SafetyPin: Encrypted Backups with Human-Memorable Secrets

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Henry Corrigan-Gibbs (EPFL and MIT CSAIL), and
David Mazières (Stanford)

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OSDI 2020

Mobile backups today

1. User only needs to remember her **screen-lock PIN**.

+ PINs are easy to remember and not known to the service provider.

- PINs have low-entropy.

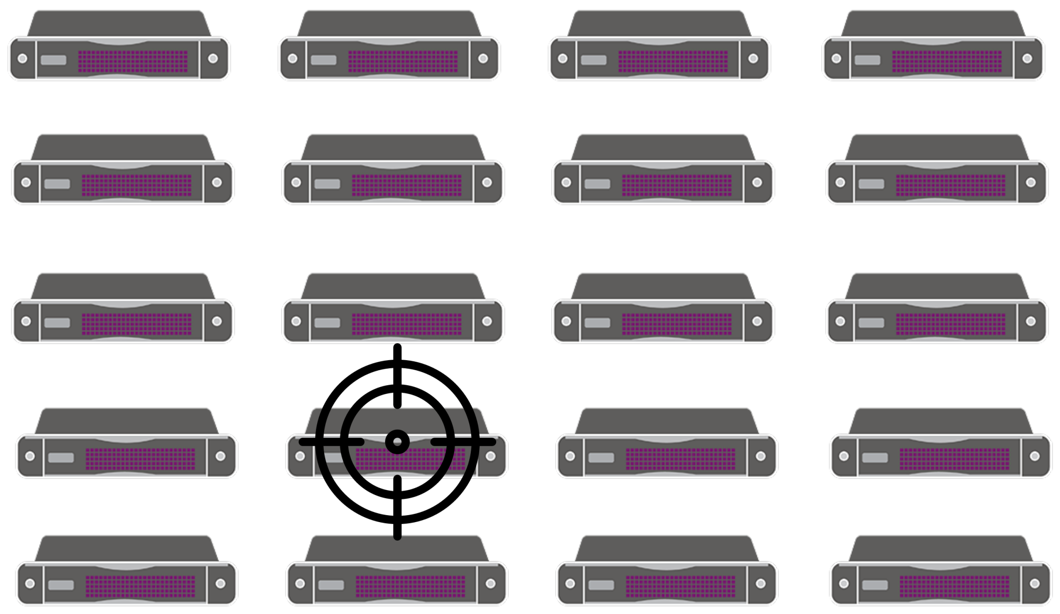
2. **Secure hardware** prevents brute-force attacks against PIN.

+ Hardware security modules (HSMs) are resistant to physical attacks.

- HSMs are not perfect.

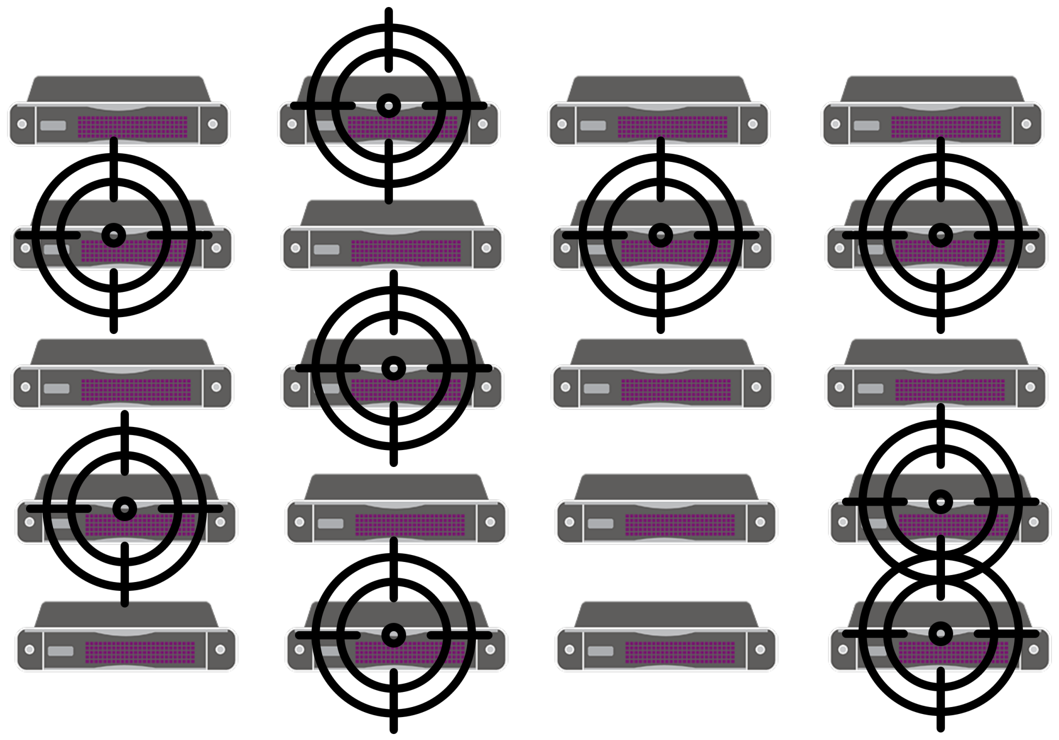
State-of-the-art vs. SafetyPin: security

State-of-the-art



1 compromise = **Millions of backups**

SafetyPin



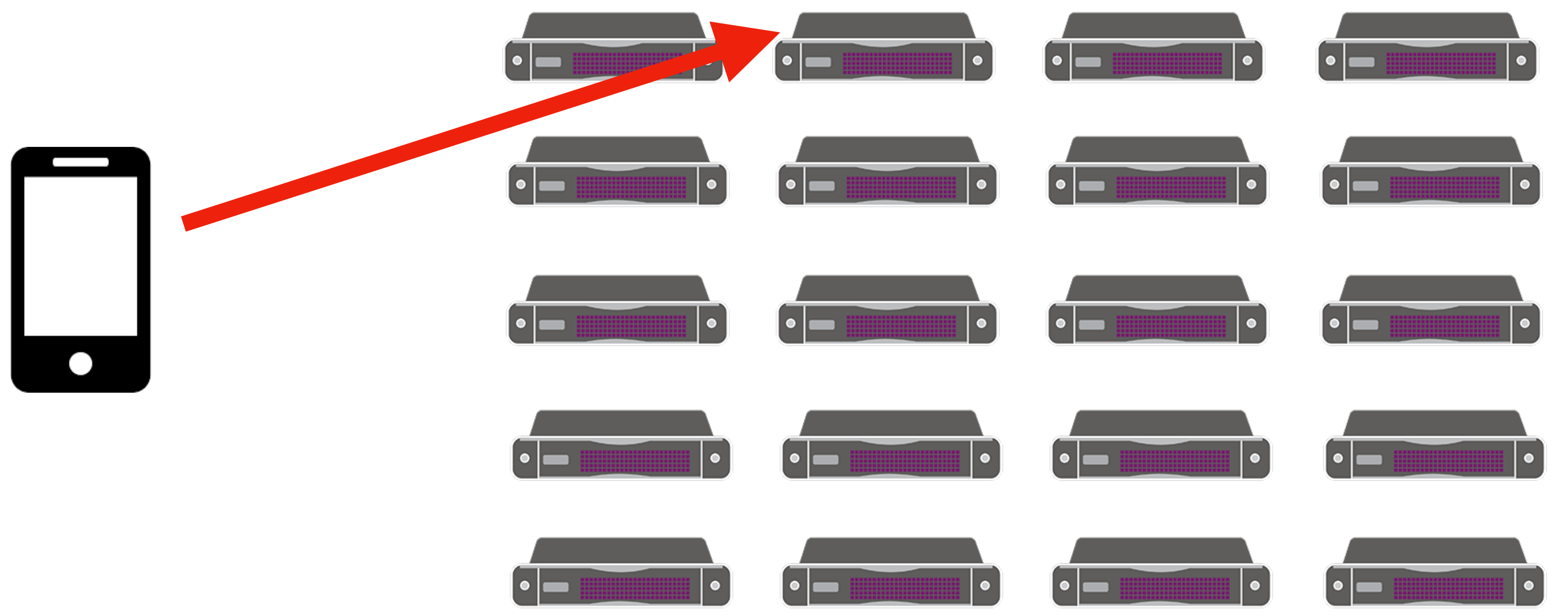
N HSMs

< N/16 compromises = **0 backups**

SafetyPin tolerates **many HSM compromises.**

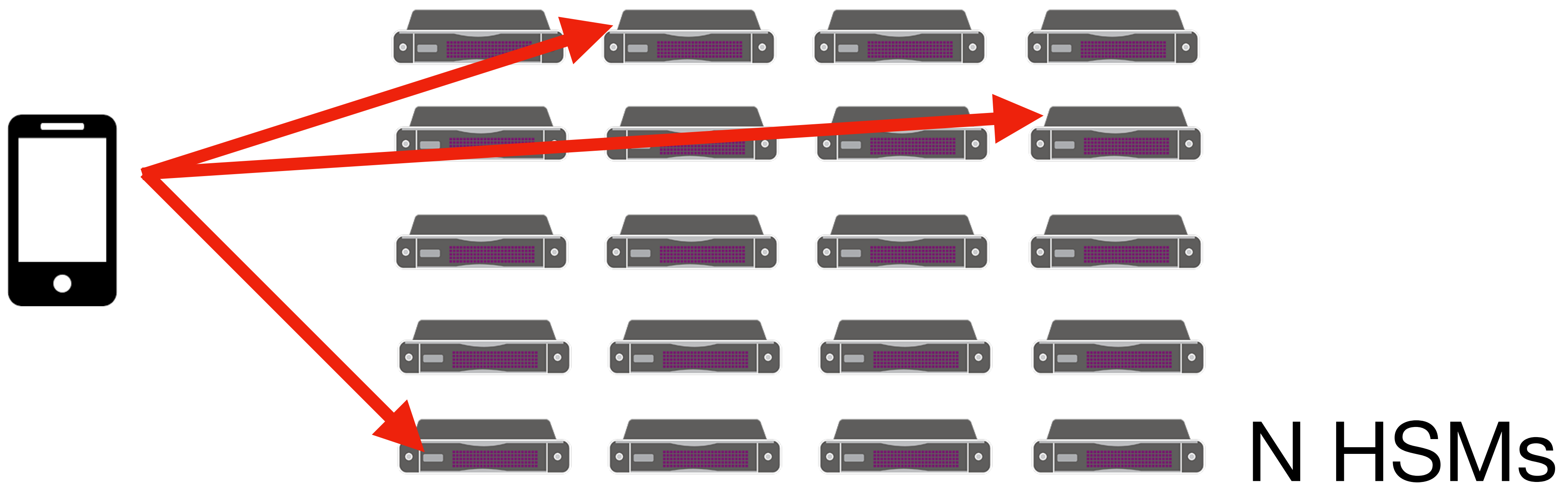
State-of-the-art vs. SafetyPin: scalability

State-of-the-art



Client talks to a **single HSM**.

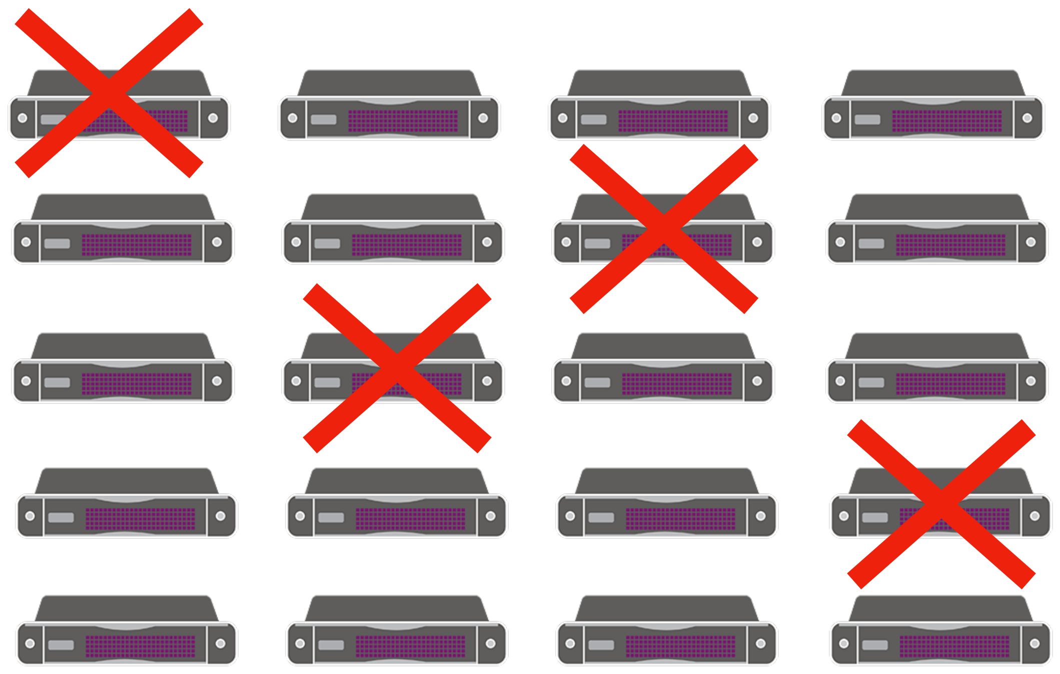
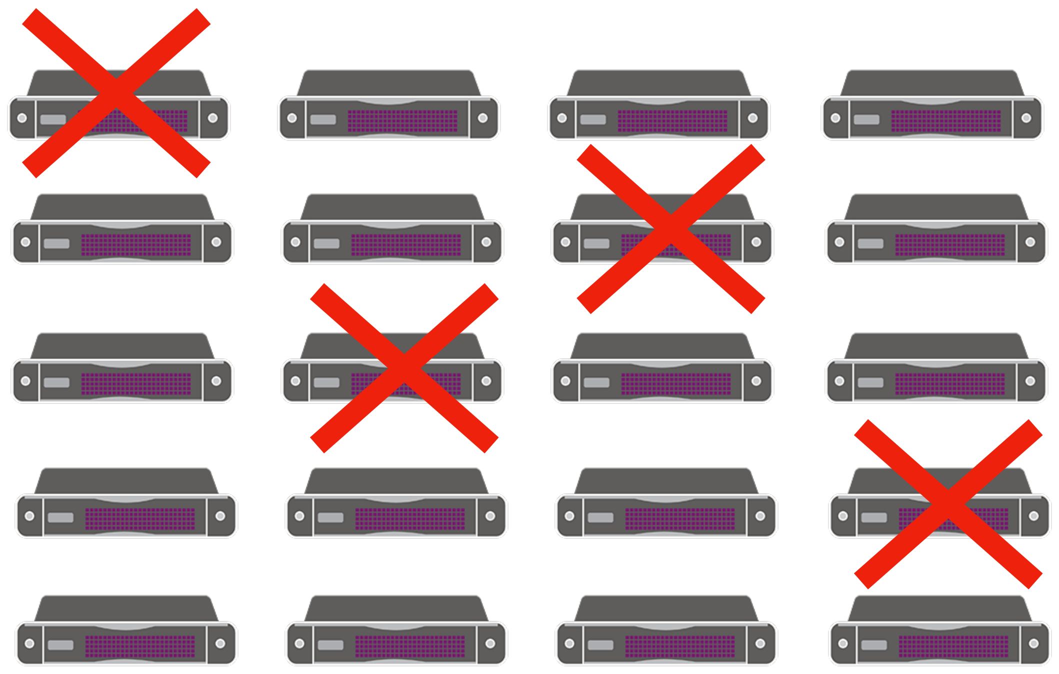
SafetyPin



Client talks to a **few HSMs** (e.g. 40).

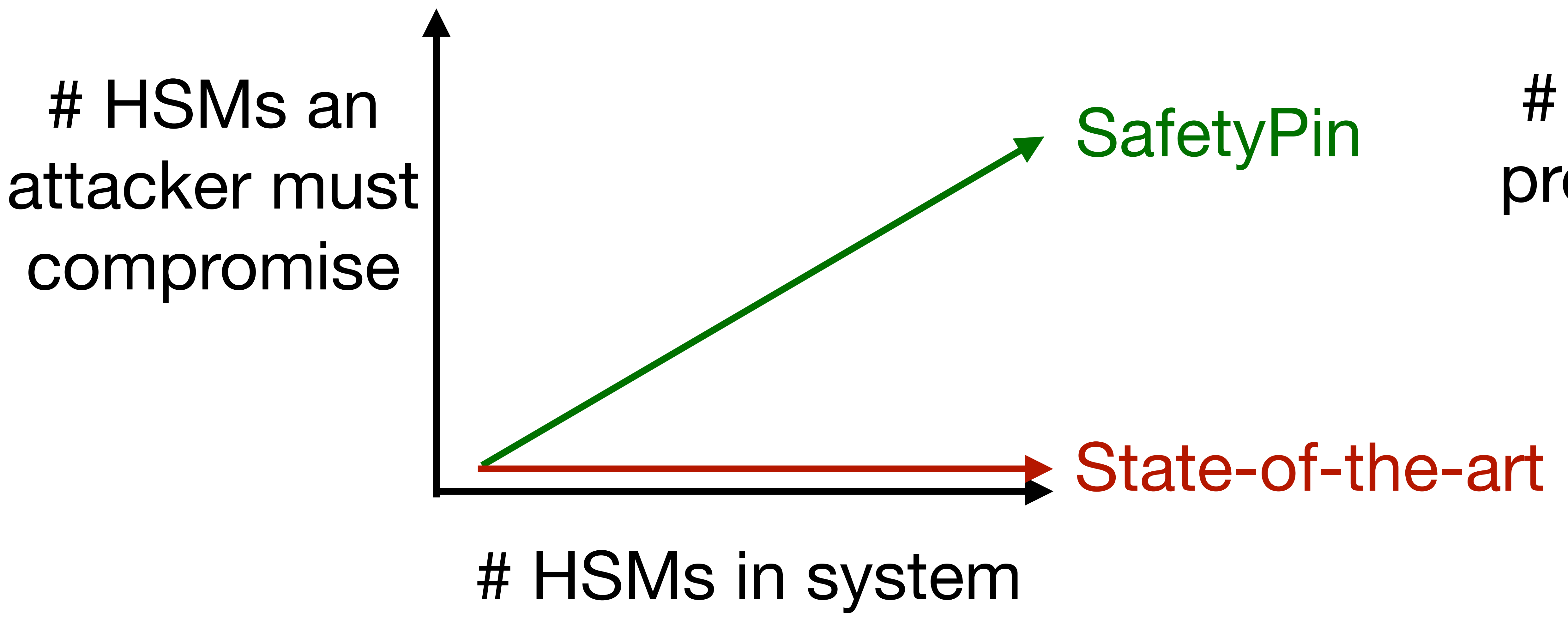
SafetyPin doesn't **sacrifice scalability**.

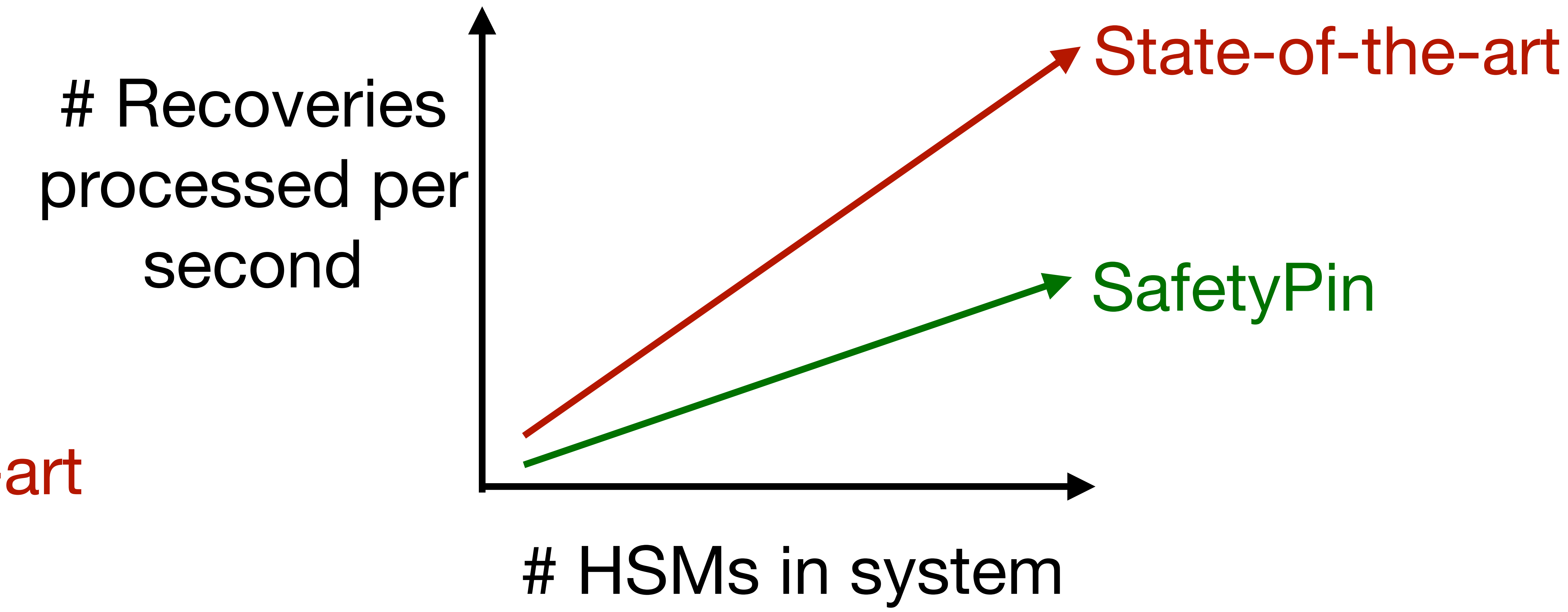
State-of-the-art vs. SafetyPin: fault tolerance

State-of-the-art		SafetyPin
	=	 N HSMs

Tolerates many failures between backups (e.g. N/64).

More HSMs improve security and performance





Claim: compromising more HSMs is more expensive

- The cost of **physical attacks** scales linearly with the number of HSMs.
- Physically attacking more HSMs increases the **risk of exposure**.
- Some protection against software bugs with diverse HSMs.

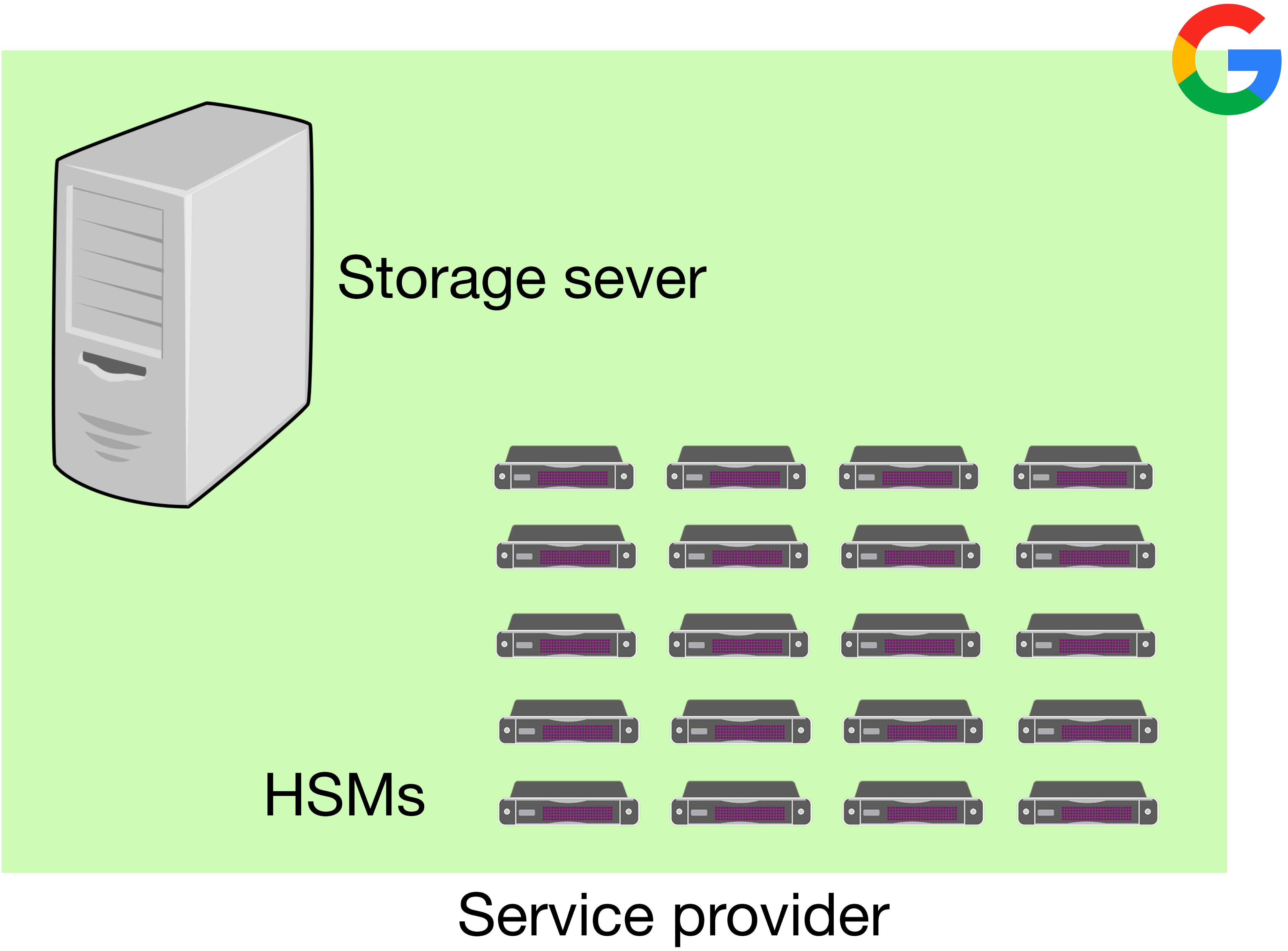
Attack scenario

Service provider (e.g. Google) sets up the system correctly.

Later, attacker wants to obtain user backups.

Attacker can:

- observe/modify network traffic,
- control the storage server, and
- adaptively compromise many HSMs.



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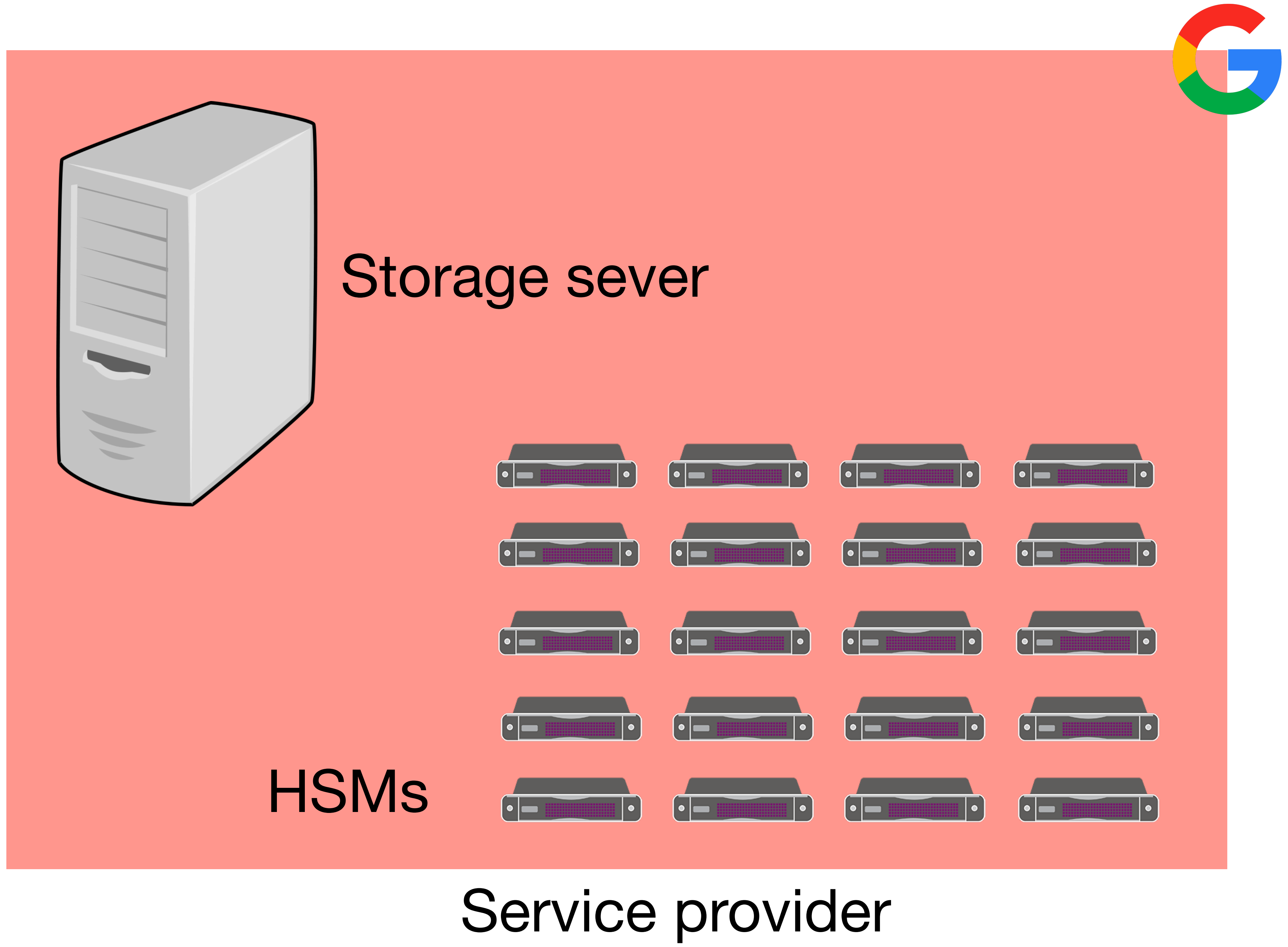

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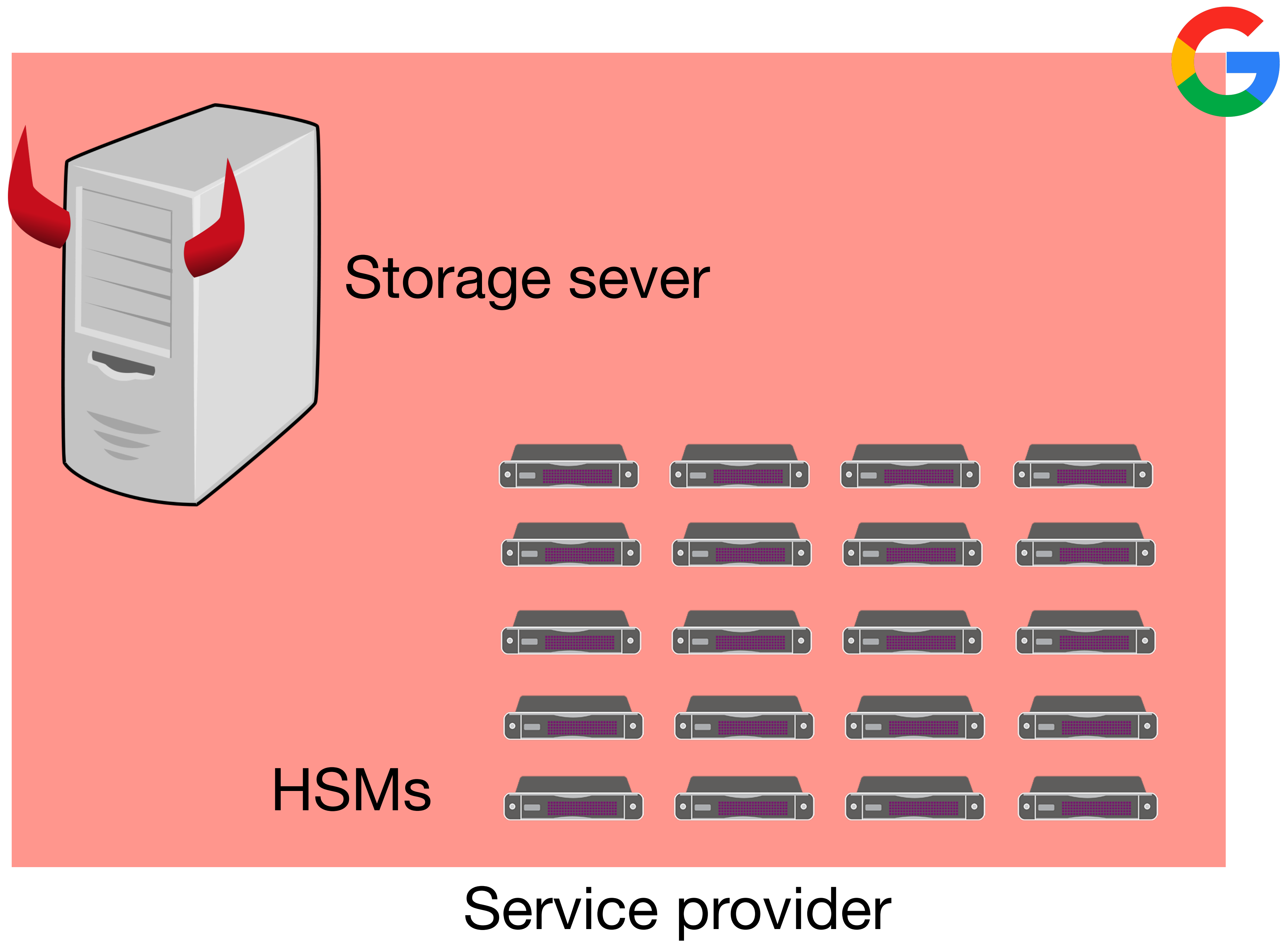

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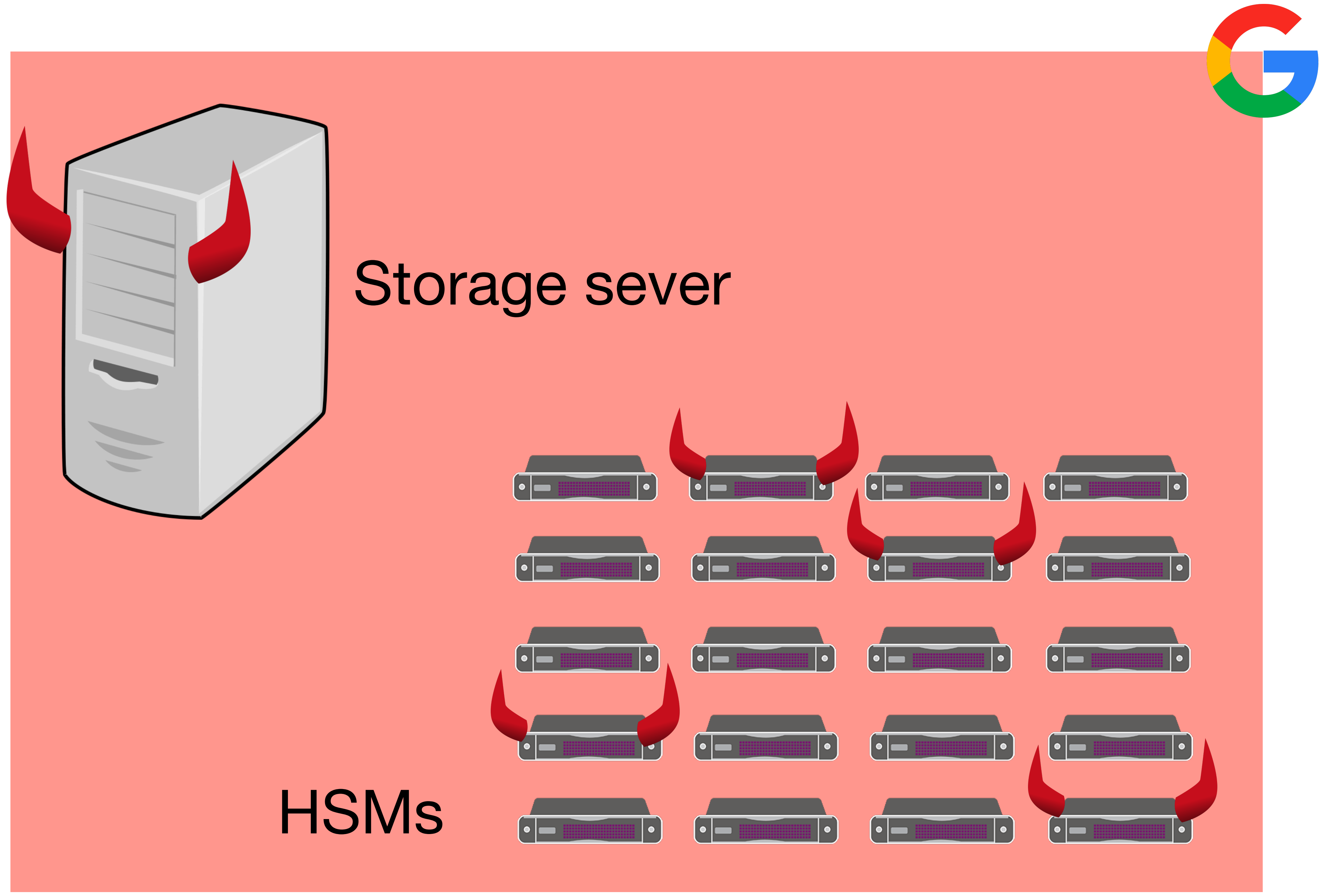


Service provider

Outline

1. **SafetyPin design**
   - **Overview**
   - Scalable rate-limiting

2. SafetyPin evaluation

SafetyPin design idea

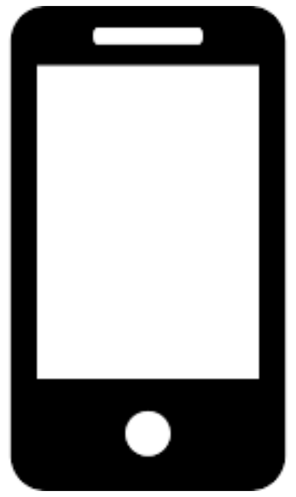
Idea: Hide the identities of a small, fixed set of HSMs a user can recover with.

- **Scalability:** The user can recover with a small set of HSMs.
- **Security:** Without the PIN, the attacker can't identify the set of HSMs.

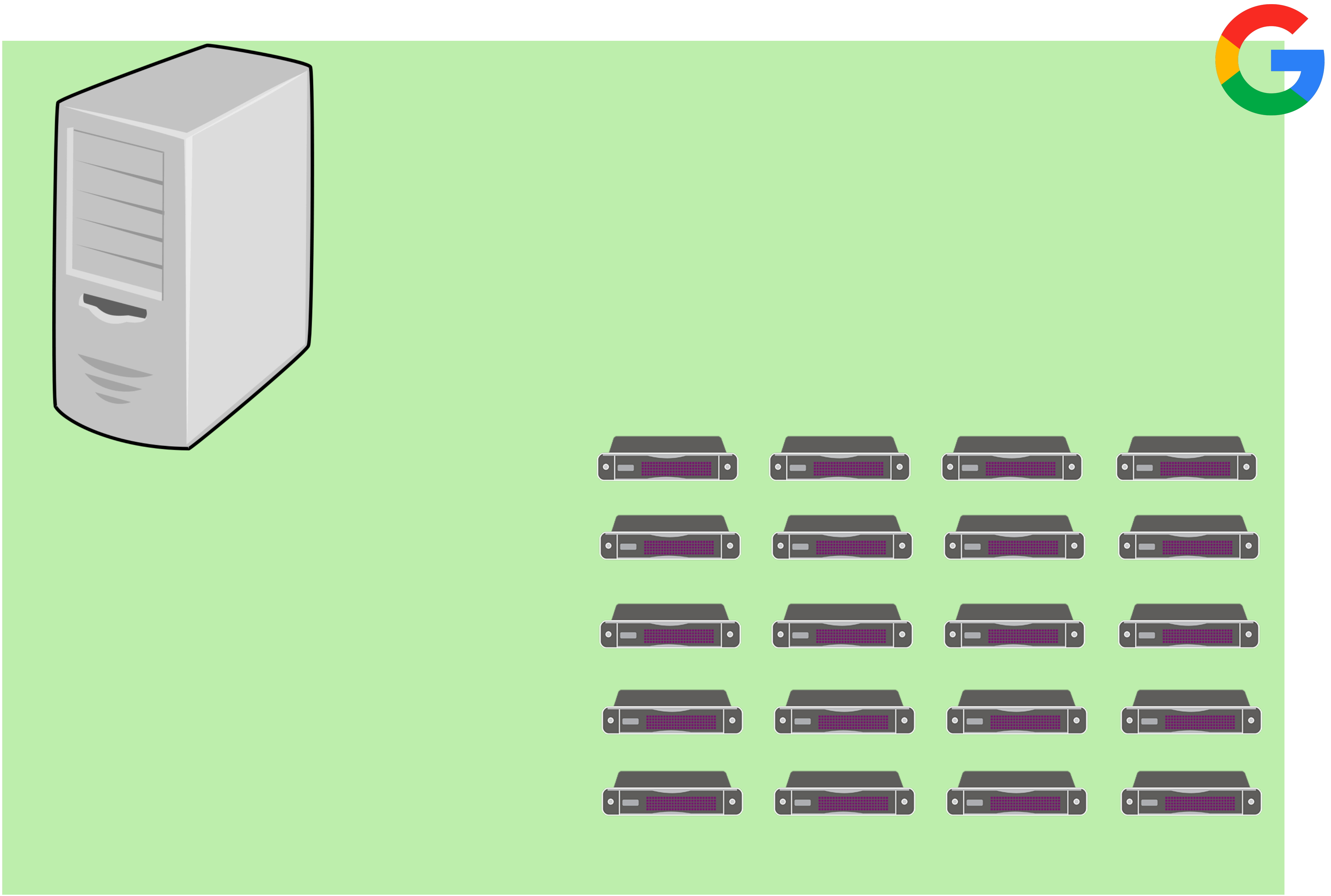
[System parameterized to support 1B recoveries per year with 128-bit security]

Backup [simplified]

1. Select $n \approx 40$ HSMs using a PIN.
2. Break message into $n \approx 40$ shares $m_1, \ldots, m_n$ such that $n/2$ needed to recover.
3. Encrypt a share m_i to each selected HSM i.



message



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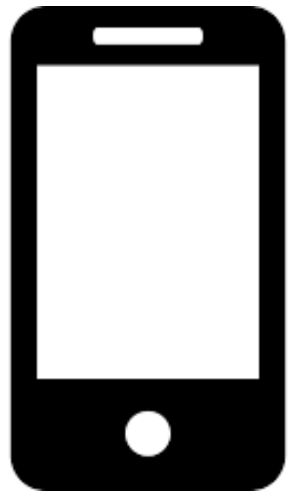
$H_{\text{user}}(\text{pin})$



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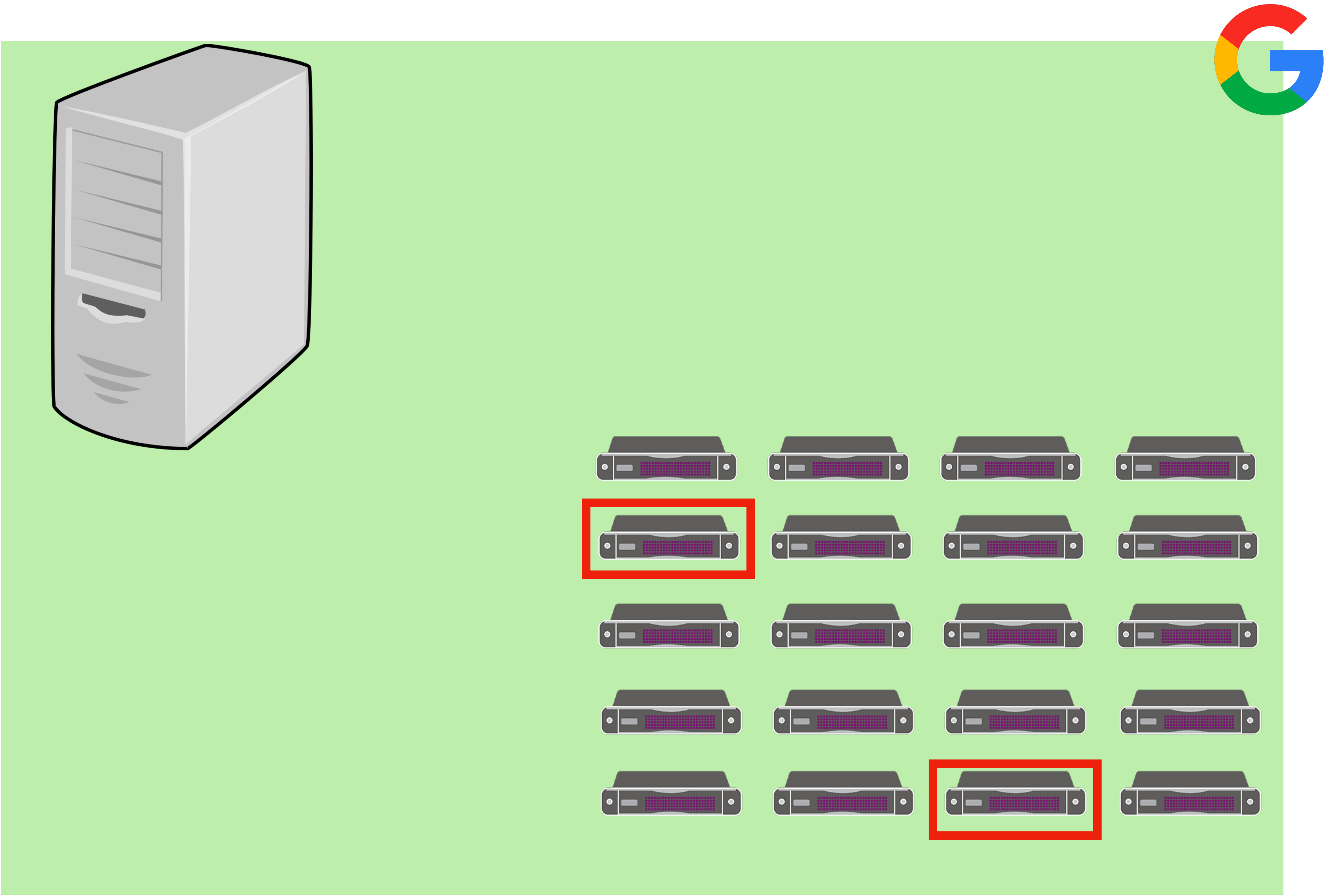

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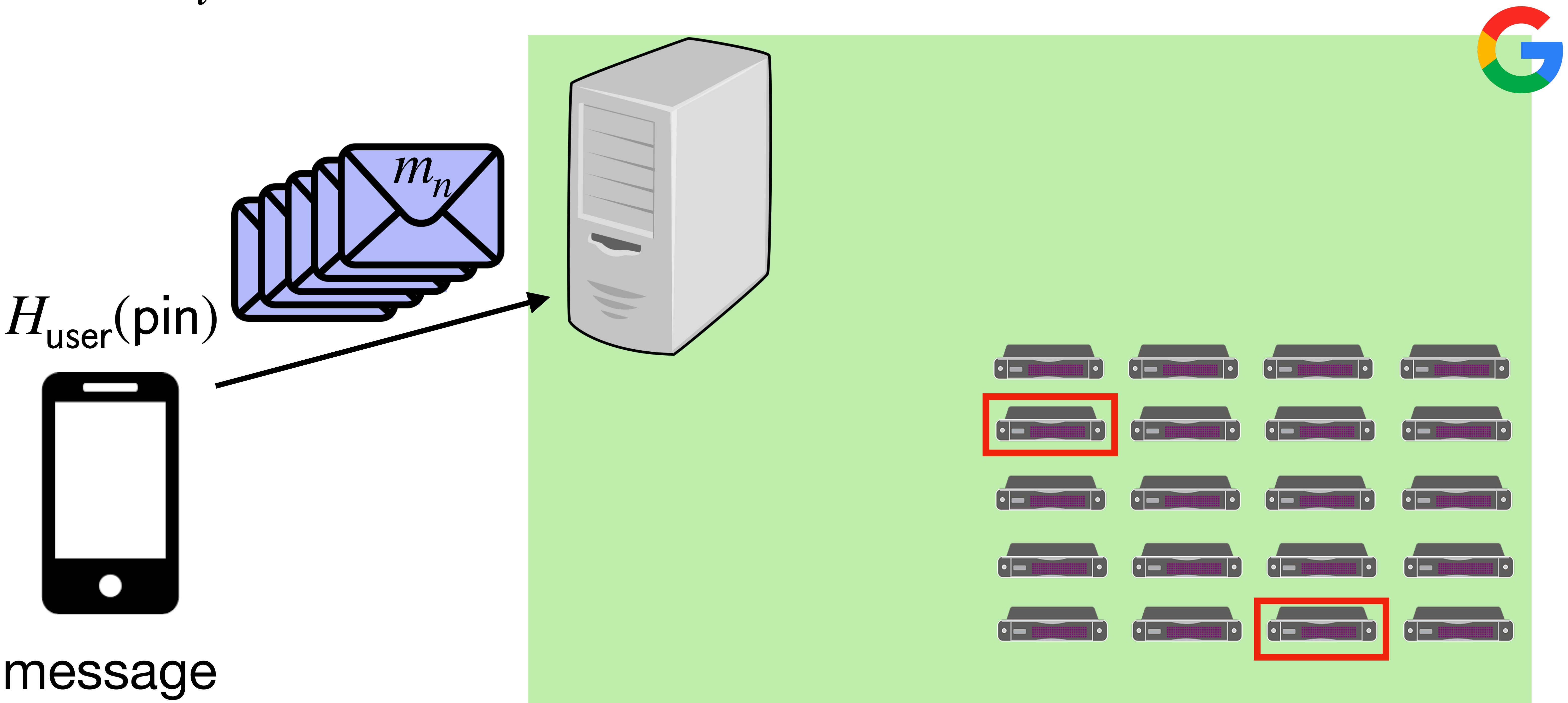

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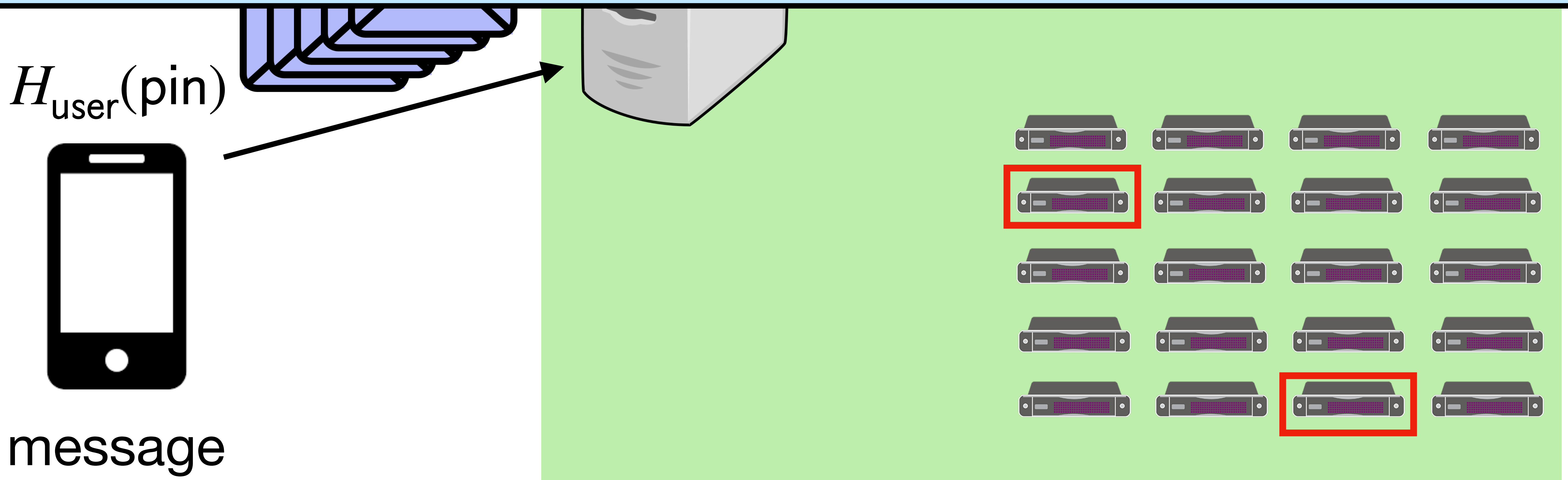
3. E

The attacker can't identify the set of HSMs without the PIN because
- client doesn't interact with HSMs, and
- ciphertexts don’t leak identities of HSMs.



Recovery [simplified]

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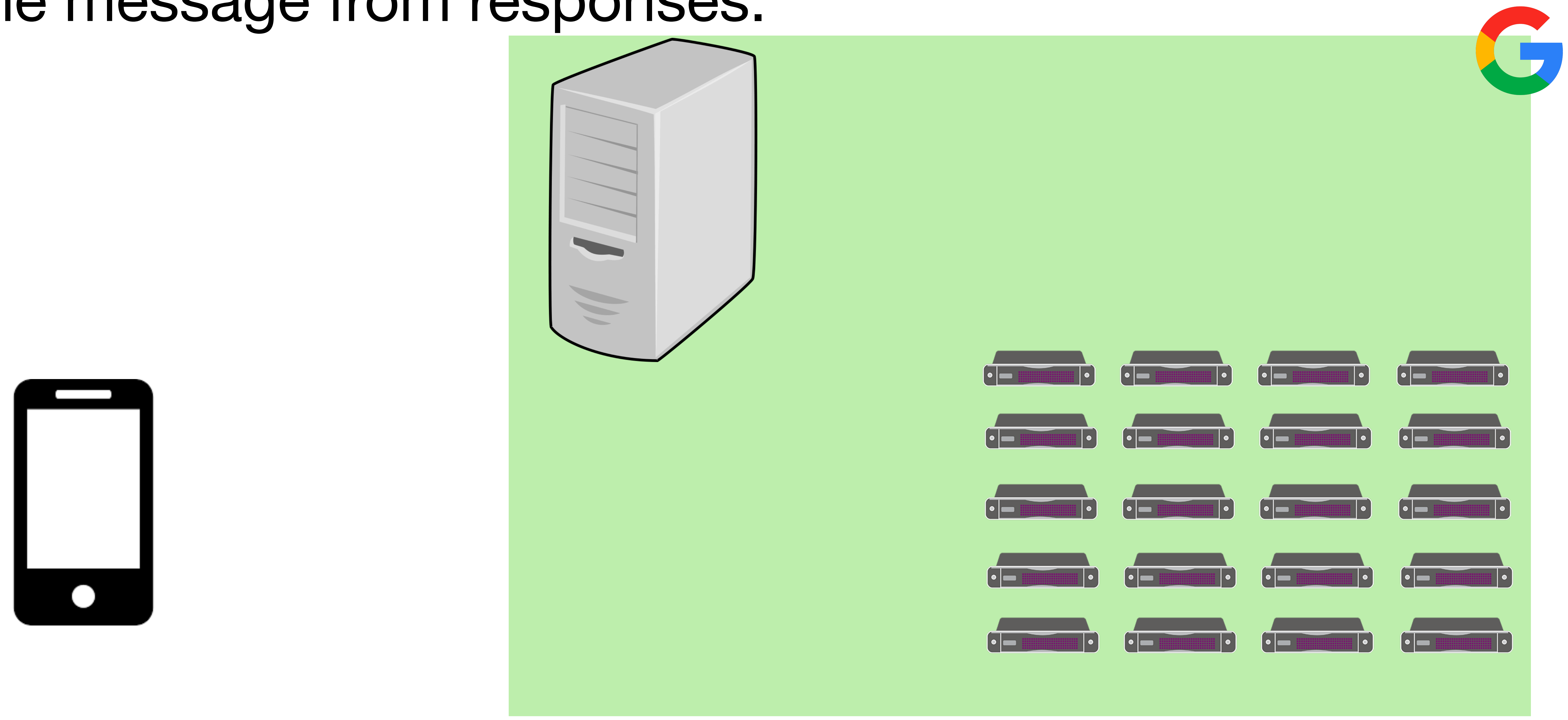
2. Compute the set of $n \approx 40$ HSMs.
3. Send the ciphertexts to the HSMs for decryption.
4. Assemble the message from responses.



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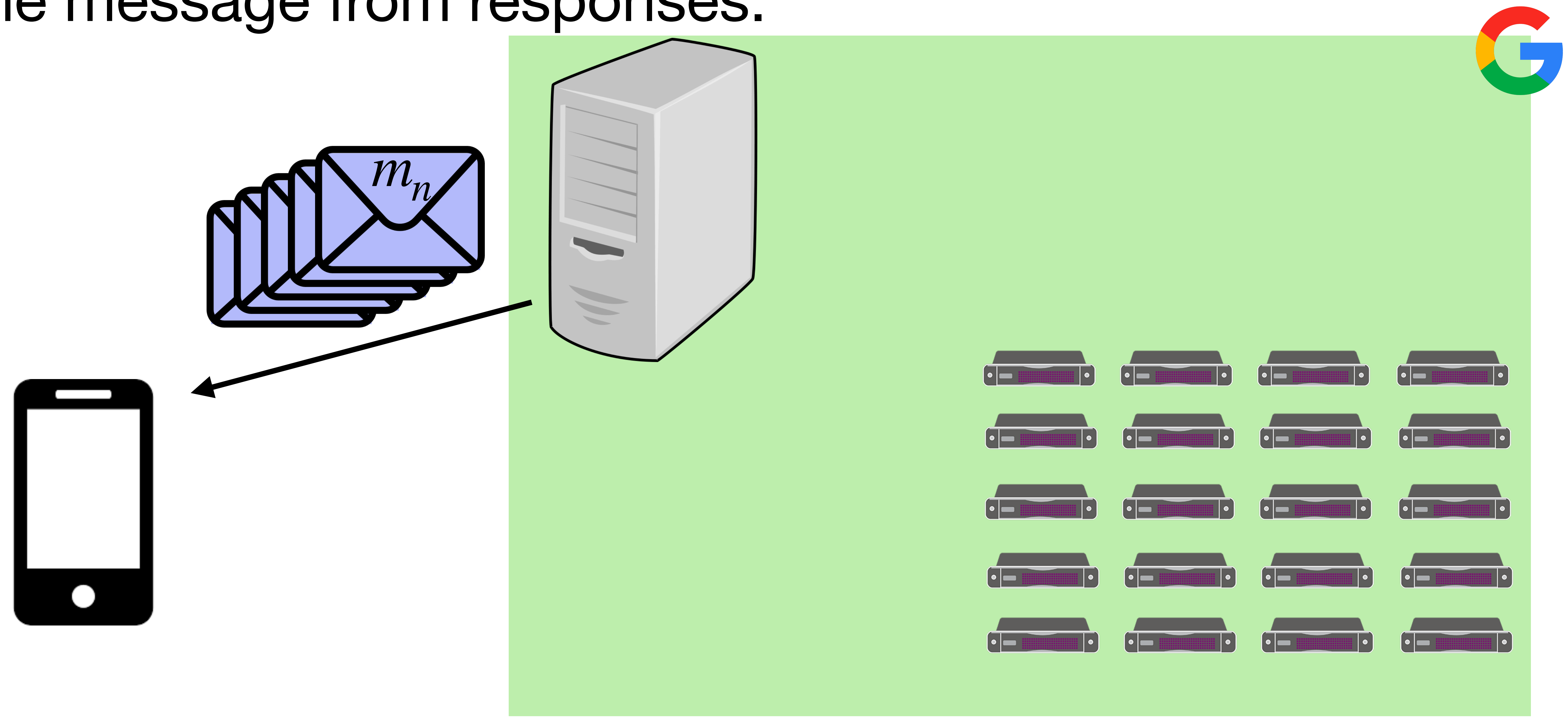

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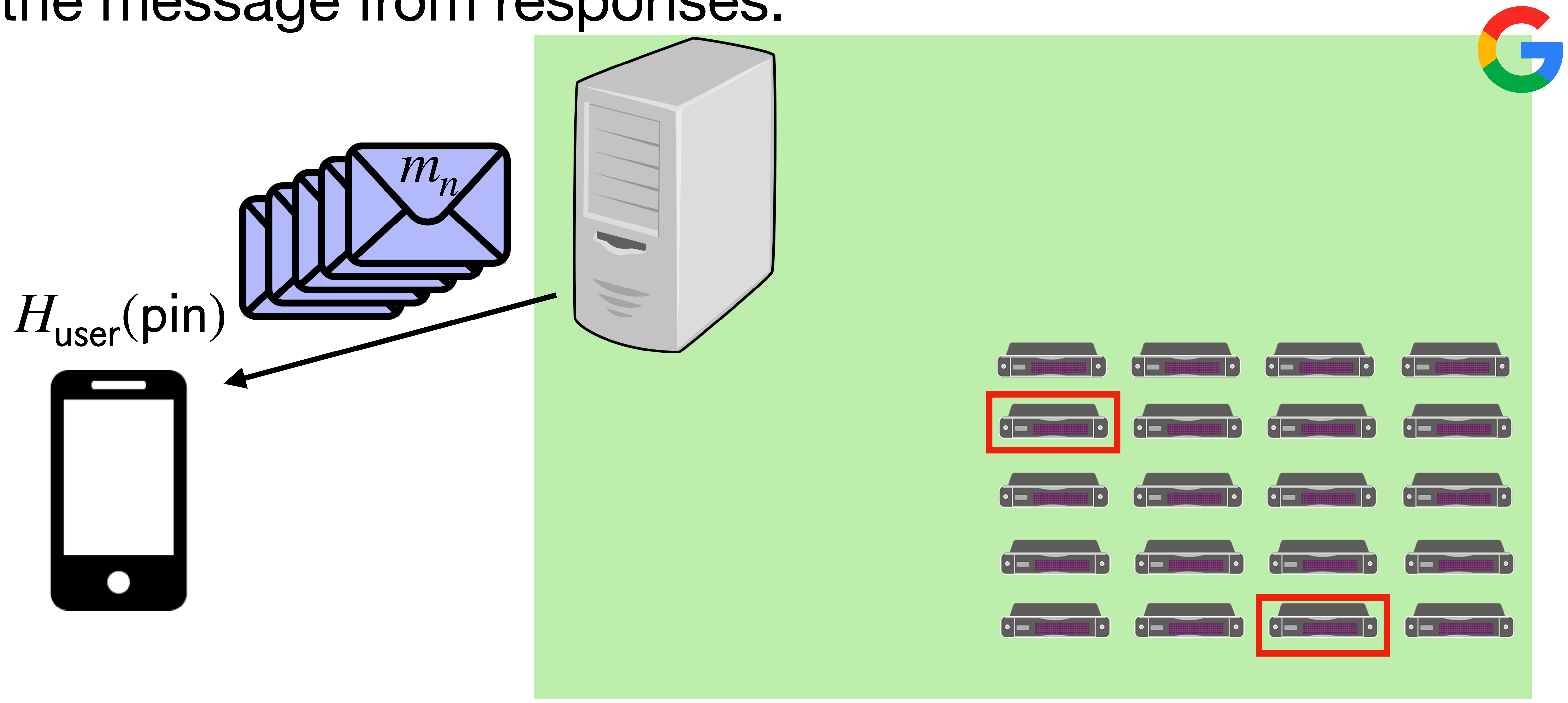

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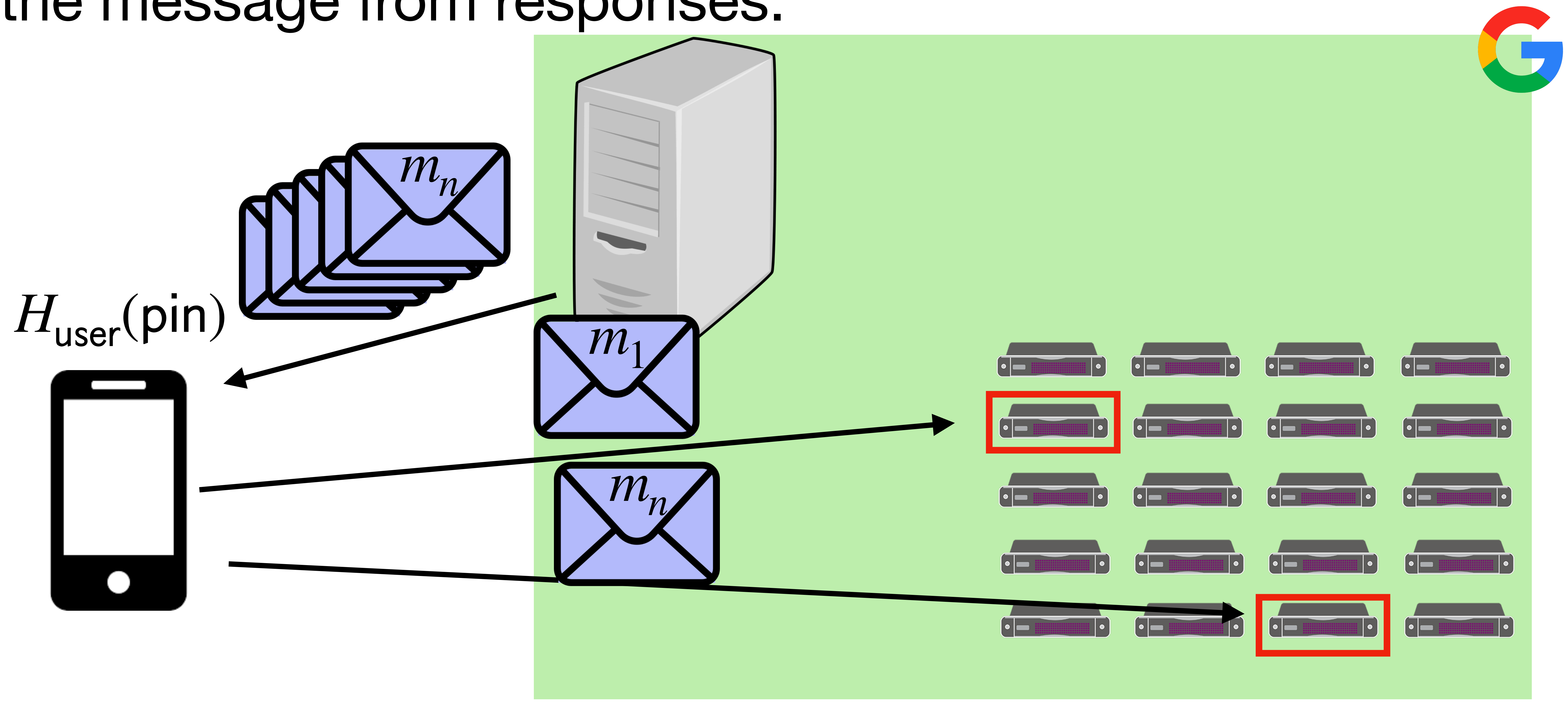

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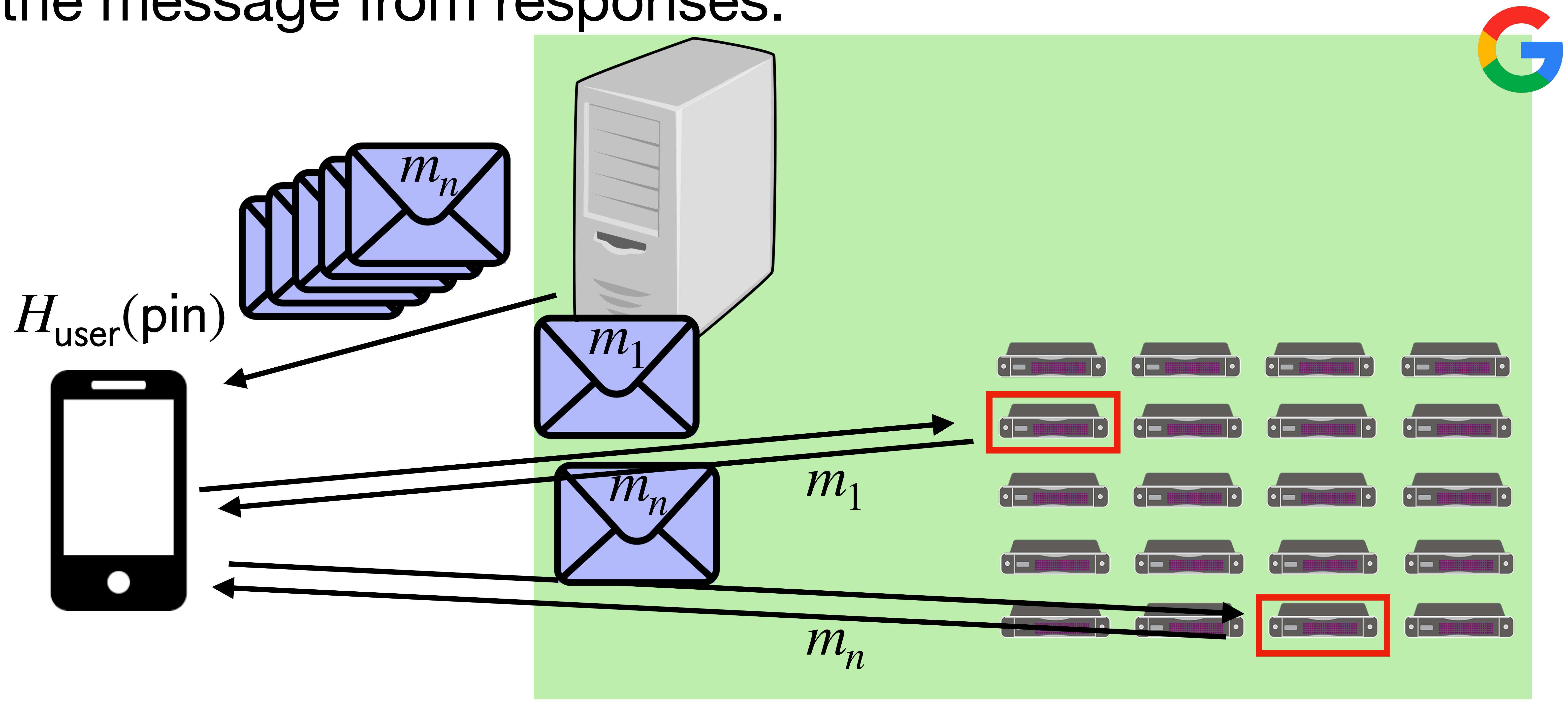

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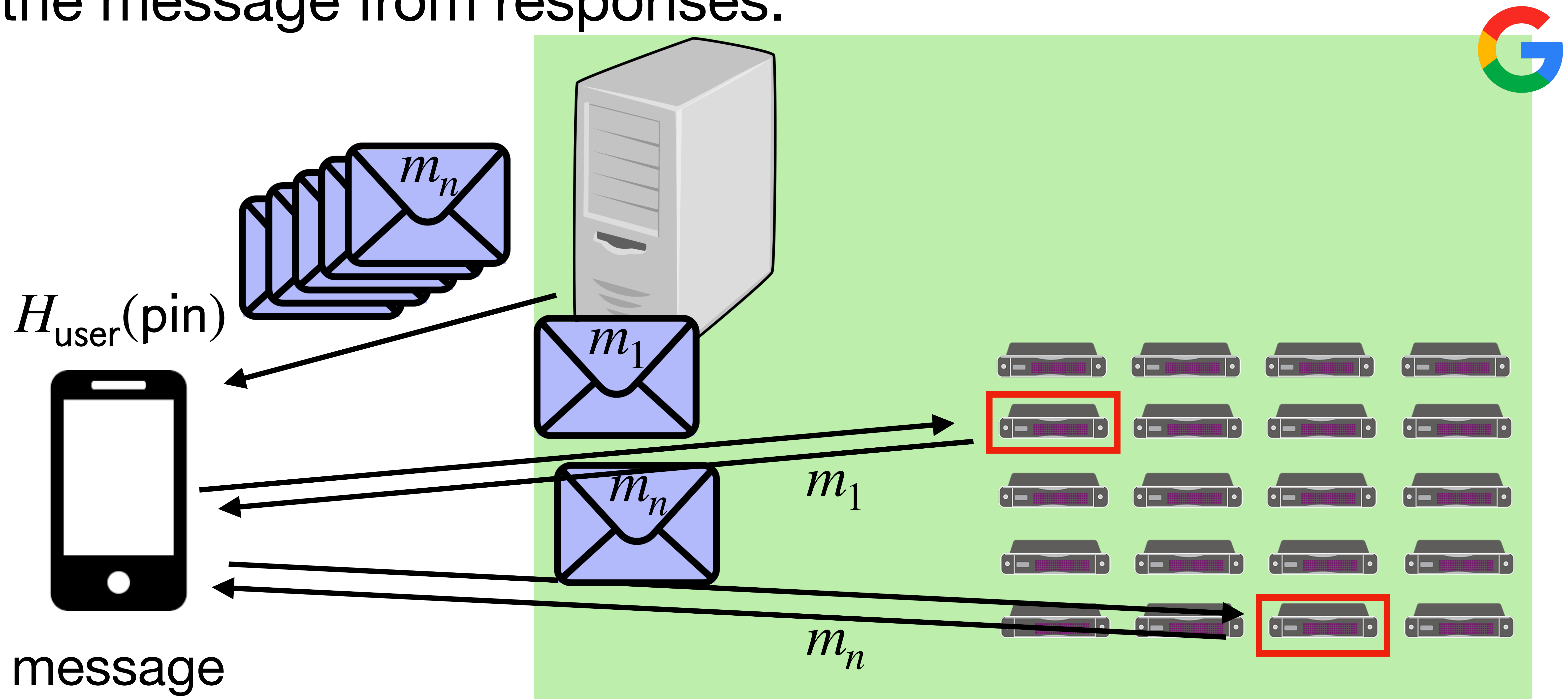

Recovery [simplified]

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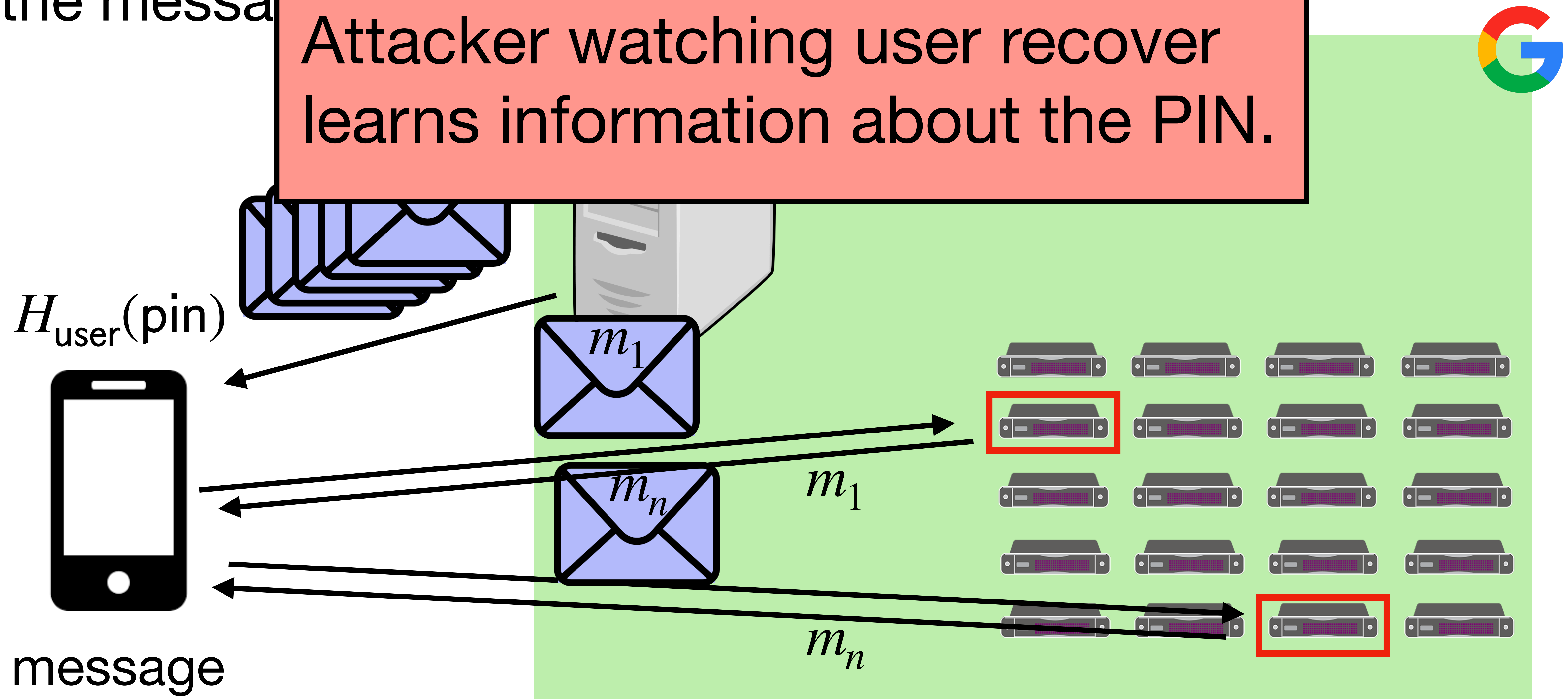
Attacker watching user recover learns information about the PIN.



Outline

1. **SafetyPin design**
    - ~~Overview~~
    - **Scalable rate-limiting**

2. SafetyPin evaluation

Scalable rate-limiting

Each HSM must enforce a global PIN attempt limit for every user.

Problem: Introduces a scalability bottleneck.

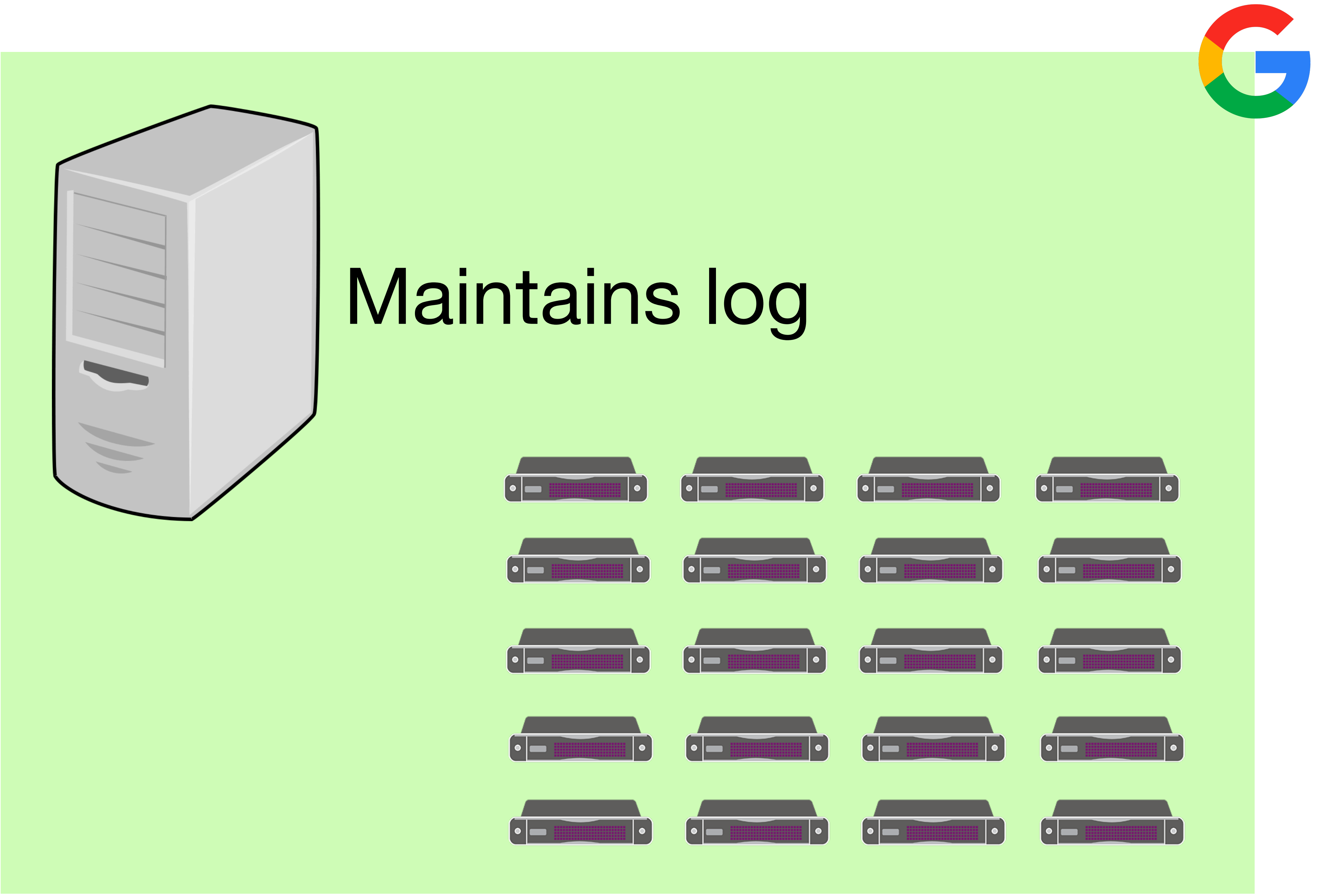
Tool: Public append-only log maintained by HSMs.

[Simplified version that allows a single recovery attempt]

Distributed log design

Log structured as set of **key-value pairs.**

Core invariant: If a HSM accepts (key, value), it will not accept (key, value’) where value != value’.



Each HSM stores log digest

Distributed log design

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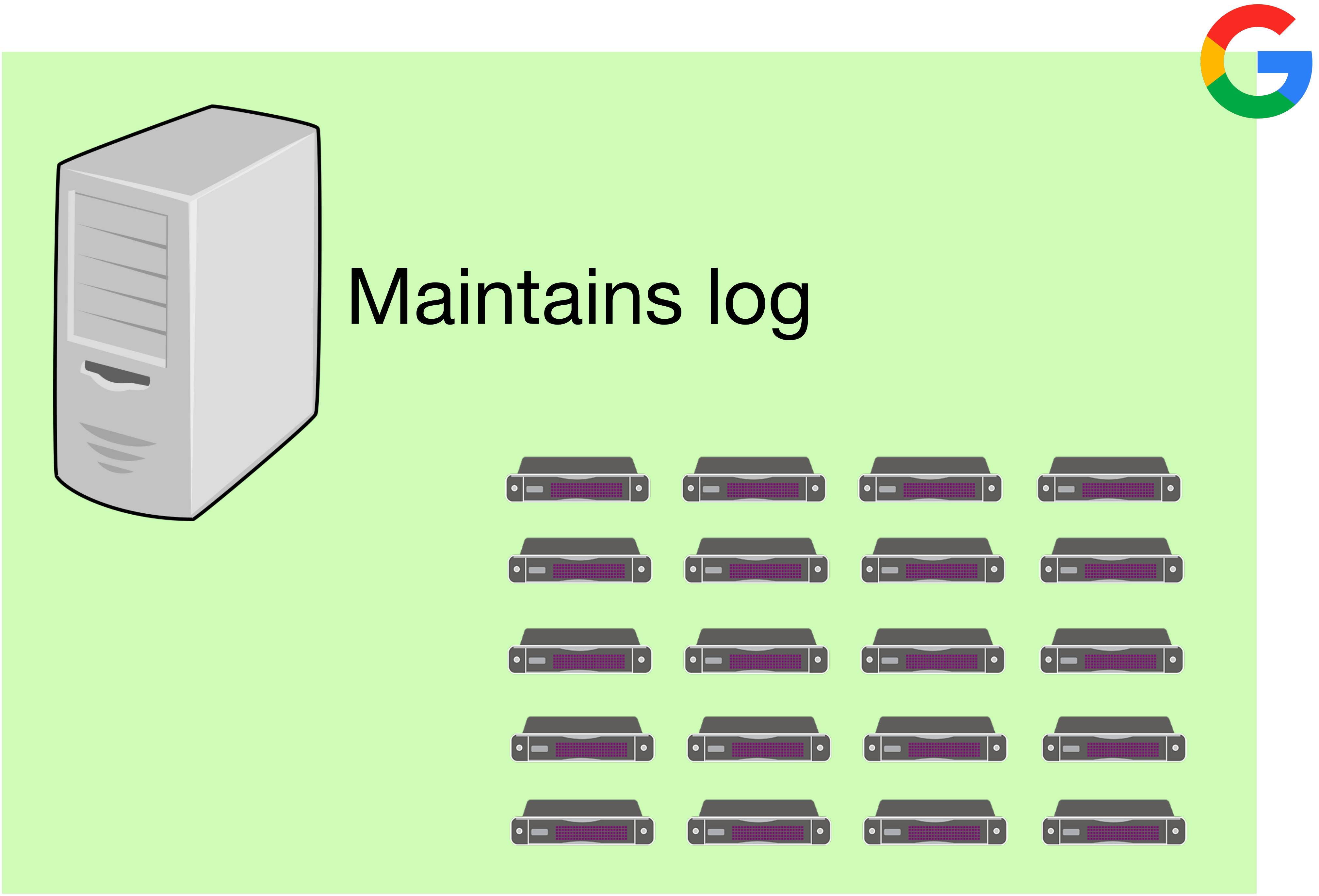


Each HSM stores log digest

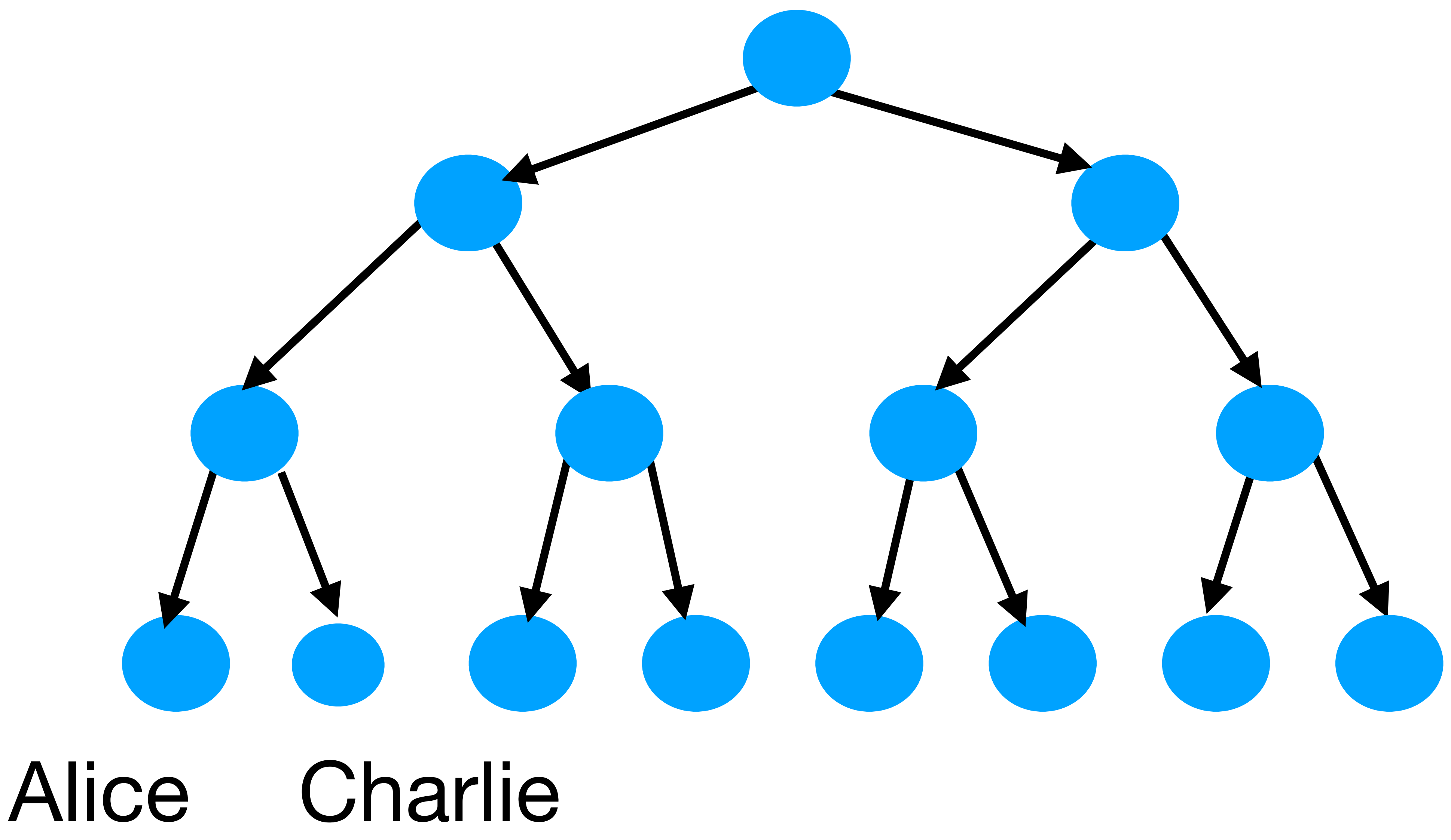
Core invariant: If a HSM accepts (key, value), it will not accept (key, value') where value != value'.

Application: scalable-rate limiting
Each key is a username, and each value commits to a recovery attempt.

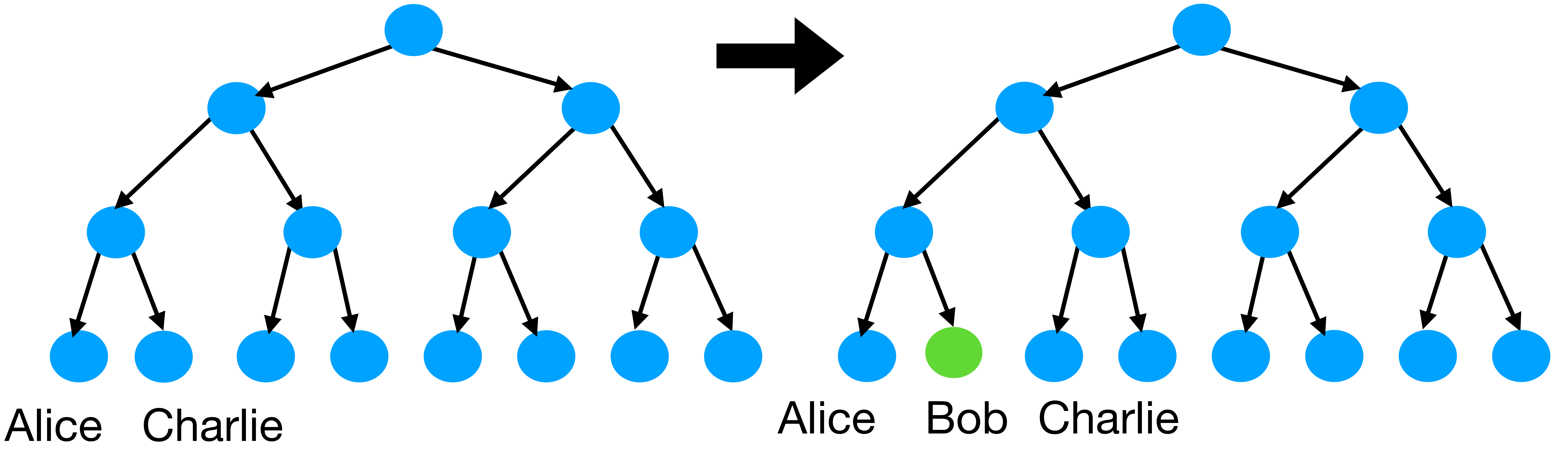
Distributed log implementation

Log structured as a binary search tree

- ordered by key (username), where
- leaves are values (commitments to recovery attempts).



Updating the log



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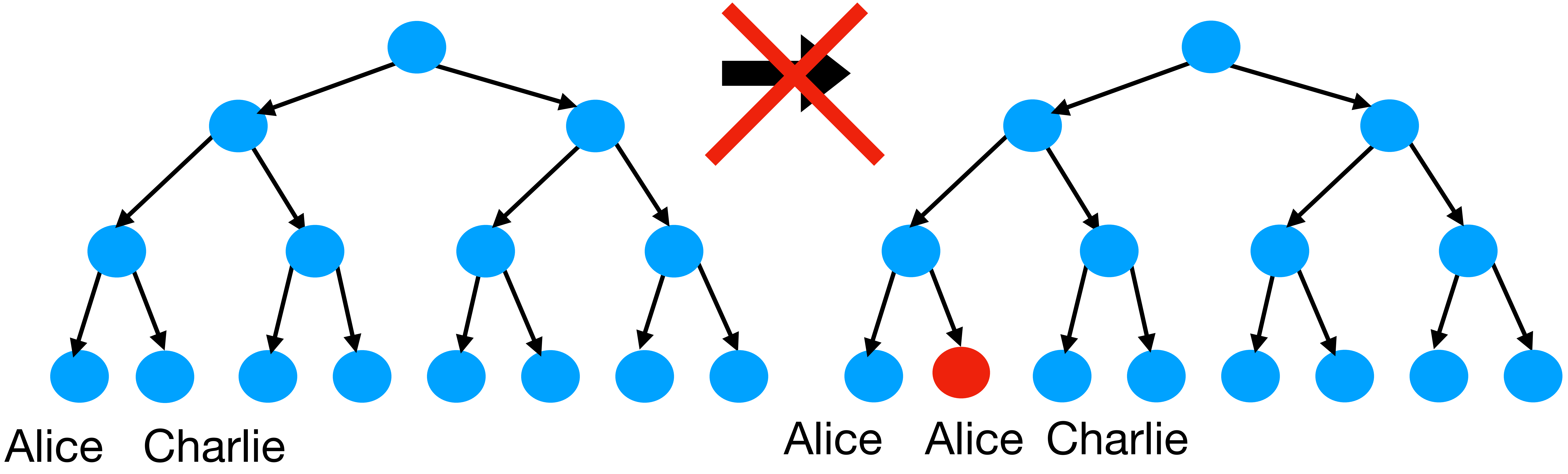


Core invariant: If a HSM accepts (key, value), it will not accept (key, value’) where value != value’.

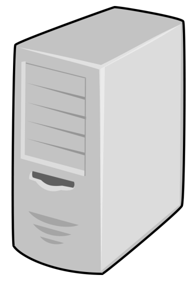
Updating the log

Periodically, service provider

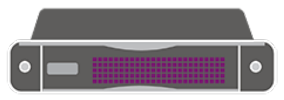
- computes a Merkle tree over the leaves, and
- sends a new Merkle root to the HSMs.

HSMs must check that the new log head extends the old log head.

Updating log digest at the HSMs with distributed auditing



Data center

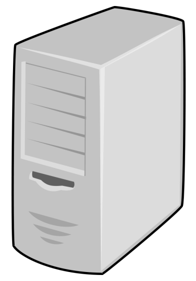


HSM

Old log L, new log L'

Old digest d, new digest d'

Updating log digest at the HSMs with distributed auditing



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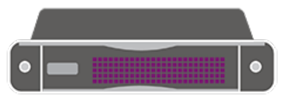

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Divide updates into N chunks.

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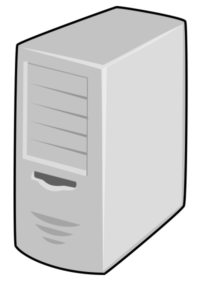

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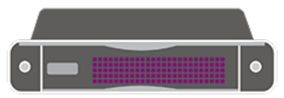

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Request $\lambda \approx 128$ chunks

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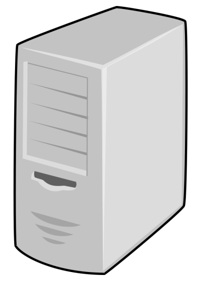

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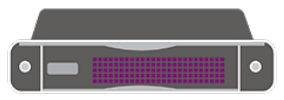

HSM

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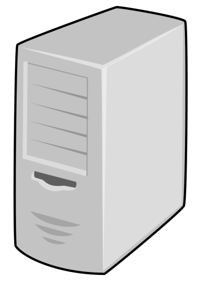
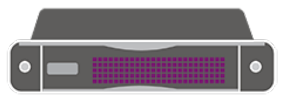
Updating log digest at the HSMs with distributed auditing

 Data center

 HSM

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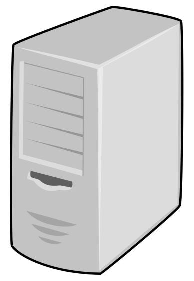
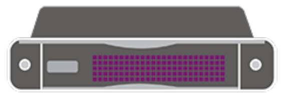
Signature

Updating log digest at the HSMs with distributed auditing

 Data center

 HSM

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Signature

Aggregate signatures from all HSMs [BGLS03].

Old digest d, new digest d'

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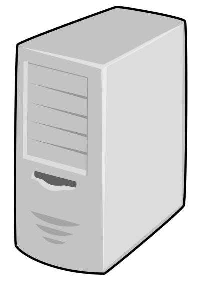
Updating log digest at the HSMs with distributed auditing



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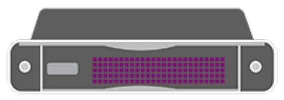

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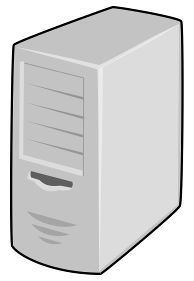
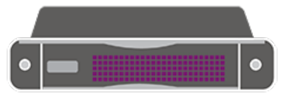
Aggregate signature

Updating log digest at the HSMs with distributed auditing

 Data center

 HSM

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Divide updates into N chunks.

Old digest d, new digest d'

Request $\lambda \approx 128$ chunks $\longleftrightarrow$

If each requested chunk keeps ≤ 1 recovery attempt per user, sign new digest d'.

$\longleftarrow$ Signature

Aggregate signatures from all HSMs [BGLS03].

Aggregate signature $\longrightarrow$

If signature verifies, accept new digest d'.

Distributed auditing properties

- **Scalability:** Each HSM checks $\lambda \approx 128$ chunks and verifies one signature.
- **Security:** The attacker corrupts the log undetected with probability 2^{-128}.
- **Transparency**:
  - **Clients** can **monitor recovery attempts** made on their behalf.
  - **External auditors** can audit the log.
    - An attacker that later compromises all HSMs can’t erase evidence.

Making SafetyPin practical for resource-limited hardware (see paper)

At recovery, the attacker sees which HSMs to compromise to obtain backup.

- **Challenge:** Revoking ability to decrypt requires large HSM secret keys
- **Idea:** Outsourced storage with secure deletion

Outline

~~1. SafetyPin design~~

- ~~Overview~~
- ~~Scalable rate-limiting~~

2. SafetyPin evaluation

Implementation setup

https://github.com/edauterman/SafetyPin

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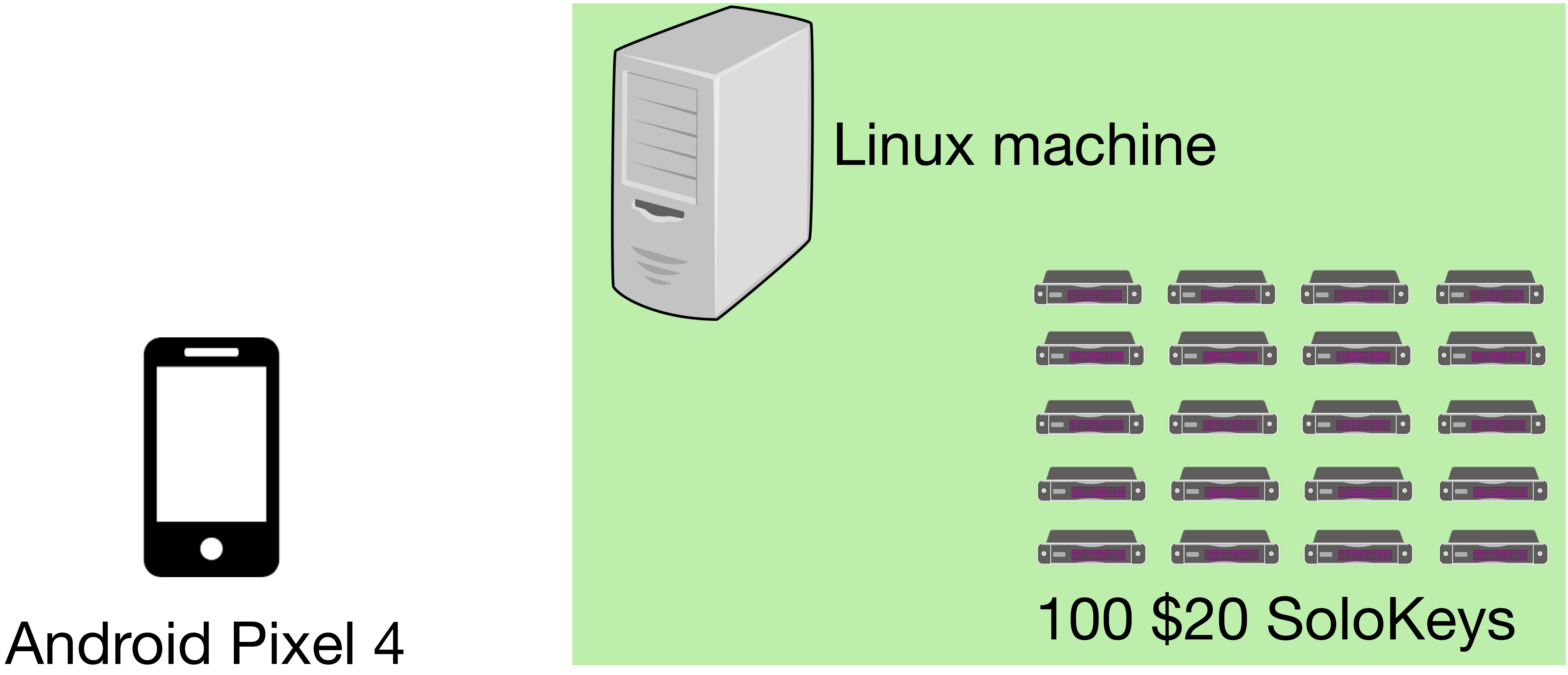

100 SoloKeys = slice of cluster that can process 1B recoveries/year

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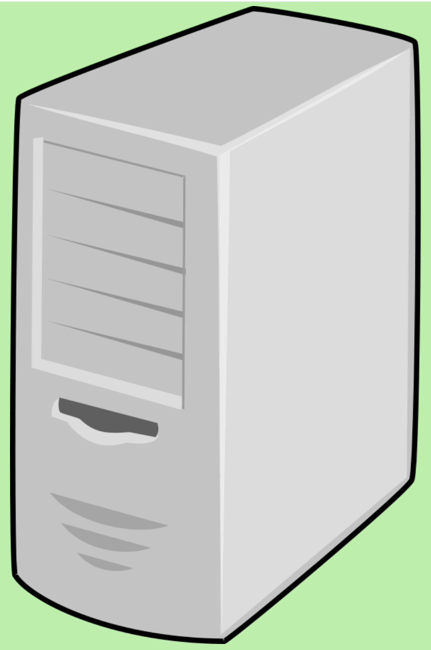
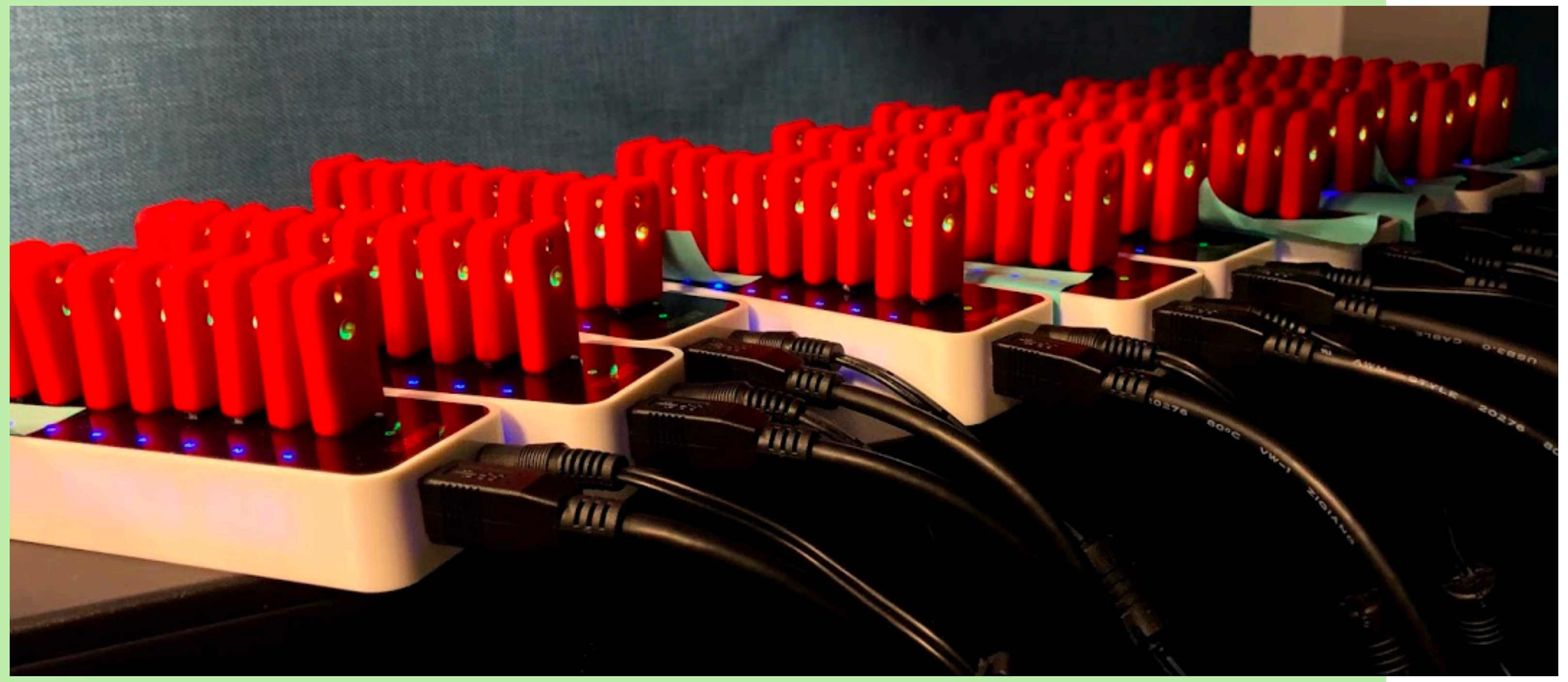
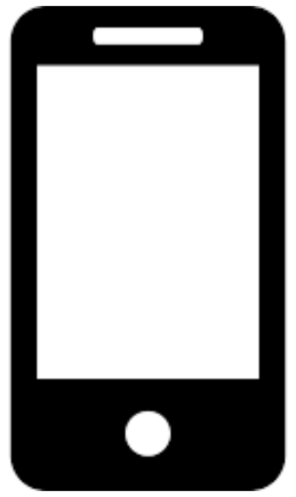


Linux machine



100 $20 SoloKeys



Android Pixel 4

100 SoloKeys = slice of cluster that can process 1B recoveries/year

Evaluation summary: experimental results

Overhead with resource-limited HSMs

- Recovering a backup takes 1.01s.

Client cost

- Generating a recovery ciphertext takes 0.37s.
- Client must download 2MB of HSM keys each day.

Evaluation summary: system estimates

Total system cost

- Supporting 1B recoveries per year costs
  - $61K with SoloKeys (hardware we used), and
  - $15M with high-quality HSMs.
- Cost of storing 4GB for 1B users: $600M.

Secure hardware doesn't need to be trusted hardware

- Today, secure hardware is often a single point of failure.
  - This doesn’t have to be the case.
- We should never settle for reduced security.
  - Computational limits of HSMs are not an excuse.

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Thanks!

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References

[BGLS] Dan Boneh, Craig Gentry, Ben Lynn, and Hovav Shacham. Aggregate and verifiably encrypted signatures from bilinear maps. In *EUROCRYPT*, pages 416–432. Springer, 2003.