Boomerang: Metadata-private Messaging under Hardware Trust

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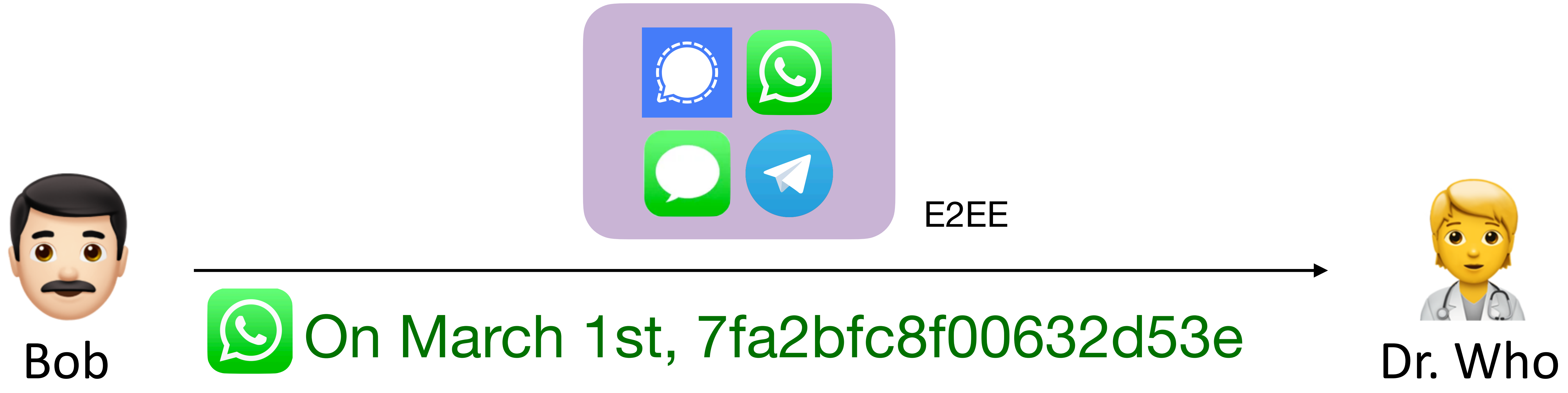
E2EE protects only payload, NOT metadata



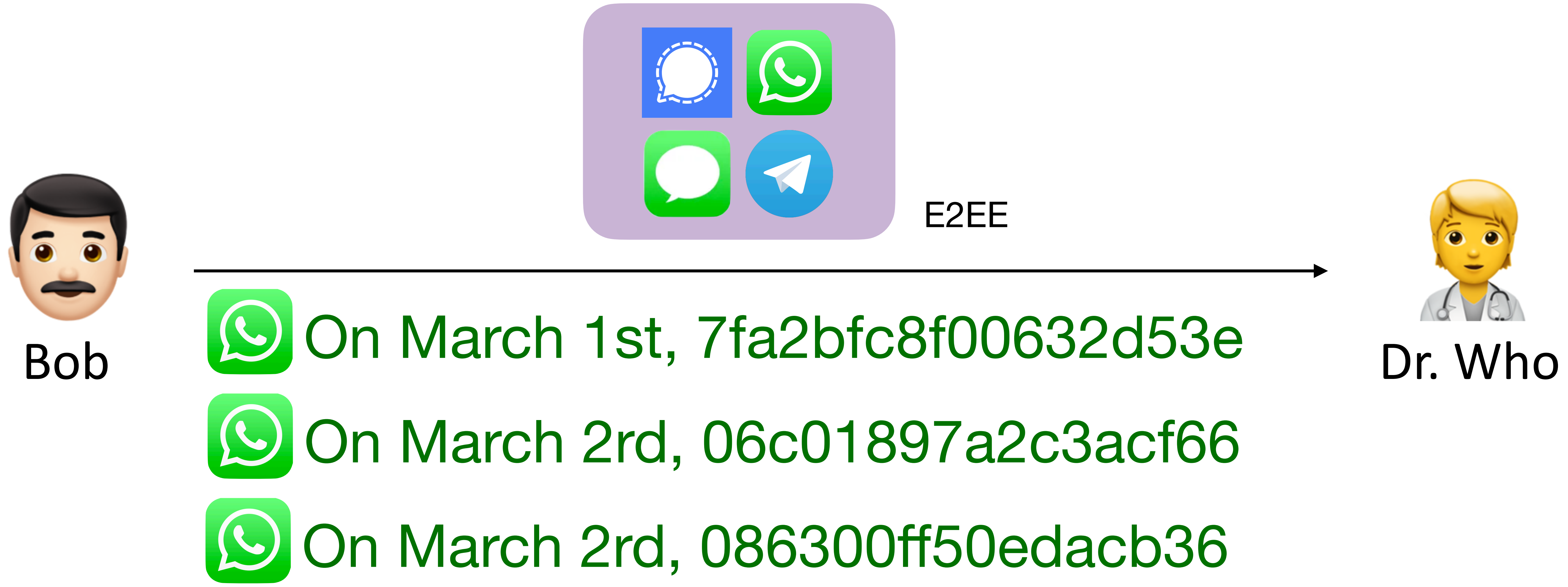
On March 1st, 7fa2bfc8f00632d53e

From: Bob
To: Dr. Who
Timestamp: 1647836660
Content: Doctor, I feel sick.

→ E2EE

From: Bob
To: Dr. Who
Timestamp: 1647836660
Content: 086300ff50edacb36

E2EE protects only payload, NOT metadata



On March 1st, 7fa2bfc8f00632d53e

On March 2rd, 06c01897a2c3acf66

On March 2rd, 086300ff50edacb36

From: Bob
To: Dr. Who
Timestamp: 1647836660
Content: Doctor, I feel sick.

→ E2EE

Exposed comm. metadata

From: Bob
To: Dr. Who
Timestamp: 1647836660
Content: 086300ff50edacb36

Metadata can be privacy-revealing

Sender identity

Receiver identity

Bob

Dr. Who

On March 1st, 7fa2bfc8f00632d53e

On March 2rd, 06c01897a2c3acf66

On March 2rd, 086300ff50edacb36

Time

Duration

Volume

Metadata can be privacy-revealing

Sender identity

Receiver identity

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Dr. Who

On March 1st, 7fa2bfc8f00632d53e

On March 2rd, 06c01897a2c3acf66

On March 2rd, 086300ff50edacb36

Time

Duration

Volume

“Bob might have got some health condition.”

Who might see metadata?

- Your ISP sees your traffic data
- E2EE service providers
- Governments around the world
- Data brokers
- Advertisers
- …

whistleblowers

tracking general users

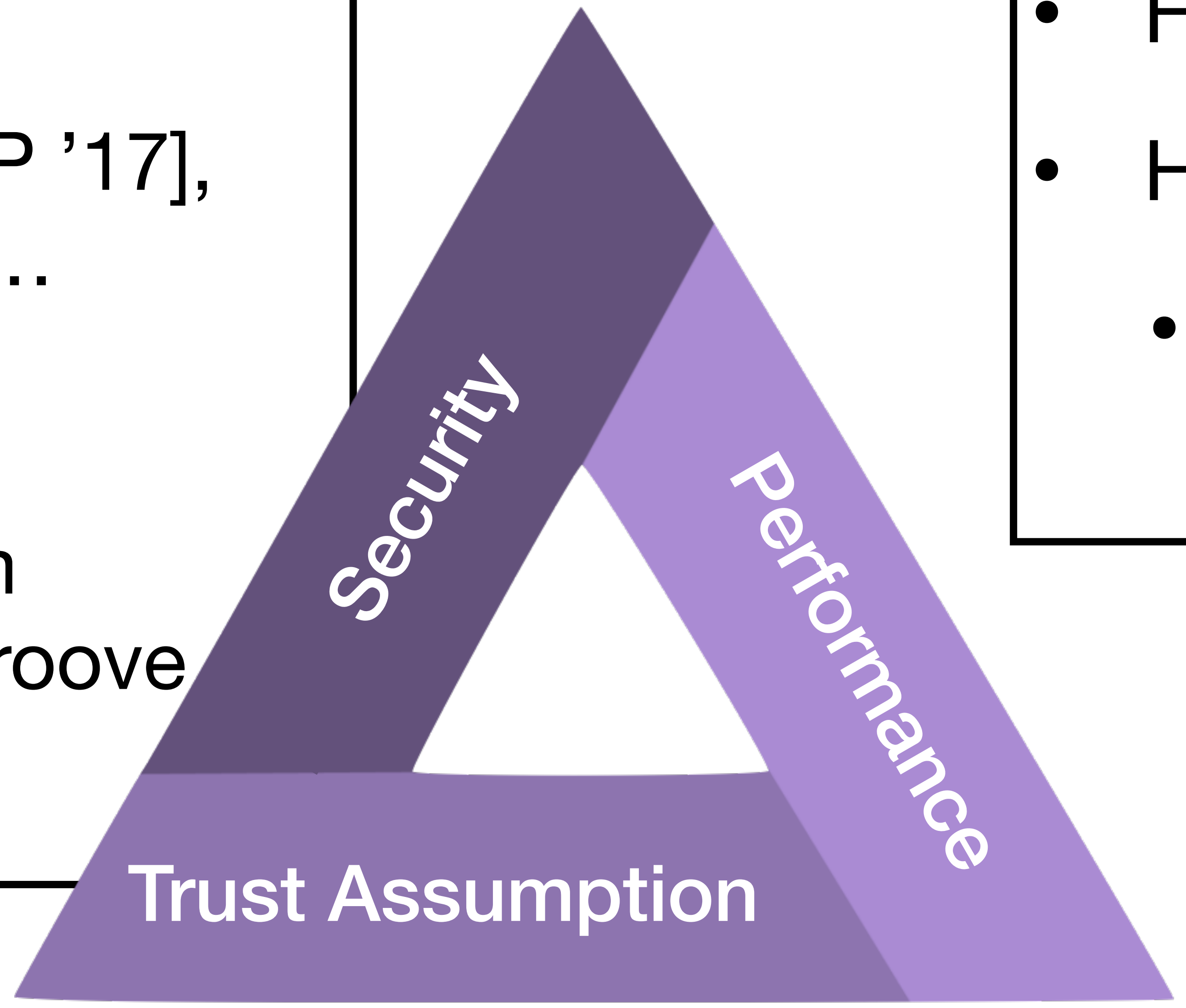
https://www.wired.com/story/opinion-data-brokers-are-a-threat-to-democracy/, April 13th, 2021

https://arstechnica.com/tech-policy/2021/03/t-mobile-will-tell-advertisers-how-you-use-the-web-starting-next-month/, March 10th, 2021

Progresses on metadata-private messaging

Balancing act among: security, performance, and trust assumption

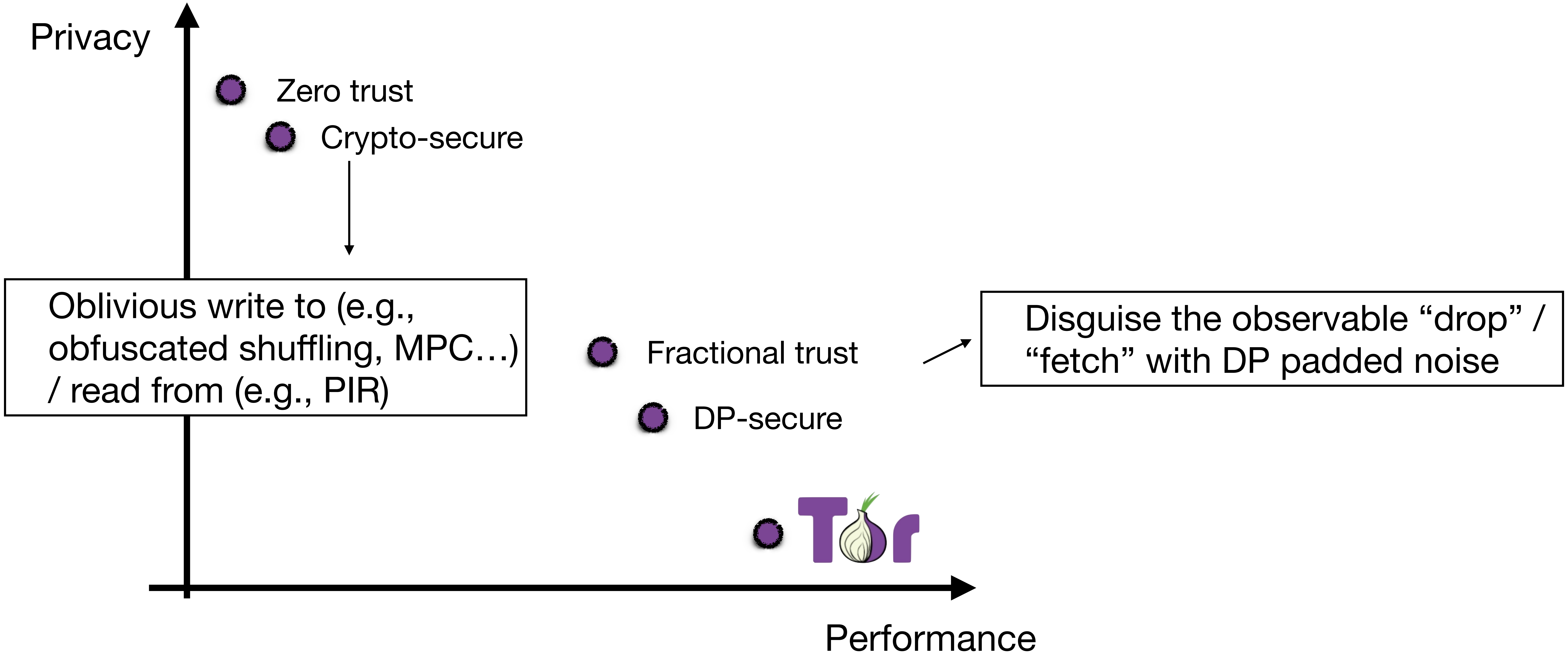
- Cryptographic security
  - E.g., Pung [OSDI ’16], Atom [SOSP ’17], XRD [NSDI ’20], Addra [OSDI’ 21]…
- Differential privacy security
  - E.g., Vuvuzela [SOSP’15], Stadium [SOSP’17], Karaoke [OSDI’ 18], Groove [OSDI ’22]…



- High throughput
- Horizontal scalability
  - E.g., Tor, Stadium [SOSP’17], Karaoke [OSDI’ 18], Yodel [SOSP’21]…

- Fractional trust
- Zero trust
  - E.g., Pung [OSDI ’16], Addra [OSDI ’21]…

Progresses on metadata-private messaging



Zero trust

Crypto-secure

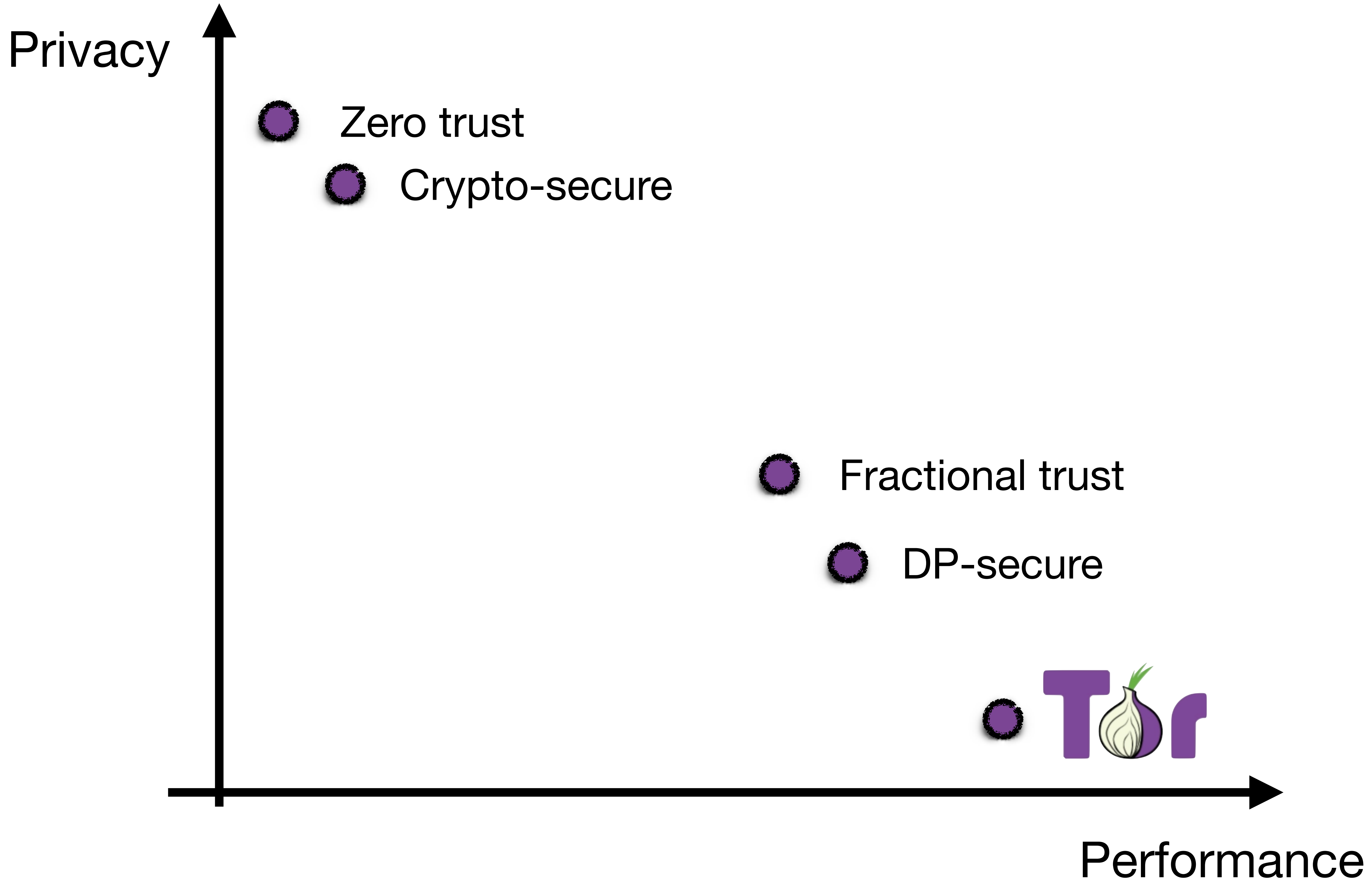
Oblivious write to (e.g., obfuscated shuffling, MPC…) / read from (e.g., PIR)

Fractional trust

DP-secure

Disguise the observable “drop” / “fetch” with DP padded noise

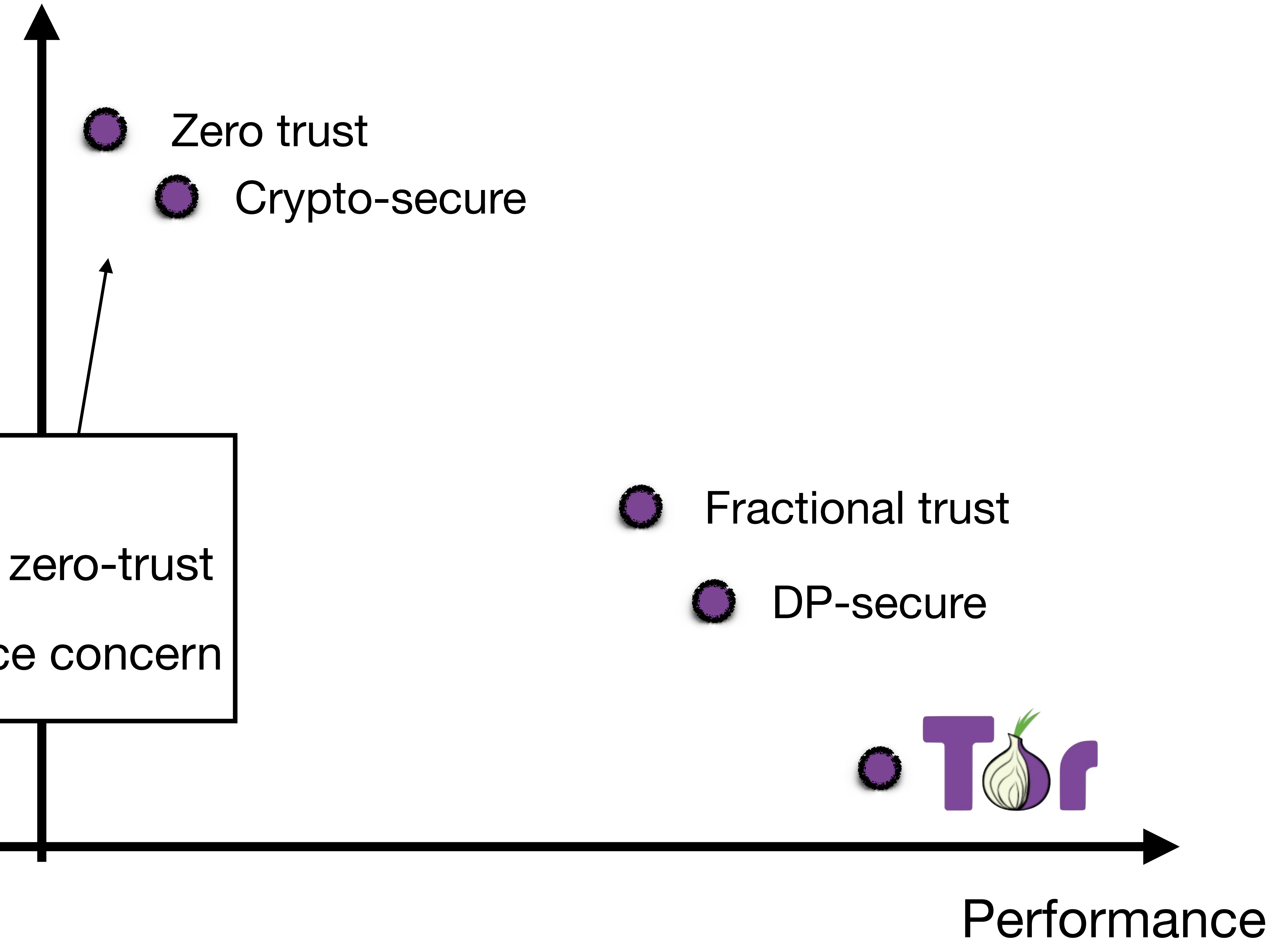
Motivation of Boomerang



Motivation of Boomerang

For whistleblowers

- Crypto secure & zero-trust
- Less performance concern



Privacy

Zero trust

Crypto-secure

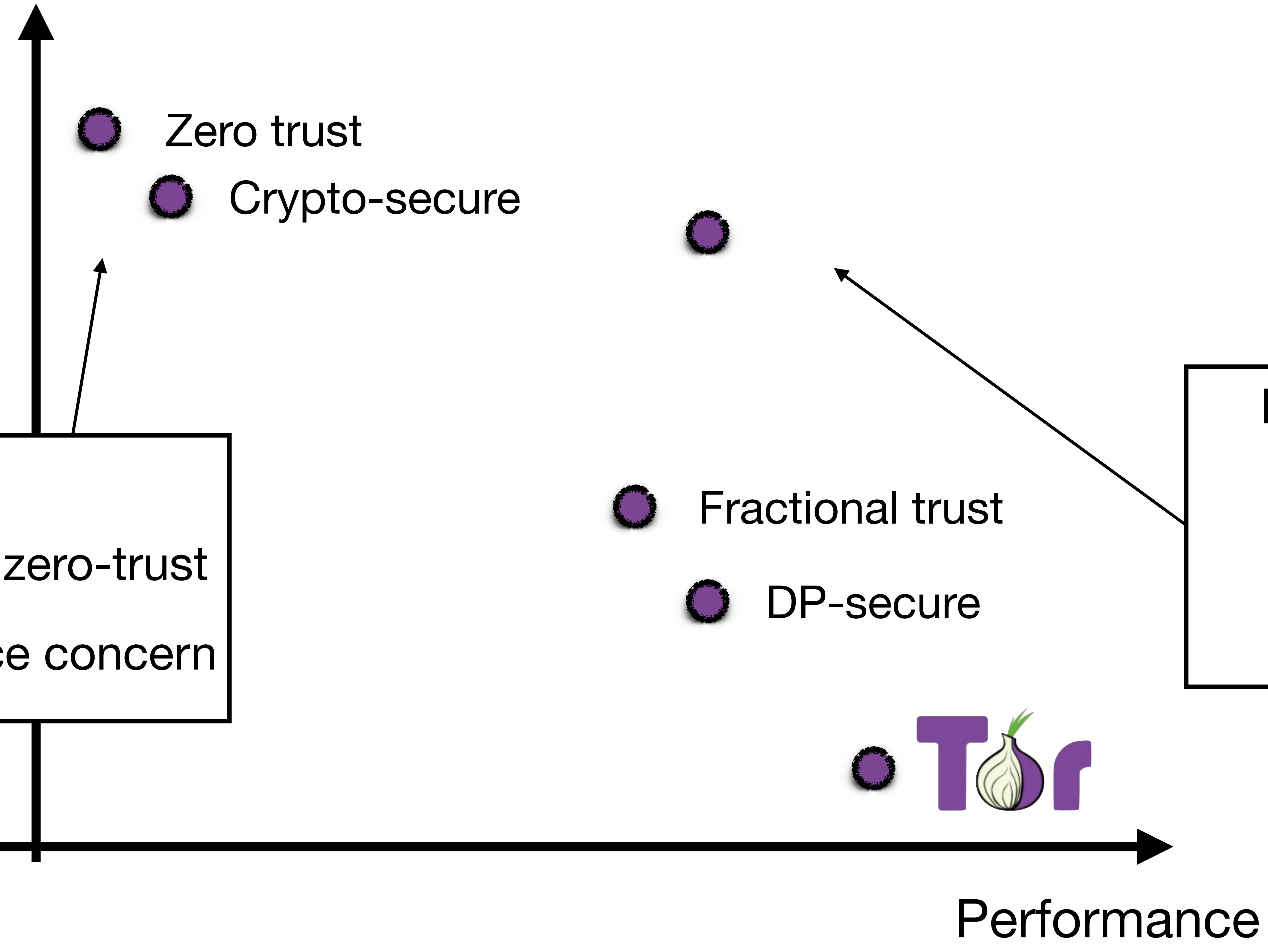
Fractional trust

DP-secure

Tor

Performance

Motivation of Boomerang



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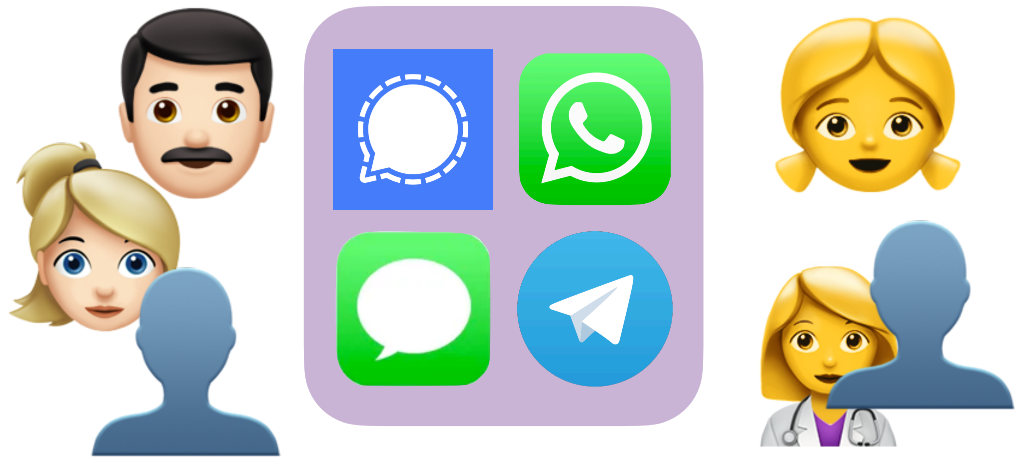

For mass general users

- More than E2EE messaging
- Lower operational cost and good performance

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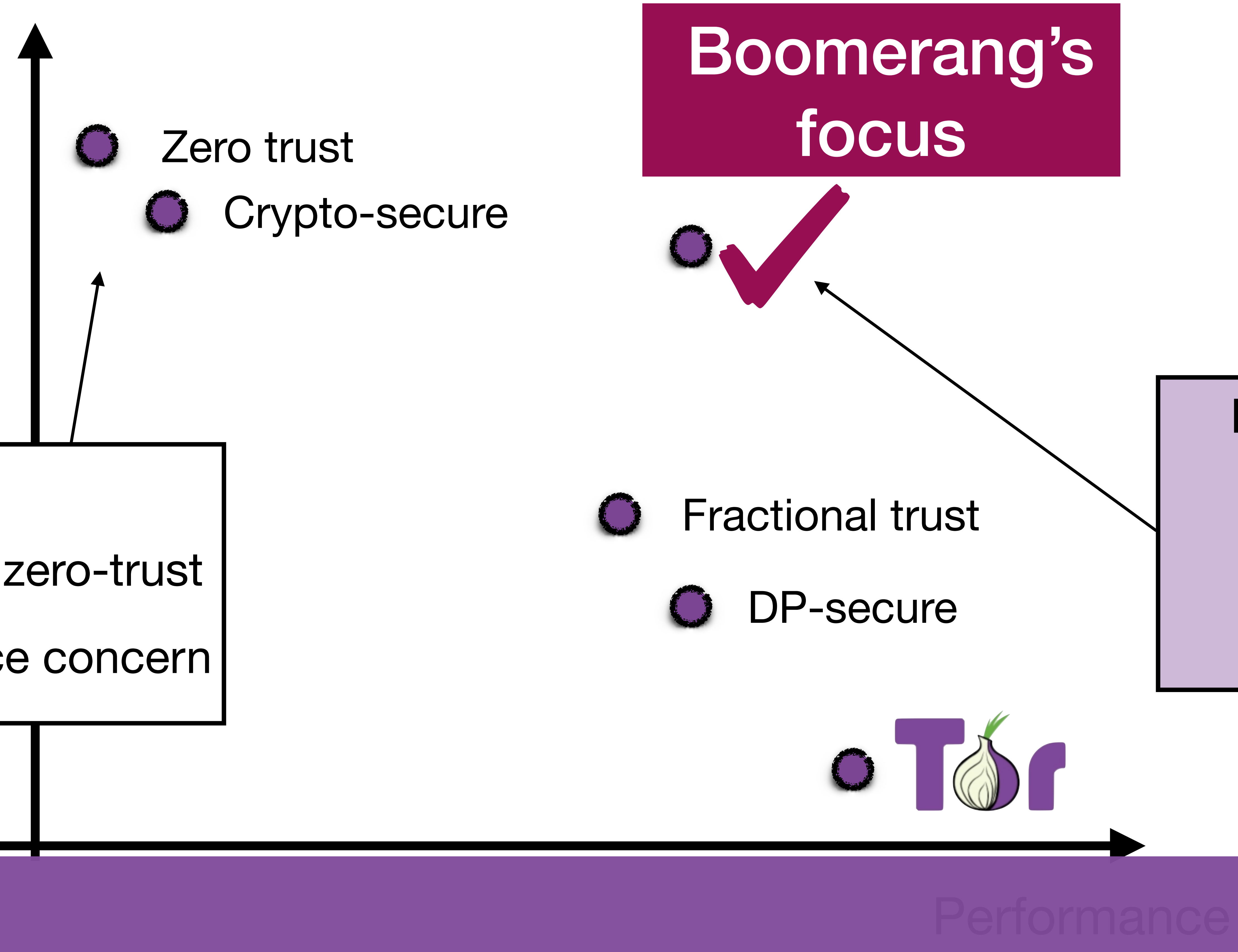
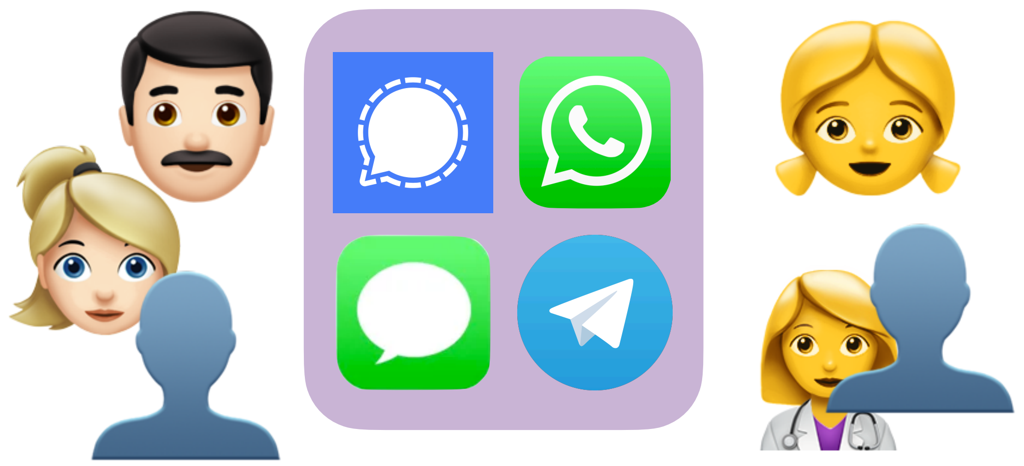


Boomerang's focus

For mass general users

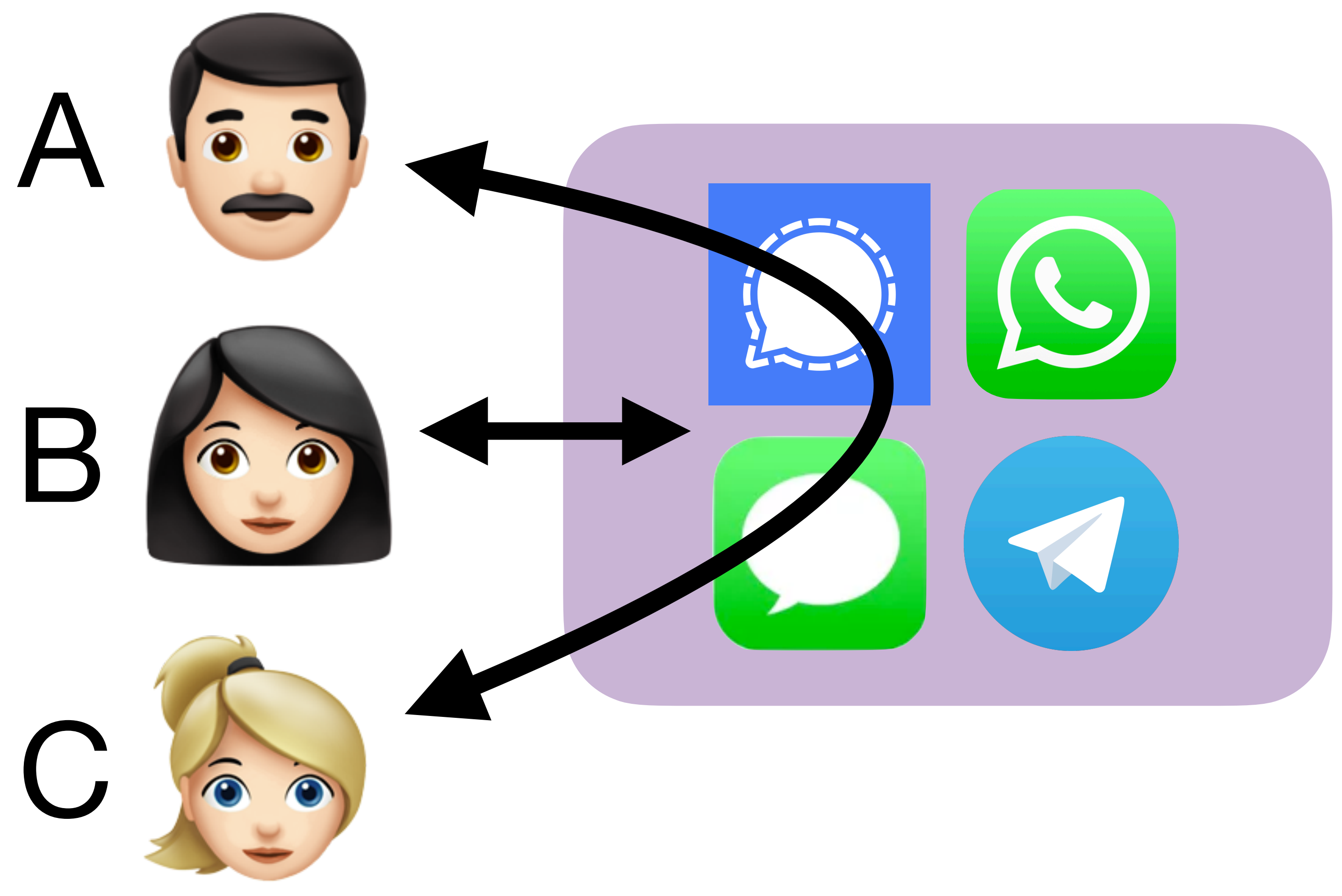
- More than E2EE messaging
- Lower operational cost and good performance



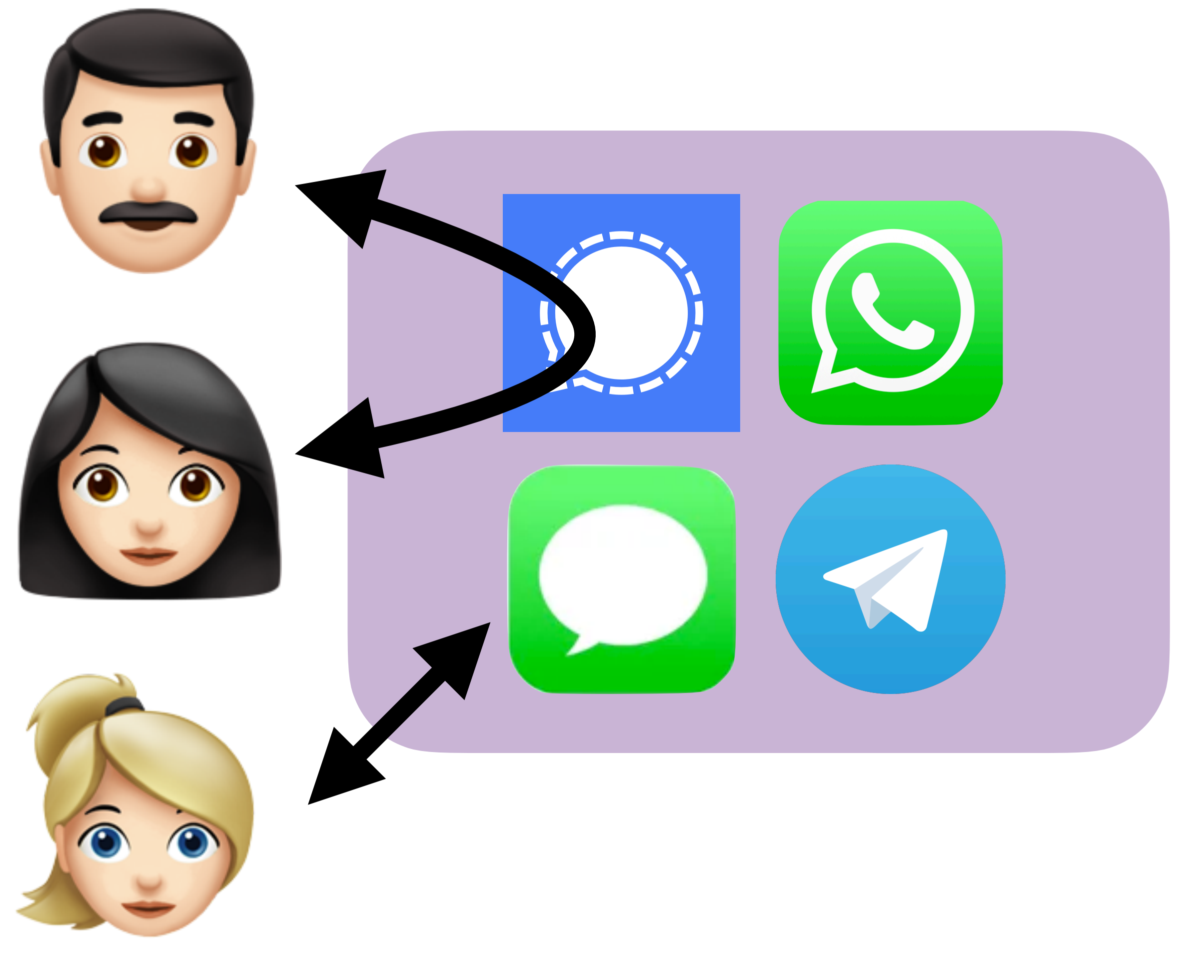
Boomerang: A performant system with cryptographic security under hardware trust

Metadata-private messaging: Goals & Threats

Goal: Hiding who is talking to whom



A talks to C



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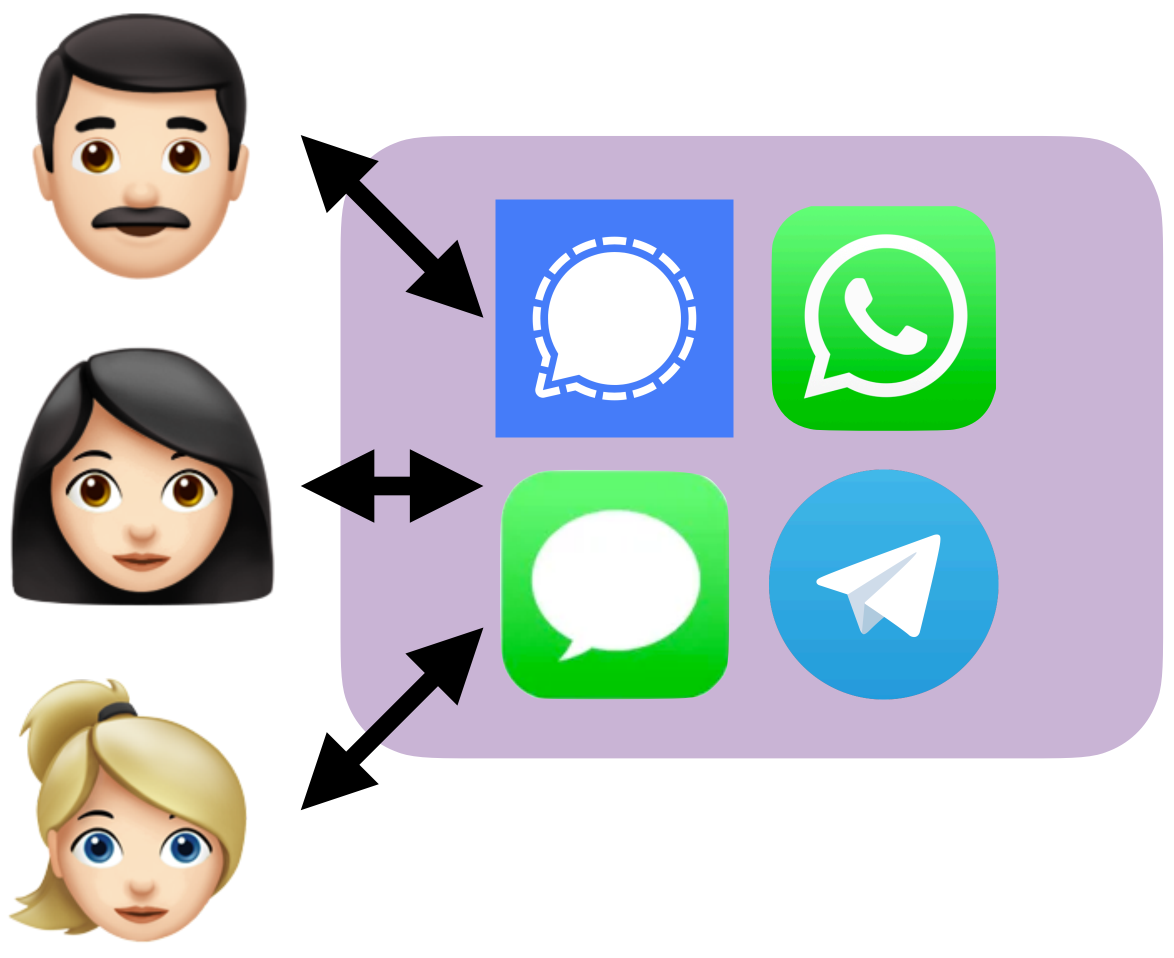

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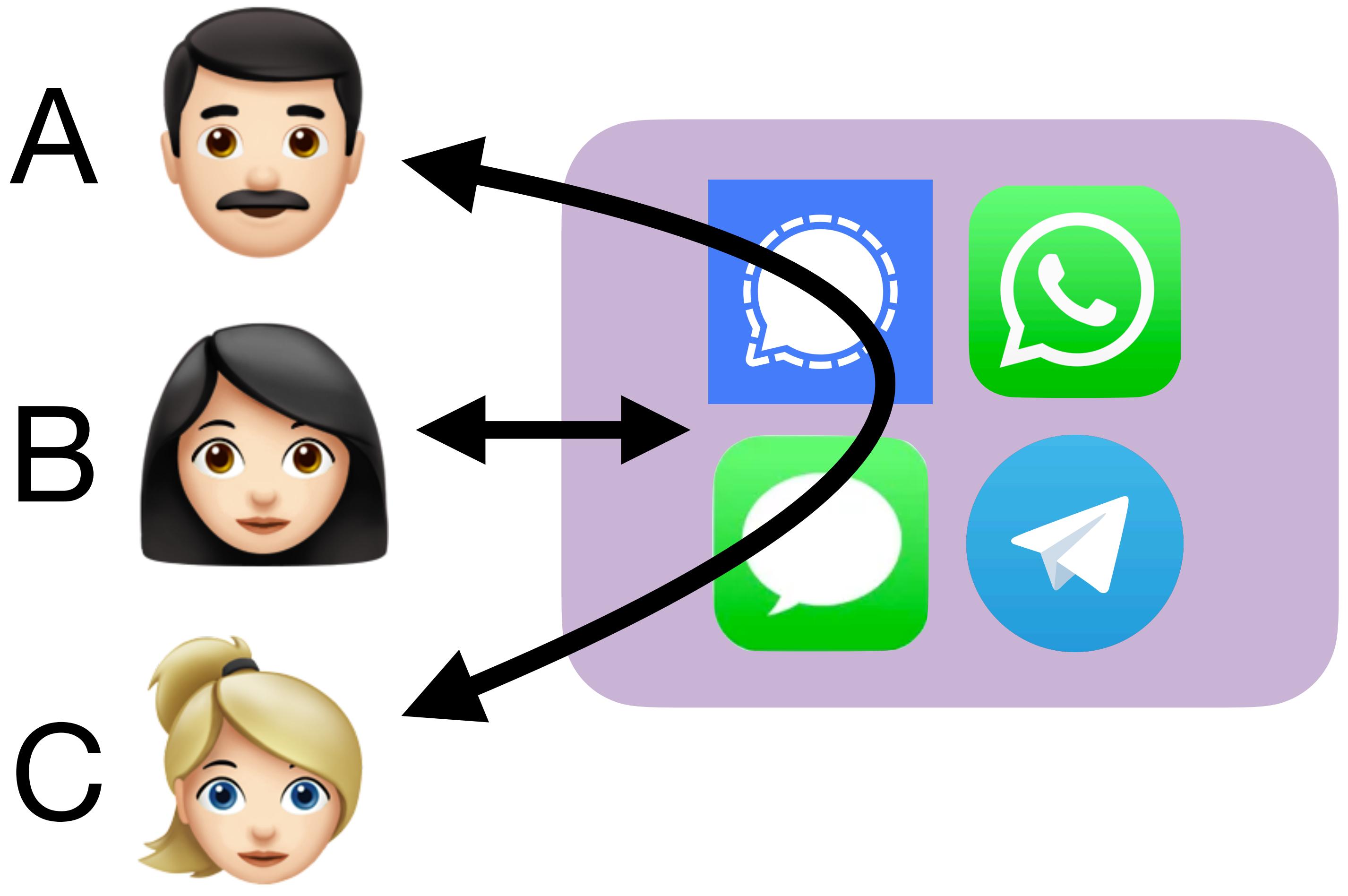

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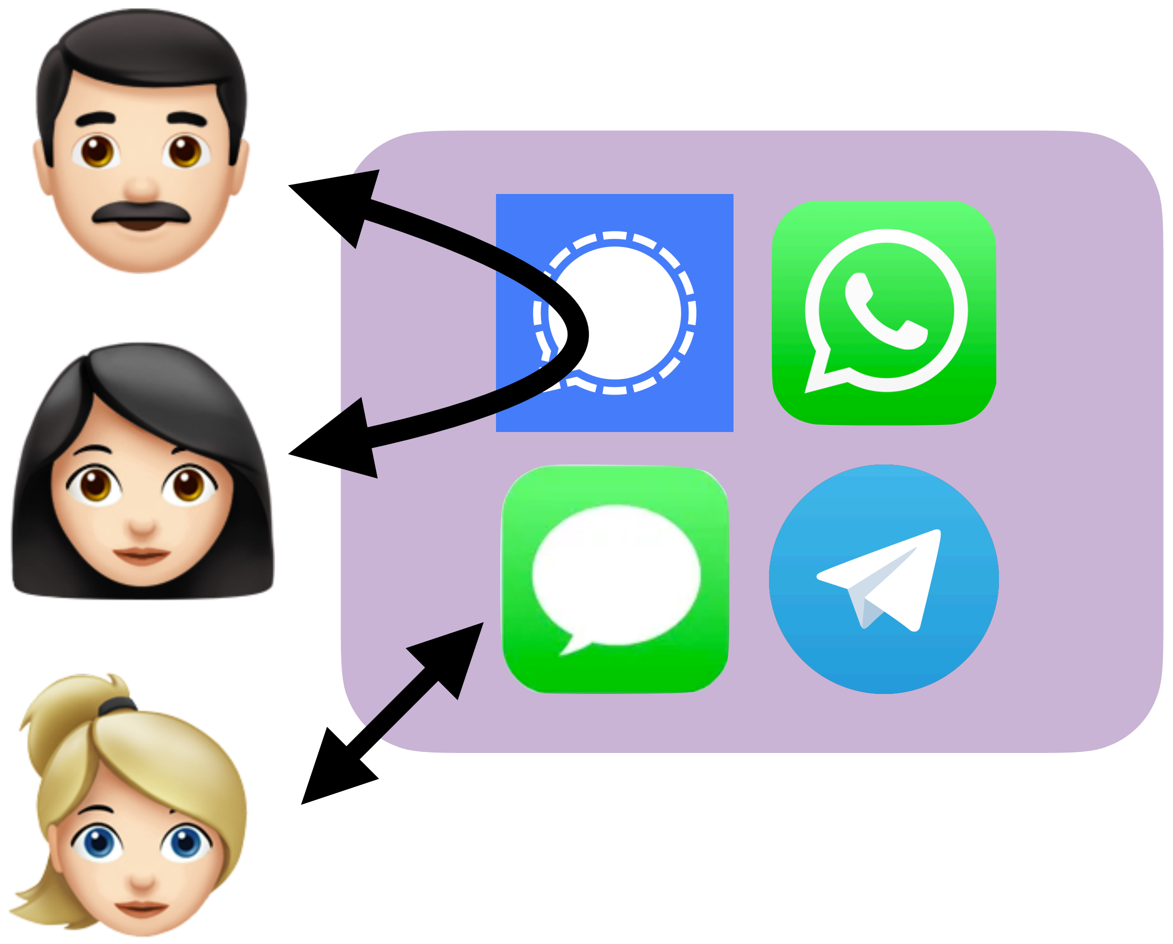

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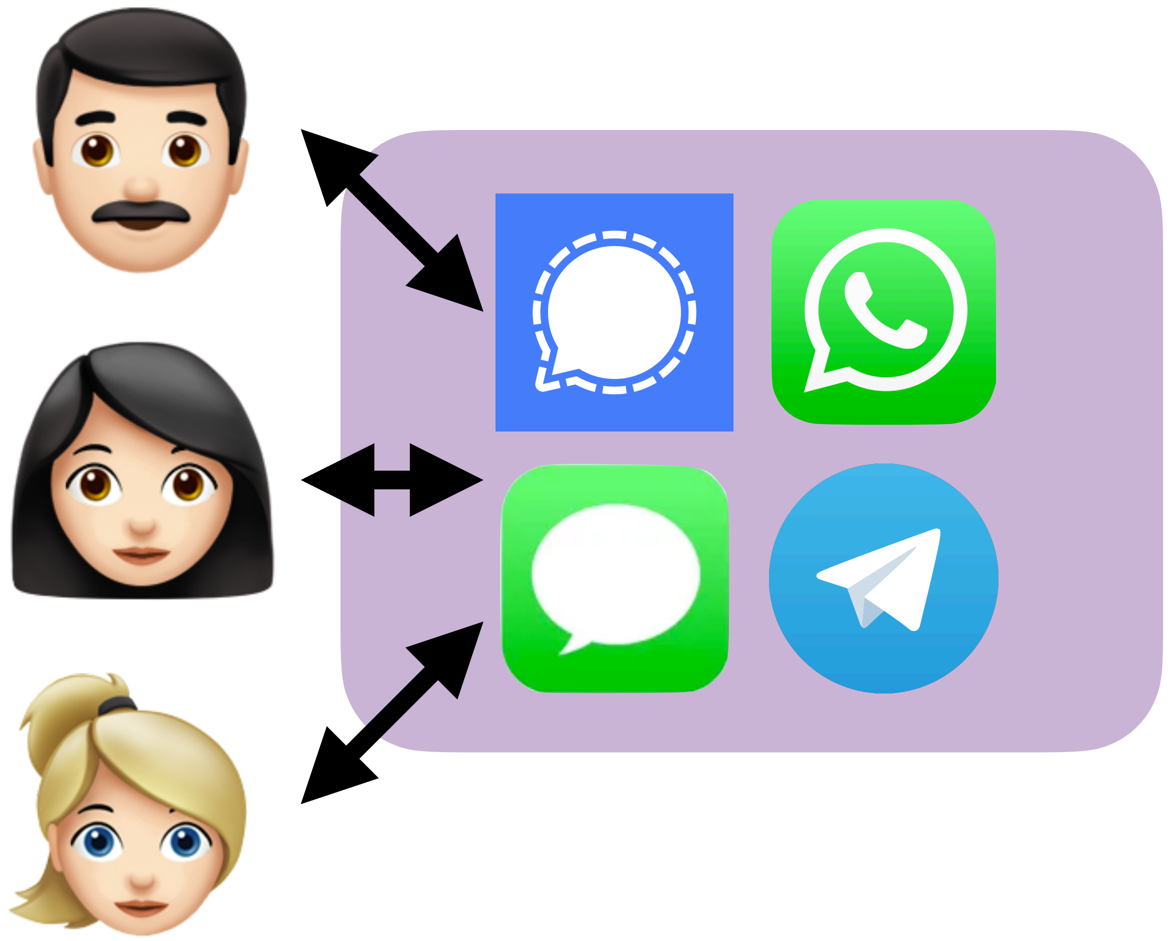

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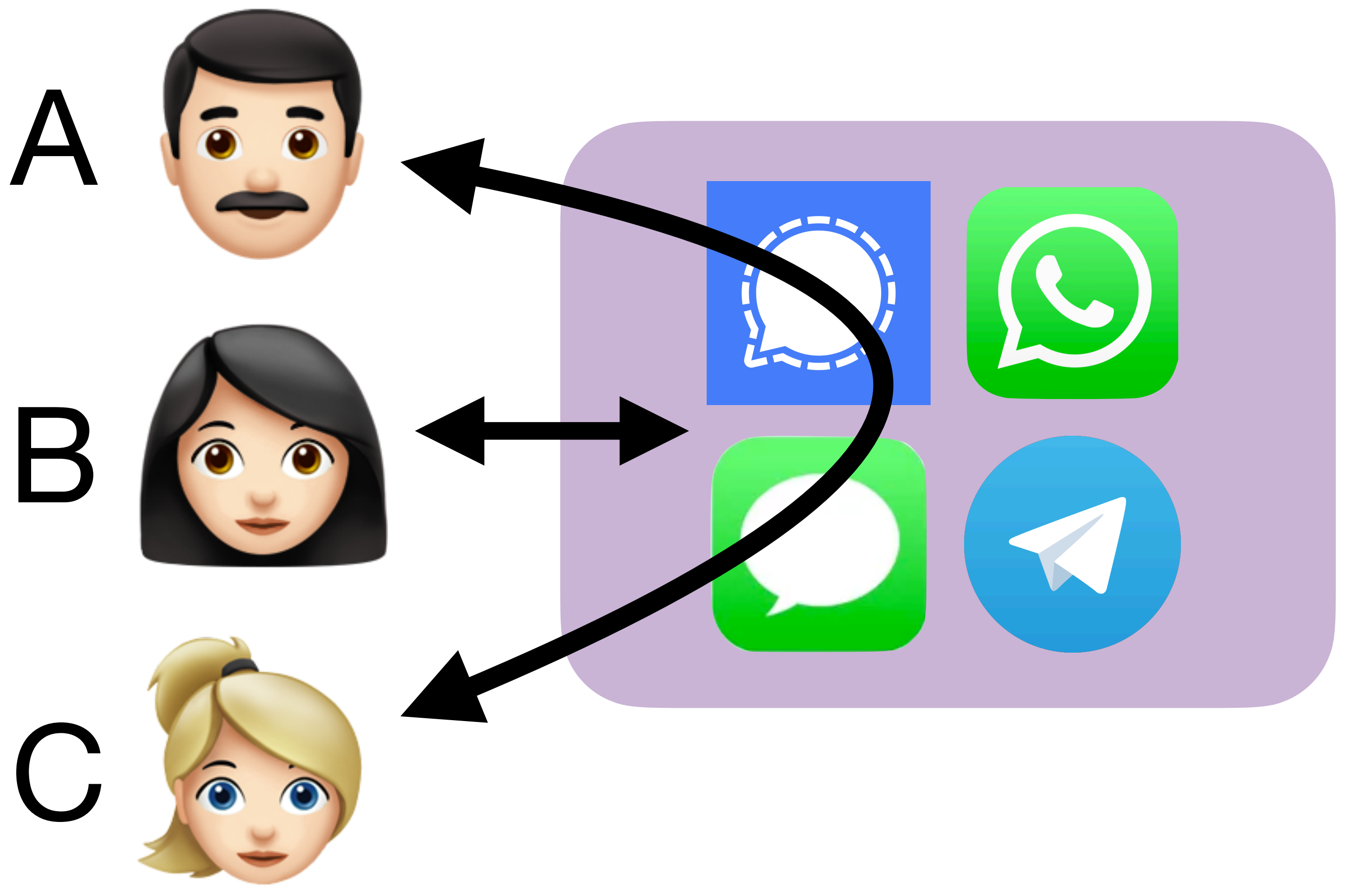

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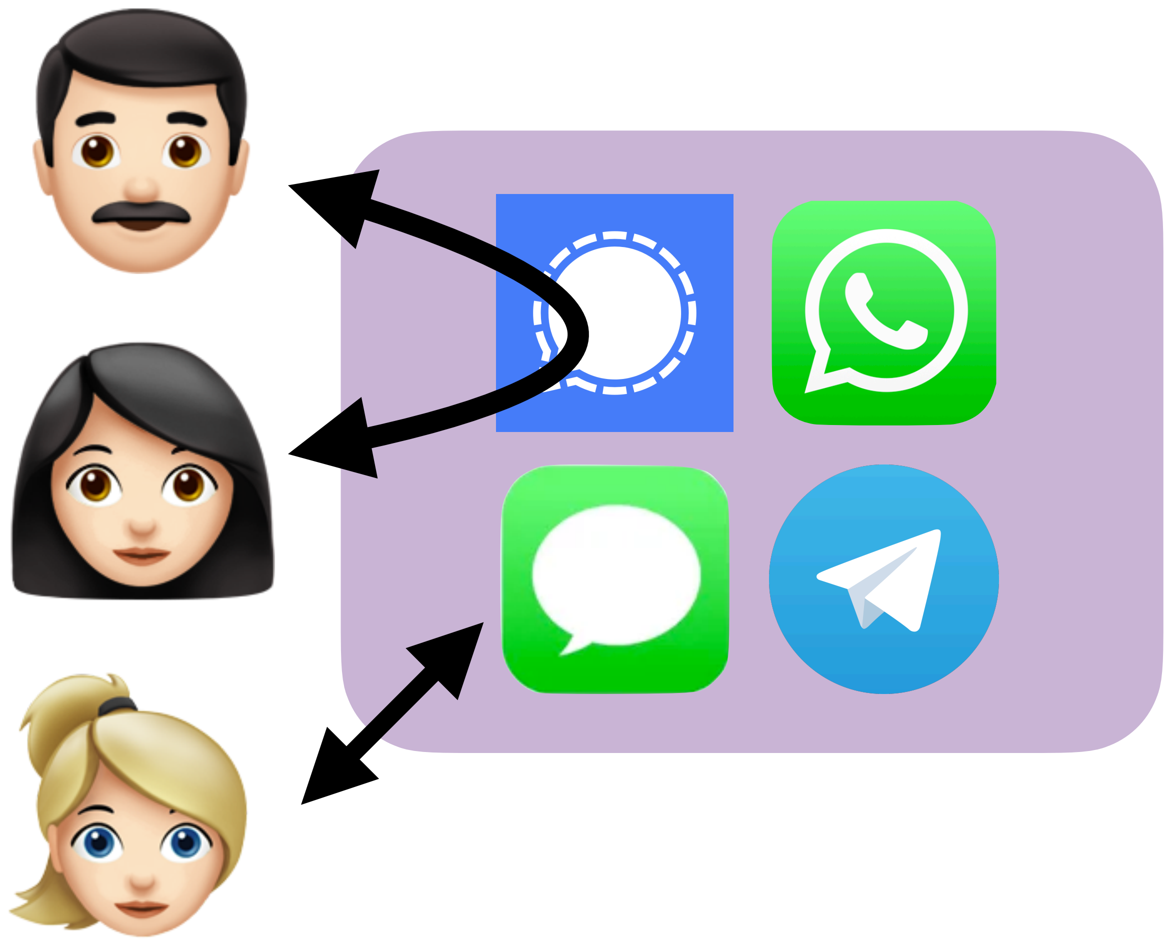

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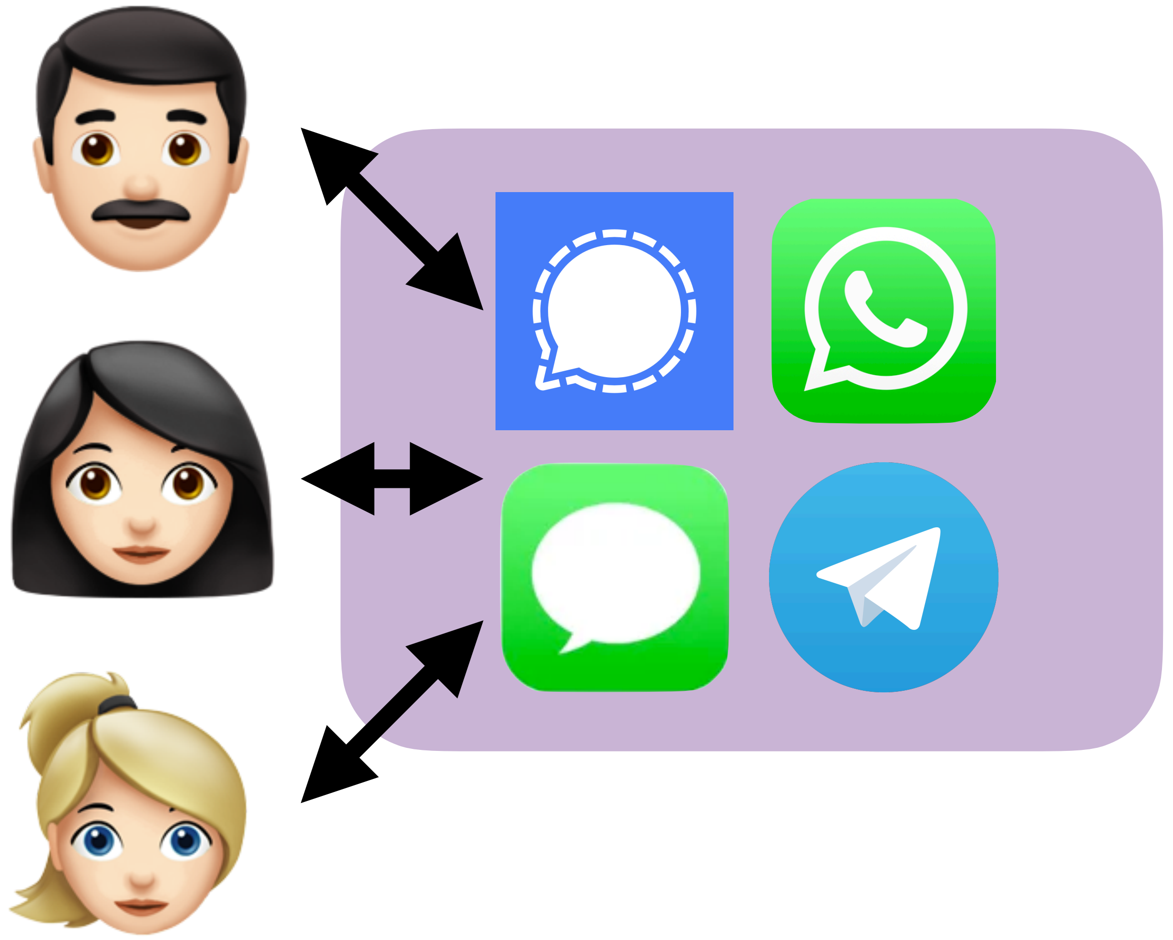

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Passive attackers

Metadata-private messaging: Goals & Threats

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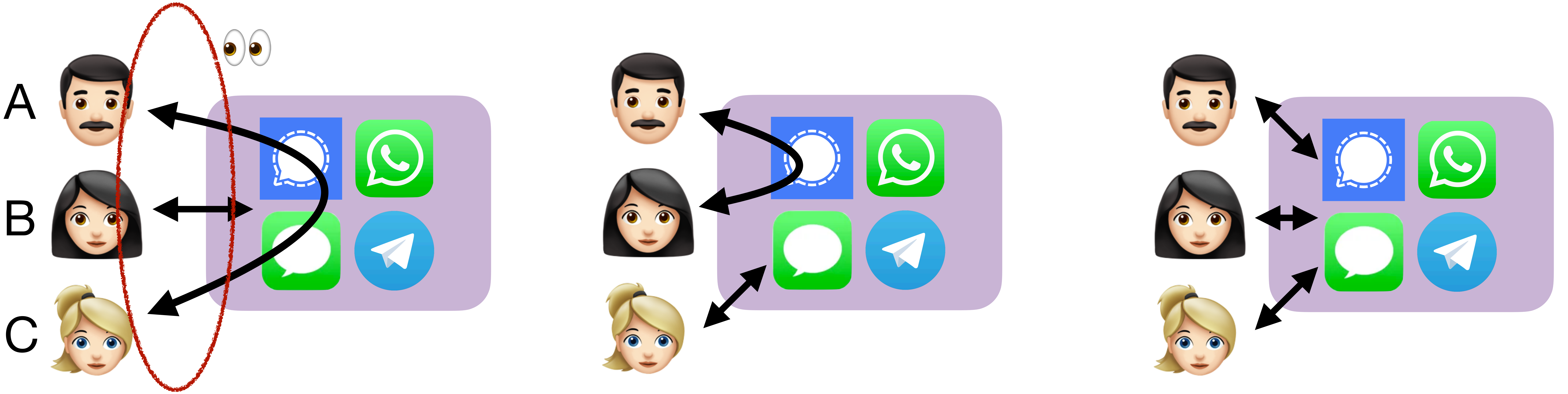

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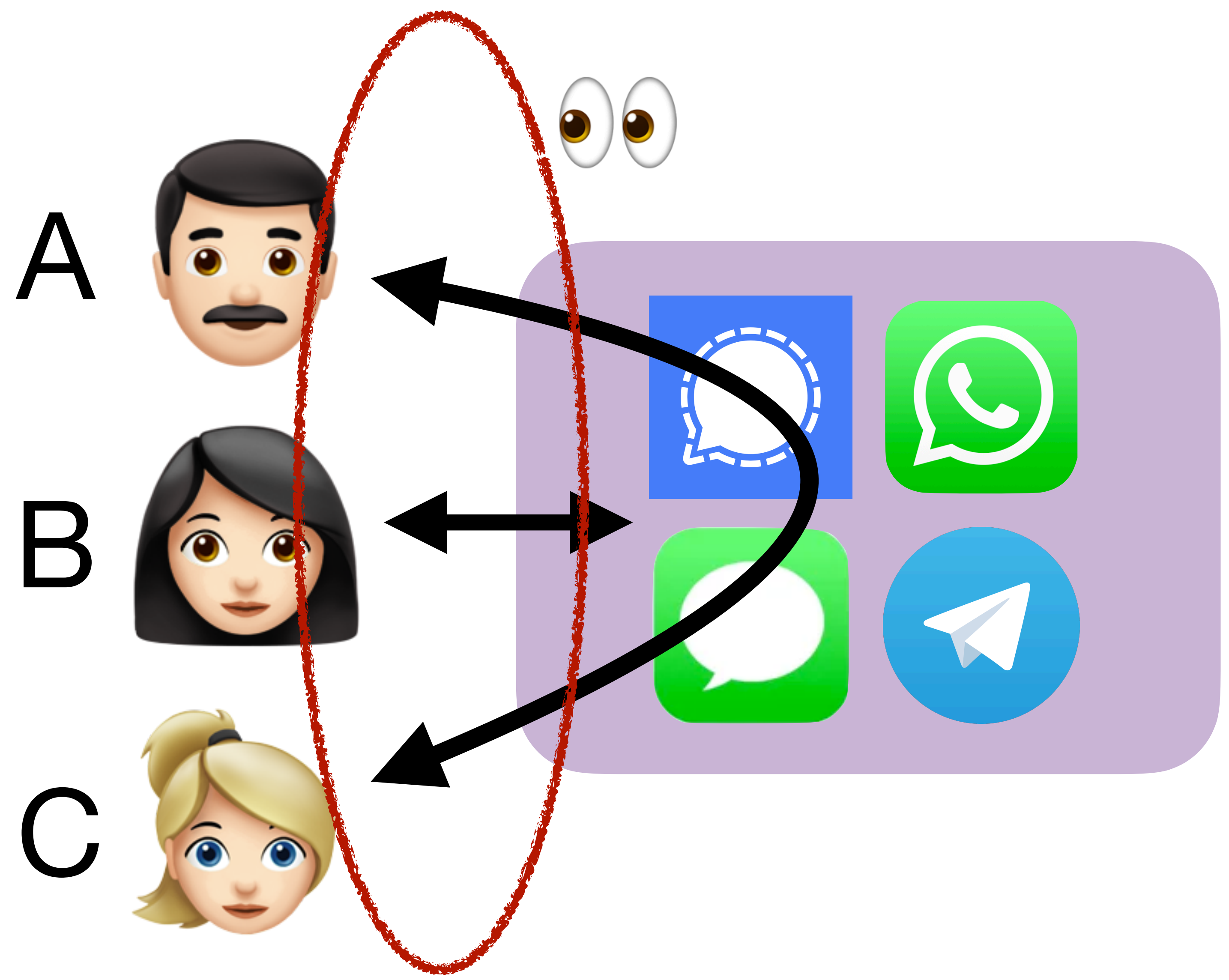

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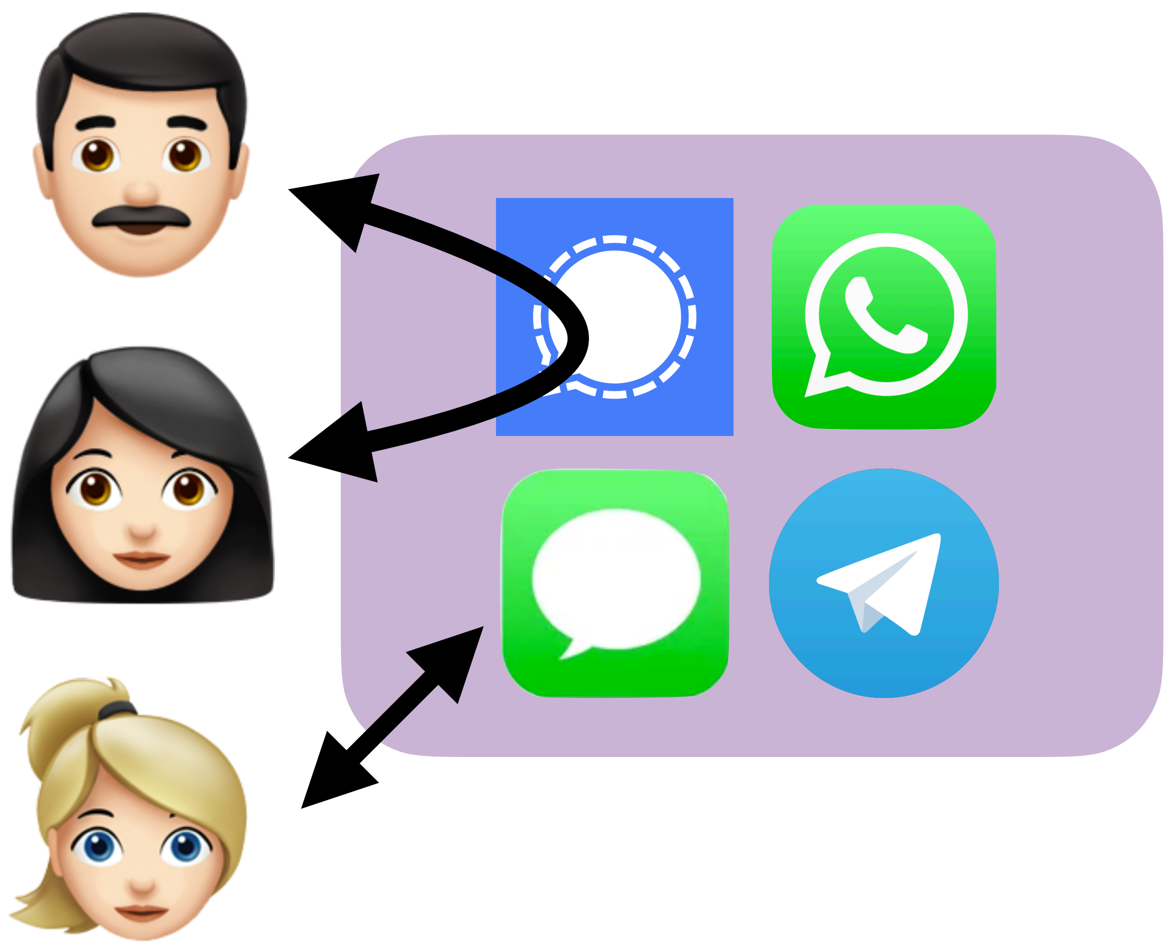

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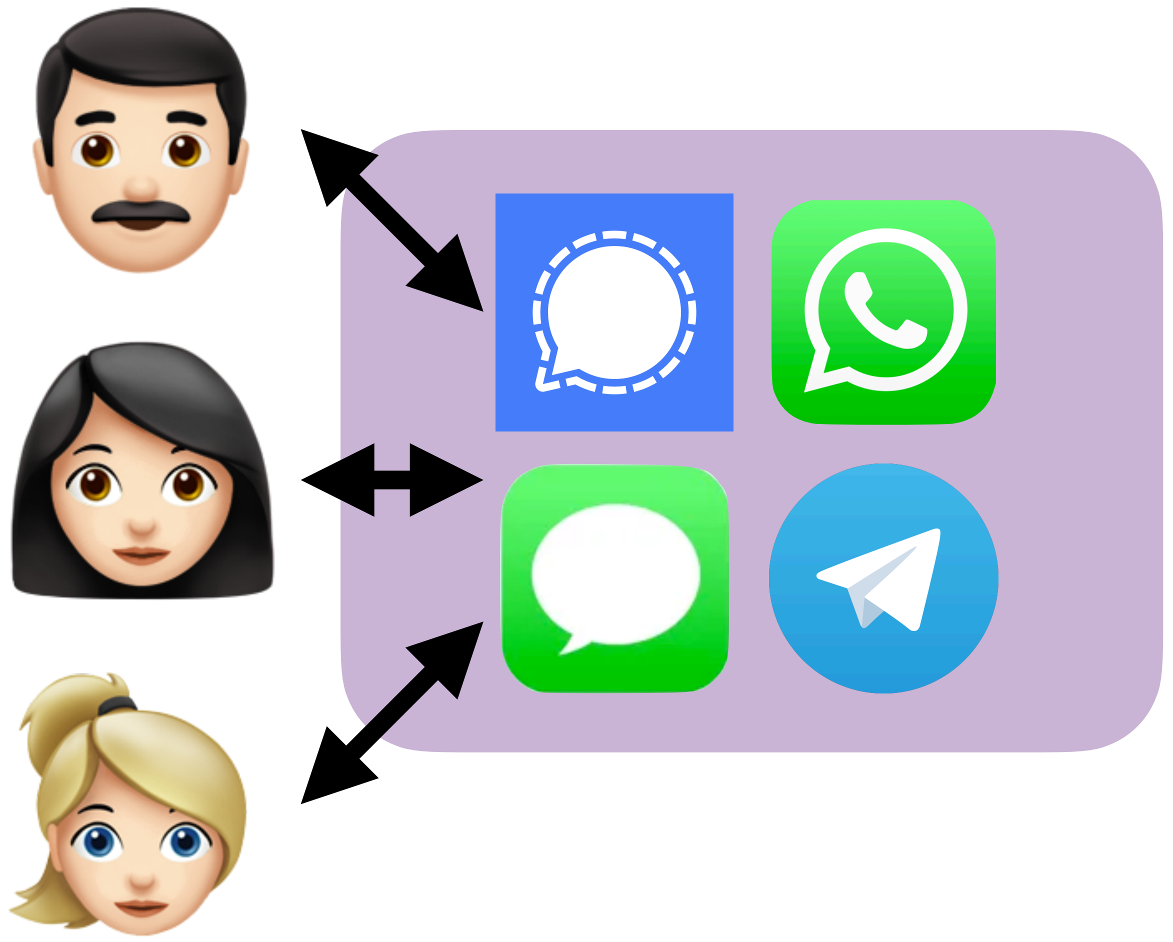

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Passive attackers

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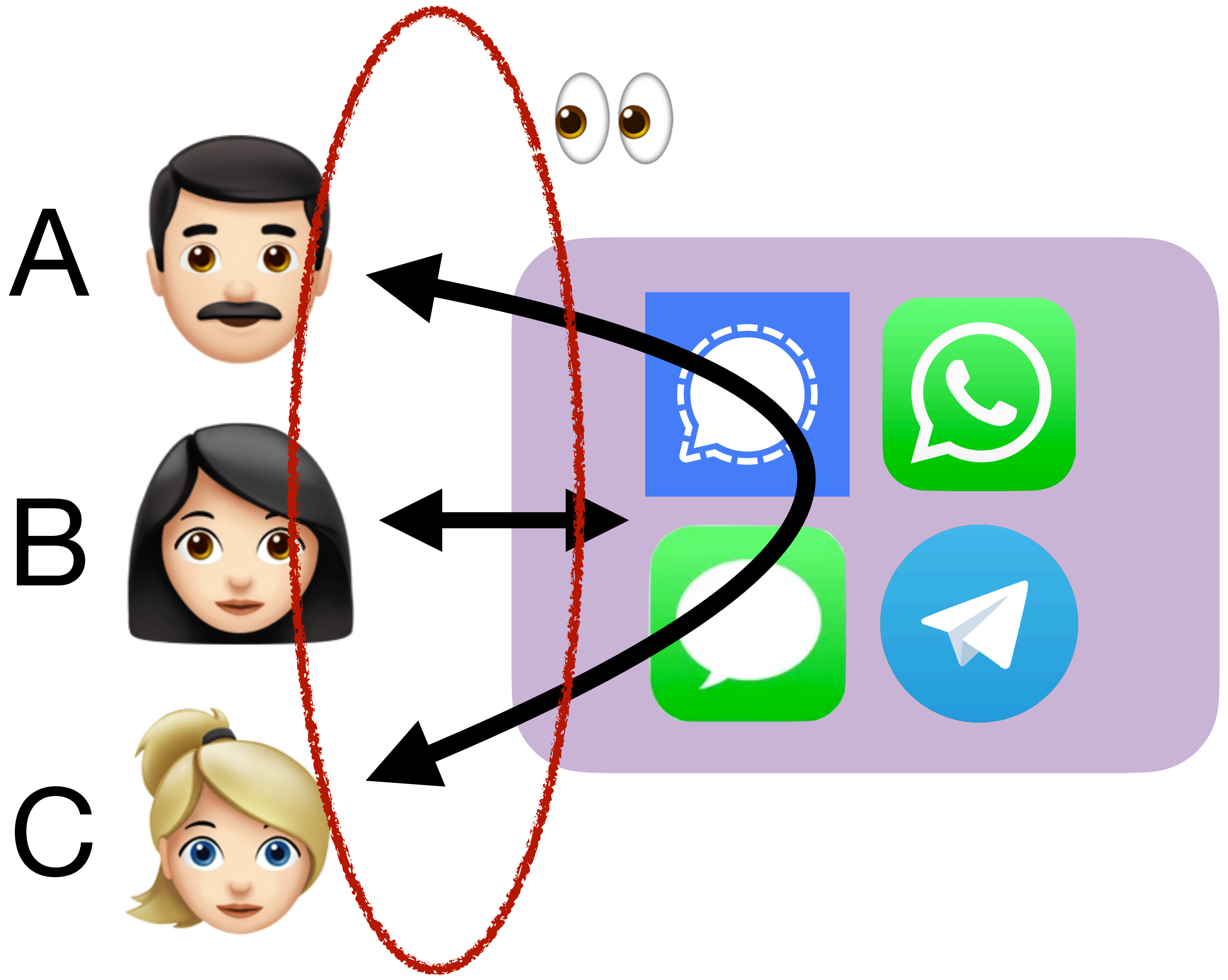

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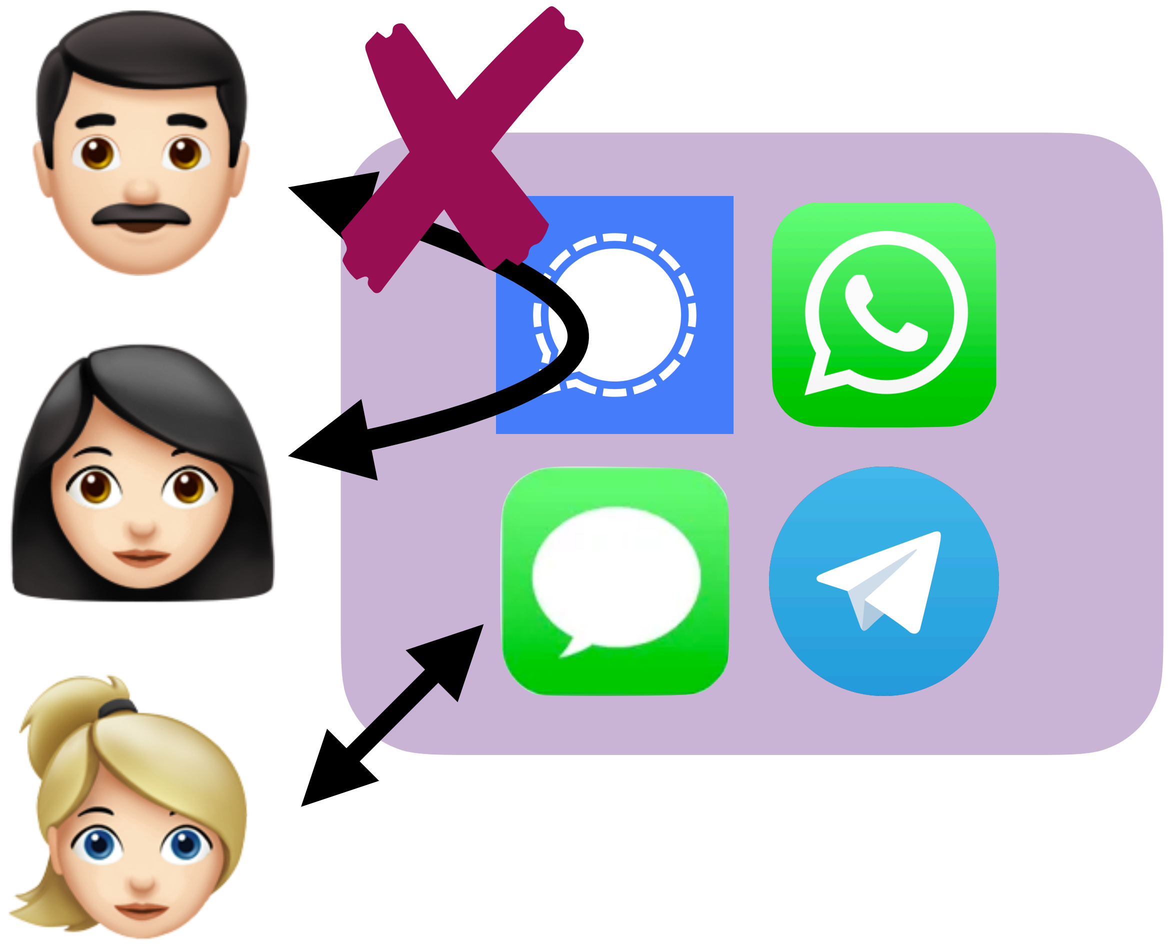

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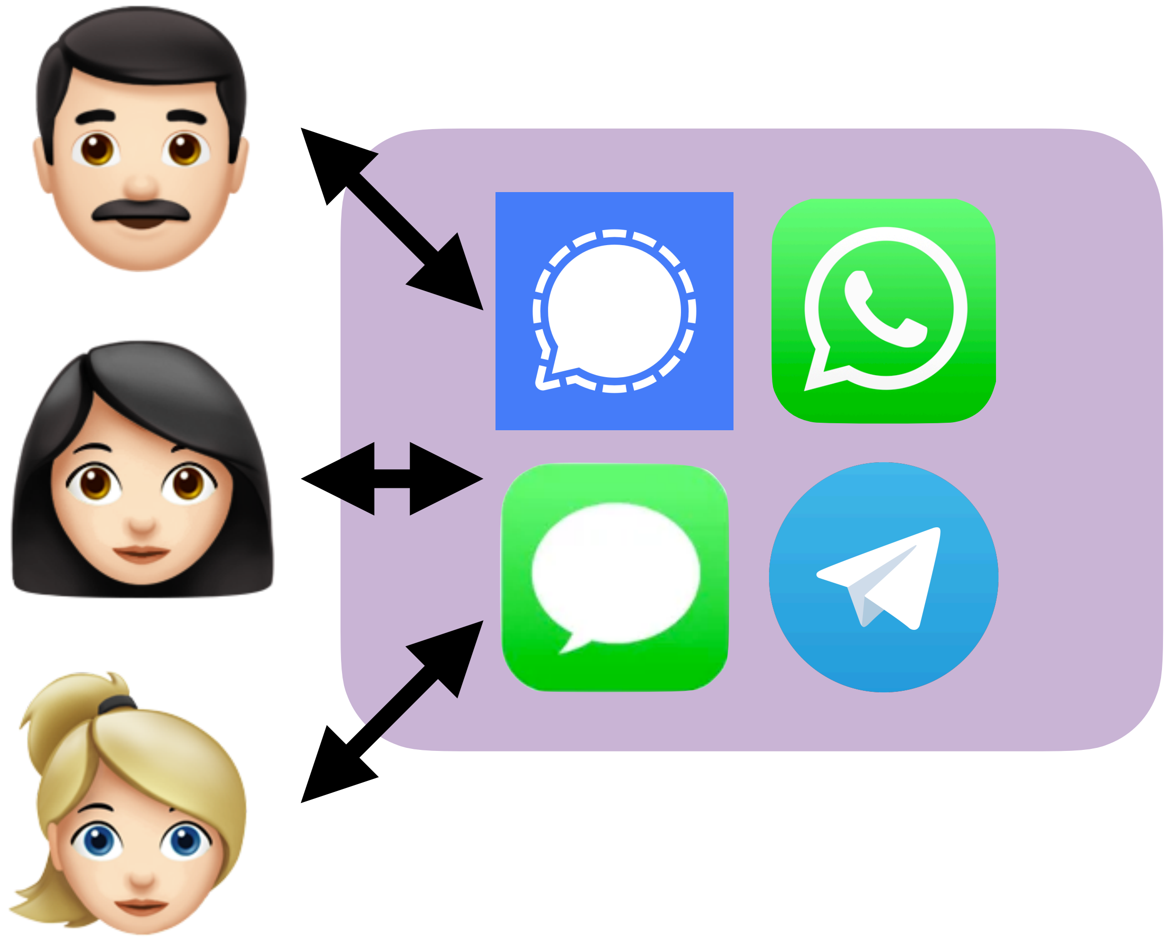

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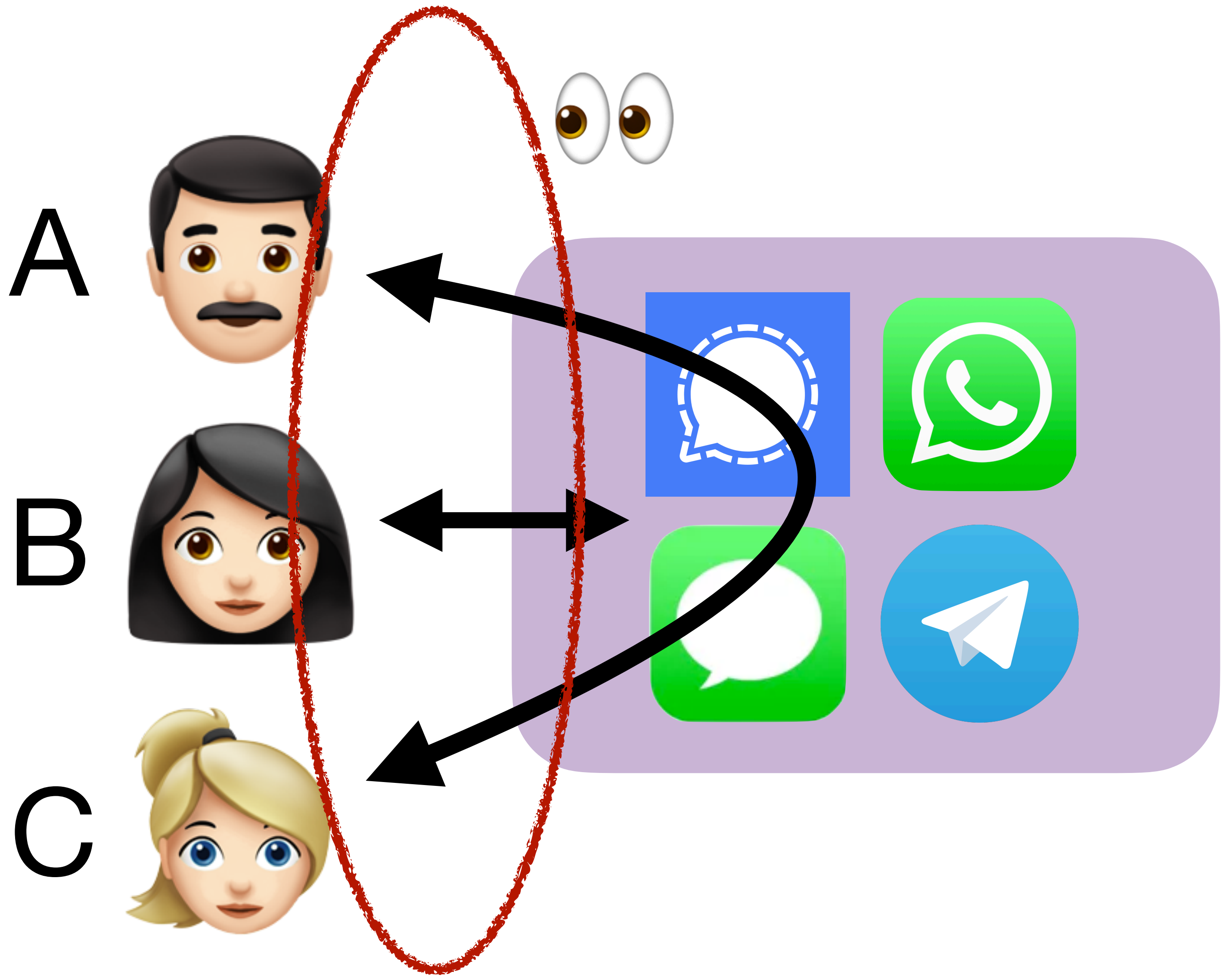

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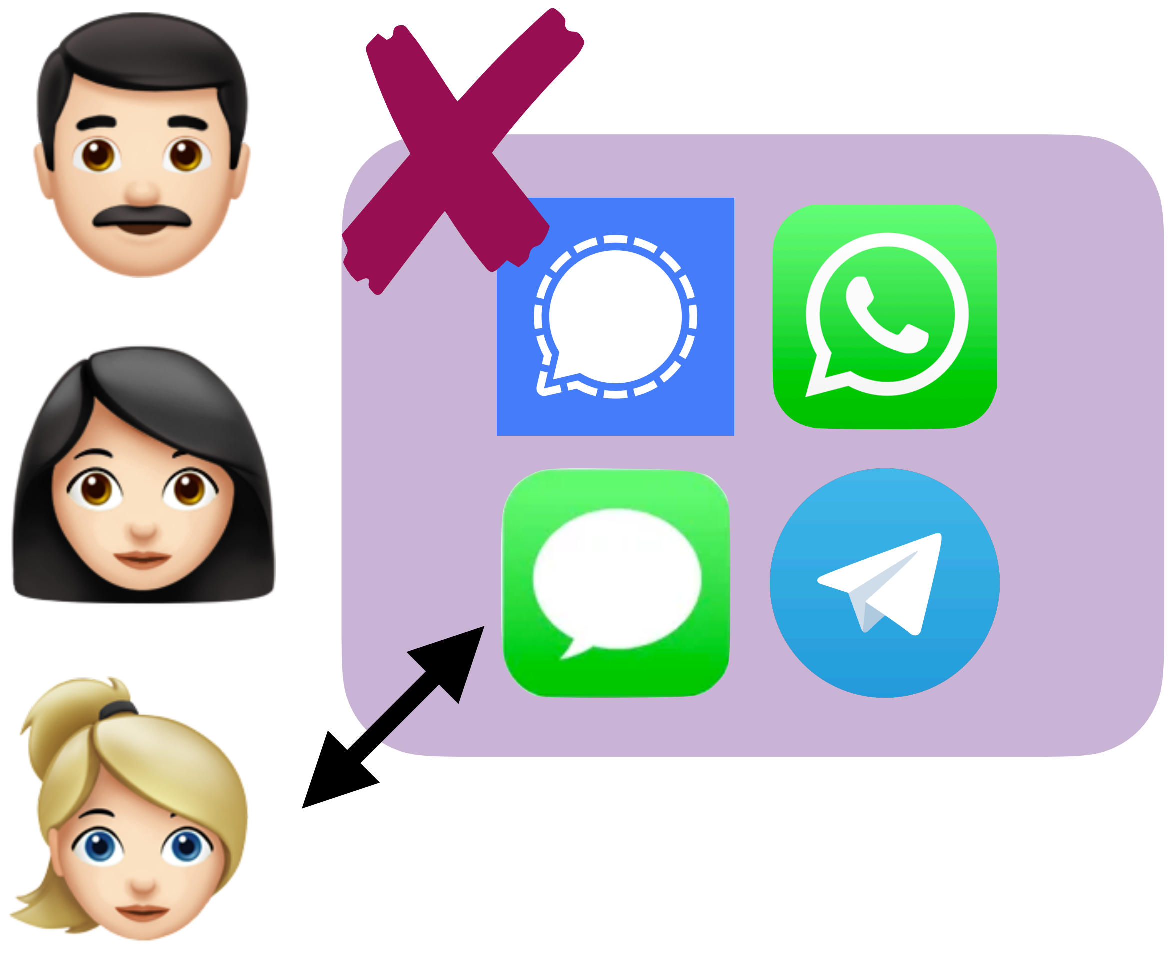

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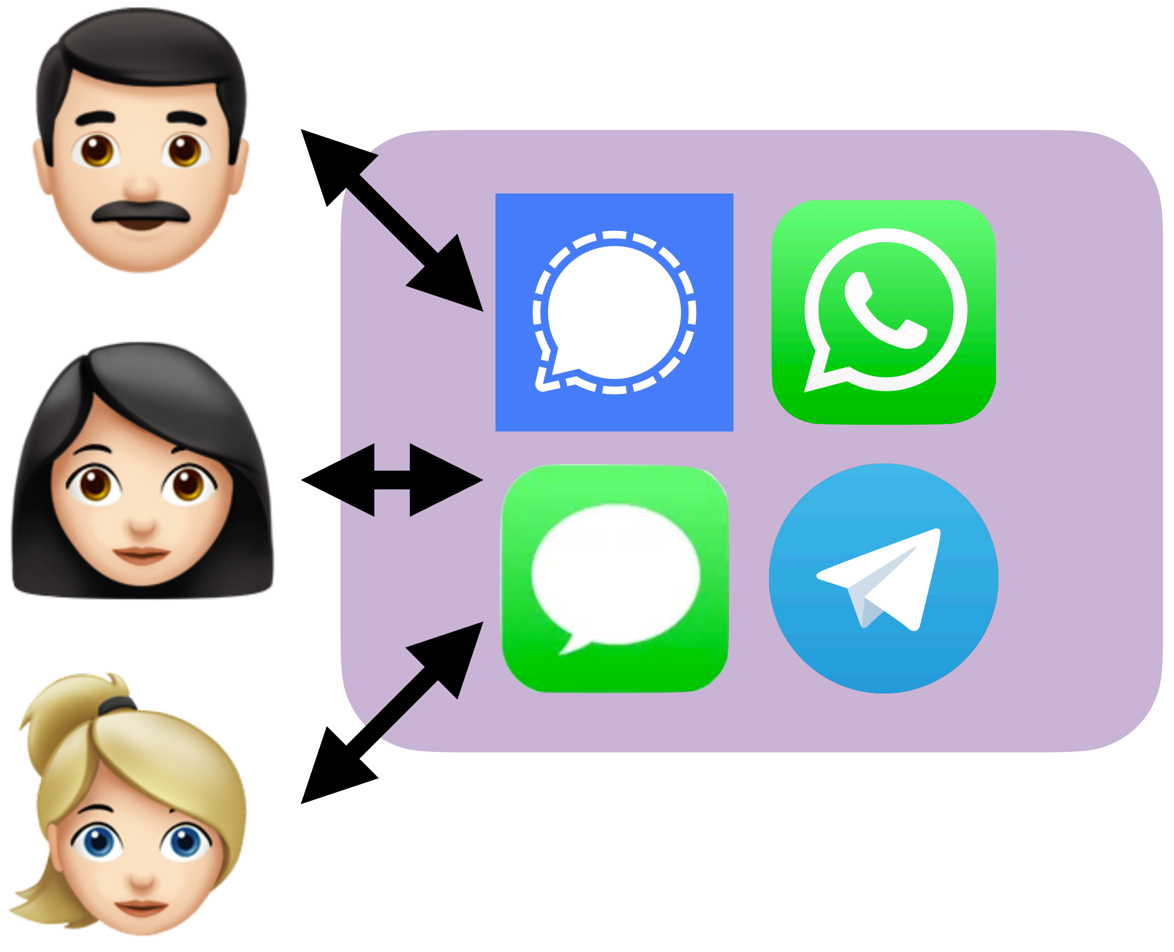

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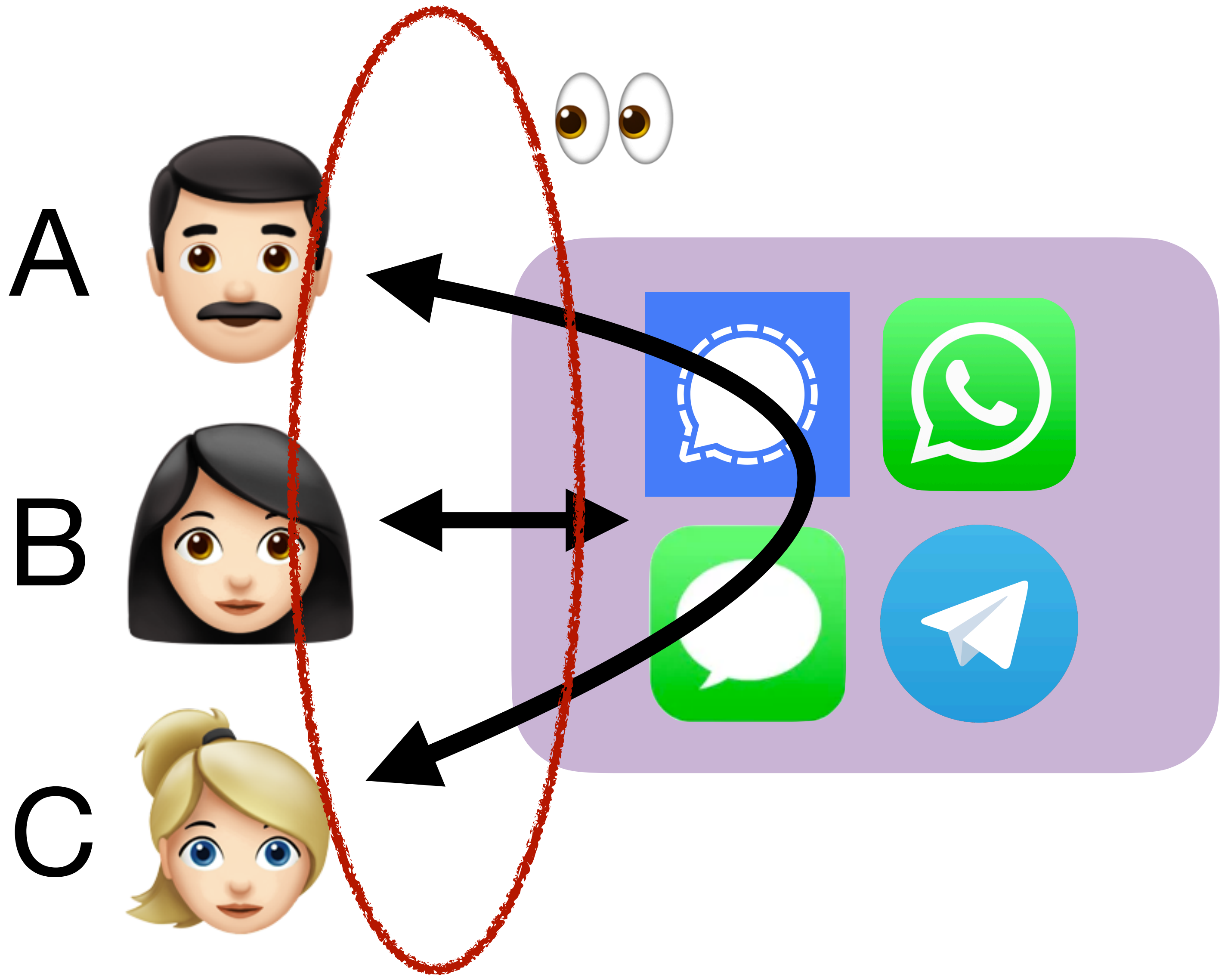

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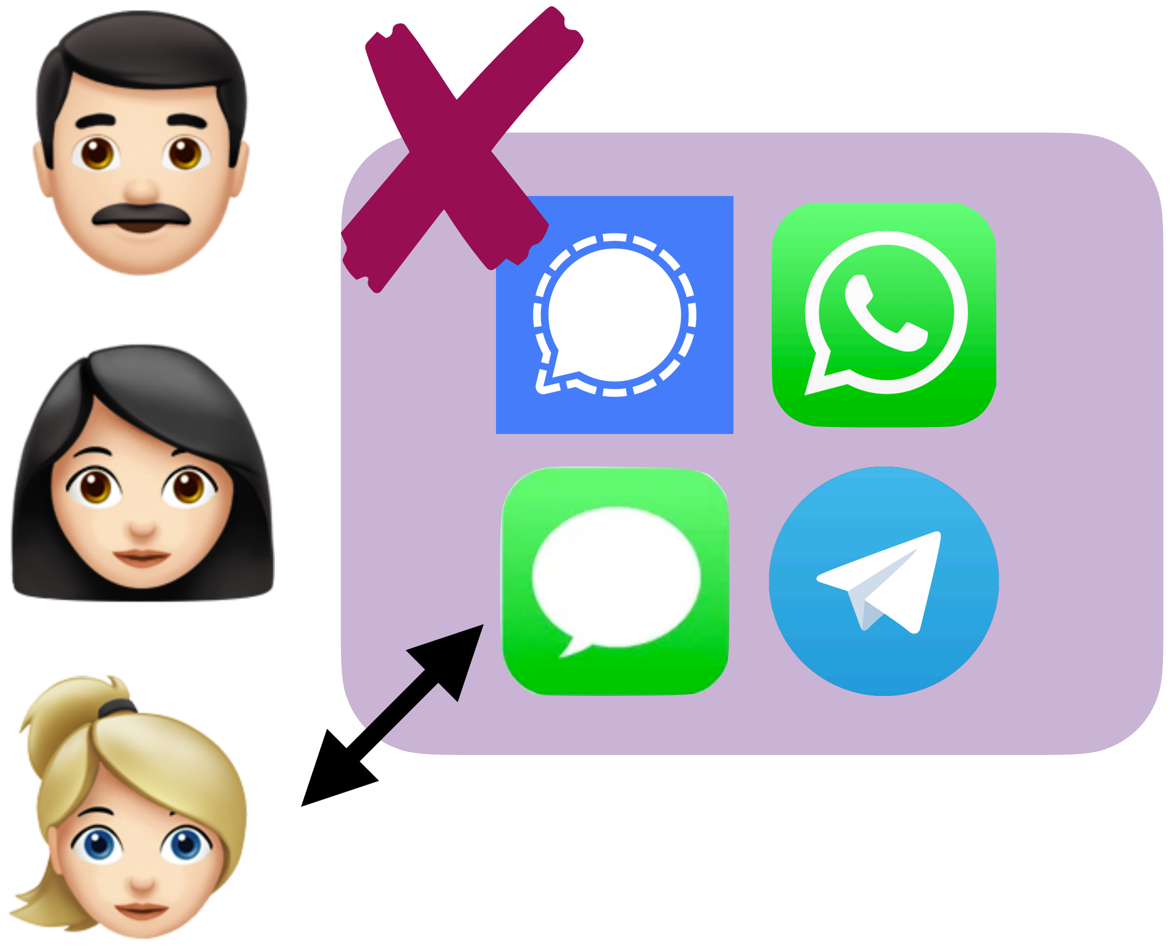

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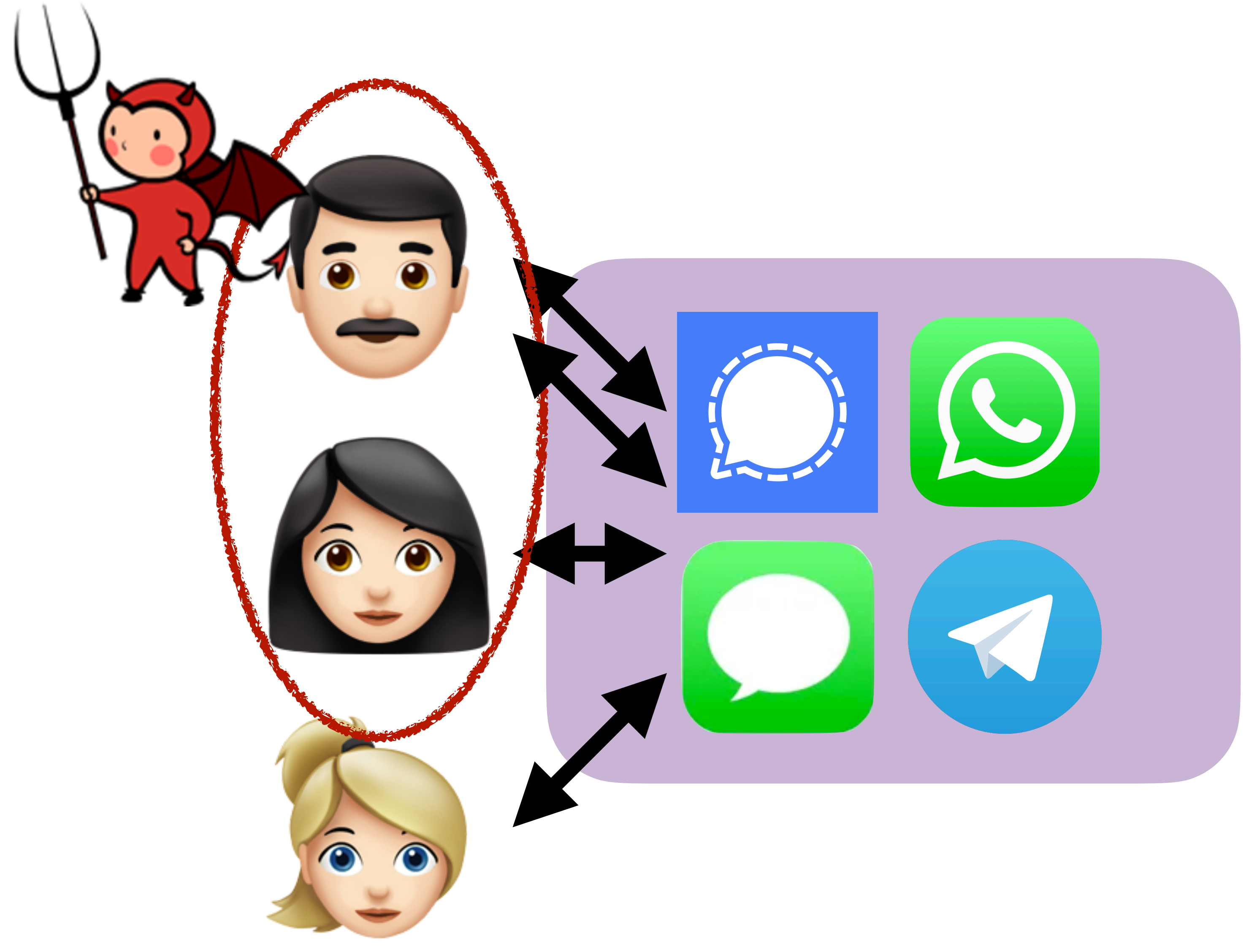

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Passive attackers

Active attackers

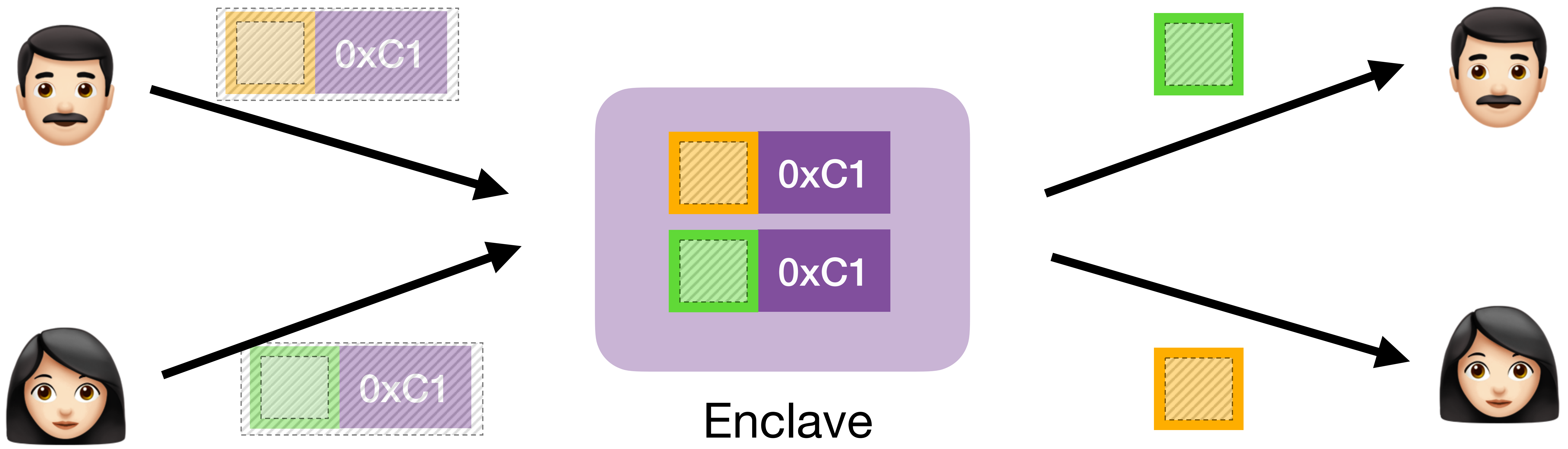
What are the challenges?

- Enclaves have unique threat models and attack surfaces
  - Memory access pattern protection
- Powerful attackers
  - Actively interfere with traffic and/or control a subset of clients
- Scalability as a security demand
  - Privacy loves company (more clients are always better)

Technical overview

- Basic single-server Boomerang
  - Oblivious pairwise message exchange using one secure enclave
  - Proactive defense against active attackers
- Scalable multi-server Boomerang+
  - Security-aware load-balancing for horizontal scalability

Boomerang design



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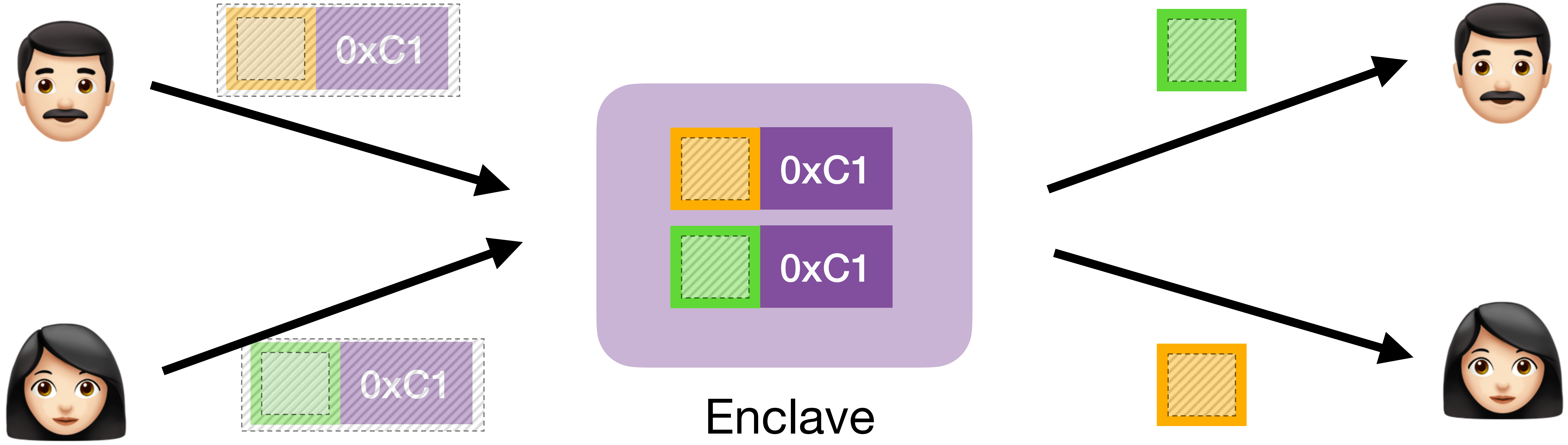
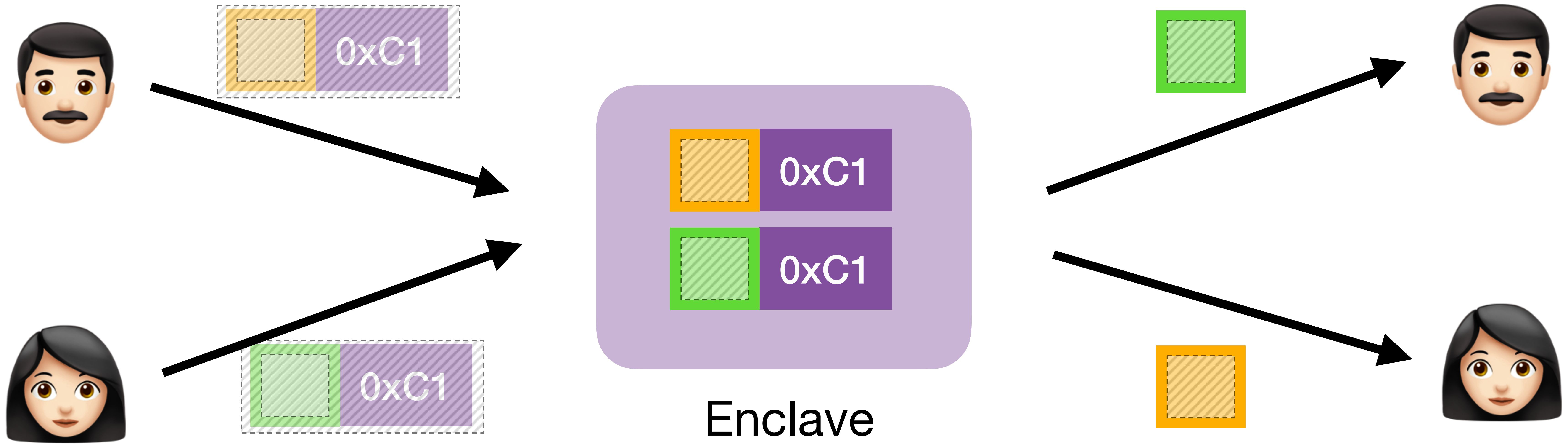


- A pair of buddies send messages tagged with pairwise private labels

Boomerang design



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- Server swaps any pair of messages with same labels

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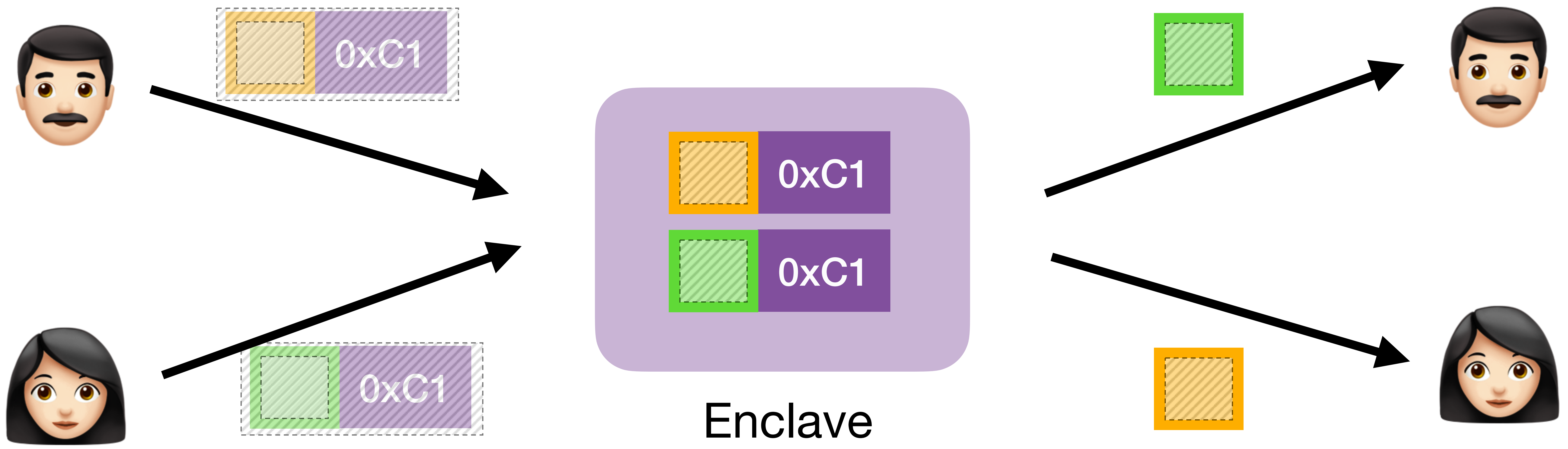

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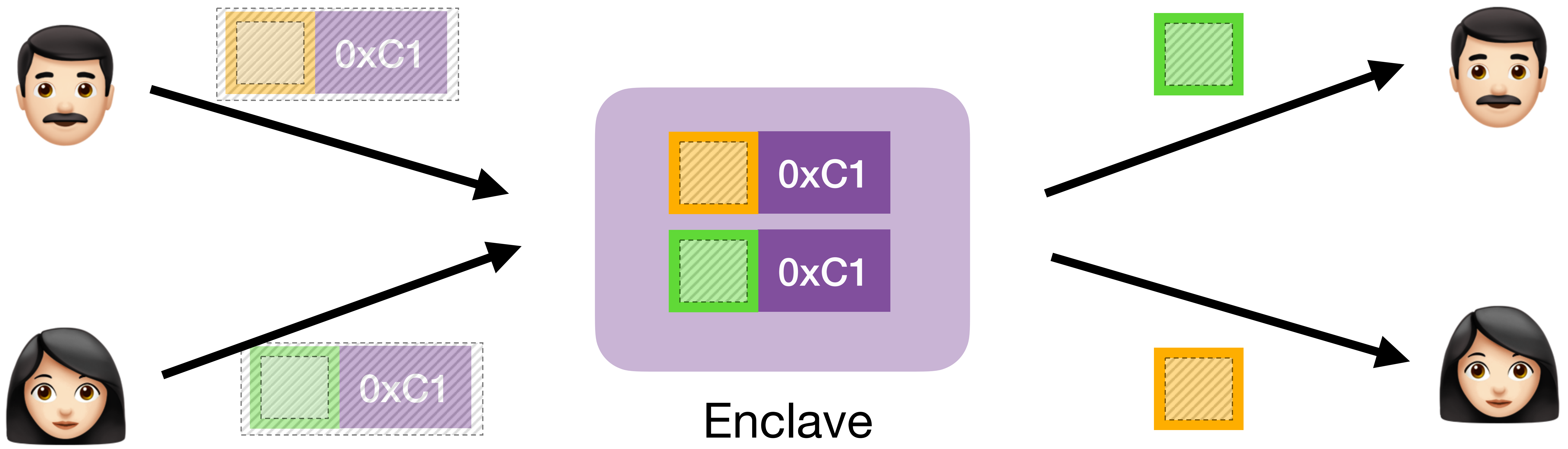

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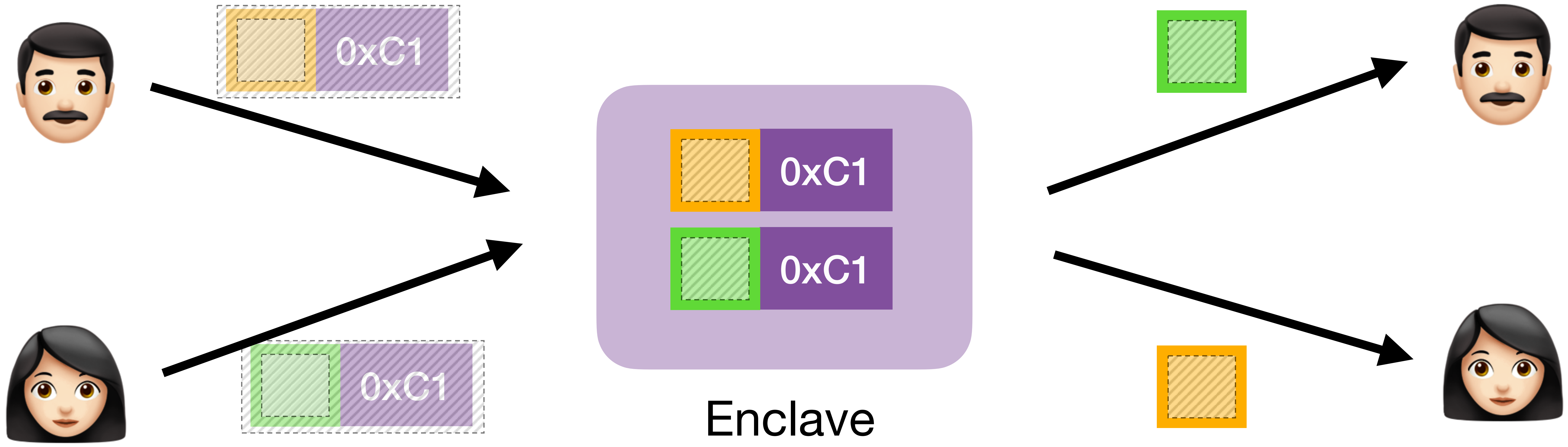
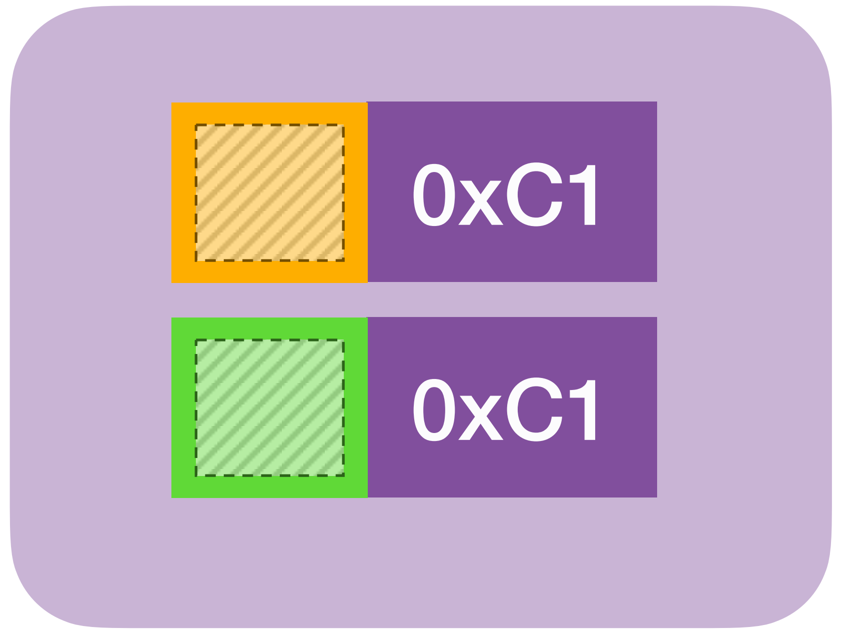
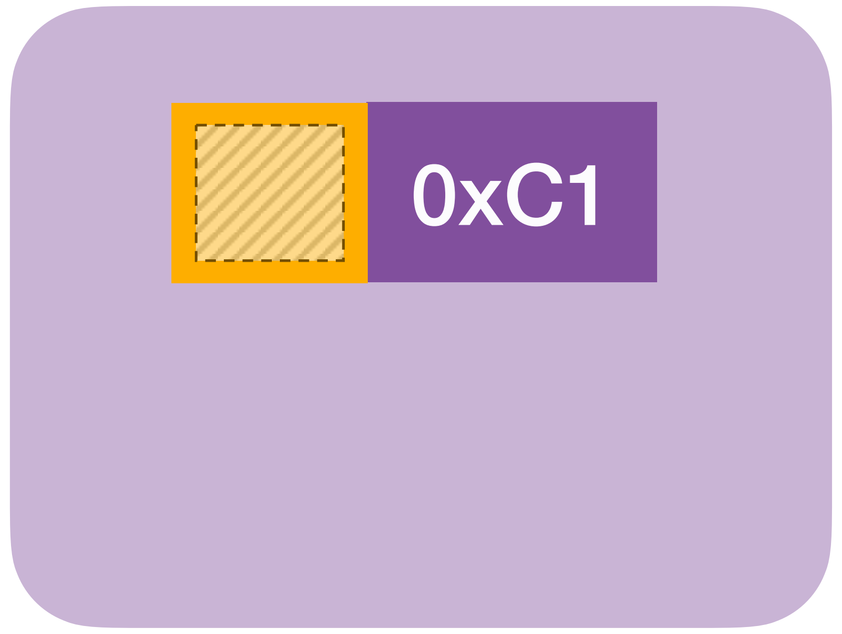


- A pair of buddies send messages tagged with pairwise private labels
- Server swaps any pair of messages with same labels
  - A regular label shows up twice each round
- But powerful attackers might disrupt the regular label pattern
  - Block selected clients or control a subset of clients to gain advantages

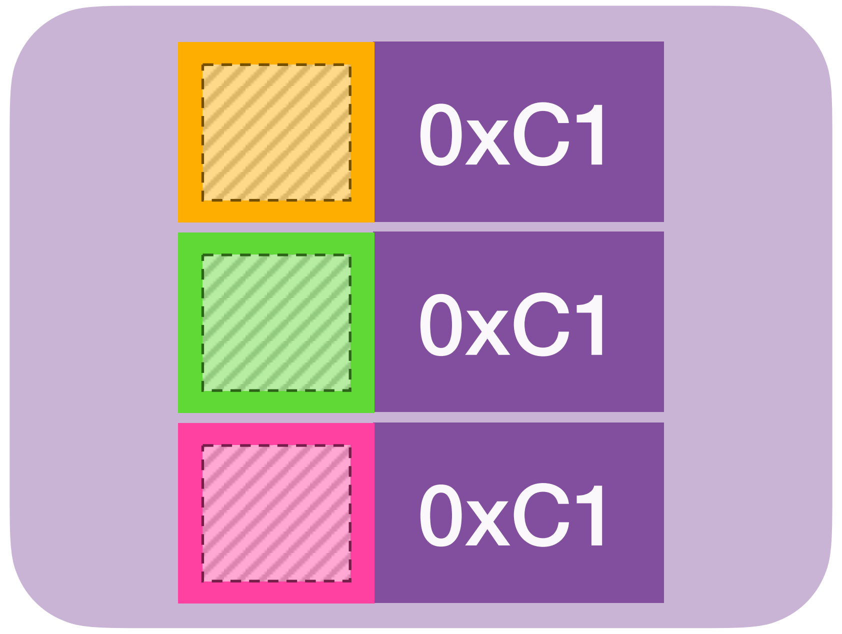
Needs to fix irregular label patterns…



Double pattern
(Regular)



Single pattern



More-than-two pattern

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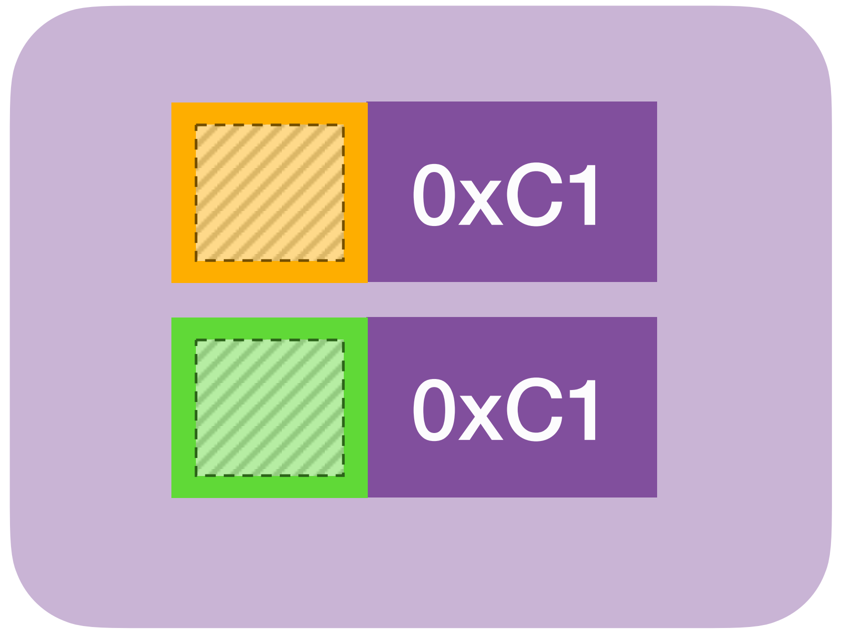

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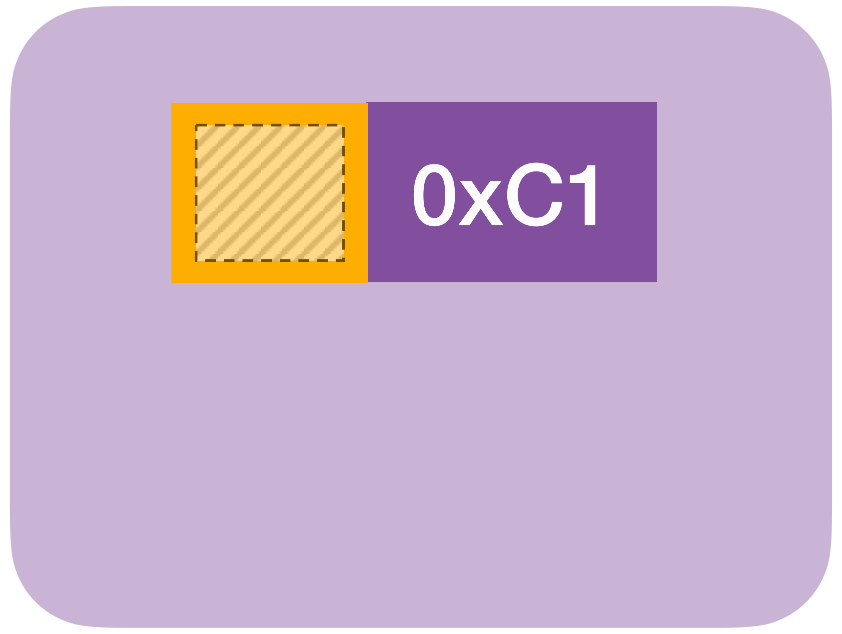

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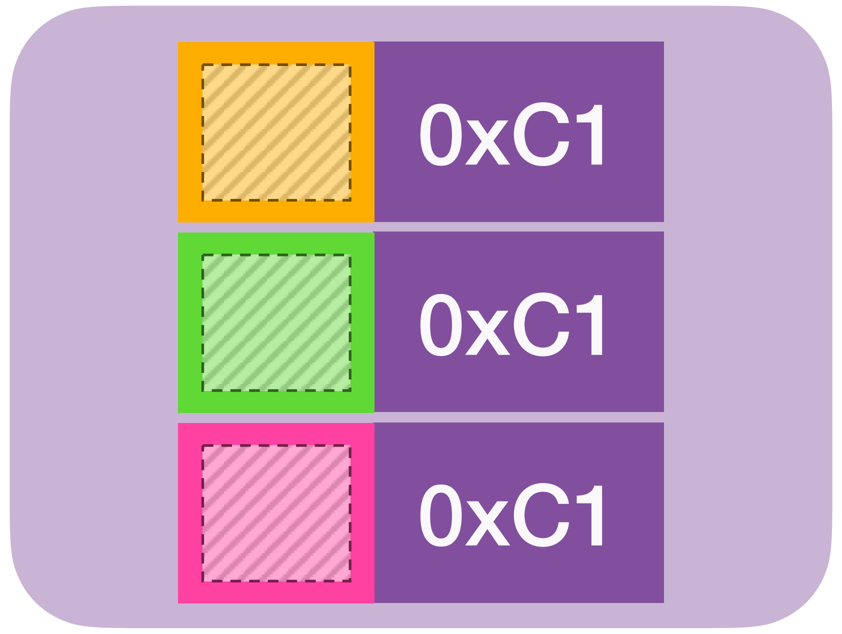

More-than-two pattern

- Build oblivious algorithms for enclaves to **proactively** detect and patch messages with irregular labels, and “return” them back to senders

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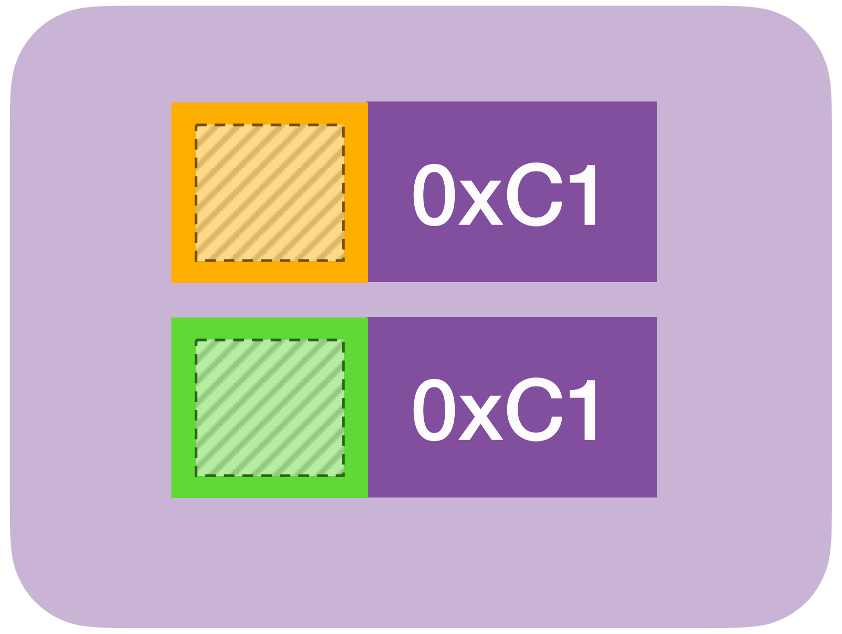

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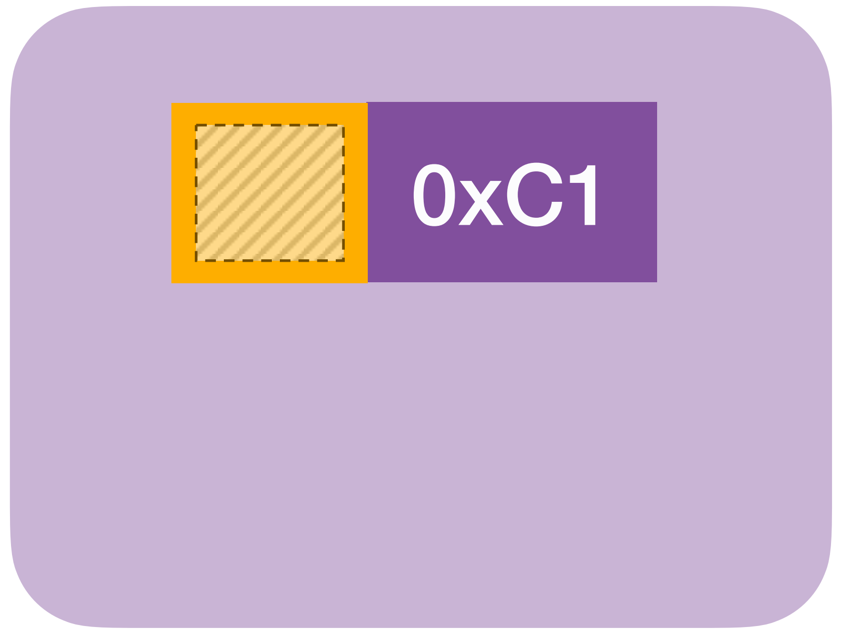

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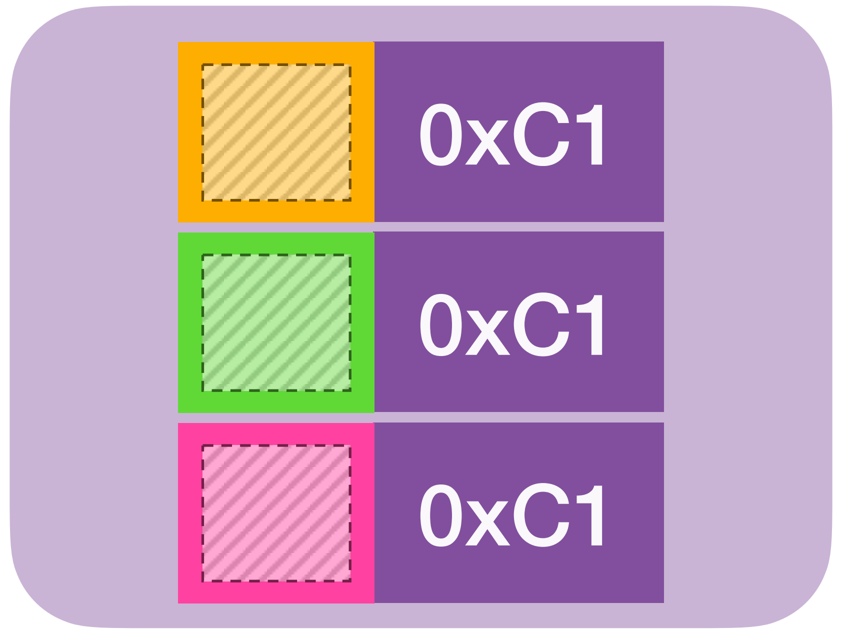
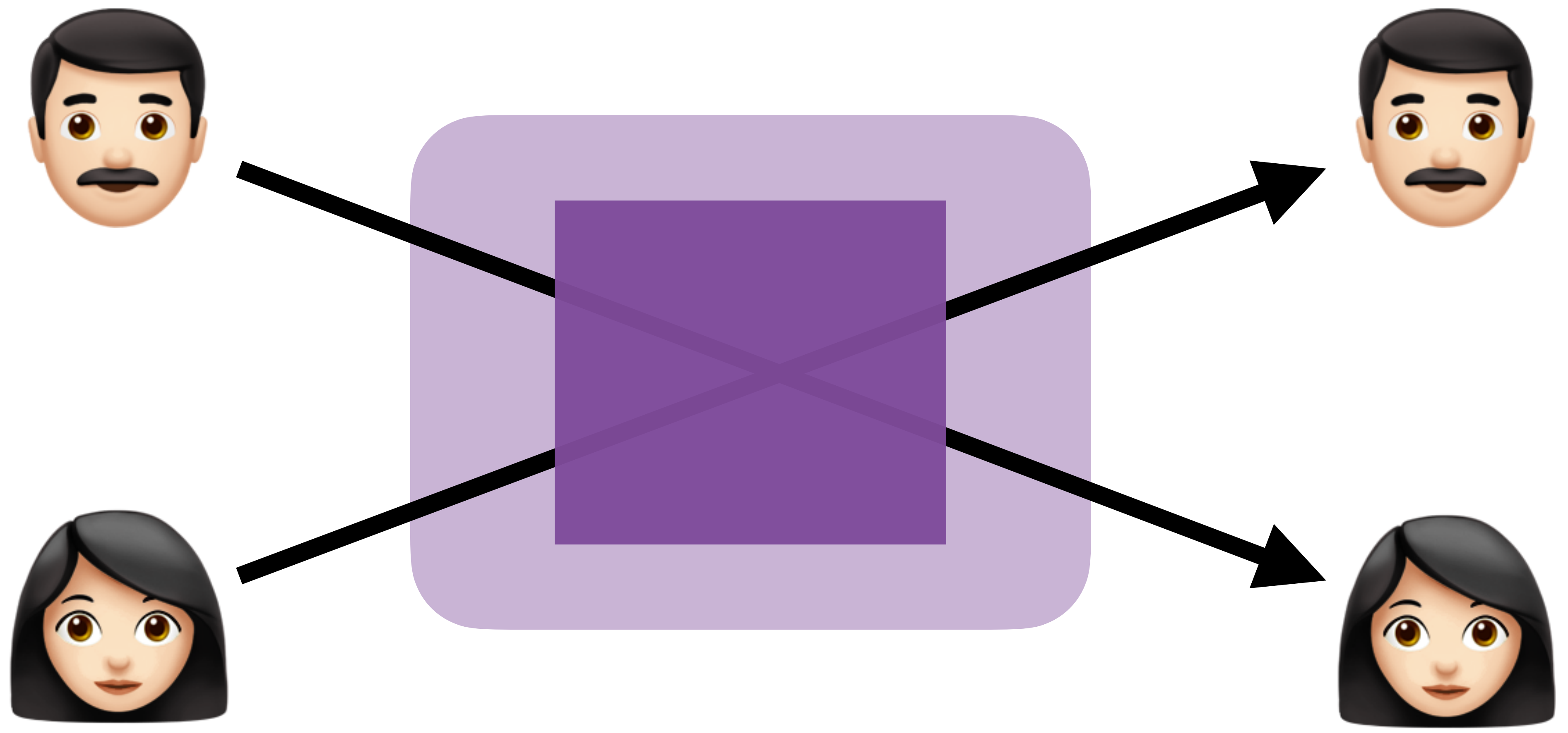


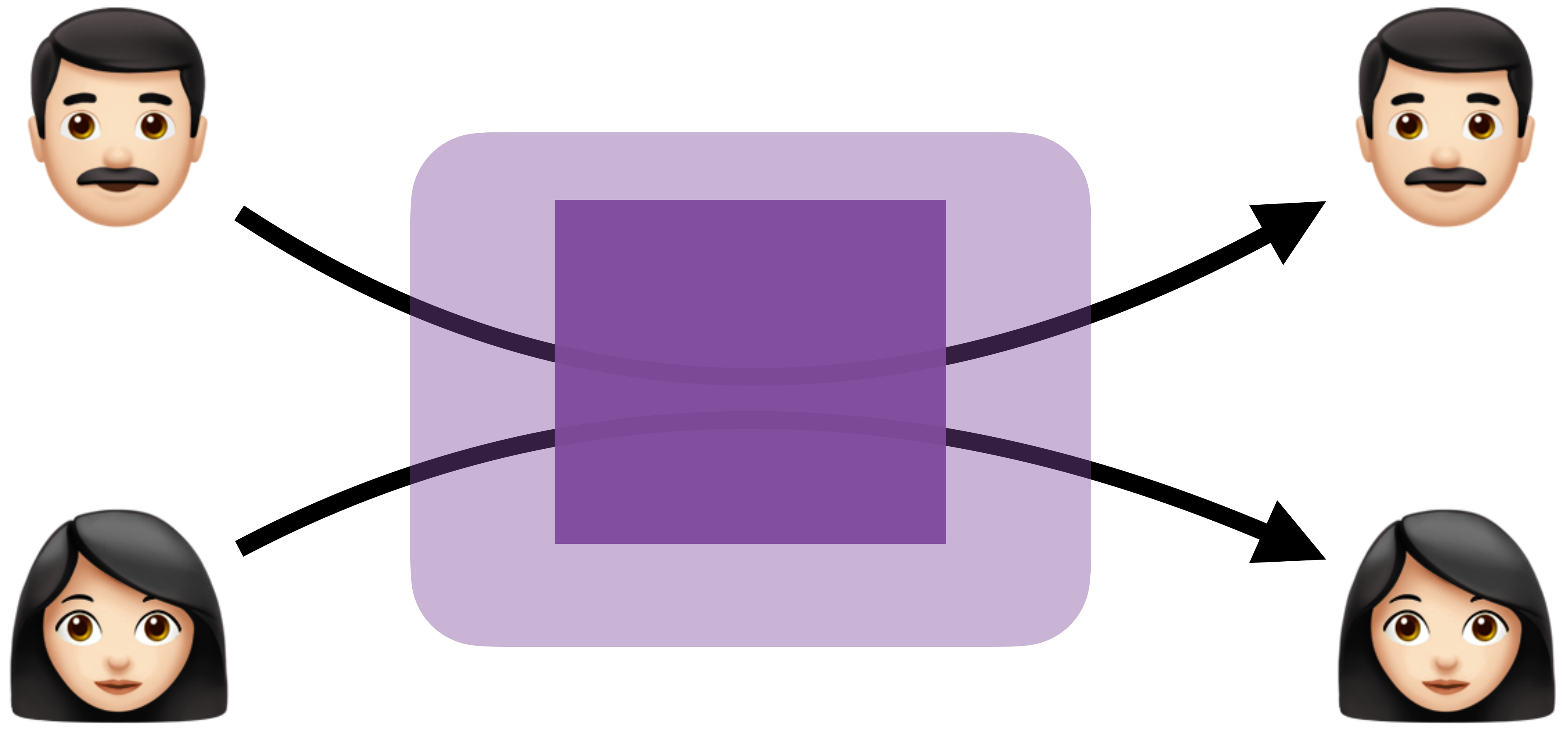
More-than-two pattern

- Build oblivious algorithms for enclaves to **proactively** detect and patch messages with irregular labels, and “return” them back to senders
- In this way, we contain the “disruptions” within problematic clients, isolated from remaining ones

Attacker blocks Alice, and infer if …



👀 Alice is talking to Bob



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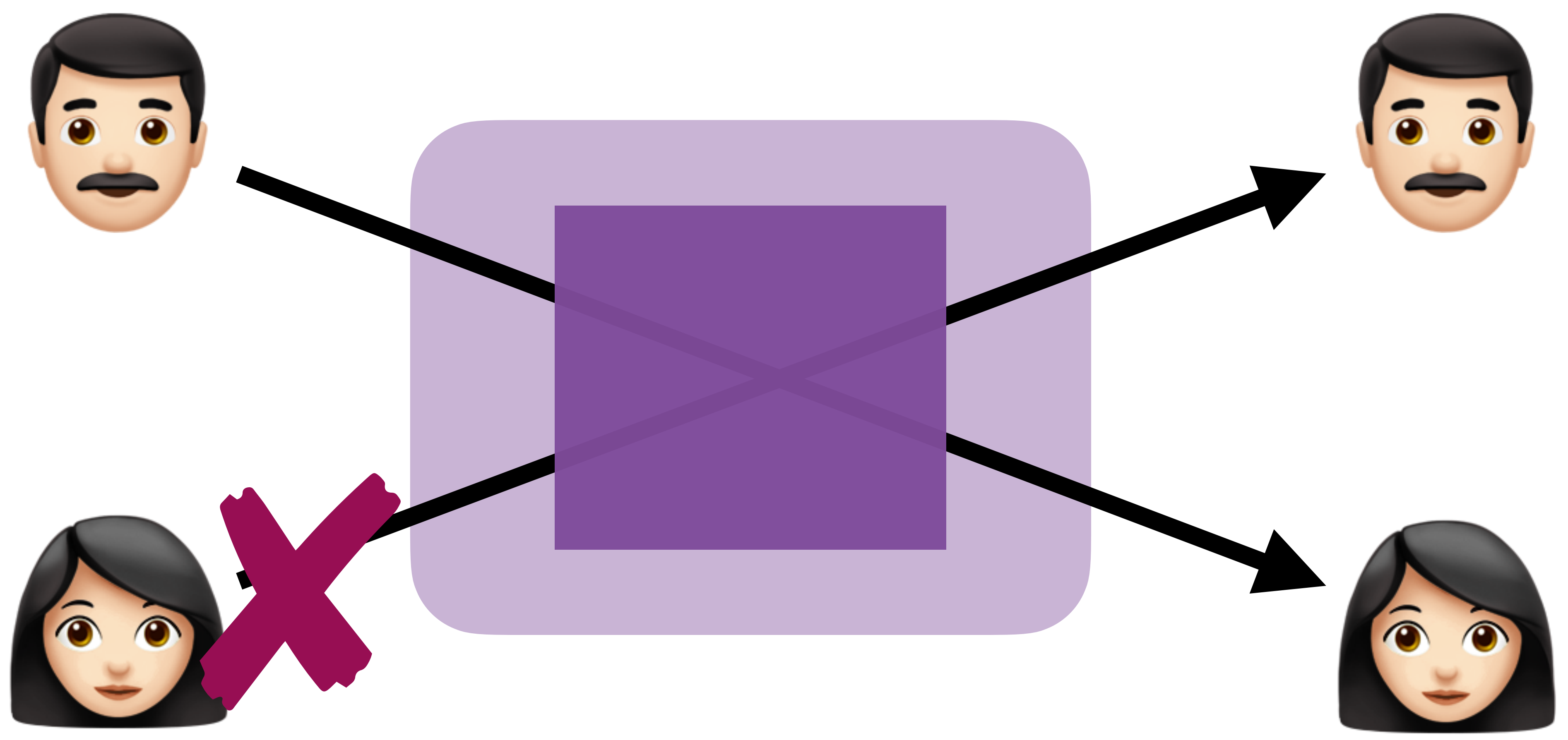

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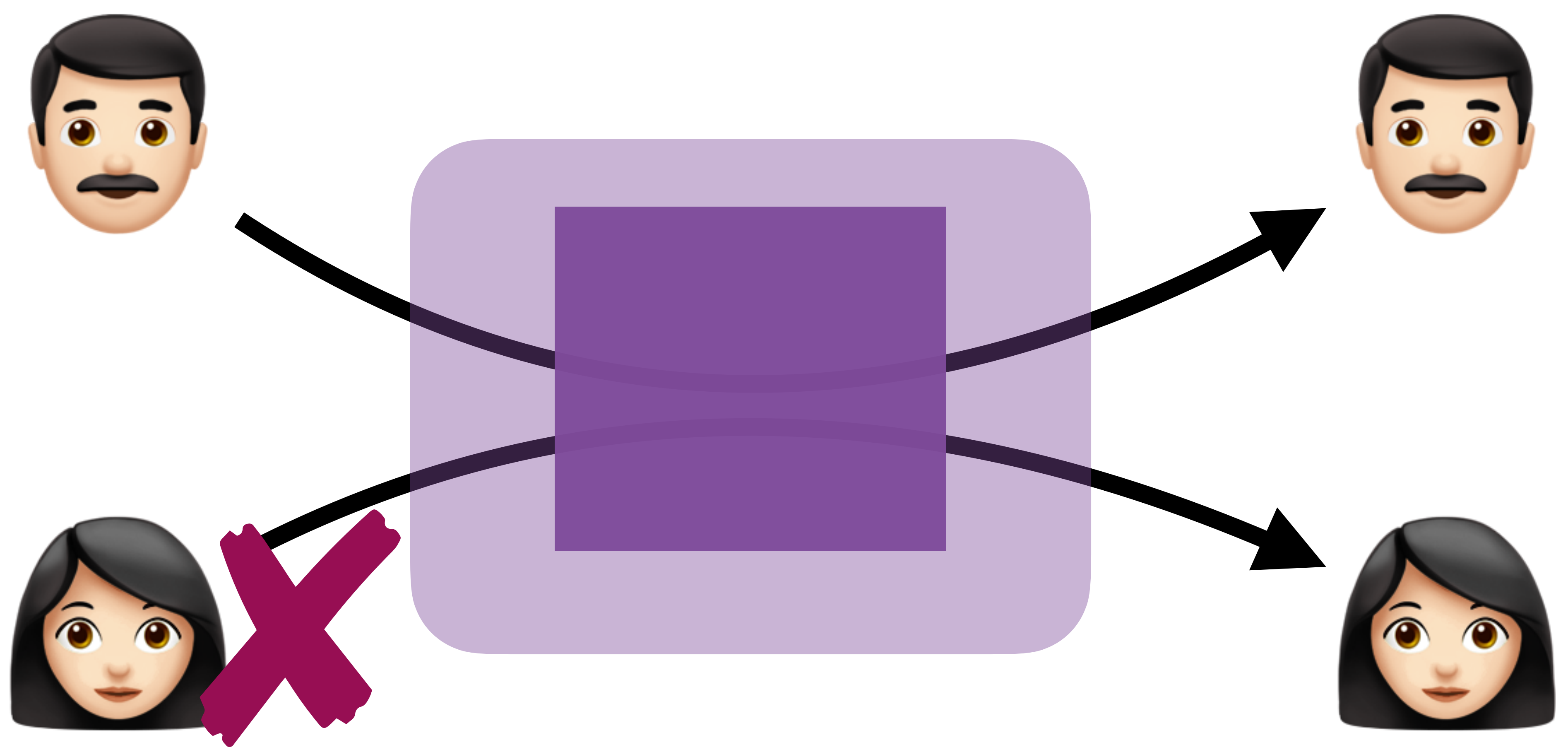

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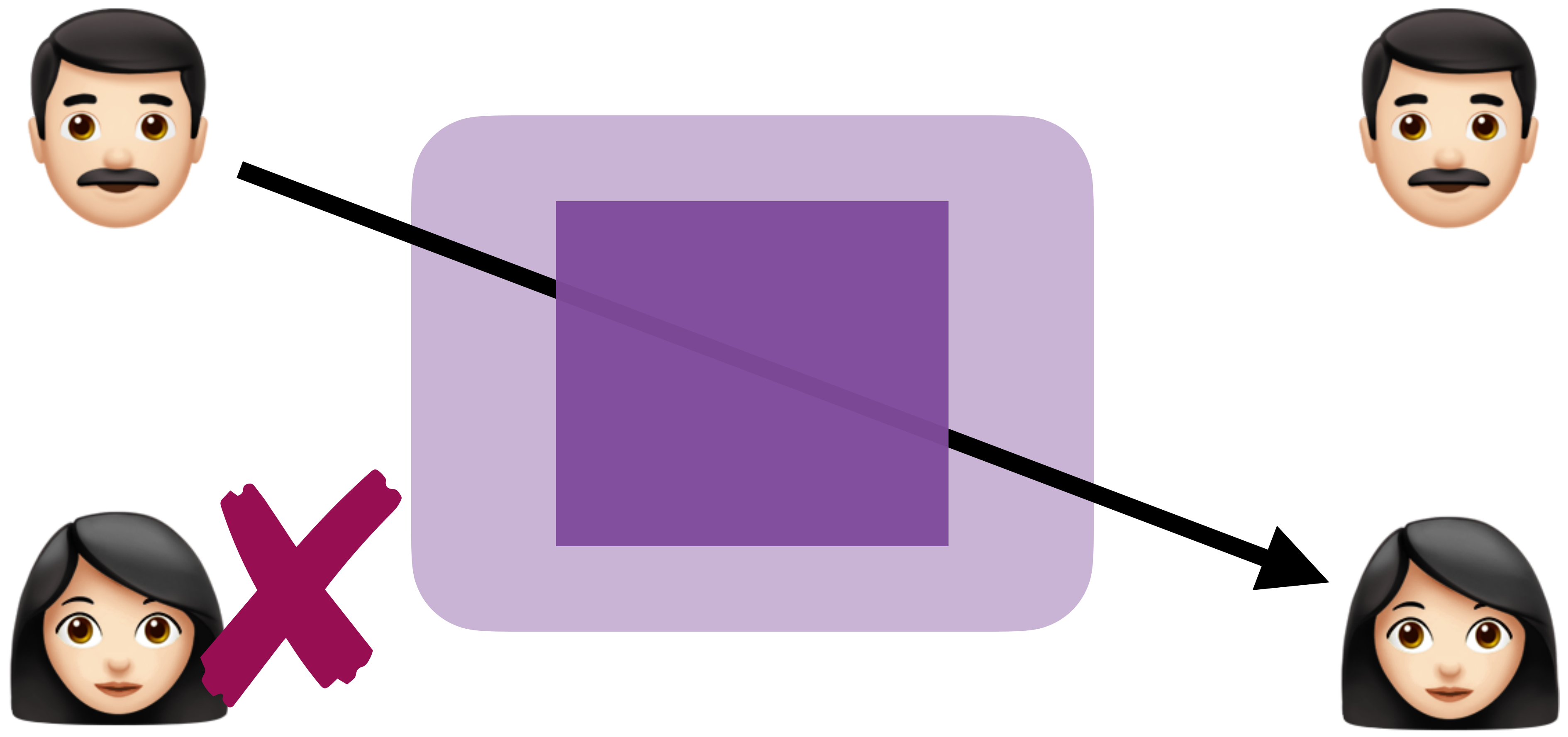

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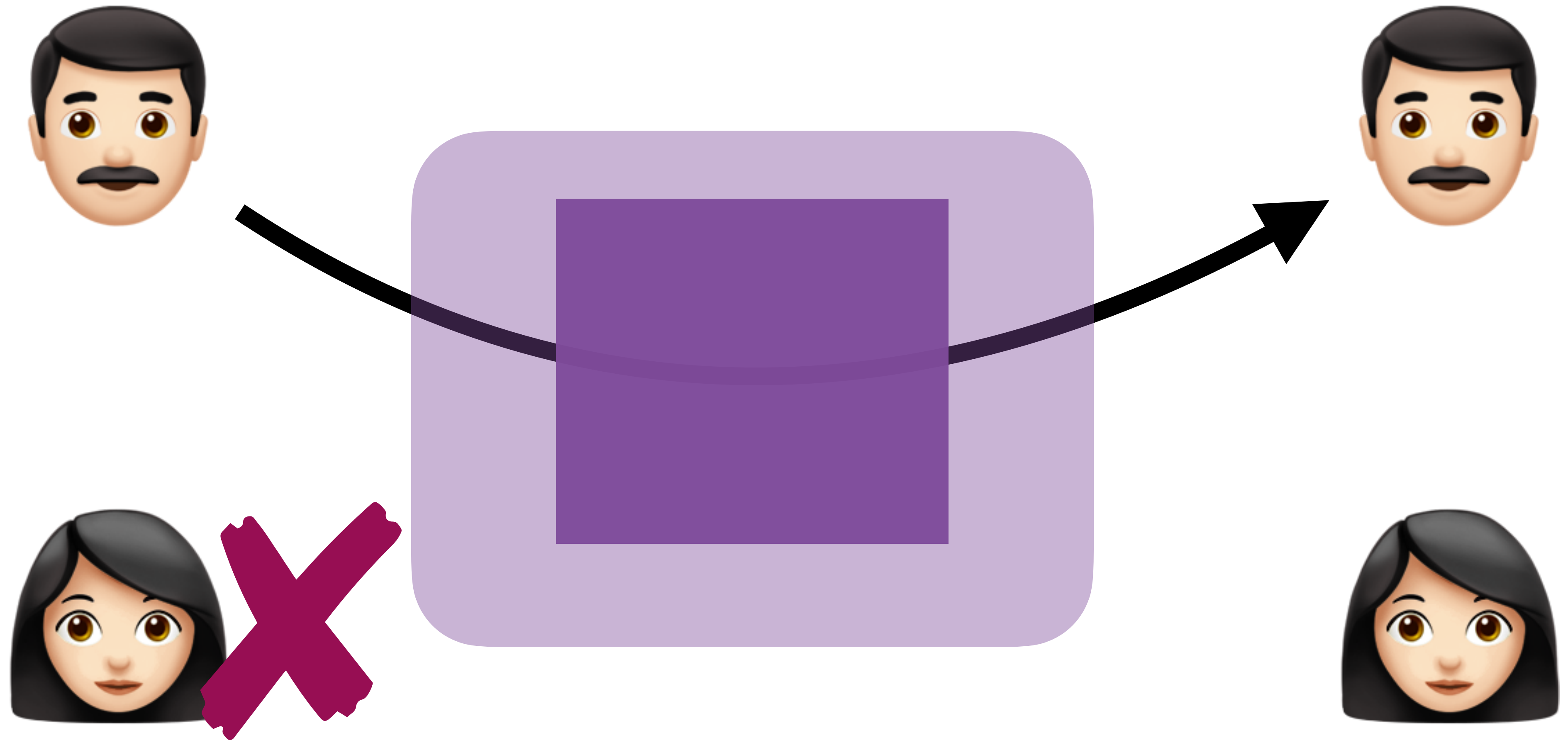

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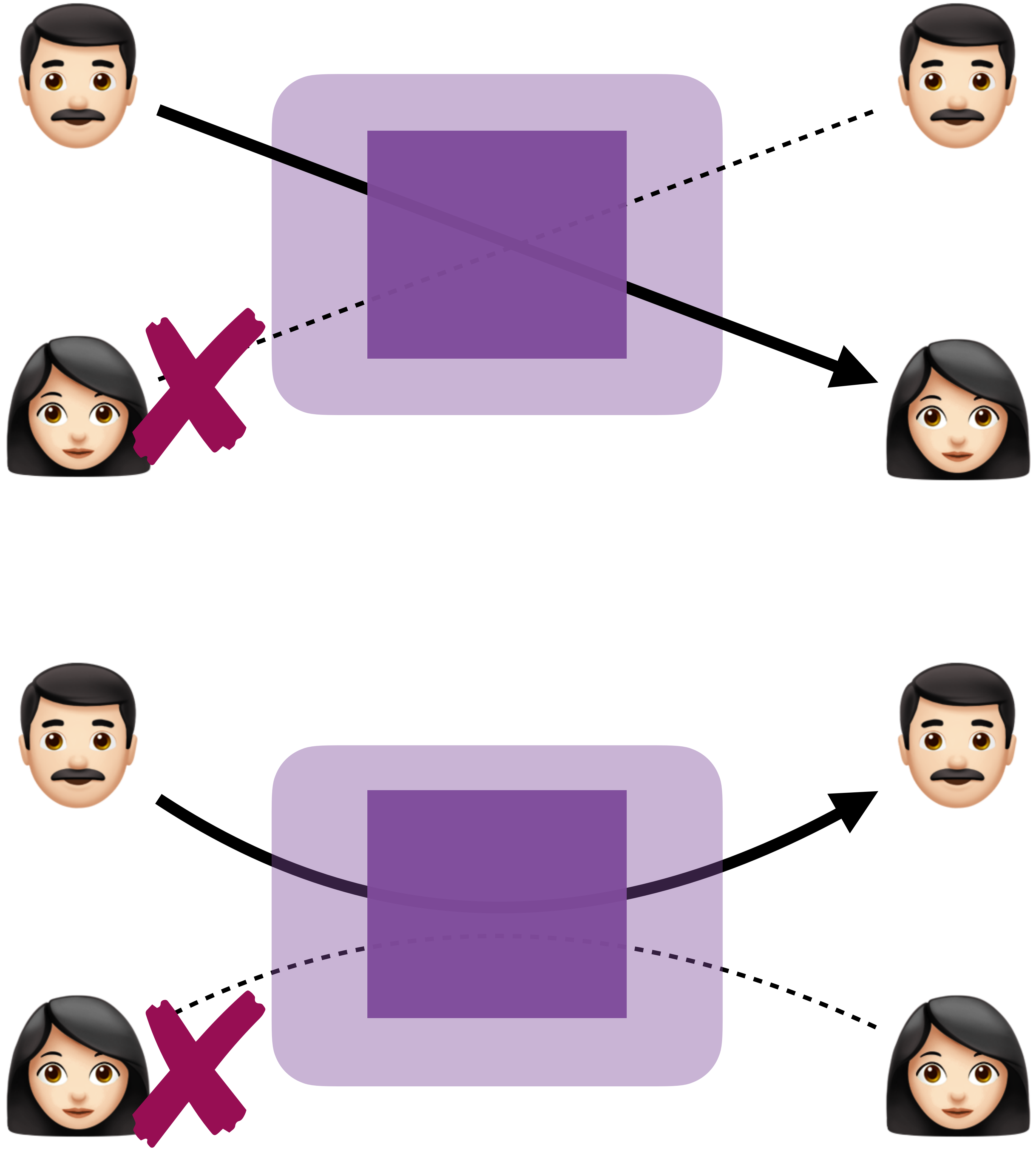
Boomerang with proactive pattern patching



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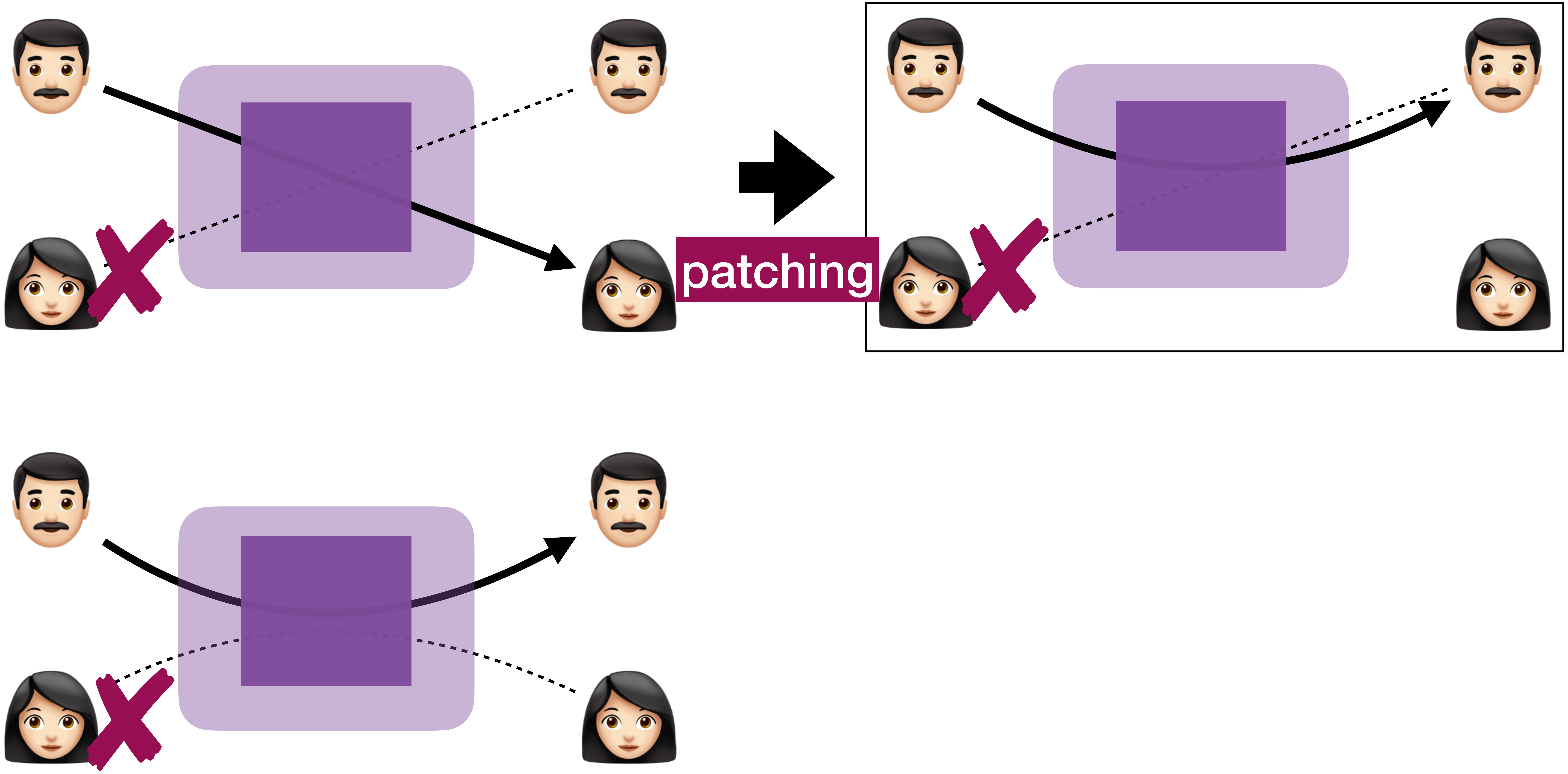

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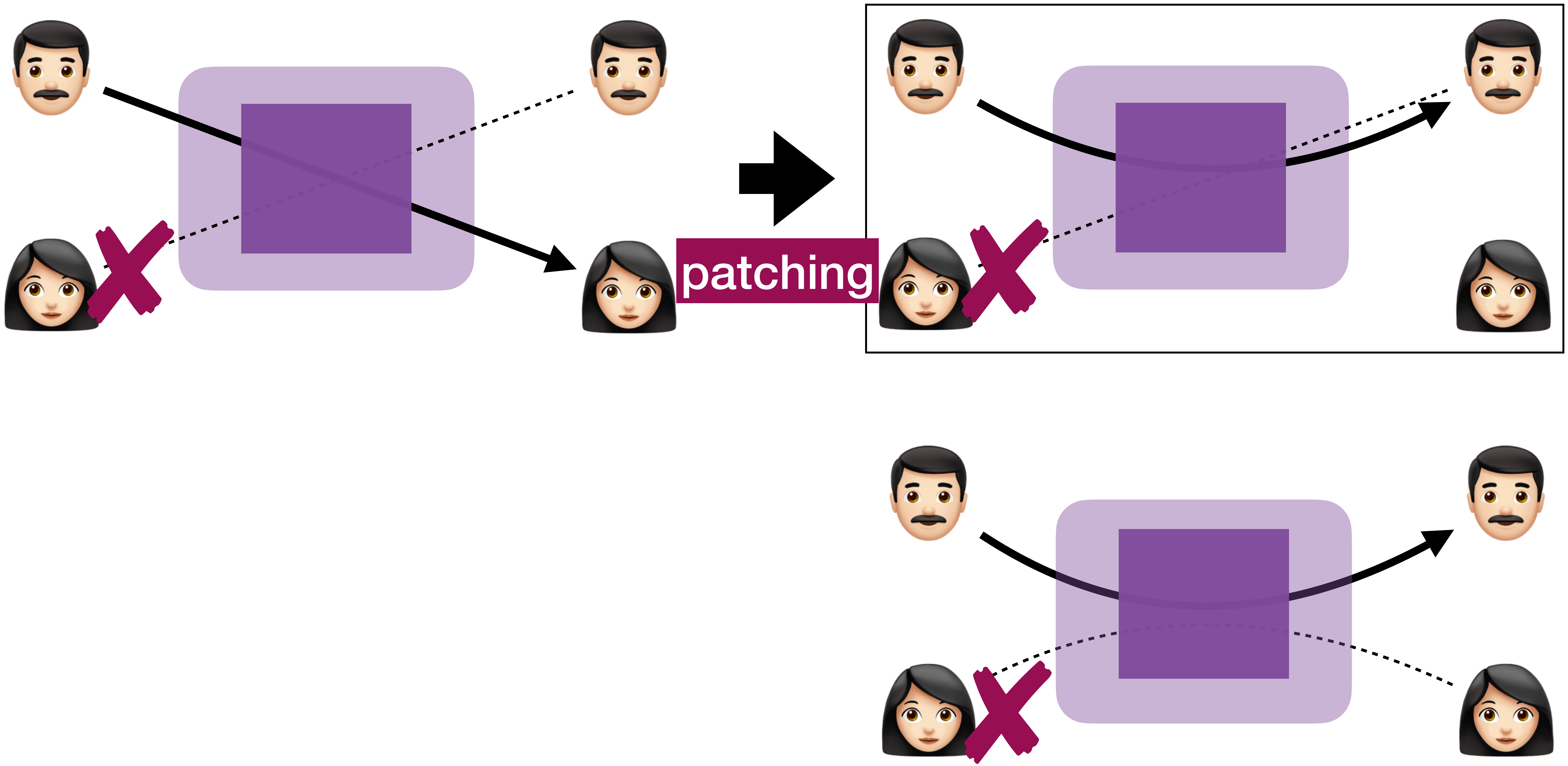
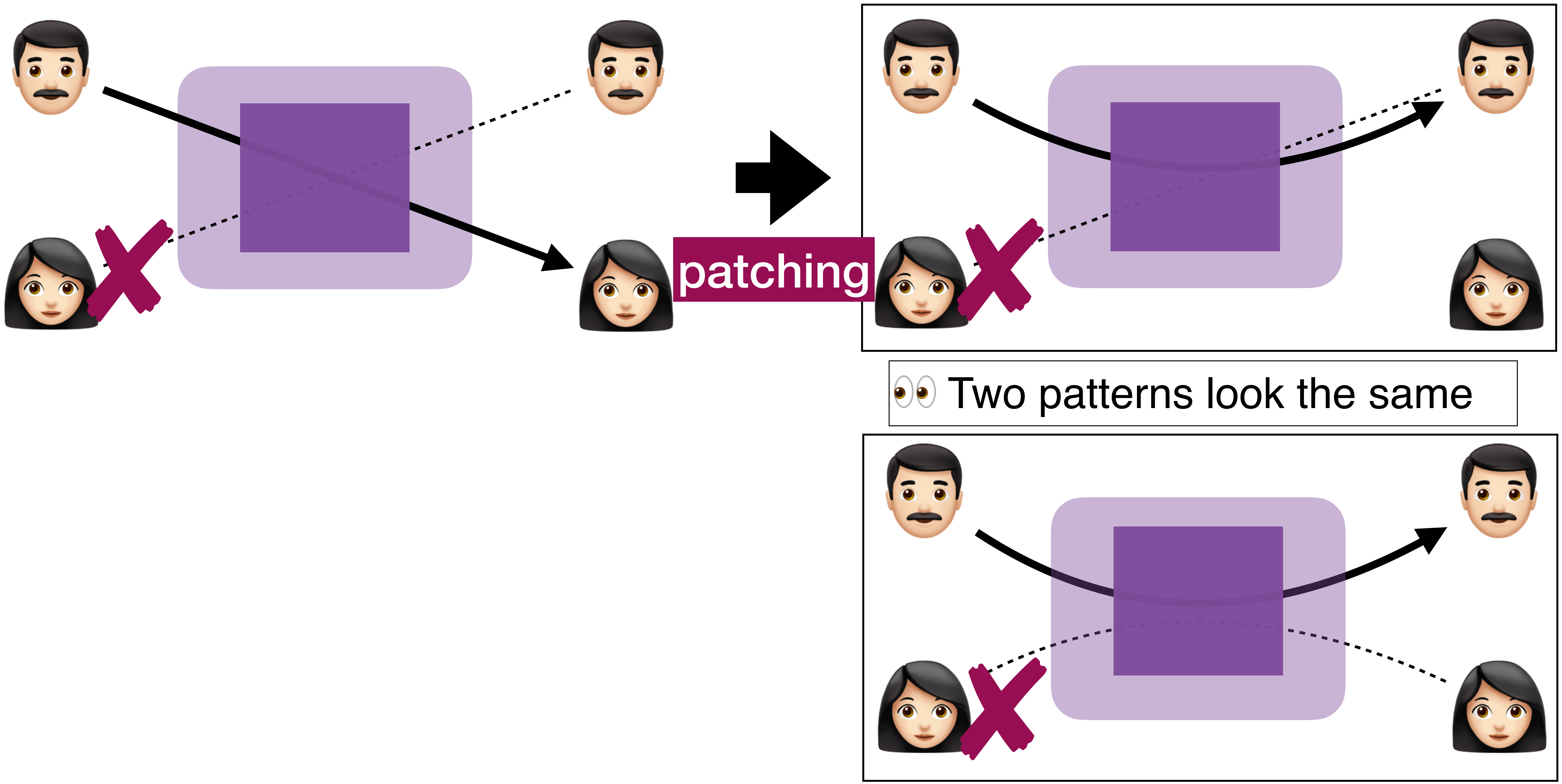


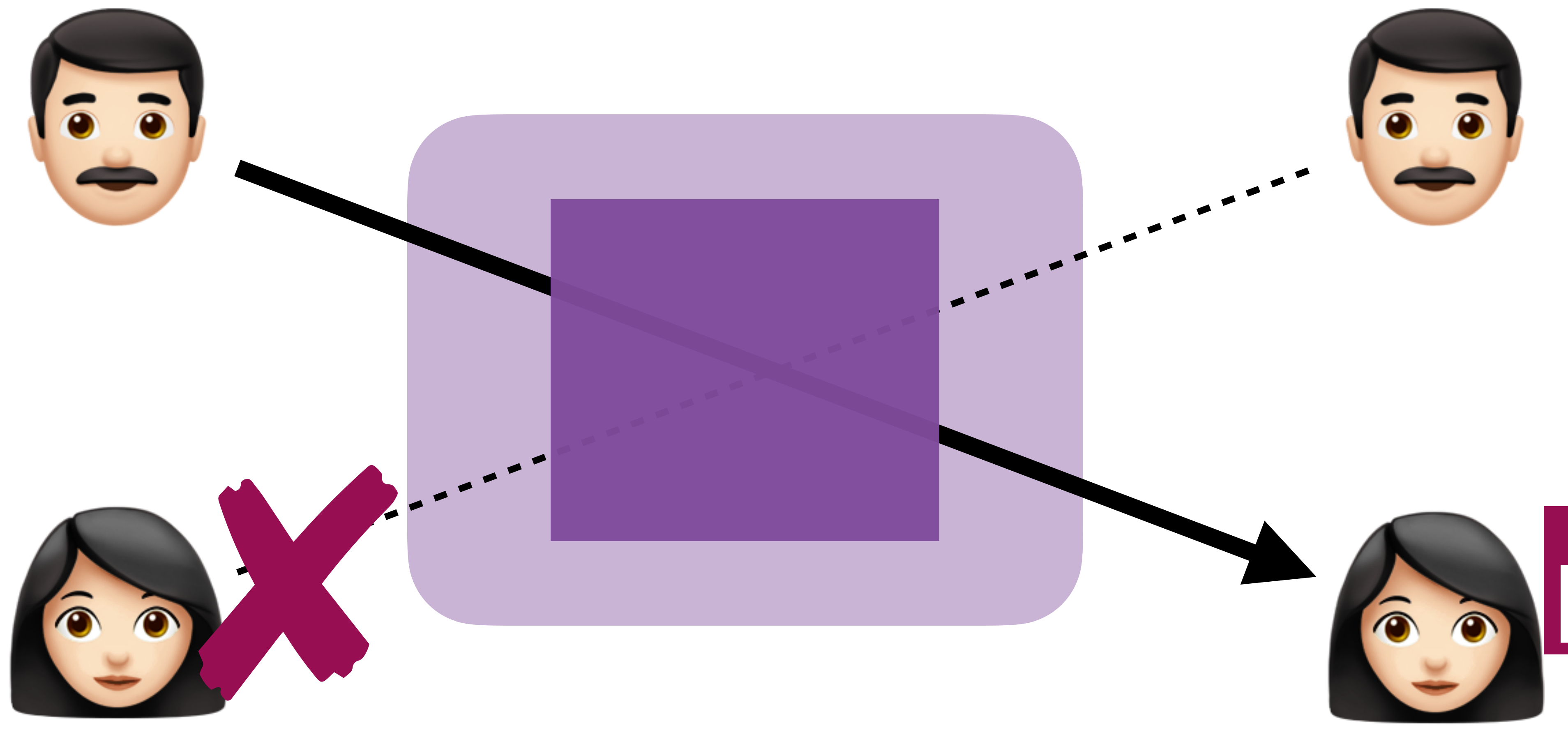
Boomerang with proactive pattern patching

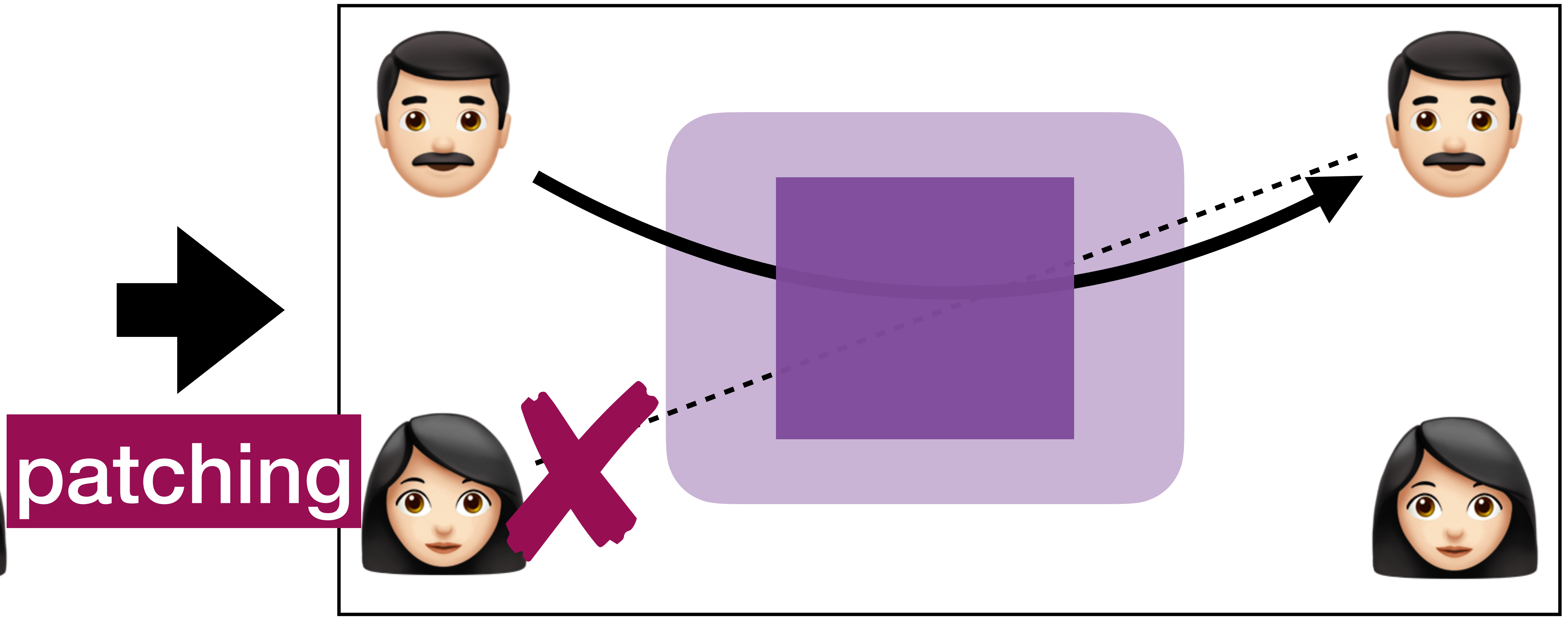


patching

👀 Two patterns look the same

Boomerang with proactive pattern patching





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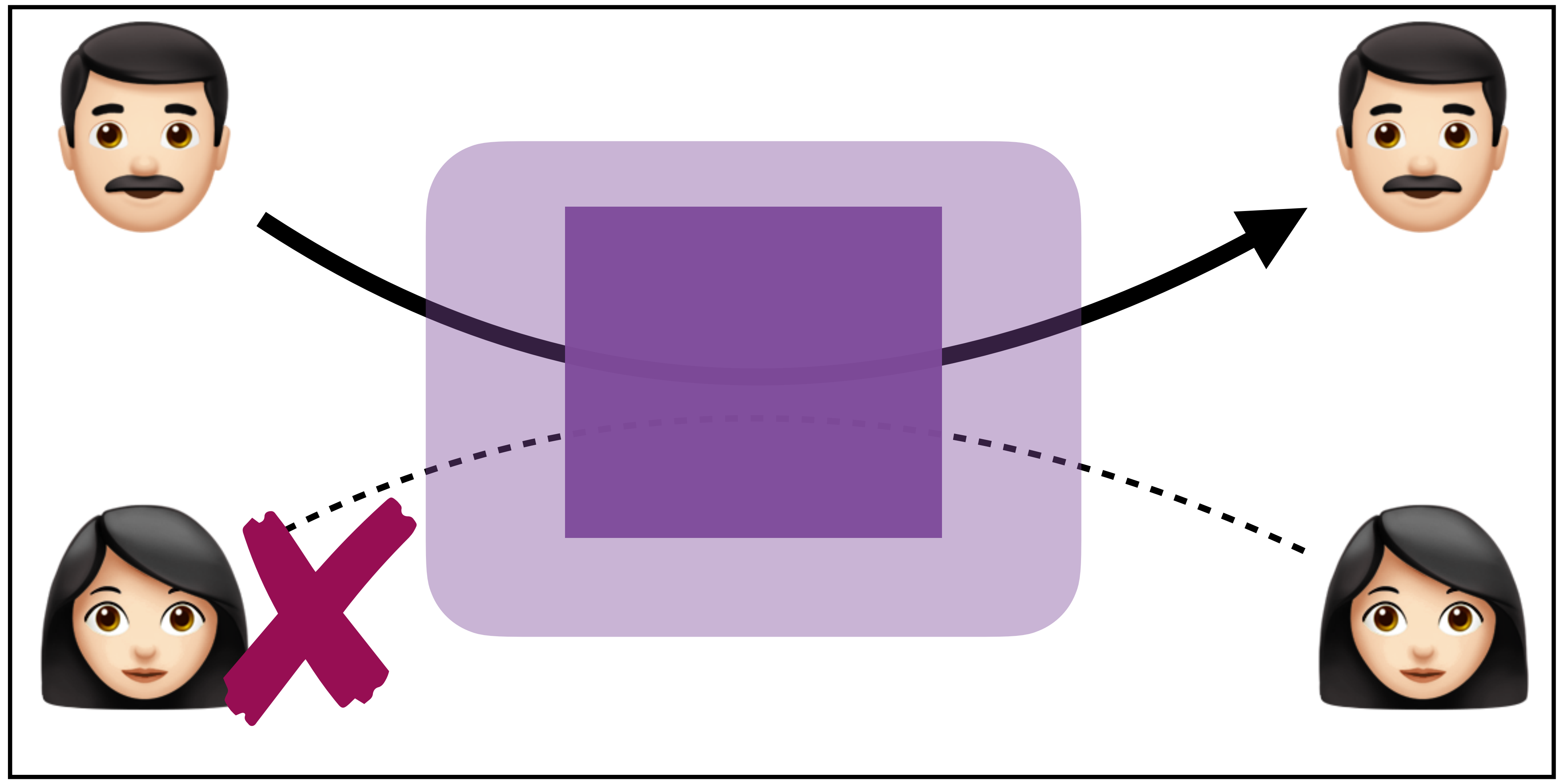

Enclave **detects** irregular label patterns, and proactively **bounces them back** to the senders.

Like a "boomerang"

Oblivious irregular pattern detection & patching

Oblivious irregular pattern detection & patching

- Obliviously sort the labels

Oblivious irregular pattern detection & patching

- Obliviously sort the labels

Label	Sender
0x0C	A
0x12	B
0x12	C
0x12	D
0x1C	E
0x1C	F
0x3F	G

Enclave’s view of message sequence

Oblivious irregular pattern detection & patching

- Obliviously sort the labels
- Linear scan with a sliding window

Label	Sender
0x0C	A
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Enclave’s view of message sequence

Oblivious irregular pattern detection & patching

- Obliviously sort the labels
- Linear scan with a sliding window
  - **Detect** and identify different patterns

Label	Sender	Pattern
0x0C	A	Single
0x12	B	>2
0x12	C	>2
0x12	D	>2
0x1C	E	Double
0x1C	F	Double
0x3F	G	Single

Enclave’s view of message sequence

Oblivious irregular pattern detection & patching

- Obliviously sort the labels
- Linear scan with a sliding window
  - **Detect** and identify different patterns
  - **Patch** irregular pattens

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Enclave's view of message sequence

Oblivious irregular pattern detection & patching

- Obliviously sort the labels
- Linear scan with a sliding window
    - **Detect** and identify different patterns
    - **Patch** irregular pattens
- All based on generic oblivious primitives (details see the paper)

Label	Sender	Pattern
0x0C	A	Single
0x12	B	>2
0x12	C	>2
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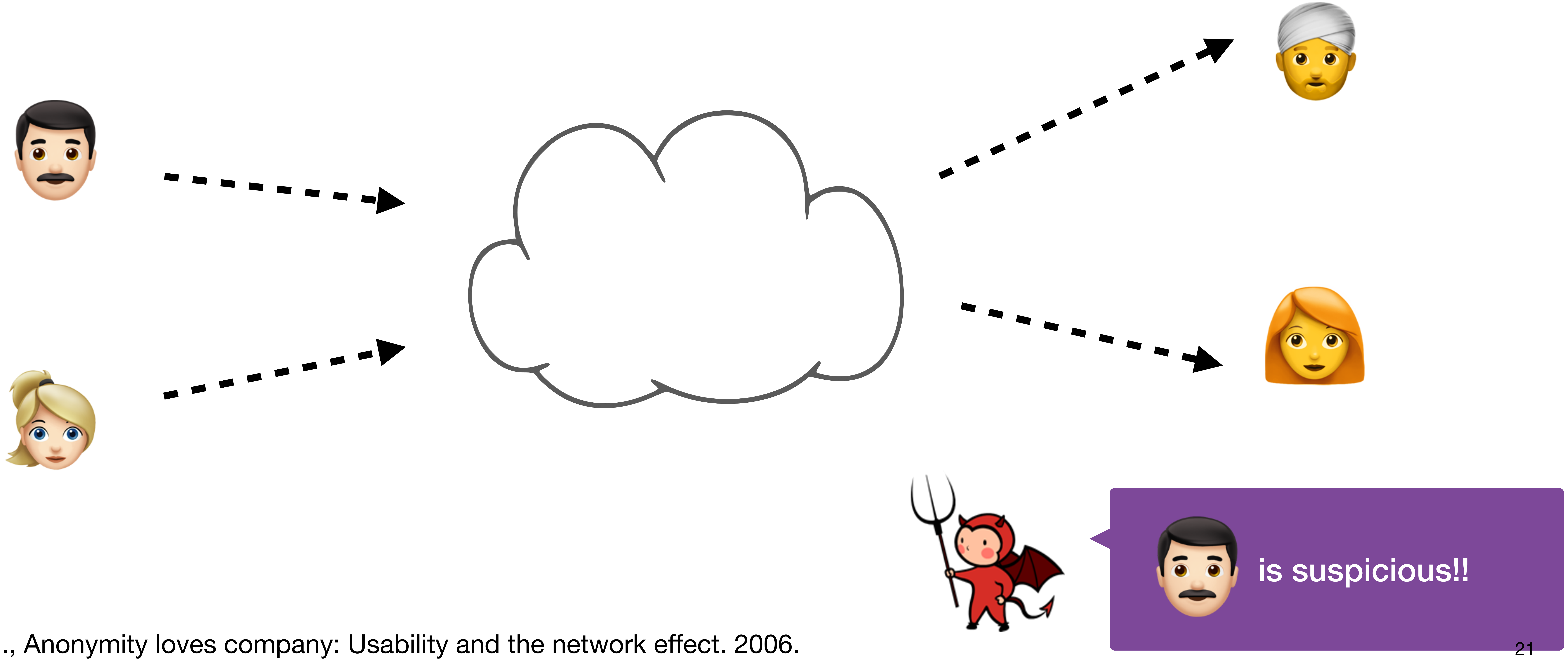
Enclave’s view of message sequence

Boomerang+: horizontal scaling

- Anonymity loves company



Dingledine et al., Anonymity loves company: Usability and the network effect. 2006.

Boomerang+: horizontal scaling

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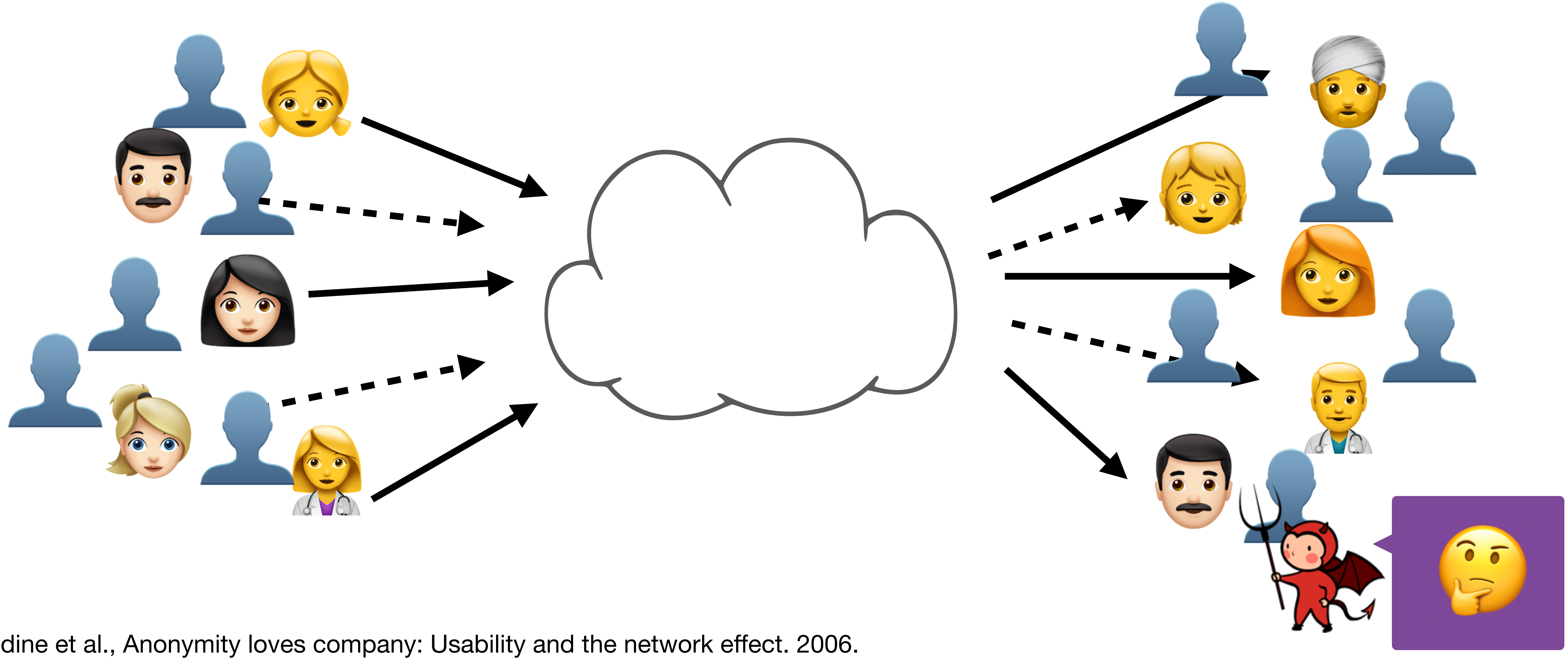
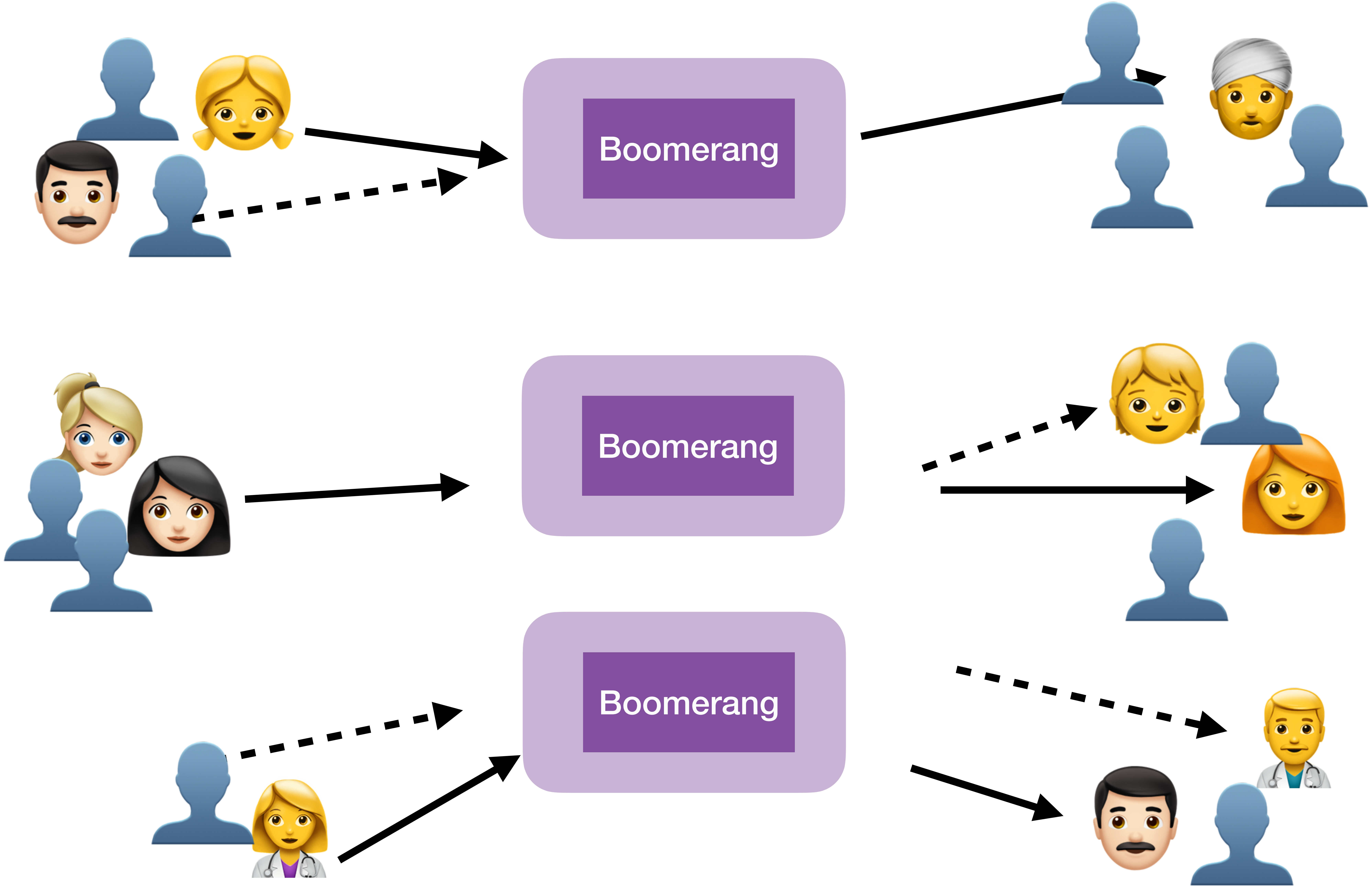


Dingledine et al., Anonymity loves company: Usability and the network effect. 2006.

Intuition 1: duplicate boomerang servers



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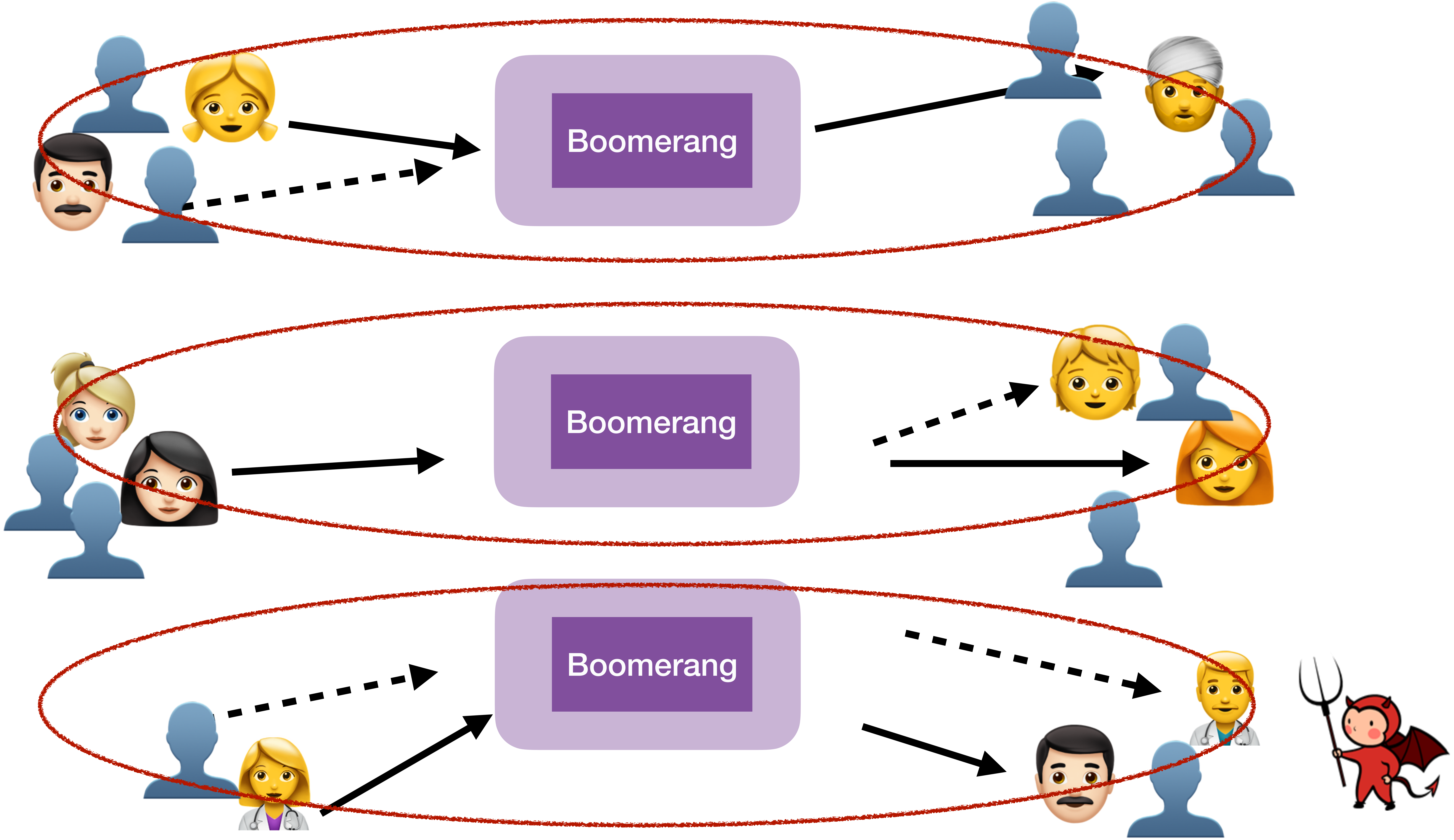
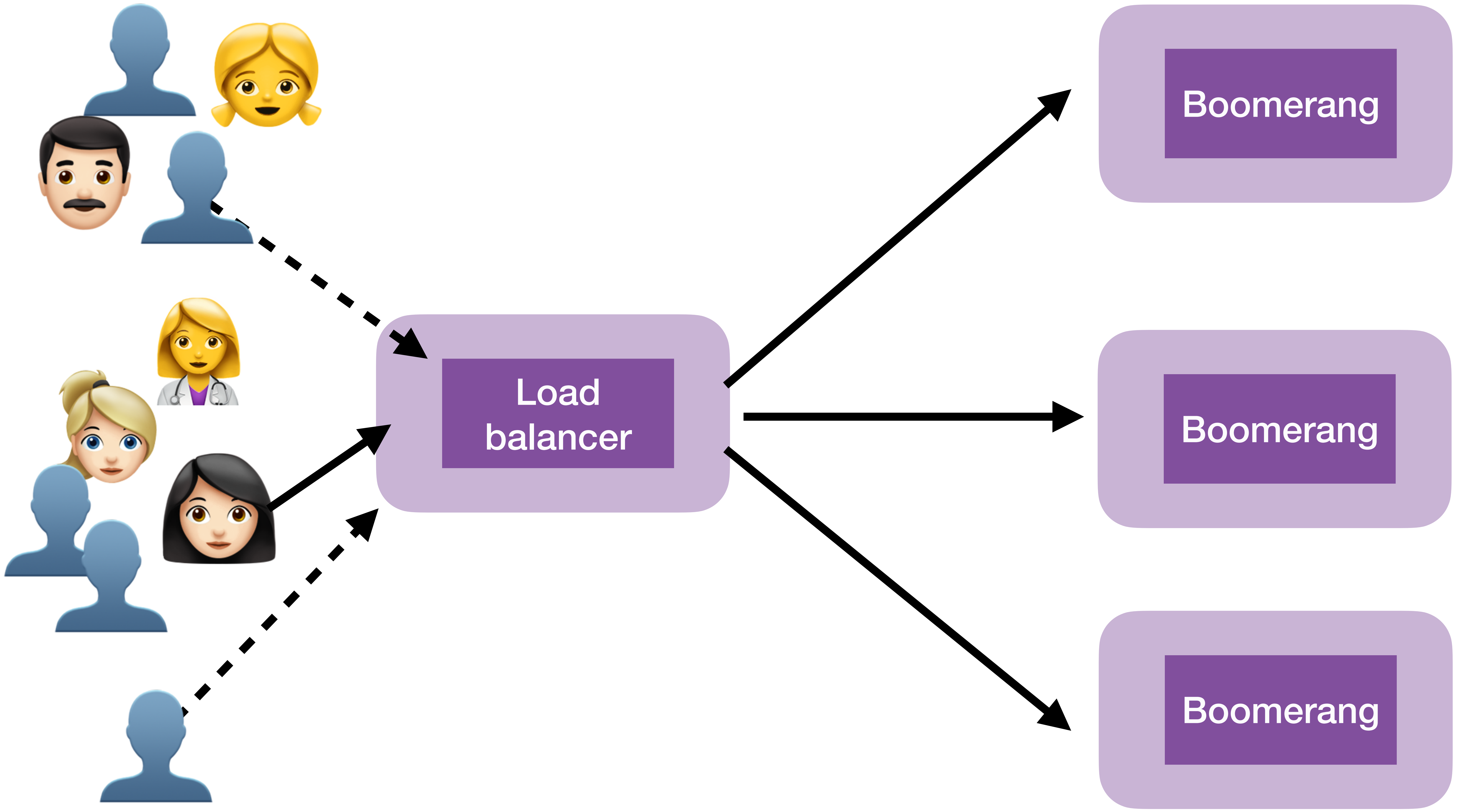


Intuition 2: use load balancers to balance traffic



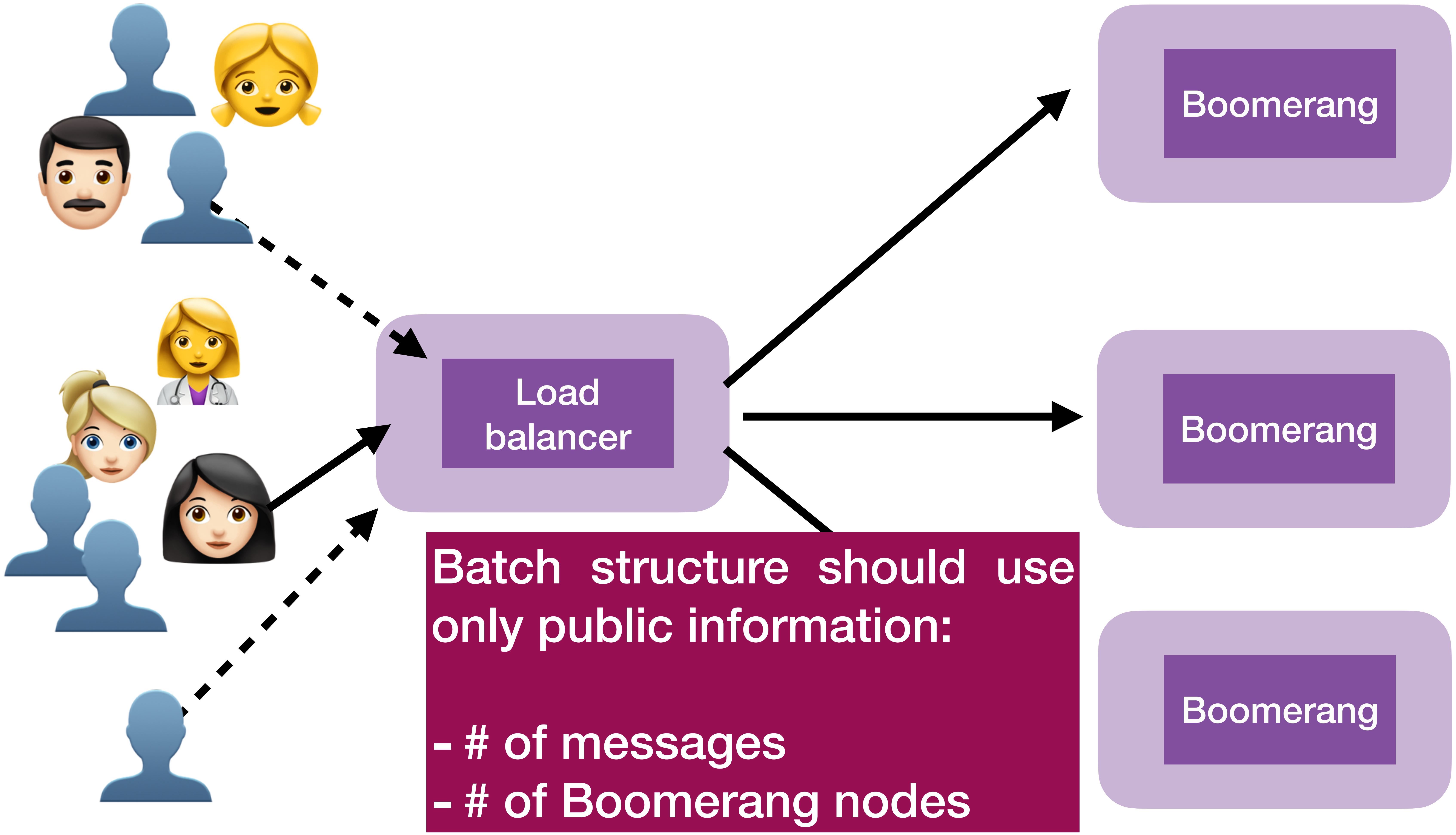
Load balancer

Boomerang

Boomerang

Boomerang

Intuition 2: use load balancers to balance traffic

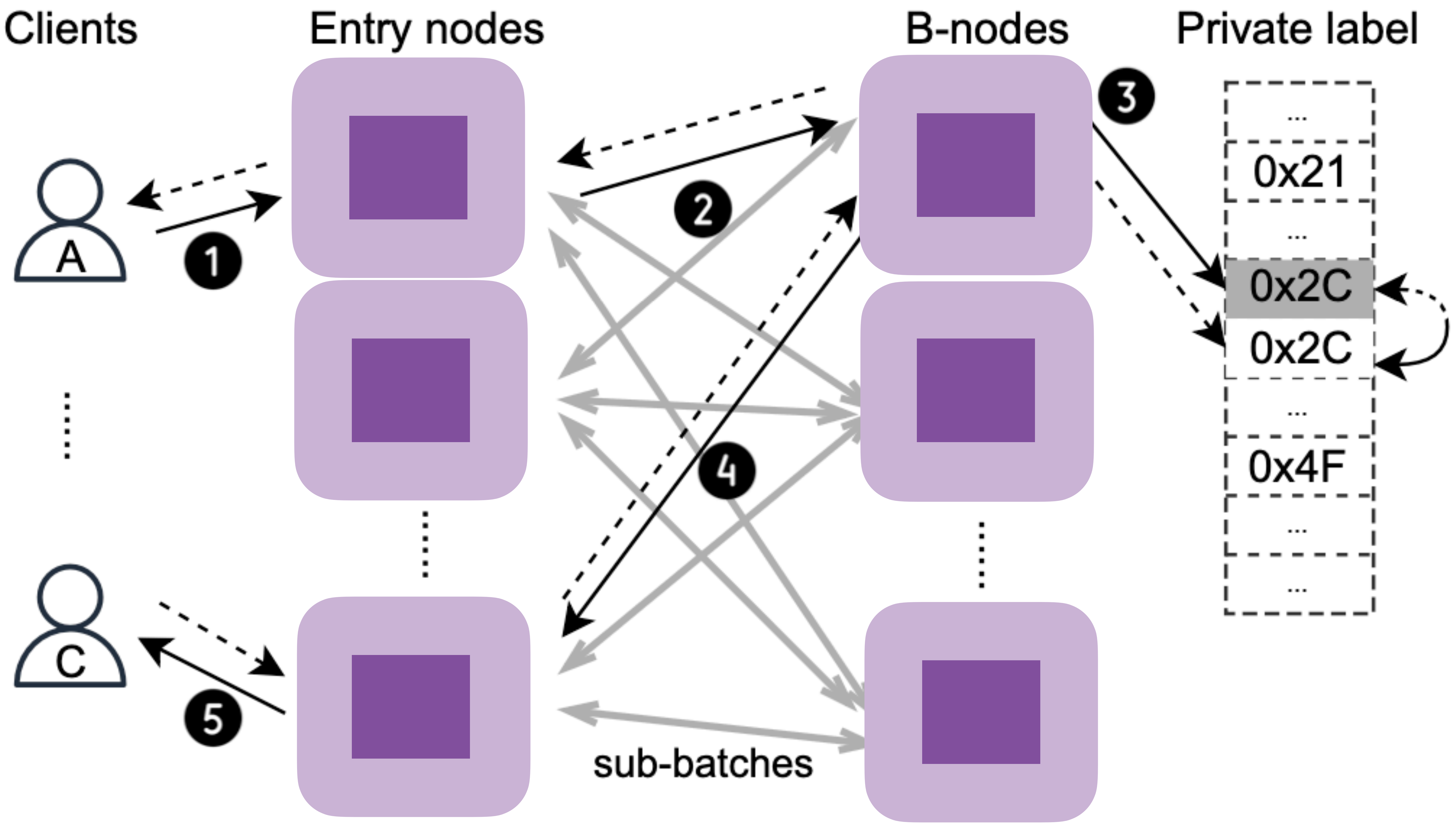


Batch structure should use only public information:

- # of messages
- # of Boomerang nodes

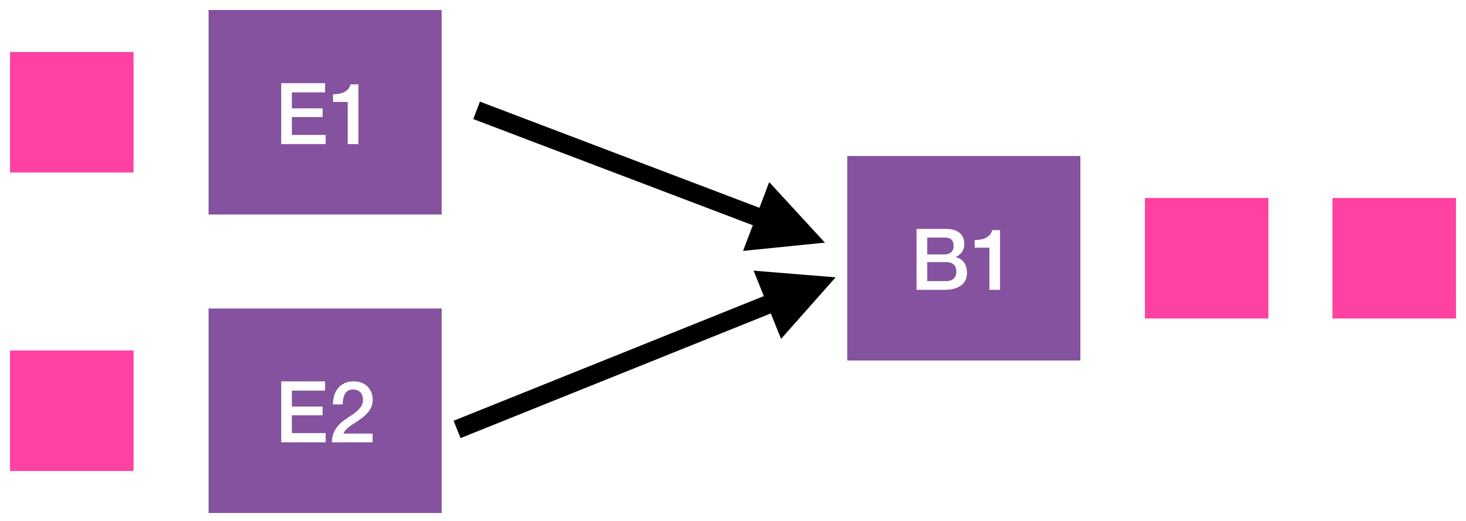
Dauterman et al., Snoopy: Surpassing the scalability bottleneck of oblivious storage. In *Proc. of ACM SOSP*, 2021.
Vuppalapati et al., SHORTSTACK: Distributed, Fault-tolerant, Oblivious Data Access. In *Proc. of* USENIX OSDI, 2022.

Boomerang+: 2-layer design



Entry node: sub-batch assignment

Function goal



always place messages between buddies to one single Boomerang node

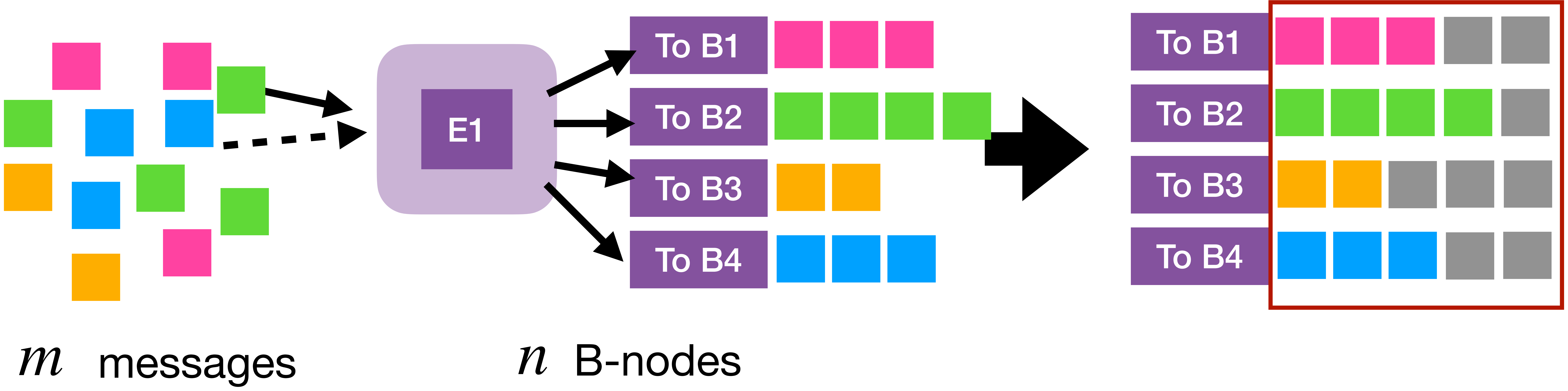
$$\mathtt{br\_id} = \mathsf{H}_k(\mathtt{priv\_label}||\mathtt{round\_num})\%n.$$

Entry node: oblivious batching

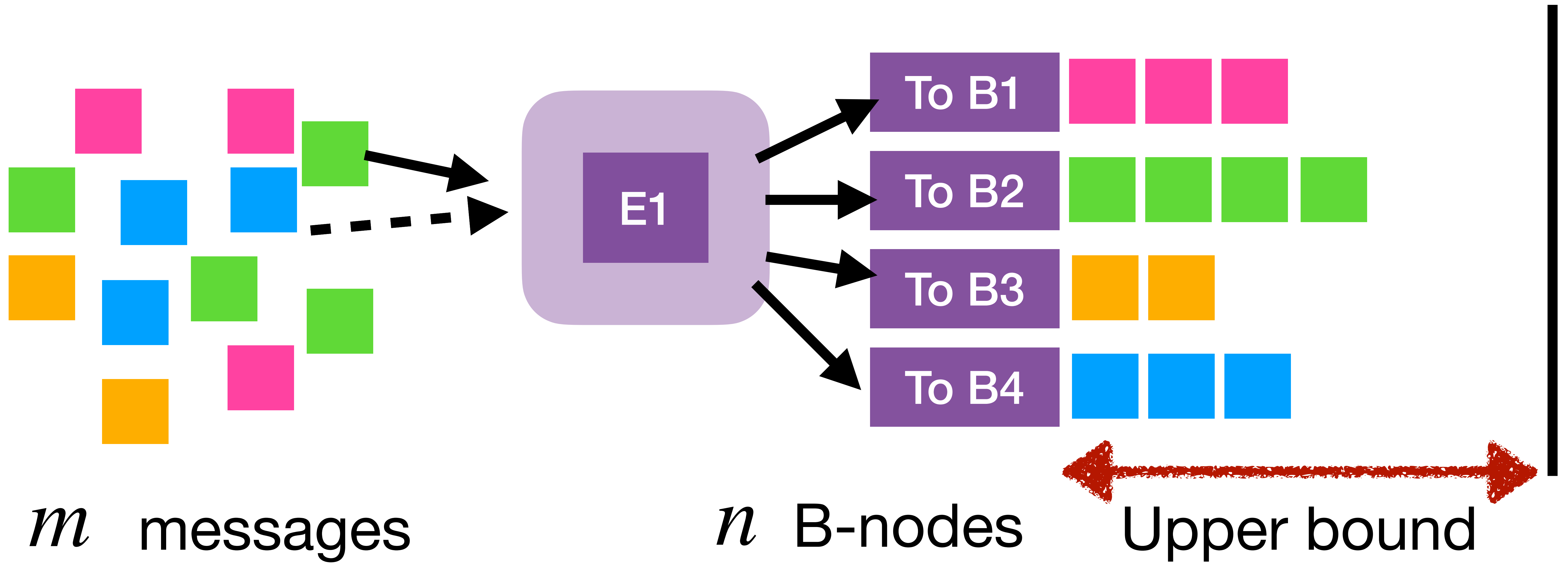
Security goal

Content-independent padding

How to choose the size? 🤔



Setting a batch size for Boomerang+



M. Raab and A. Steger, “balls into bins” - A simple and tight analysis. *Proc. RANDOM*, 1998.

Setting a batch size for Boomerang+

- Requirements:
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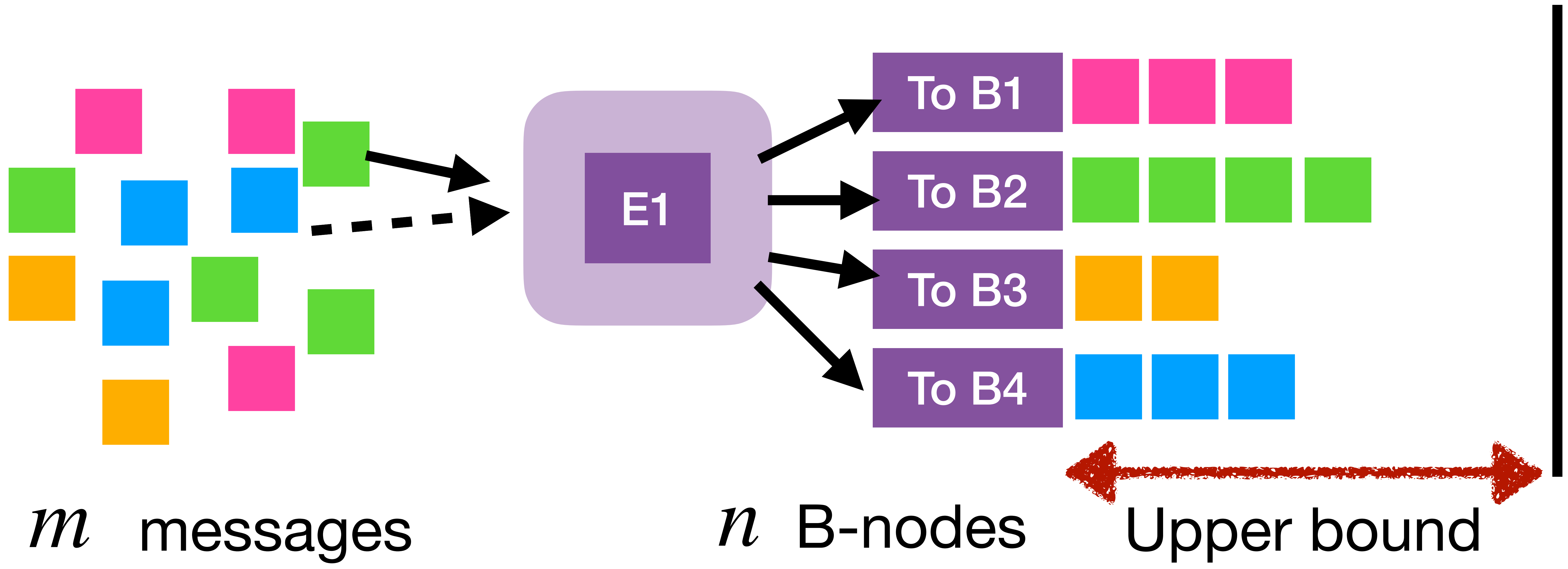
  - For efficiency —> as small as possible



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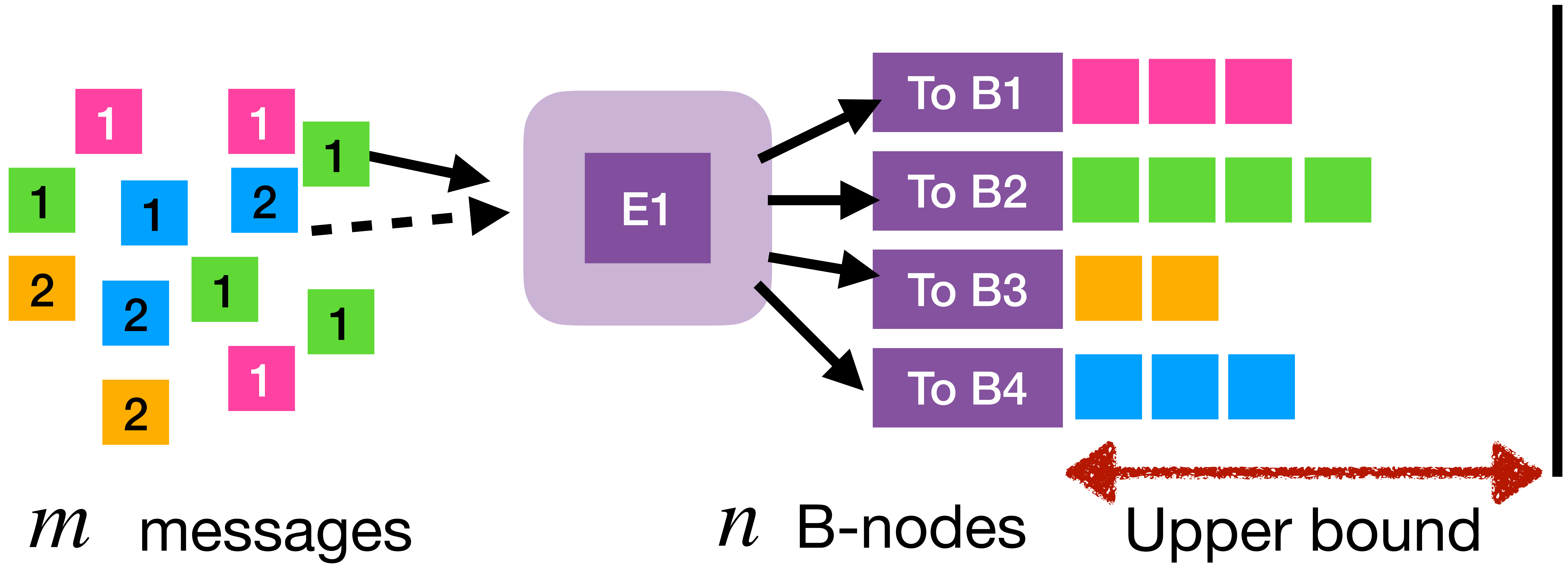

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Setting a batch size for Boomerang+

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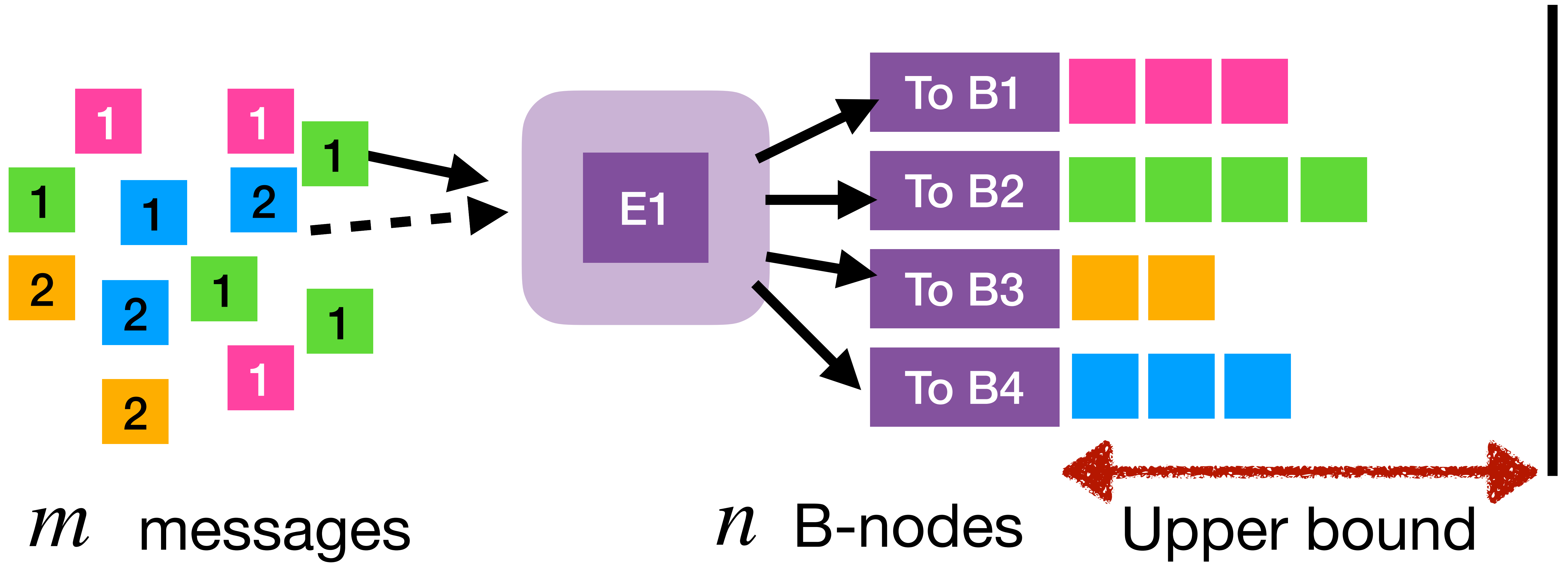
  - Single, double, more-than-two (which we patch)



m messages

n B-nodes

Upper bound

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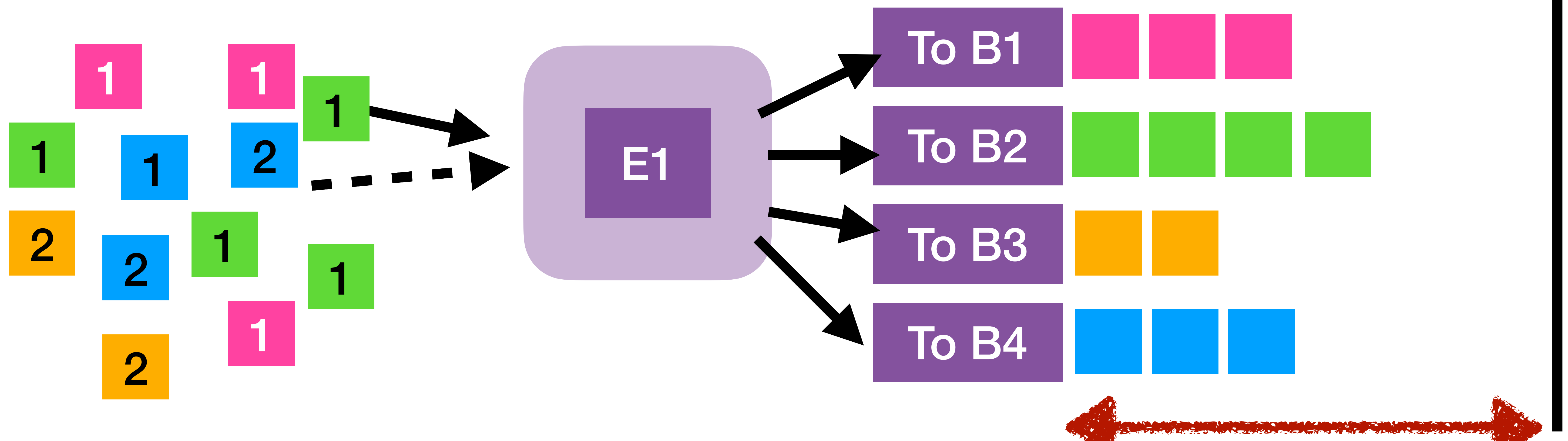

m messages

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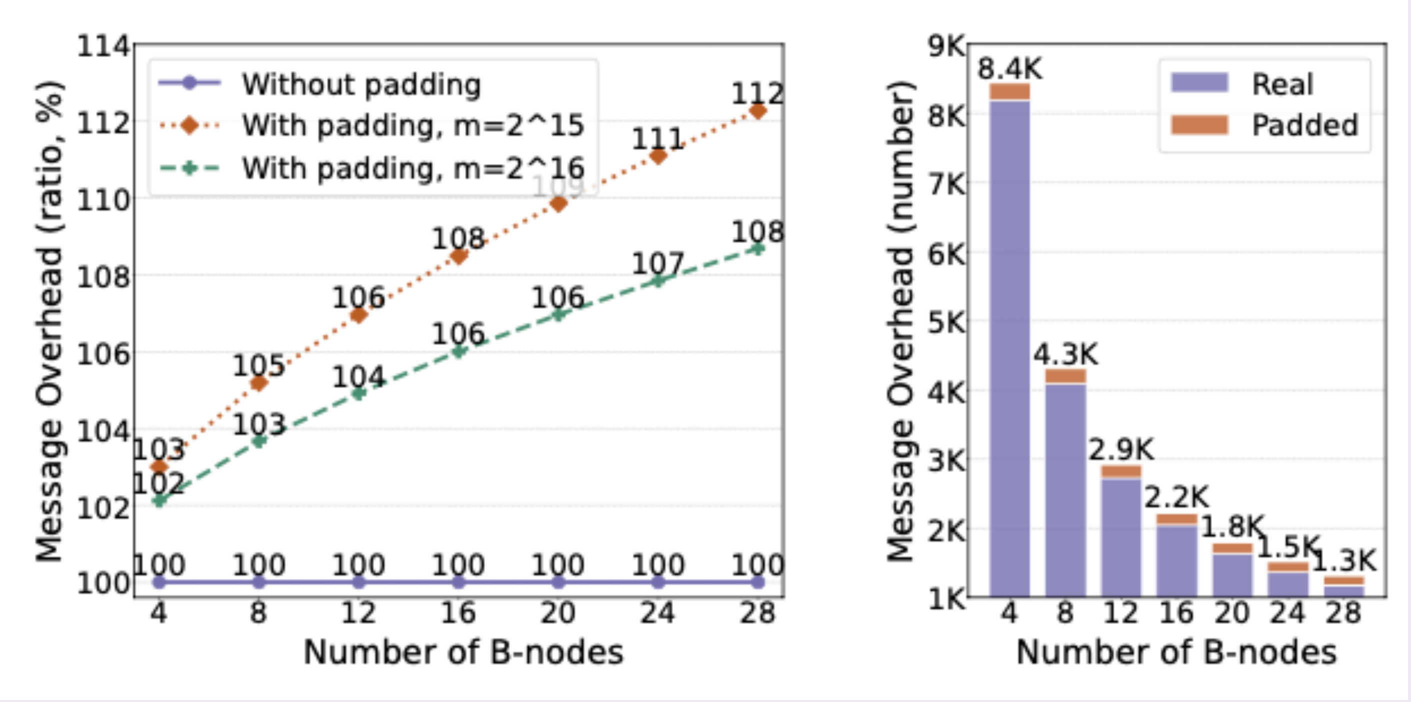
Upper bound

Our results:

$$B = \left\lceil \frac{m}{n} + 4\sqrt{\frac{m \ln n}{3n}\left(1 - \frac{1}{\lambda}\frac{\ln \ln n}{2 \ln 2}\right)} \right\rceil$$



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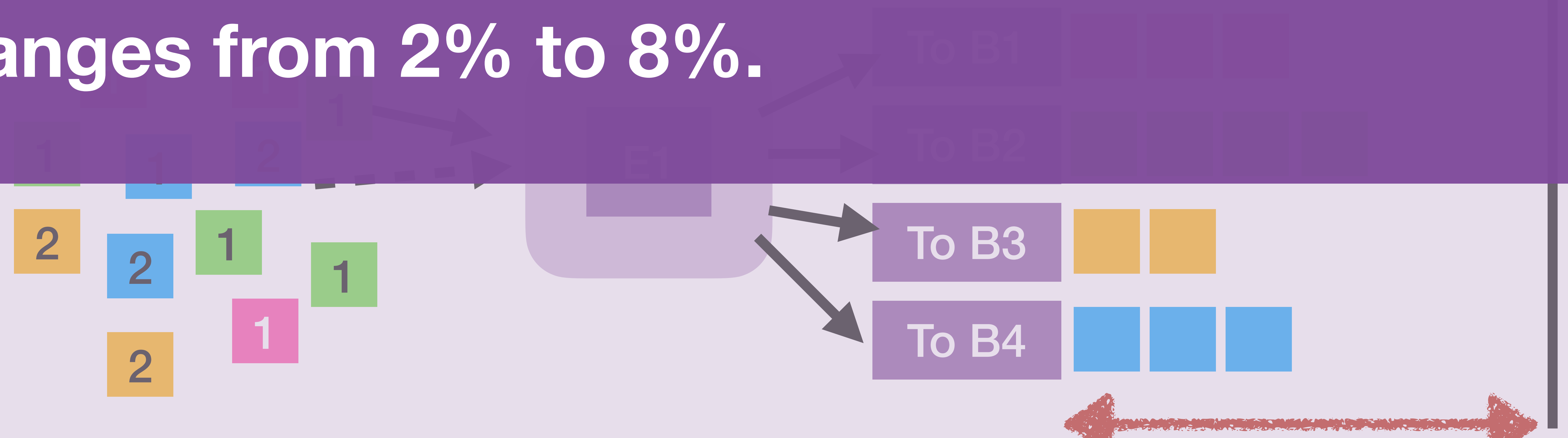
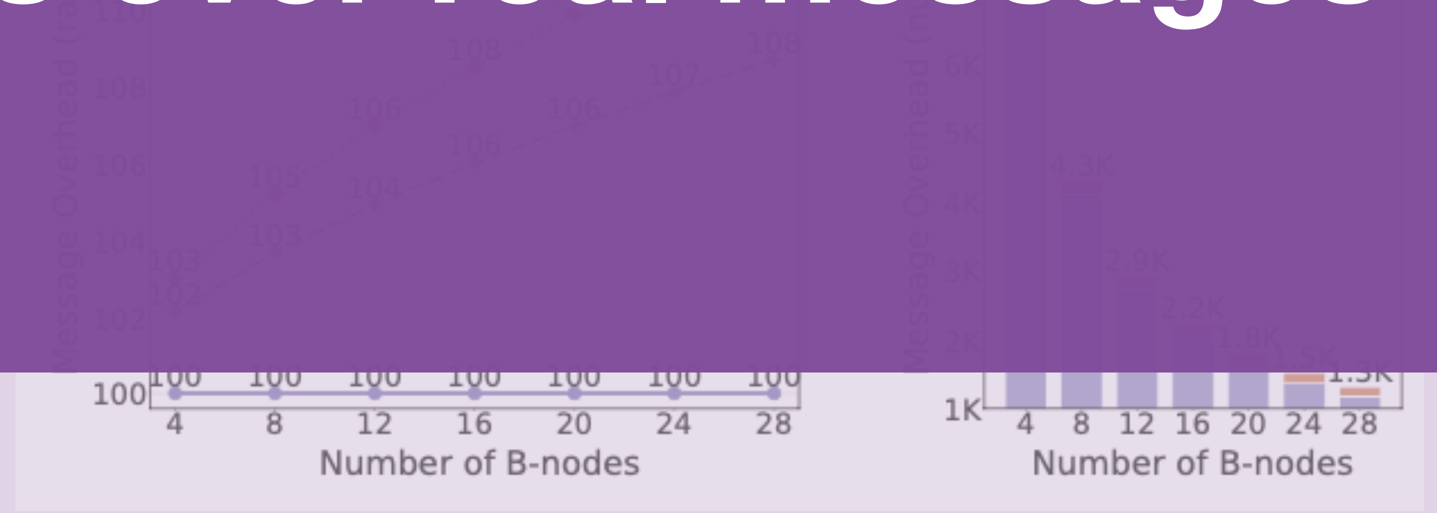
- **With λ = 128 and m = 2^16, when we scale the number of Boomerang nodes n from 4 to 28, the ratio of extra paddings over real messages ranges from 2% to 8%.**



m messages n B-nodes Upper bound



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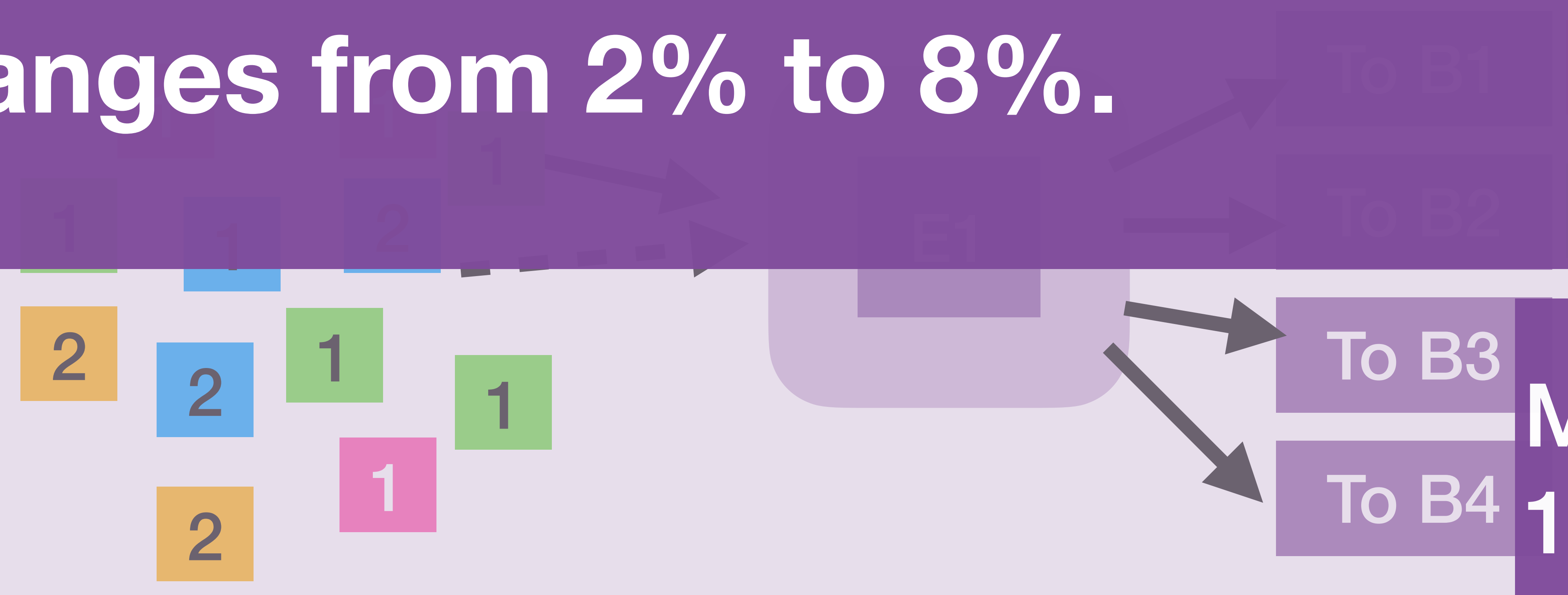


m messages

n B-nodes

More details:

1. Server churn
2. Oblivious padding and batching
3. Message exchange on Boomerang nodes

M. Raab and A. Steger, “balls into bins” - A simple and tight analysis. *Proc. RANDOM*, 1998.

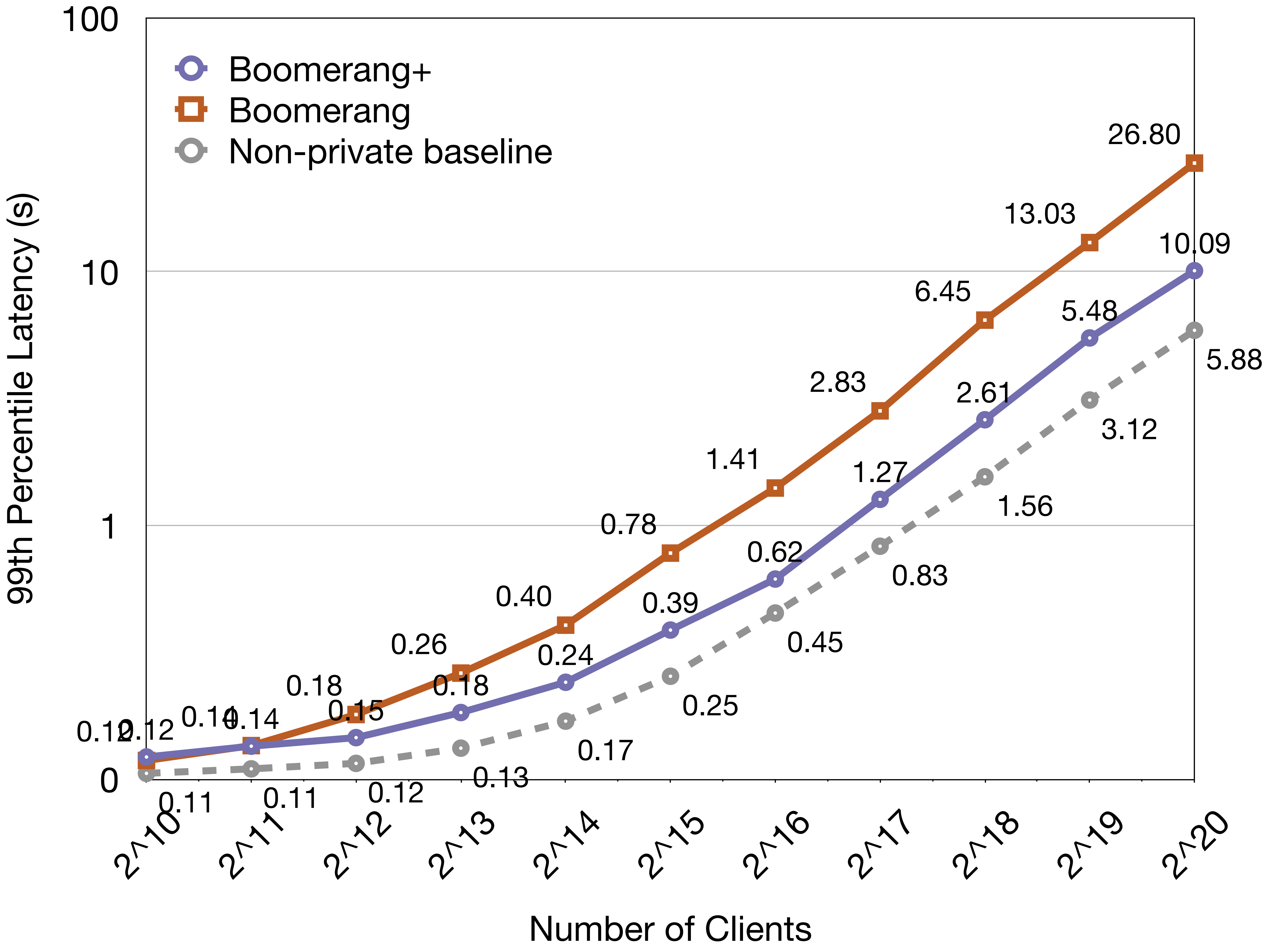
Evaluation

- How fast are Boomerang and Boomerang+?
- Can Boomerang+ scale by adding servers?

Implementation

- ~4,000 lines of C++ code
- 16 M6ce.4XLARGE128 instances with Intel Xeon Ice Lake processors with Intel SGX support (16 vCPU, 128 GB of memory, and 13 Gbps of network bandwidth)
- Compared with 3 existing systems with crypto guarantee (Pung, Addra, XRD)

Evaluation: how fast are Boomerang(+)?



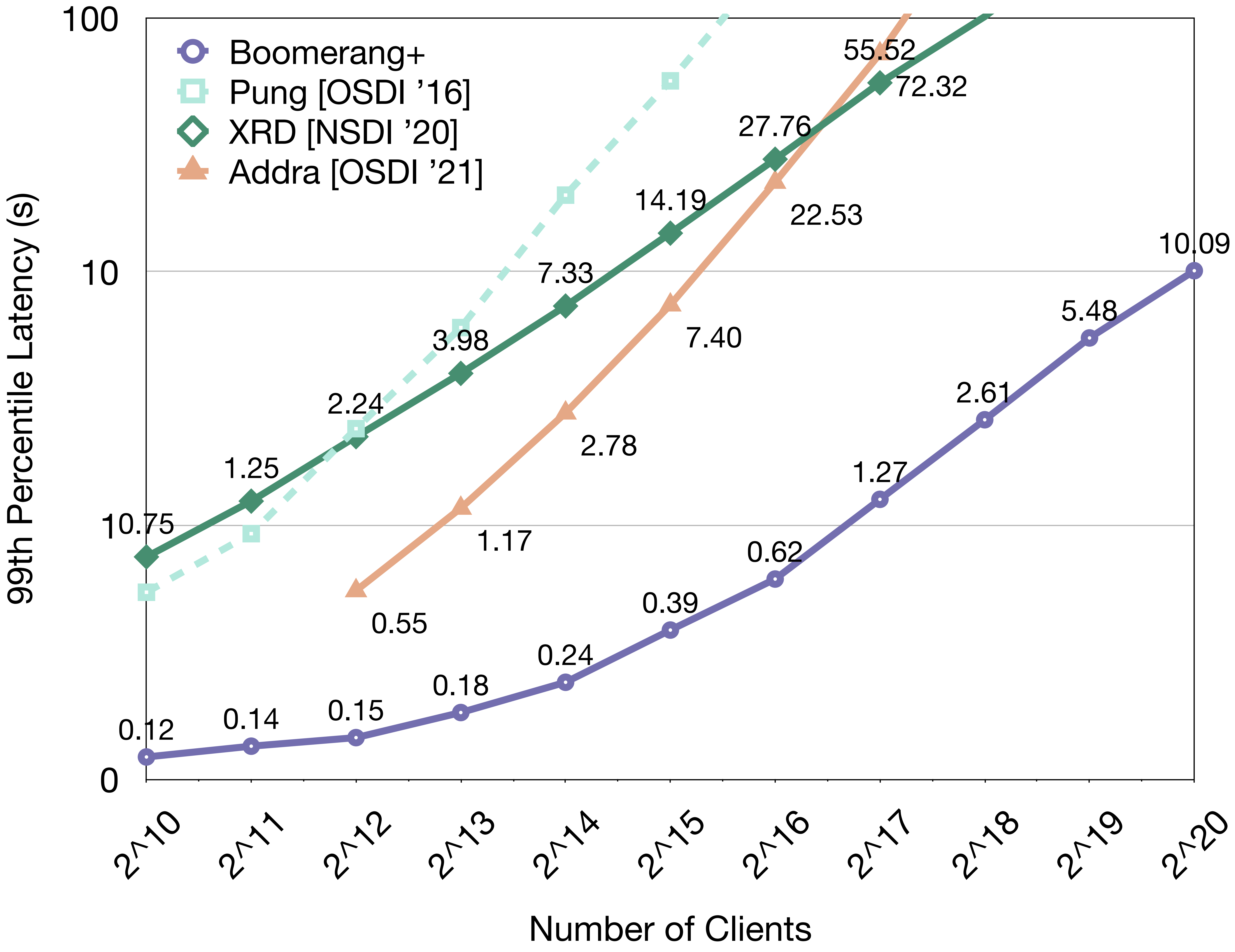
Boomerang+ (on 16 servers):

- For 2^16 clients, latency = 0.62s
- For 2^20 clients, latency = 10.09s

Boomerang (on 1 server):

- For 2^16 clients, latency = 1.41s
- For 2^20 clients, latency = 26.80s

Evaluation: how fast are Boomerang(+)?

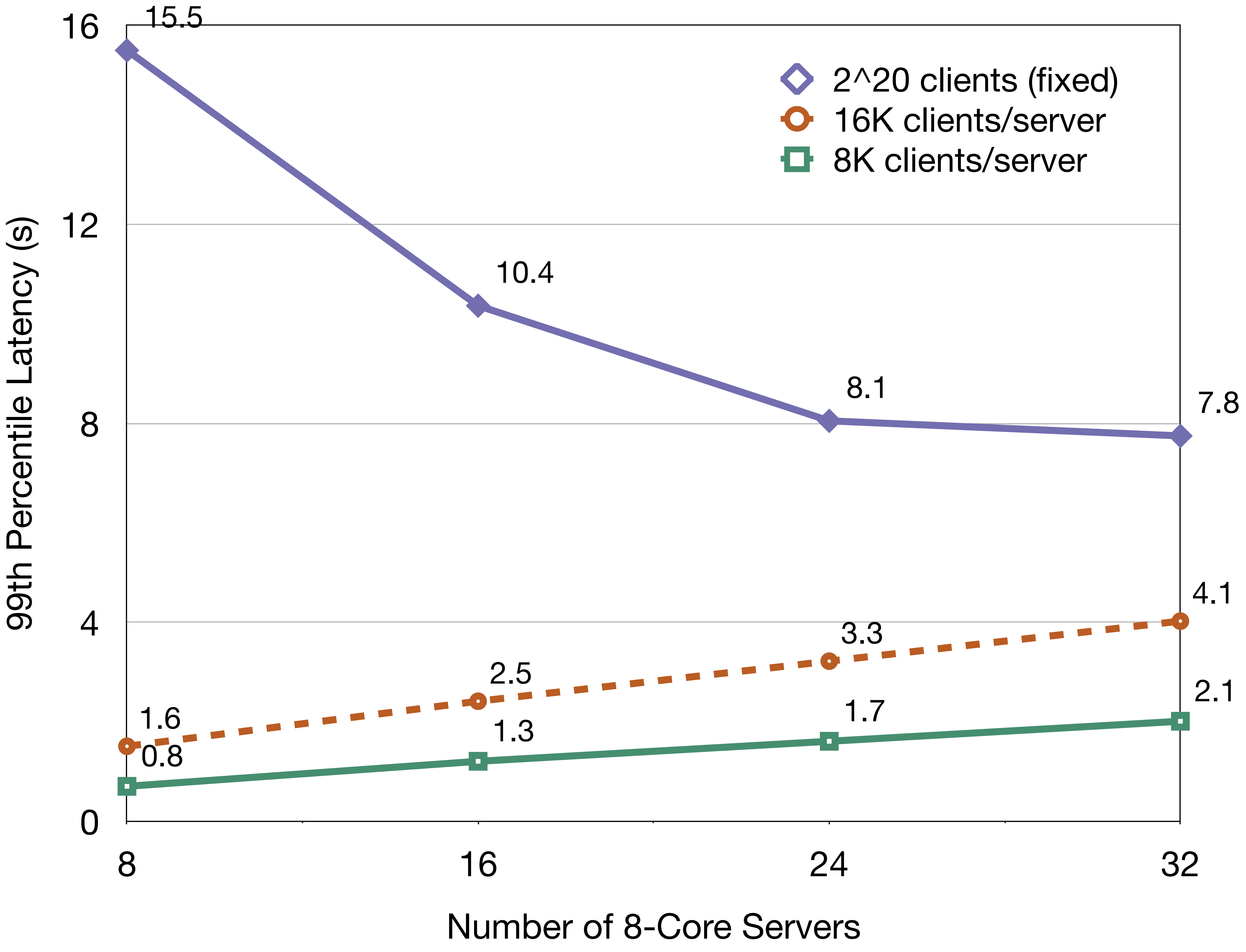


Try our best to make the comparison fair:

keep the same budget for cloud servers.

As expected, Boomerang+ runs faster than crypto-based systems, thanks to the trusted hardware

Evaluation: can Boomerang+ scale by adding servers?



Boomerang+ can reduce latency by adding **more servers**:

- **16 servers**: **10.4s** over 2^20 clients
- **32 servers**: **7.8s** over 2^20 clients

Boomerang+ can remain low latency while **keeping a constant per server workload**:

- **8K clients/server**: **0.8s~2.1s**
- **16K clients/server**: **1.6s~4.1s**

Takeaways

- Enclave-based metadata-private messaging for low cost and accessibility to the mass
  - Oblivious detection and patching algorithms (boomerang trick)
  - A scalable design with oblivious batching algorithms
  - Code available at https://github.com/CongGroup/boomerang

- Future work
  - A planner that can adaptively allocate the entry nodes and B-nodes
  - Boomerang as a backend mixing network for other applications

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Thank you! Questions?

pp.jiang@my.cityu.edu.hk

- Future work
  - A planner that can adaptively allocate the entry nodes and B-nodes
  - Boomerang as a backend mixing network for other applications