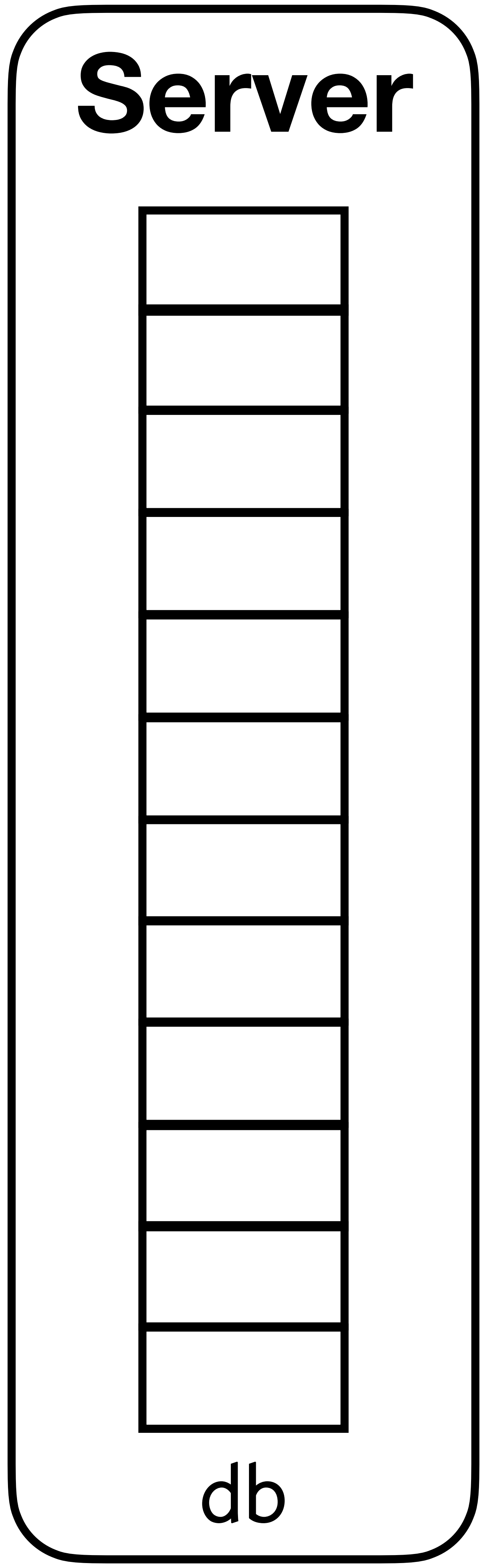
Maliciously-secure PIR (almost) for free

Brett Falk | ***Pratyush Mishra*** | **Matan Shtepel**

UPenn | UPenn | CMU

Private Information Retrieval (PIR) [CKSG95, KO97]



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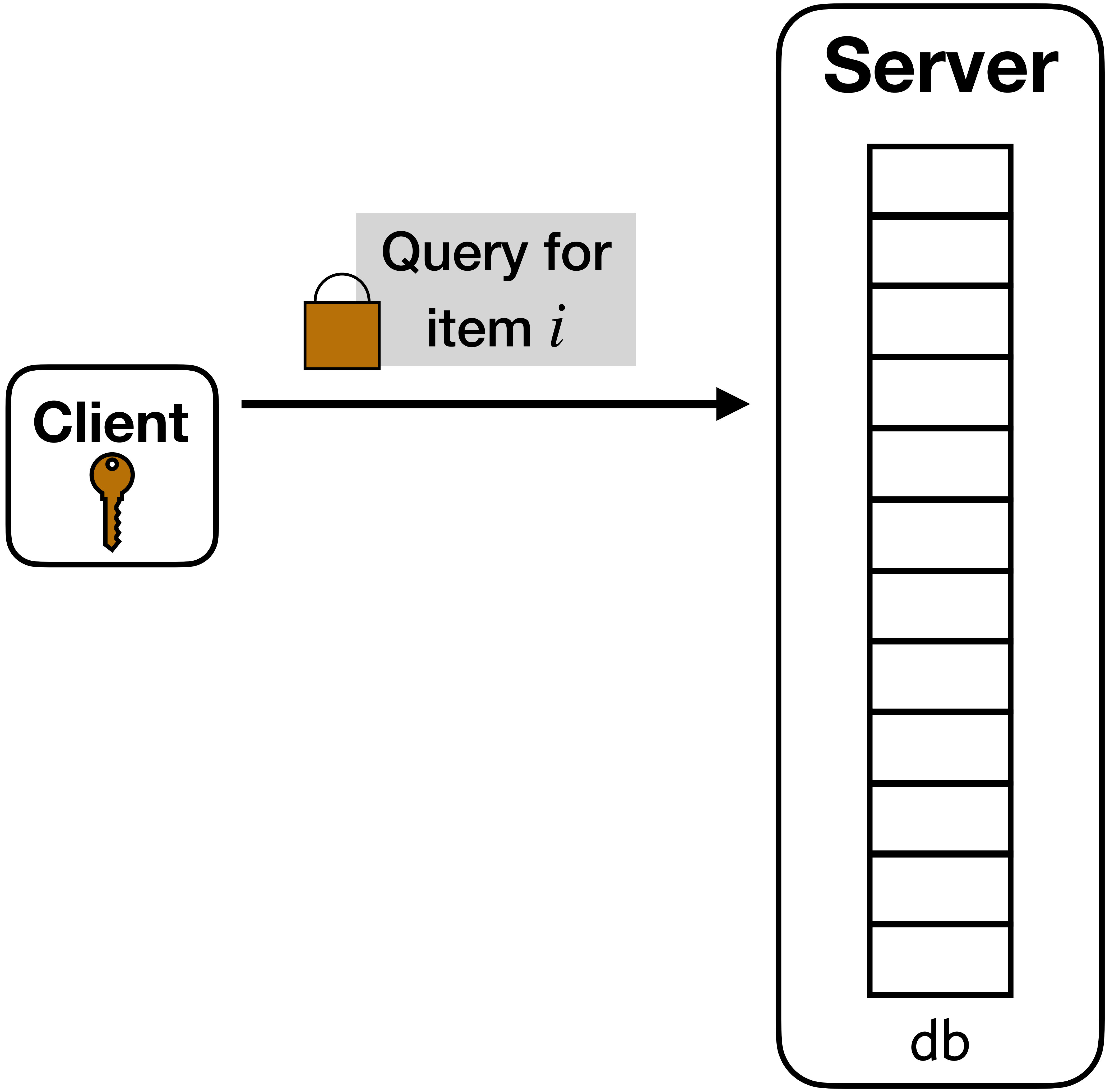

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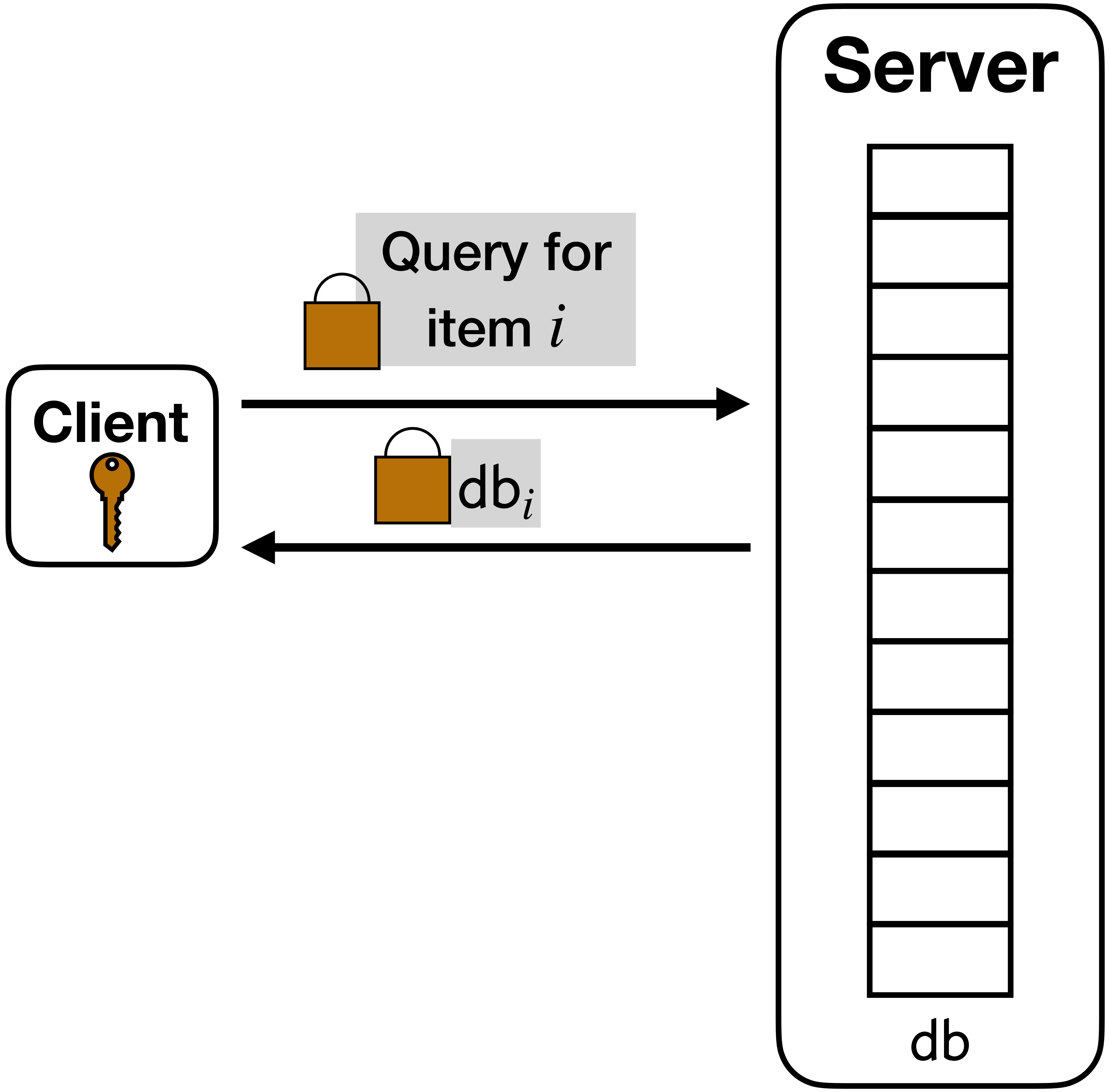

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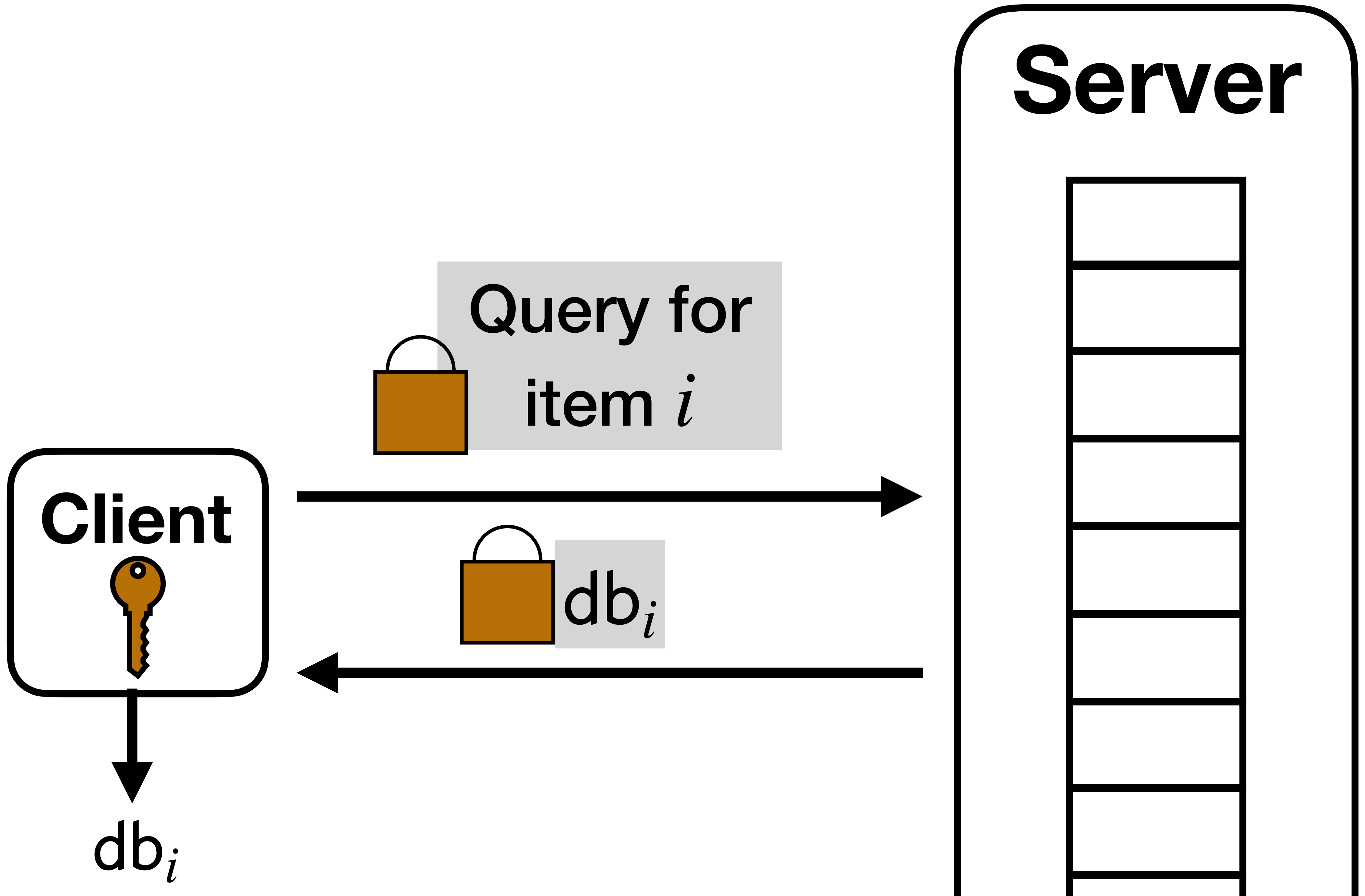

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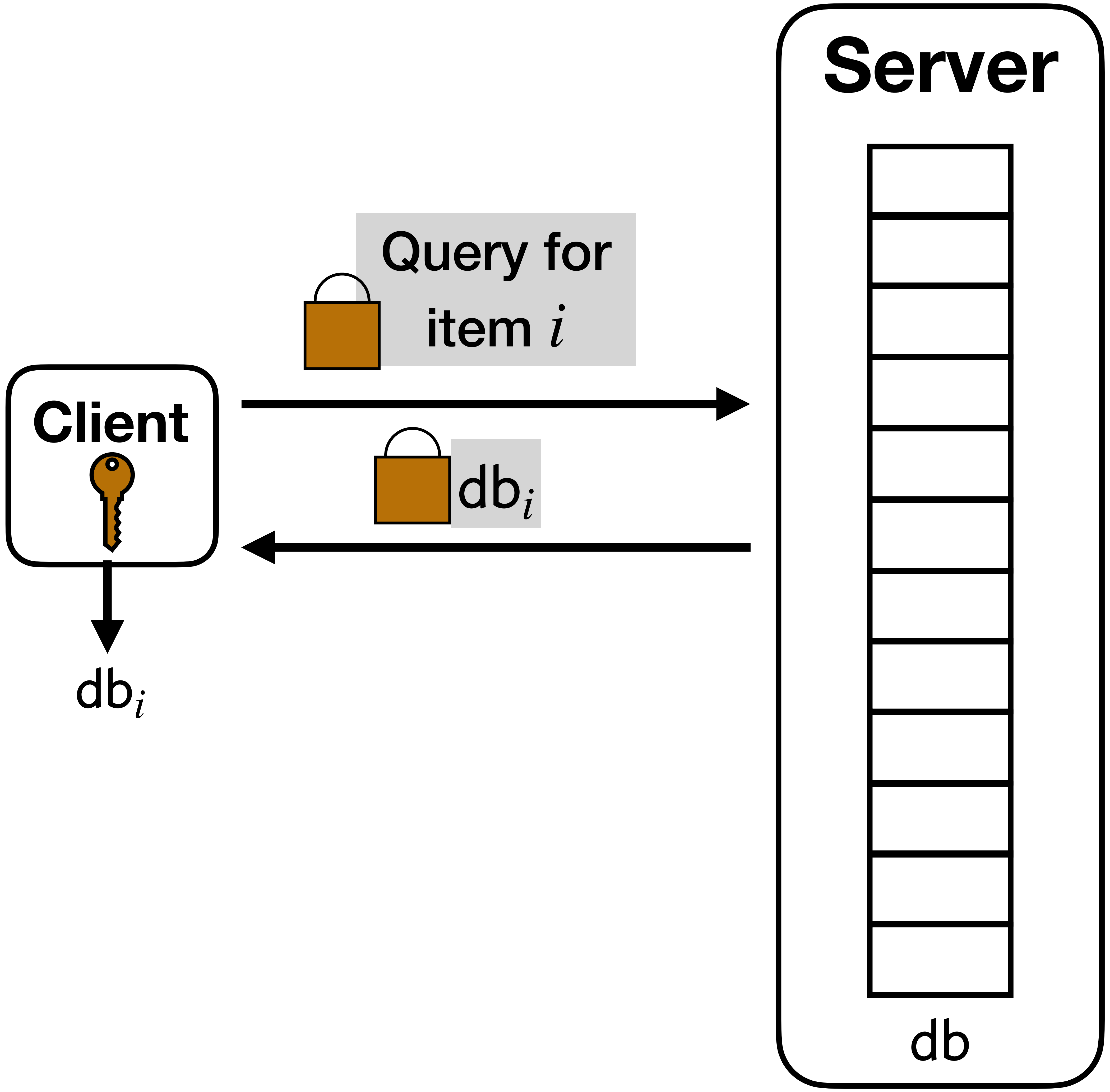

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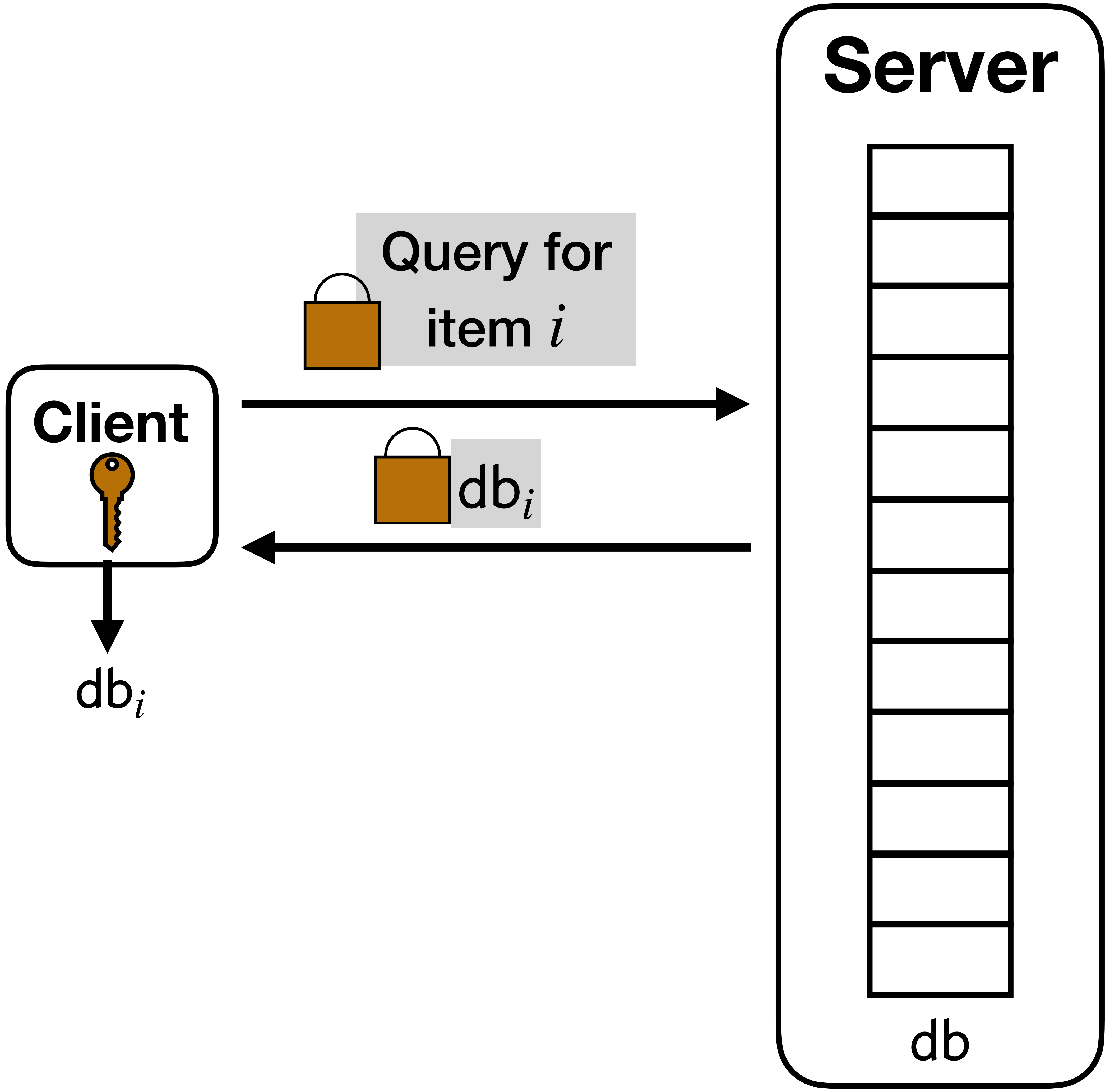

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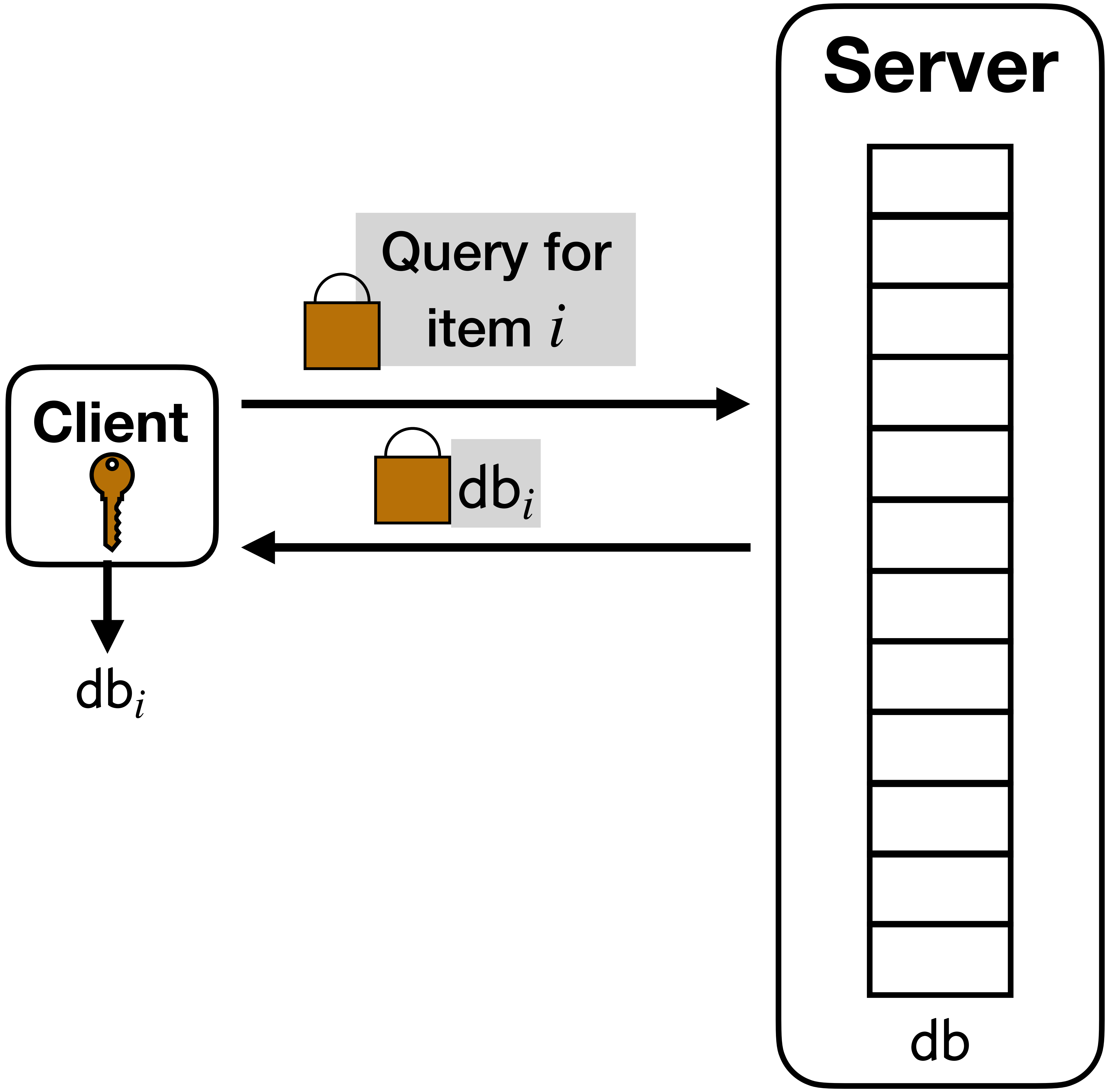

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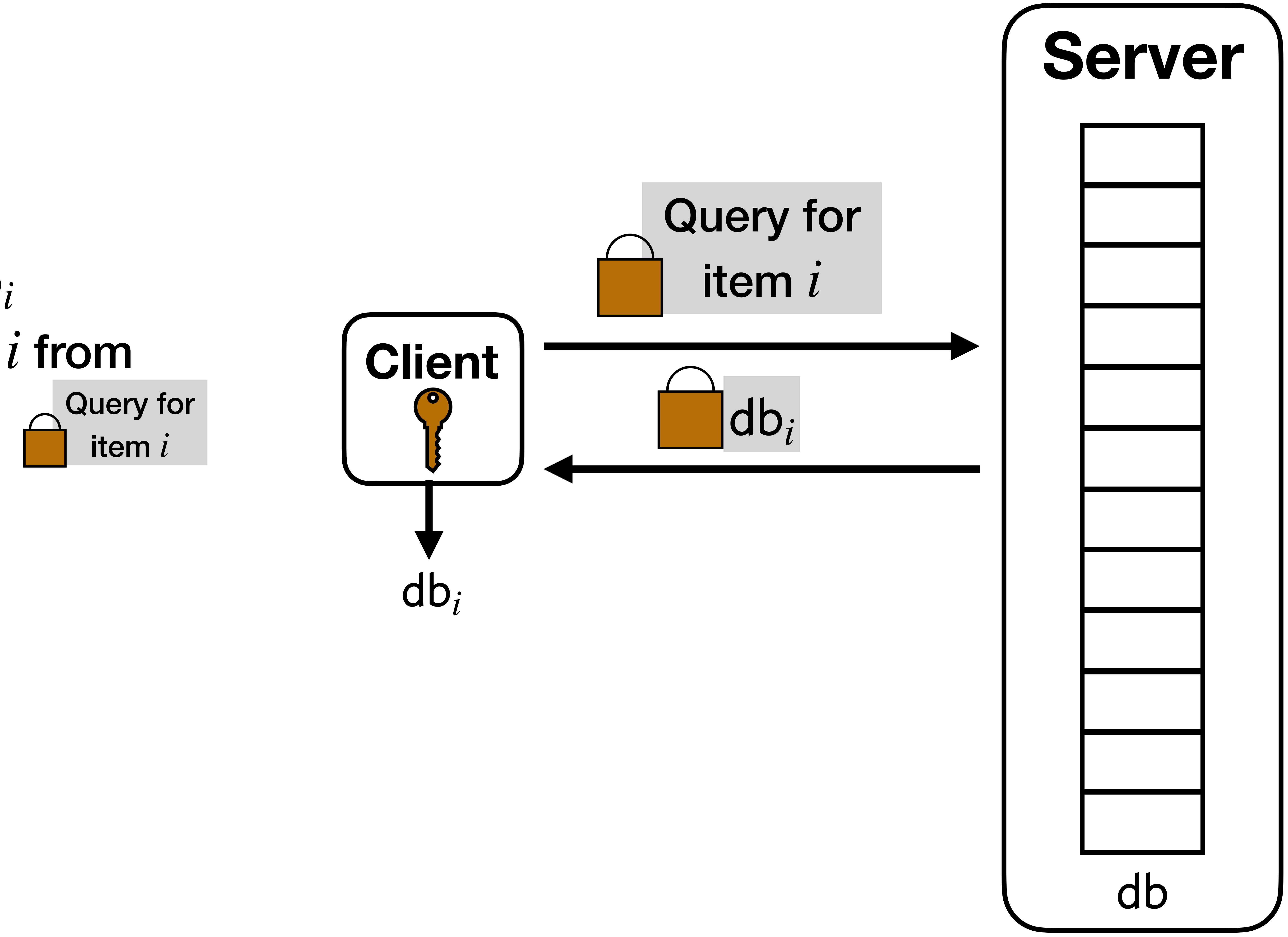

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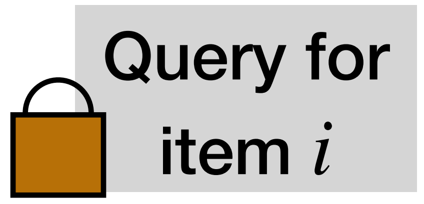
2. Privacy: server does not learn i from 

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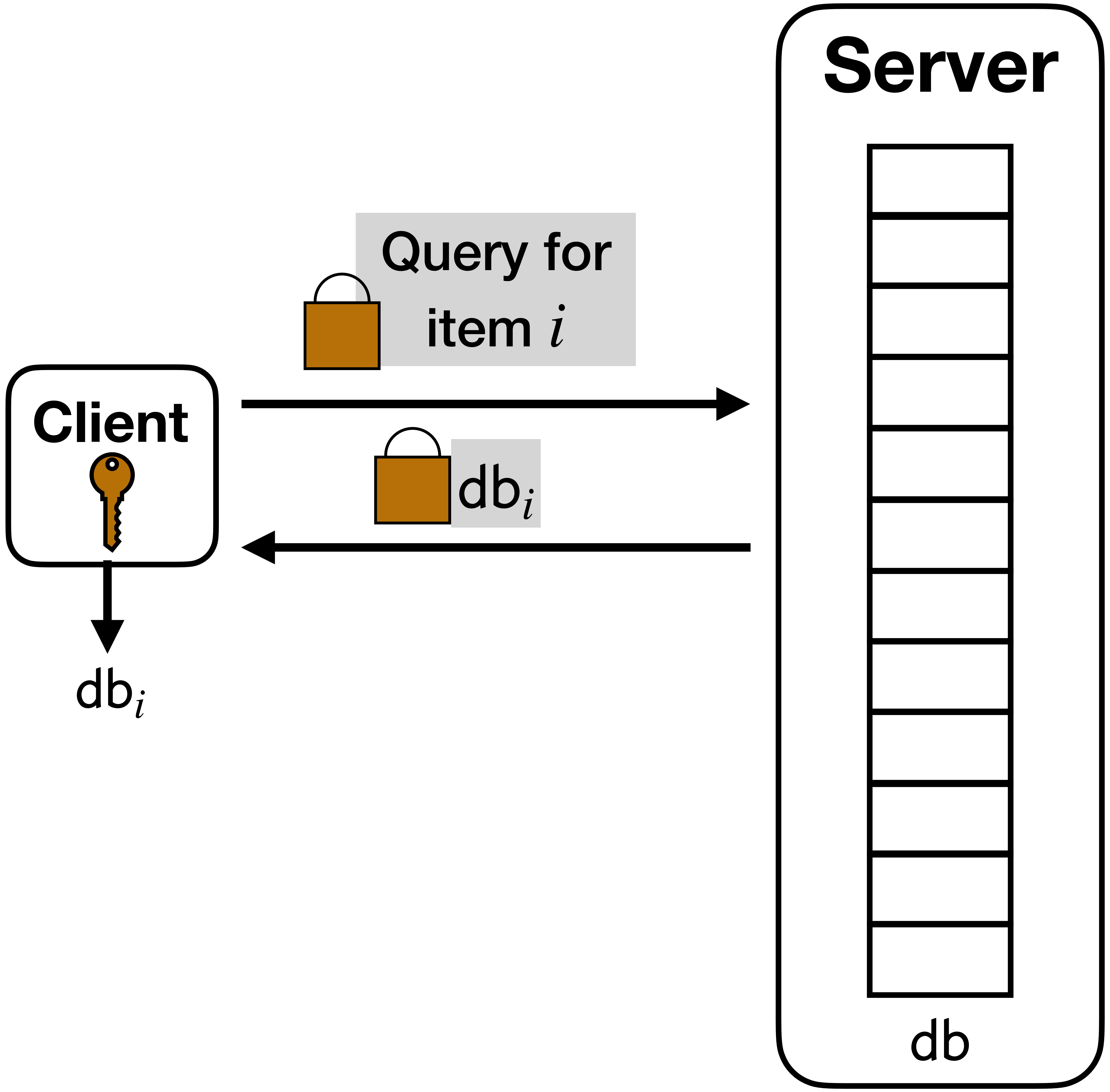

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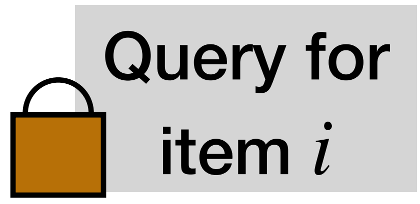

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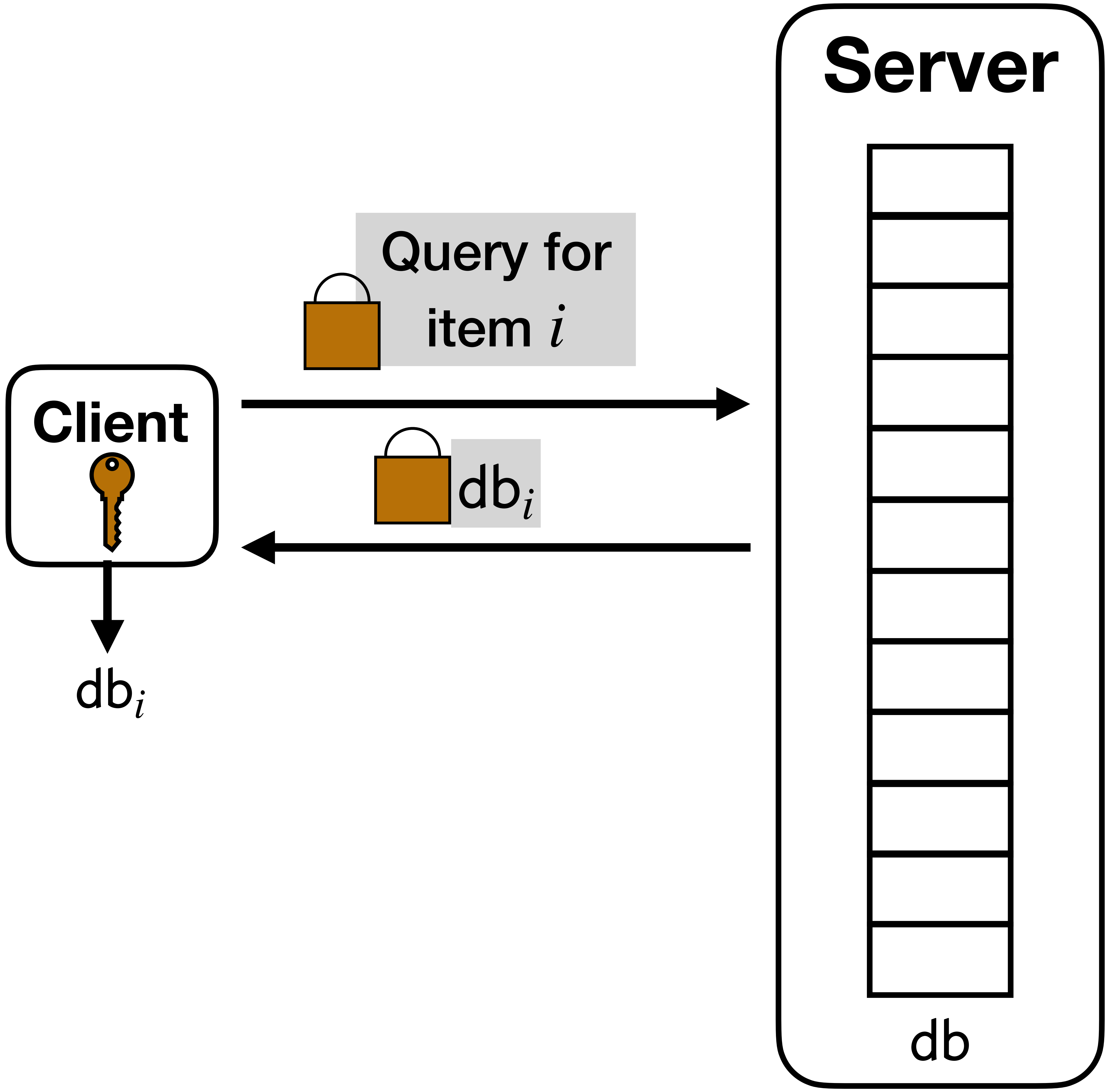
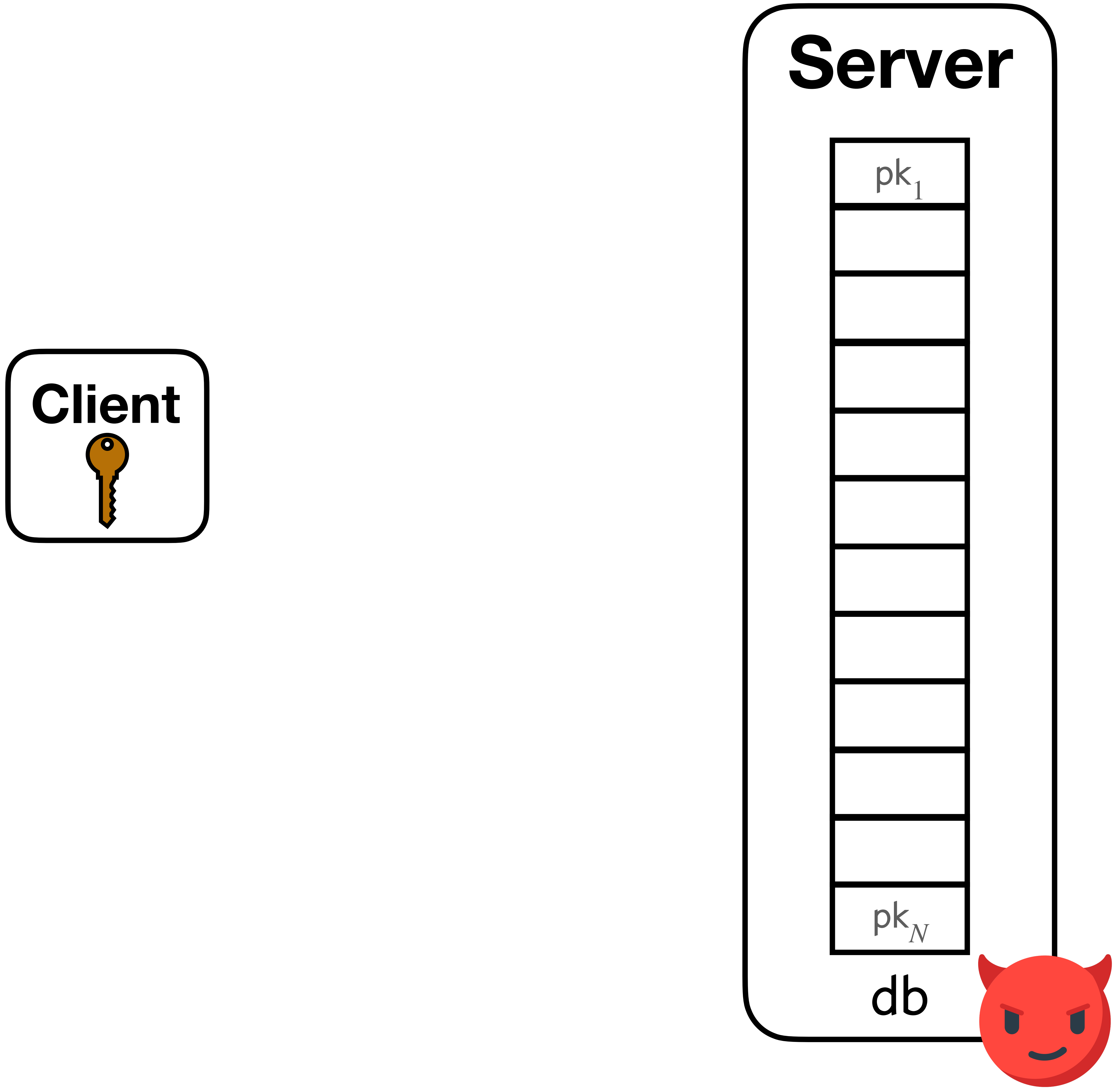


* focus on single-server

What if the server is malicious?

Selective Failure Attack



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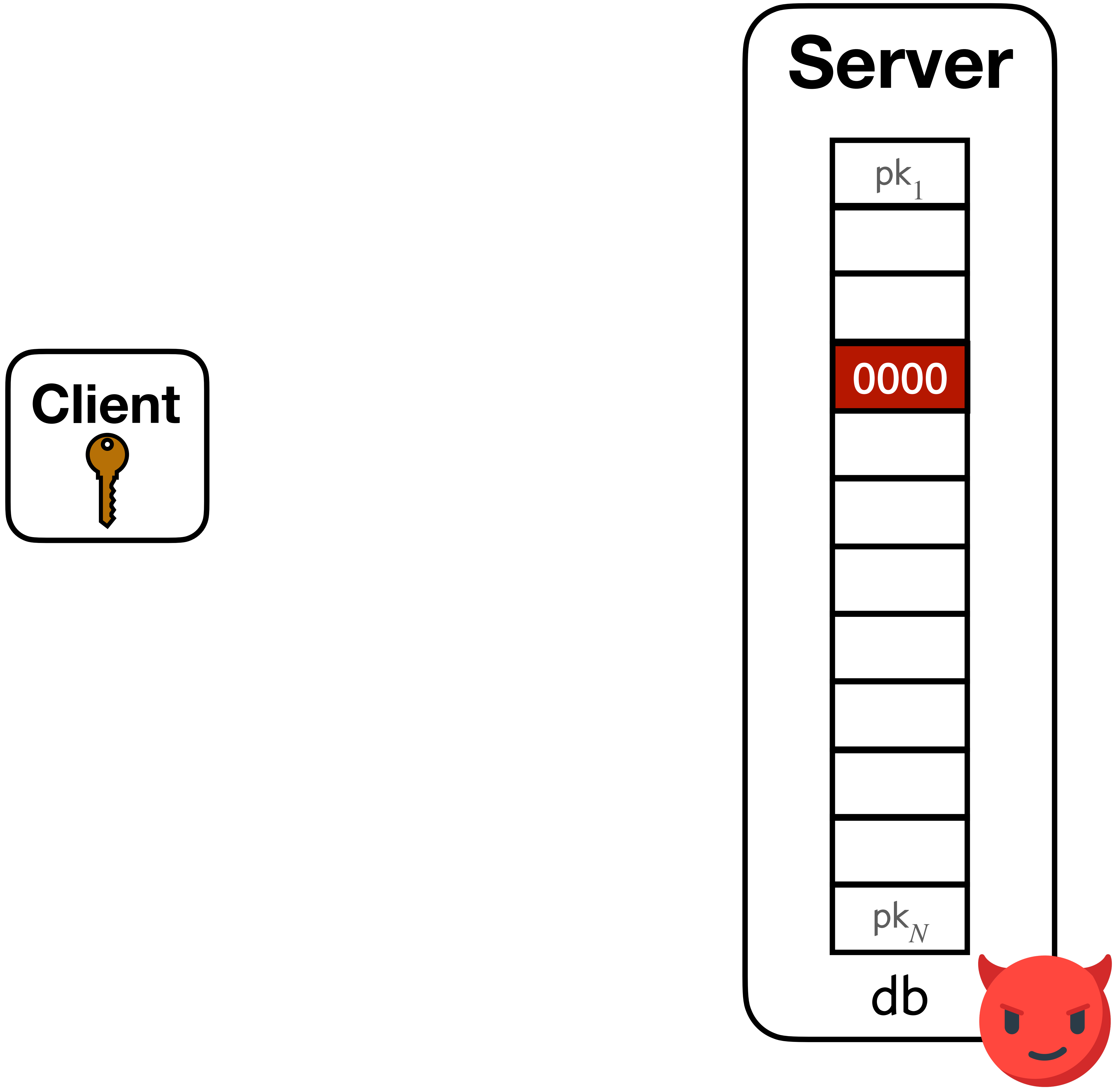

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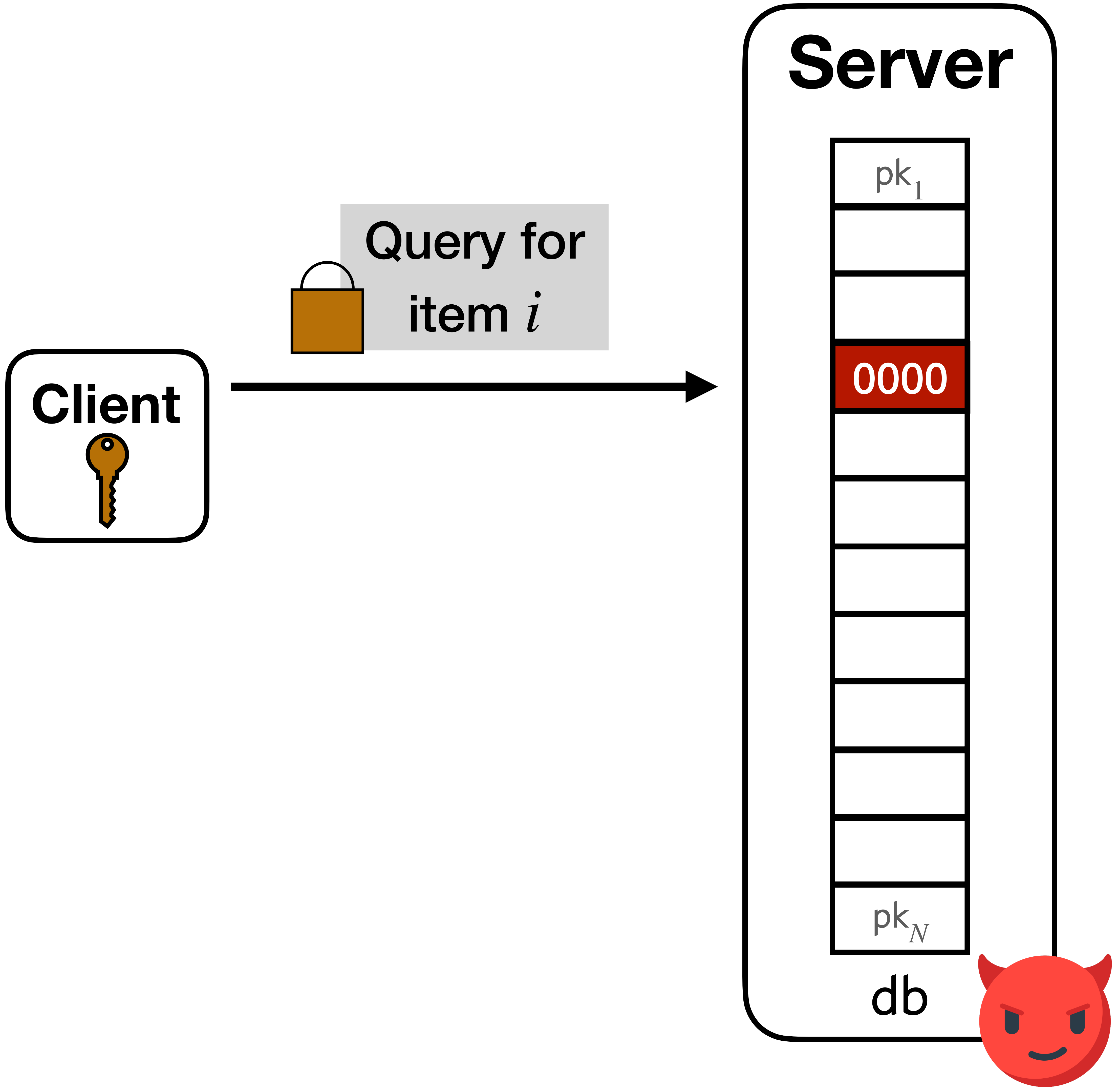

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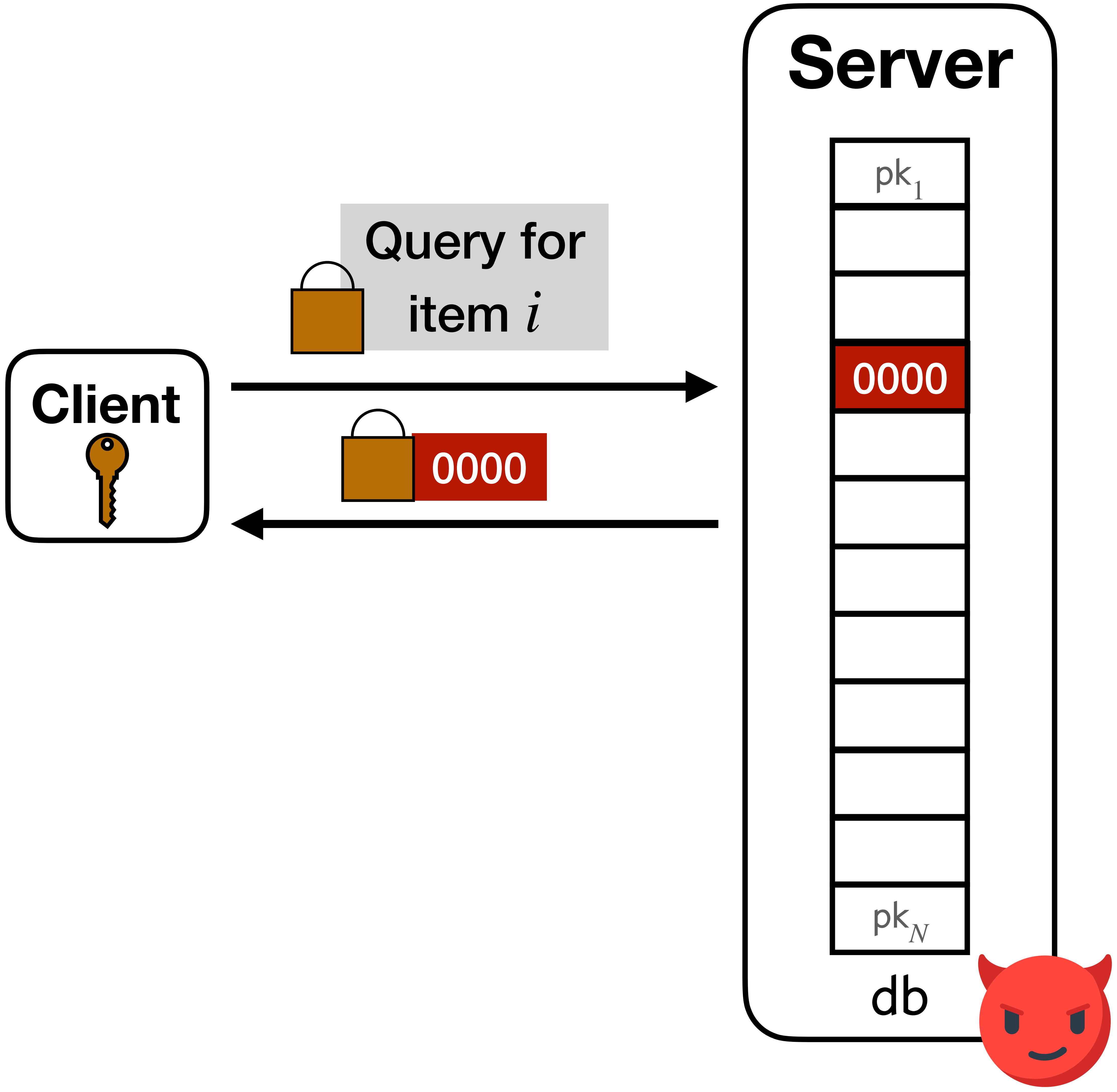

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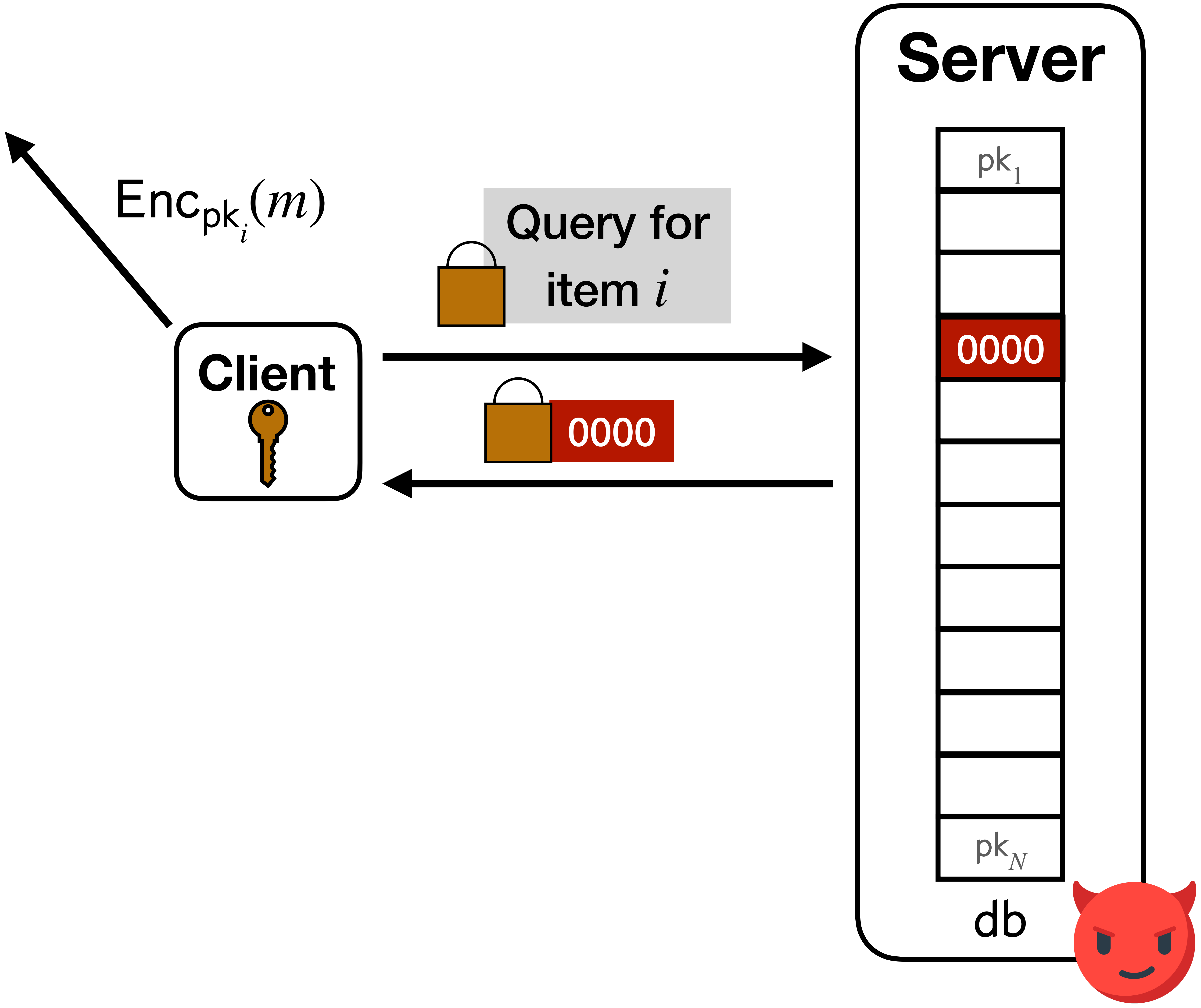

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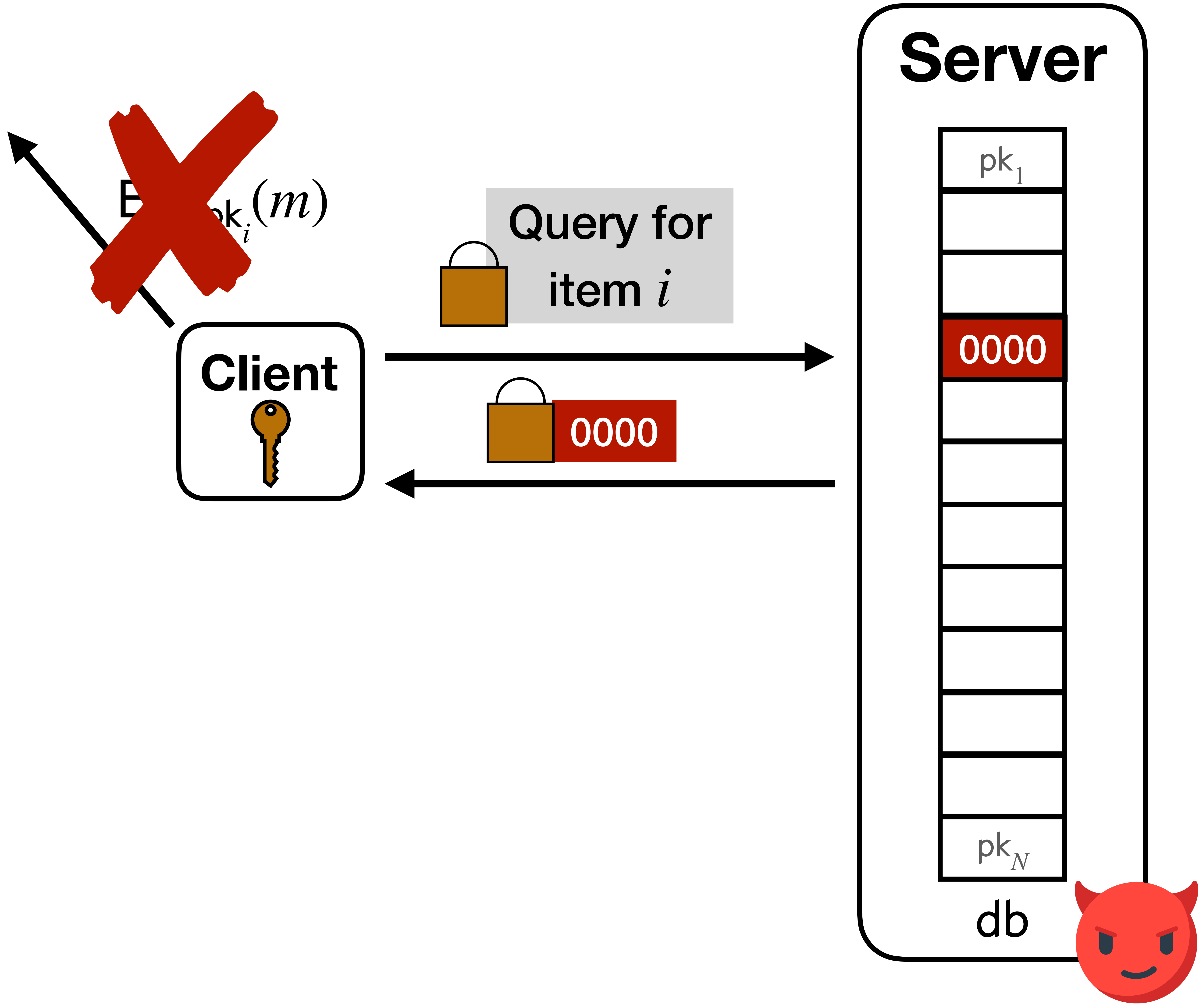

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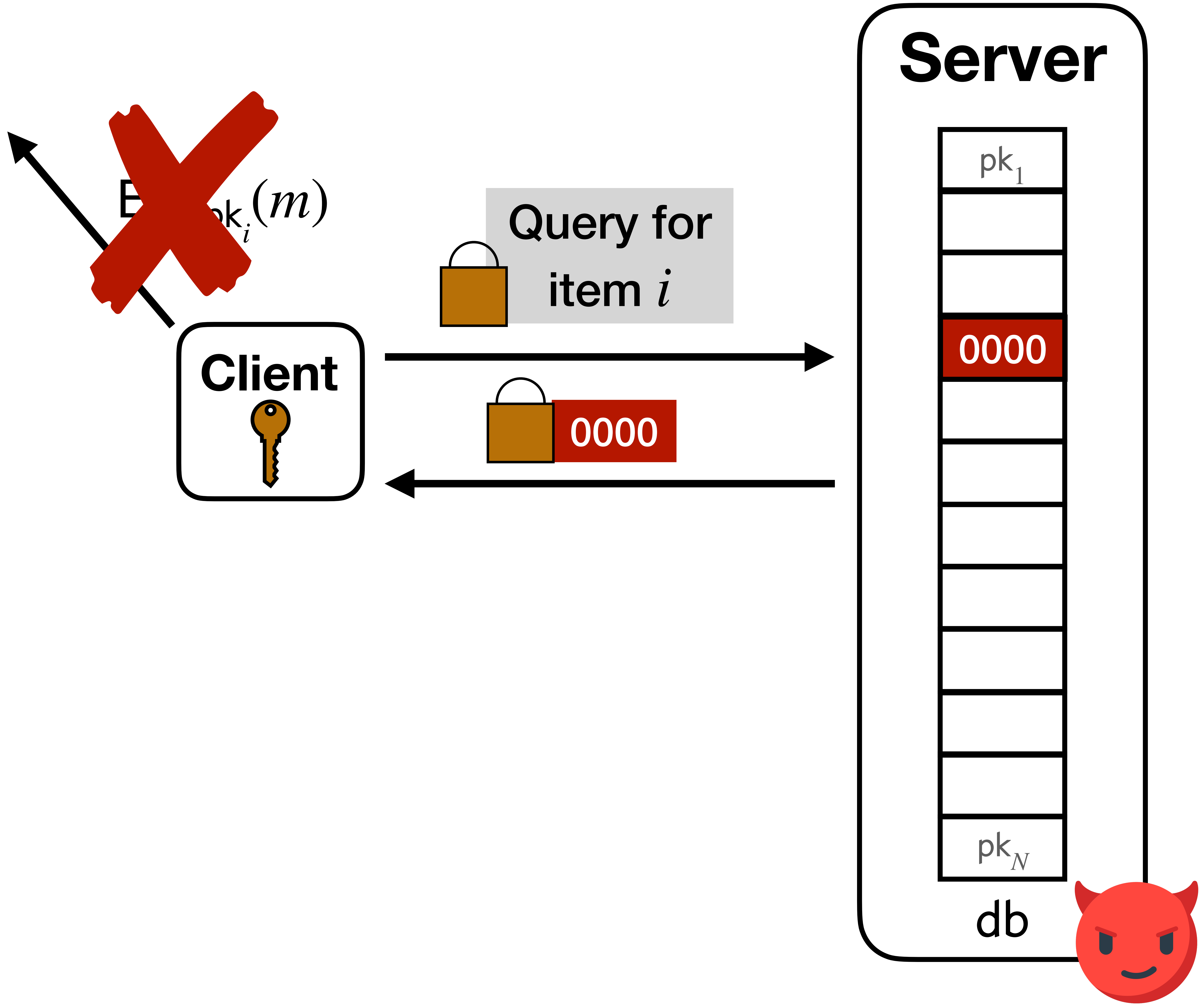

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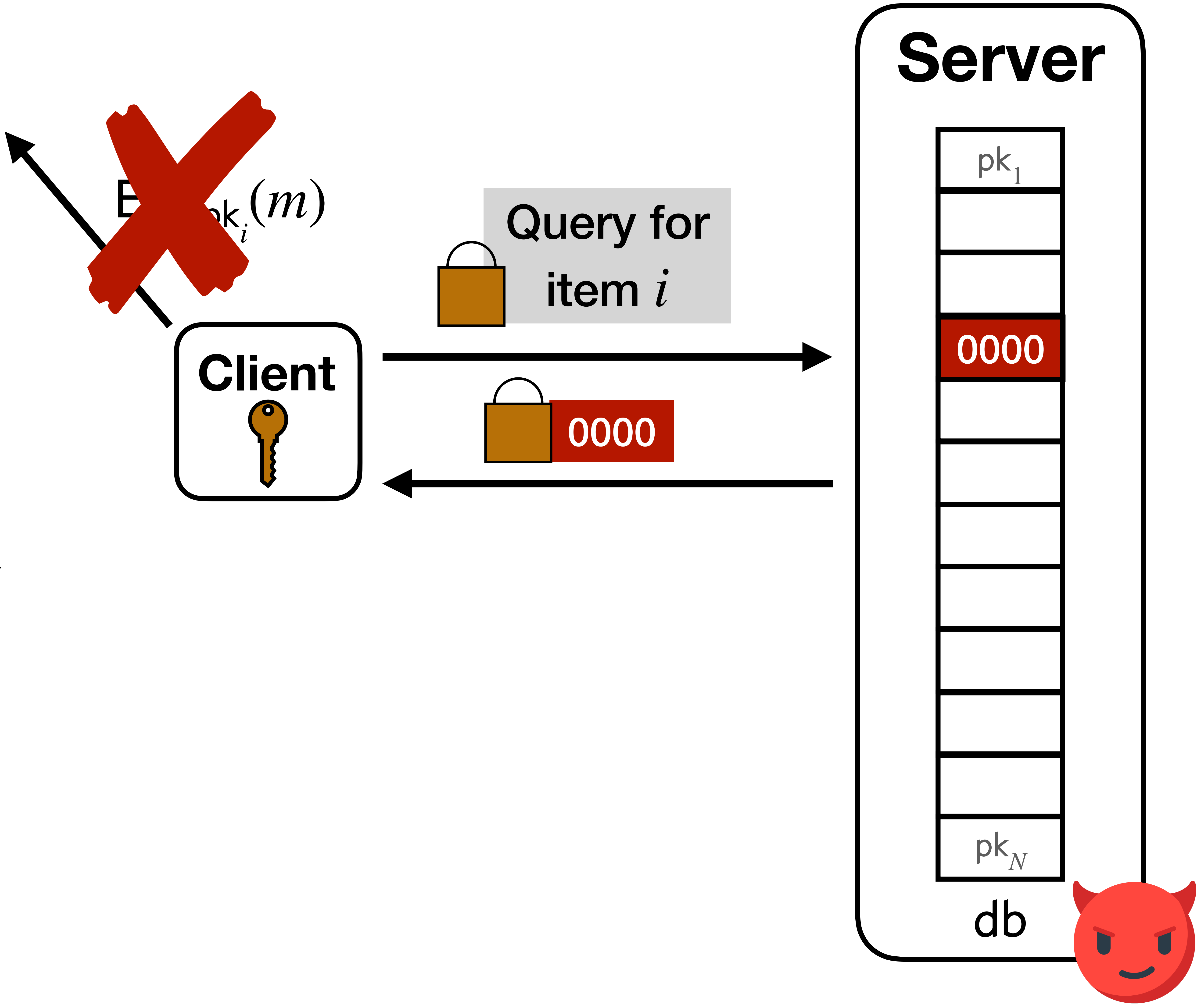

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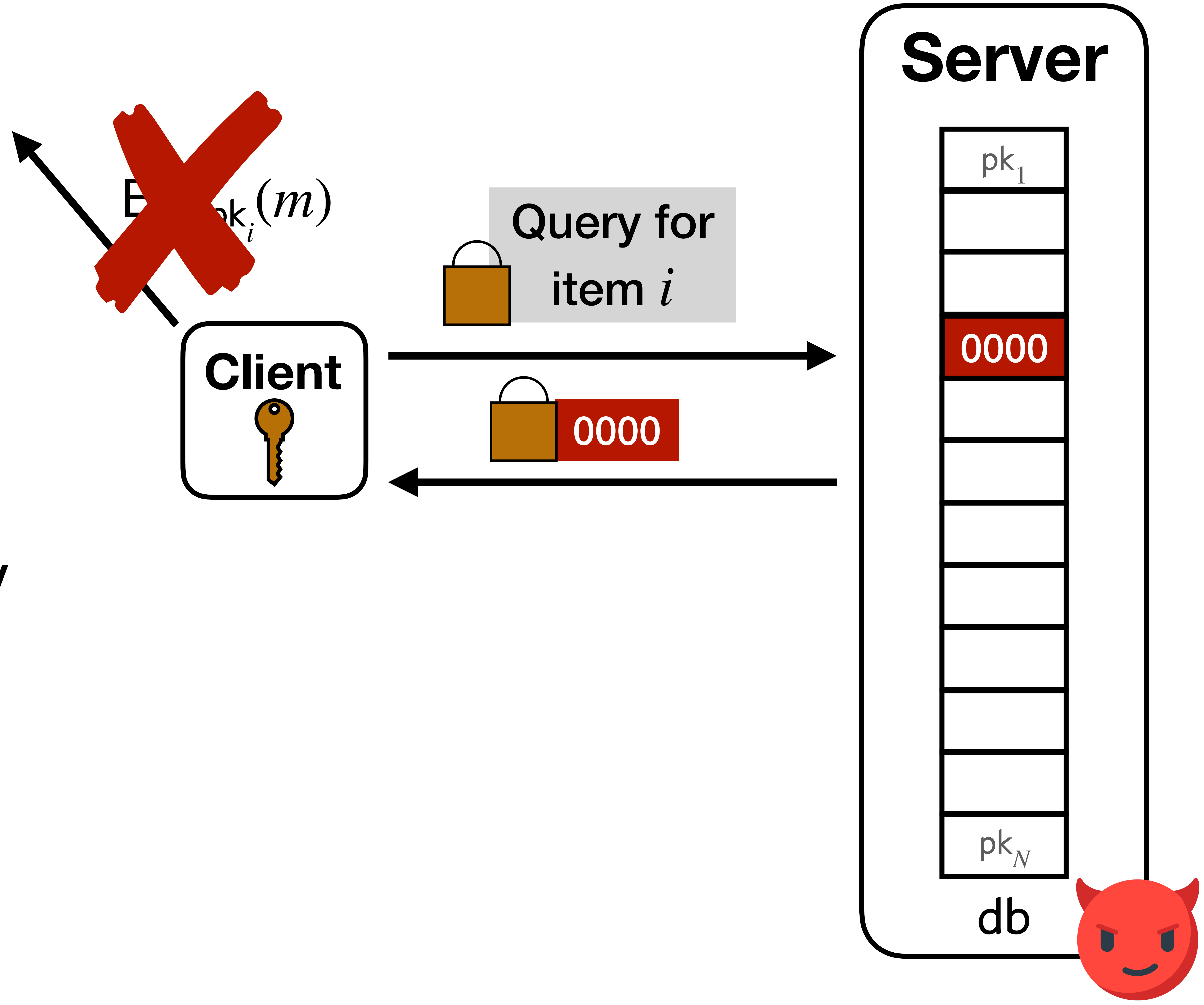

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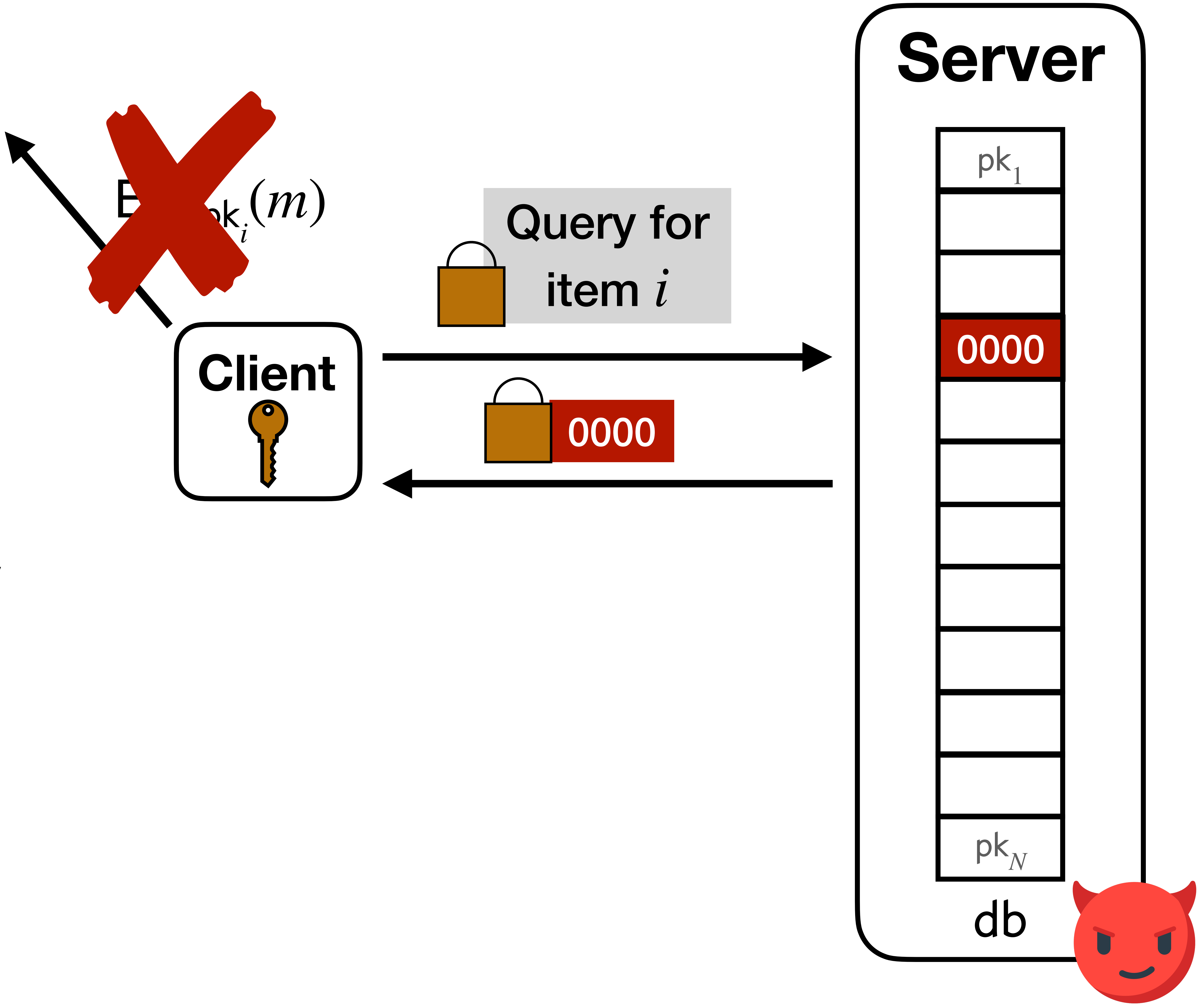

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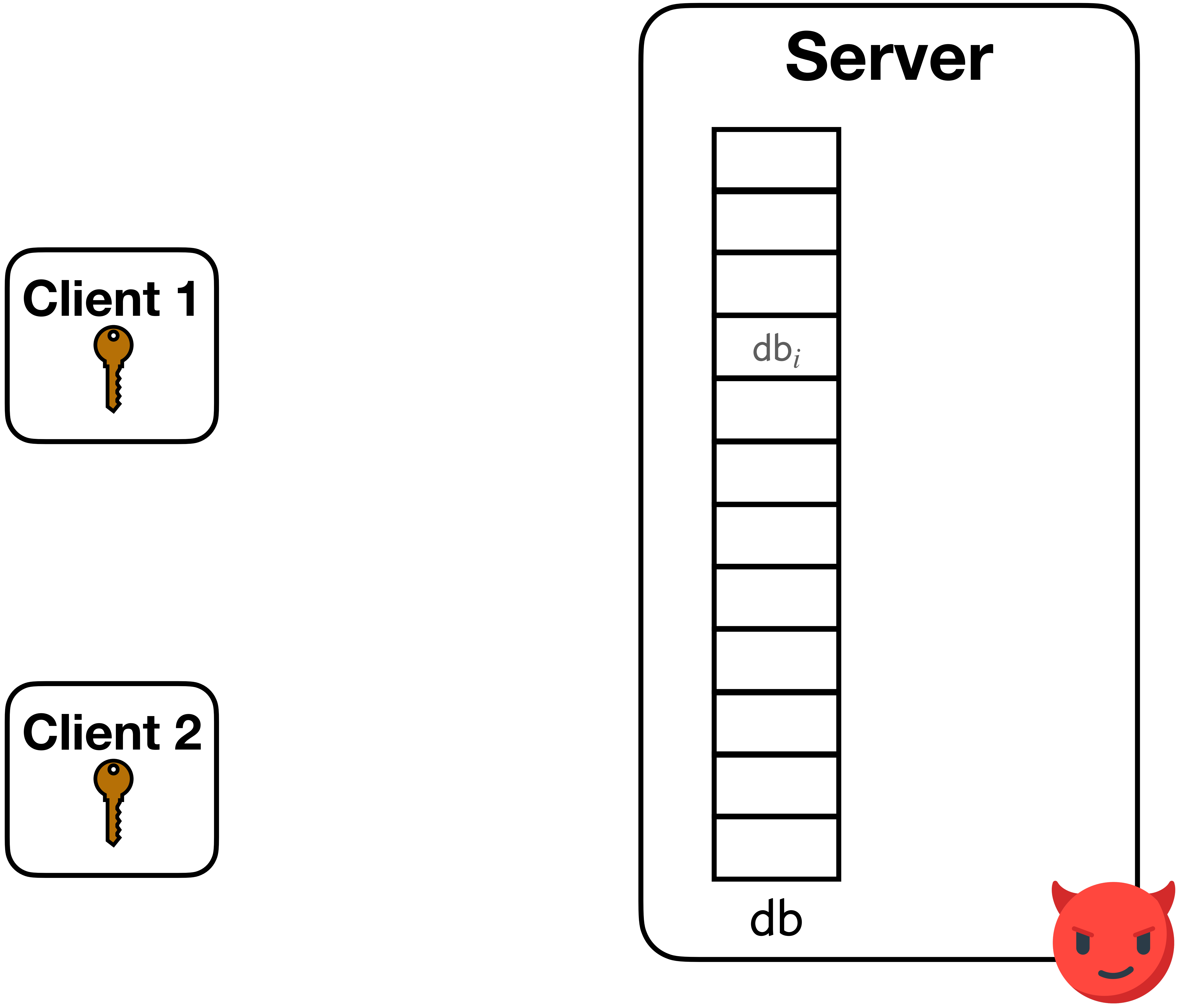
Incoherent views



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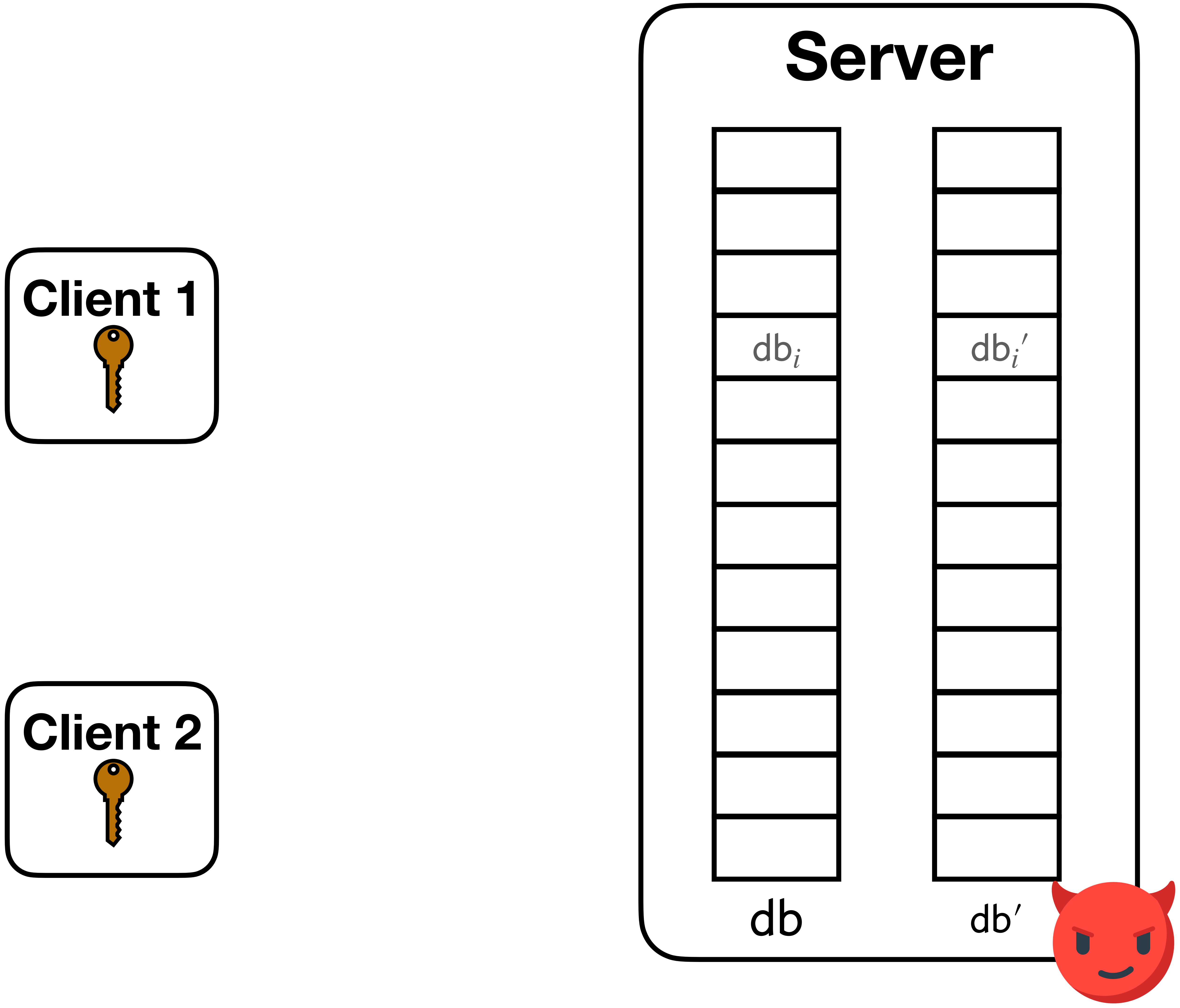

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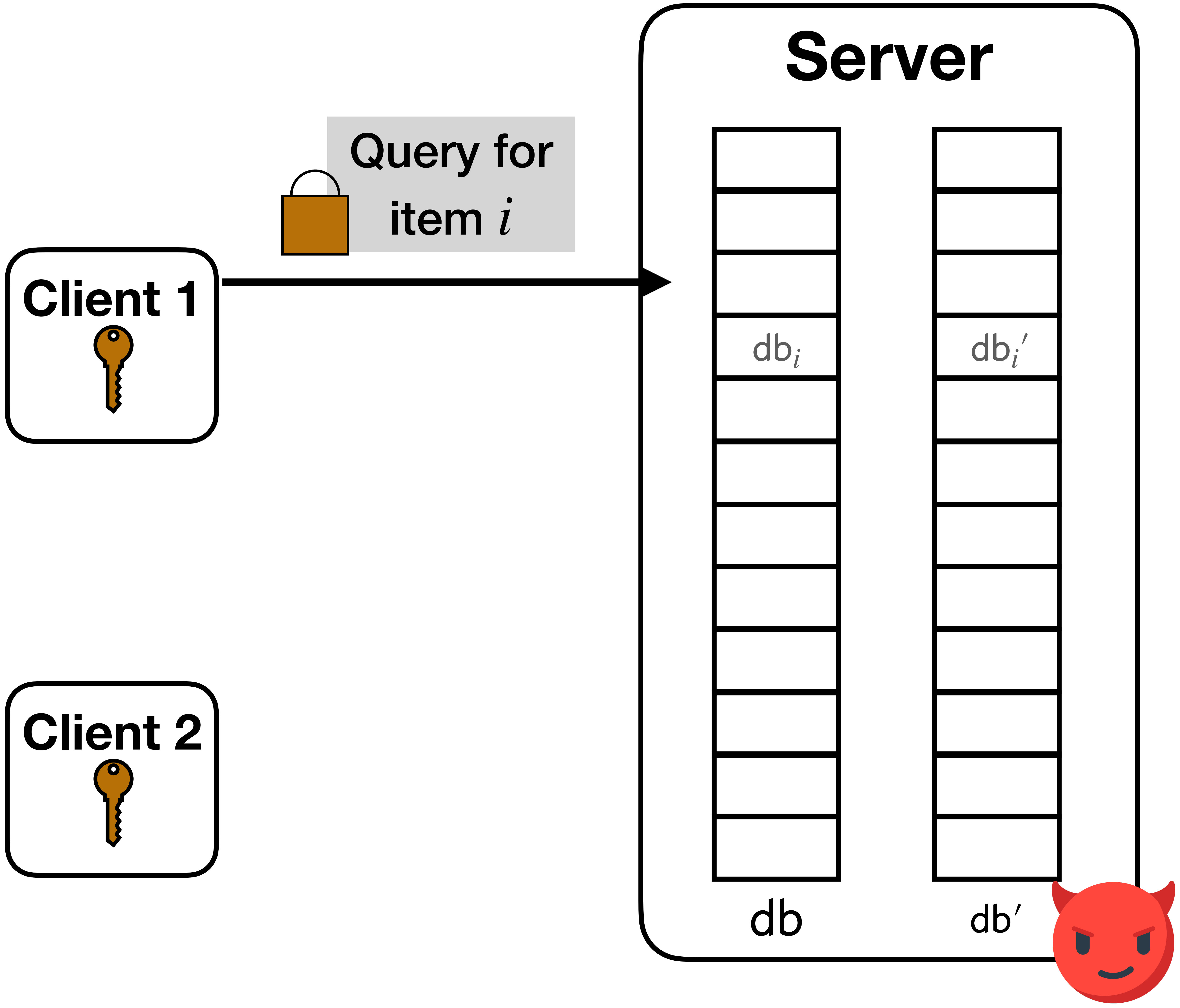

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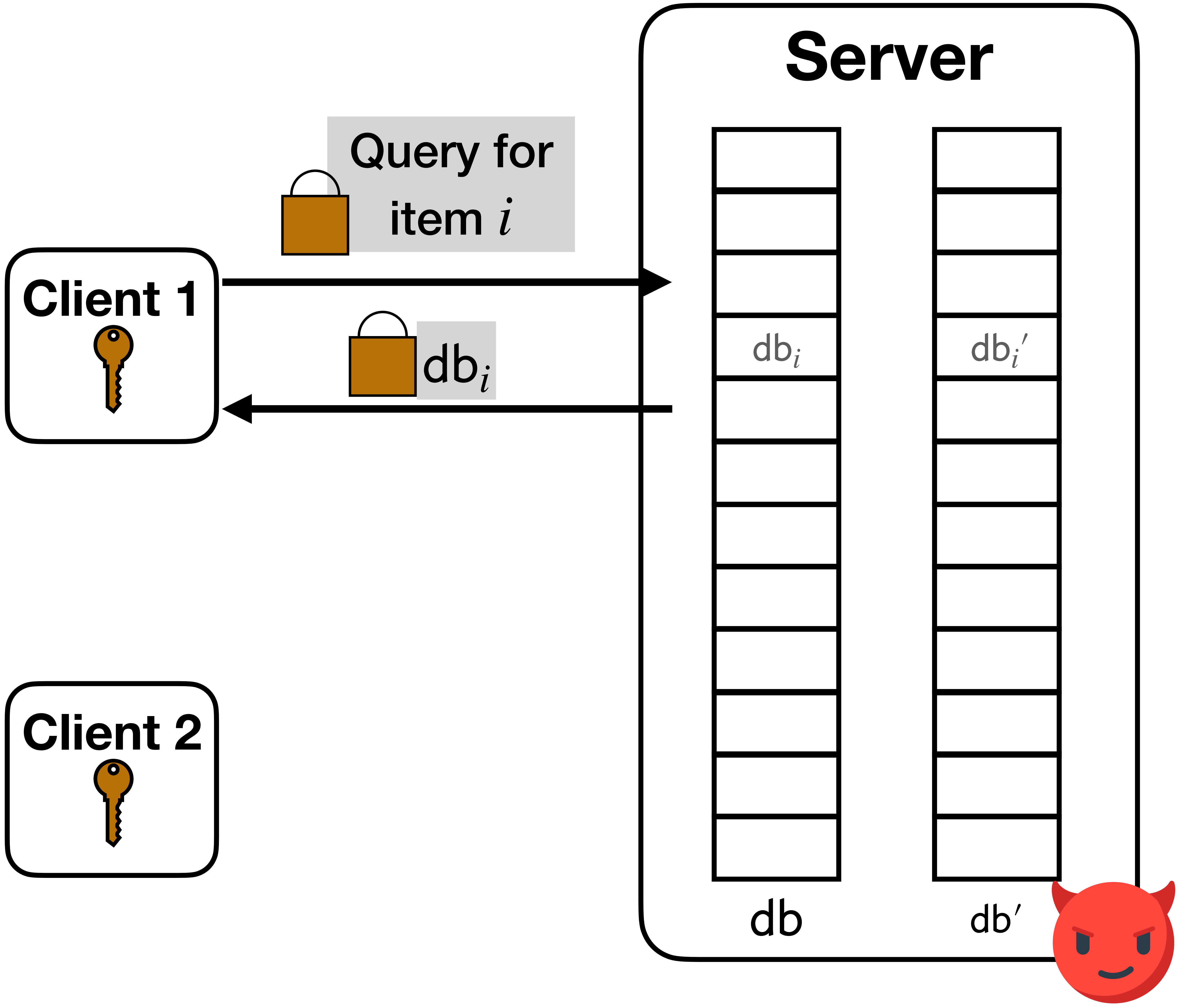

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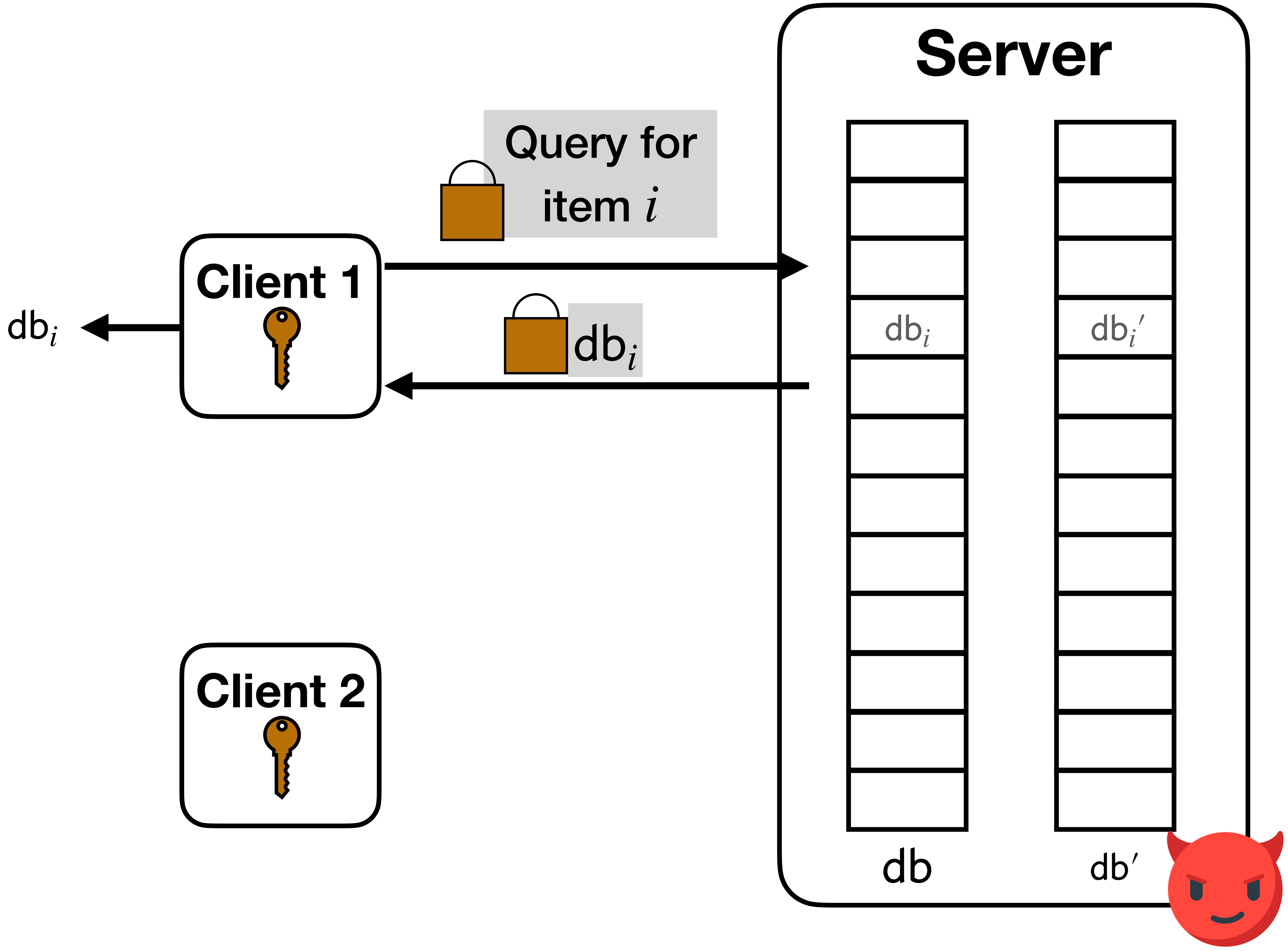

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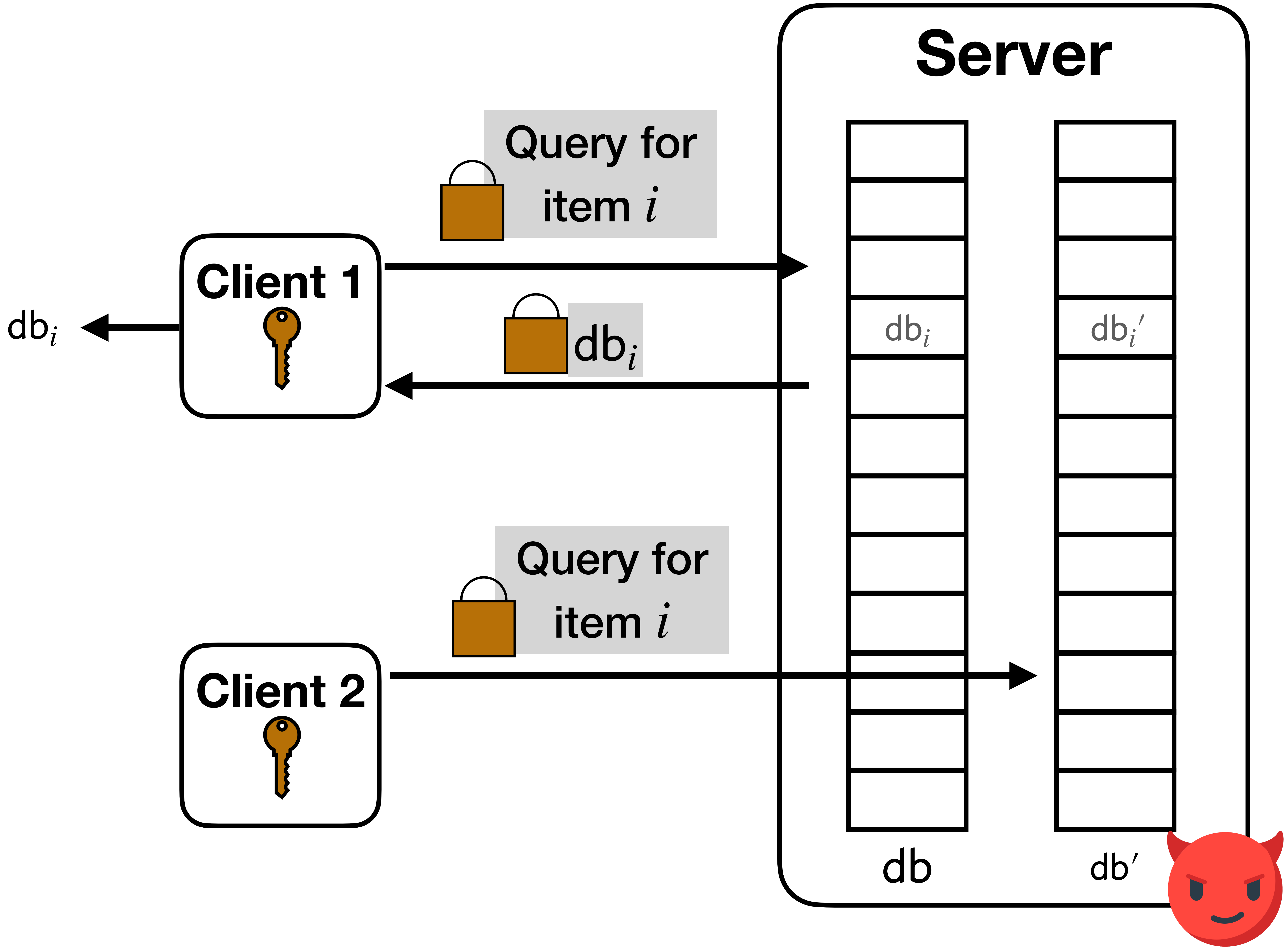

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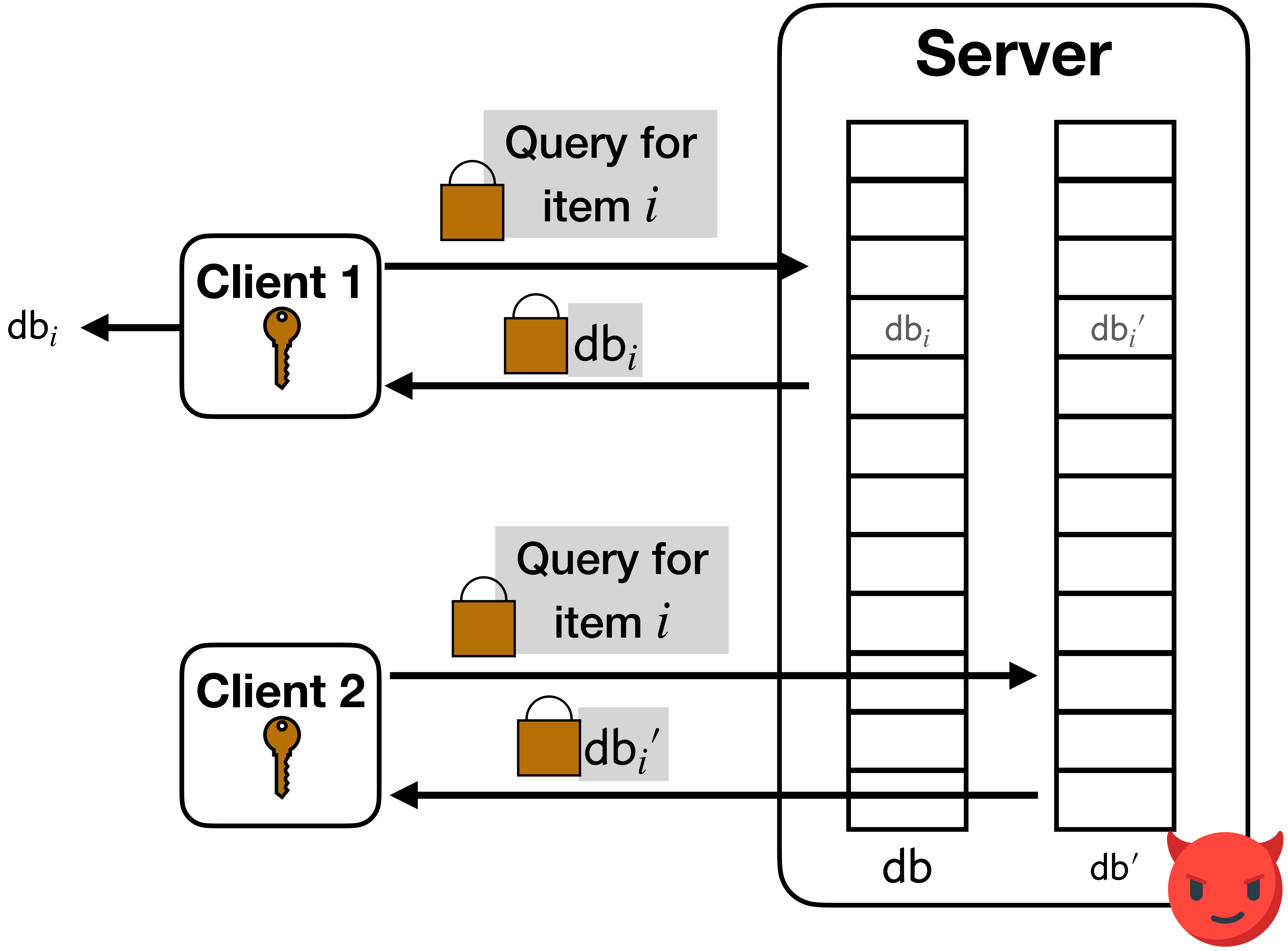

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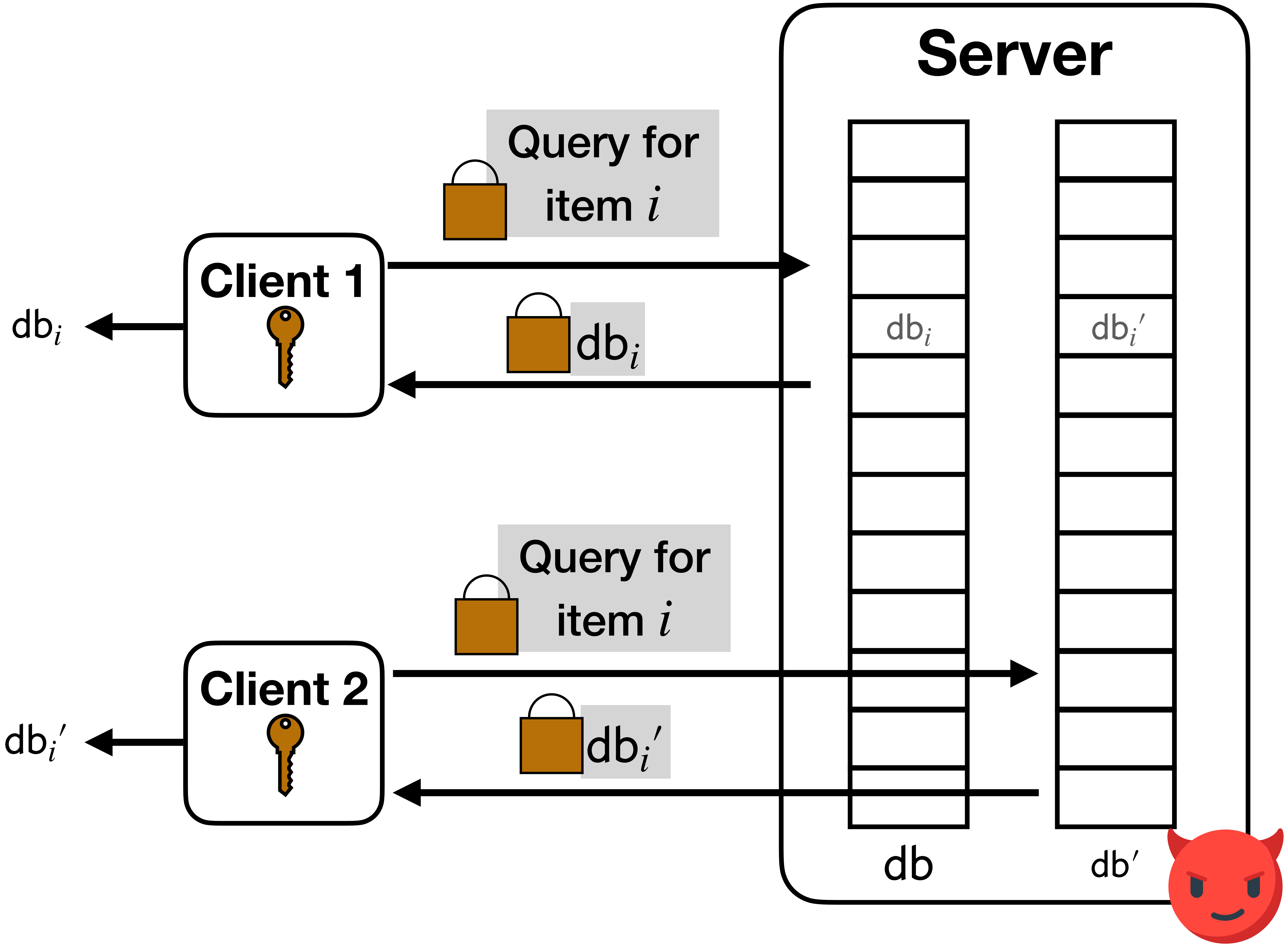

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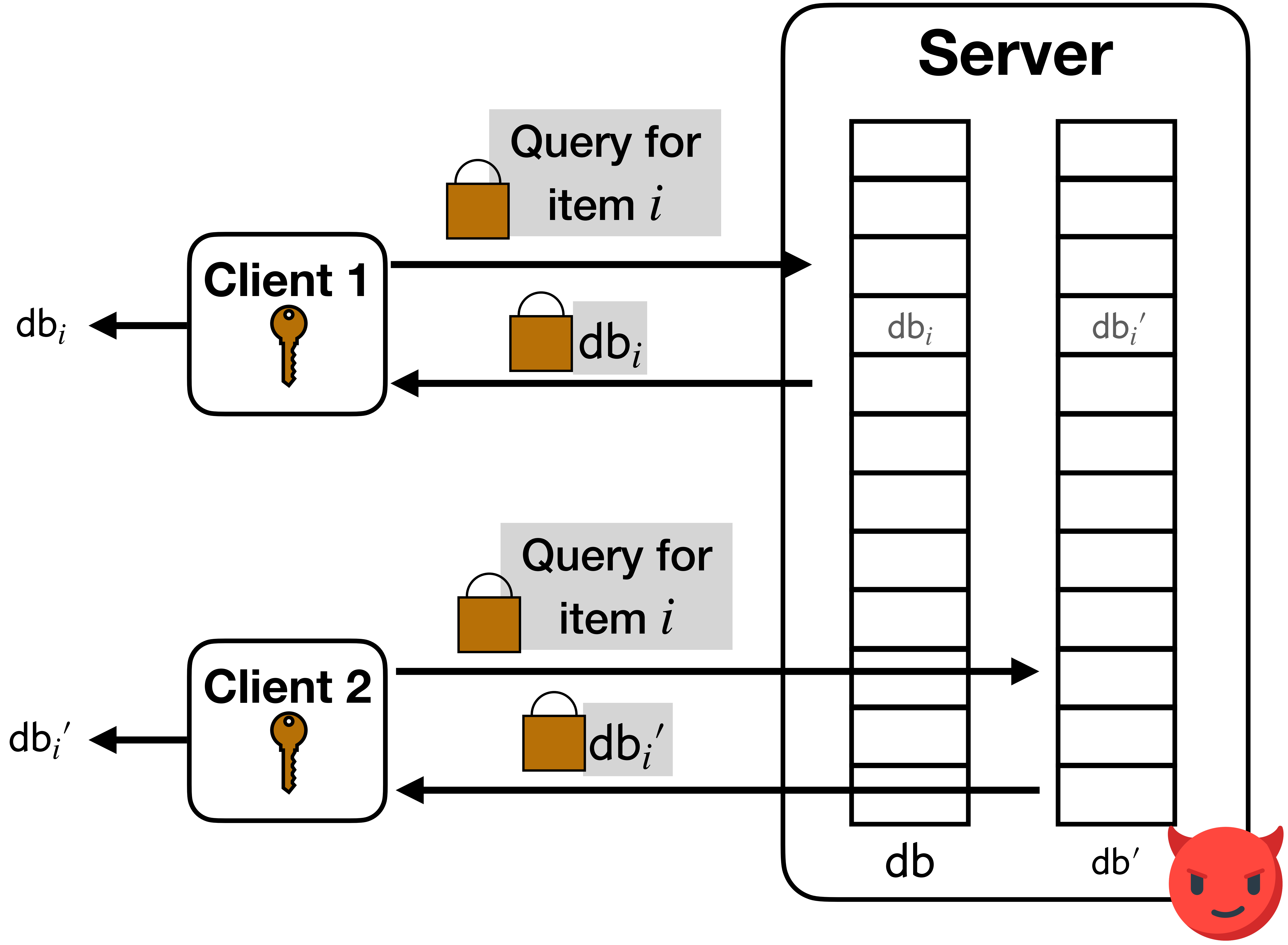
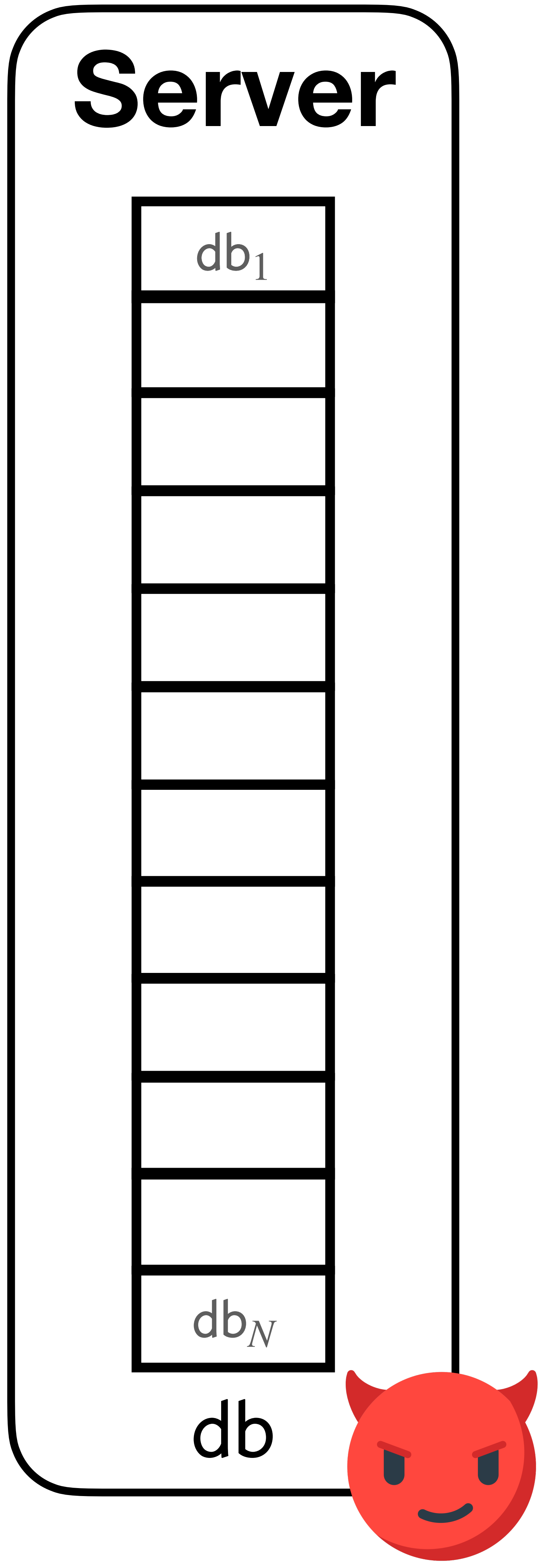
Incoherent views

Problem: clients do not agree on database.



Prior work

Maliciously-secure PIR (mPIR) [CNCWF23; WZLY23; DT23; CL24]



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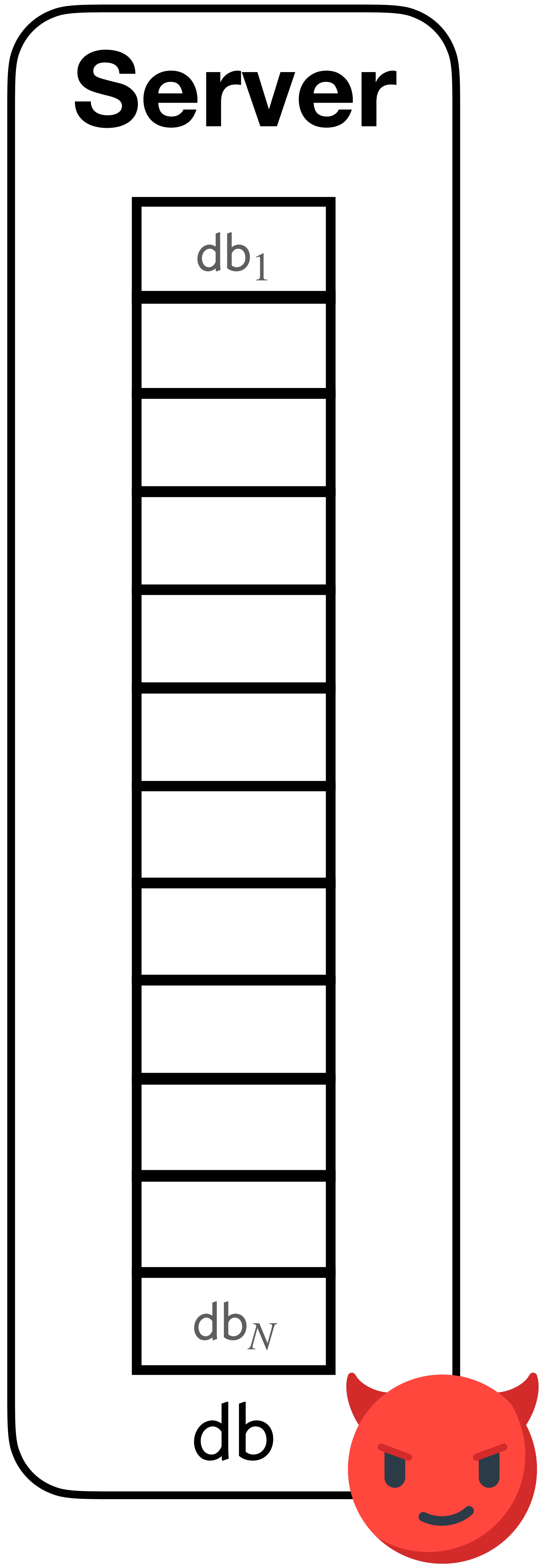
Offline



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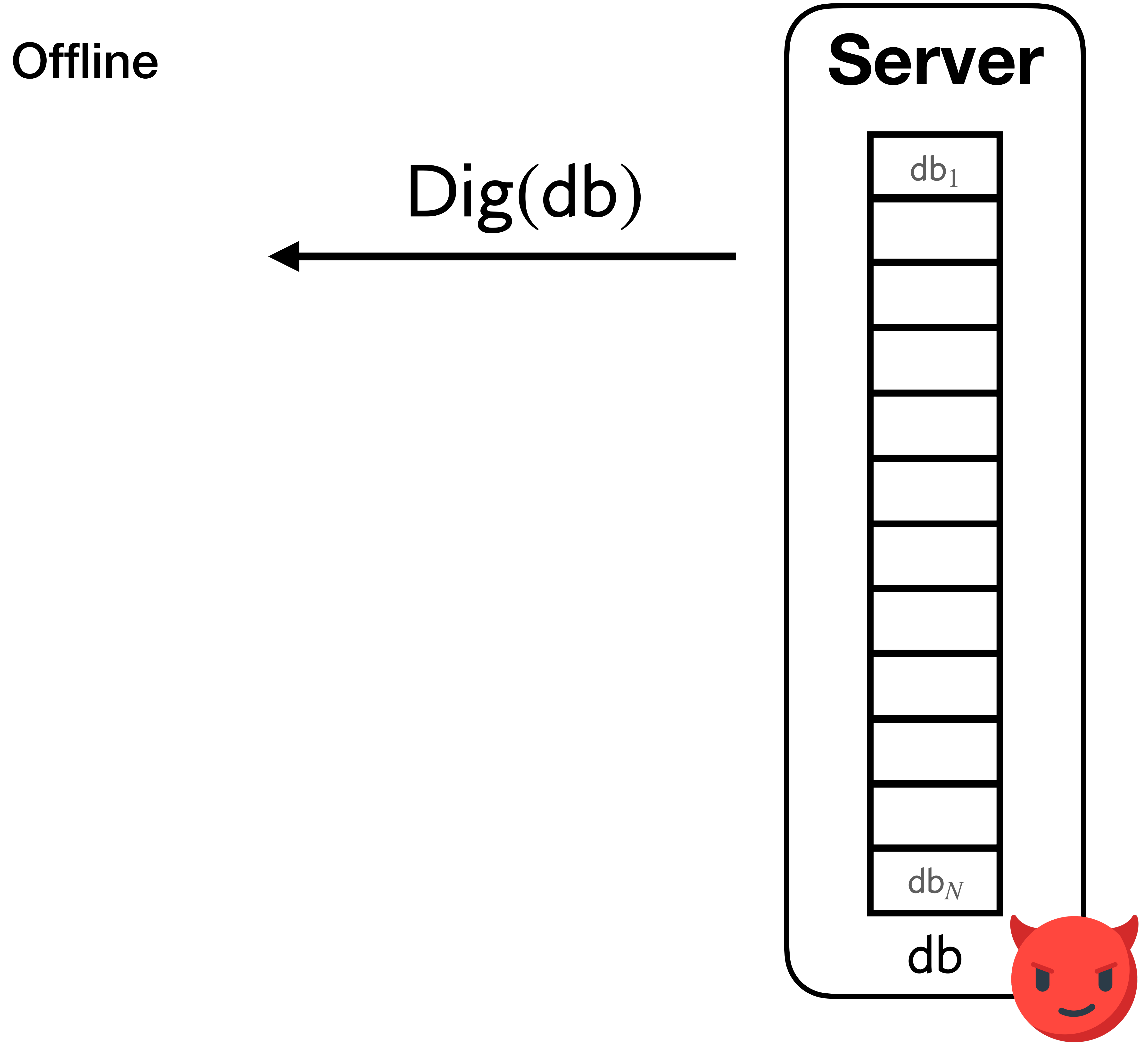

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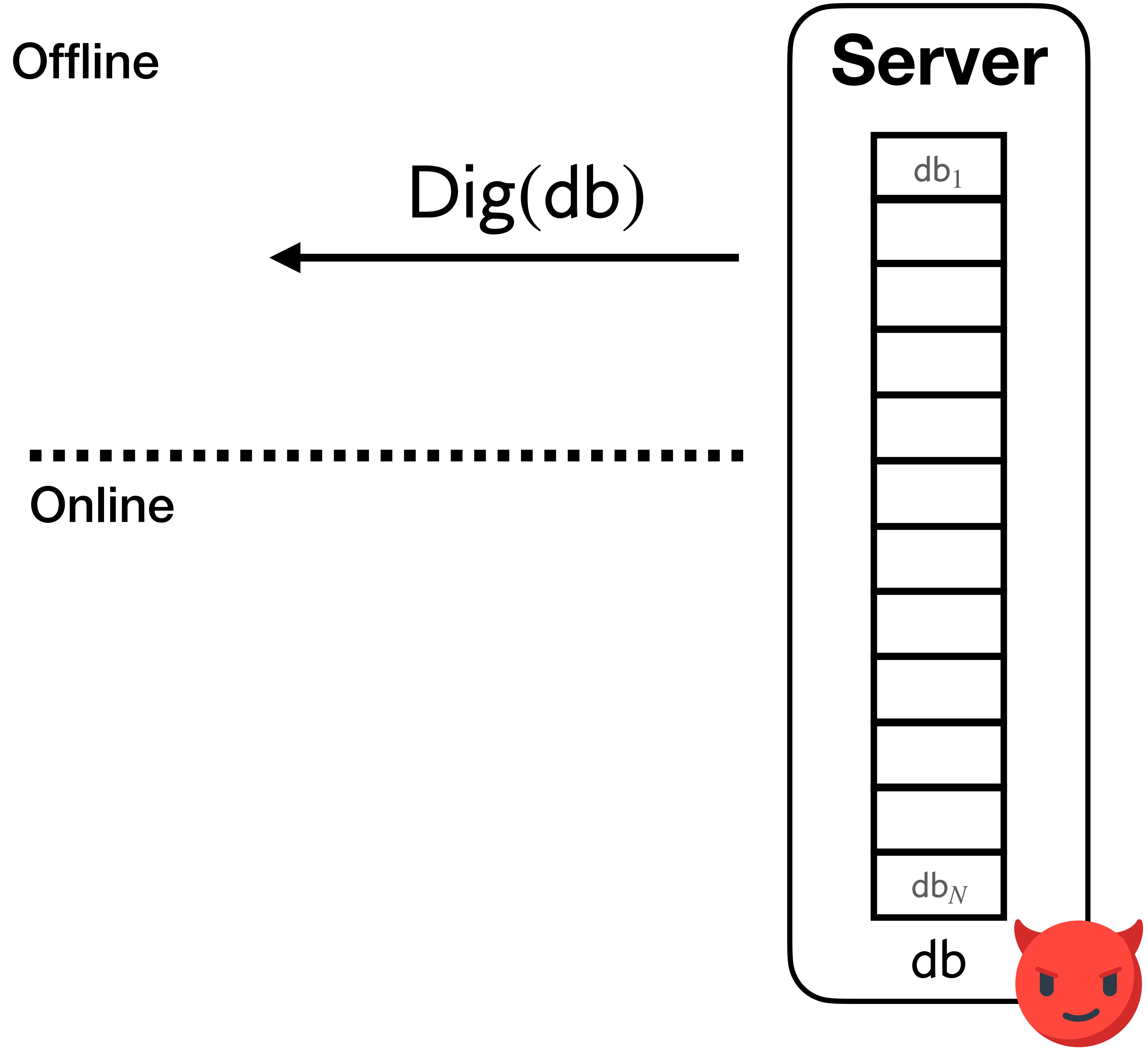

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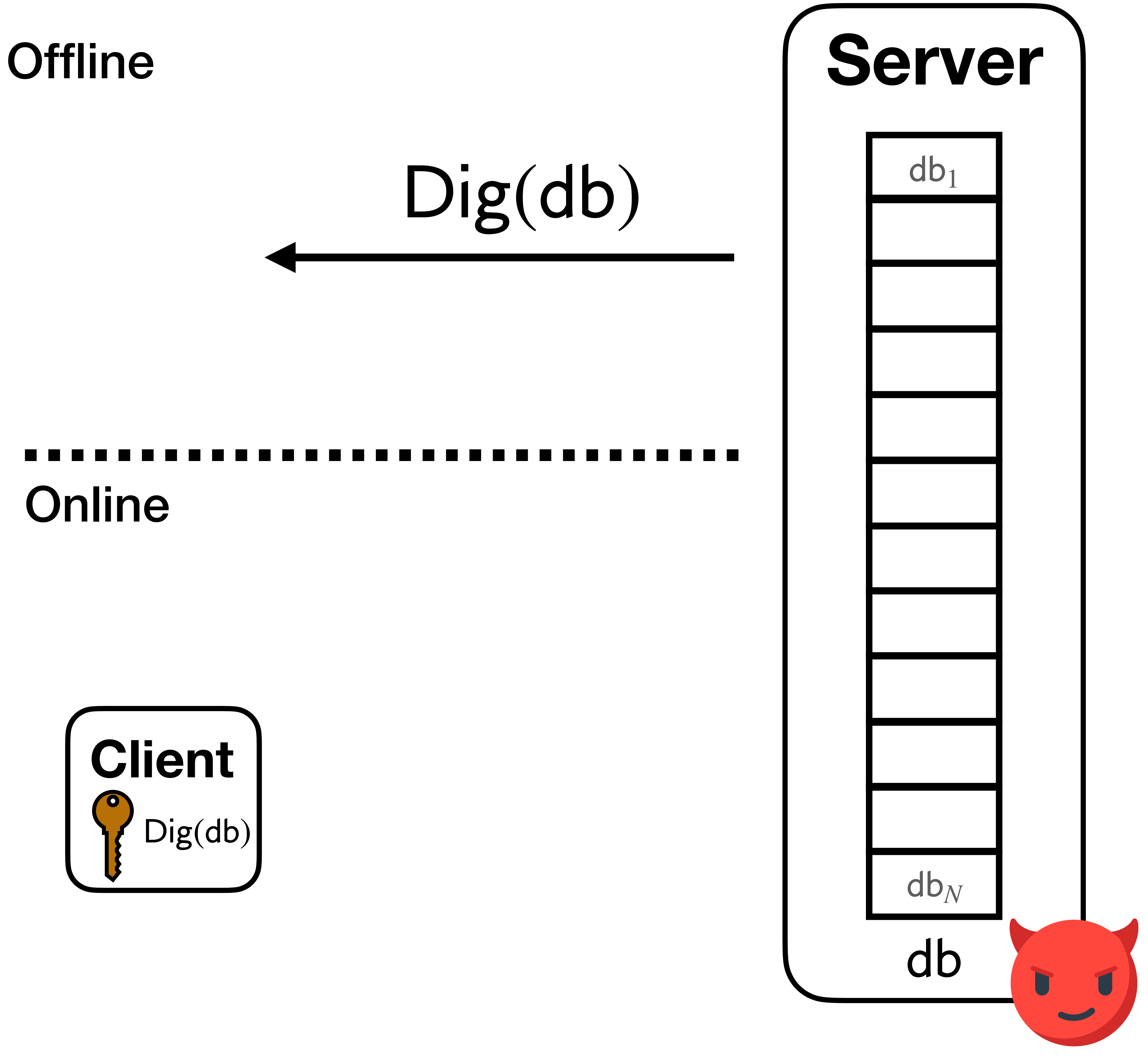

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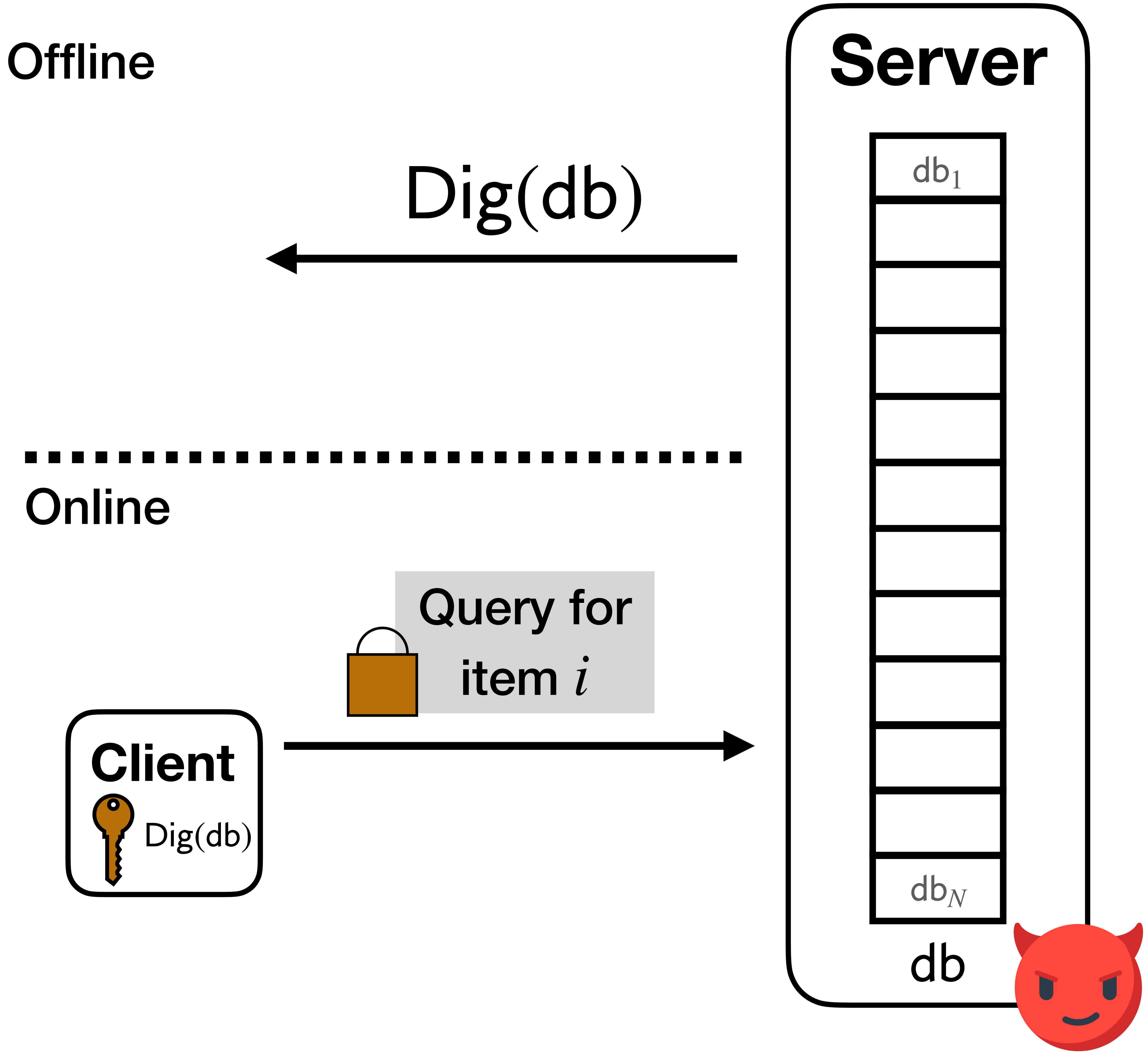

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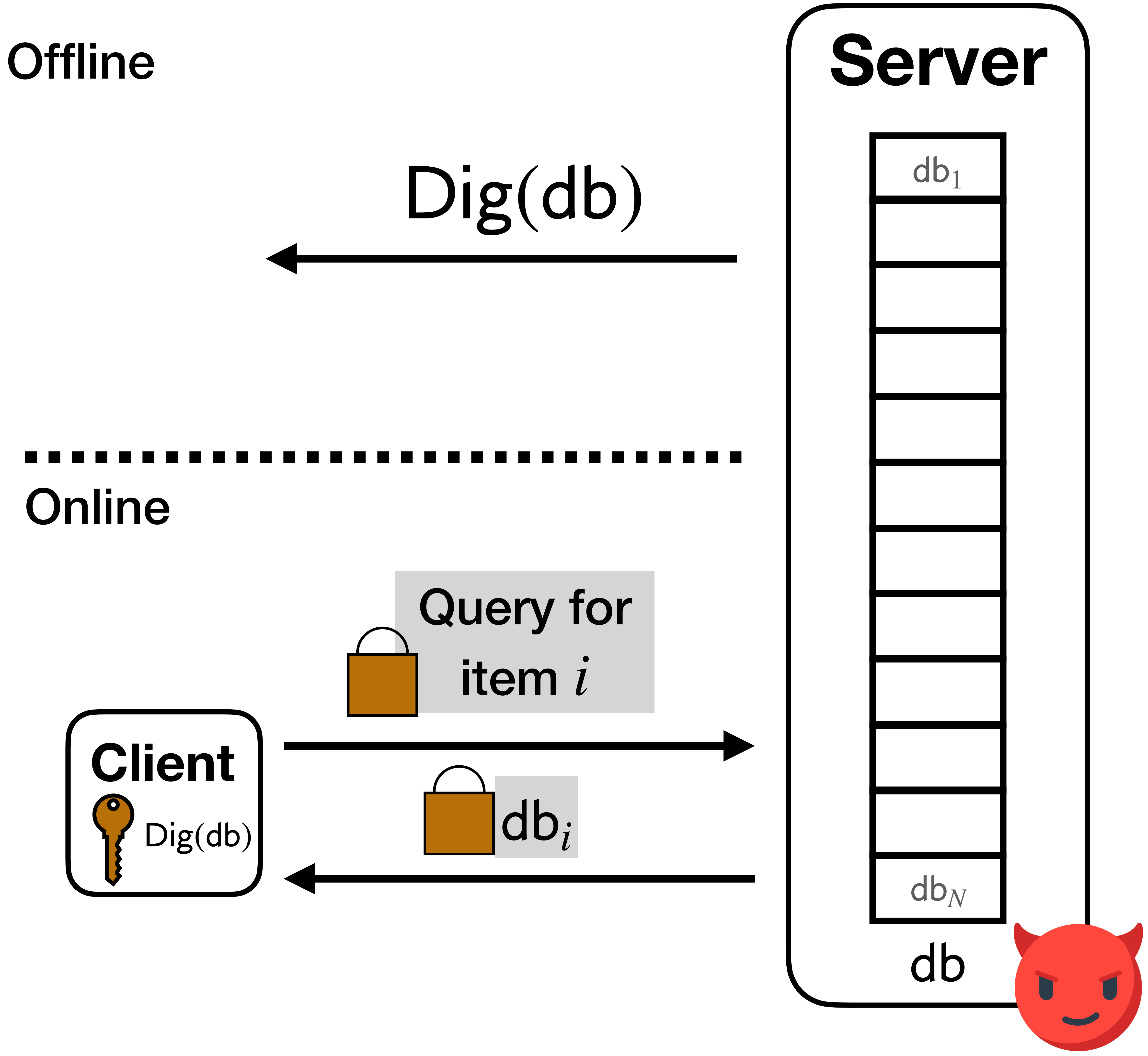

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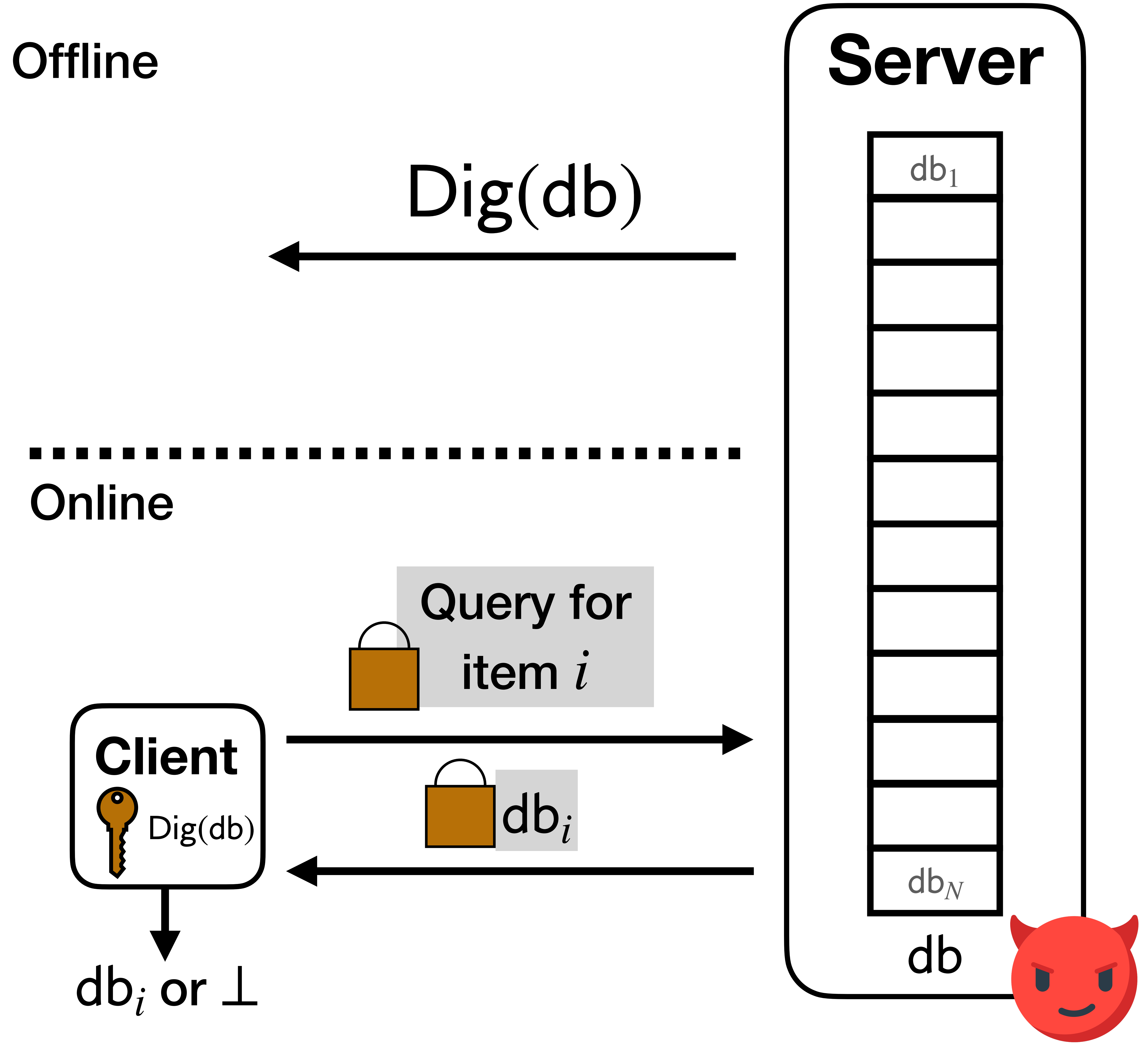

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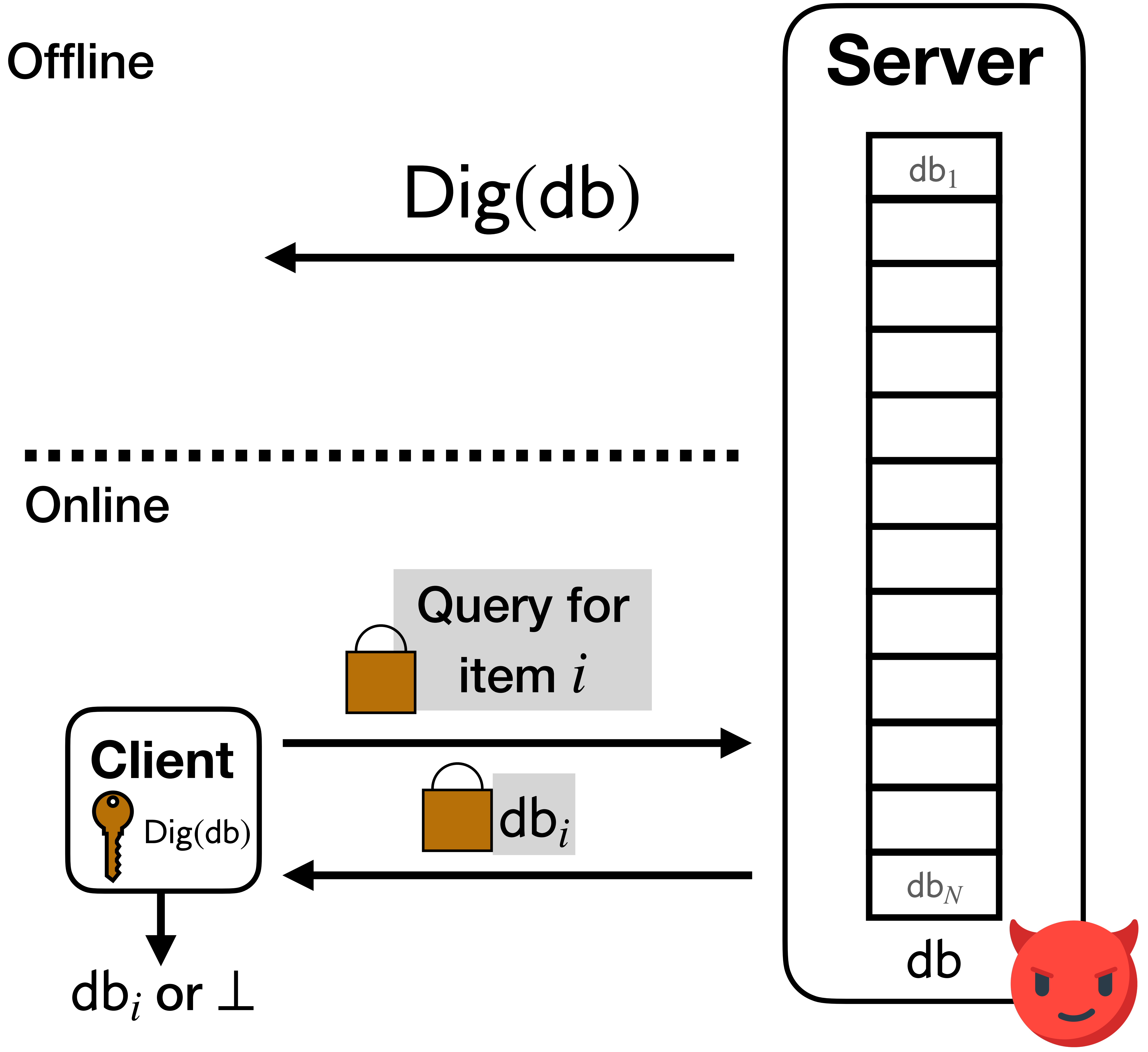

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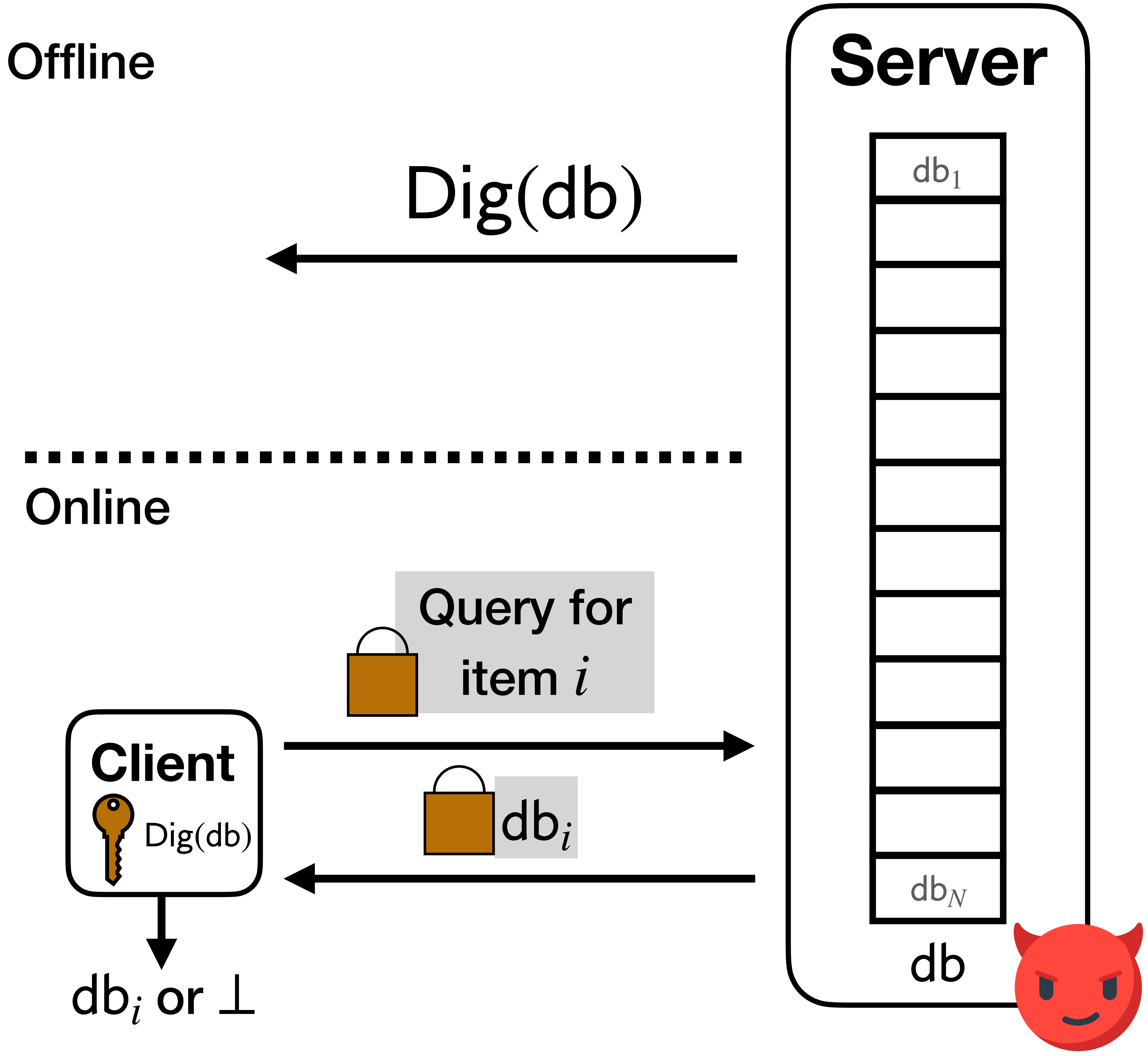

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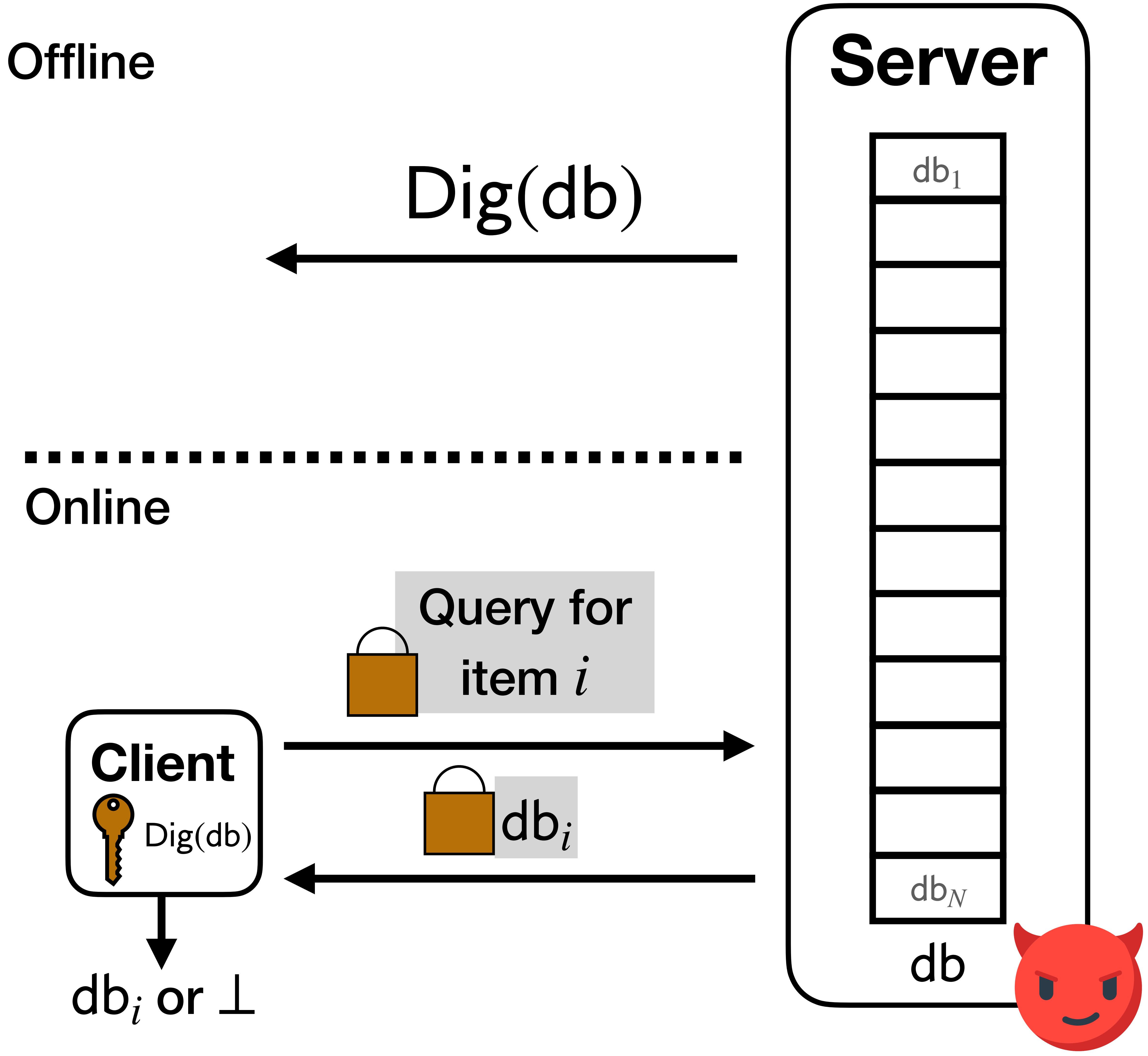

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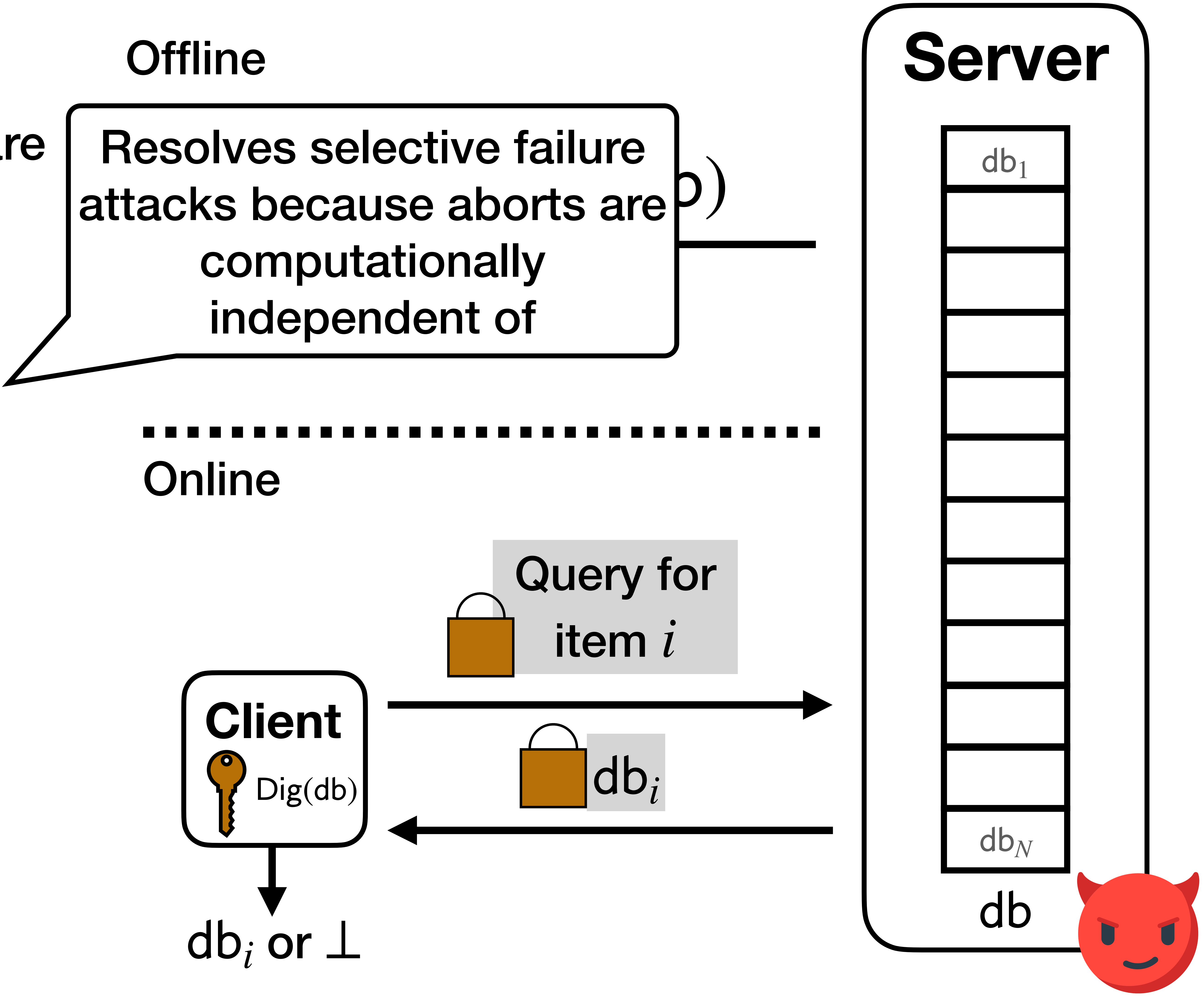

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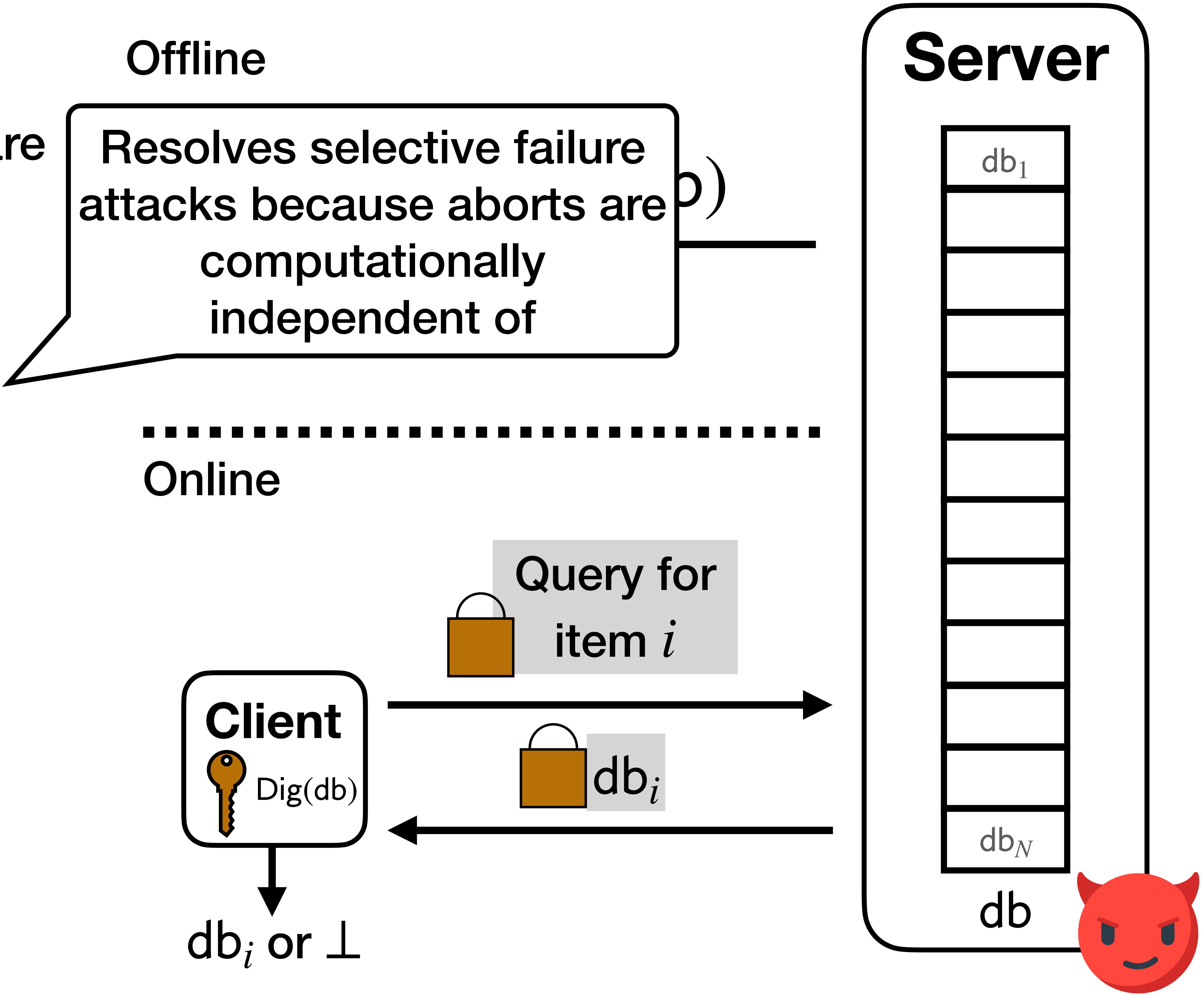

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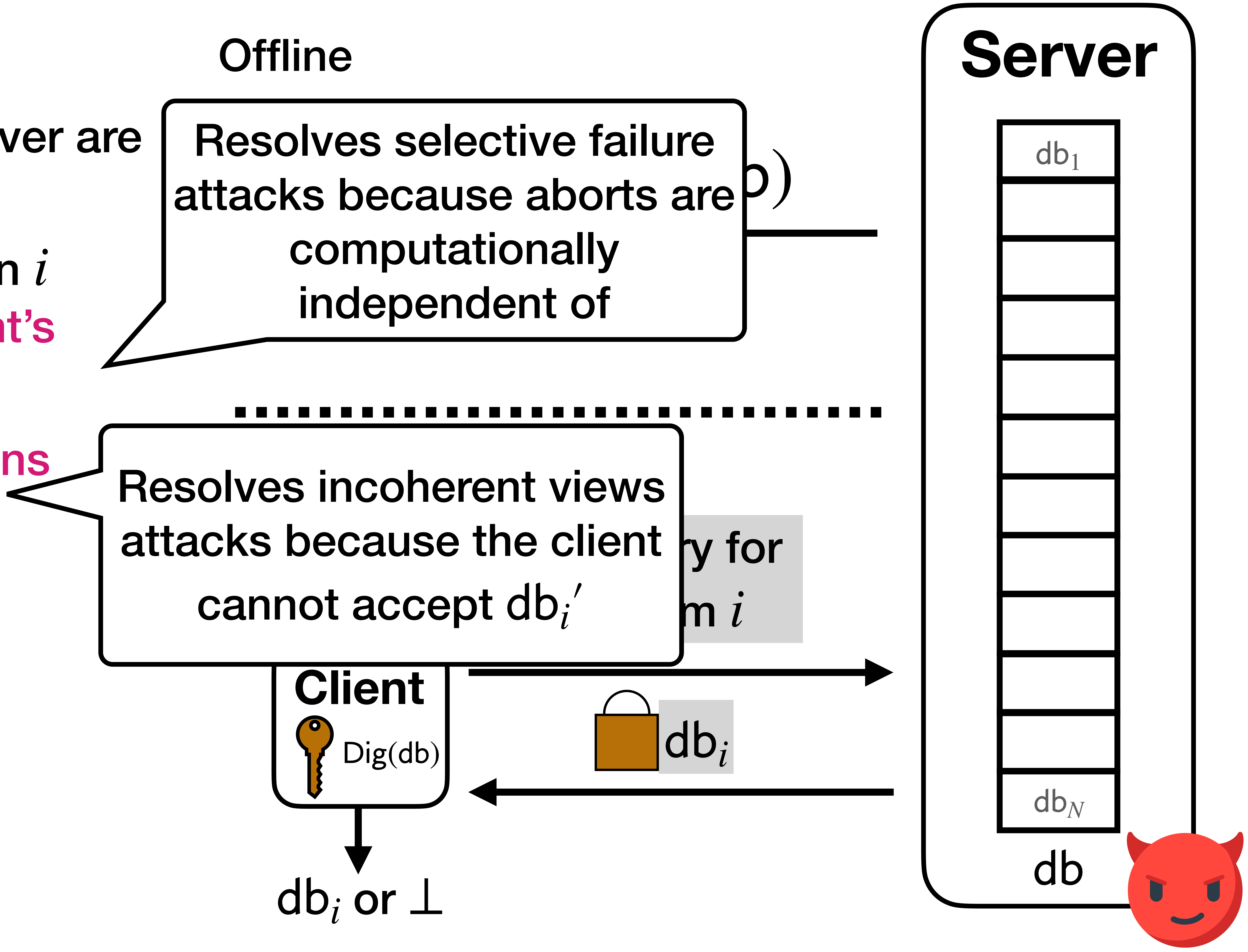

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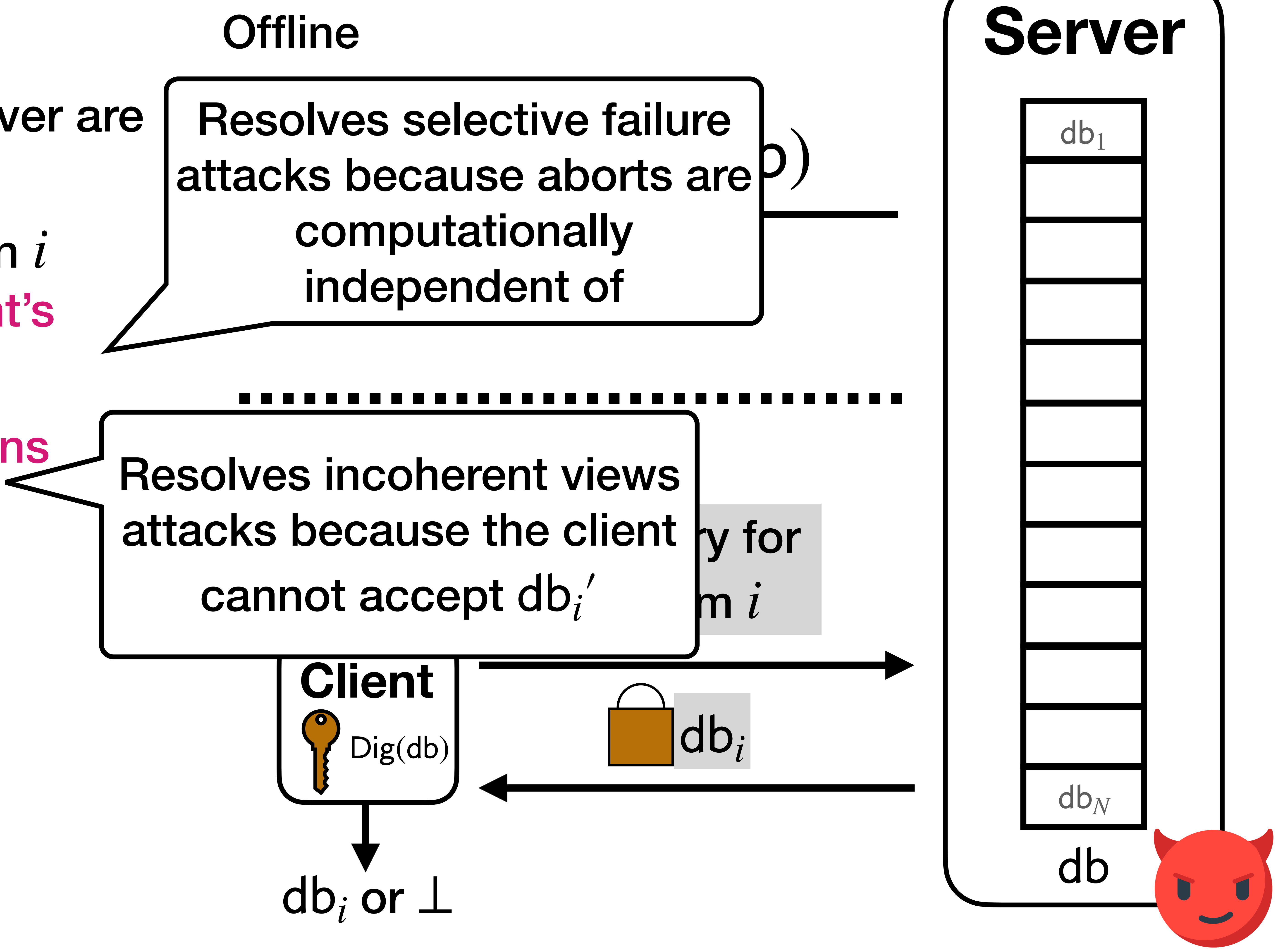

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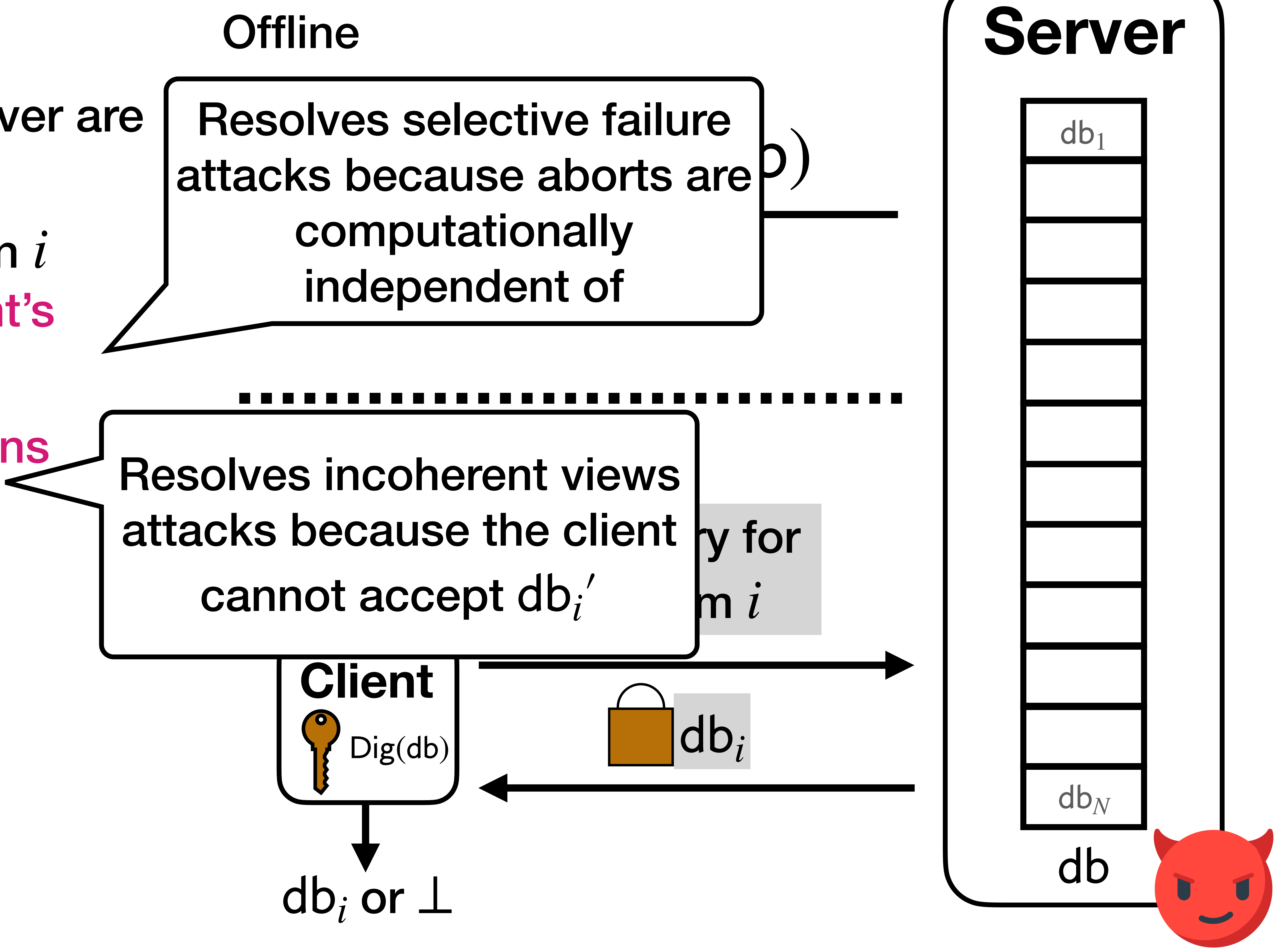

* Throughout this talk we assume the digest is produced honestly. In the paper we show how to work around that.

Prior work: are we done?

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Scheme	Communication	Computation	Digest size	Assumptions	Methodology
CNCWF23	$O\left(N^{1/2}\right)$	$O(N)$	$O\left(N^{1/2}\right)$	LWE, DDH	Ad-hoc
WZLY23*	$O\left(N^{1/2}\right)$	$O\left(N^{1/2}\right)$	$O\left(N^{1/2}\right)$	OWF*	Ad-hoc
DT23	$O\left(N^{1/2}\right)$	$O(N)$	$O\left(N^{1/2}\right)$	DDH	Ad-hoc
CL24	$O\left(N^{1/2}\right)$	$O(N)$	$O\left(N^{1/2}\right)$	LWE	Ad-hoc

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Gaps:

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Gaps:

1. Methodology: direct constructions

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Gaps:

1. Methodology: direct constructions
2. Assumptions: limited

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Gaps:

1. Methodology: direct constructions
2. Assumptions: limited
3. PIR Overhead: $\Omega\left(N^{1/2}\right)$

Contributions

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Theorem 1:
maliciousness compiler
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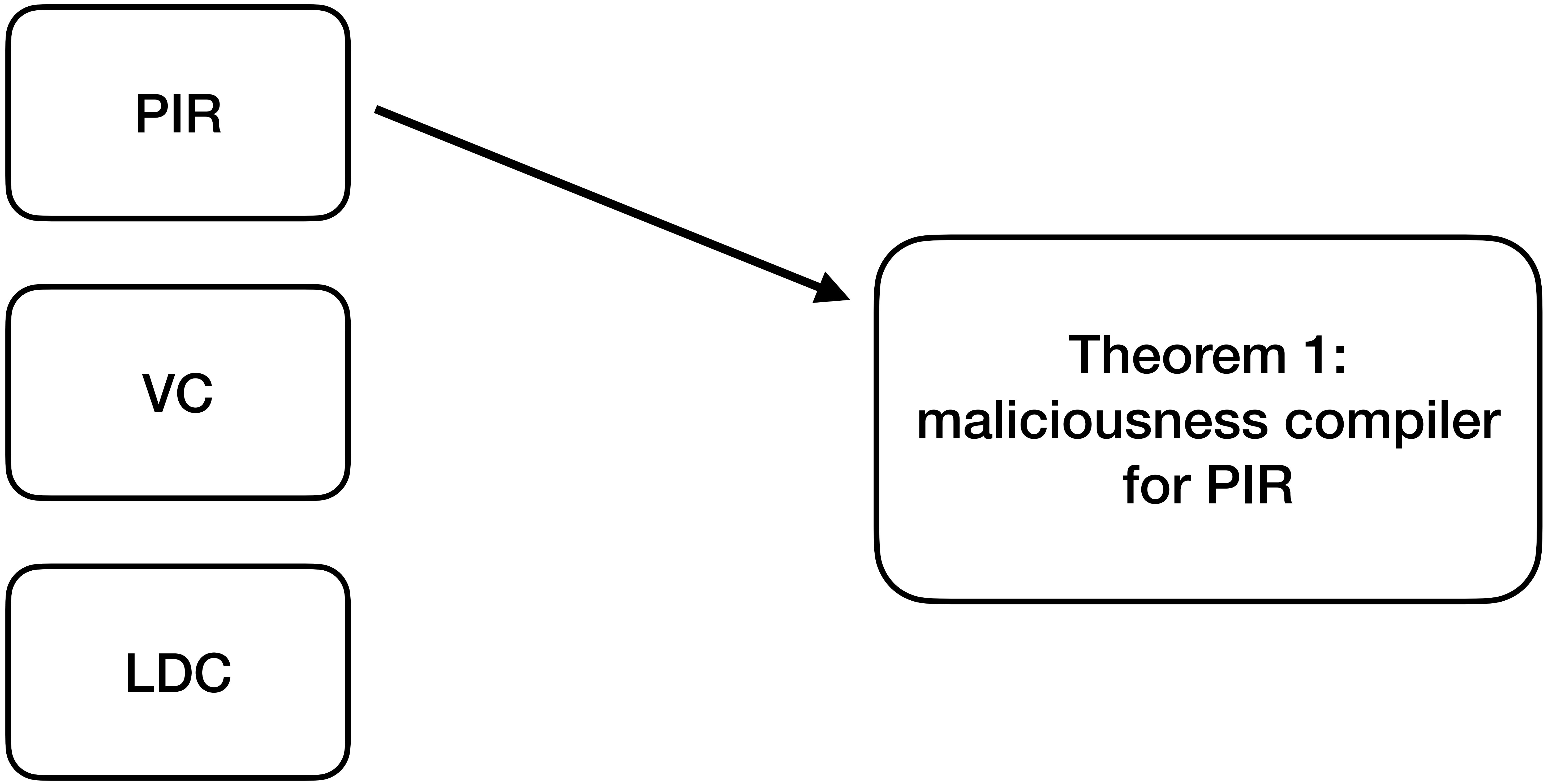
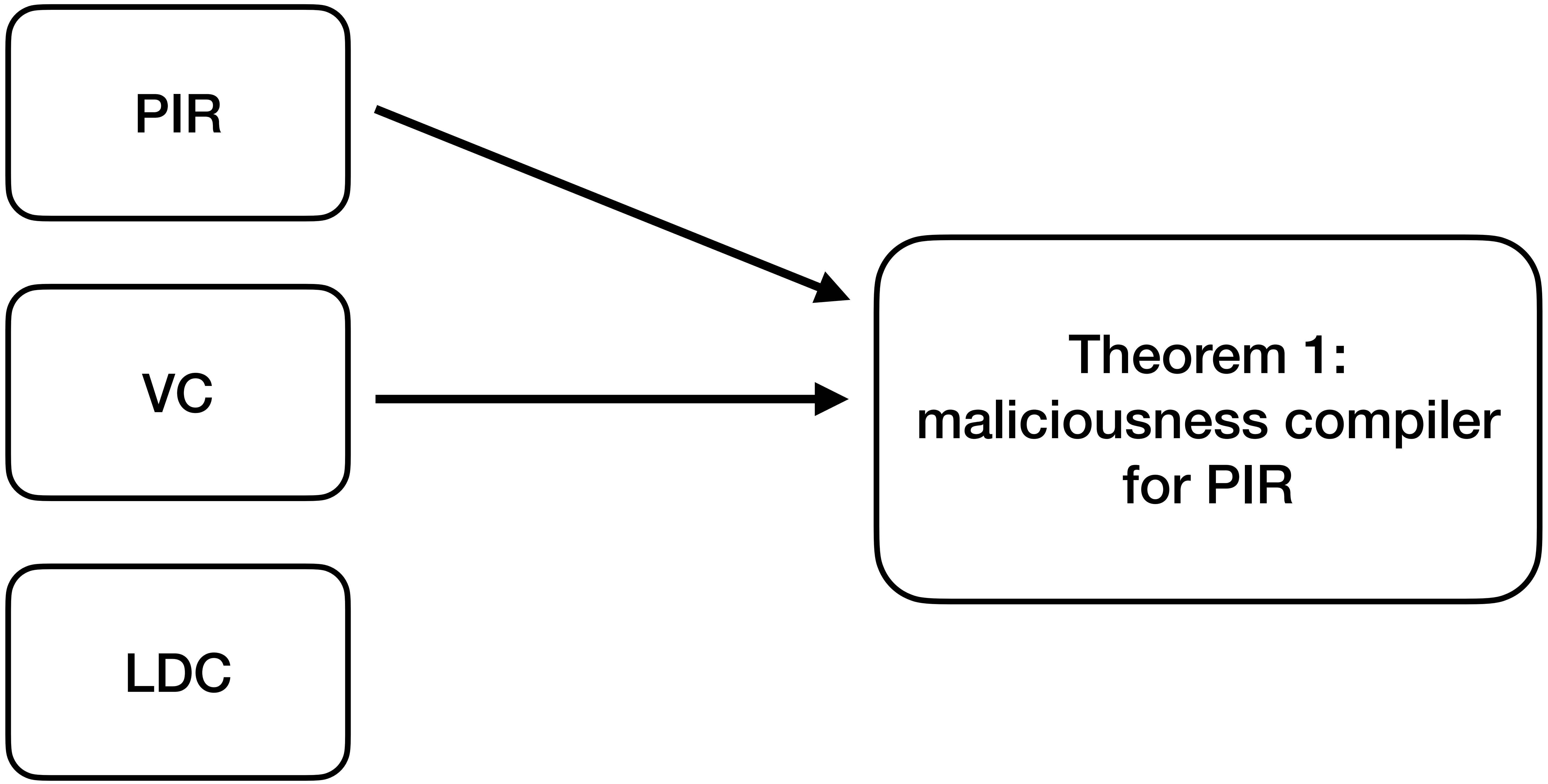
for PIR

Contributions



Contributions



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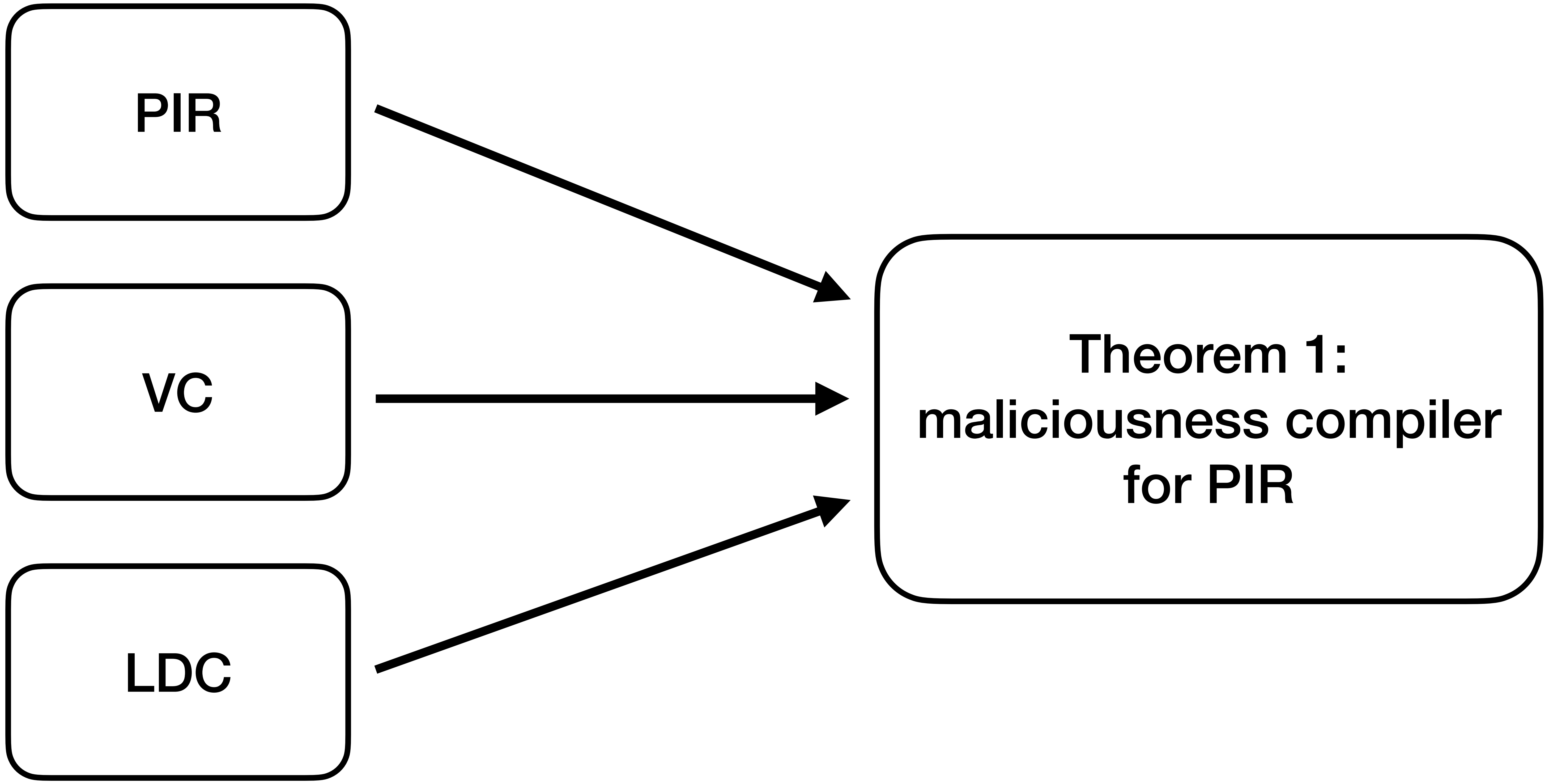
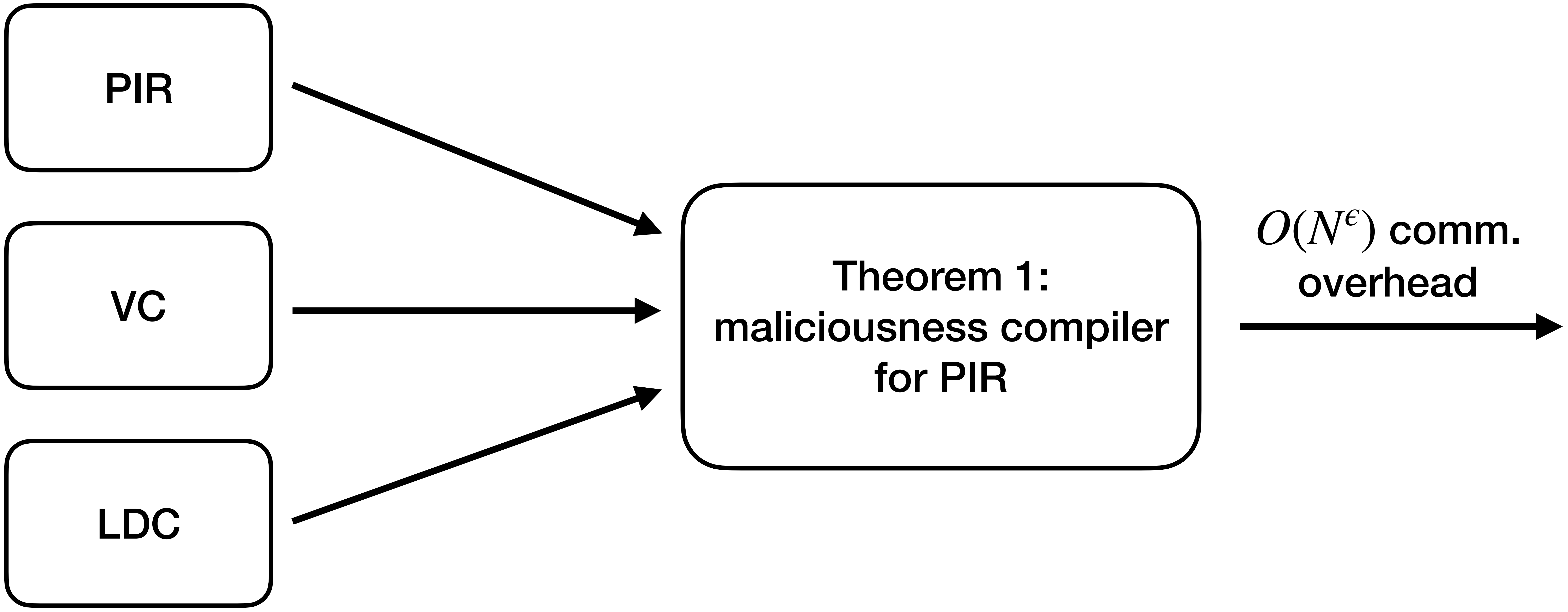
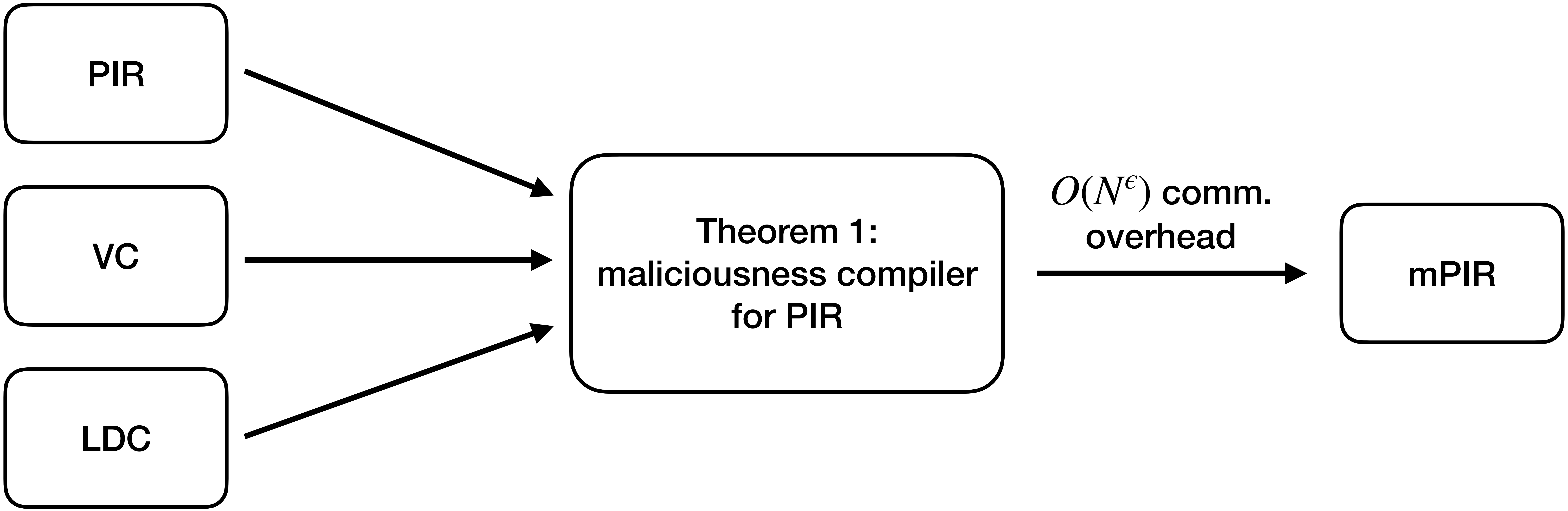


Contributions

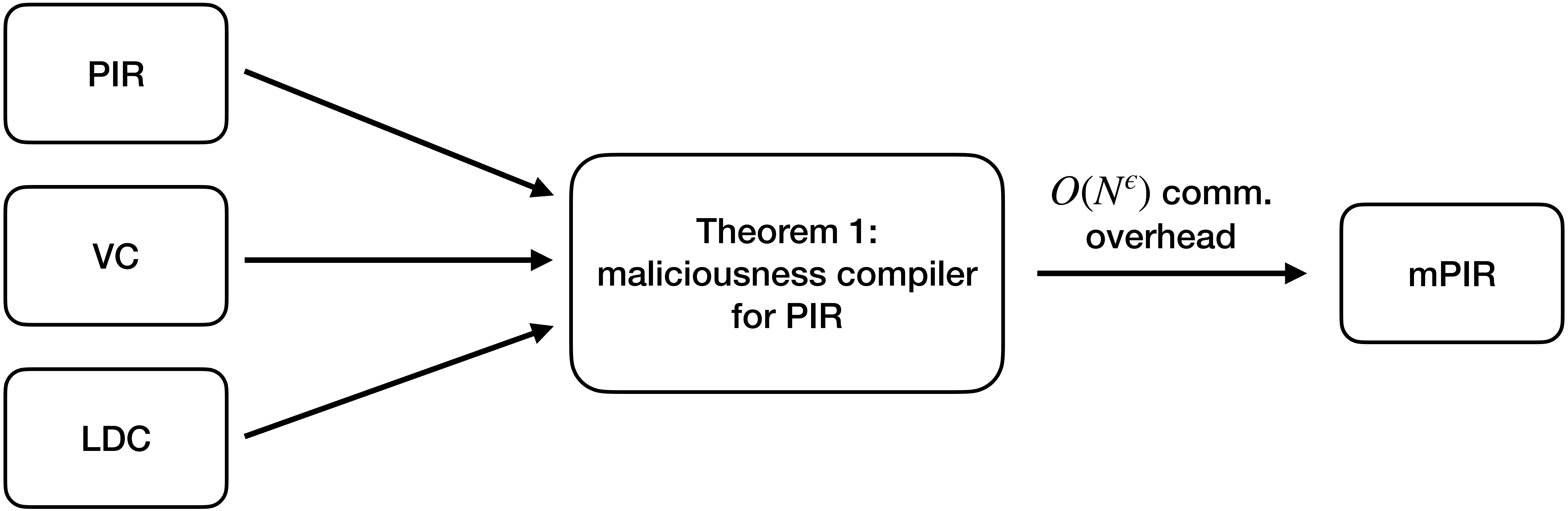


Contributions



Contributions

1. Methodology: generic compiler



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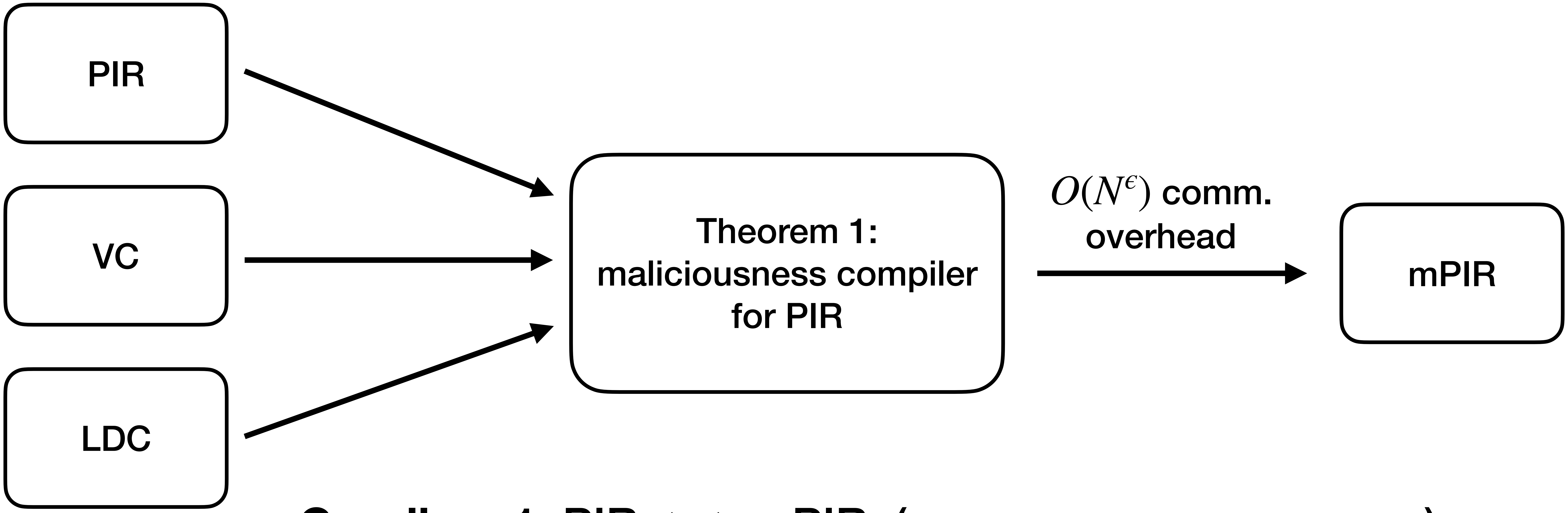
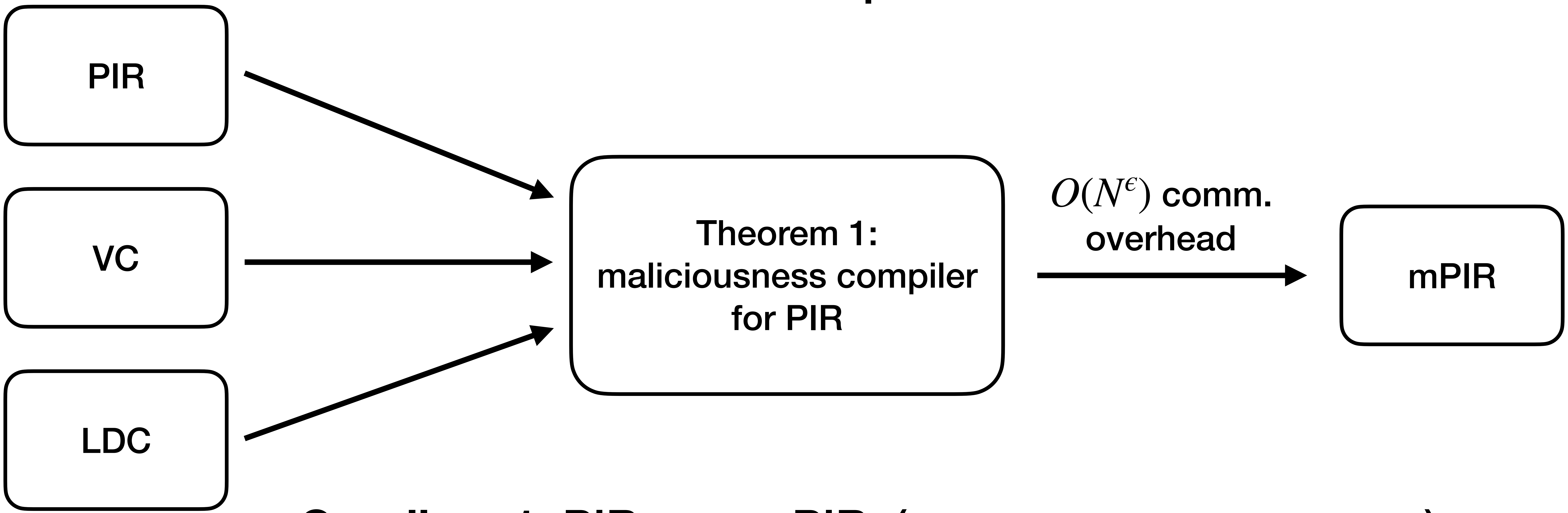


Corollary 1: PIR $\Longleftrightarrow$ mPIR (PIR $\Longrightarrow$ CRH $\Longrightarrow$ Merkle tree (VC))

Contributions

1. Methodology: generic compiler
2. Assumptions: from PIR



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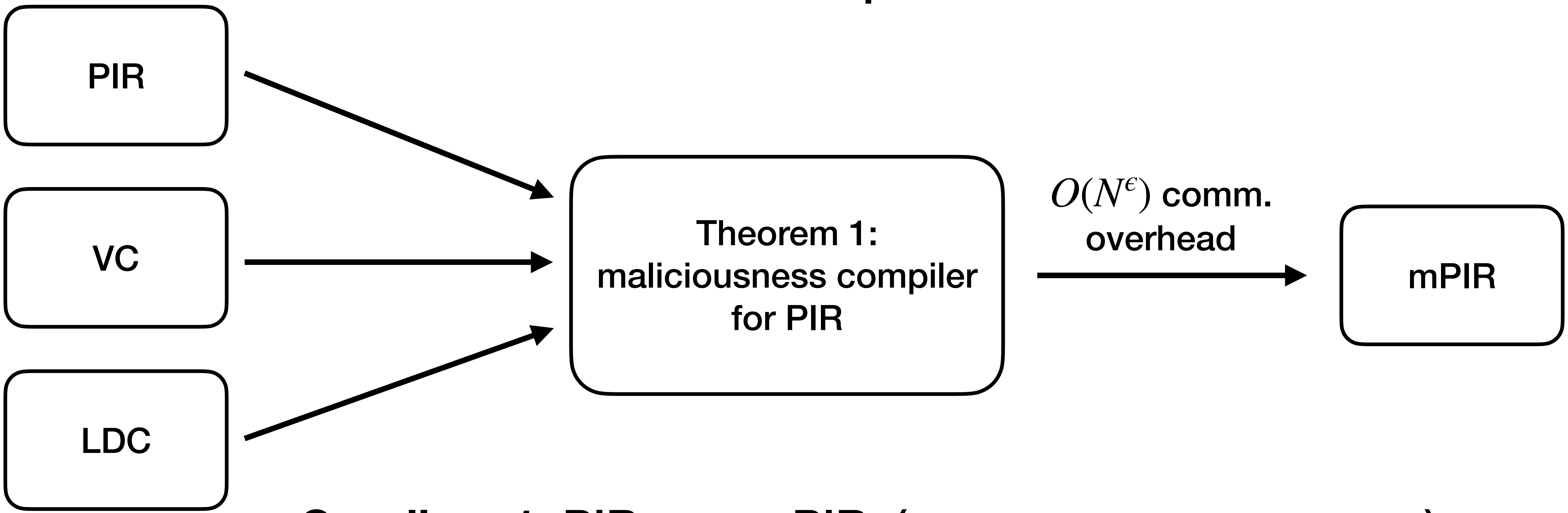
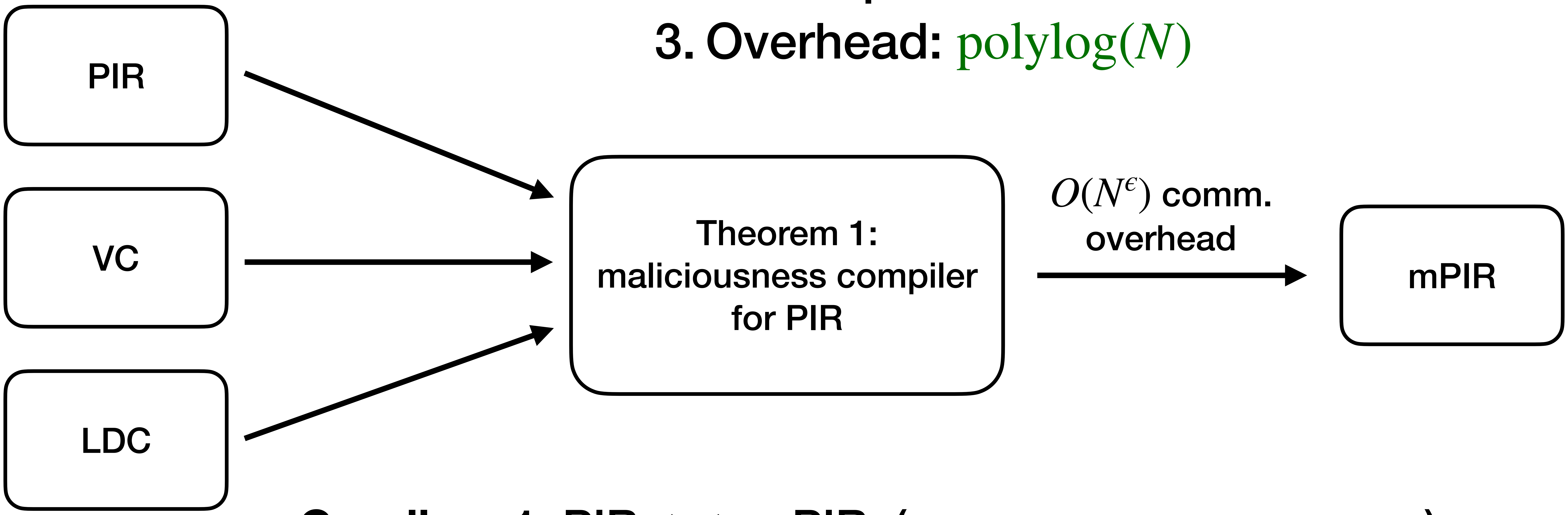


Corollary 1: PIR $\iff$ mPIR (PIR $\implies$ CRH $\implies$ Merkle tree (VC))

Theorem 2: there exists doubly-efficient ($\mathrm{polylog}(N)$) mPIR.

Contributions

1. Methodology: generic compiler
2. Assumptions: from PIR
3. Overhead: $\mathrm{polylog}(N)$



Corollary 1: PIR $\Longleftrightarrow$ mPIR (PIR $\Longrightarrow$ CRH $\Longrightarrow$ Merkle tree (VC))

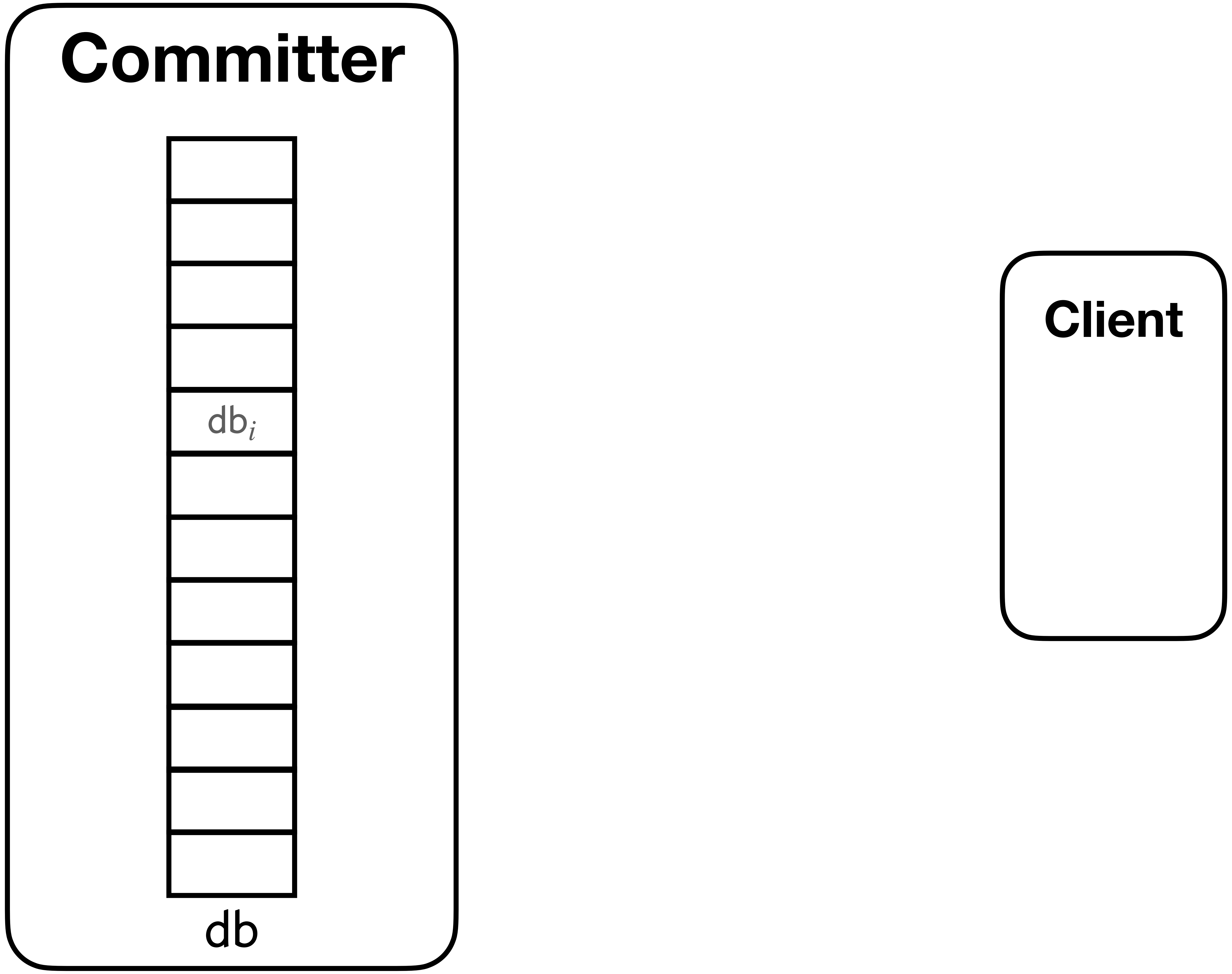
Theorem 2: there exists doubly-efficient ($\mathrm{polylog}(N)$) mPIR.

Contributions

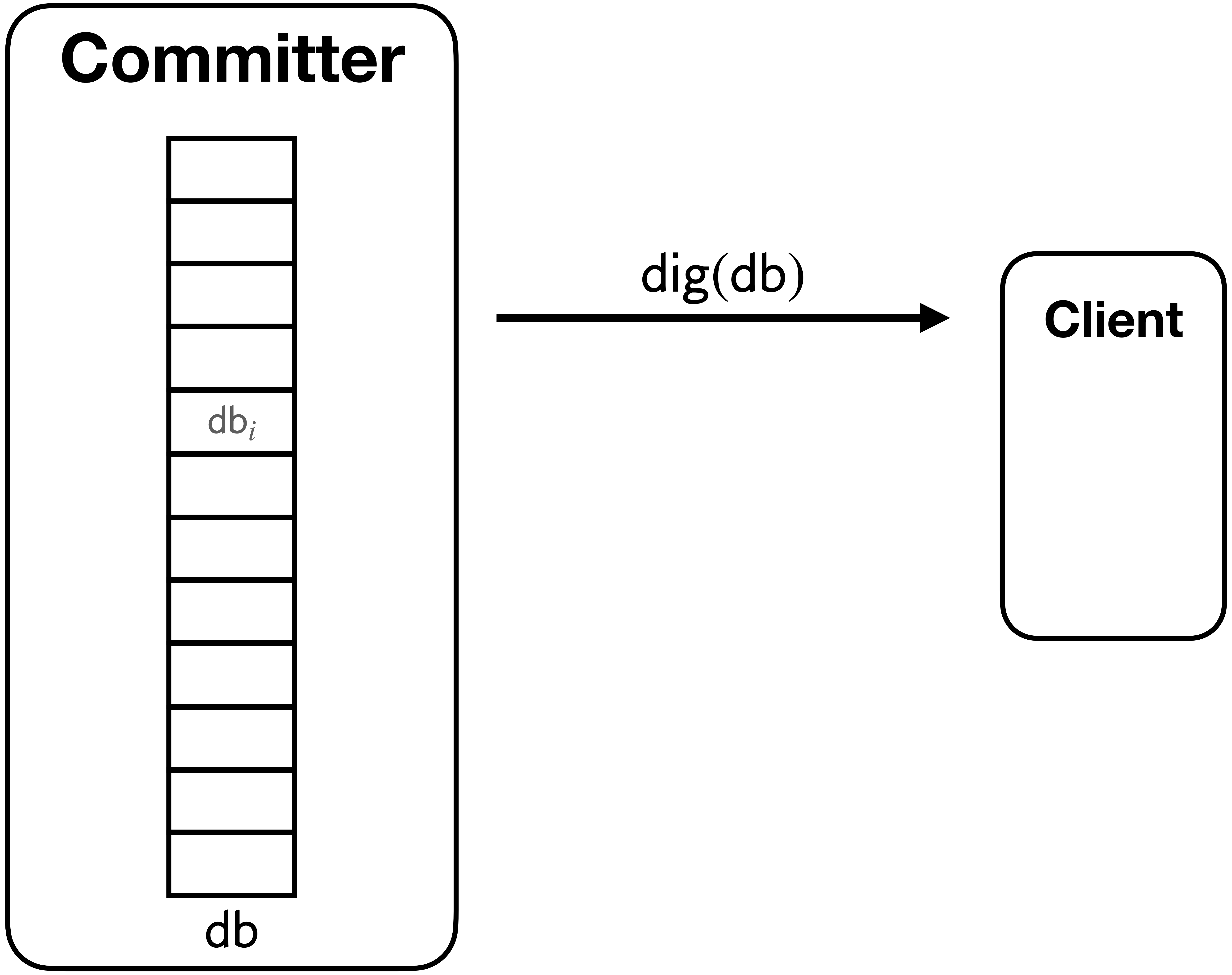
Scheme	Communication	Computation	Digest	Assumptions	Methodology
CNCWF23	$O\left(N^{1/2}\right)$	$O\left(N\right)$	$O\left(N^{1/2}\right)$	LWE, DDH	Ad-hoc
WZLY23	$O\left(N^{1/2}\right)$	$O\left(N^{1/2}\right)$	$O\left(N^{1/2}\right)$	OWF*	Ad-hoc
DT23	$O\left(N^{1/2}\right)$	$O\left(N\right)$	$O\left(N^{1/2}\right)$	DDH	Ad-hoc
CL24	$O\left(N^{1/2}\right)$	$O\left(N\right)$	$O\left(N^{1/2}\right)$	LWE	Ad-hoc
Ours (any PIR)	$\times O\left(N^{\epsilon}\right)$	$\times O(1)$	$\omega(\log N)$	PIR	Compiler
Ours (DePIR)	$O(\text{polylog } N)$	$O(\text{polylog } N)$	$\omega(\log N)$	RingLWE	Compiler

Construction

Vector Commitments (VC)



Vector Commitments (VC)



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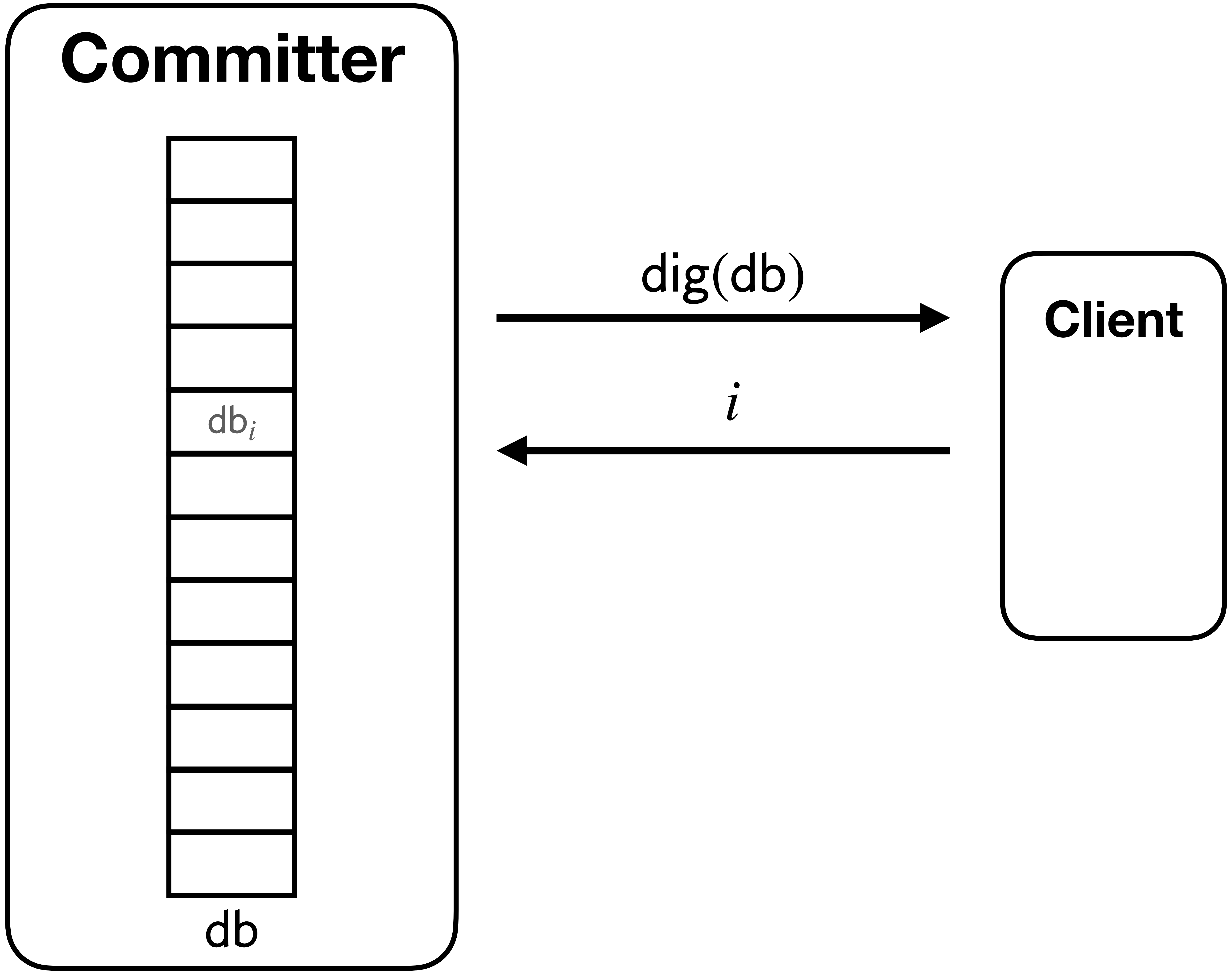

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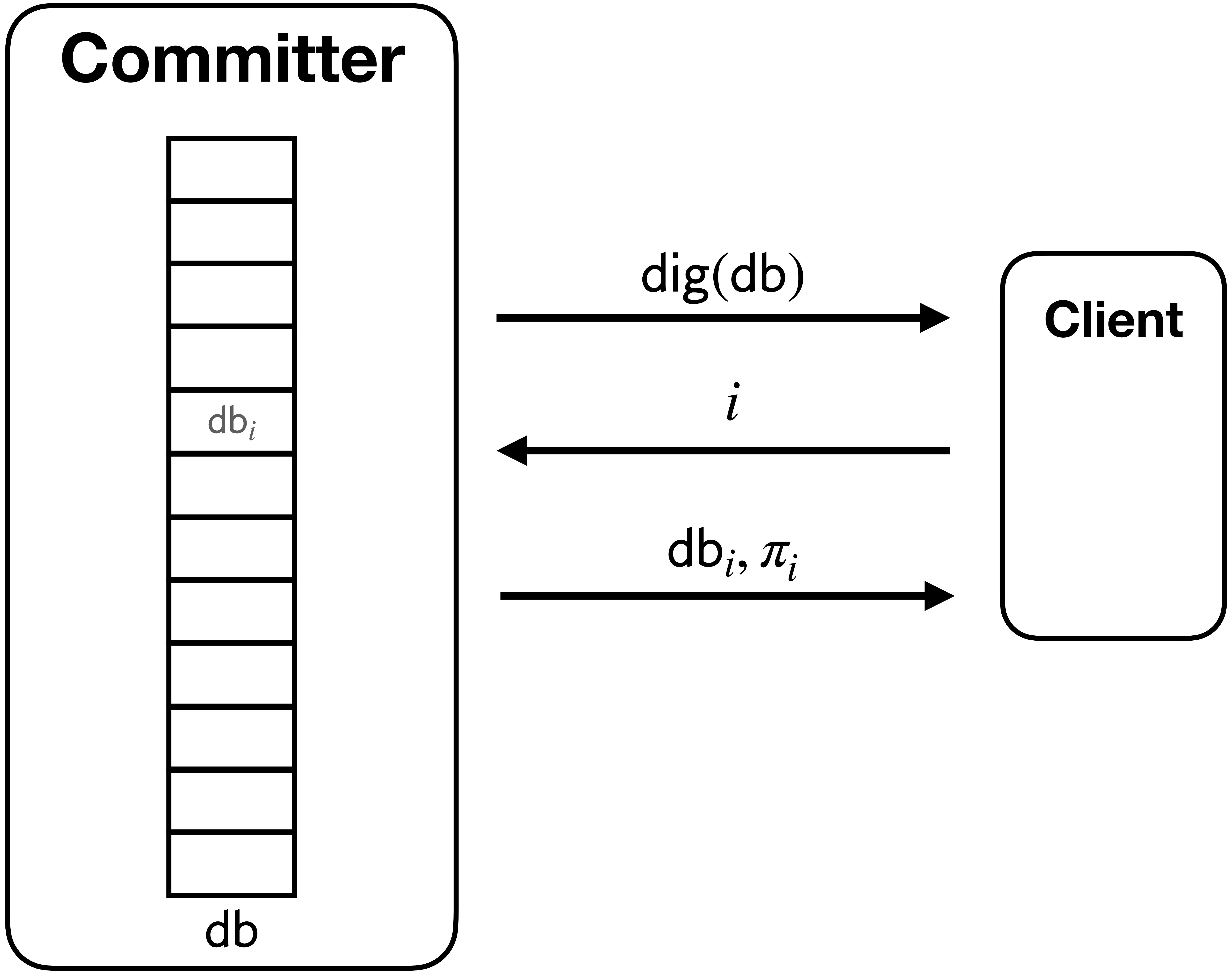
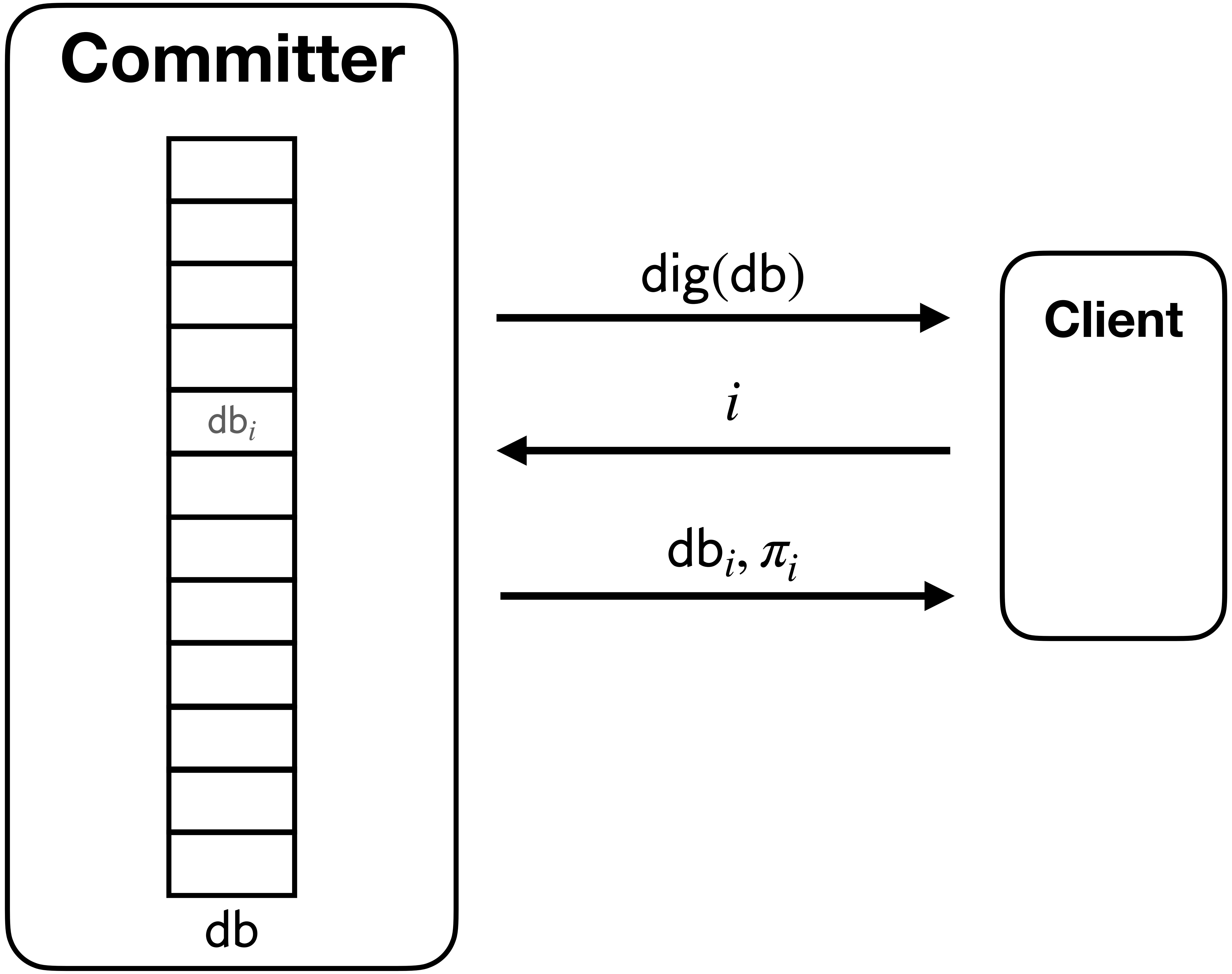


Vector Commitments (VC)

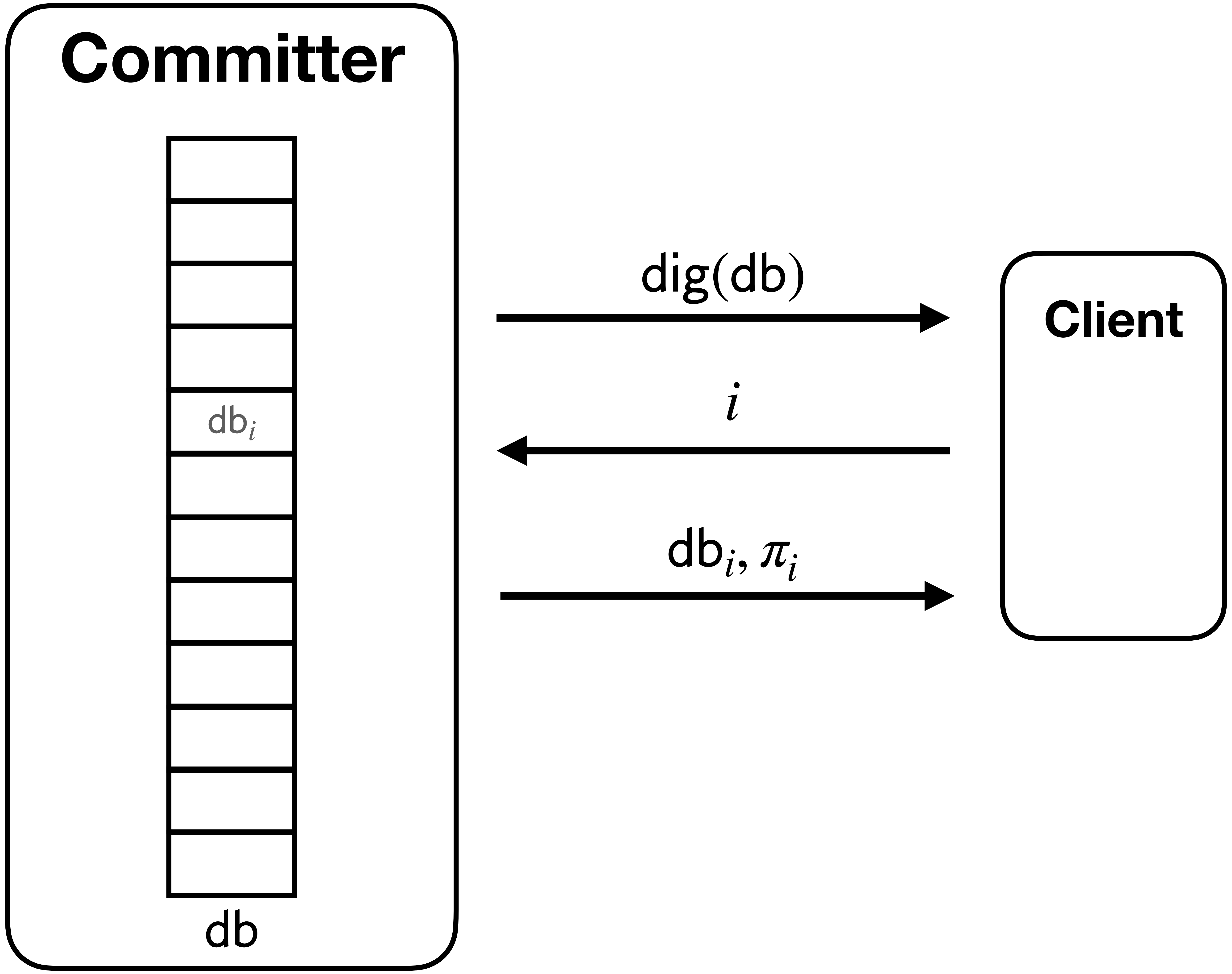
Properties:



Vector Commitments (VC)

Properties:

1. Completeness: honest committer convinces



Vector Commitments (VC)

Properties:

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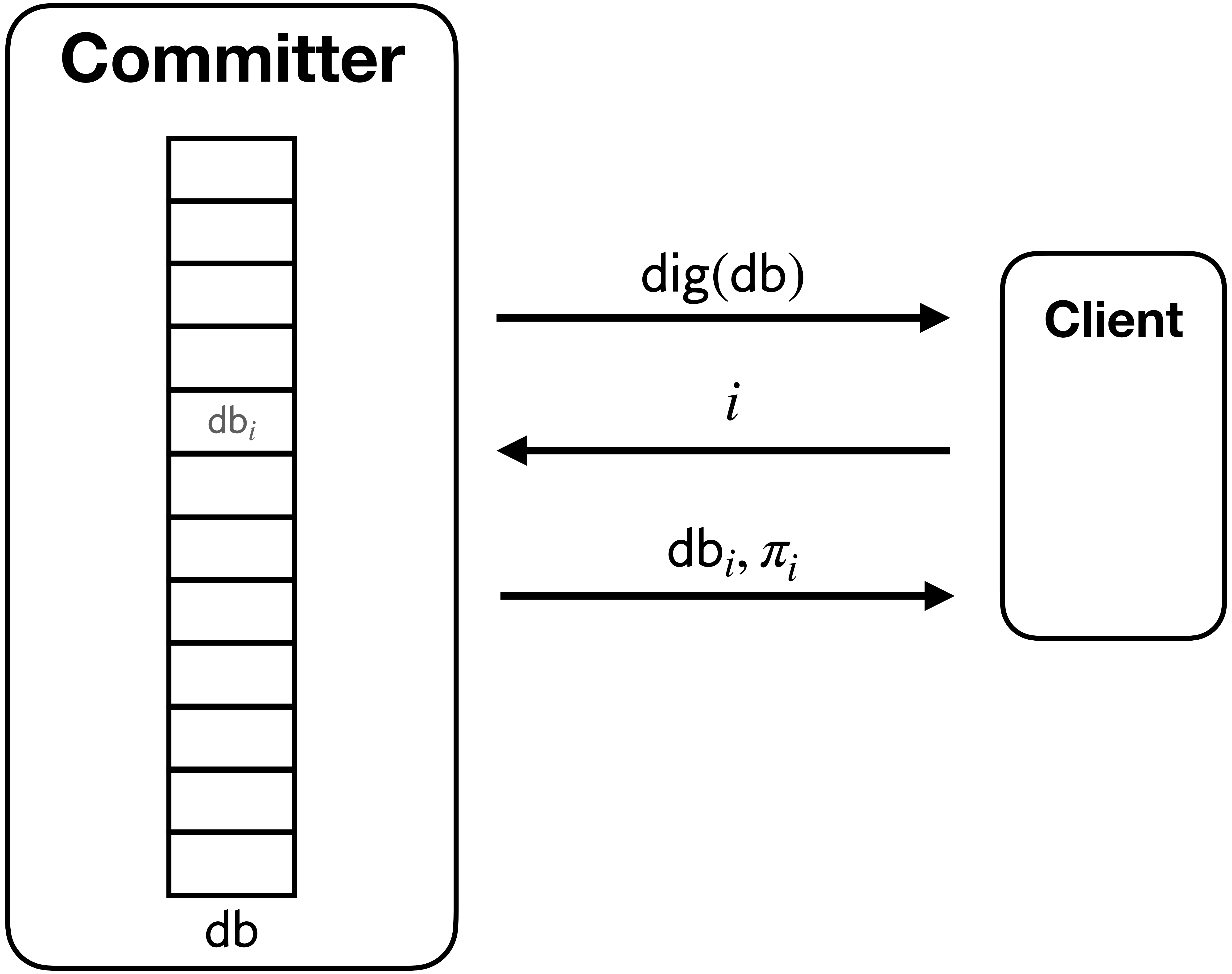
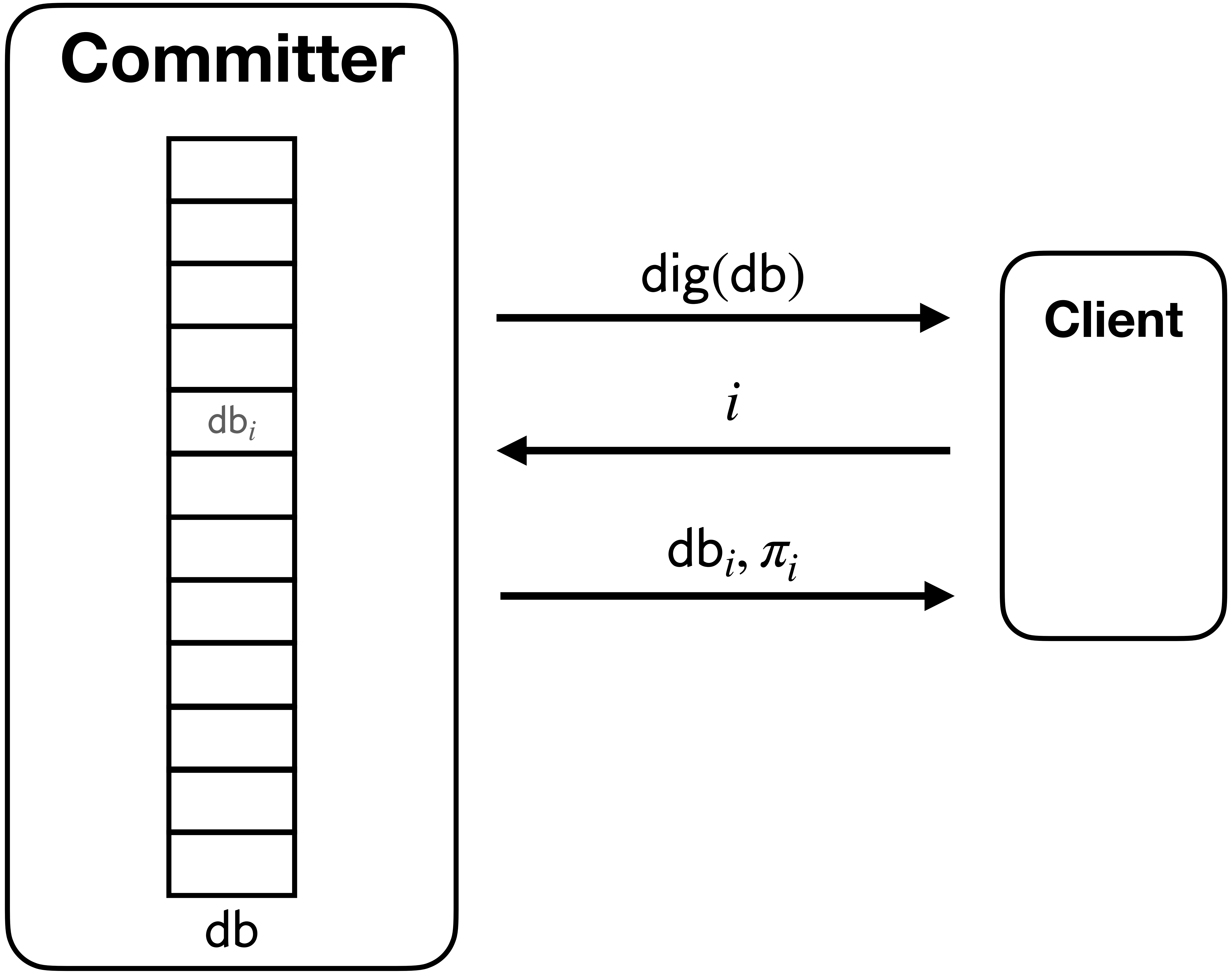


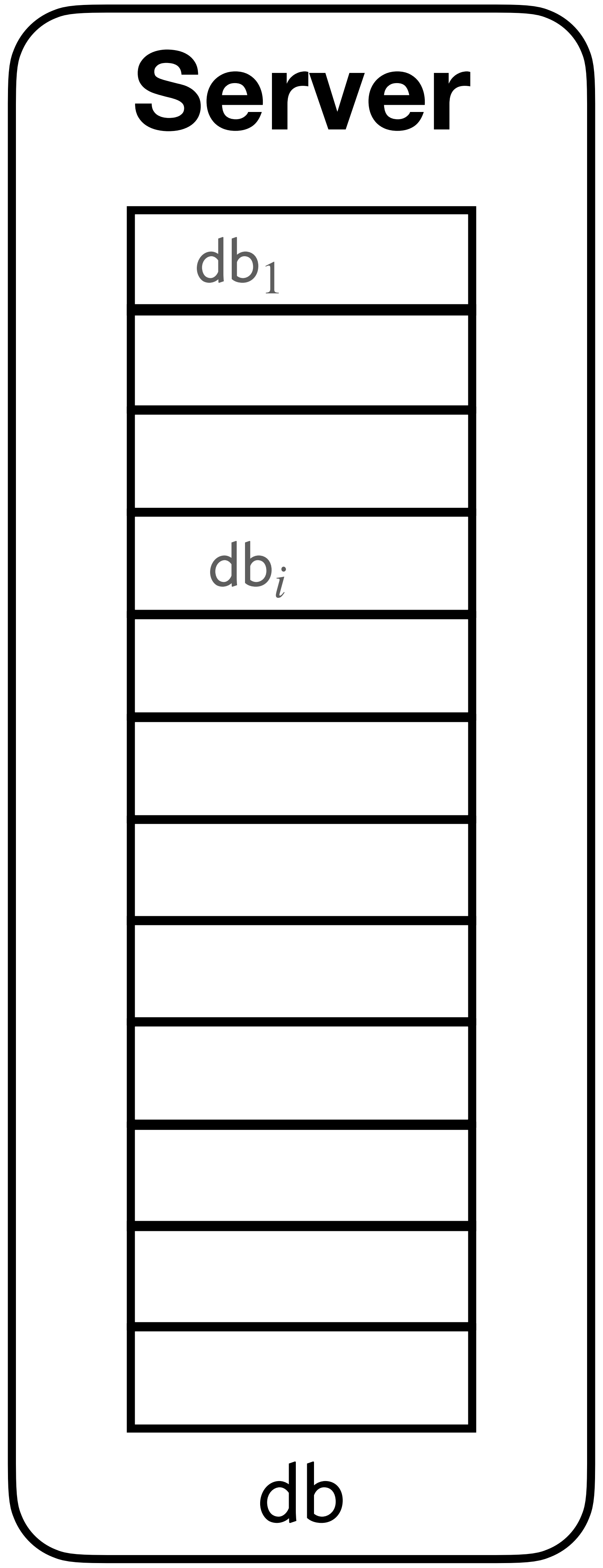
Vector Commitments (VC)

Properties:

1. Completeness: honest committer convinces
2. Soundness: cannot provide different openings for i
3. Efficiency: small $\mathrm{dig}(\mathrm{db})$, π_i



Attempt 1: VC + PIR



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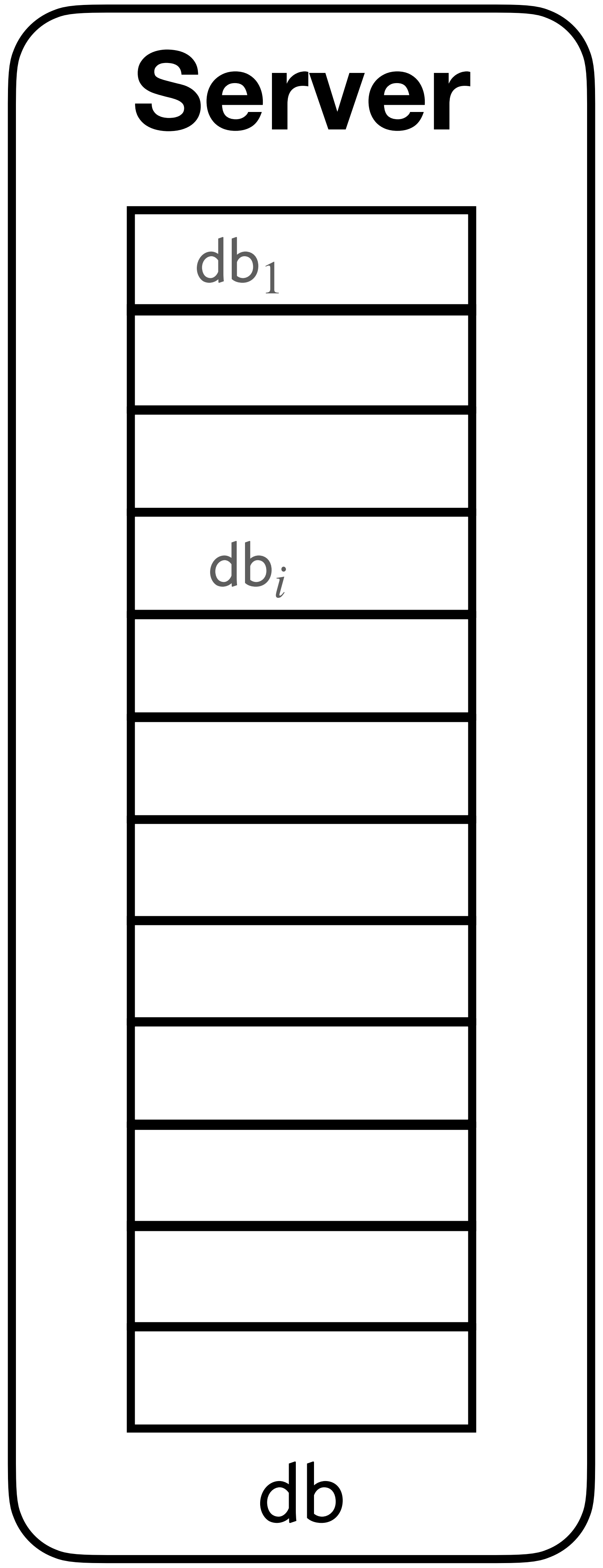
Offline



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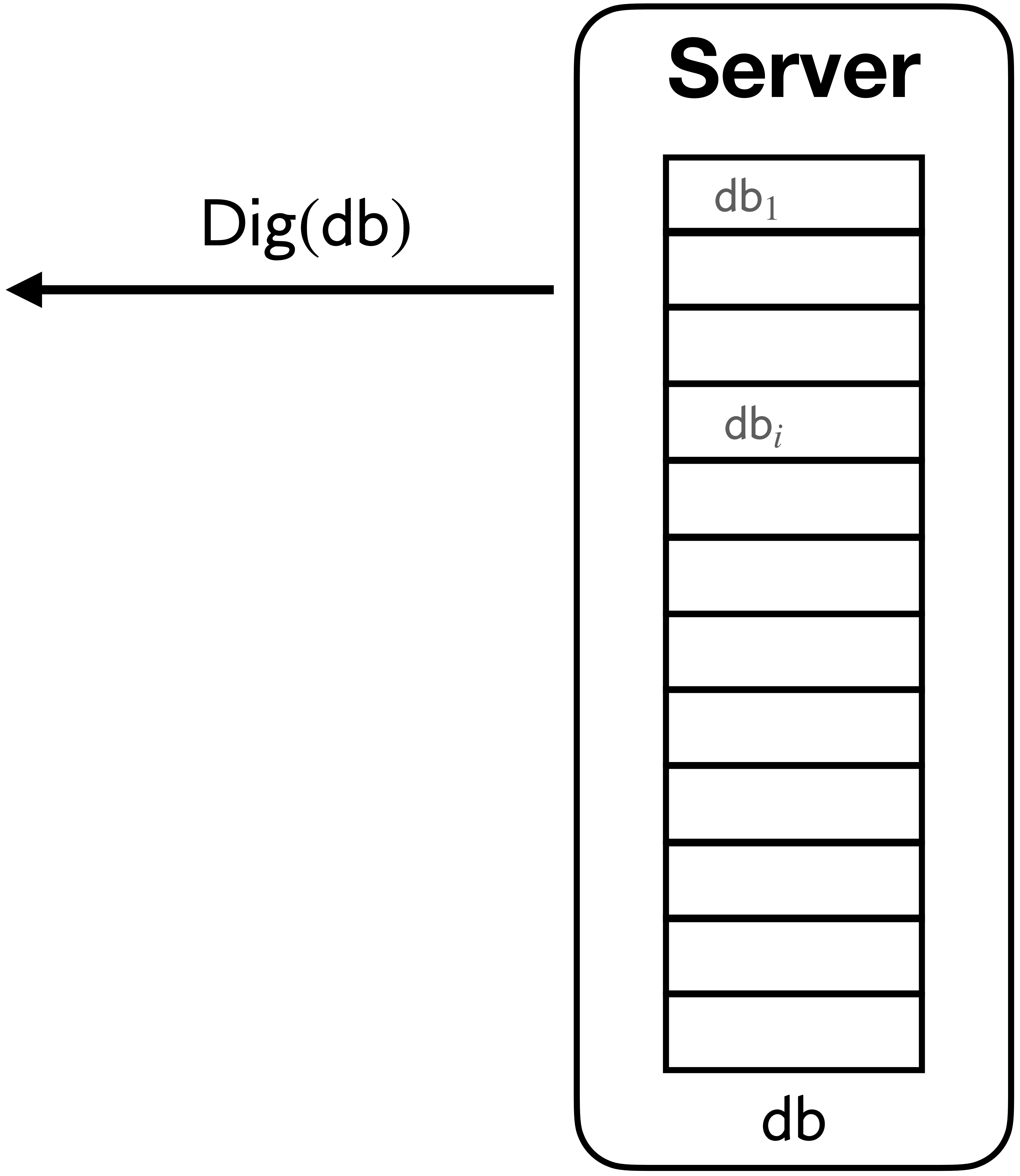

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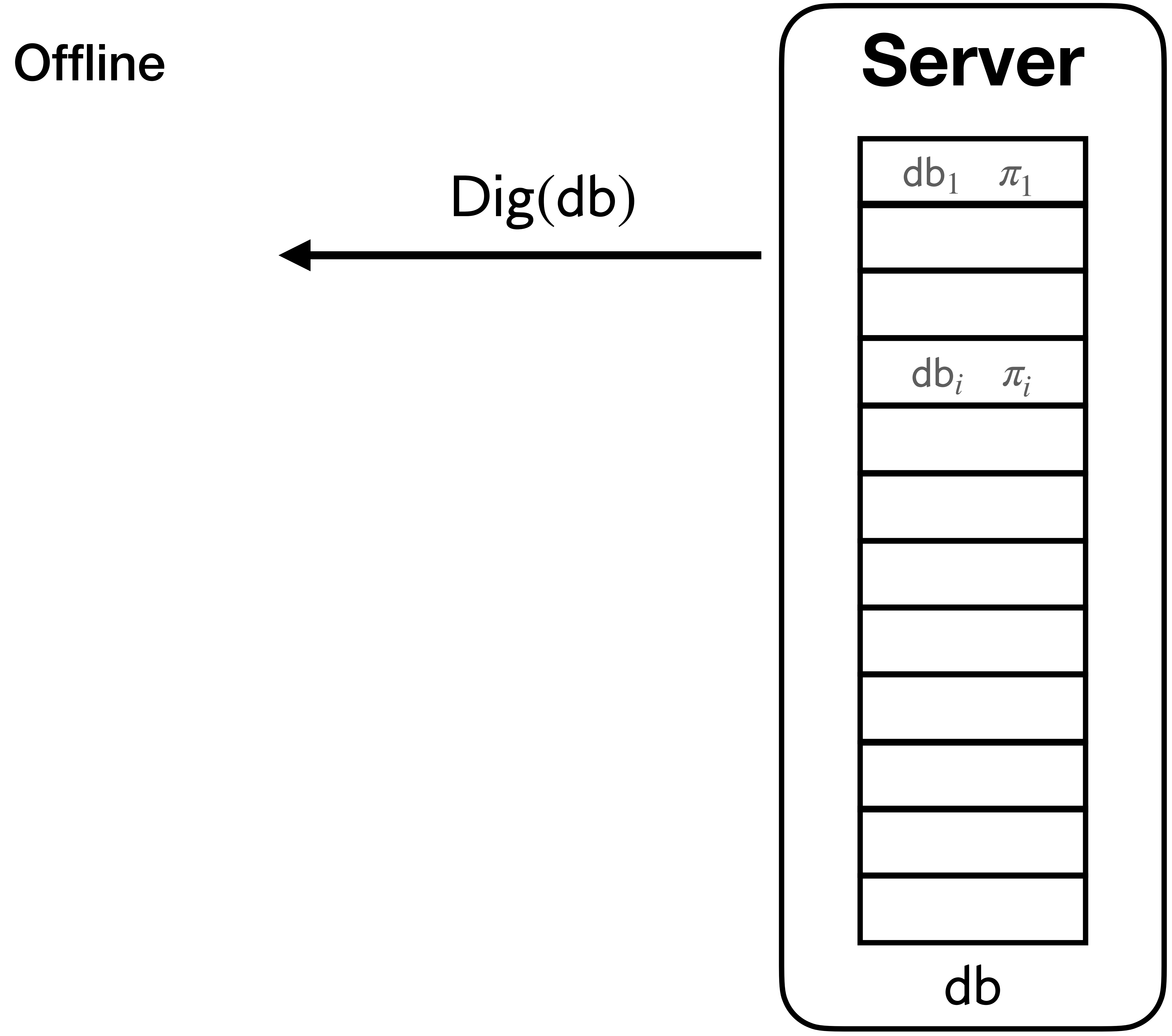

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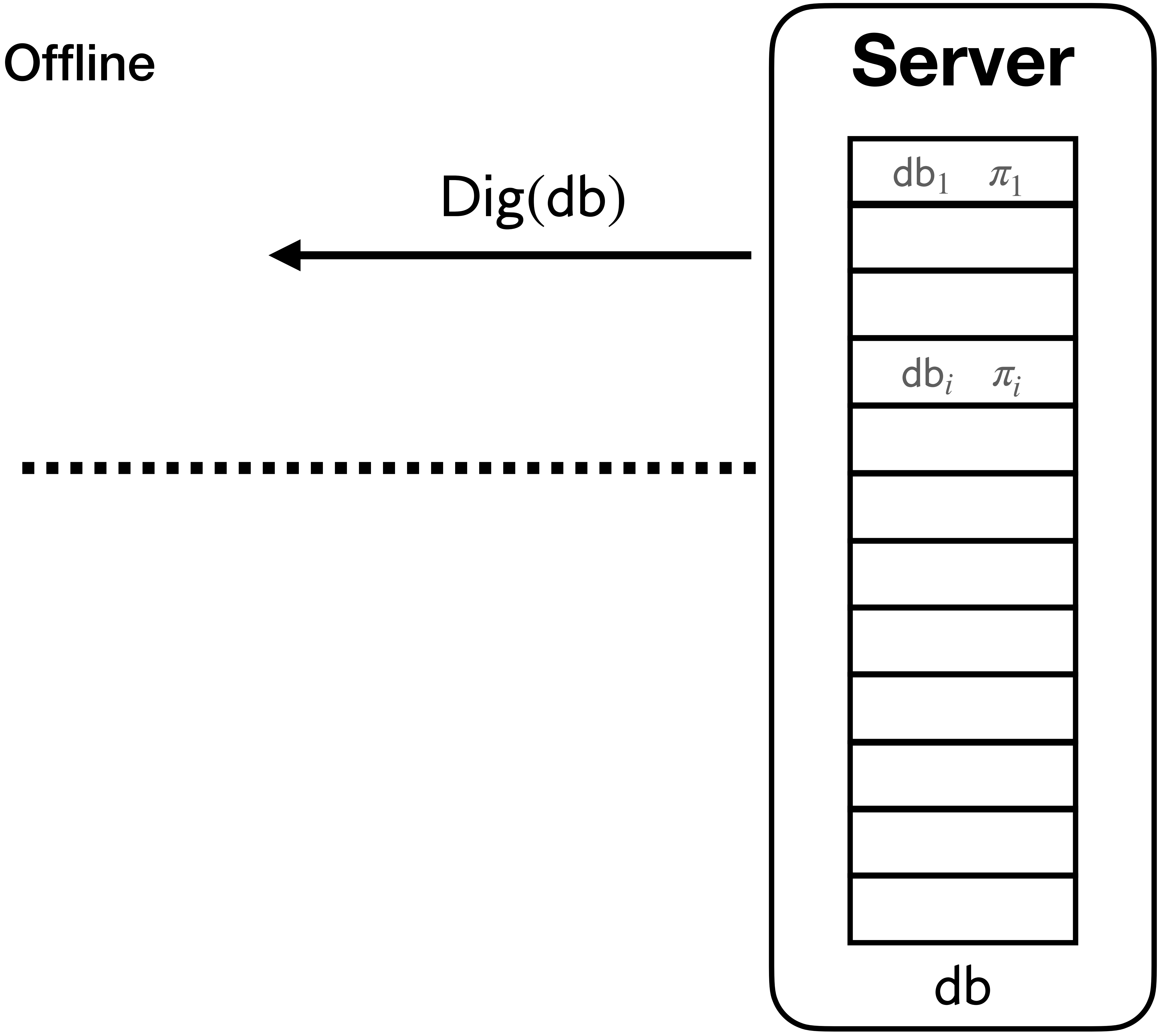

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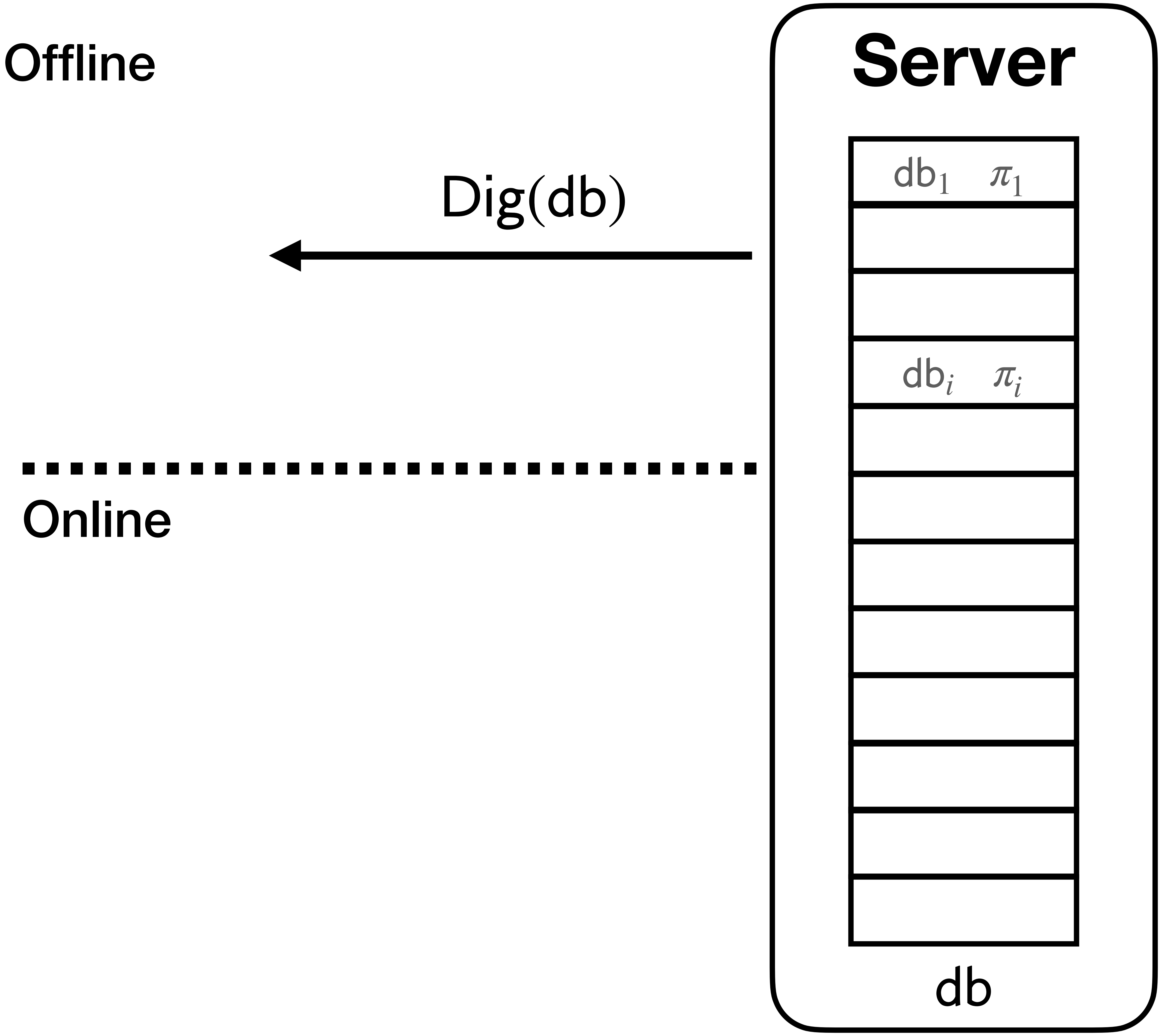

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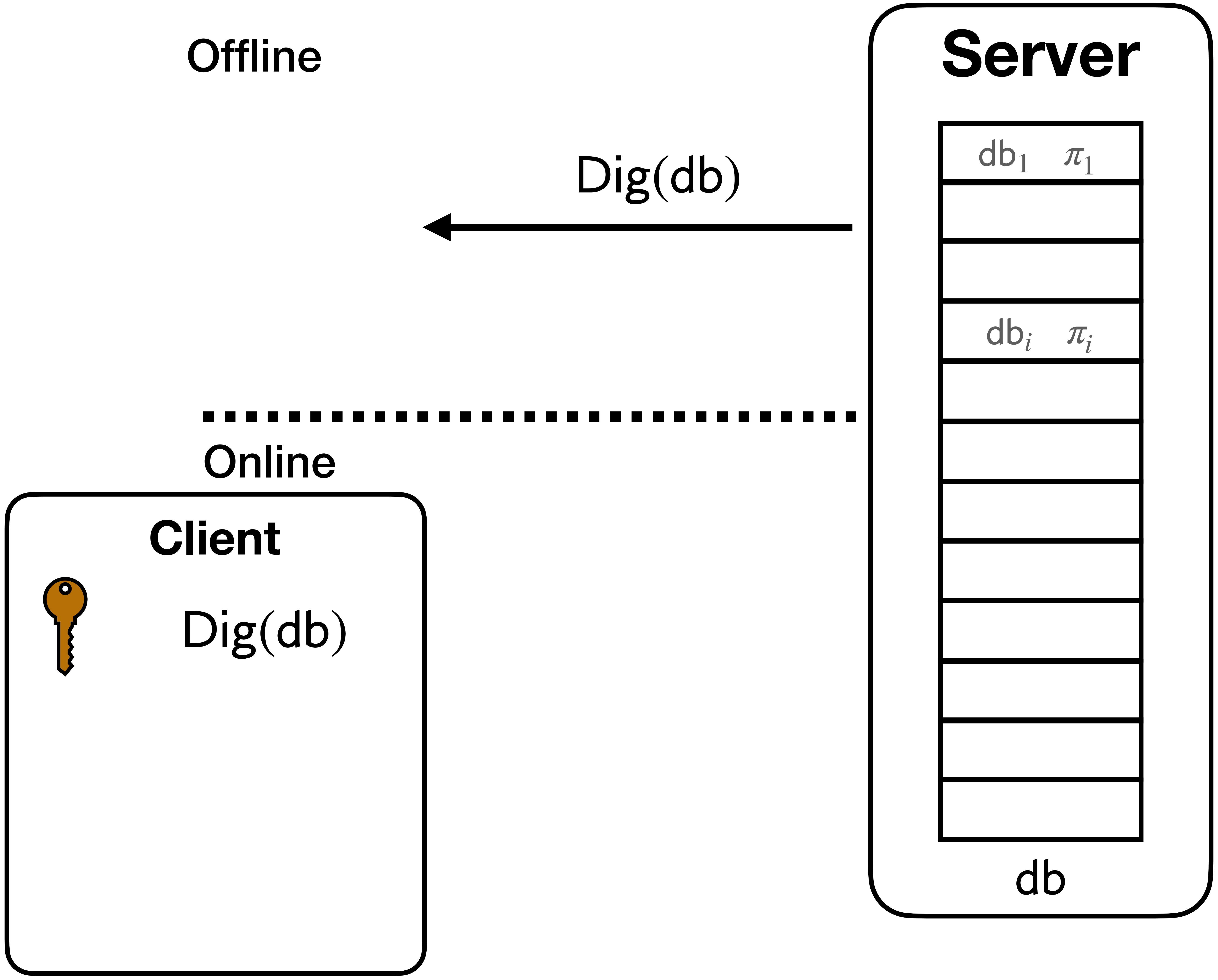

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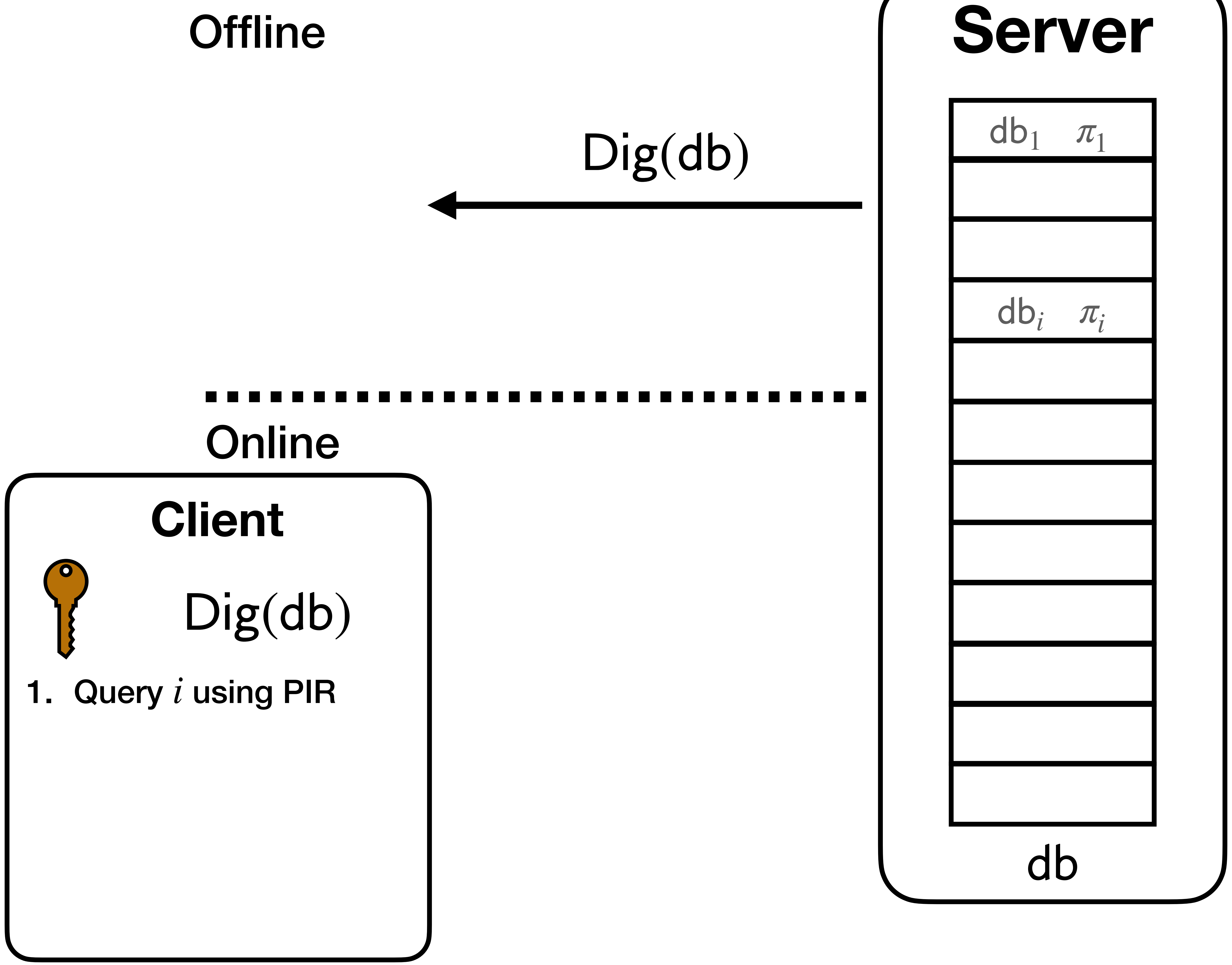

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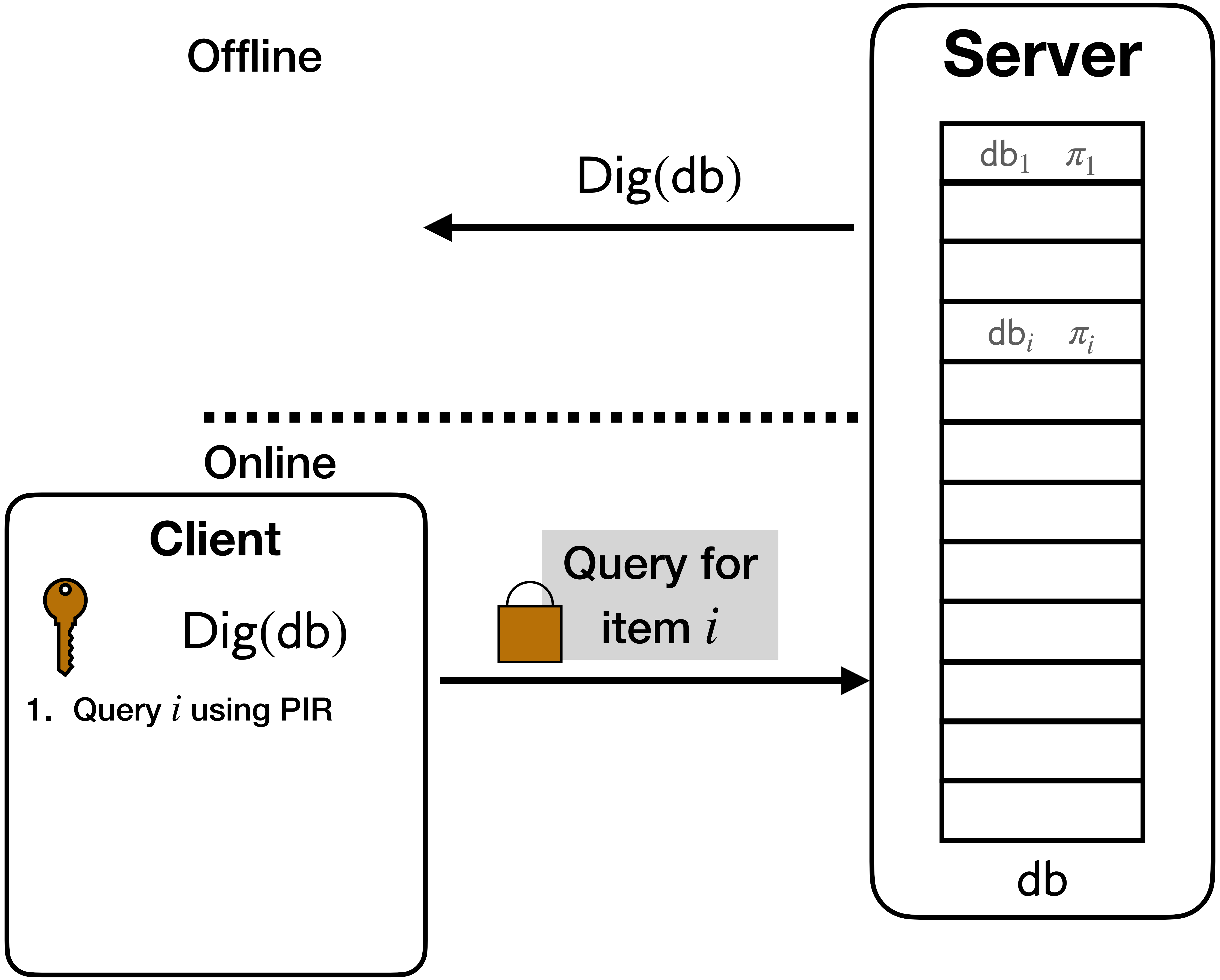

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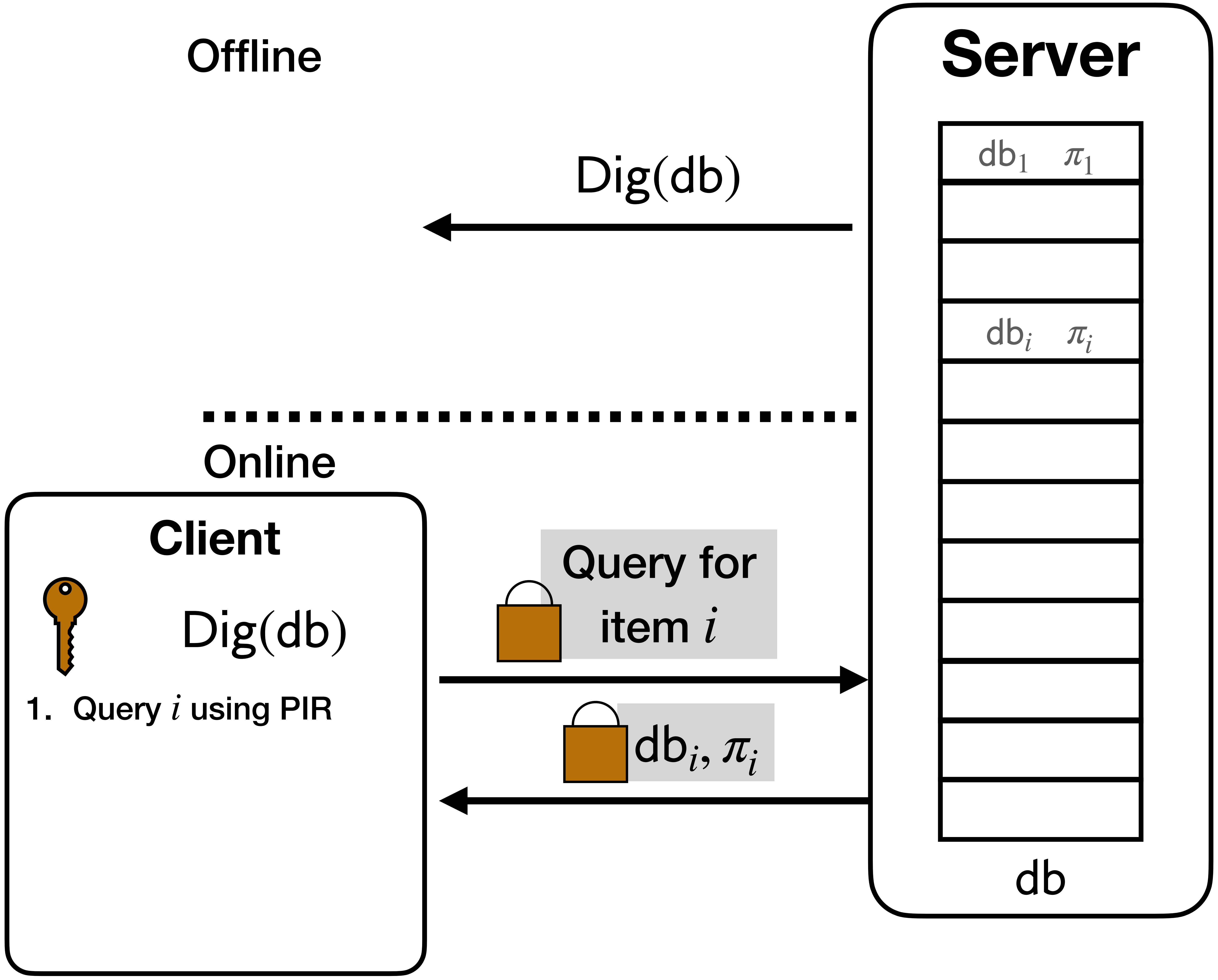

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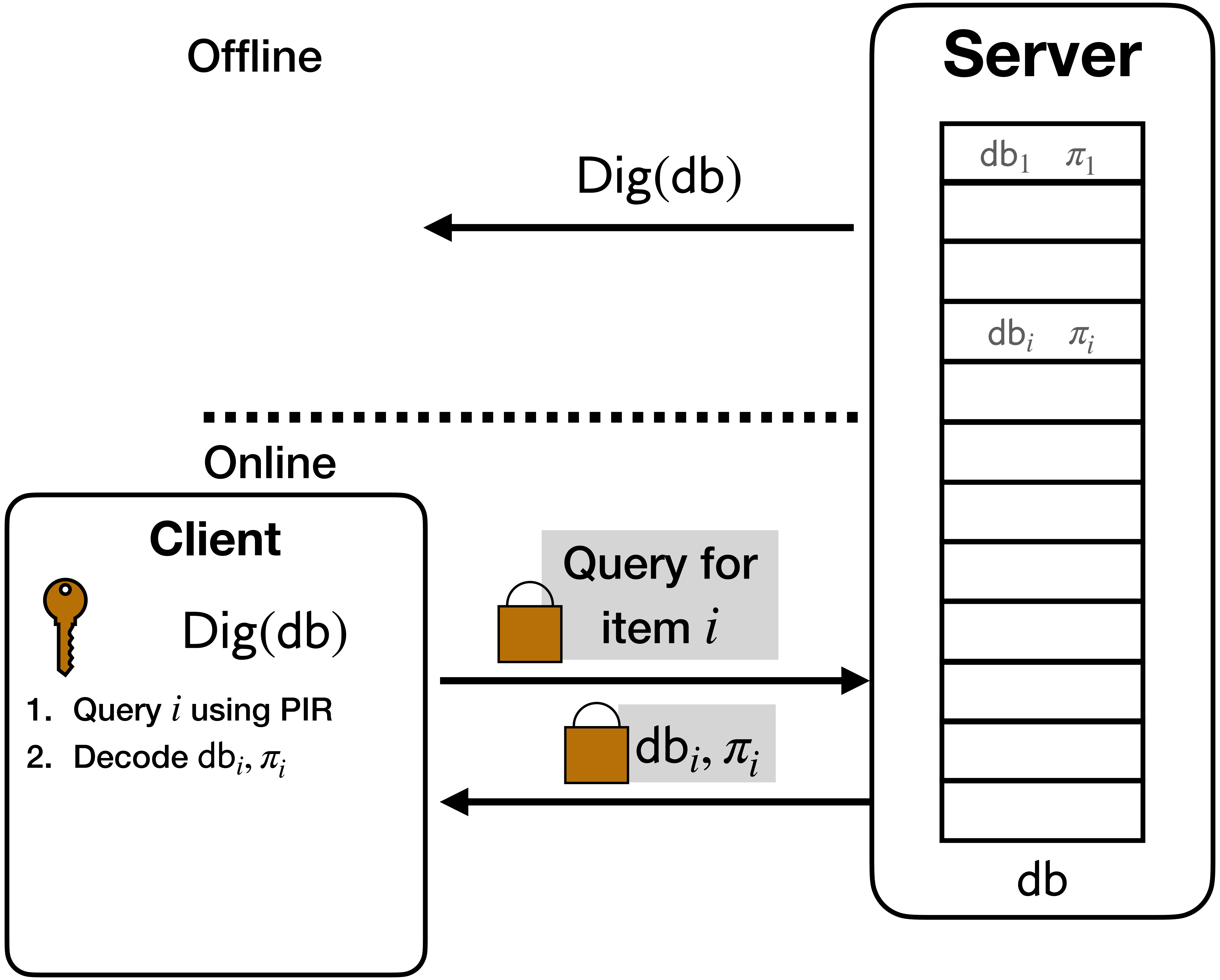

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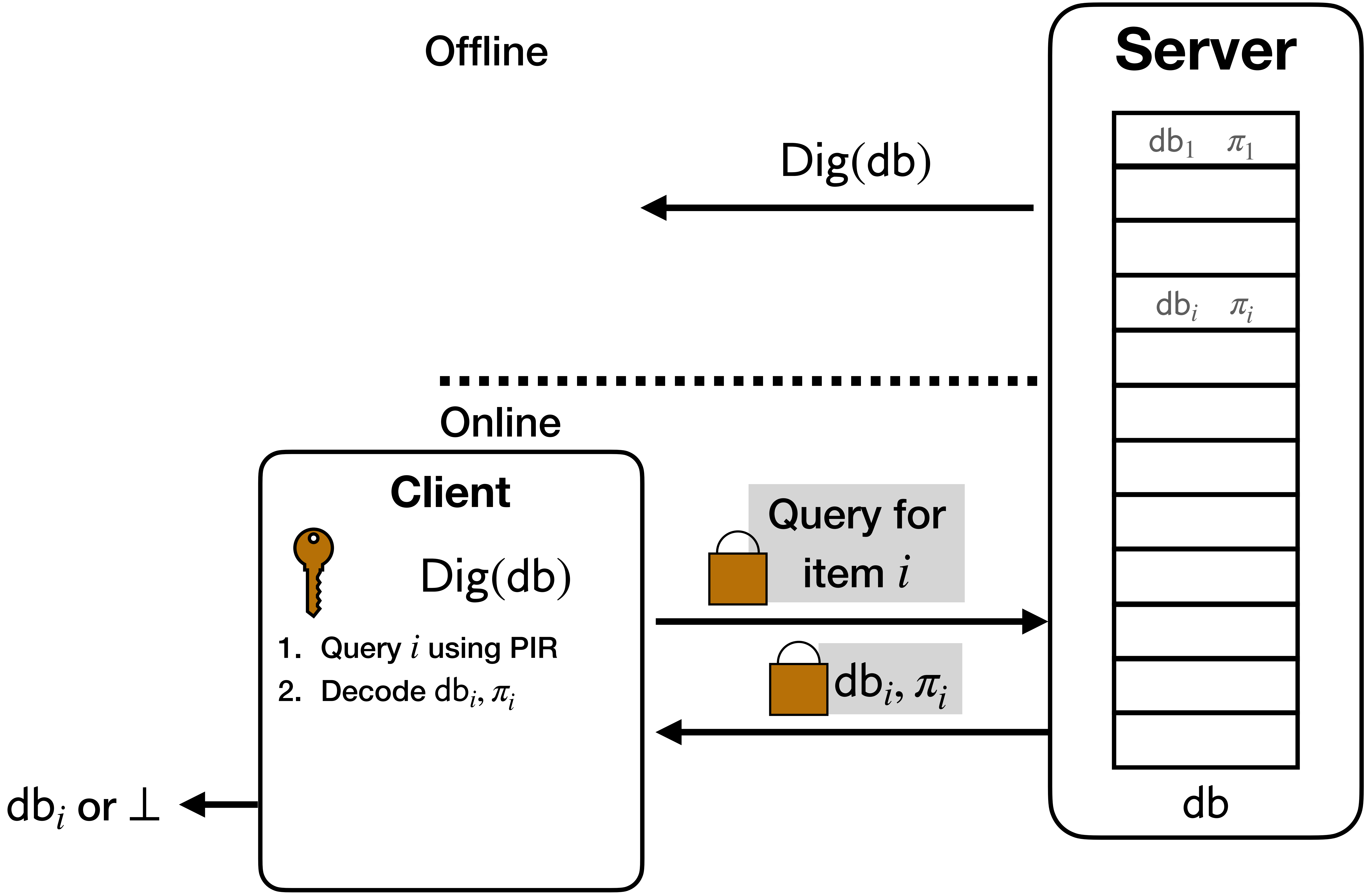

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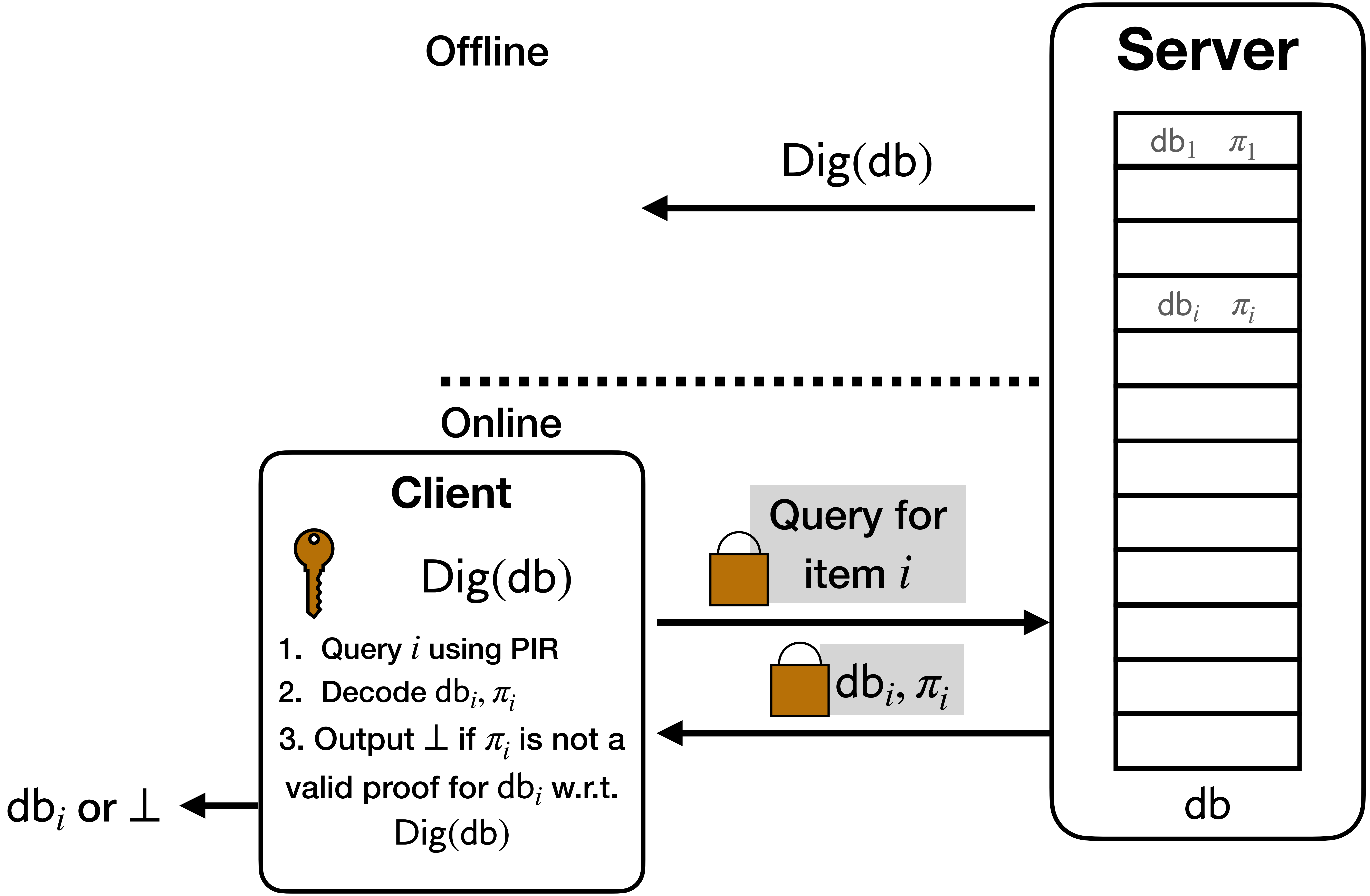

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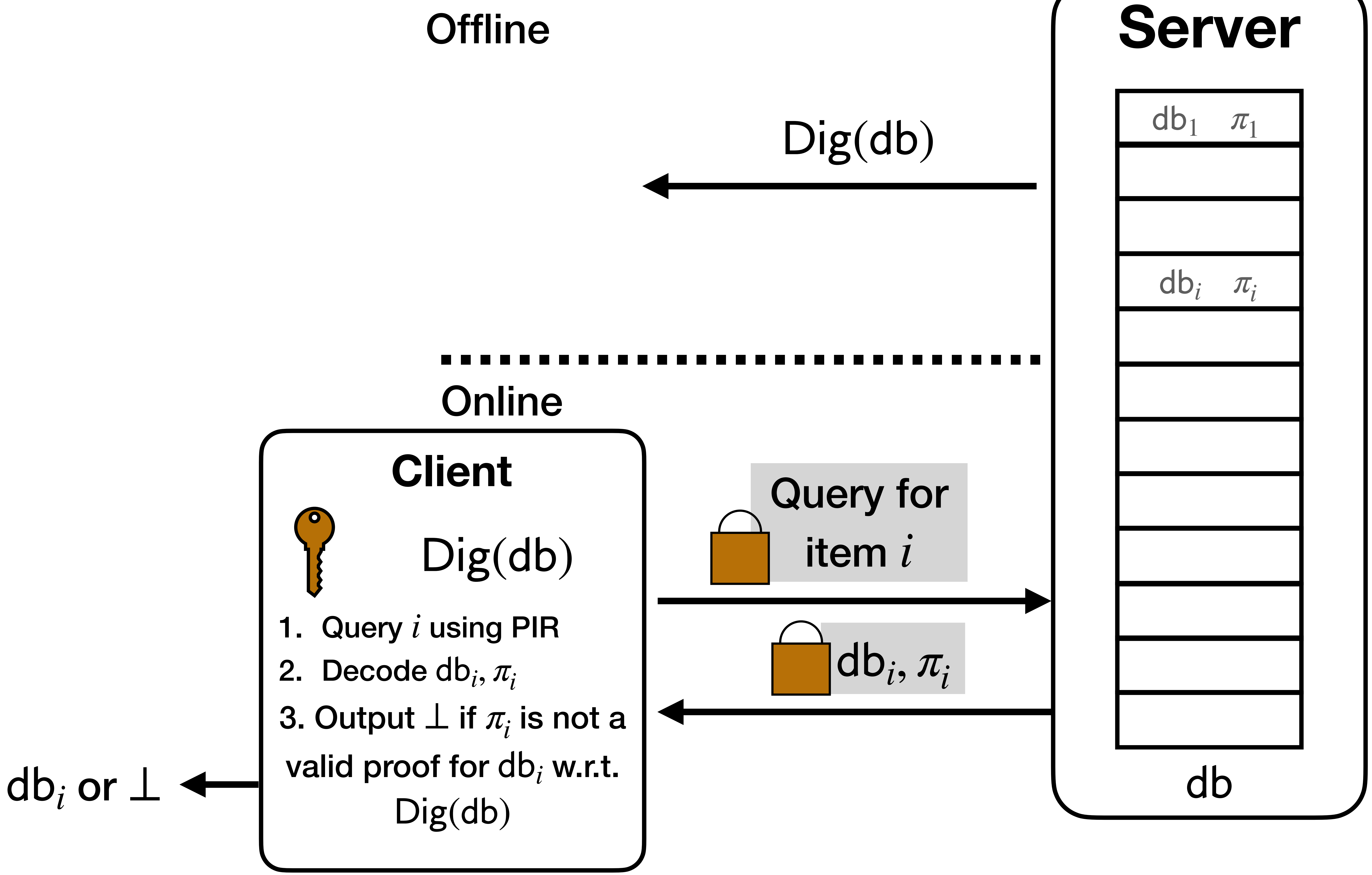
Properties:



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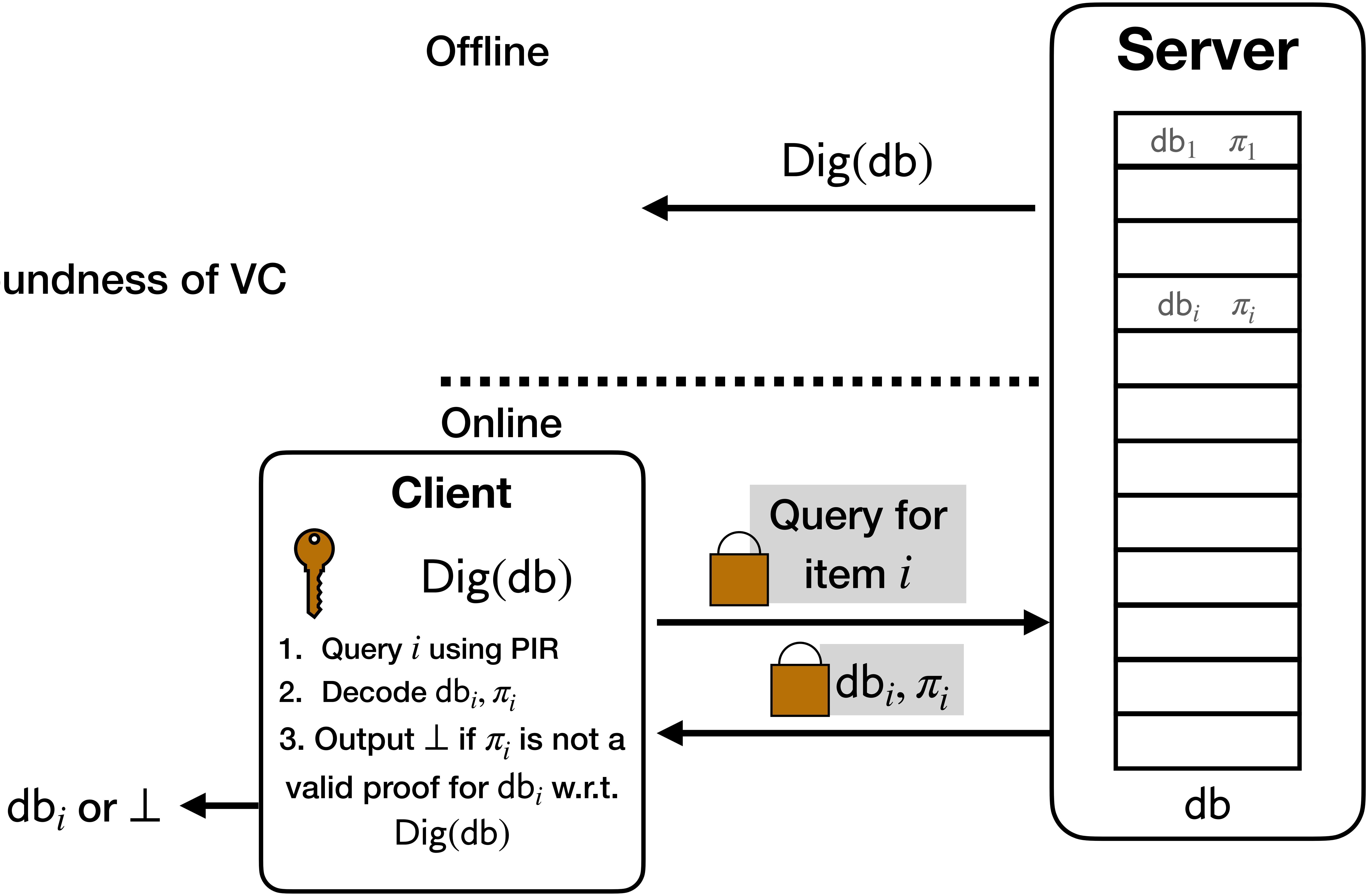

Properties:

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Properties:

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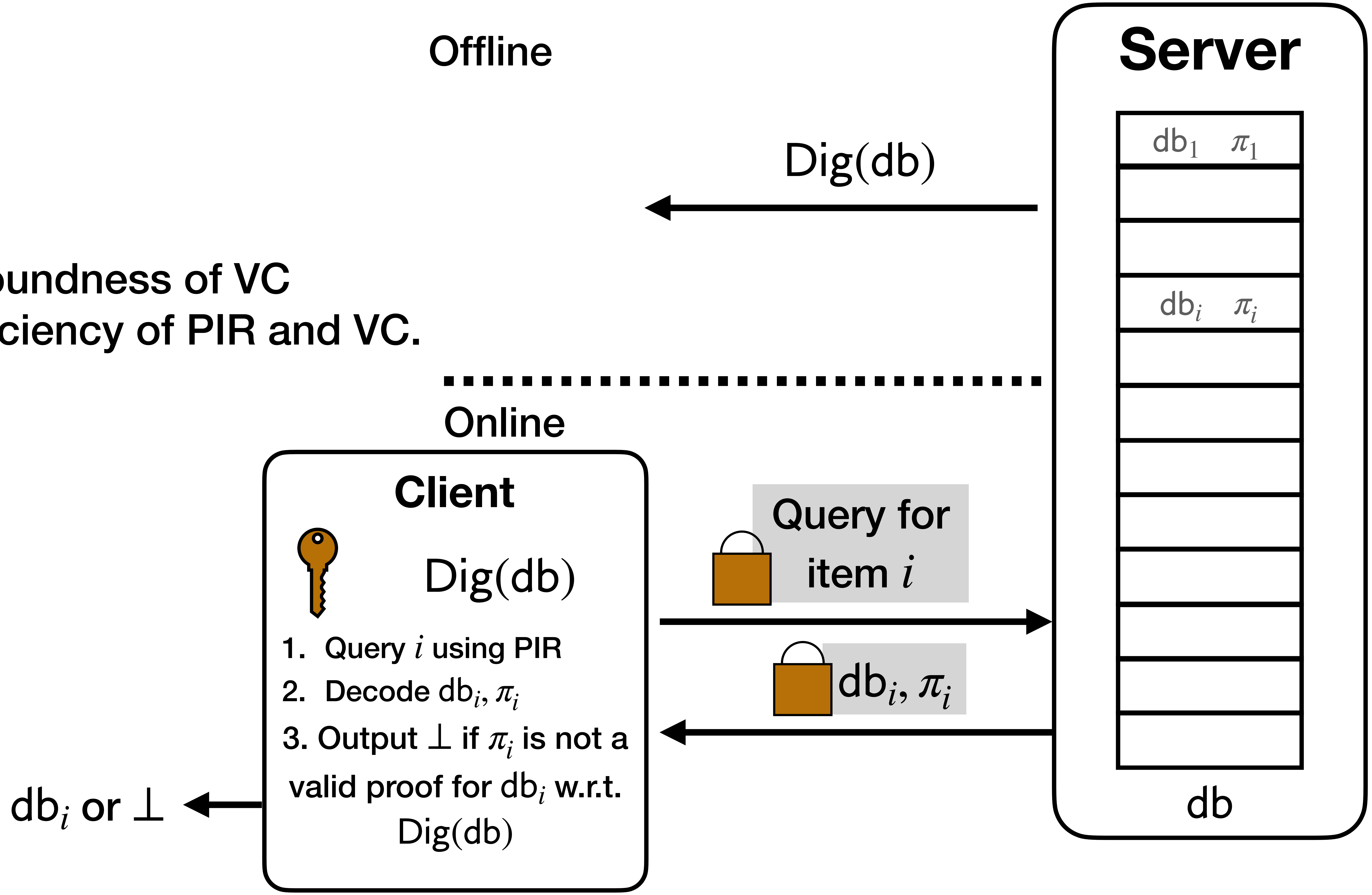
2. Efficiency: by efficiency of PIR and VC.



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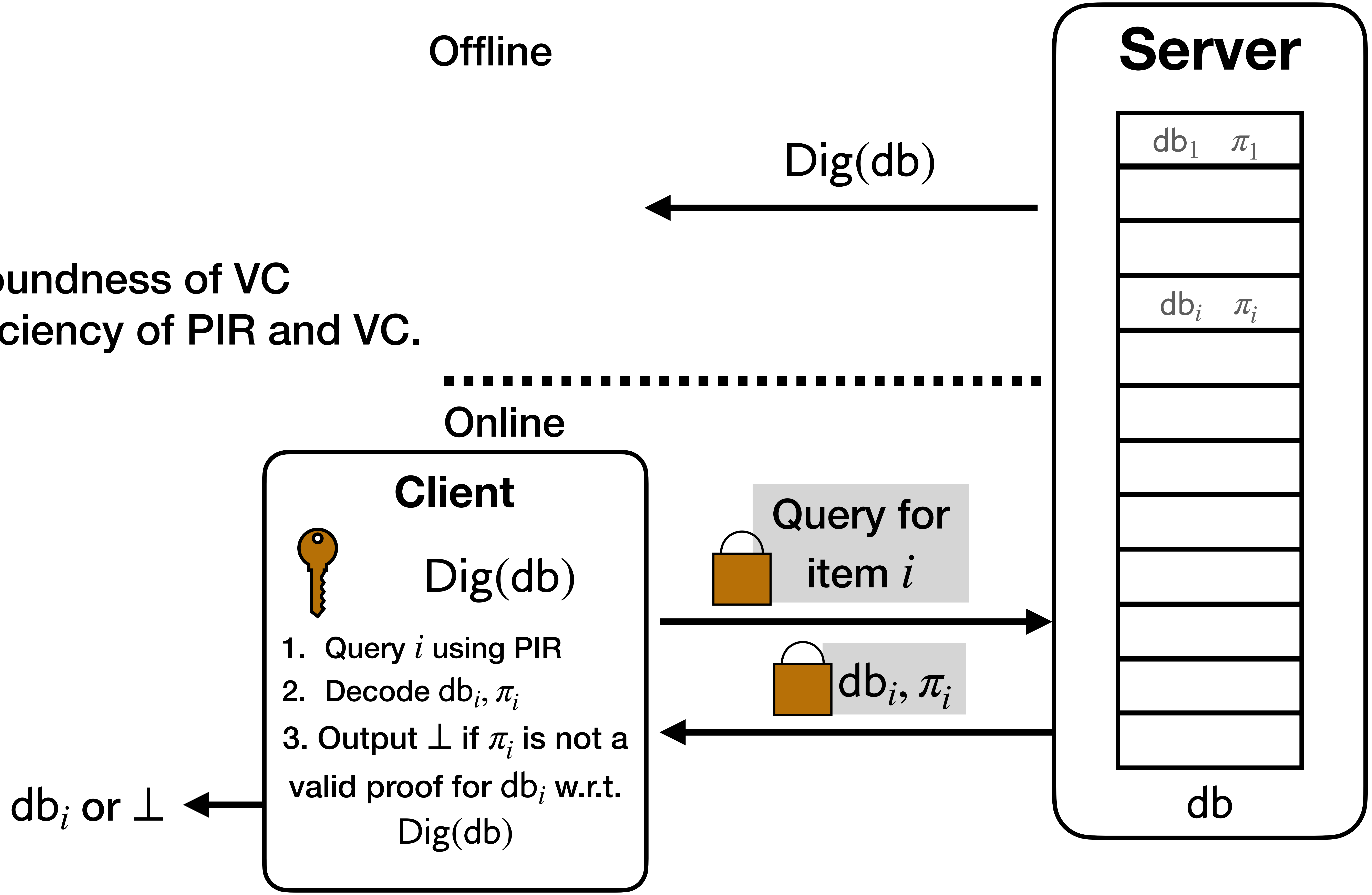
Privacy?



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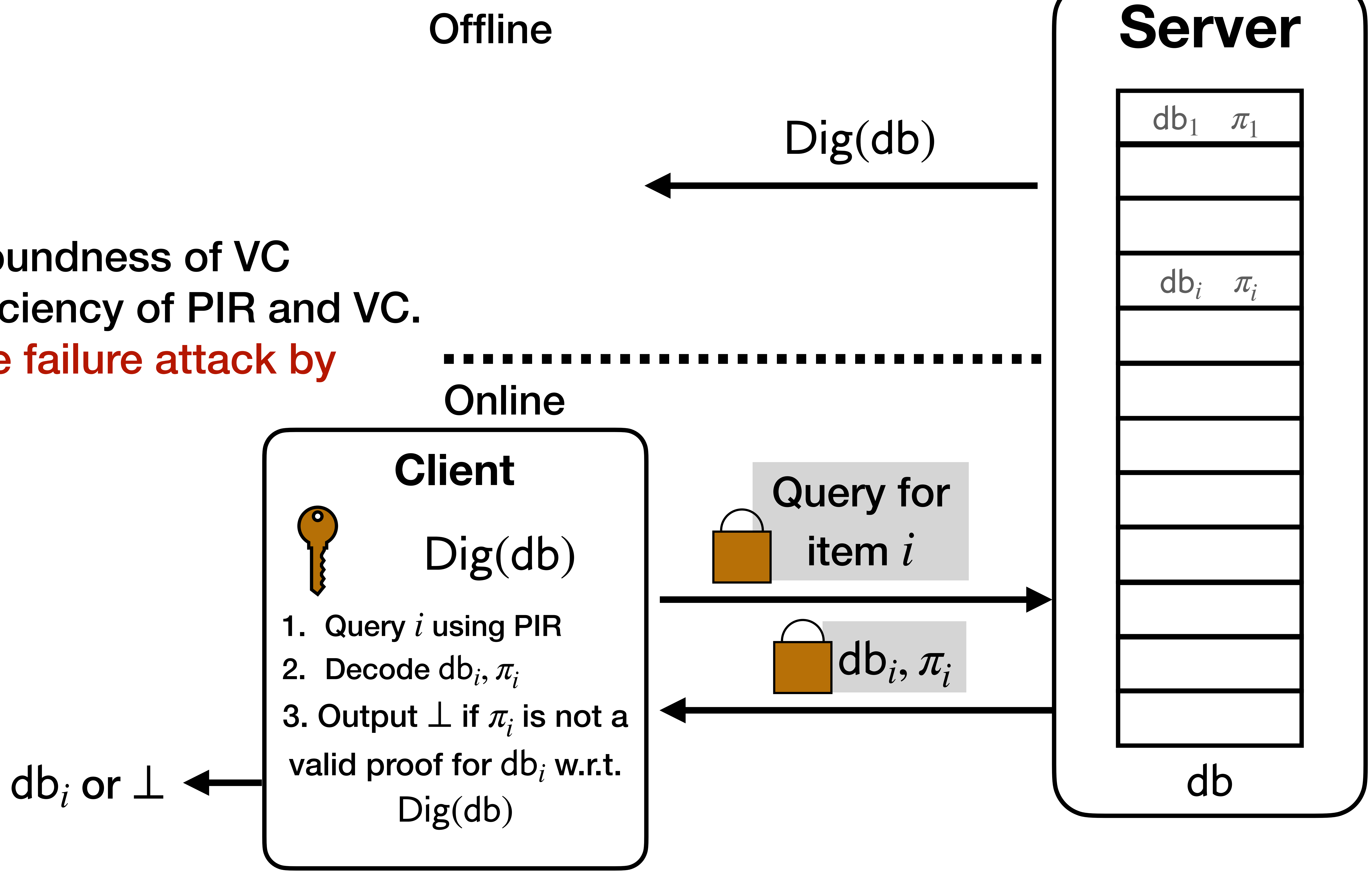

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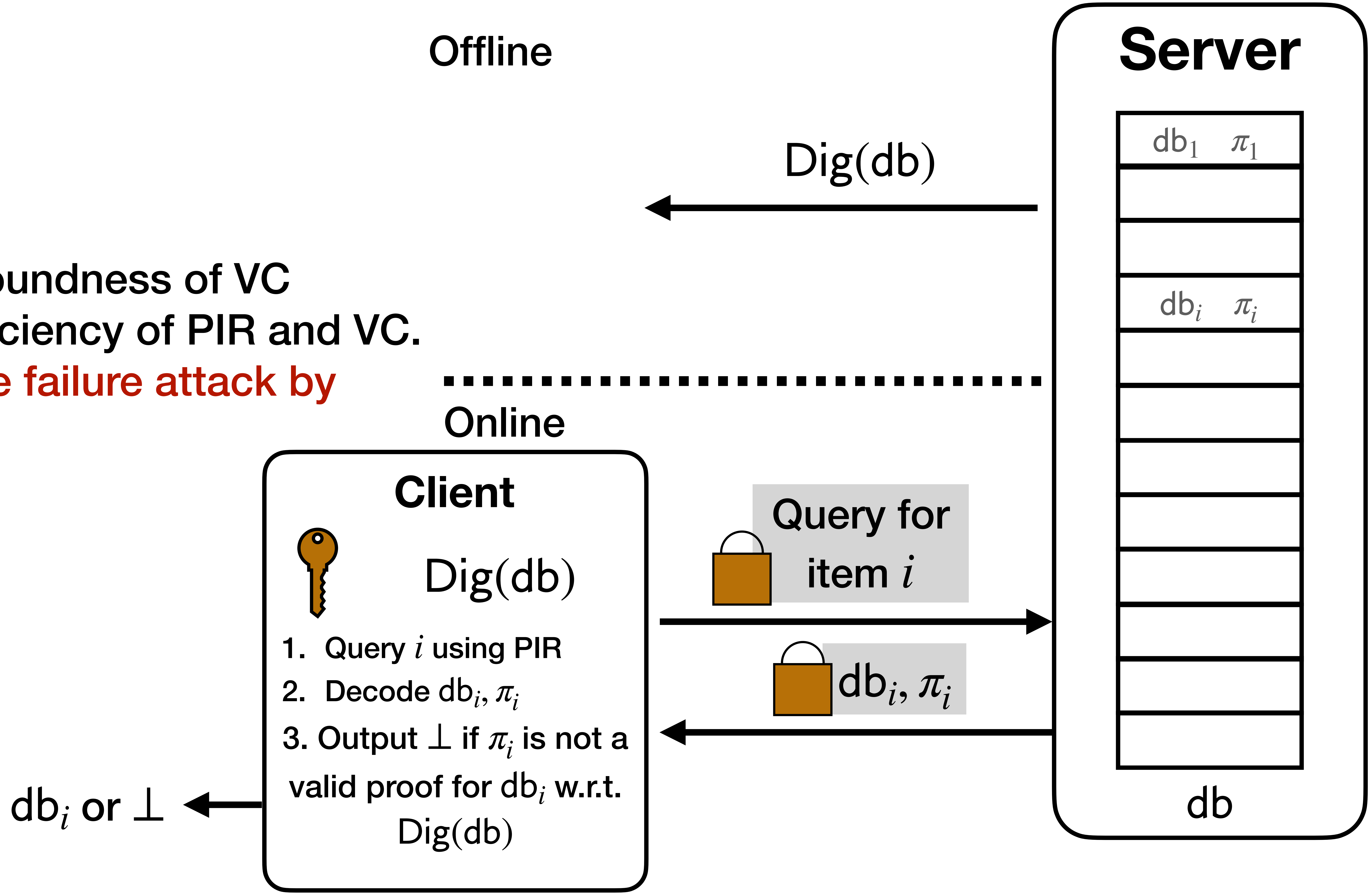

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Locally decodable codes (LDC)

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Encoding

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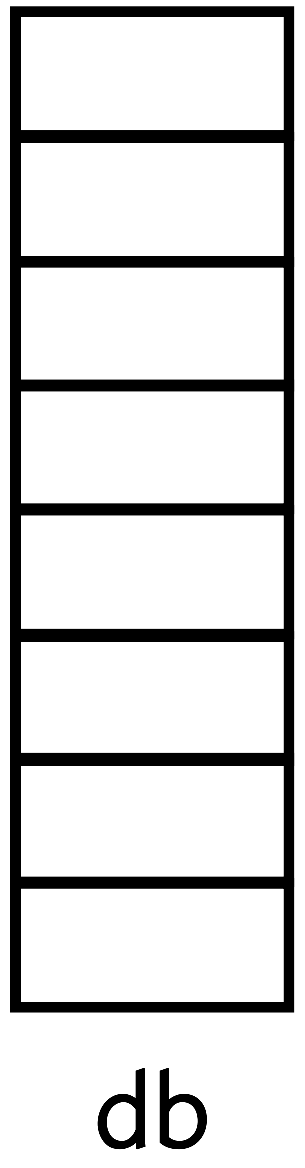

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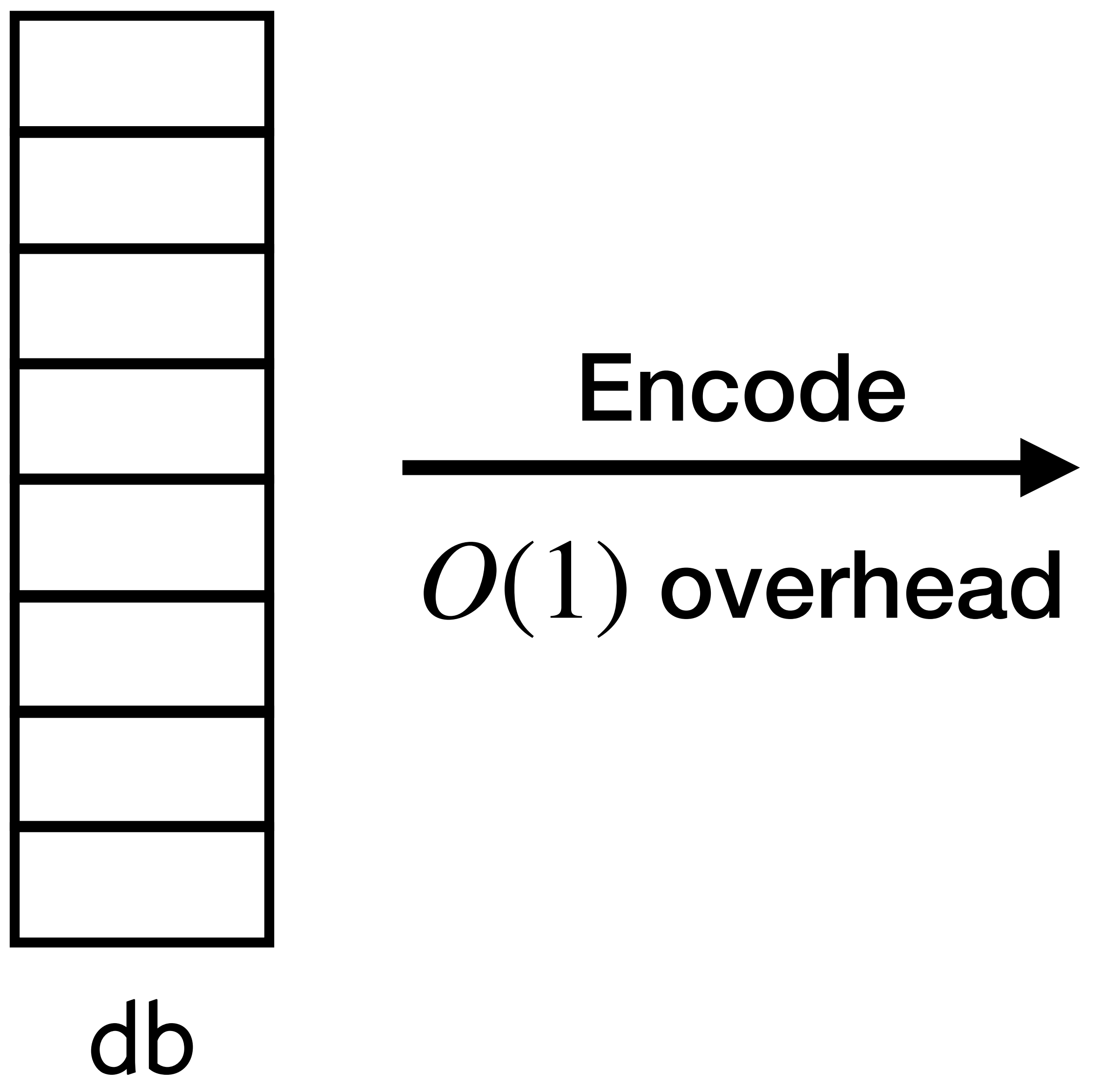

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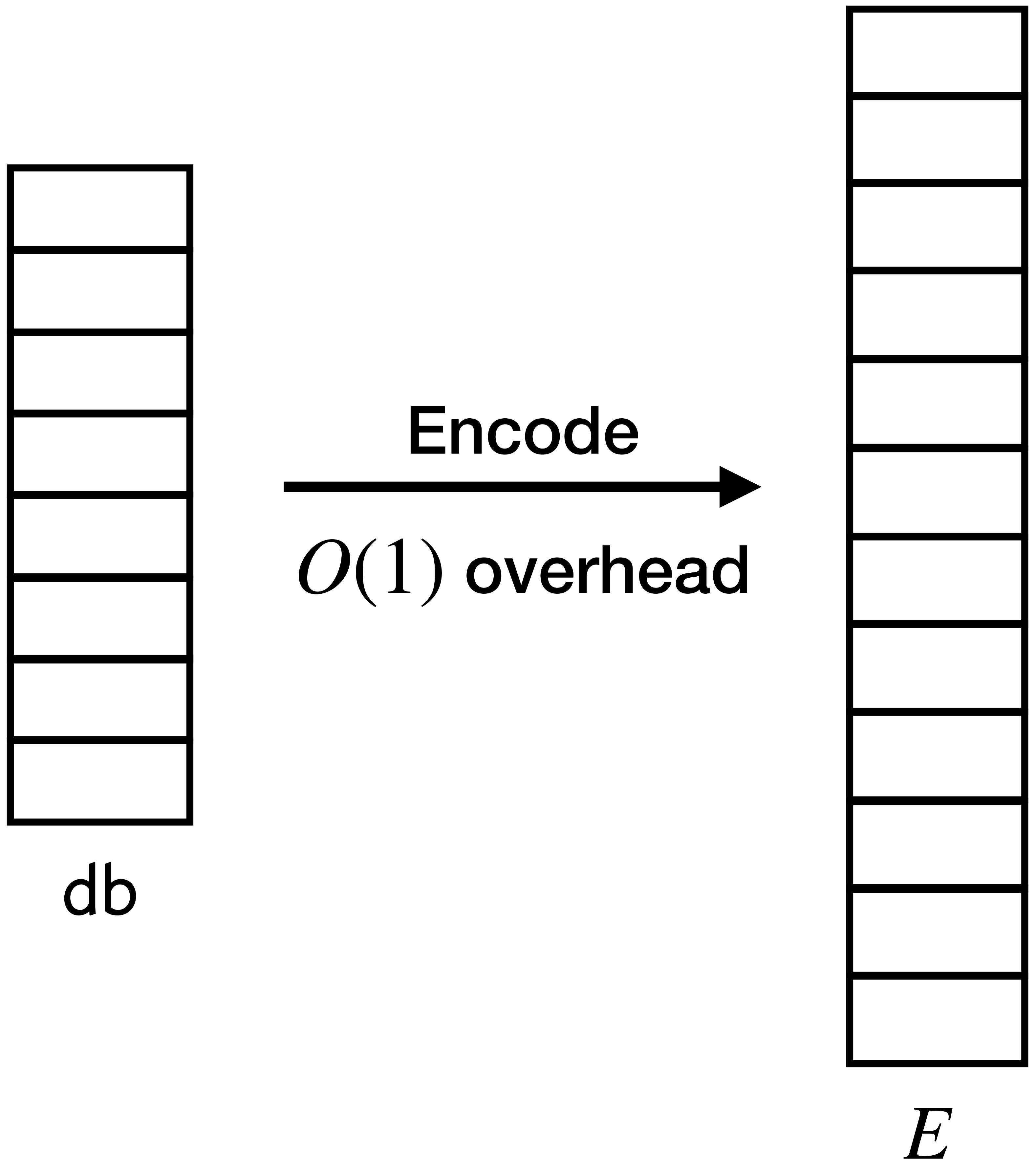

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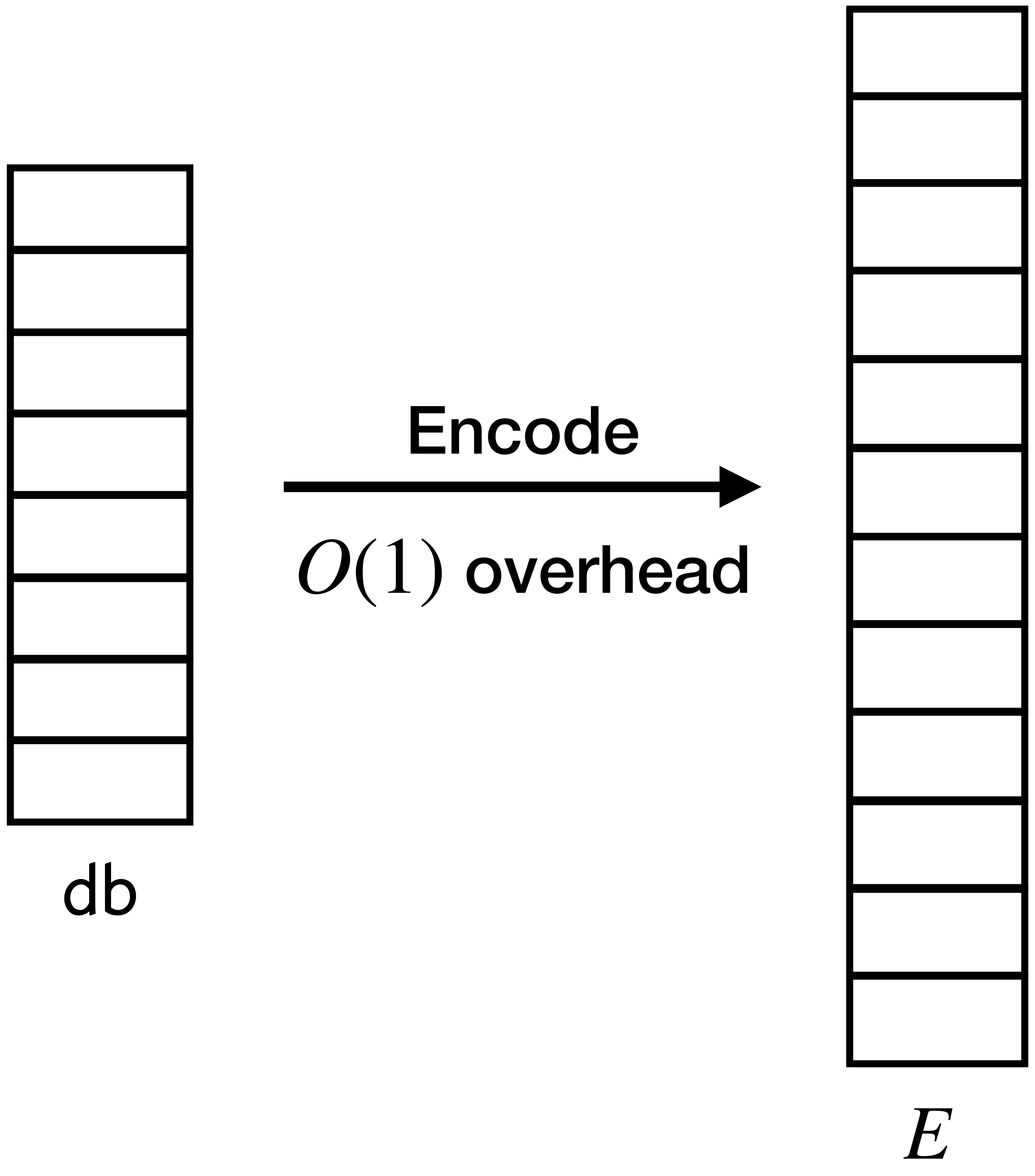

***Local* Decoding**

Locally decodable codes (LDC)

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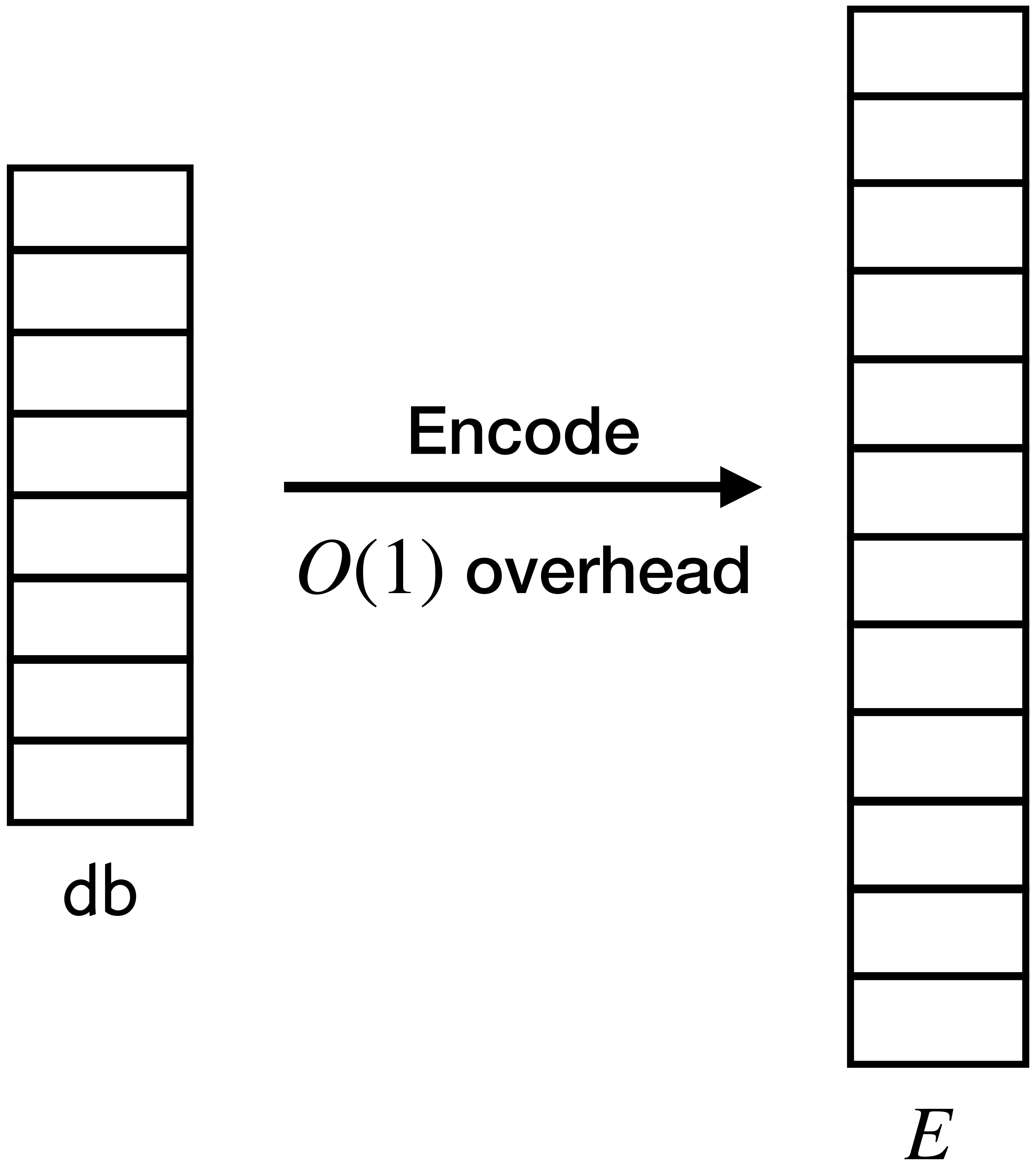

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If there are $< 1/3$ corruptions, for all i:

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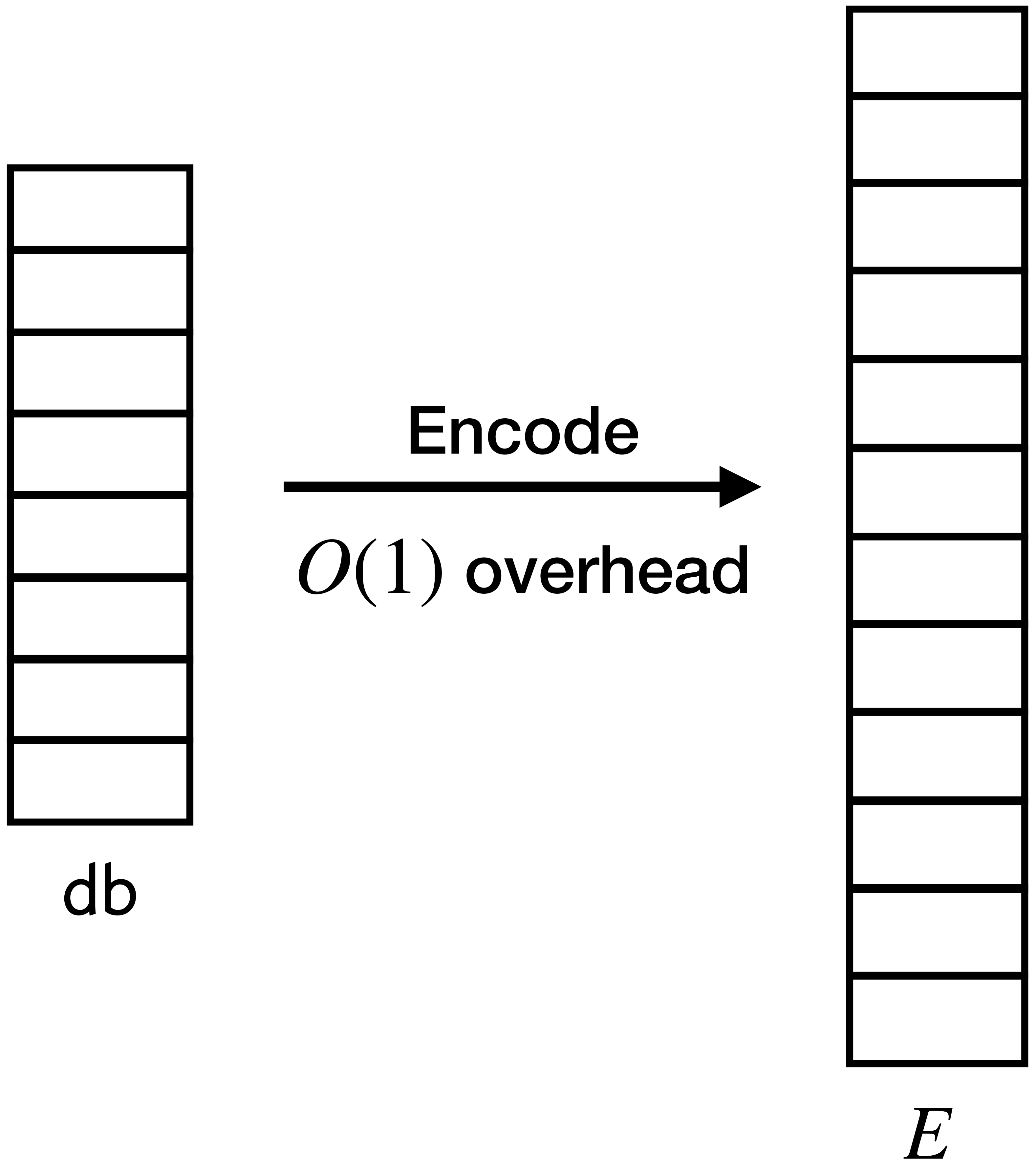

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If there are $< 1/3$ corruptions, for all i:

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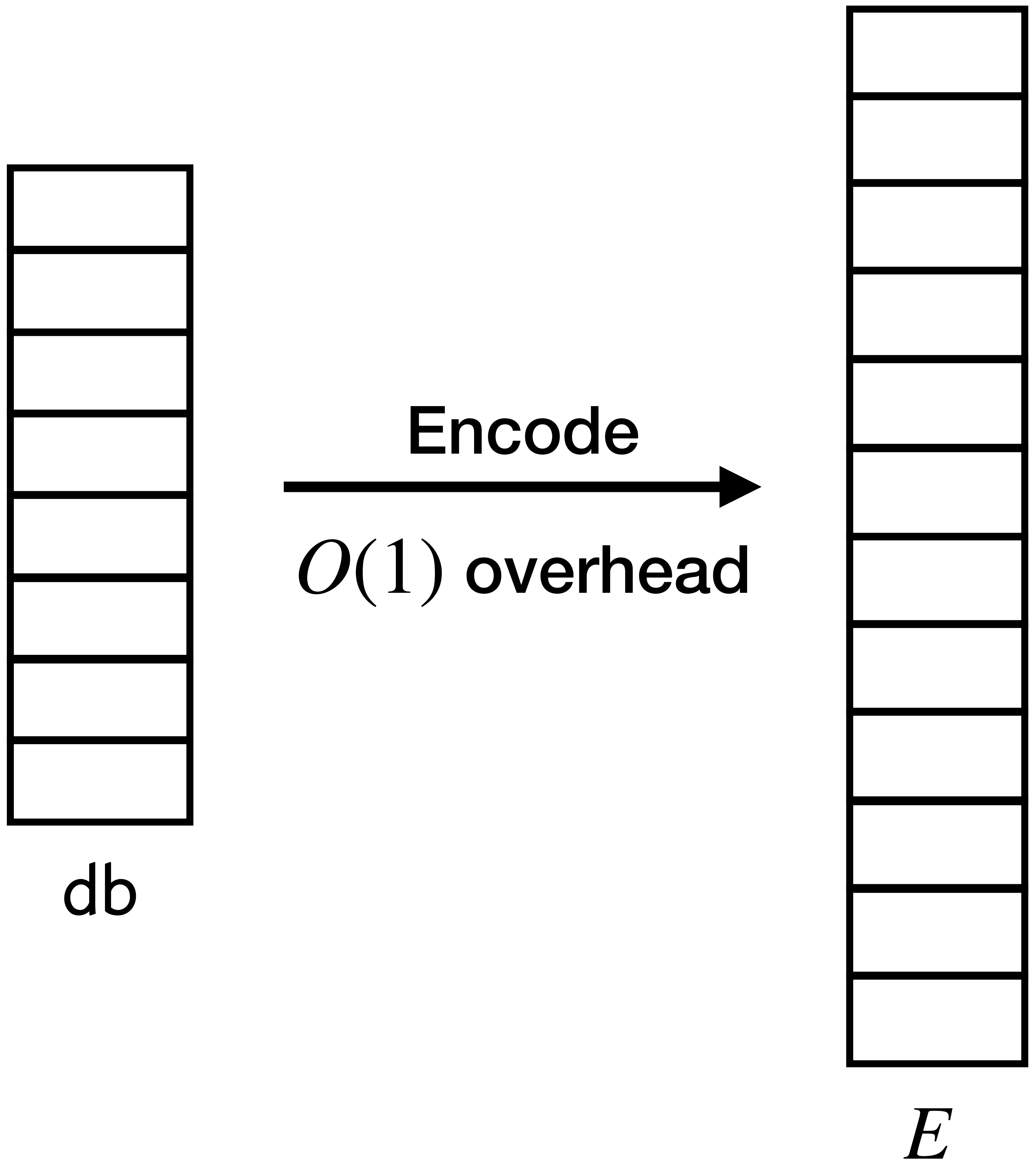

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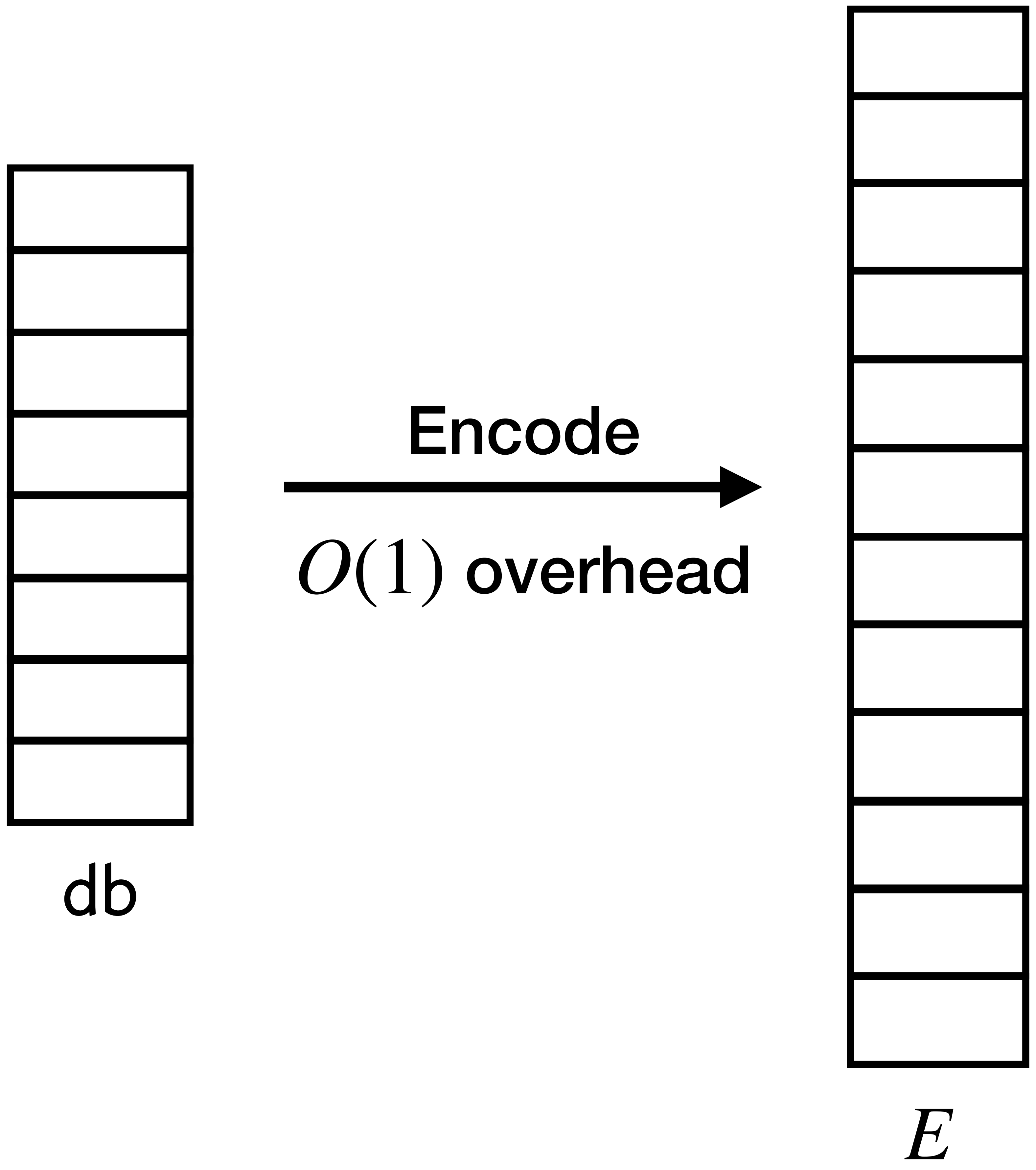

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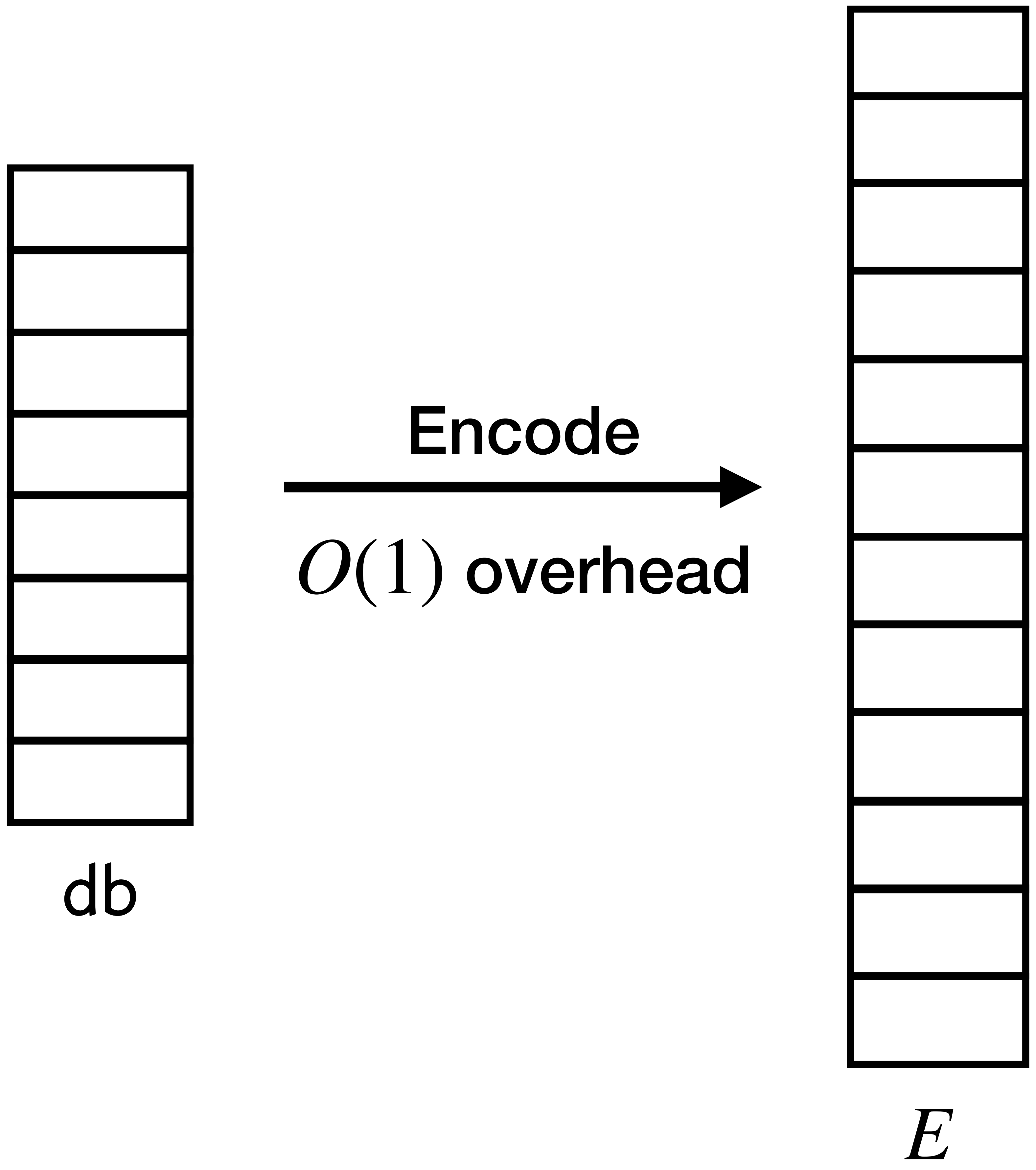

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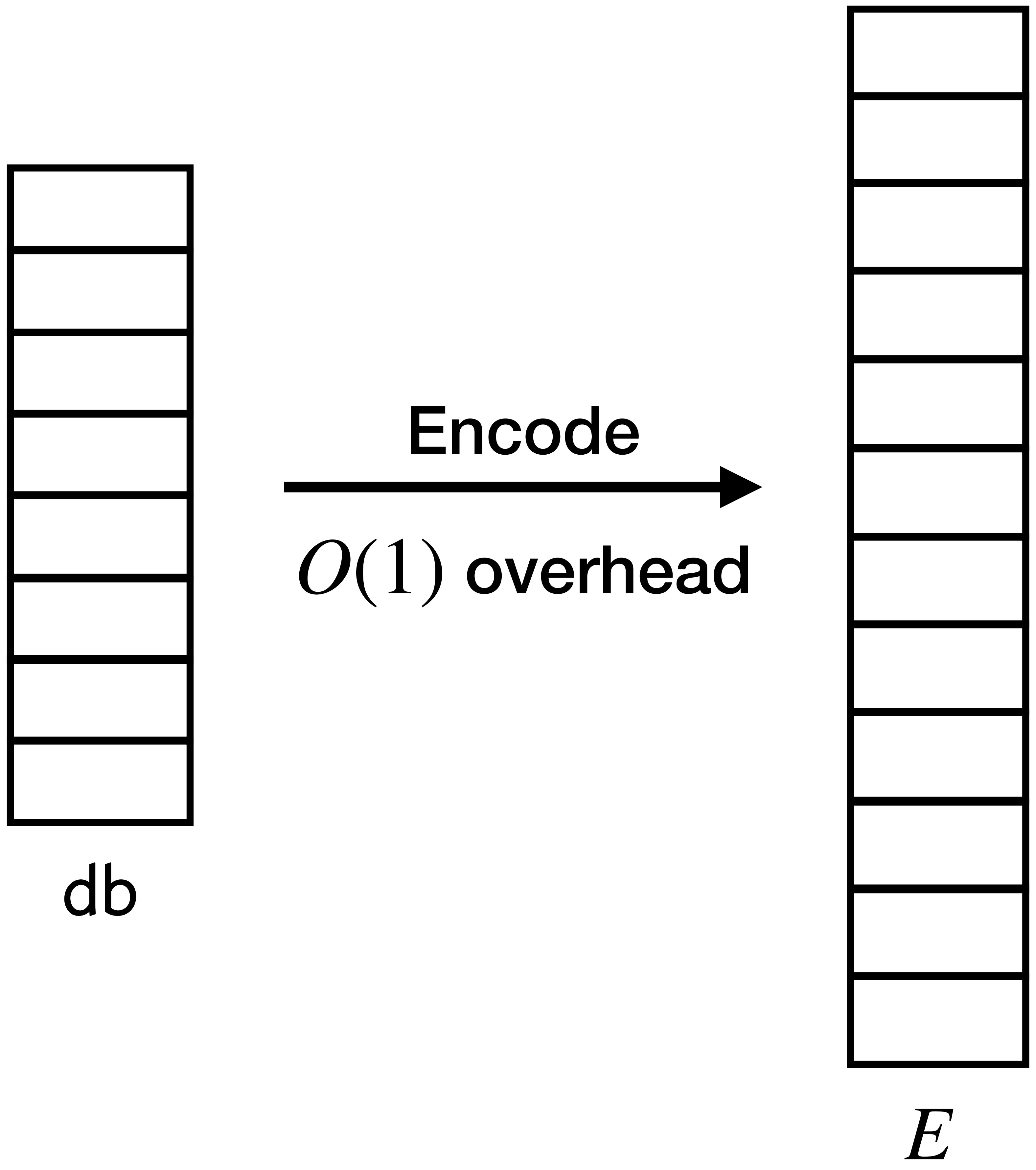

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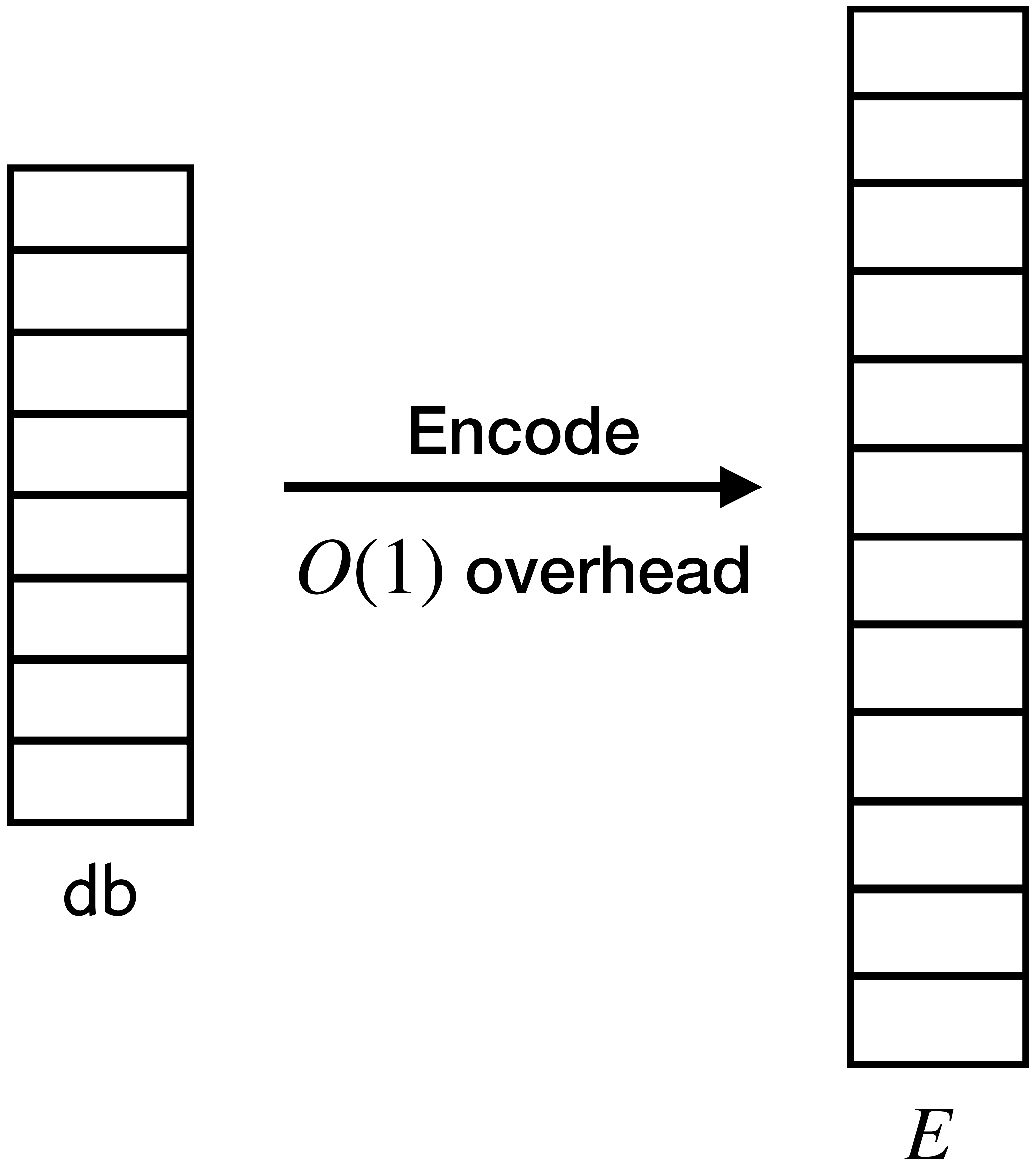

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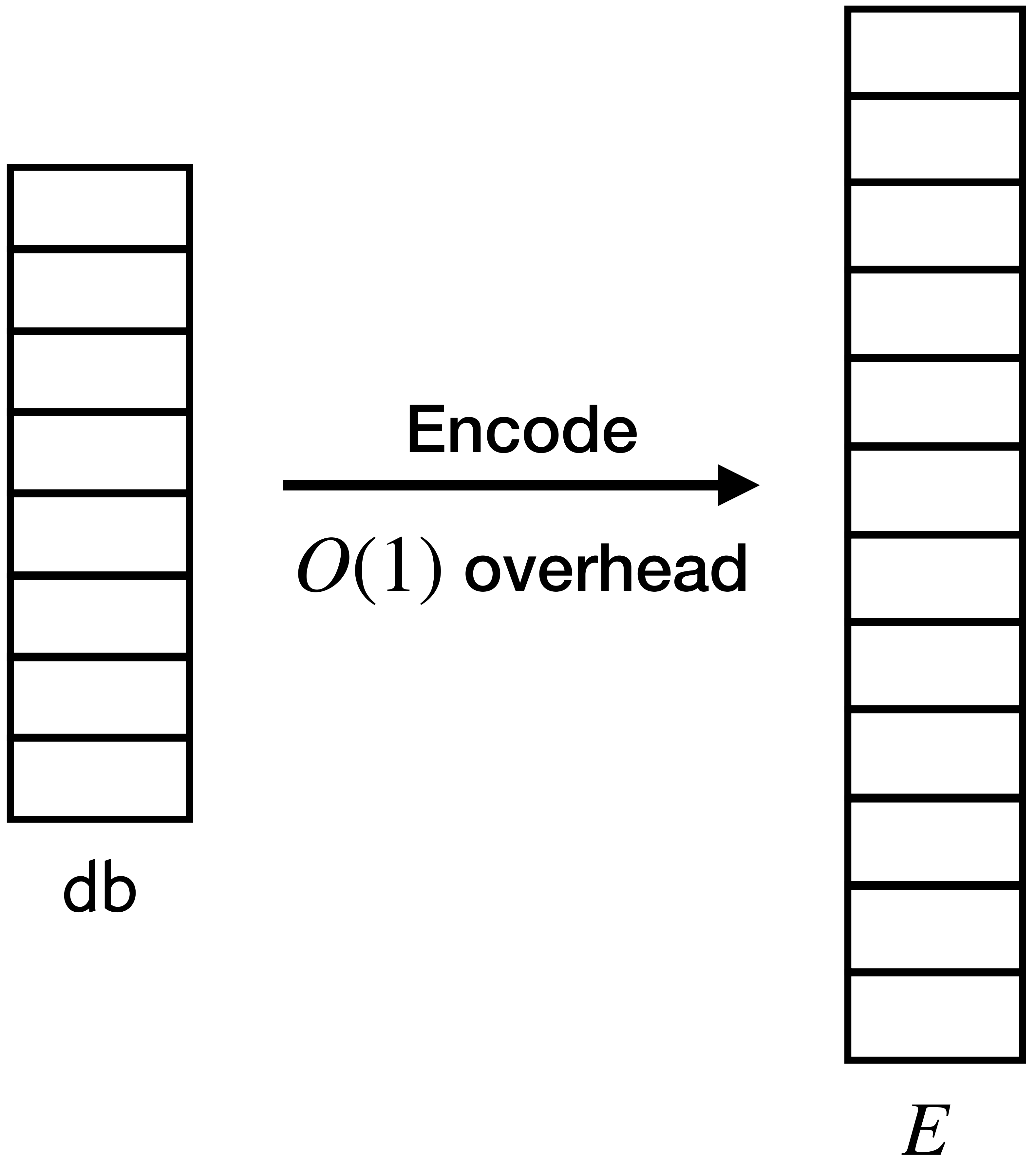

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Smoothness:

Locally decodable codes (LDC)

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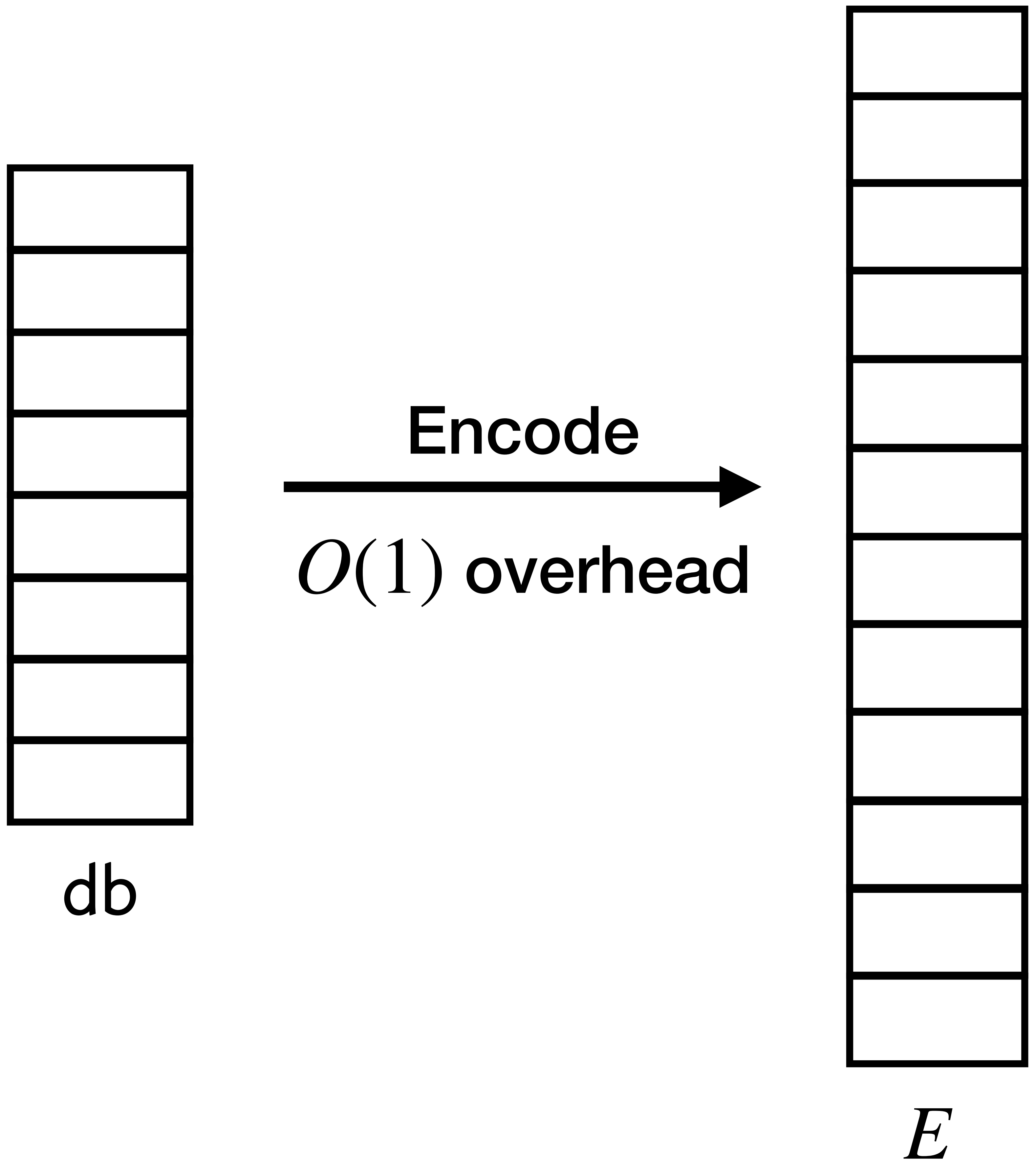

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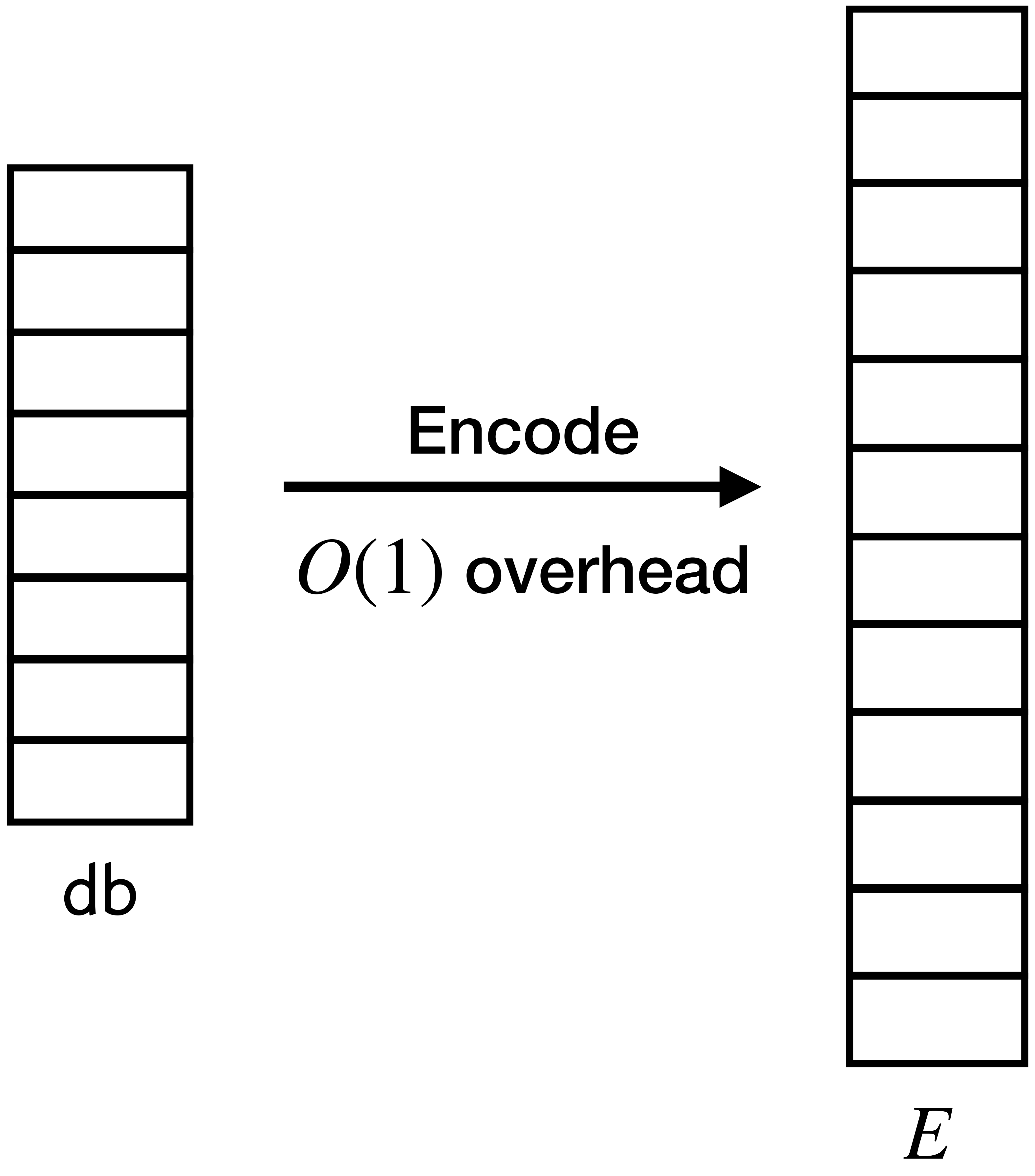

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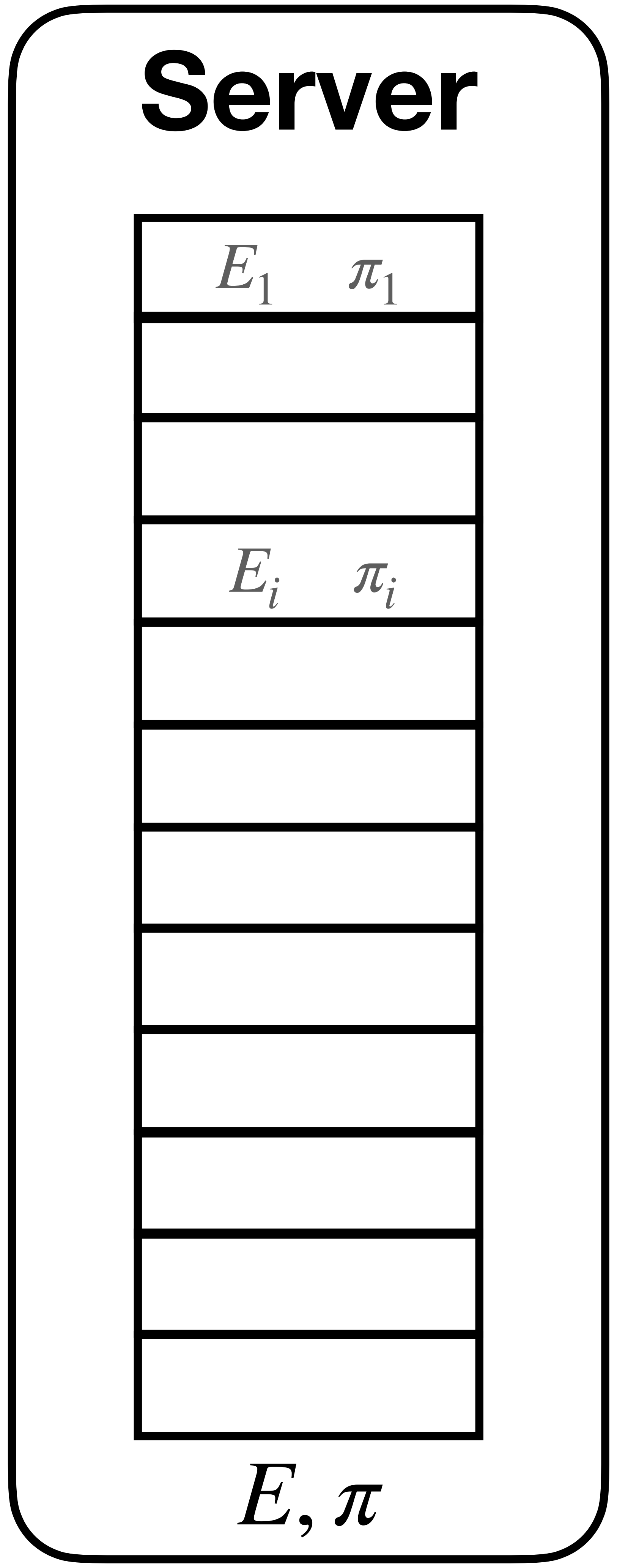
(Which means Q is “pretty random”).

Smoothness:

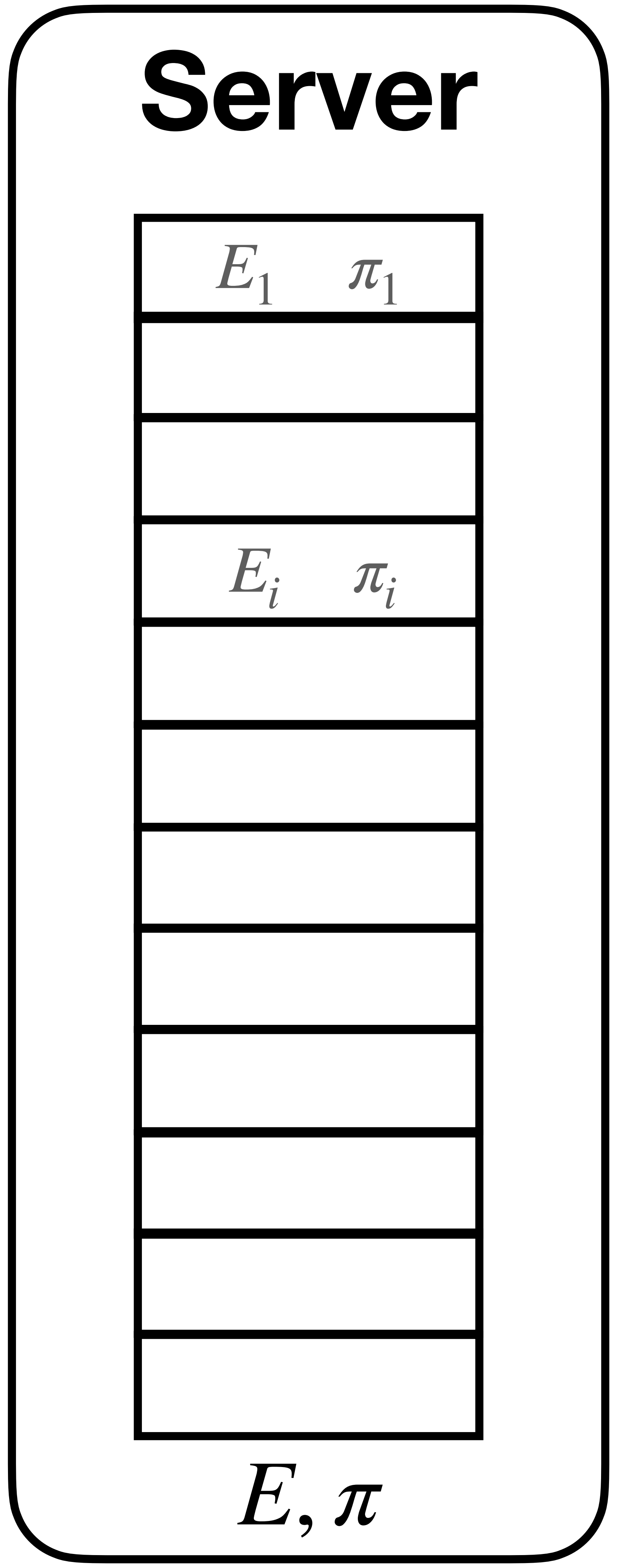
For all i: $x \leftarrow \{Q \leftarrow \text{LDC.Que}(i)\}$
is *uniformly random in* $[|E|]$

Attempt 2: LDC + VC + PIR



Attempt 2: LDC + VC + PIR

Offline



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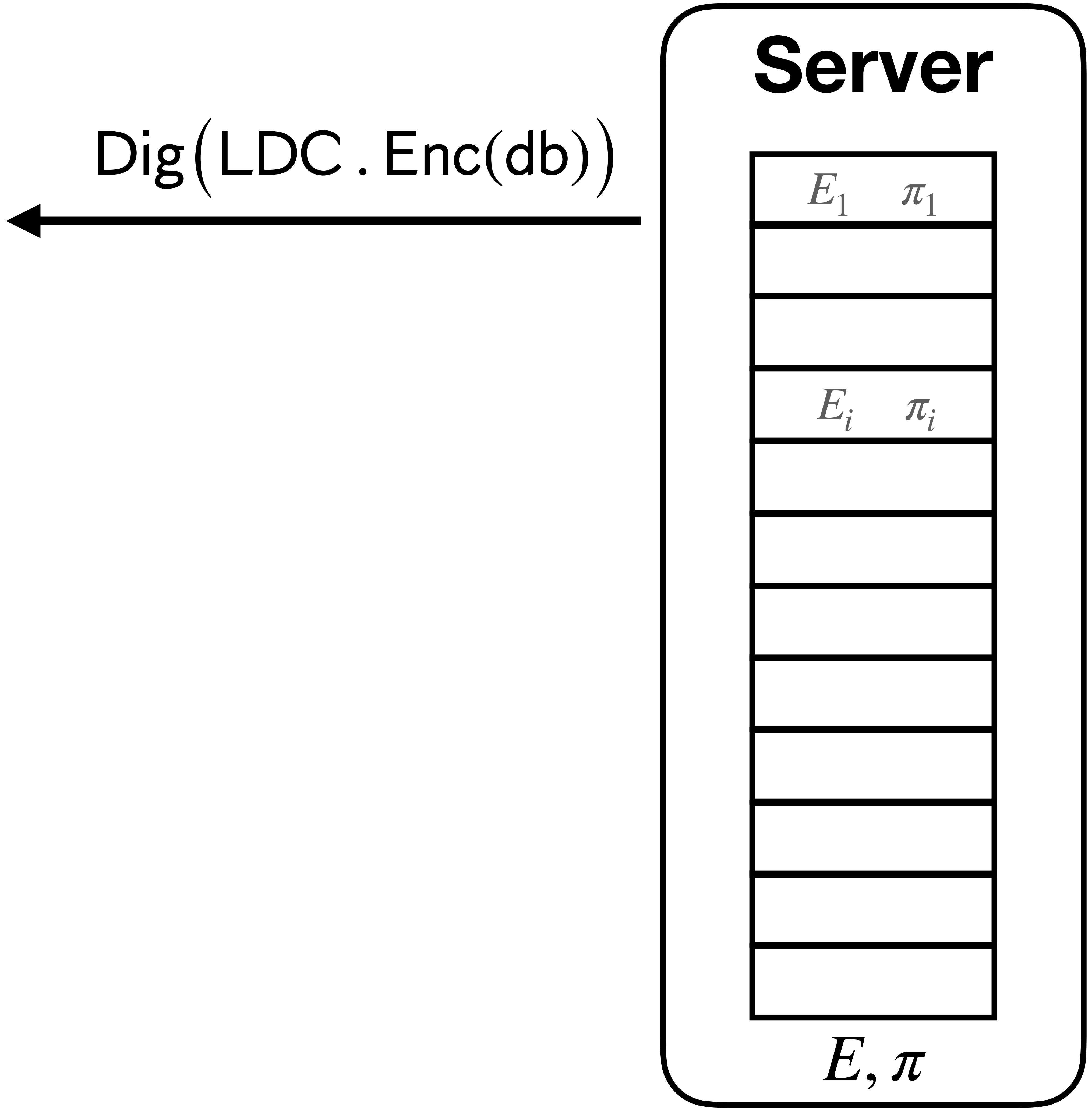

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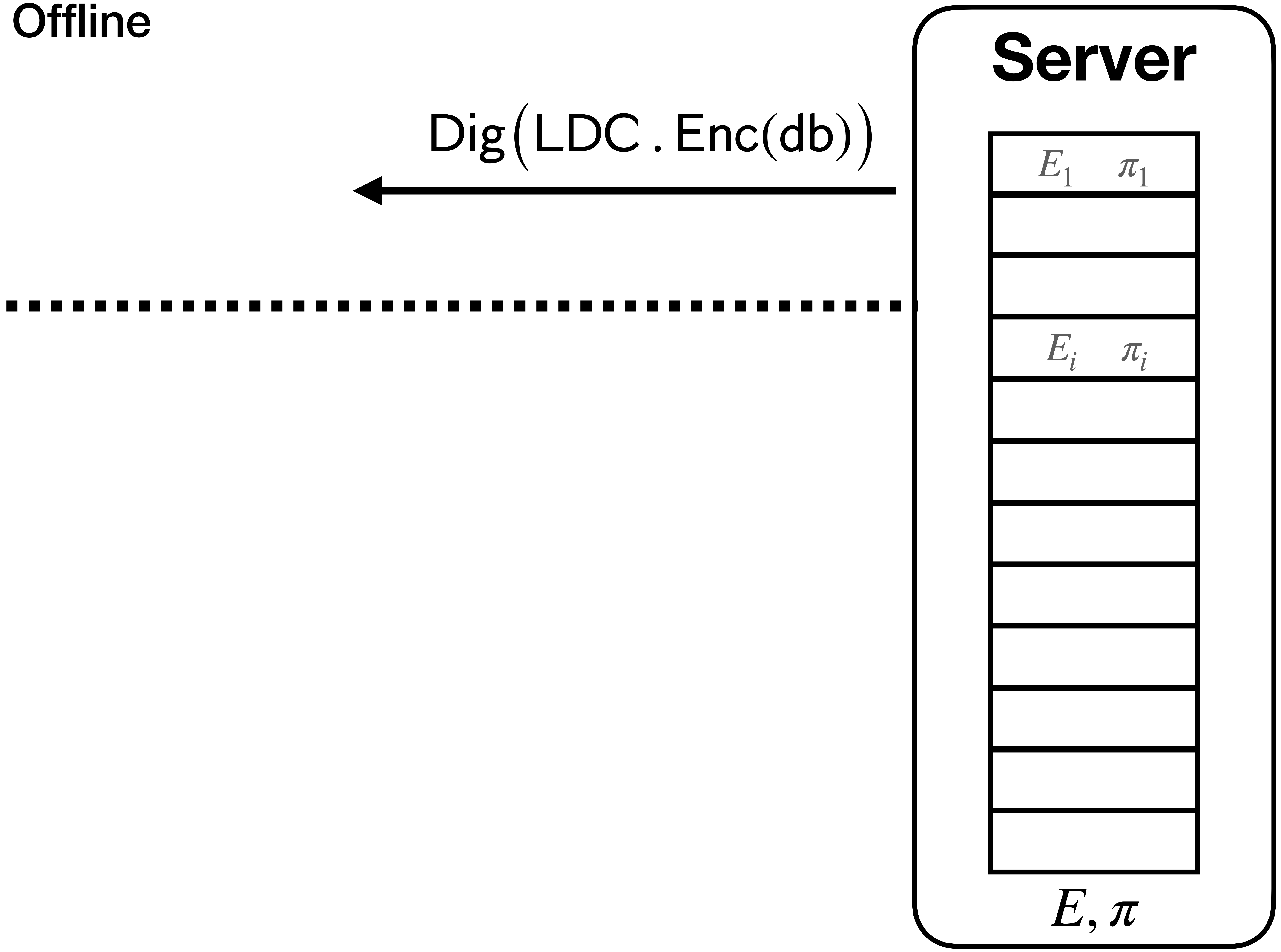

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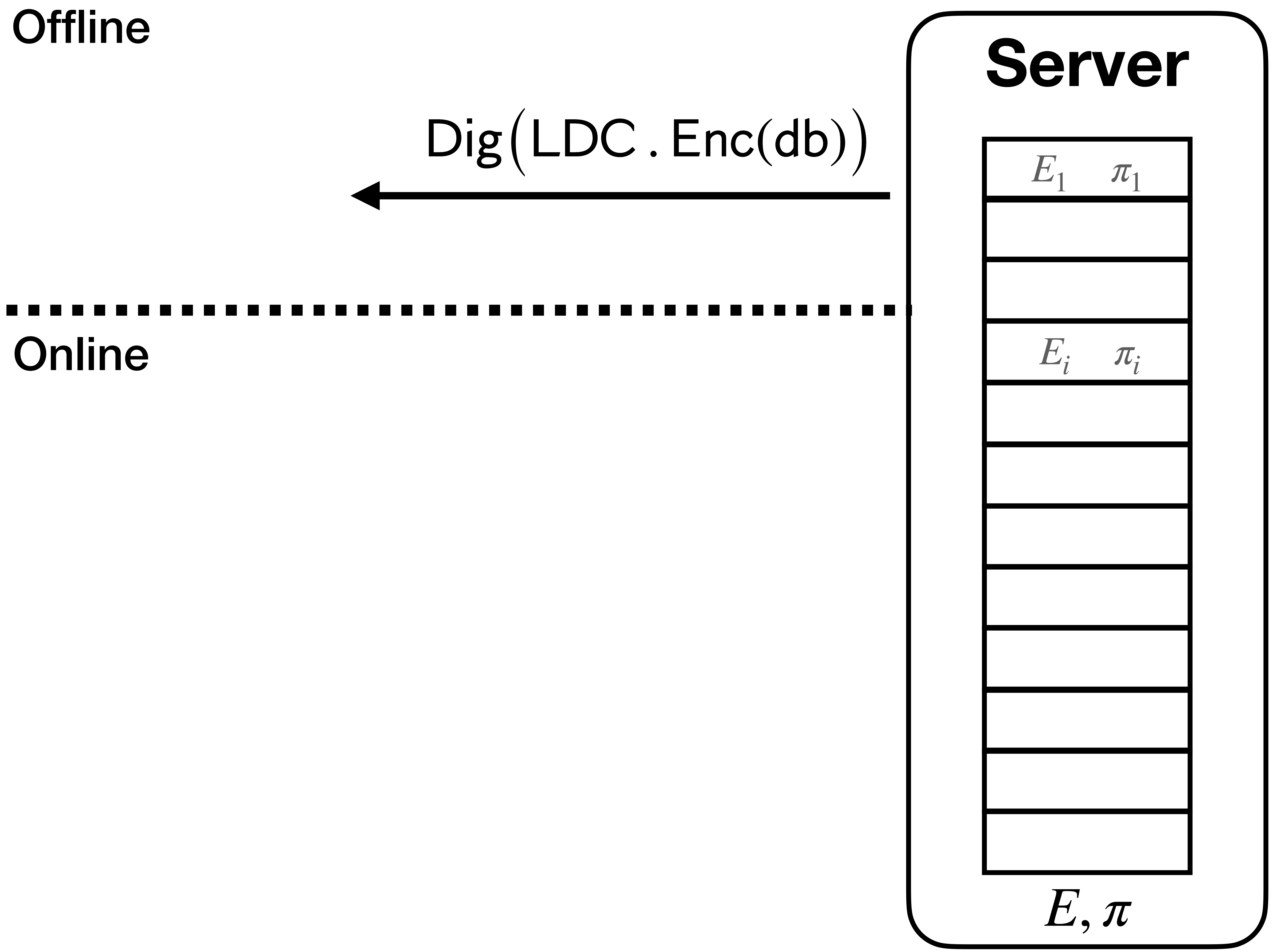

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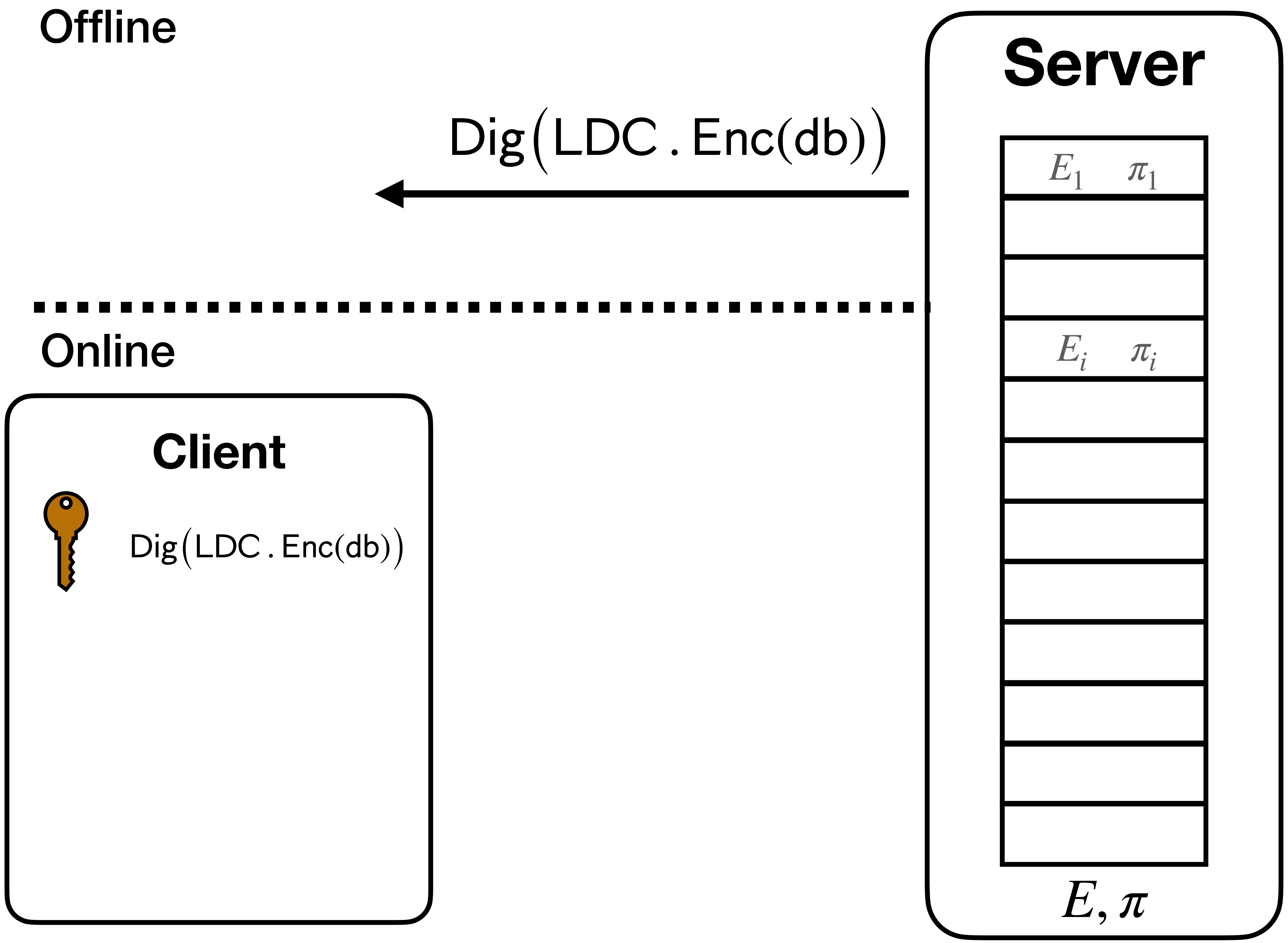
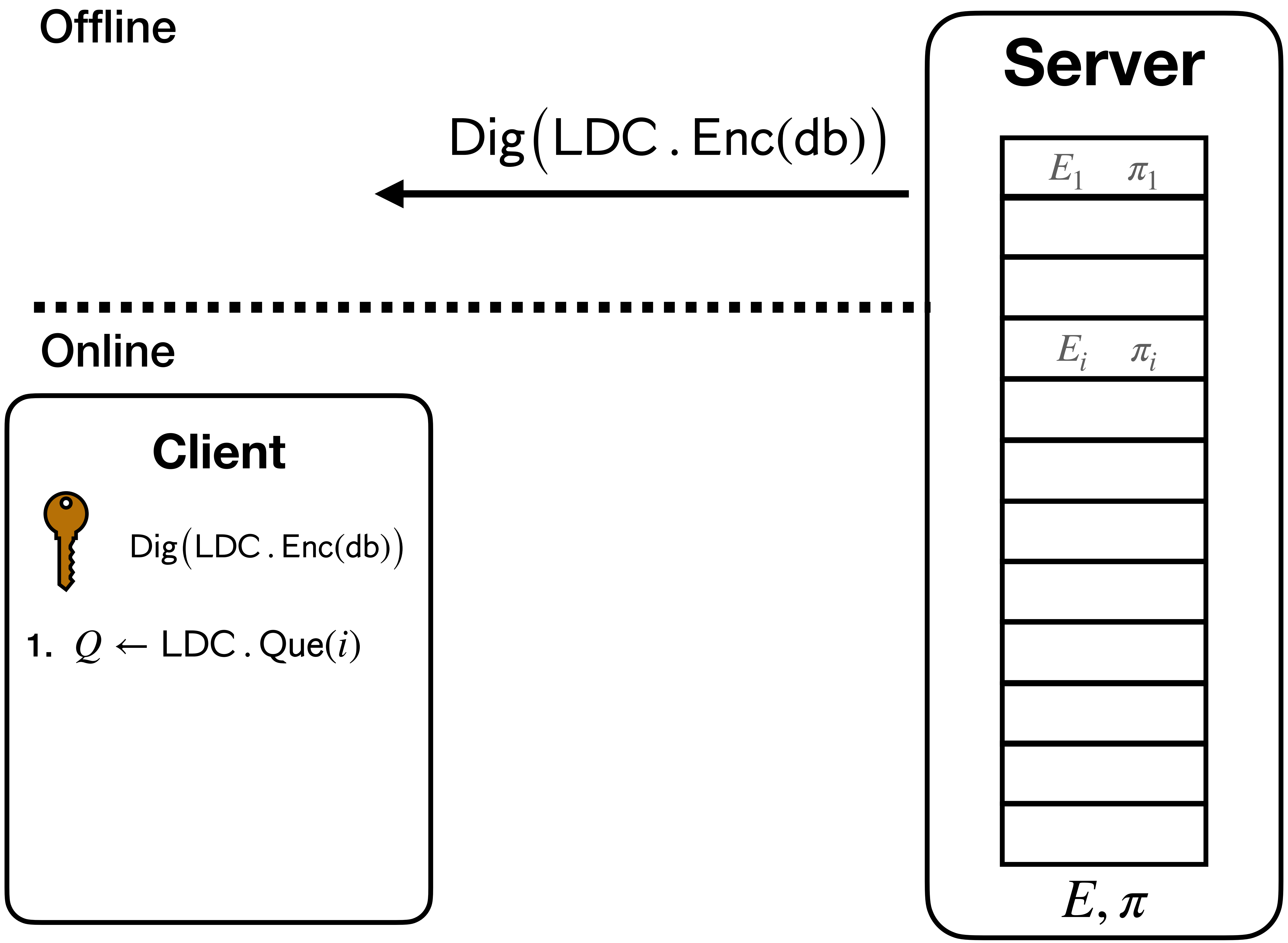


Attempt 2: LDC + VC + PIR



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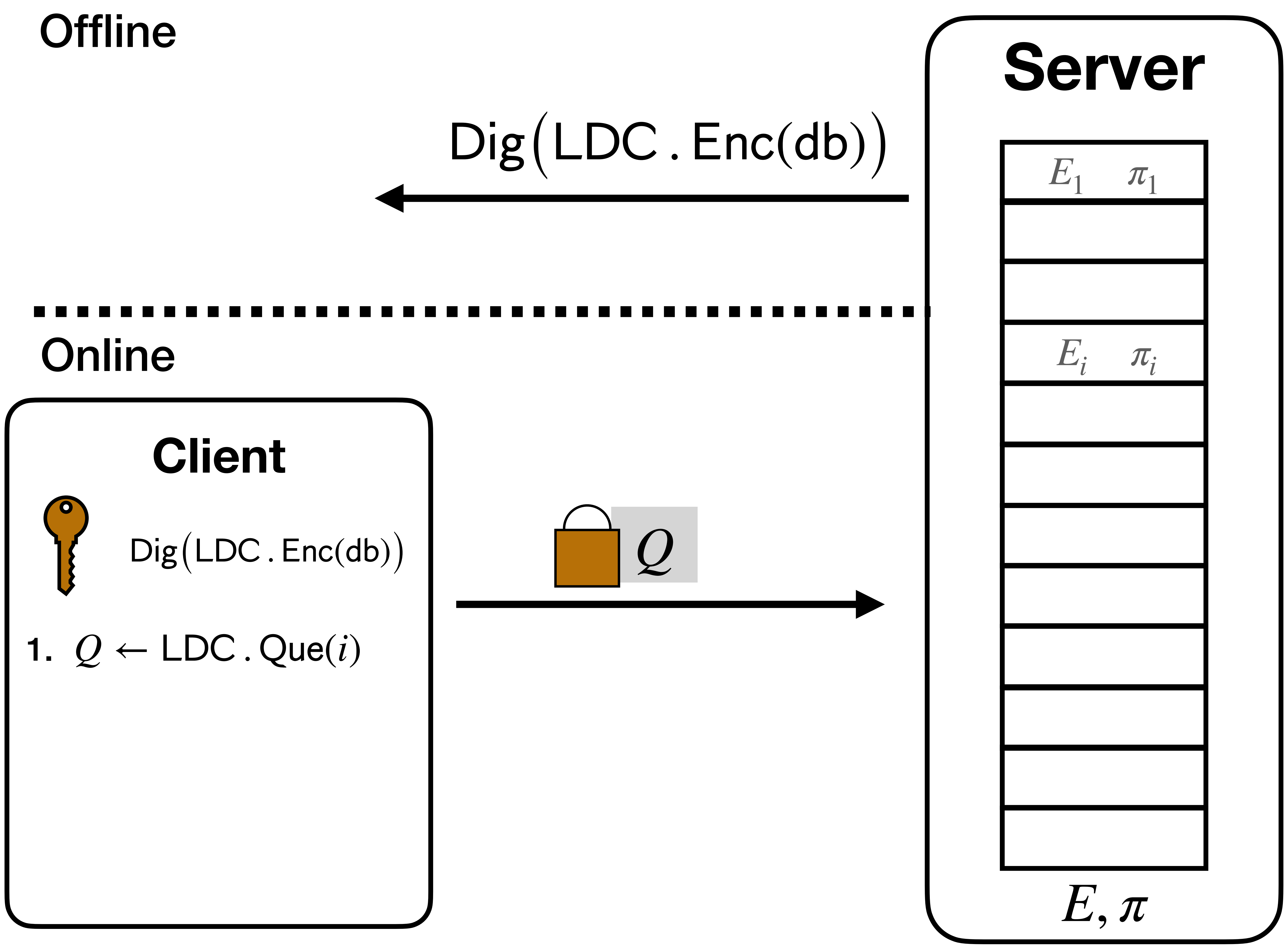

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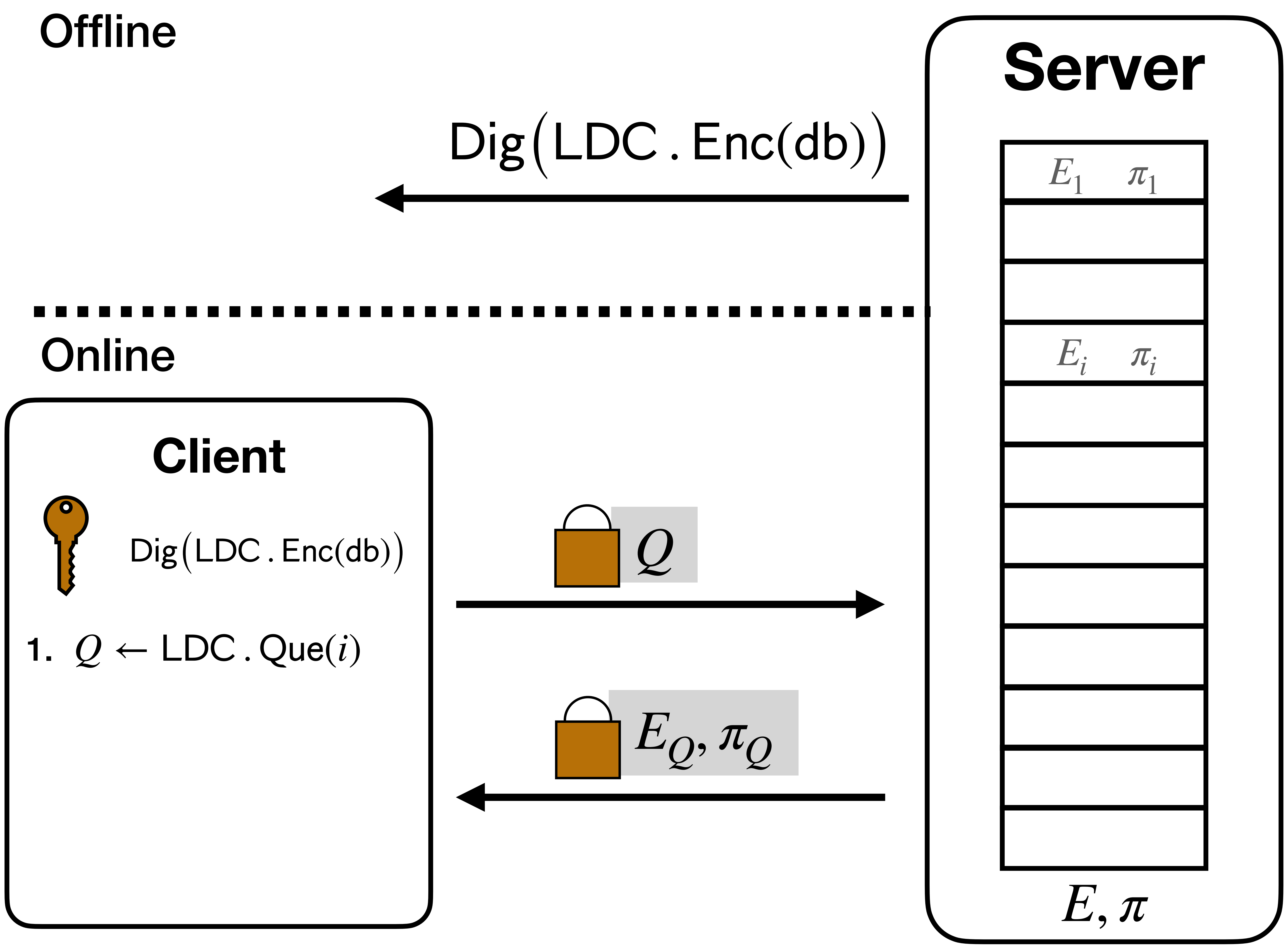

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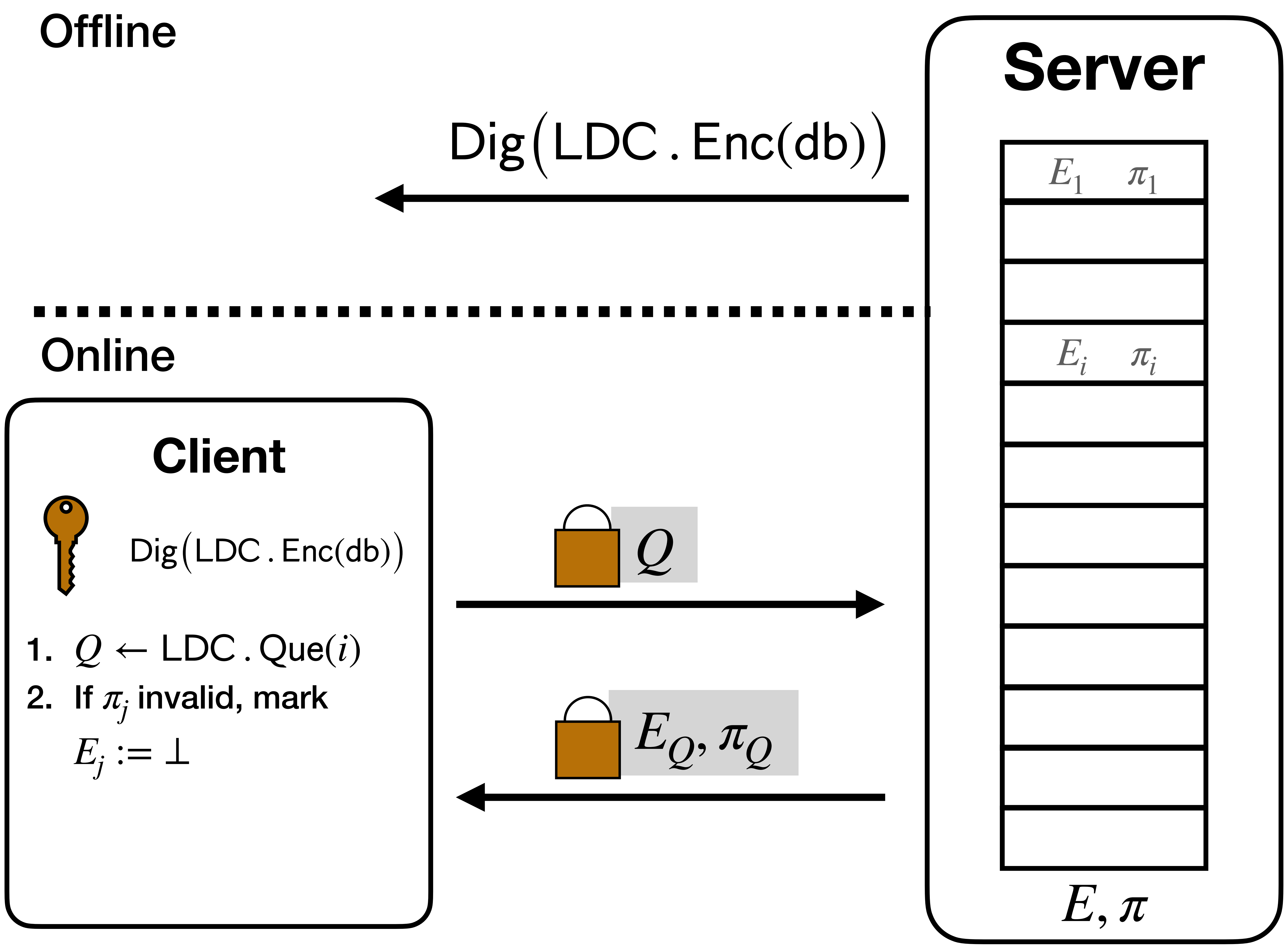

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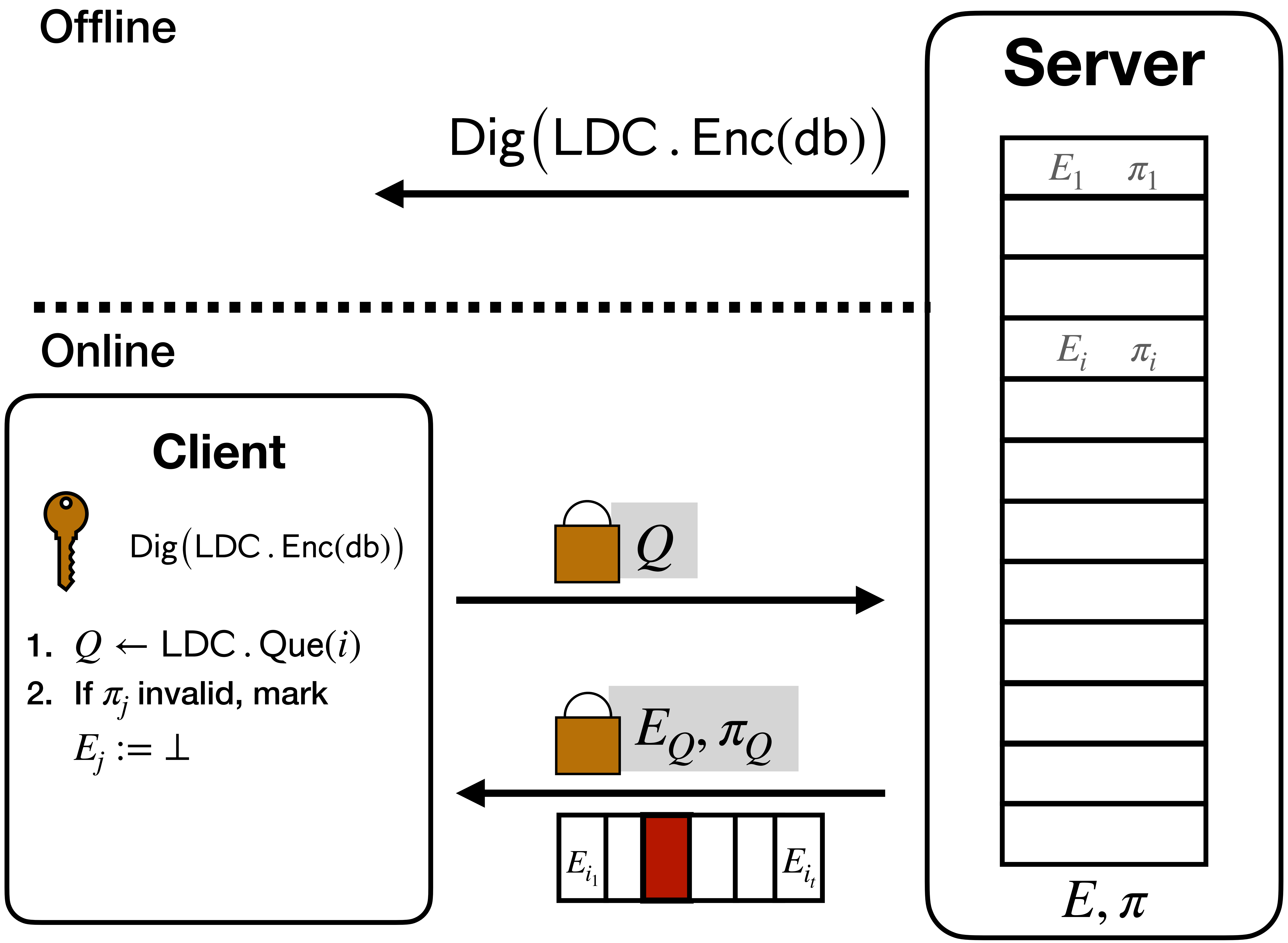

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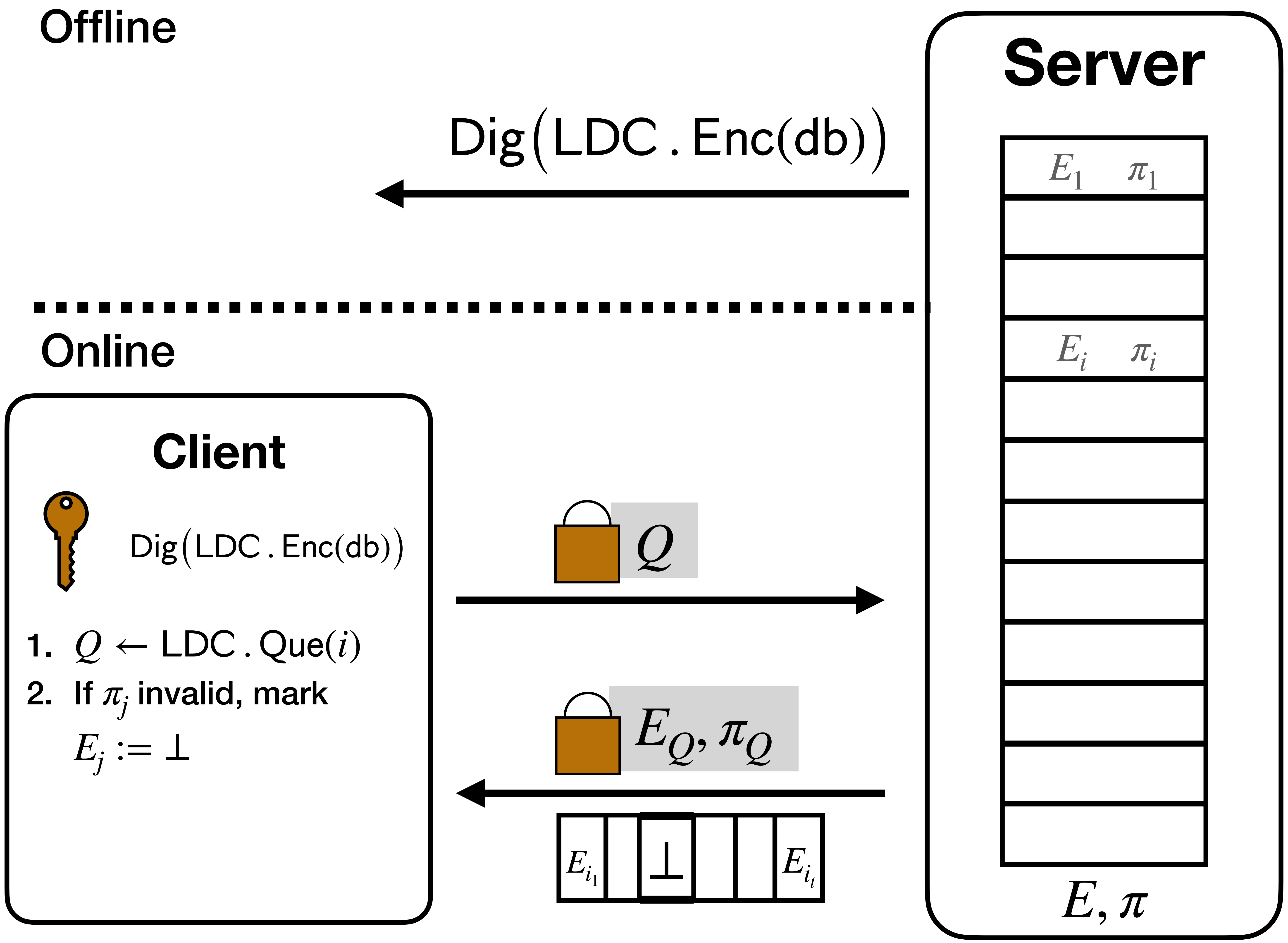

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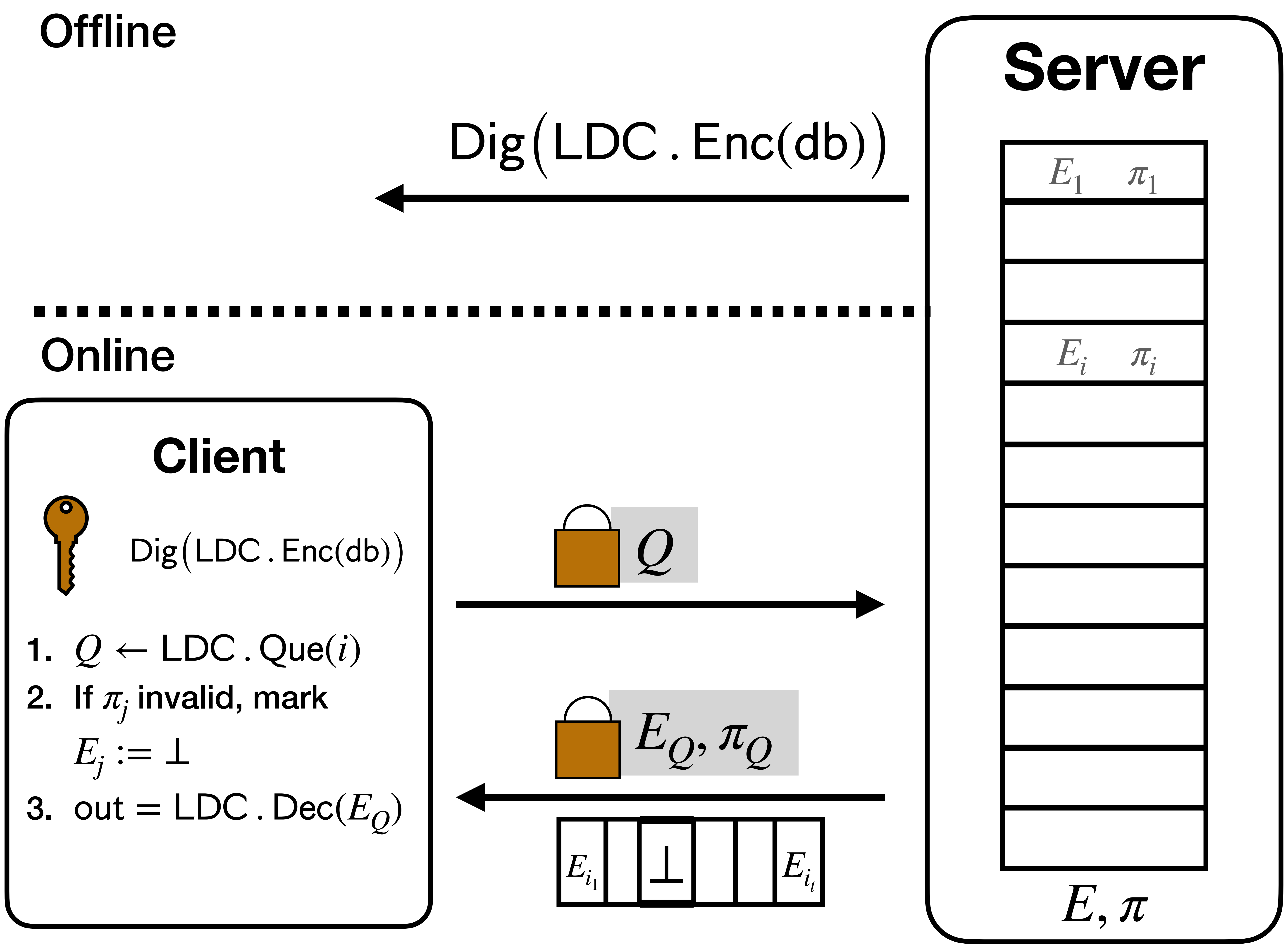

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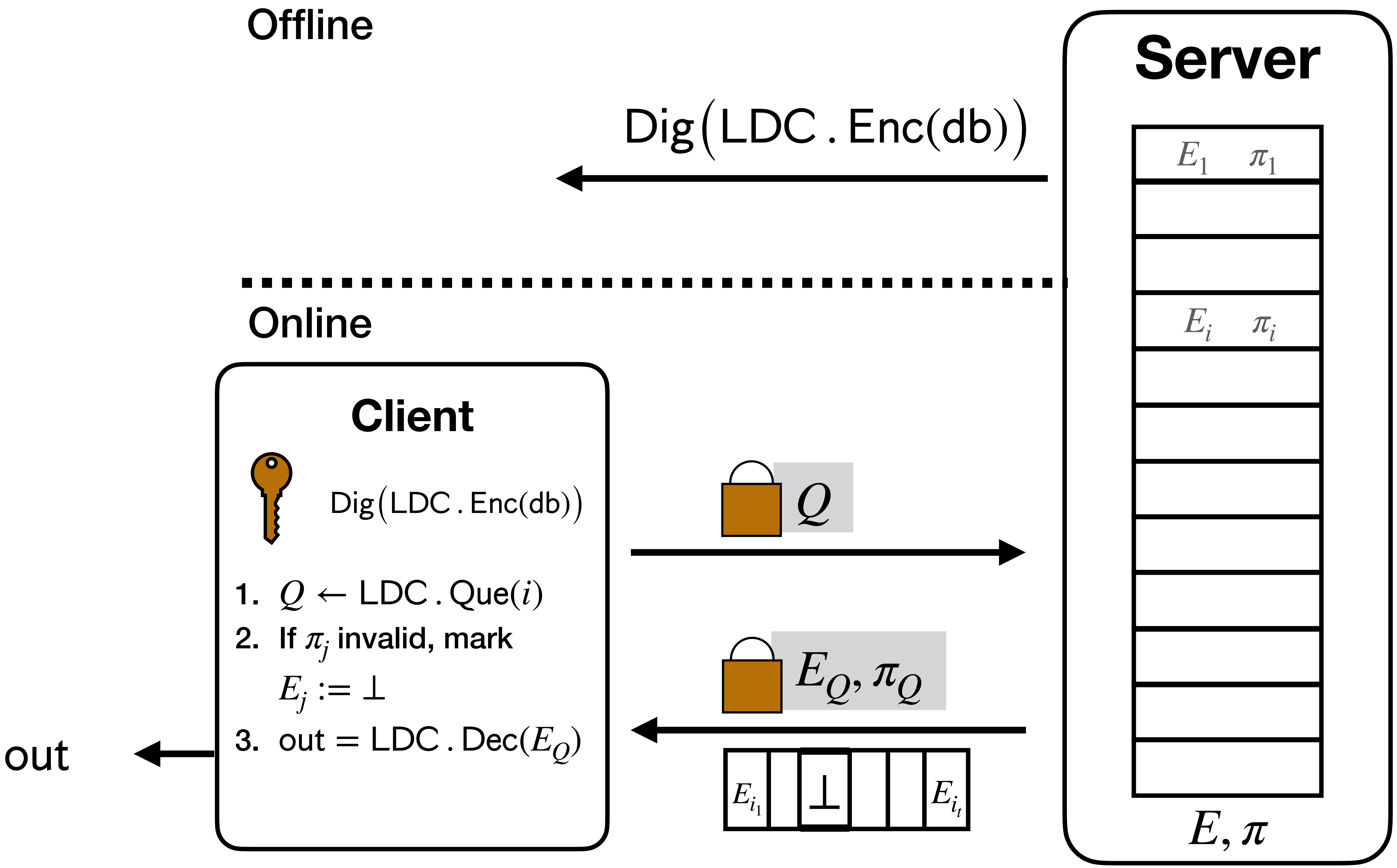
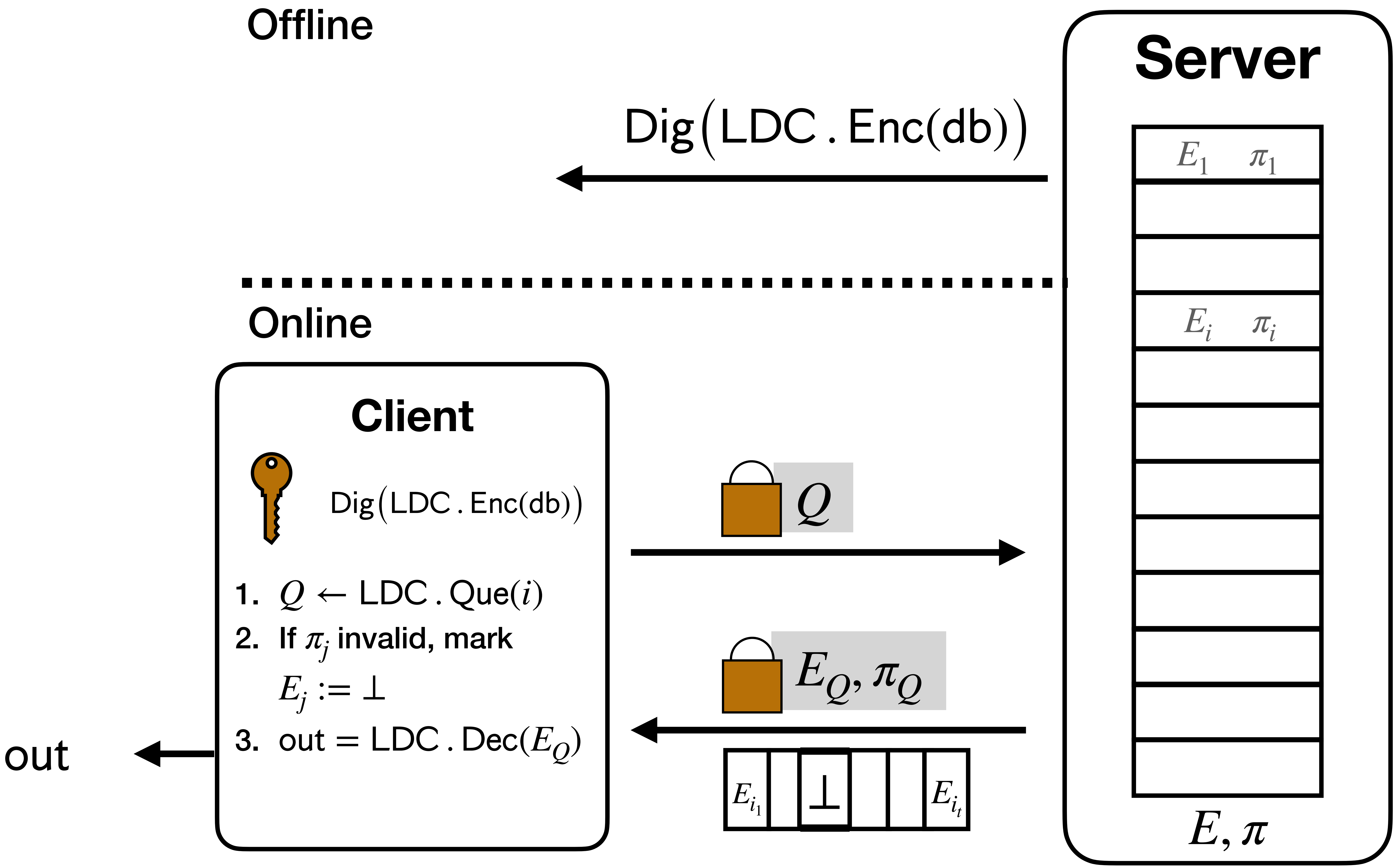


Attempt 2: LDC + VC + PIR

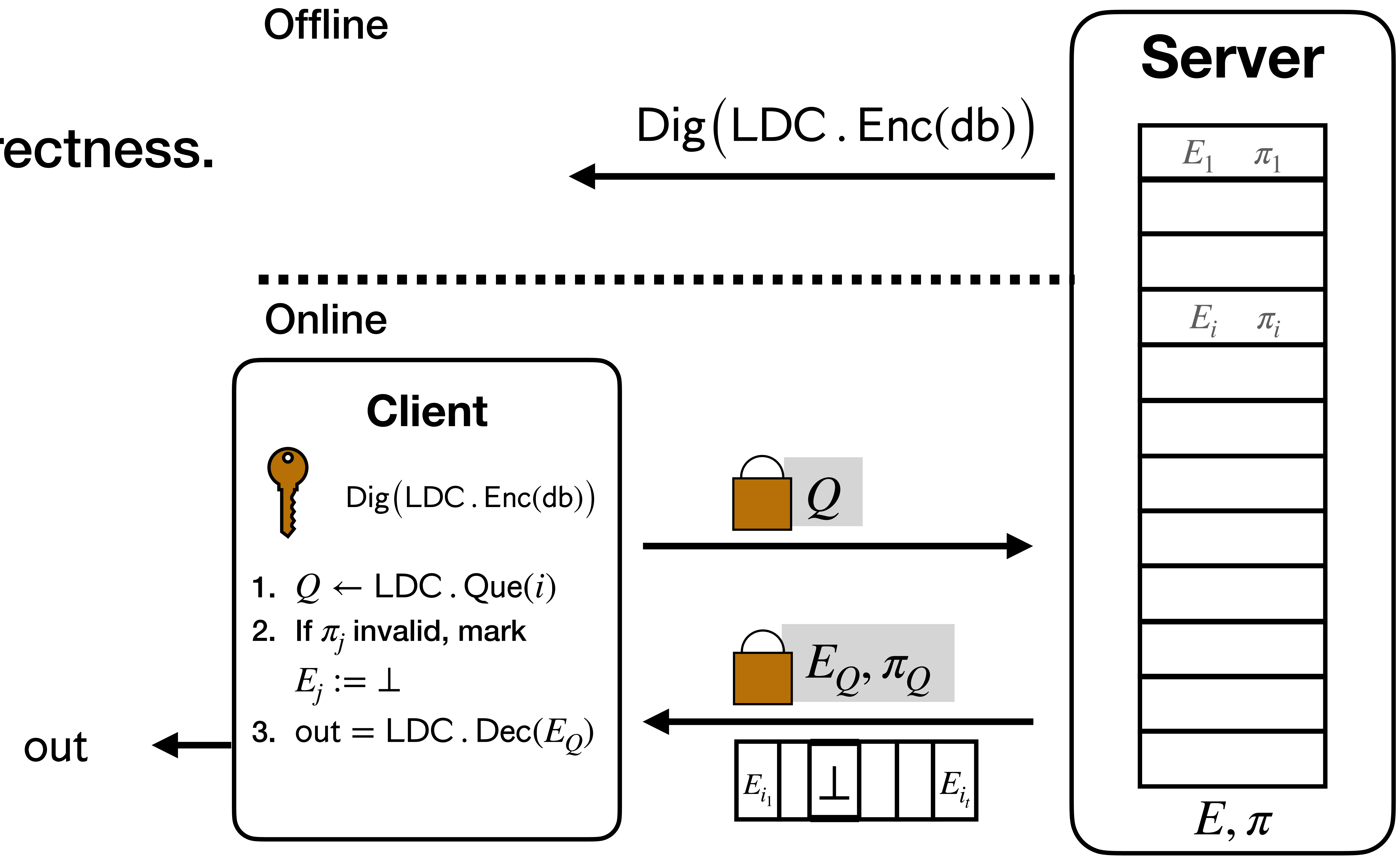
Properties



Attempt 2: LDC + VC + PIR

Properties

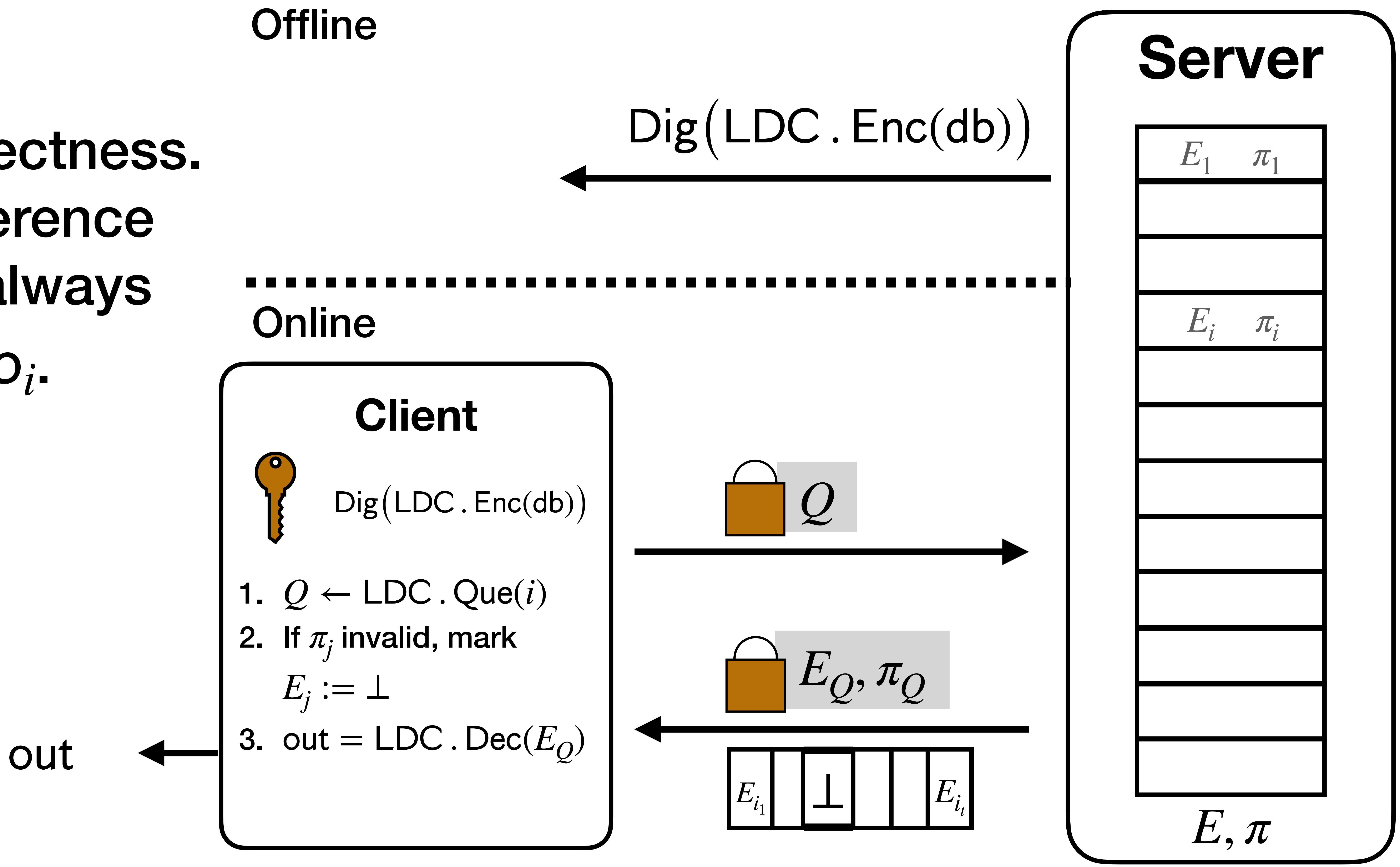
1. Preserves correctness.



Attempt 2: LDC + VC + PIR

Properties

1. Preserves correctness.
2. Preserves coherence because LDC always outputs $\perp$ or db_i.



Attempt 2: LDC + VC + PIR

Properties

1. Preserves correctness.
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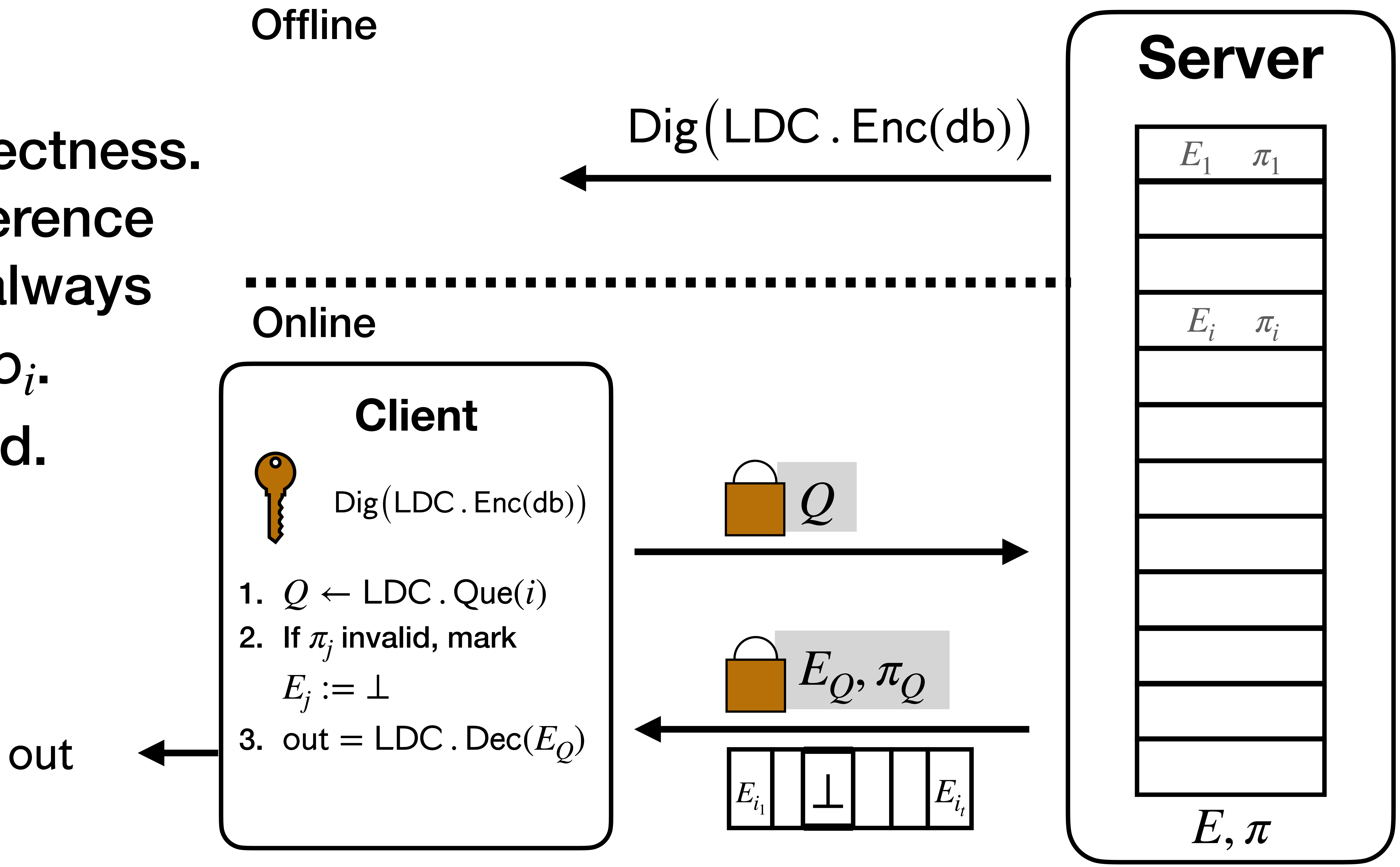
3. $O(N^{\epsilon})$ overhead.



Attempt 2: LDC + VC + PIR

Properties

1. Preserves correctness.
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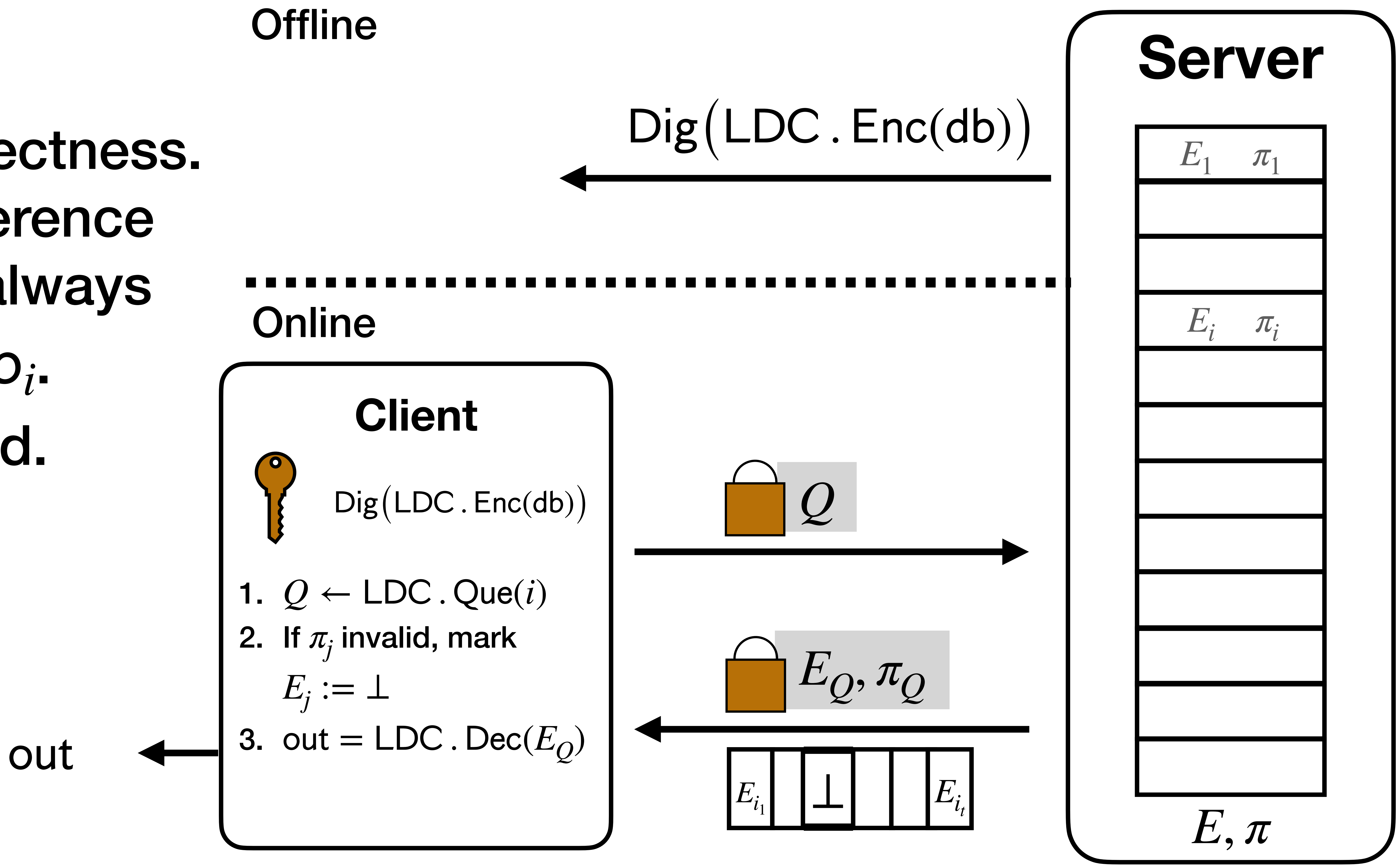
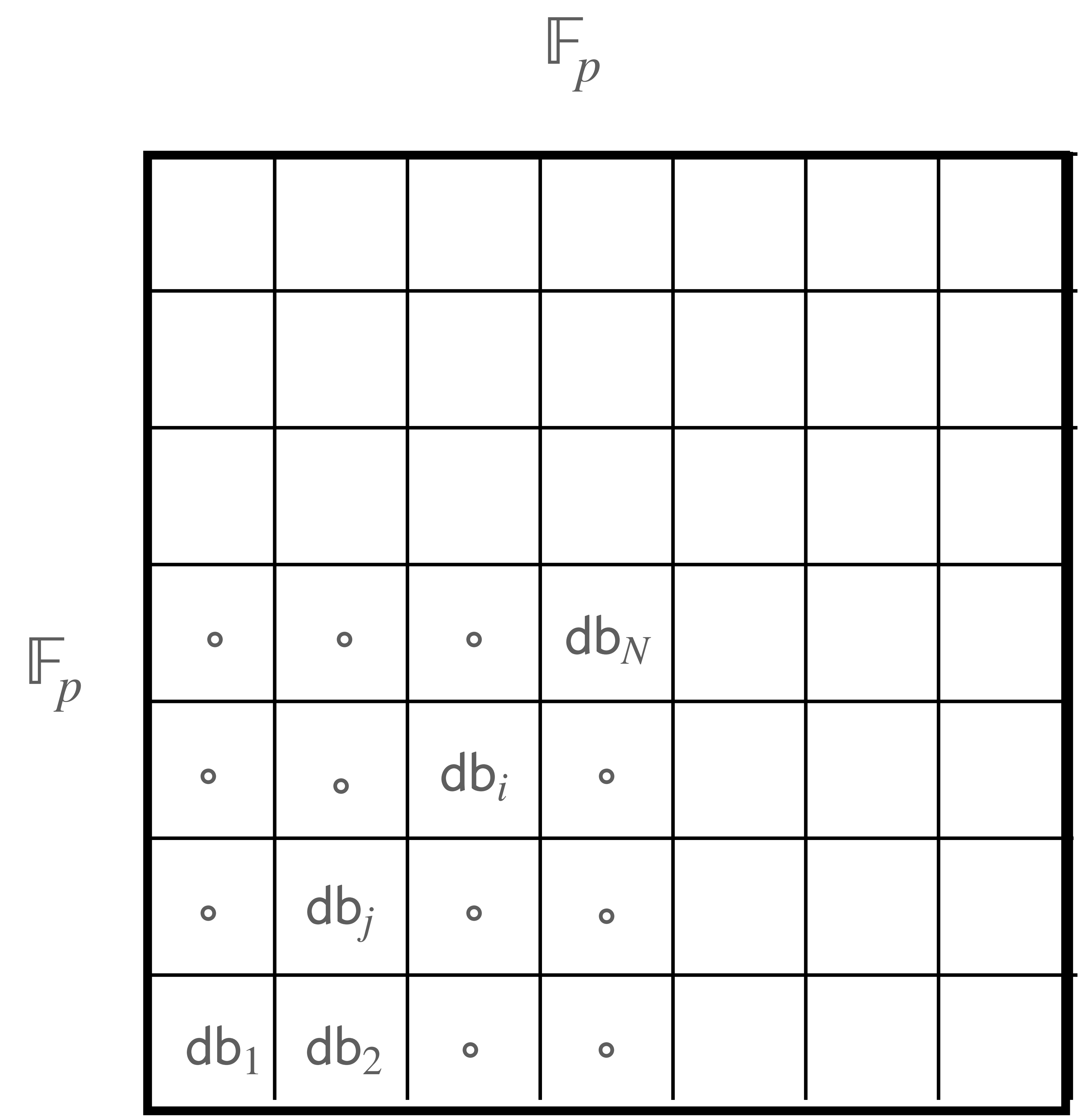
3. $O(N^\epsilon)$ overhead.
4. Privacy?

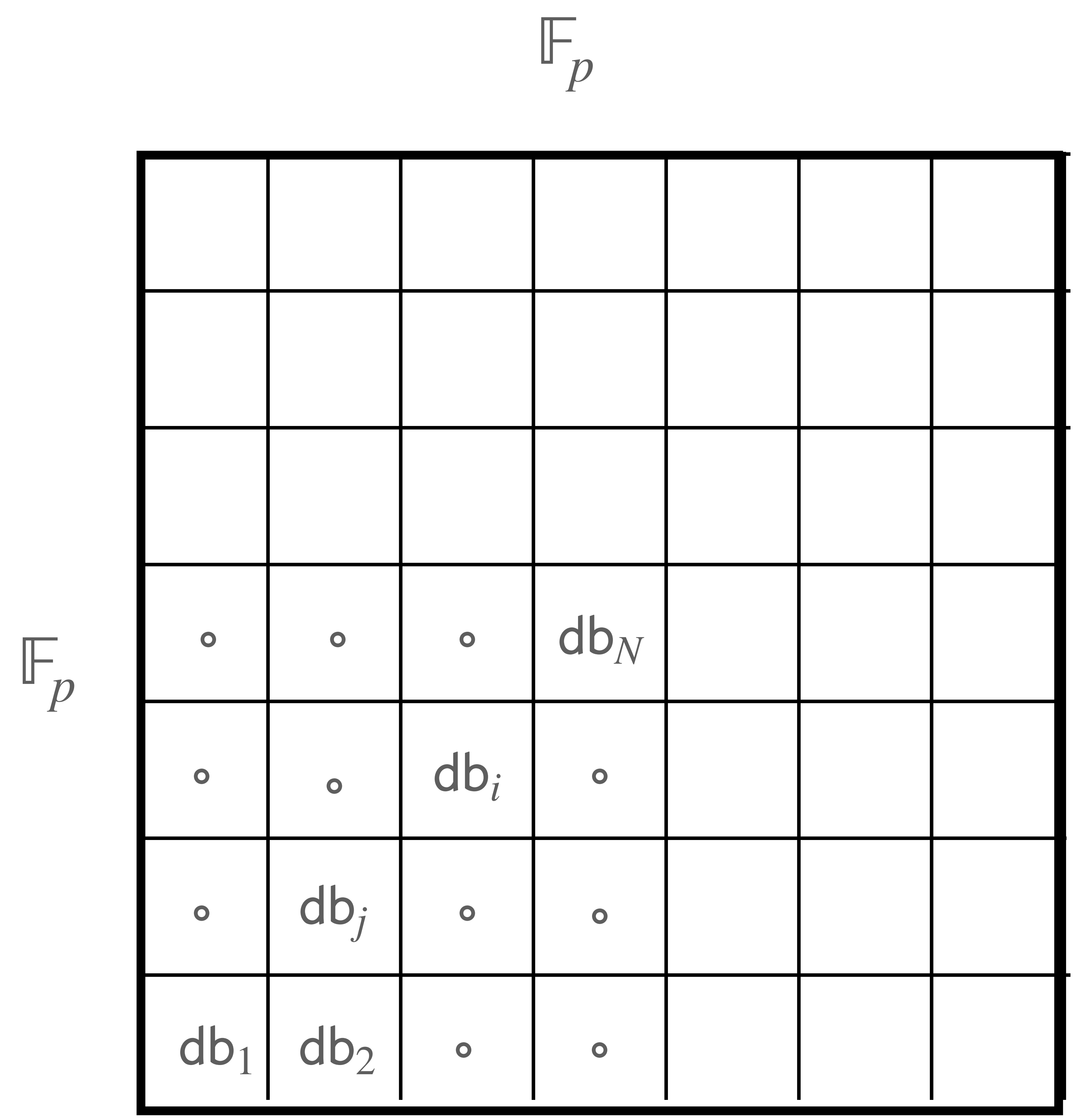


The Reed-Muller (RM) LDC



The Reed-Muller (RM) LDC

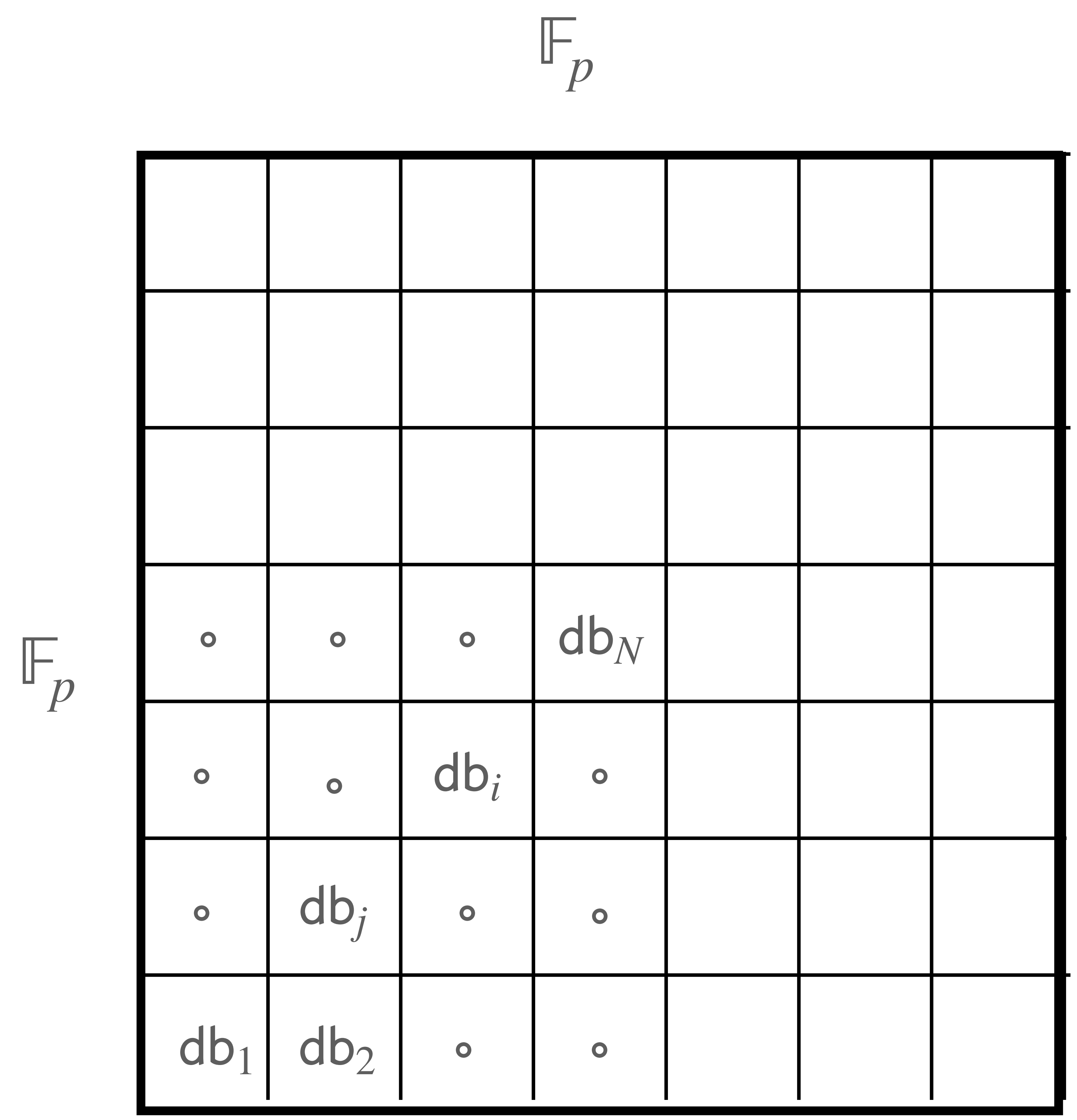
Encoding



The Reed-Muller (RM) LDC

Encoding

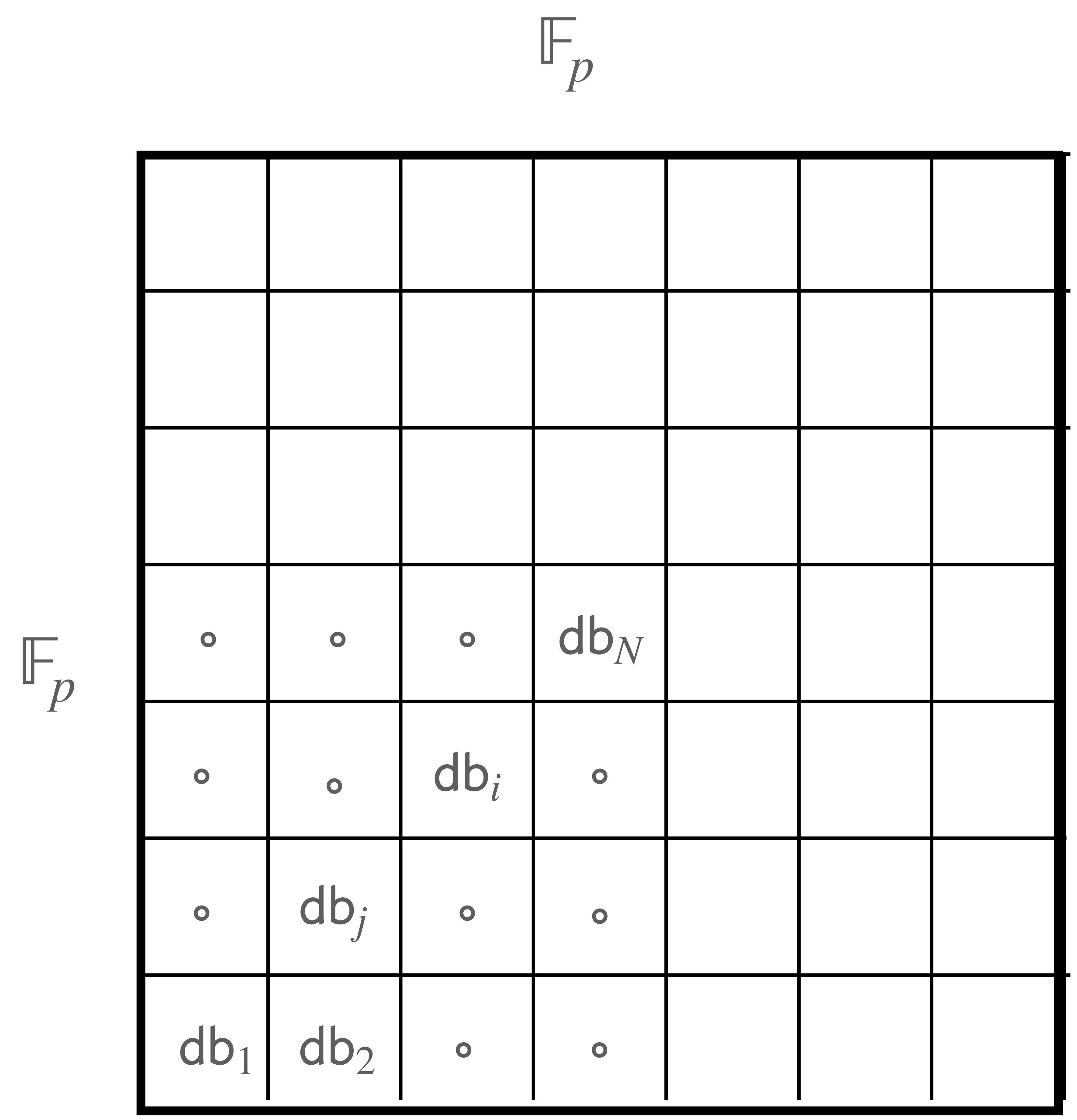
1. Interpolate a bivariate polynomial $f(X, Y)$ of total degree $d < p = O(\sqrt{N})$ that agrees with db.



The Reed-Muller (RM) LDC

Encoding

1. Interpolate a bivariate polynomial $f(X, Y)$ of total degree $d < p = O(\sqrt{N})$ that agrees with db.
2. The codeword E is the evaluations of $f(x, y)$ for all $x, y \in \mathbb{F}_p \times \mathbb{F}_p$



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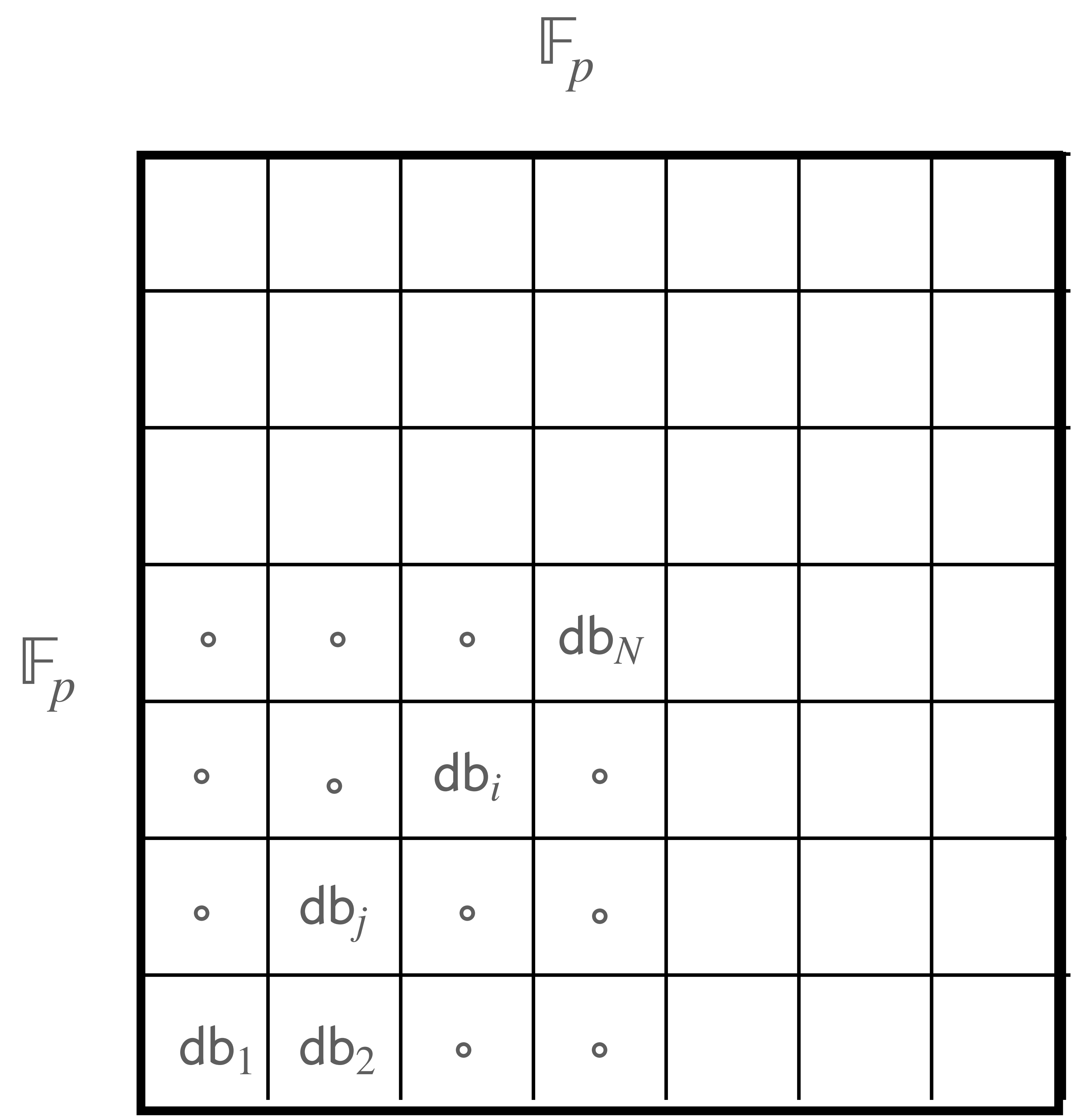
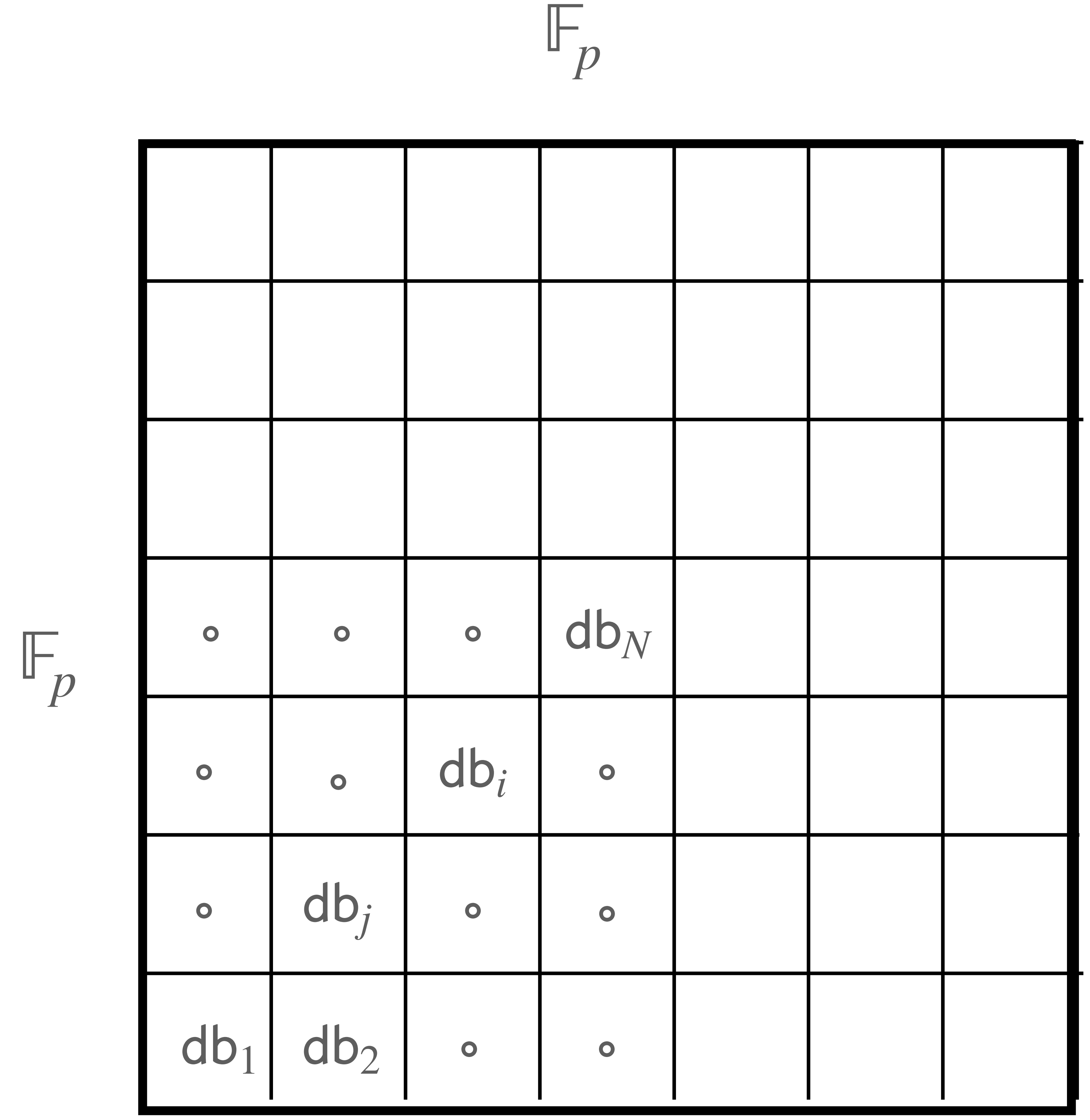


The Reed-Muller (RM) LDC

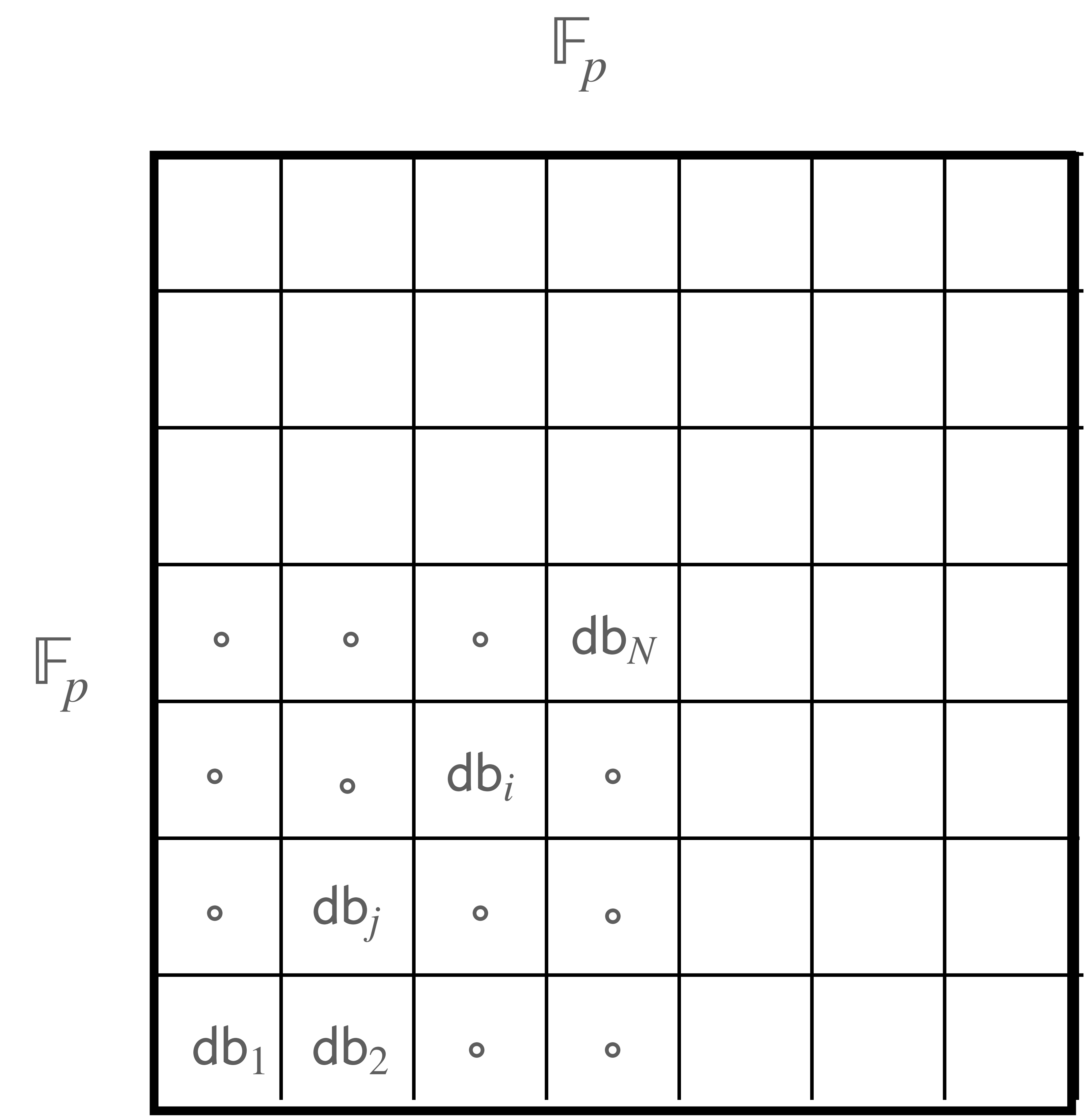
Local decoding



The Reed-Muller (RM) LDC

Local decoding

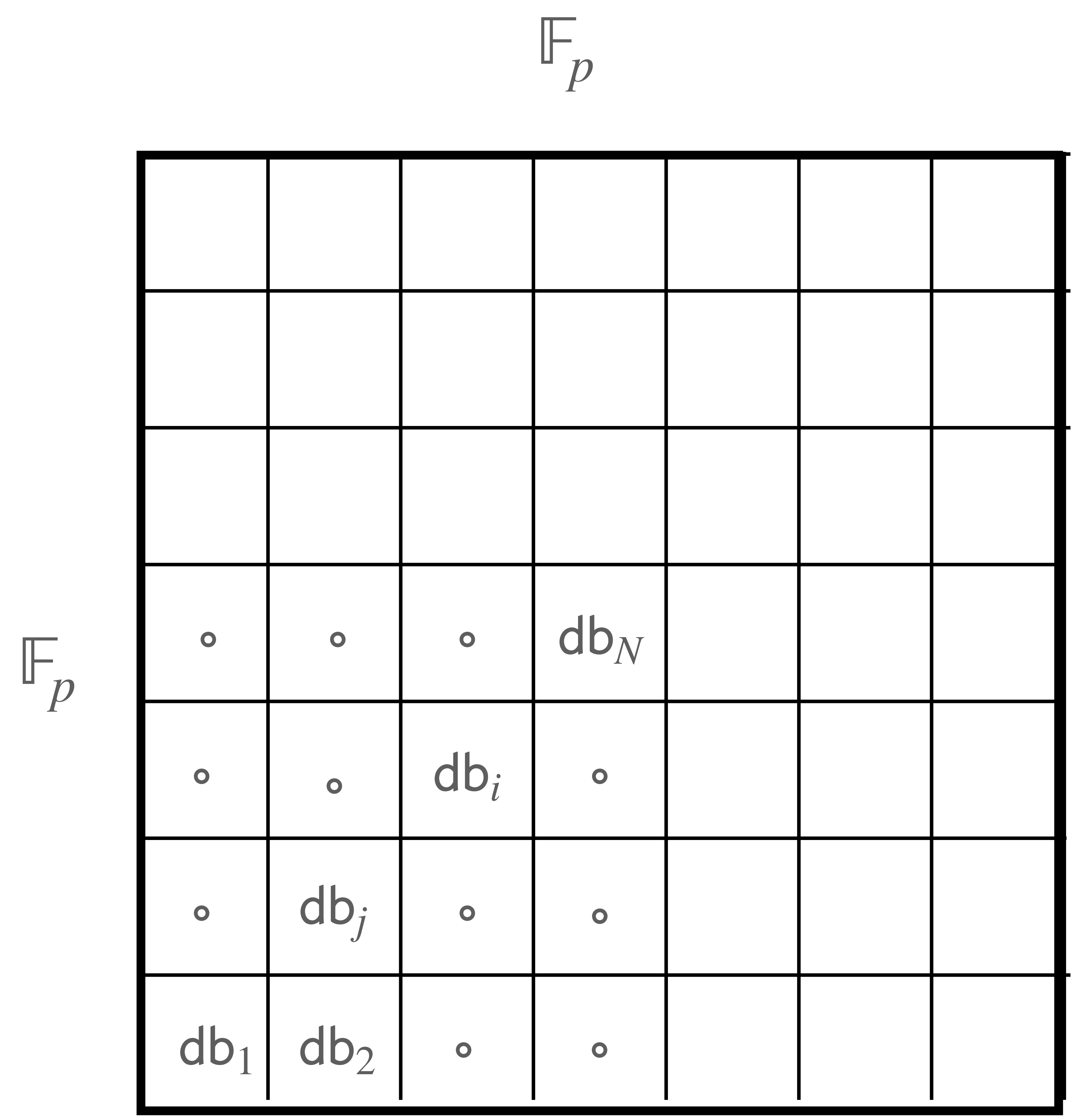
1. Want: db_j



The Reed-Muller (RM) LDC

Local decoding

1. Want: db_j
2. $\mathsf{RM}.\mathsf{Que}(j) \to Q$: let Q be a random line through db_j.



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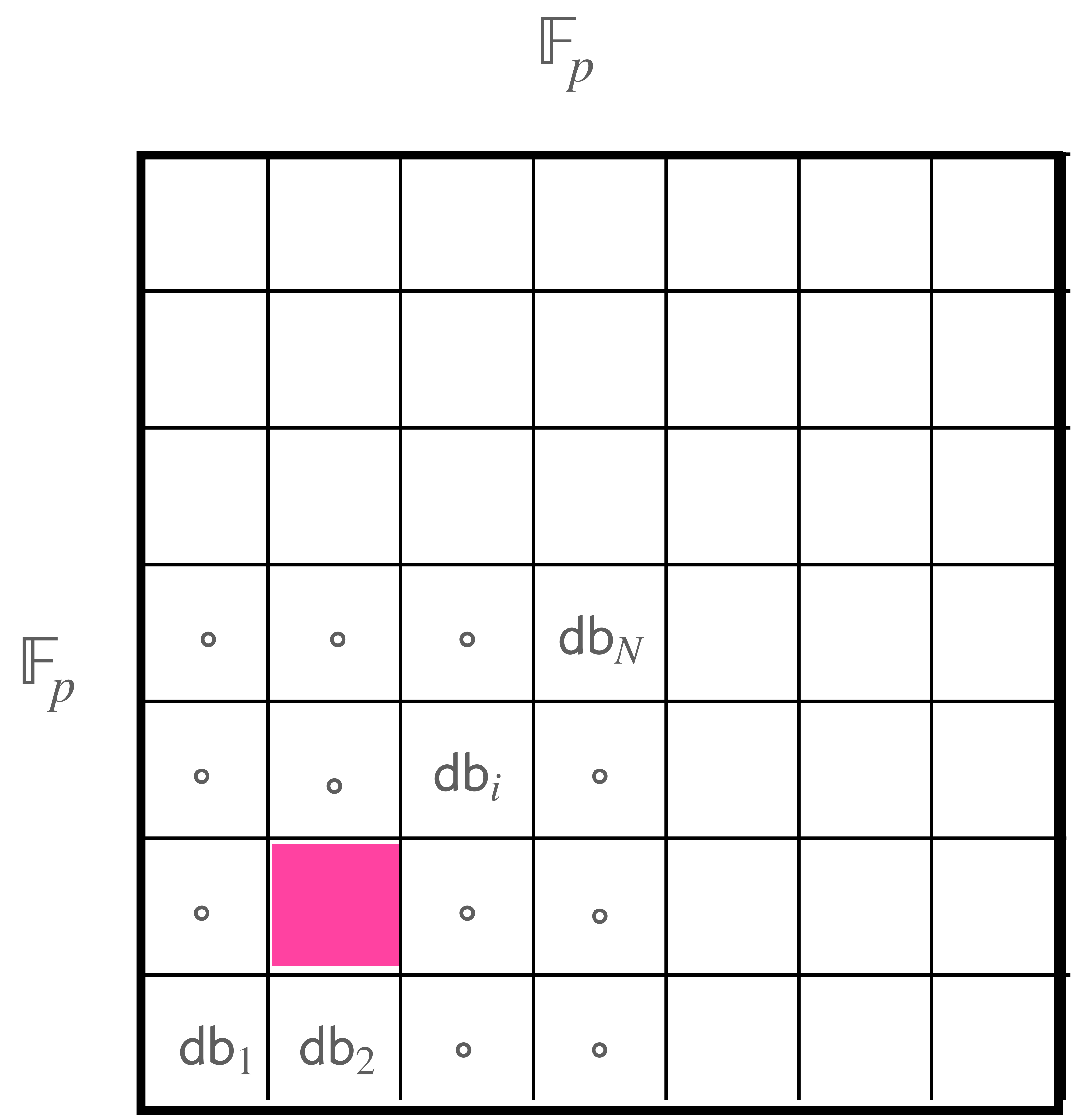

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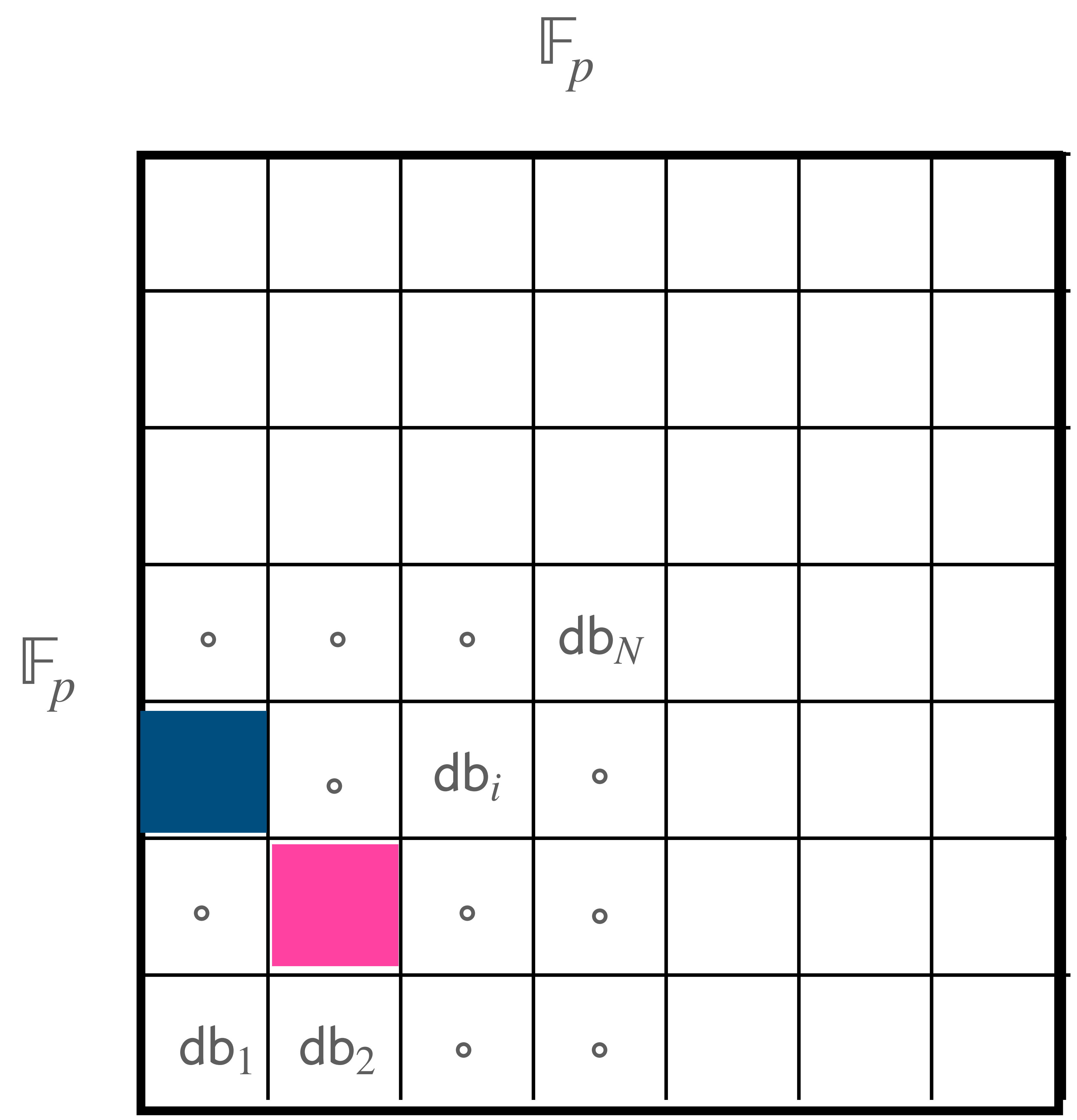

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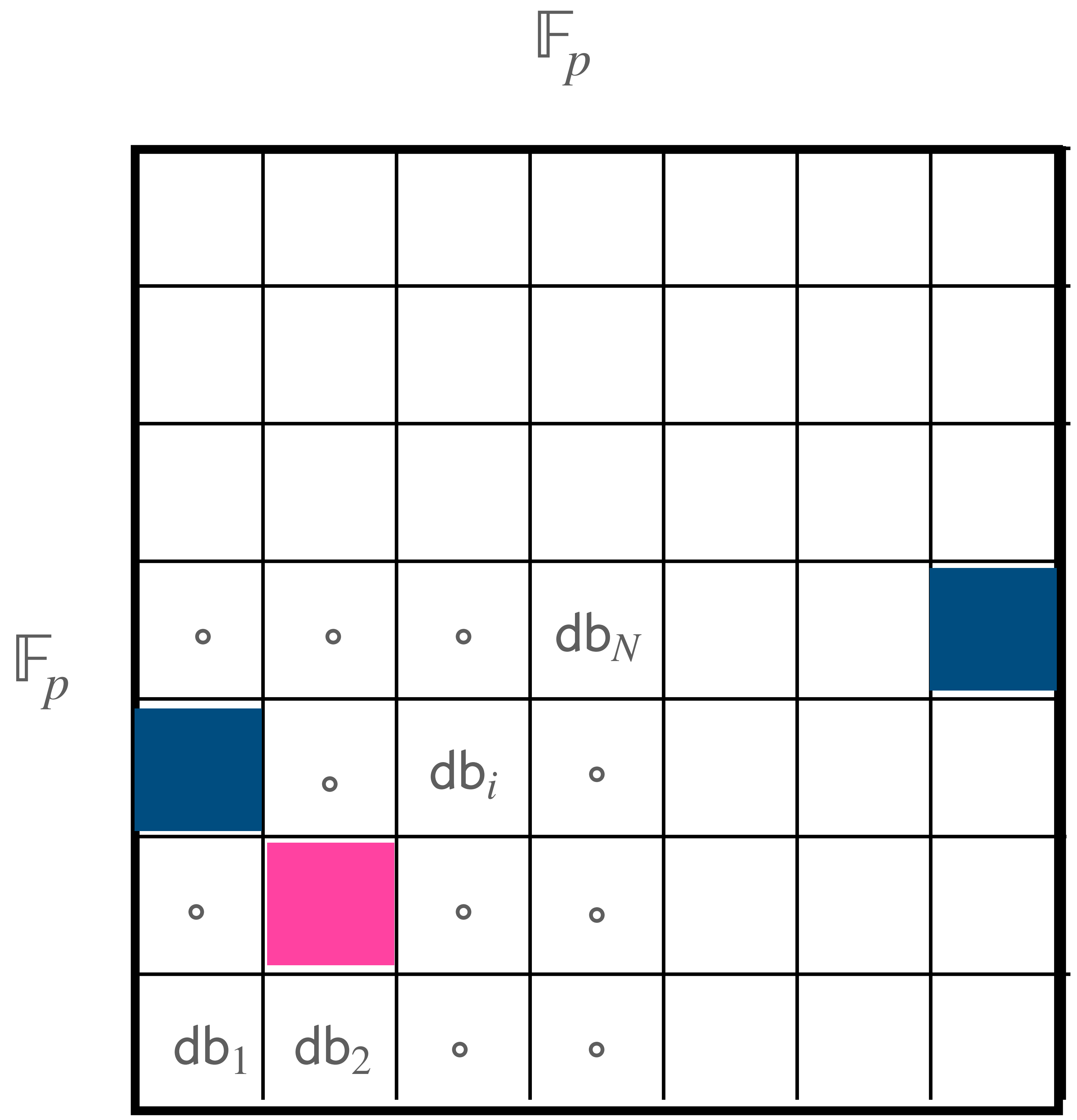

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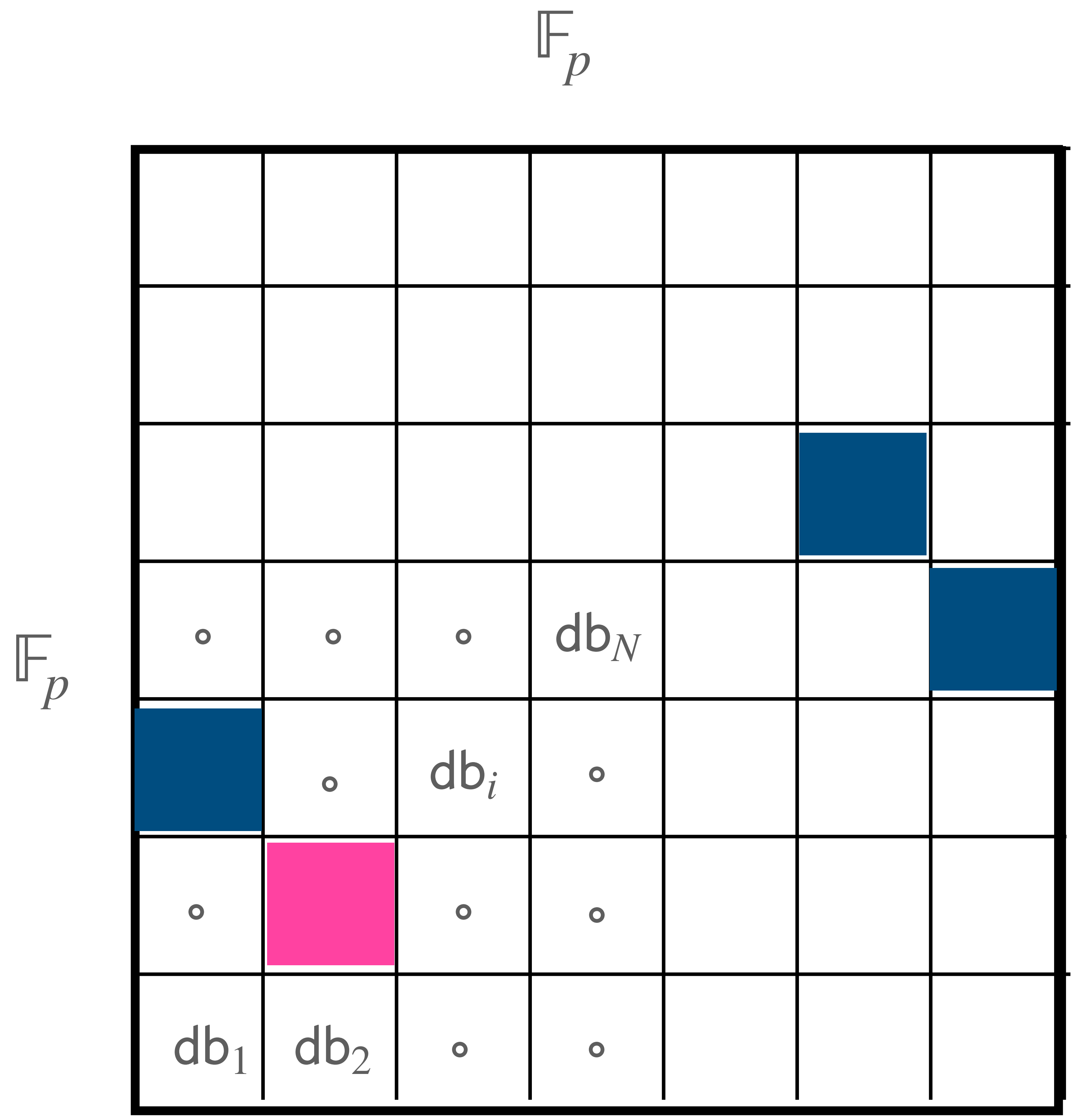

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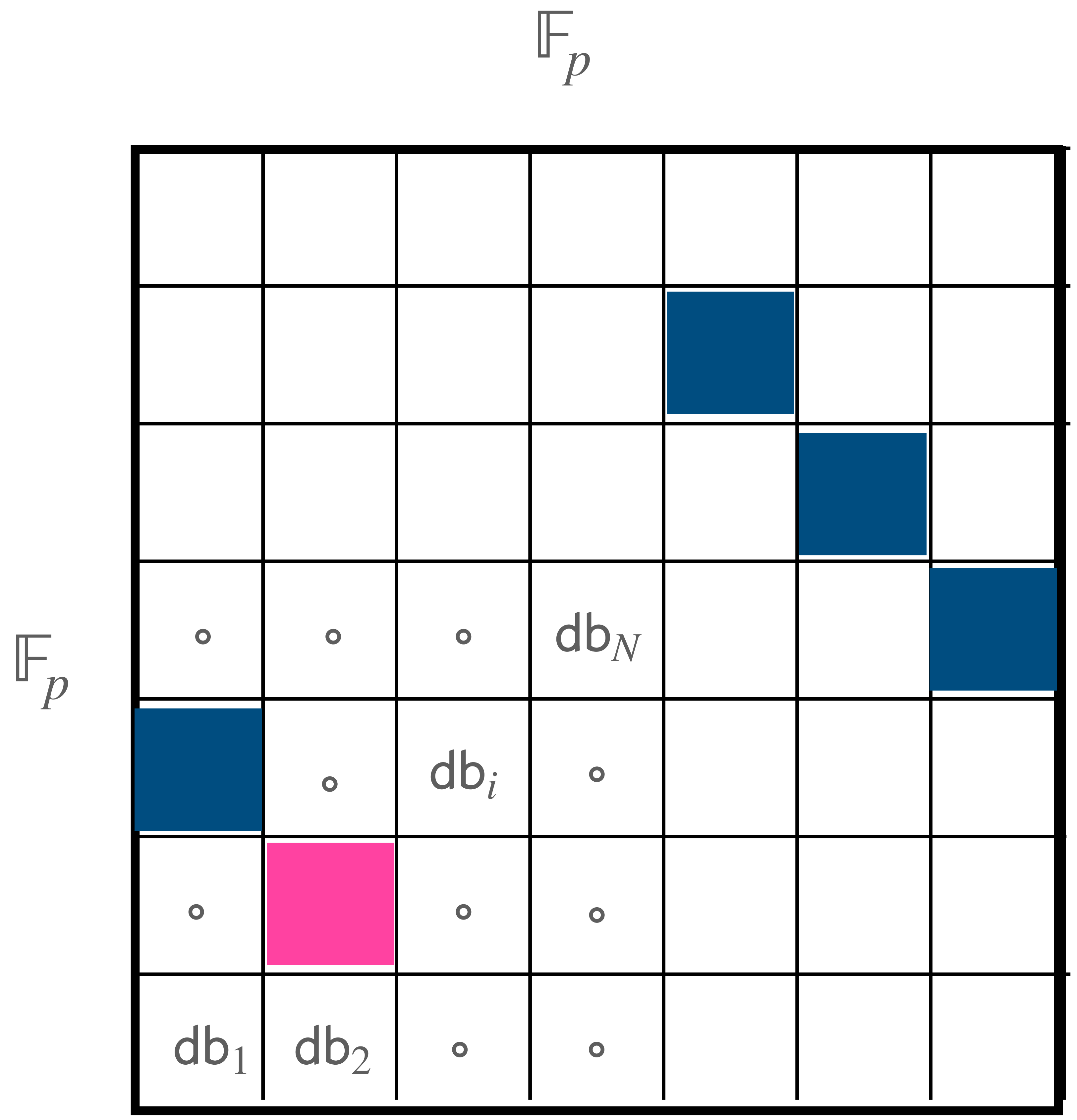

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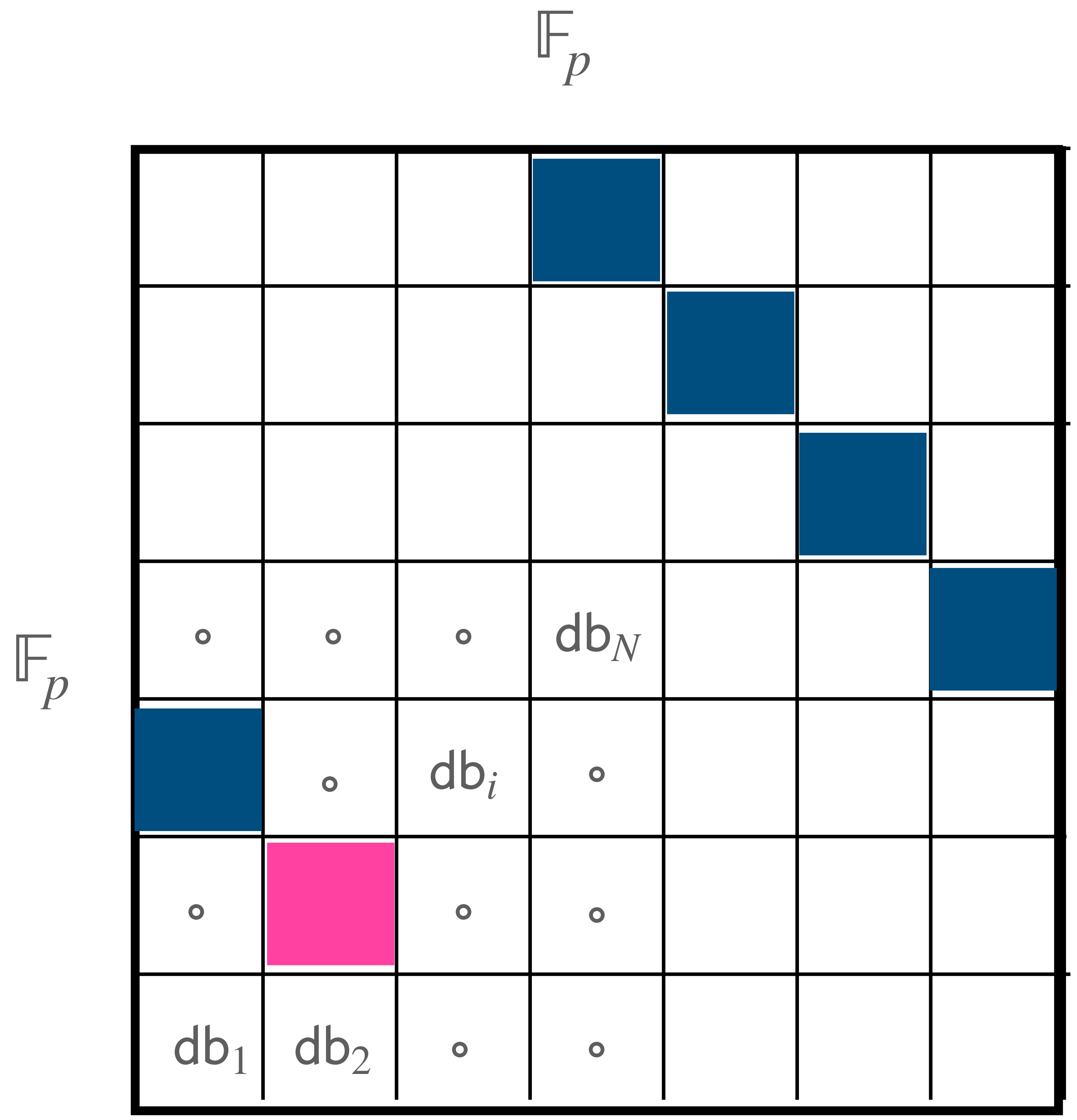

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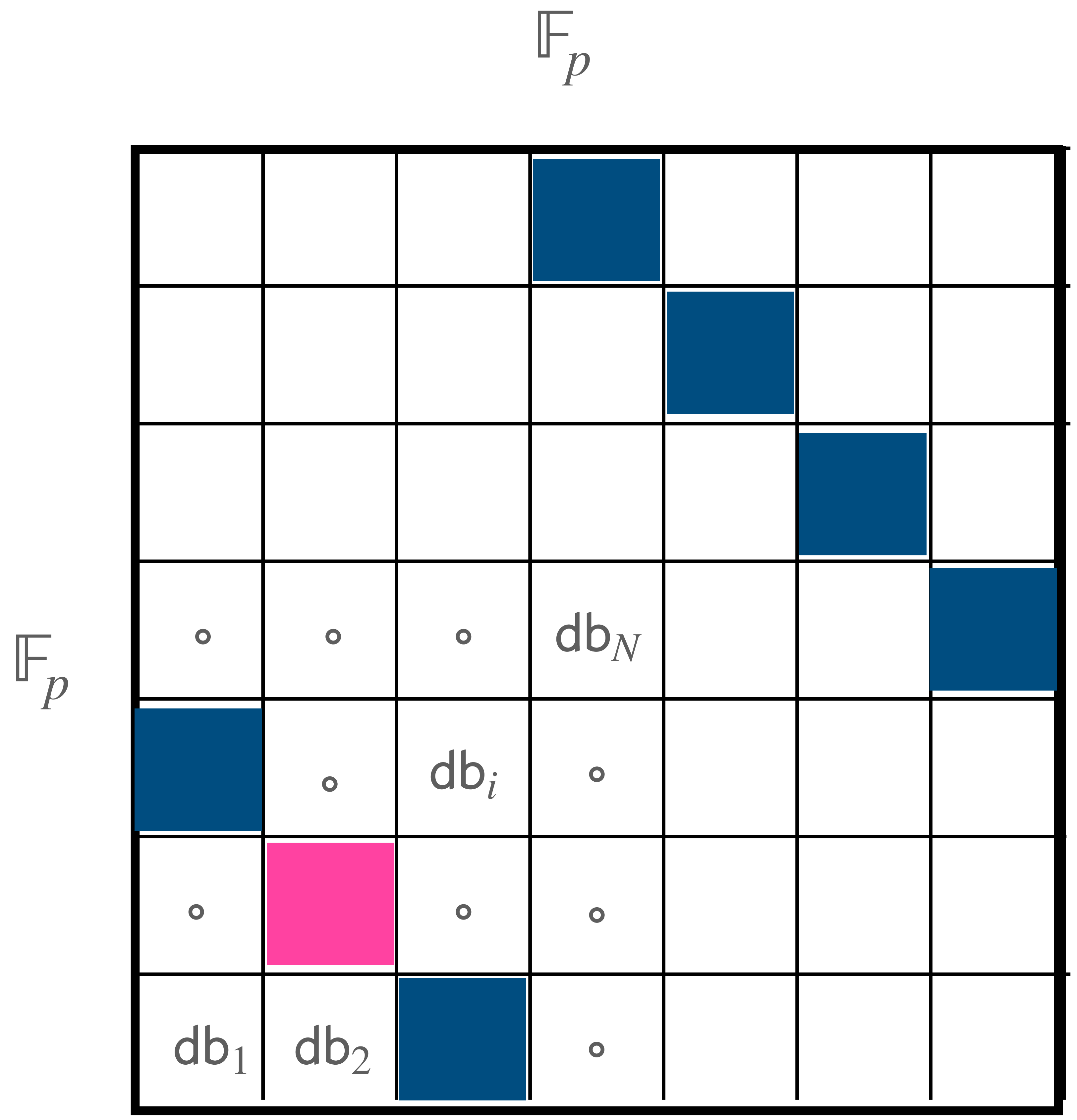
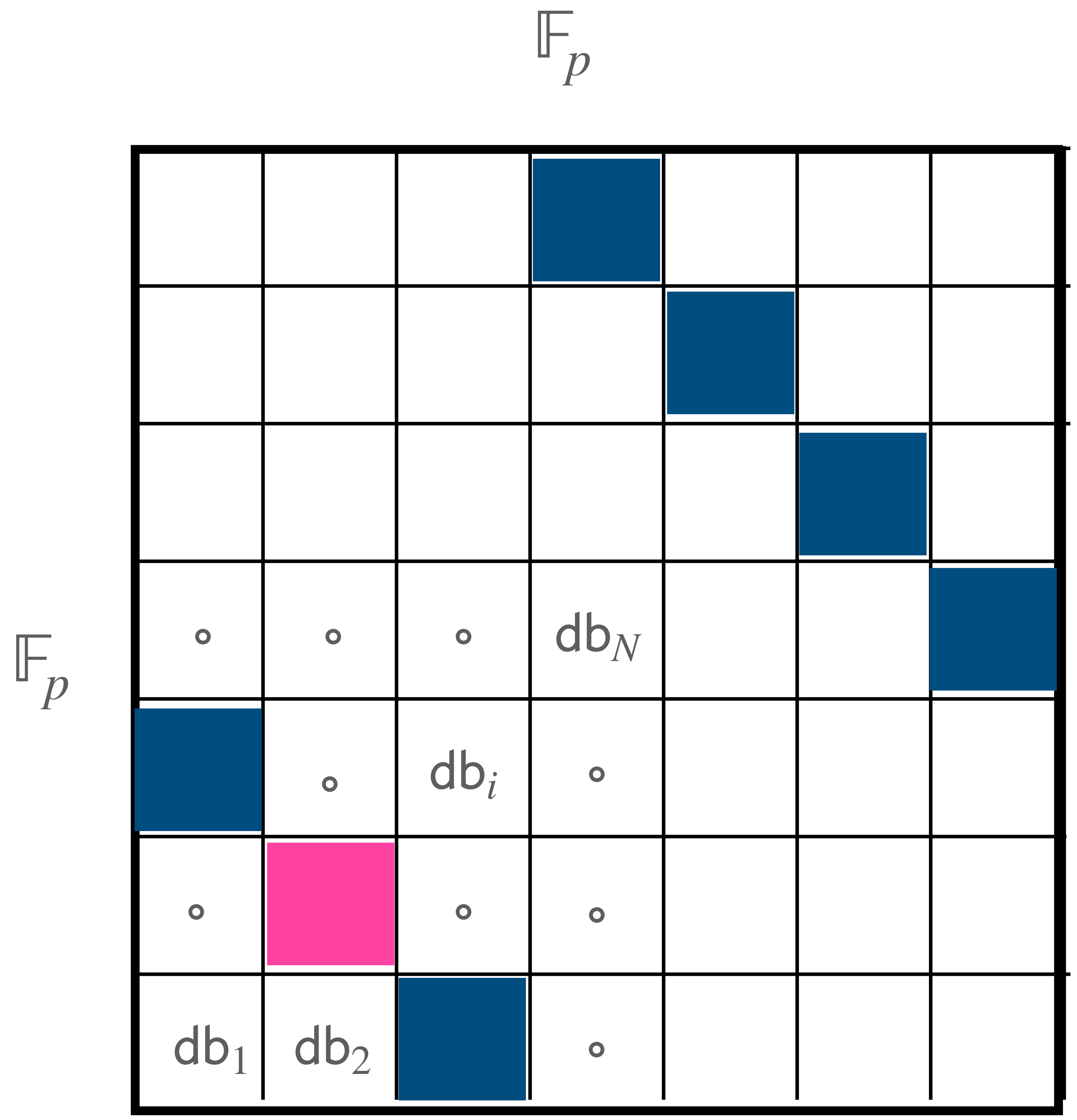


The Reed-Muller (RM) LDC

Local decoding

1. Want: db_j
2. $\mathsf{RM}.\mathsf{Que}(j) \to Q$: let Q be a random line through db_j.
3. $\mathsf{RM}.\mathsf{Dec}(E_Q) \to \mathsf{db}_j$: E_Q is a univariate polynomial. Can retrieve db_j from E_Q.

Decoder reads only $p = O(N^{1/2})$ elements!



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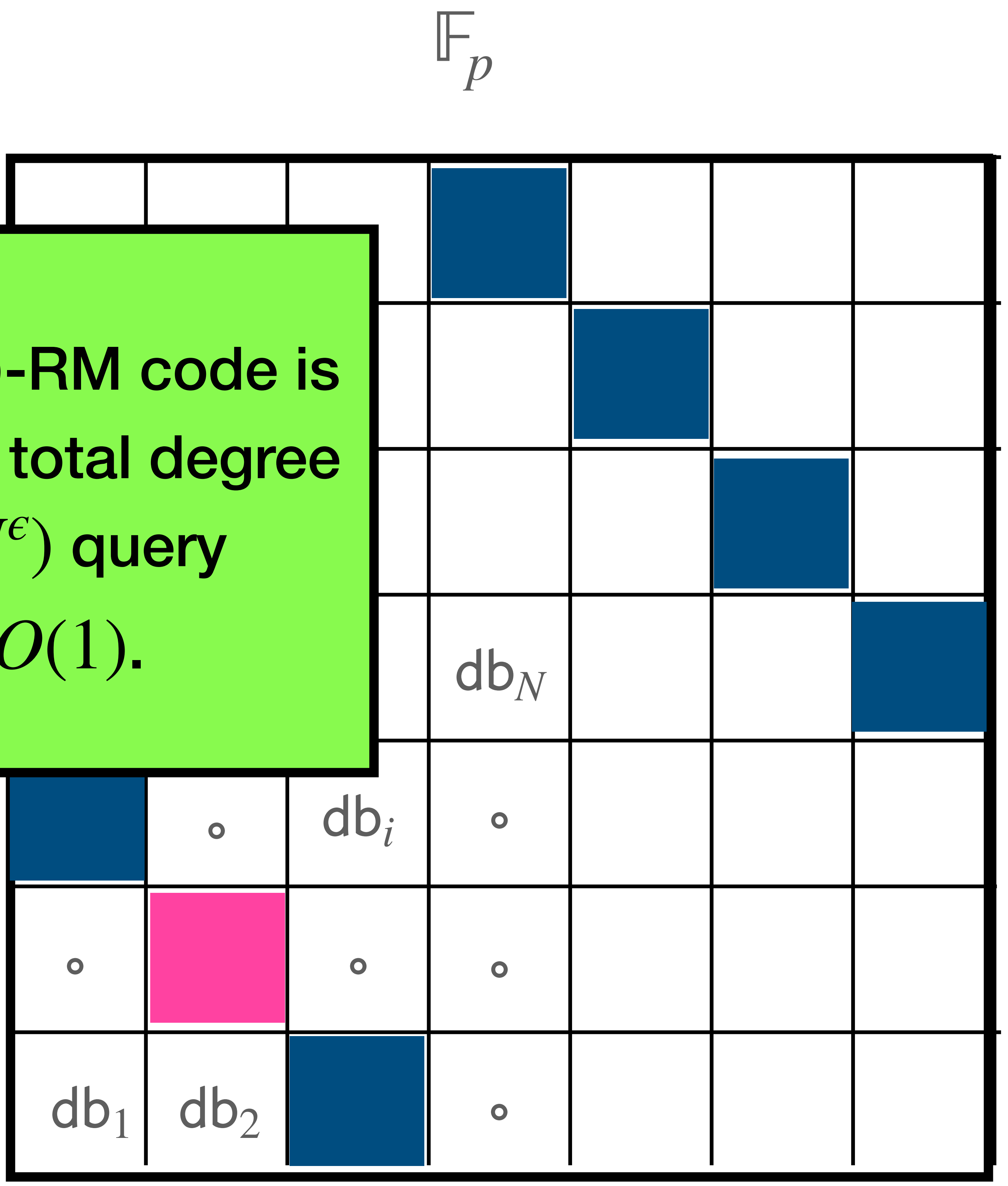
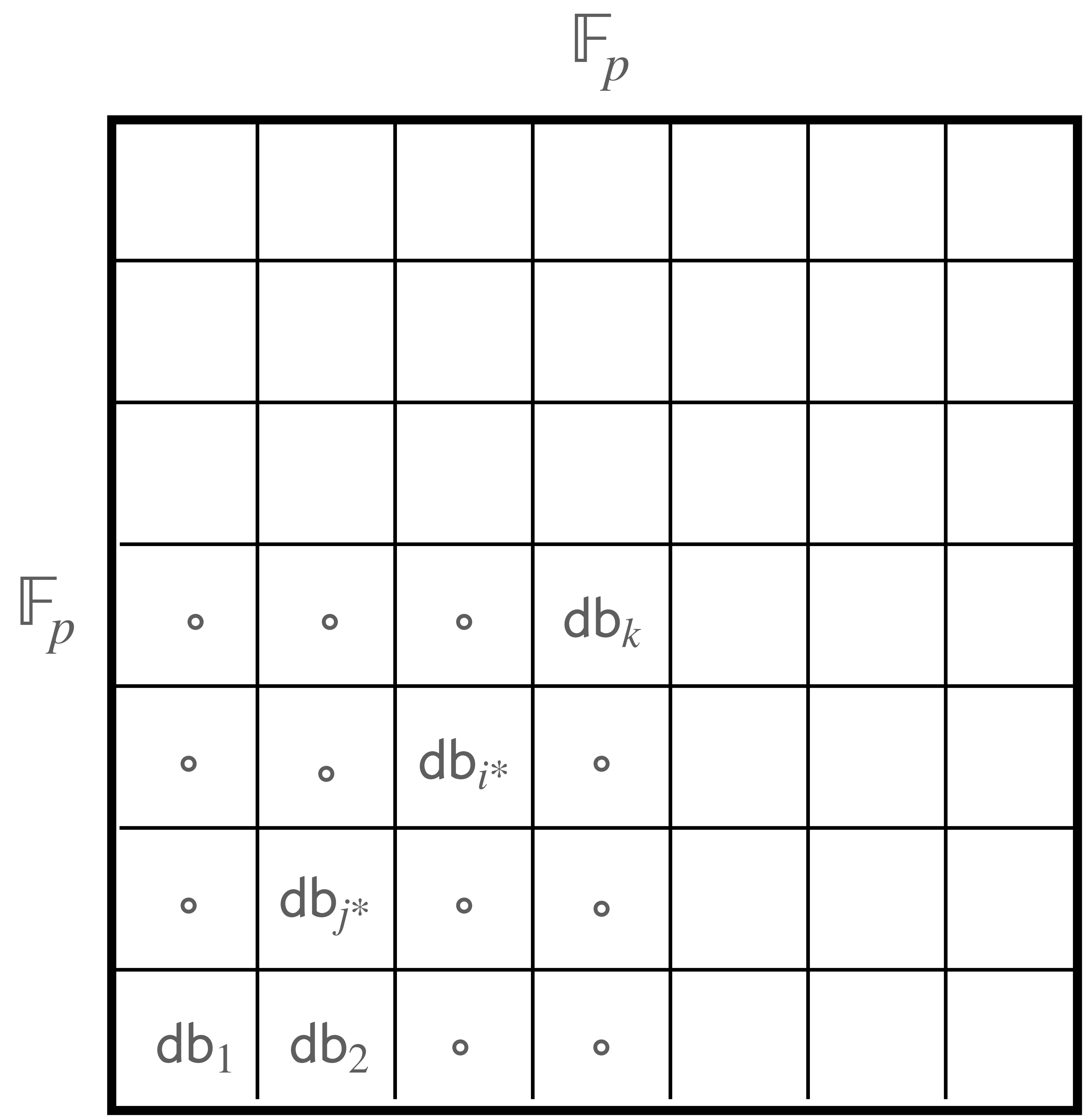
More generally (q, m, d)-RM code is m-variate polynomial of total degree d over $\mathbb{F}_q$. Has $O(N^\epsilon)$ query complexity, rate $O(1)$.



Analyzing privacy: “variance attack”



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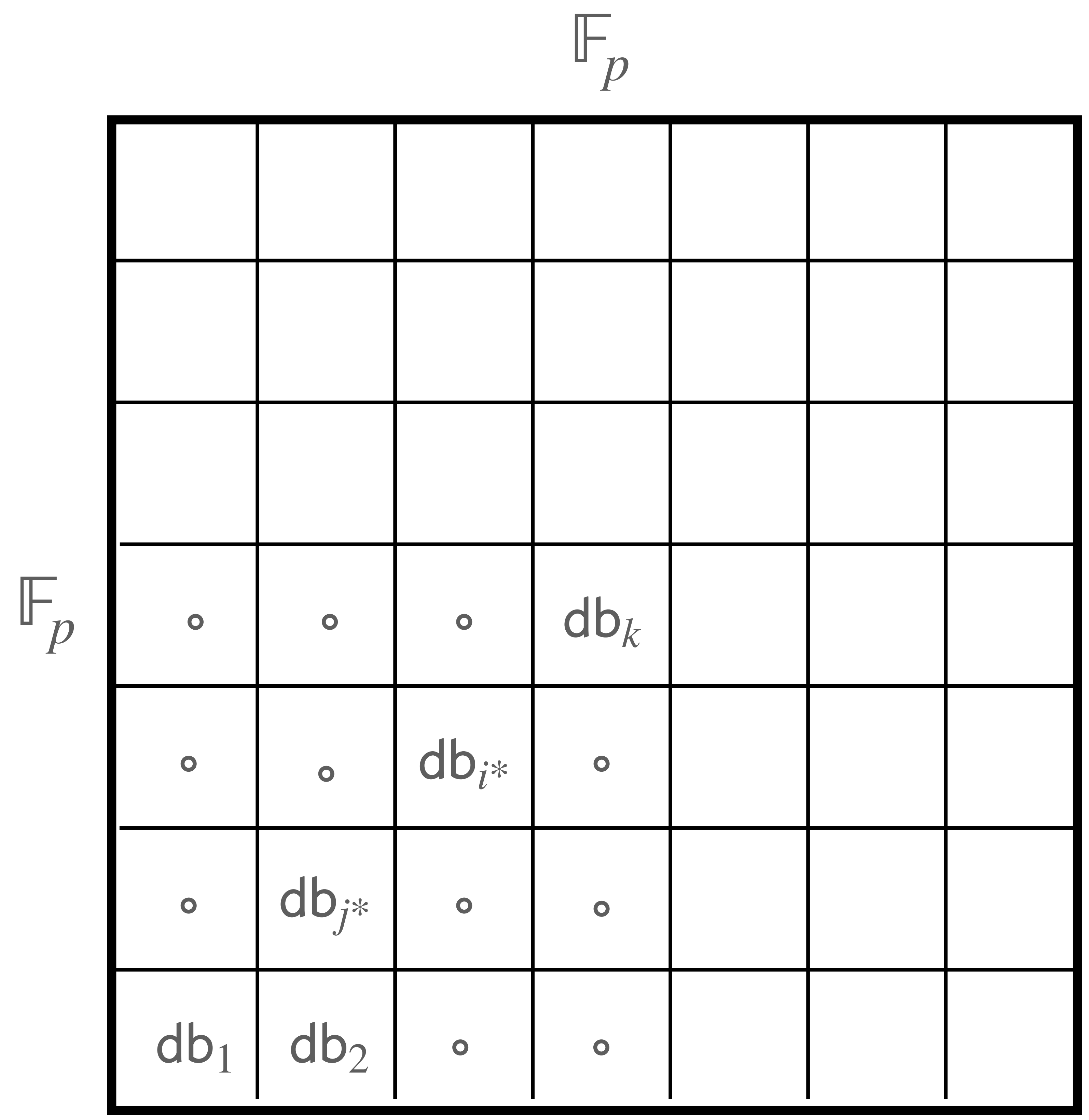
To introduce selective failure on index i, the adversary corrupts (opening proofs on) line ℓ through db_i:



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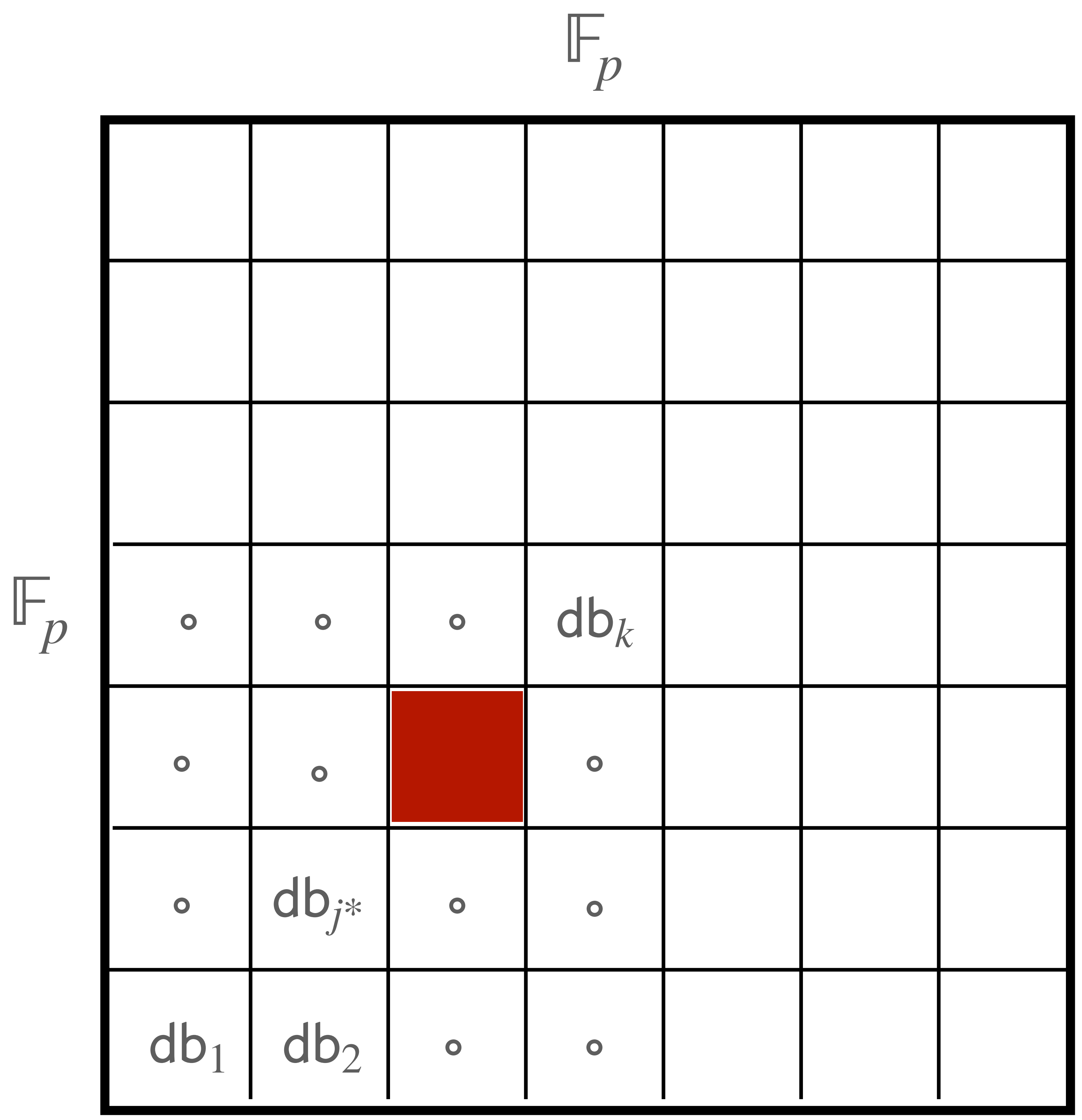

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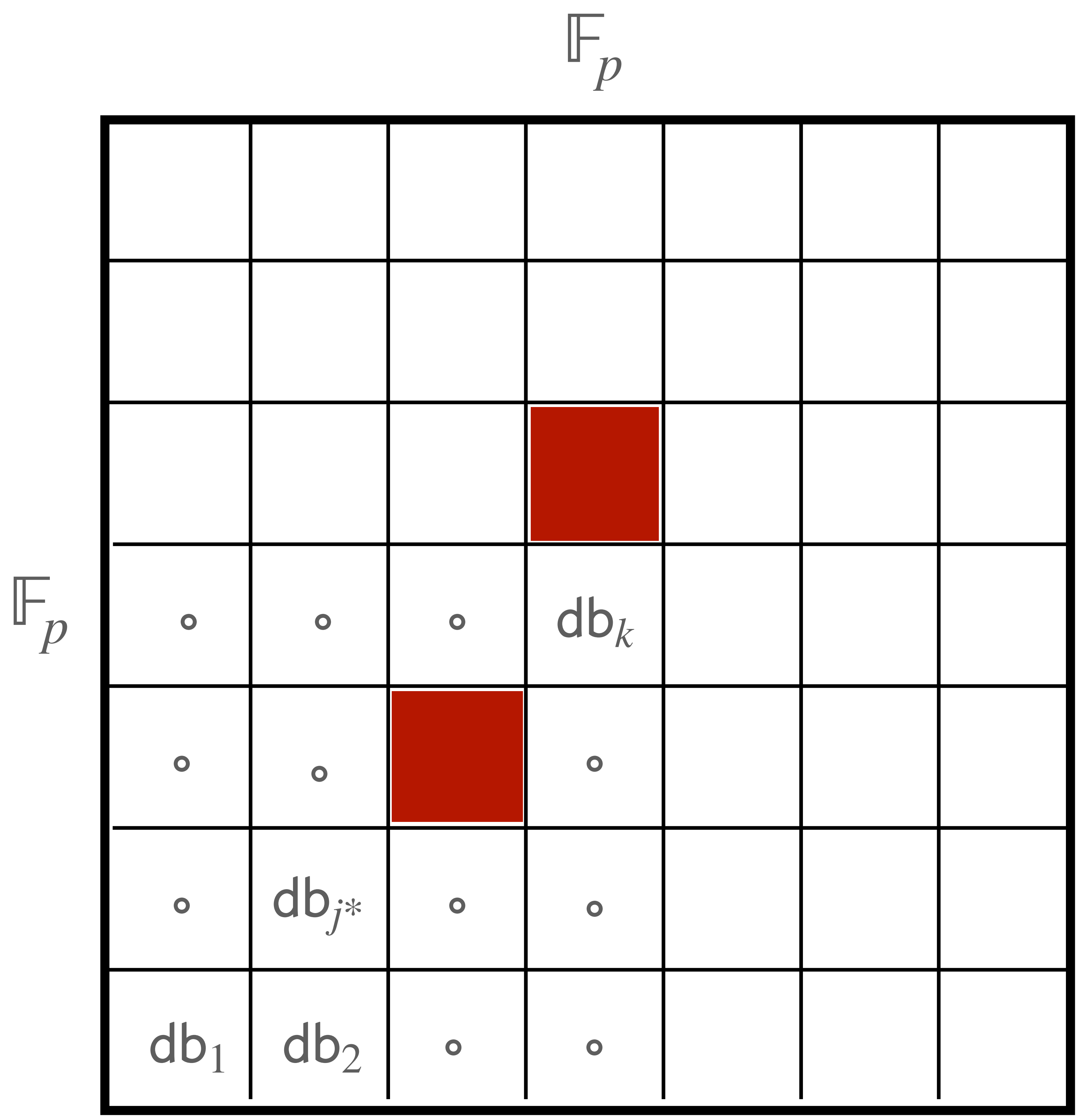

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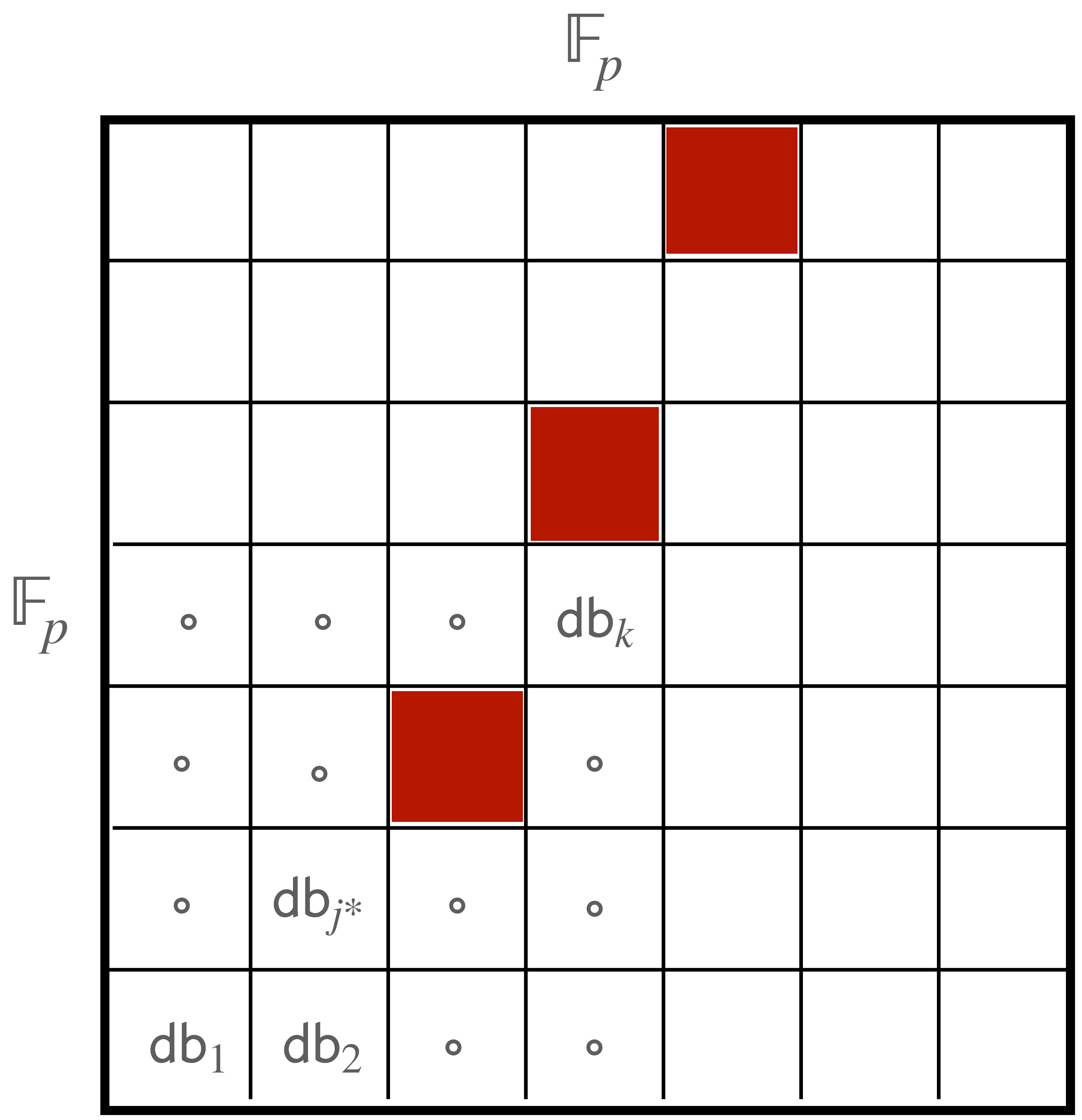

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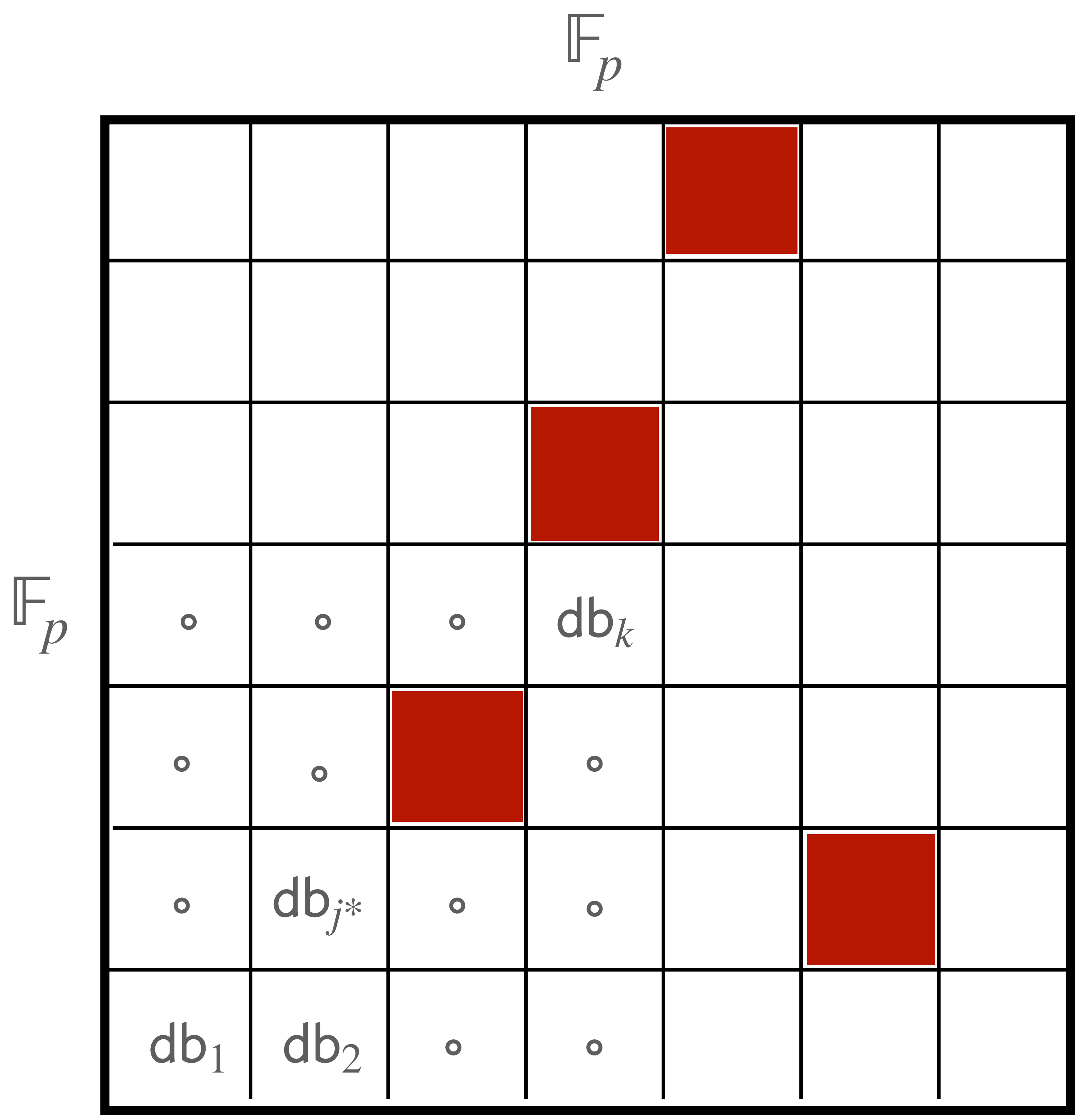

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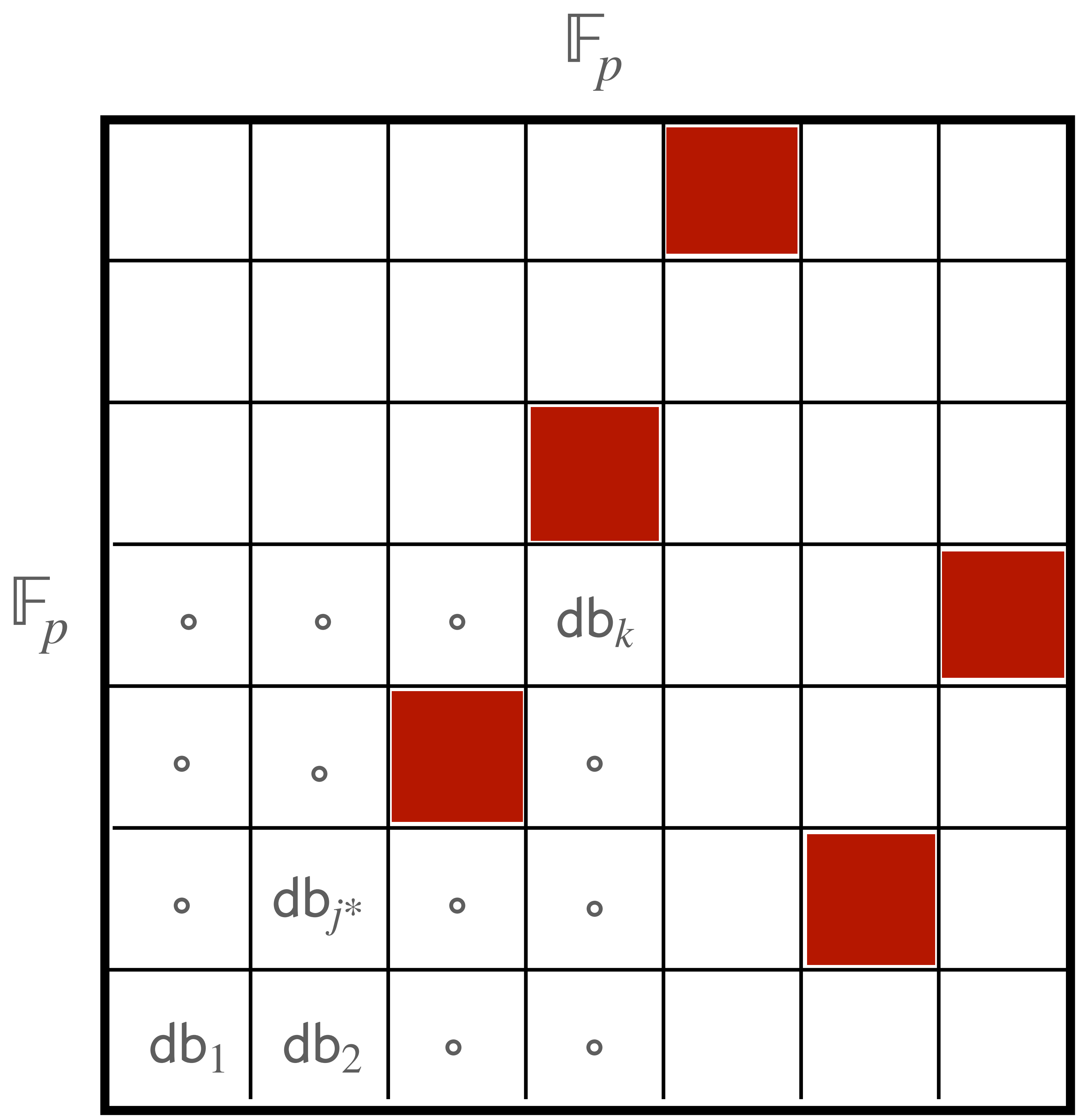

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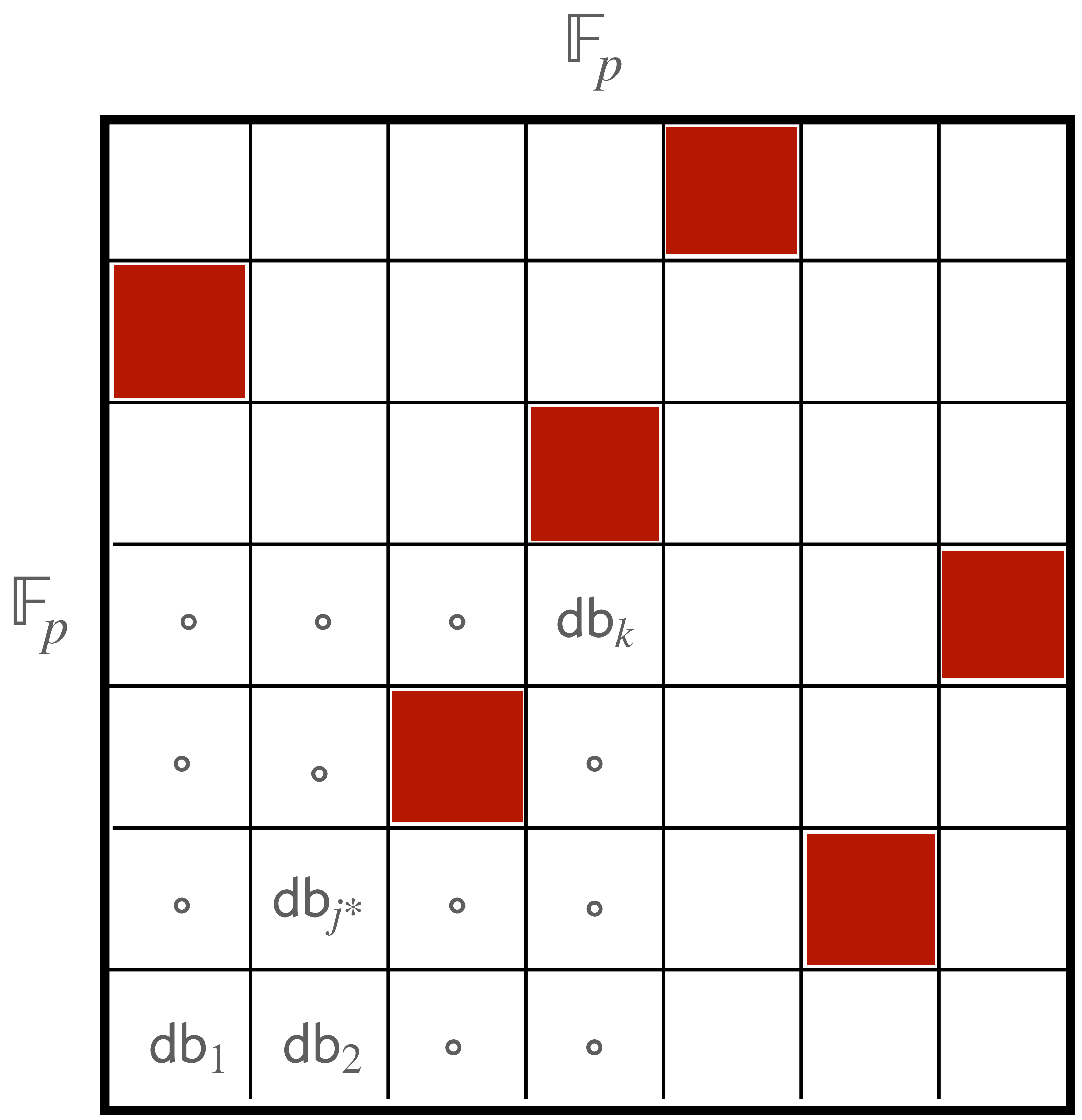

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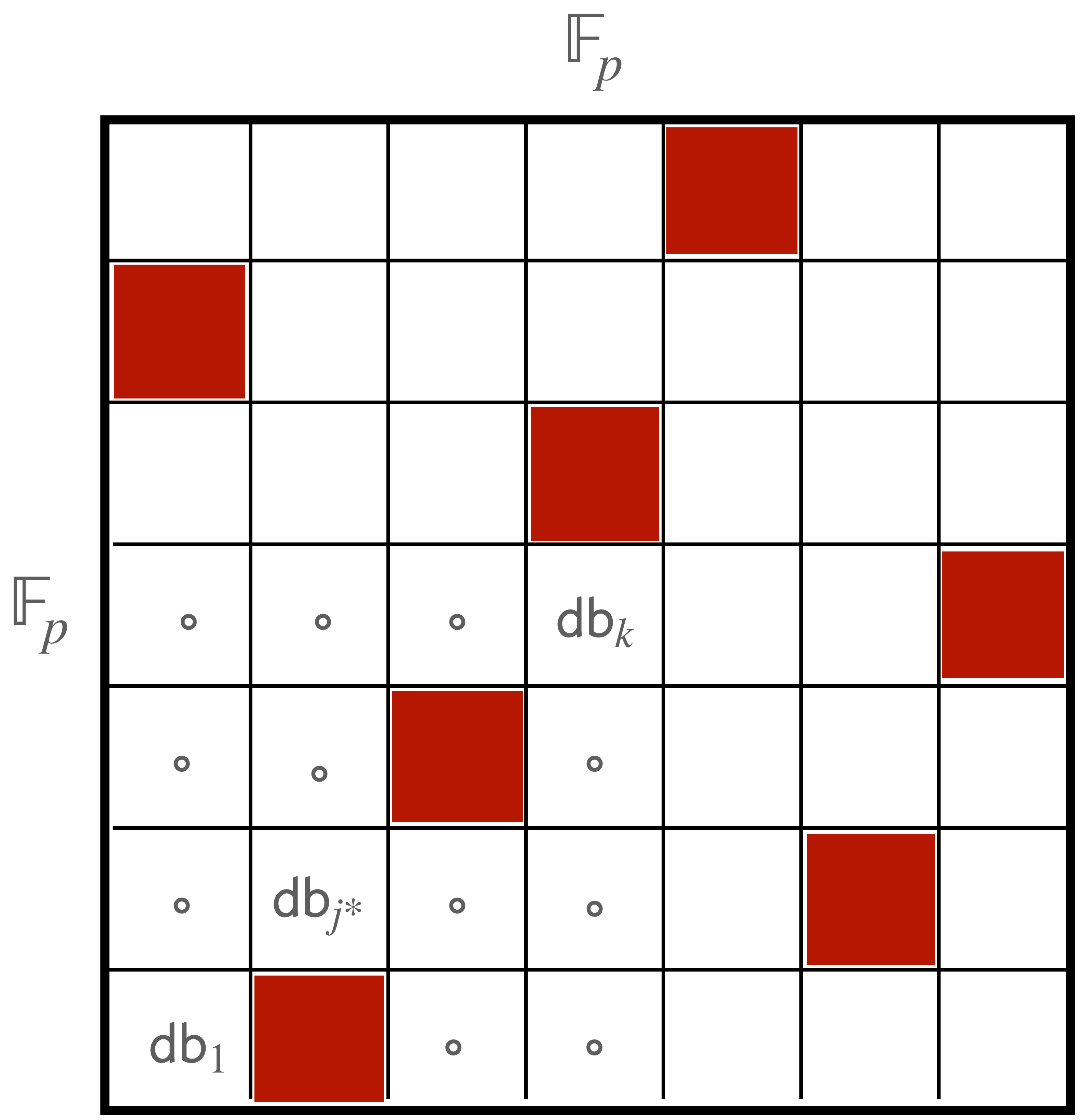

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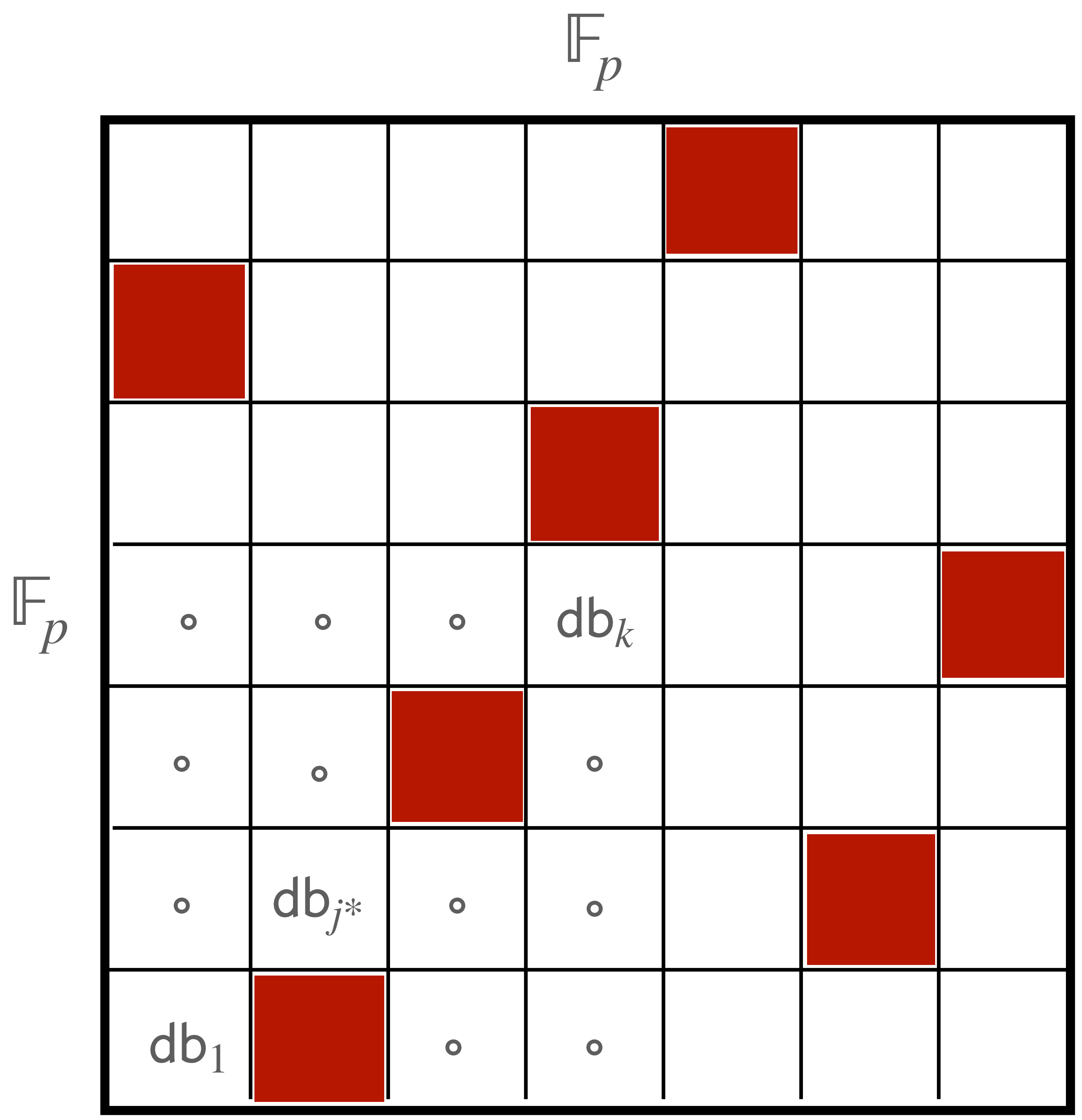
To introduce selective failure on index i, the adversary corrupts (opening proofs on) line ℓ through db_i:

- Client queries for i: query line ℓ w/ prob. $1/\text{poly}(N)$ (there are poly-many lines) and aborts.



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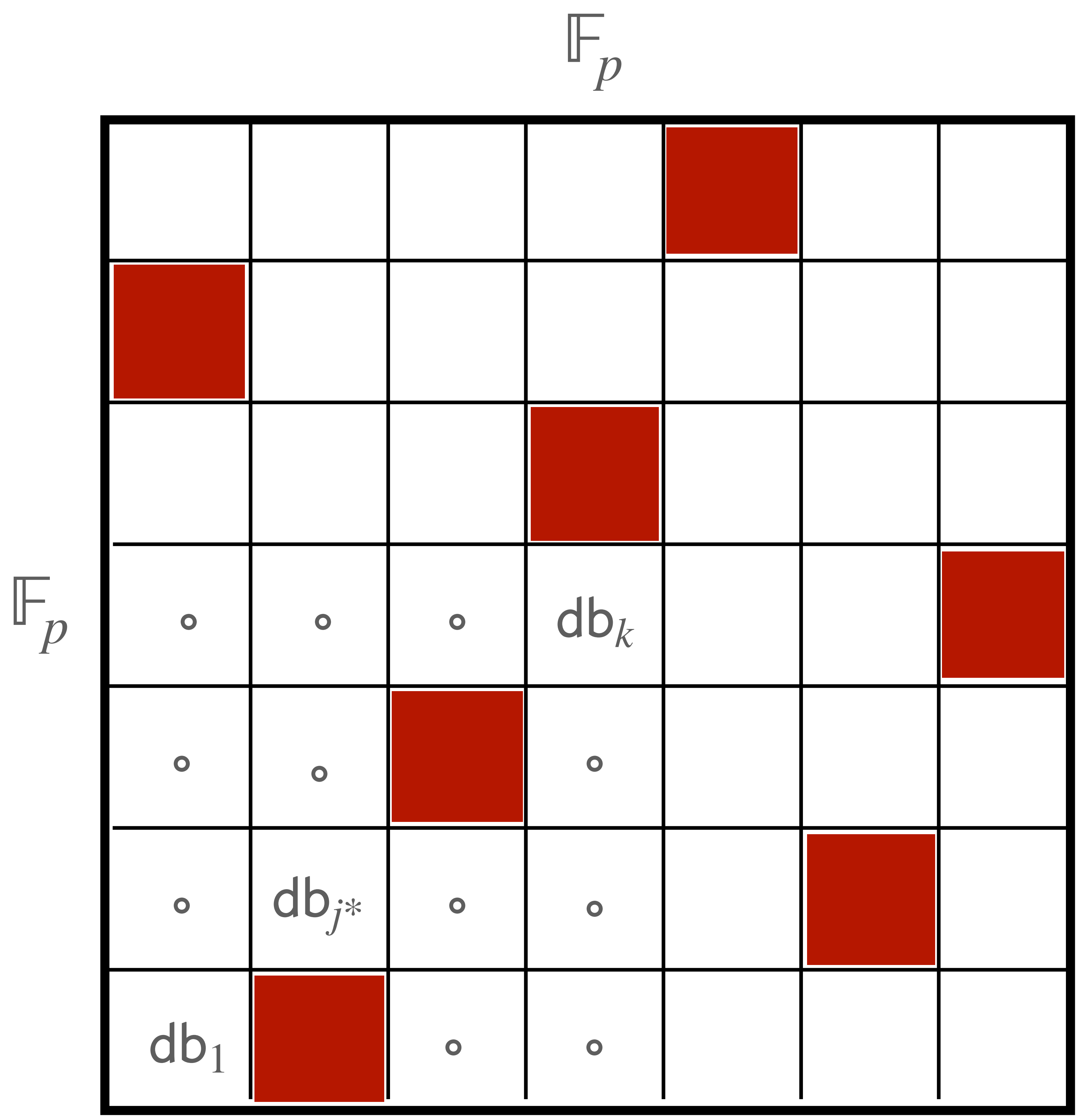

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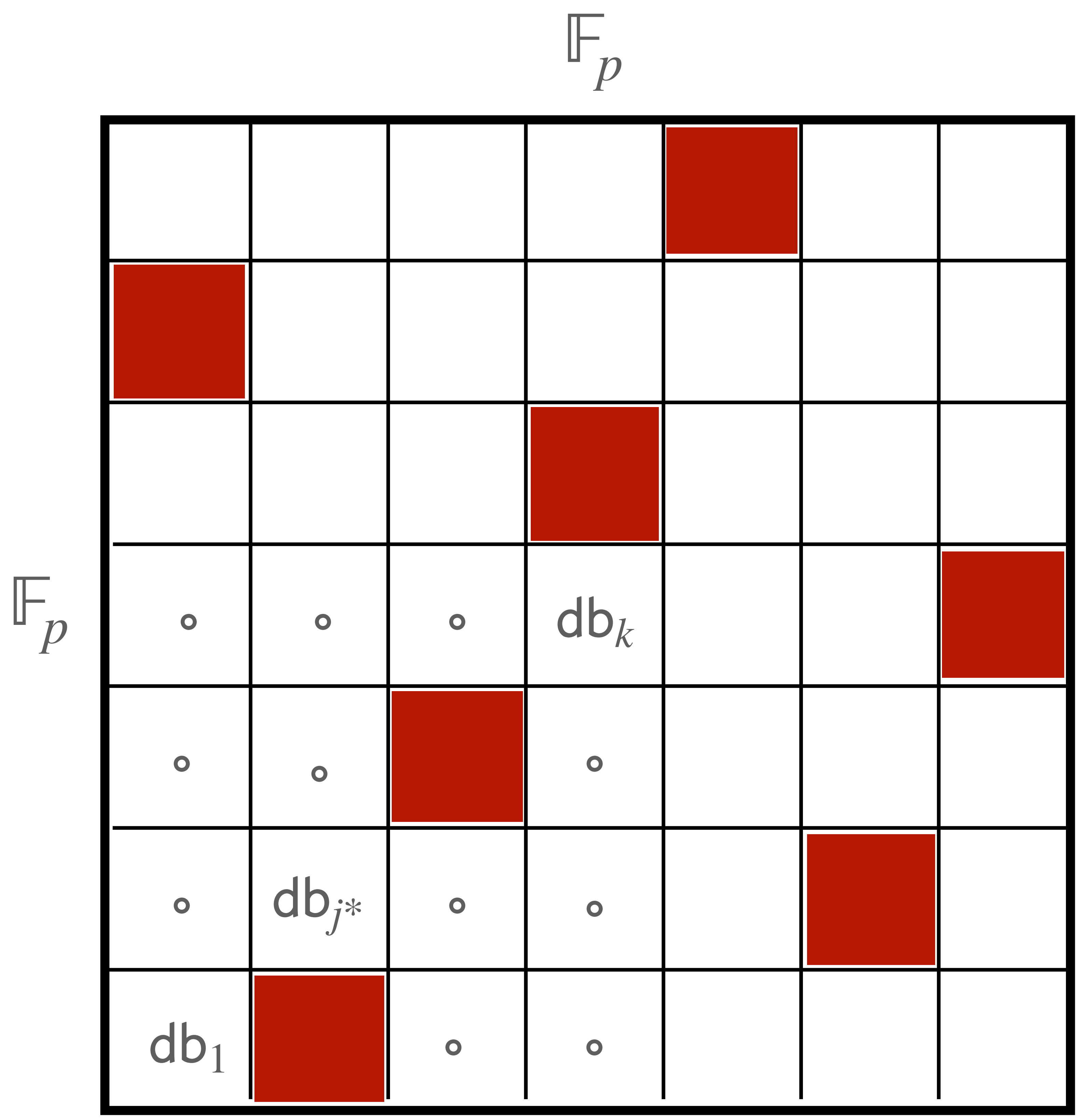

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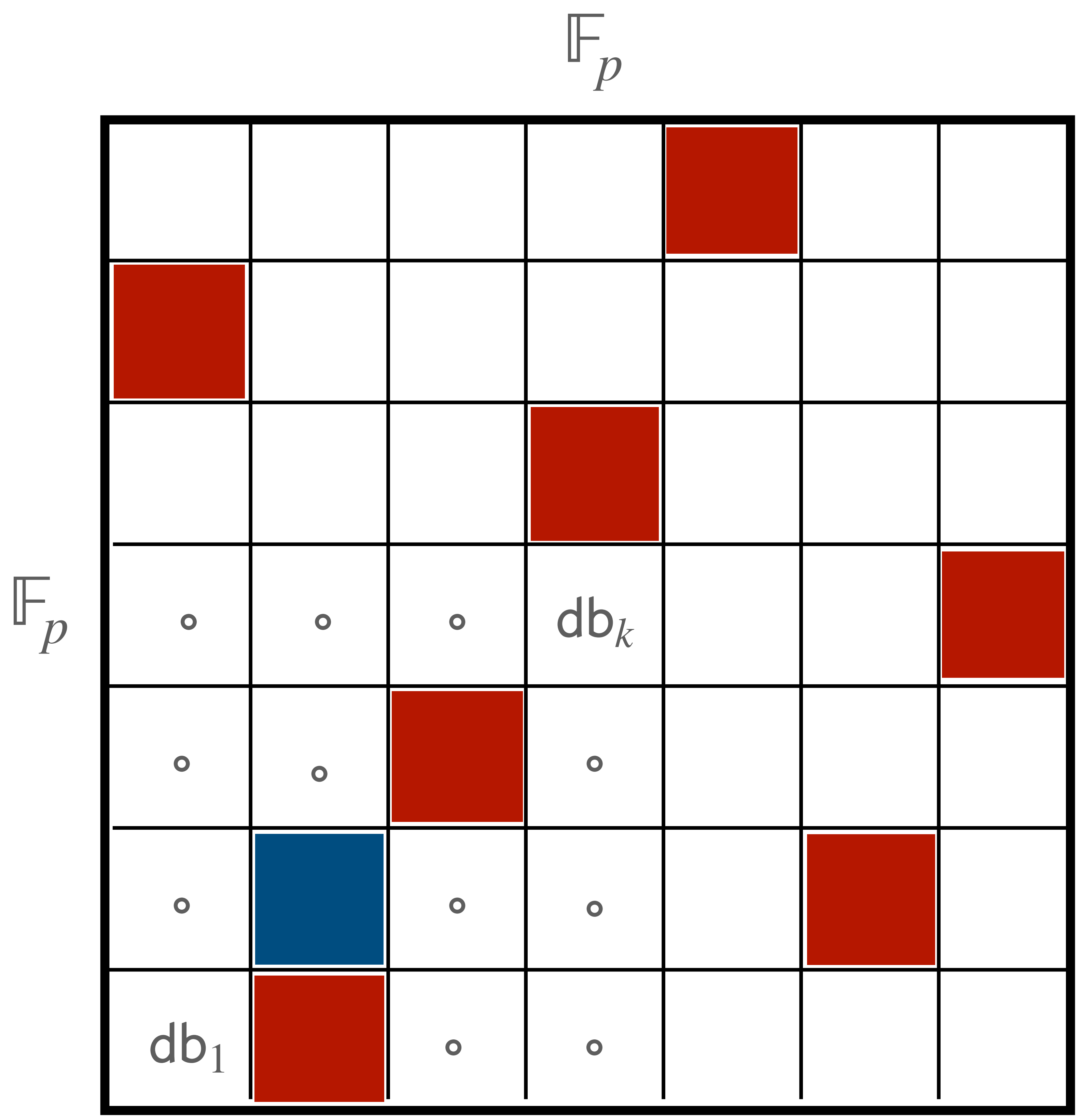

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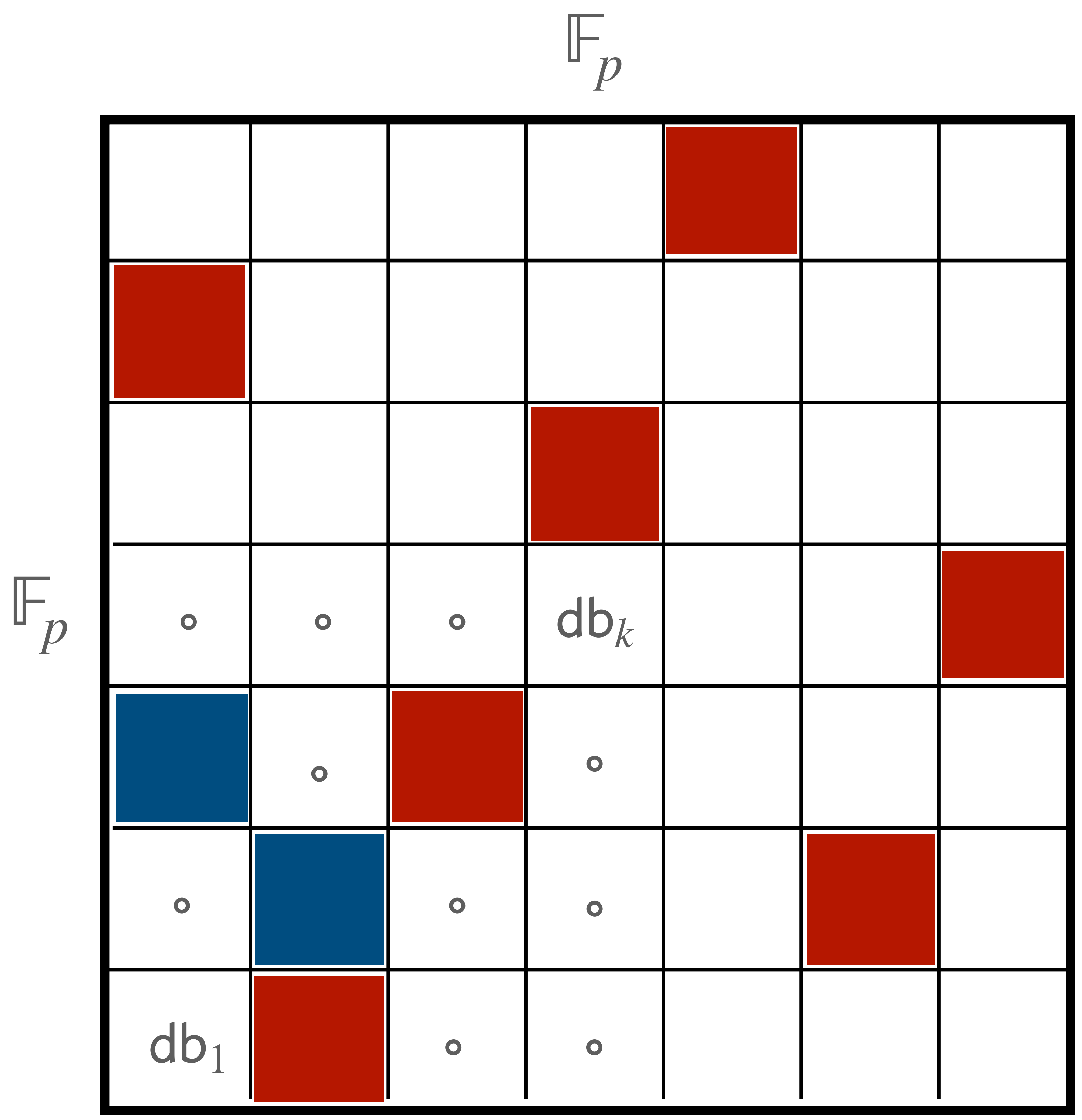

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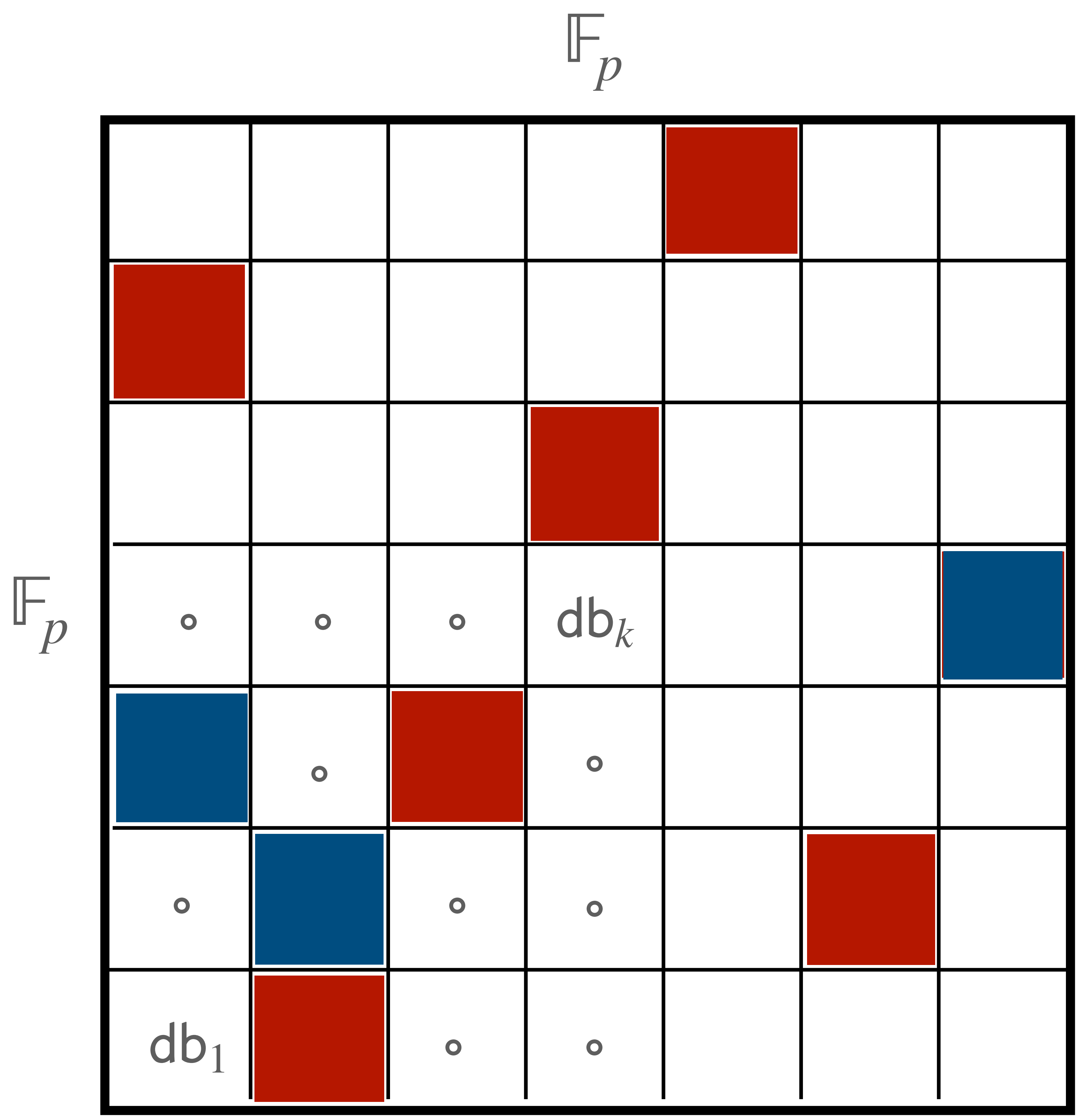

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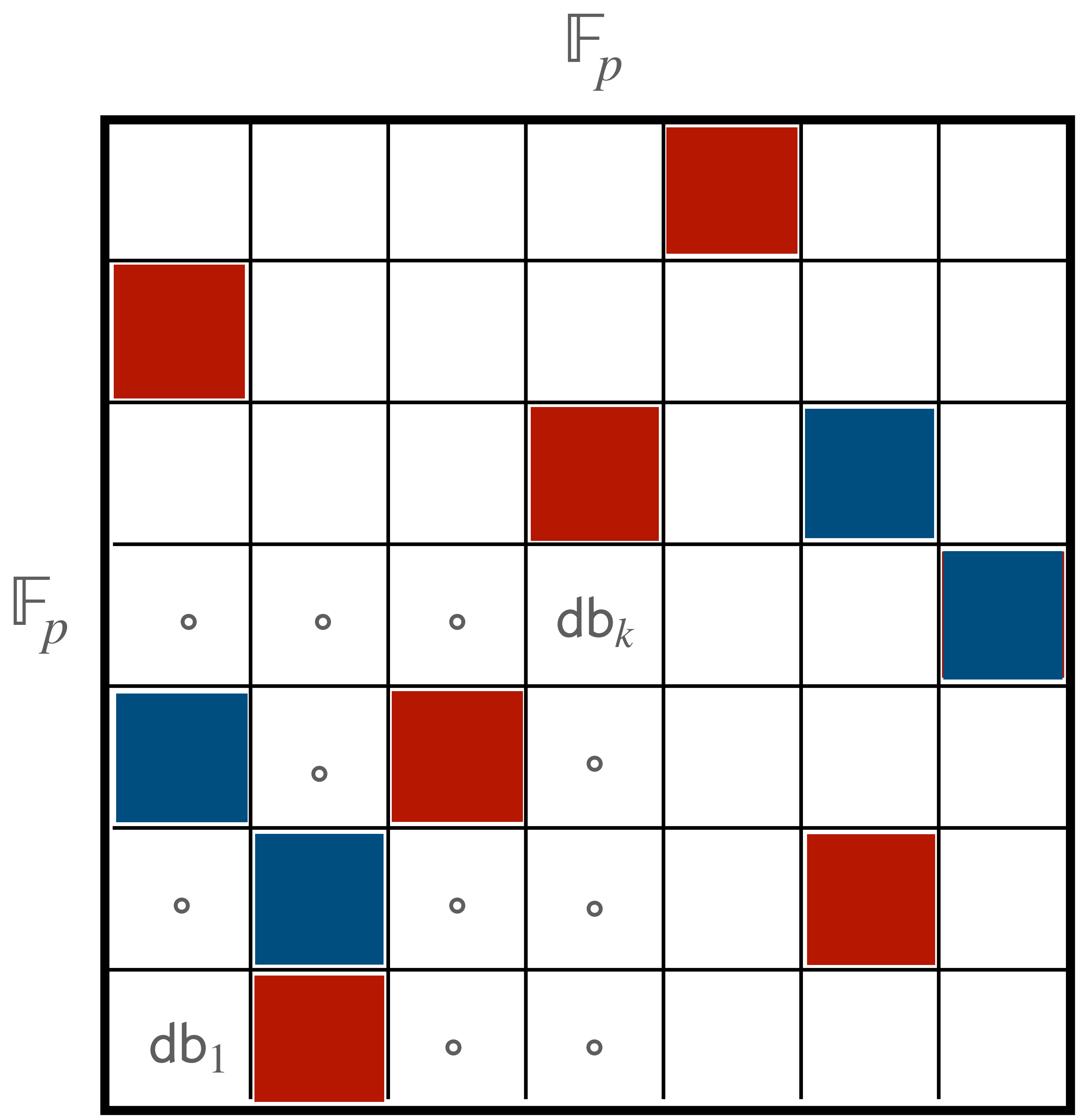

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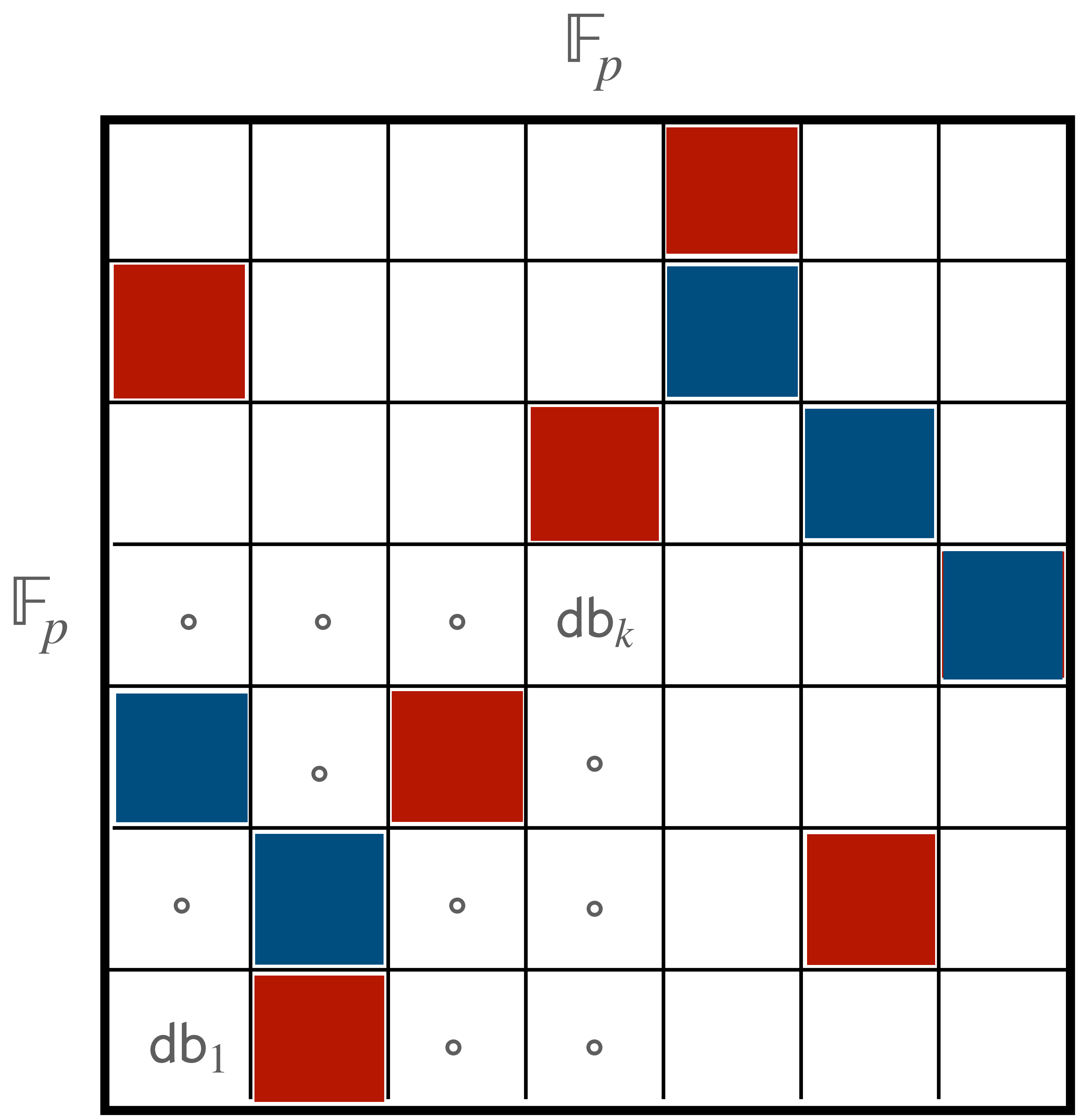

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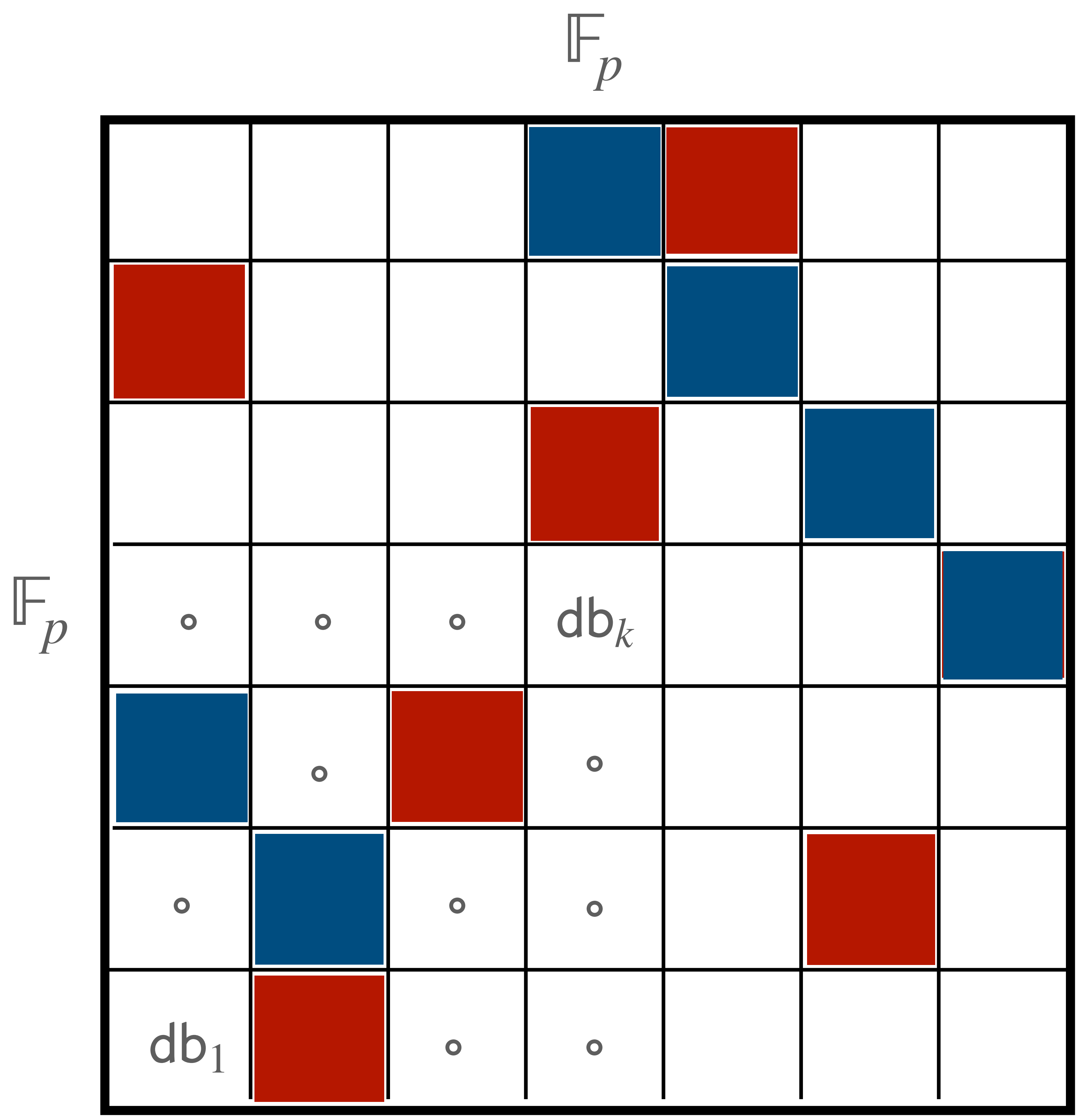

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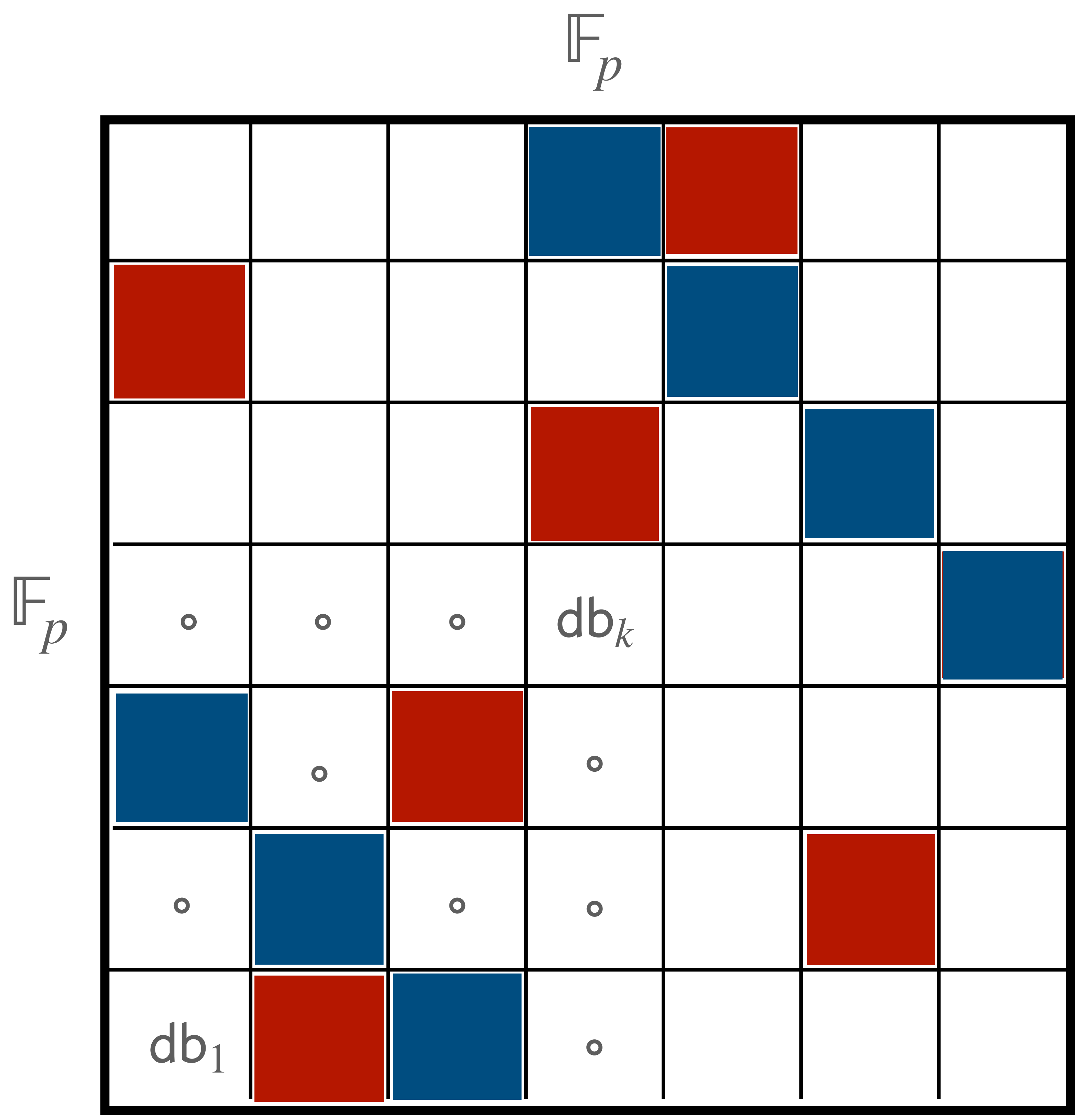

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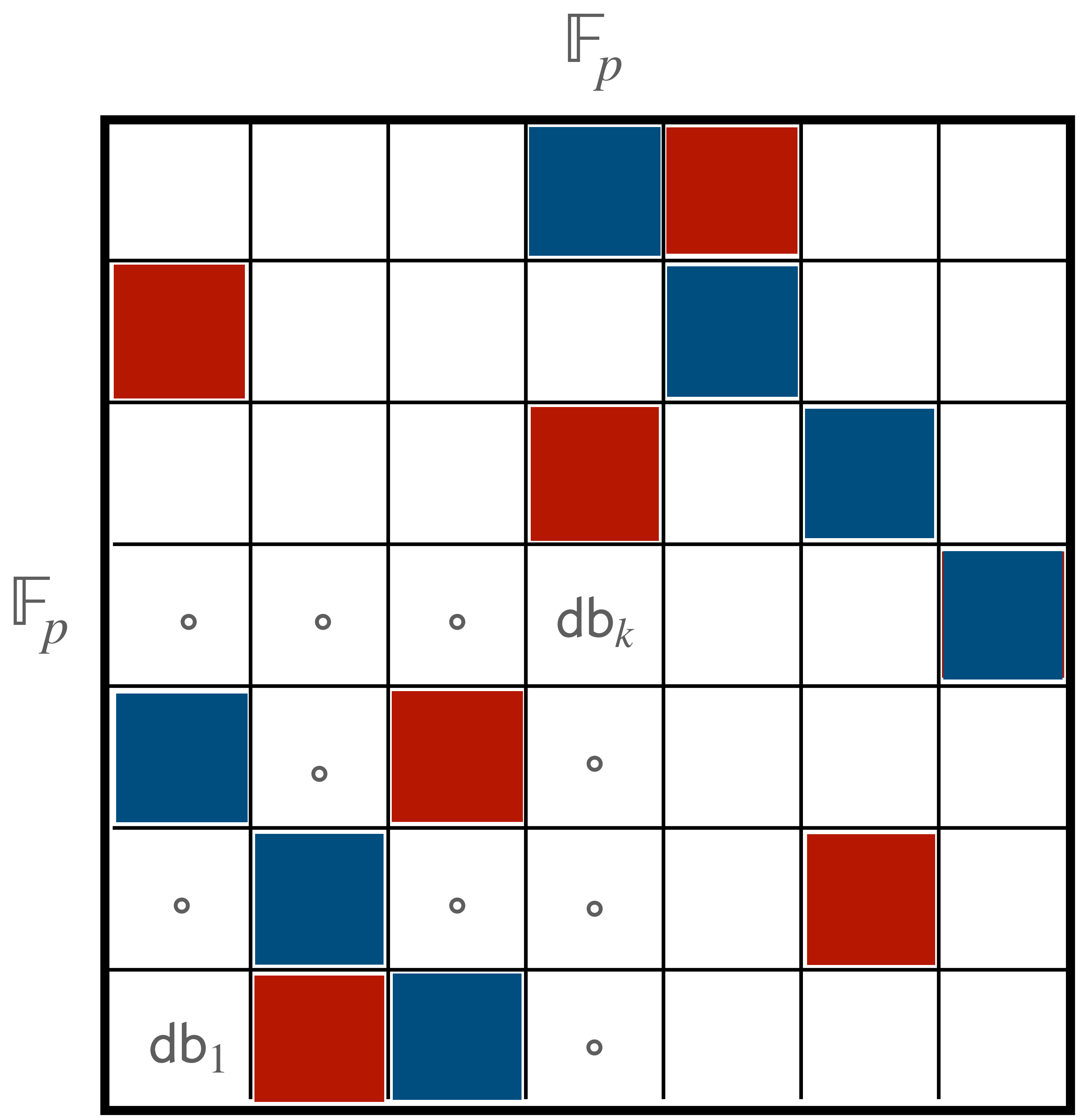
Selective Failure attack!



Ana nce attack”

Both indices decoded with good probability

To introd
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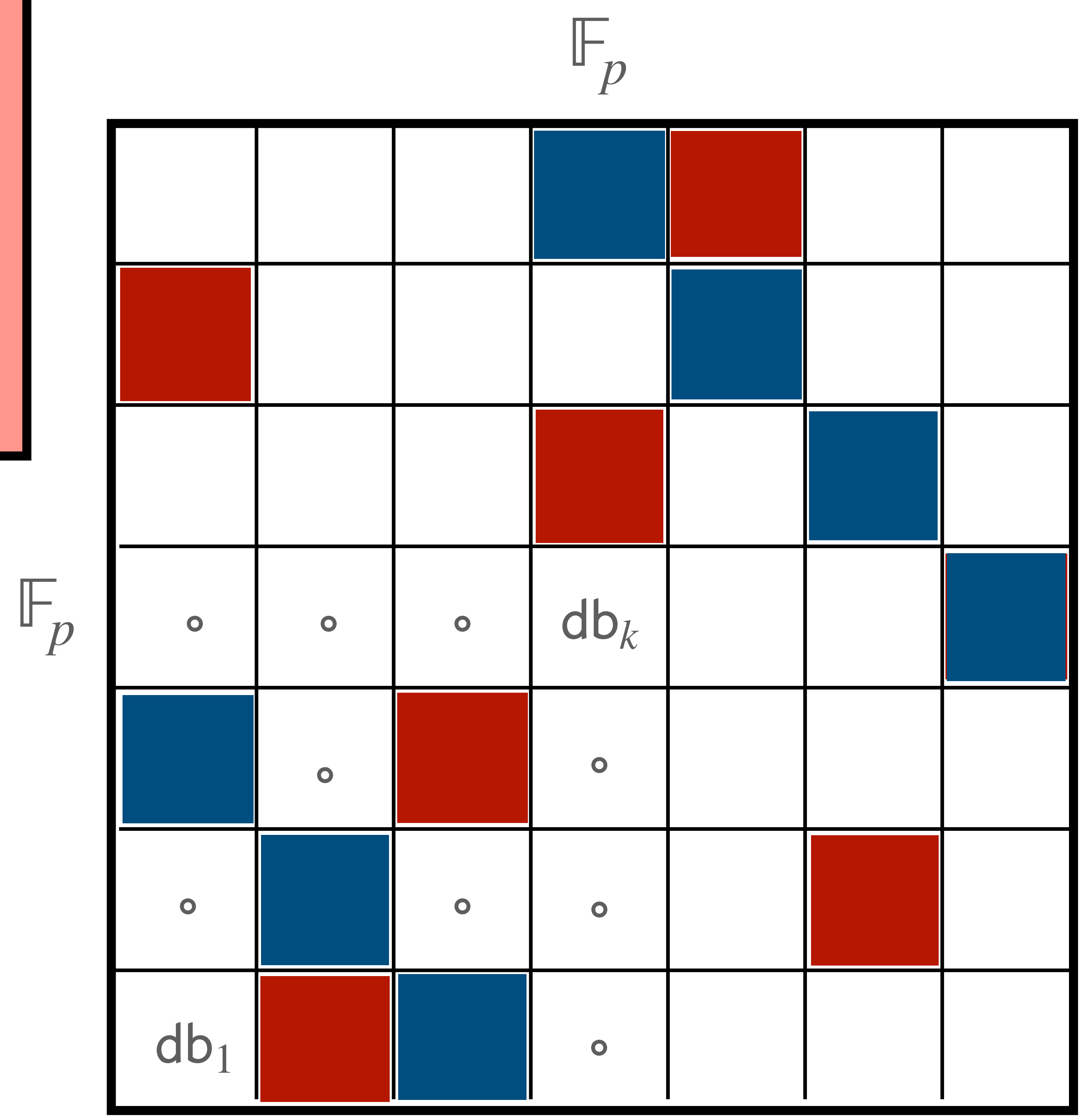

Ana… nce attack”

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$\Pr[\text{decode } i] > 2/3$

To introd…
adversar…
ℓ throug…

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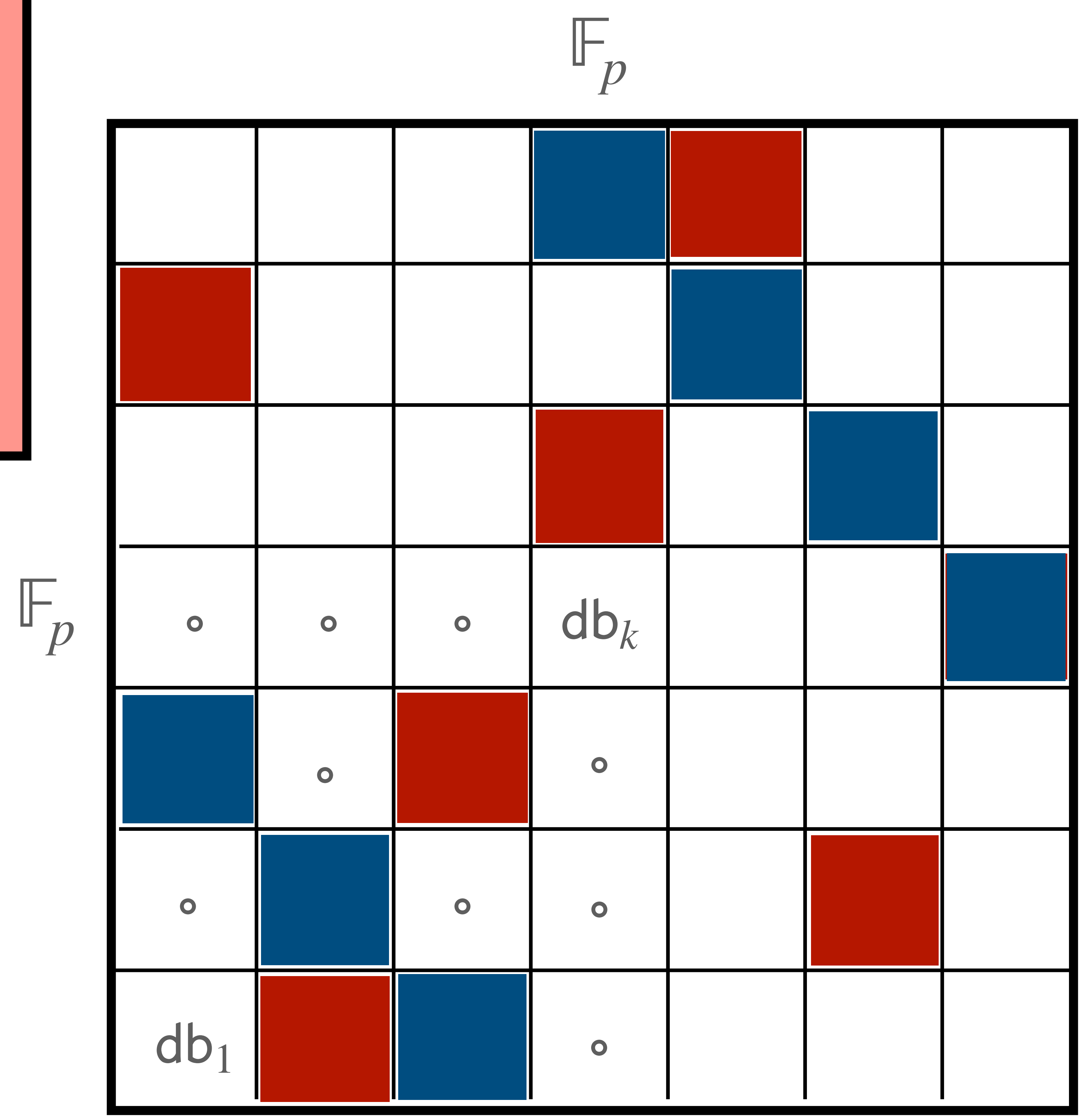
  aborts.
- If client queries for $j \neq i$: only one point on the line is corrupt. Client never aborts.

Selective Failure attack!



Ana… …nce attack”

Both indices decoded with good probability

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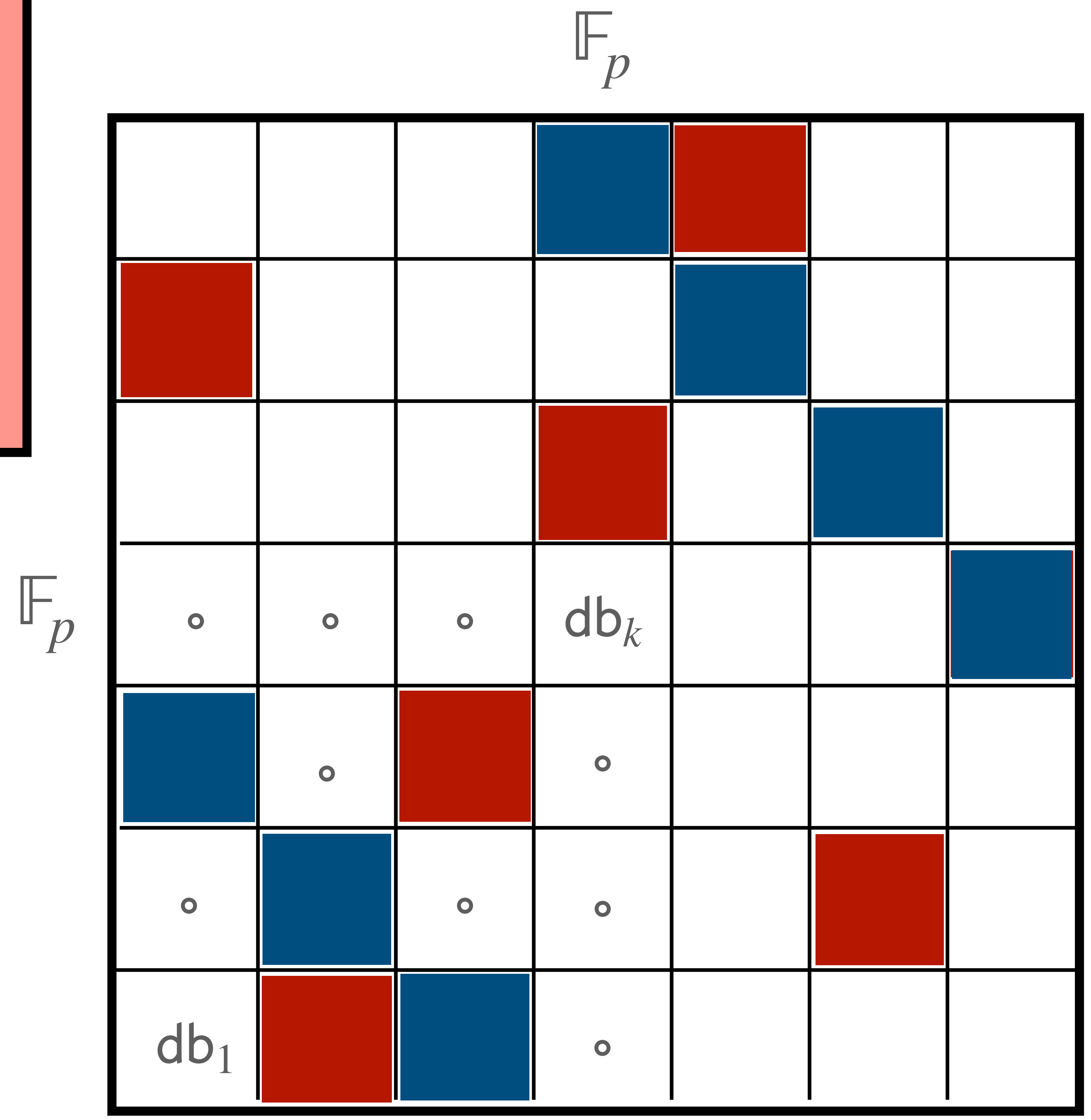

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However, there could be a big gap between the decoding probabilities:

$|\Pr[\text{decode } i] - \Pr[\text{decode } j]| > \text{notice}(n)$

To introd

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ℓ throug

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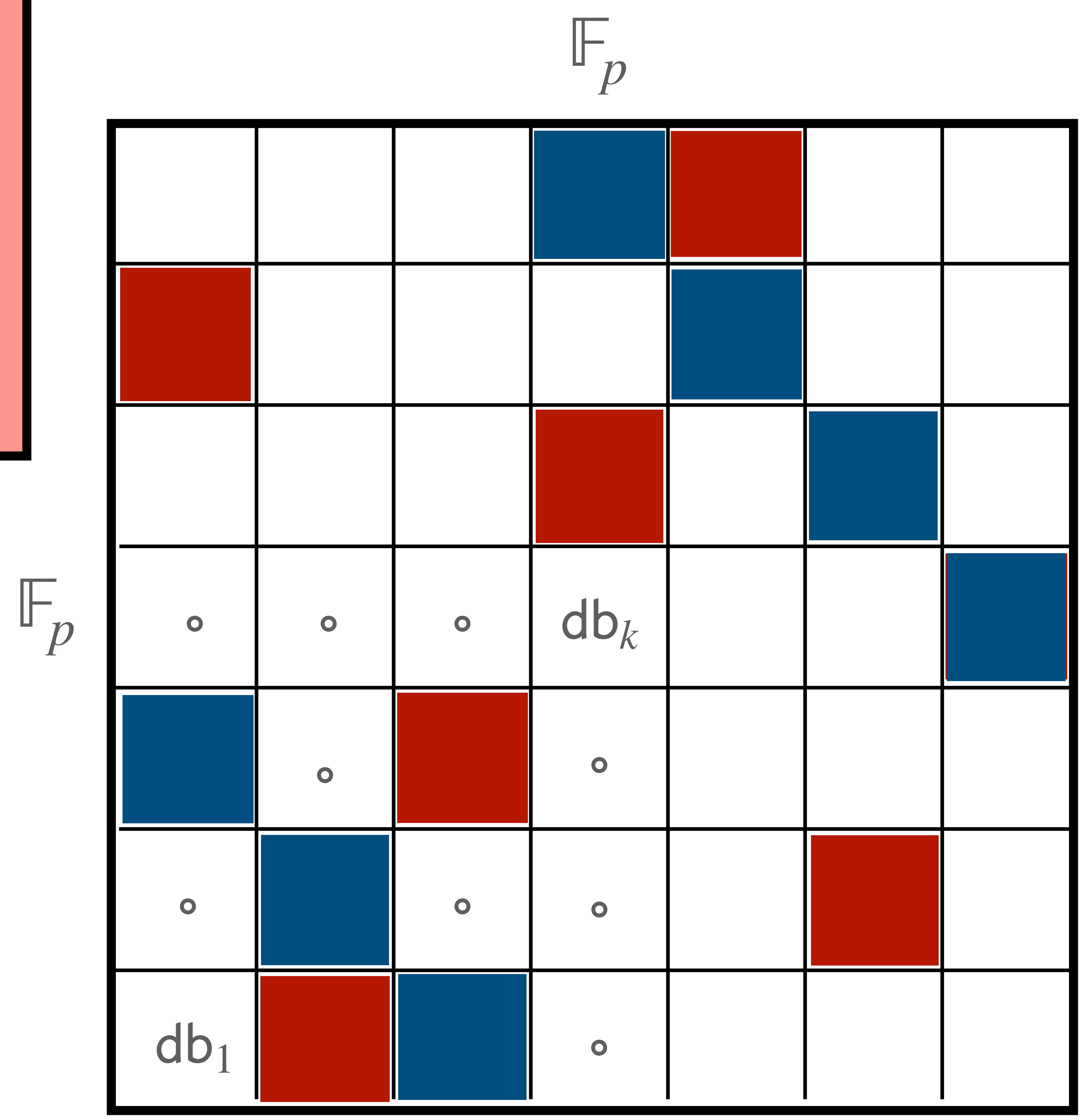
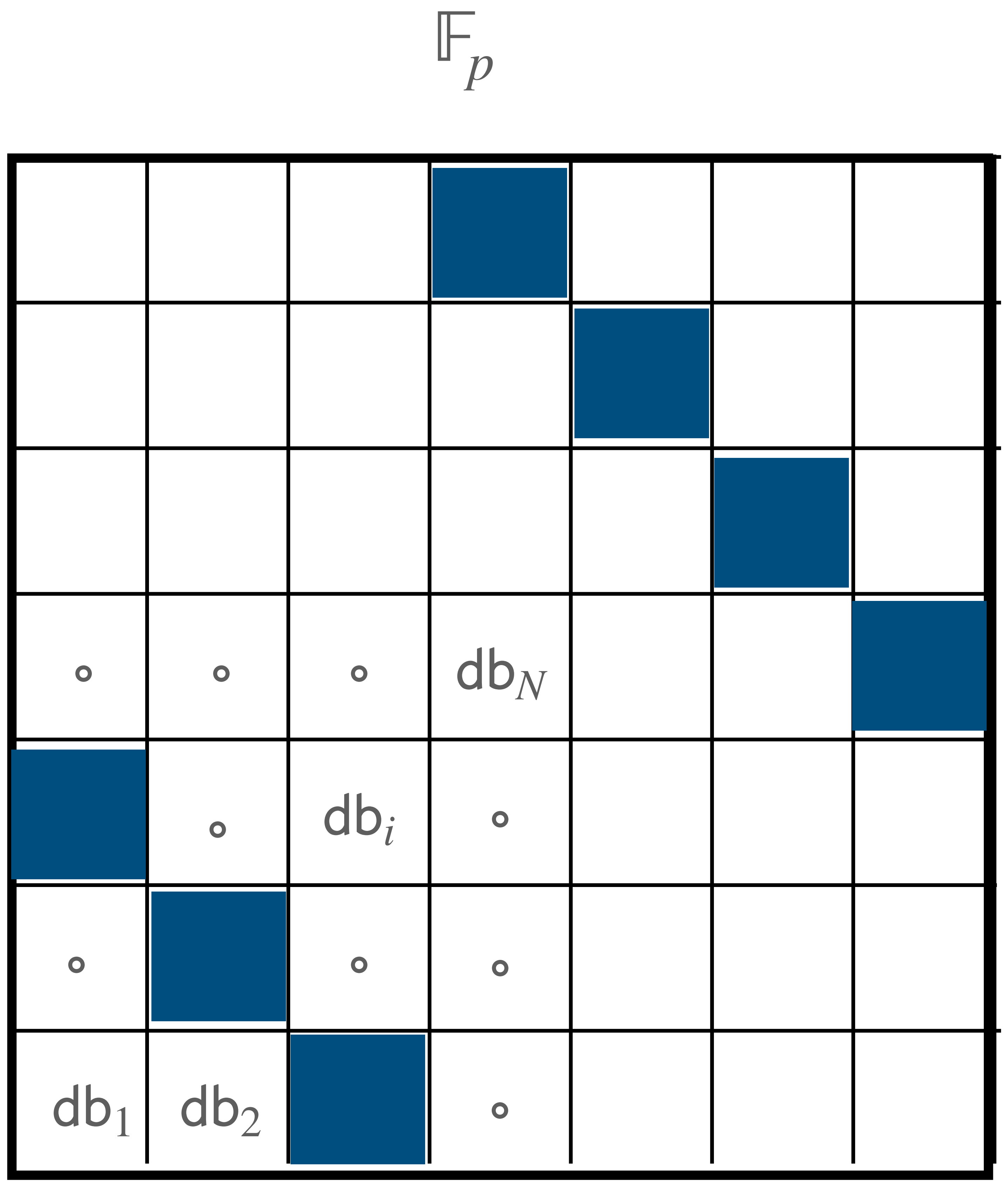


Decrease decoder's success probability: test points



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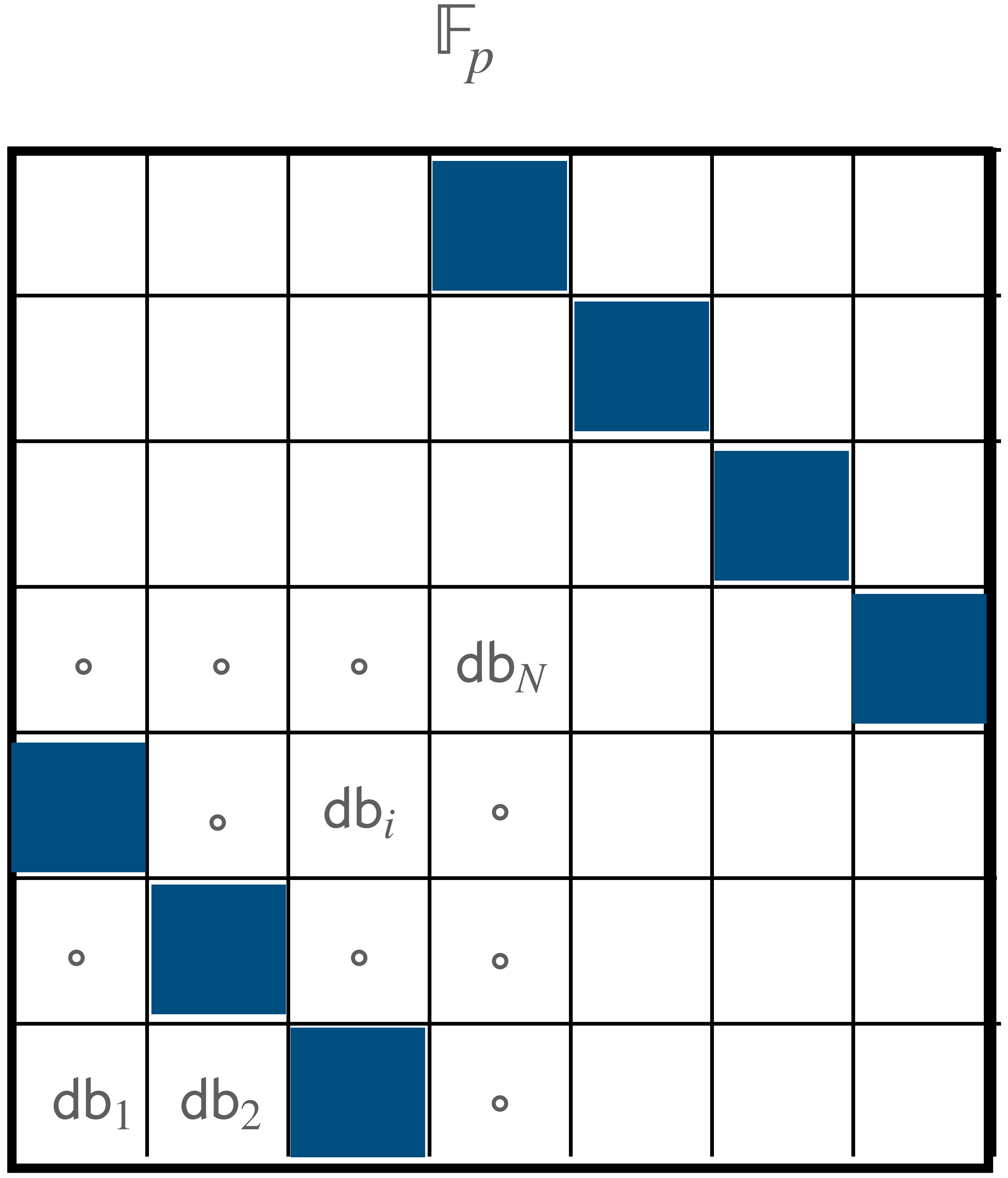

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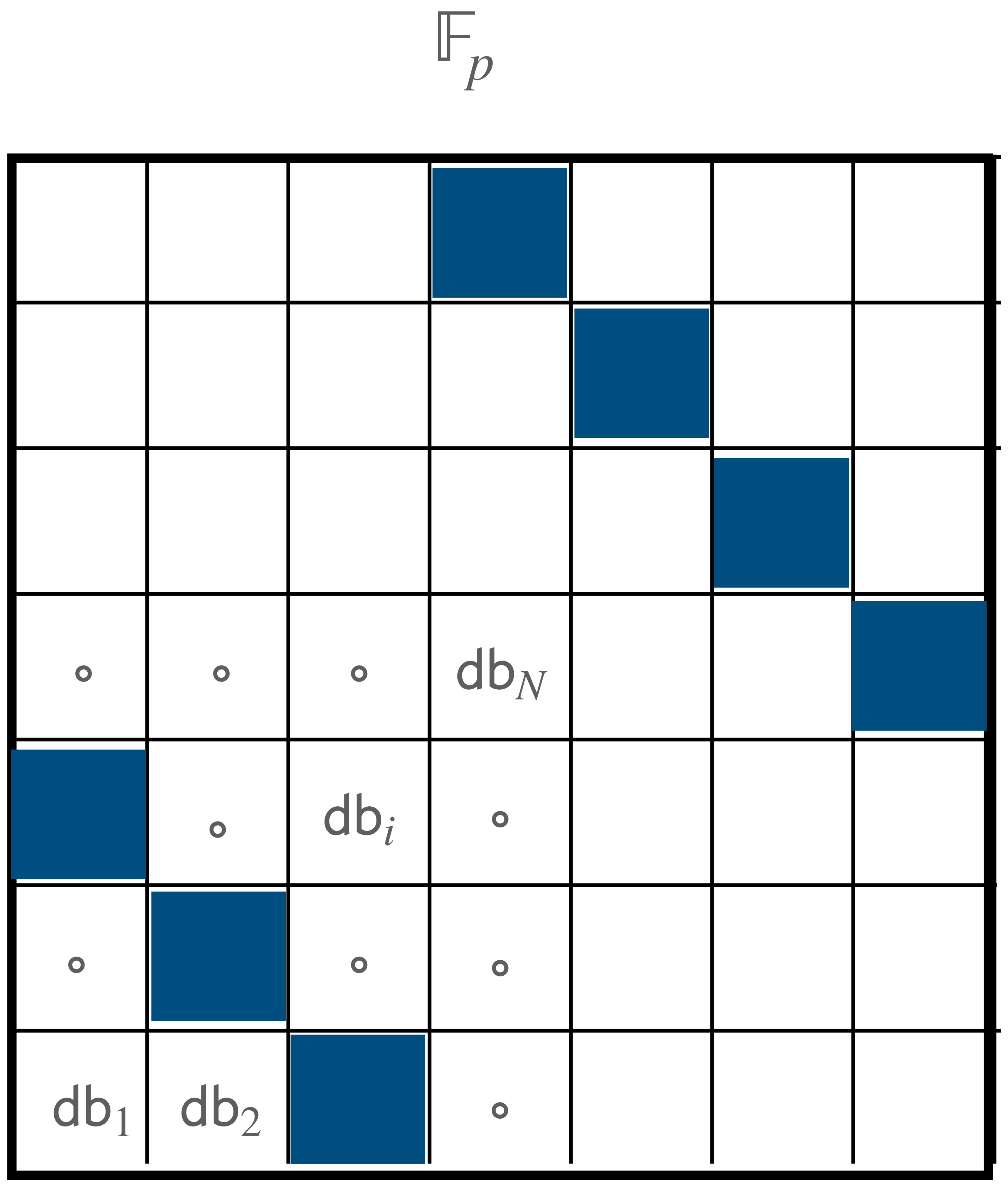

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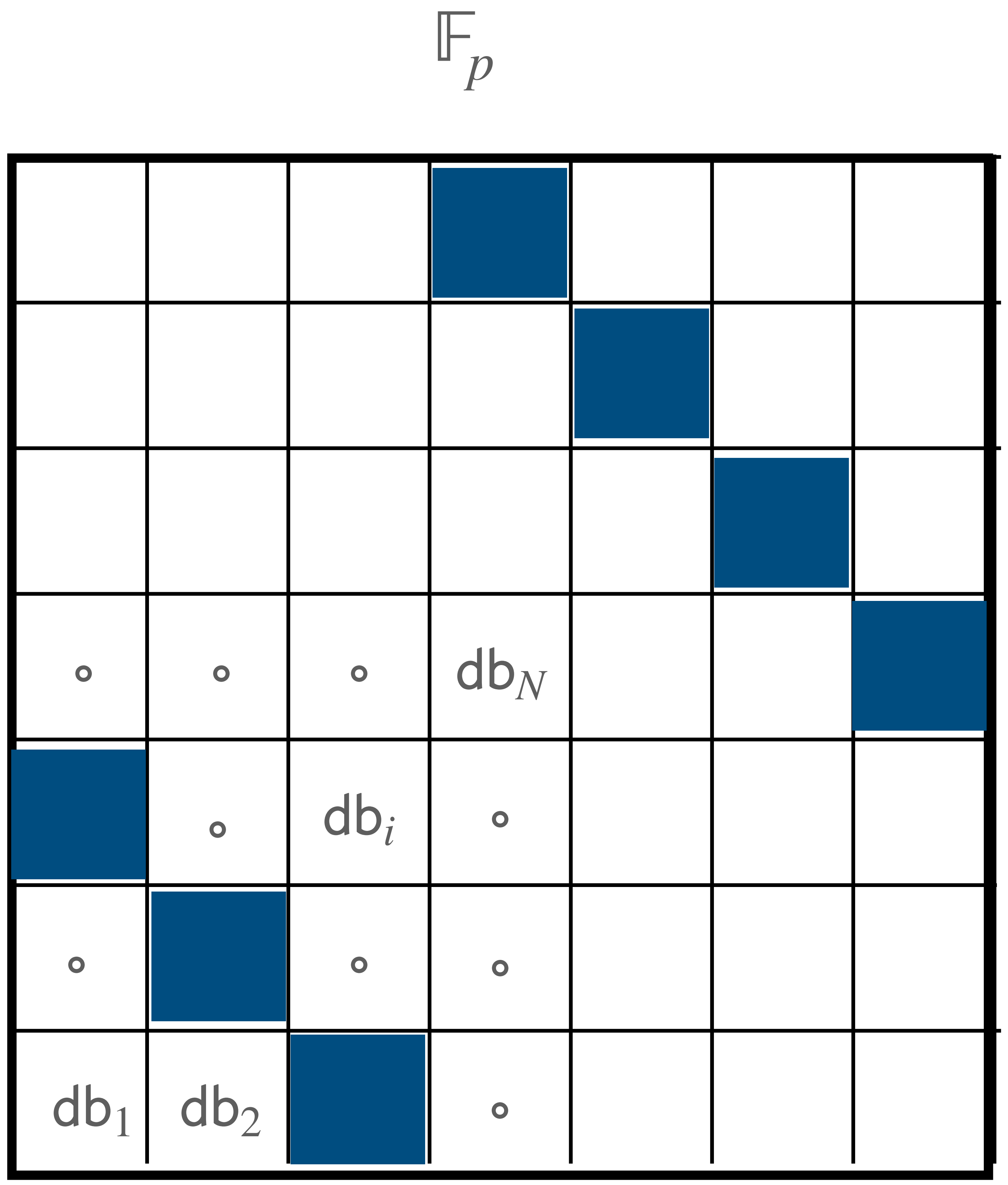

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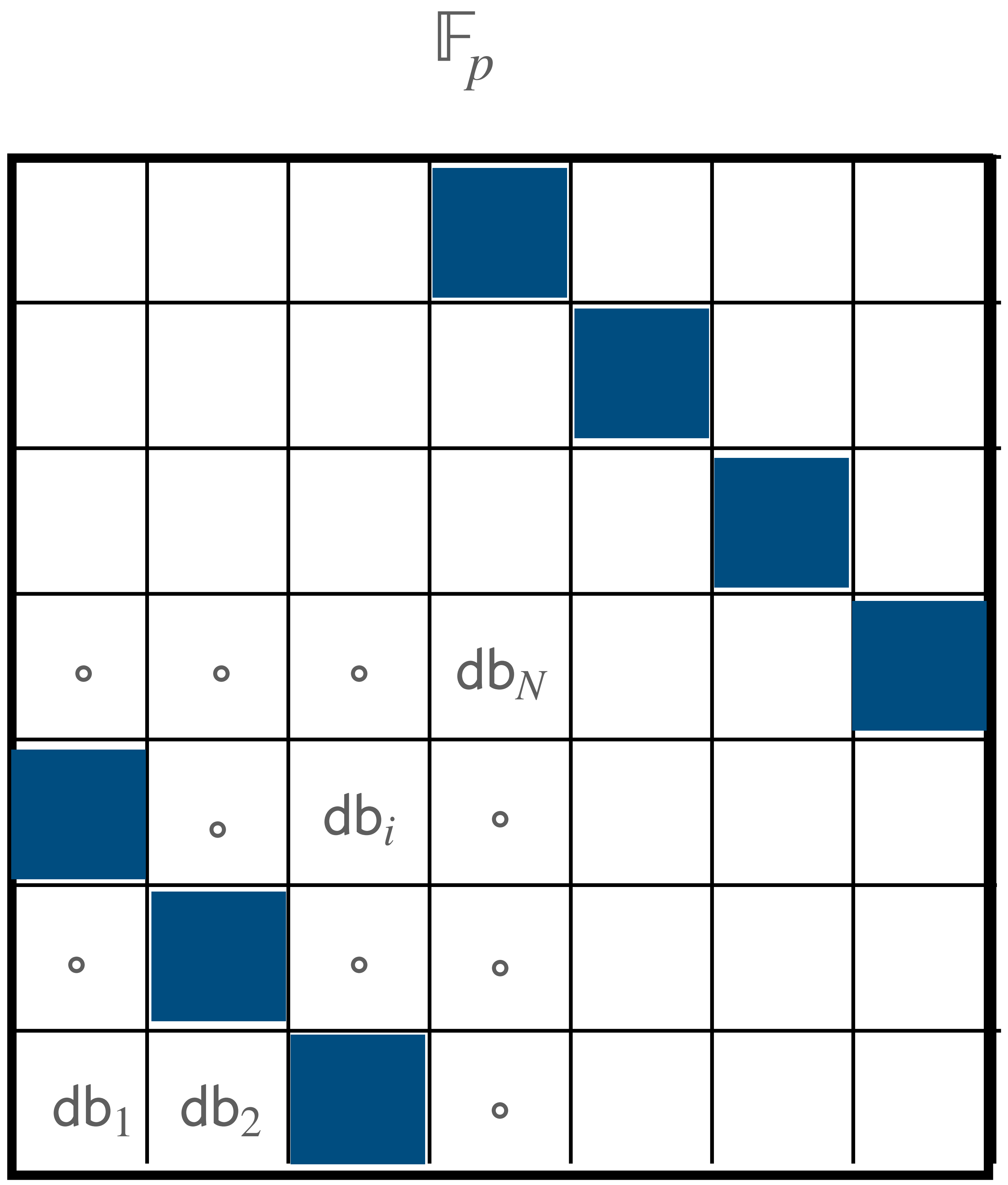

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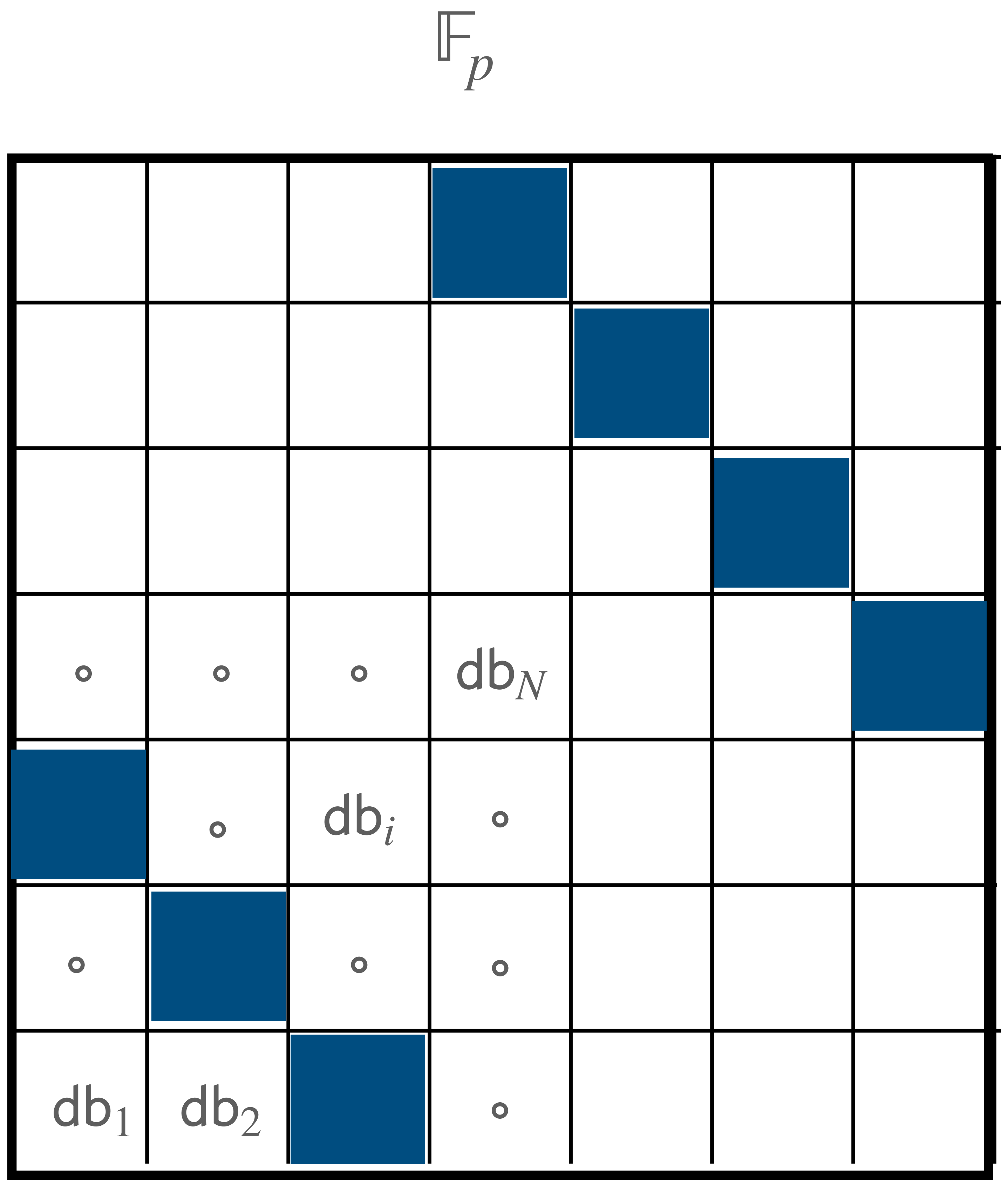

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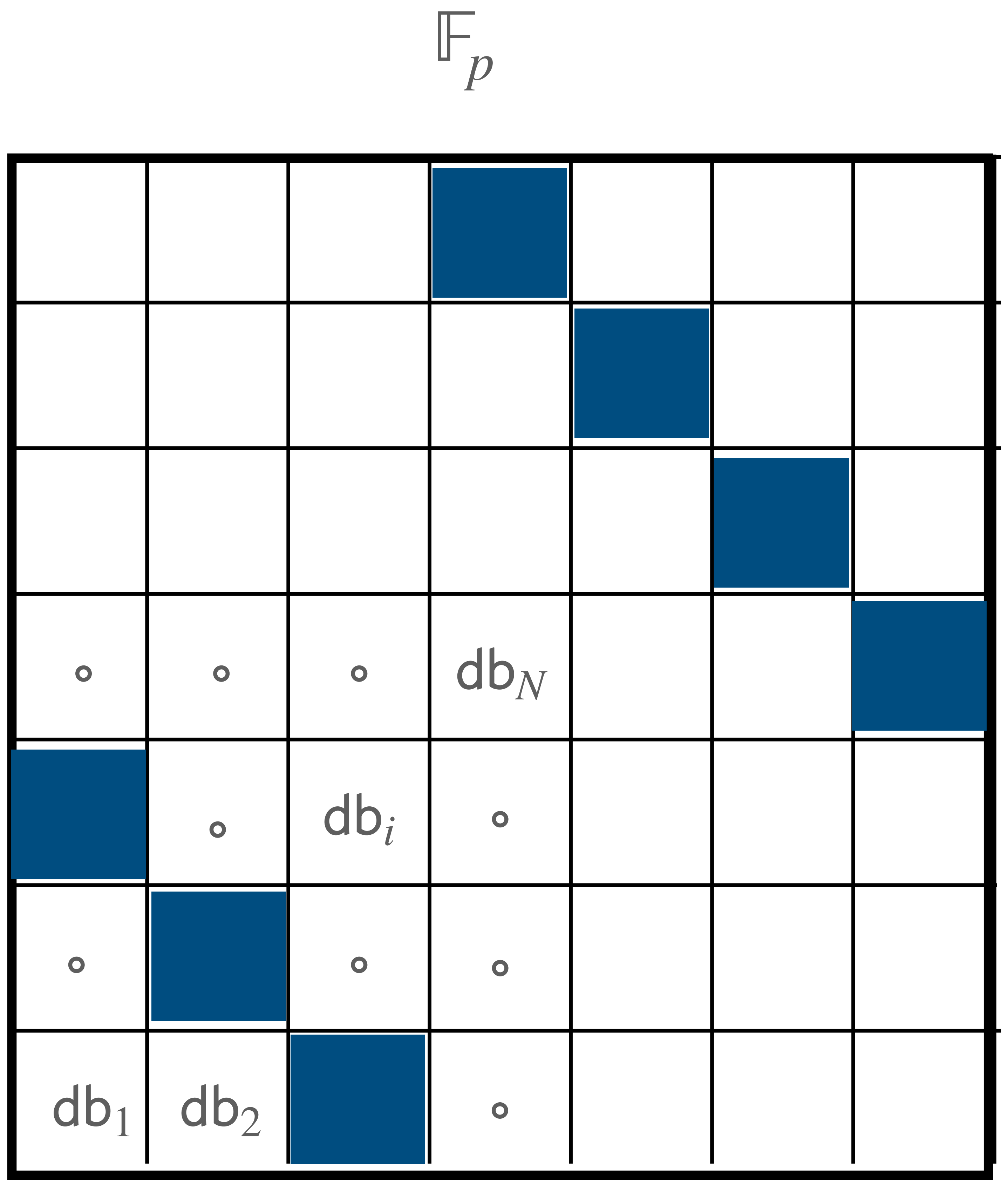
  - Instead we detect corruptions on a set of random *test* points.



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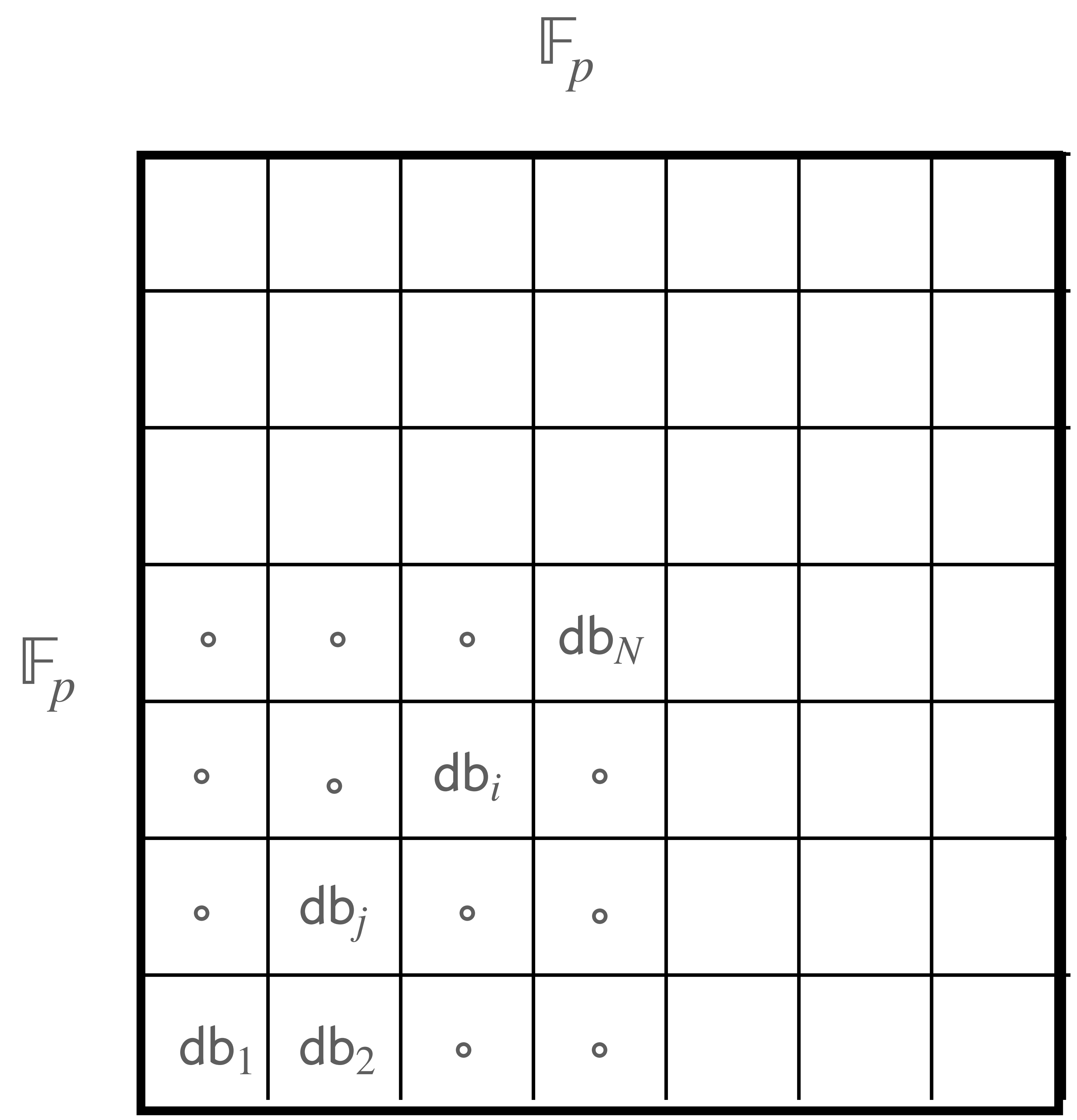
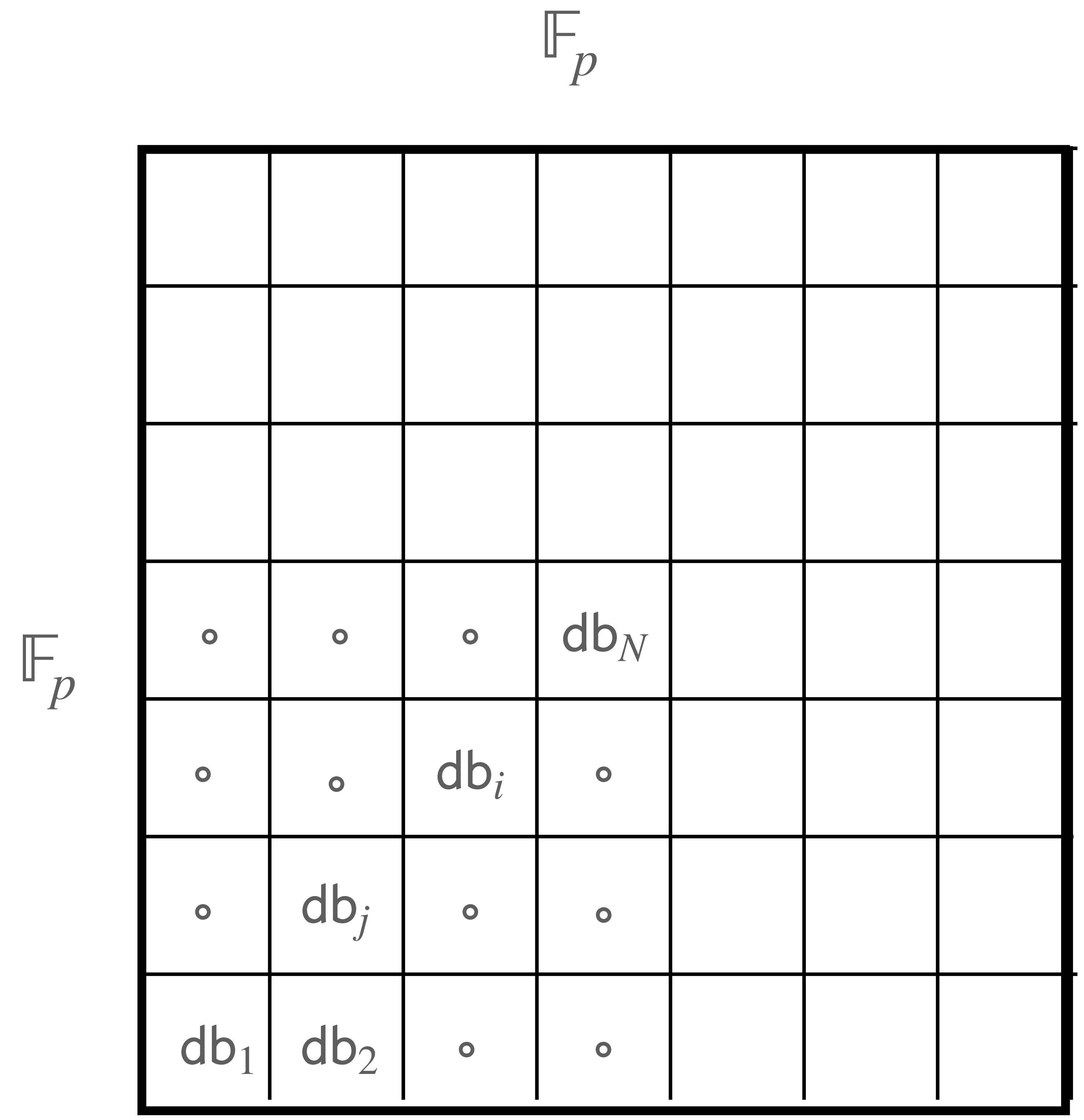


Decrease decoder's success probability: test points

Modified local decoding with test queries



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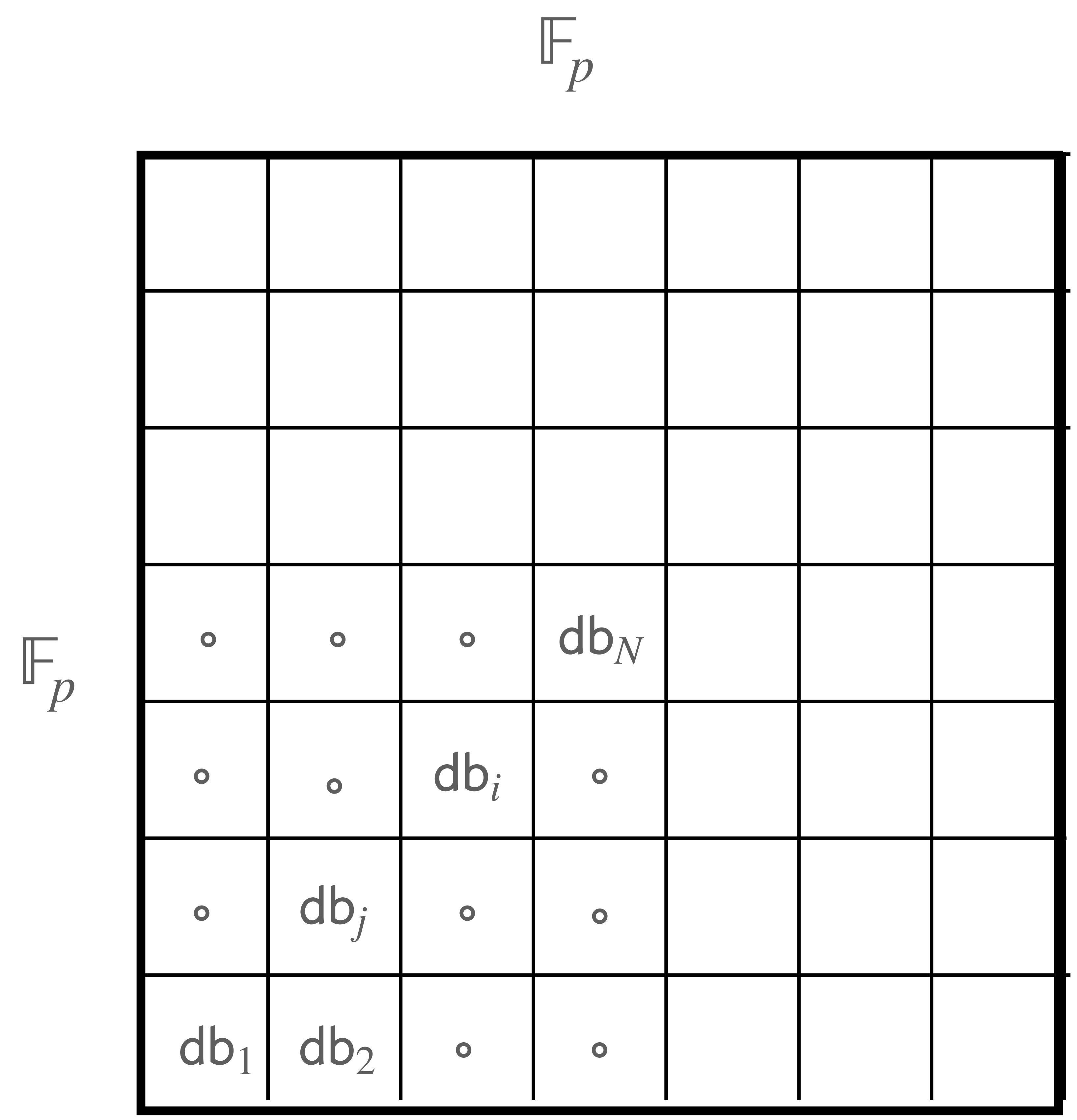

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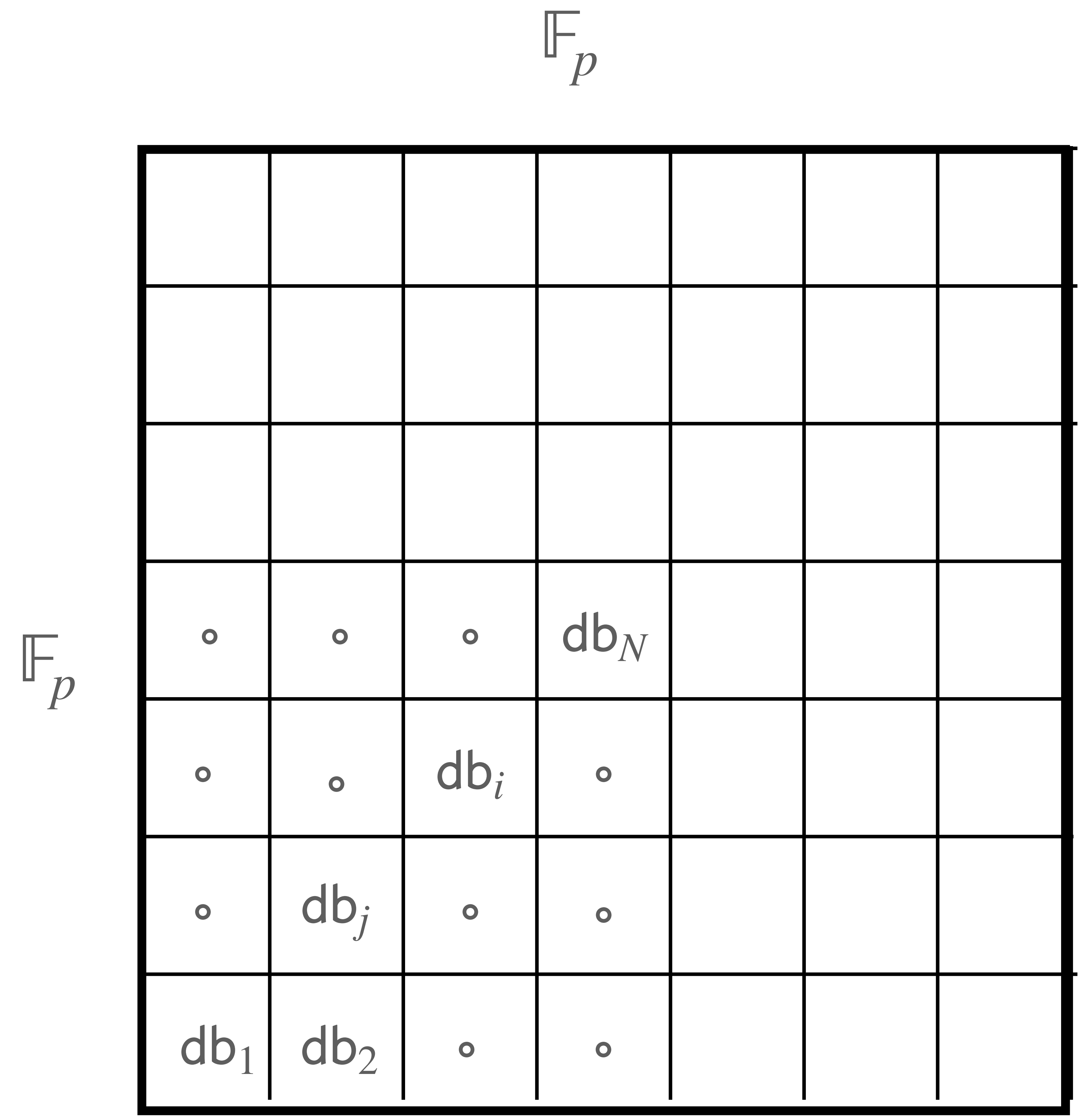

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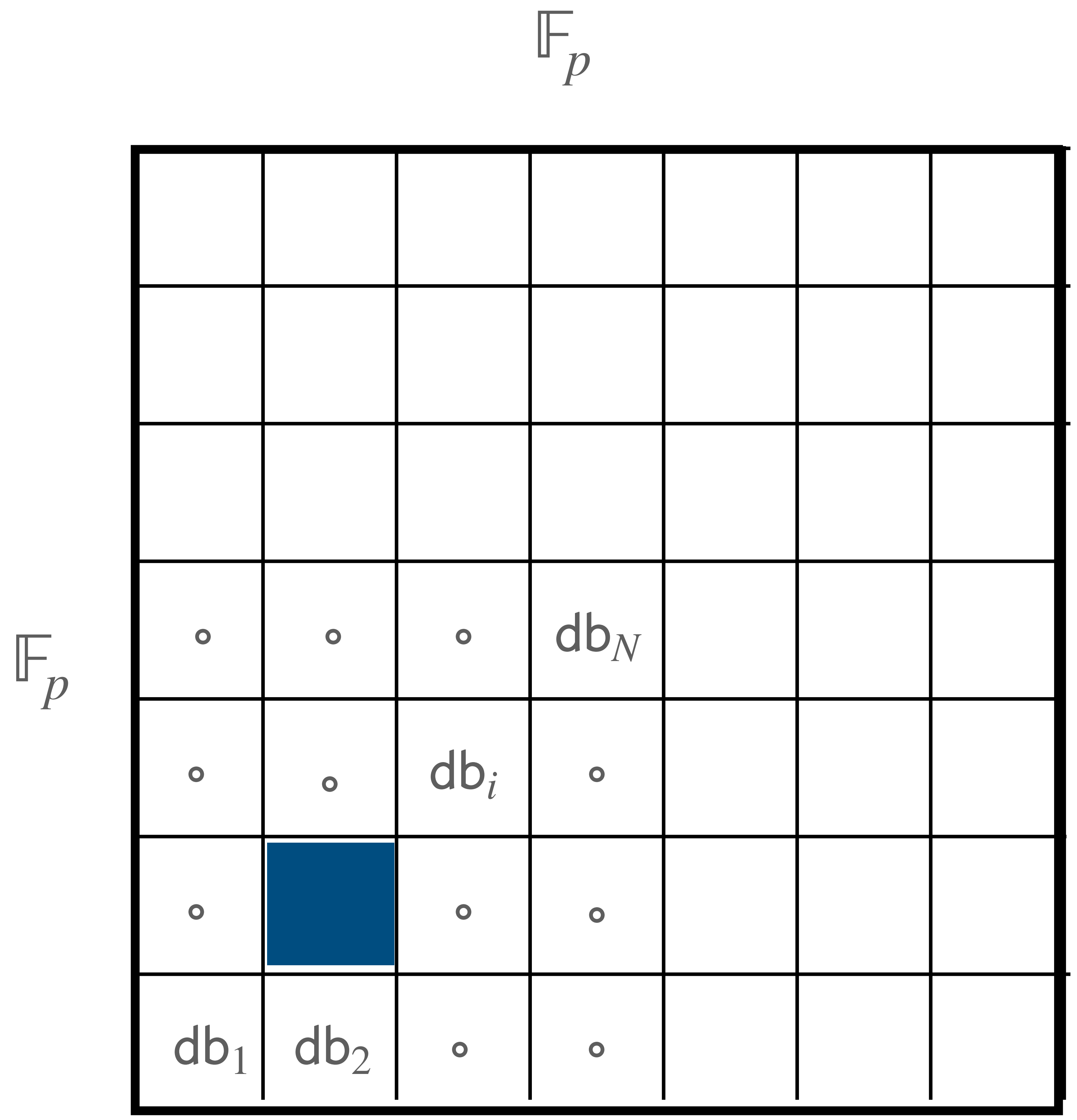

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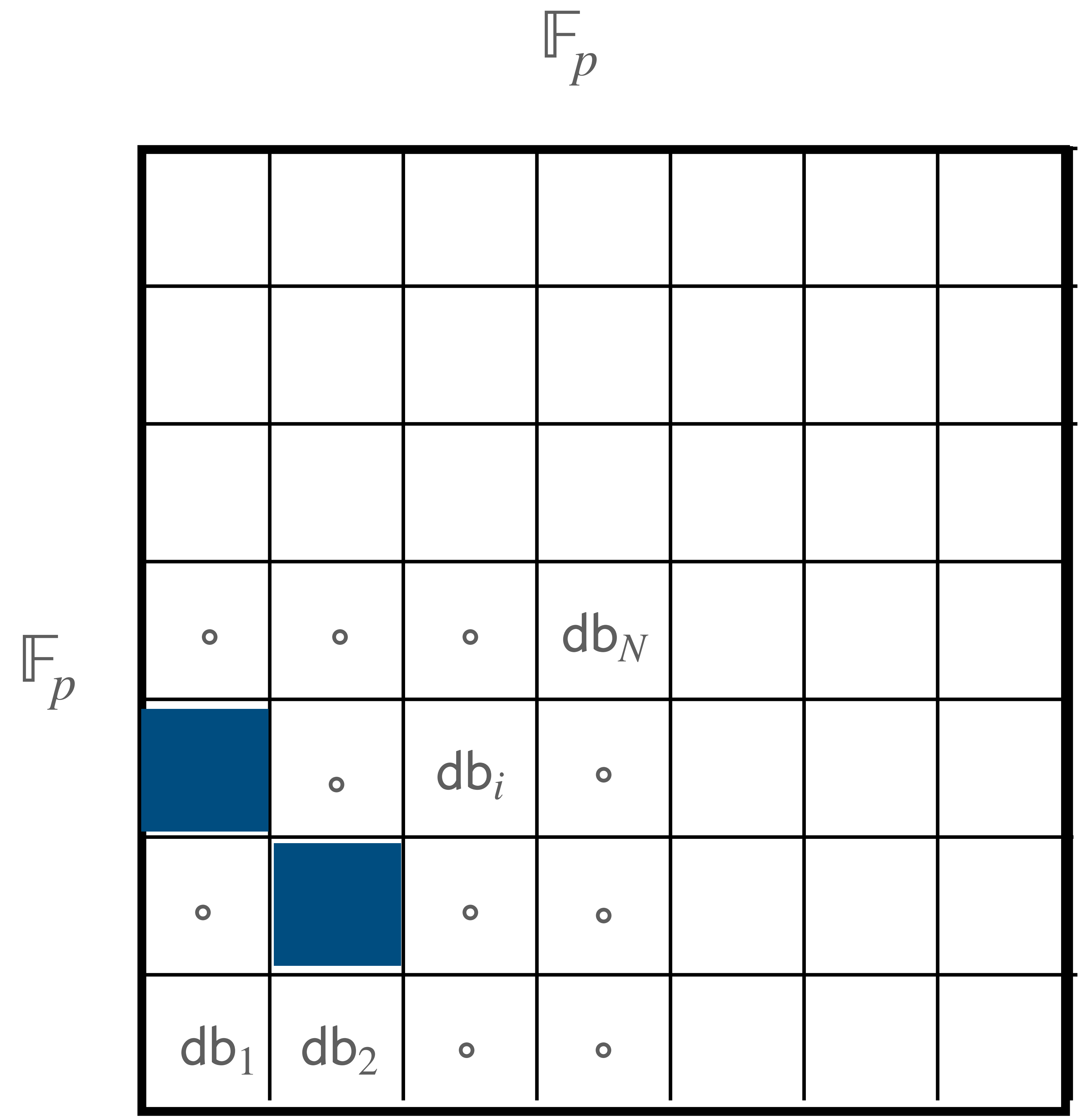

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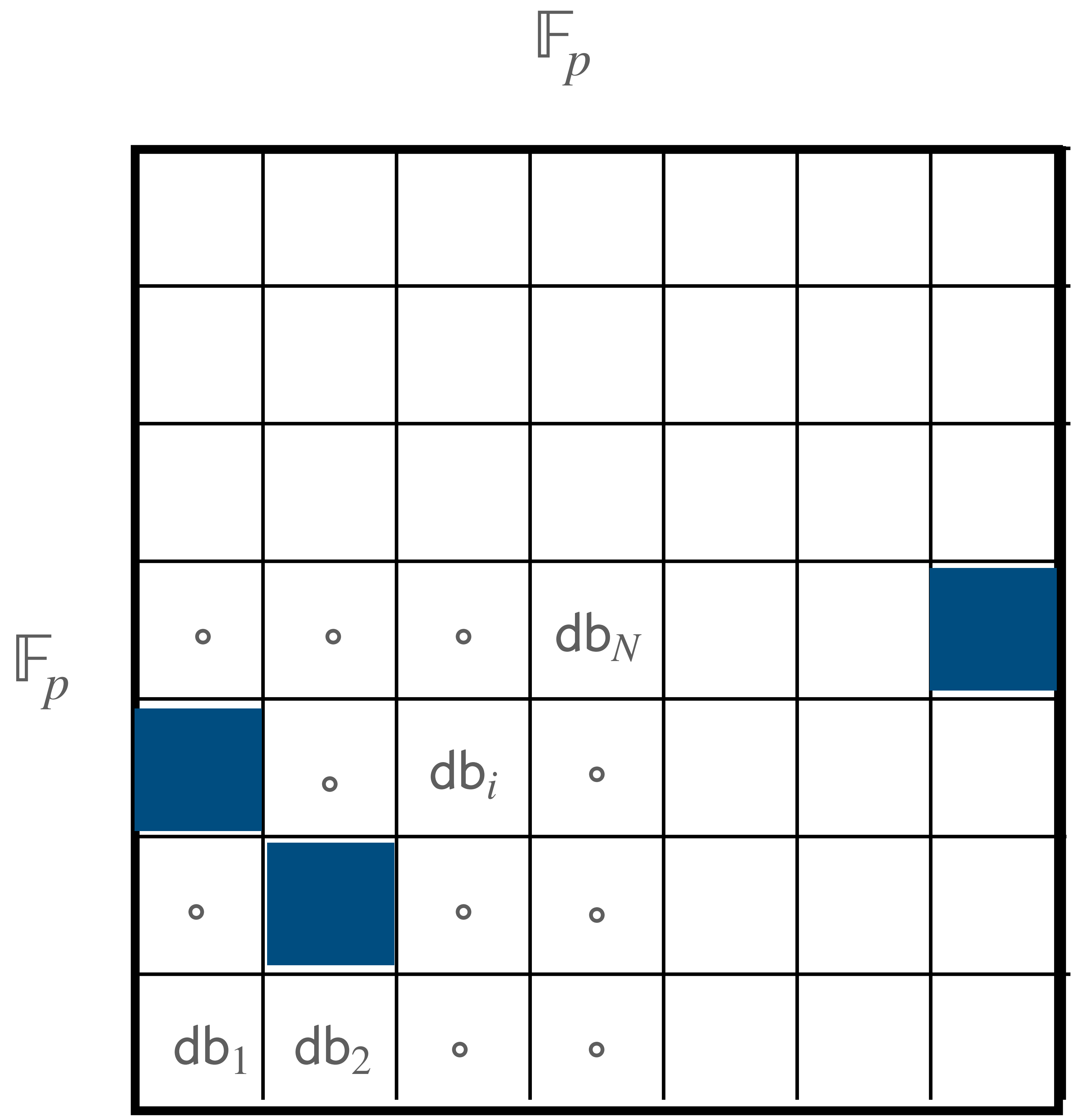

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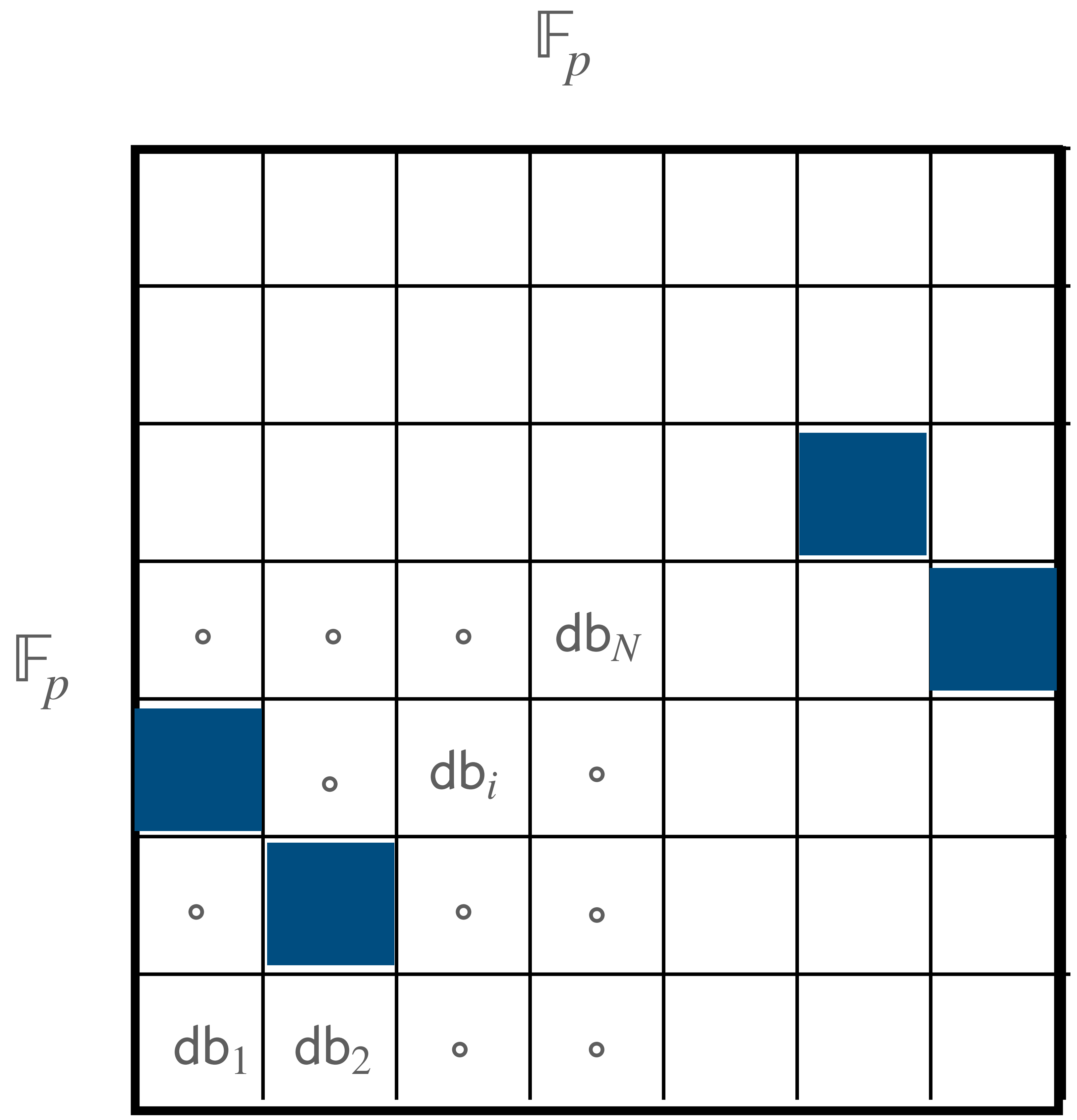

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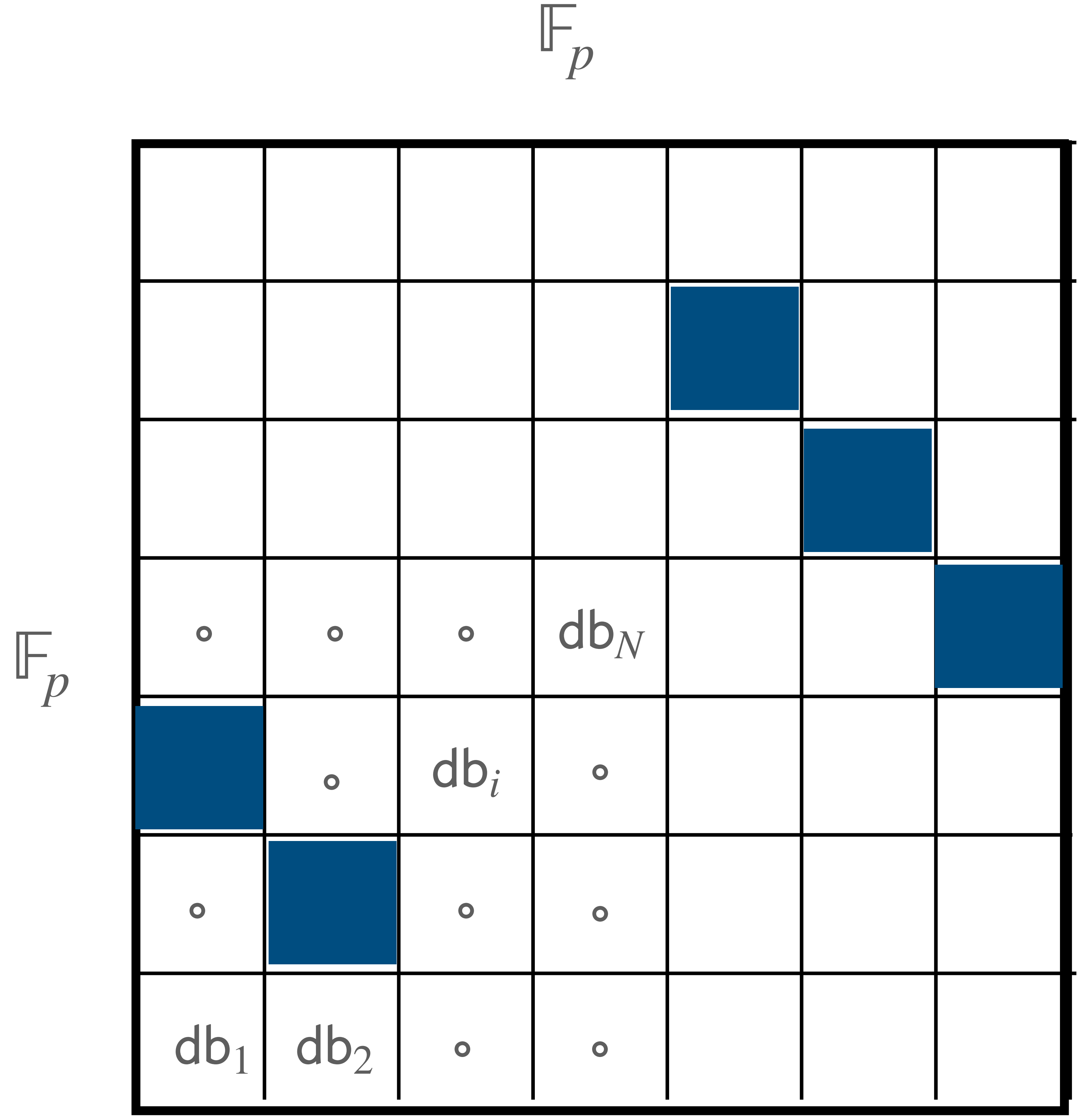

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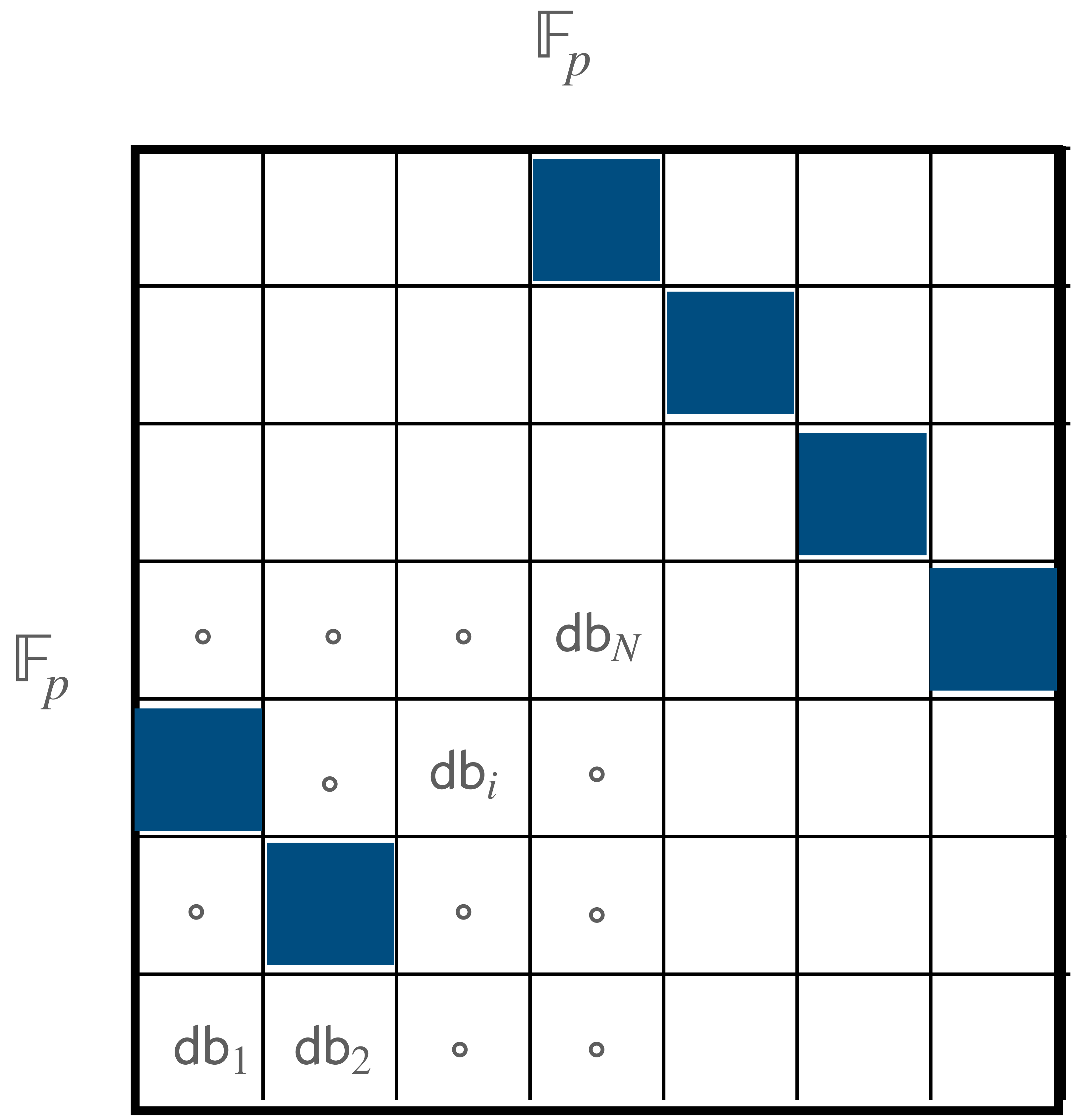

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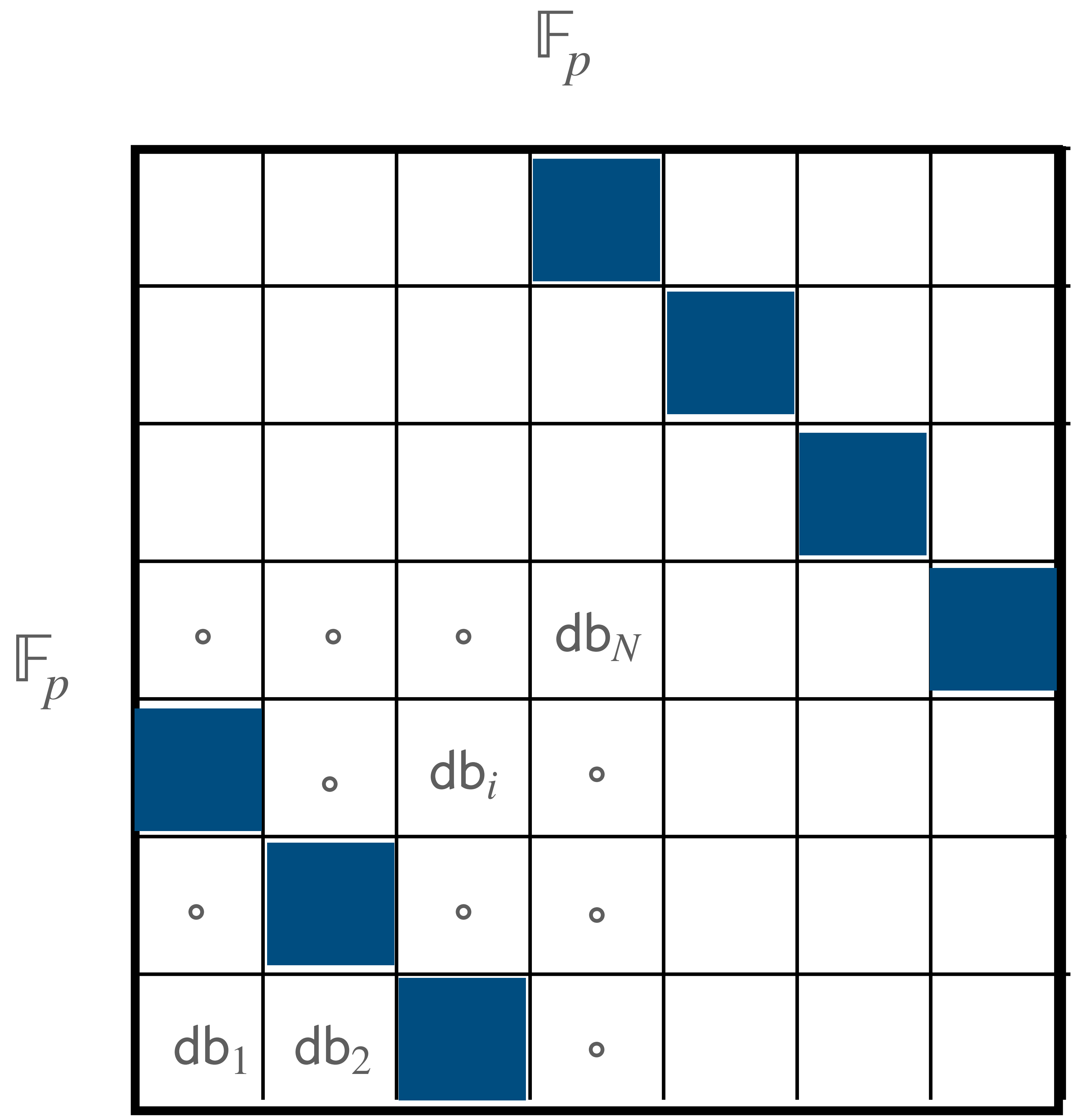

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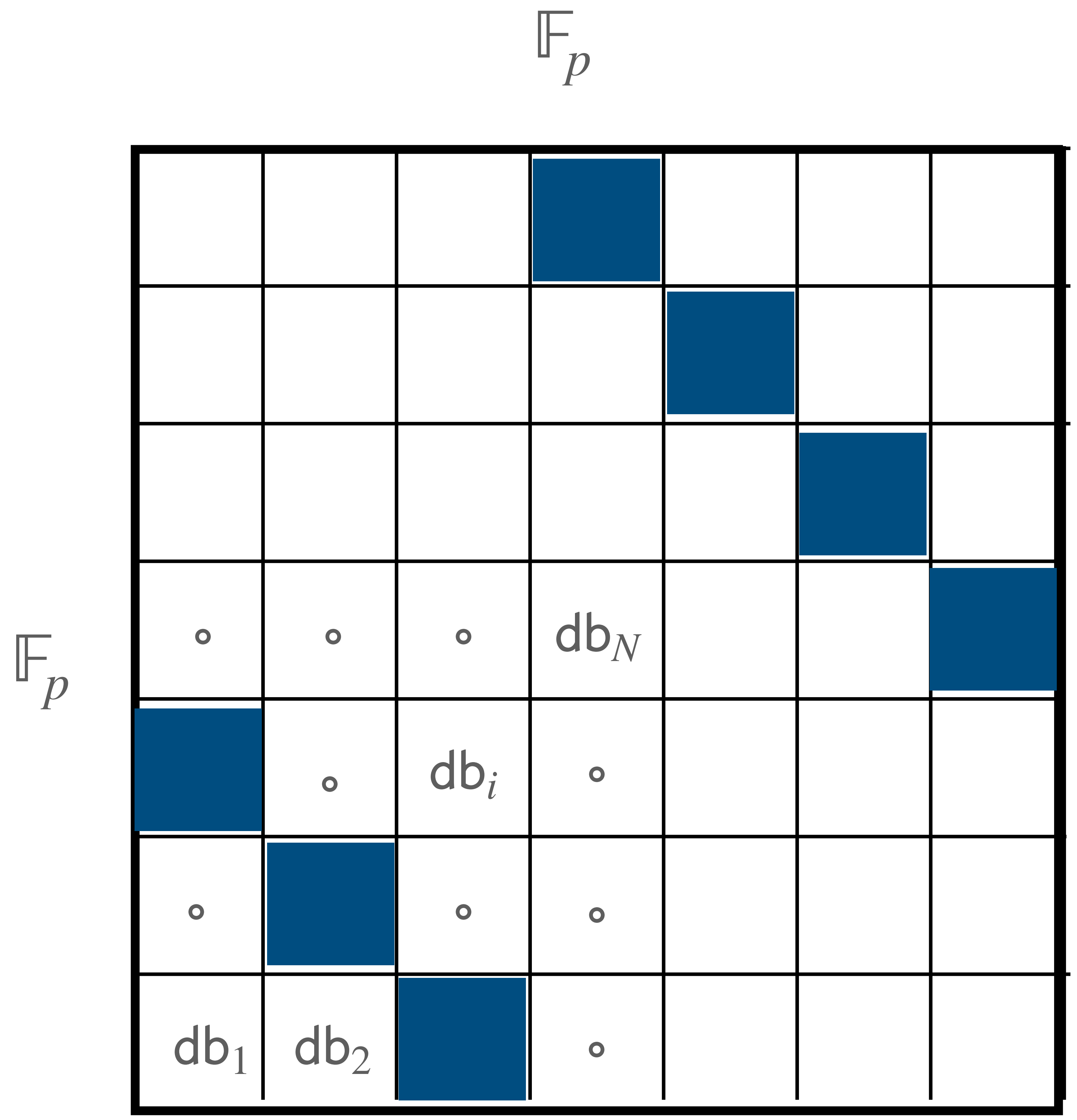

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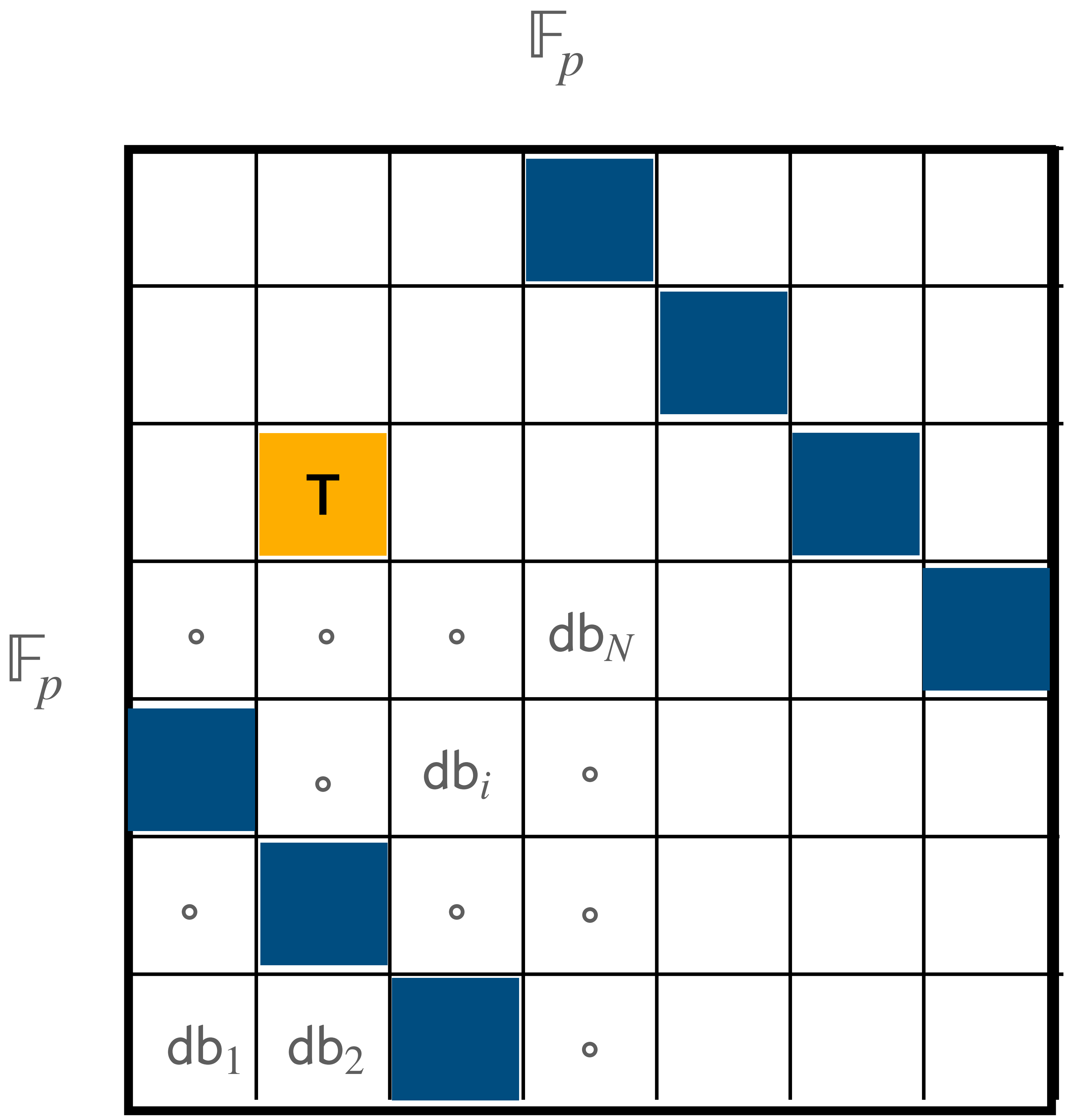

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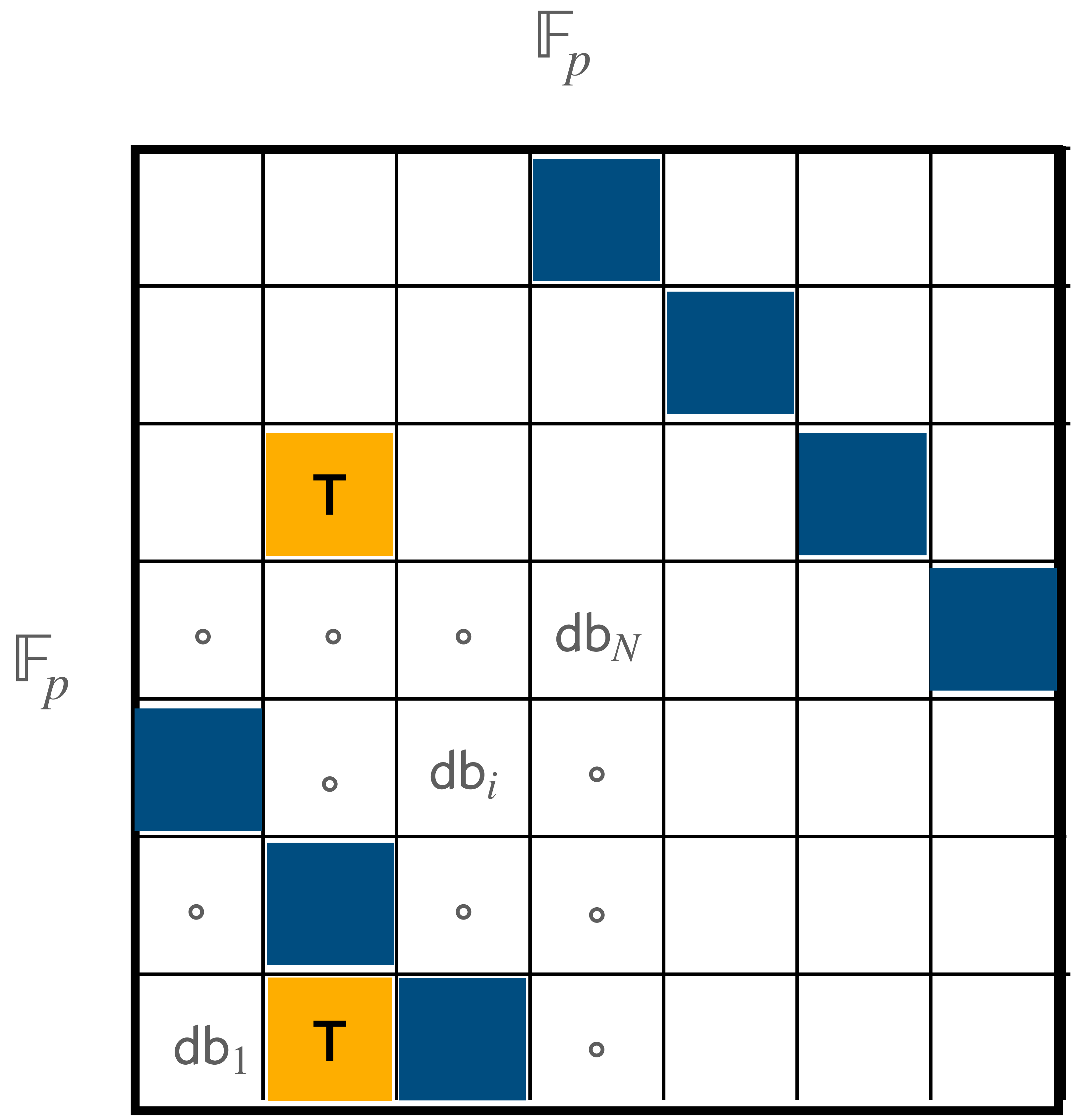

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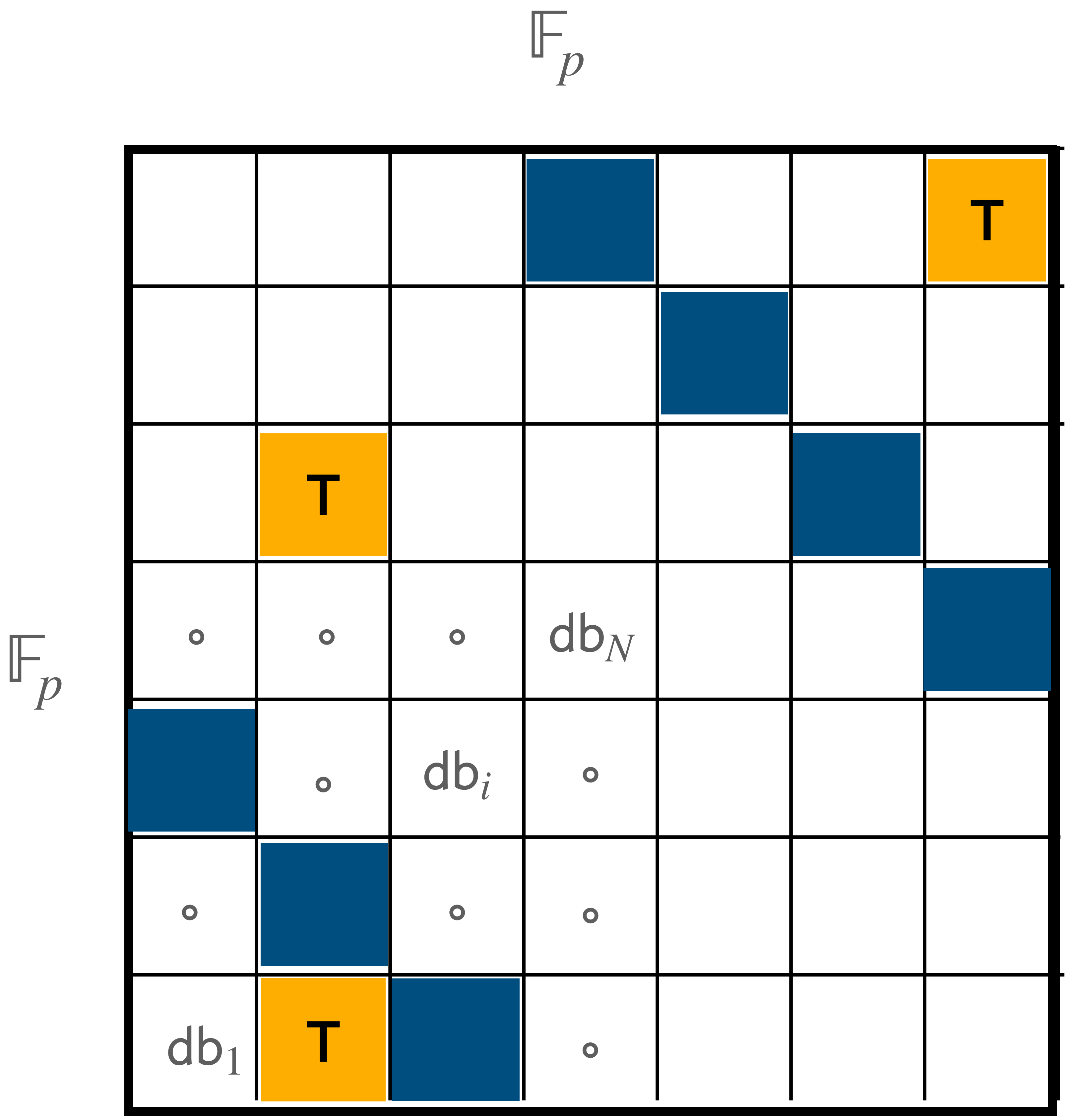

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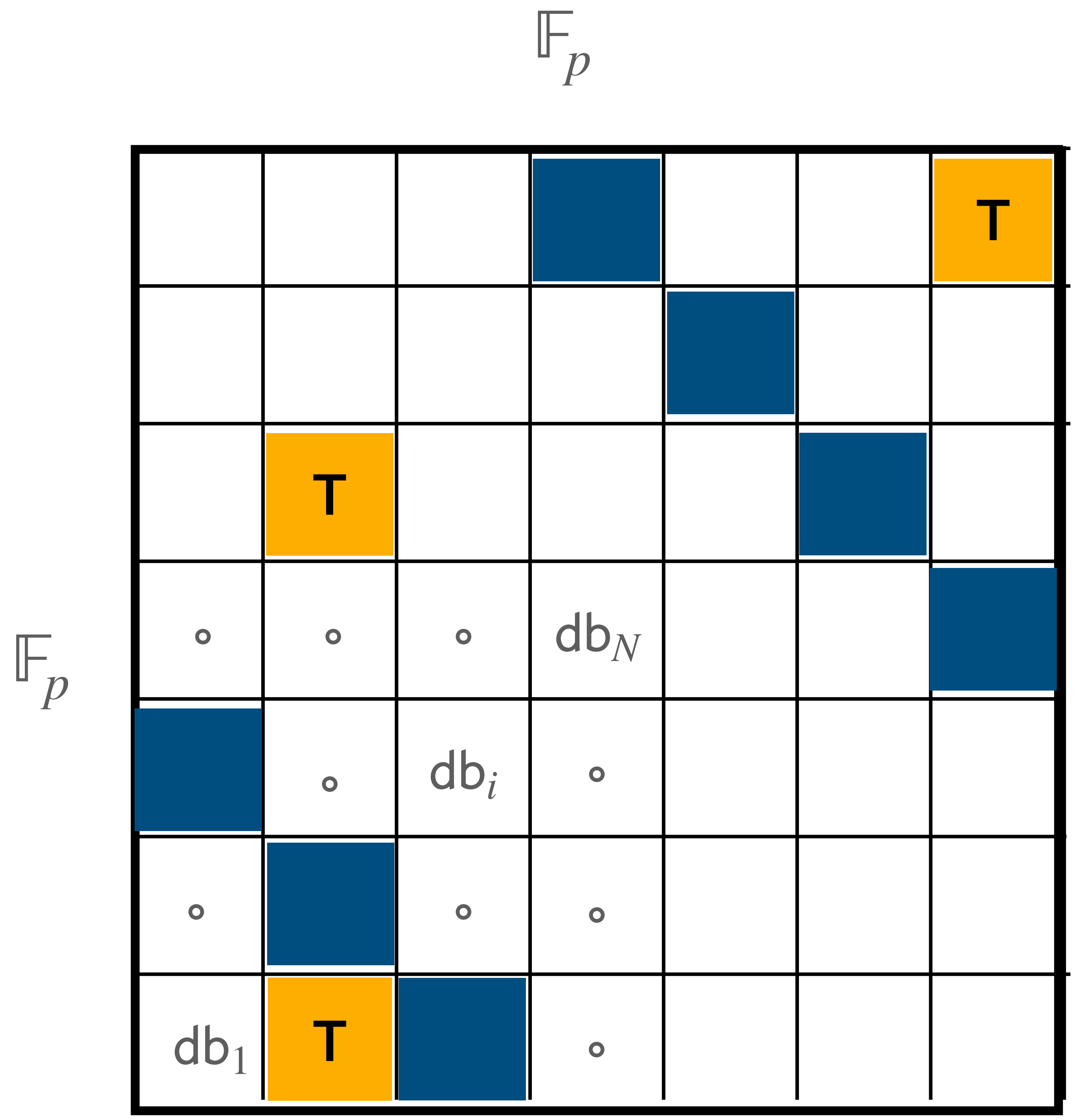

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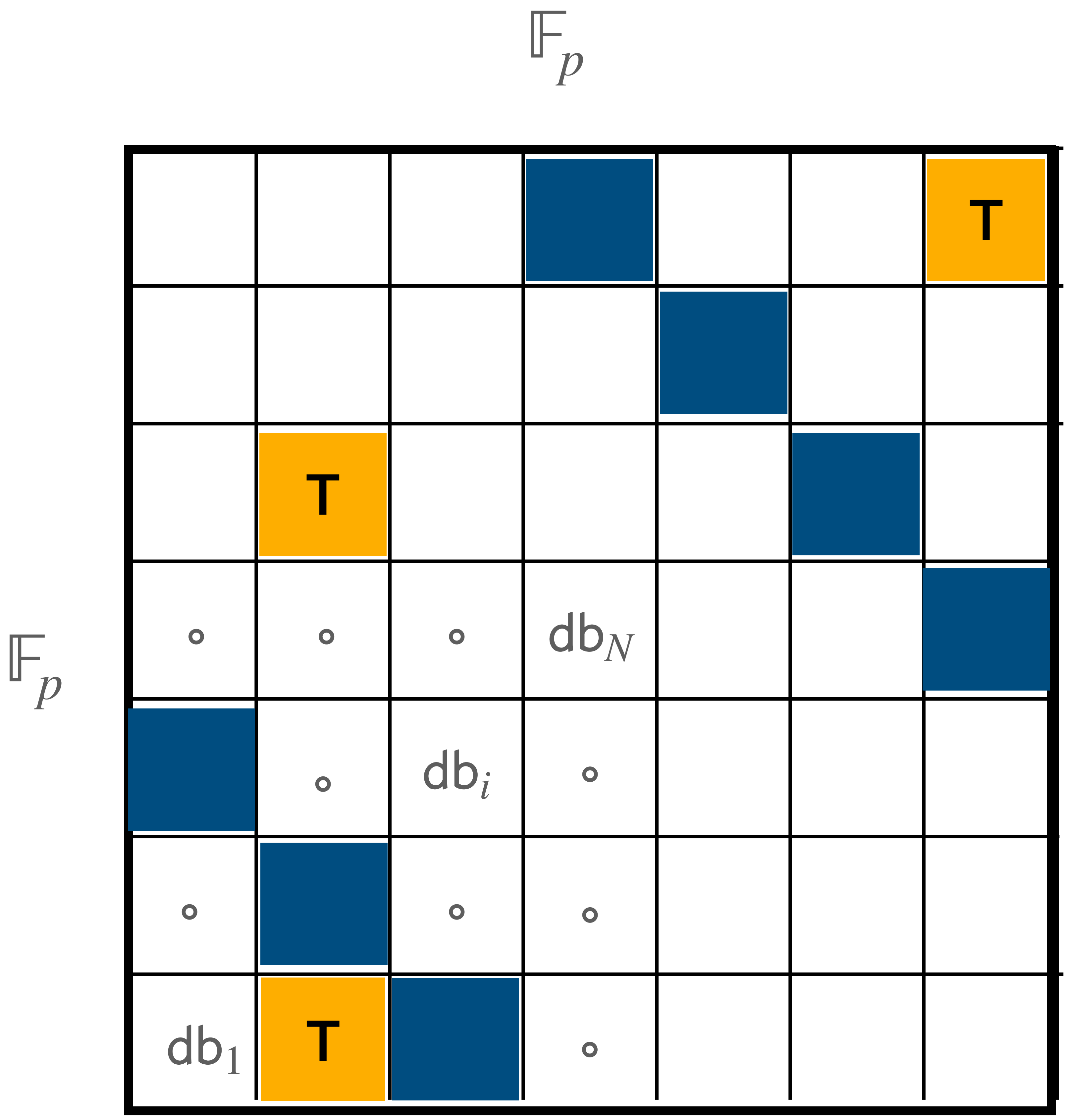

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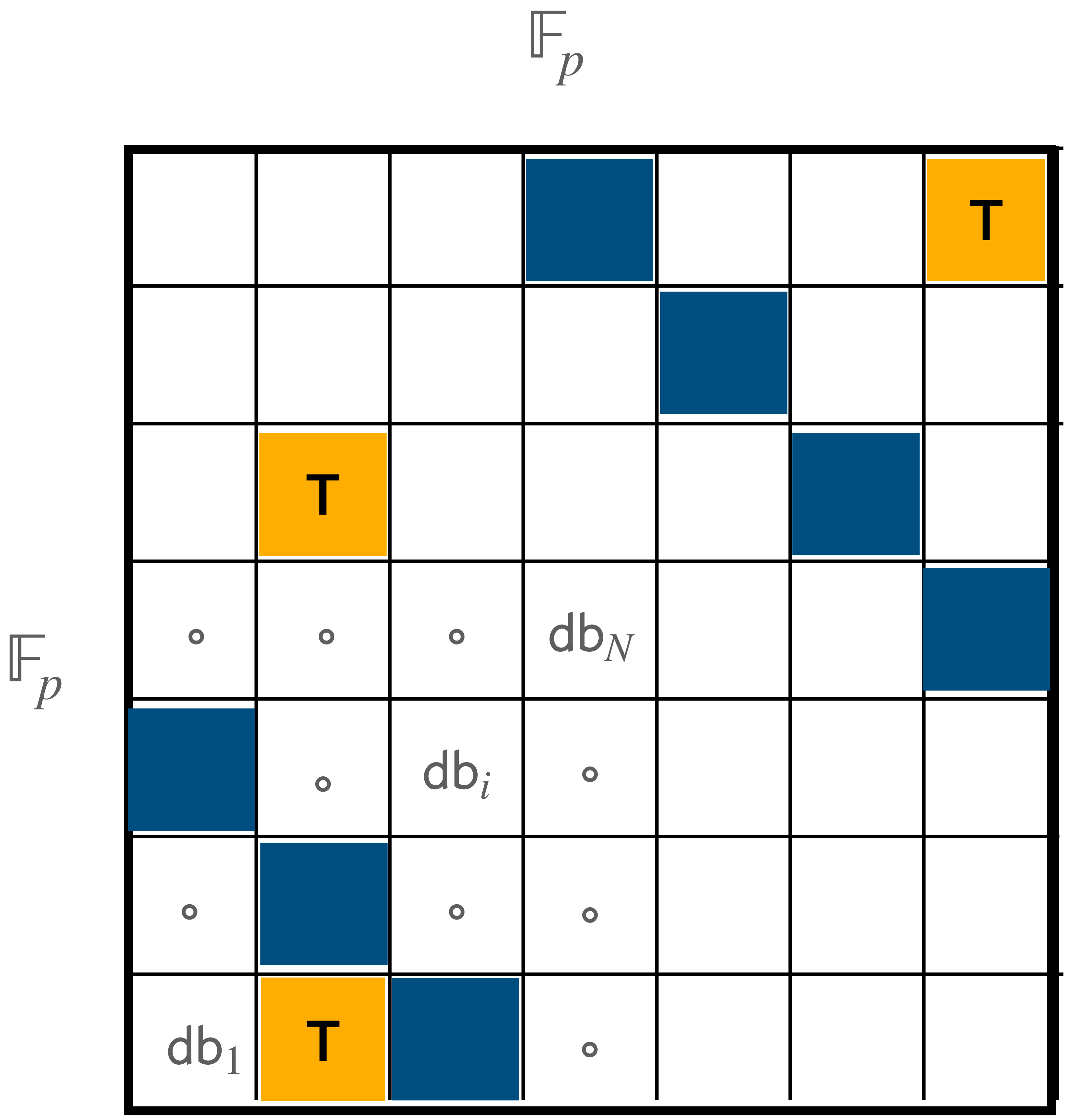

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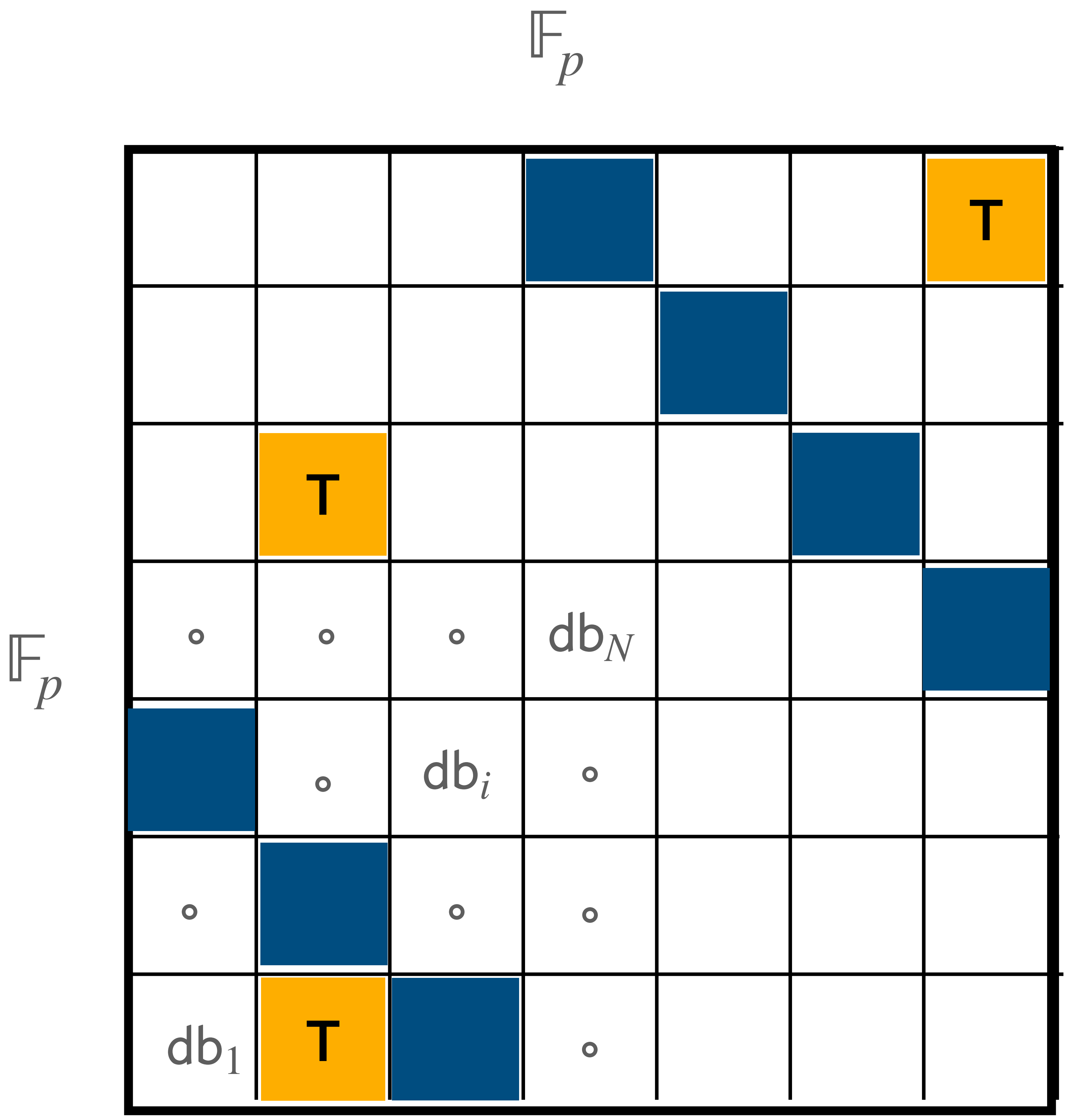

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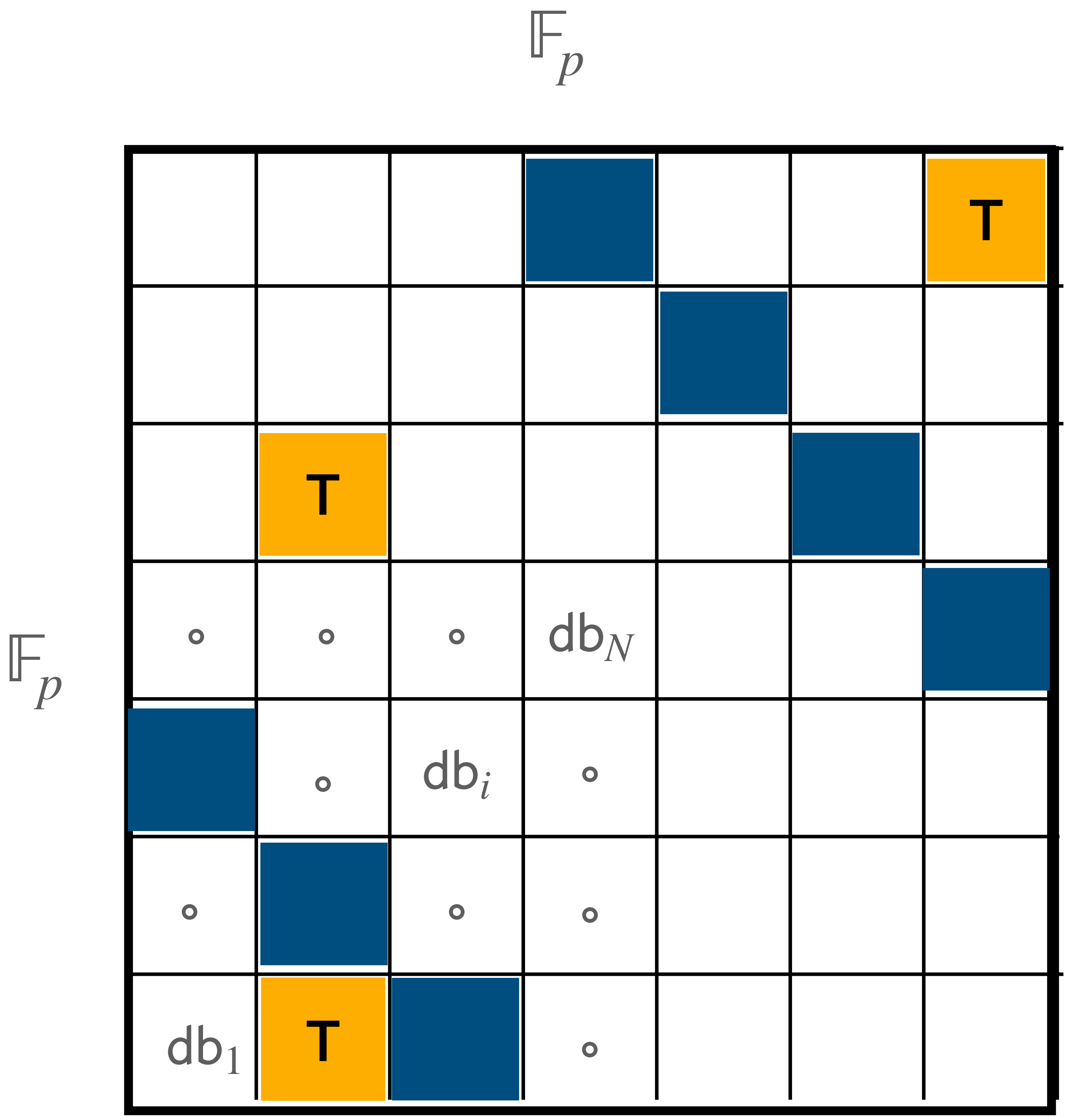

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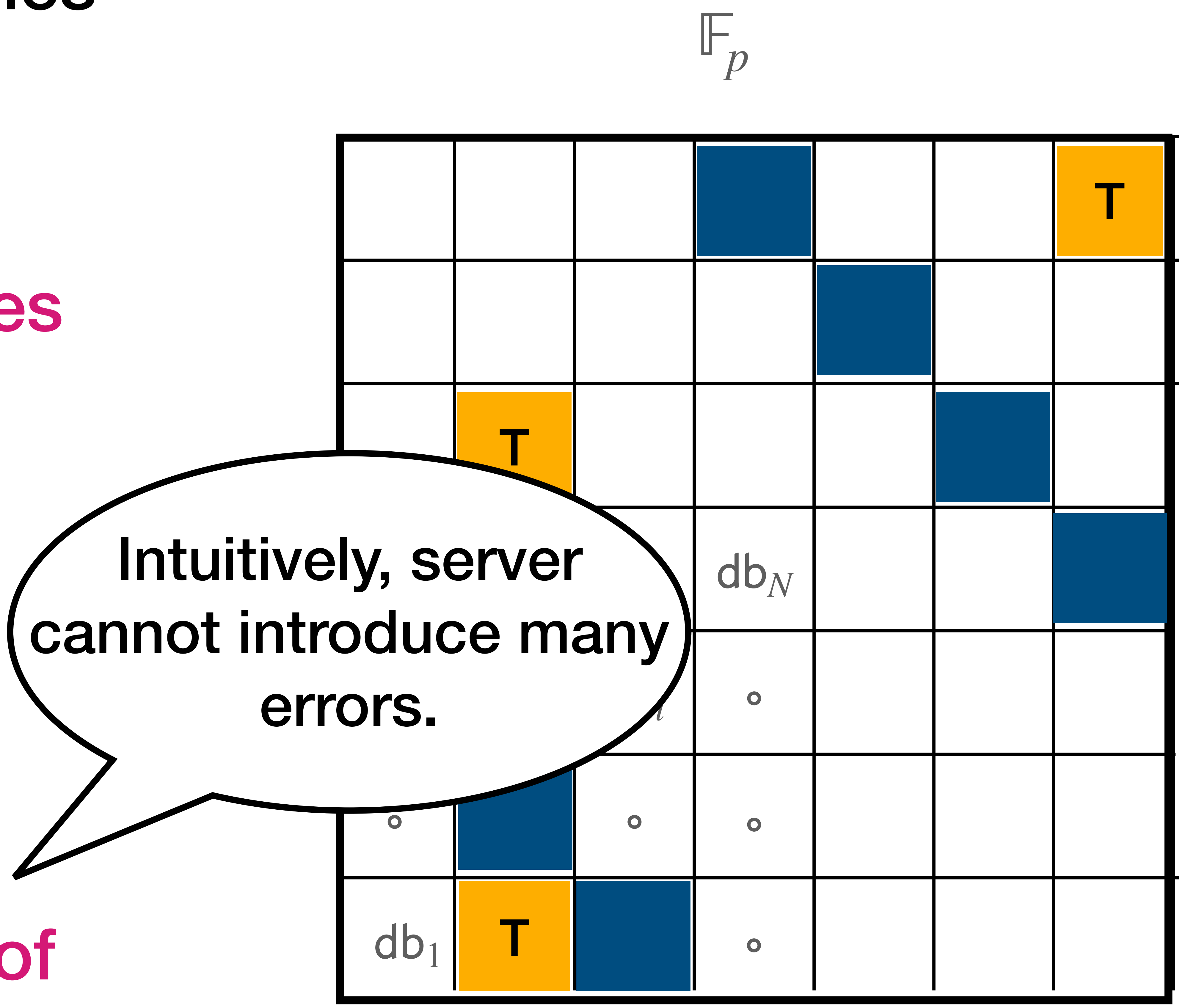

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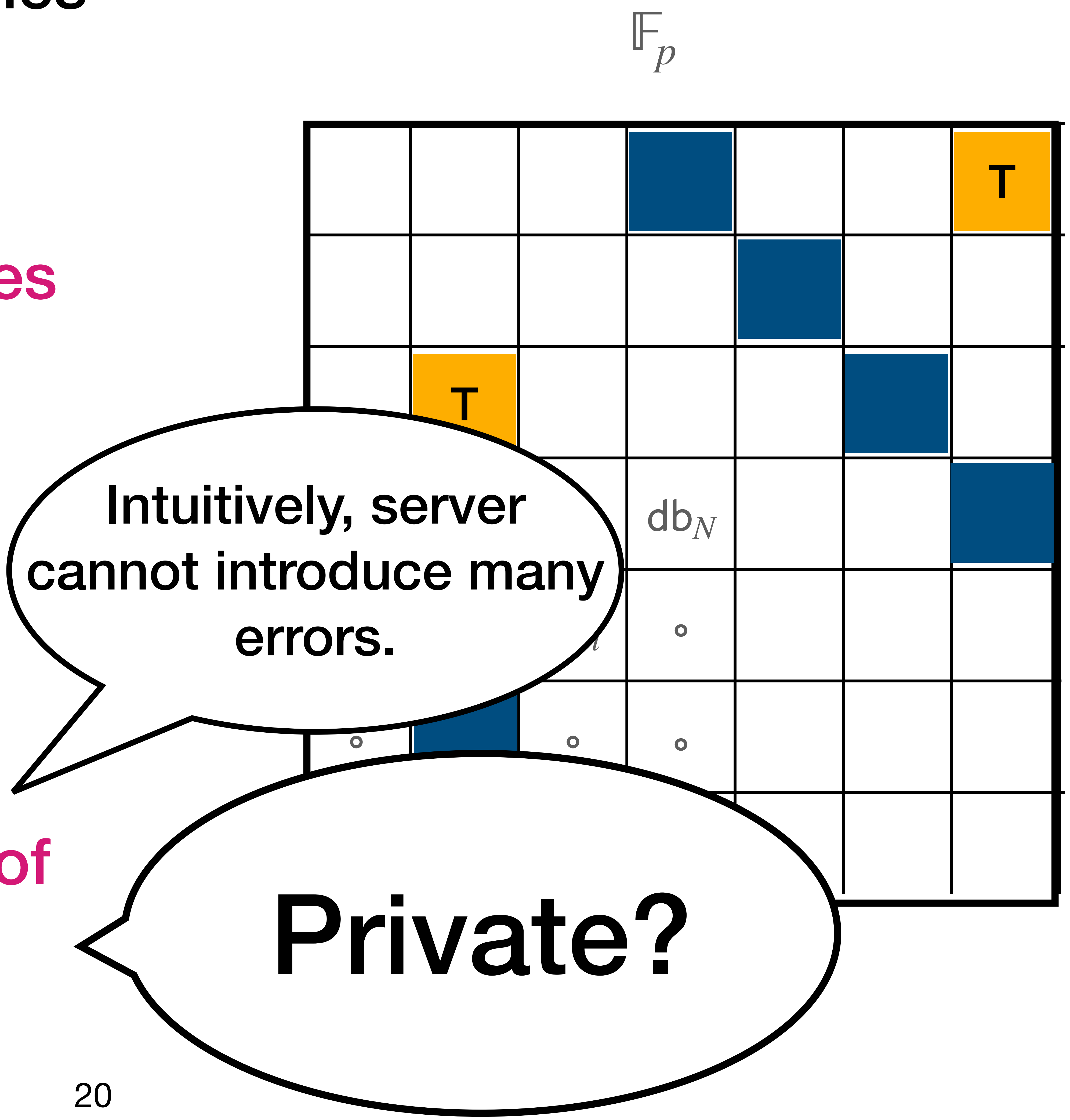

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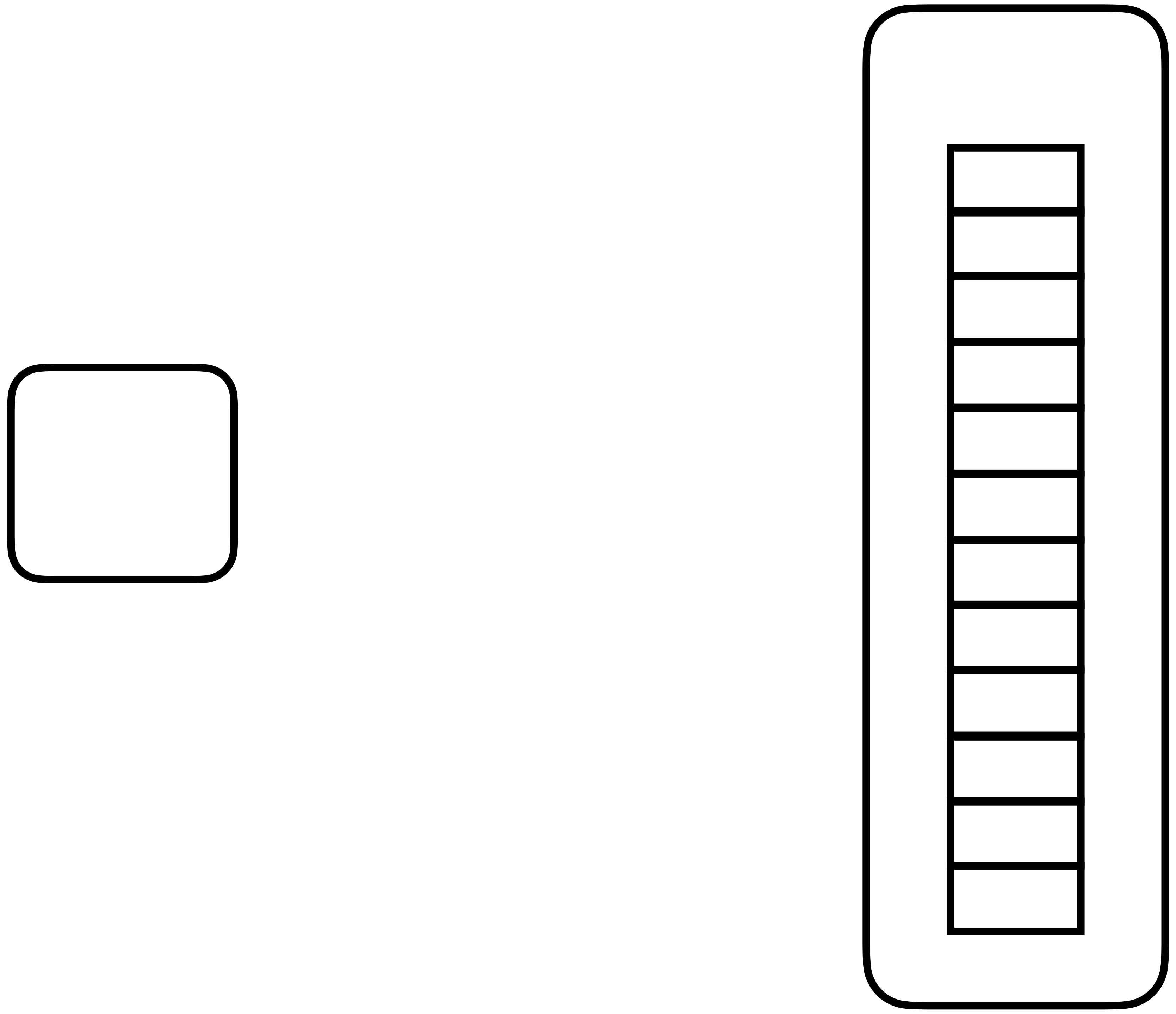

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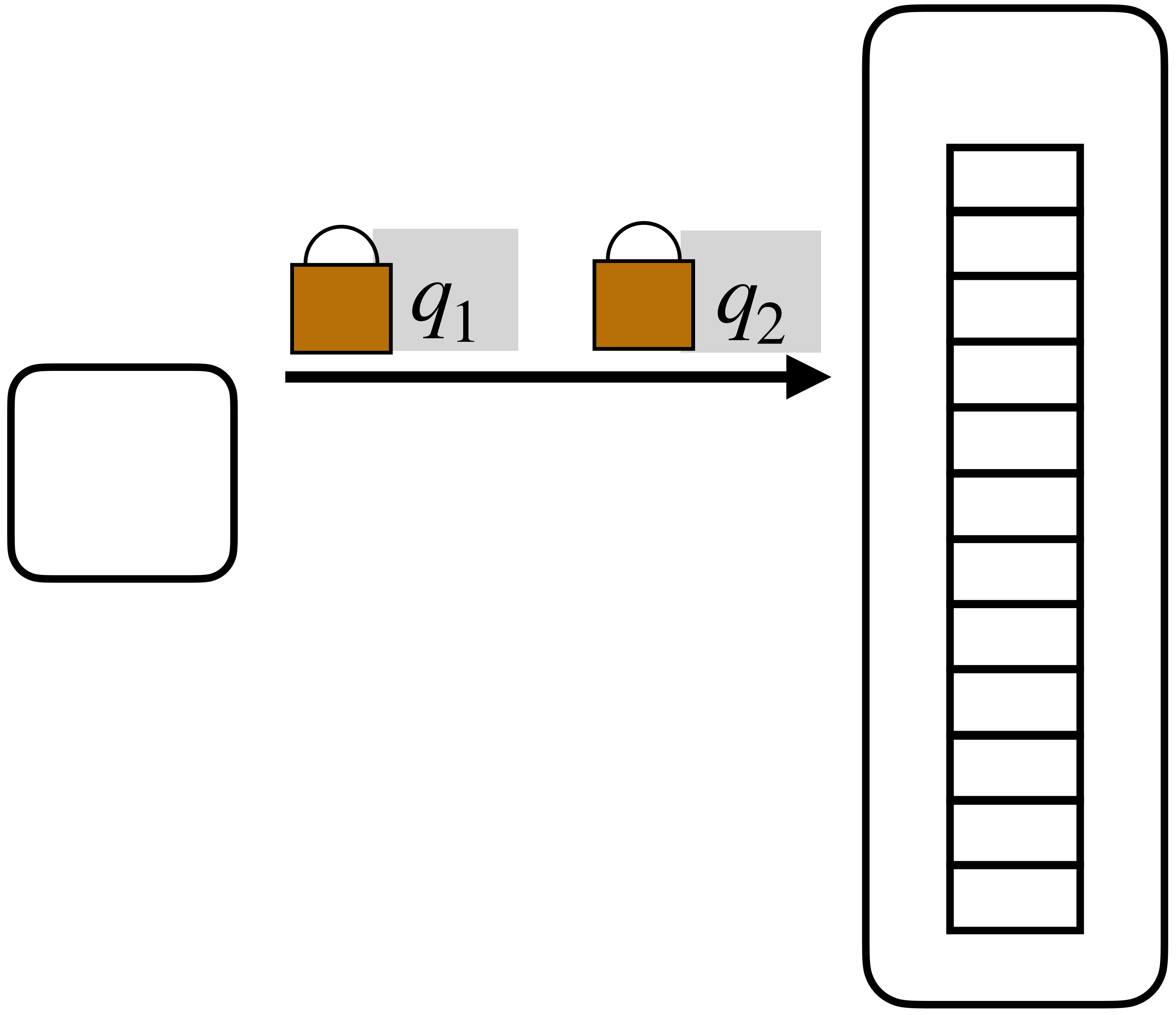

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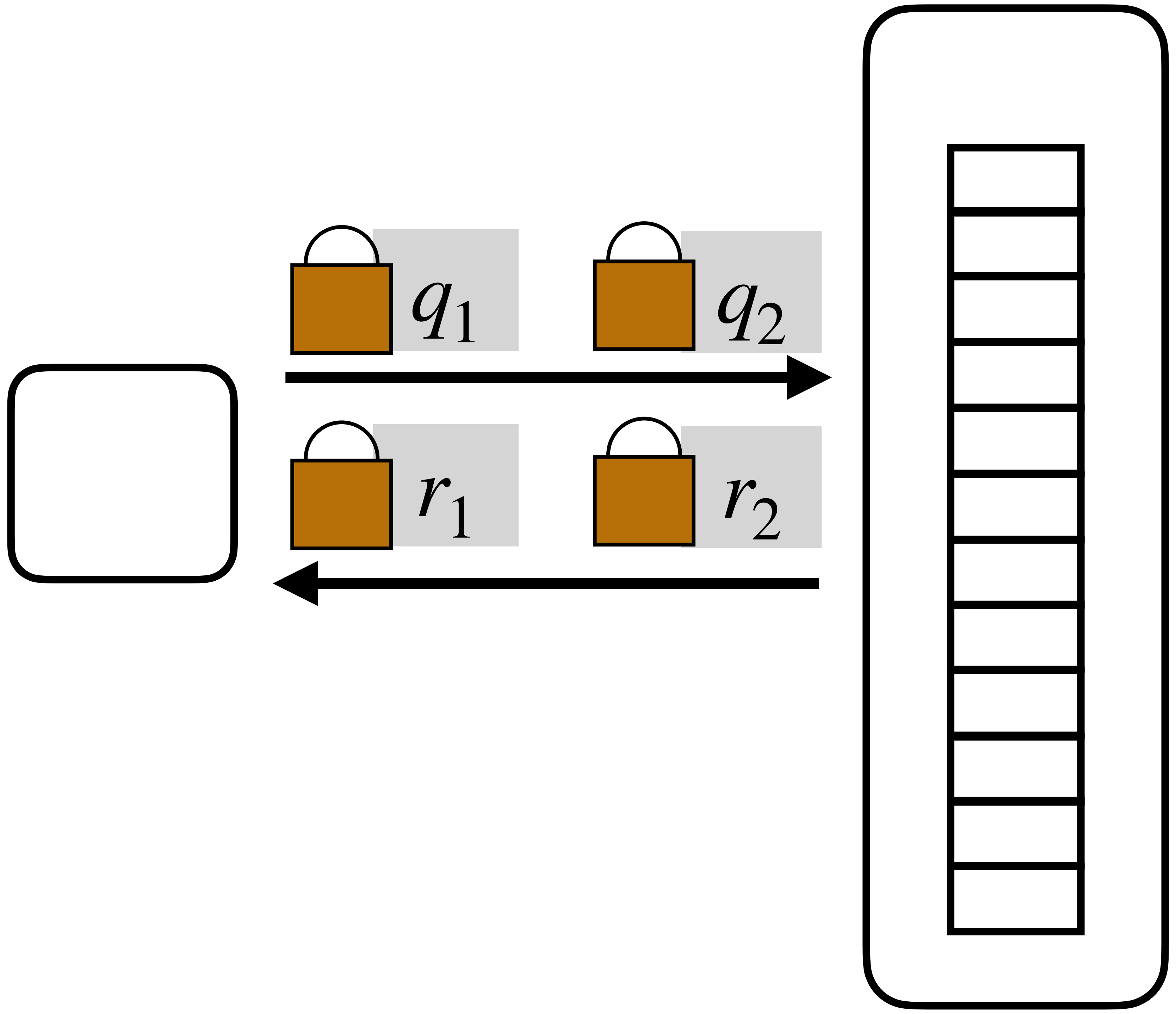

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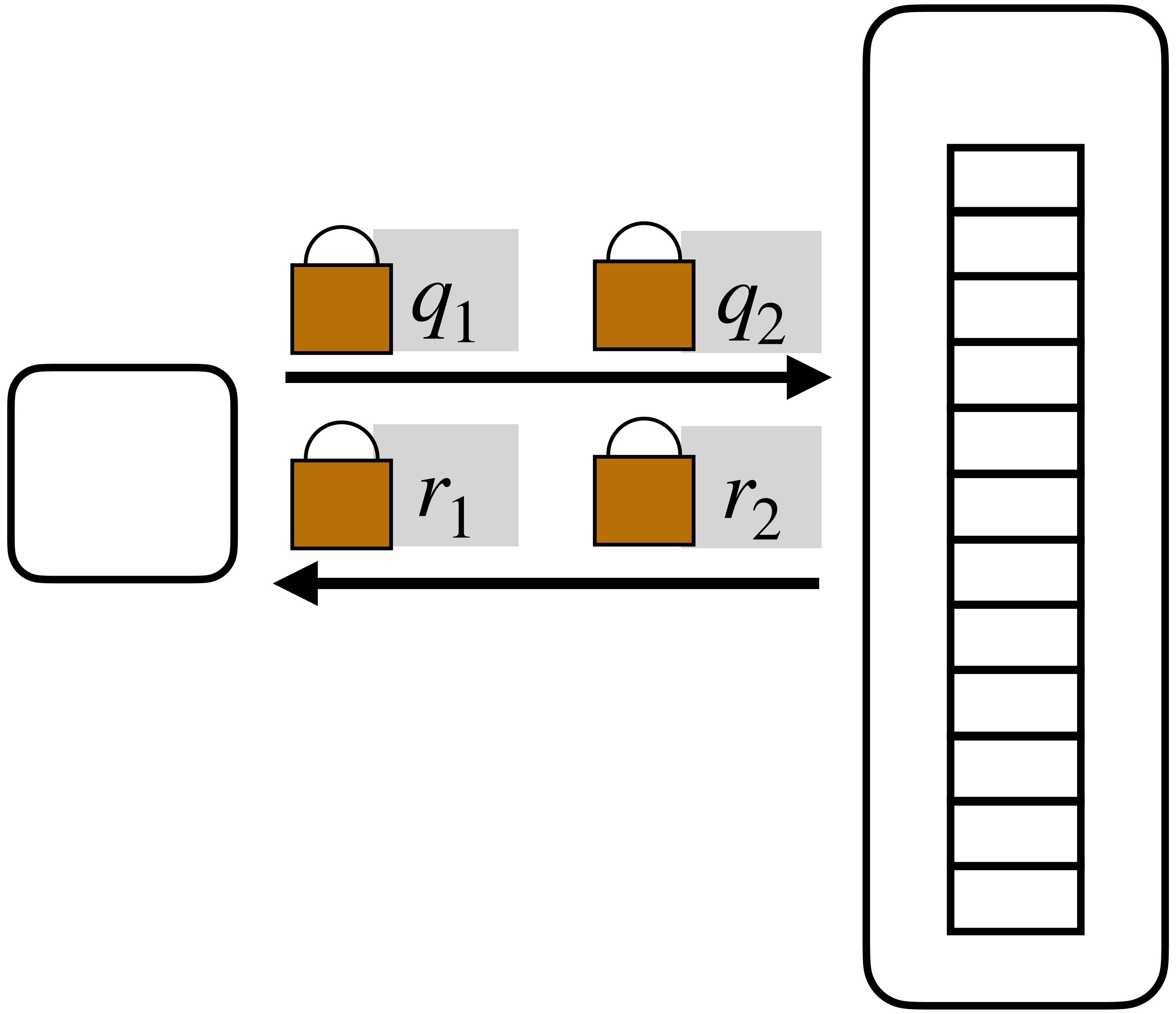

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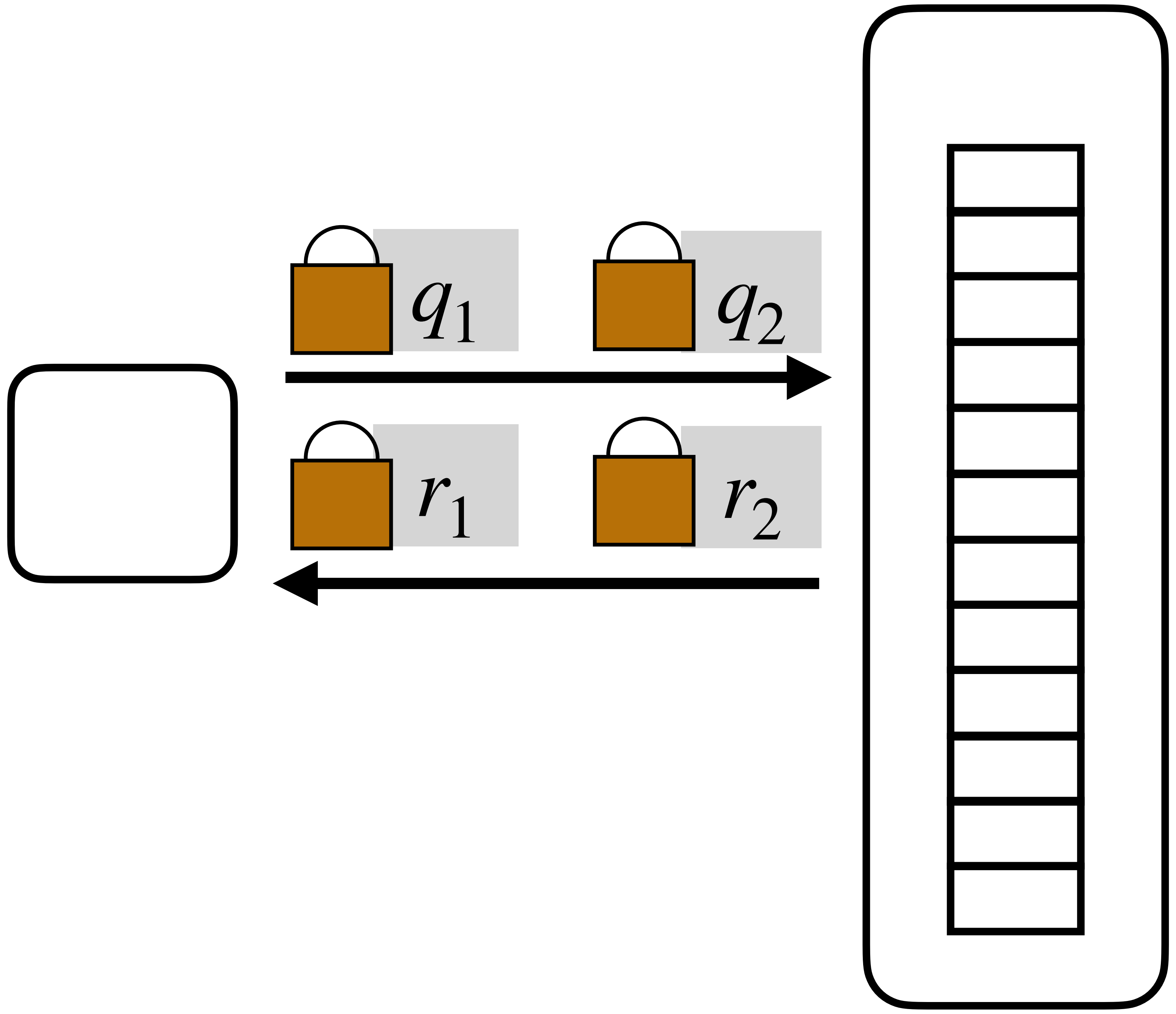

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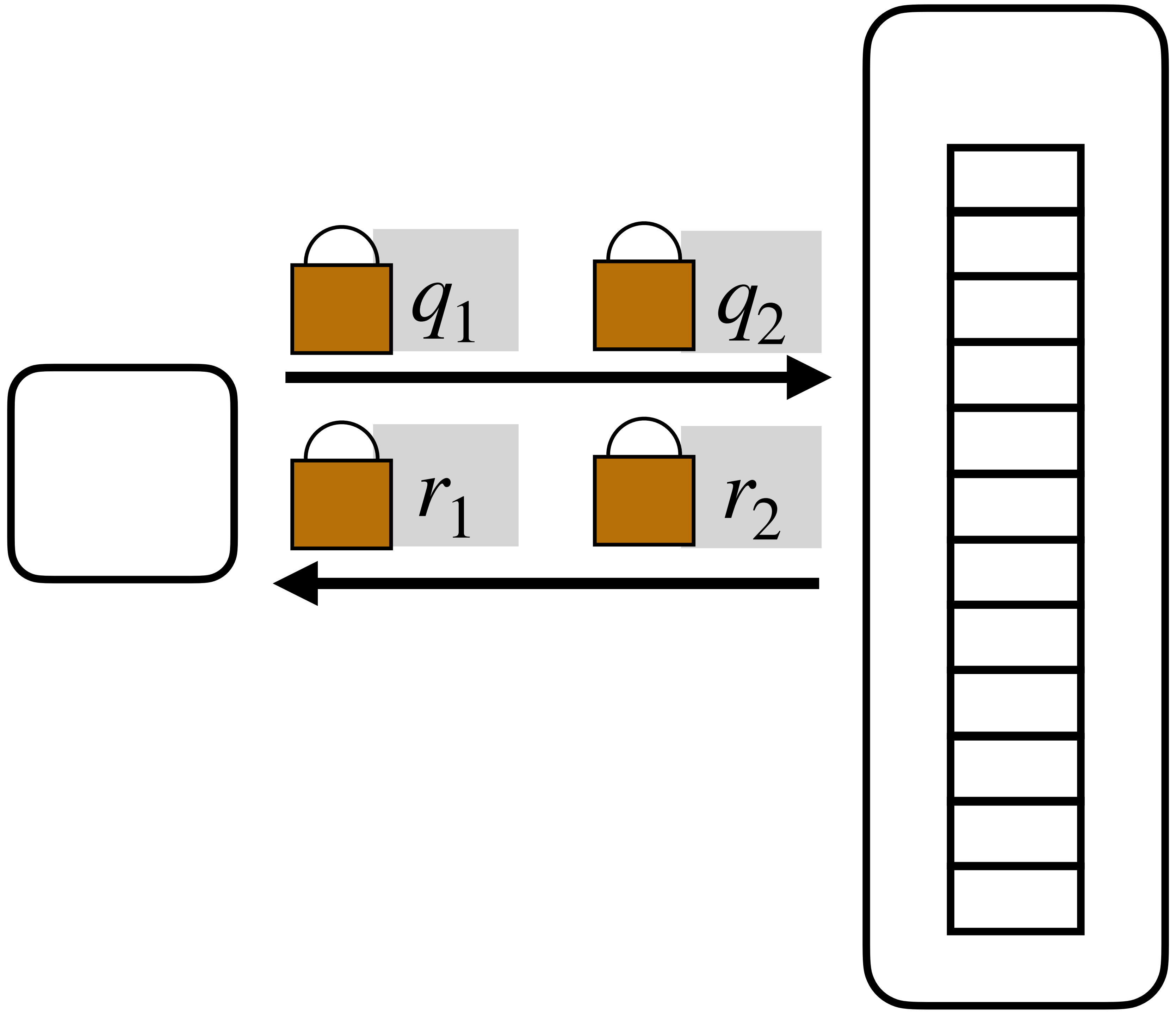

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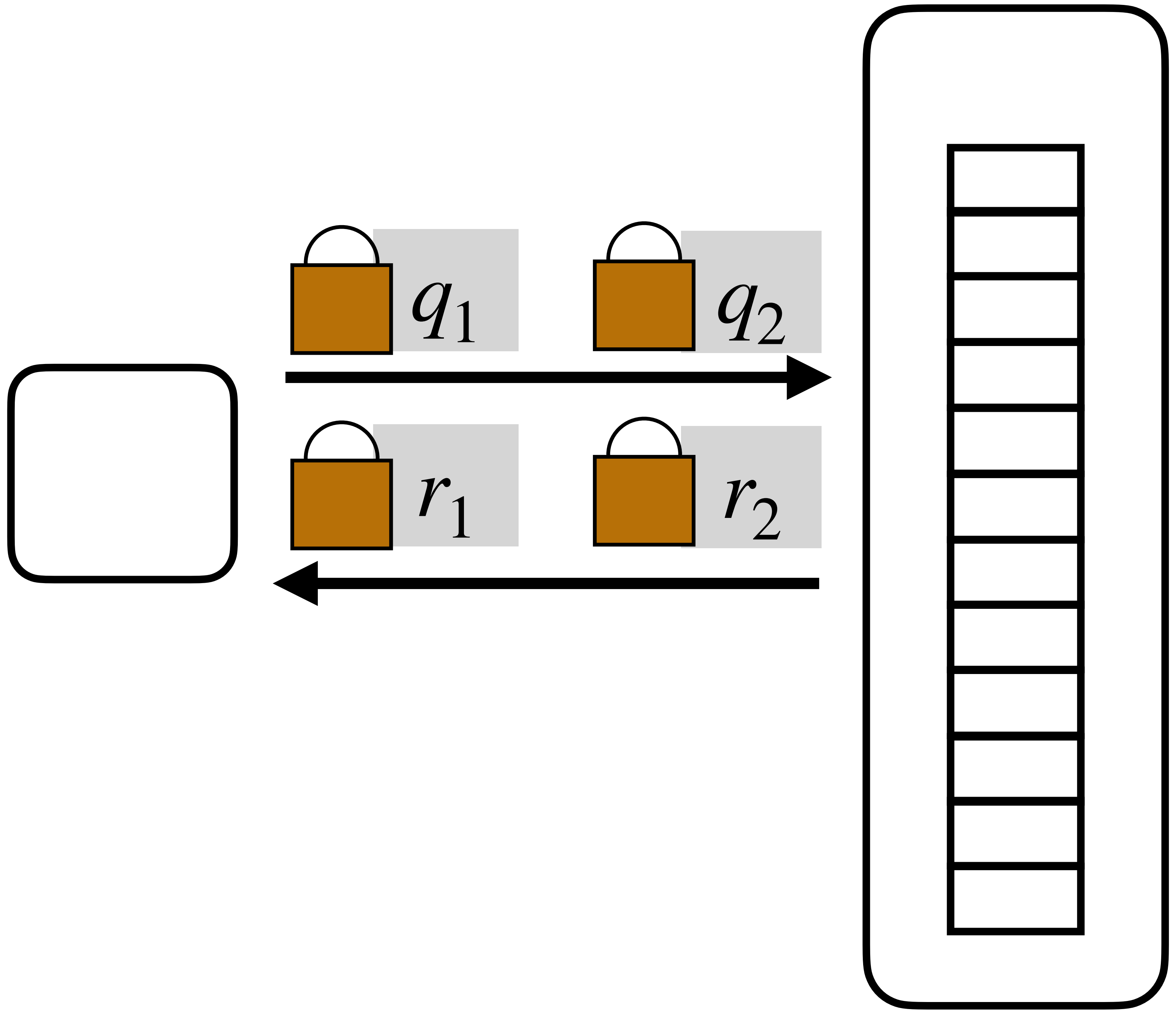

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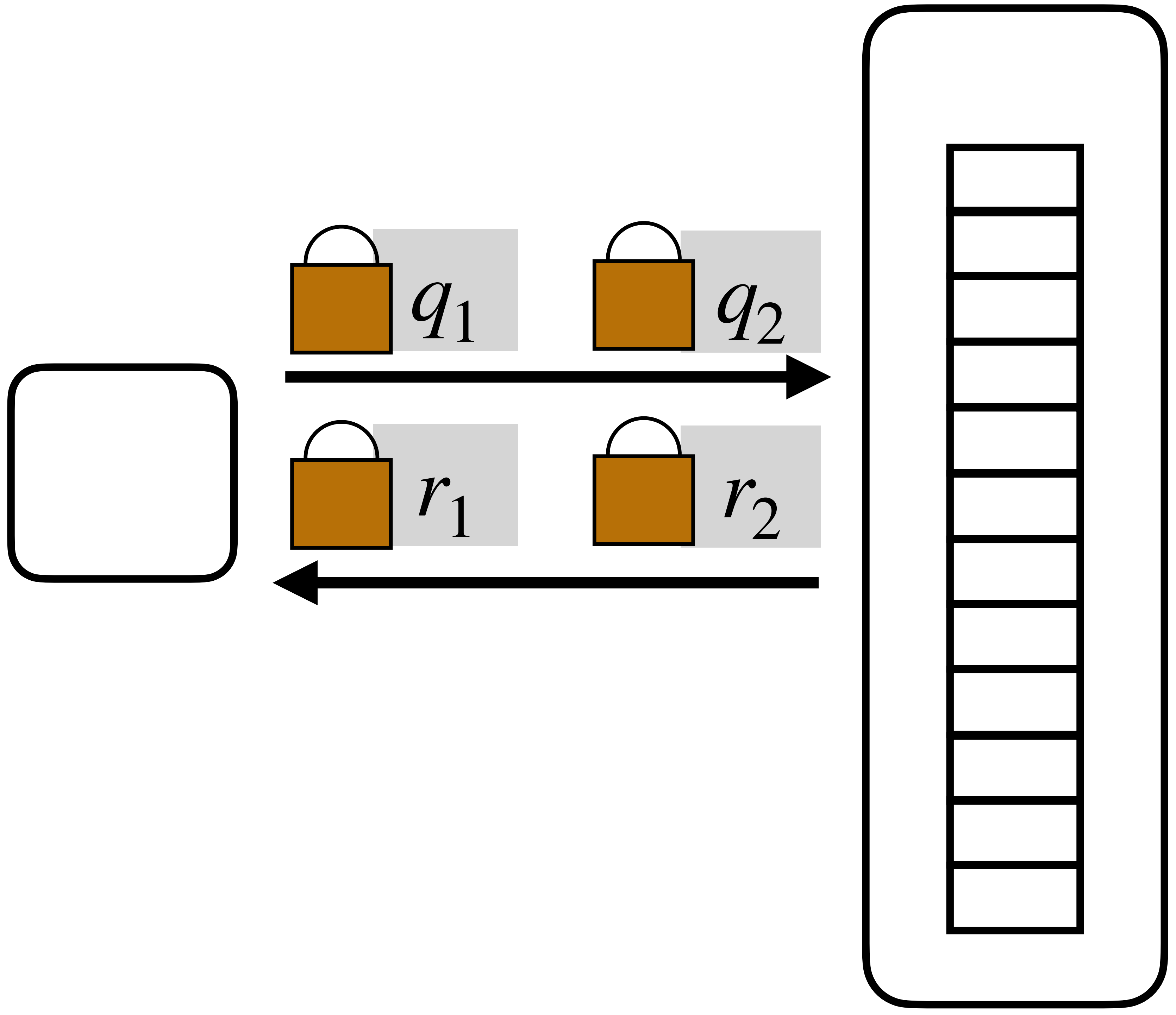

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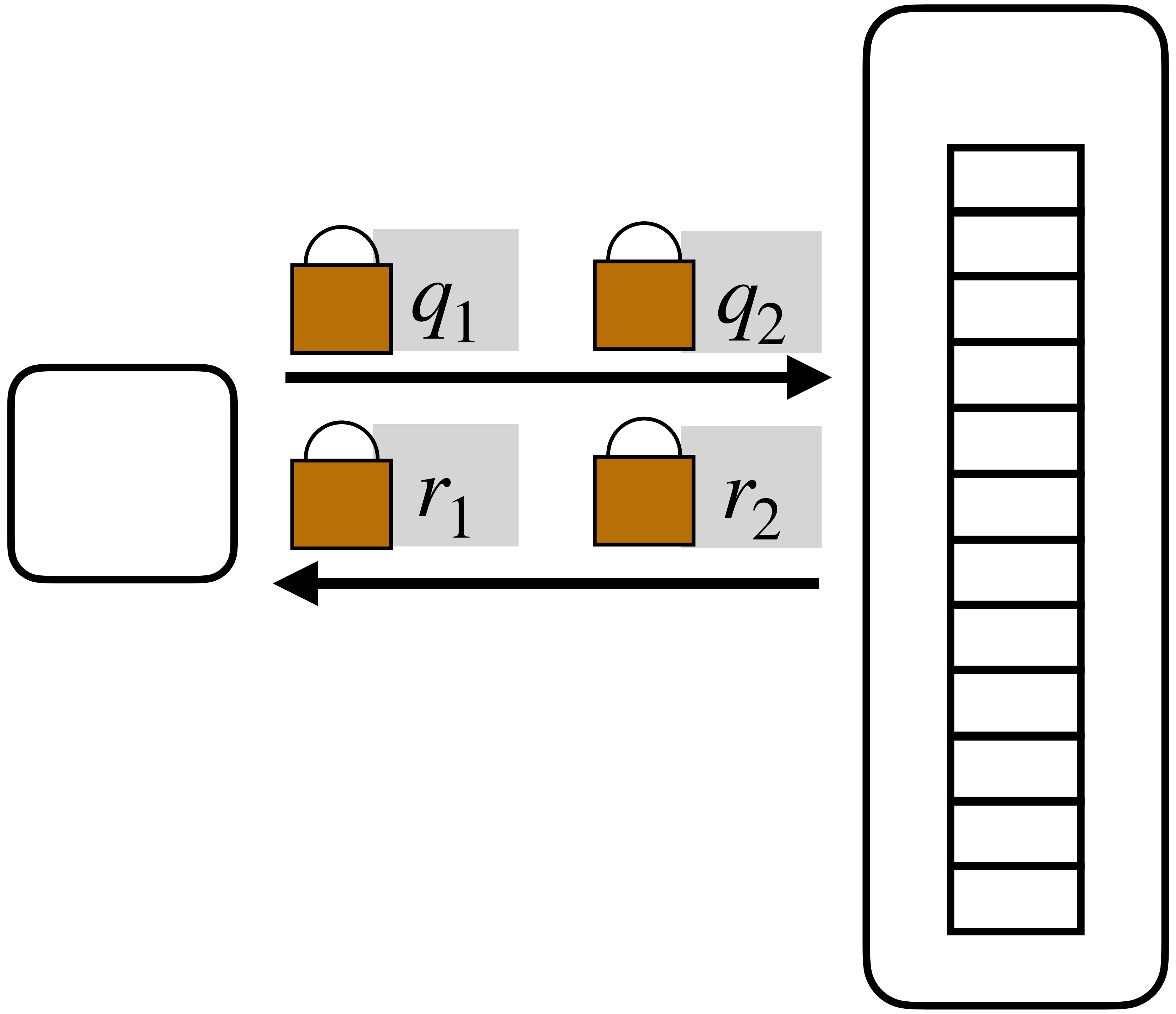

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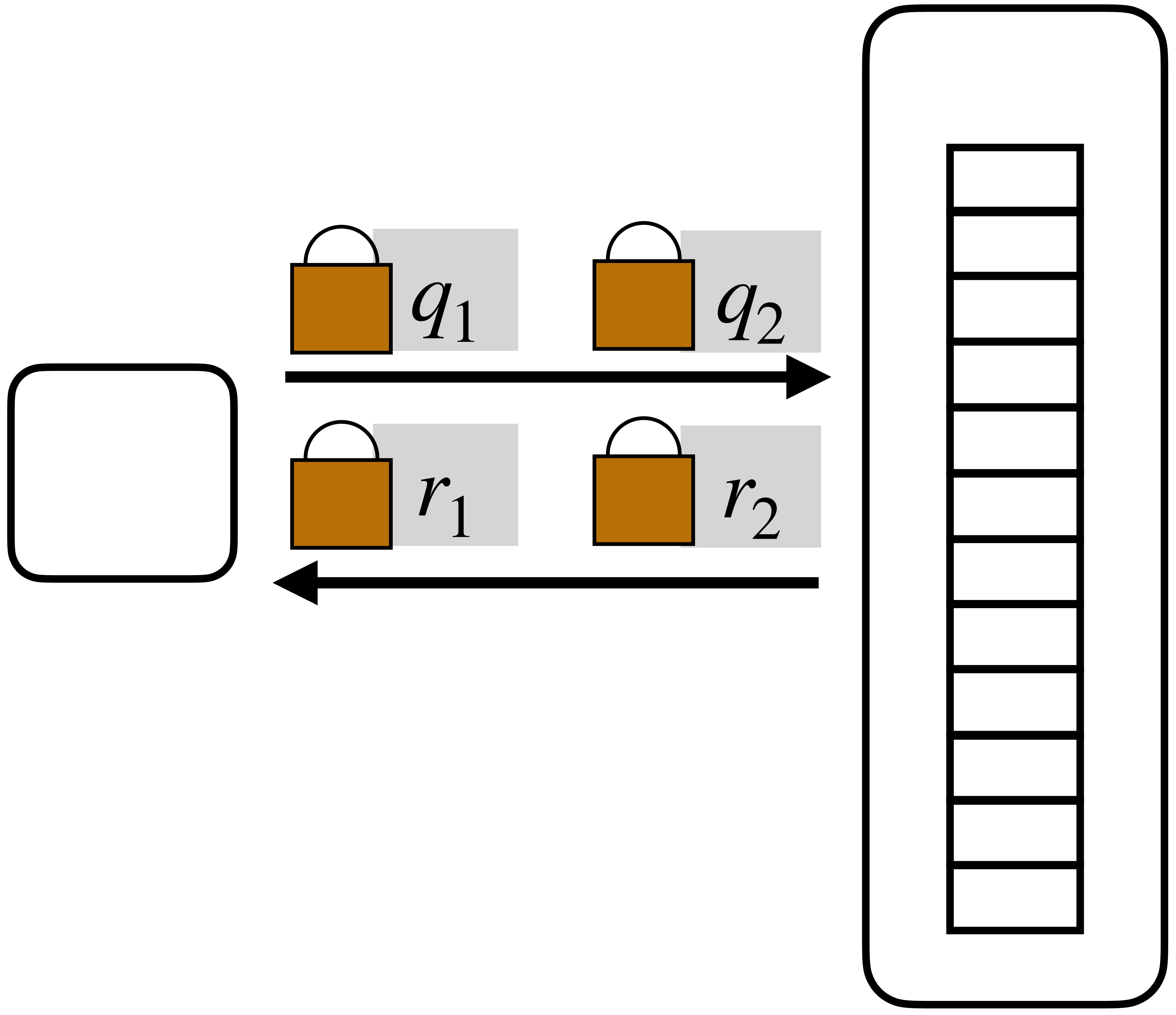
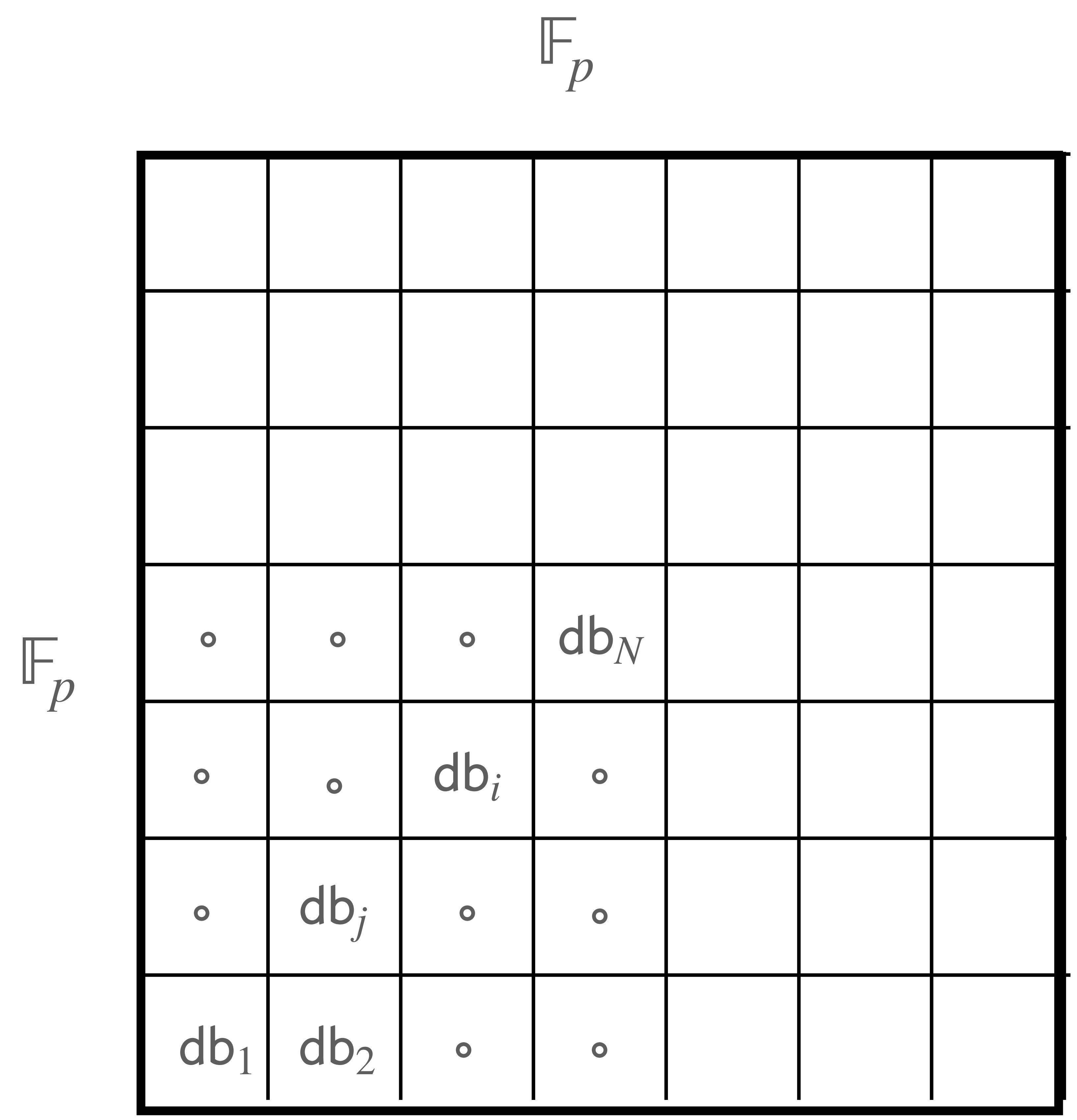
- We show how to overcome this barrier by constructing decoder against NS adversaries with only overhead λ



Our construction



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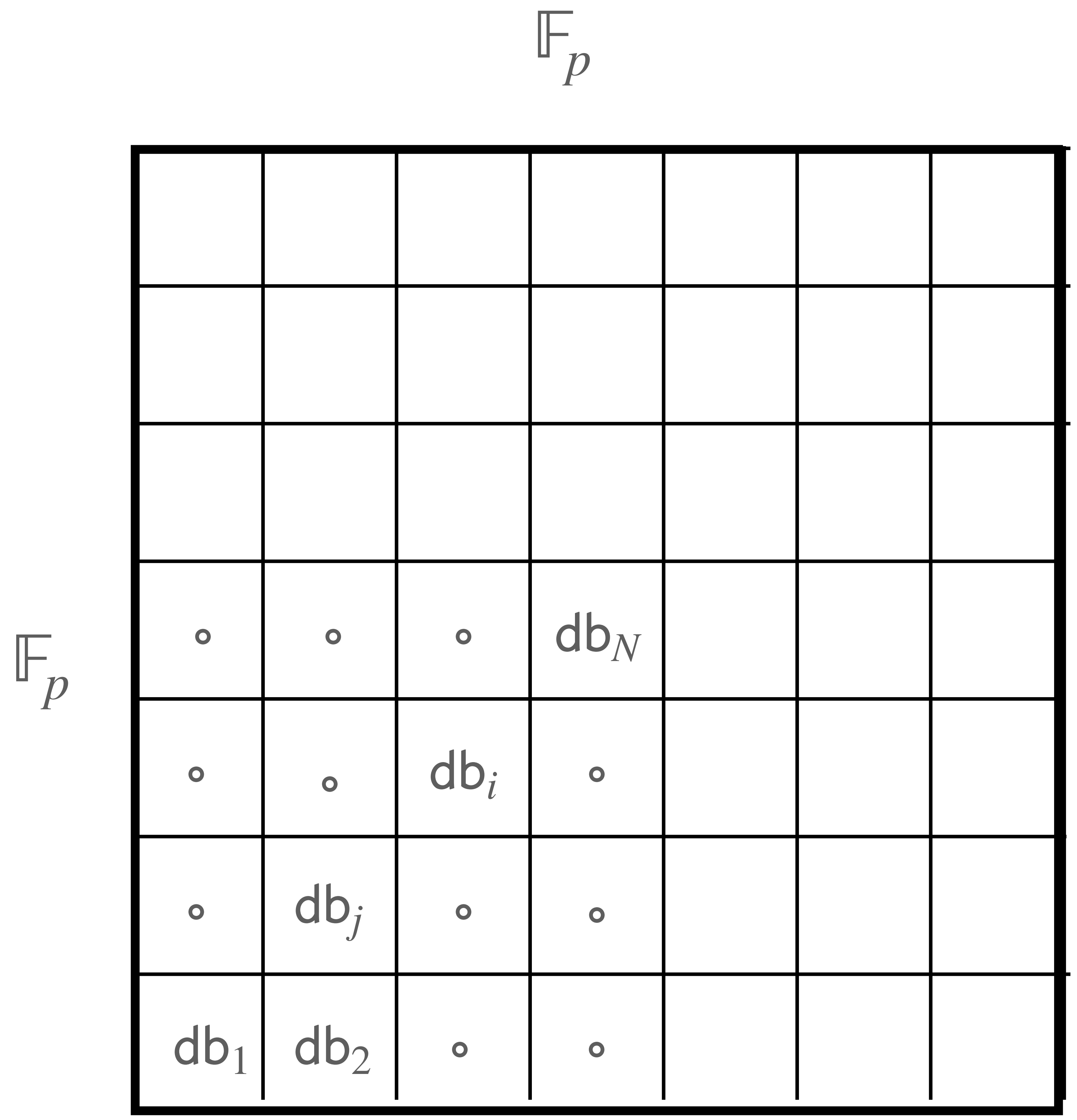

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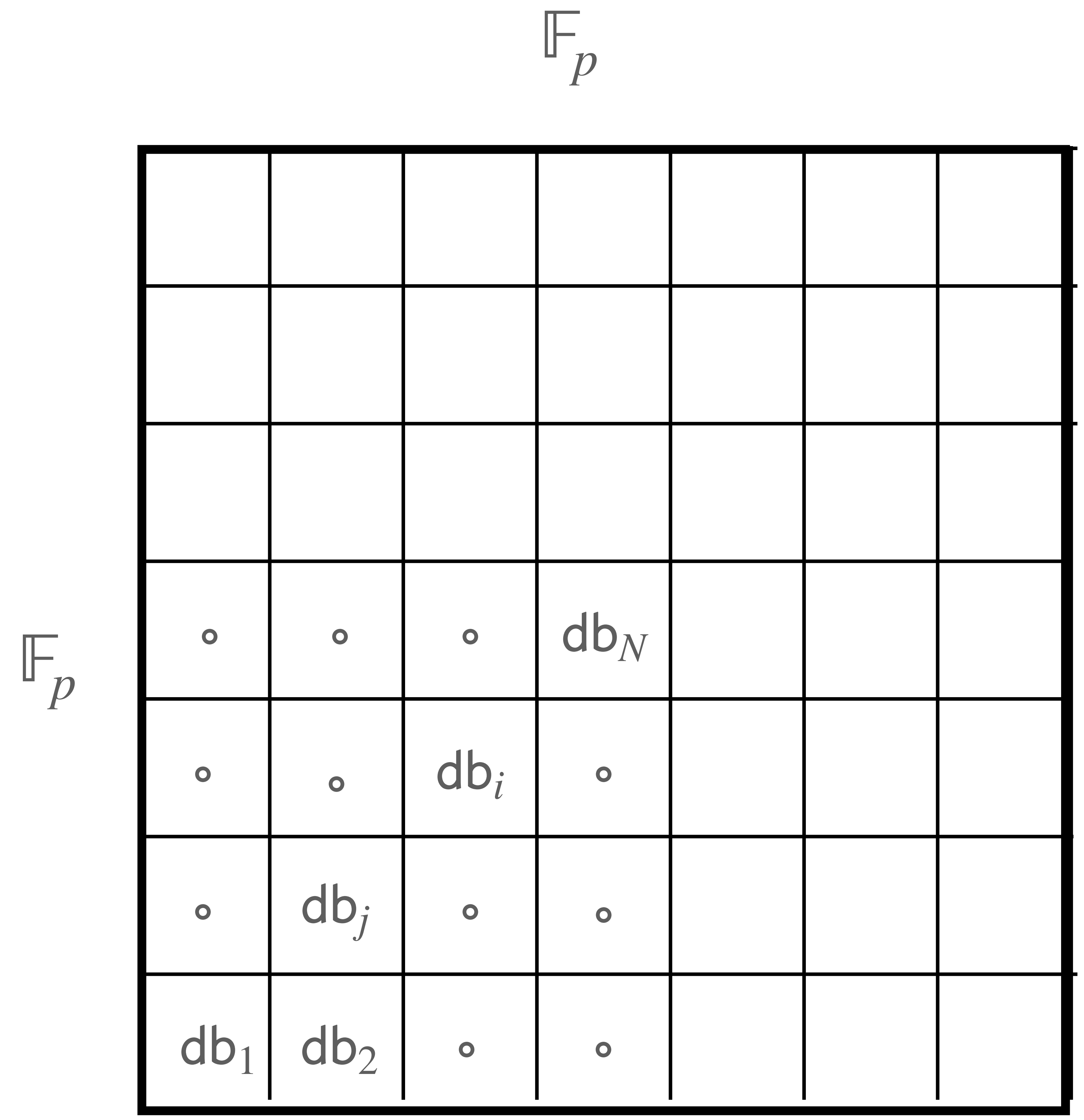

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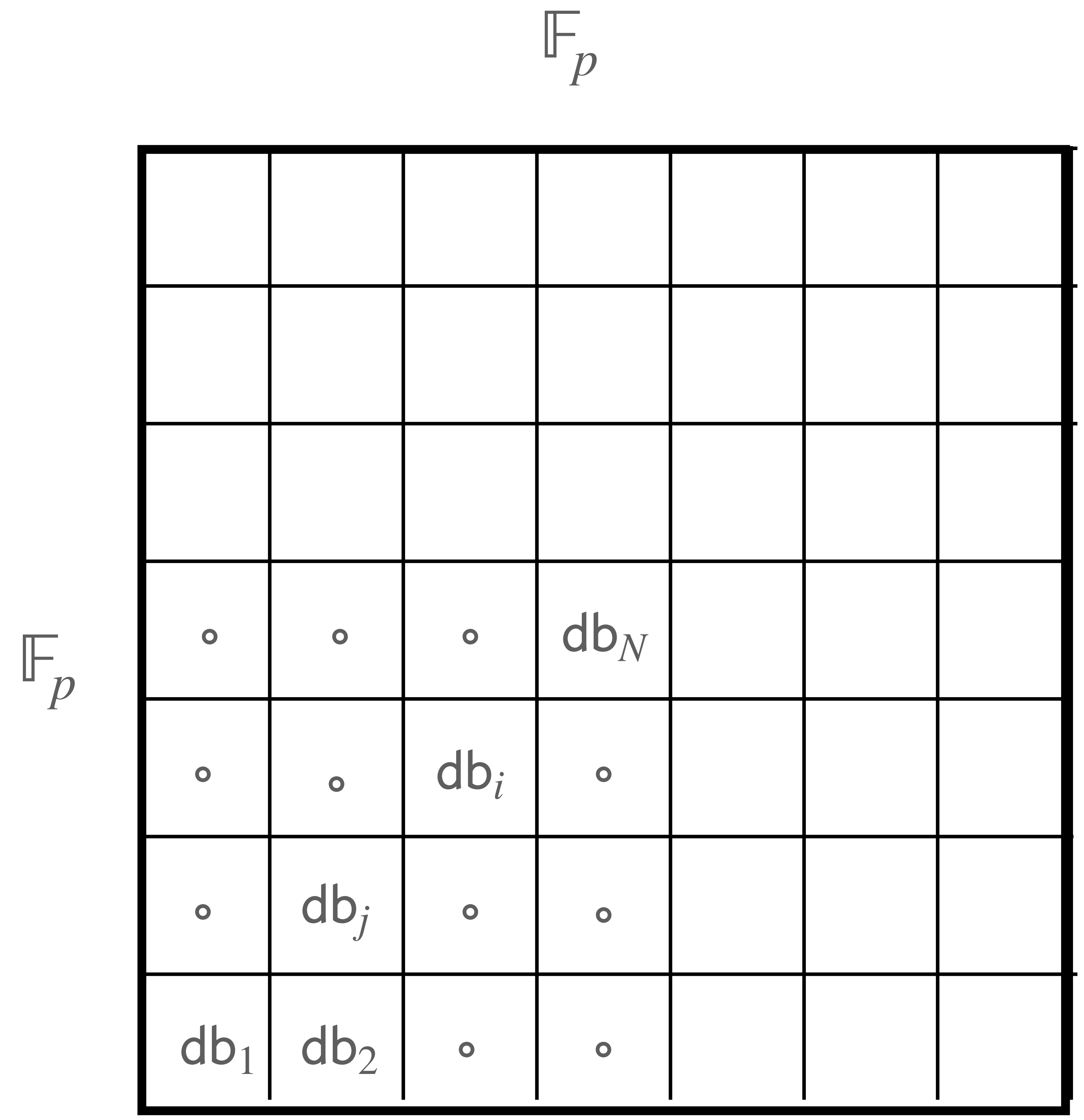

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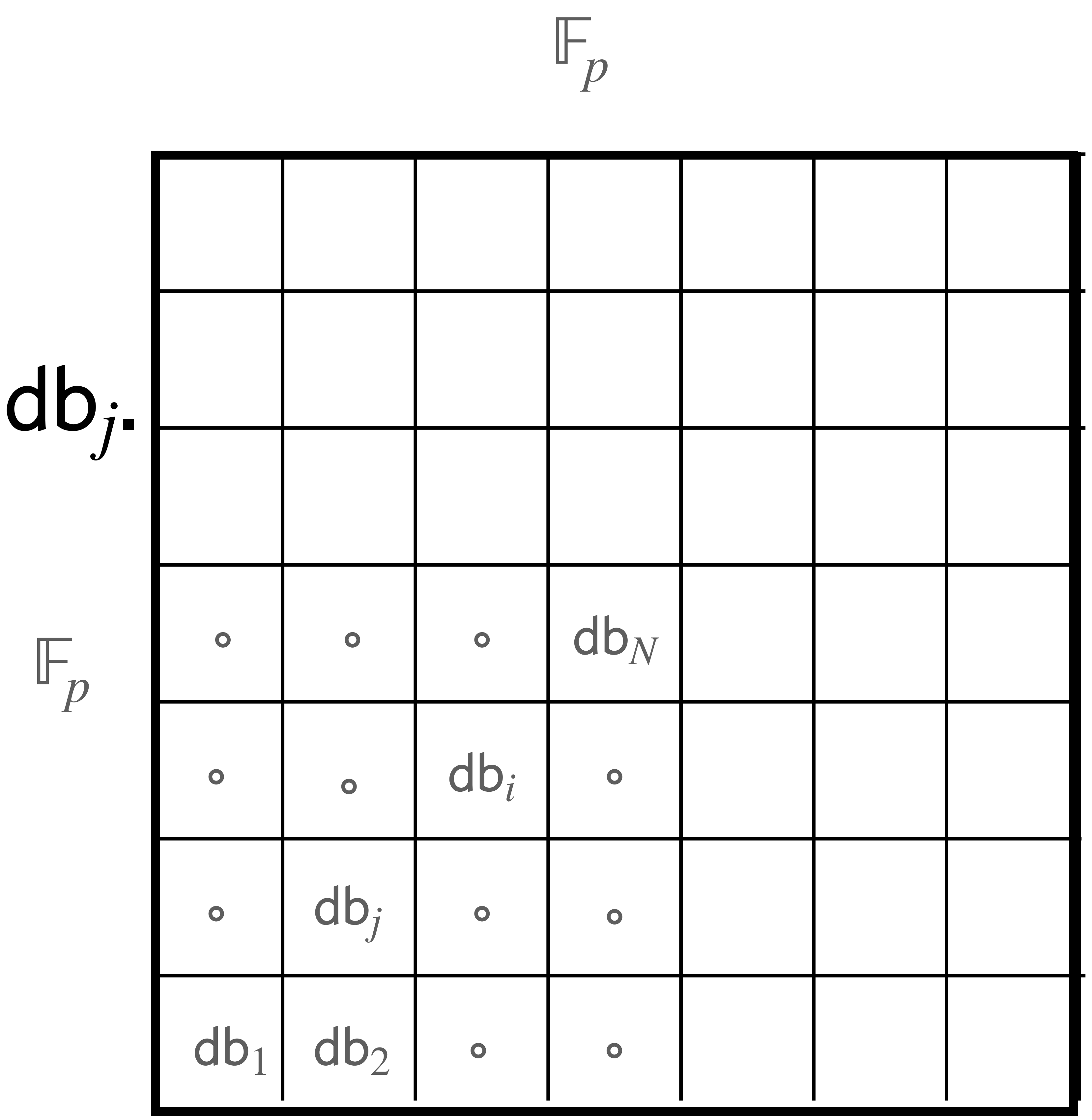

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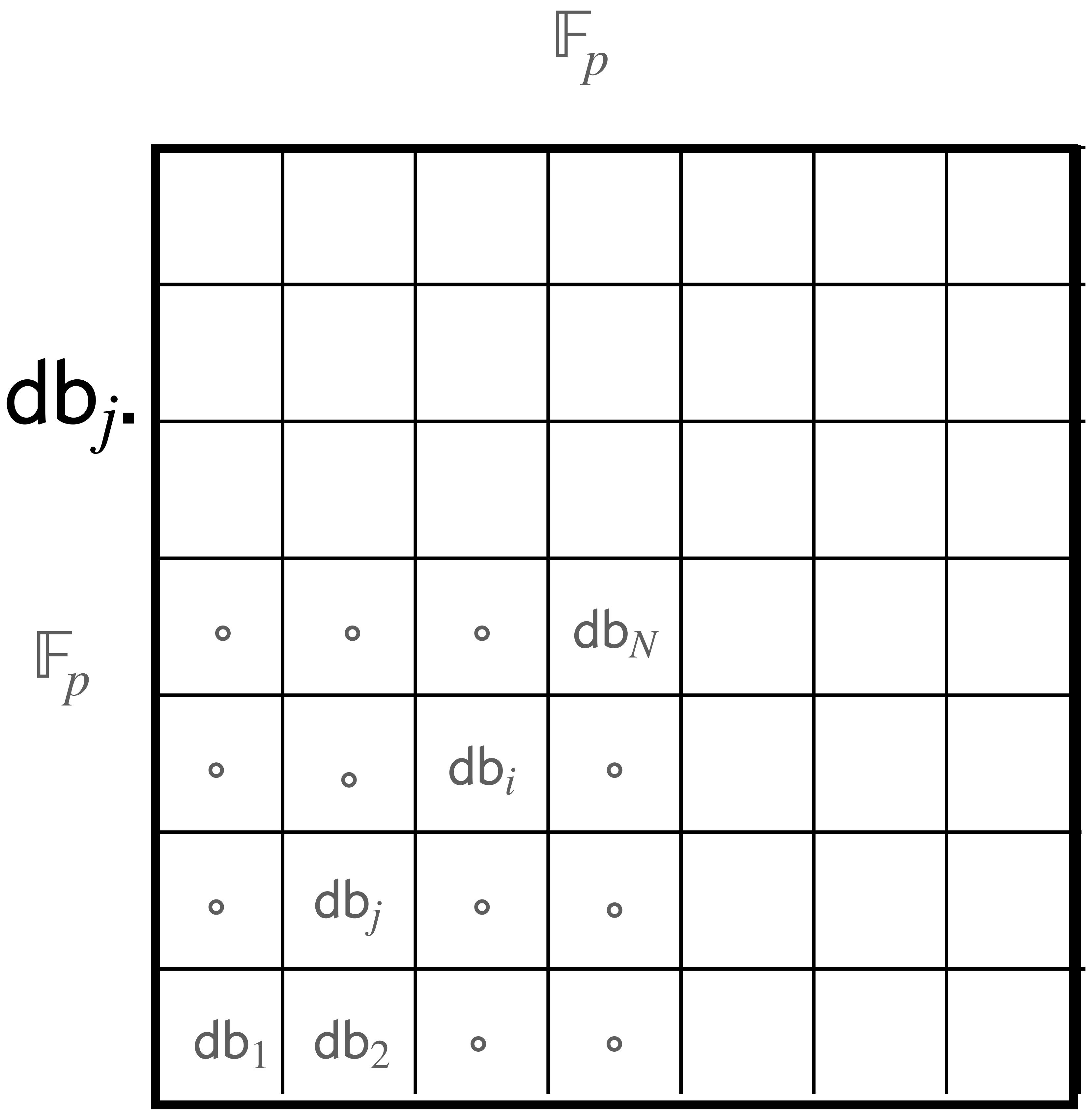

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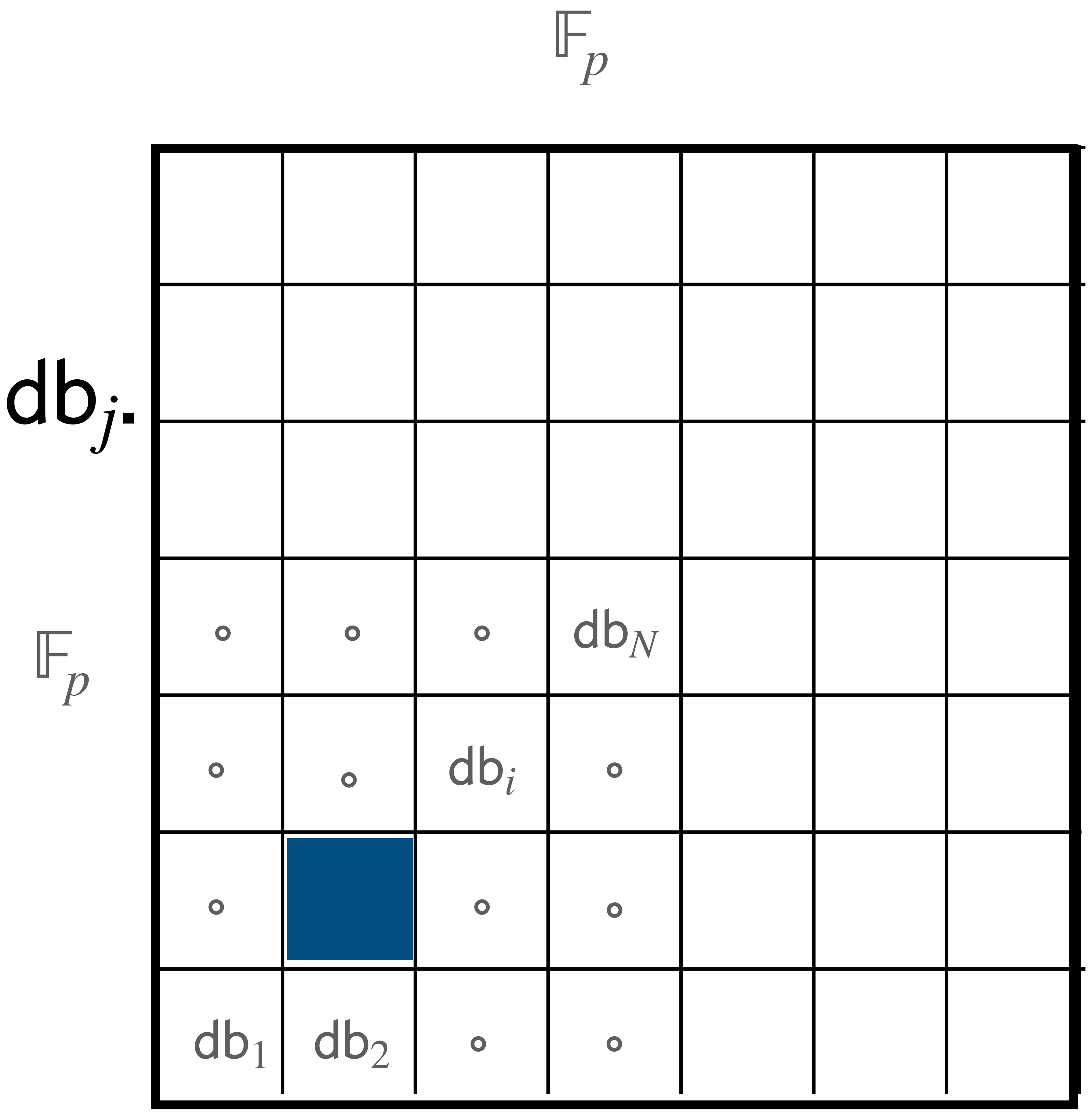

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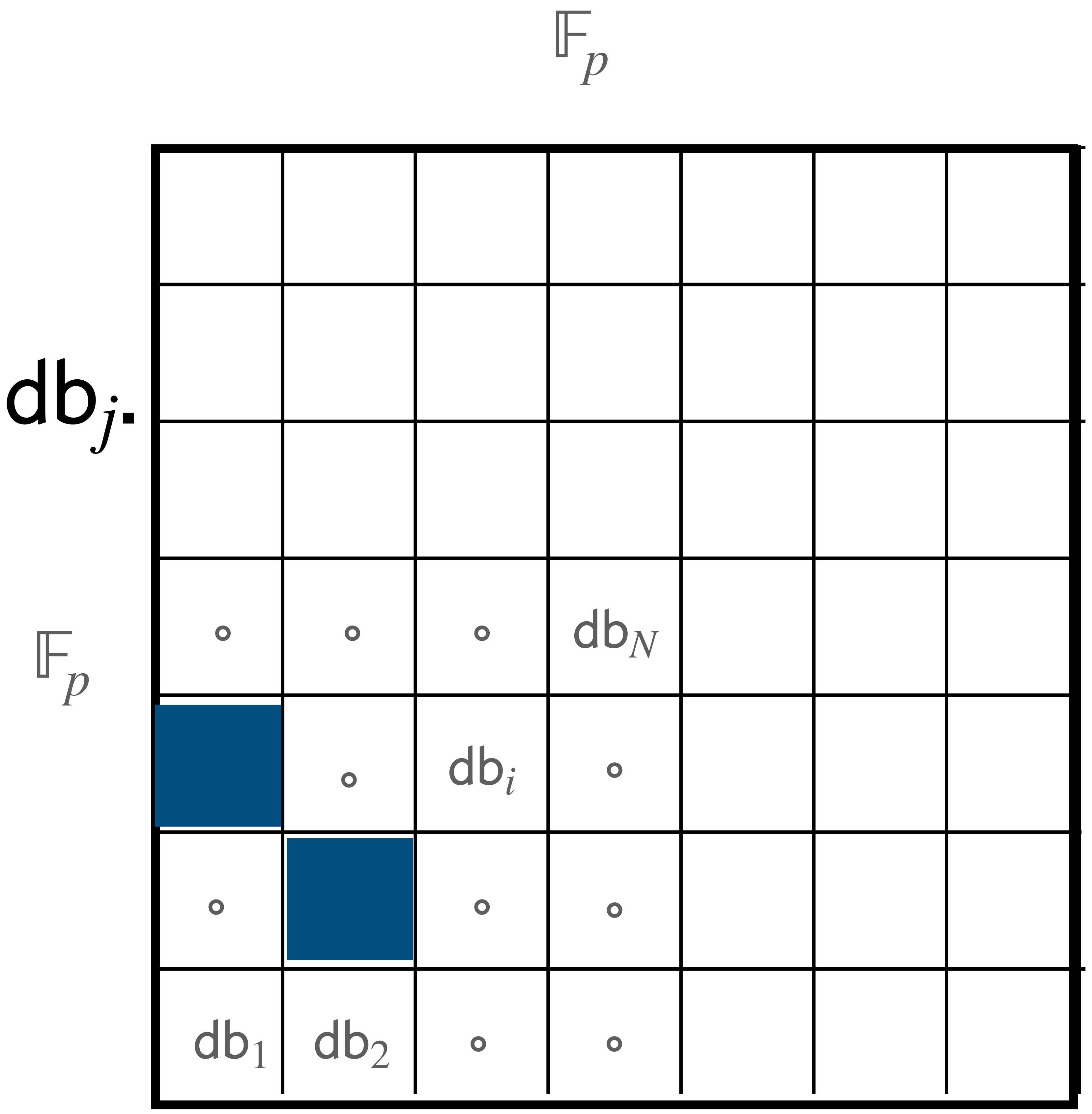

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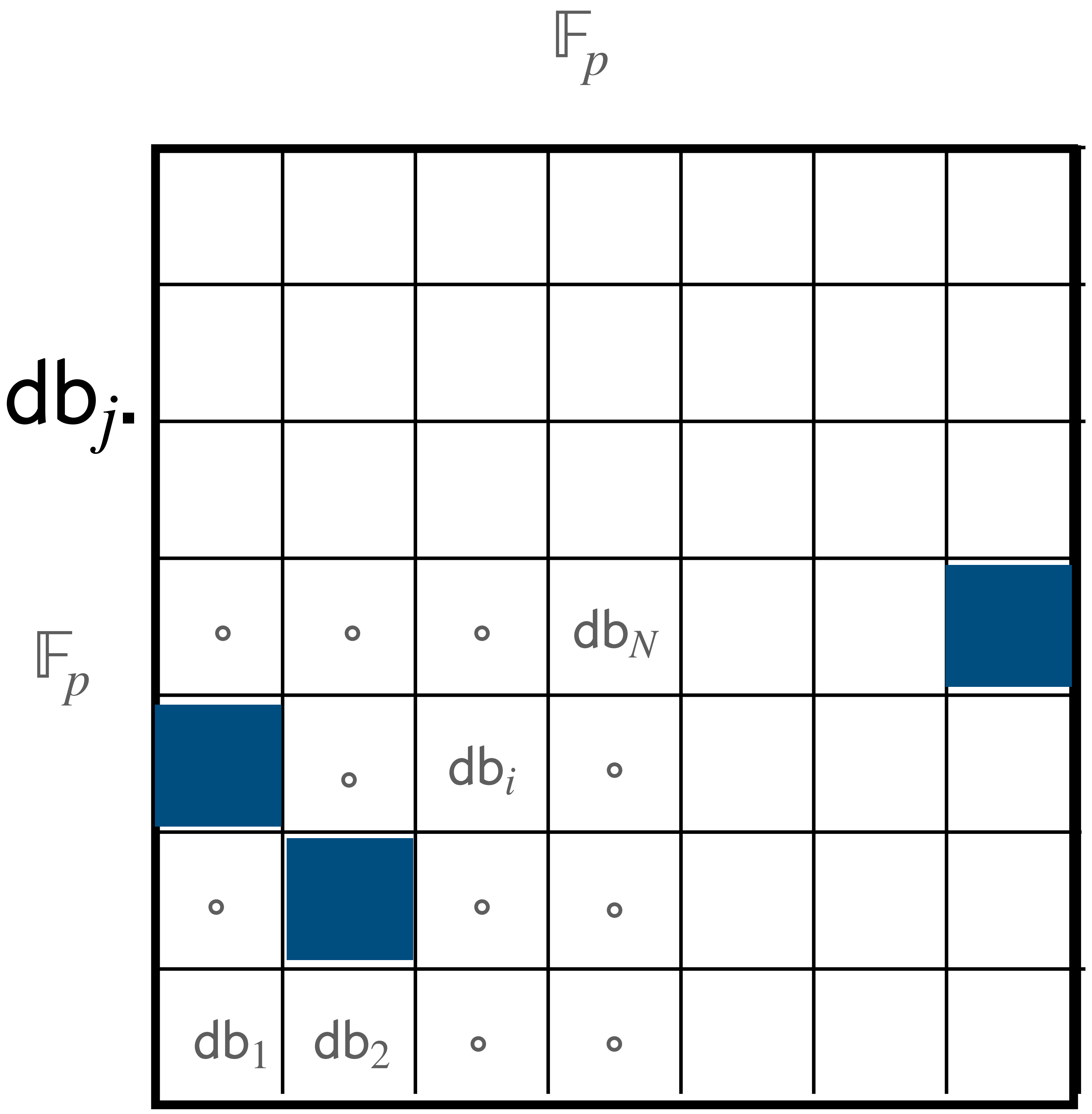

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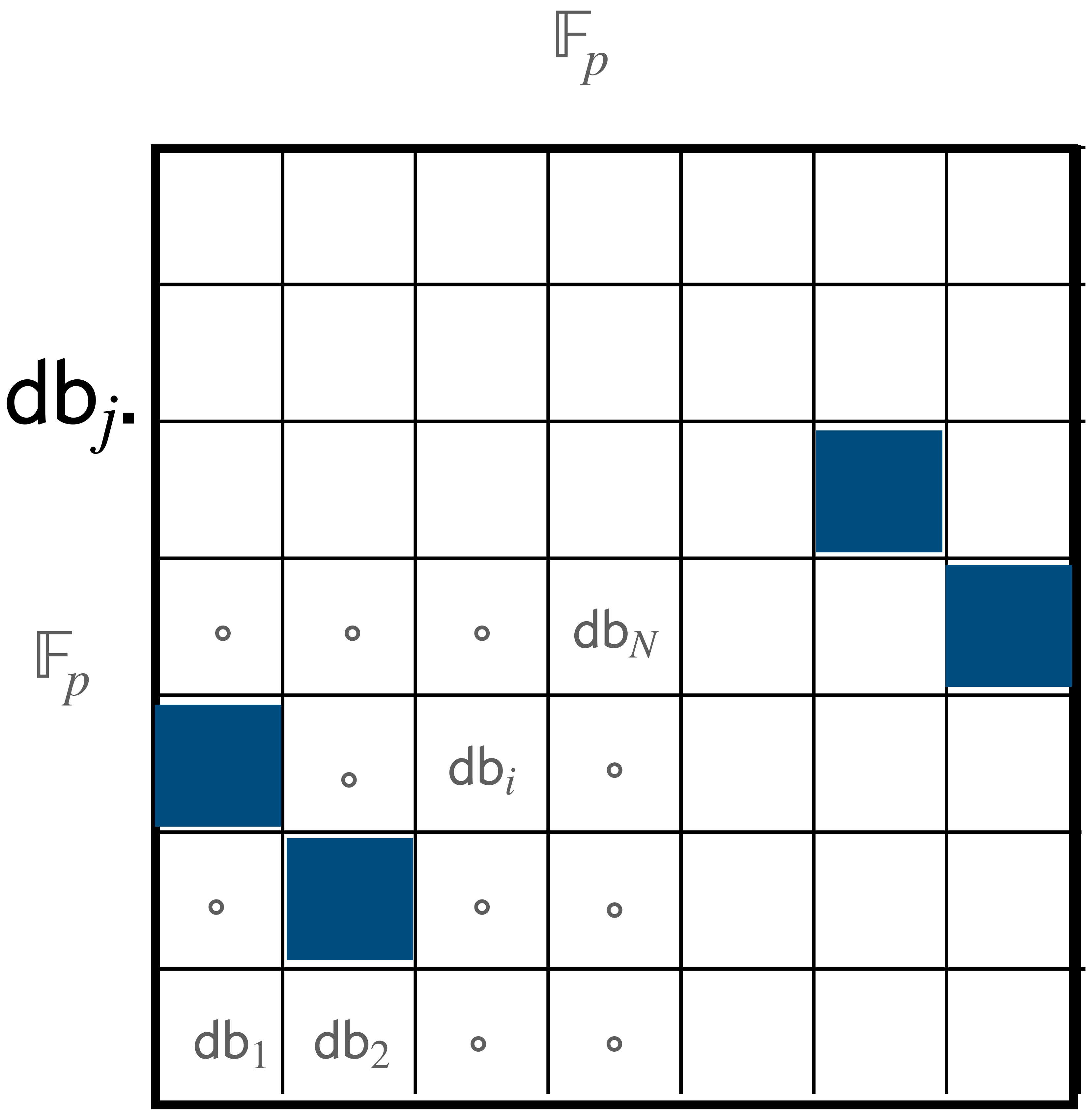

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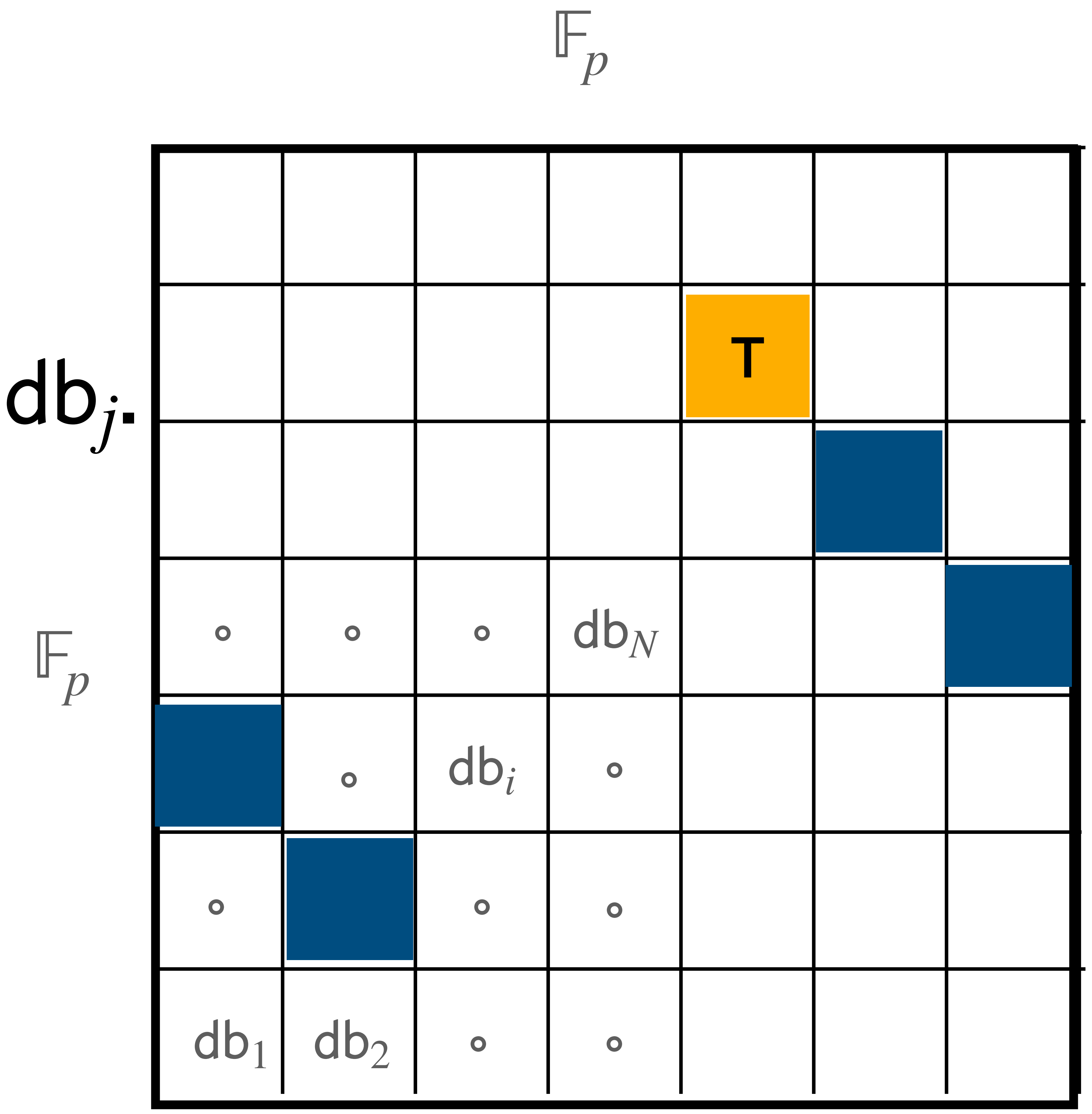

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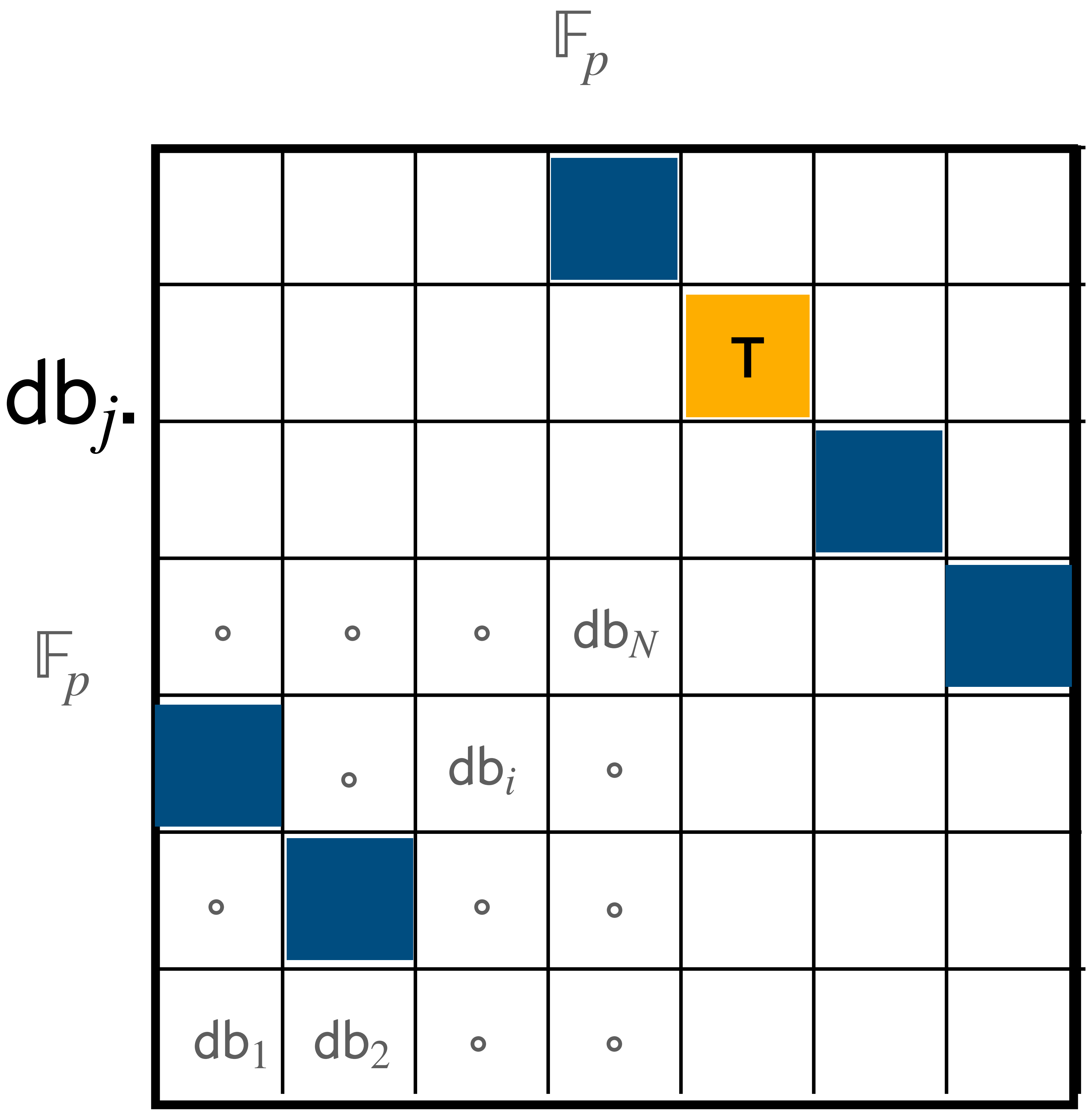

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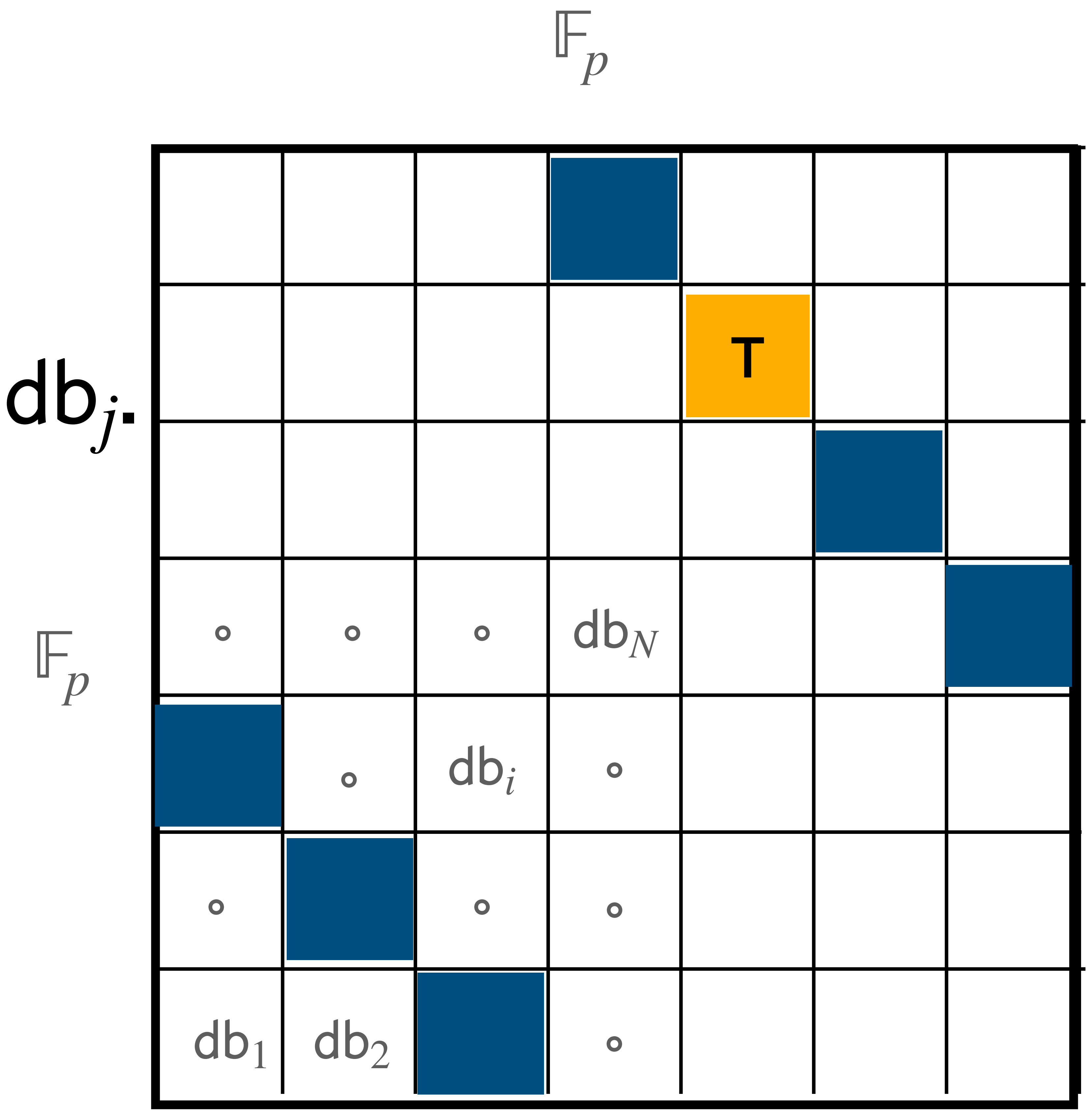

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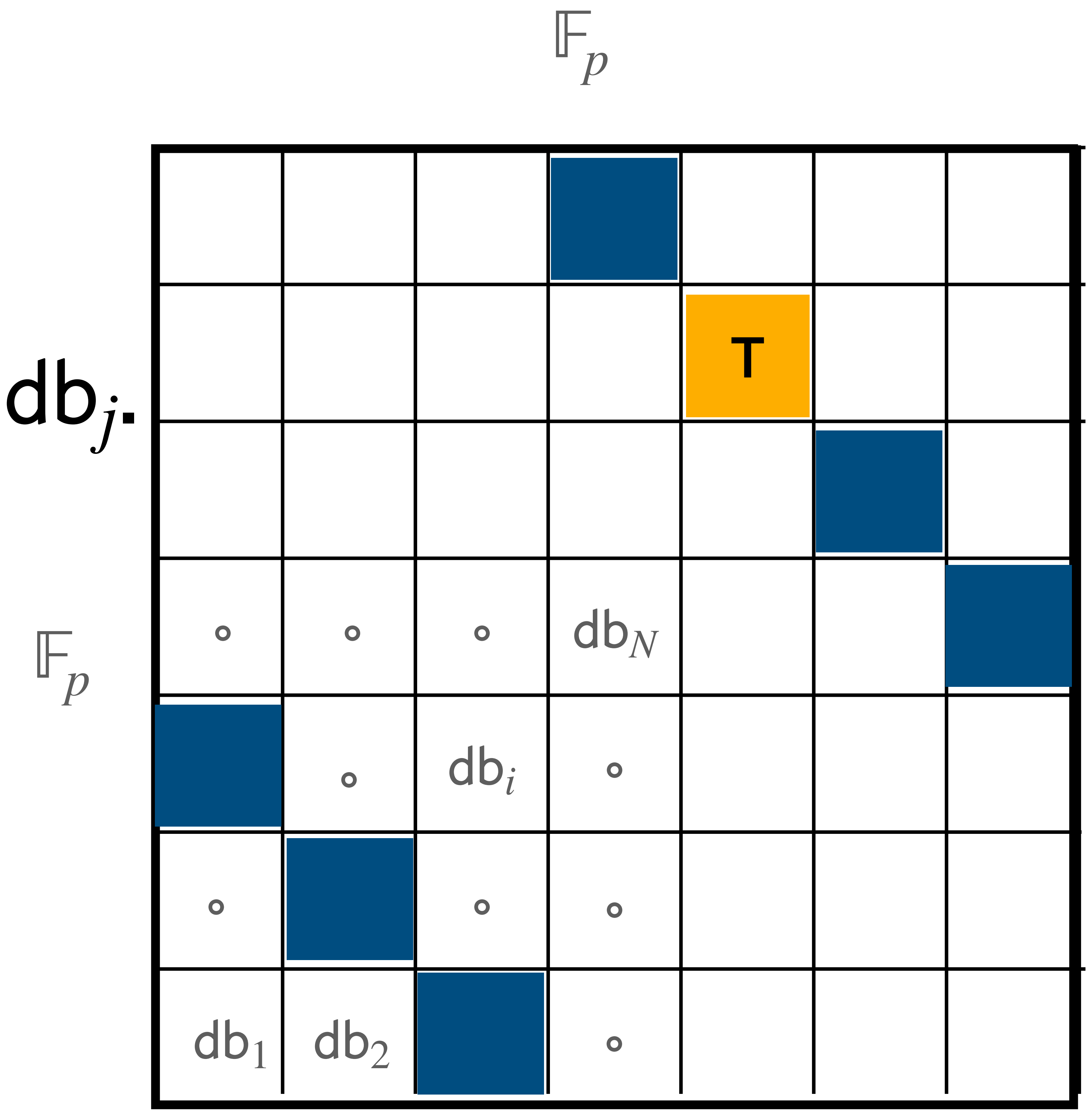

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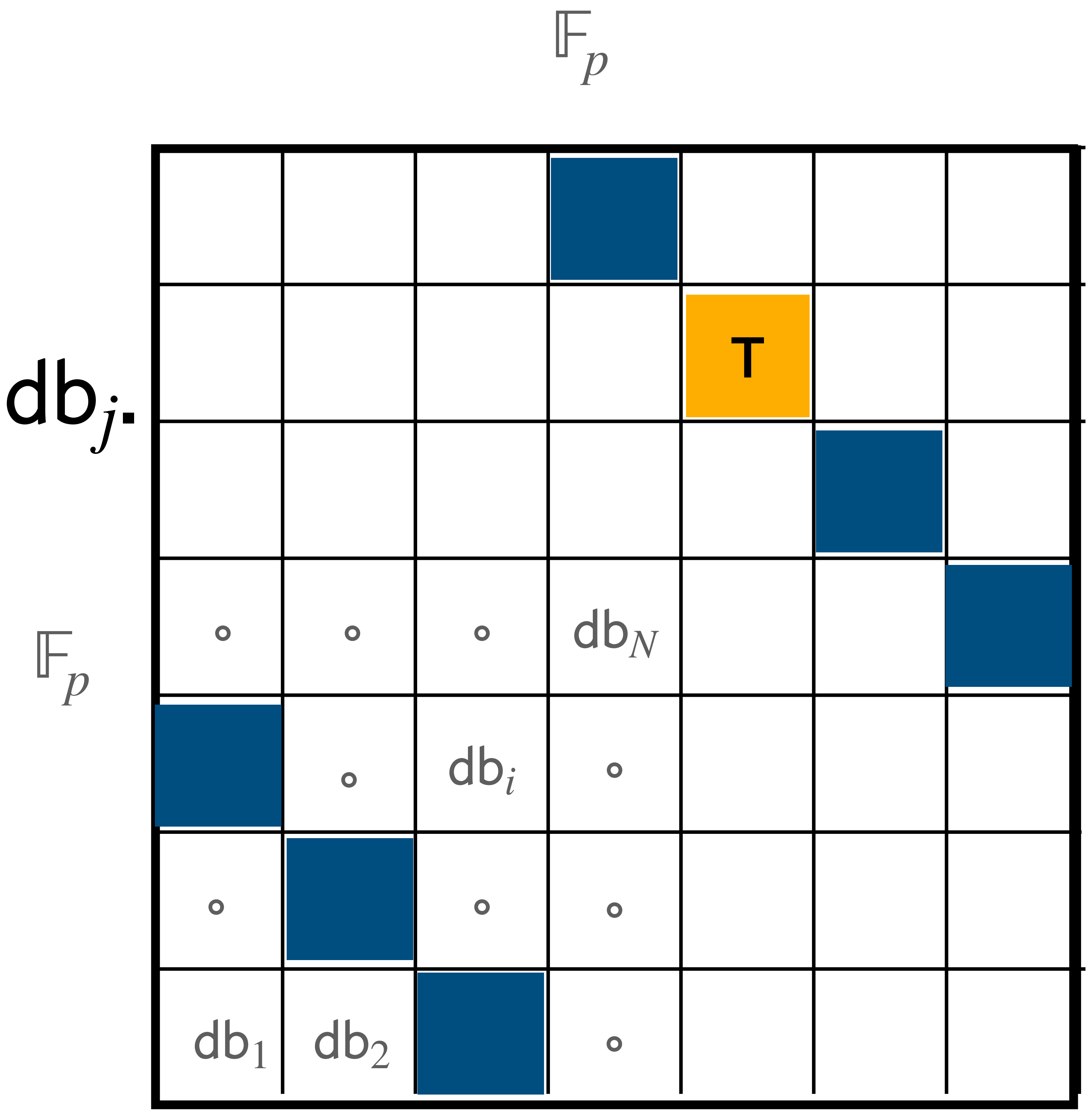

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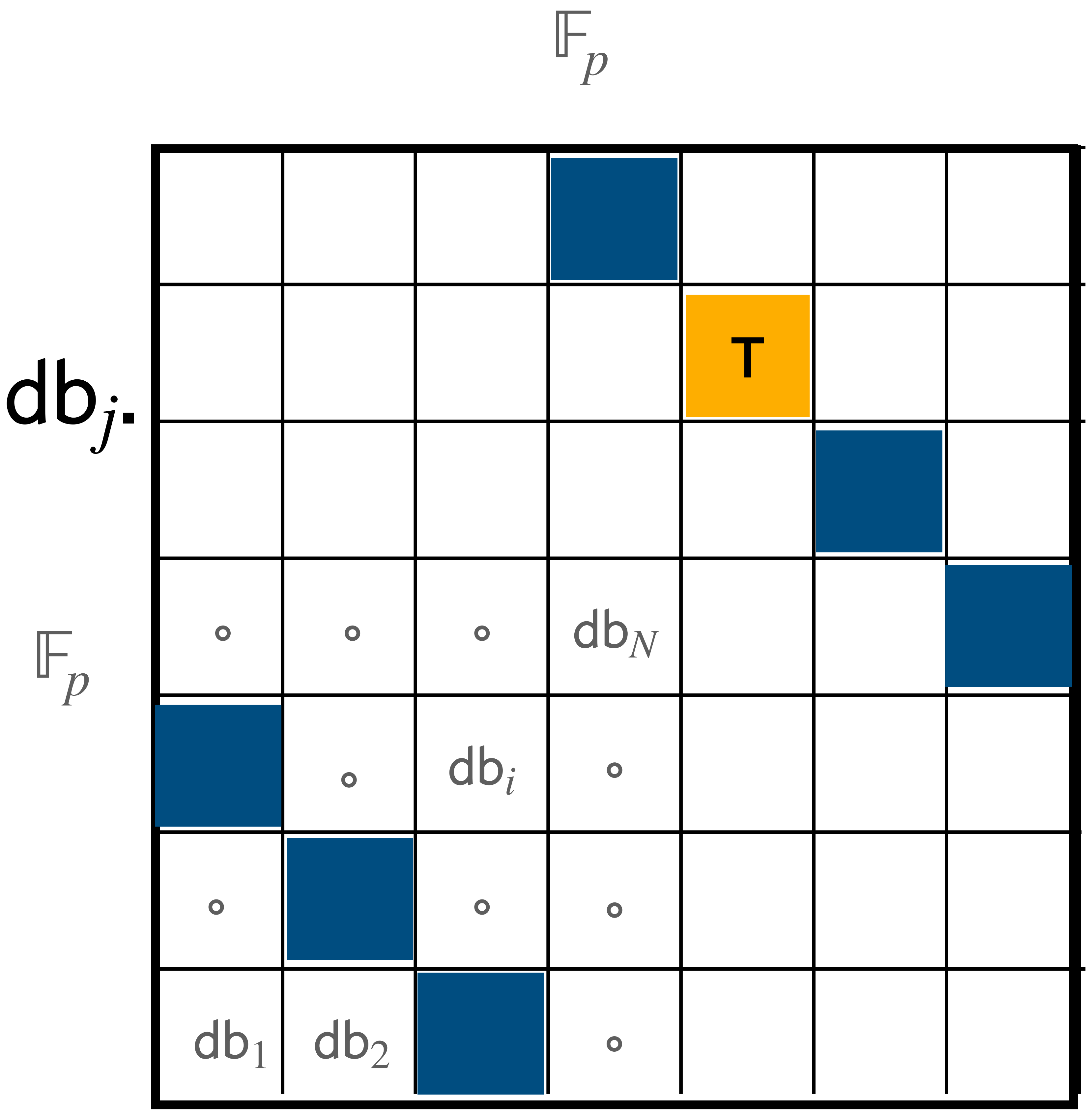

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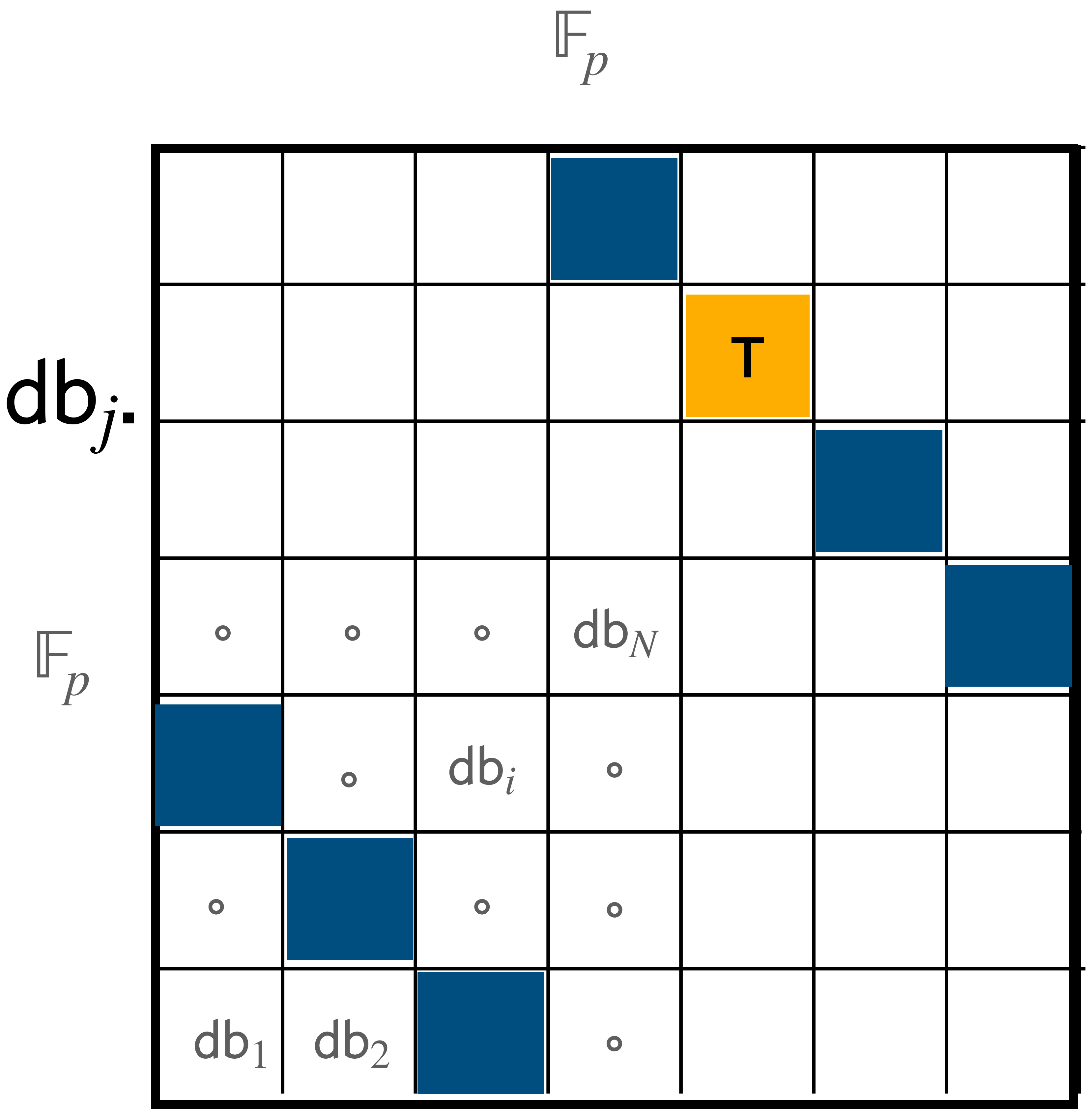
3. $\mathsf{RM.Dec}(E_Q) \to \mathsf{db}_j$:
   1. If E_T has corruptions, output $\perp$
   2. Else, decode $E_{L_1}, \ldots, E_{L_t}$ as before.



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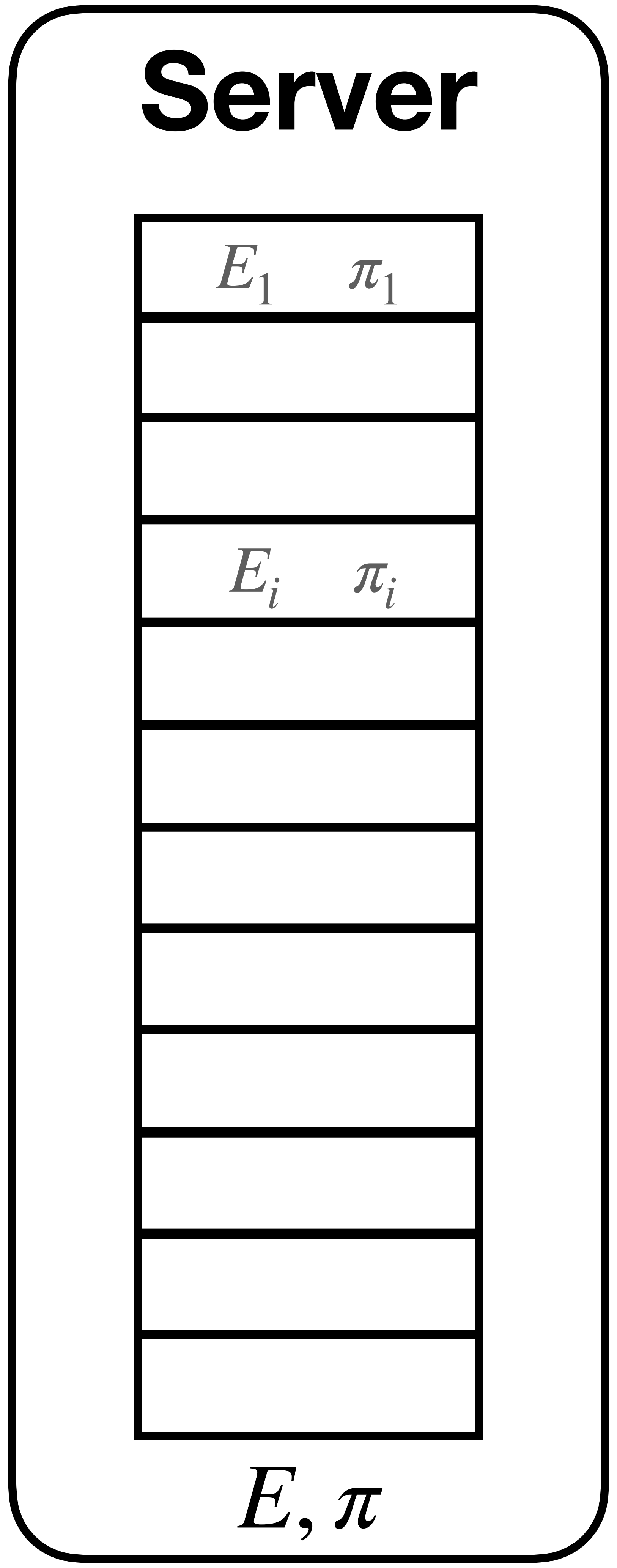
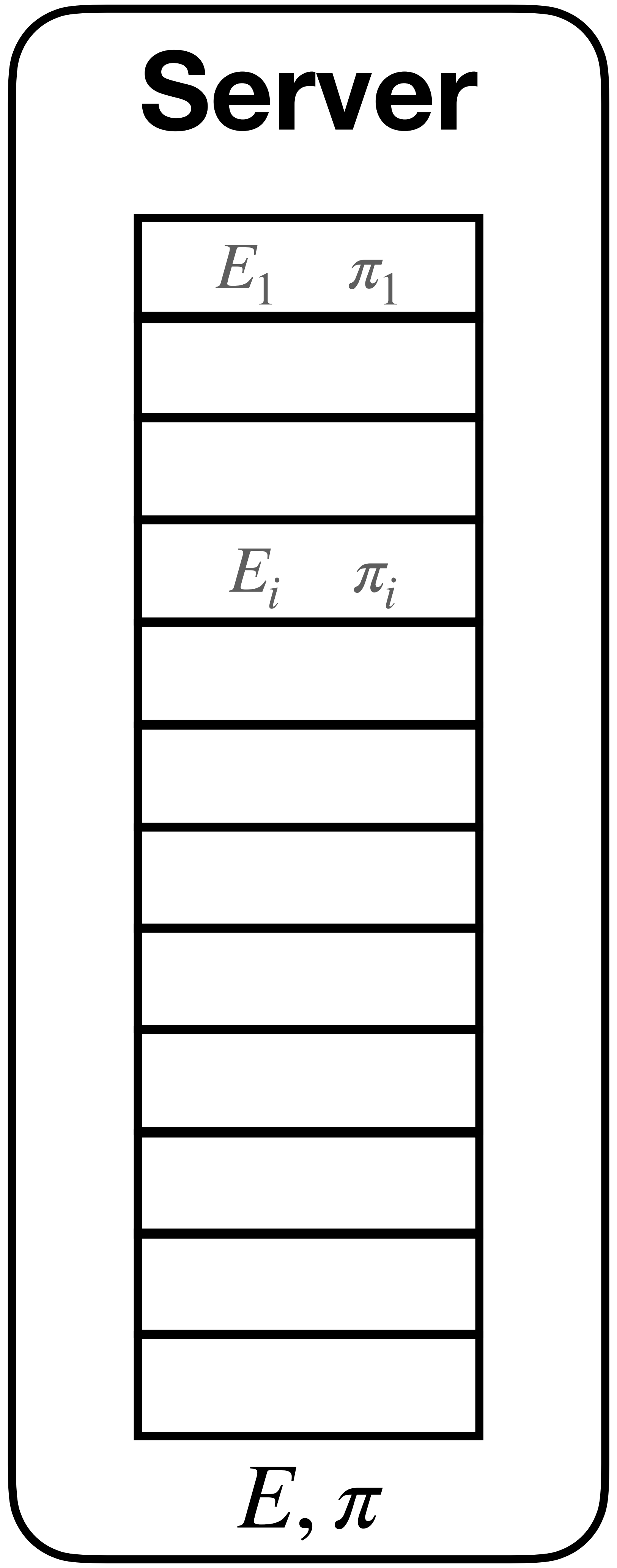


Final Construction

Offline



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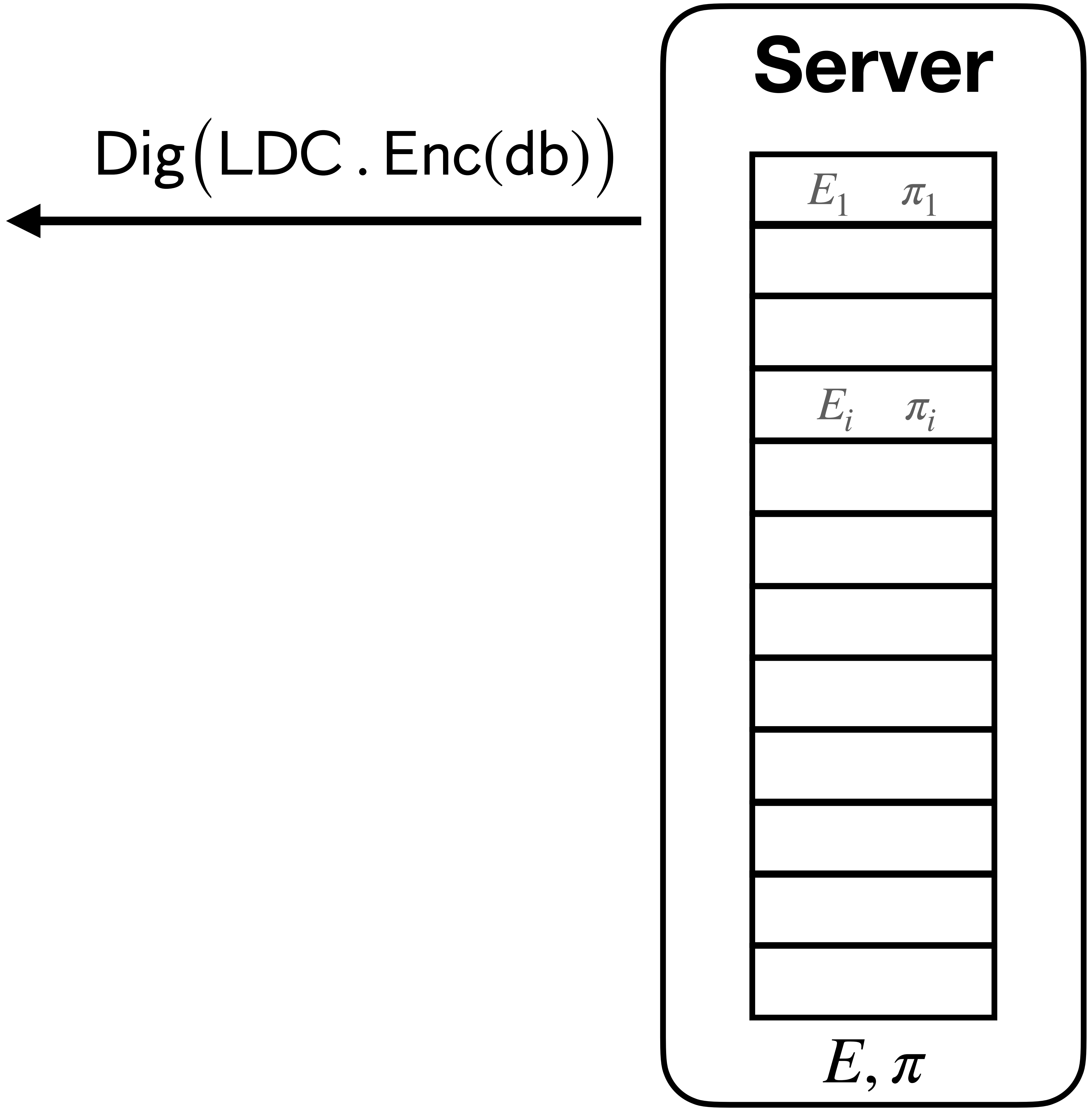

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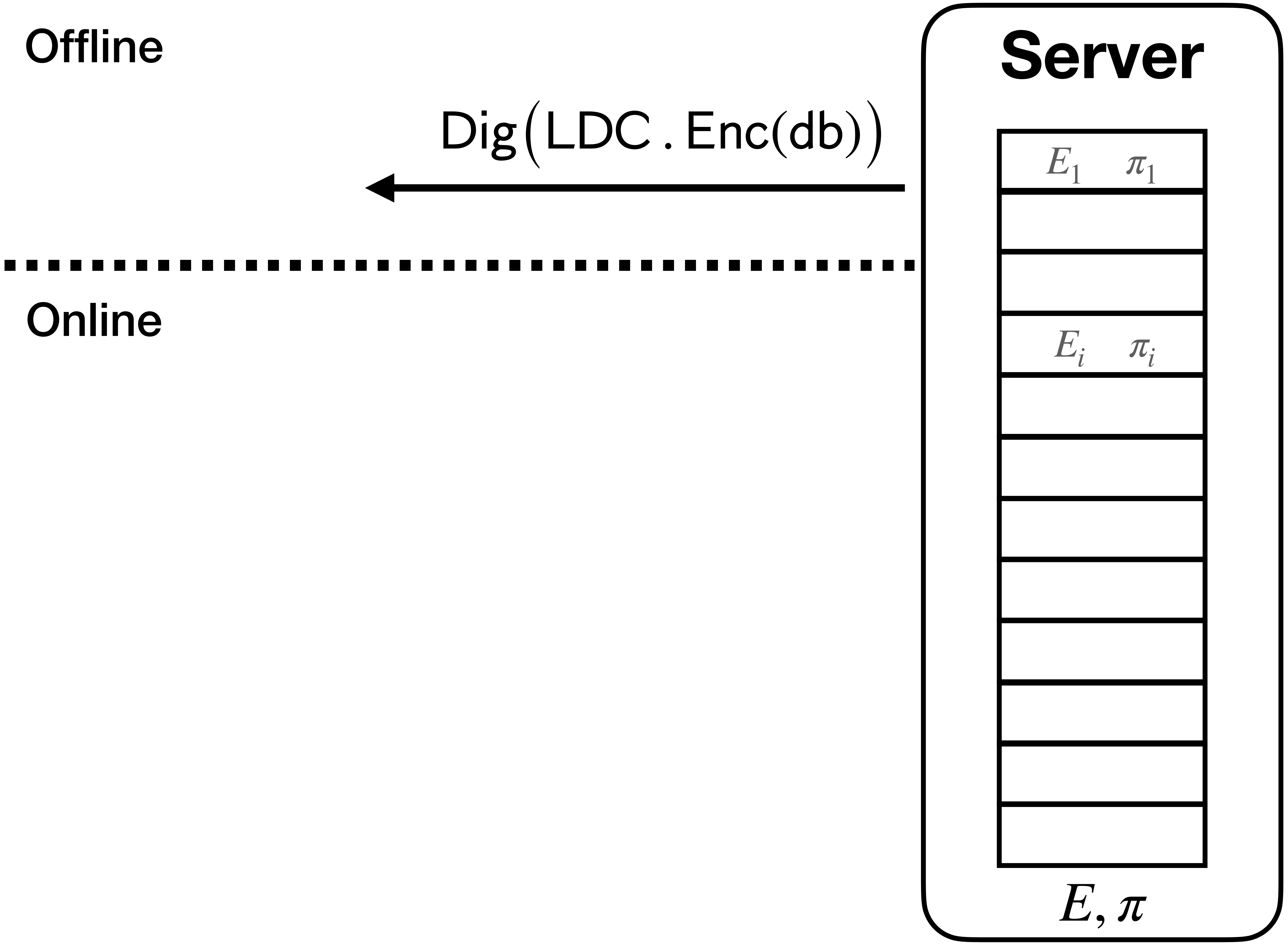

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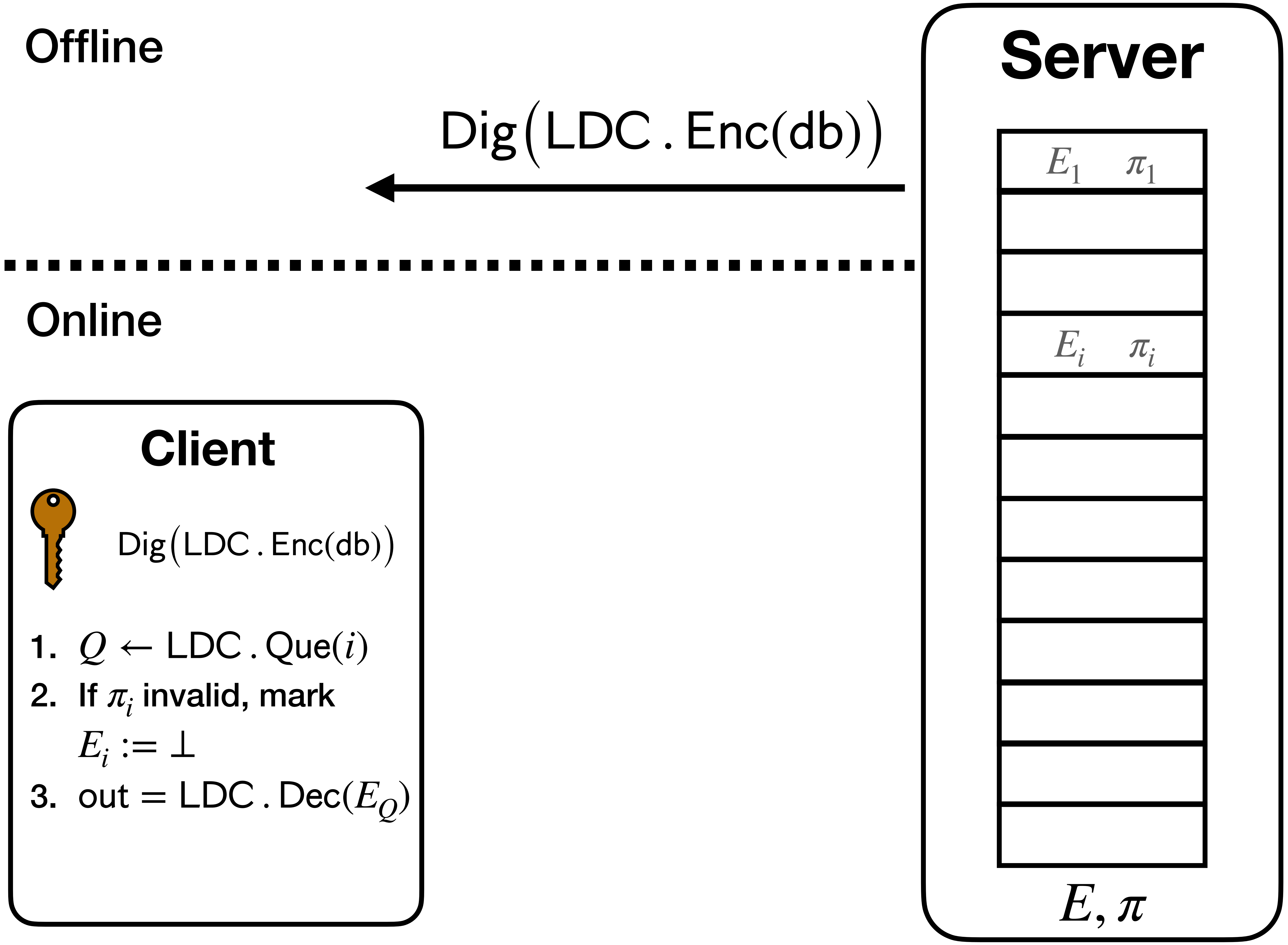

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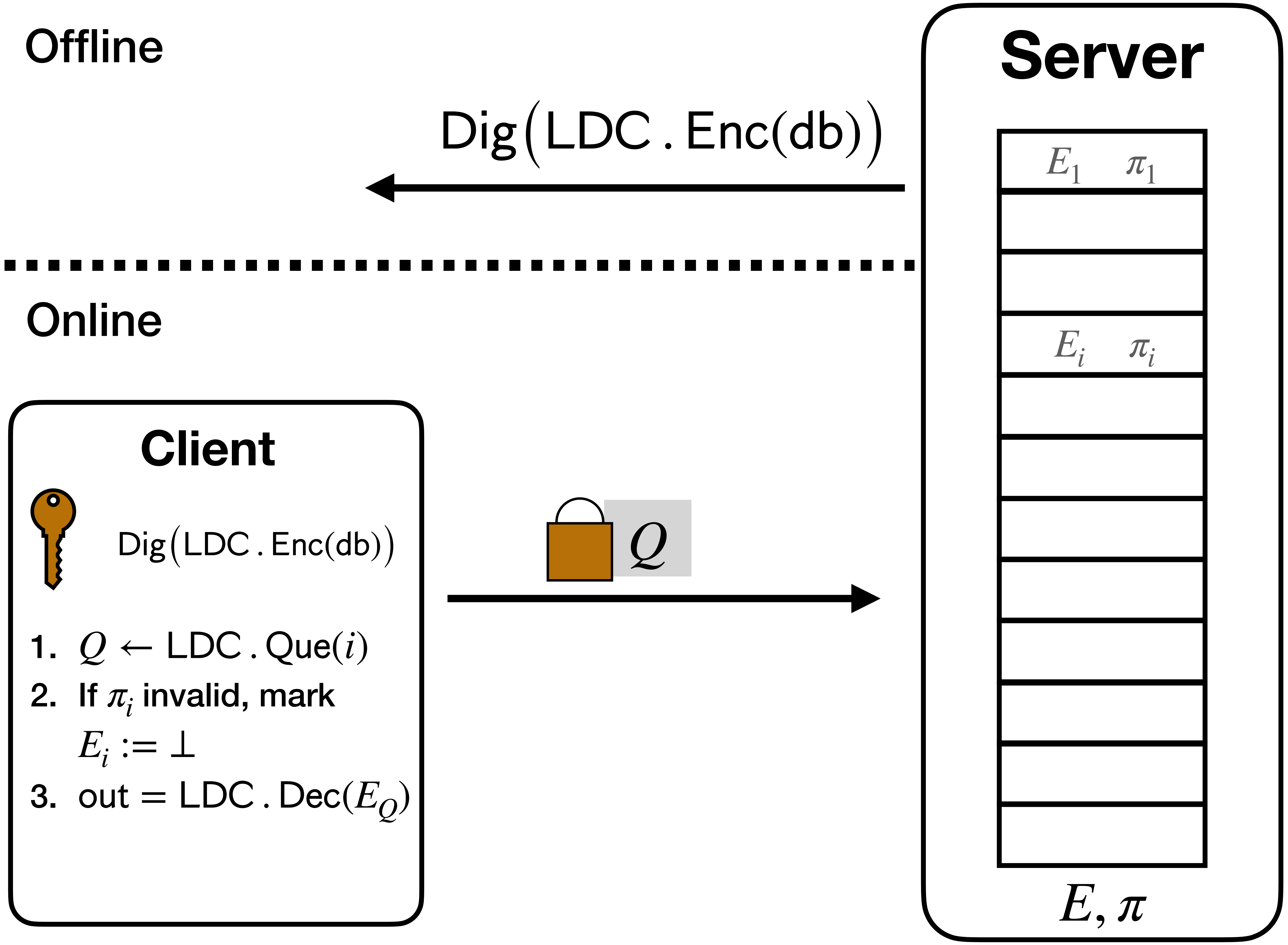

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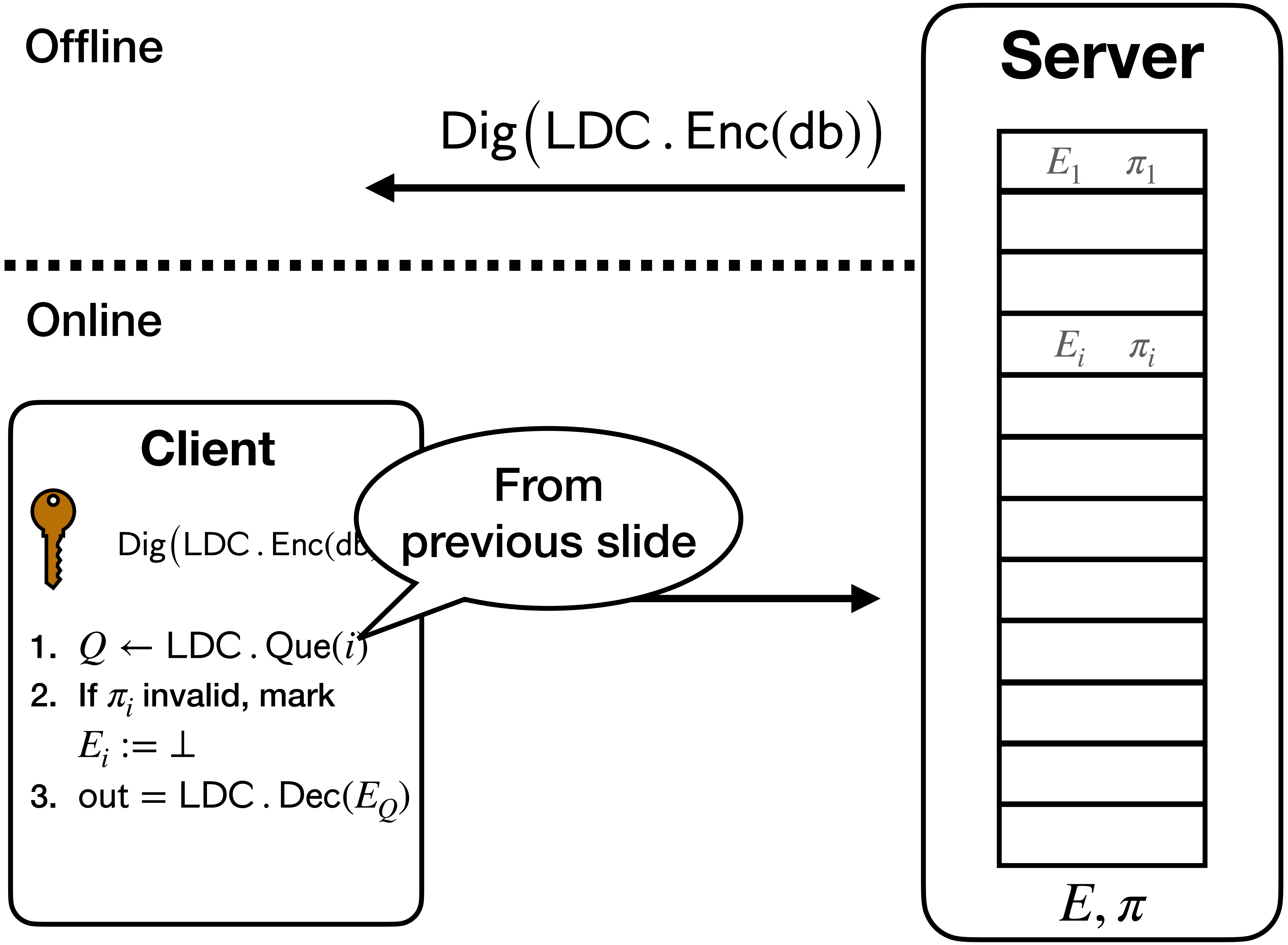

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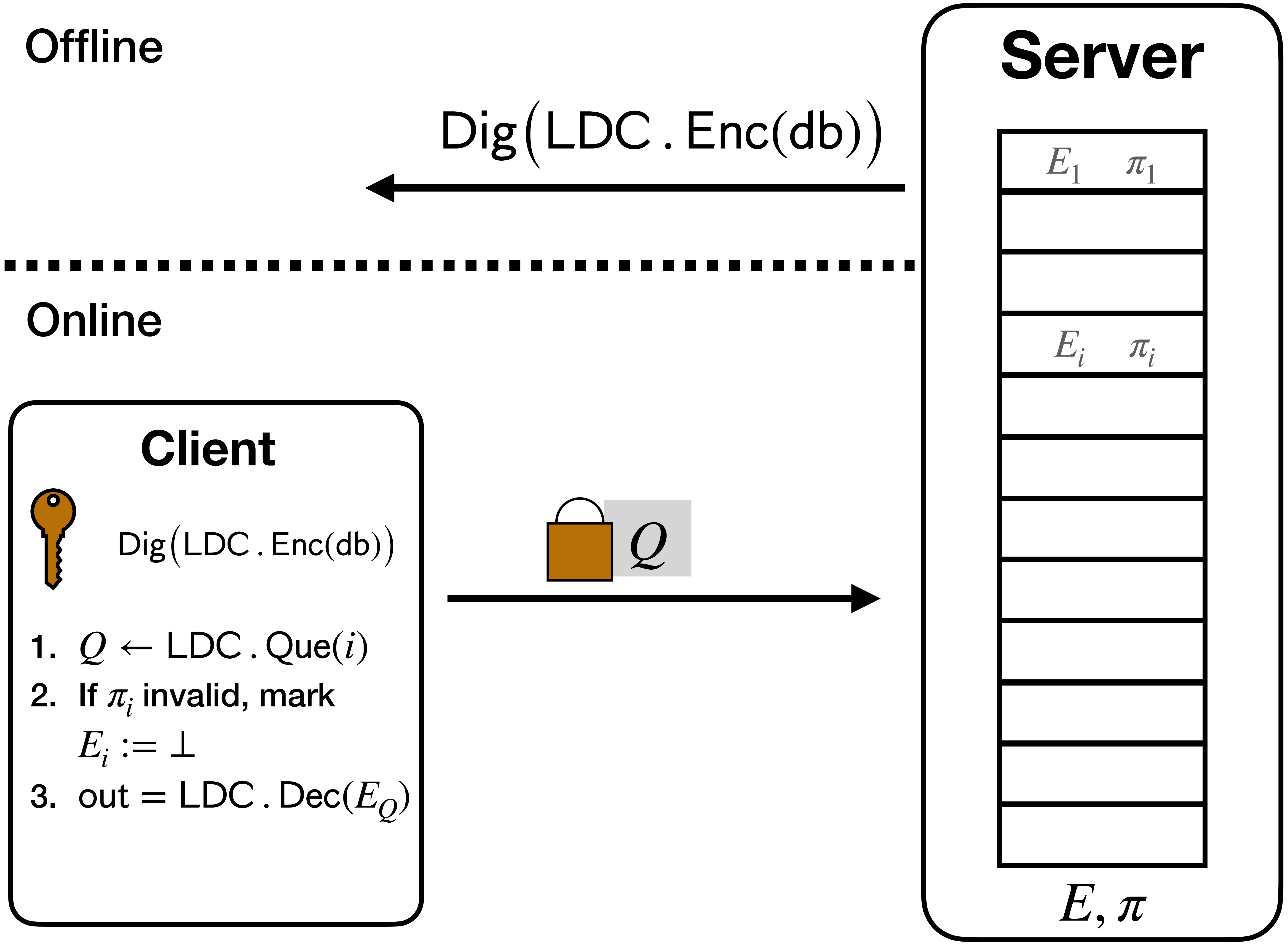

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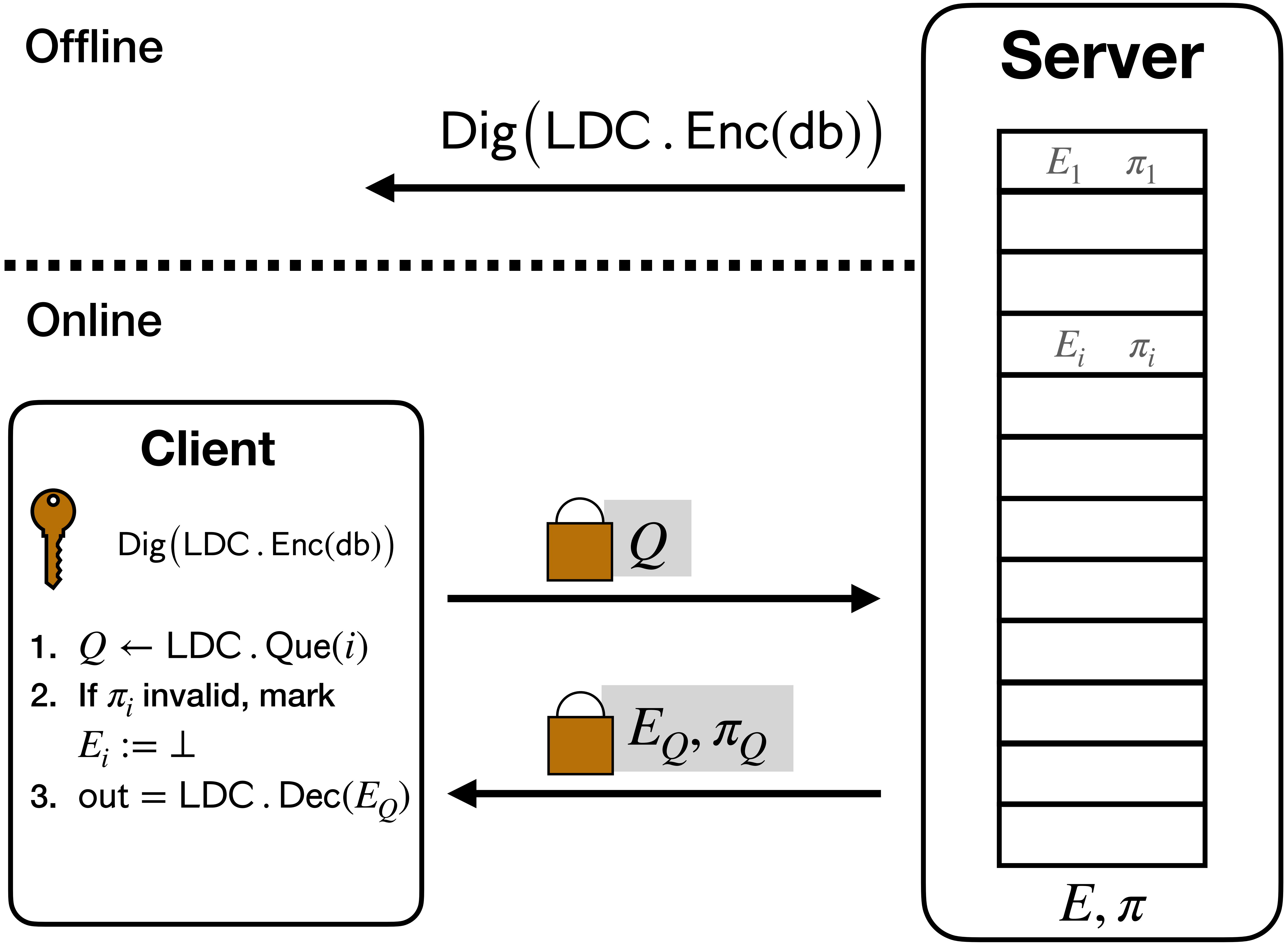

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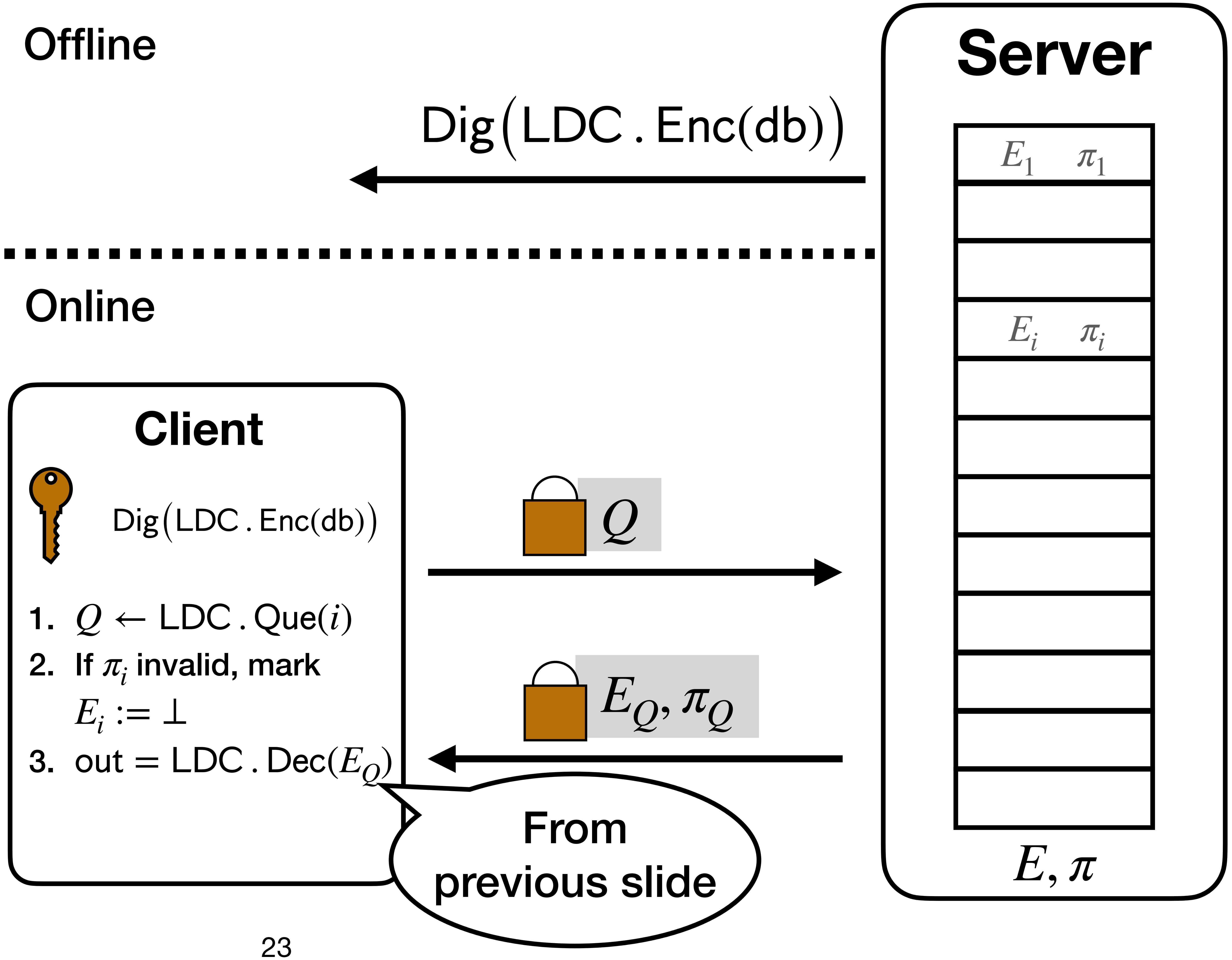

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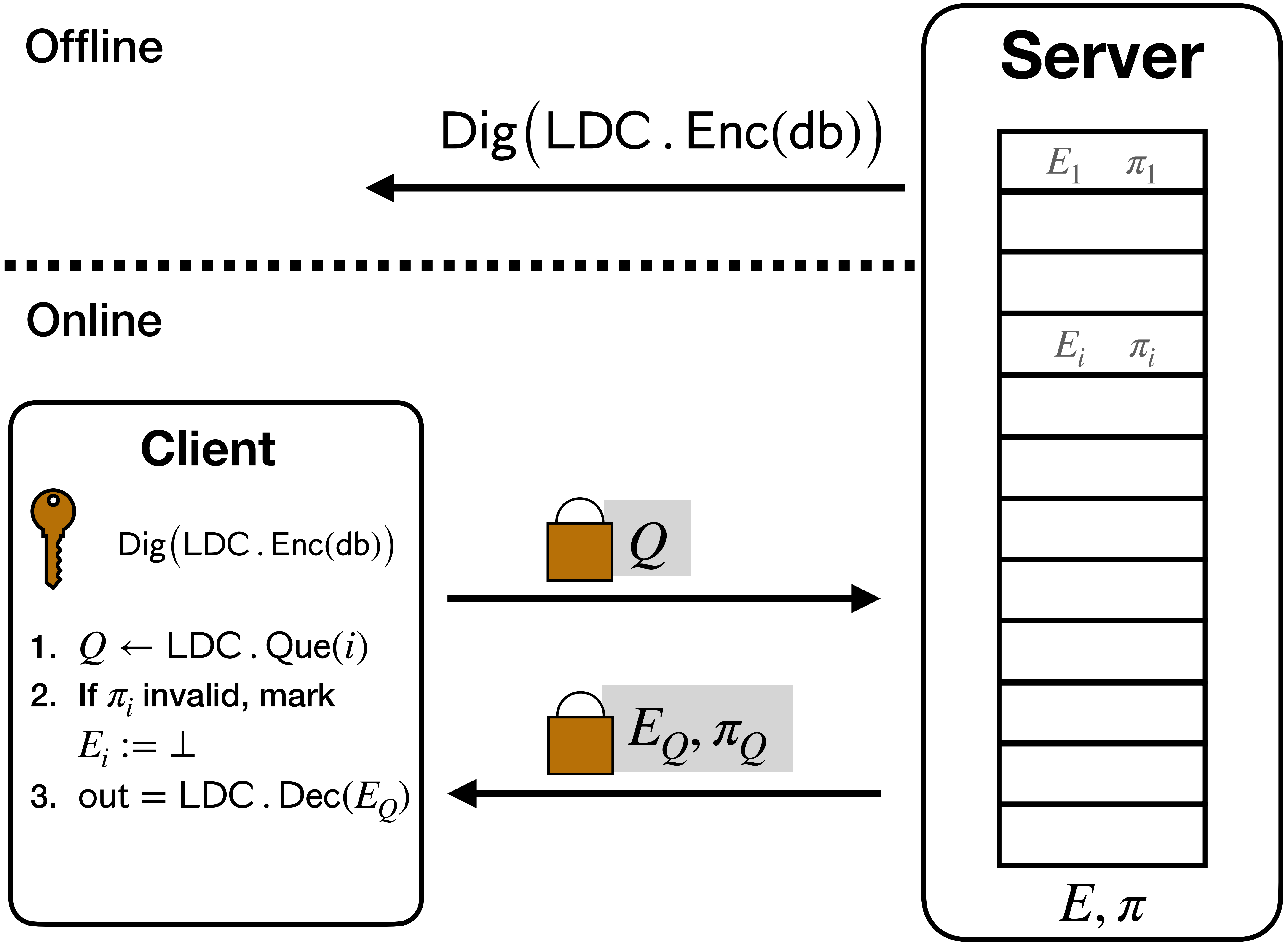

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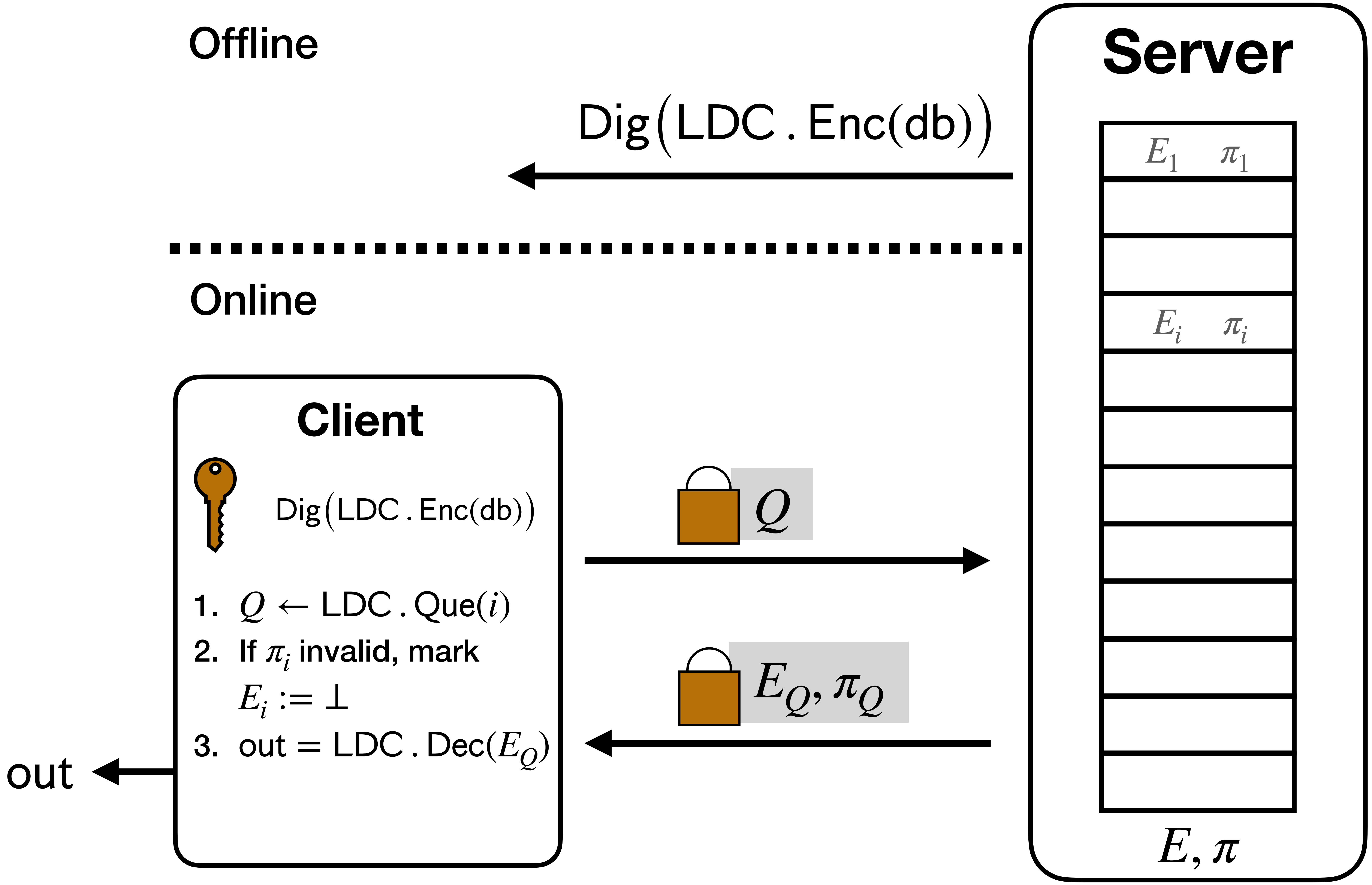

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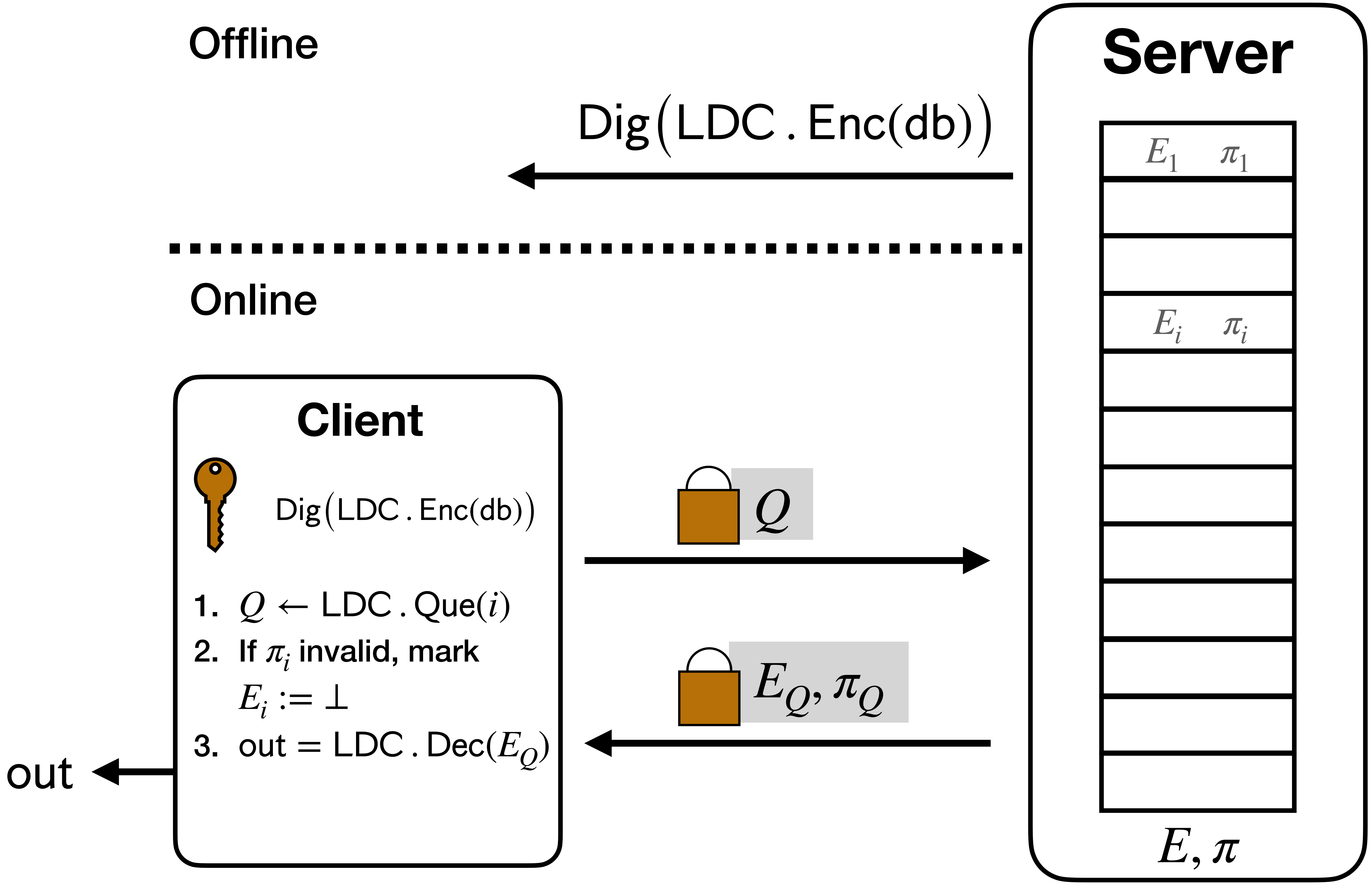

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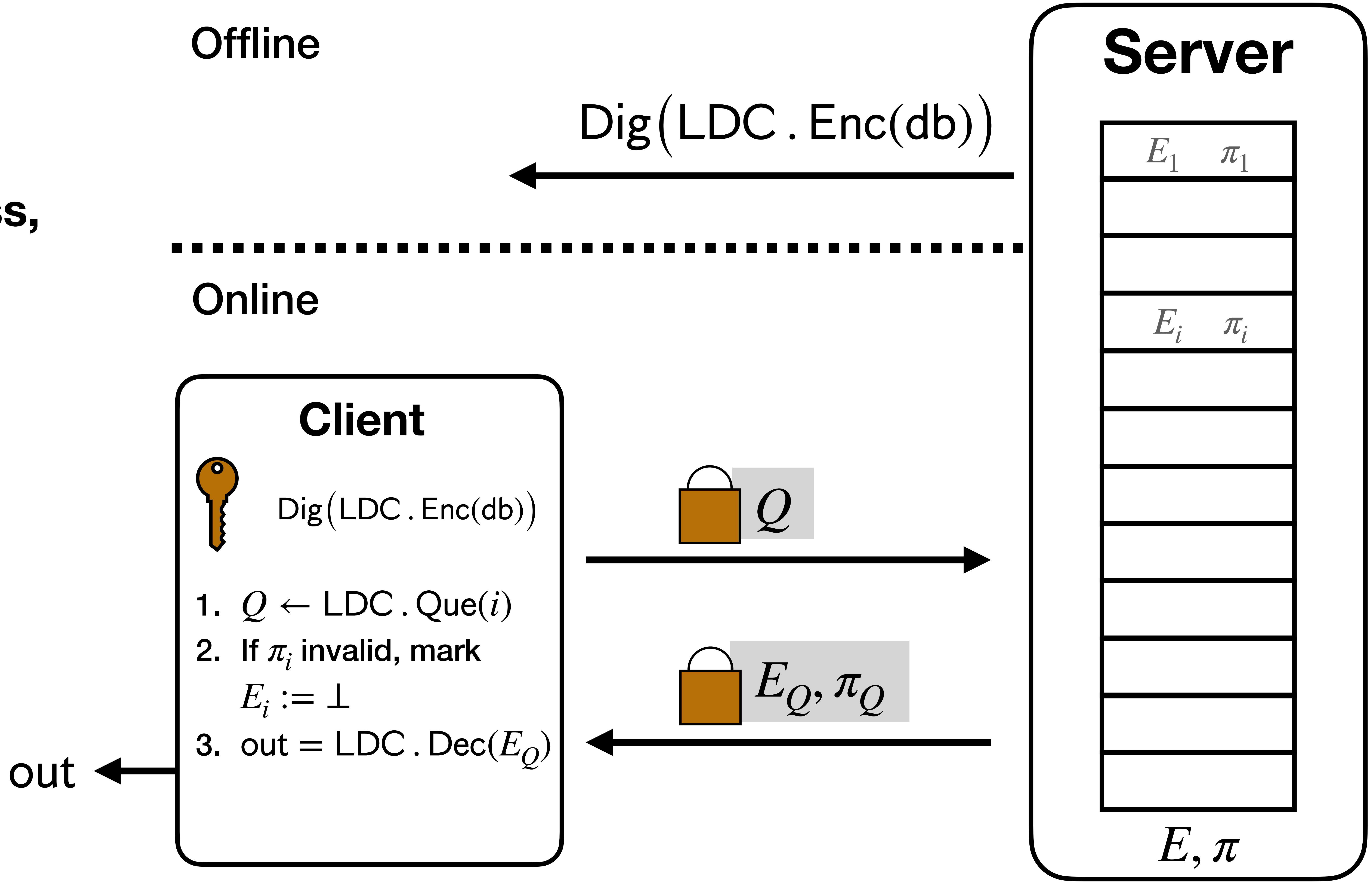

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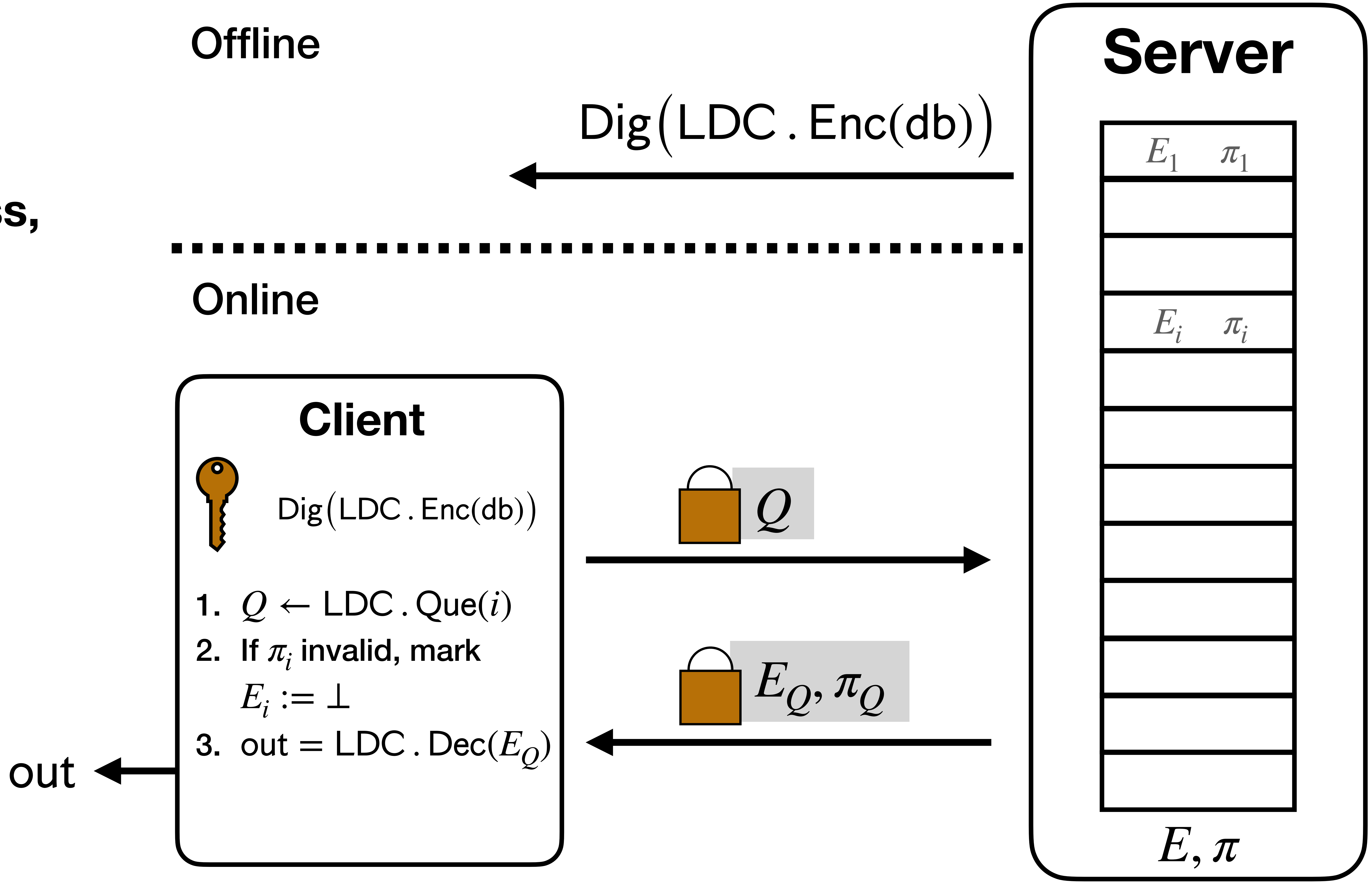

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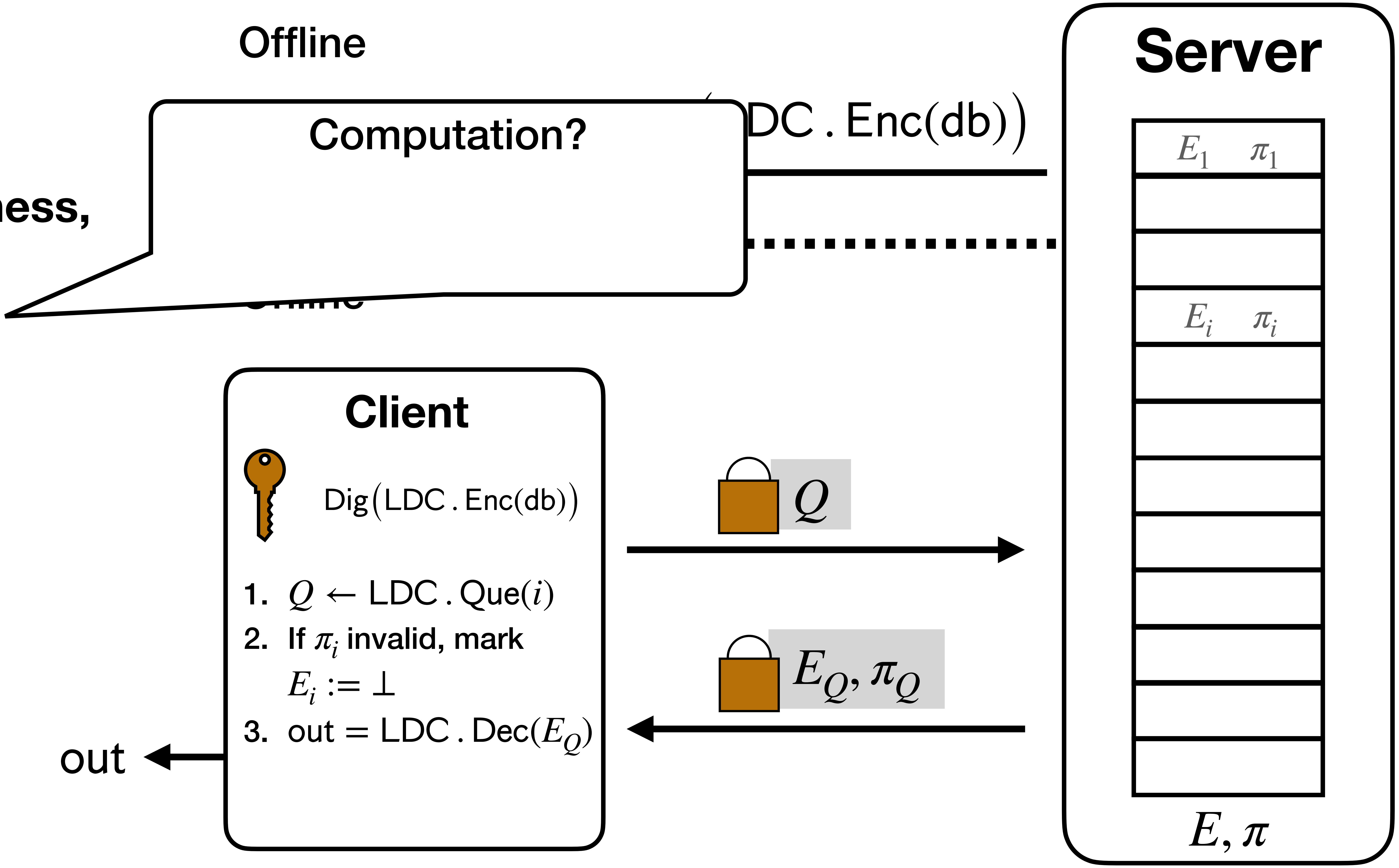

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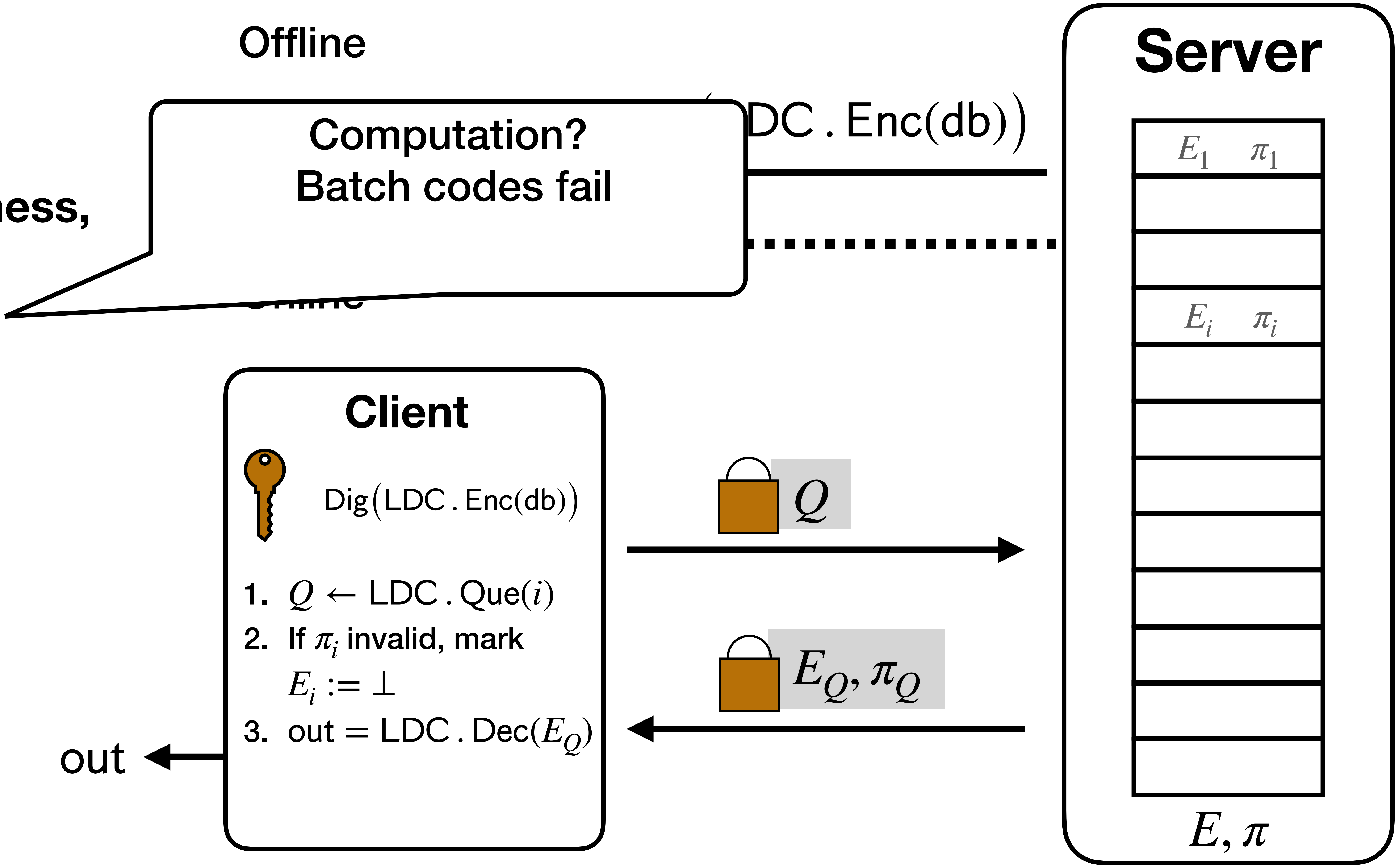

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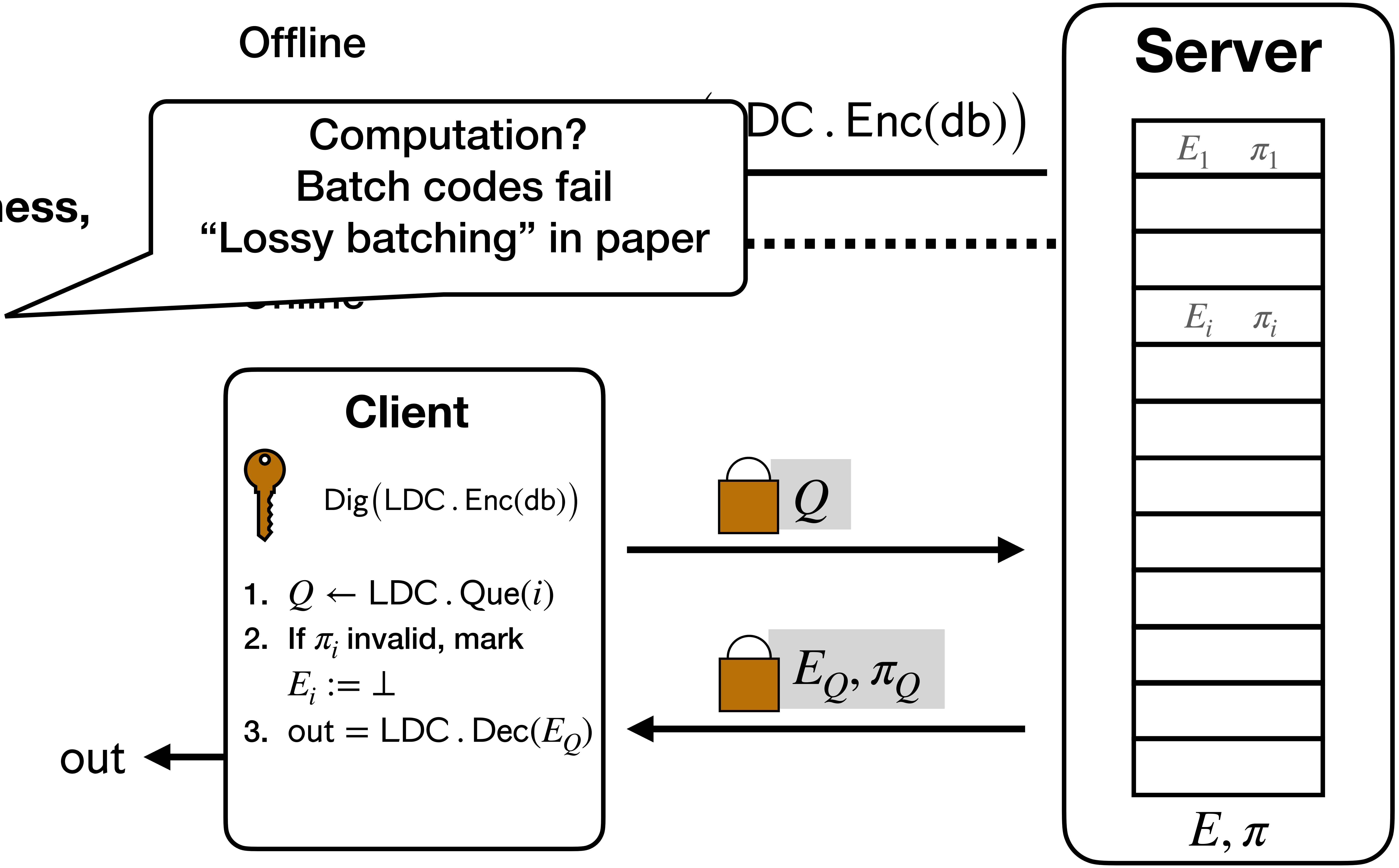

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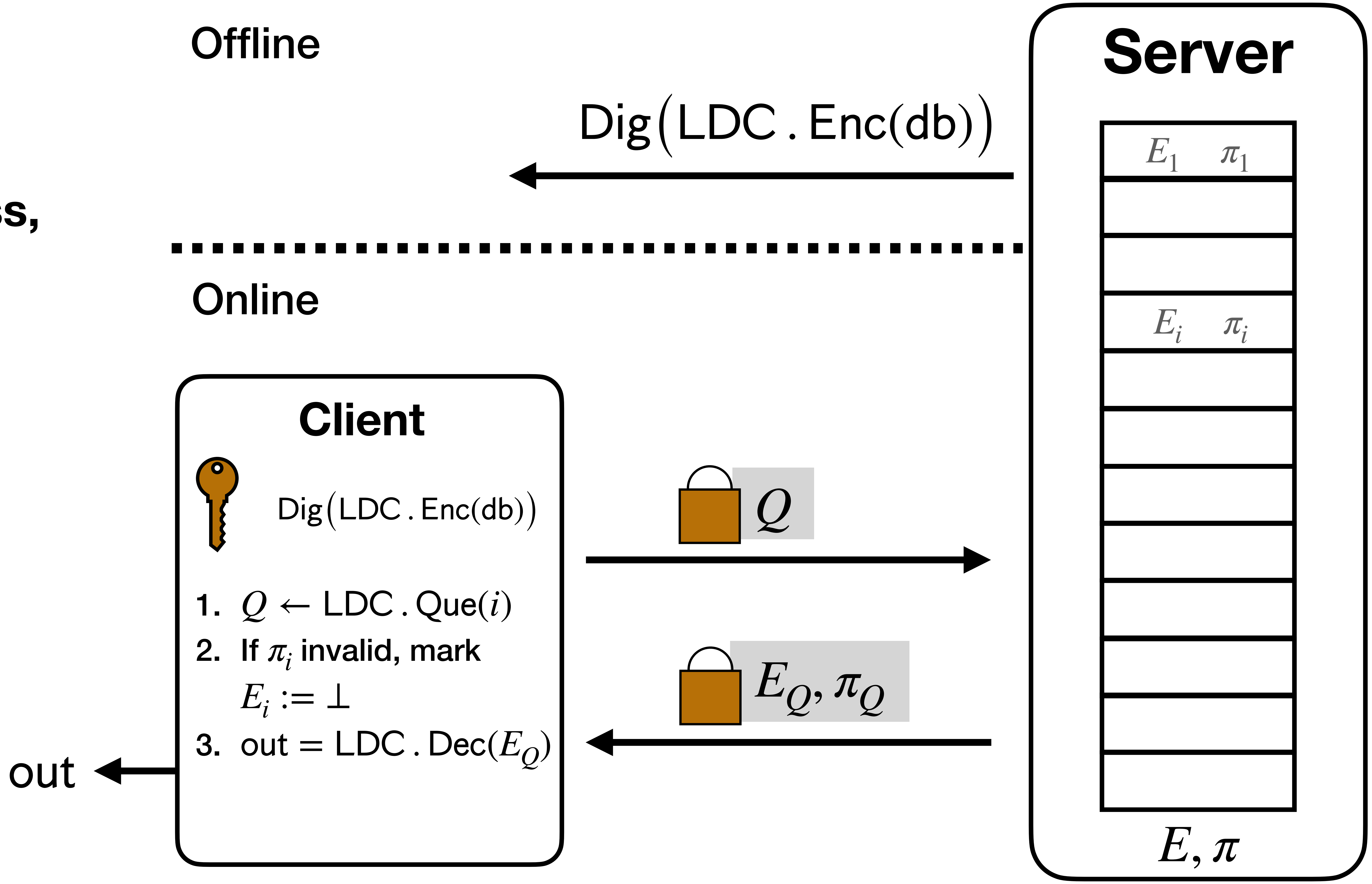

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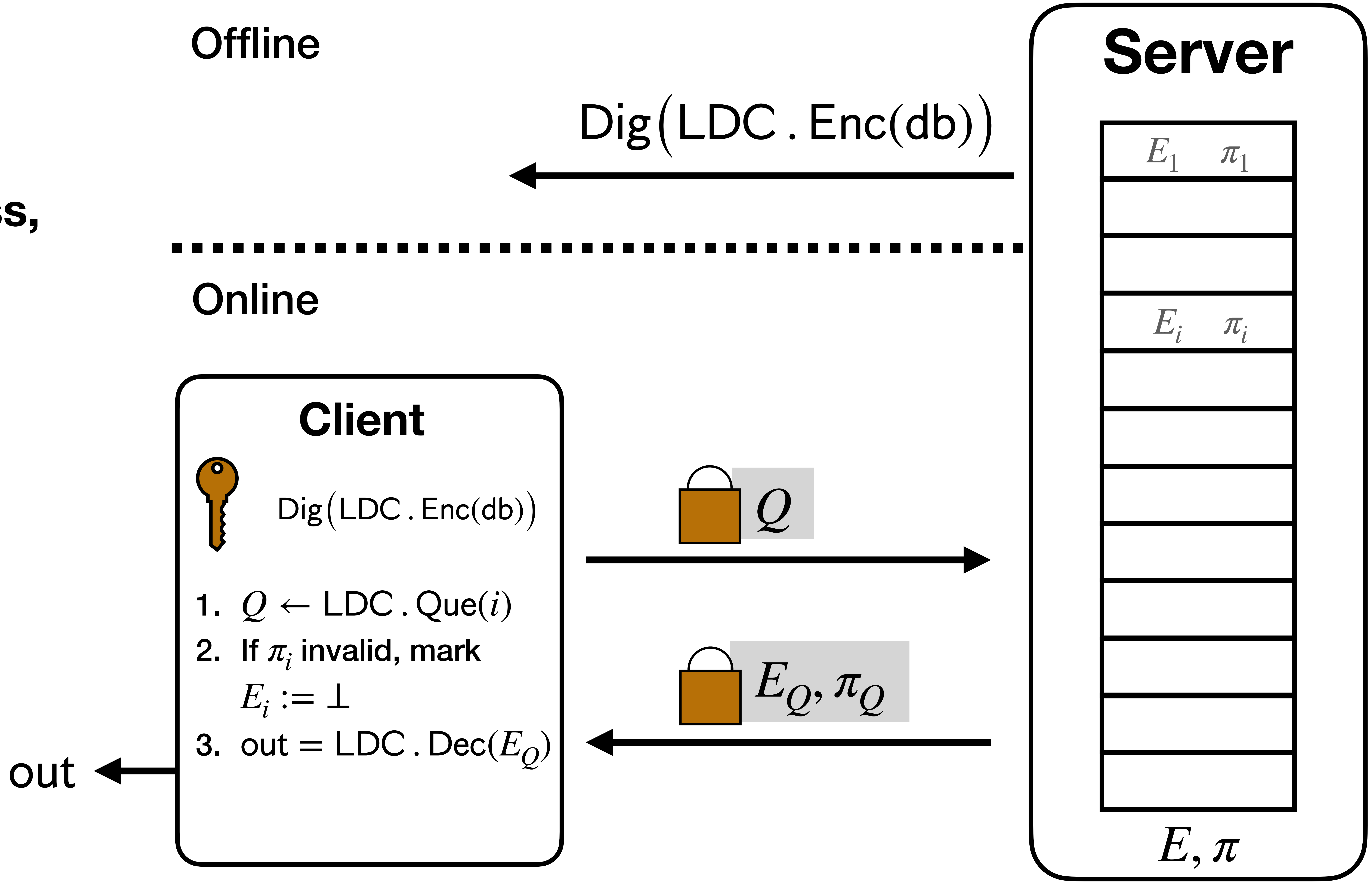

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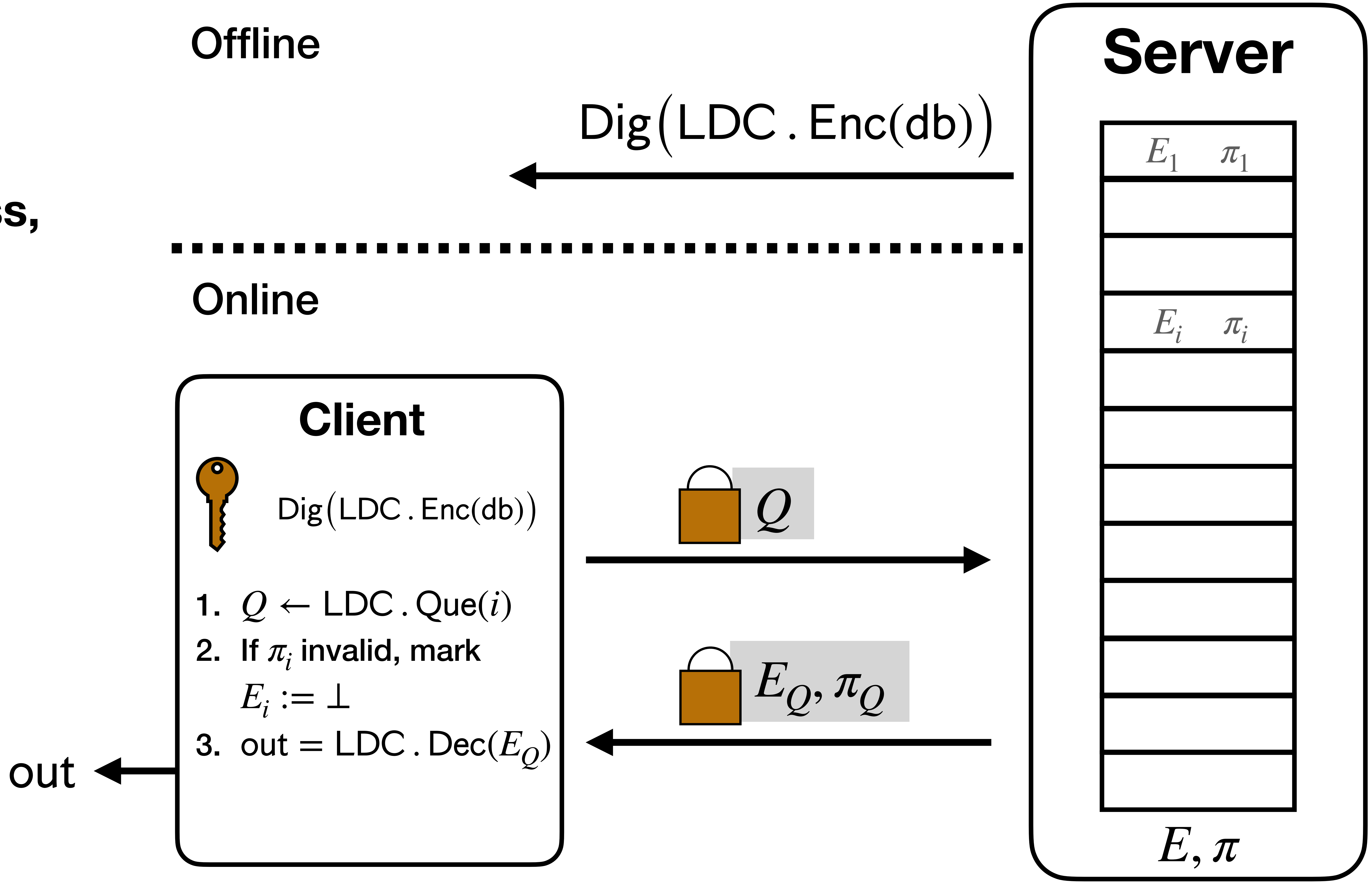

Final Construction

Offline

$\mathrm{Dig}\big(\mathsf{LDC.Enc}(\mathsf{db})\big)$

Properties

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3. **Privacy:**

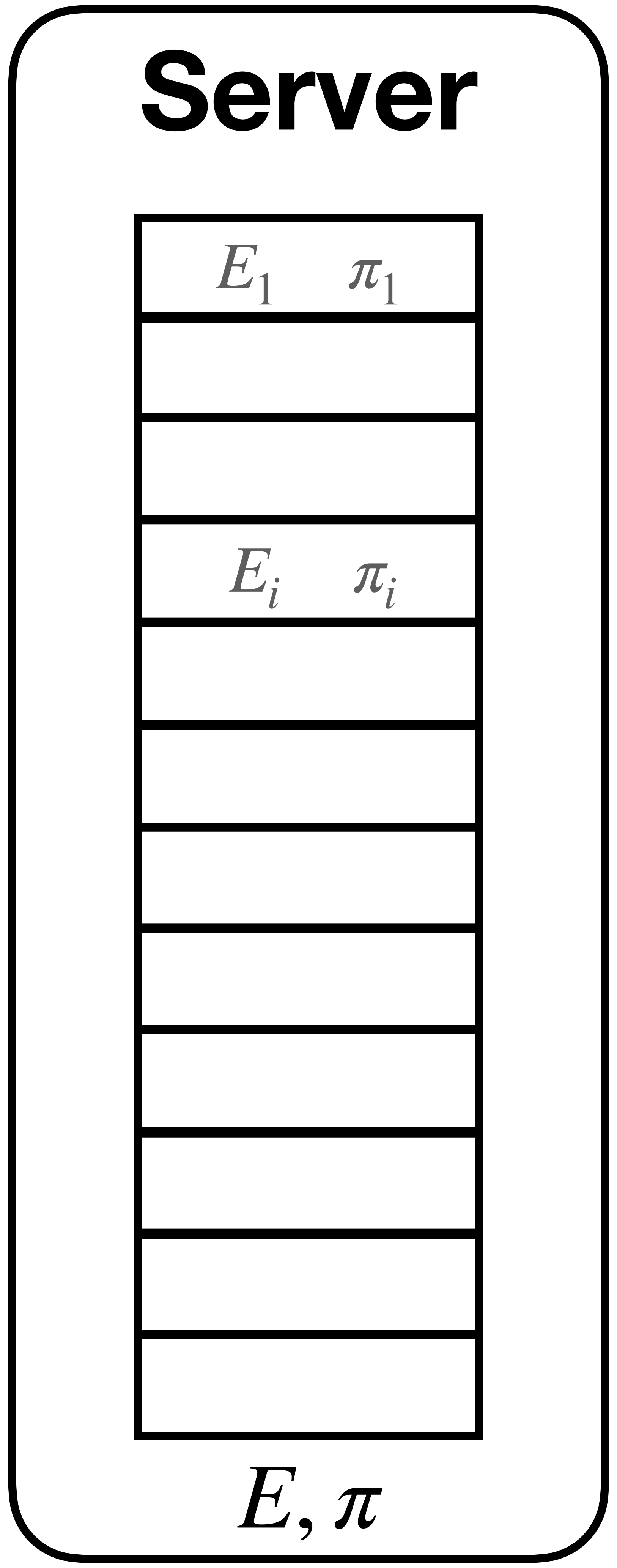
1. $\Pr[\perp$ **on** $i] = \Pr[\perp$ **on** $j]$**: by smoothness of code, test queries are uniformly random and independent of** i **. By non-signaling server must output the same on these distributions.**
2. $\Pr[$**not** $\perp$ **and can't decode**$] = \mathrm{negl}(\lambda)$**: even information theoretic adversary can't guess all test queries!**

$E_i := \perp$

3. $\mathsf{out} = \mathsf{LDC.Dec}(E_Q)$

out

E_Q, π_Q



Conclusion

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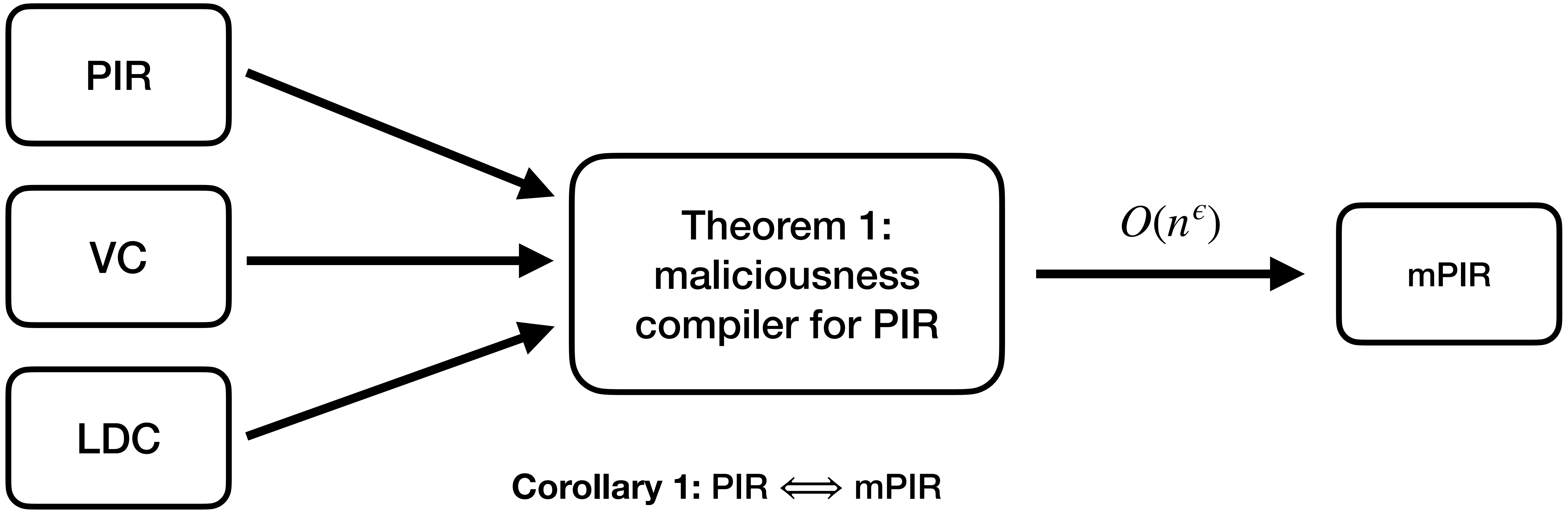

Corollary 1: PIR $\Longleftrightarrow$ mPIR

Theorem 2: there exists doubly-efficient mPIR.

Scheme	Communication	Computation	Digest	Assumptions	Methodology
CNCWF23	$O\left(N^{1/2}\right)$	$O(N)$	$O\left(N^{1/2}\right)$	LWE, DDH	Ad-hoc
WZLY23	$O\left(N^{1/2}\right)$	$O\left(N^{1/2}\right)$	$O\left(N^{1/2}\right)$	OWF*	Ad-hoc
DT23	$O\left(N^{1/2}\right)$	$O(N)$	$O\left(N^{1/2}\right)$	DDH	Ad-hoc
CL24	$O\left(N^{1/2}\right)$	$O(N)$	$O\left(N^{1/2}\right)$	LWE	Ad-hoc
Ours (any PIR)	$\times\, O\left(N^{\epsilon}\right)$	$\times\, O(1)$	$\omega(\log N)$	PIR	Compiler
Ours (DePIR)	$O(\text{polylog } N)$	$O(\text{polylog } N)$	$\omega(\log N)$	RingLWE	Compiler

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    2. What are the properties of LDC with "consistent" decoding?
    3. How well can we decode in the face of non-signaling adversaries?
2. Practice:
    1. Can we implement these ideas in a practically efficient mPIR?

Thank you!

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