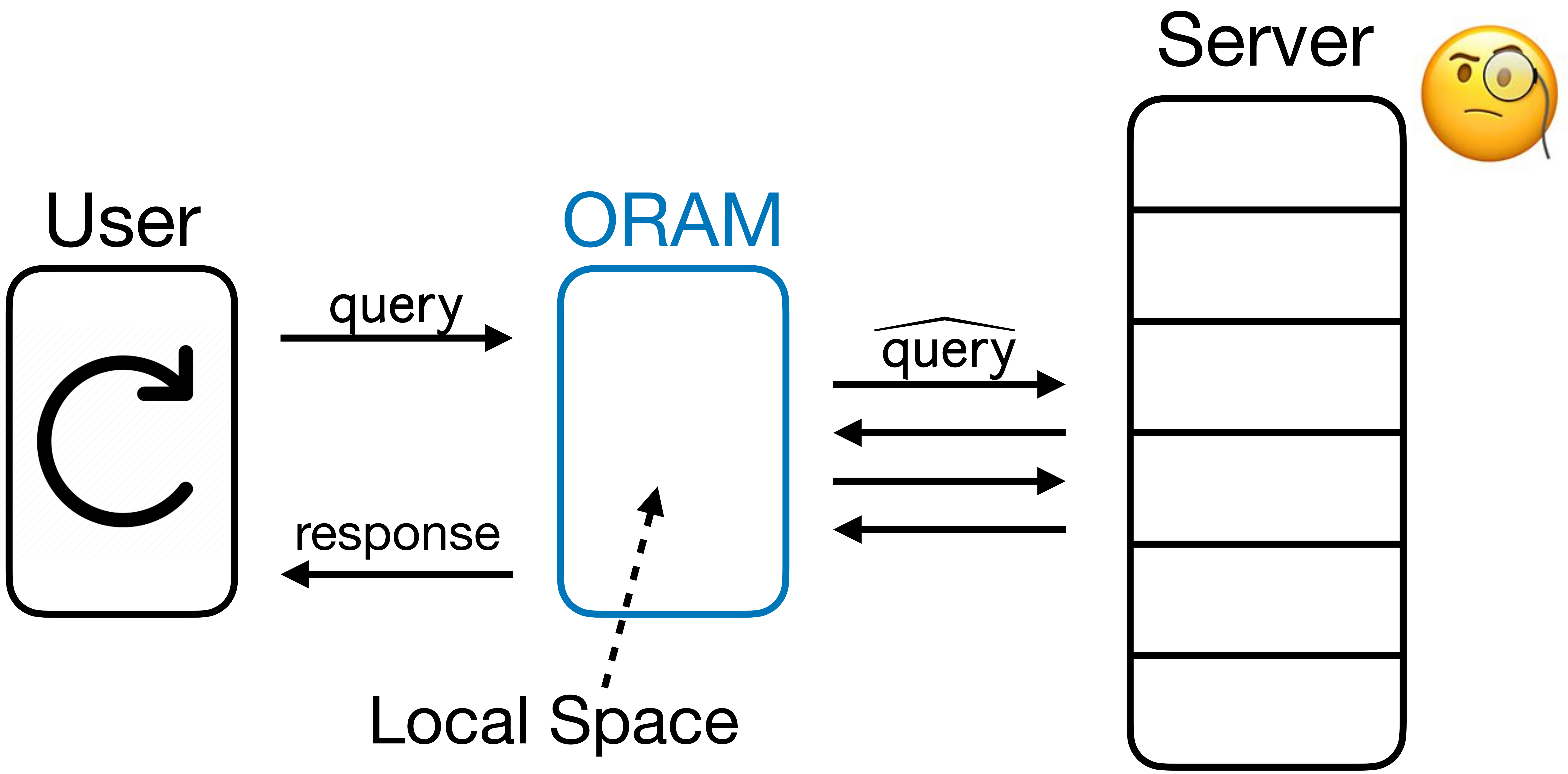

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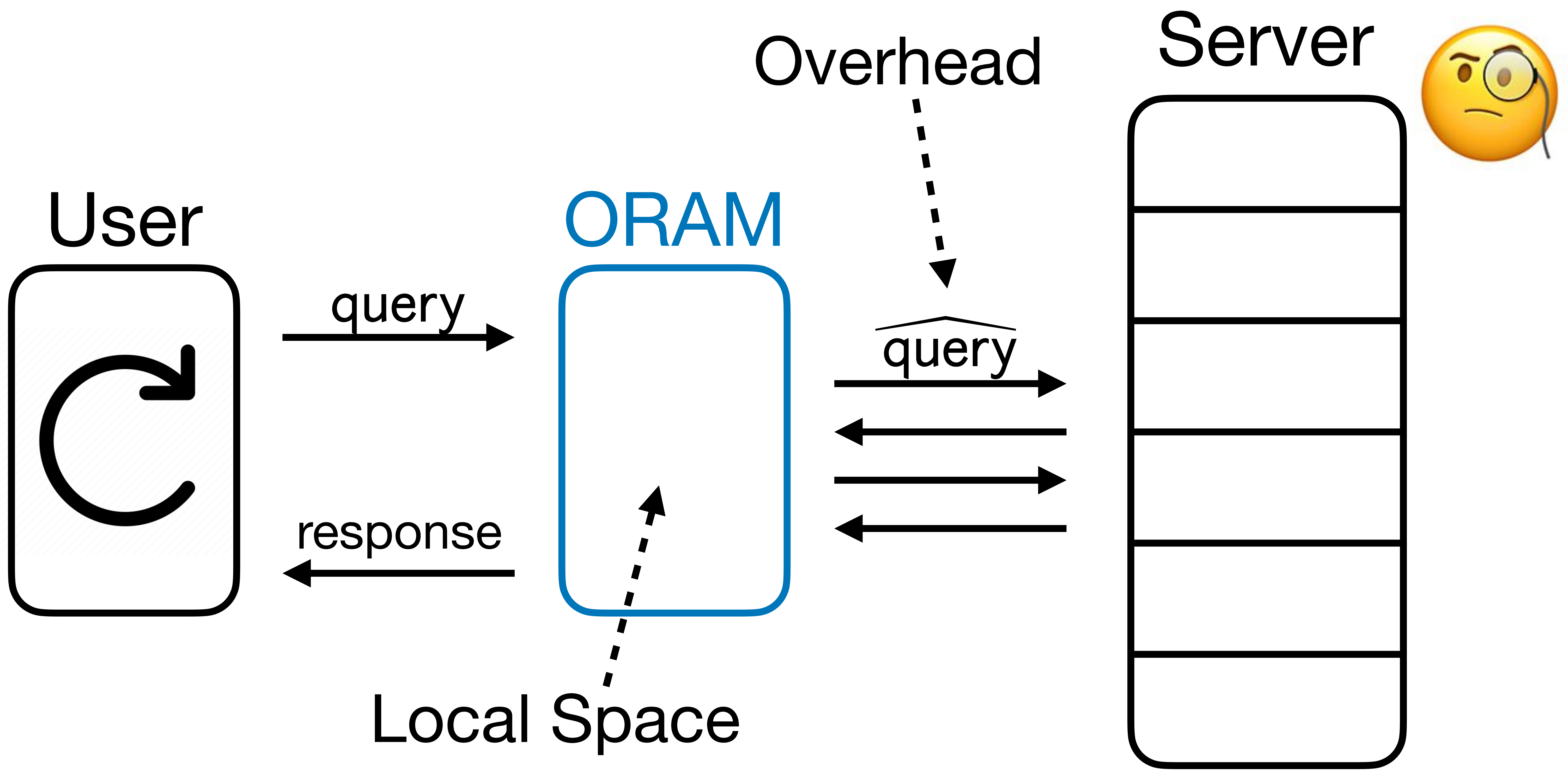

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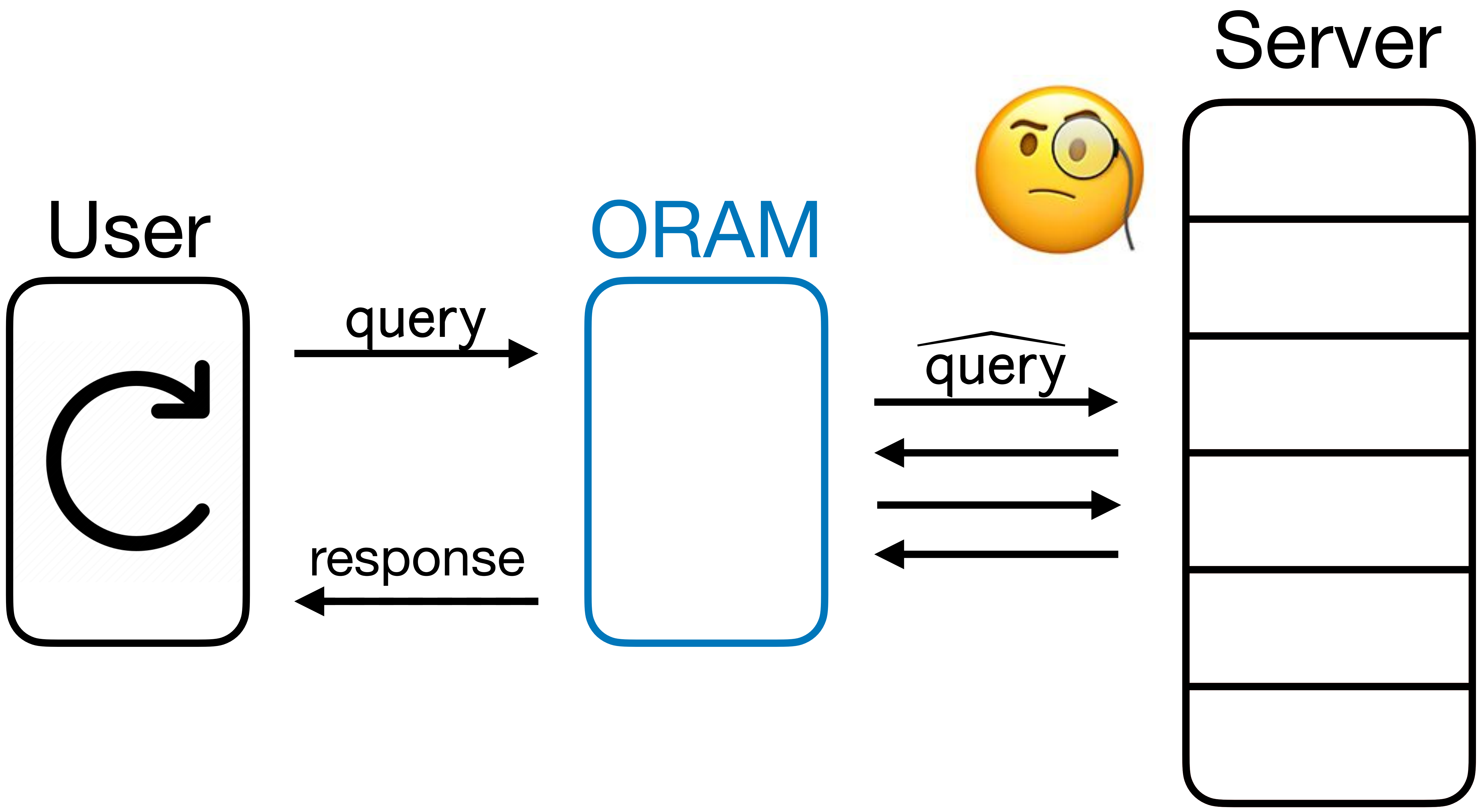

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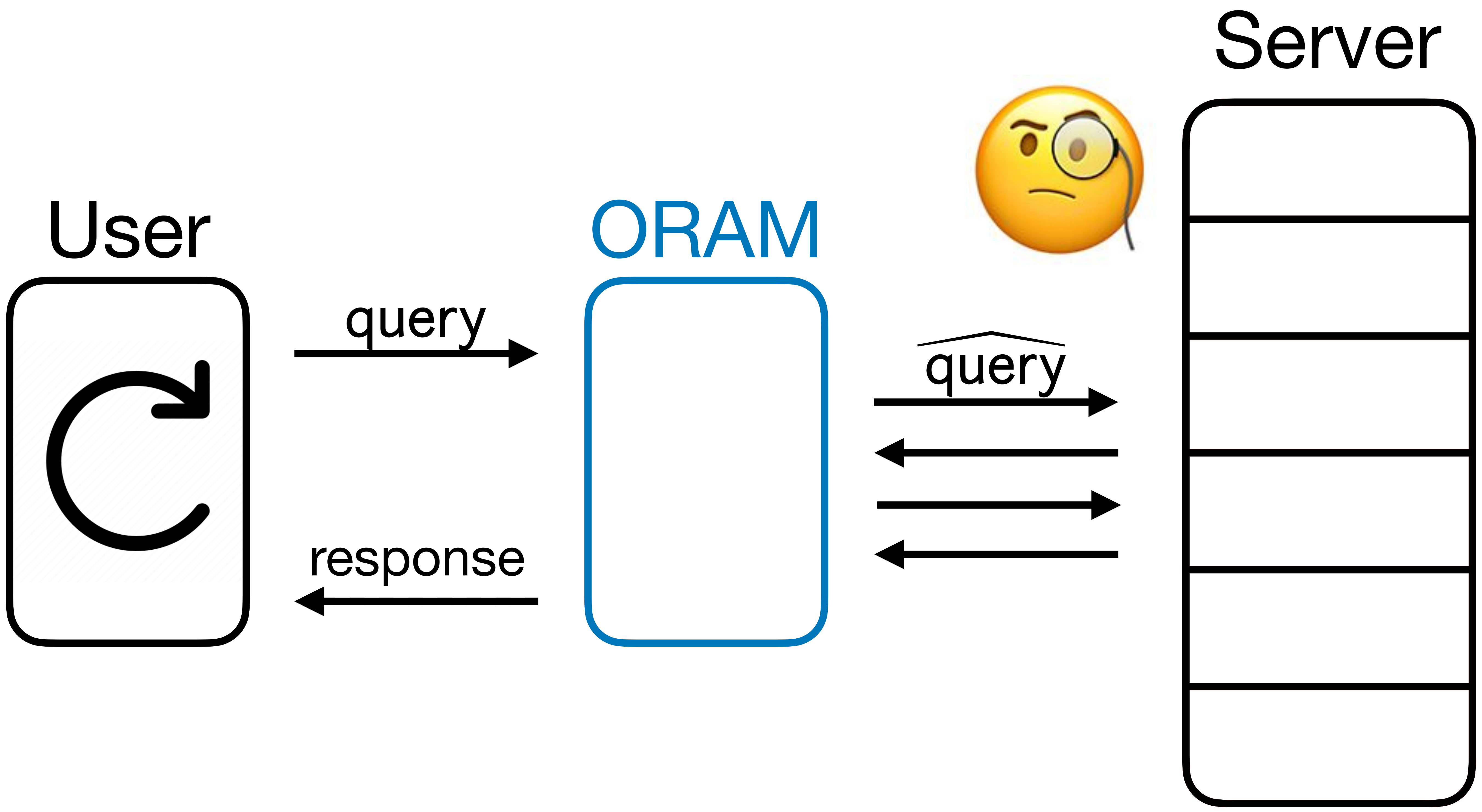

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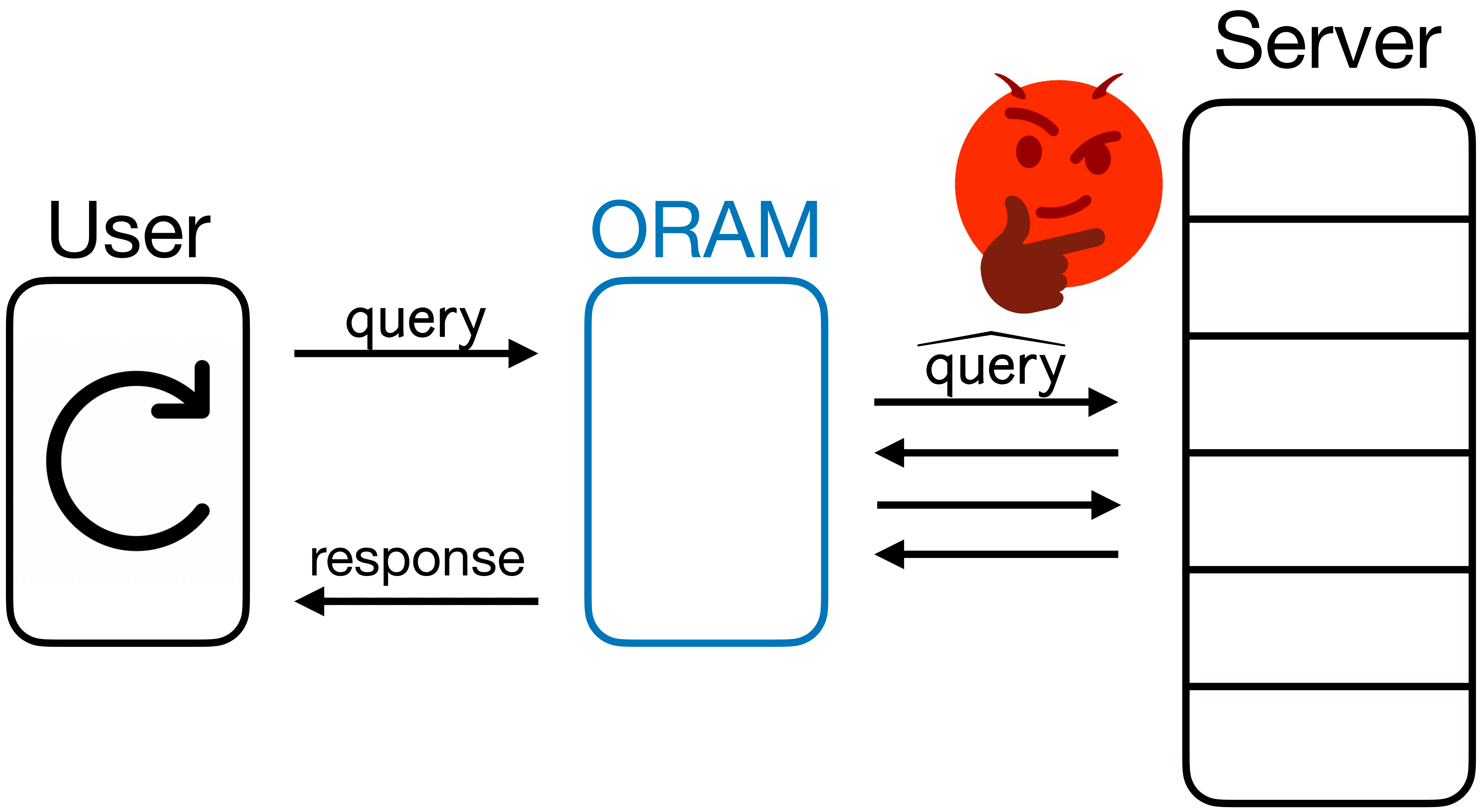

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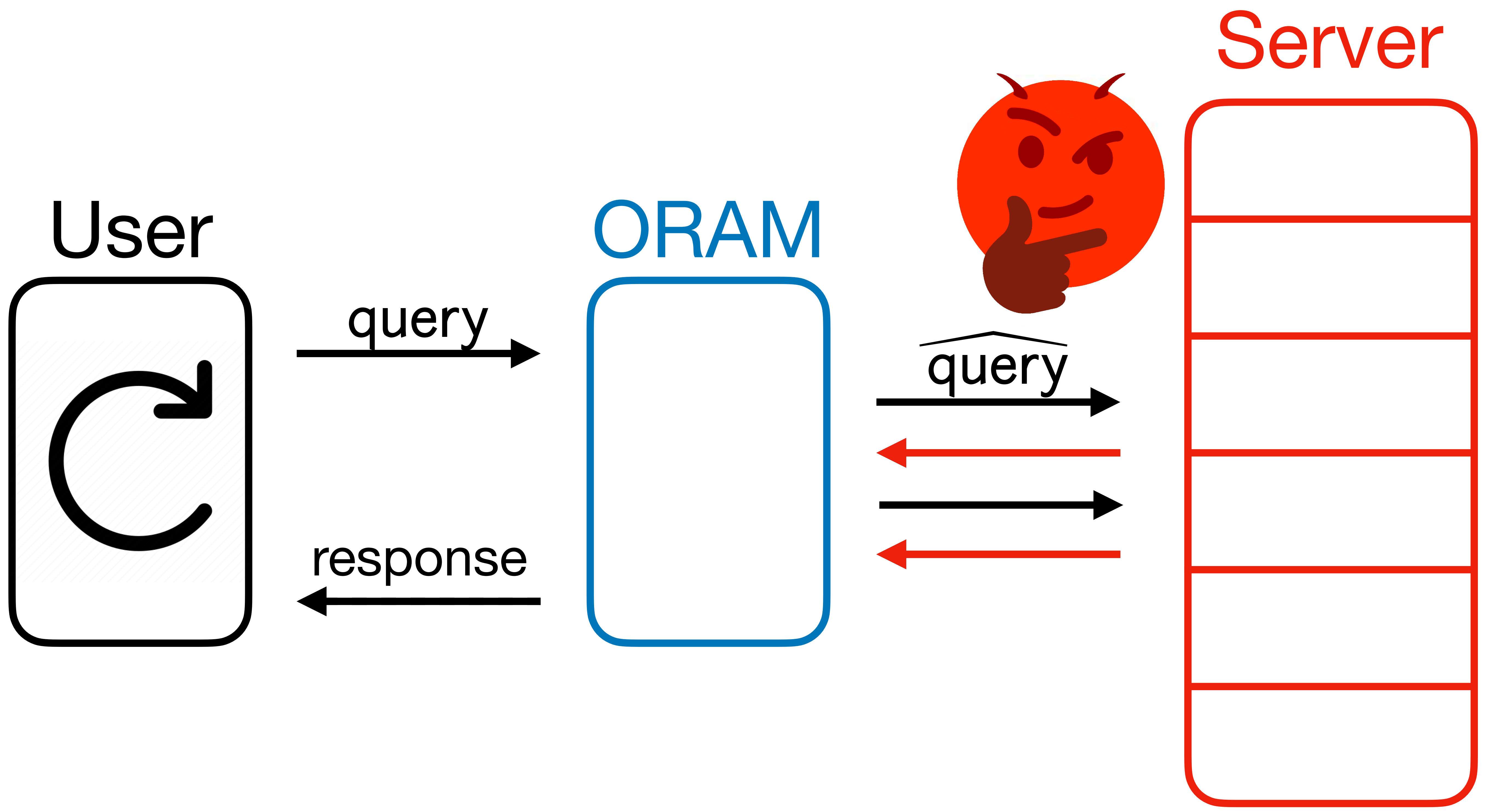

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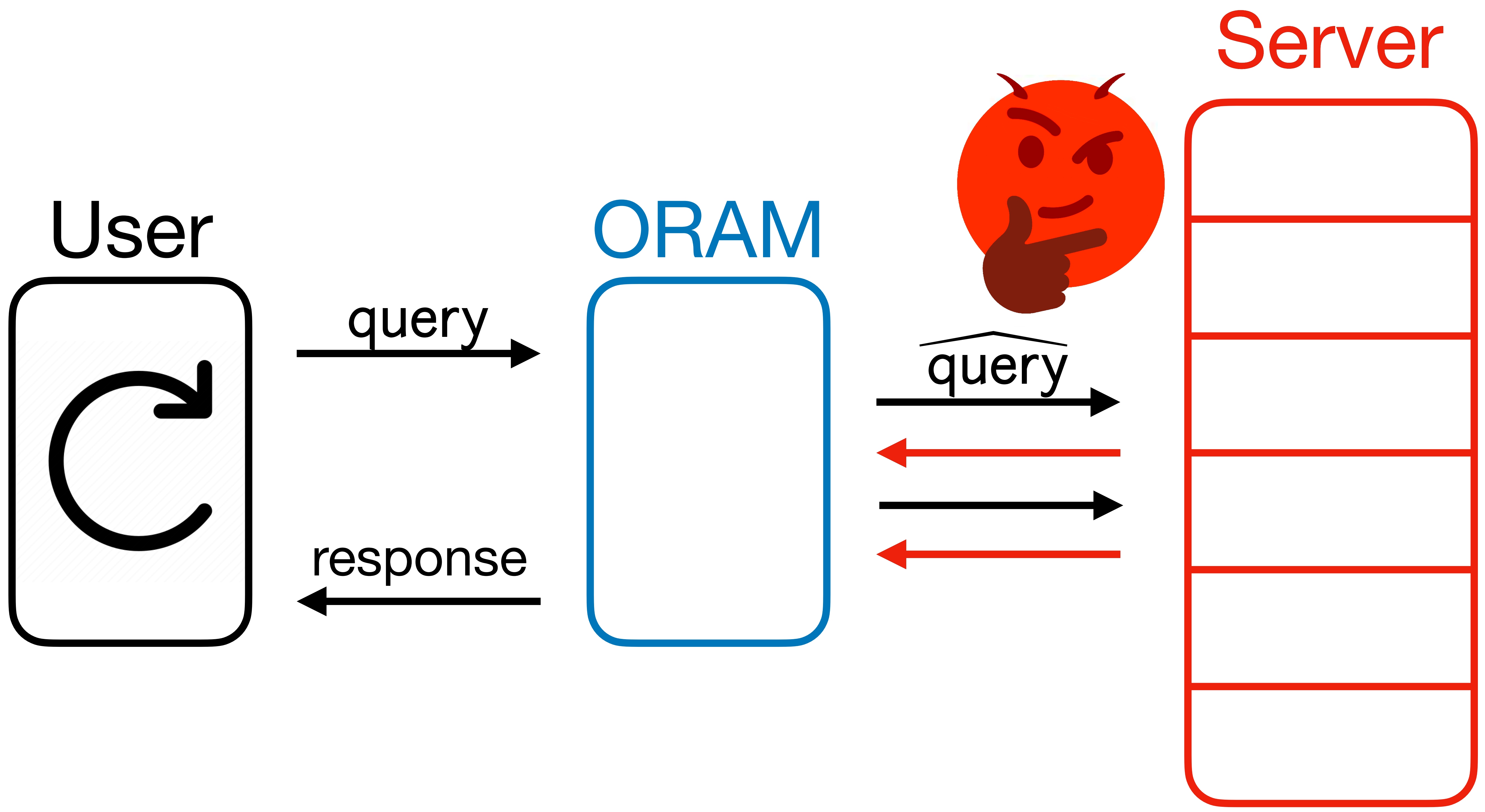

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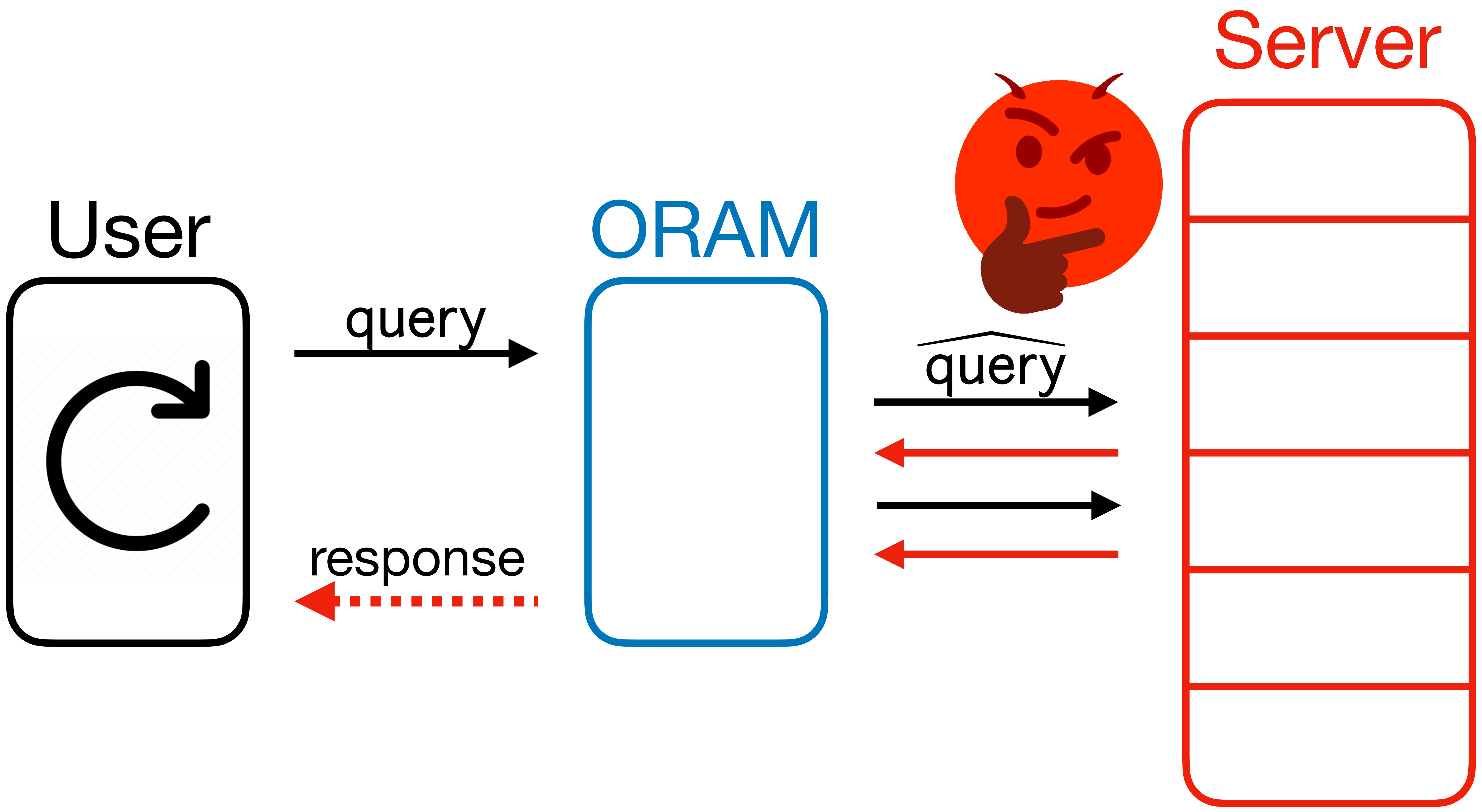

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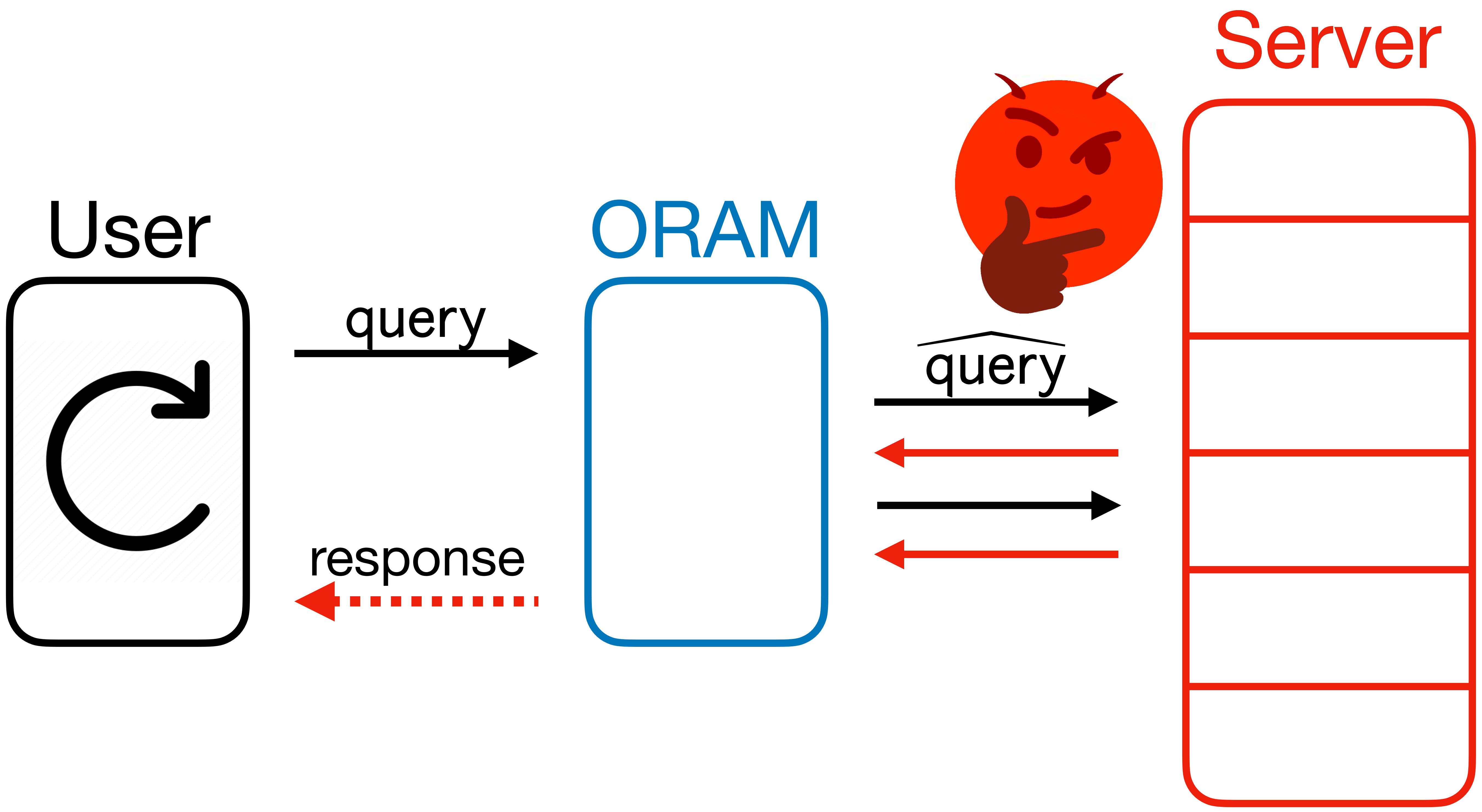

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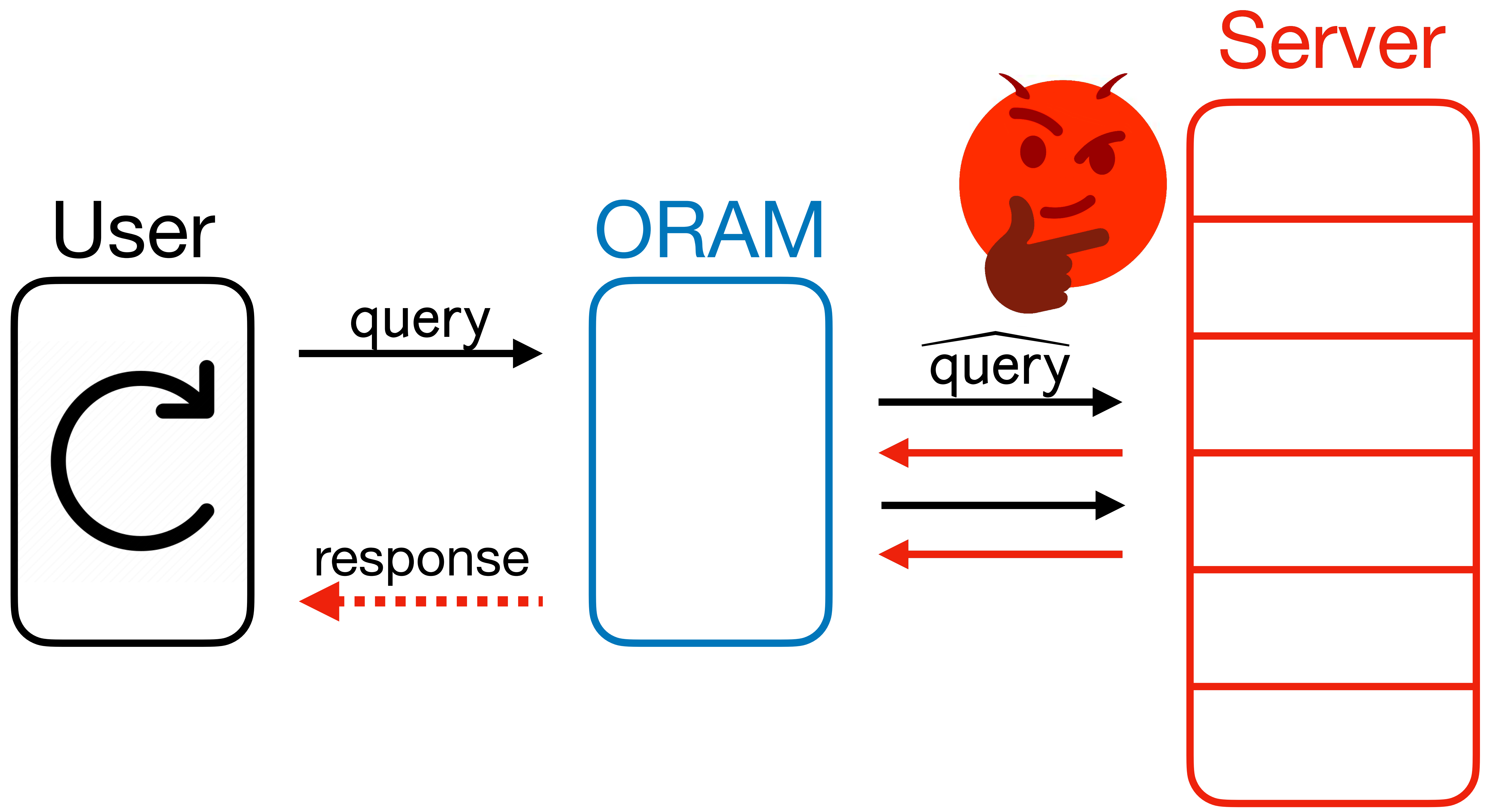

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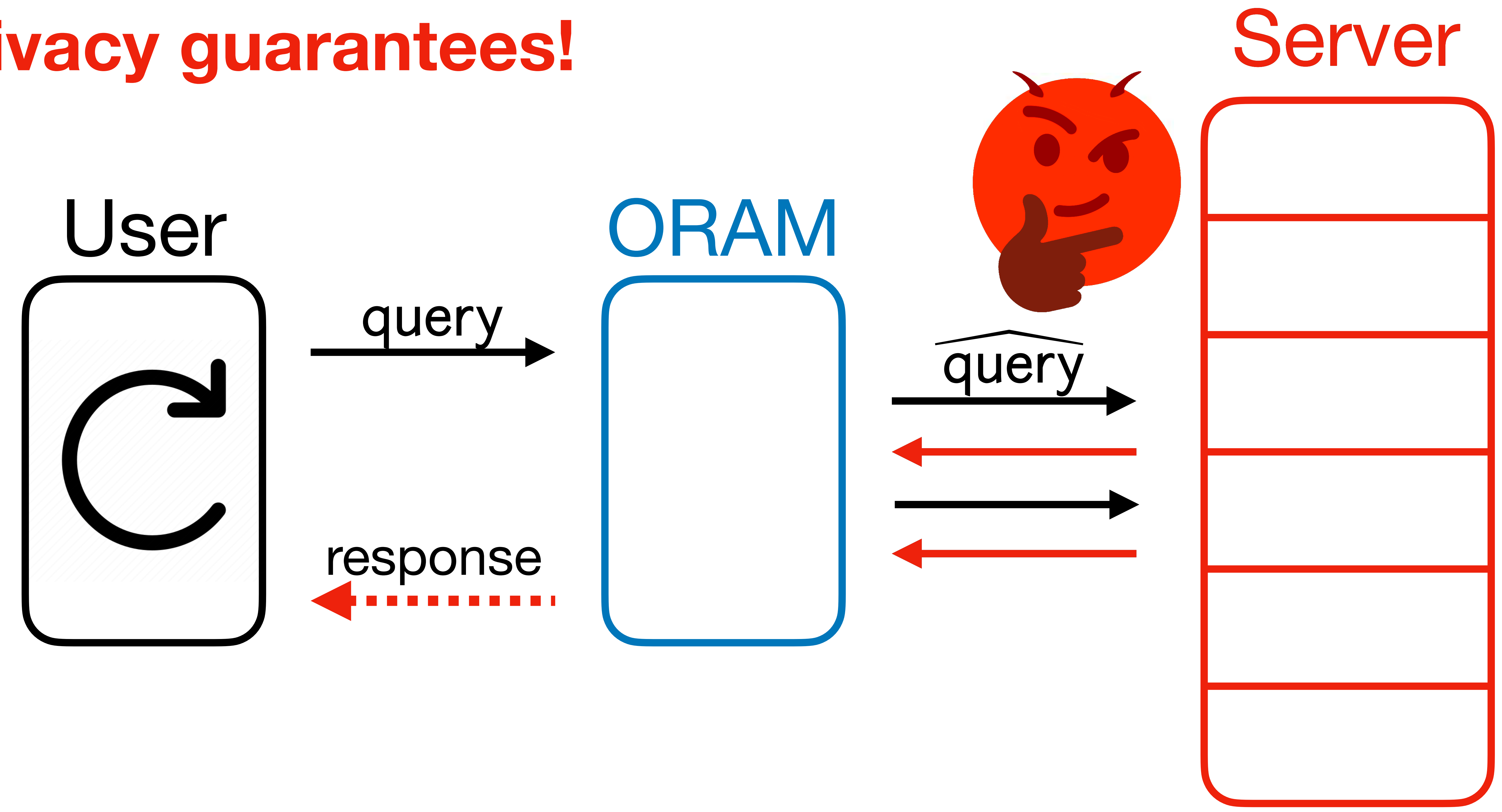

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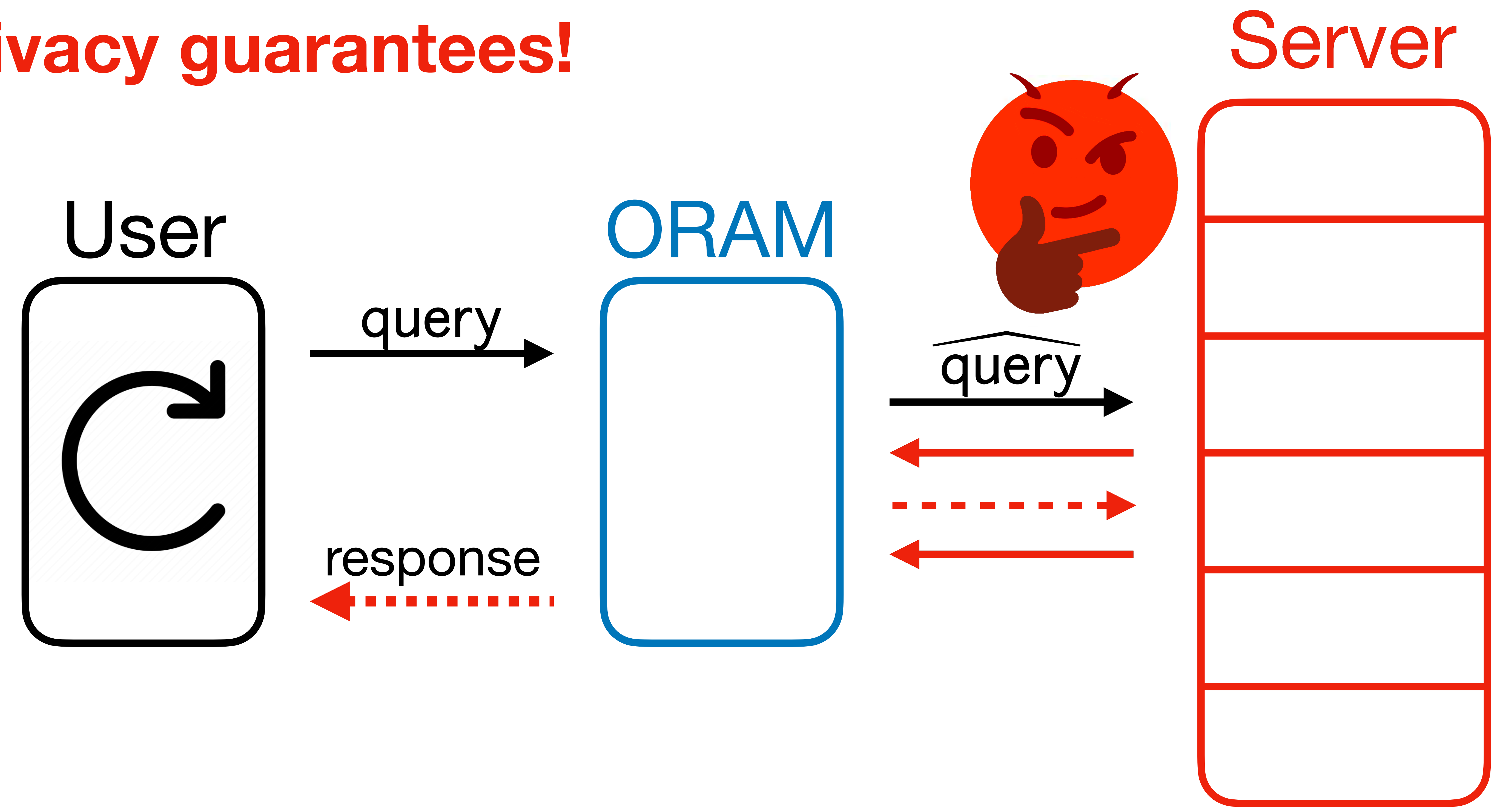

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We start with **OptORAMa** [Asharov, Komargodski, Lin, Nayak, Peserico, Shi] - a **honest-but-curious** ORAM with **optimal** $O(\log N)$ overhead.

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- A memory checker is a protocol that detects whether a malicious server tampered with RAM. [Blum, Evans, Gemmell, Kannan, Naor ’94]

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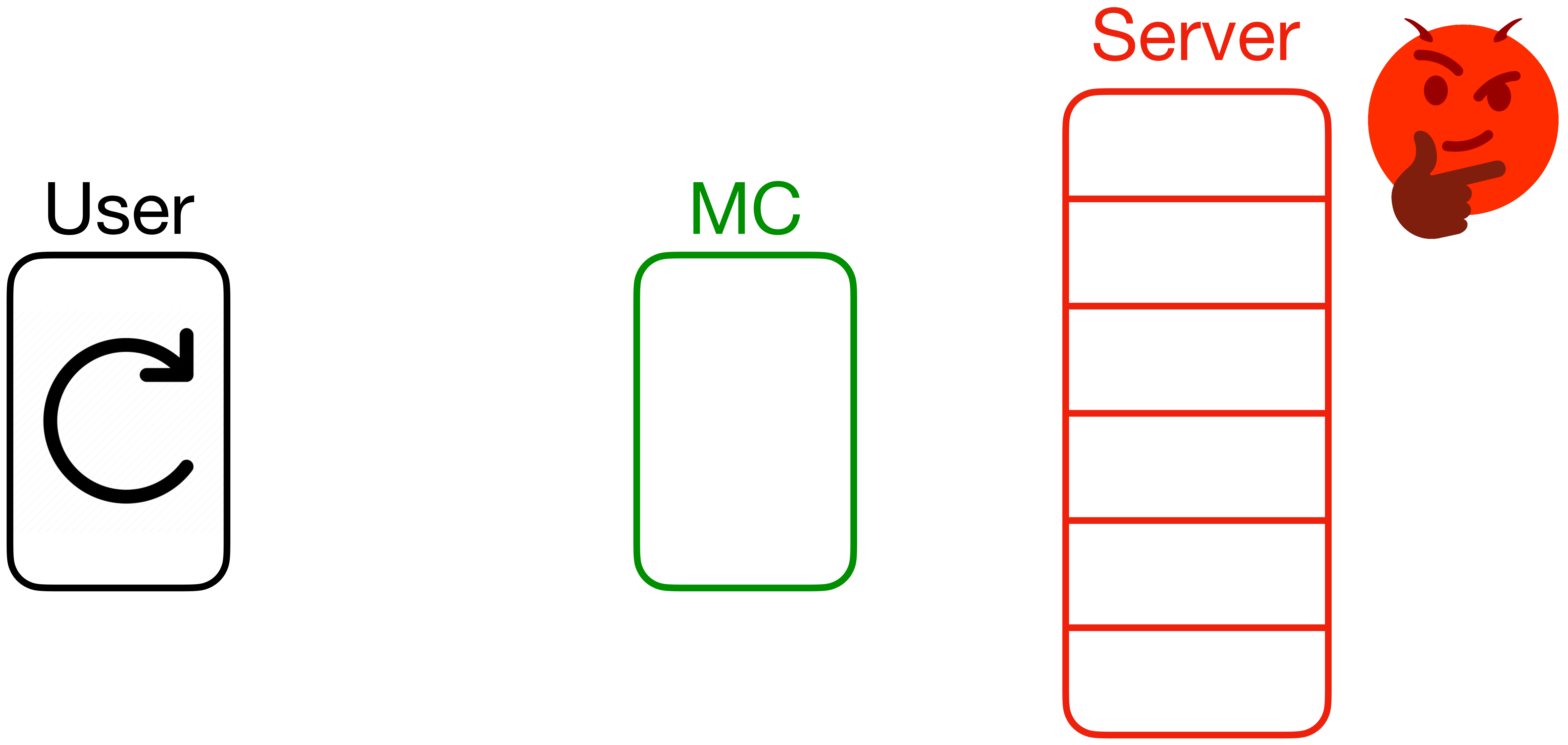

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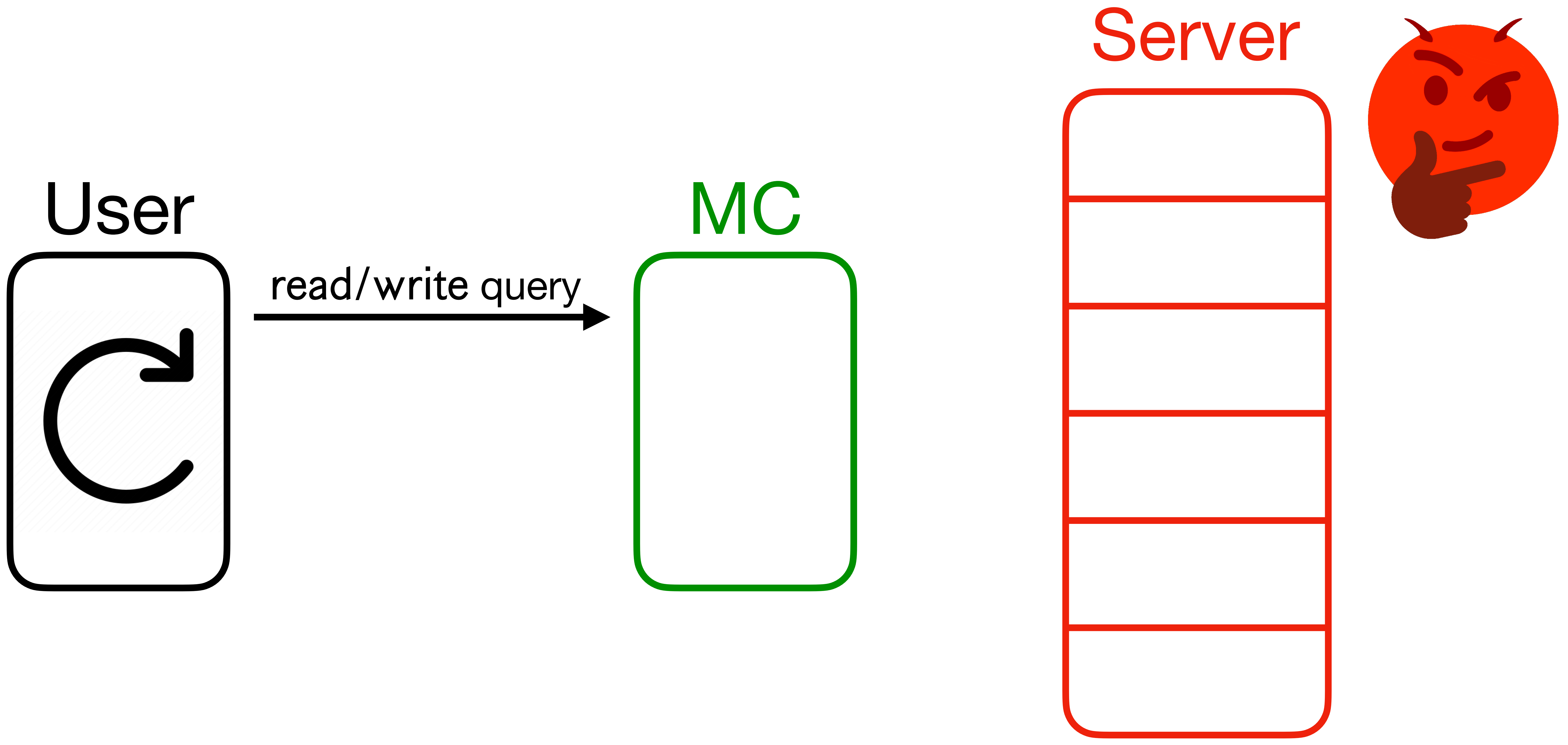

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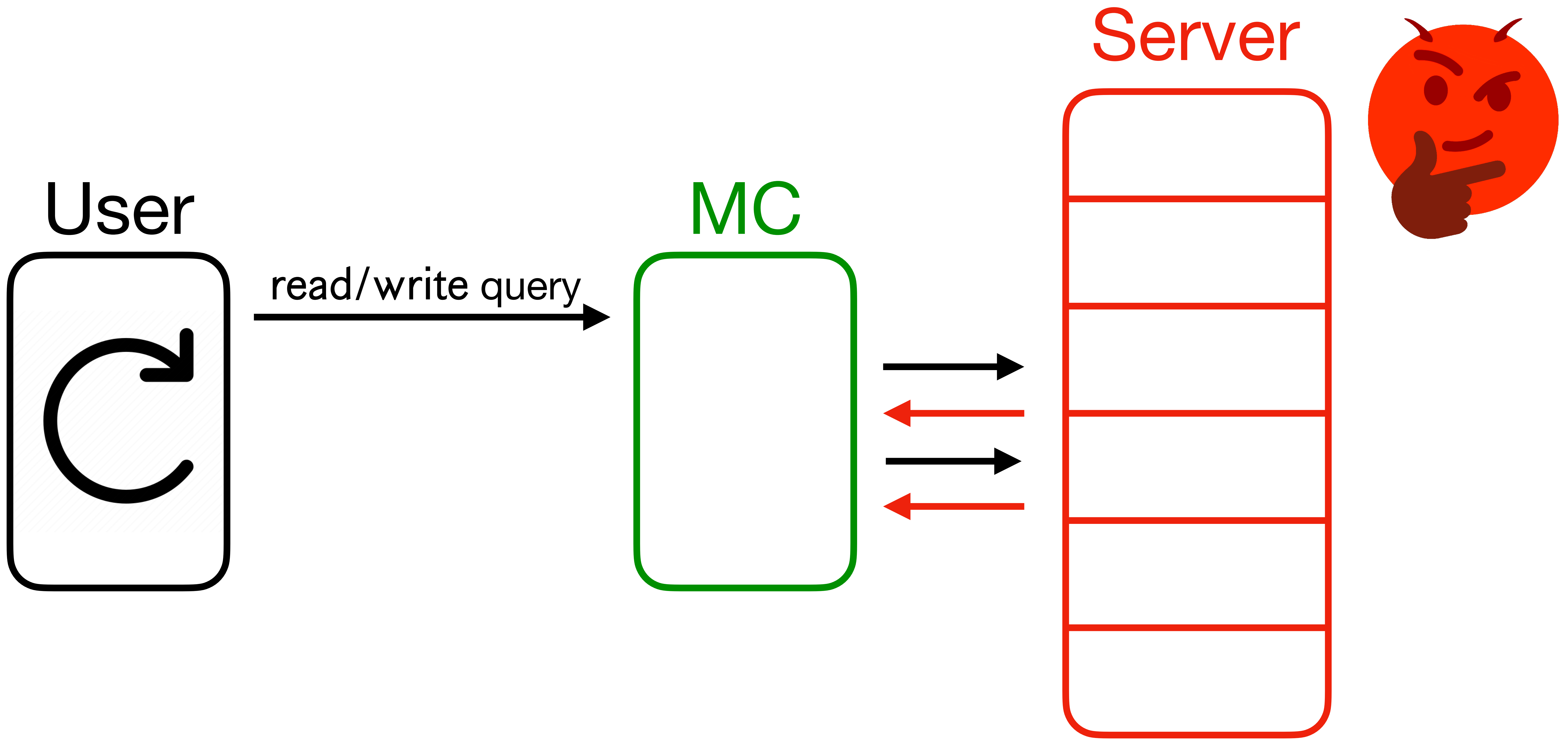

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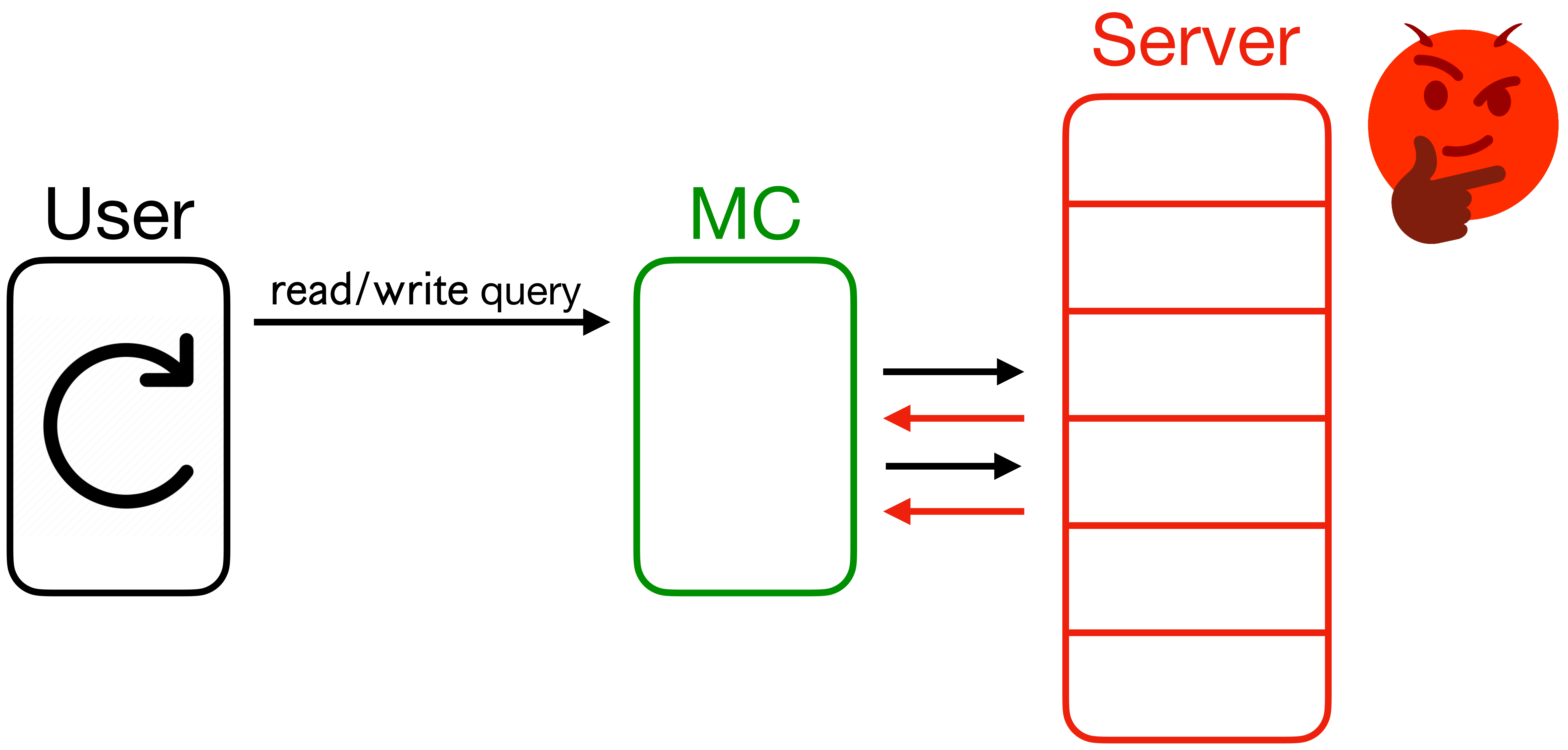

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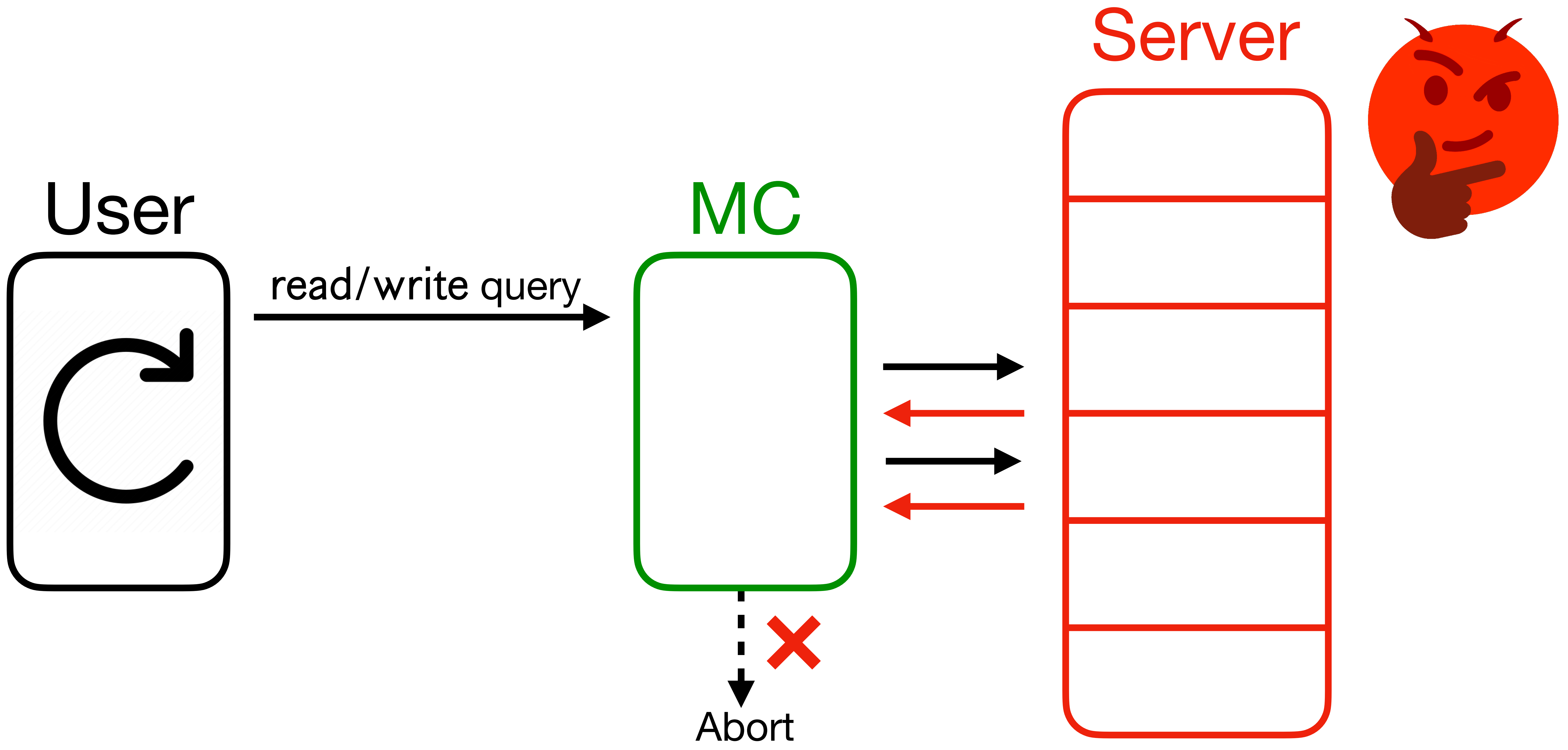

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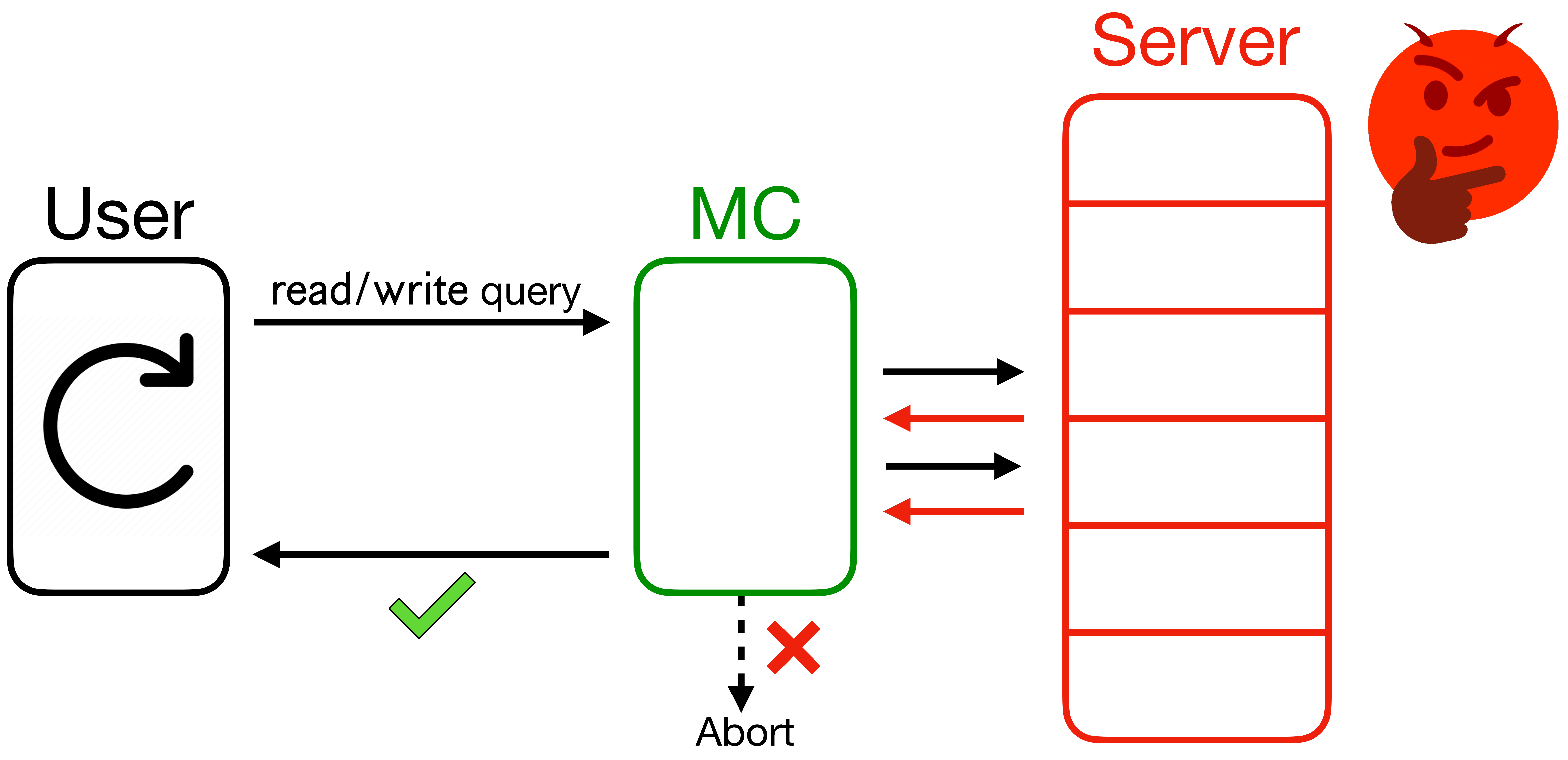

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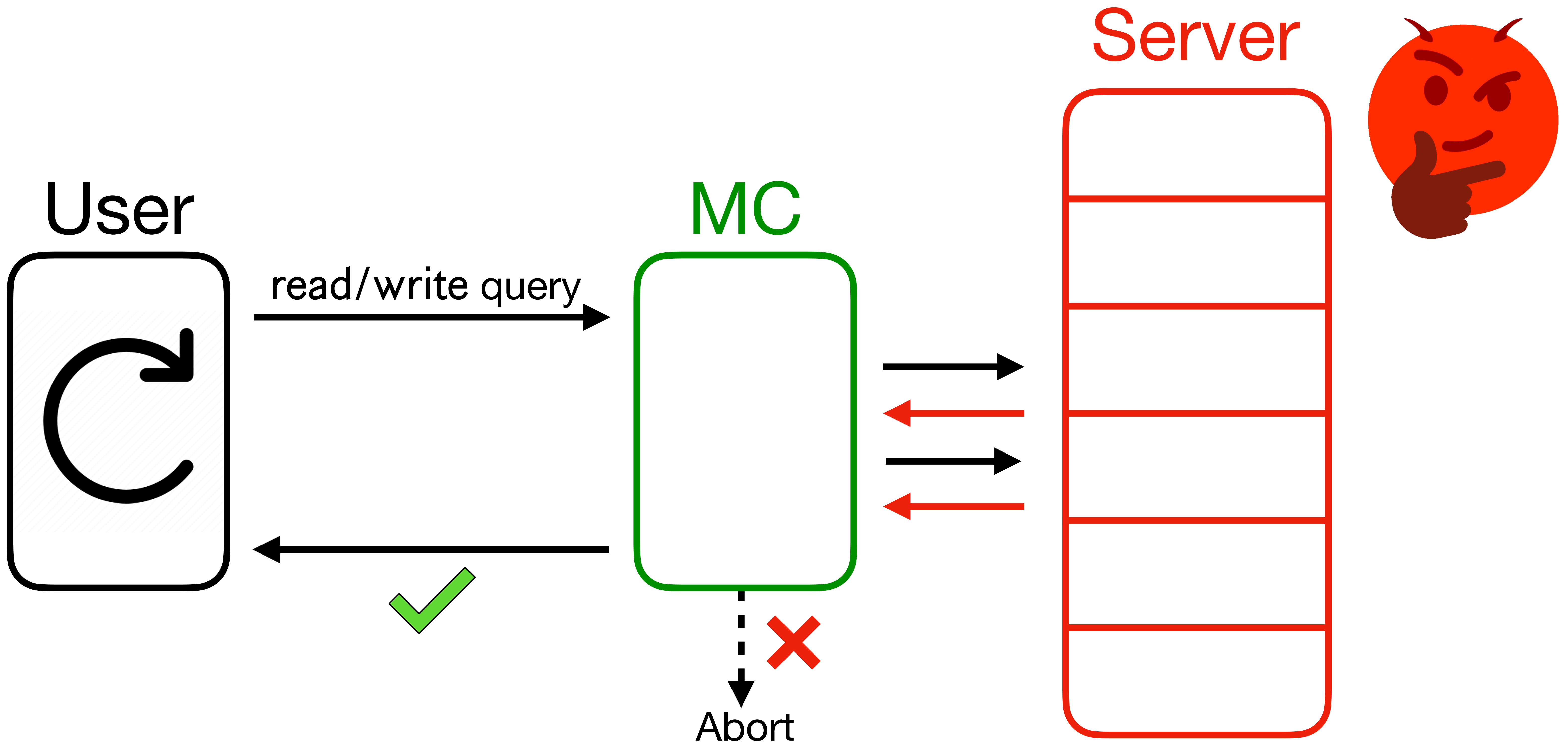

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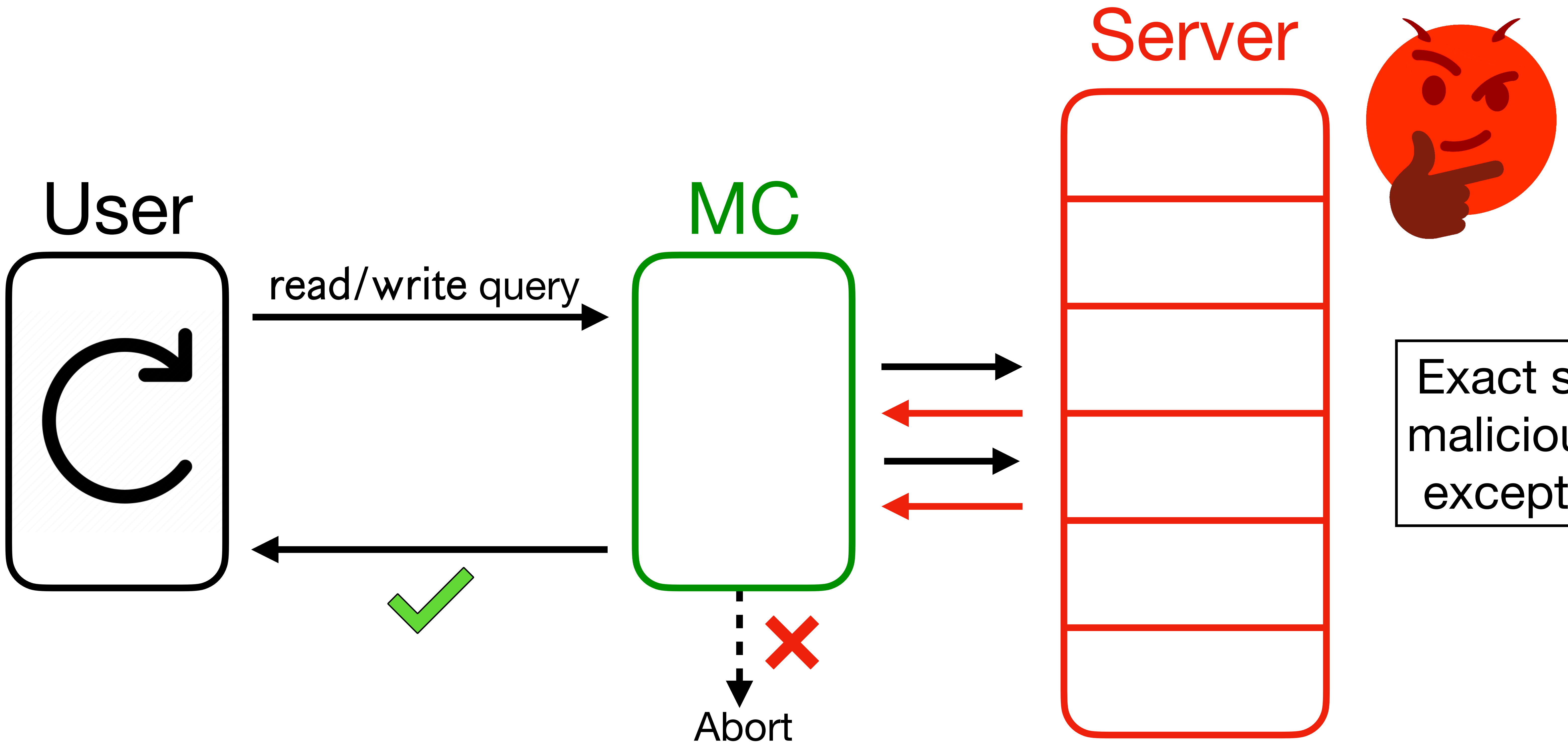

Exact same properties as maliciously secure ORAM, except no obliviousness.

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  - **Lower bound** of $\Omega(\log N / \log \log N)$ overhead for deterministic, non-adaptive memory checkers (which the existing constructions are).

[Dwork et al. ’09]

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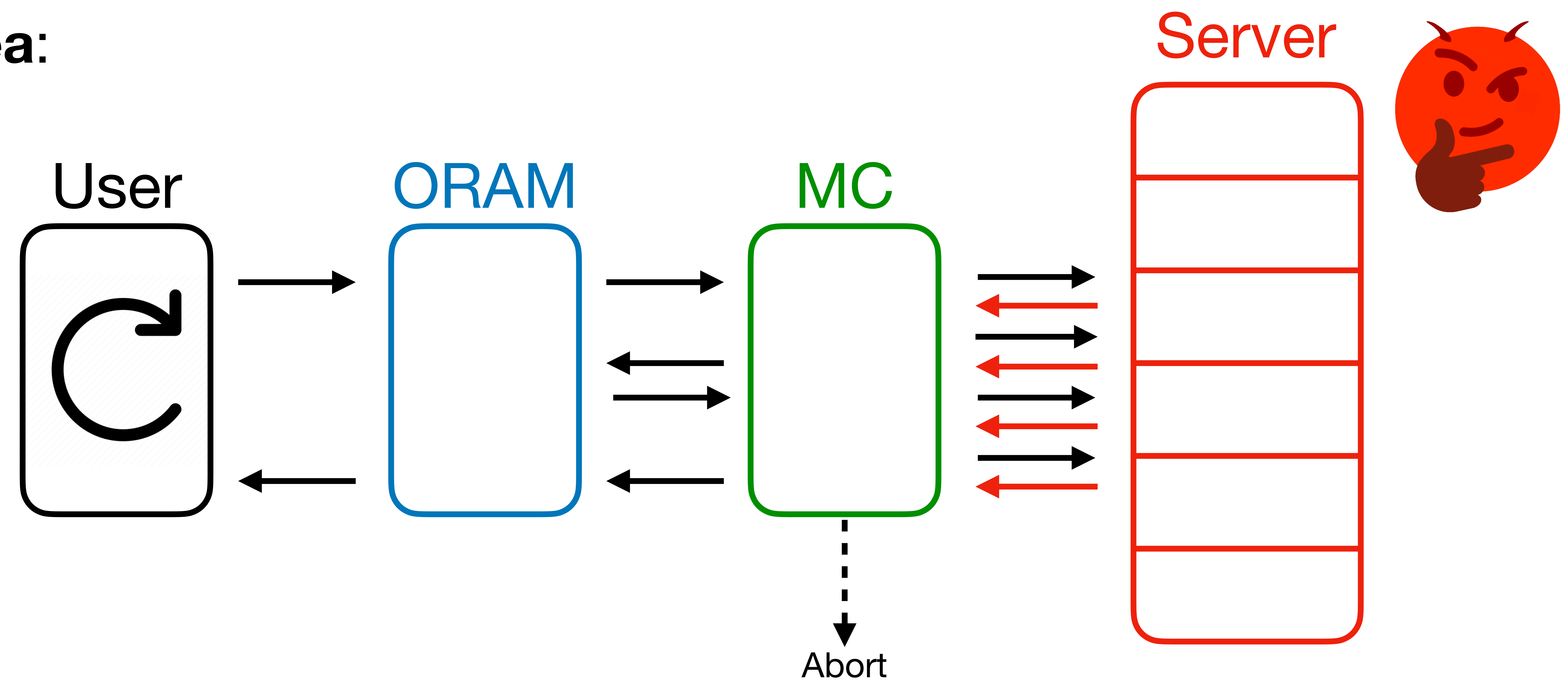

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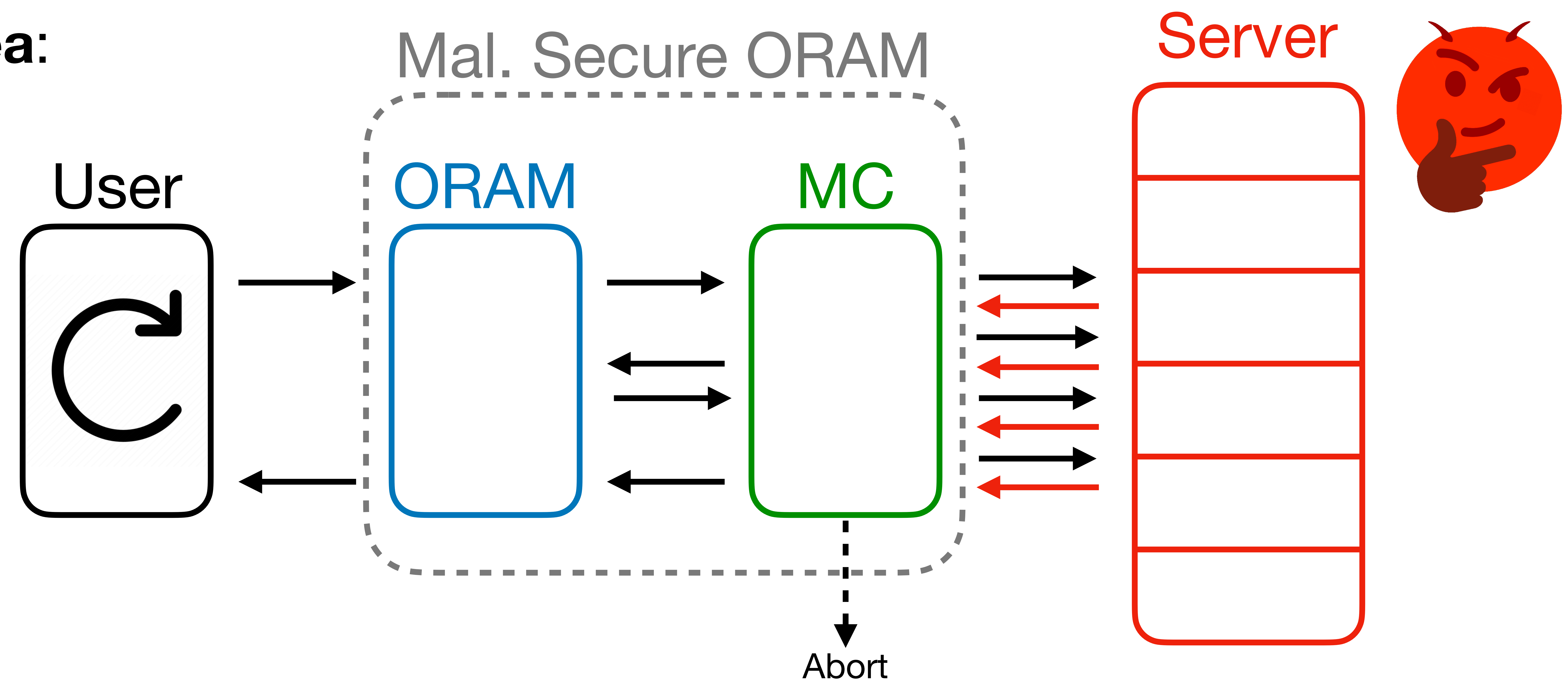

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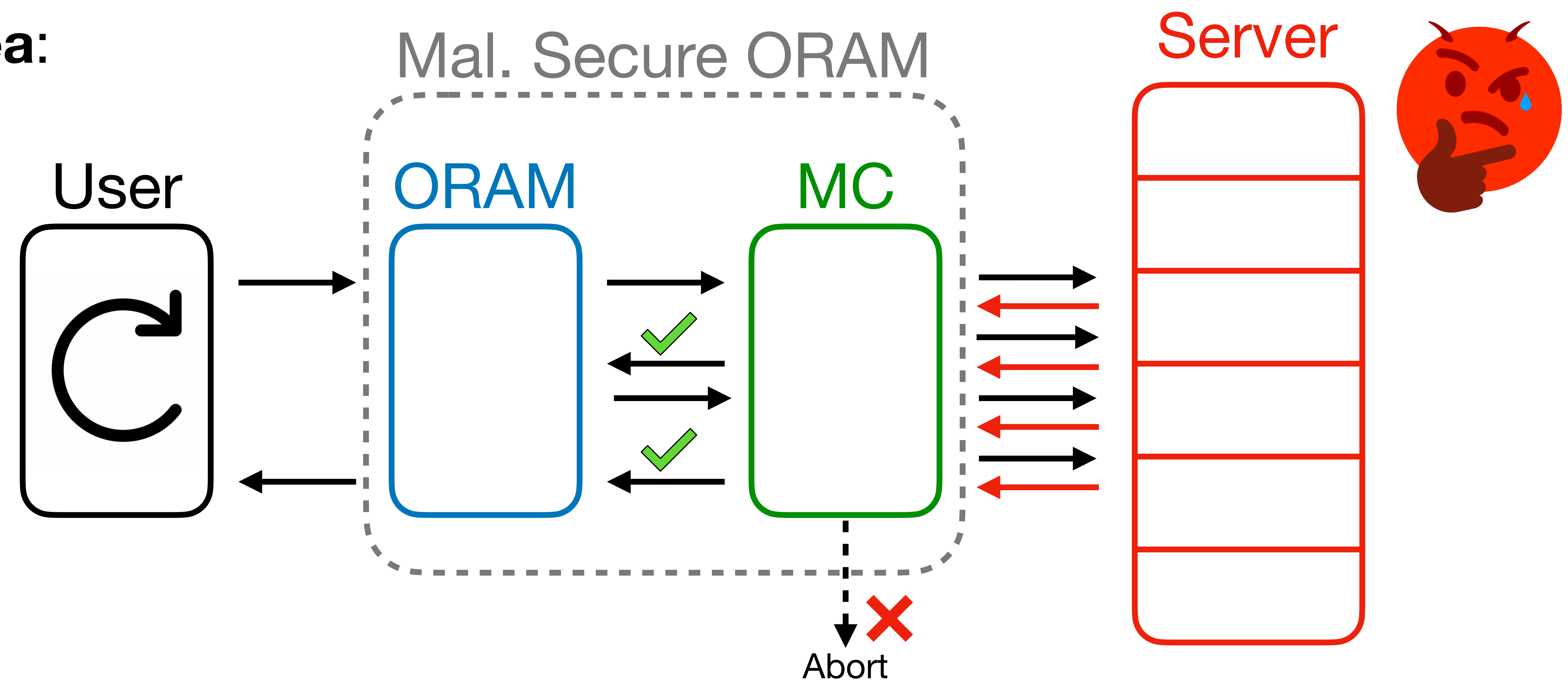

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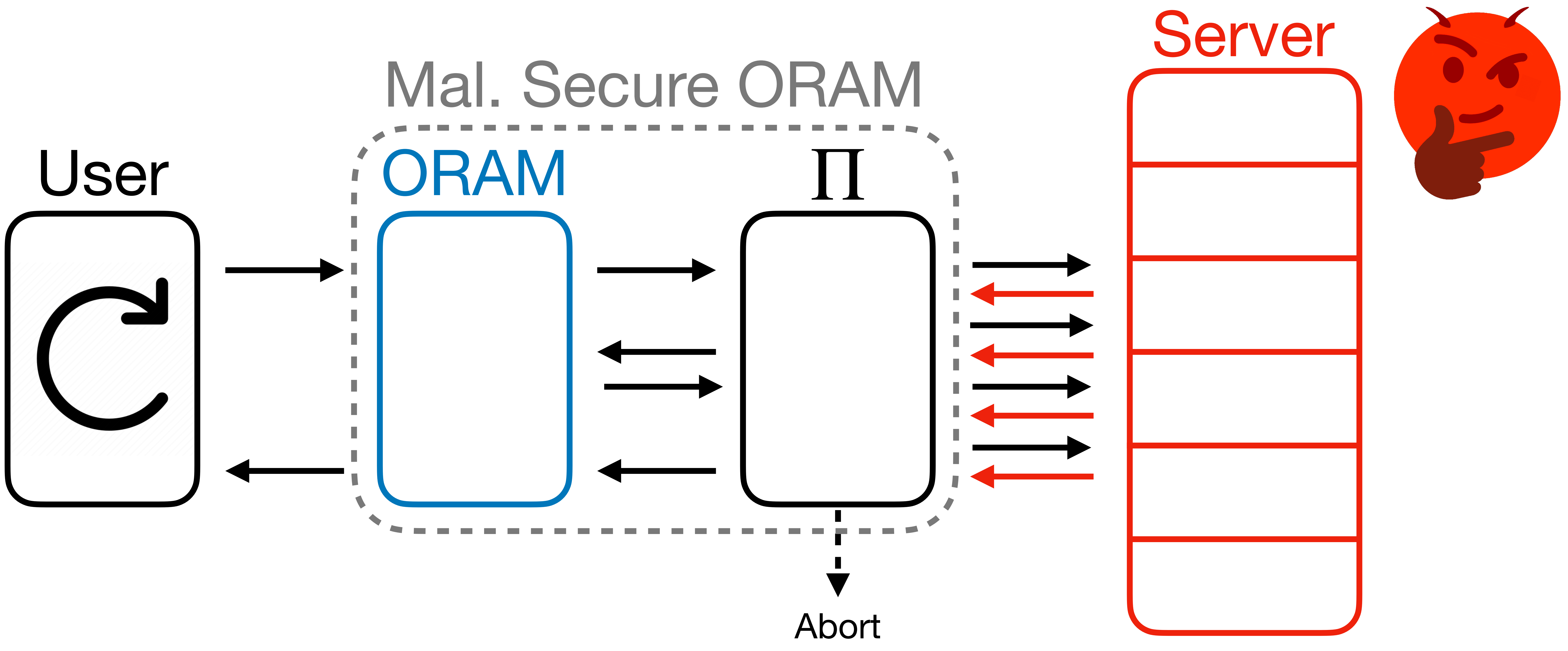

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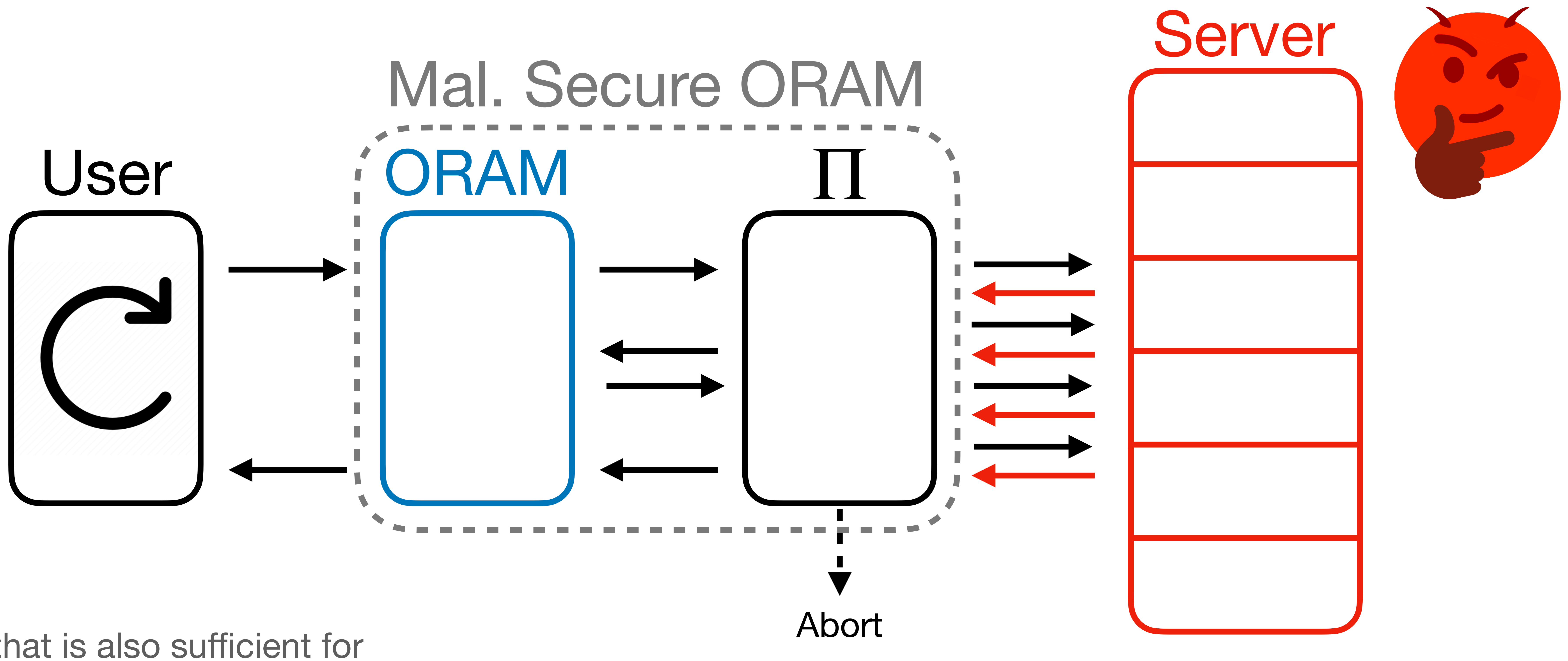

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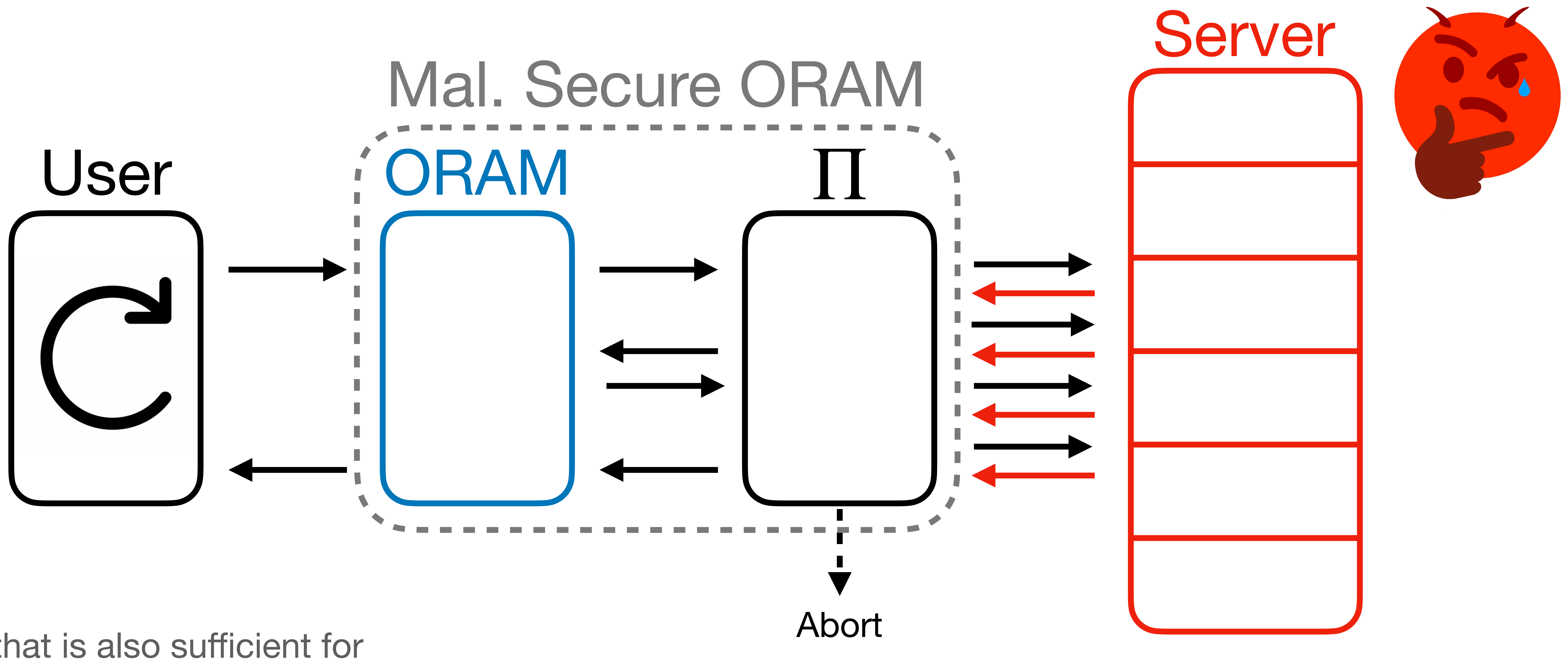

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We have to handle OptORAMa in a white-box way!

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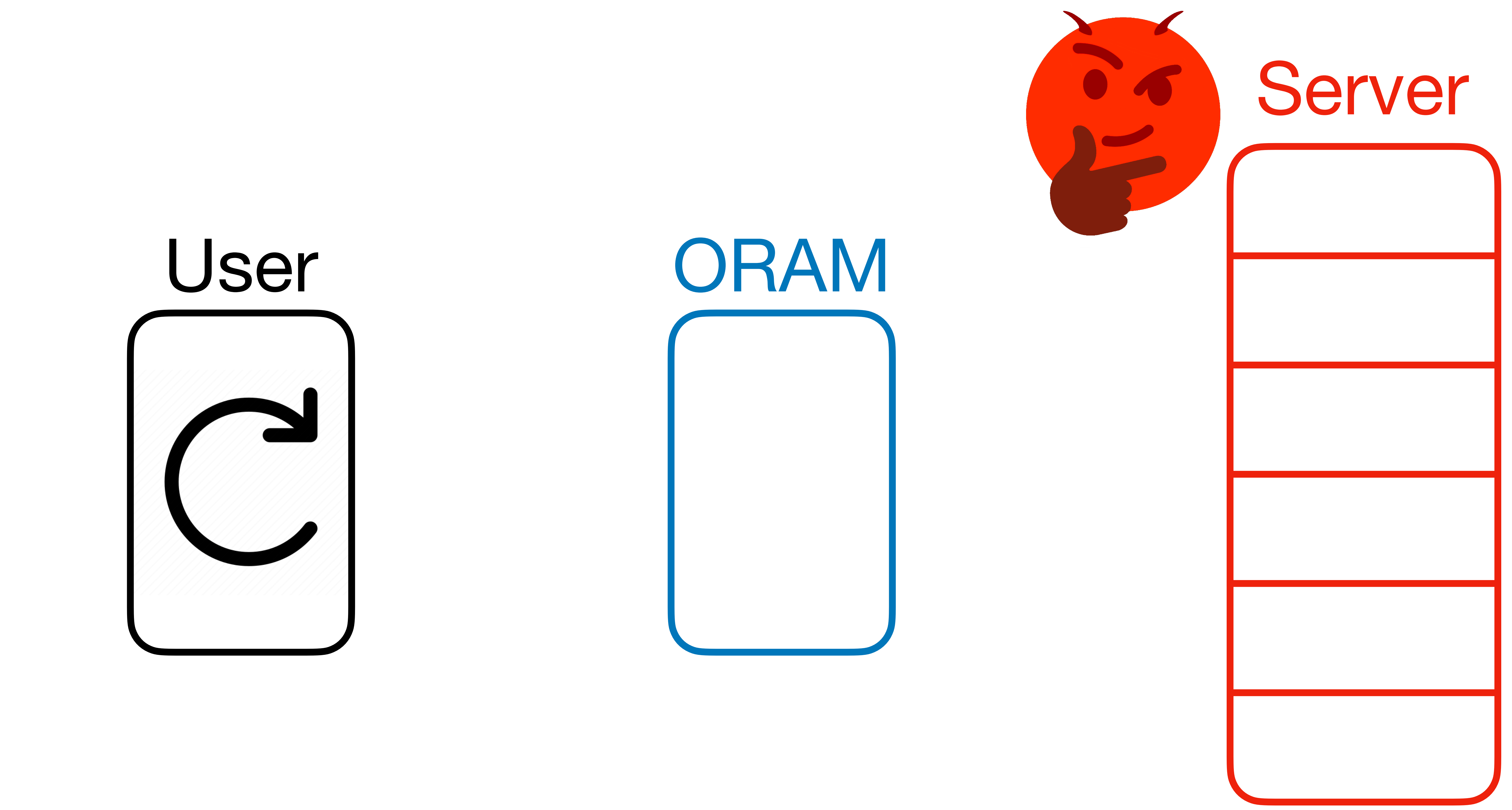

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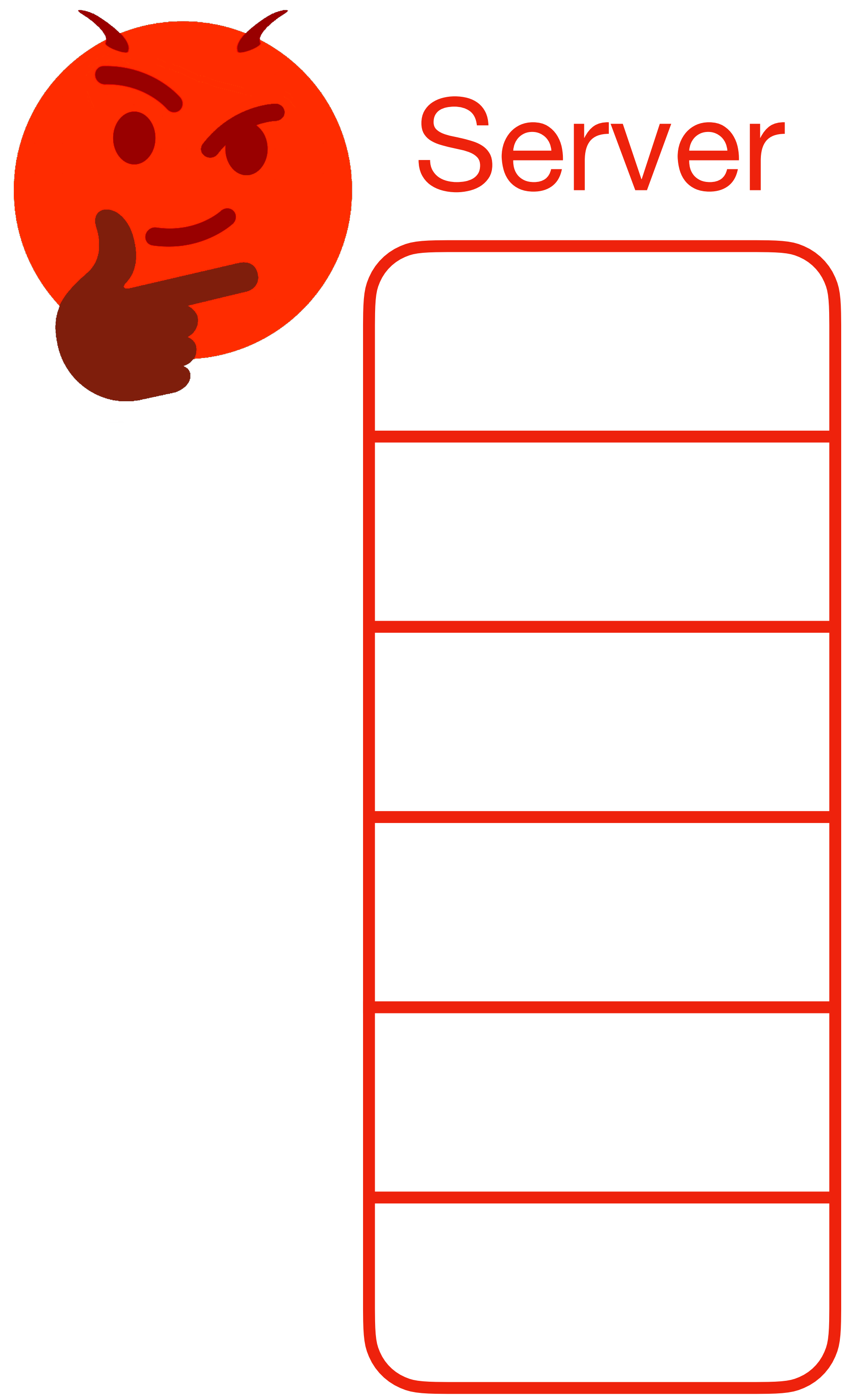

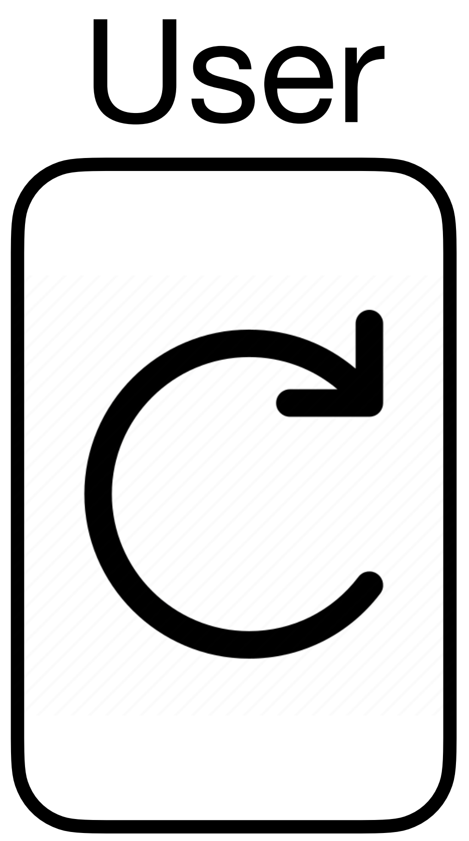

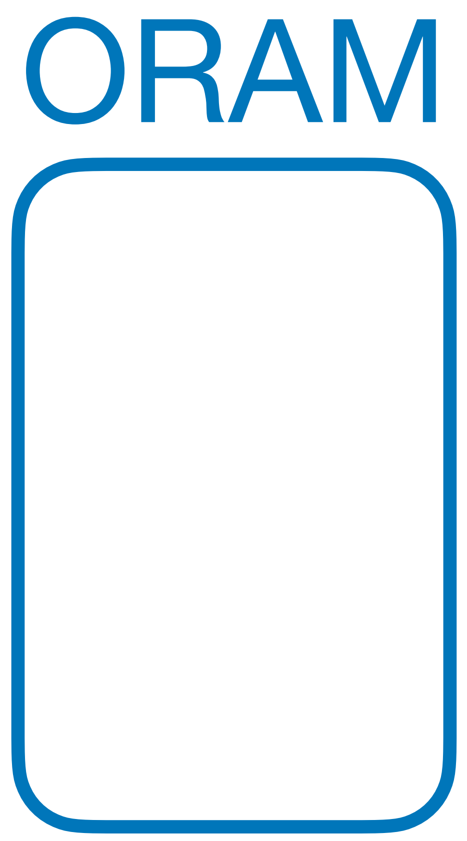

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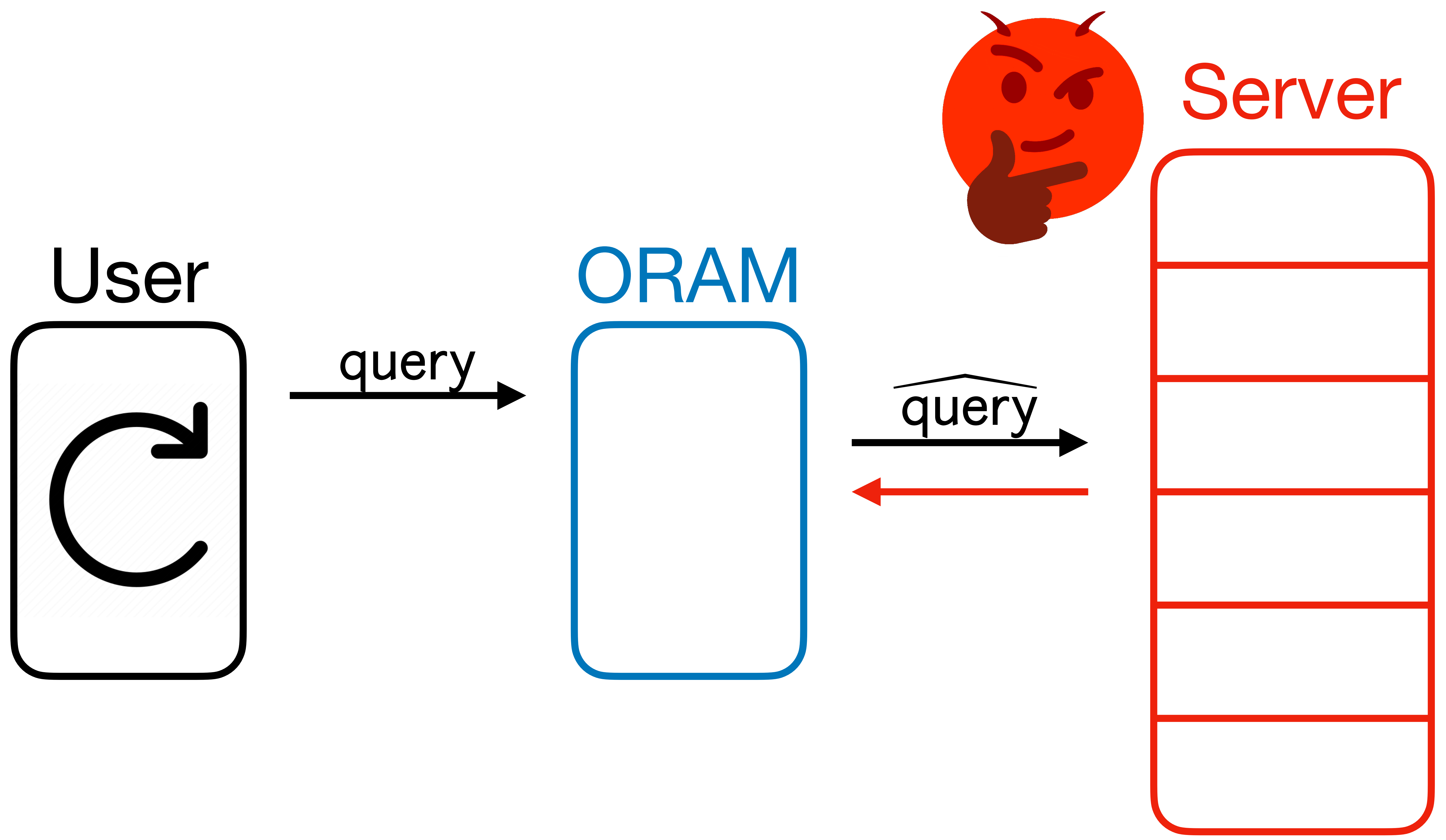

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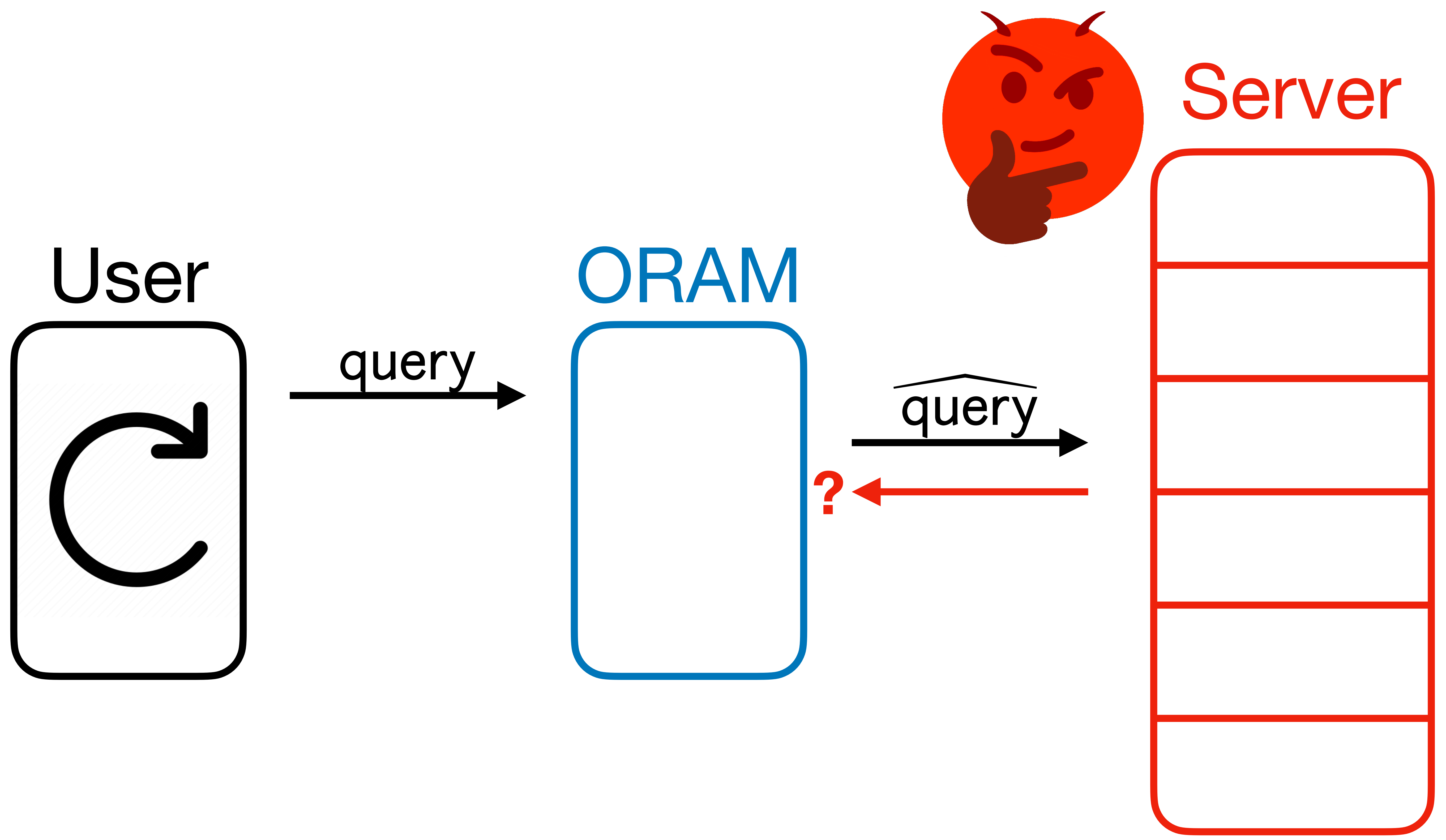

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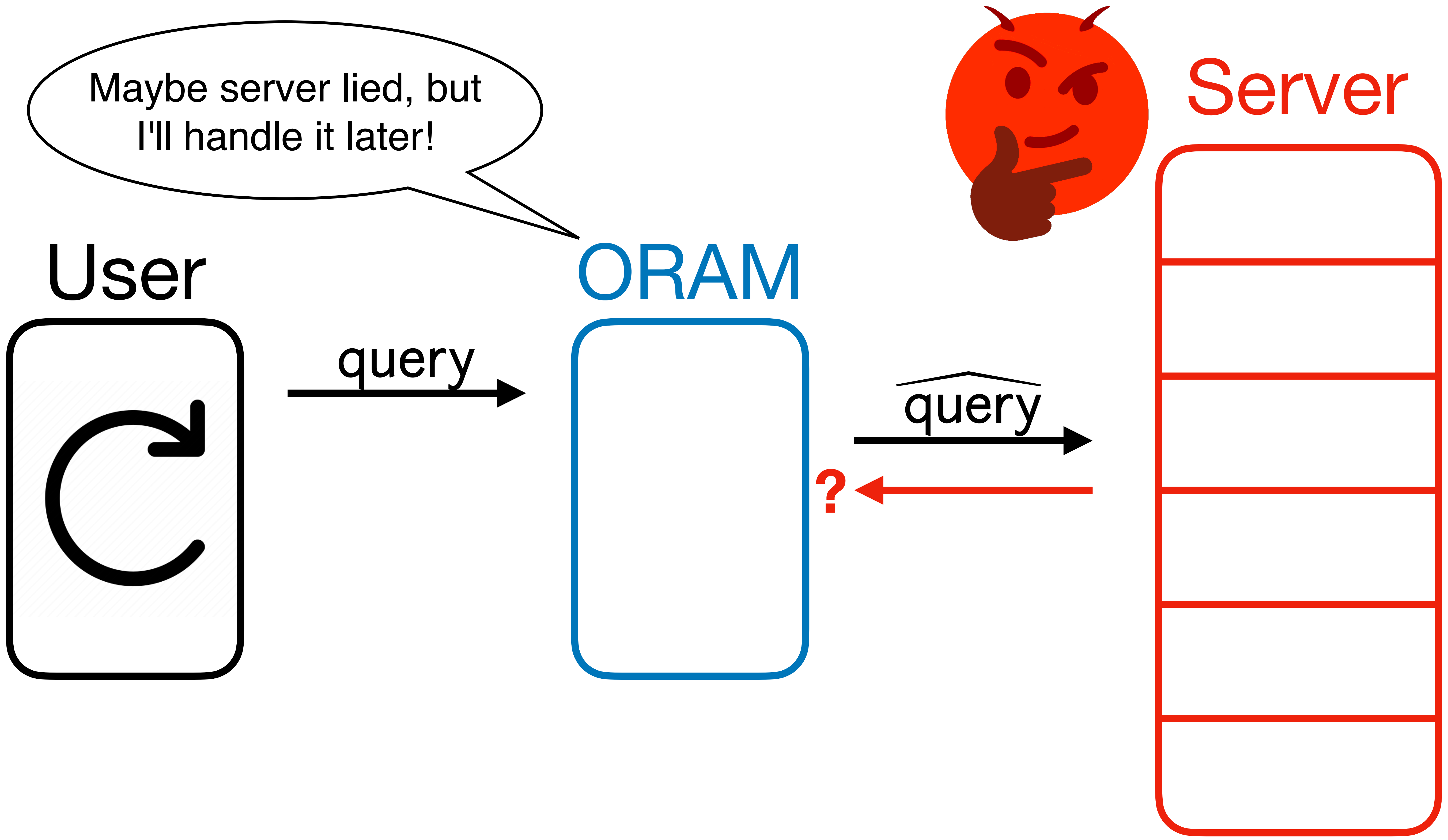

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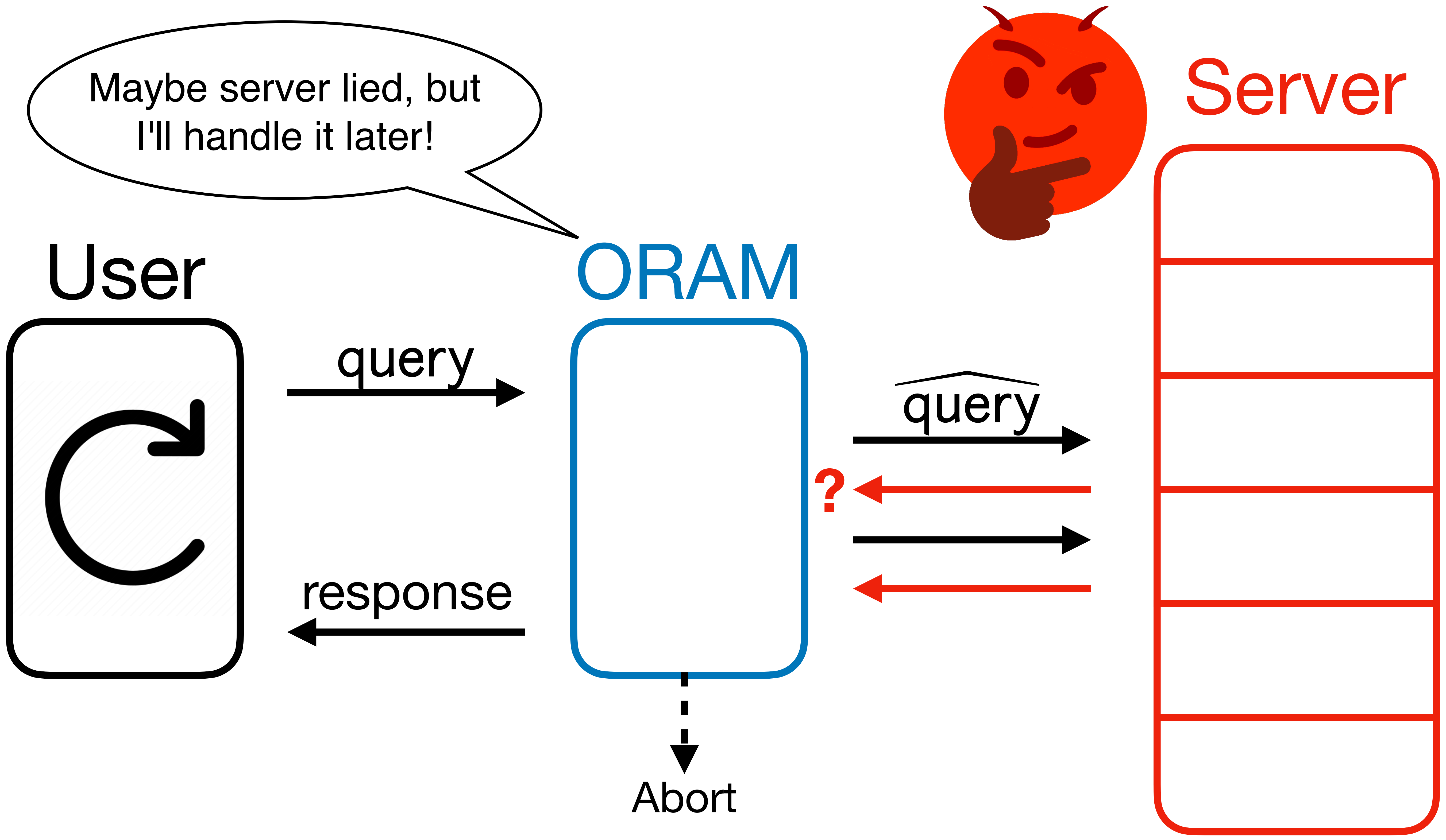

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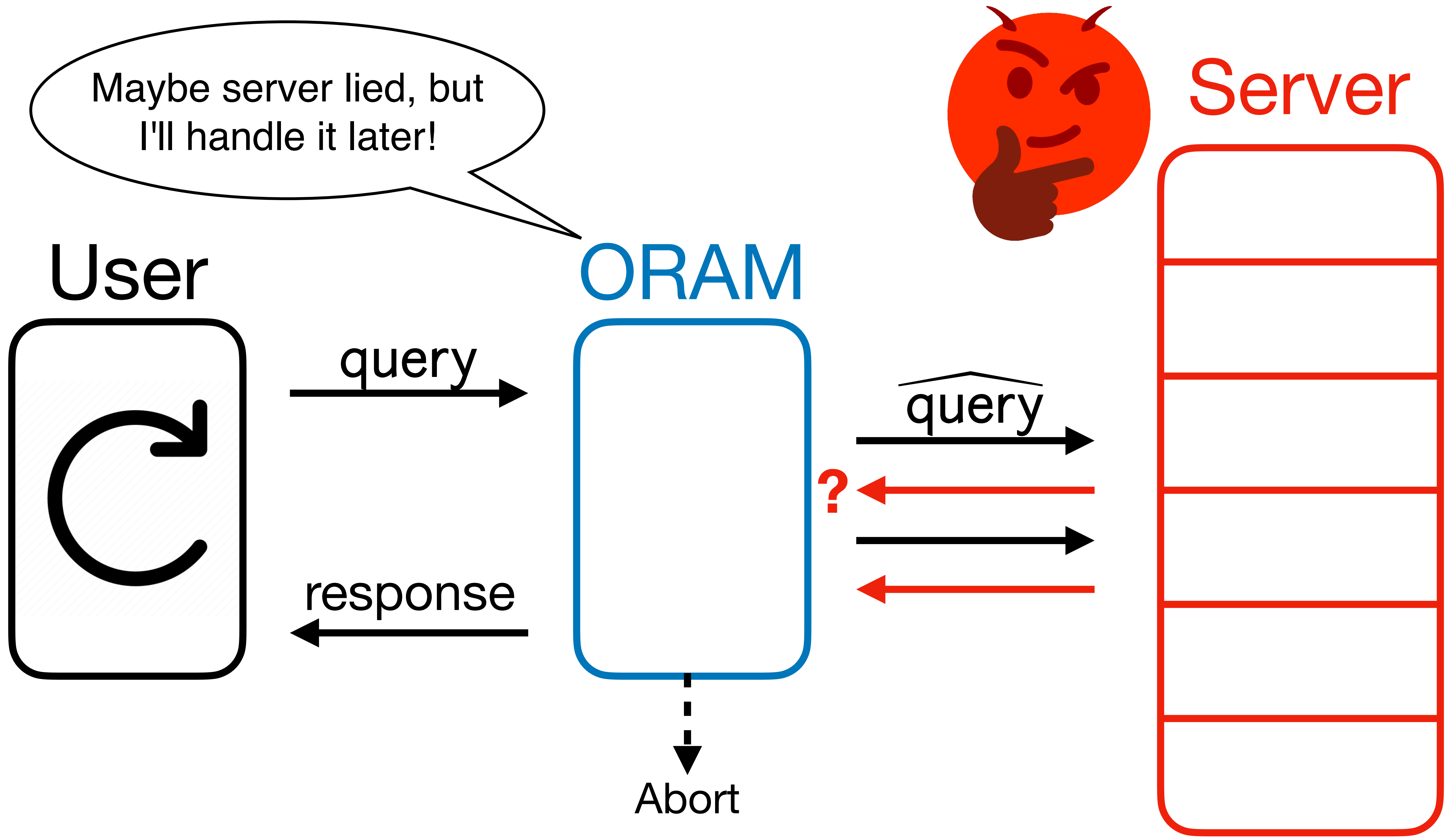
- **Our Idea**: Use weaker, more efficient **"batched"** notion of memory checking to capitalize on this!



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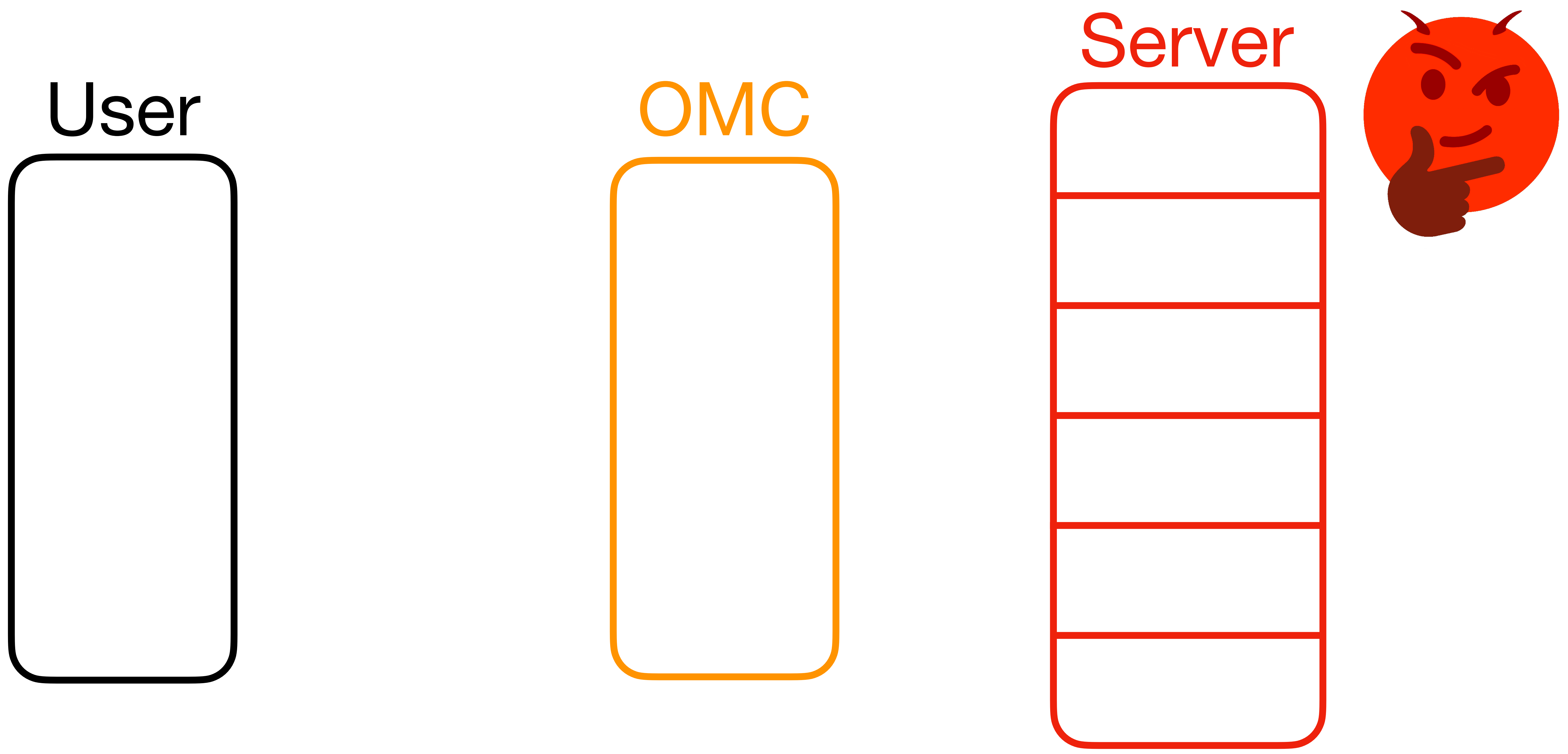

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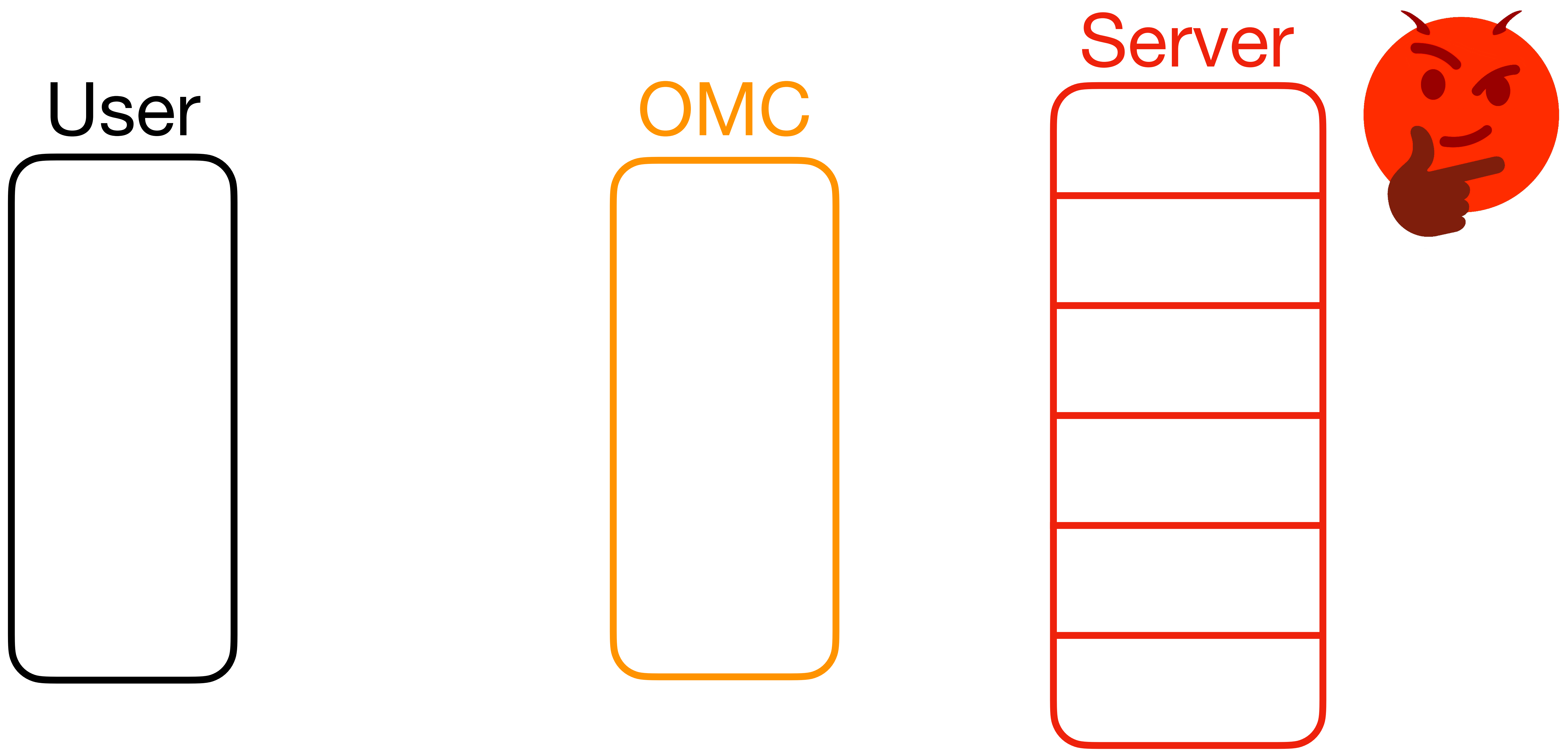

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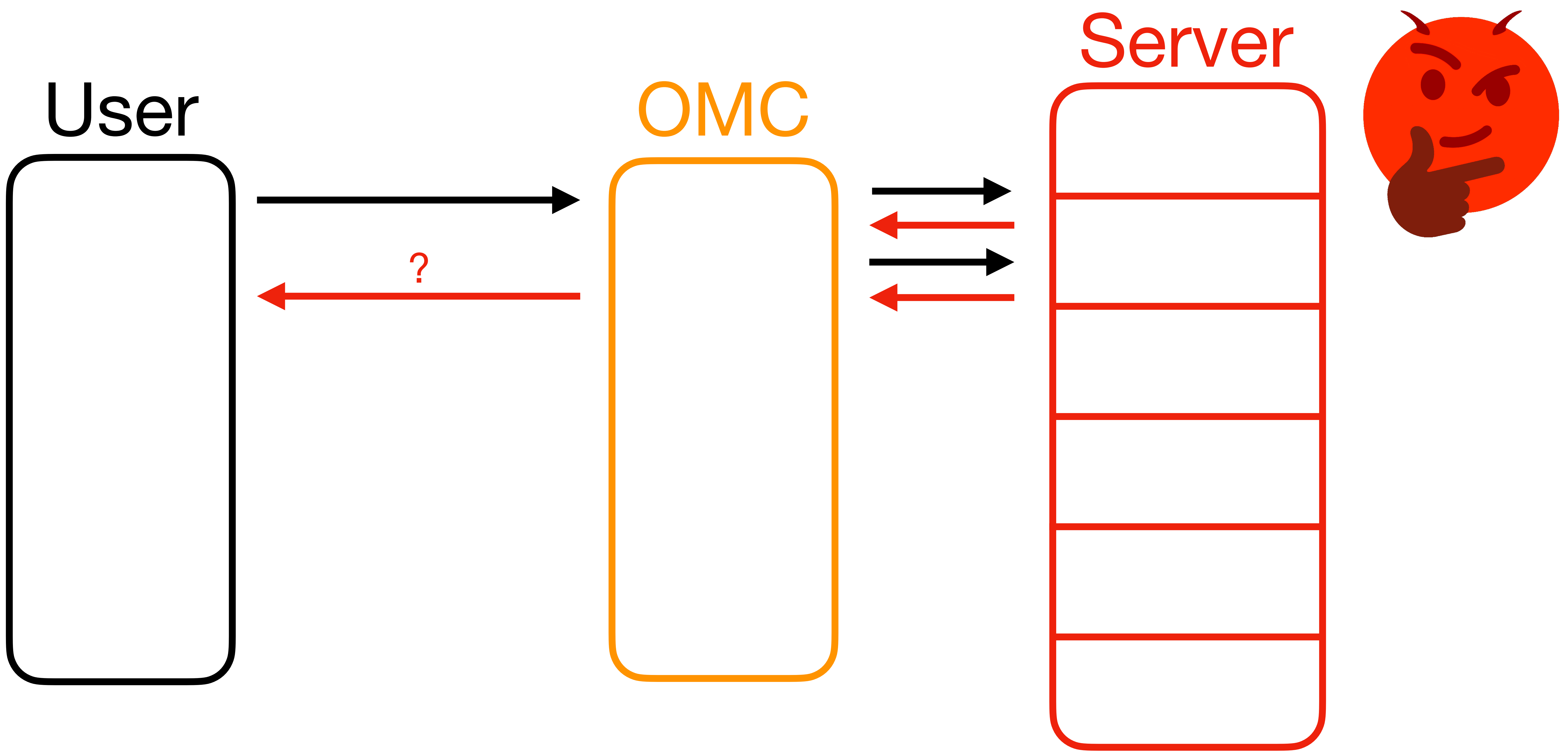

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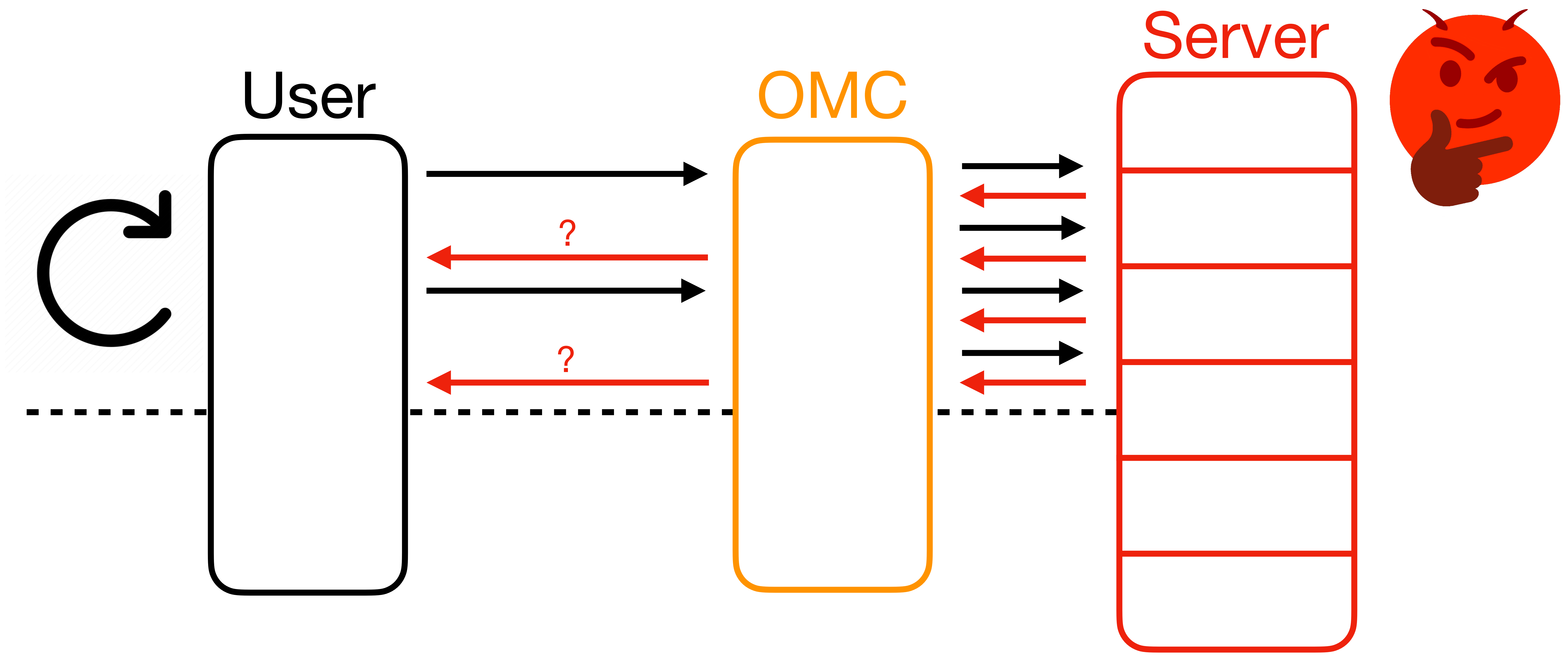

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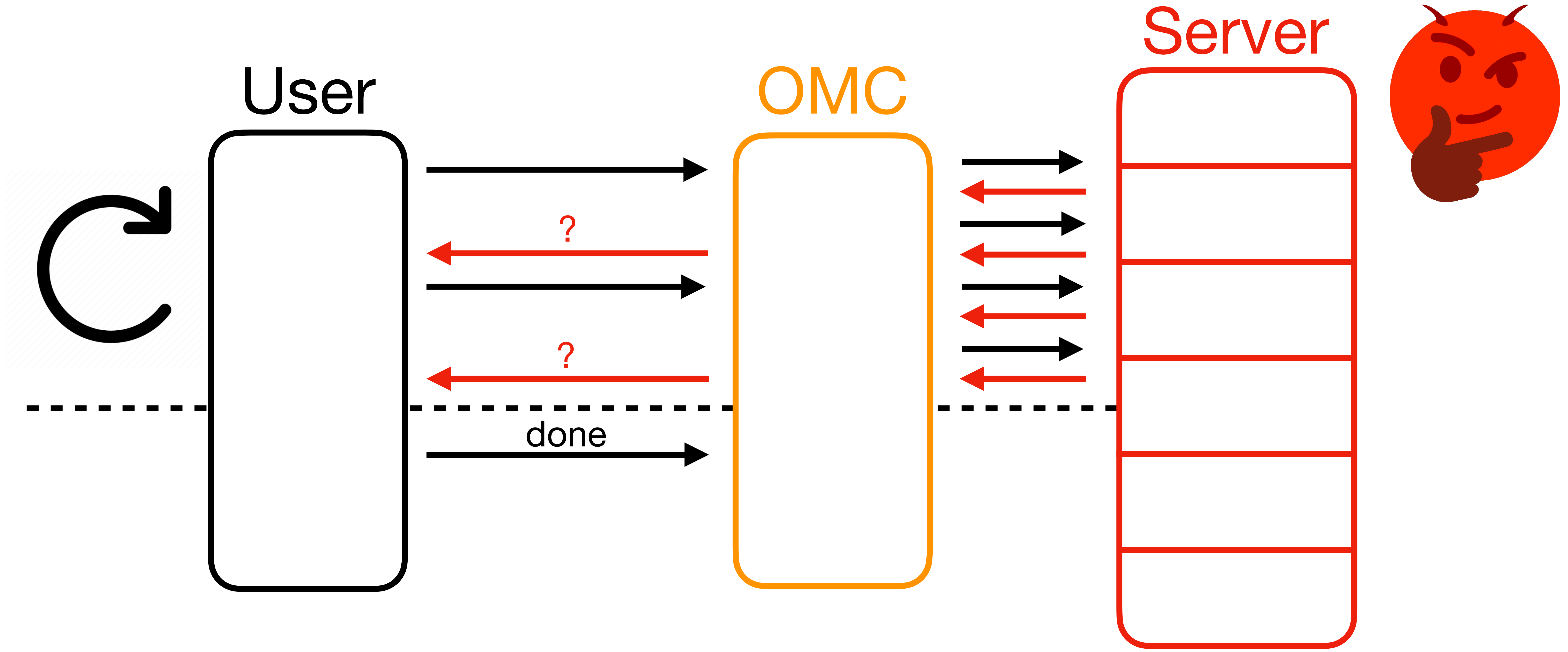

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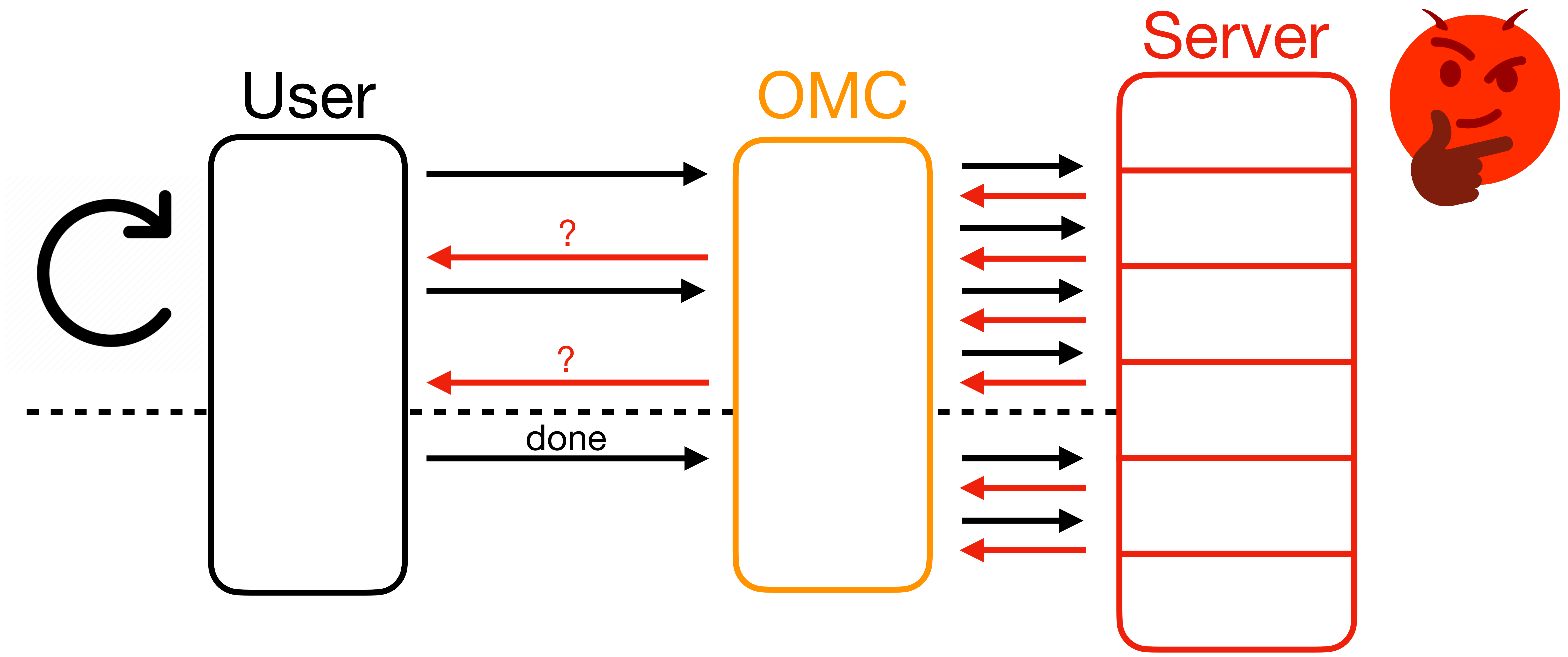

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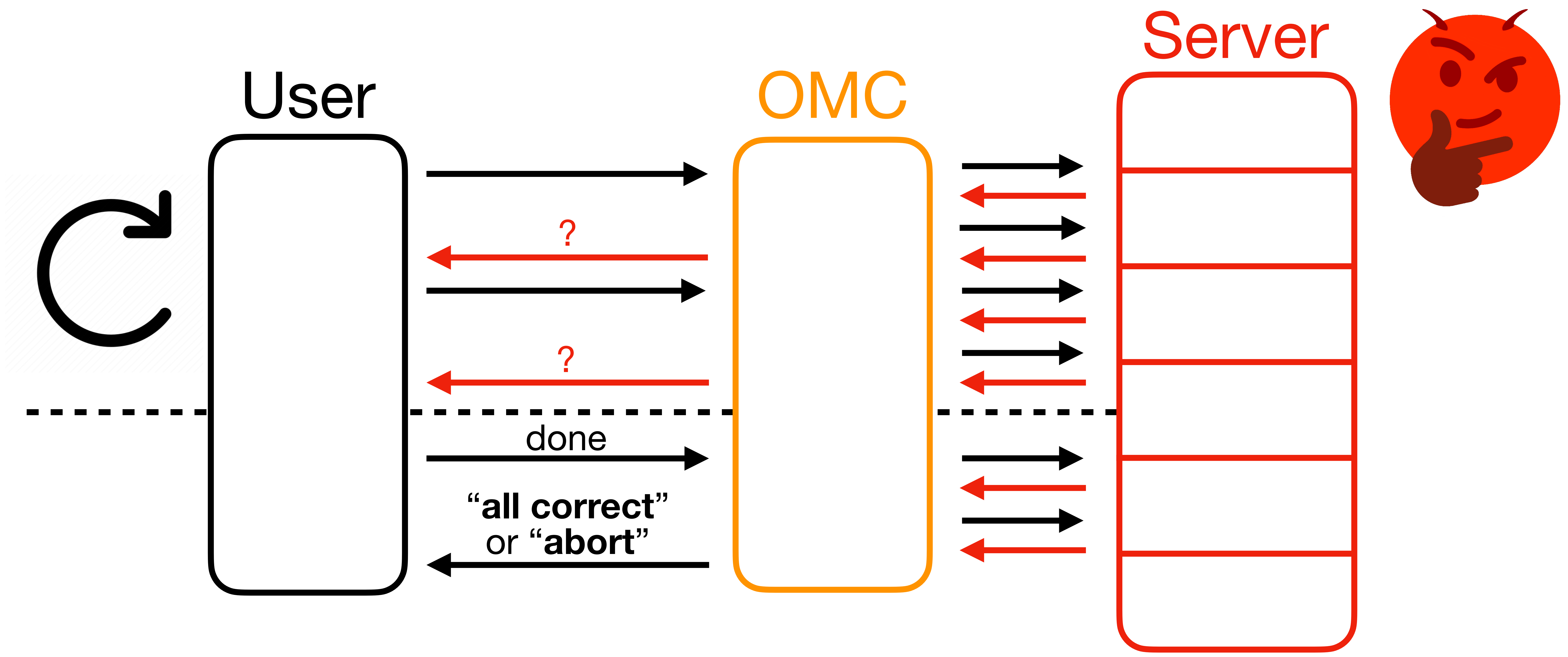
- An **Offline Memory Checker** (OMC) is a memory checker with a weaker correctness condition: [Blum et al. '94]
- Just needs to abort **by the end** – intermediate responses from the OMC may be incorrect! (Think "batching" a regular memory checker.)



Offline Memory Checking

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

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

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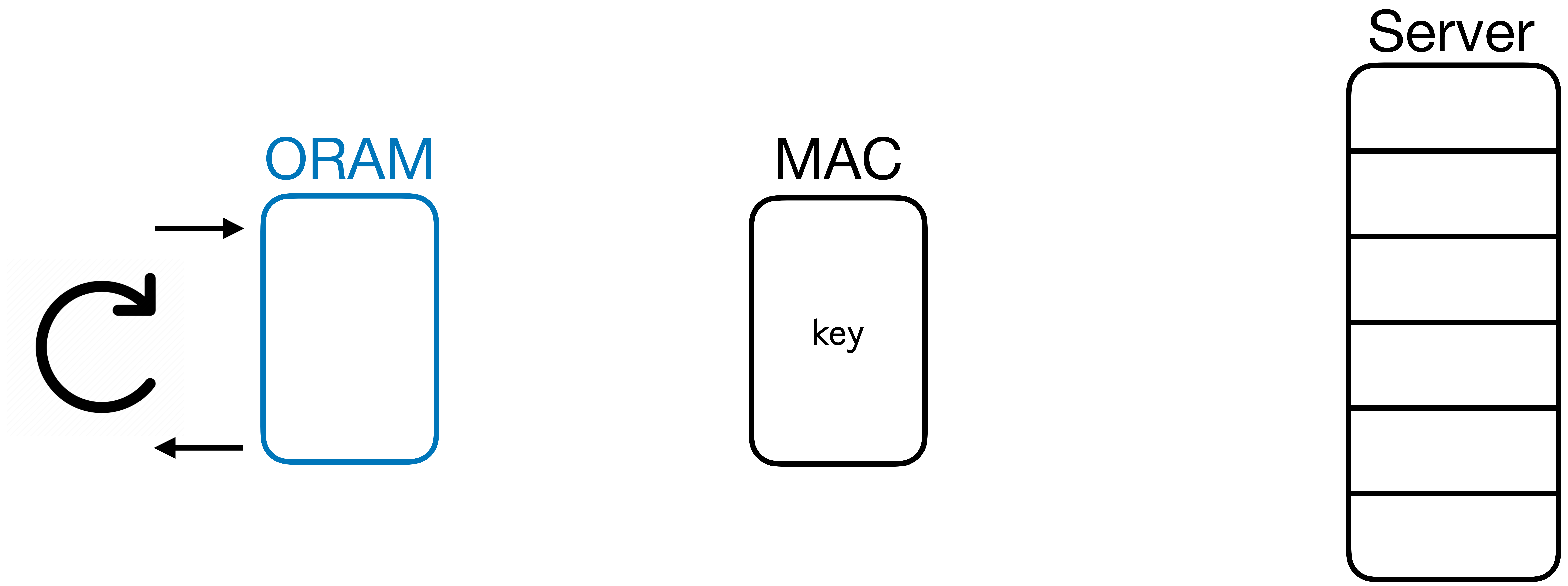
We need another technique!

Technique #2: MACs

- What about Message Authentication Codes (MACs)?



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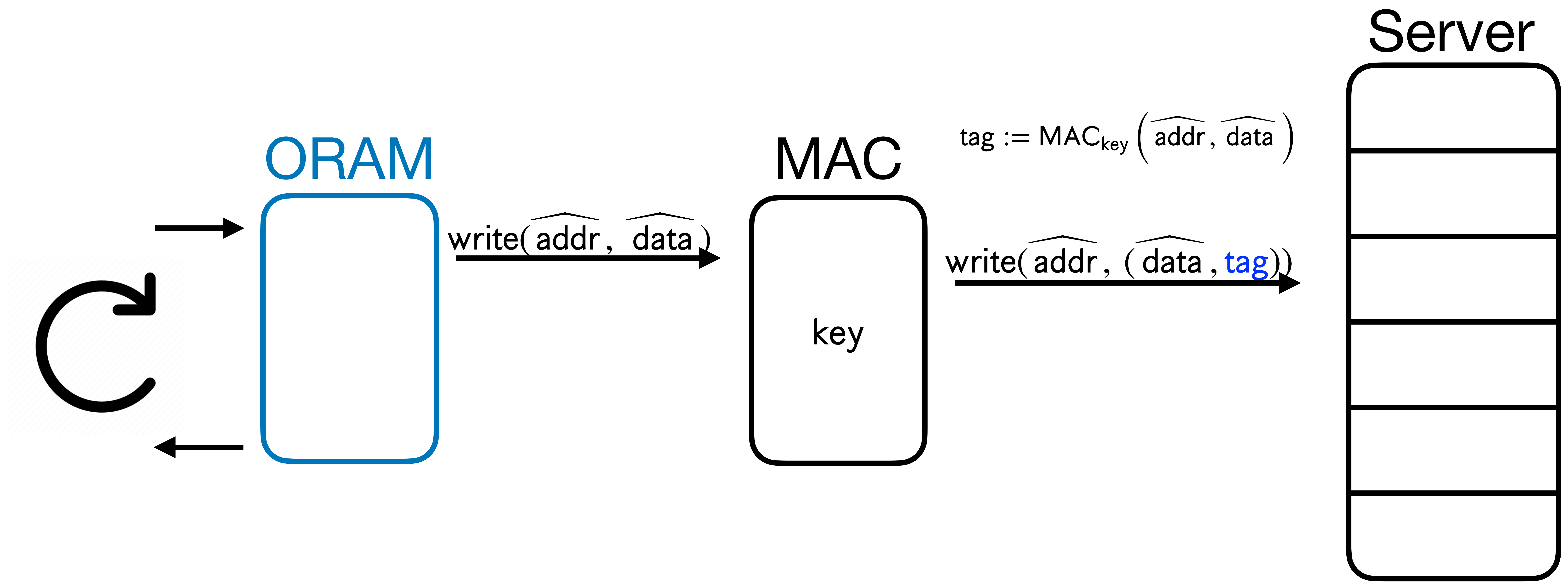
ORAM
$\mathrm{write}(\widehat{\mathrm{addr}}, \widehat{\mathrm{data}})$
MAC
key
$\mathrm{tag} := \mathrm{MAC}_{\mathrm{key}}\left(\widehat{\mathrm{addr}}, \widehat{\mathrm{data}}\right)$
$\mathrm{write}(\widehat{\mathrm{addr}}, (\widehat{\mathrm{data}}, \mathrm{tag}))$
Server

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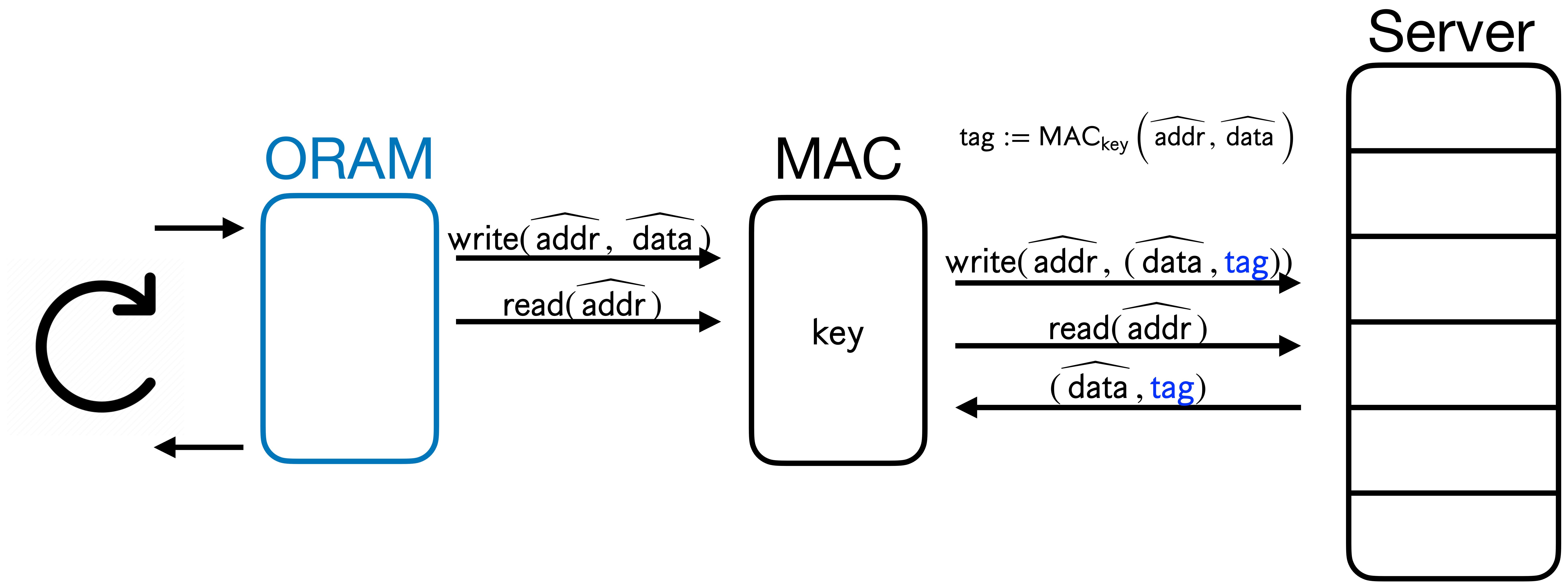
ORAM
MAC
Server
key
$\widehat{\text{write}(\widehat{\text{addr}}, \widehat{\text{data}})}$
$\text{read}(\widehat{\text{addr}})$
$\text{tag} := \text{MAC}_{\text{key}}\left(\widehat{\text{addr}}, \widehat{\text{data}}\right)$
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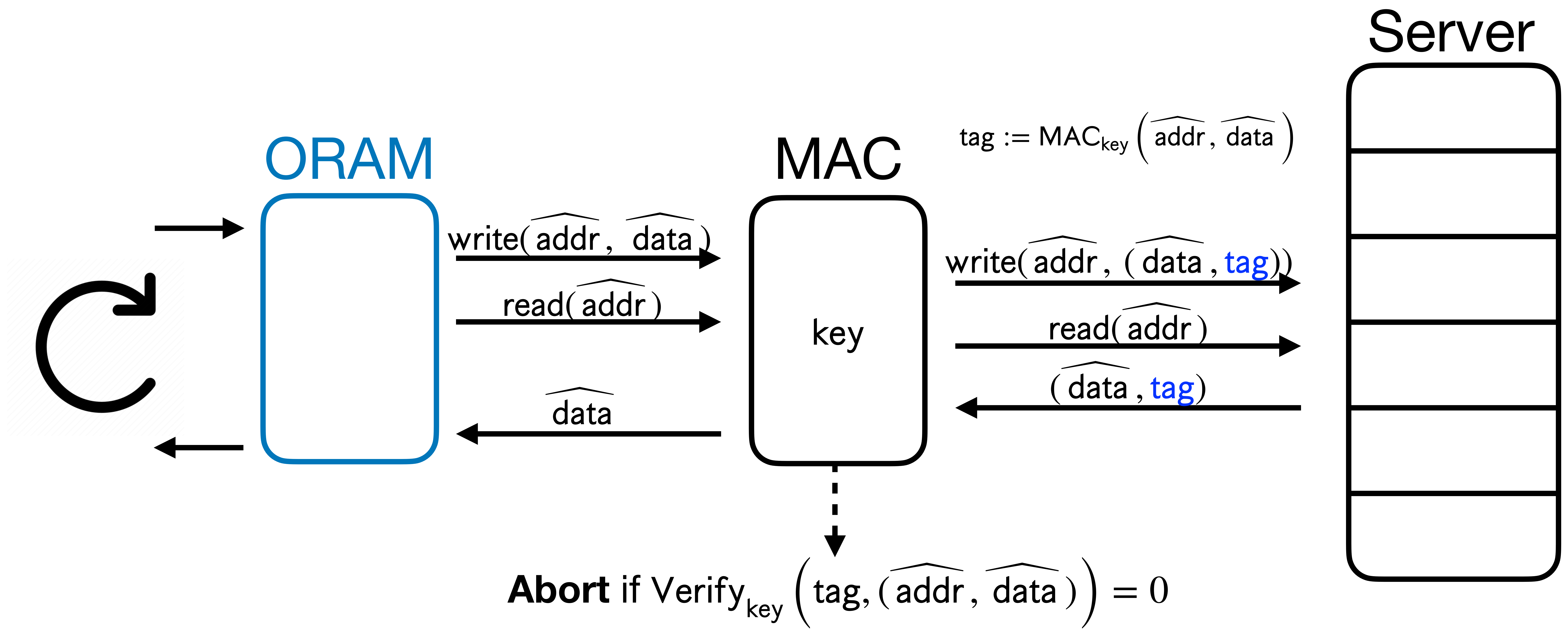
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MAC
Server
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$\text{tag} := \text{MAC}_{\text{key}}\left(\widehat{\text{addr}}, \widehat{\text{data}}\right)$
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$\text{read}(\widehat{\text{addr}})$
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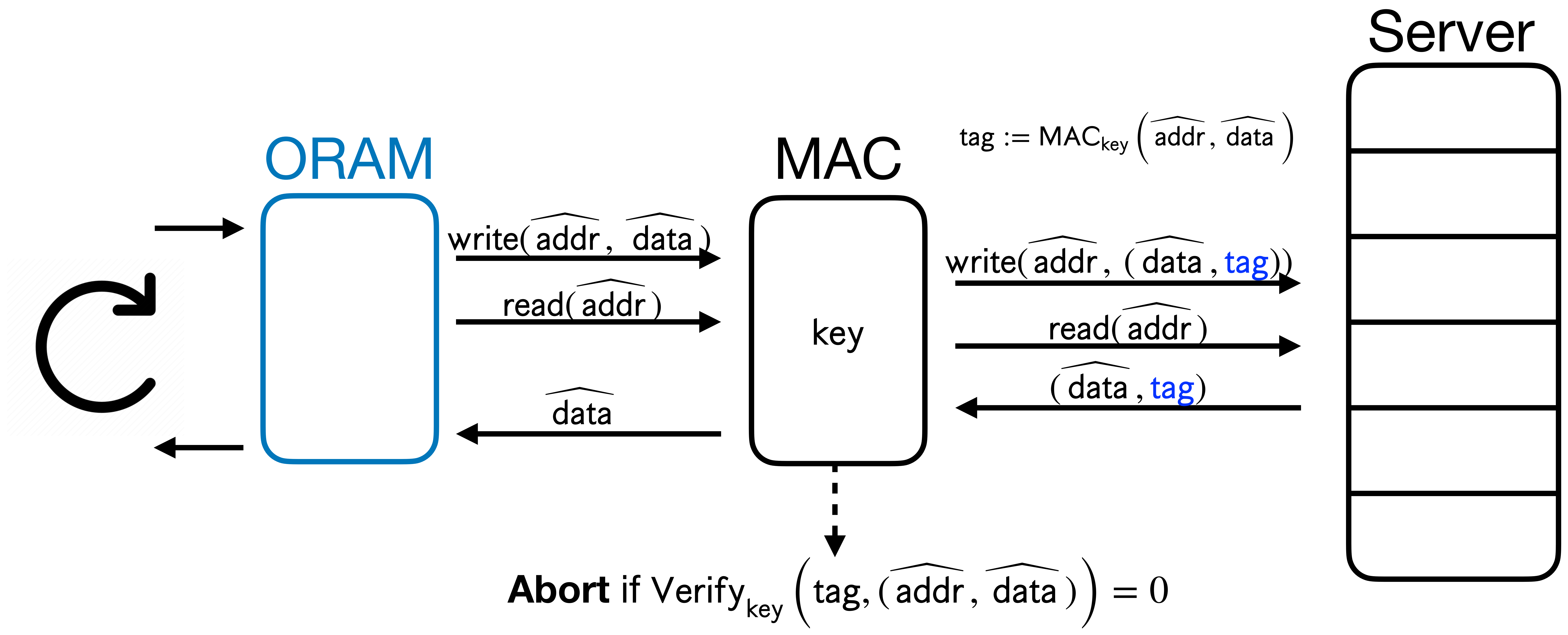
- MACs force the server to only send back values it has already seen.



Server
ORAM
MAC
key
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$\text{read}(\widehat{\text{addr}})$
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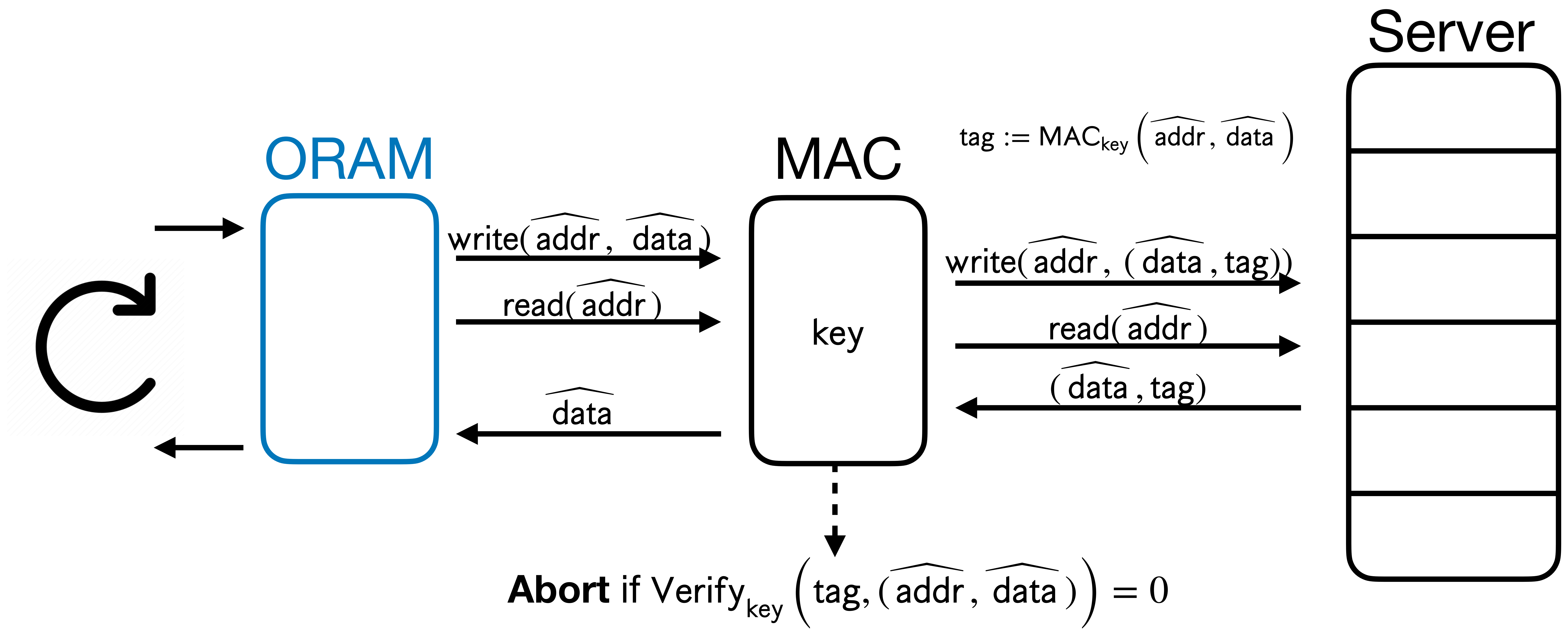
- MACs are **insufficient** because the server can do *replay attacks*.



ORAM
MAC
Server
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$\text{write}(\widehat{\text{addr}}, \widehat{\text{data}})$
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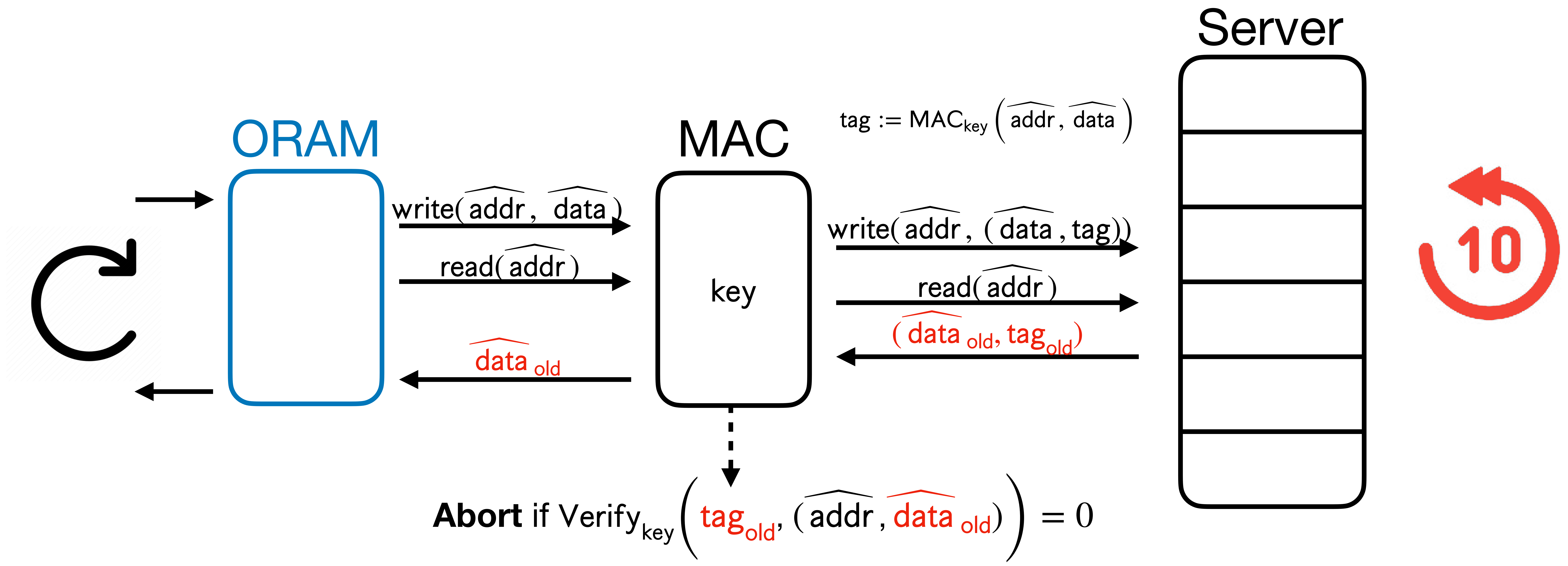
ORAM
MAC
Server
key
$\mathrm{write}(\widehat{\mathrm{addr}}, \widehat{\mathrm{data}})$
$\mathrm{read}(\widehat{\mathrm{addr}})$
$\widehat{\mathrm{data}}_{\mathrm{old}}$
$\mathrm{tag} := \mathrm{MAC}_{\mathrm{key}}(\widehat{\mathrm{addr}}, \widehat{\mathrm{data}})$
$\mathrm{write}(\widehat{\mathrm{addr}}, (\widehat{\mathrm{data}}, \mathrm{tag}))$
$\mathrm{read}(\widehat{\mathrm{addr}})$
$(\widehat{\mathrm{data}}_{\mathrm{old}}, \mathrm{tag}_{\mathrm{old}})$
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10

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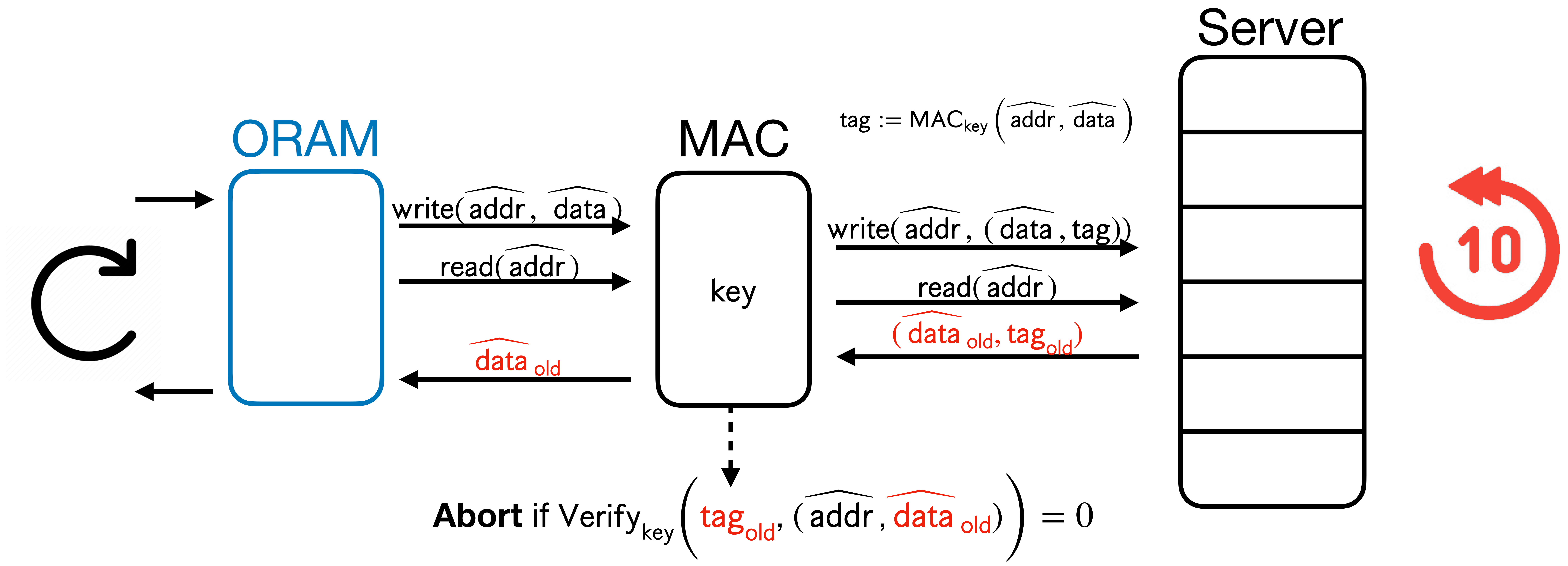
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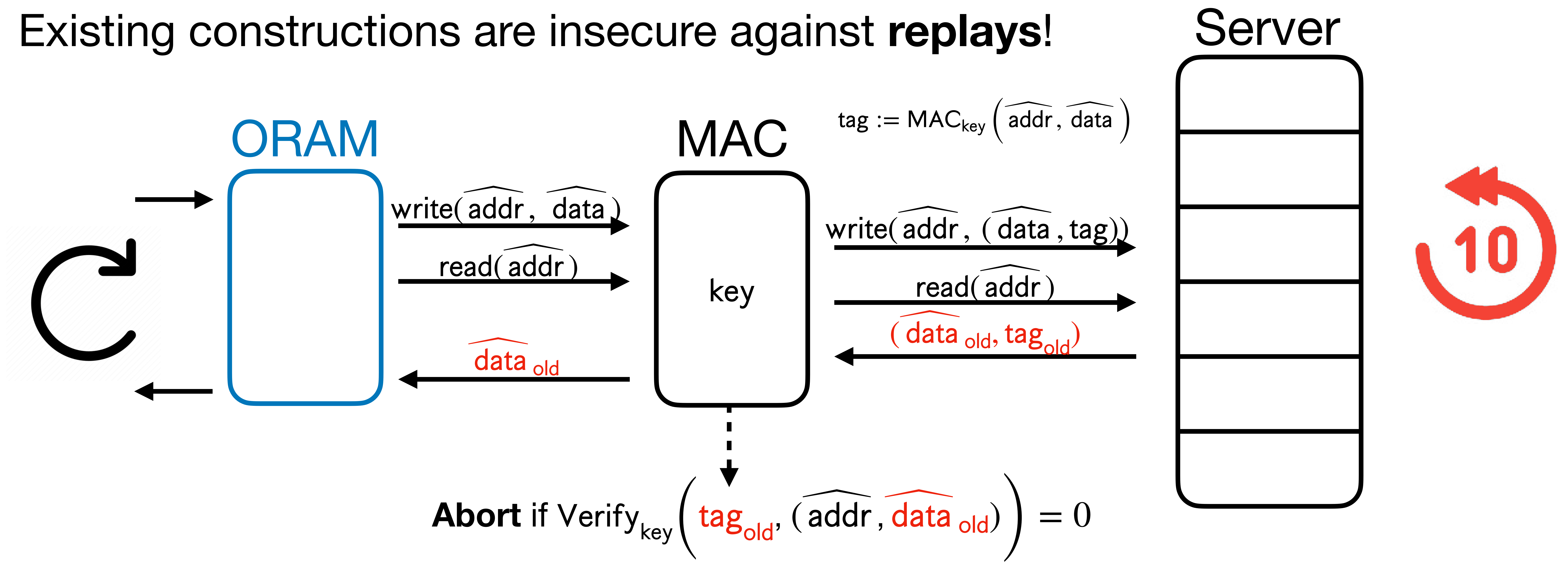
Server
ORAM
MAC
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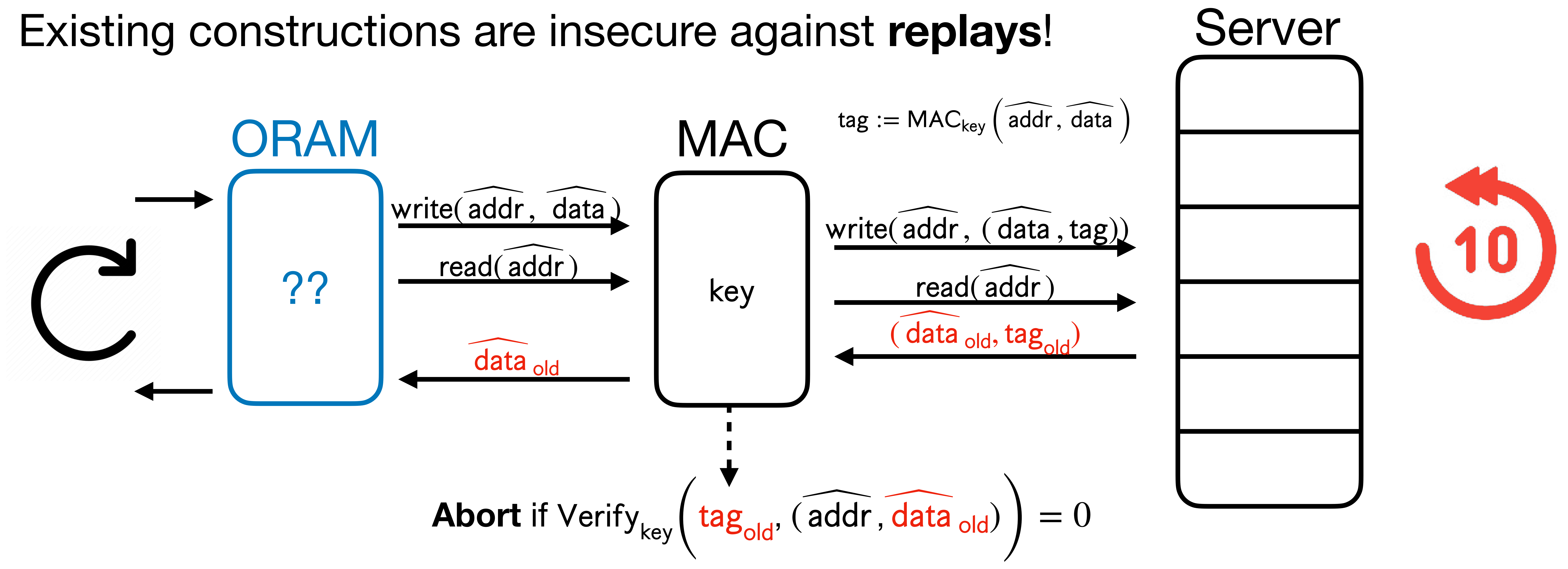
Server
ORAM
??
MAC
key
$\text{tag} := \text{MAC}_{\text{key}}\left(\widehat{\text{addr}}, \widehat{\text{data}}\right)$
$\text{write}(\widehat{\text{addr}}, \widehat{\text{data}})$
$\text{read}(\widehat{\text{addr}})$
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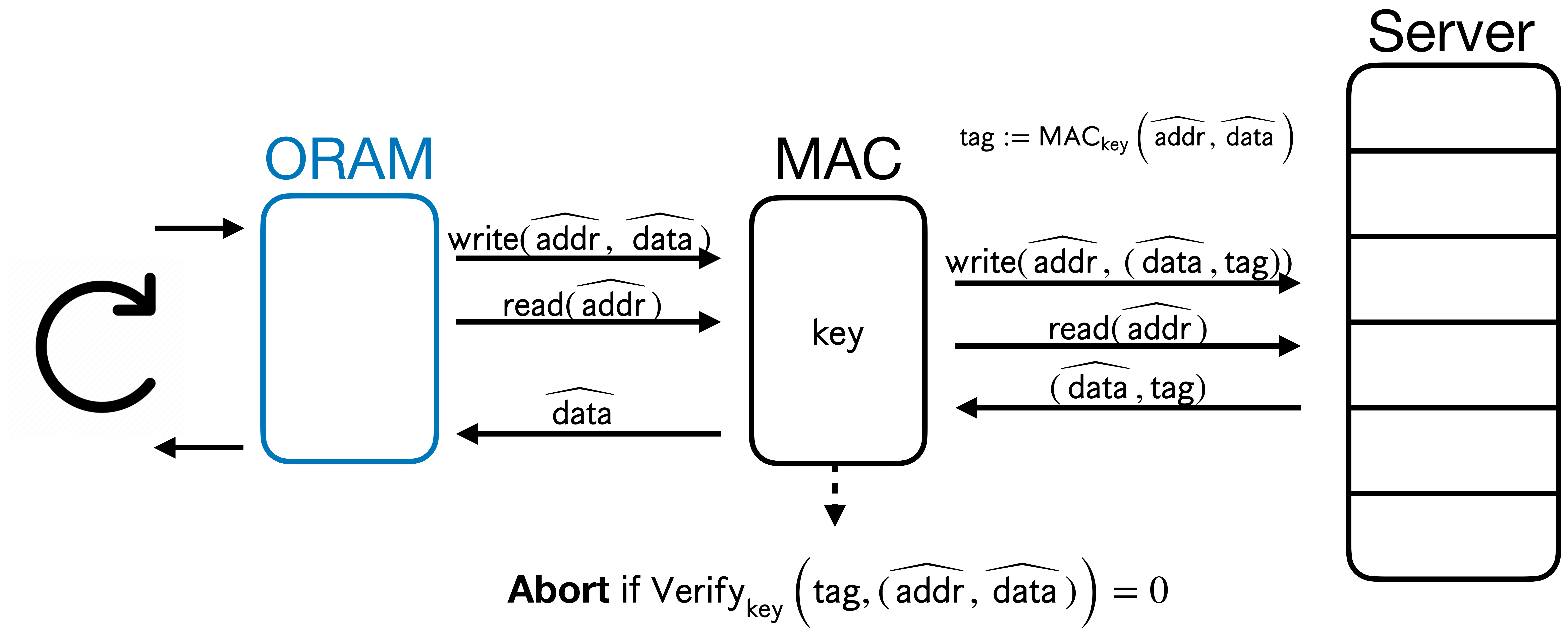
ORAM
MAC
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Server
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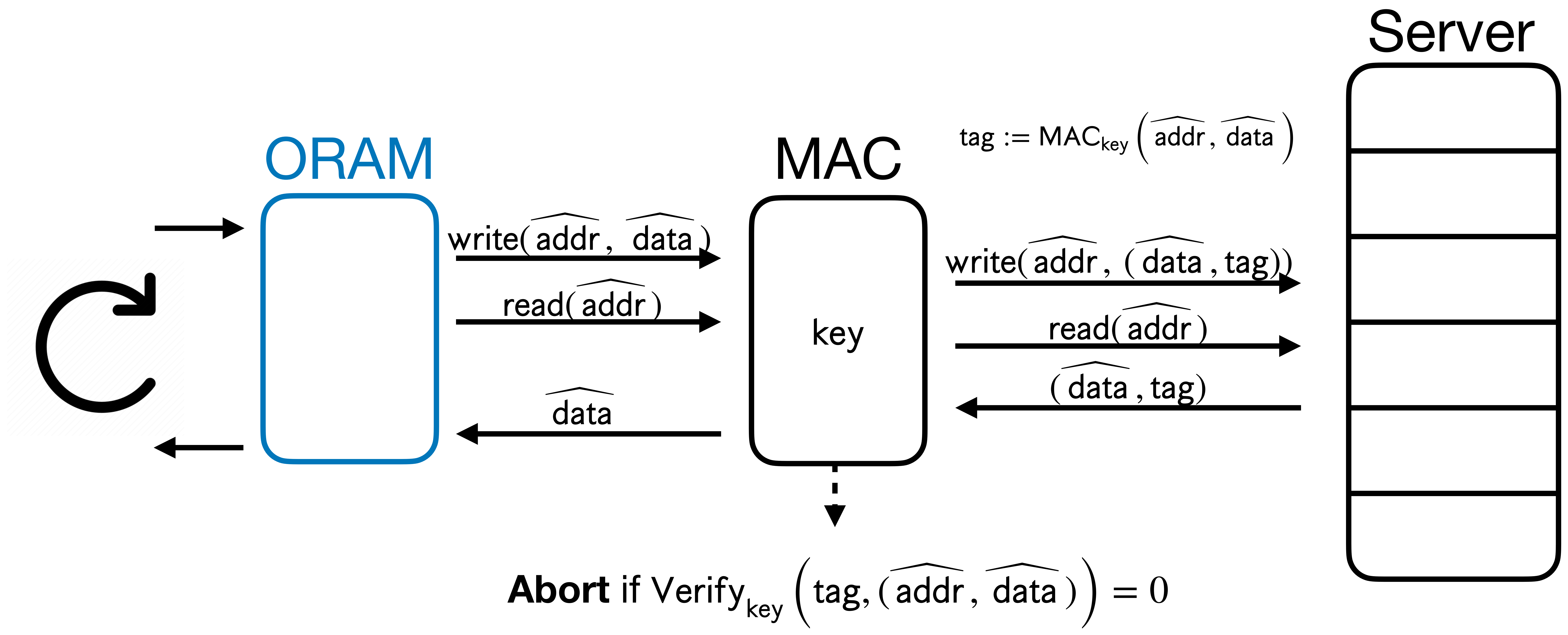
ORAM
MAC
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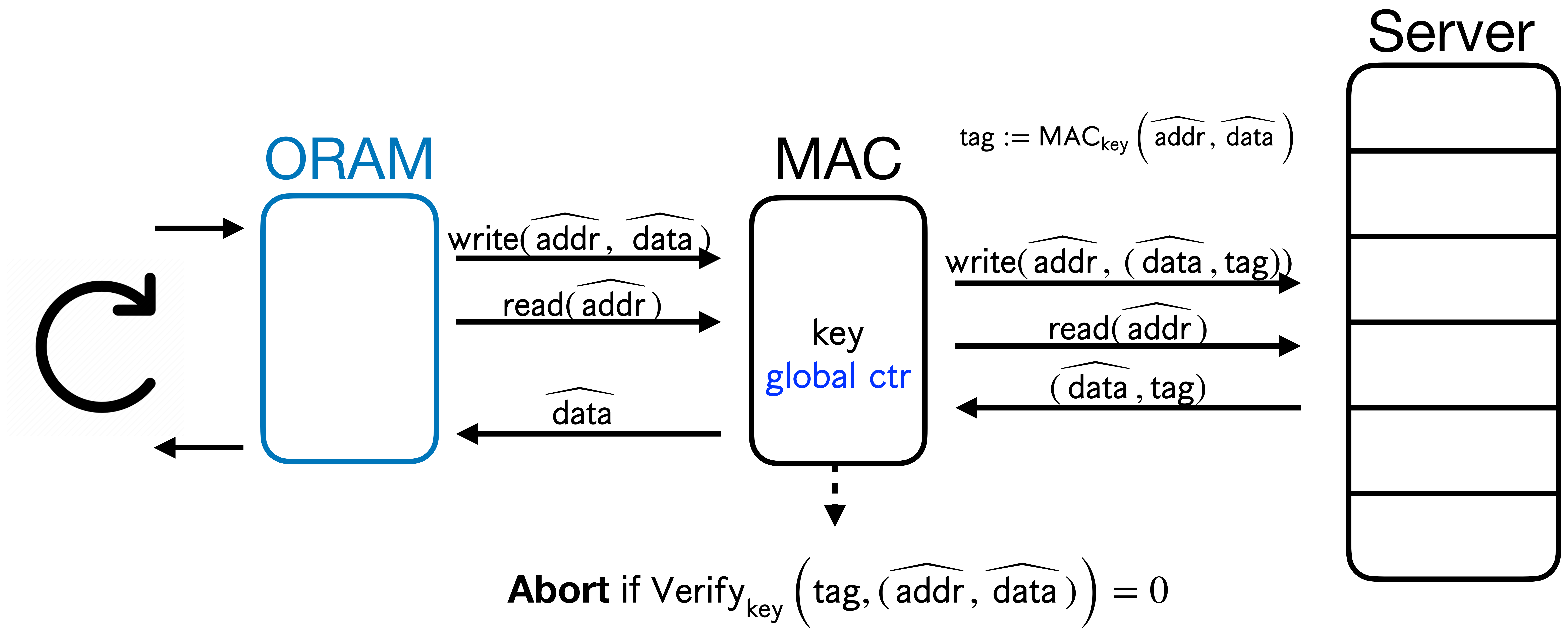
ORAM
MAC
Server
key
global ctr
$\text{write}(\widehat{\text{addr}}, \widehat{\text{data}})$
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$\widehat{\text{data}}$
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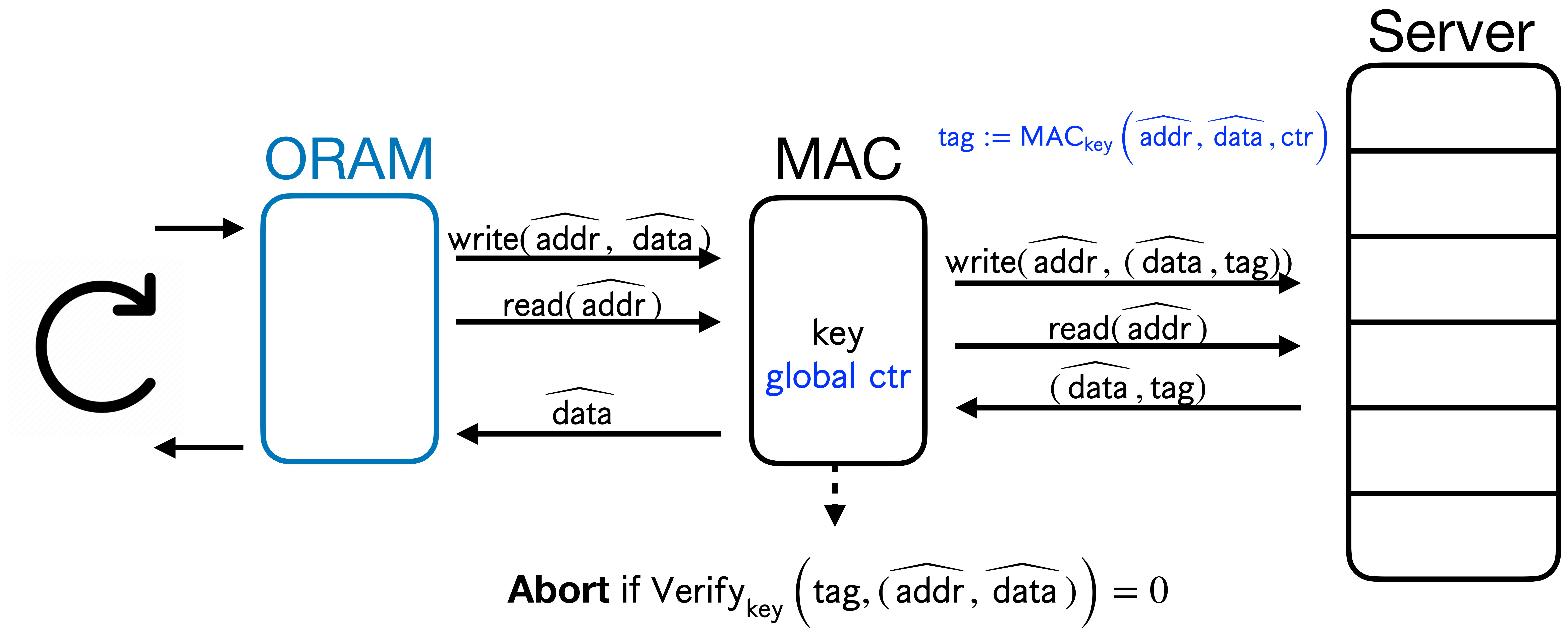

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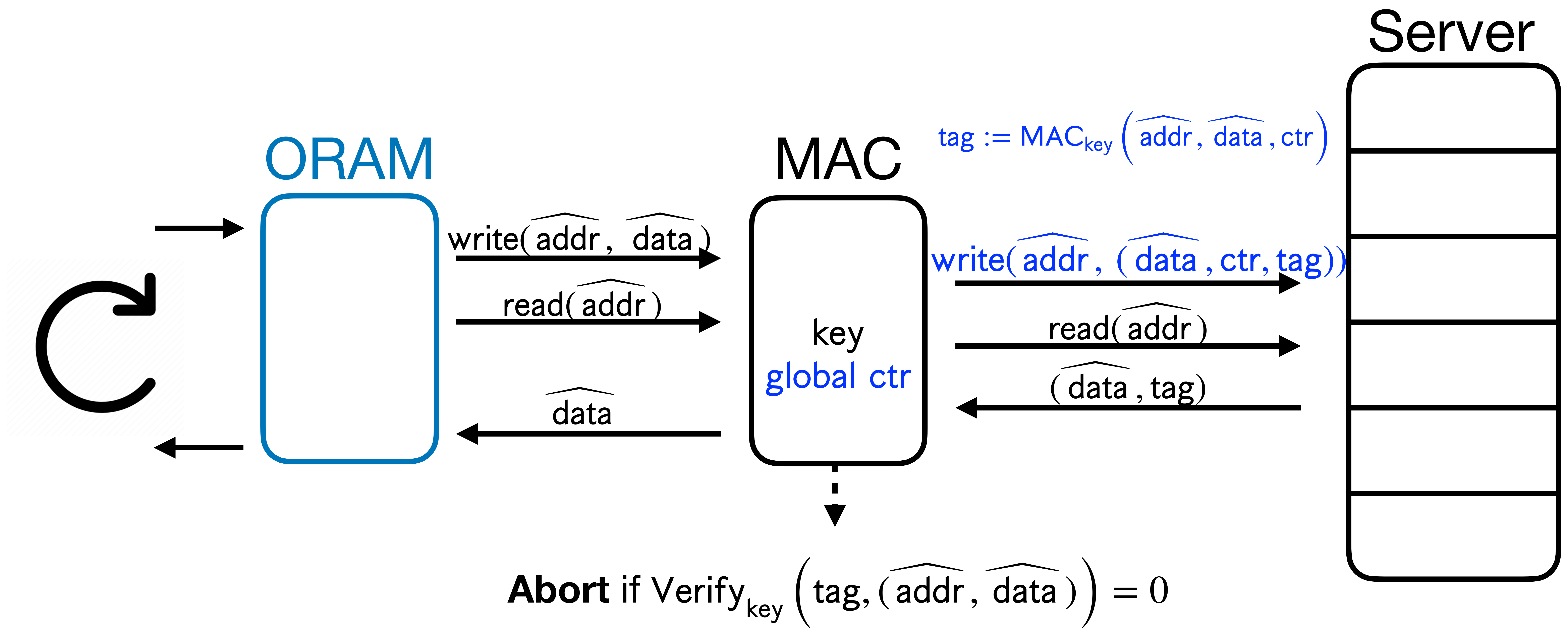

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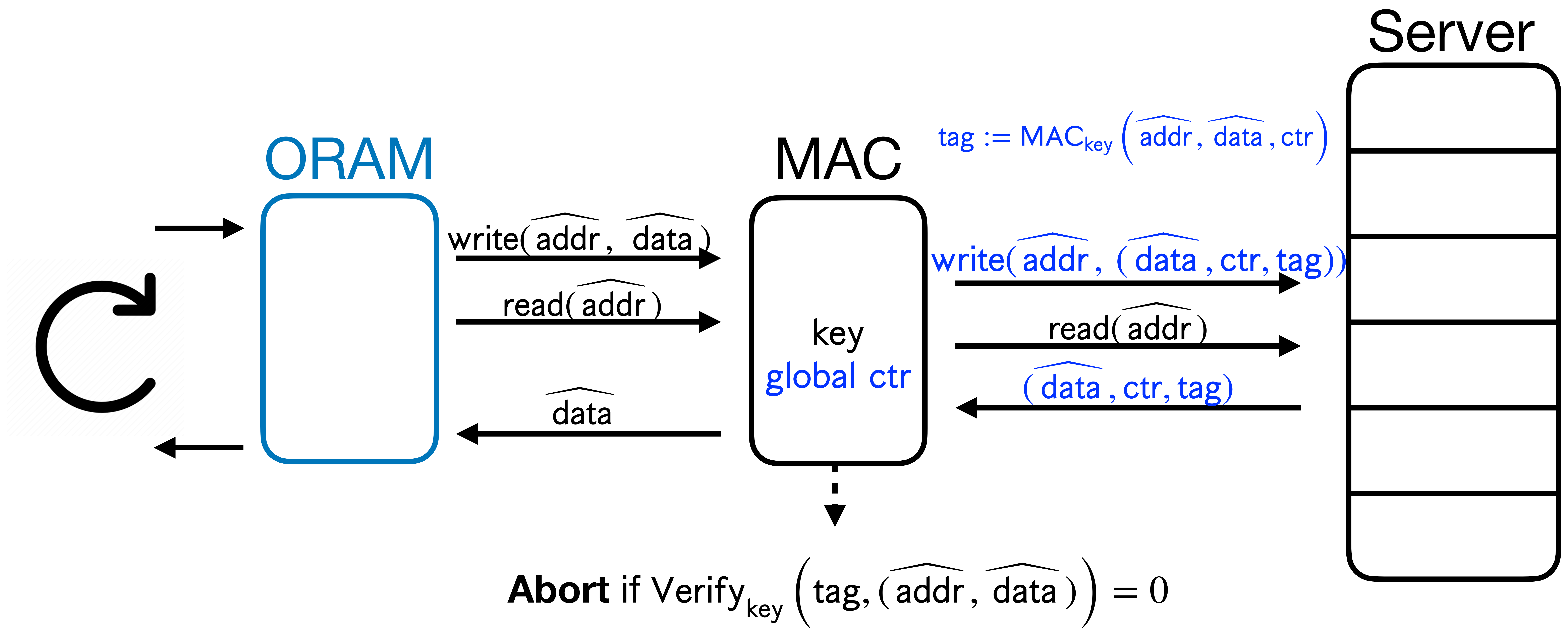

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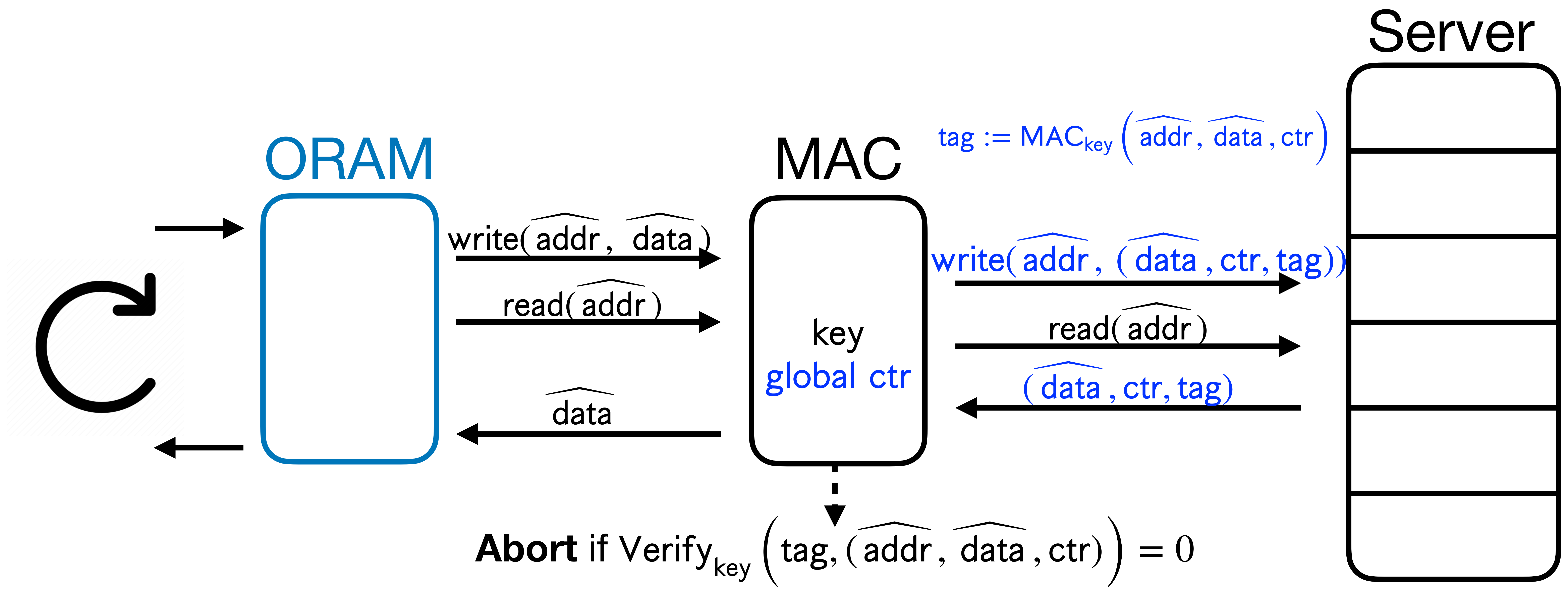

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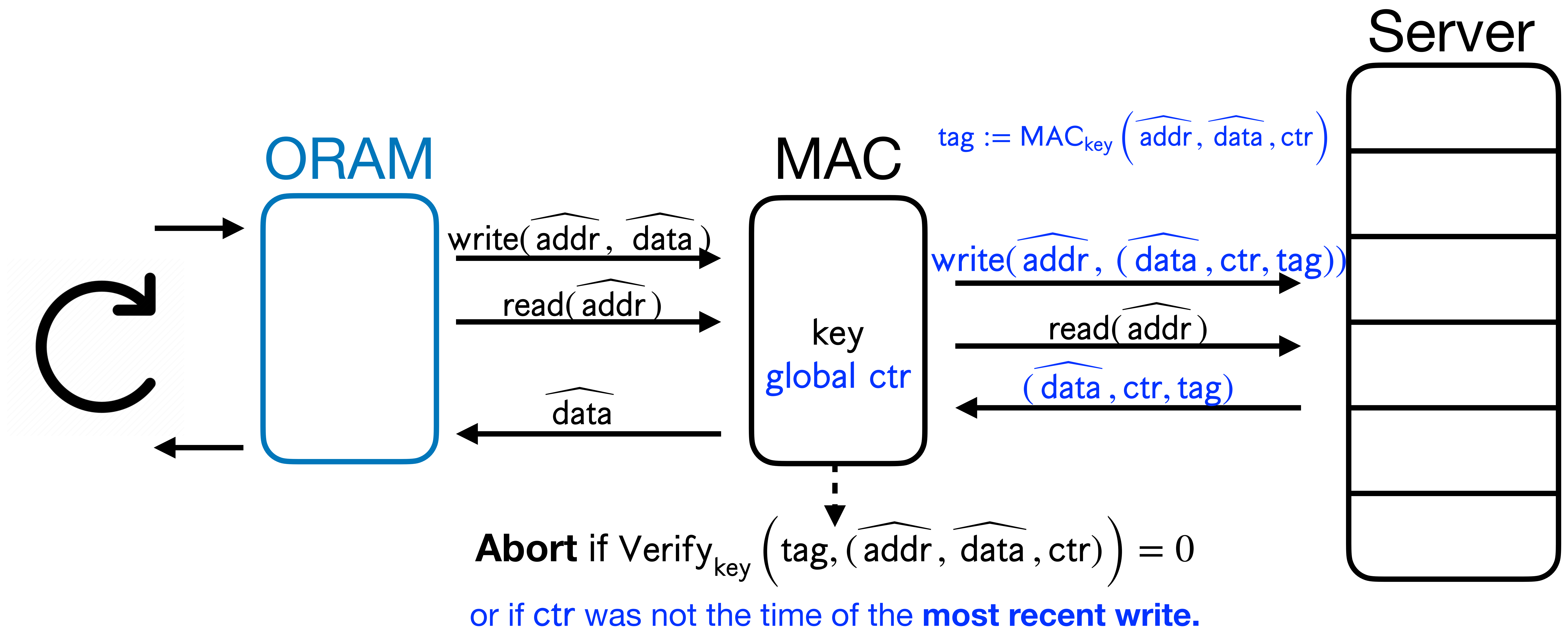
Server
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key
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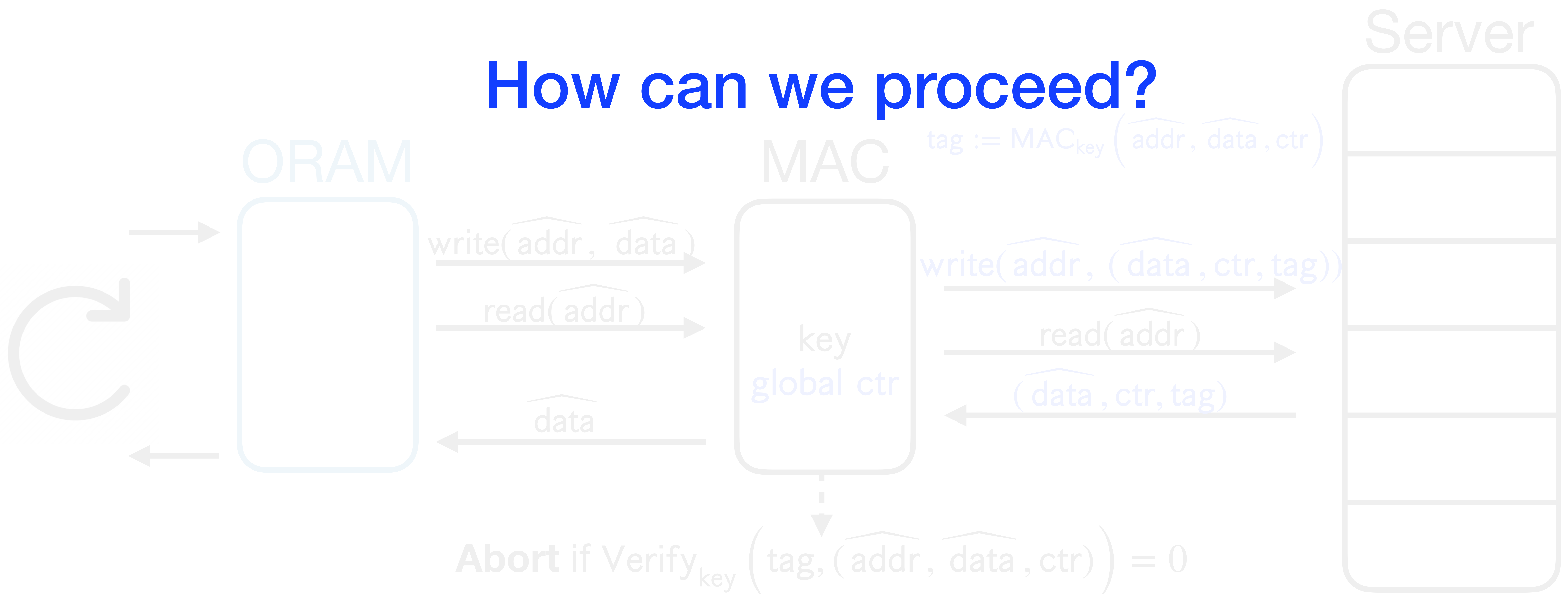

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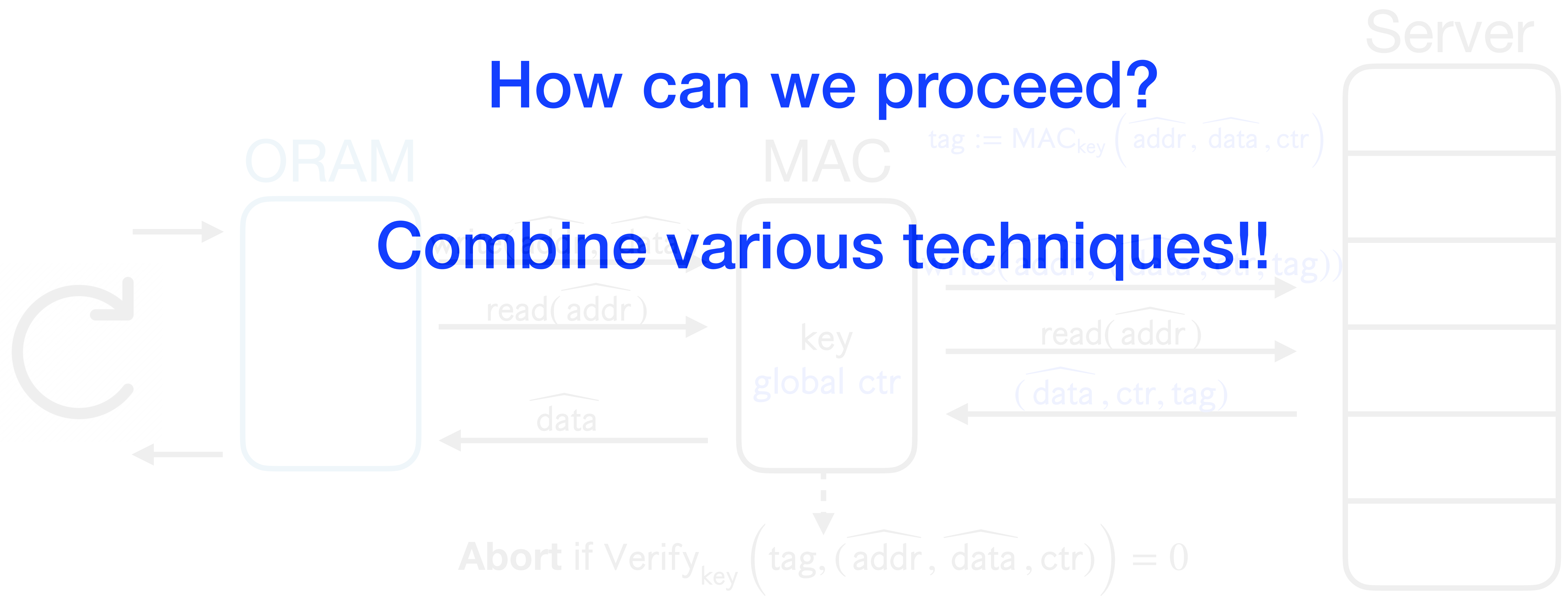
Combine various techniques!!



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Created by Dall-E

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    - Assumptions are **provably minimal** (OWF necessary and sufficient).
- An overhead-preserving black-box 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.

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- Any memory checker with $O(1)$ overhead? Any lower bounds? (Best constructions have $O(\log N)$ overhead.)

Thanks!

Bonus Slides

Dall-E's Attempts

ORAM vs. PIR

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    - In PIR, the database is typically **public**.
    - Unlike ORAM, PIR allows **many clients** to access database.
    - PIR clients typically do not perform writes.
- Because ORAMs can be **stateful**, we have better constructions under minimal assumptions.

Ideal Malicious Security

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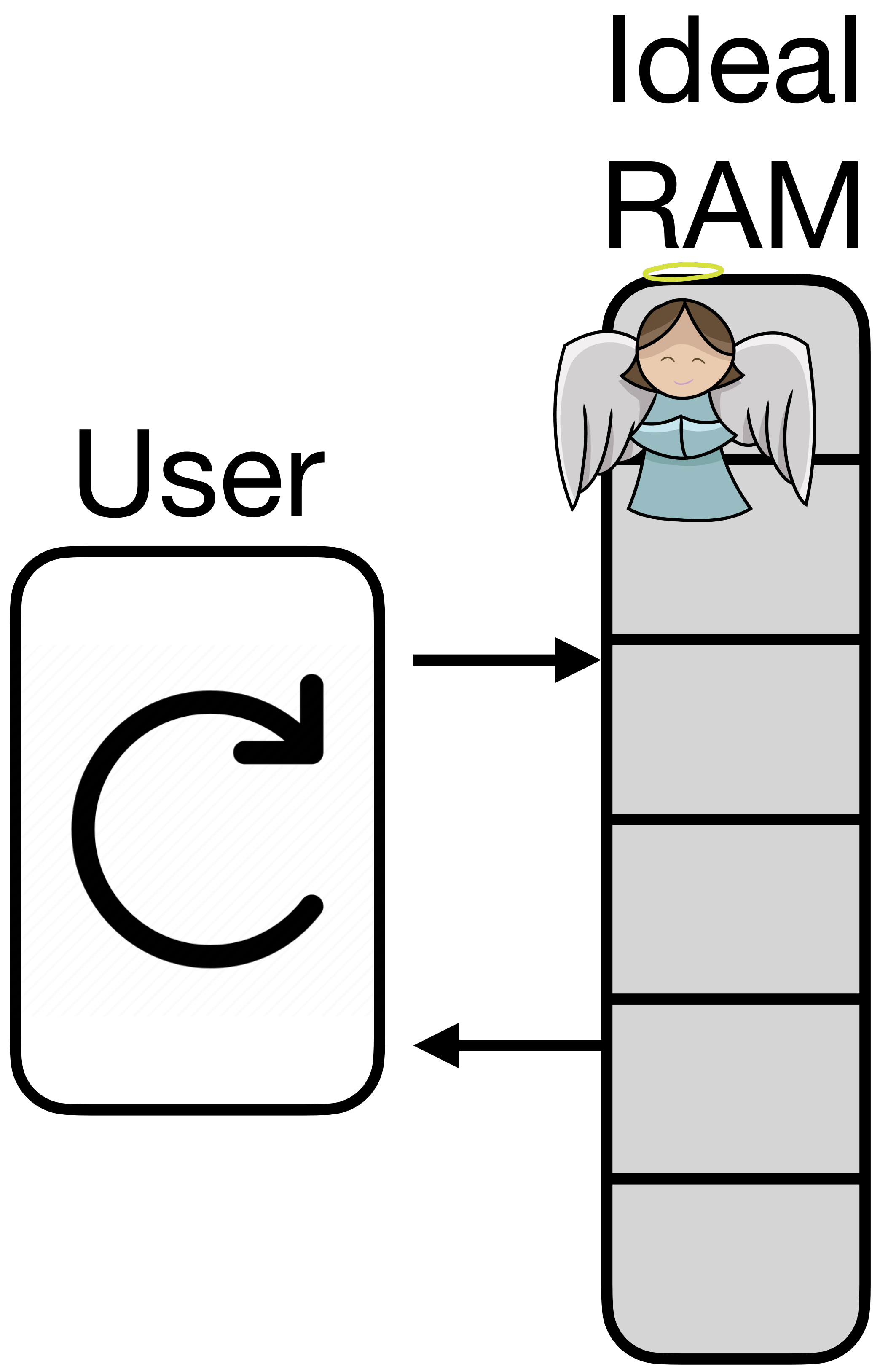

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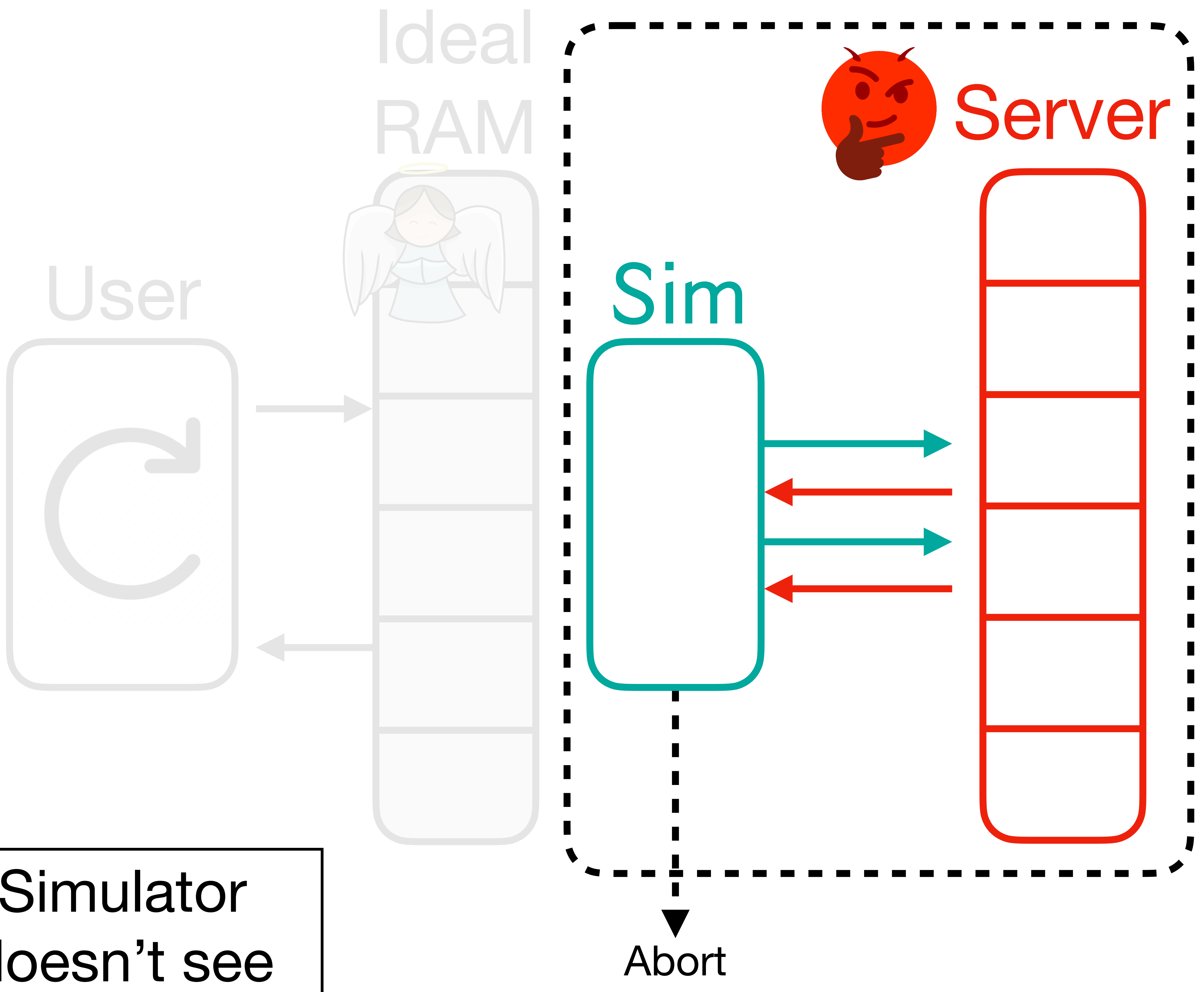

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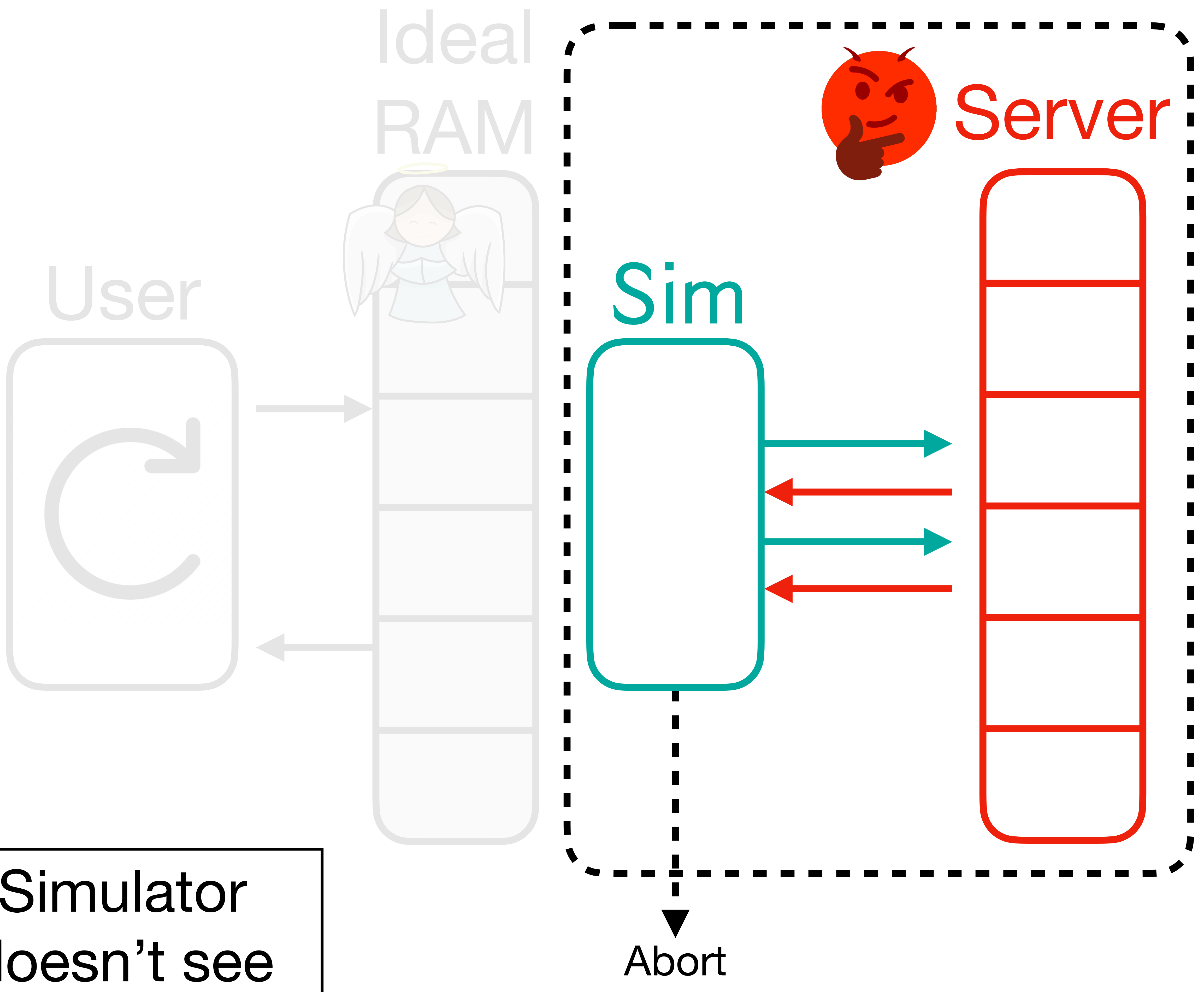

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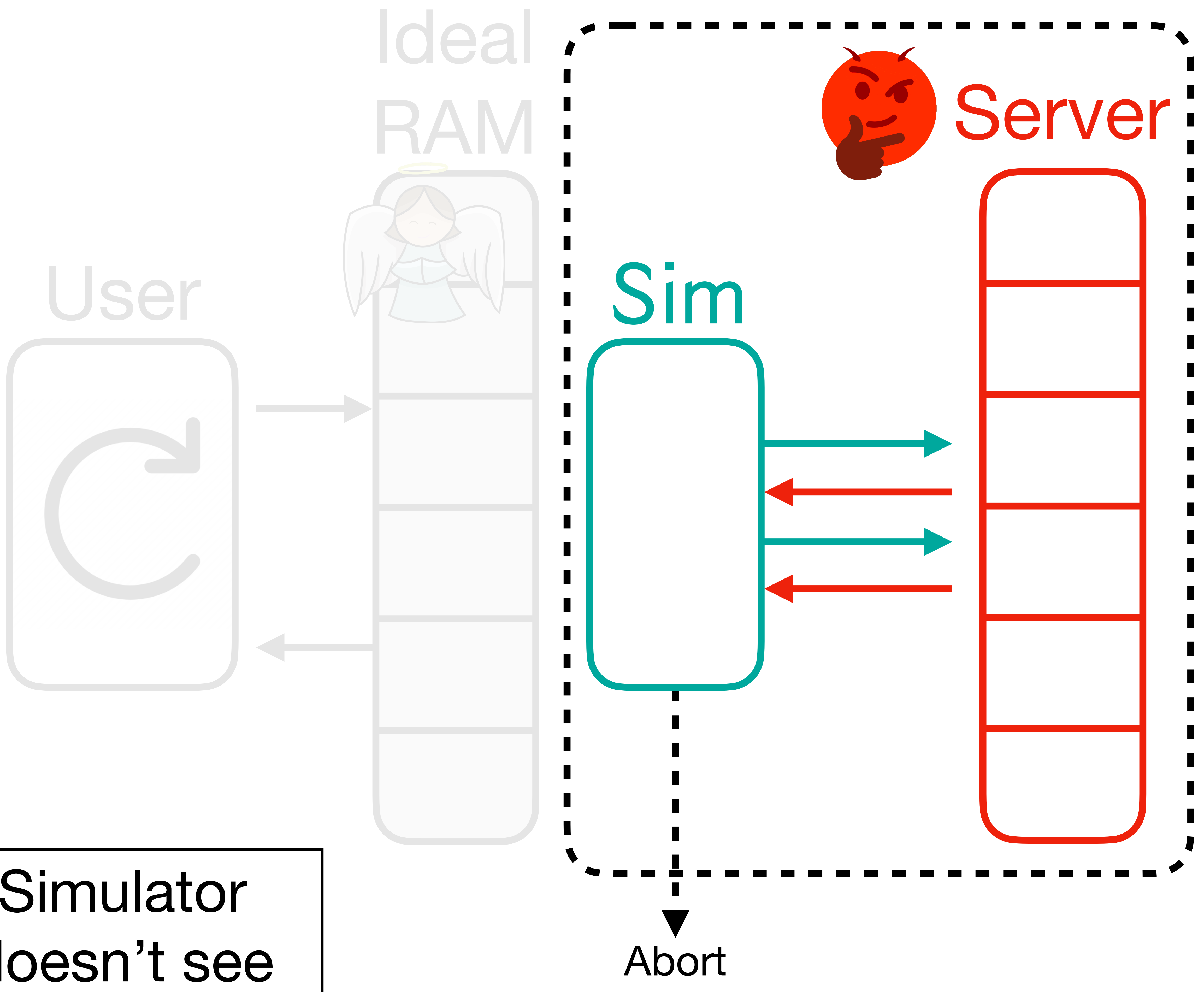

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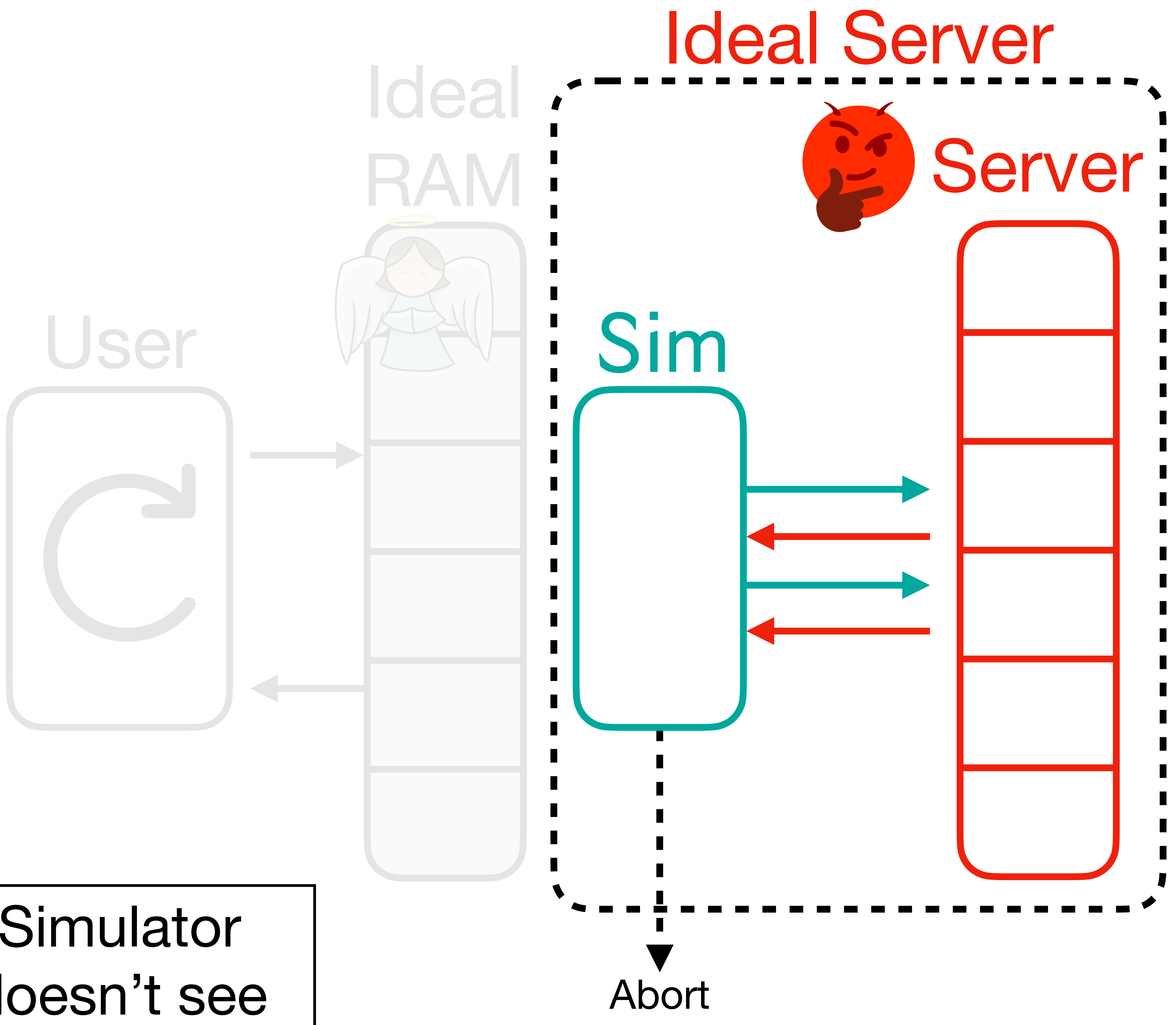

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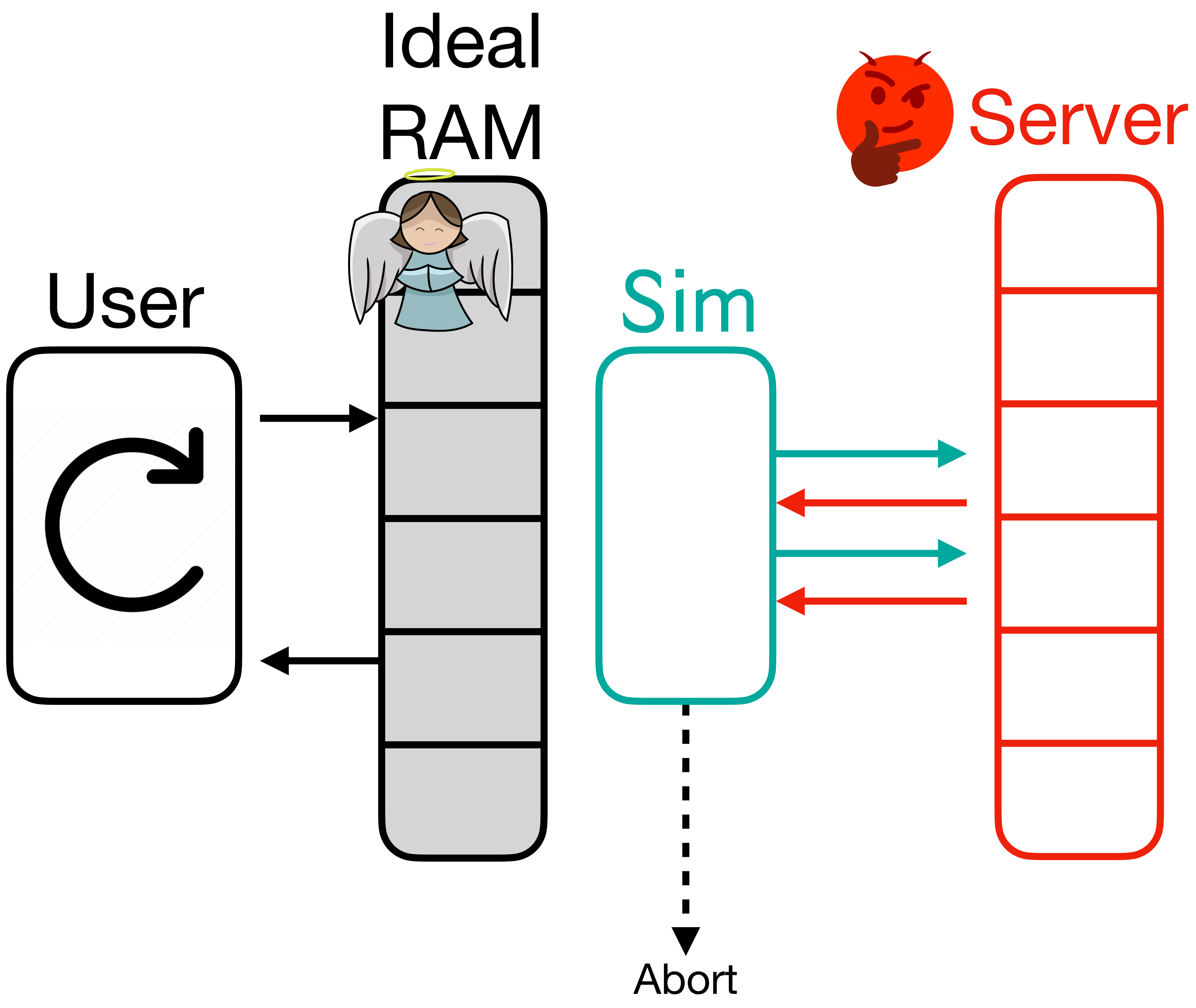

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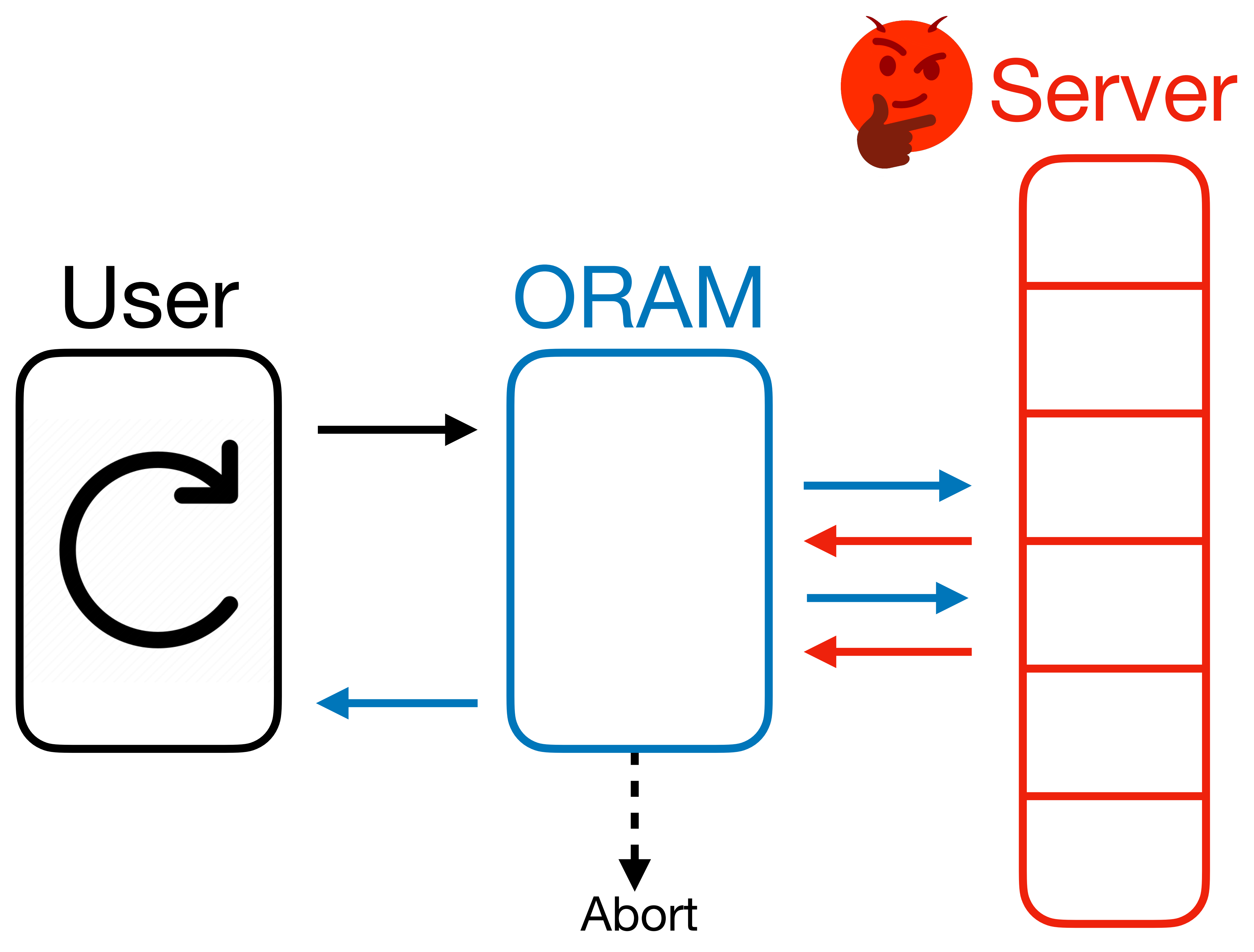

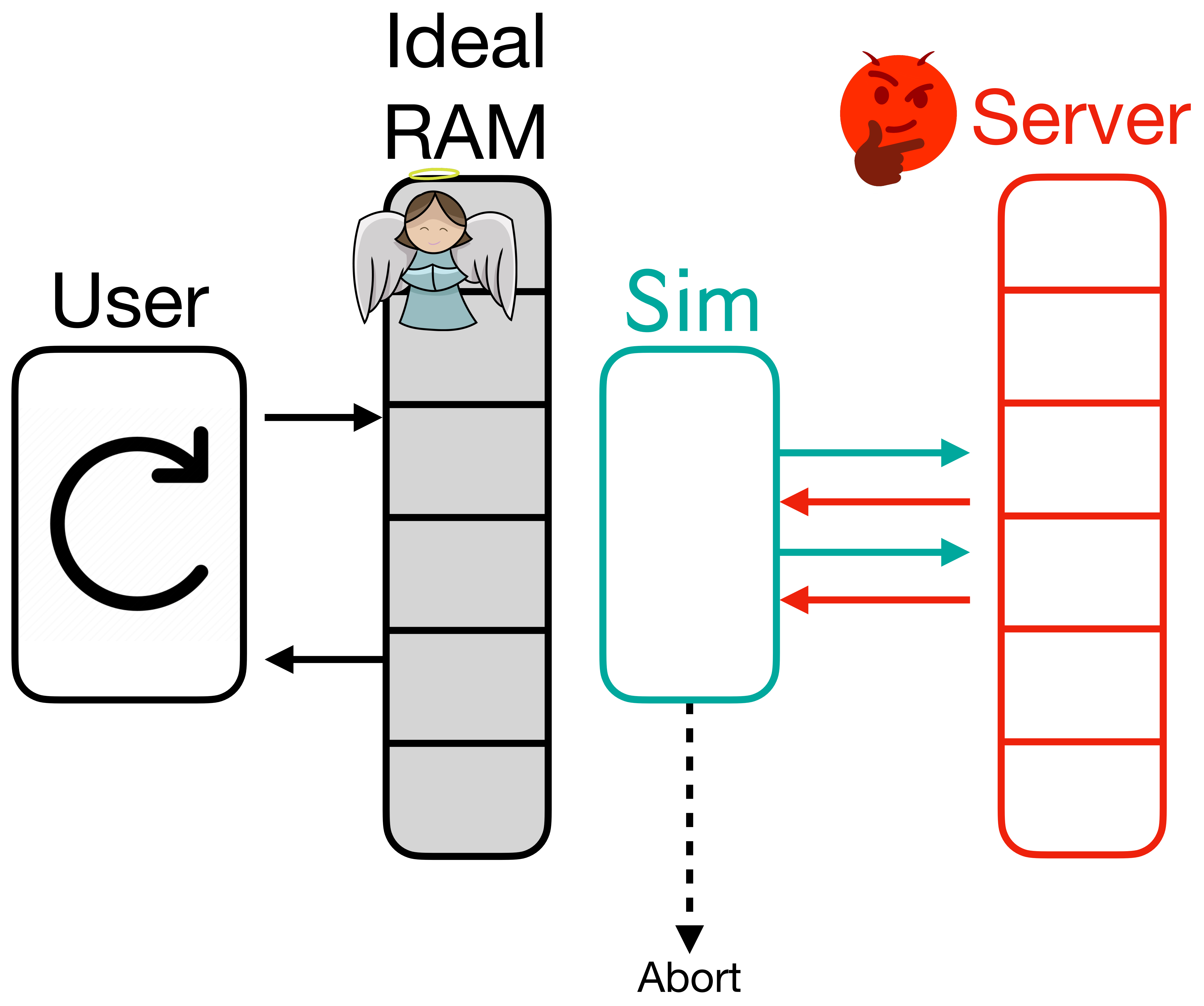

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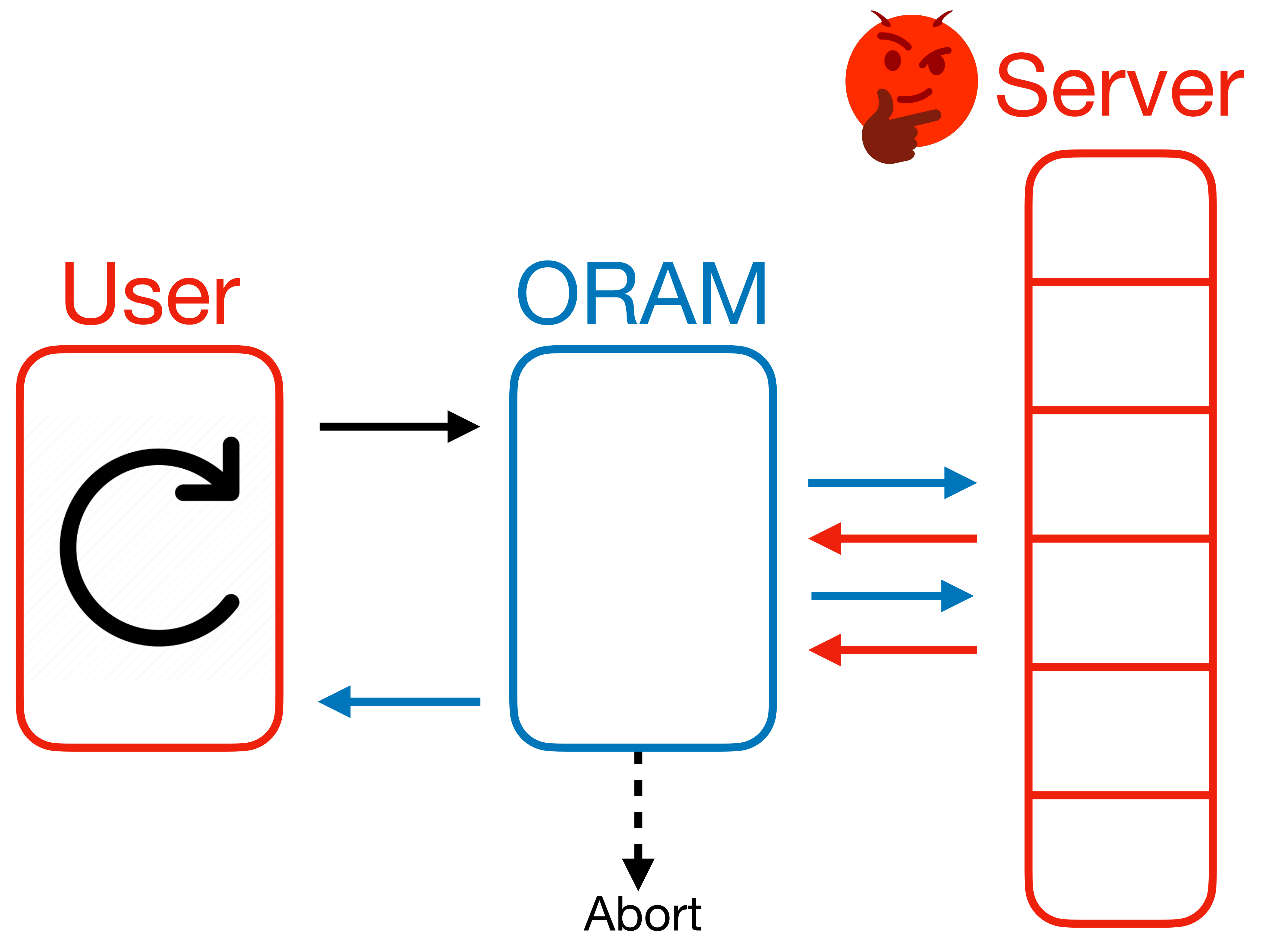

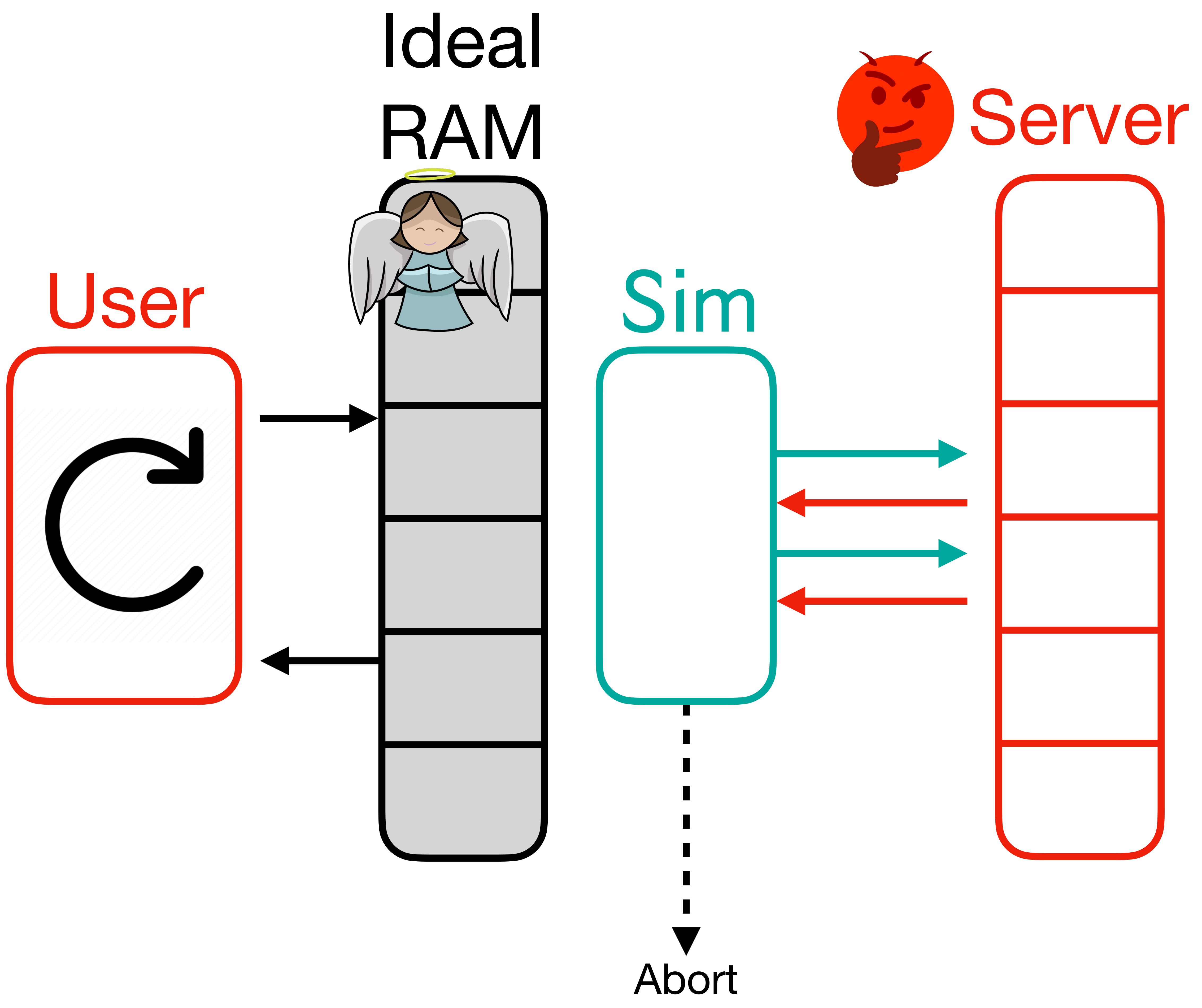

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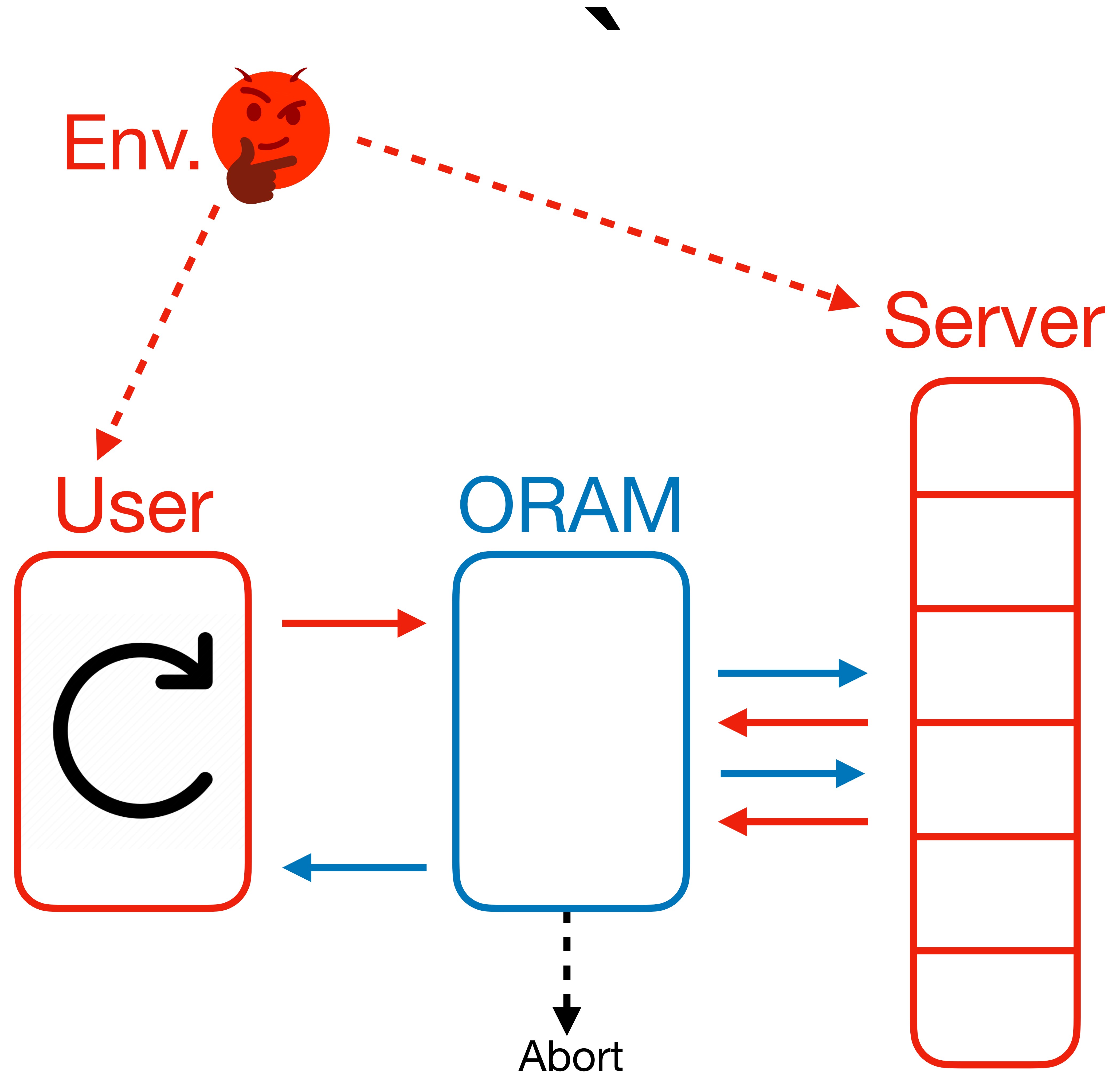
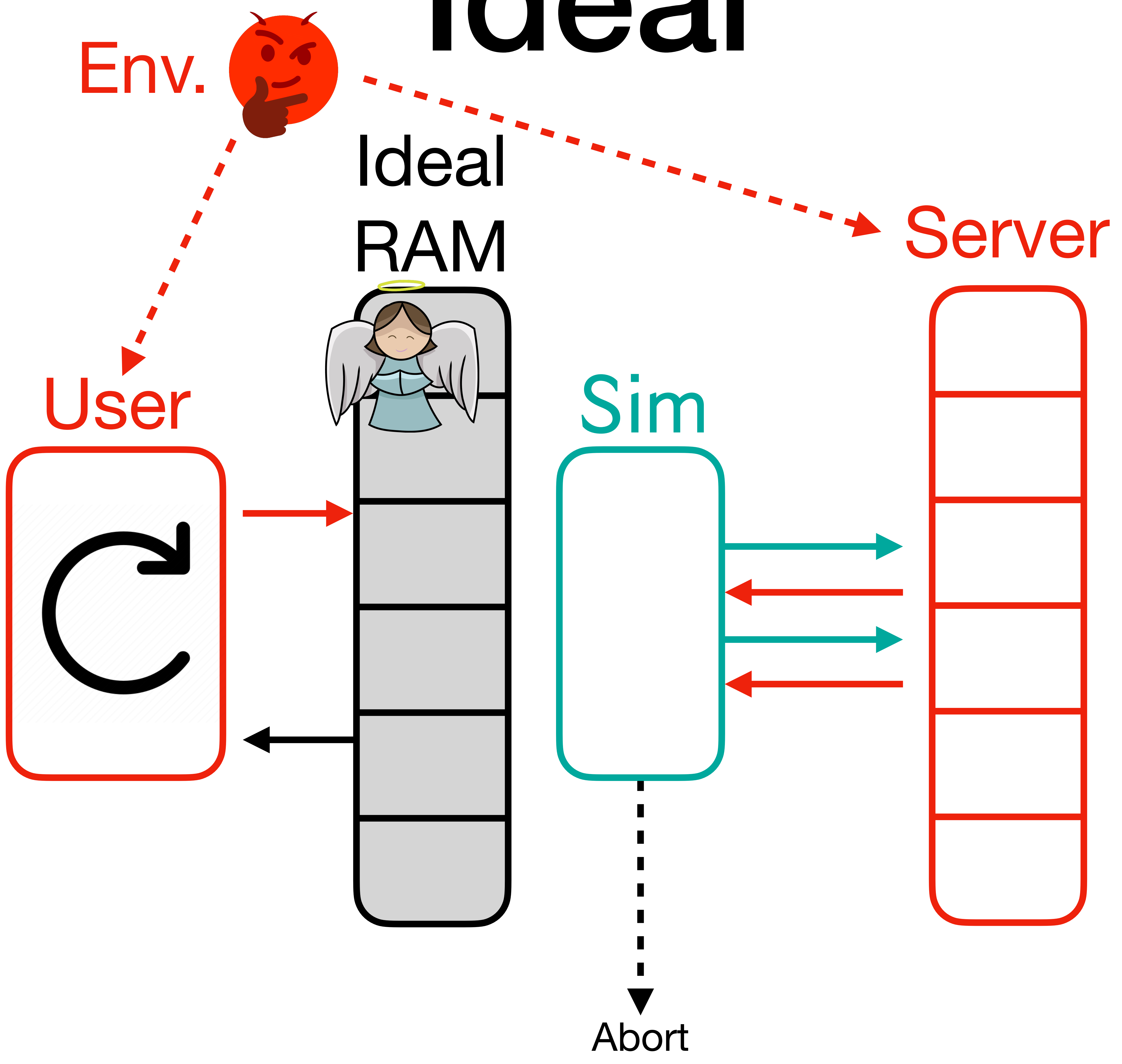

Env.
Server
User
ORAM
Abort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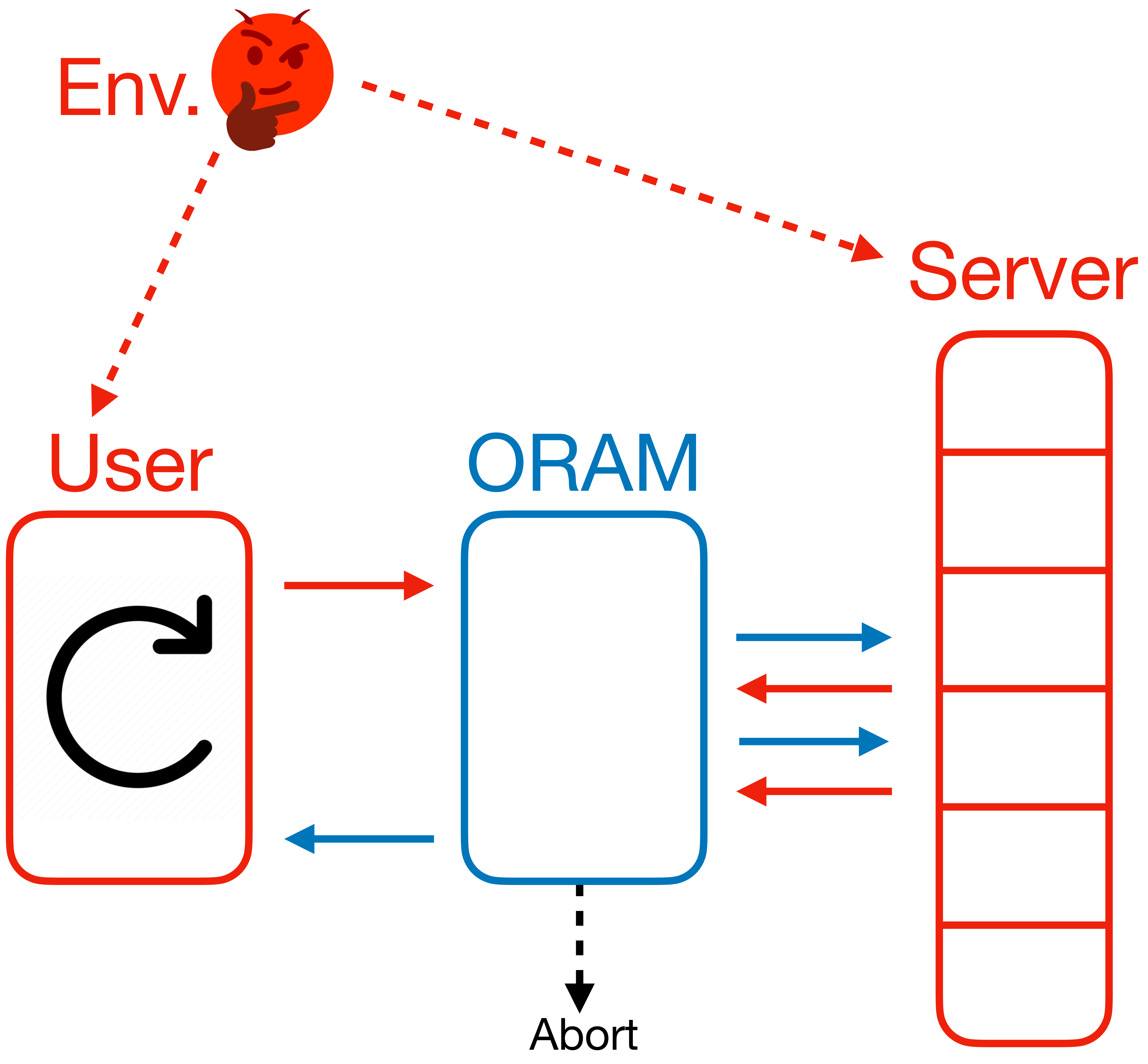
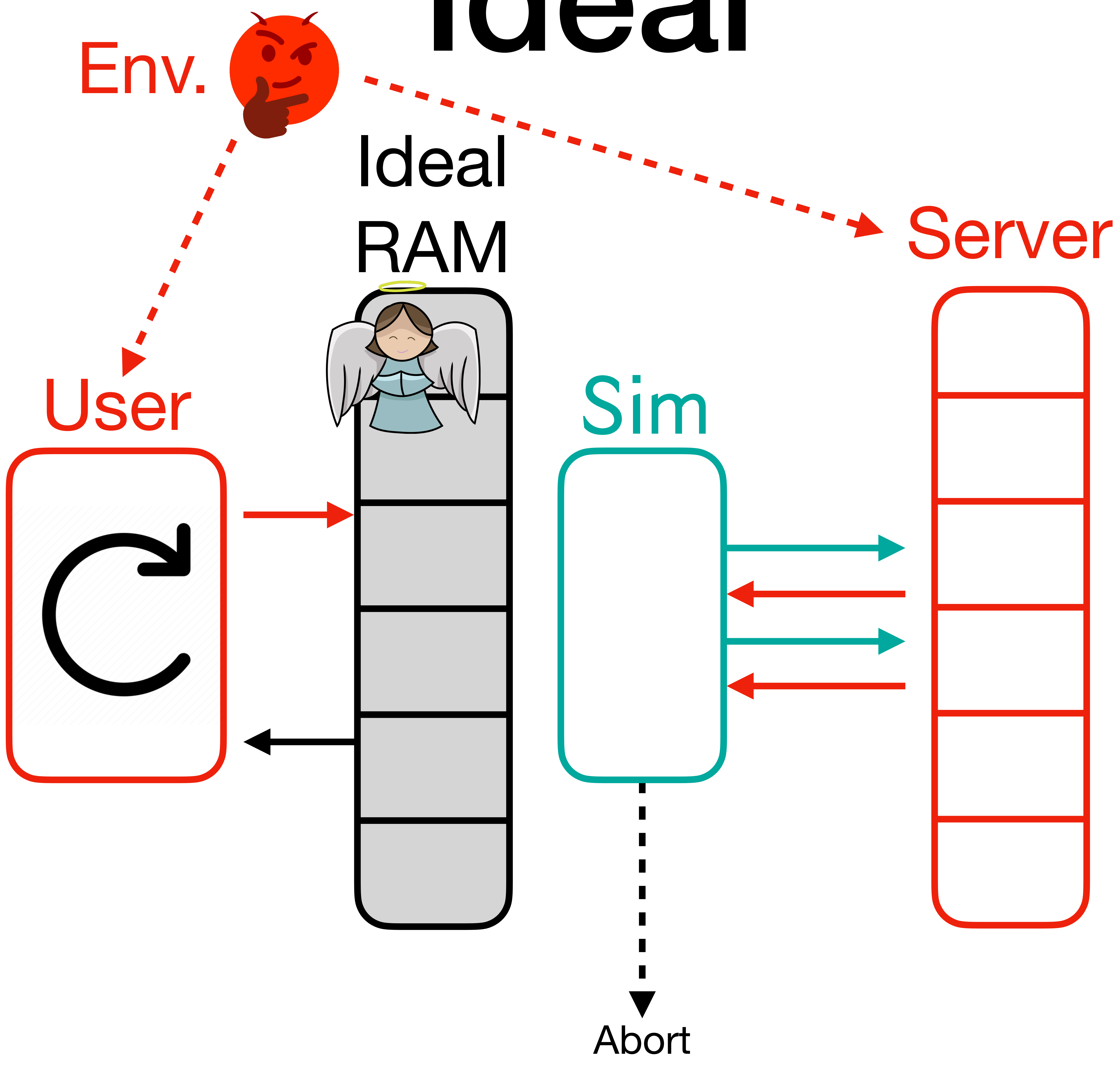
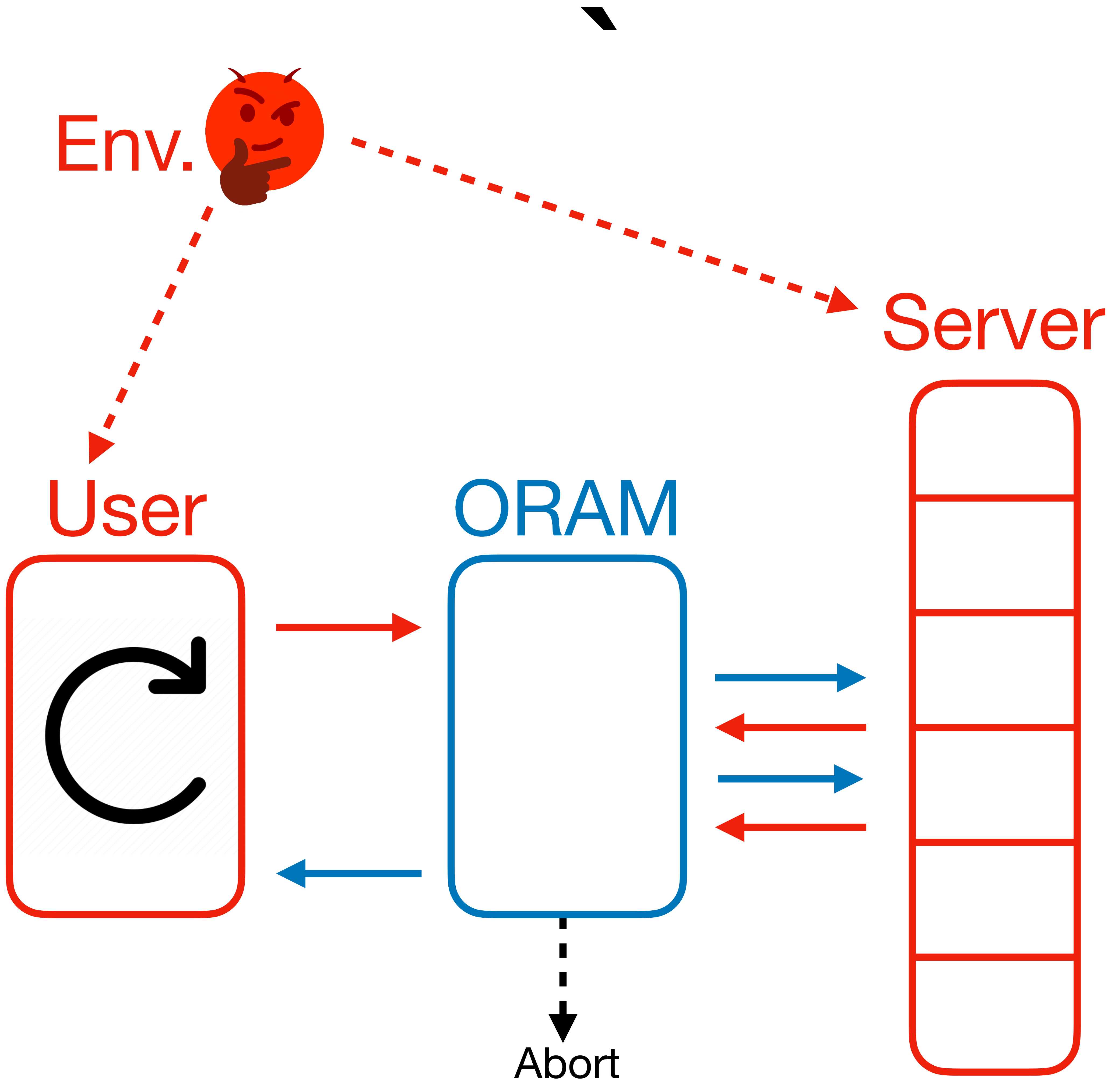
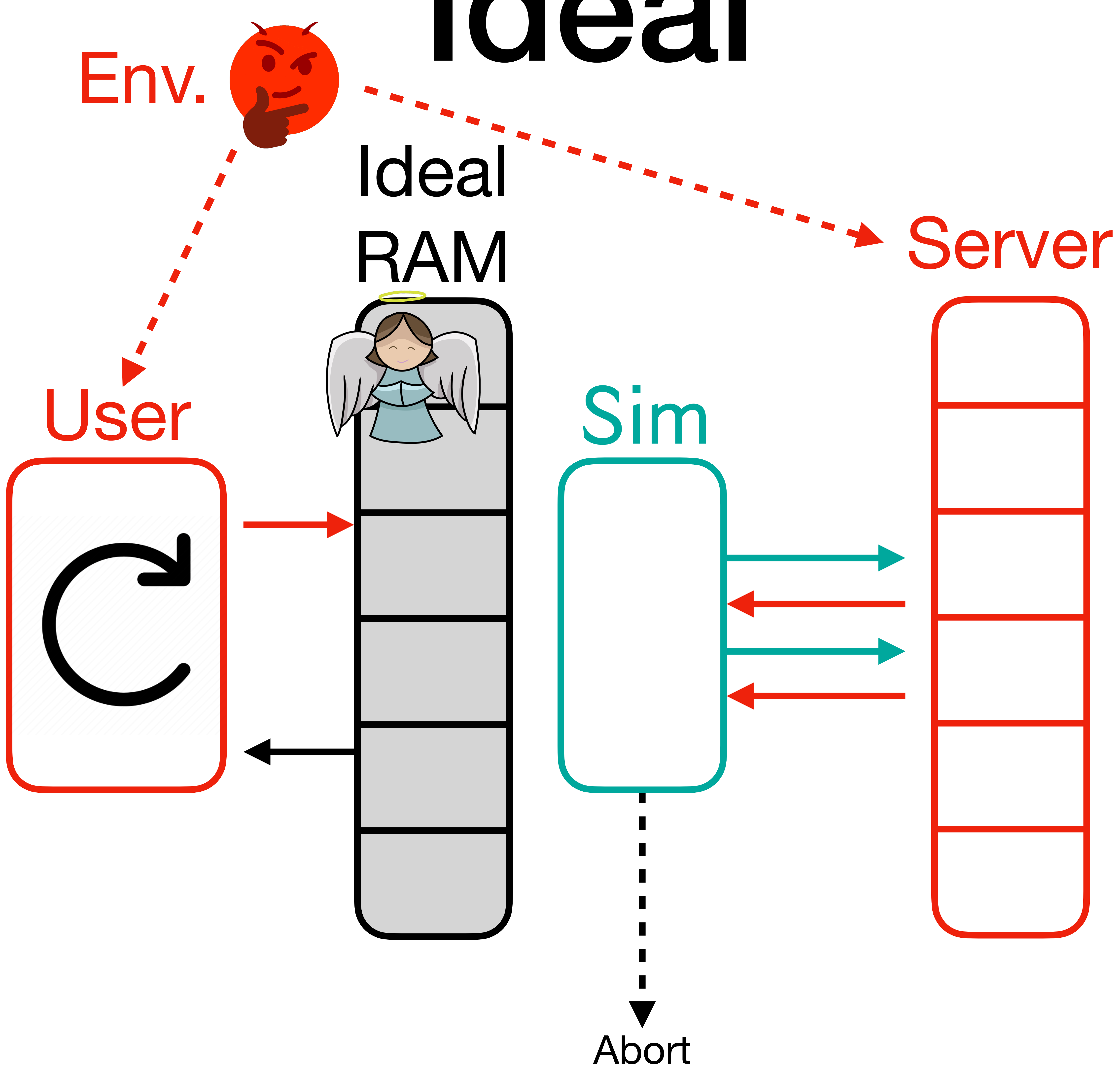




Our Definition: ORAM is *maliciously secure* if ∃Sim such that for all 🤔, Real $\approx_{\text{comp}}$ Ideal

Ideal





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).

Background: Hierarchical ORAM

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  - **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.

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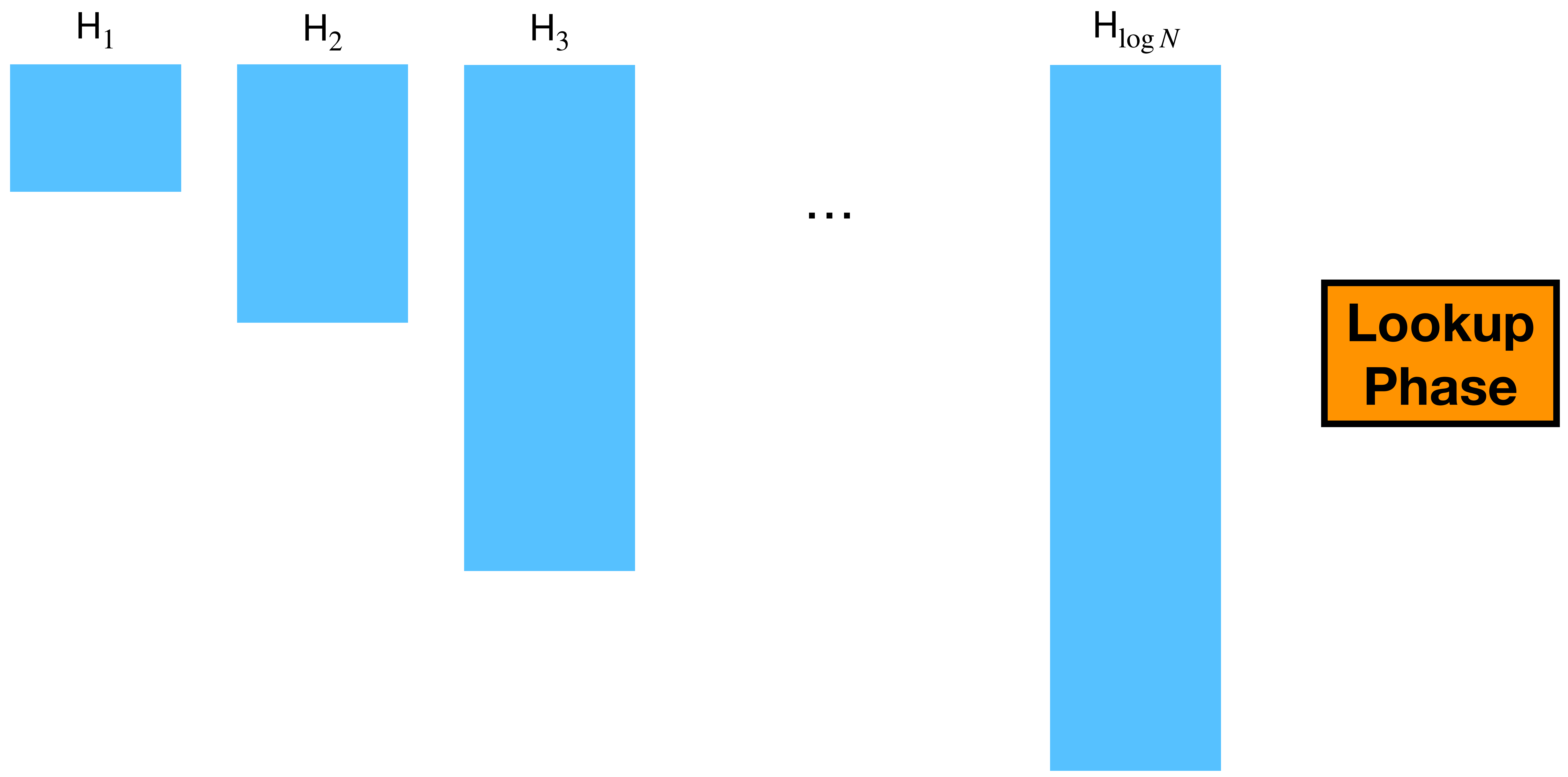
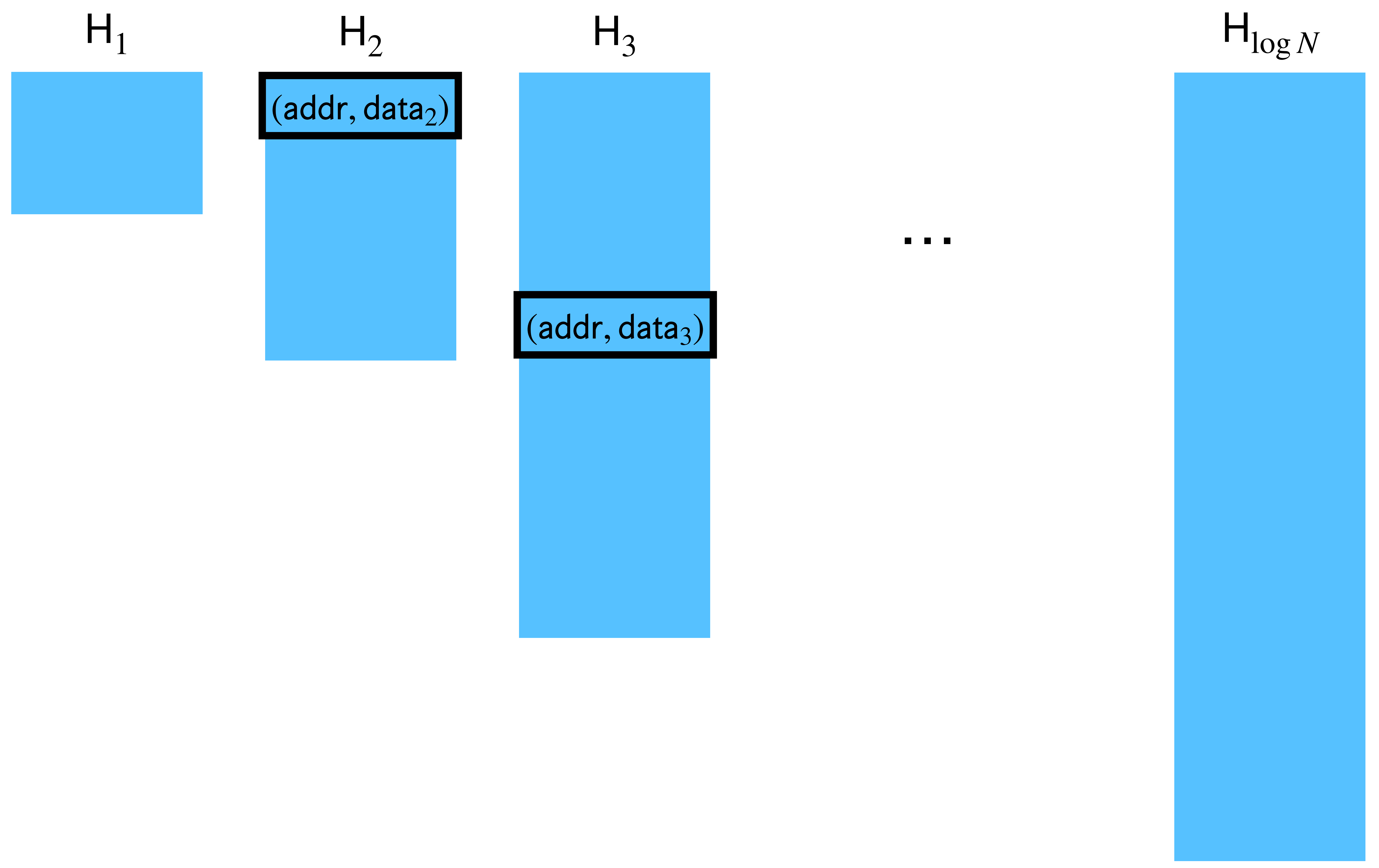
  - **Rebuild Phase**: Every 2^i queries, obliviously merge $\mathsf{H}_1 \to \mathsf{H}_2 \to \cdots \to \mathsf{H}_{i+1}$ into new H_{i+1}, removing duplicate addresses by keeping the version from the smaller H_j.

Hierarchical Construction: Lookup



Hierarchical Construction: Lookup

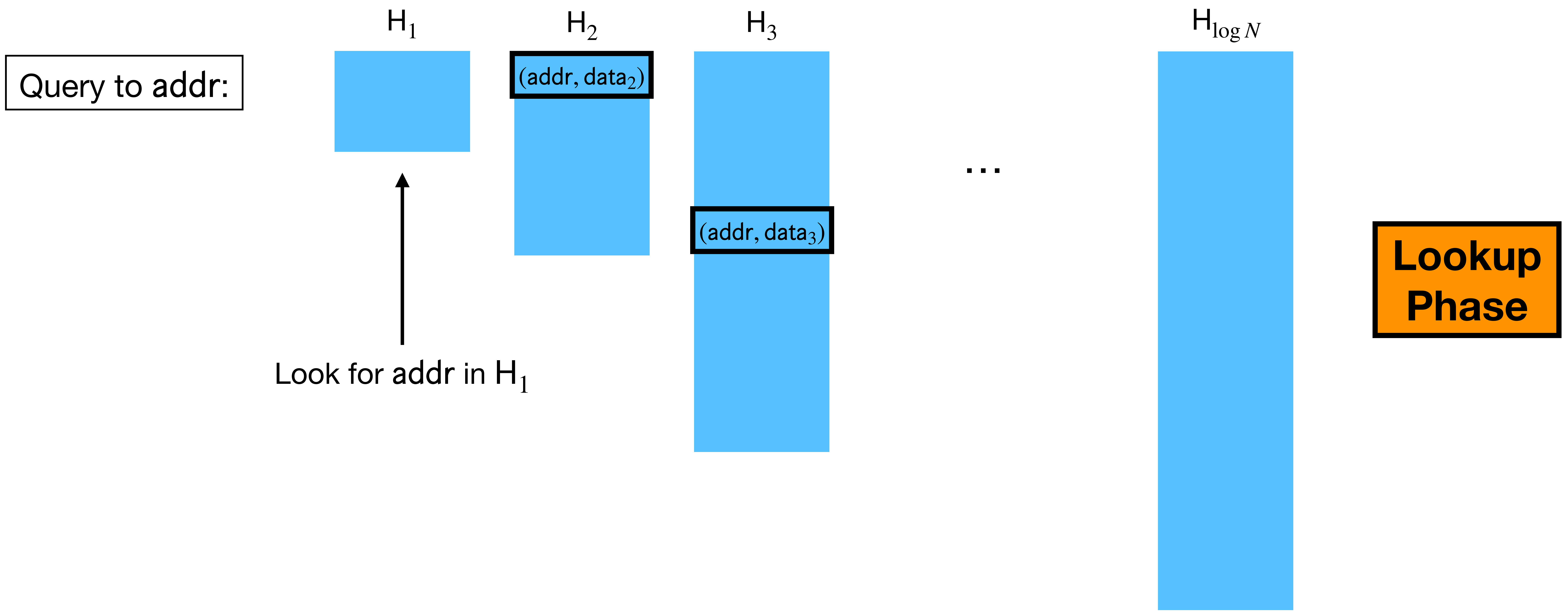
Query to addr:



H_1
H_2
H_3
$H_{\log N}$
$(\text{addr}, \text{data}_2)$
$(\text{addr}, \text{data}_3)$
…

Lookup Phase

Hierarchical Construction: Lookup



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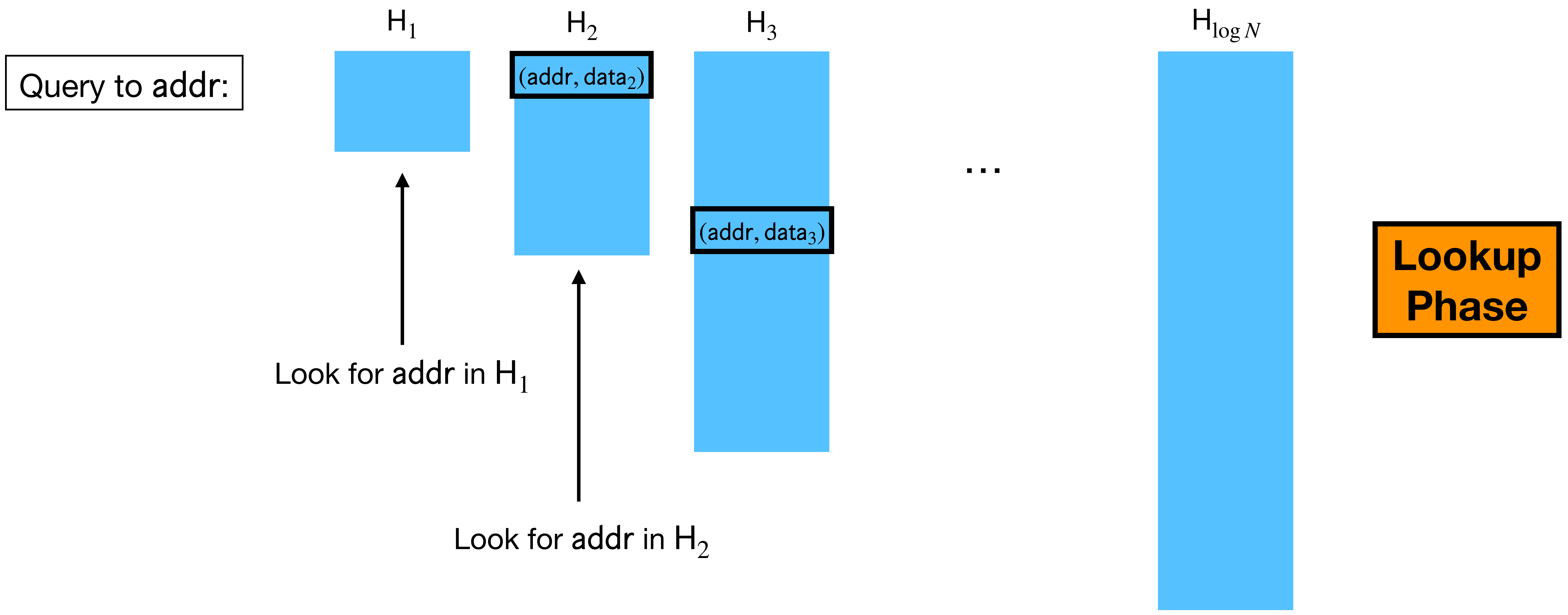

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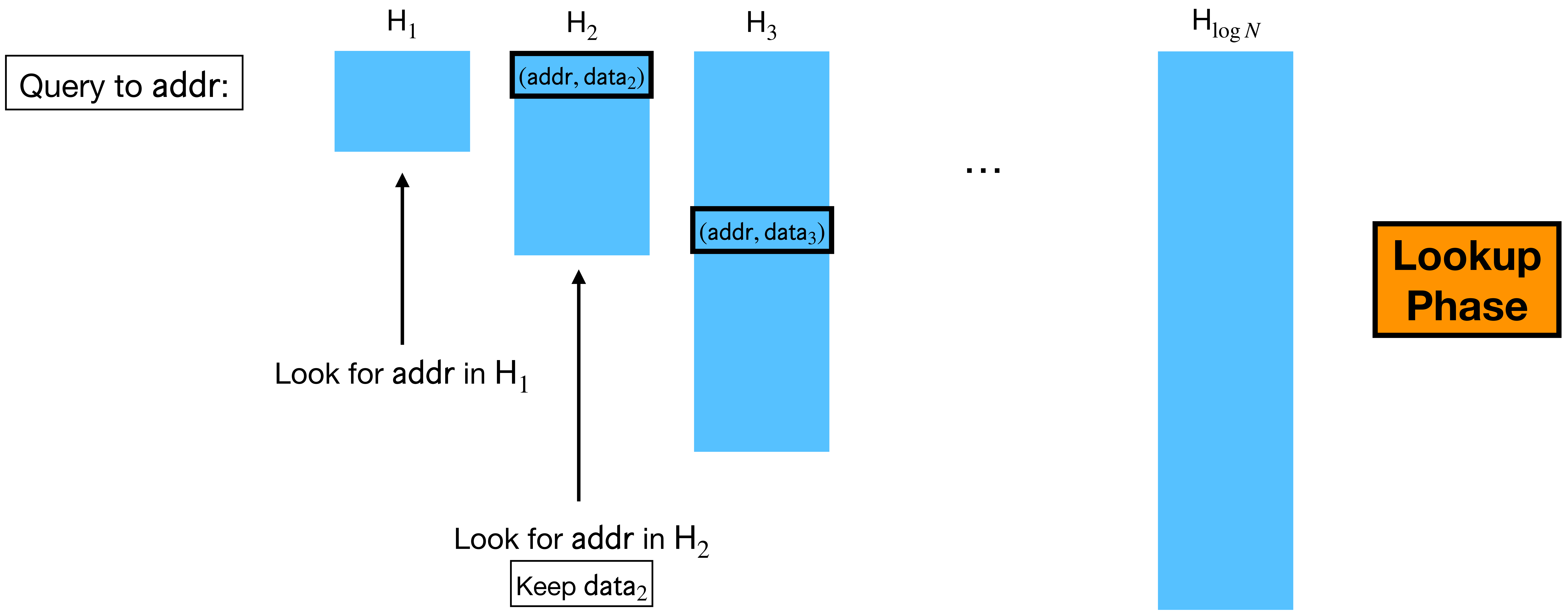

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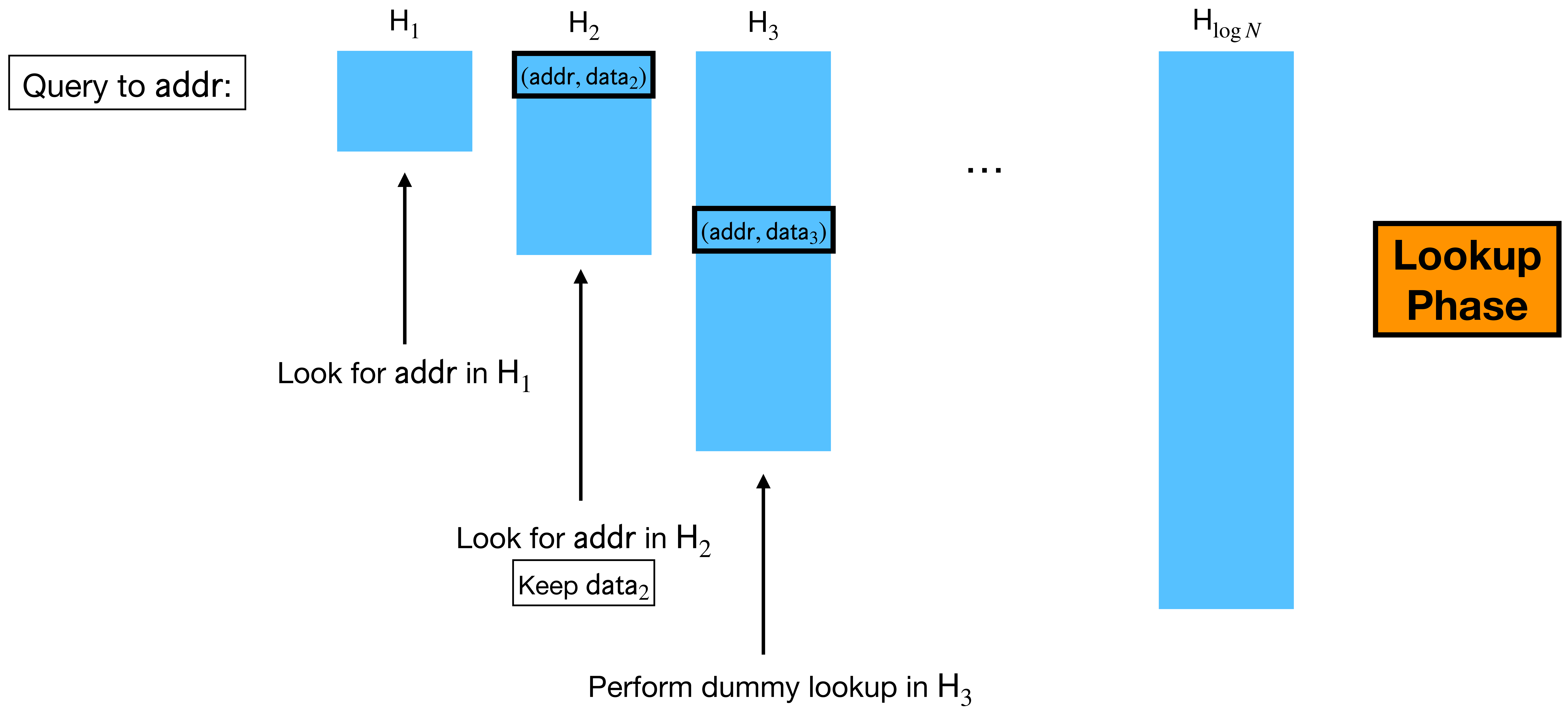

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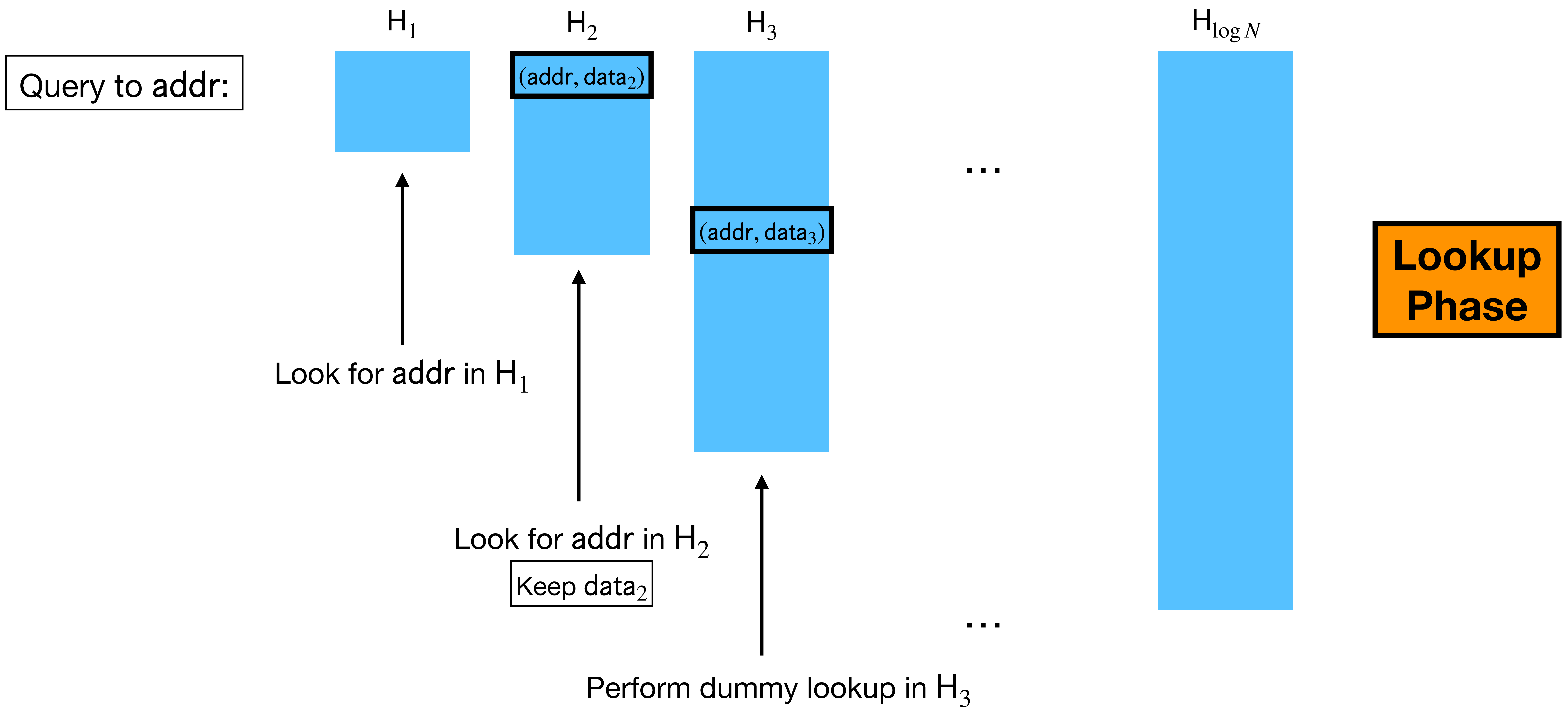

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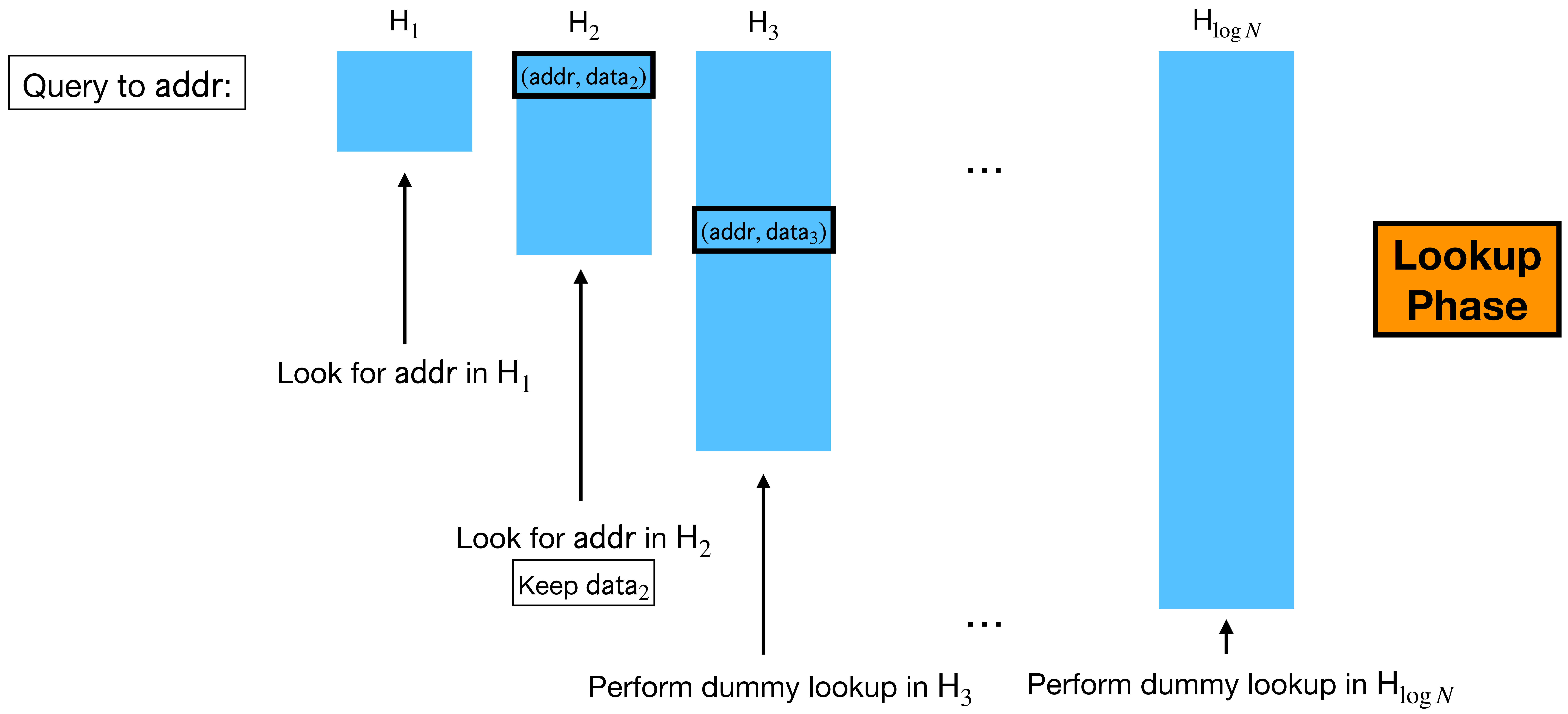

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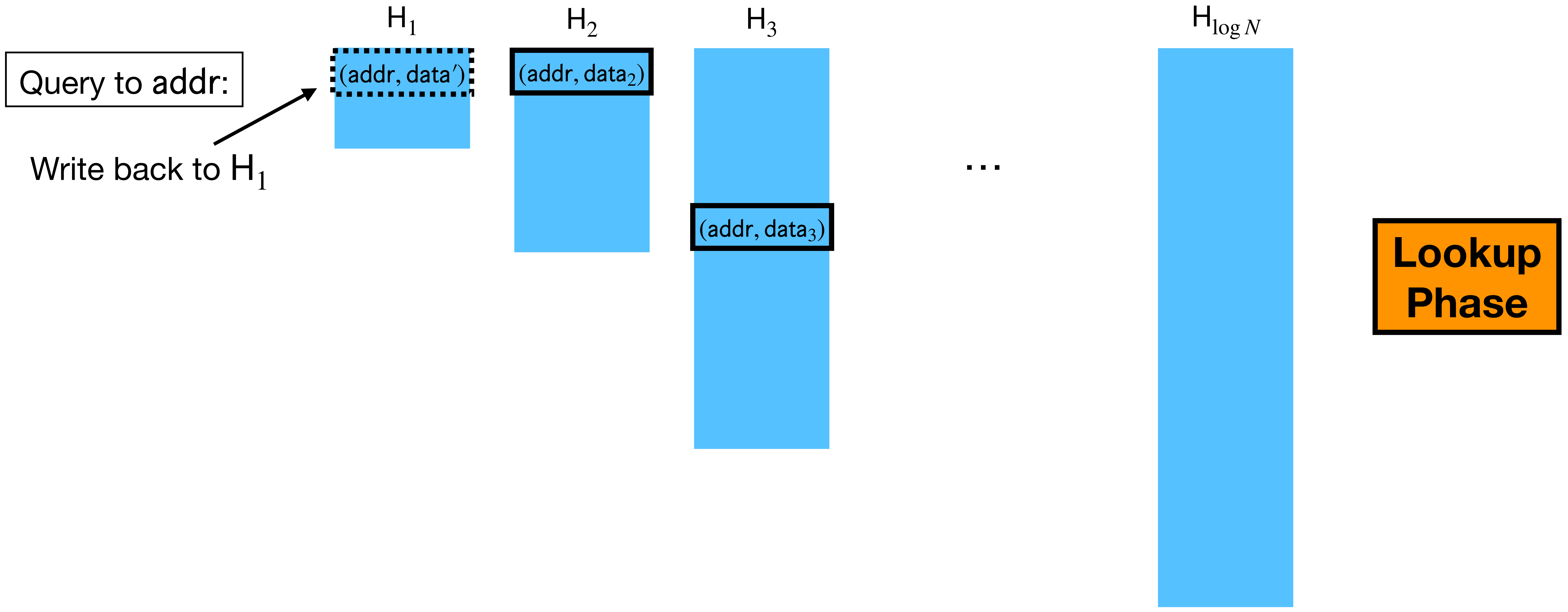

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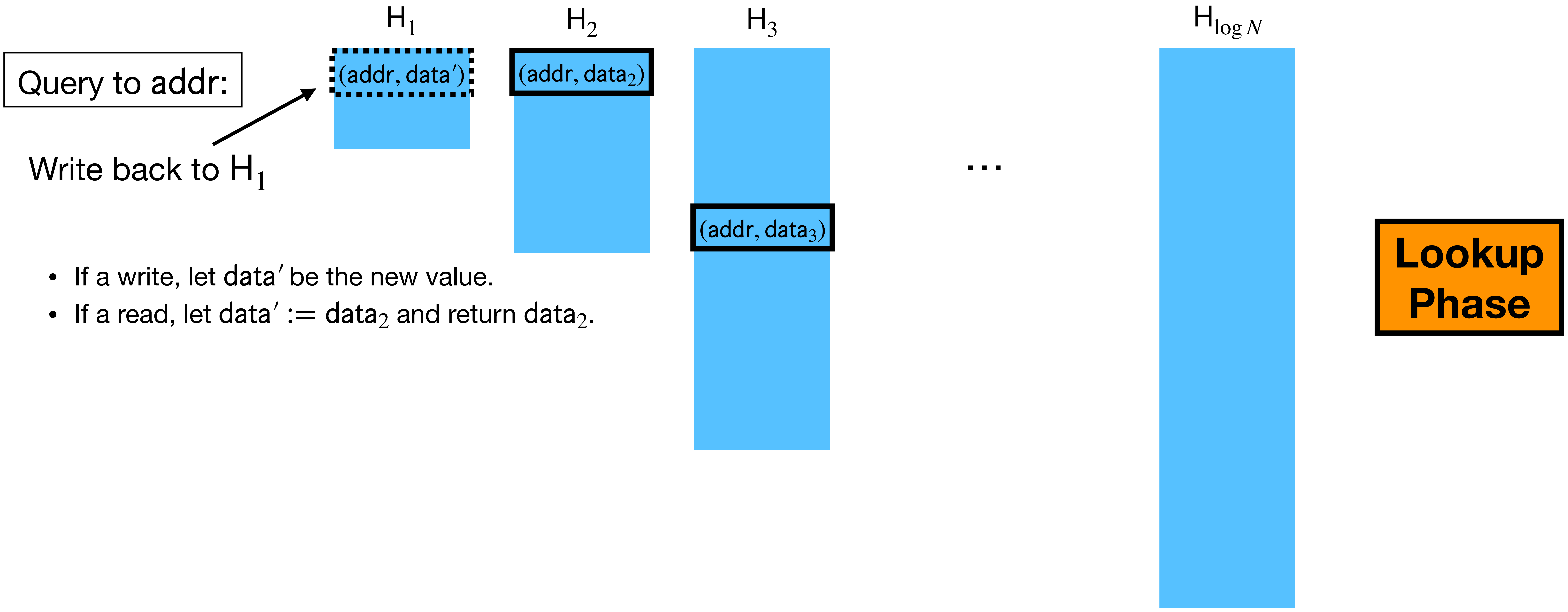
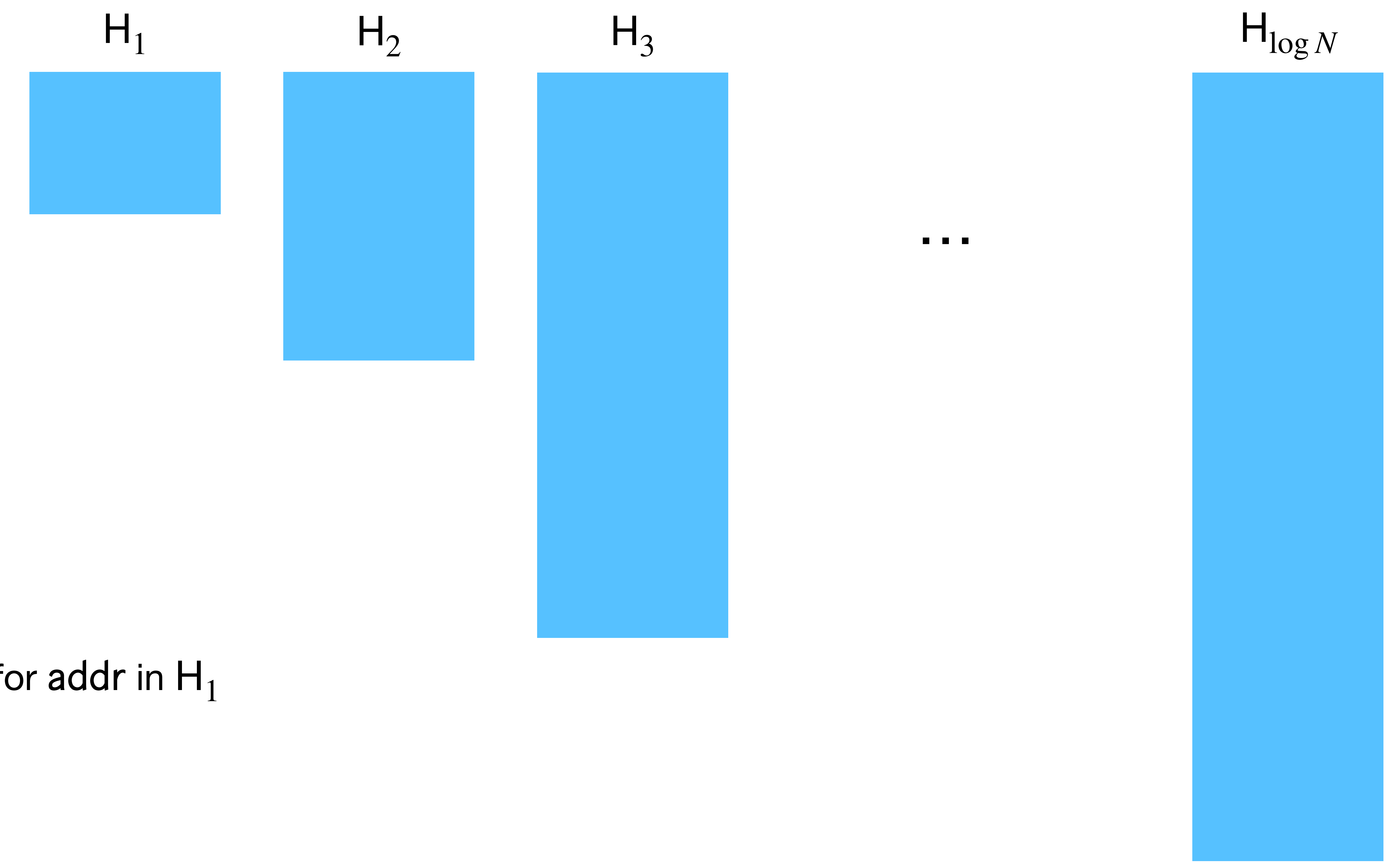

Query to addr:
Write back to H_1
H_1
$(\mathsf{addr}, \mathsf{data}')$
H_2
$(\mathsf{addr}, \mathsf{data}_2)$
H_3
$(\mathsf{addr}, \mathsf{data}_3)$
$\cdots$
$H_{\log N}$
Lookup Phase

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

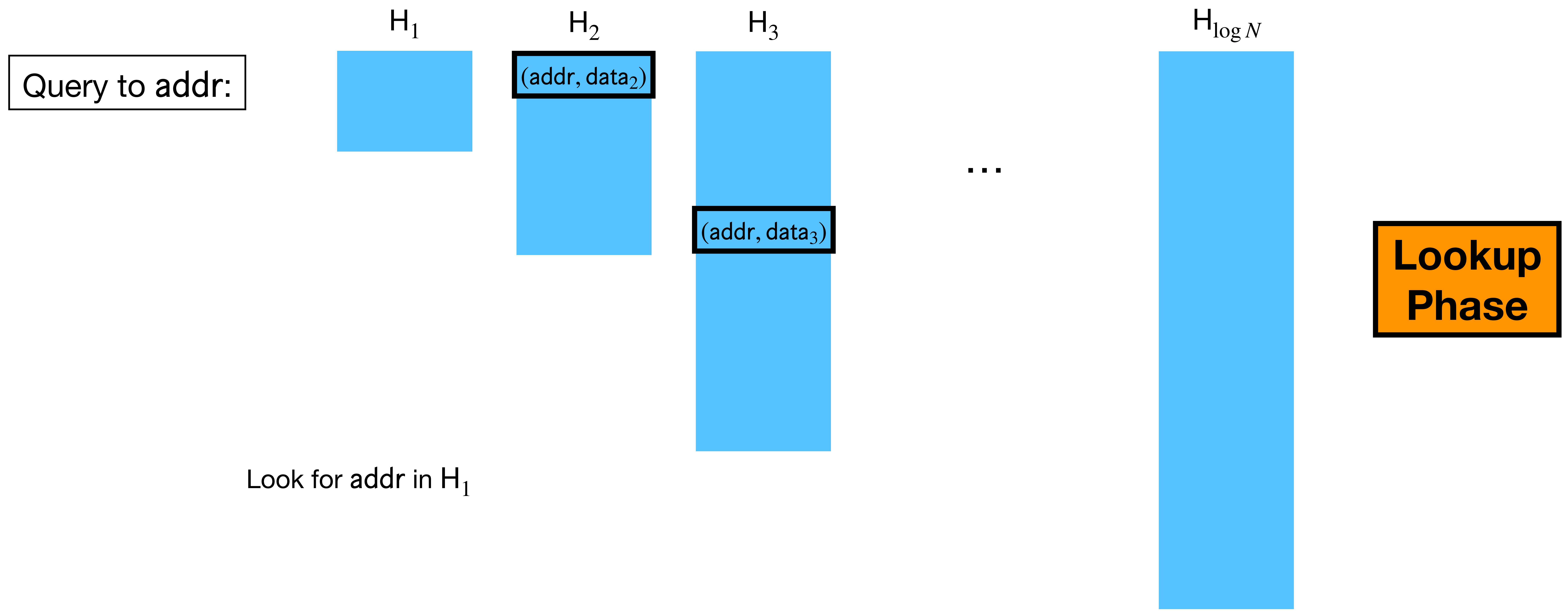
Hierarchical Construction: Lookup



Lookup Phase

Look for addr in H_1

Hierarchical Construction: Lookup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H_3
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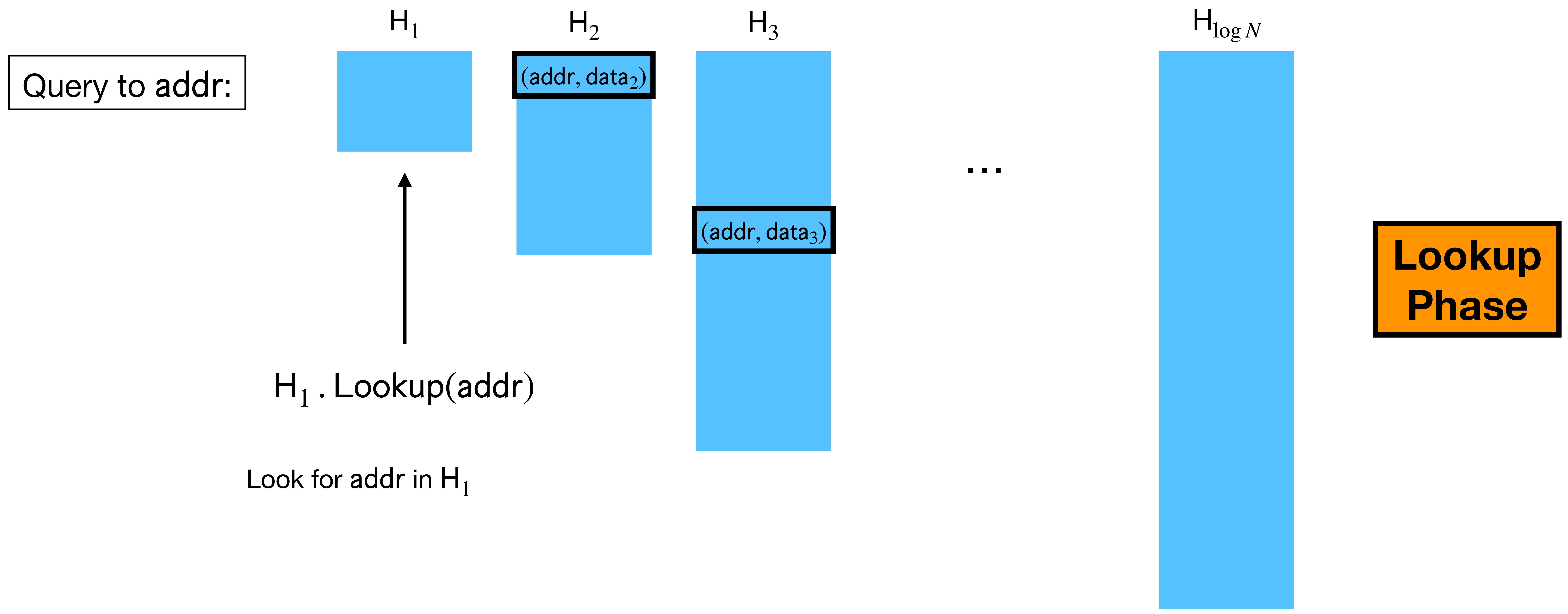

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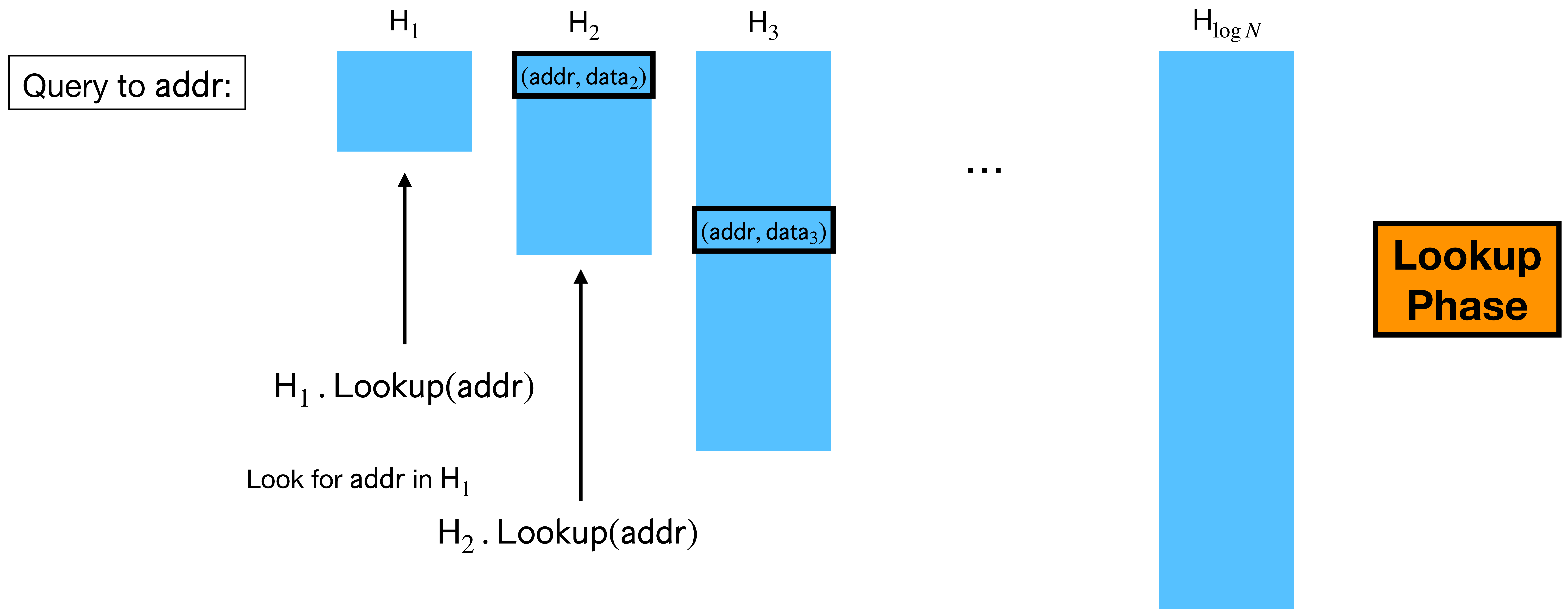

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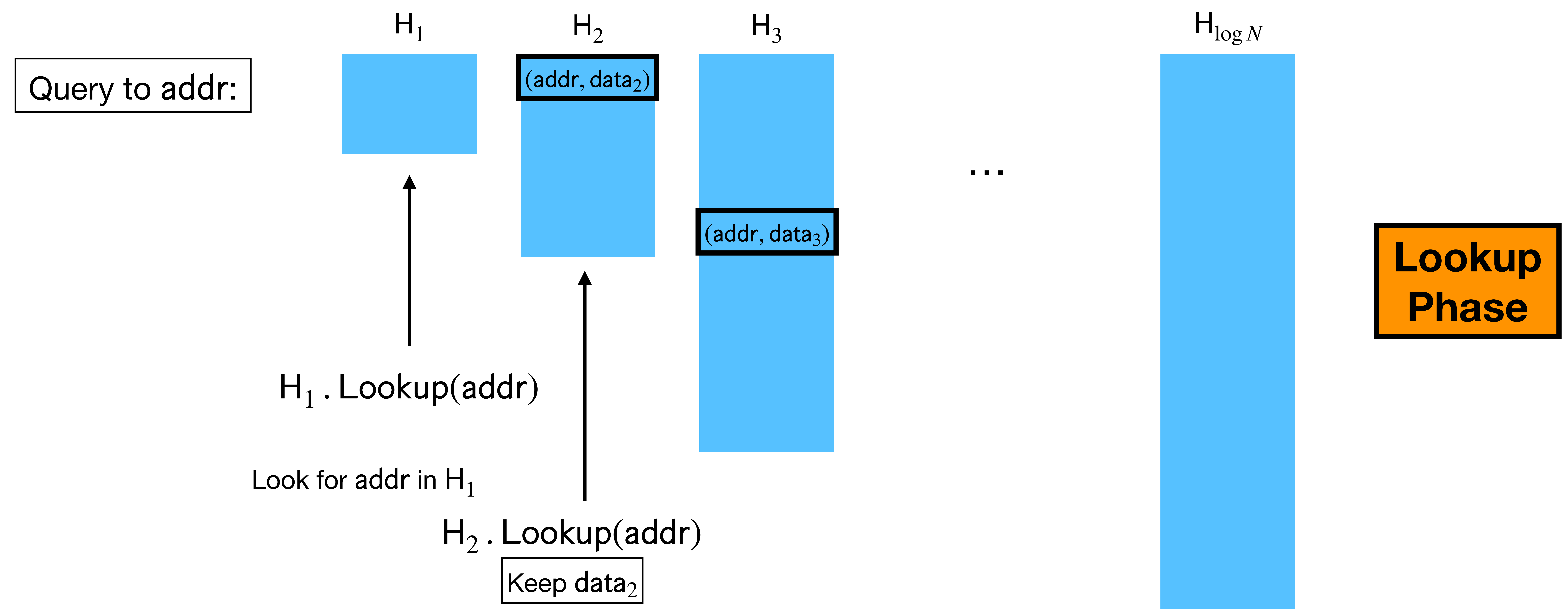

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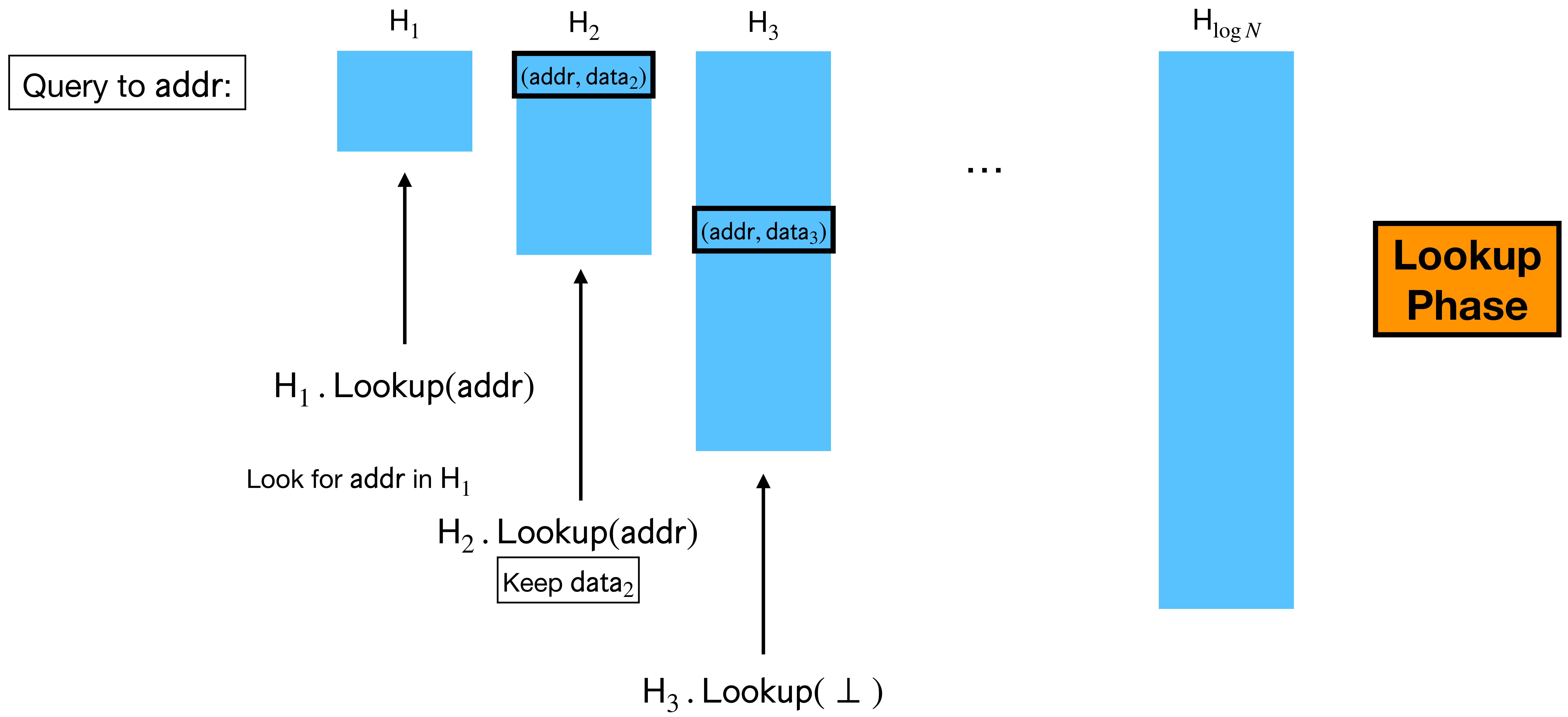

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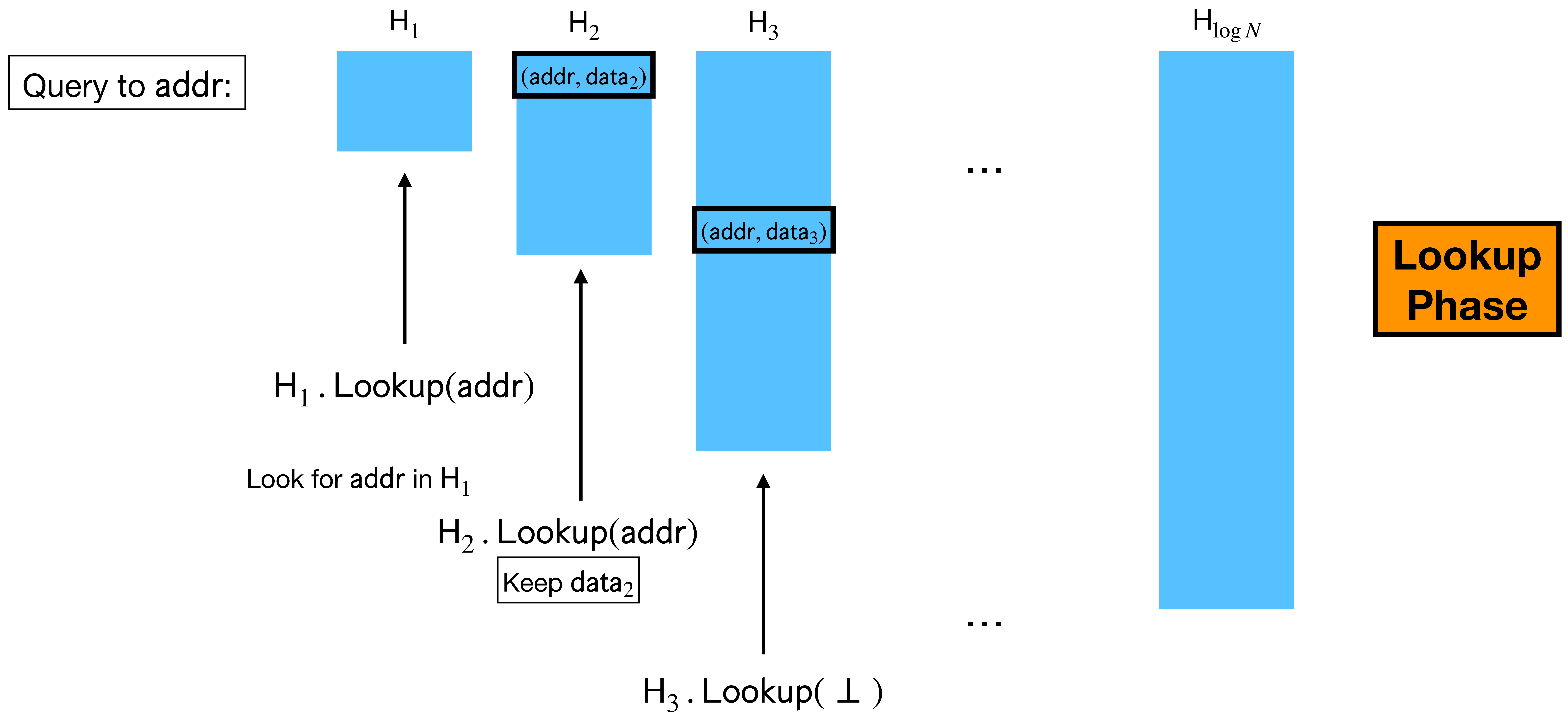
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H_3
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...
$H_1.\text{Lookup}(\text{addr})$
Look for addr in H_1
$H_2.\text{Lookup}(\text{addr})$
Keep data_2
$H_3.\text{Lookup}(\perp)$
...
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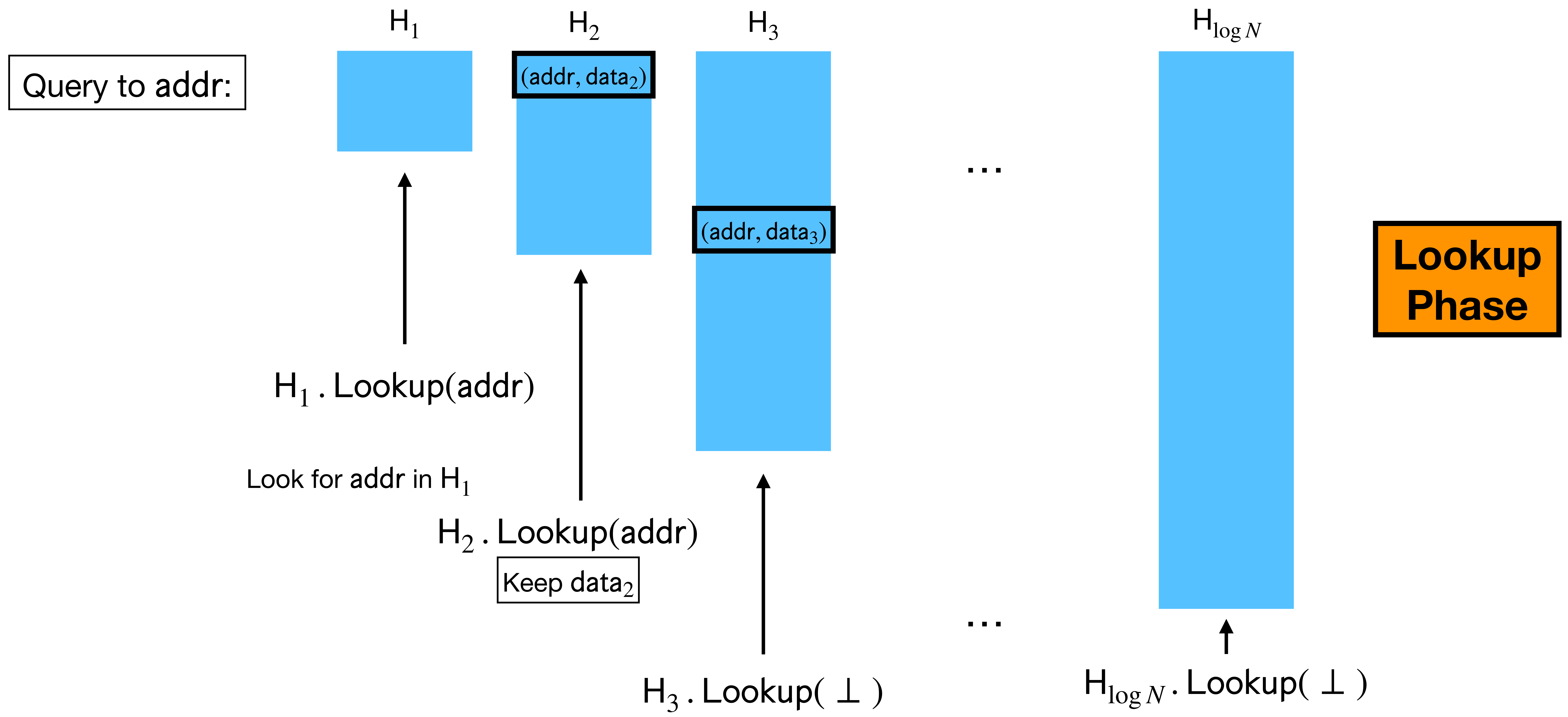

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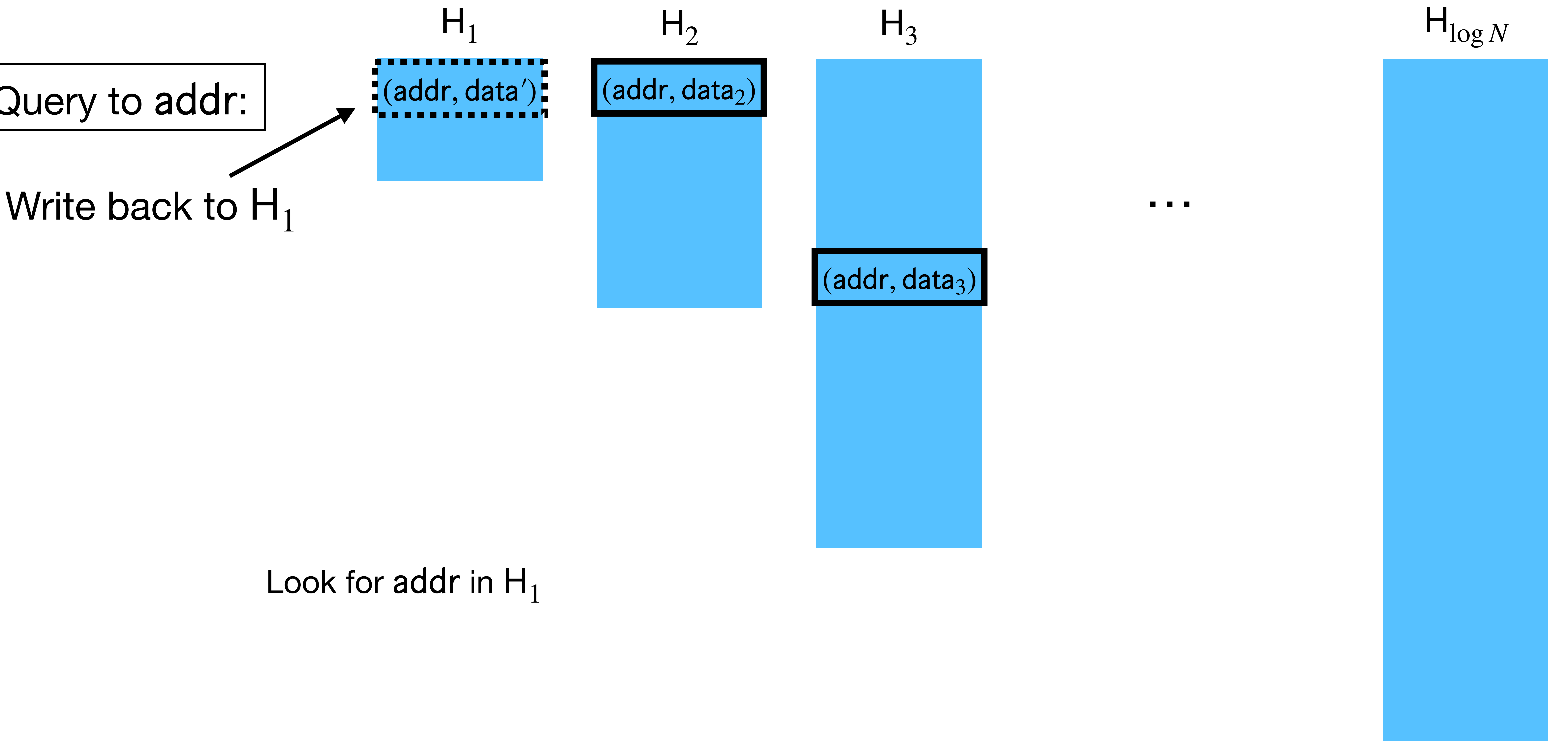

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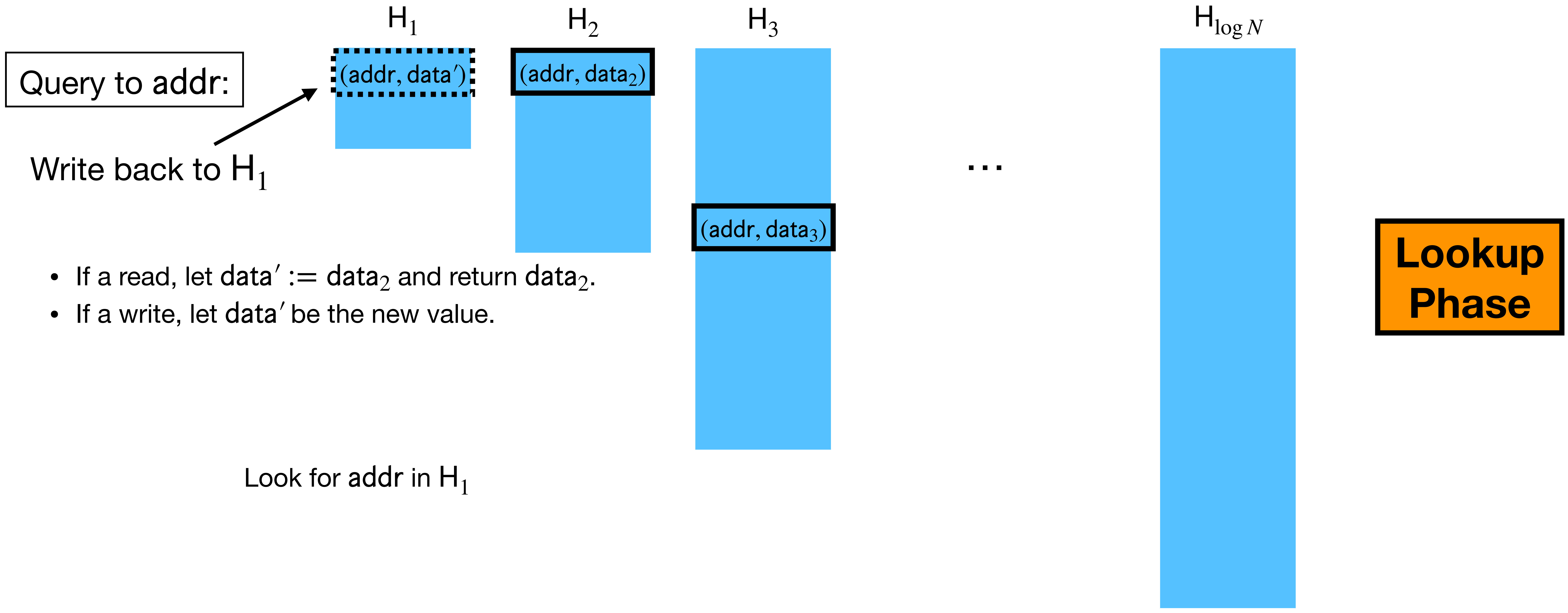
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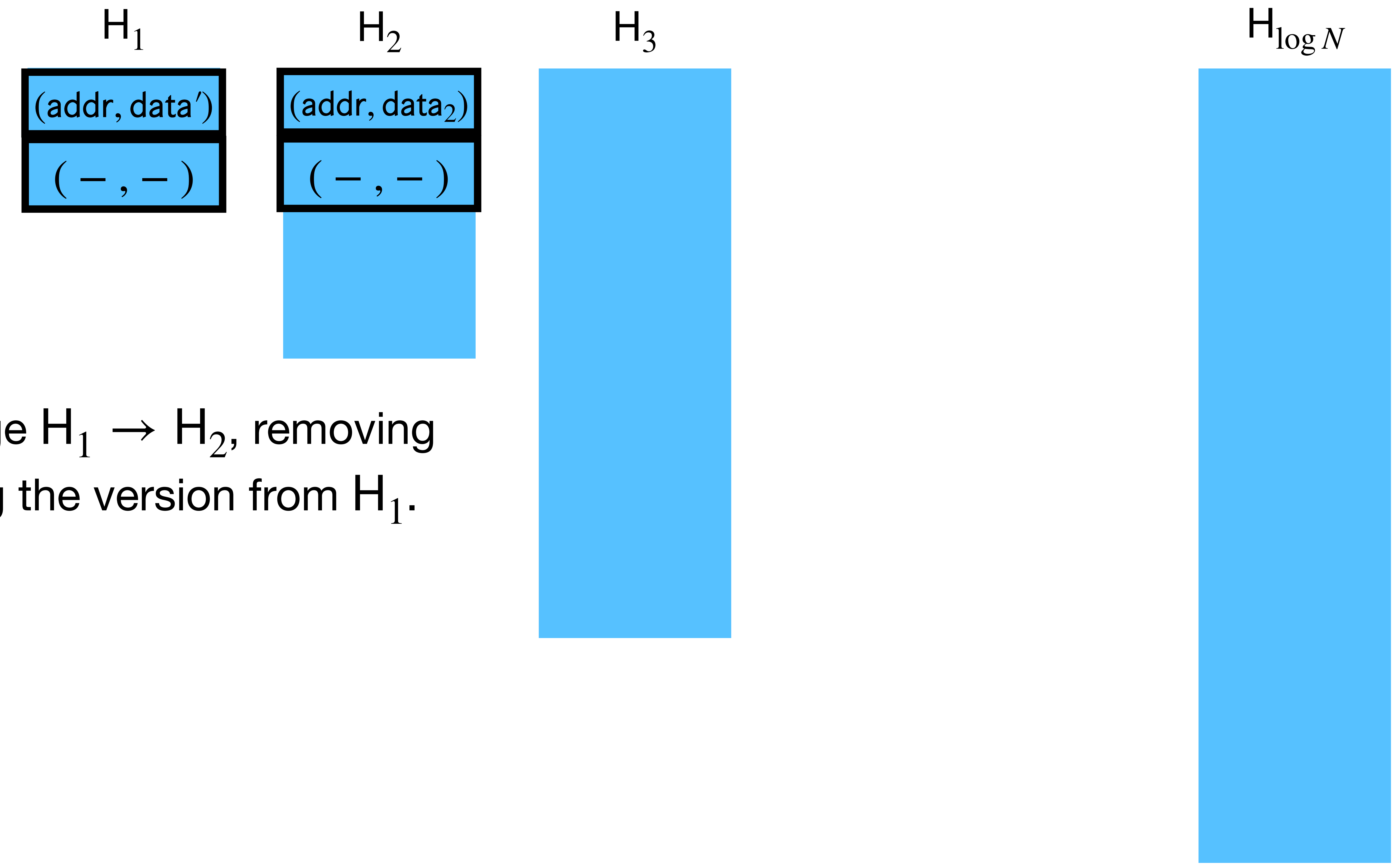
Hierarchical Construction: Rebuild



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Rebuild Phase

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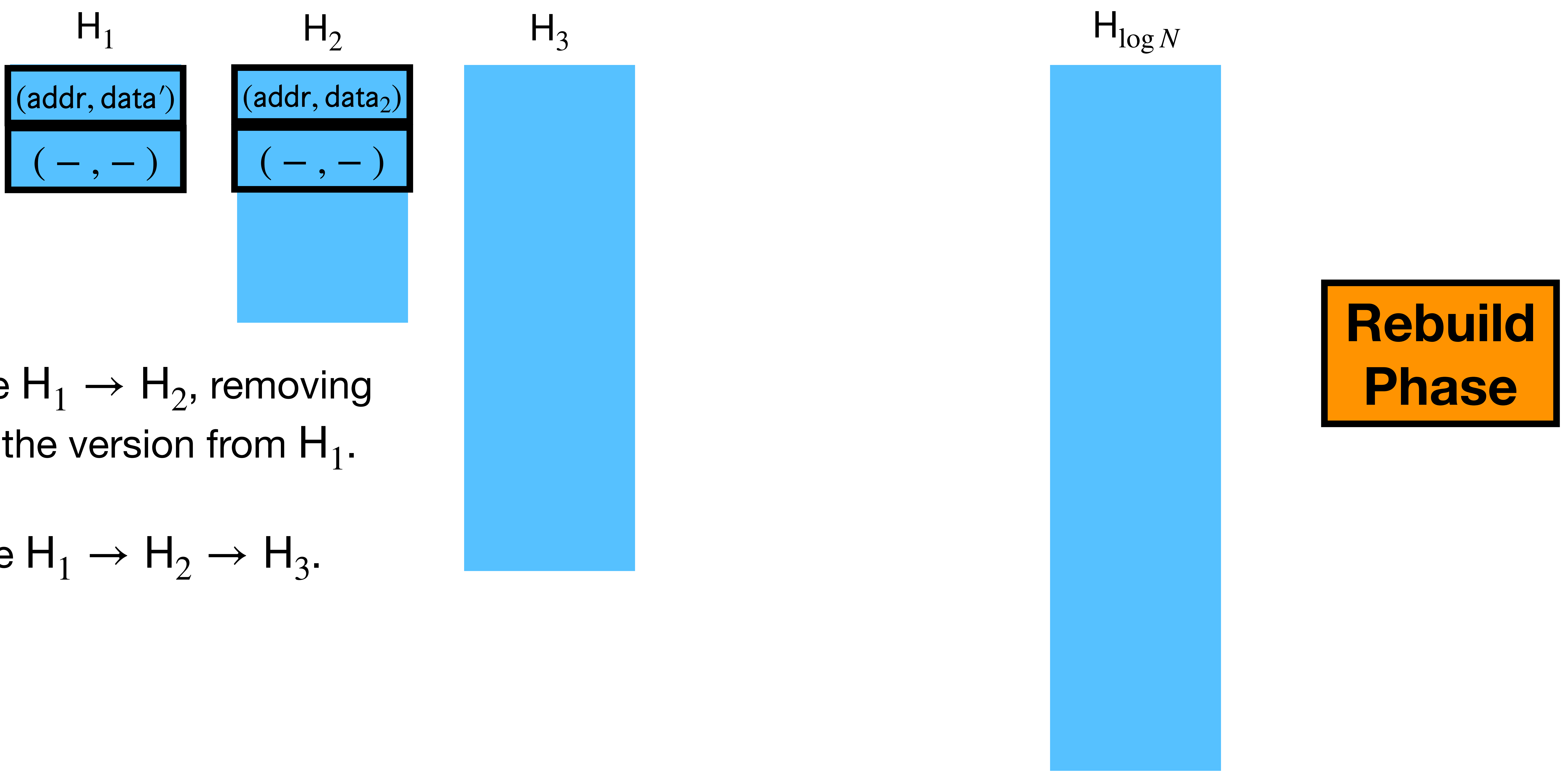

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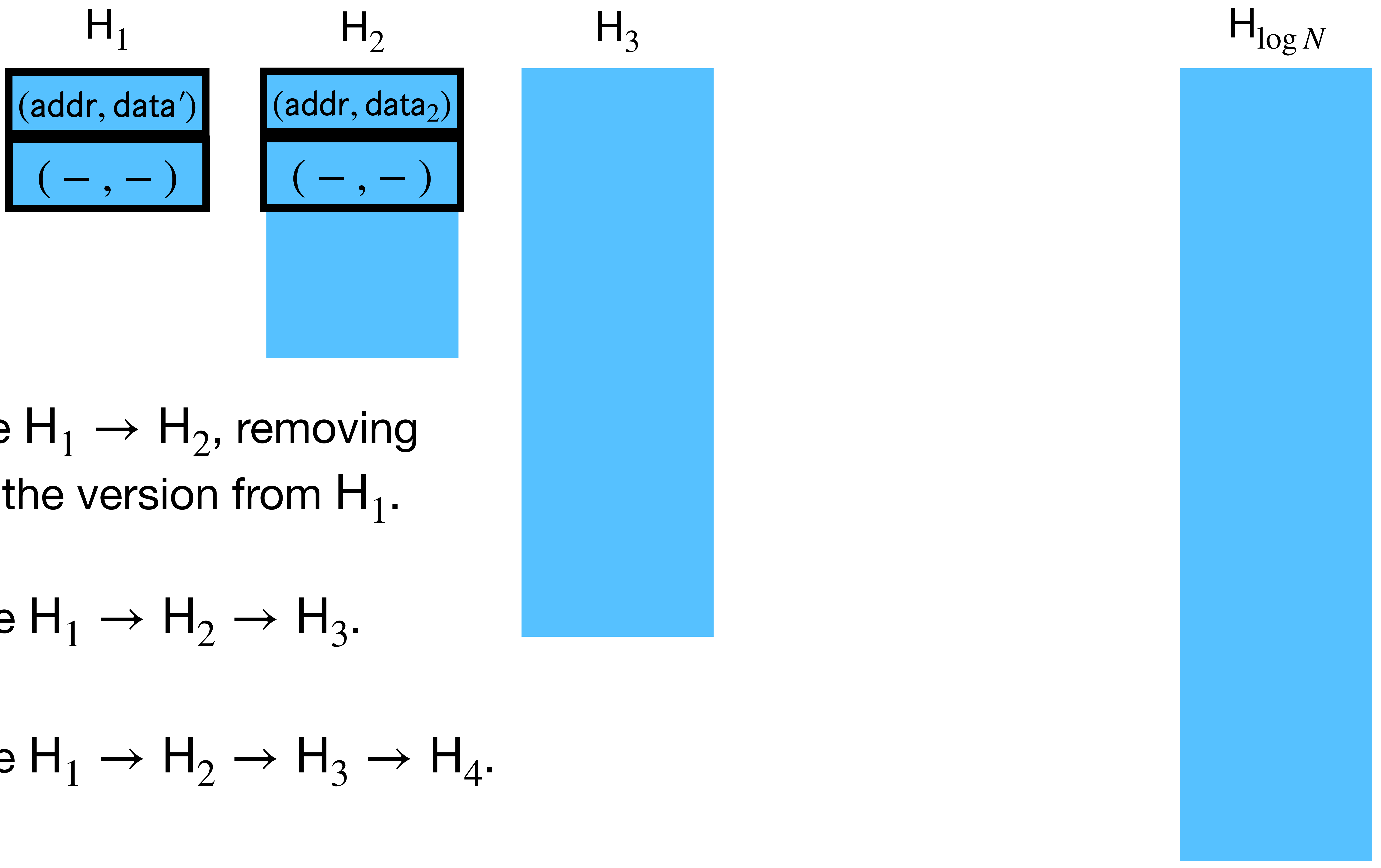

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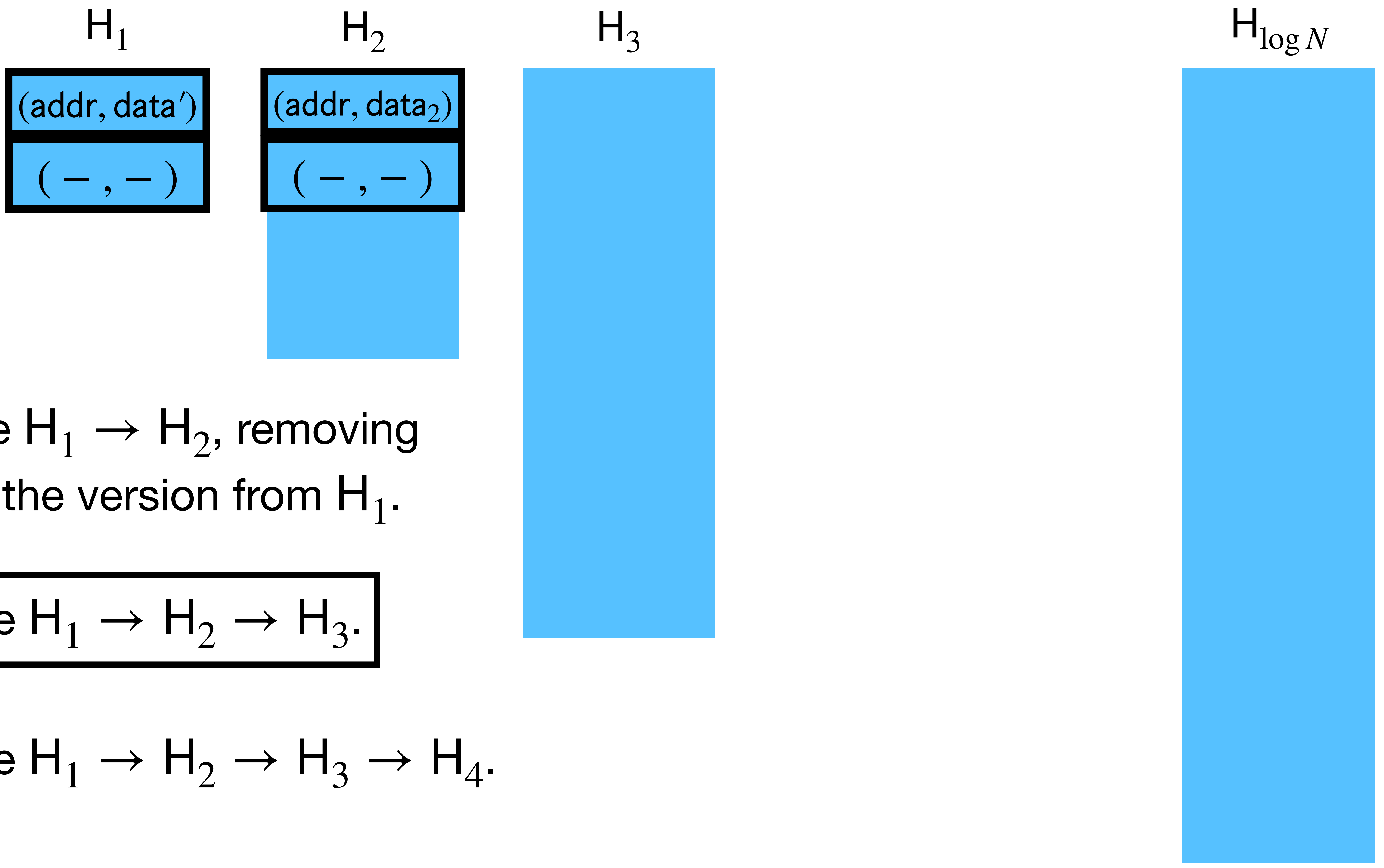

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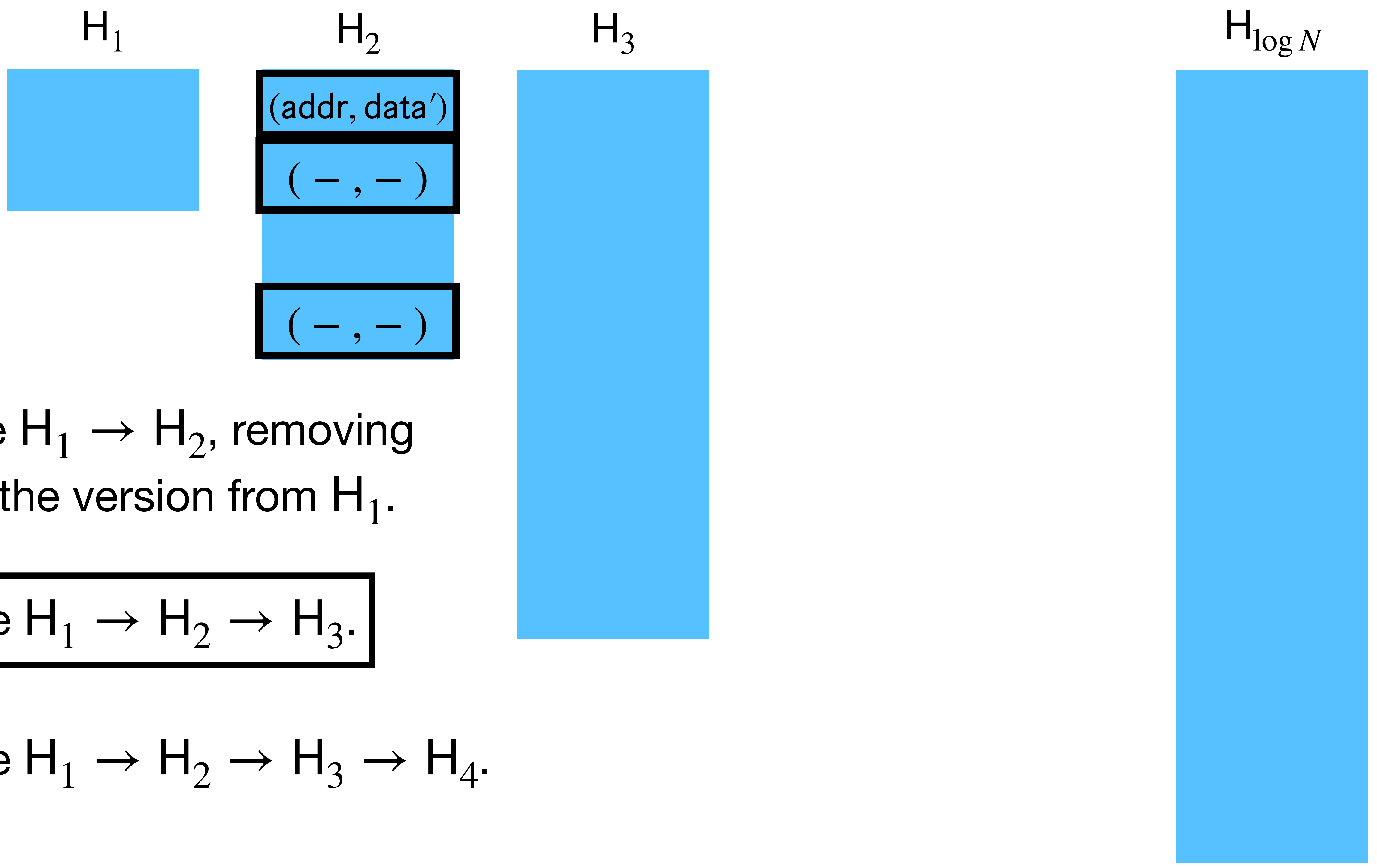

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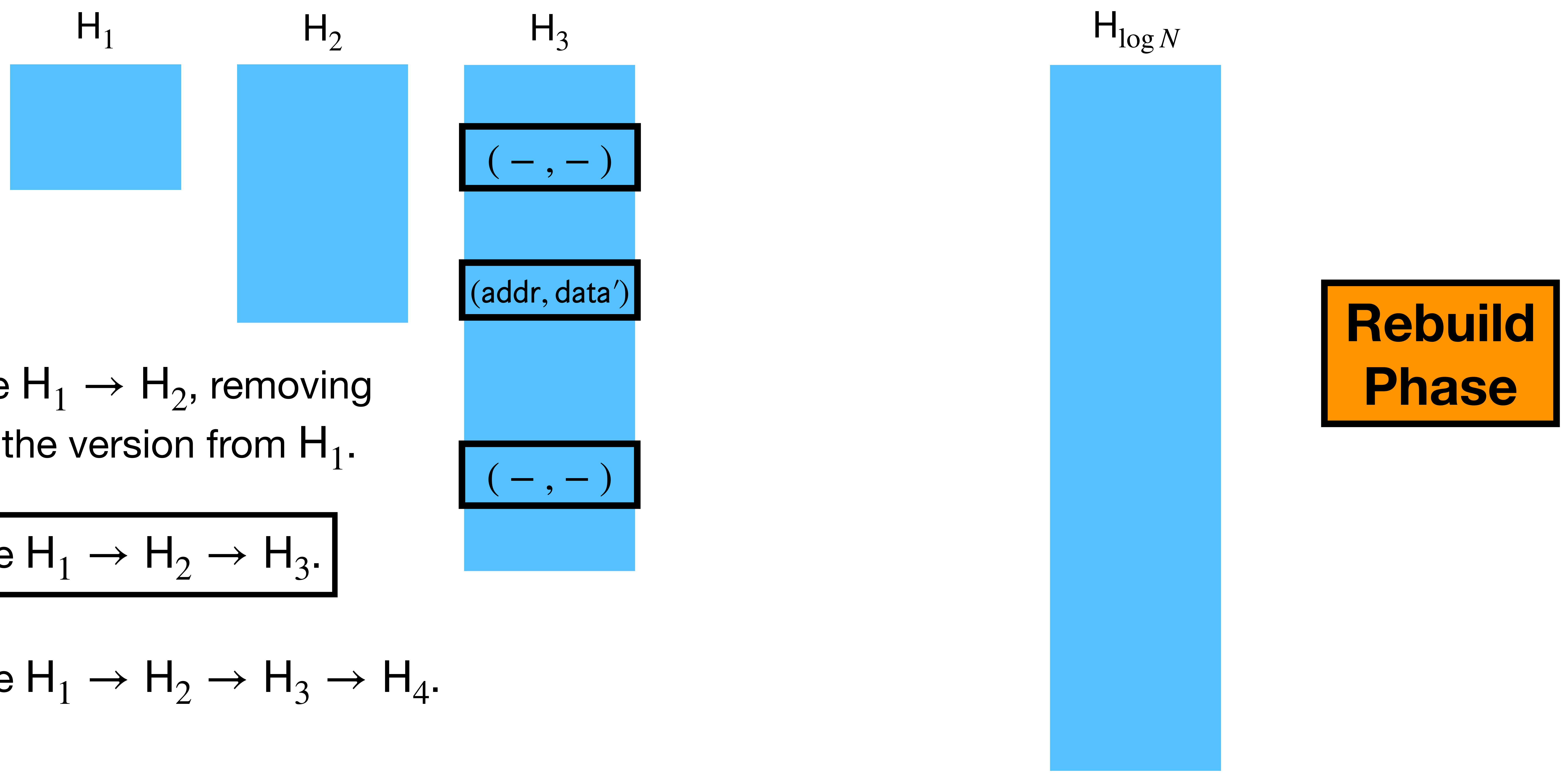

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[Goodrich-Mitzenmacher '11]

*Ignoring cuckoo hash-table stashes.

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

Replay Attack for Hierarchical Framework

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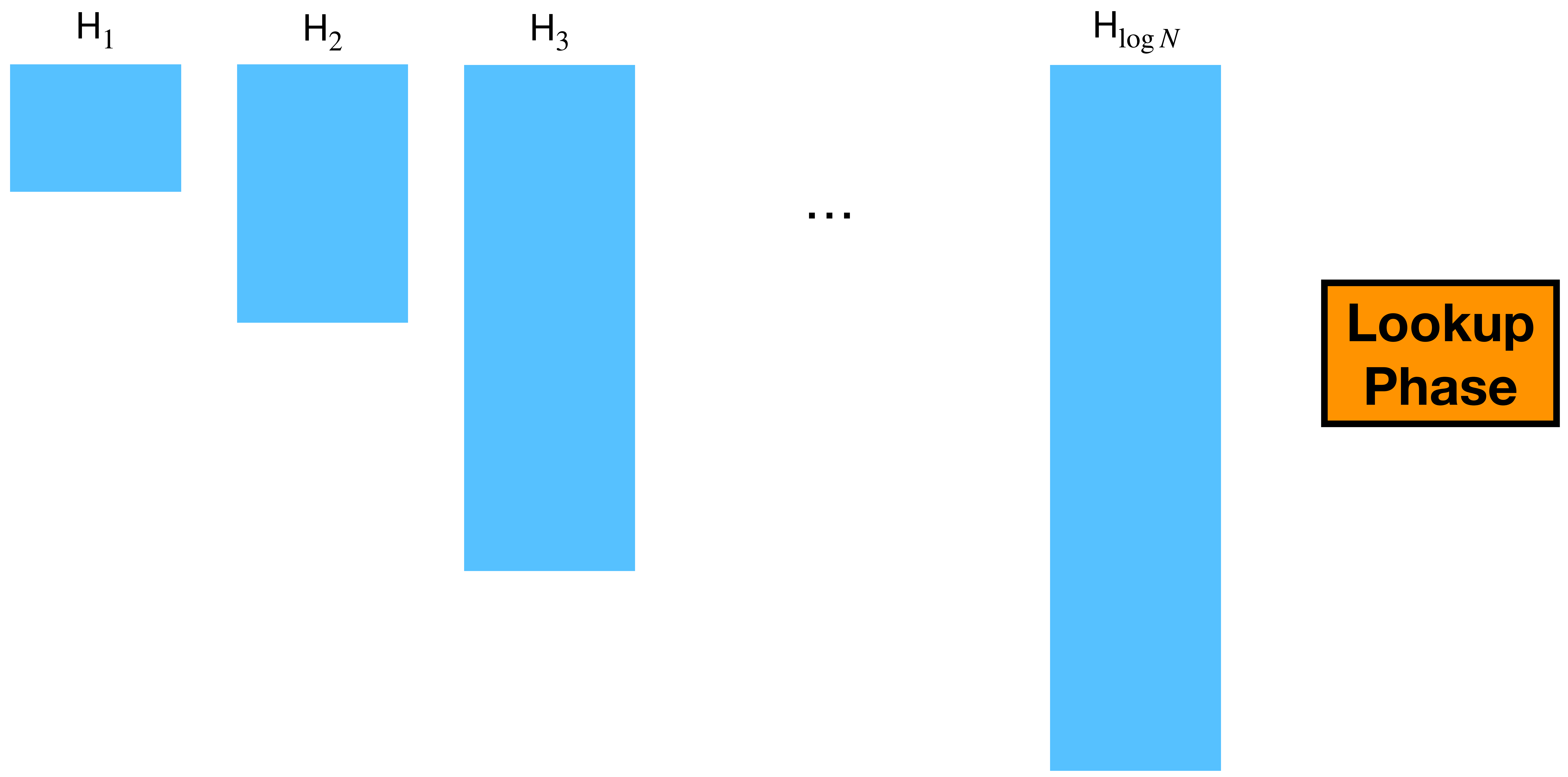
Replay Attack for Hierarchical Framework

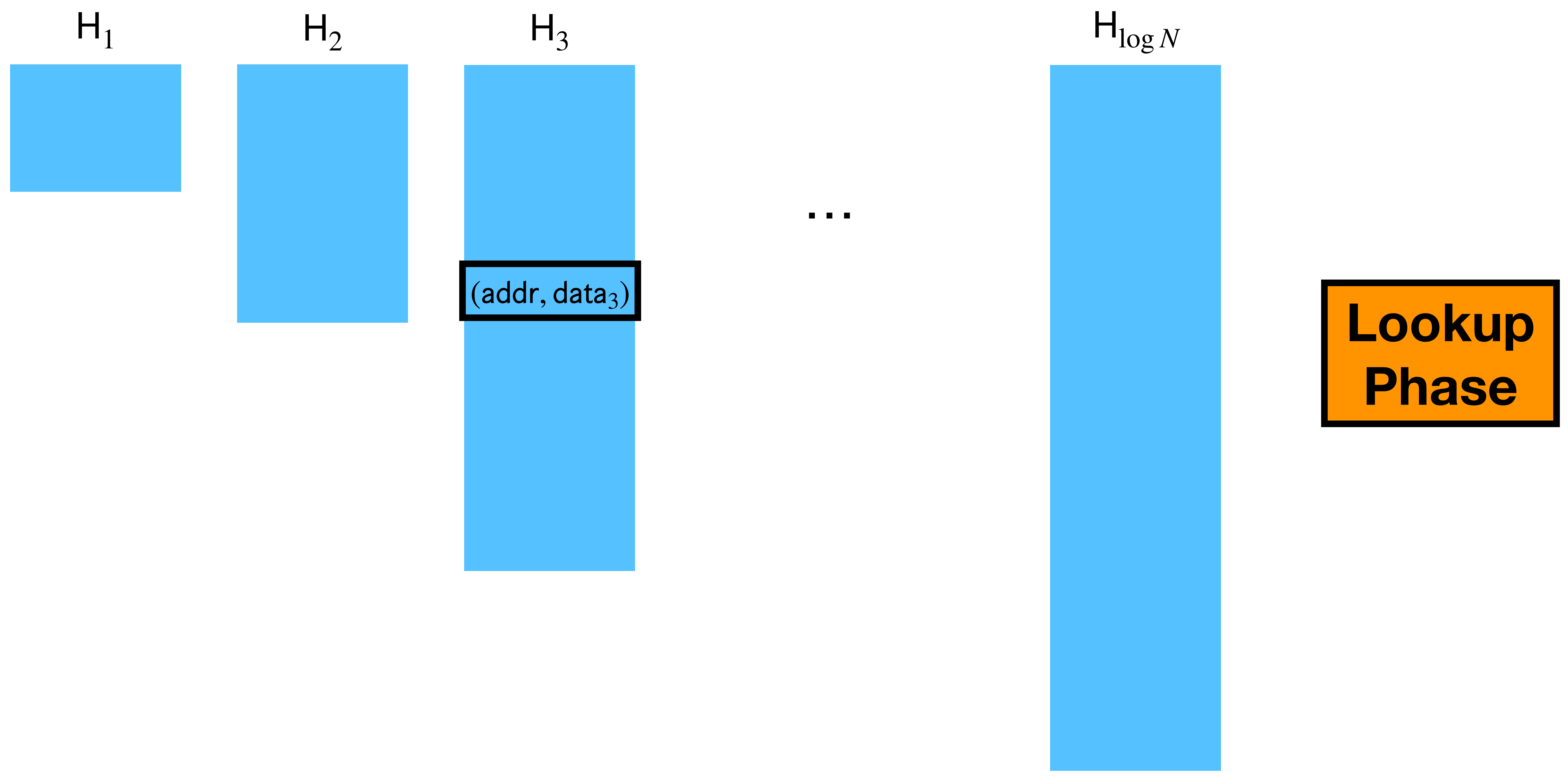
- **Key fact**: Oblivious hash tables are oblivious only if lookups are *non-recurrent*.
  - If you look up the same addr twice in some H_i without rebuilding in between, **access pattern to H_i will be identical – not oblivious***.*
  - In honest-but-curious setting, looking up **dummies** and rebuilding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

Replay Attack



Replay Attack

Read addr:



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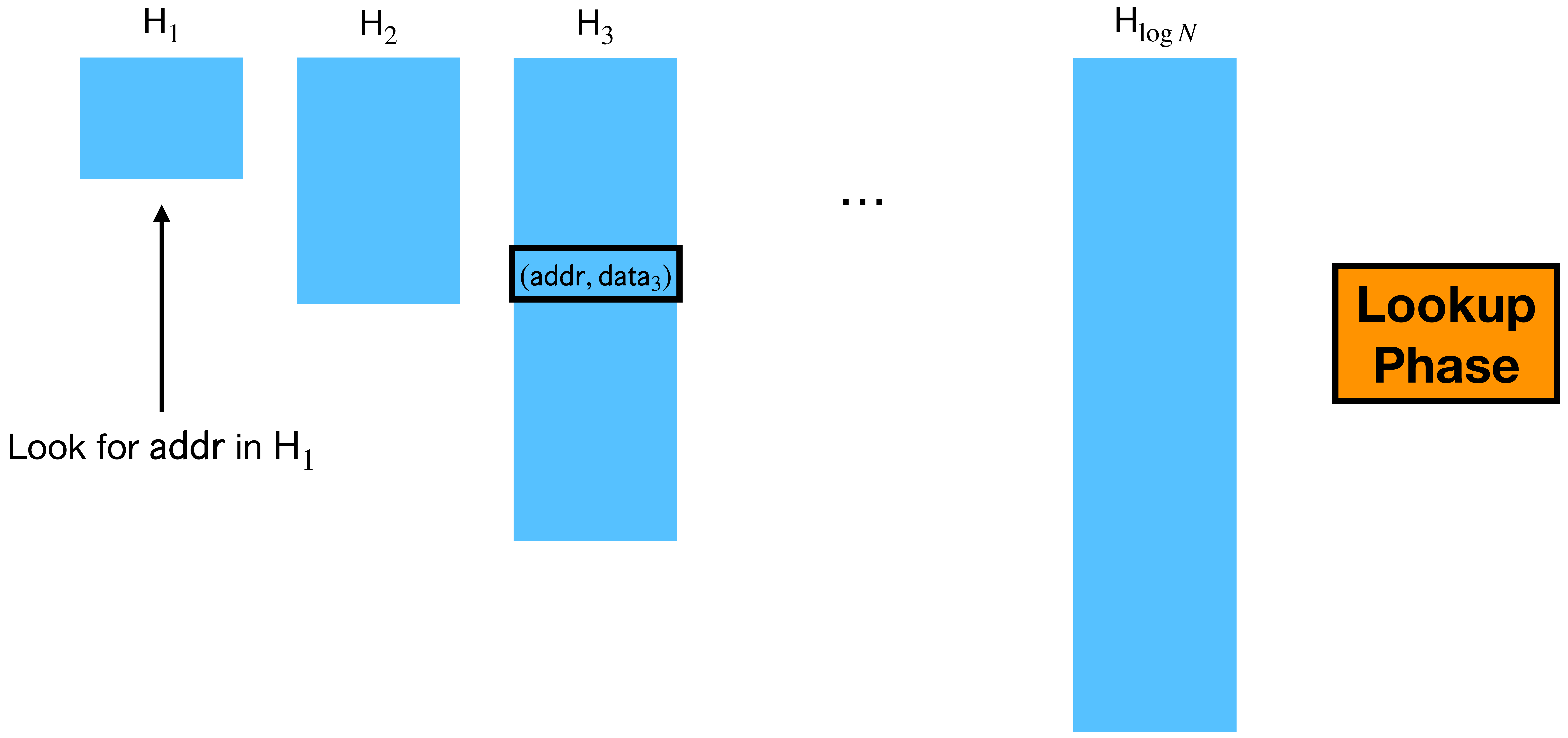

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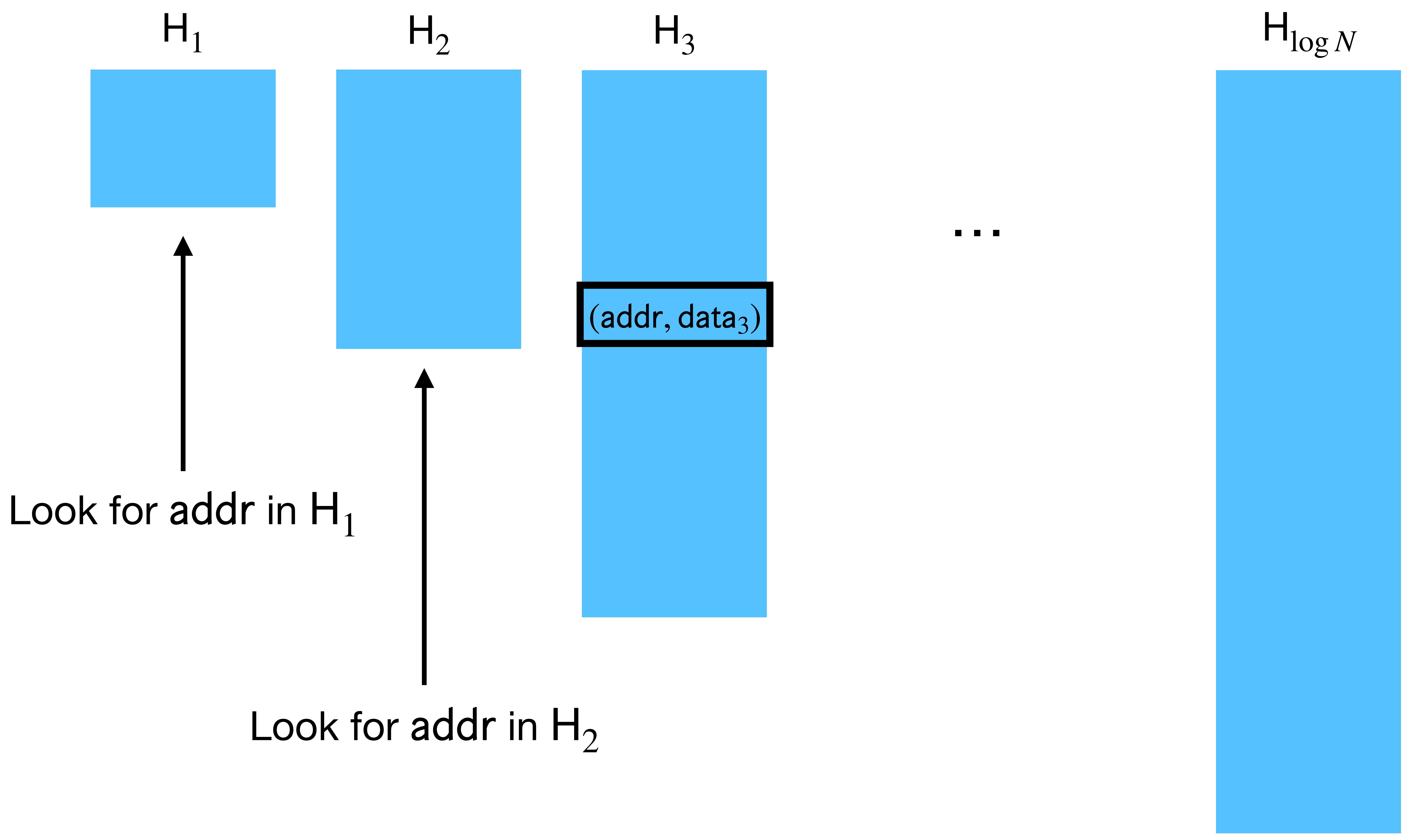
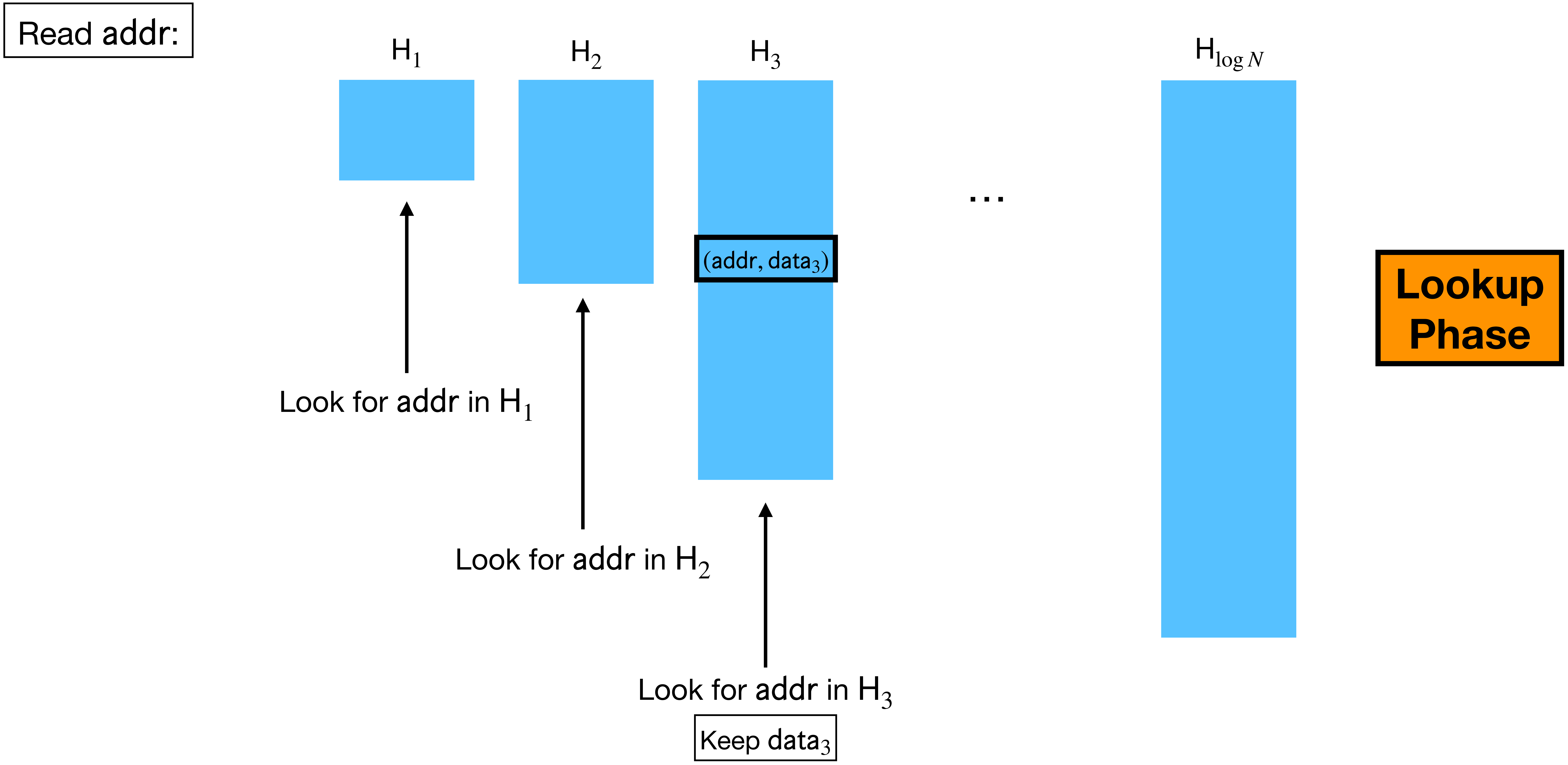


Lookup Phase

Replay Attack



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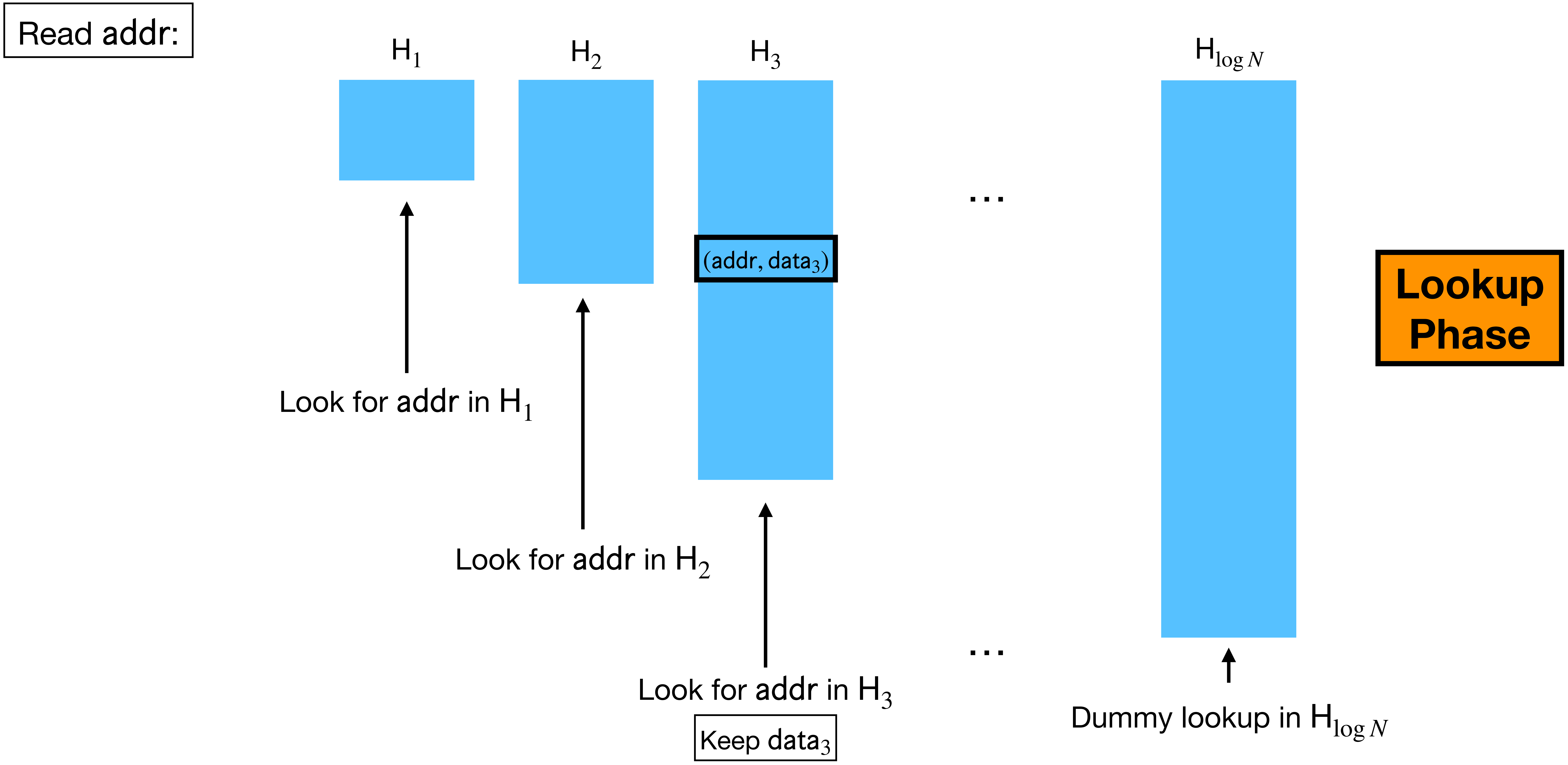

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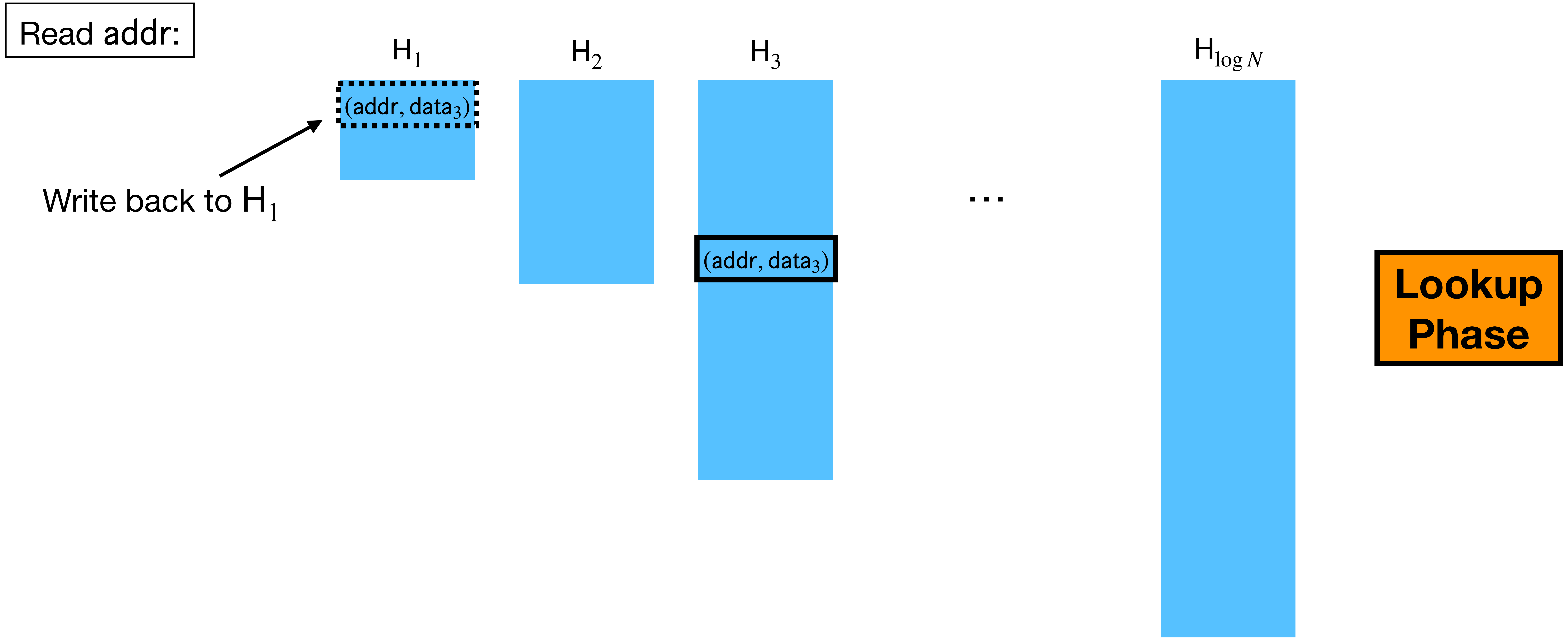

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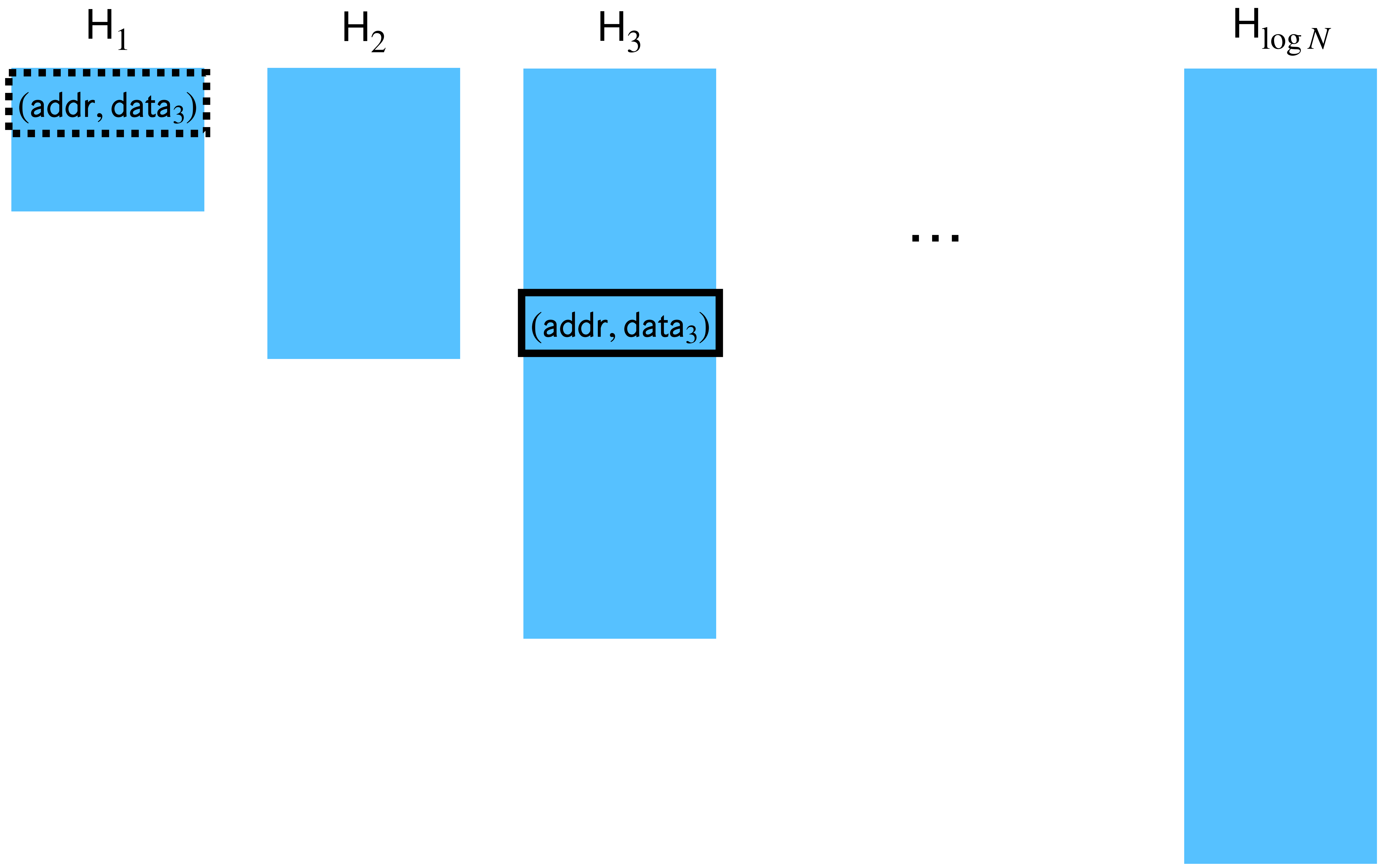

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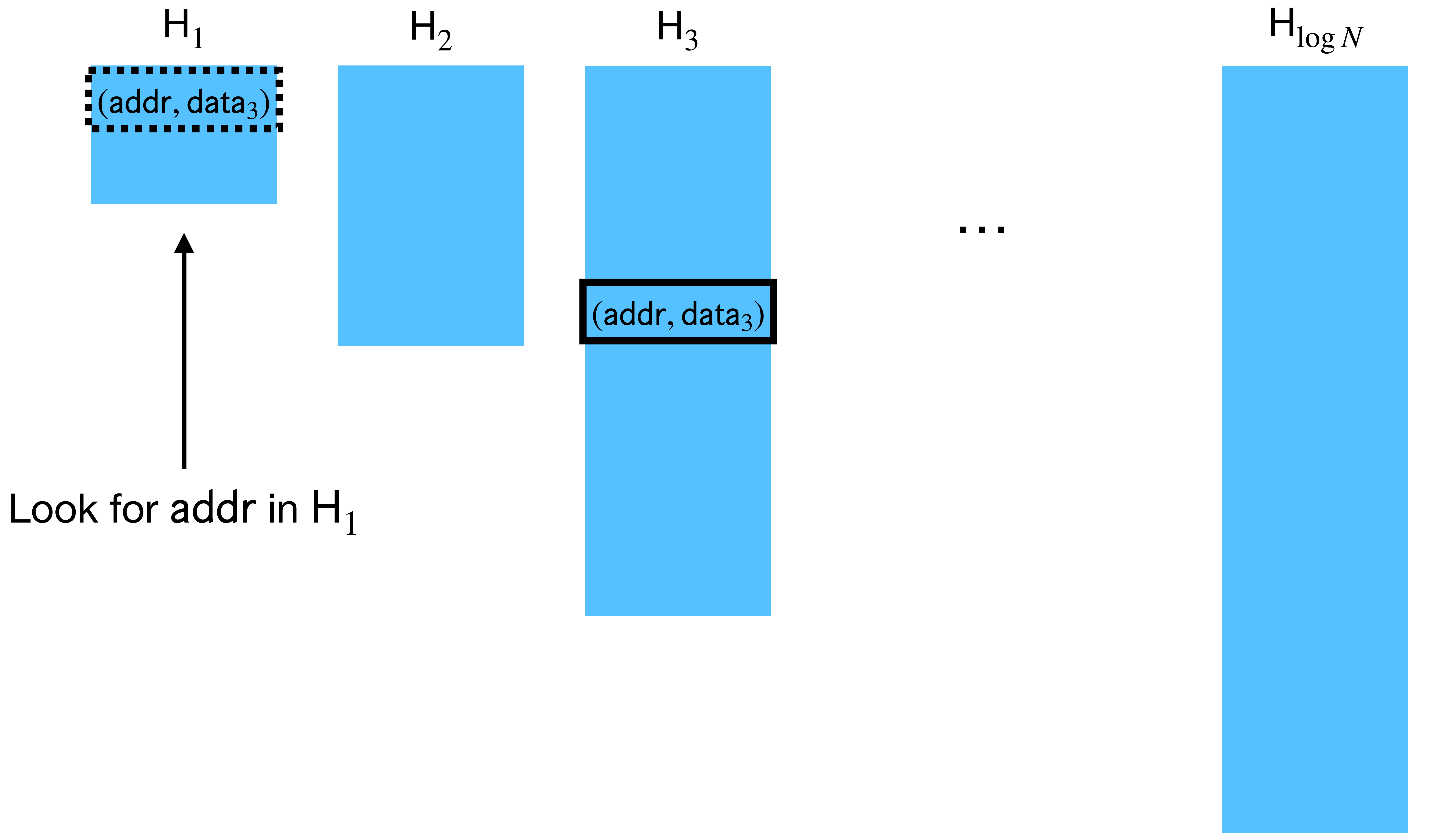

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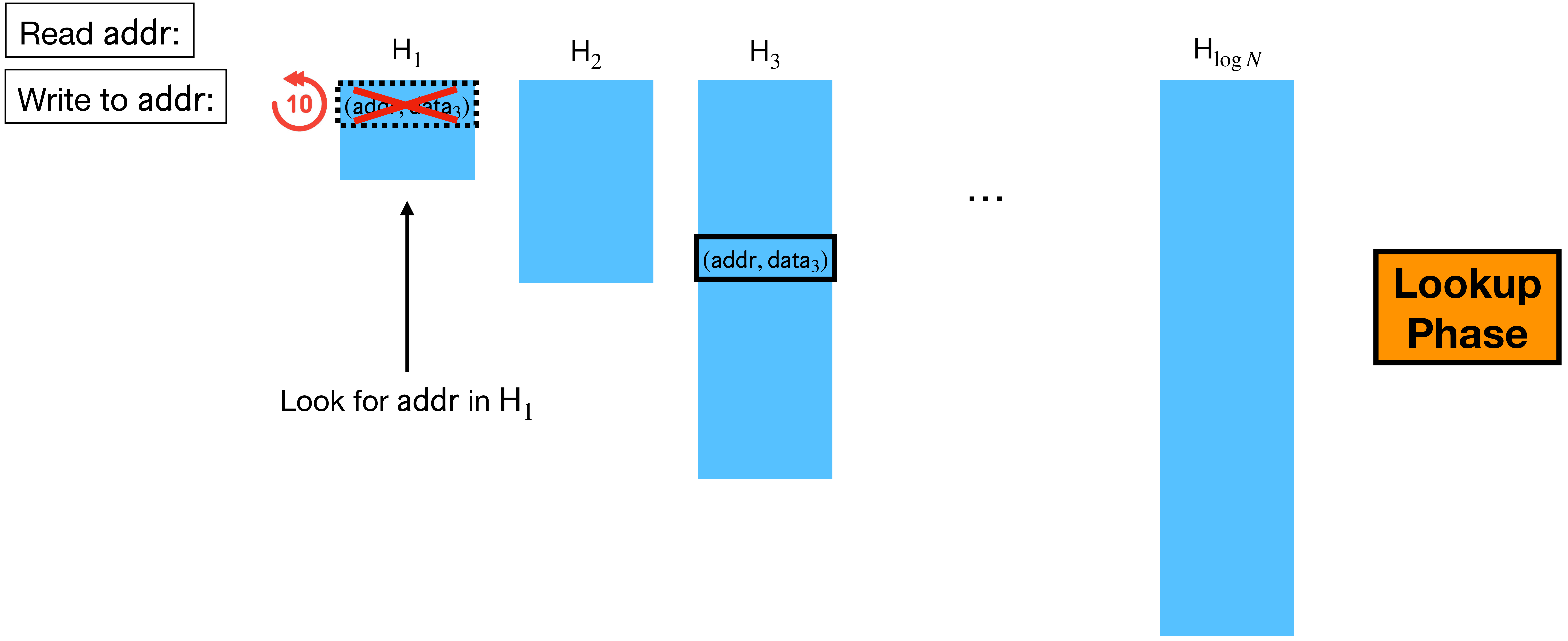

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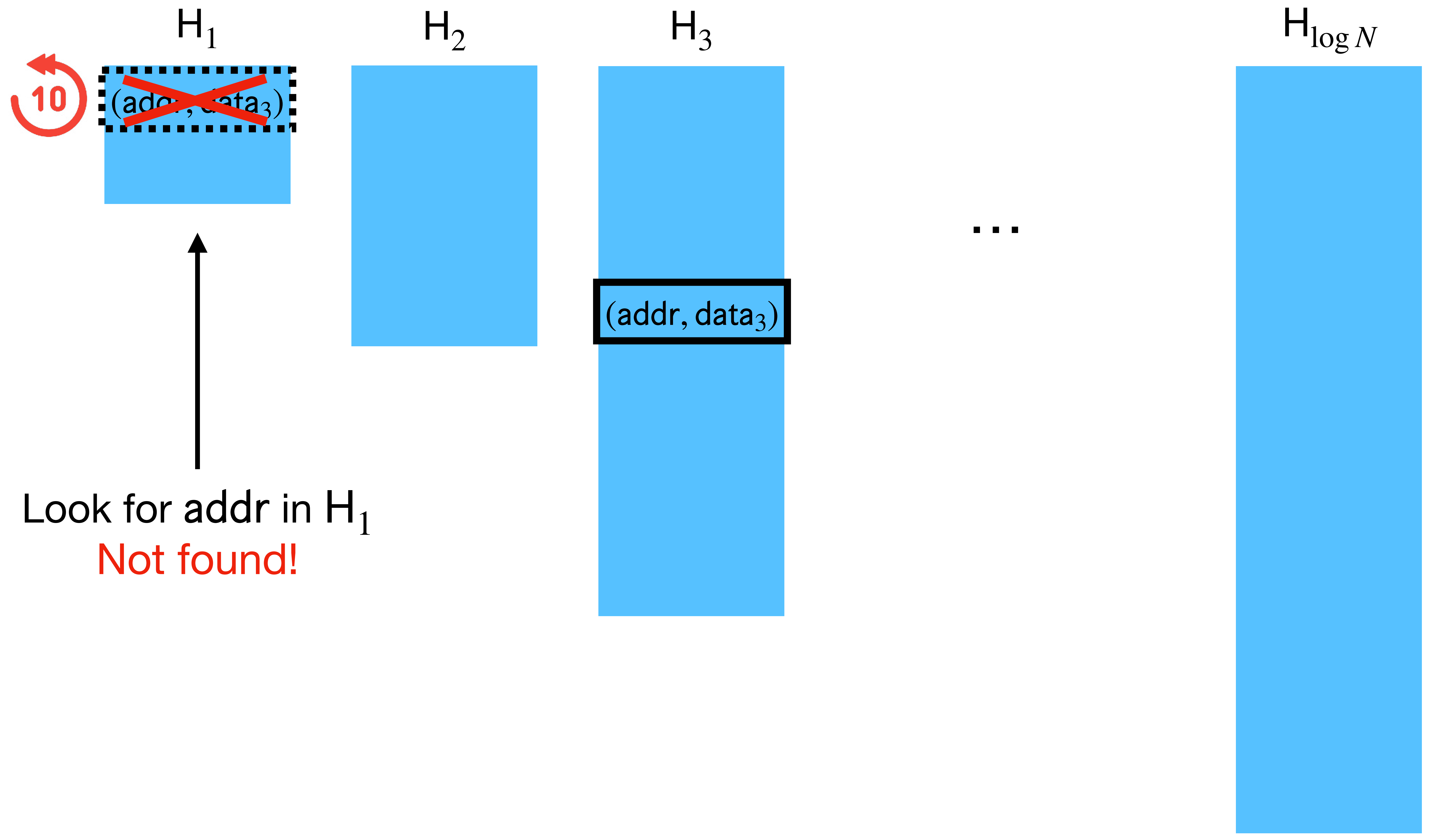

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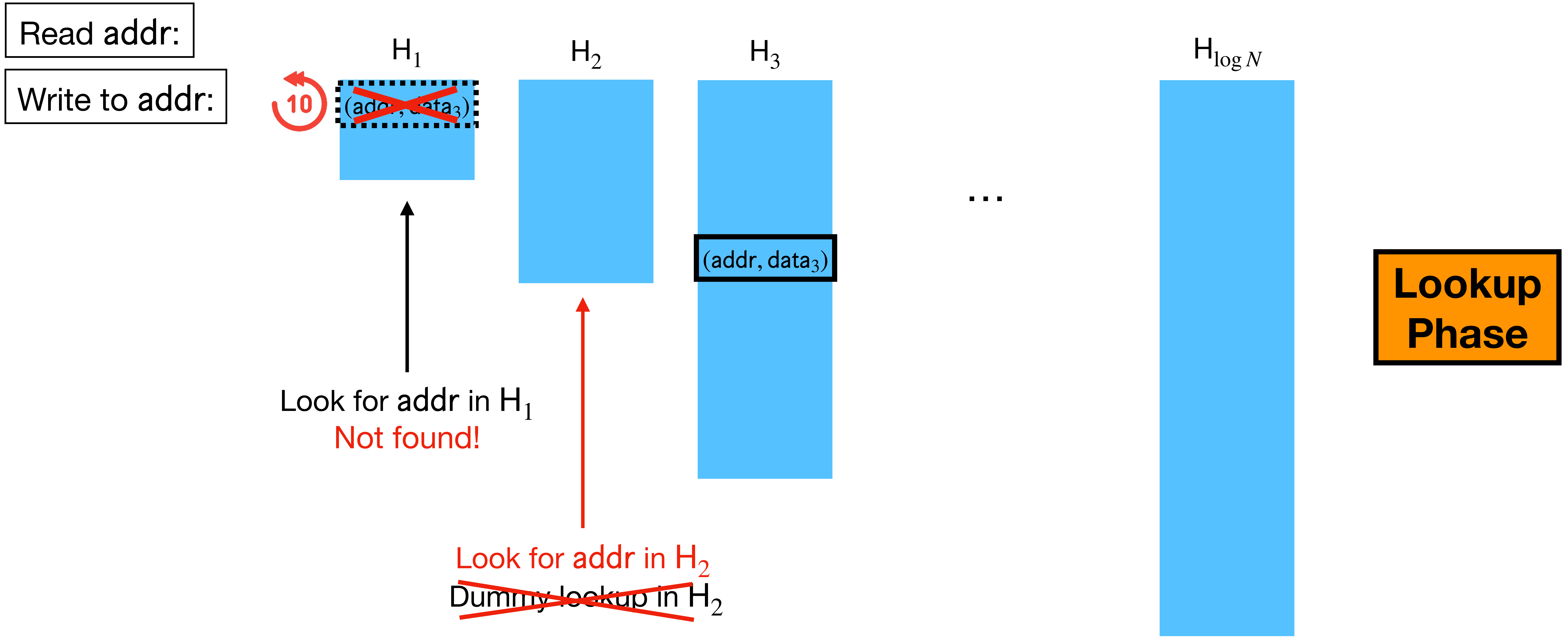

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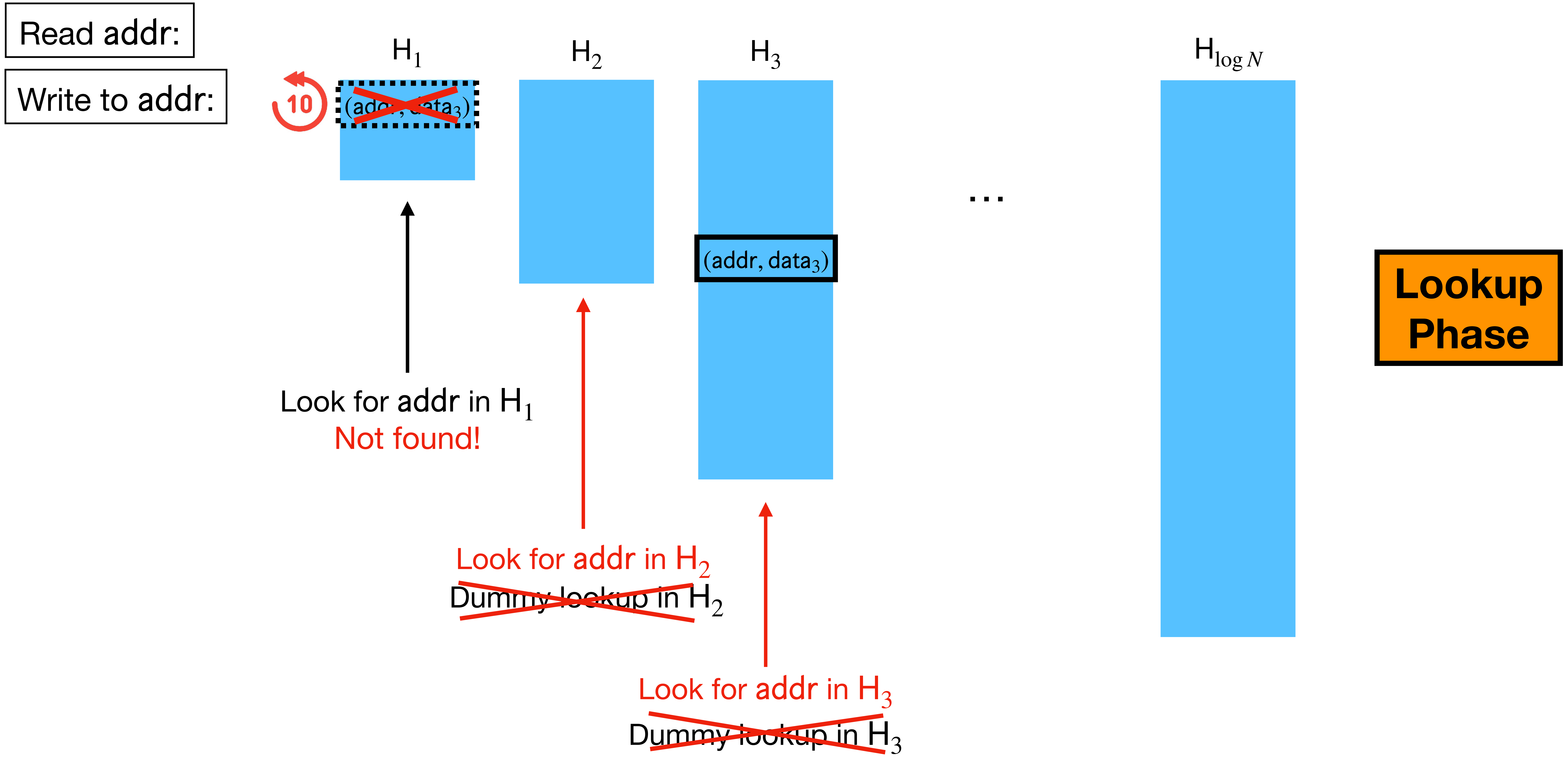

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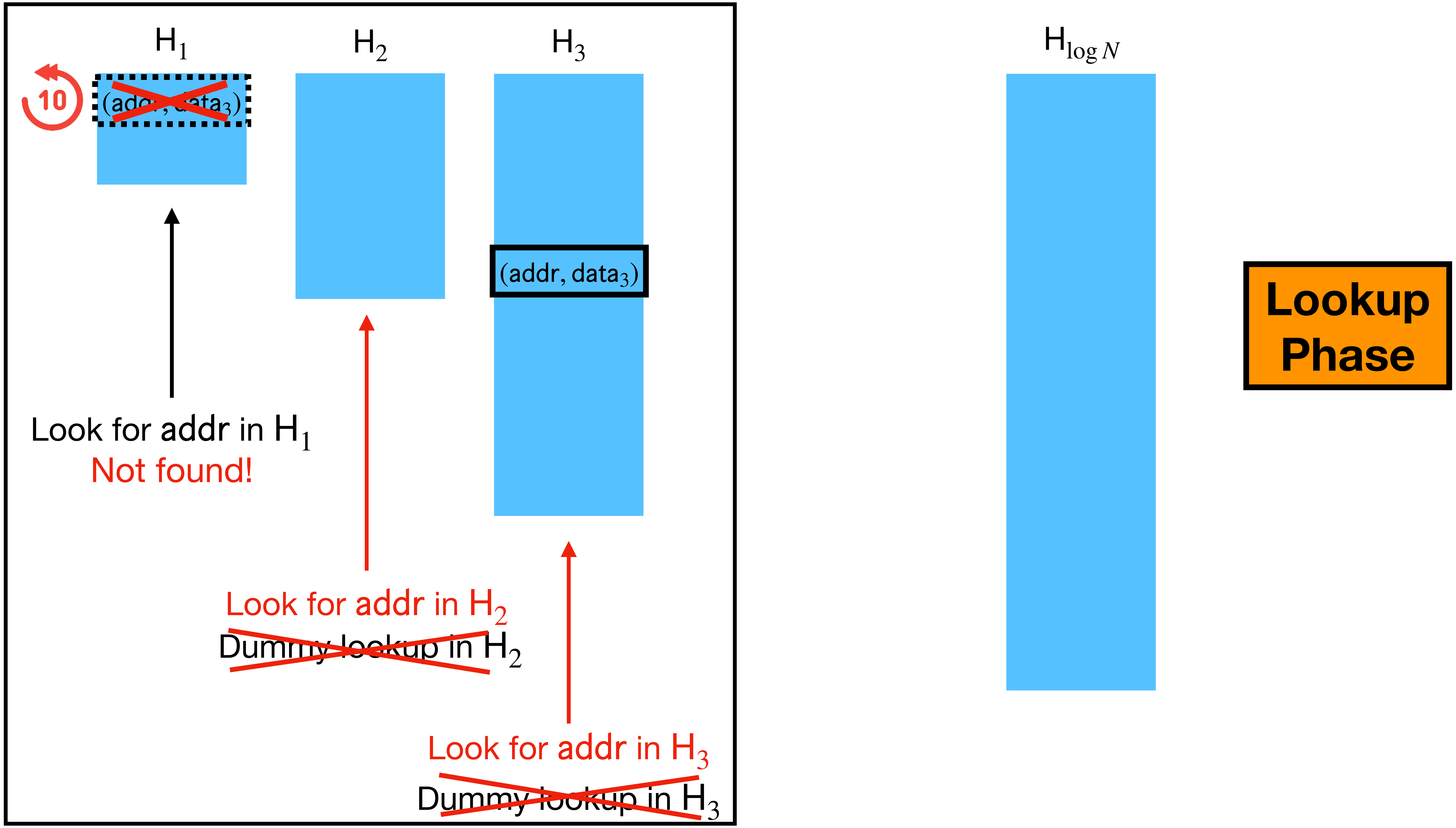
Leaks repeated address.



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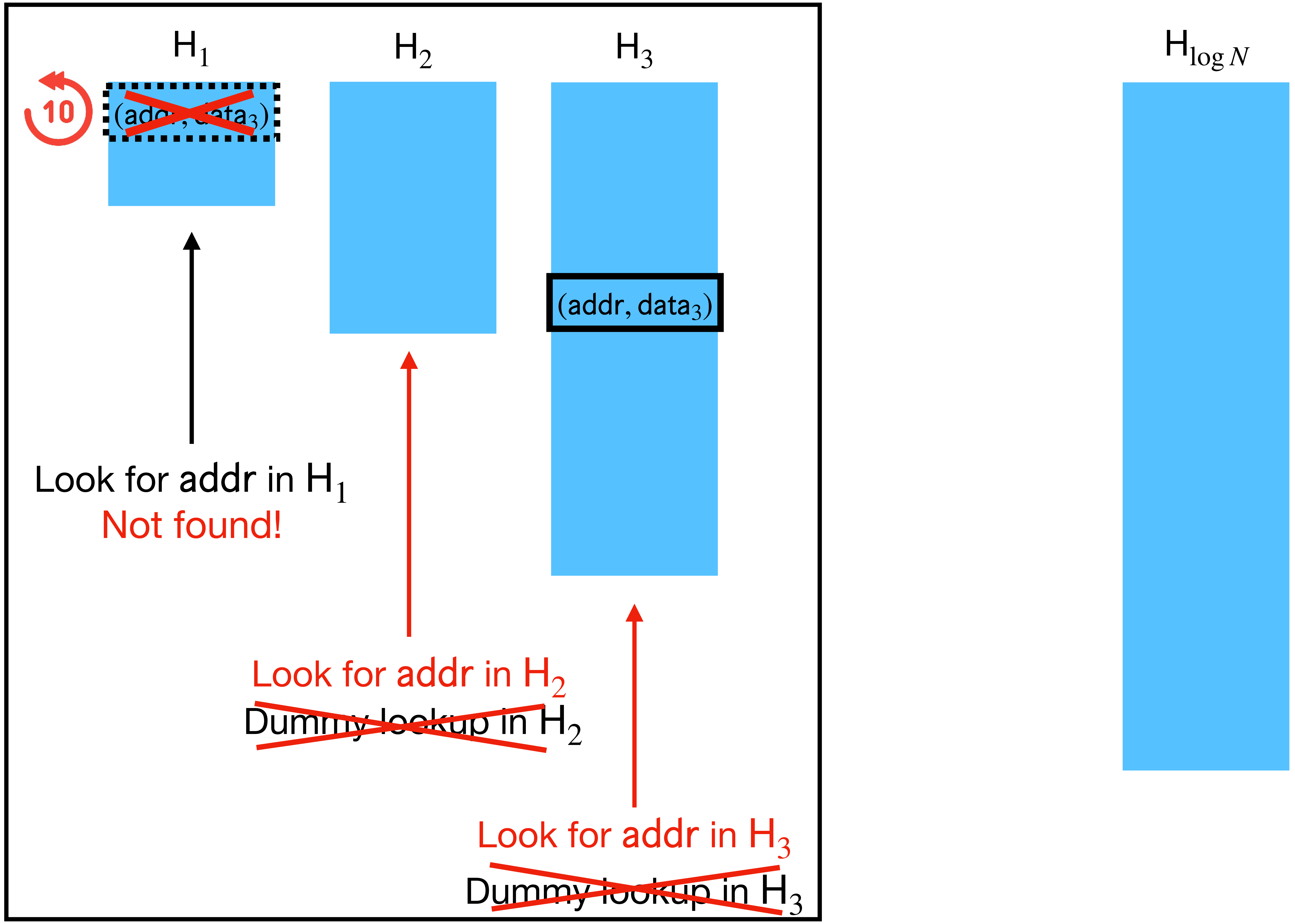
Obliviousness of H_i lookups depends on **correctness** of $H_{<i}$ lookups!



Lookup Phase

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).

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- **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

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

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All entries are MAC'ed
Current time: ctr

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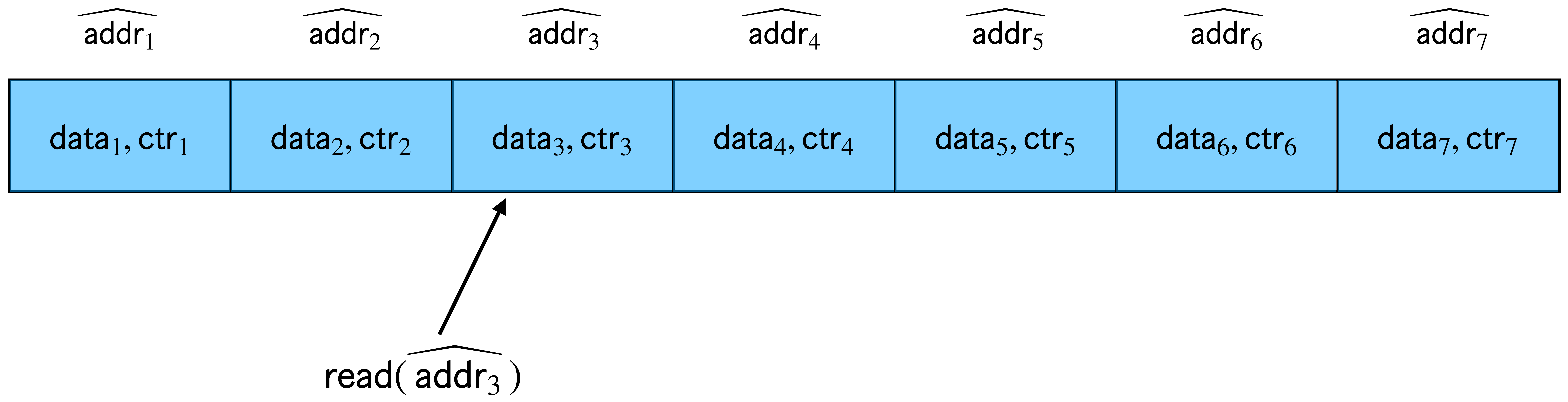
$\widehat{\text{addr}}_1$
$\widehat{\text{addr}}_2$
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$\widehat{\text{addr}}_5$
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$\widehat{\text{addr}}_7$
$\text{data}_1, \text{ctr}_1$
$\text{data}_2, \text{ctr}_2$
$\text{data}_3, \text{ctr}_3$
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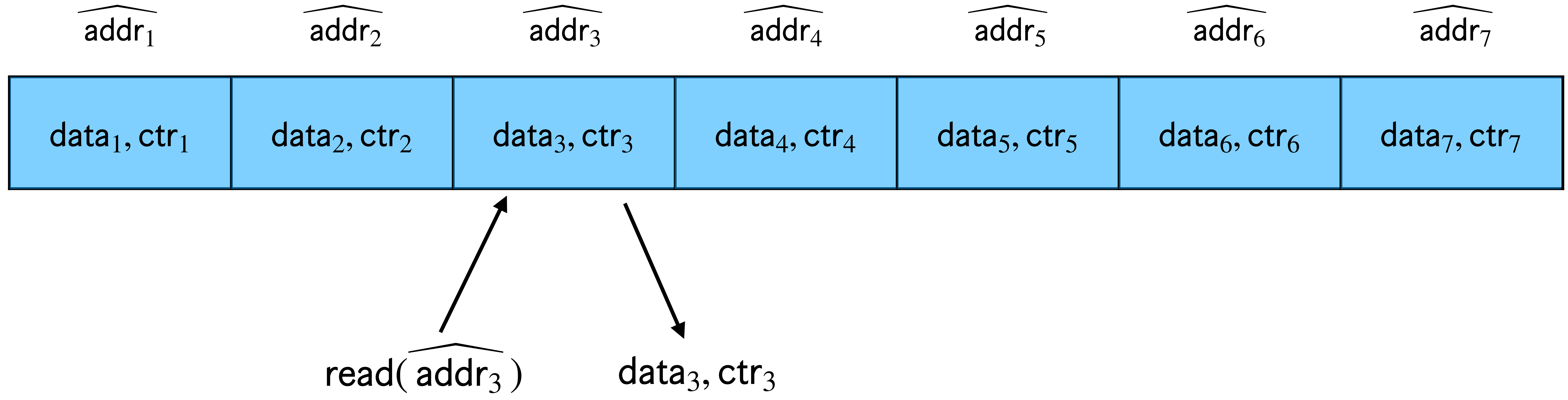

$\widehat{\text{addr}_1}$
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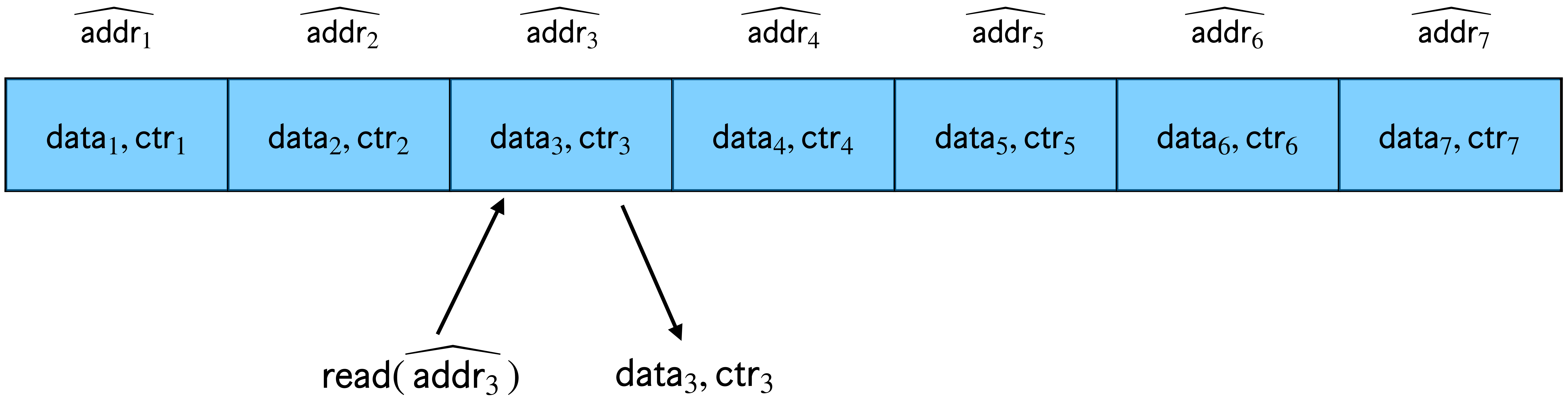

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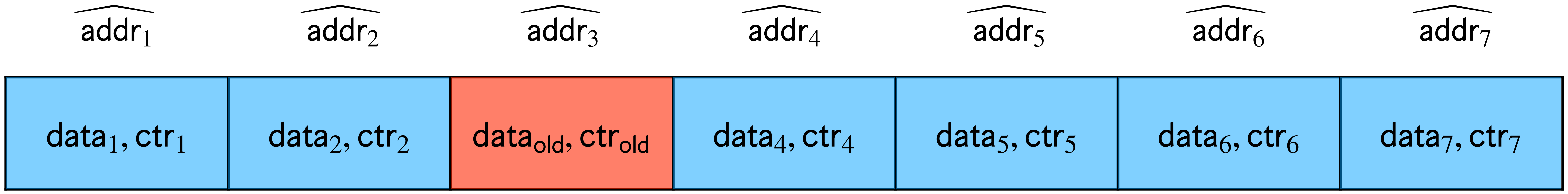
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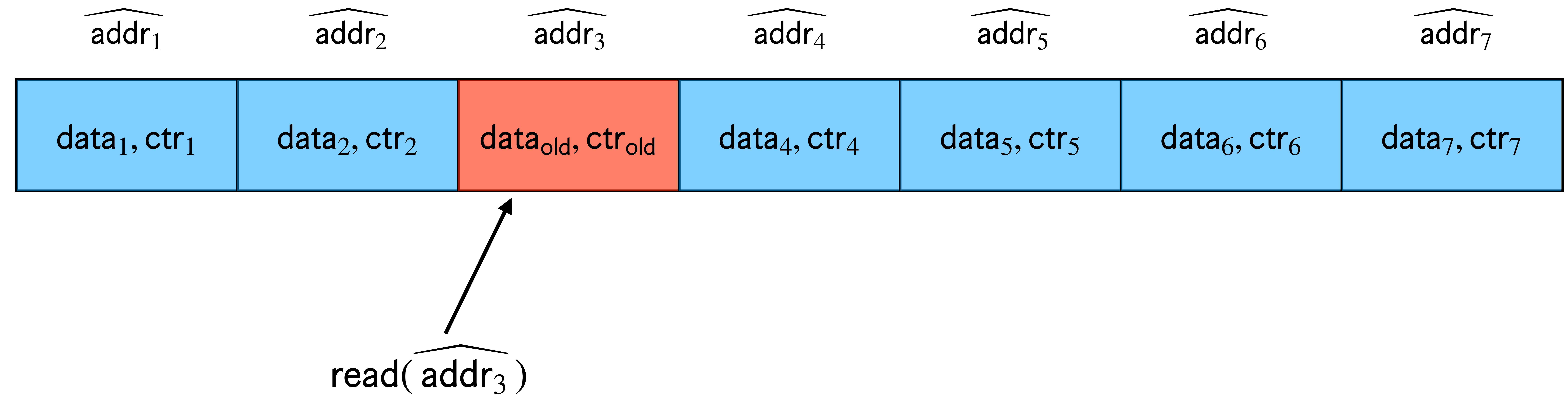

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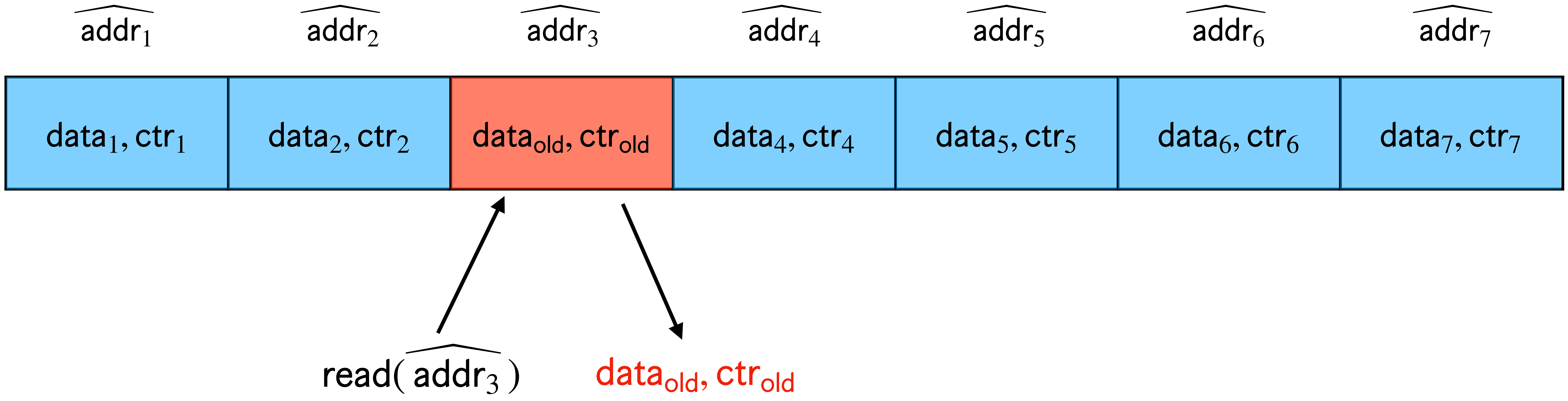
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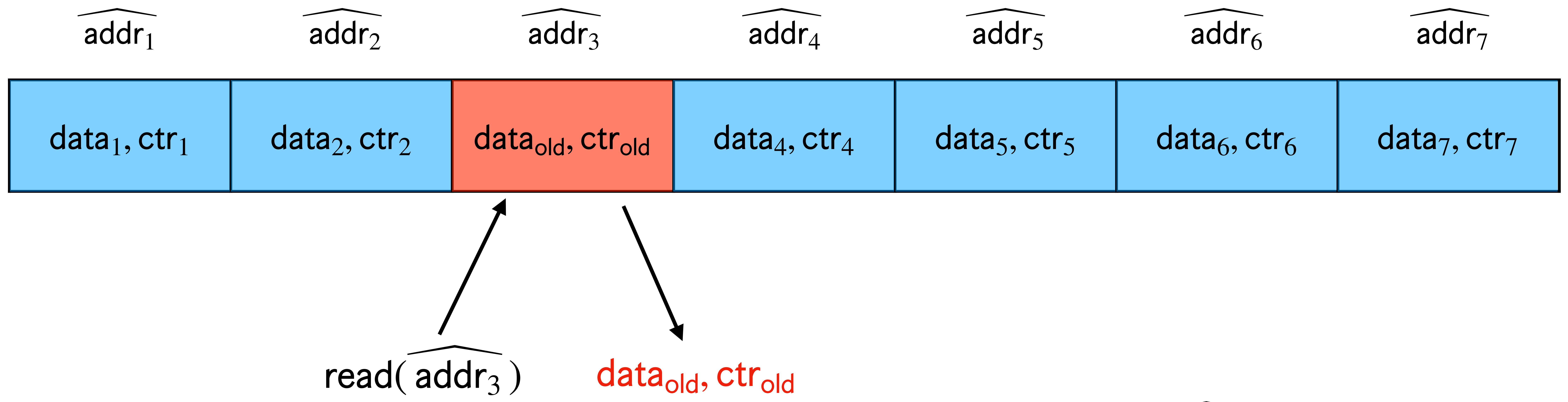

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Since $\text{ctr}_{\text{old}} < \text{ctr}_3 = \text{PrevTime}(\text{ctr}, \widehat{\text{addr}}_3)$,
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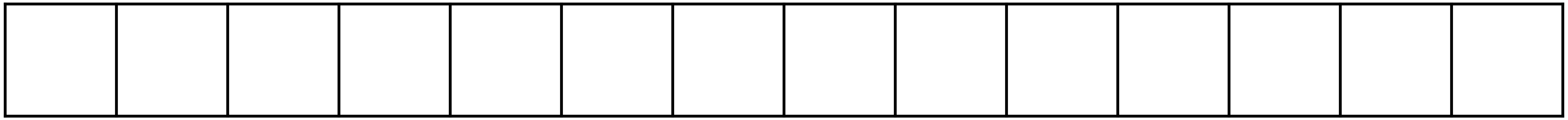

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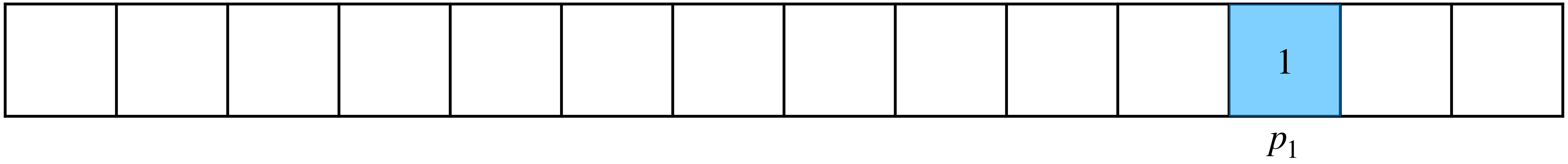

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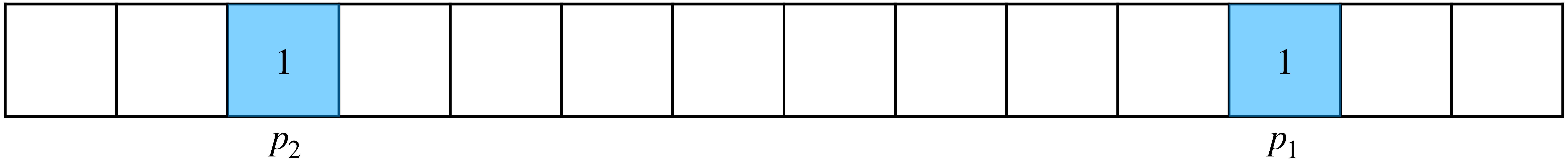

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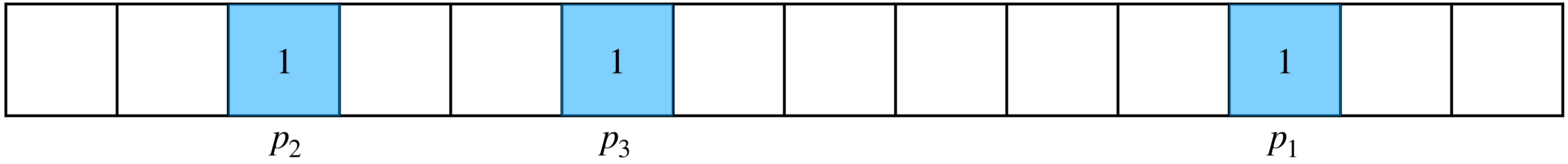

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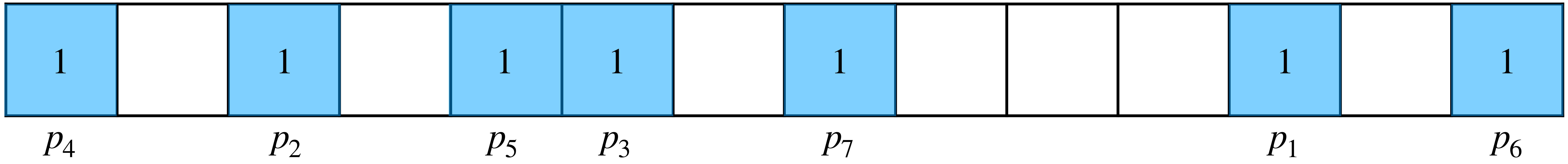

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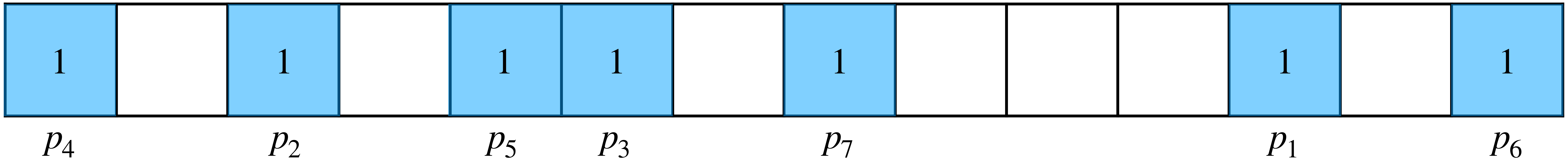

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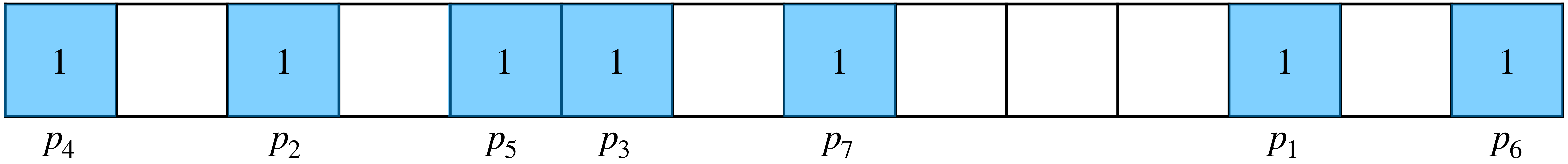

  - If you can time-stamp this access pattern, you can recover all p_i.

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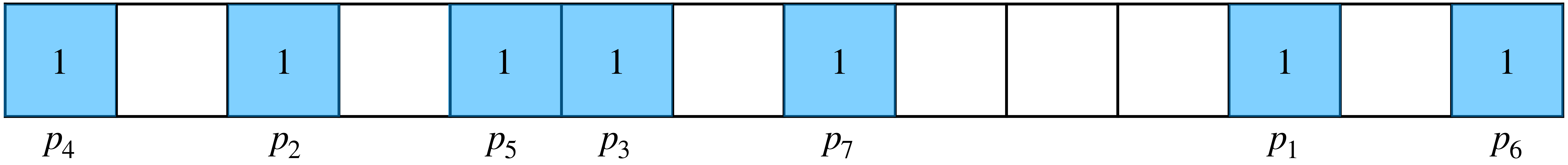
- Unfortunately, **the recent hierarchical ORAM constructions cannot be time-stamped**
- **Unconditionally** requires $\Omega(N)$ bits of local space to time-stamp **OptORAMa**.
- Example: **Marking** (appears in oblivious hash tables in **PanORAMa** and **OptORAMa**)
  - Setup: Mark positions $p_i \in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



  - 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.

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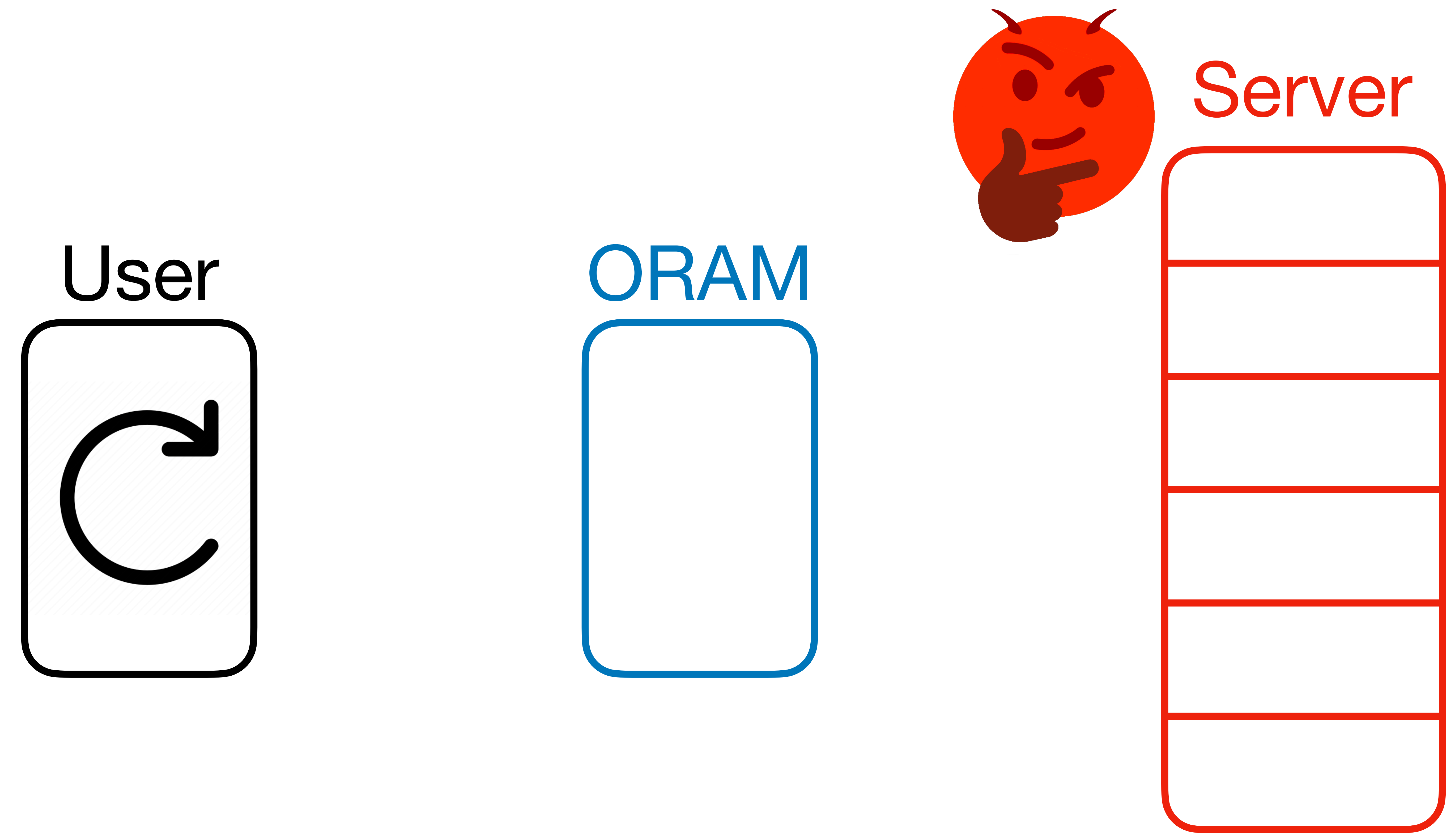

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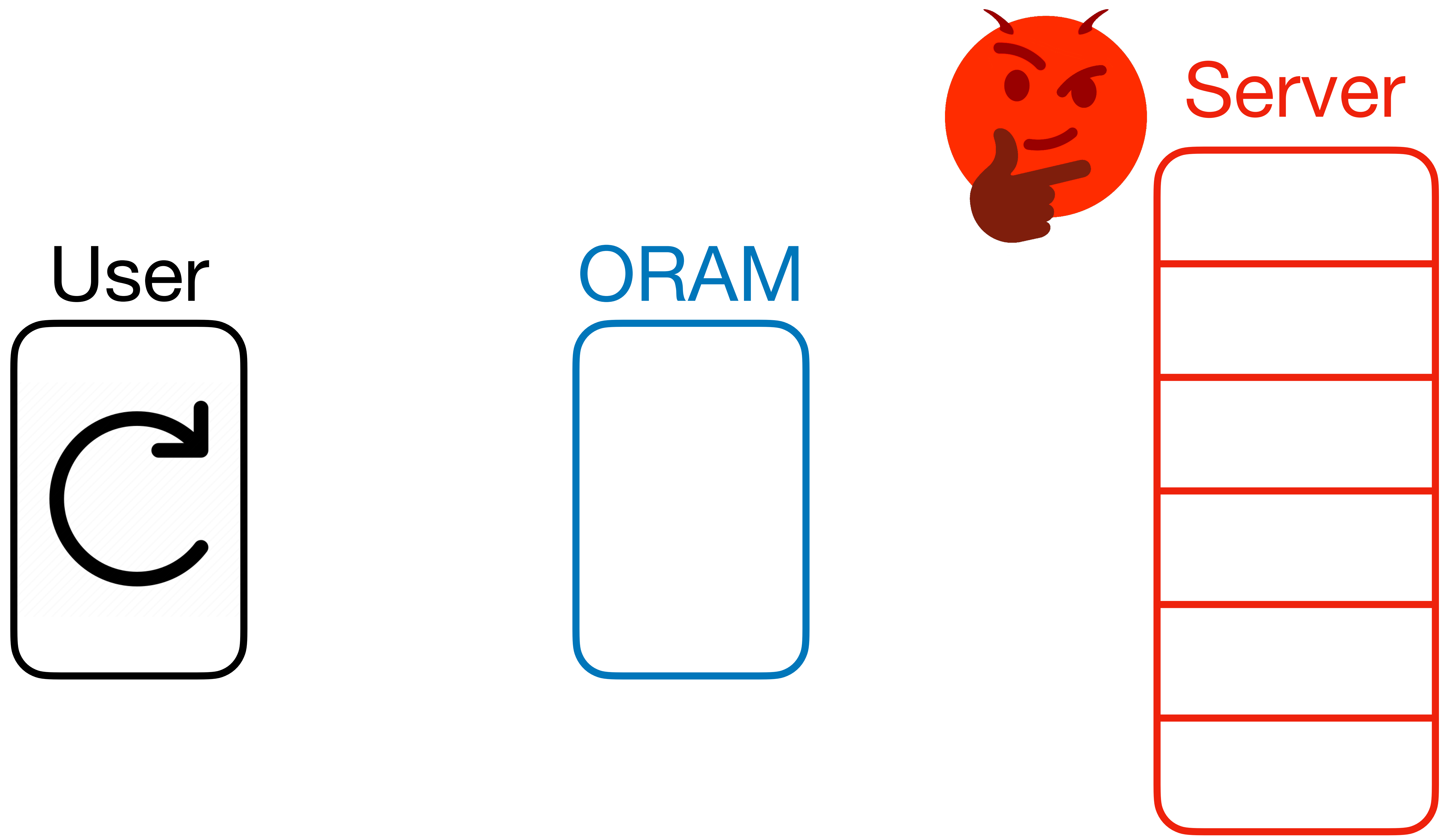

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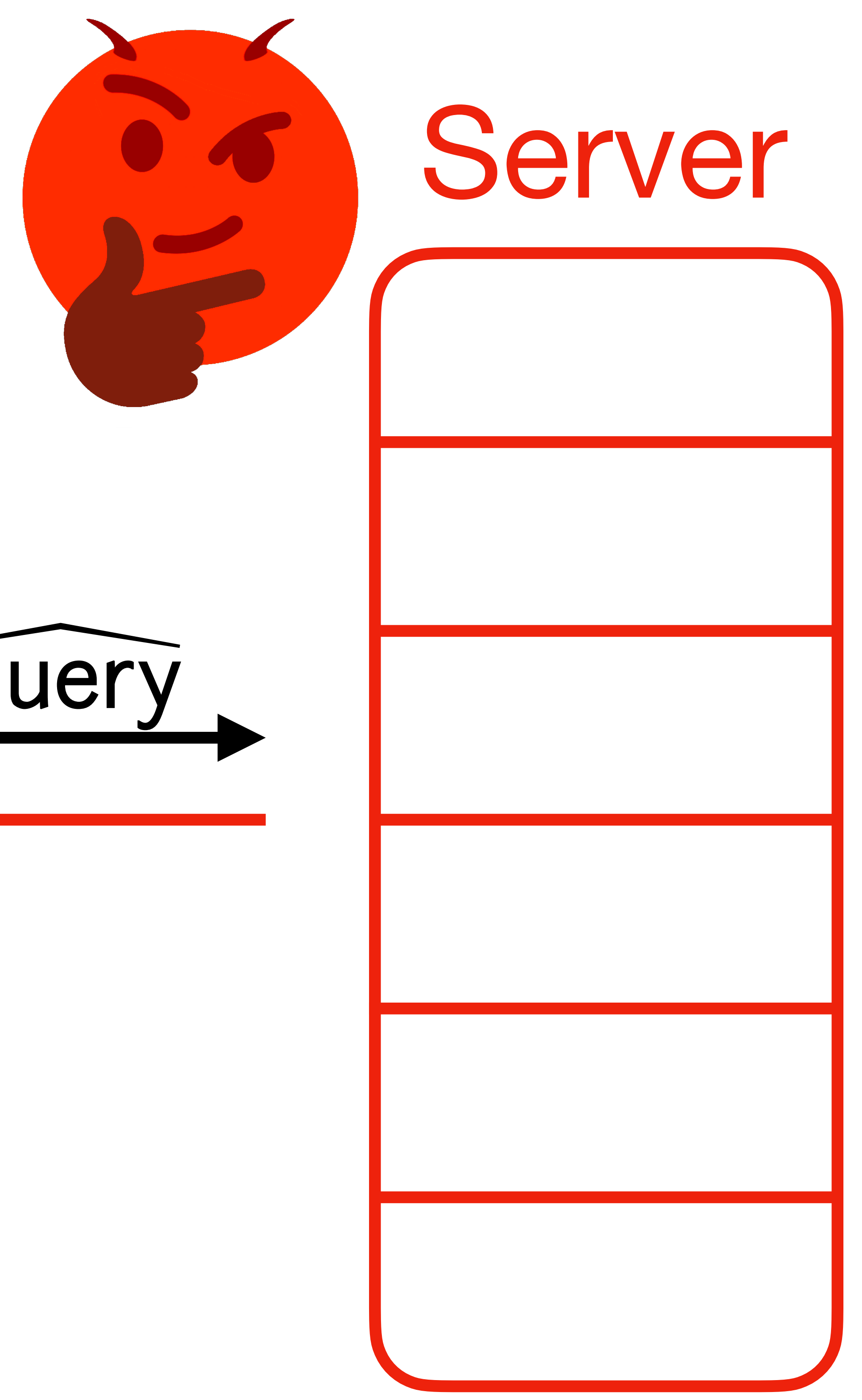

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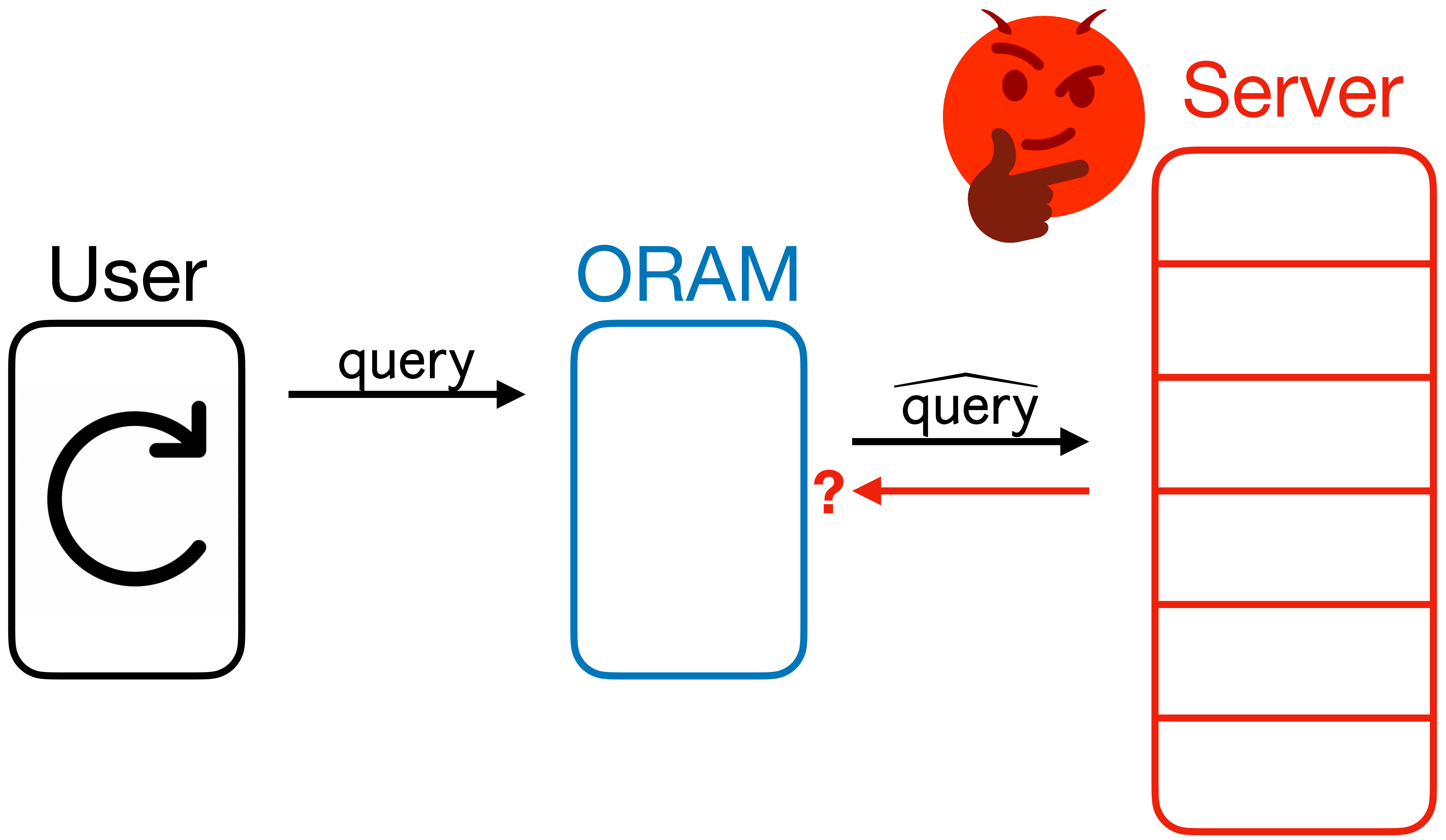

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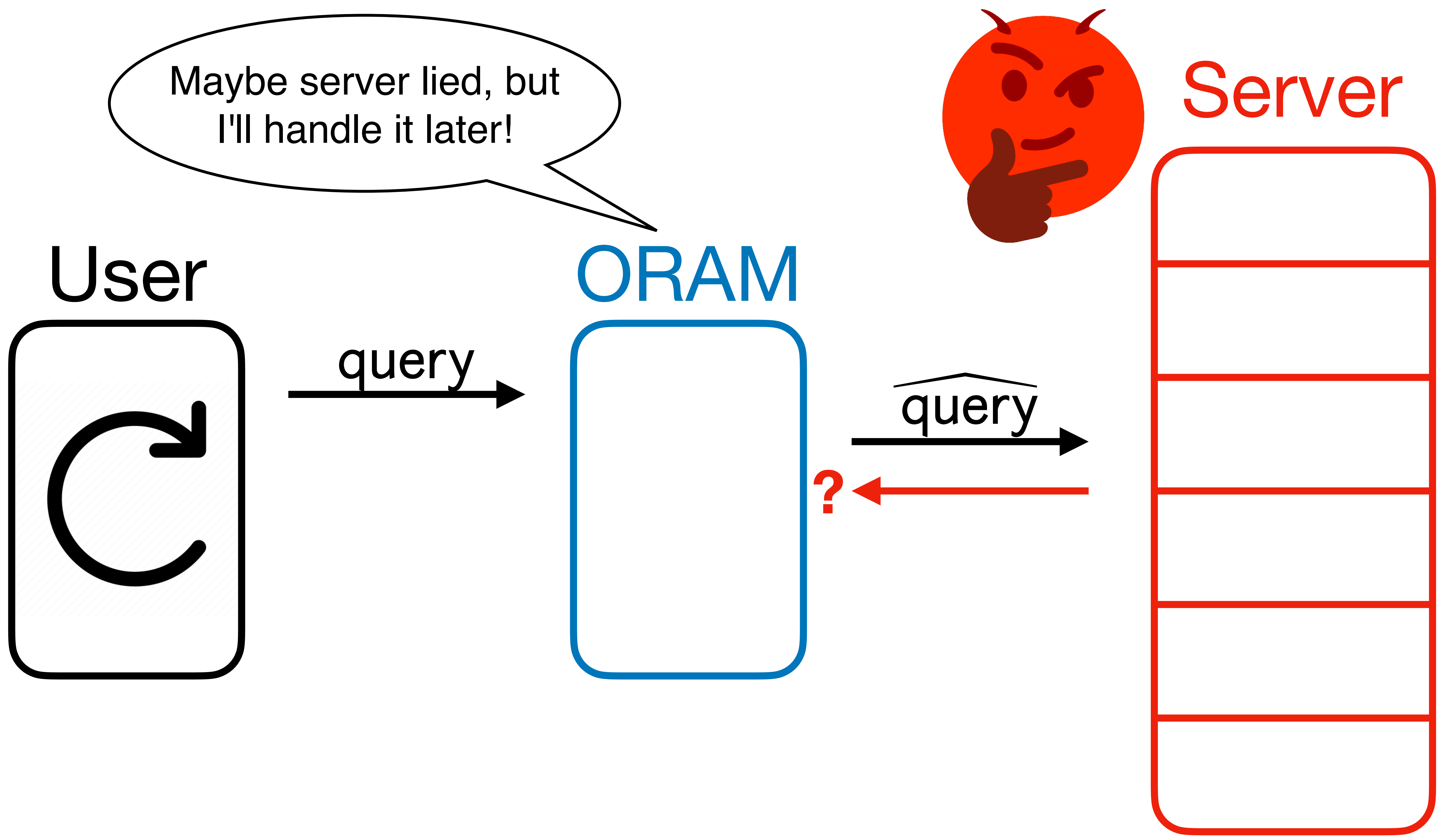

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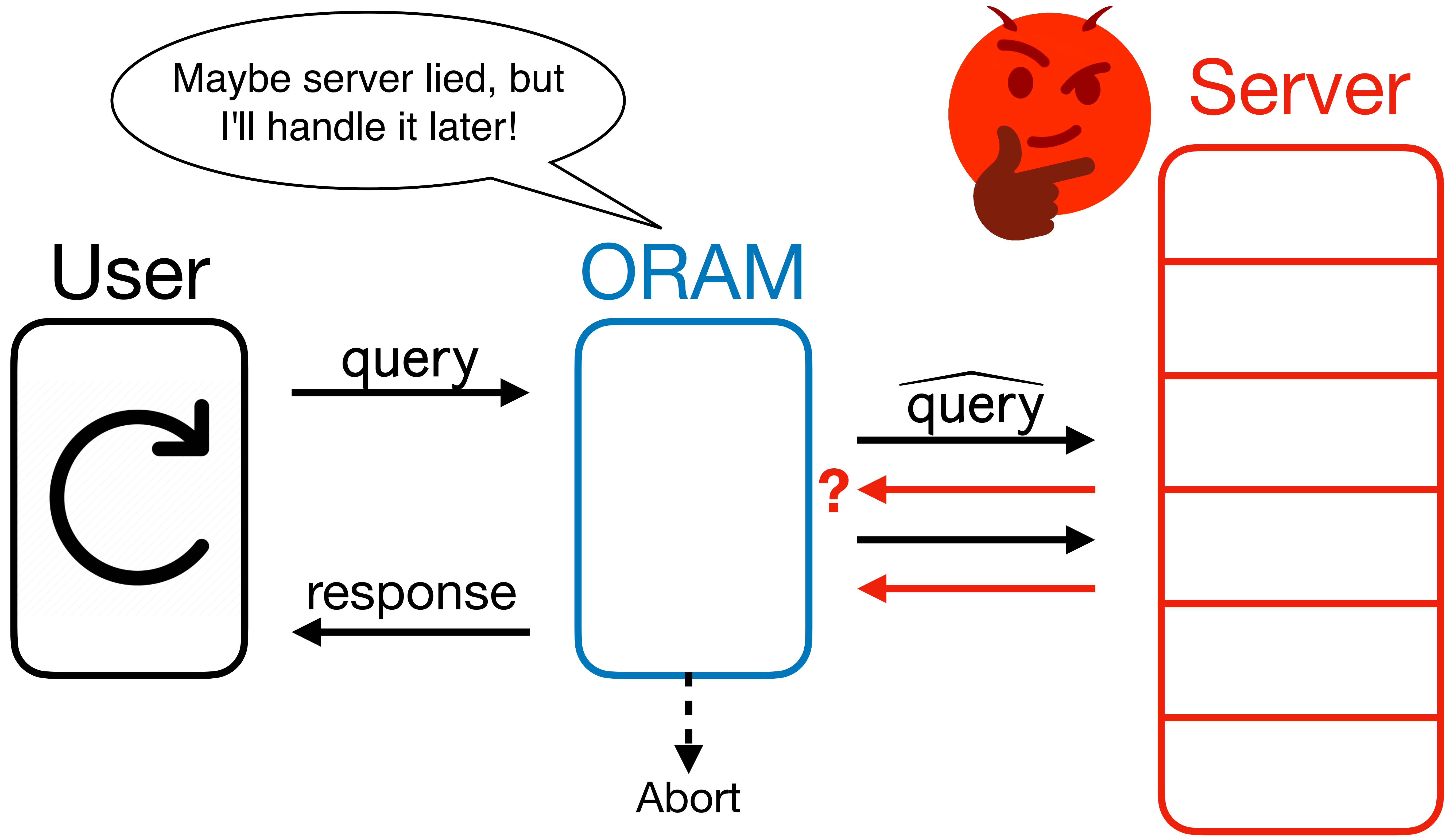

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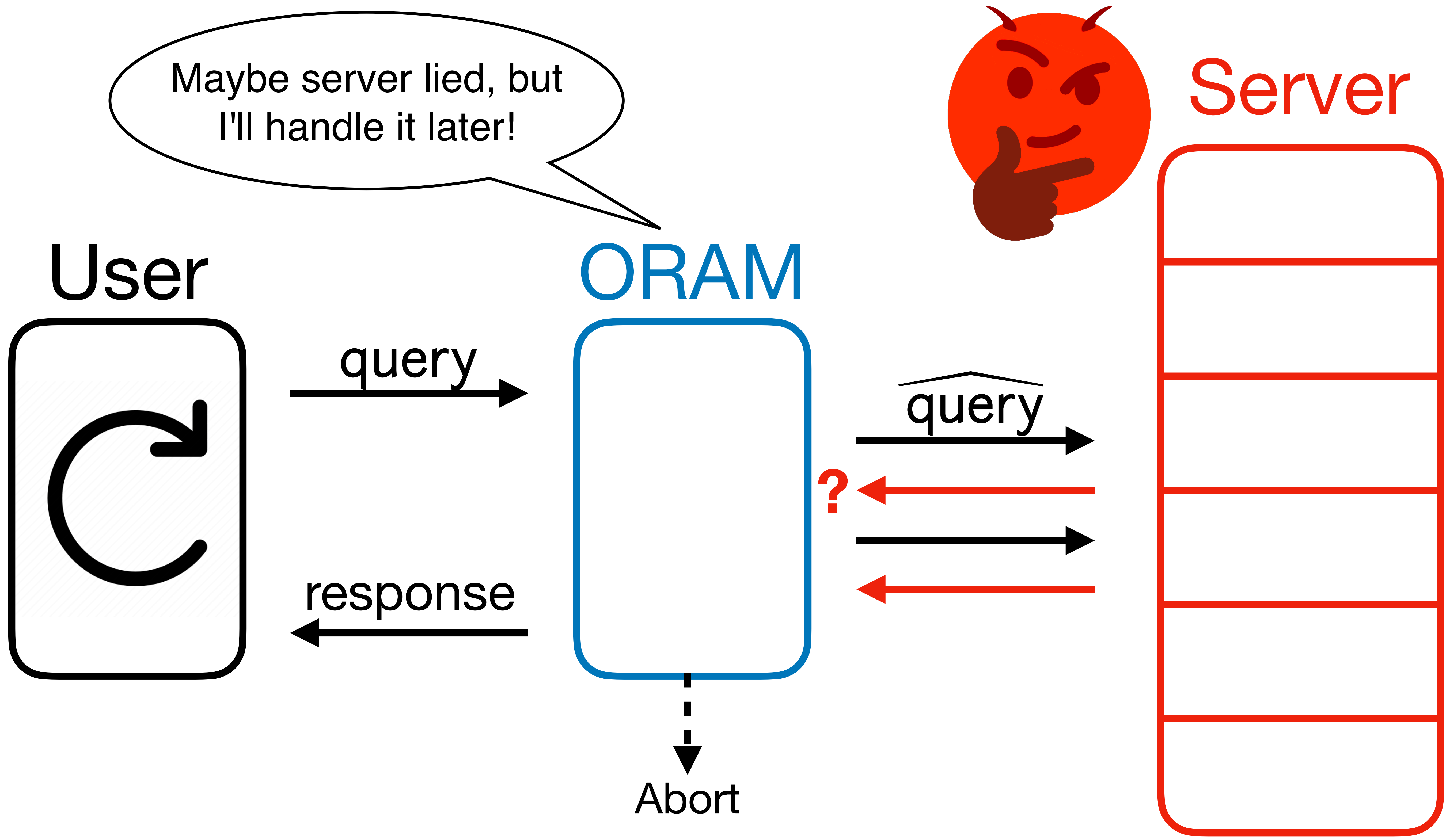
- **Our Idea**: Use weaker, more efficient notion of memory checking to capitalize on this!



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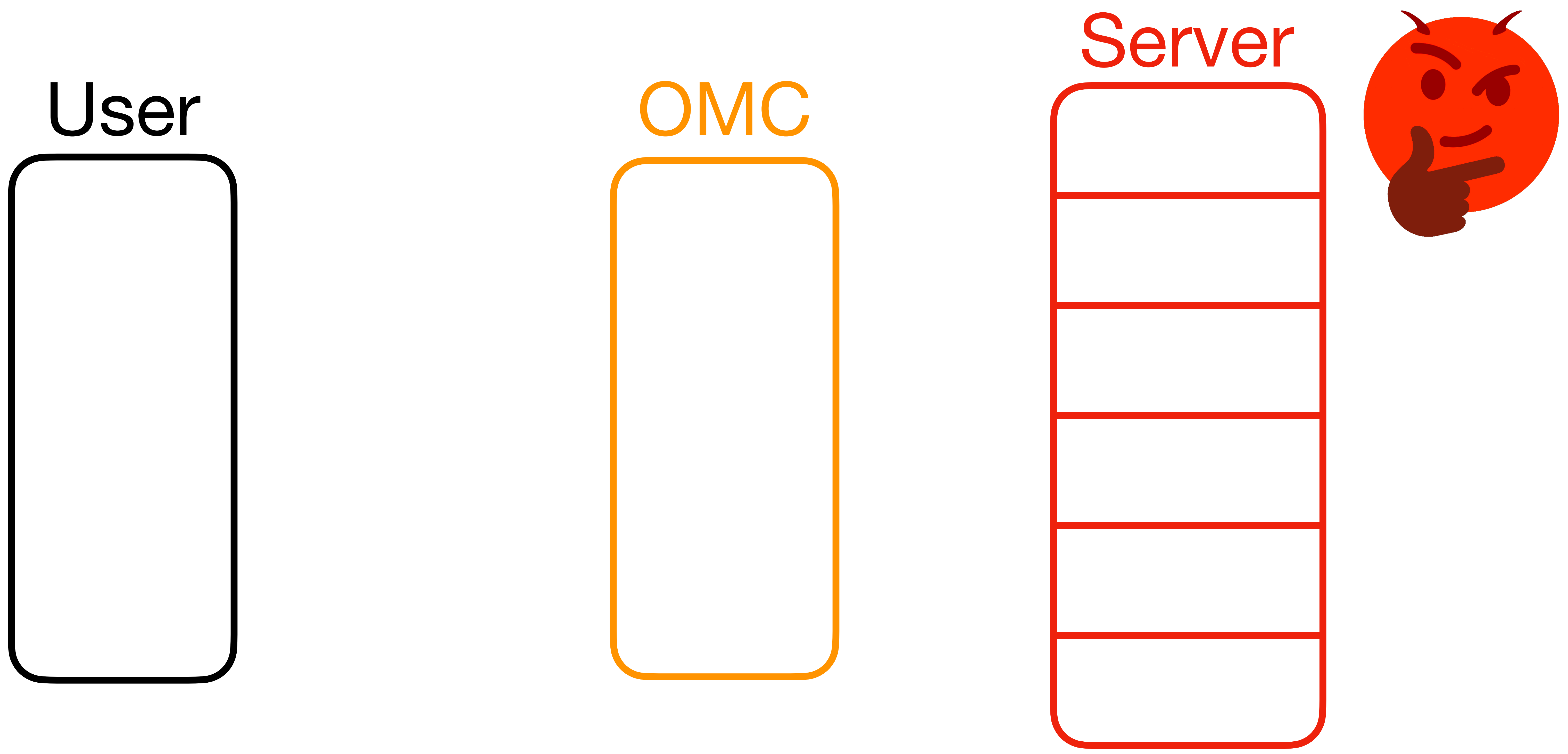

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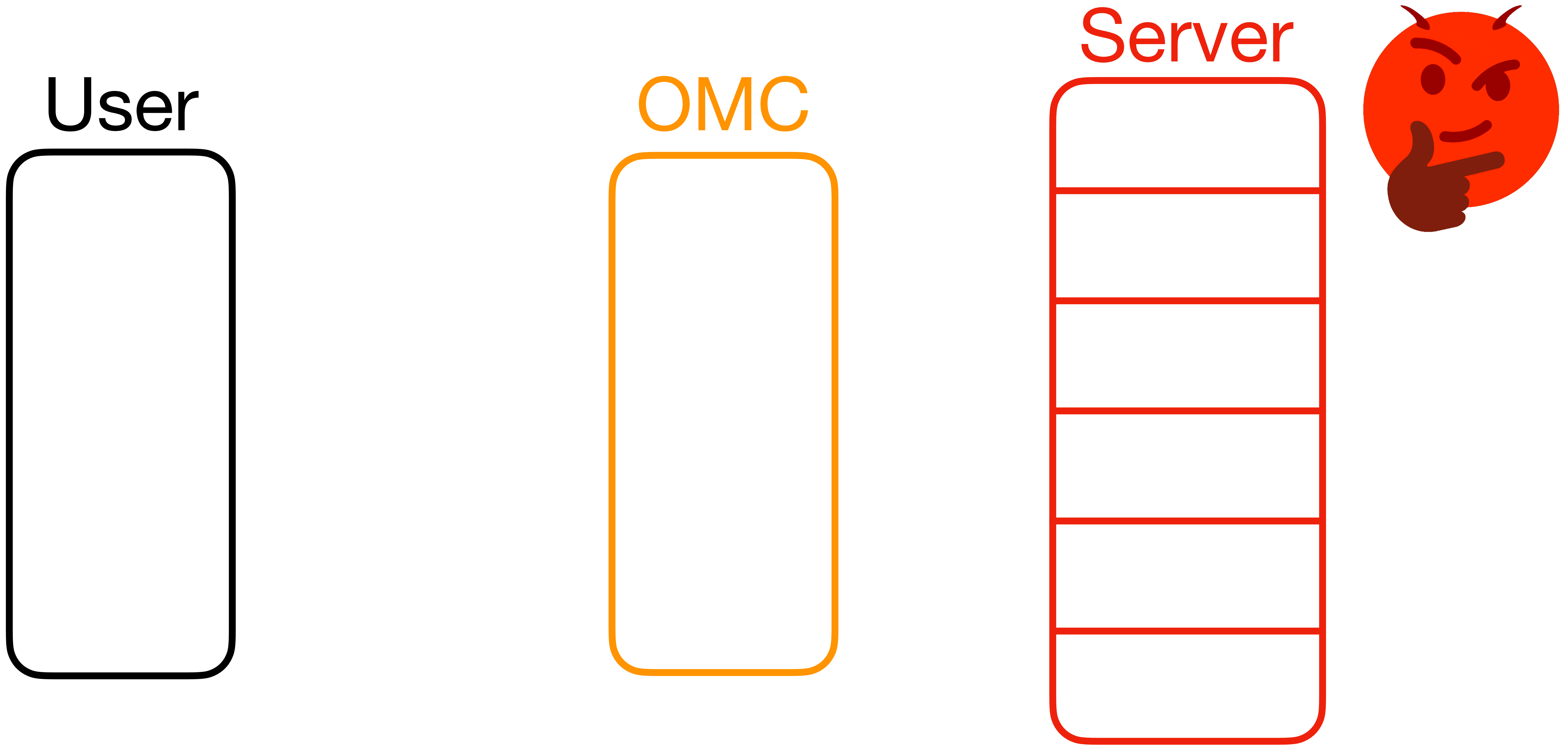

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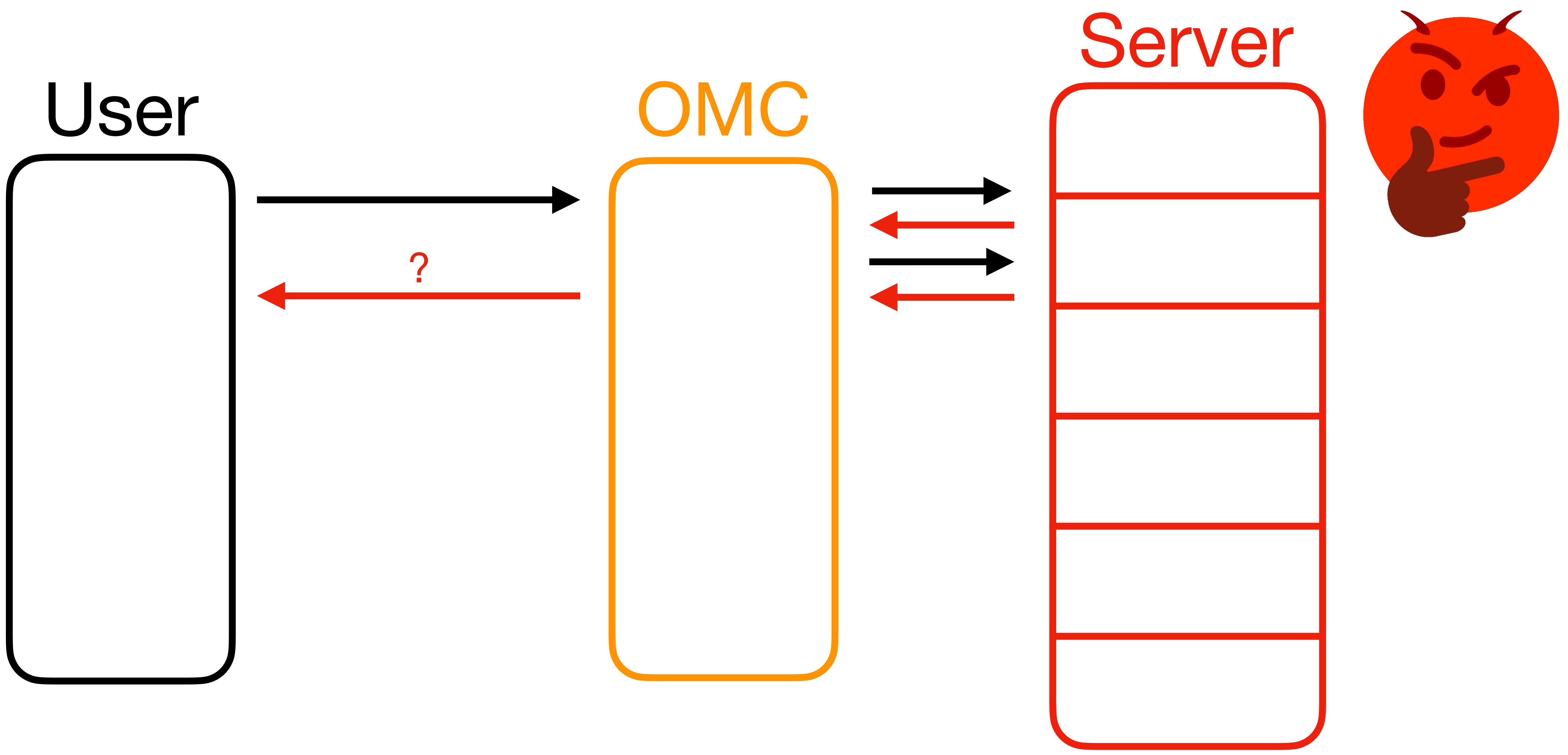

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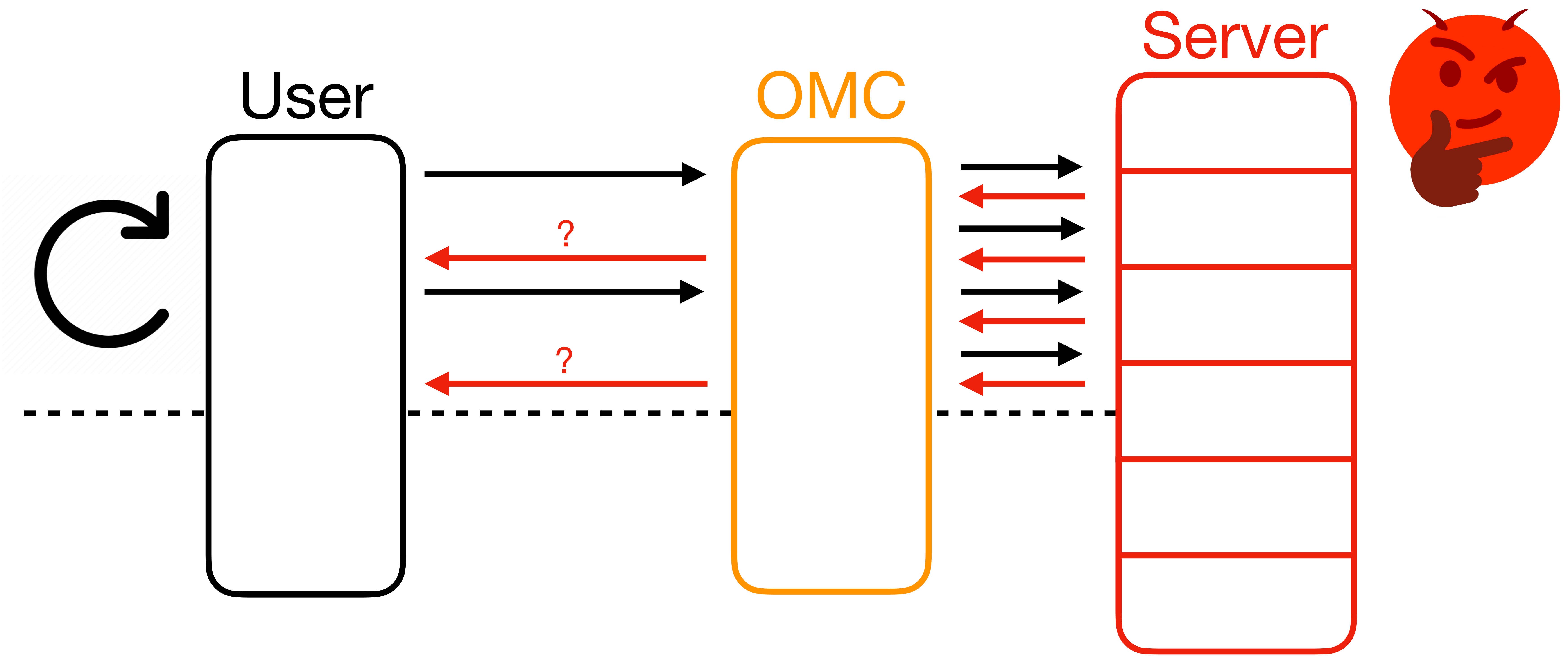

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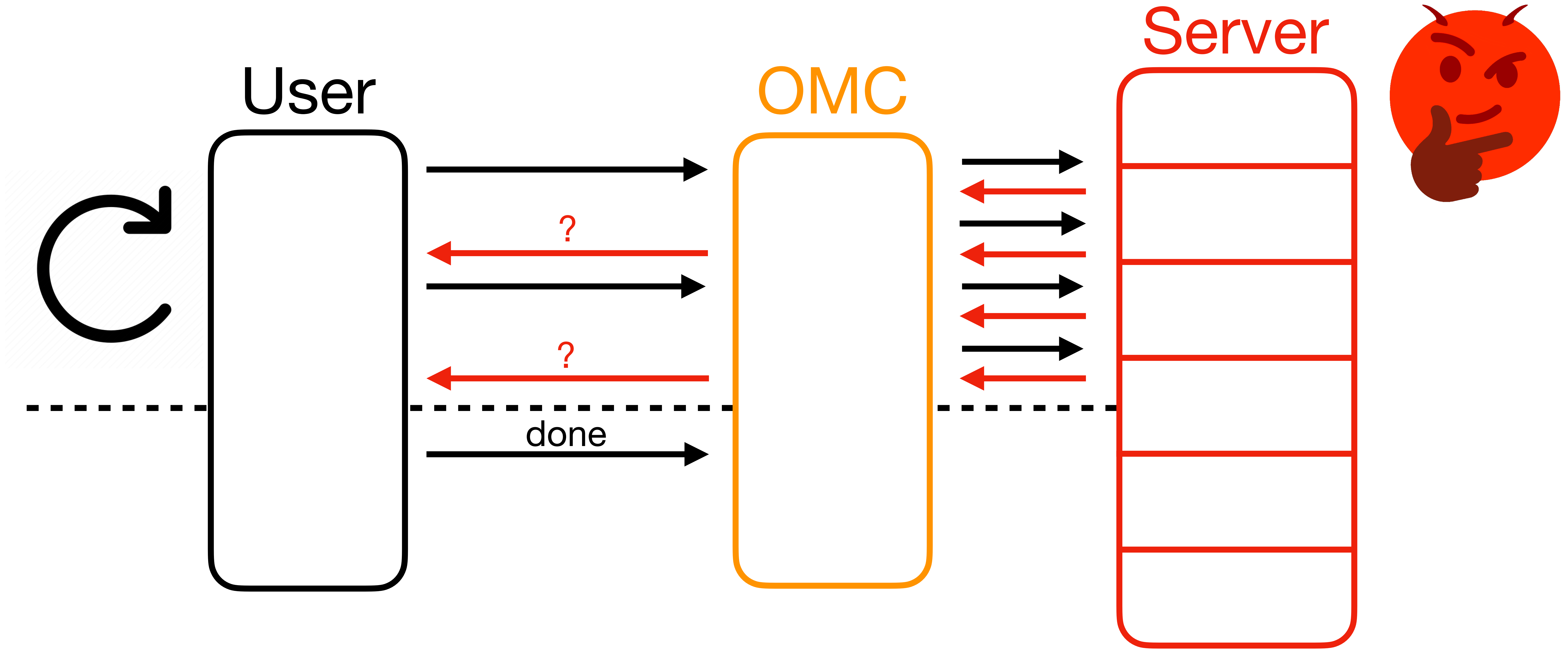

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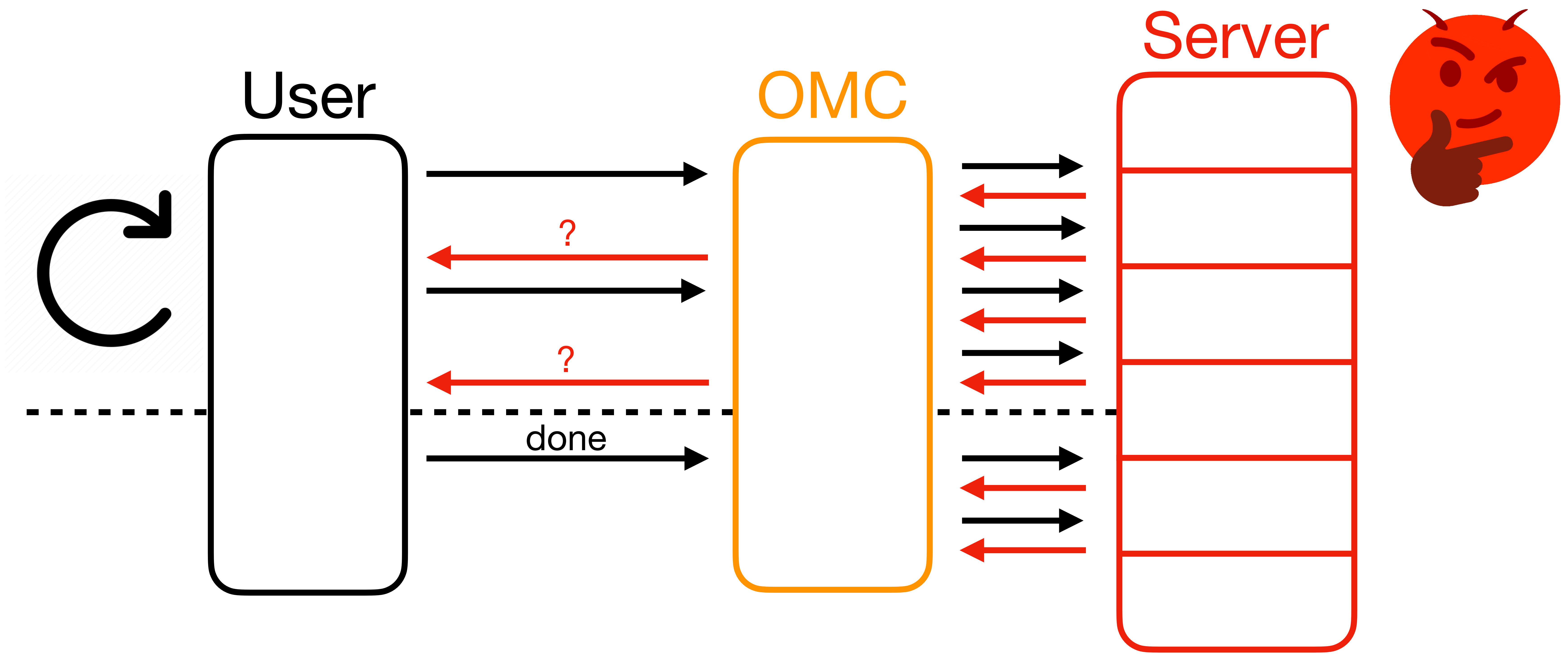

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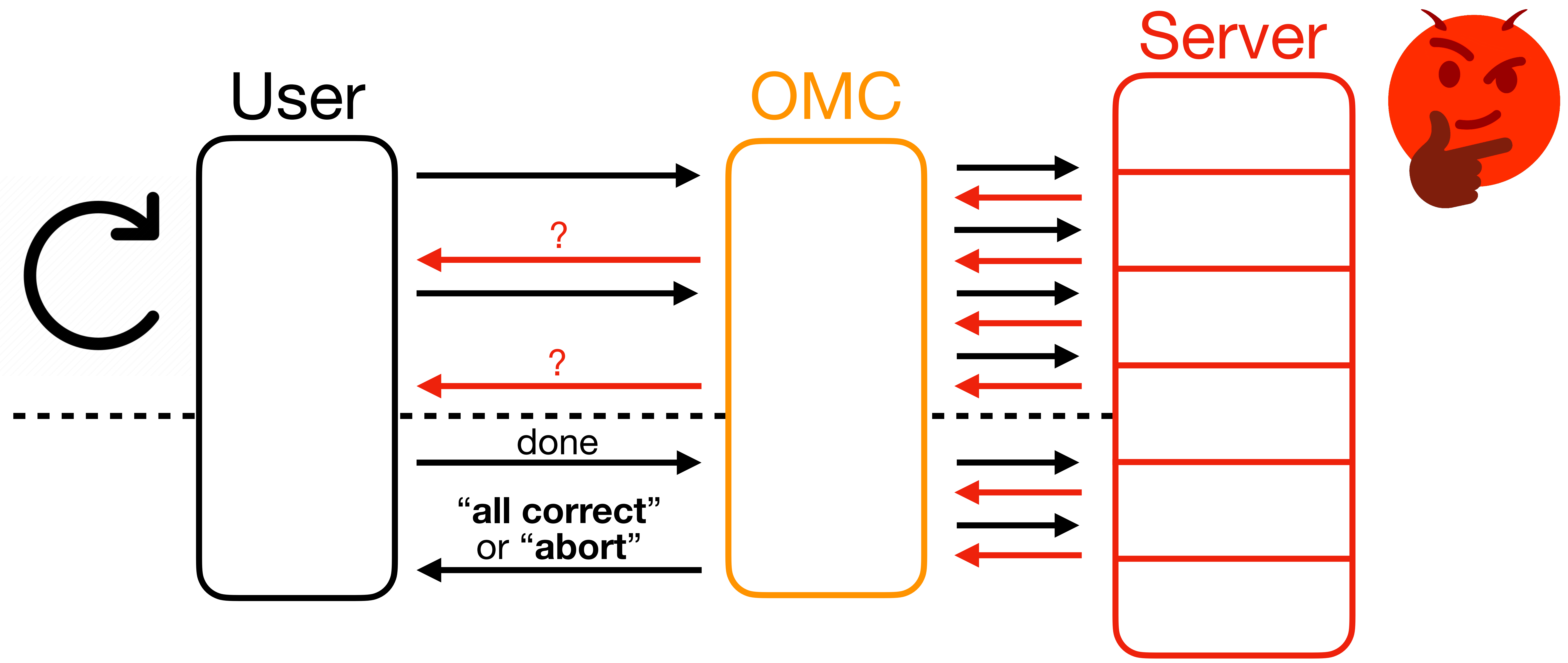

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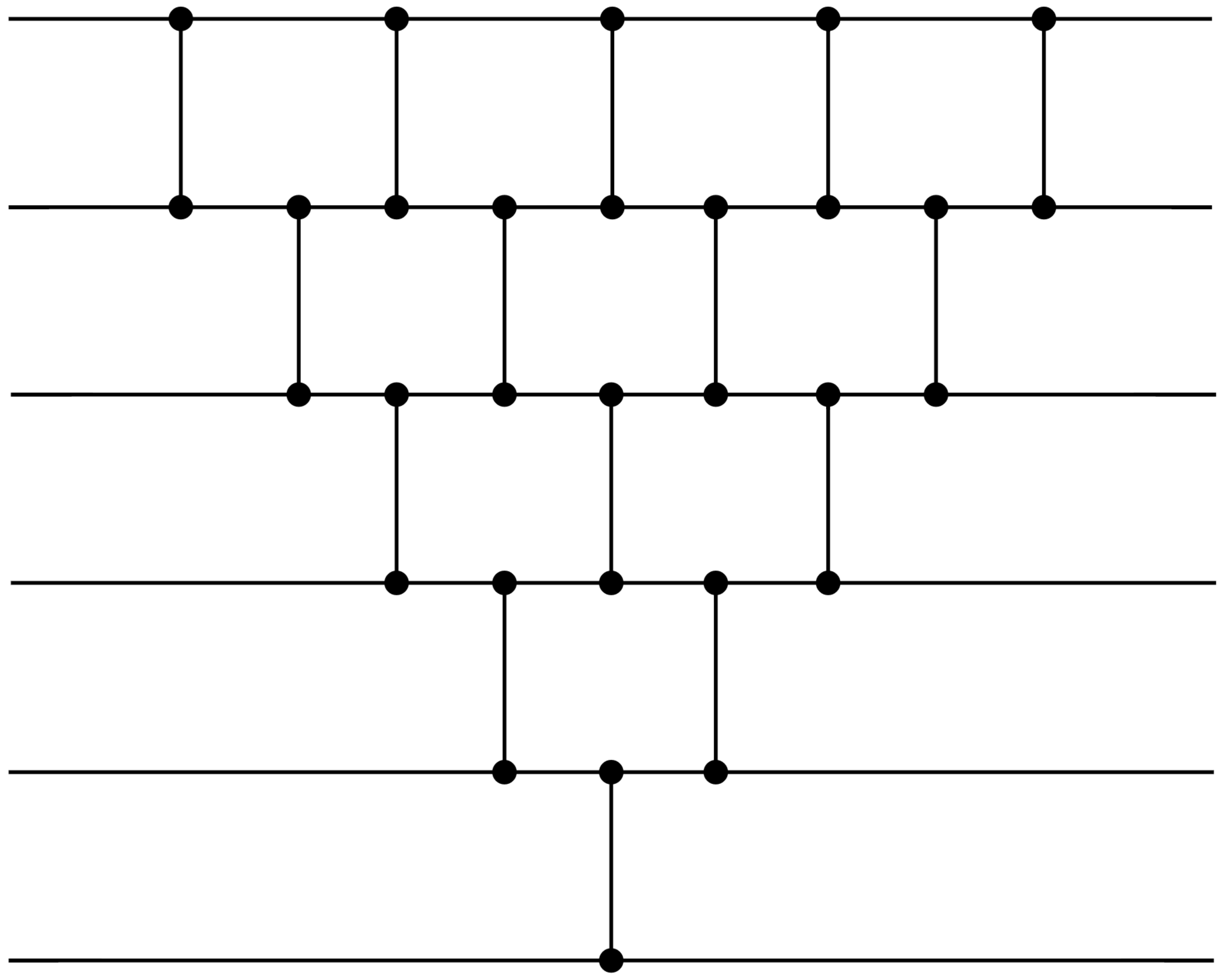

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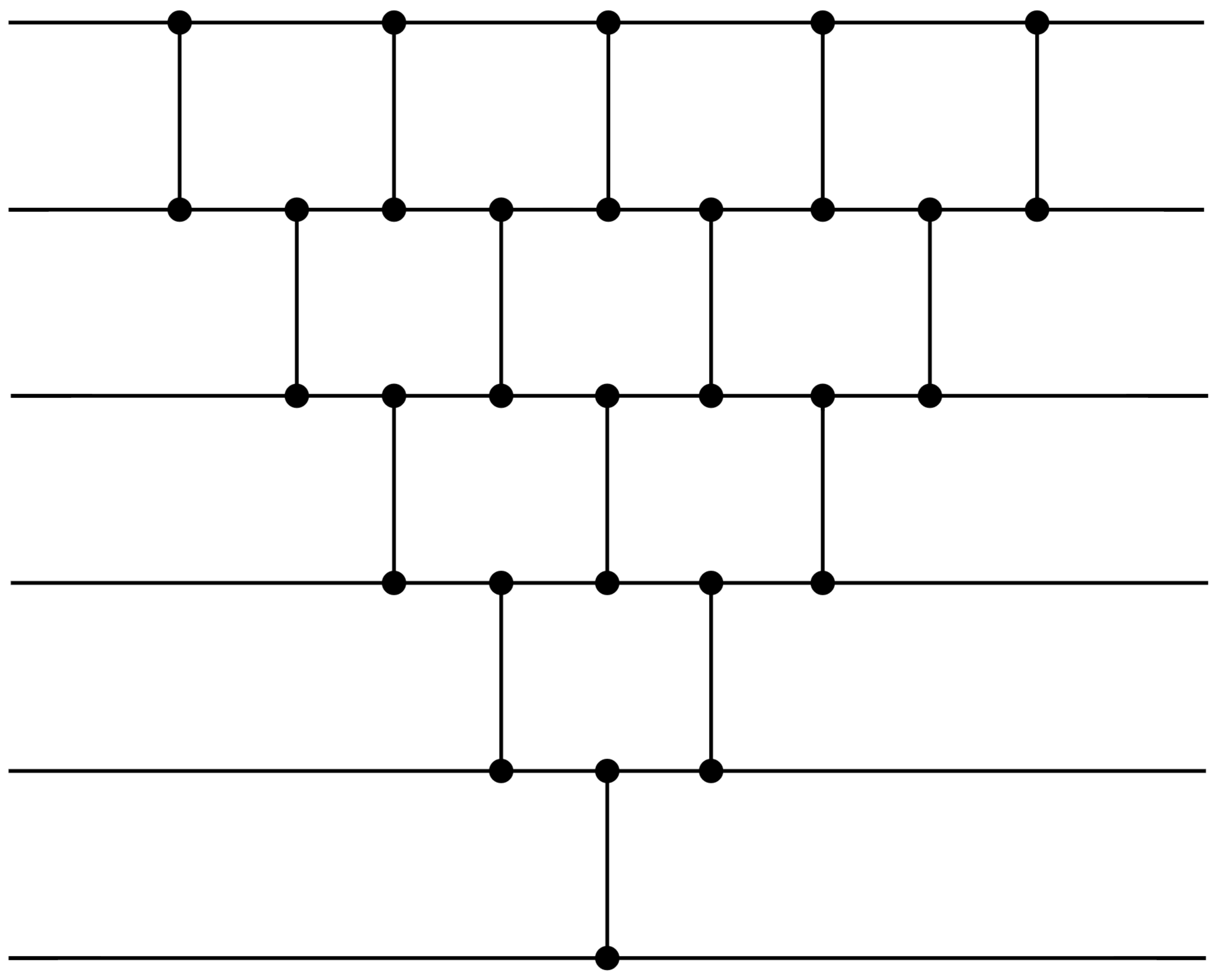

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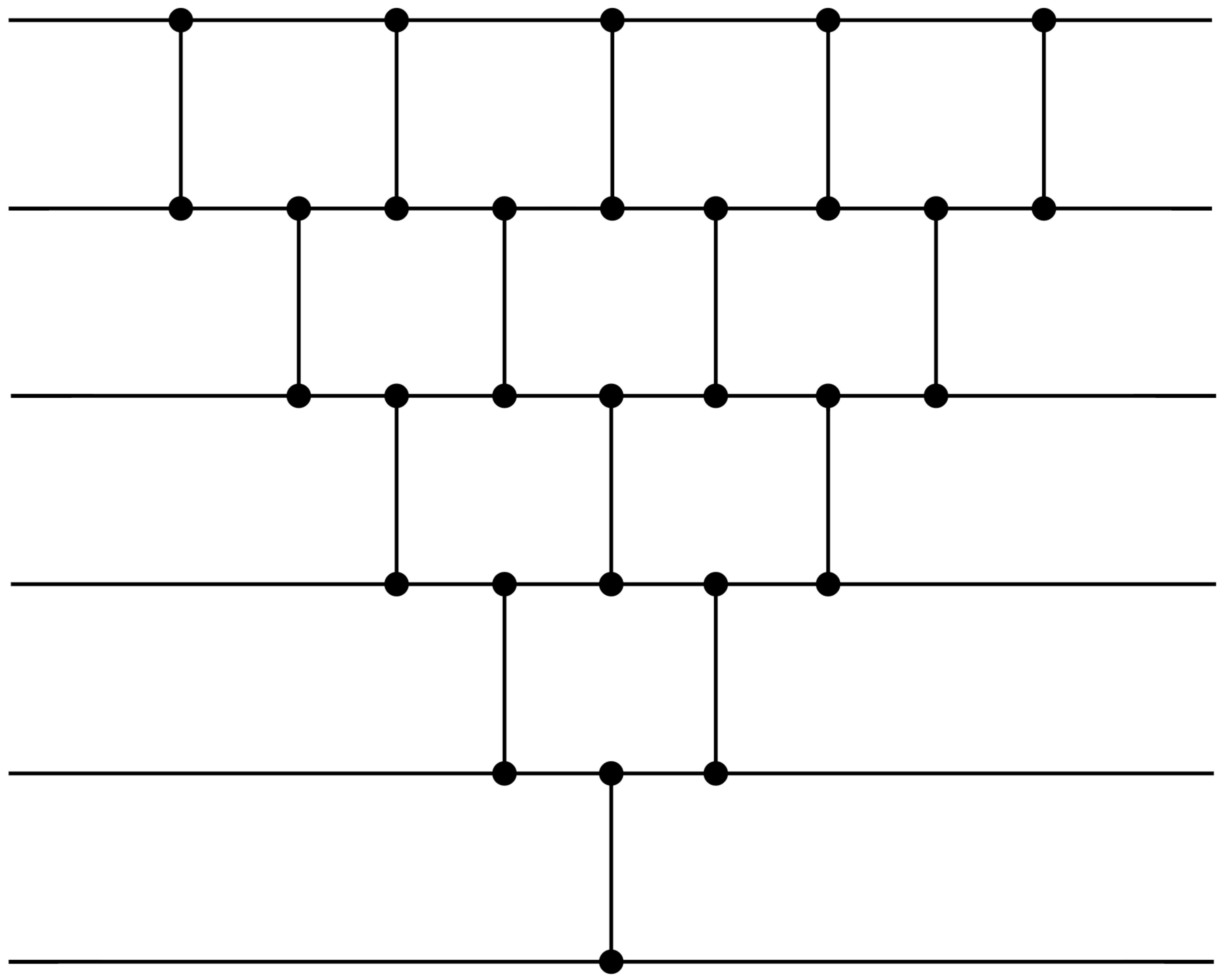

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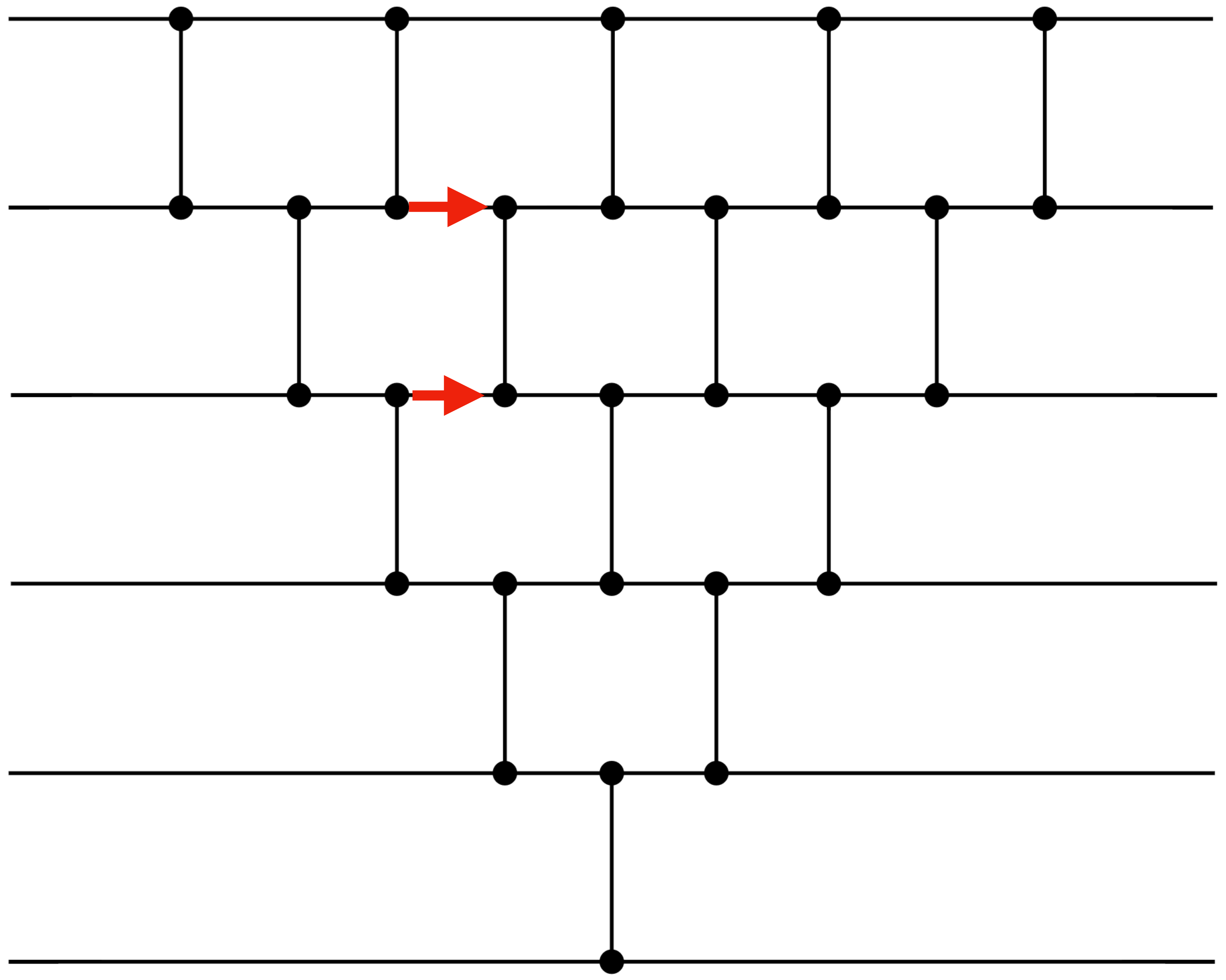

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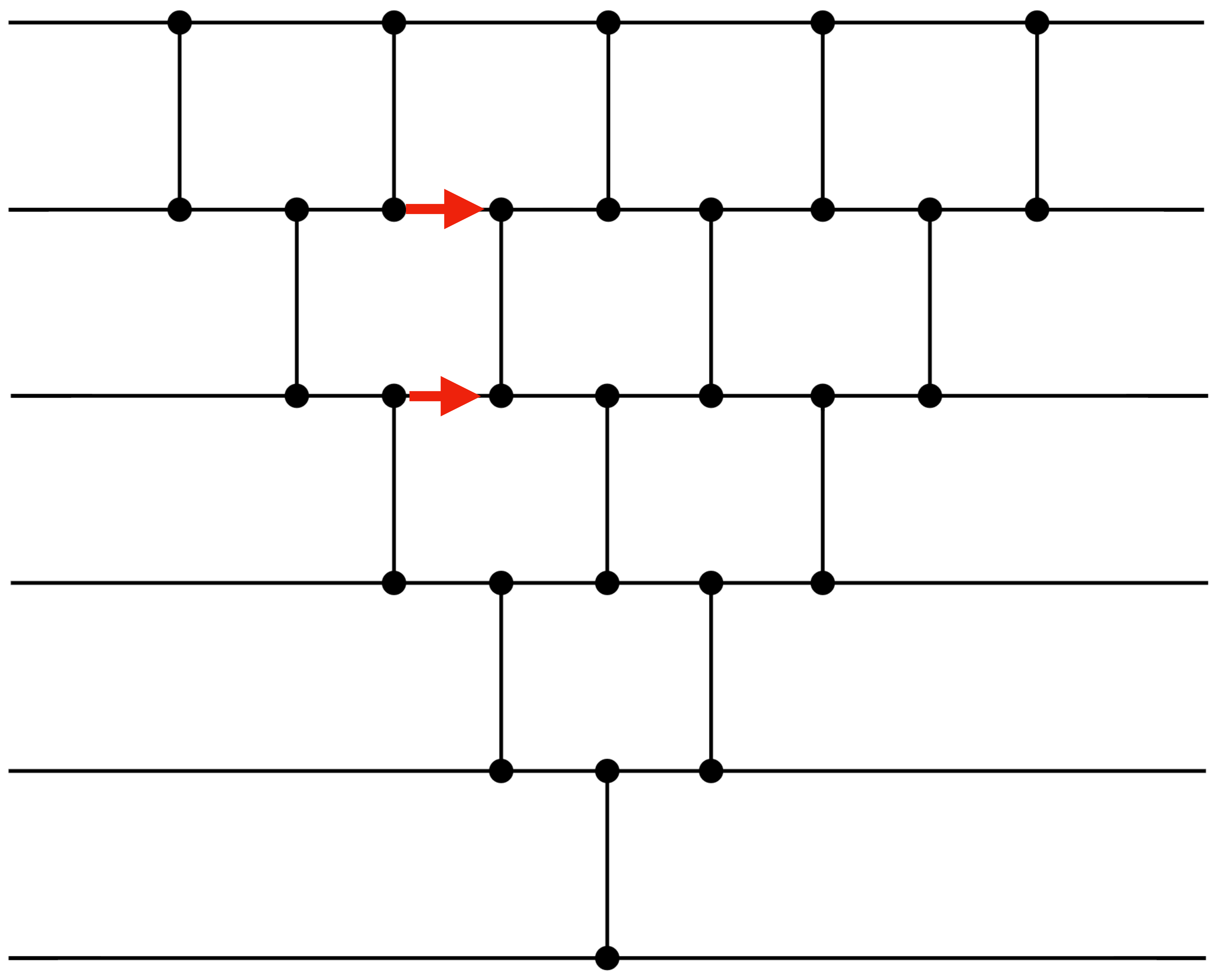

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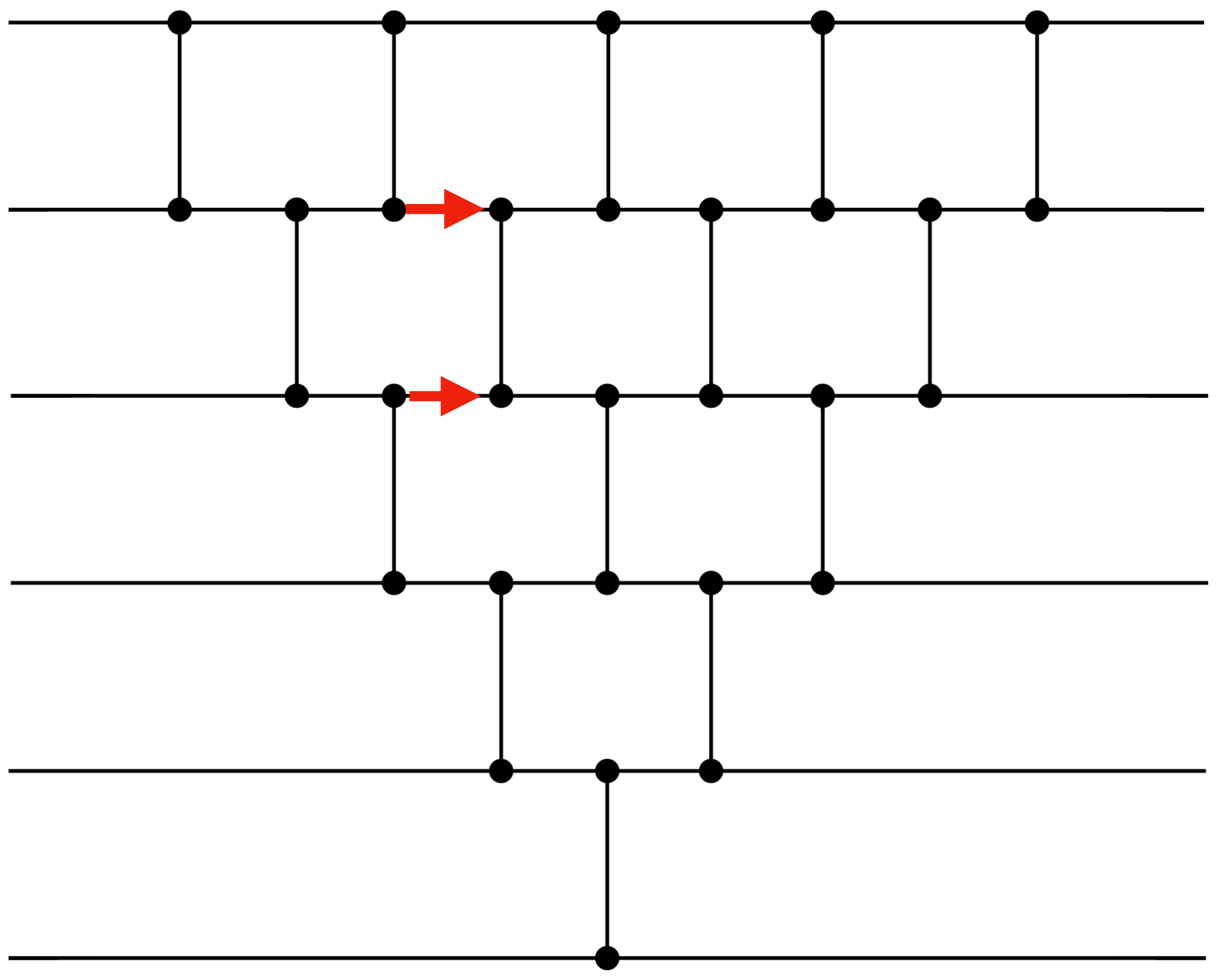

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- In our work, we generalise this further to capture more classes of algorithms.

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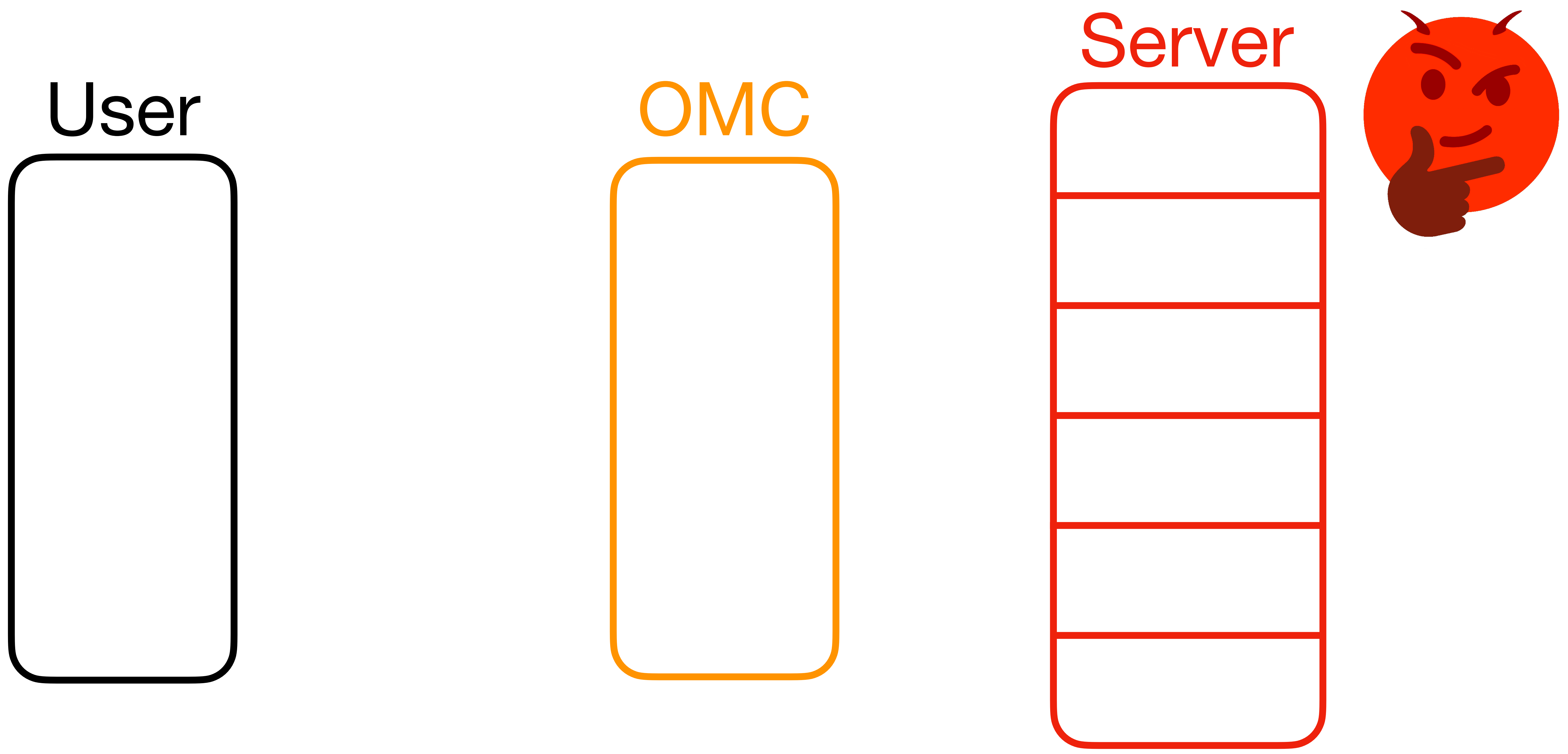

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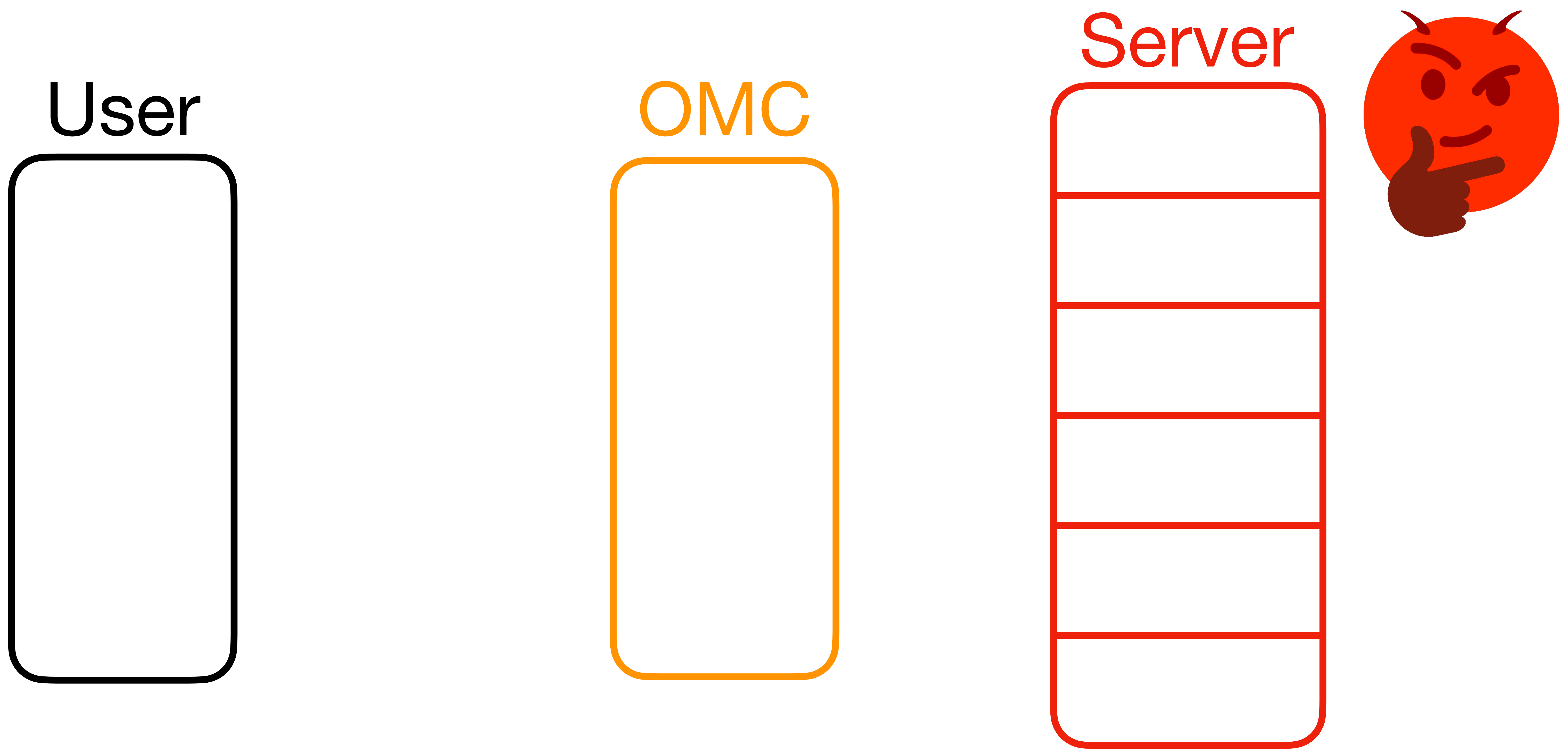

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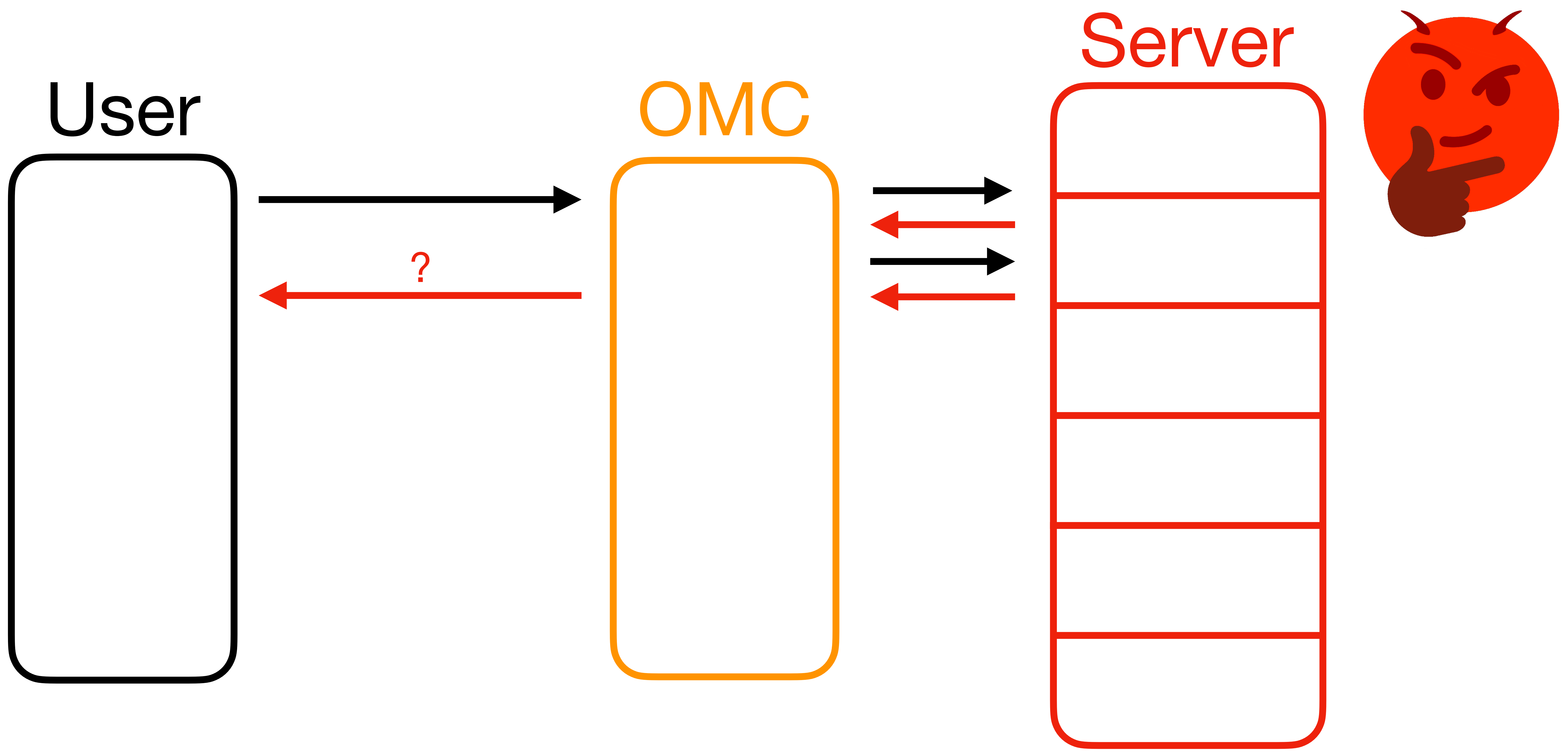

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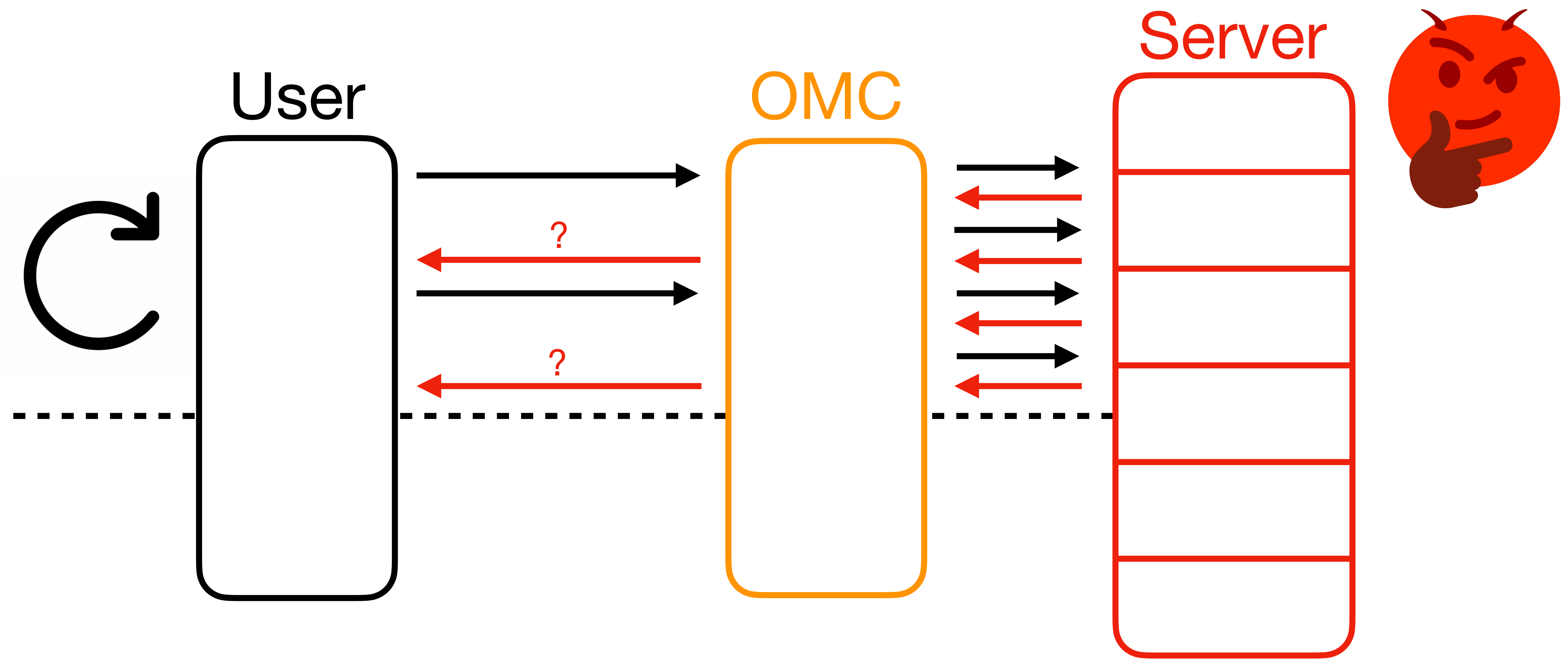

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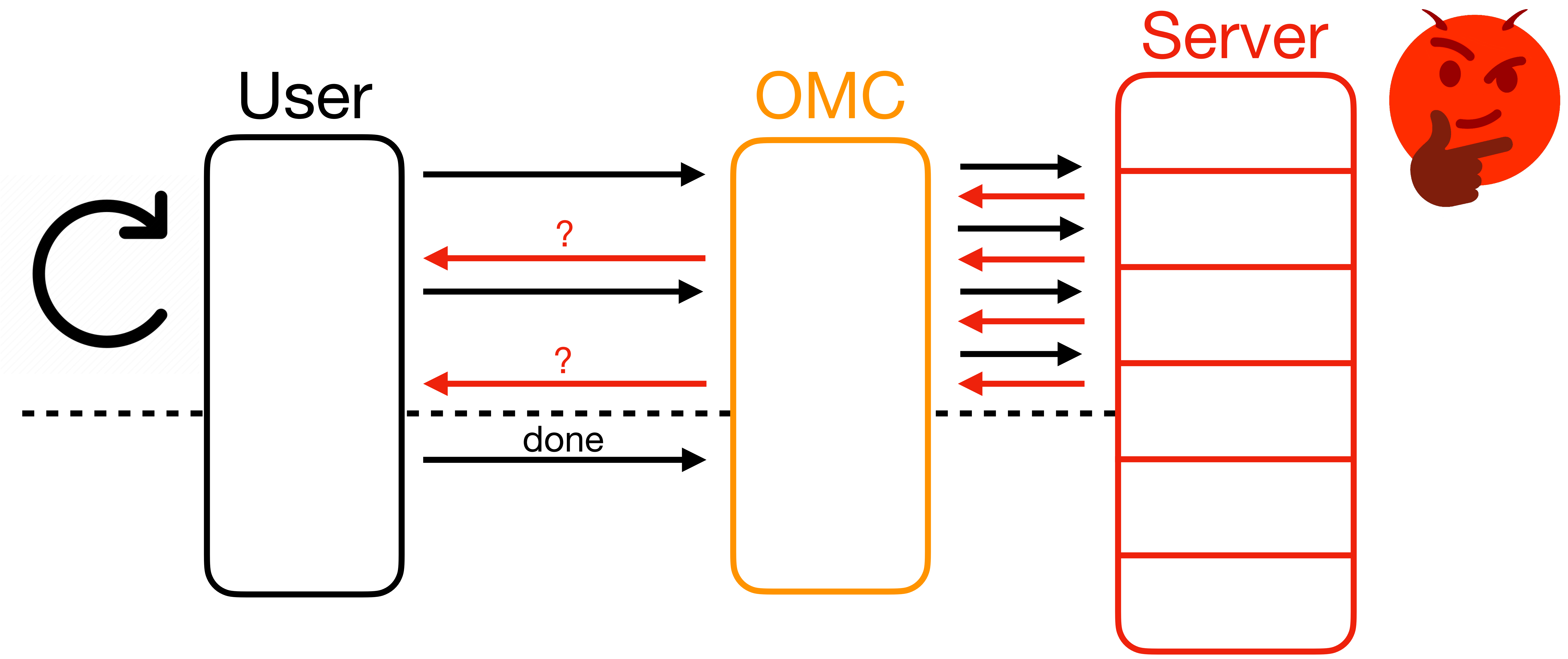

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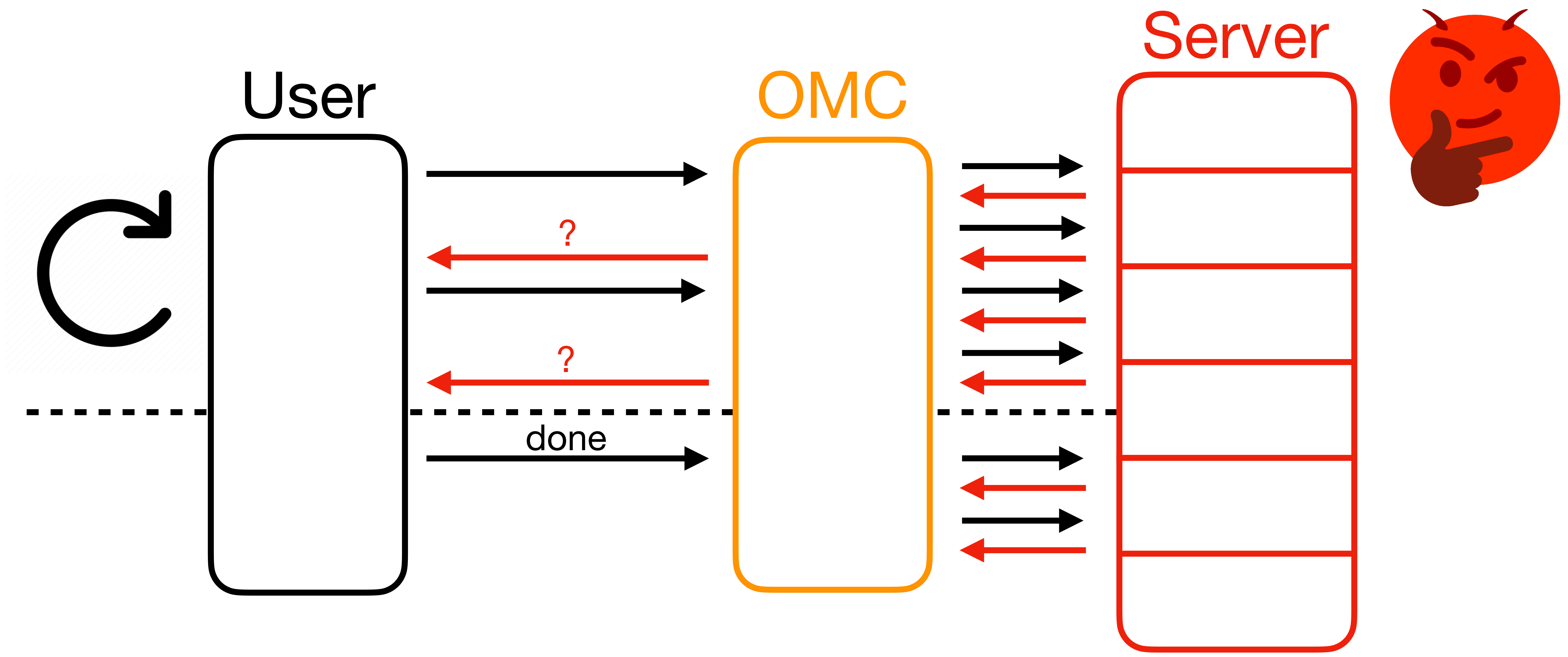

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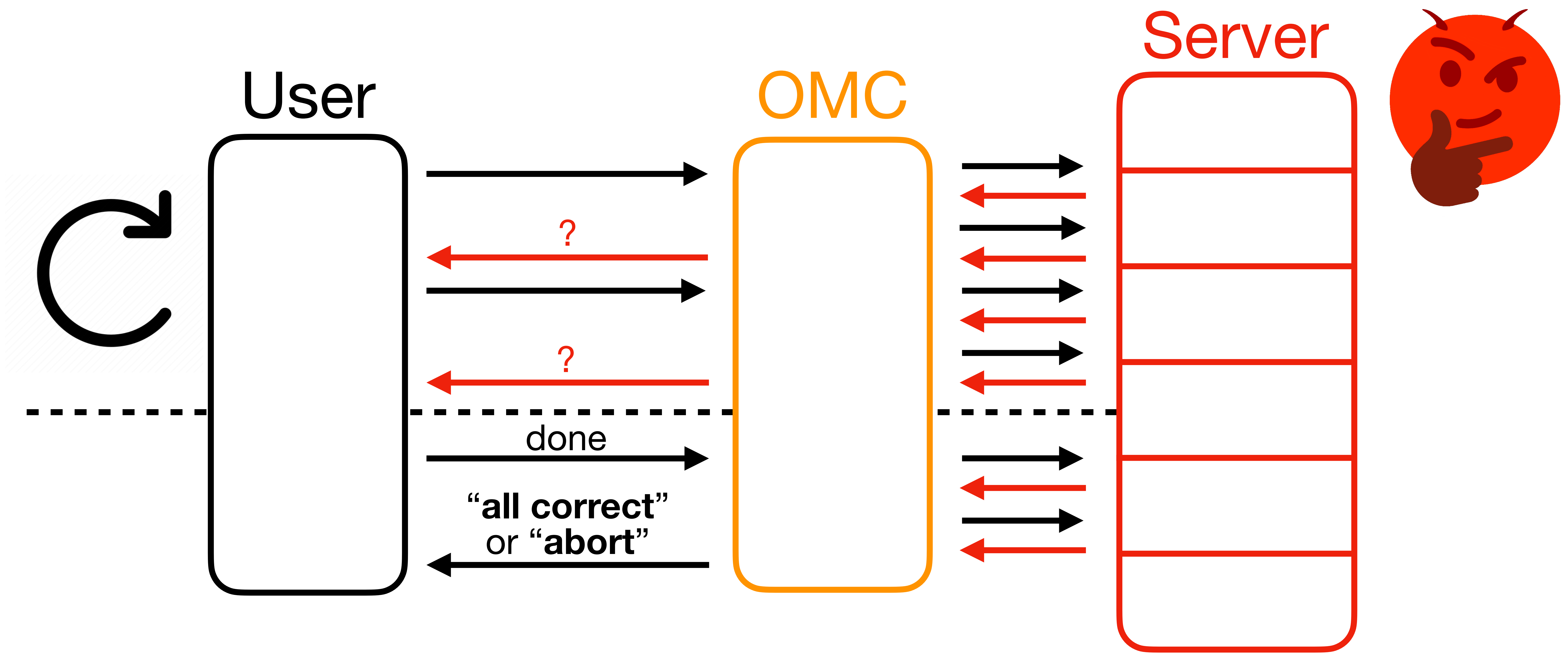

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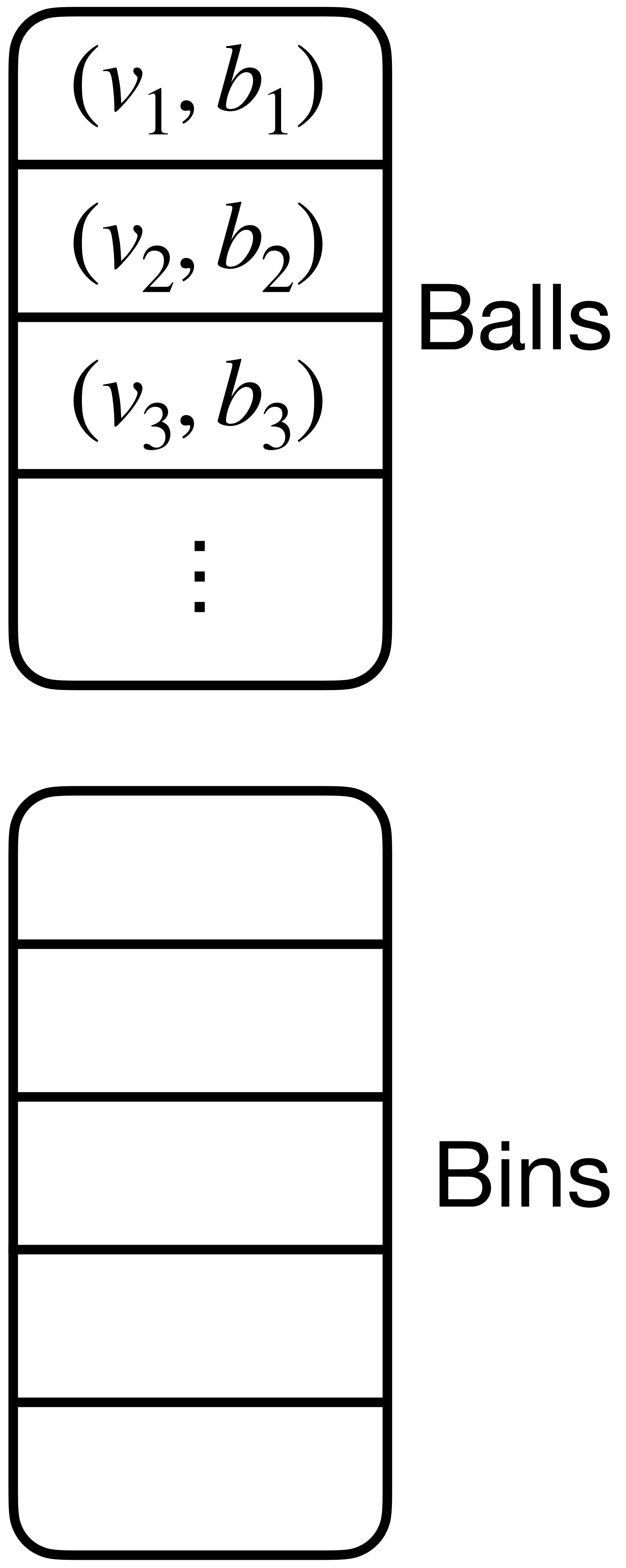

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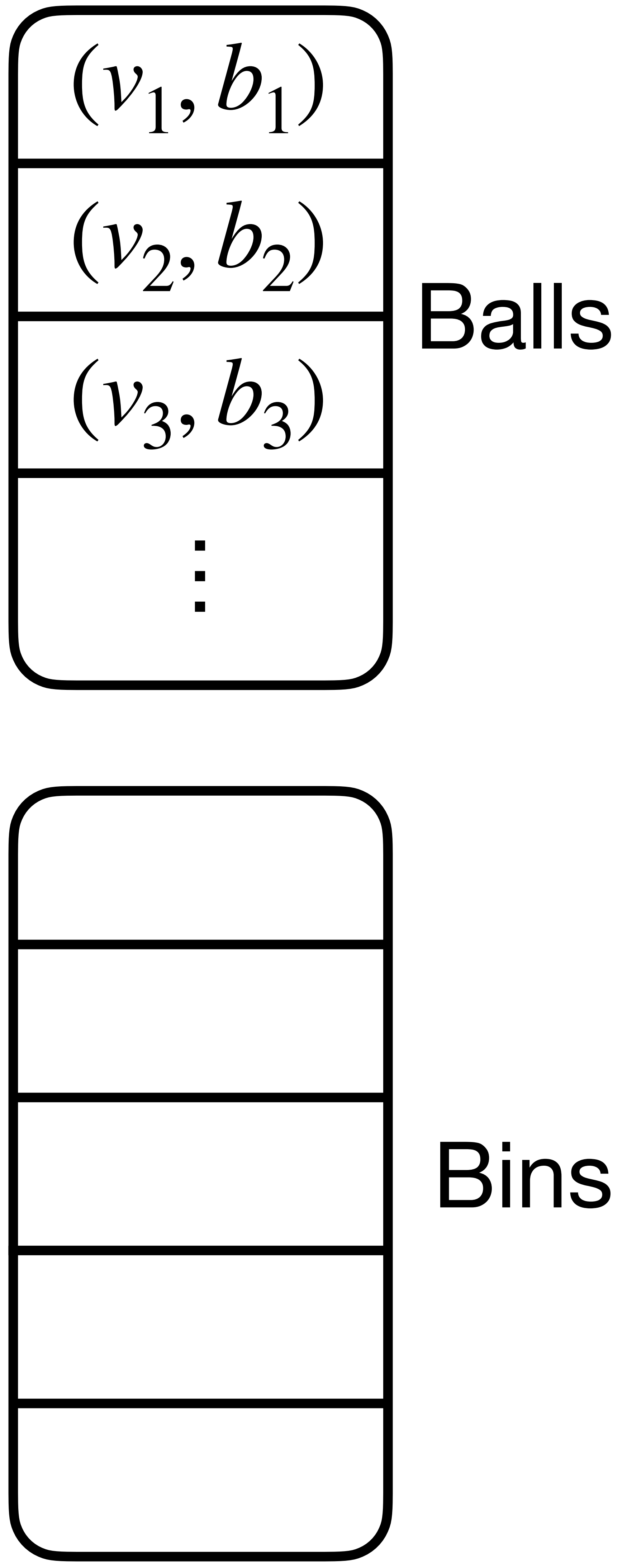

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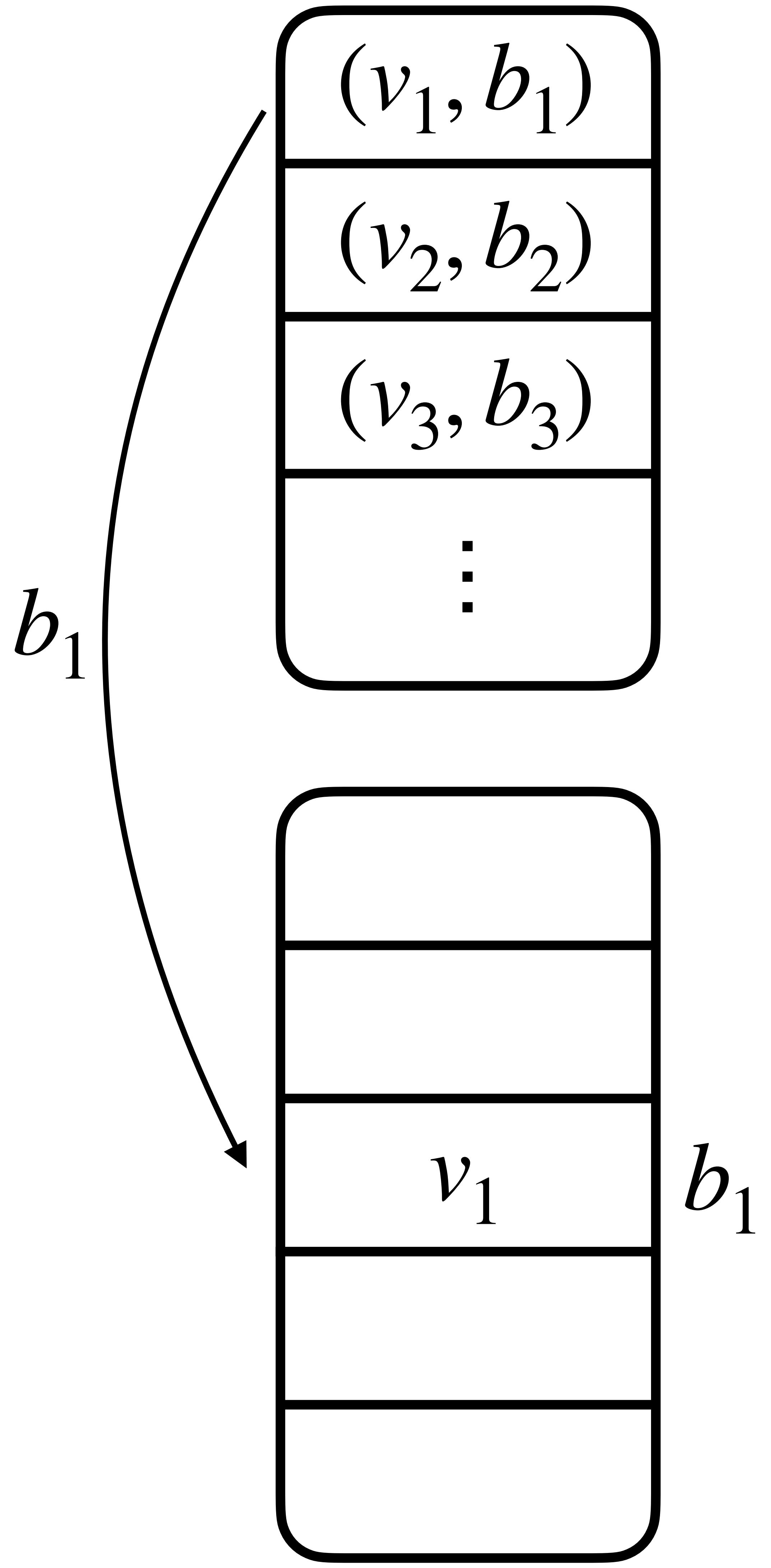

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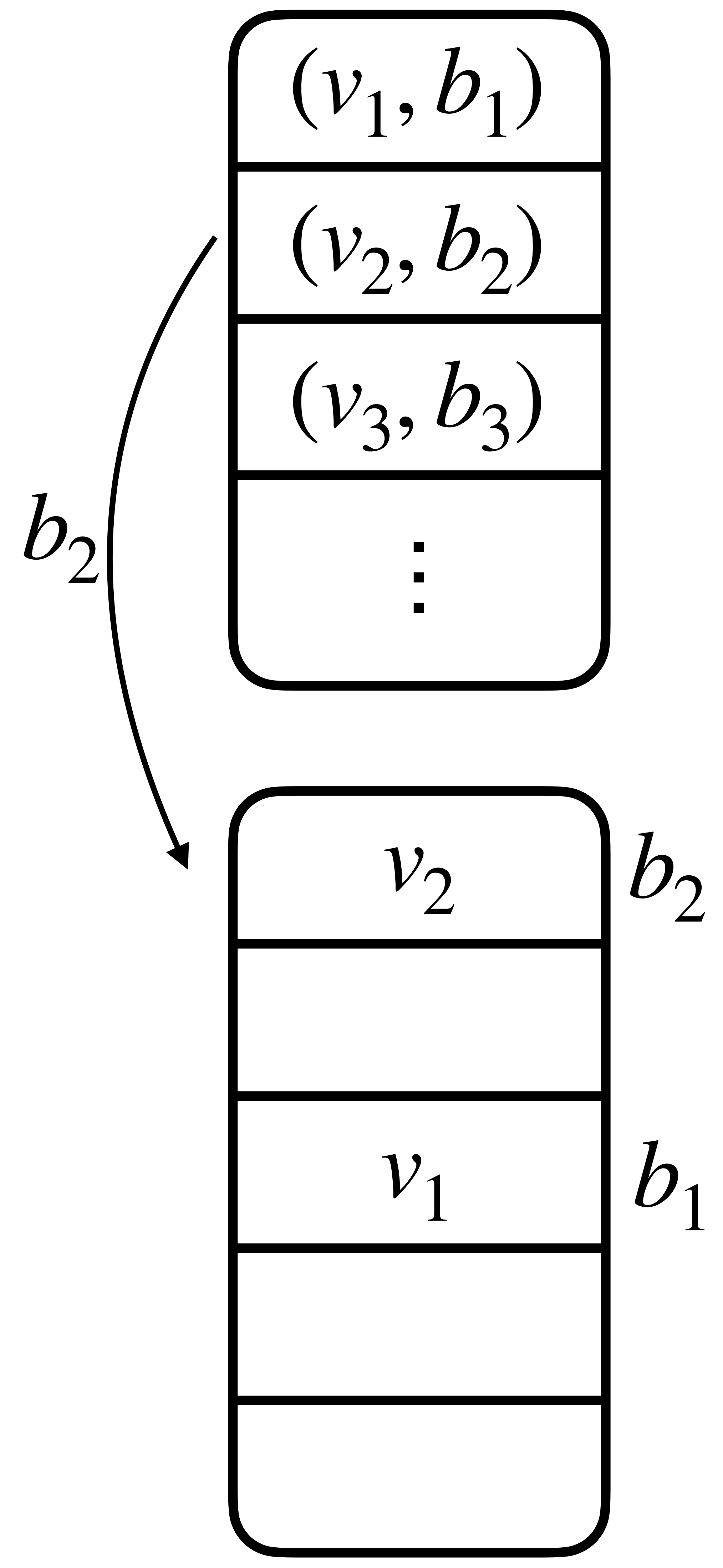

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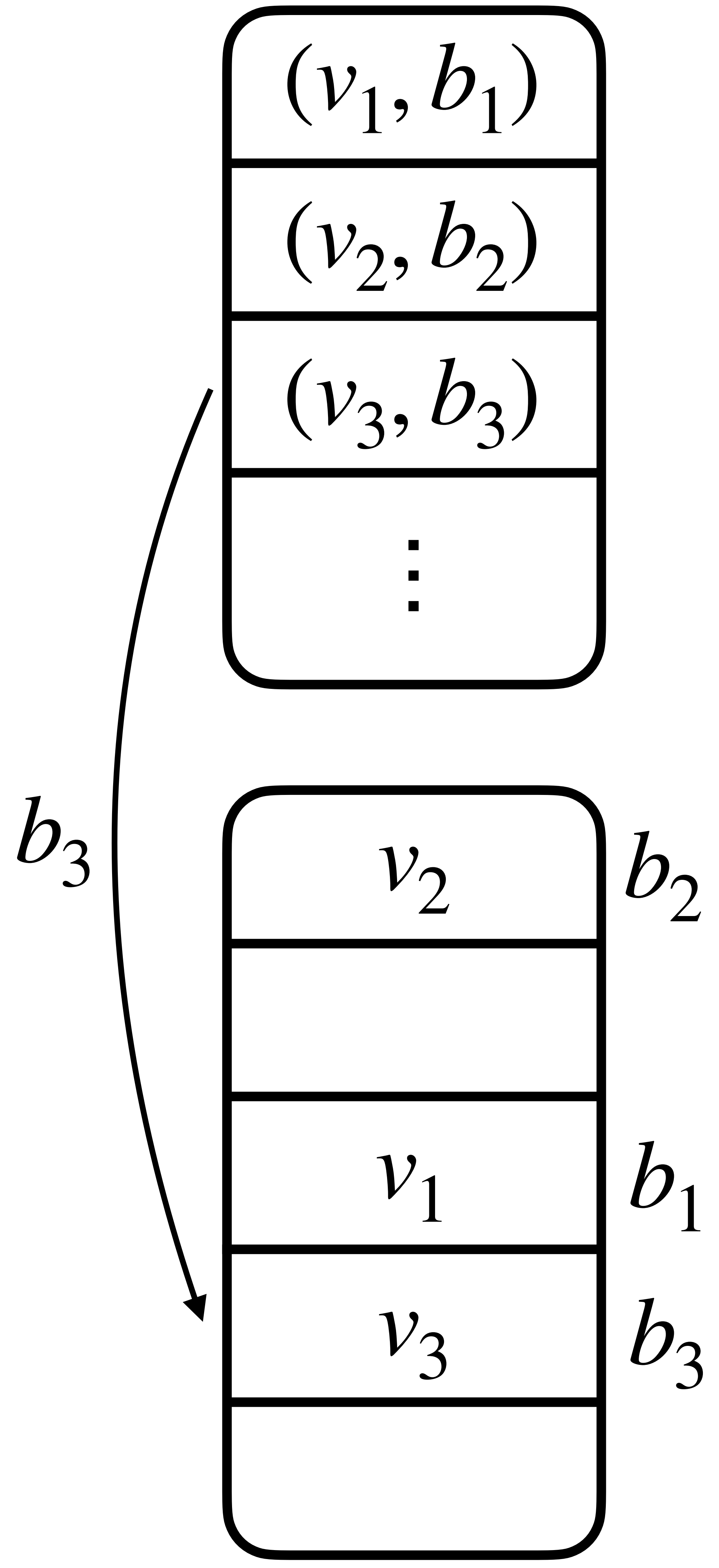

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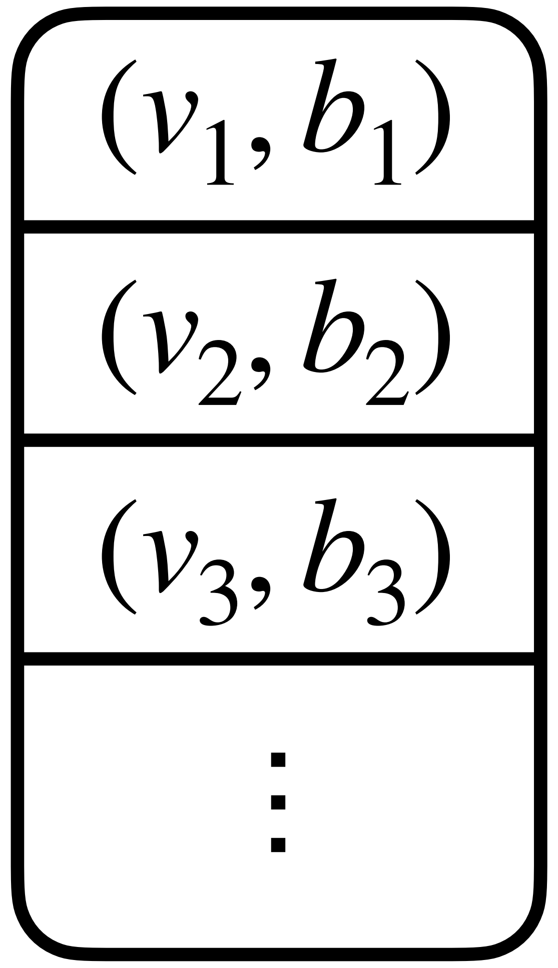

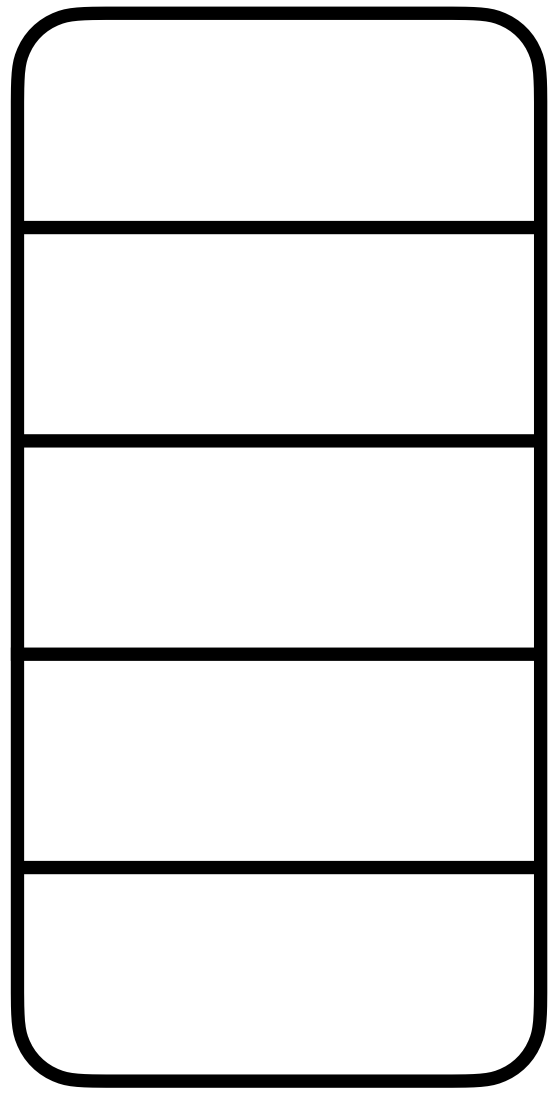

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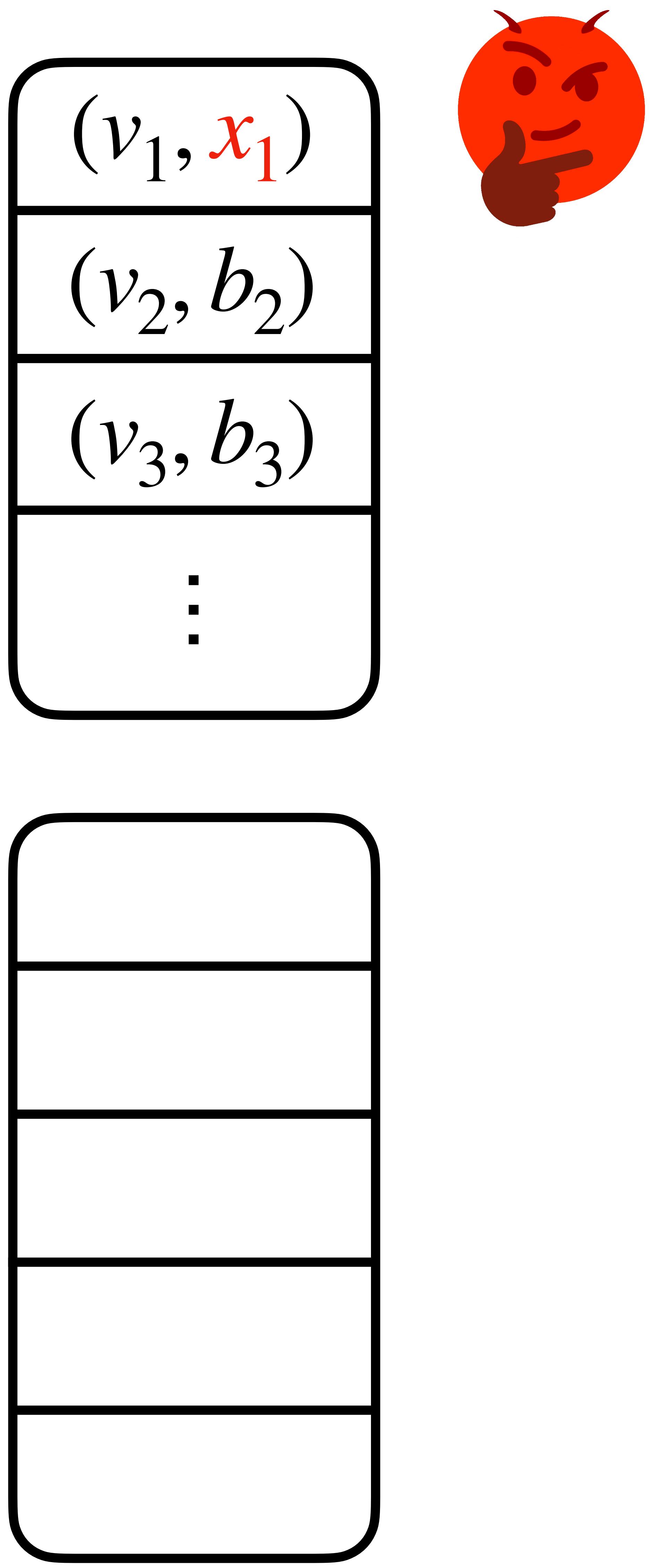

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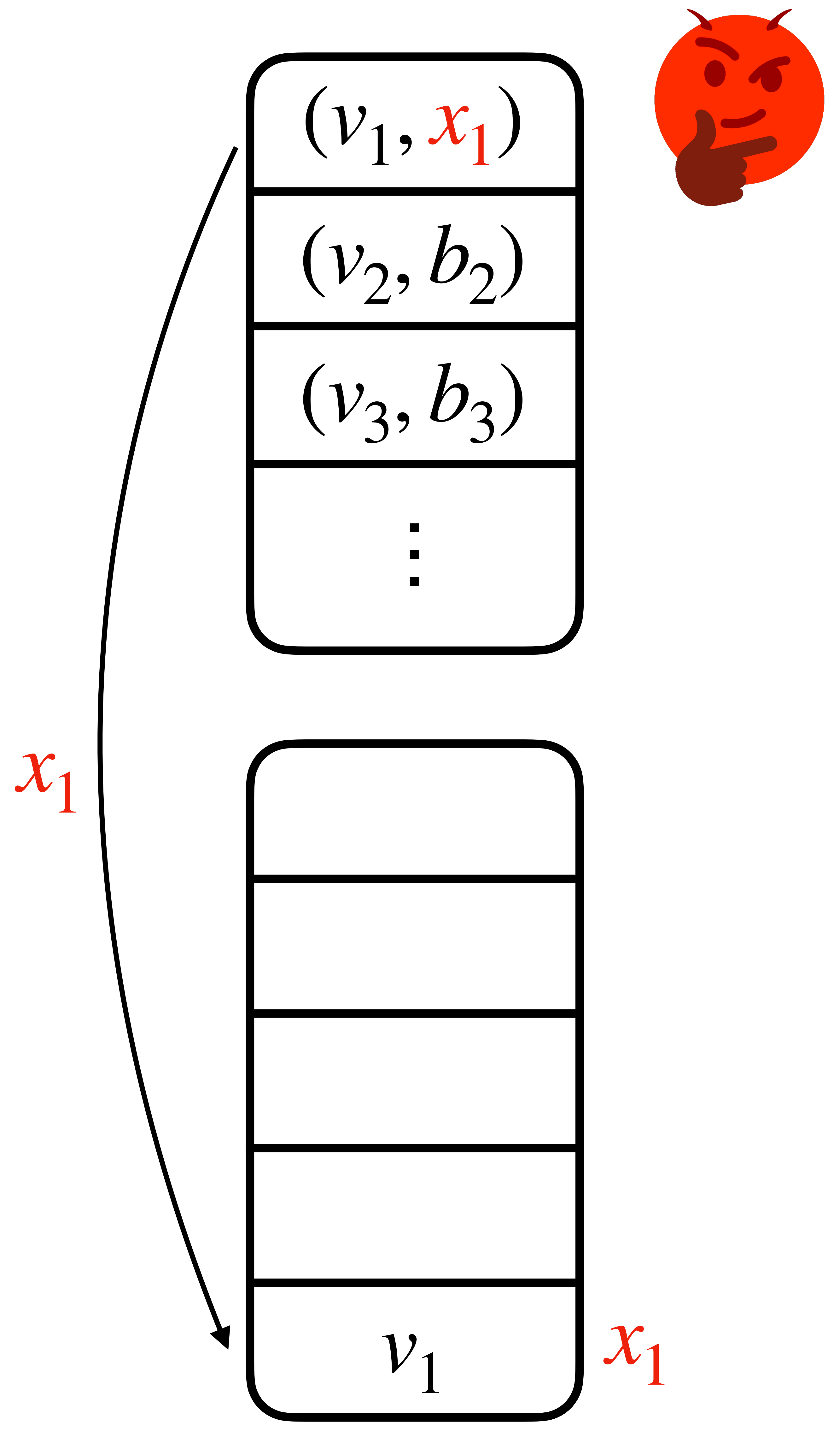

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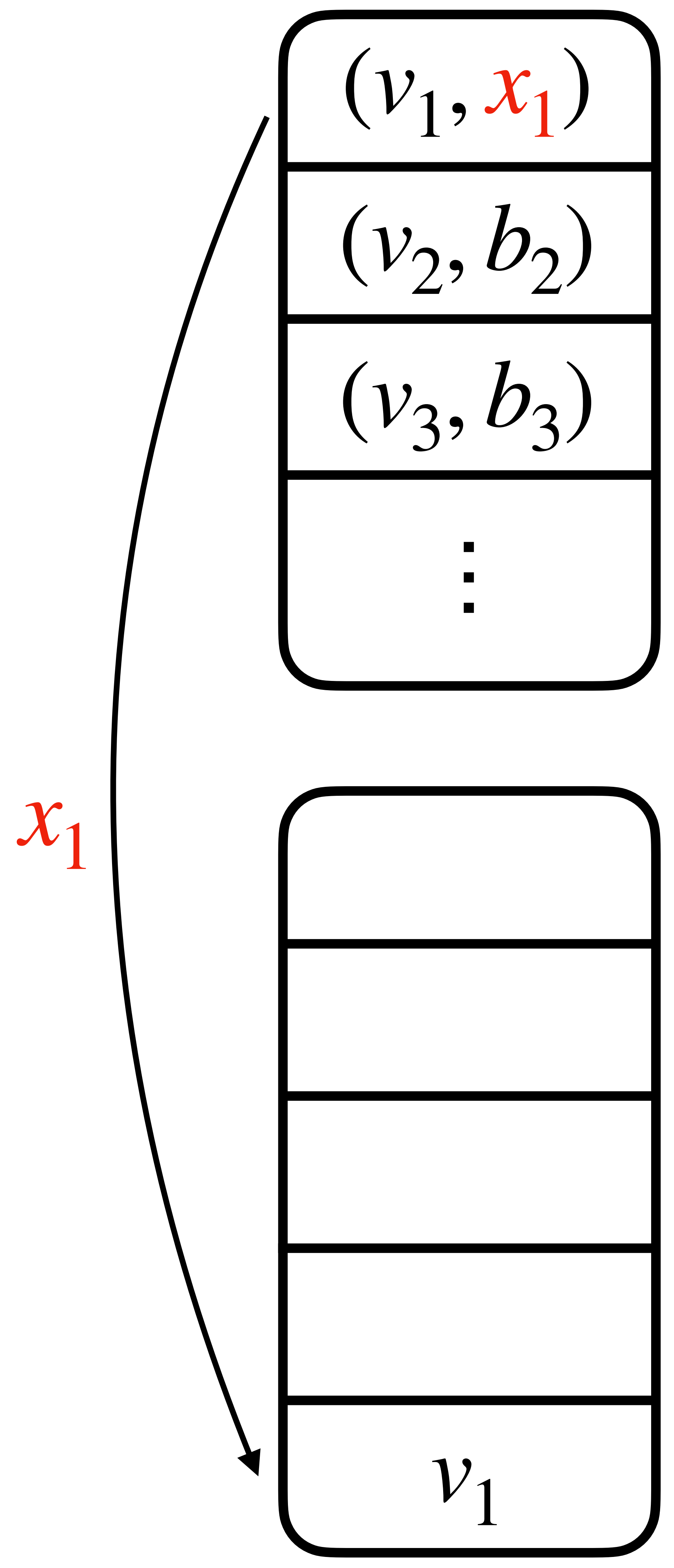
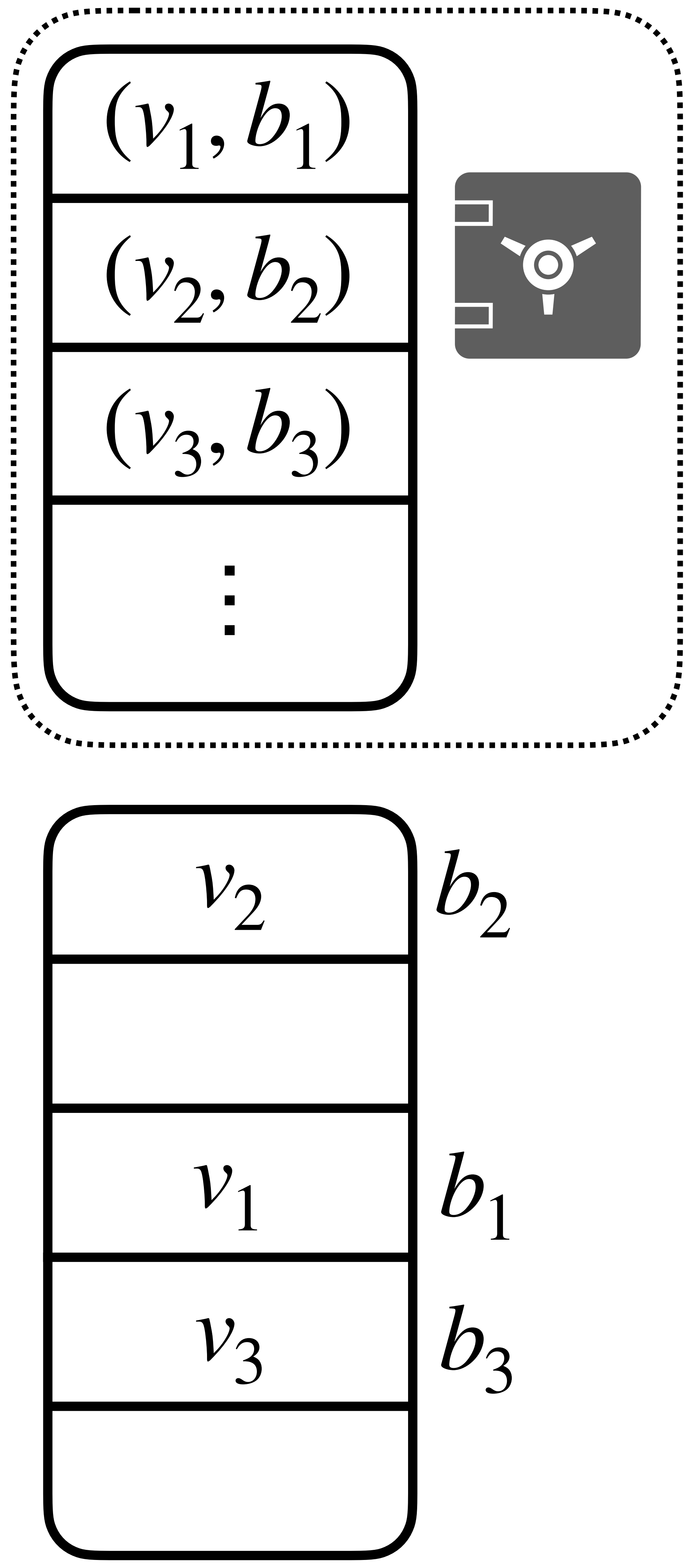


Combining Time-Stamping + Offline Checking



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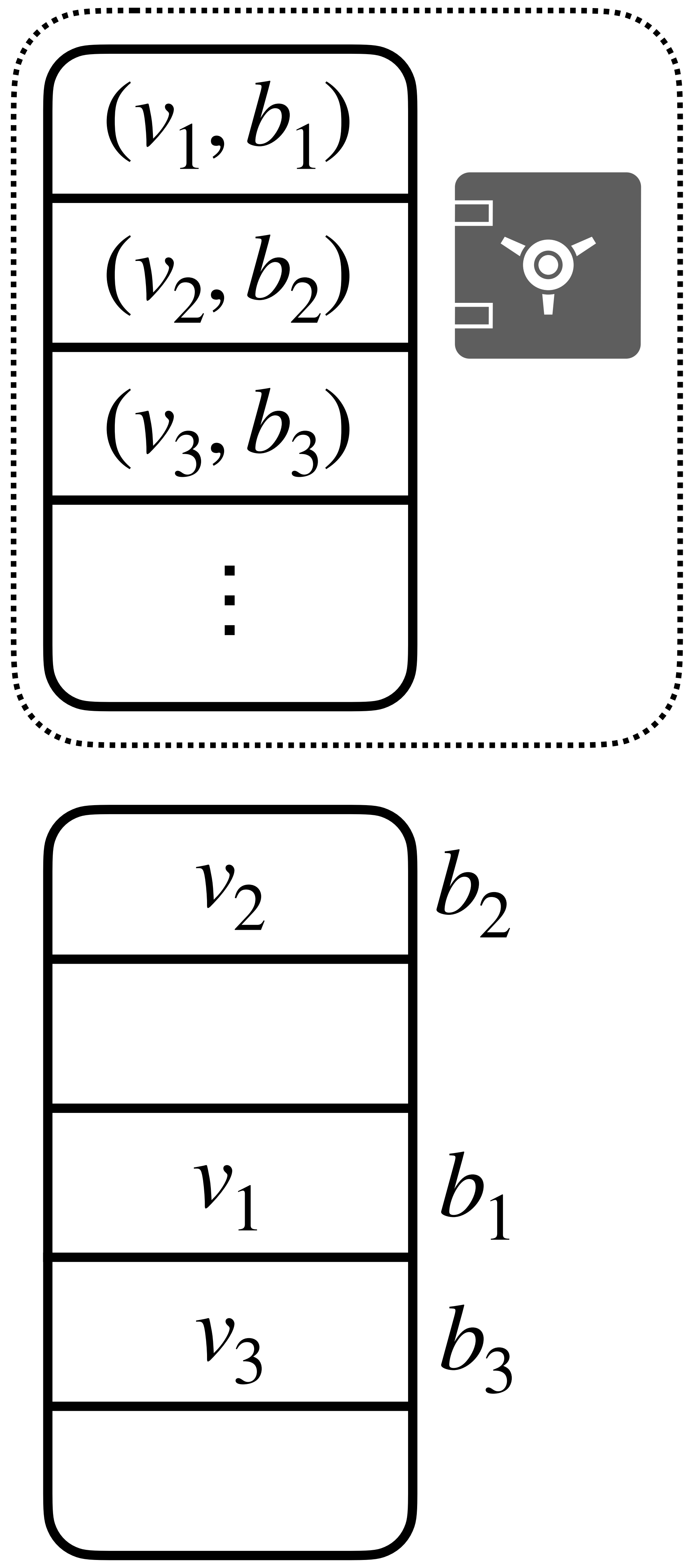

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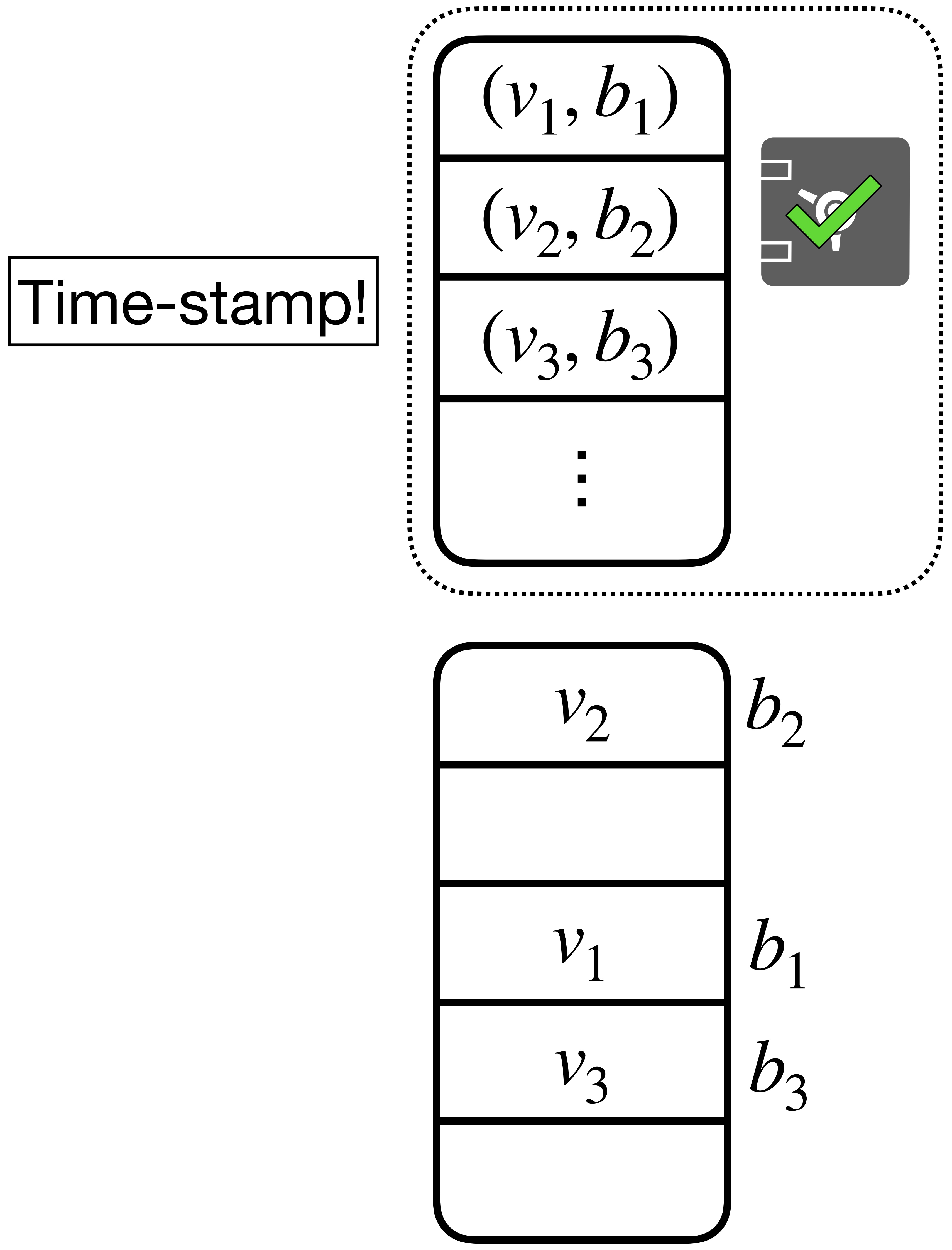

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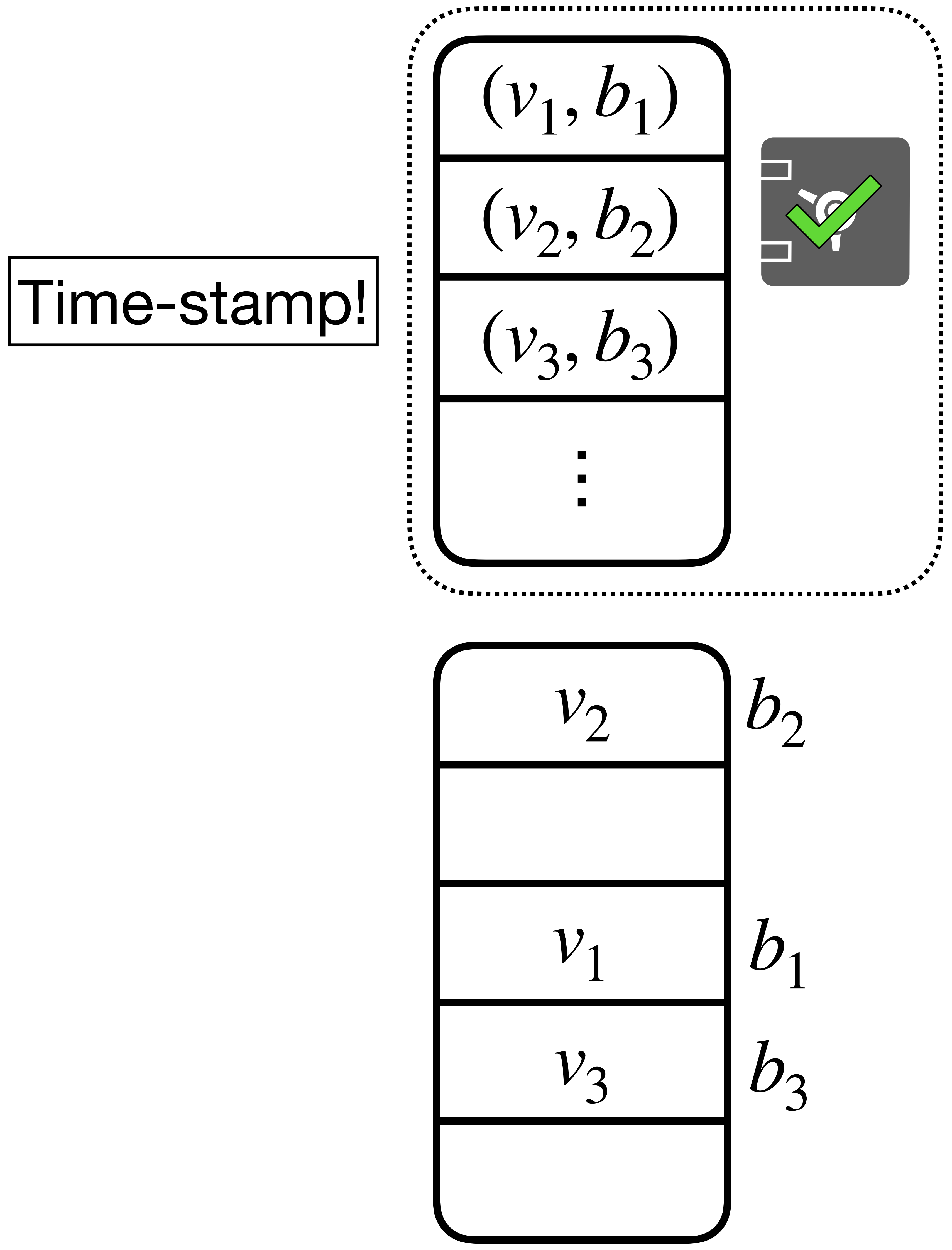

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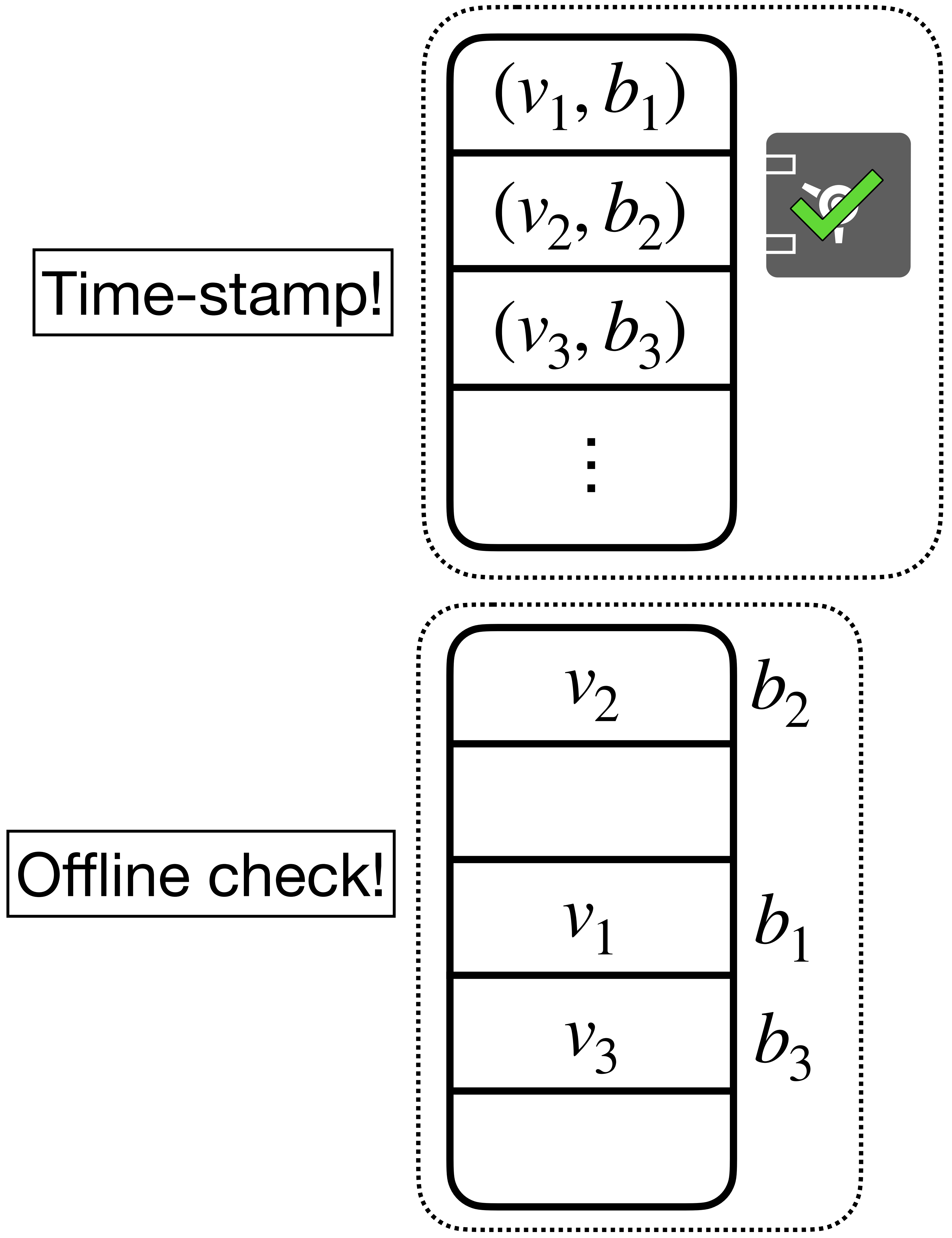

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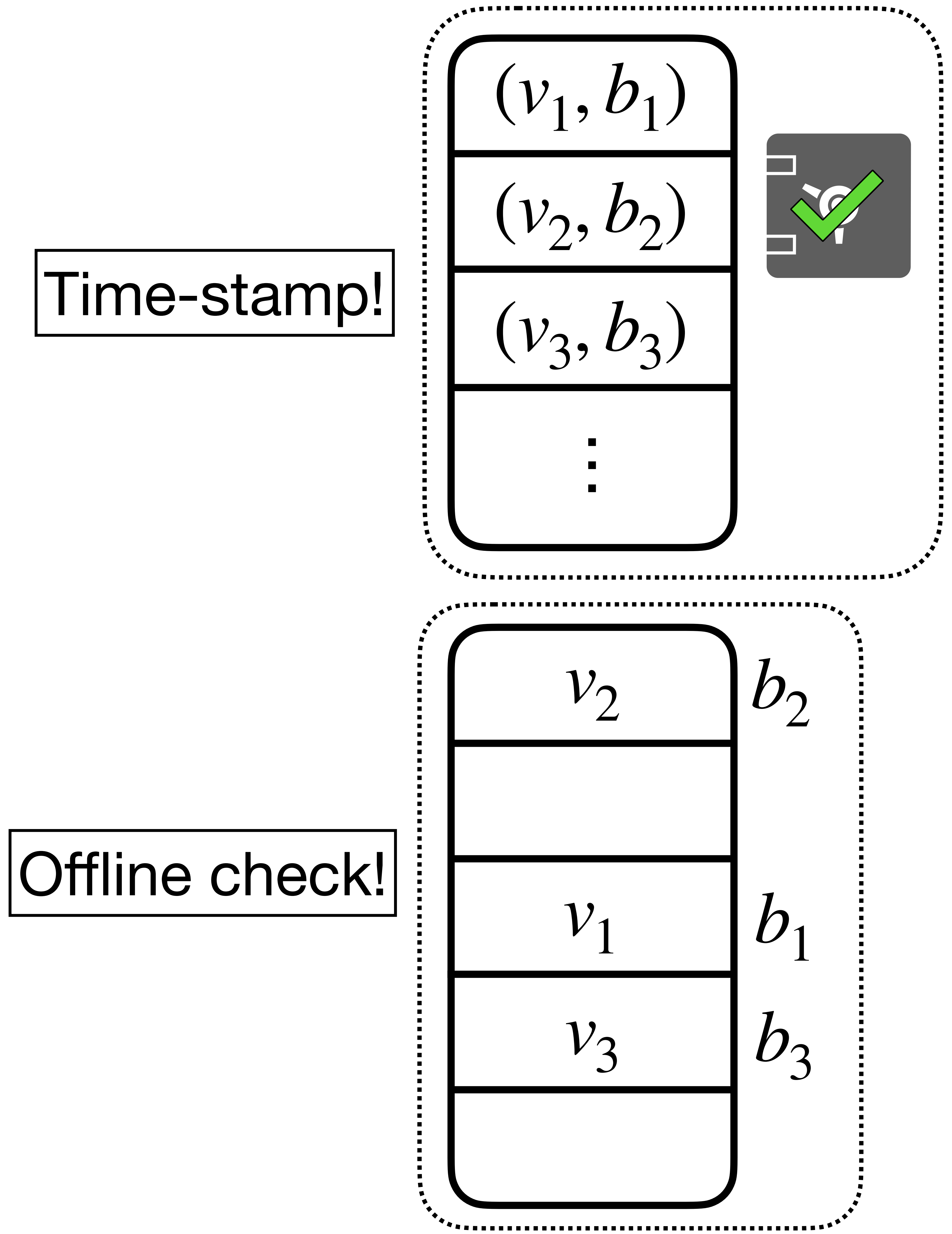

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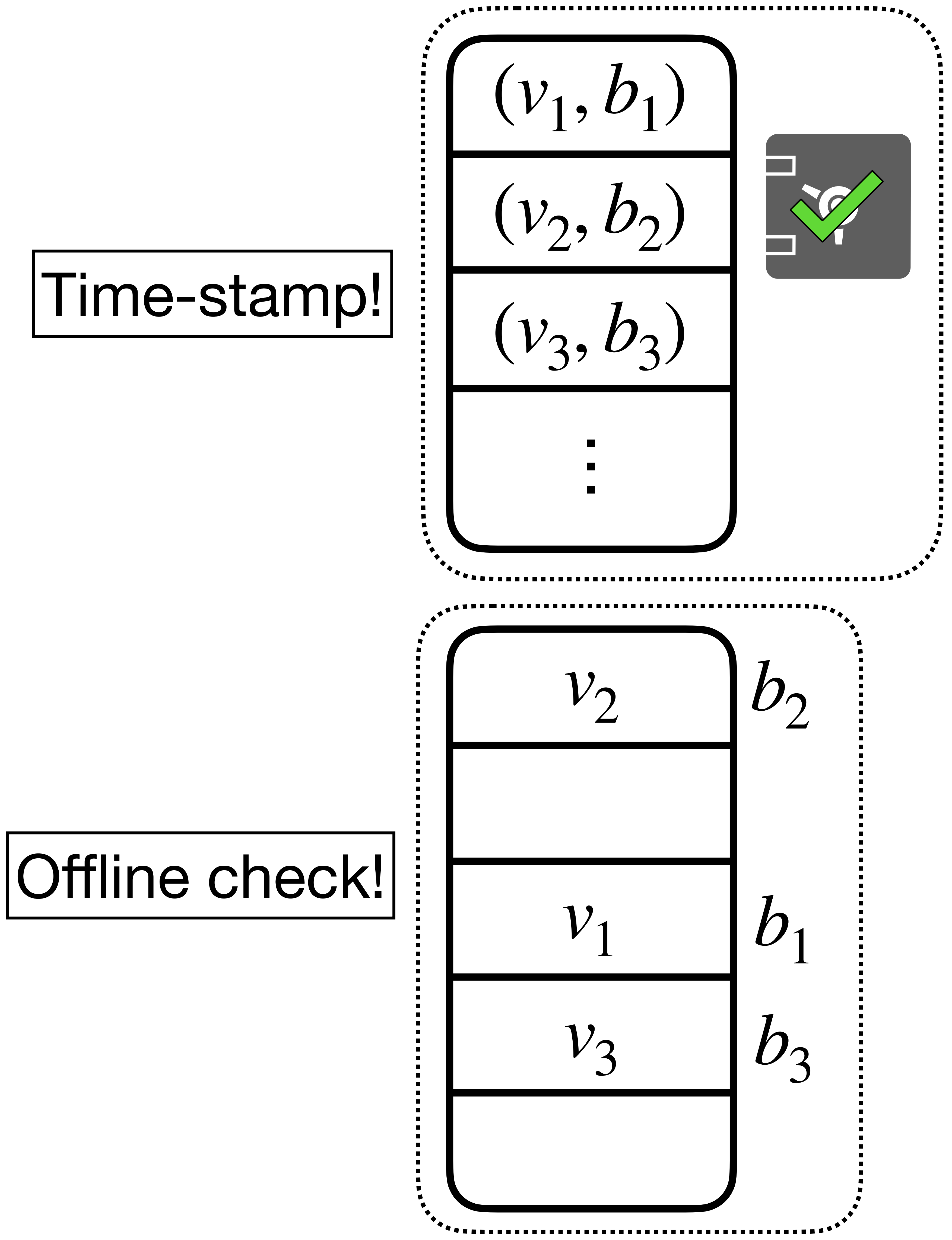

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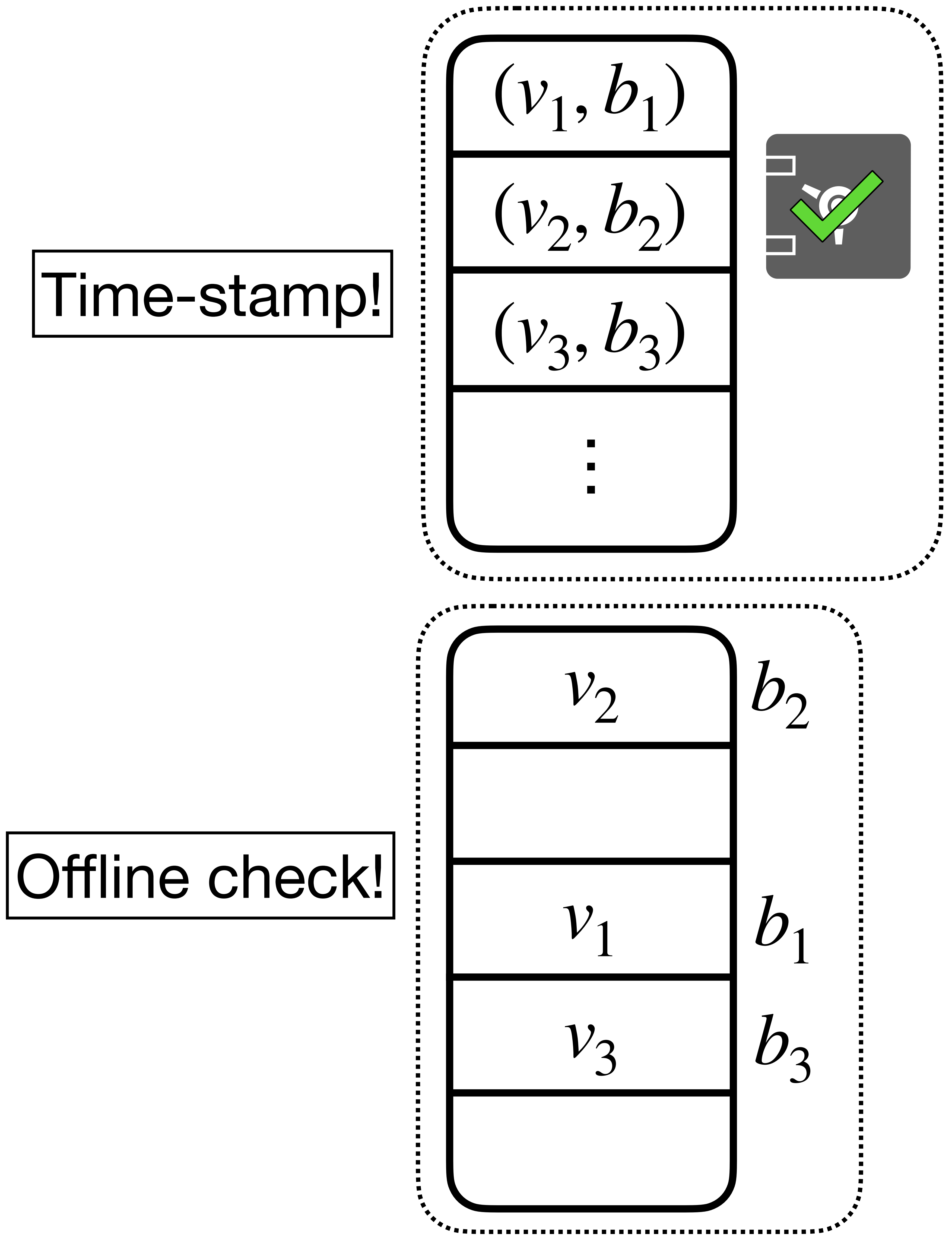

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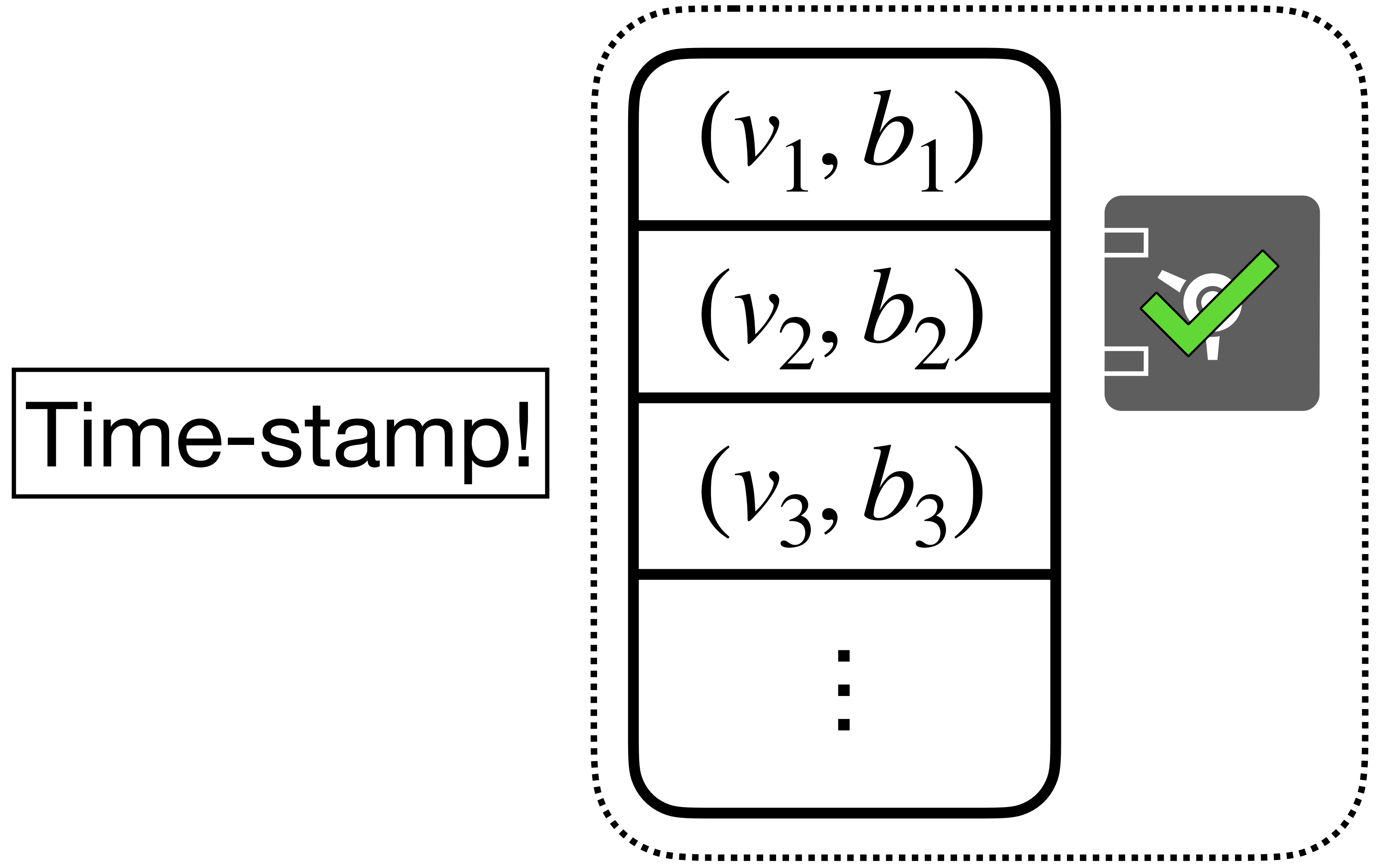
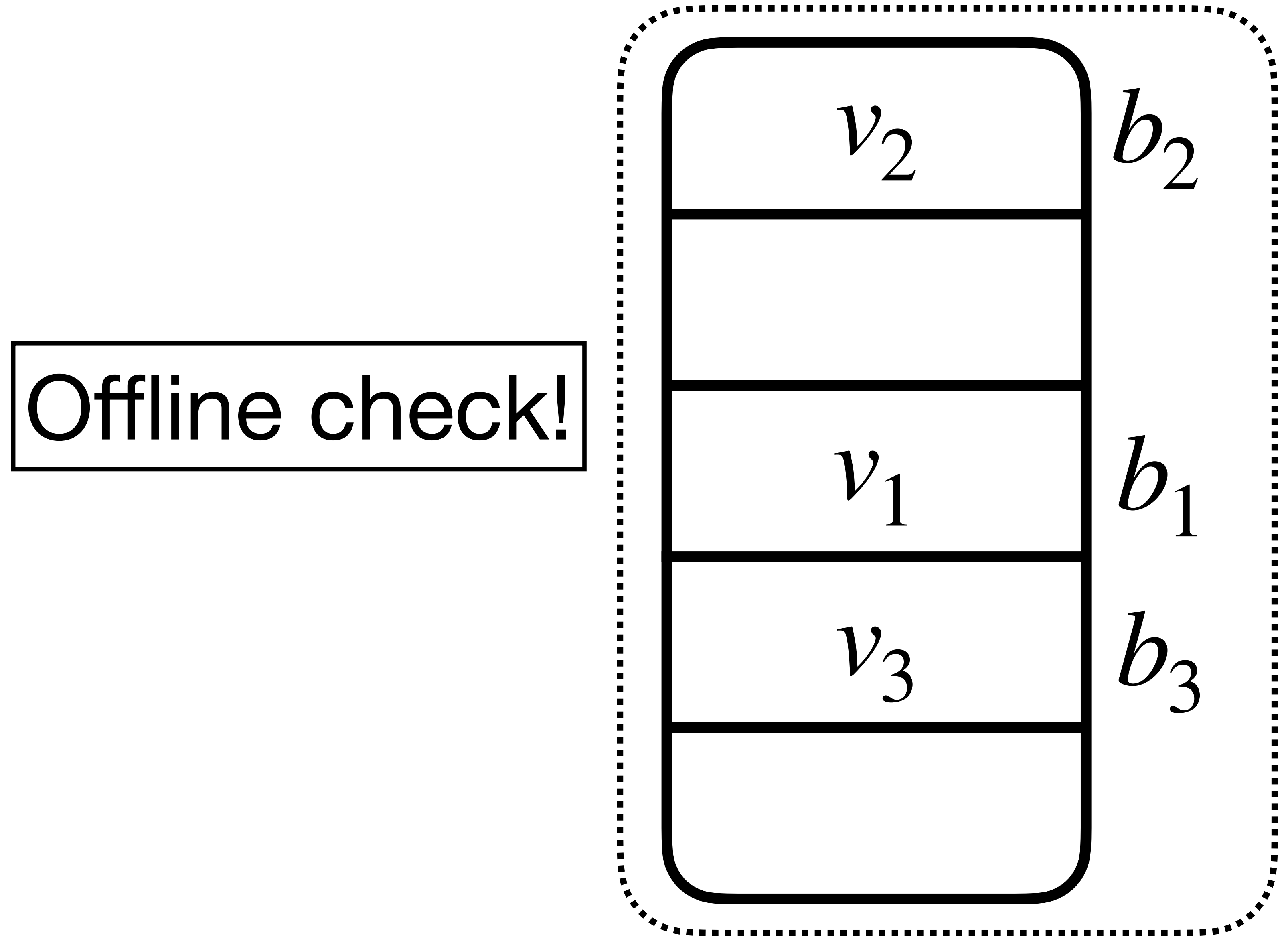
  - Converts **honest-but-curious** to **malicious** security!





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- 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!