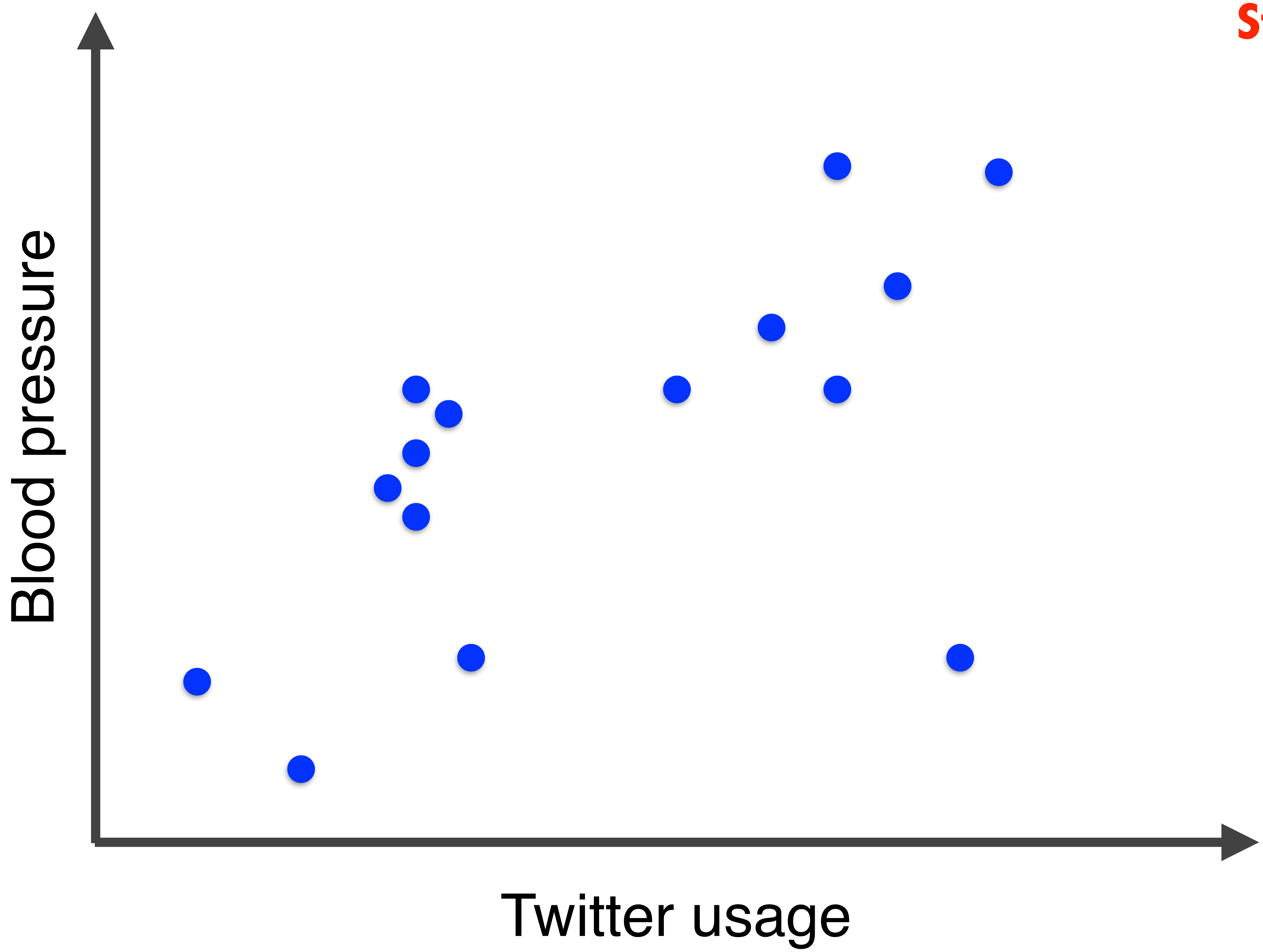
Prio: Private, Robust, and Efficient Computation of Aggregate Statistics

Henry Corrigan-Gibbs and Dan Boneh
Stanford University

Appeared at NSDI 2017

Today: Non-private aggregation



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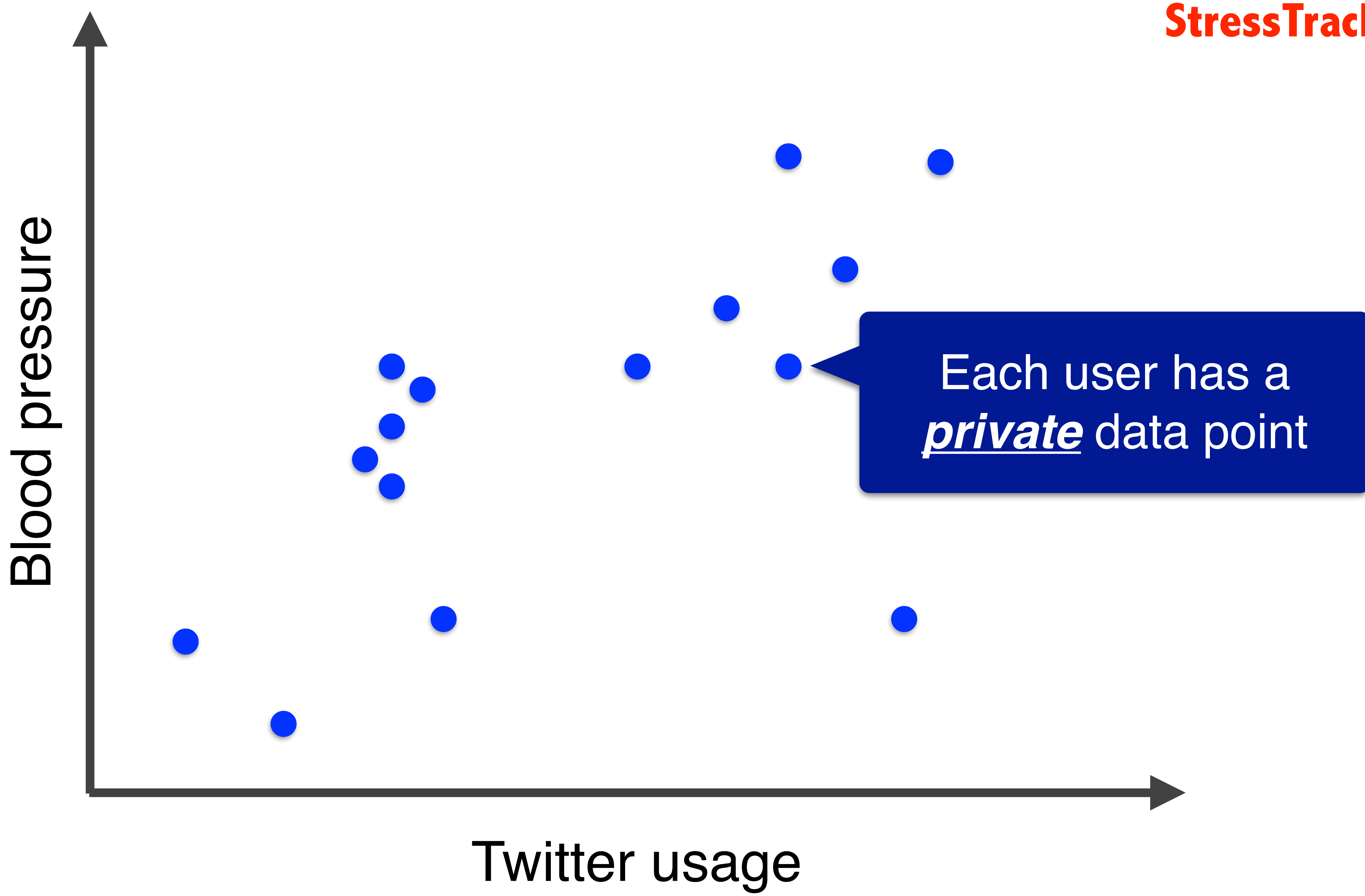

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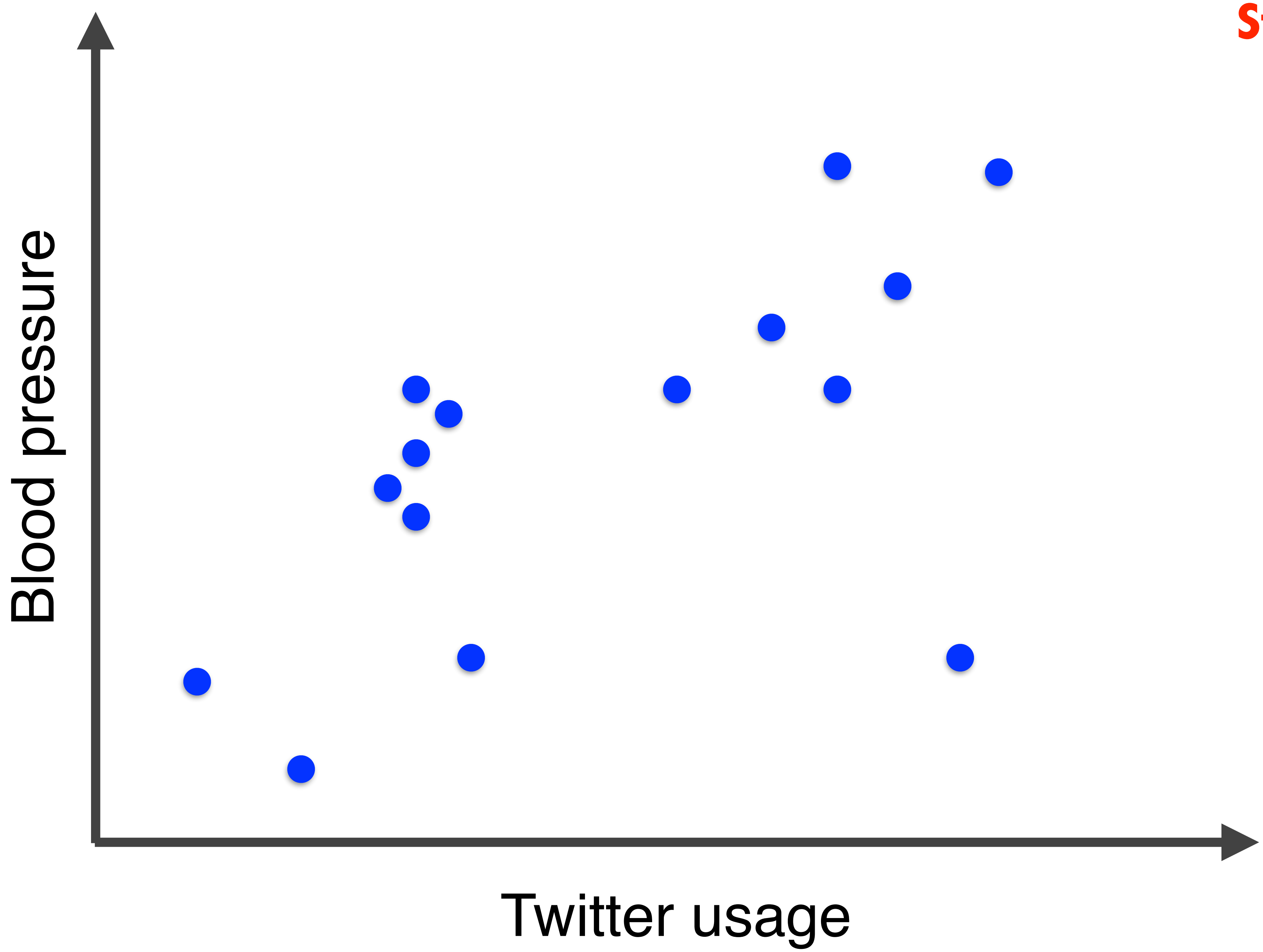

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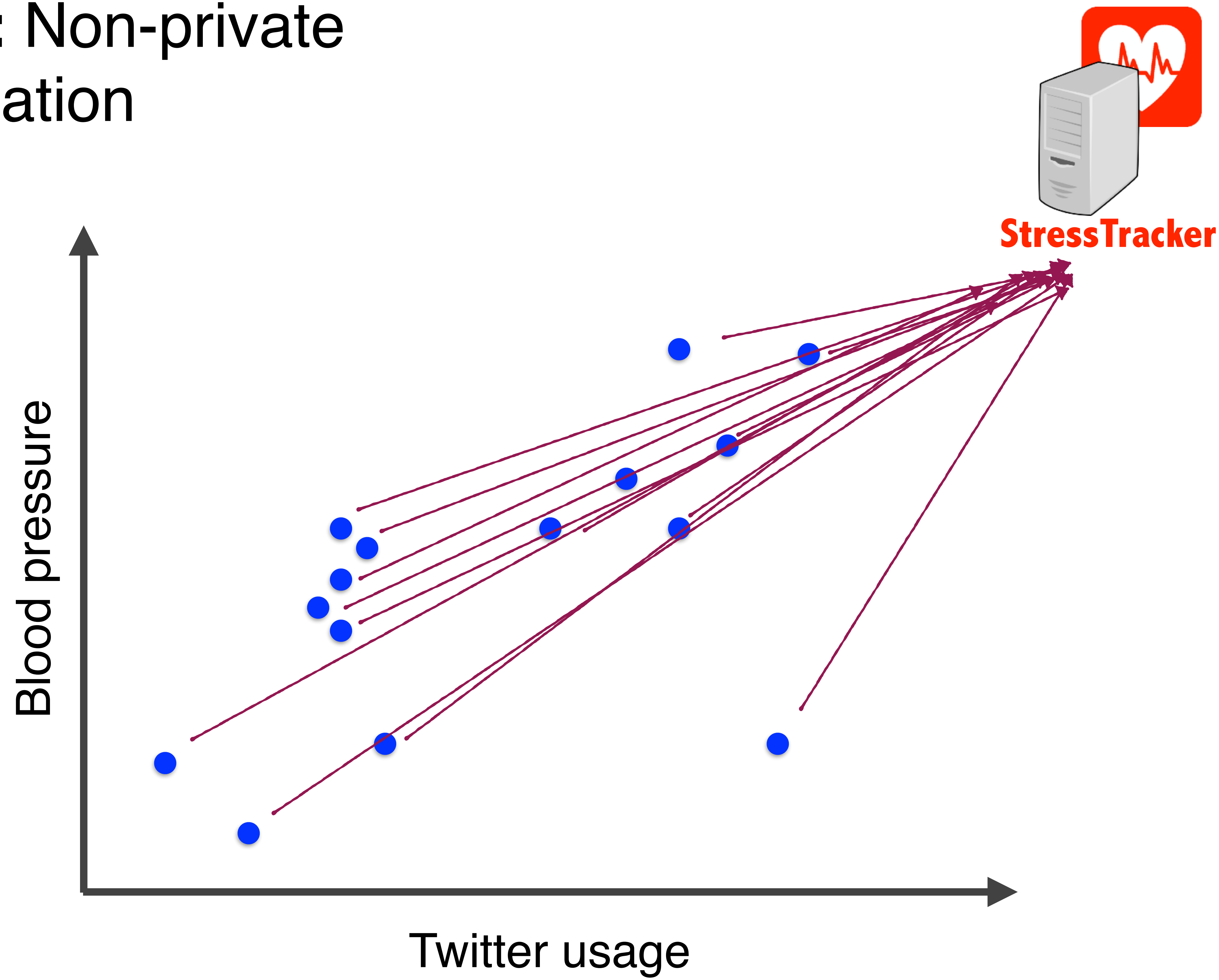

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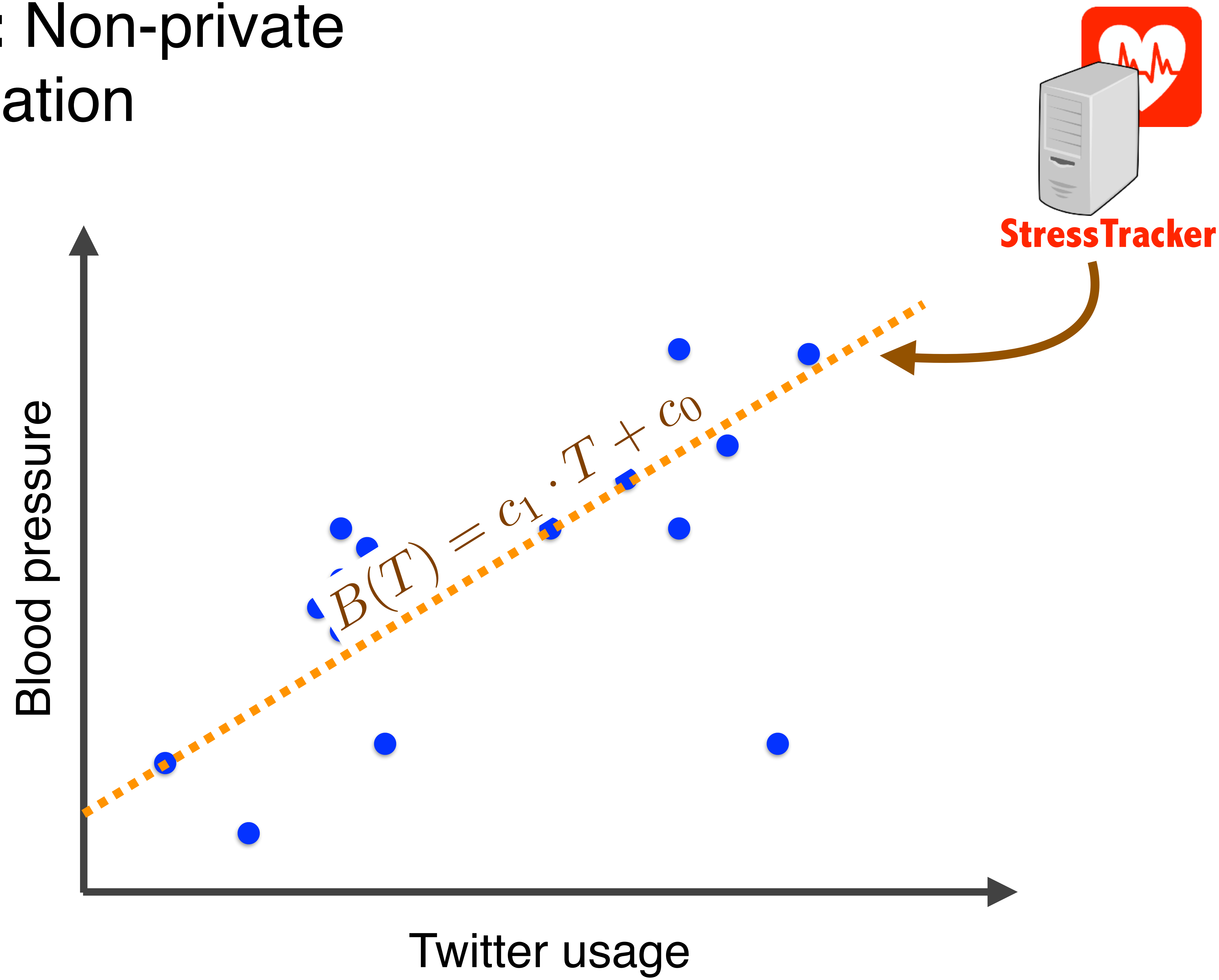

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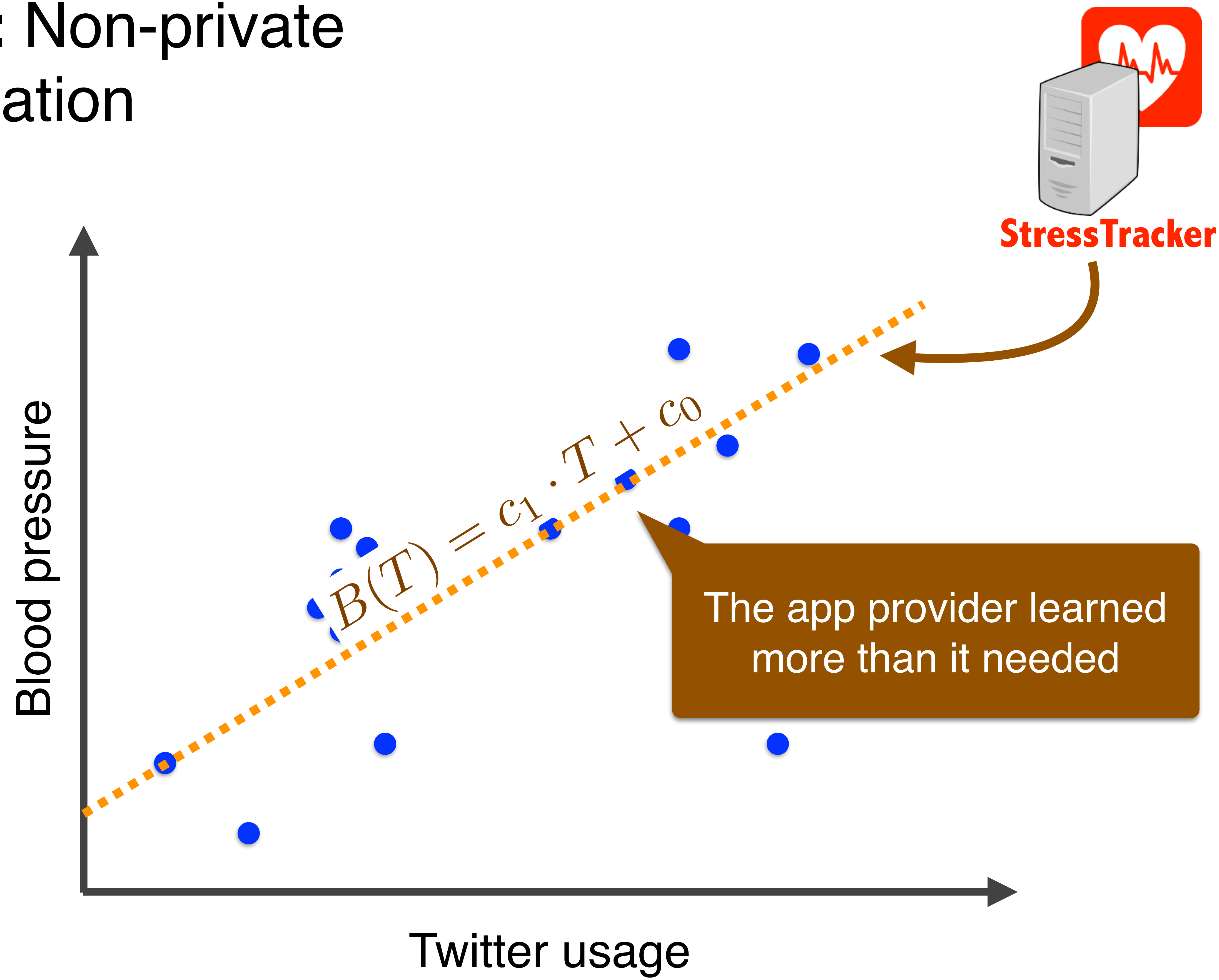

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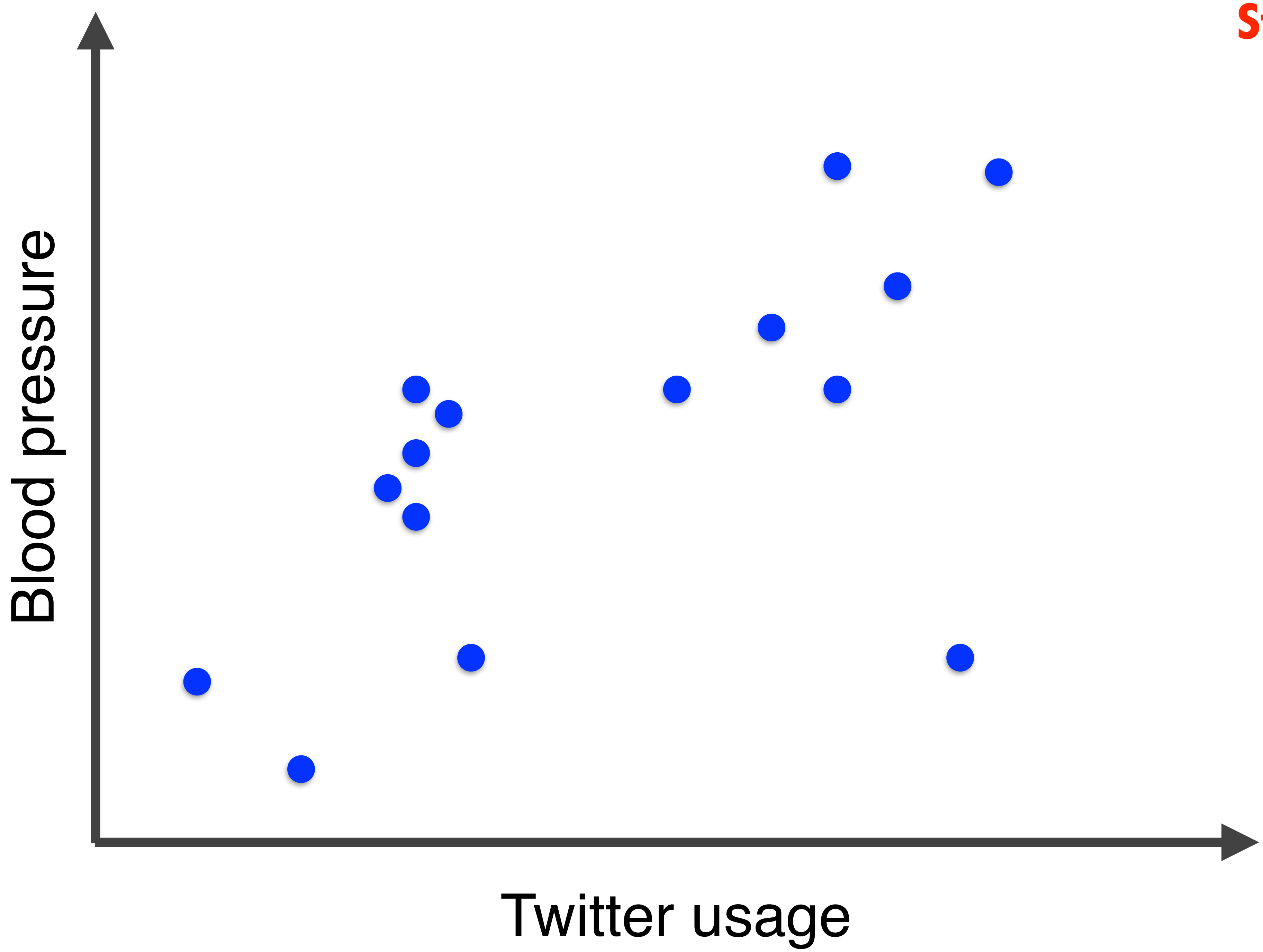

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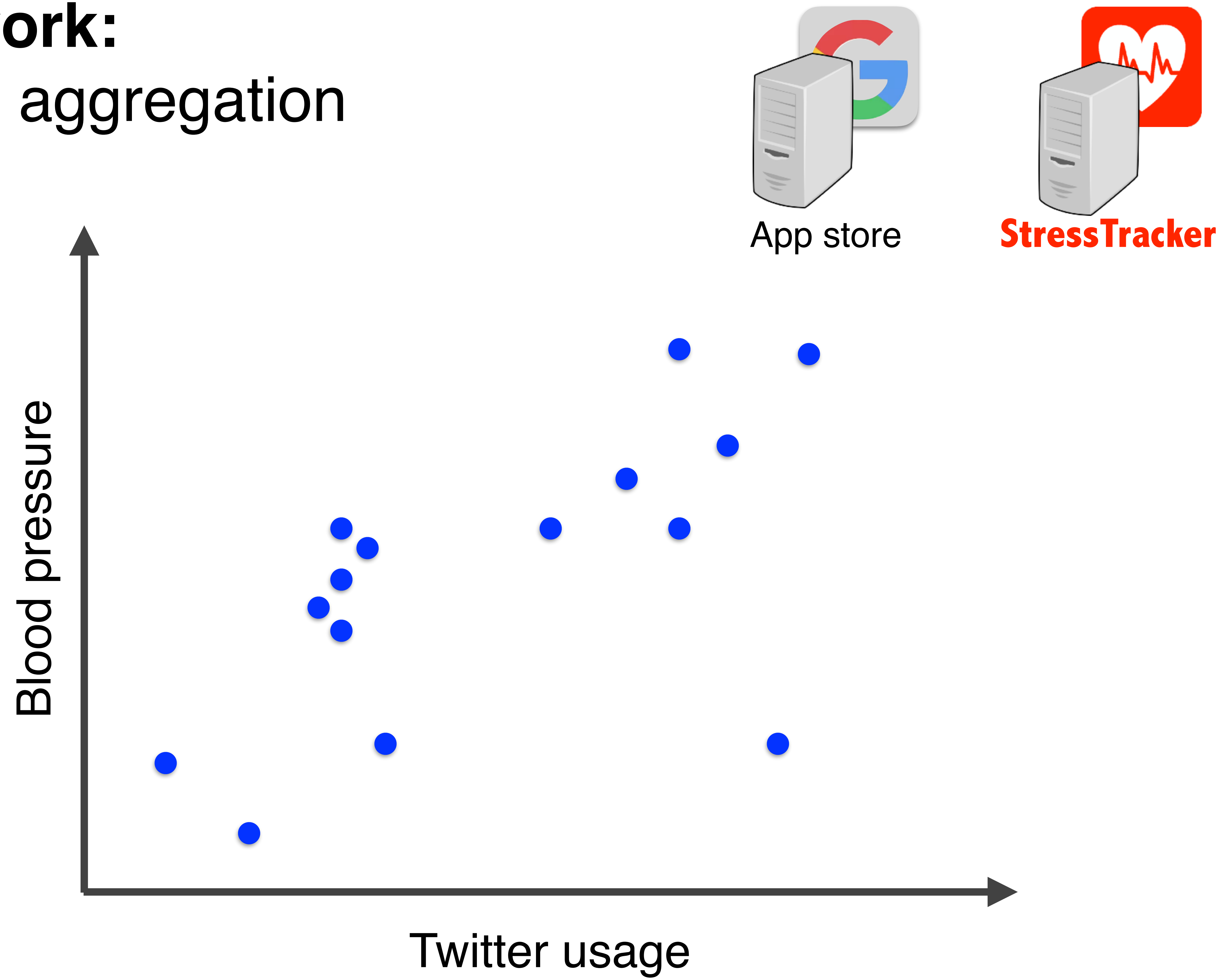
Private aggregation



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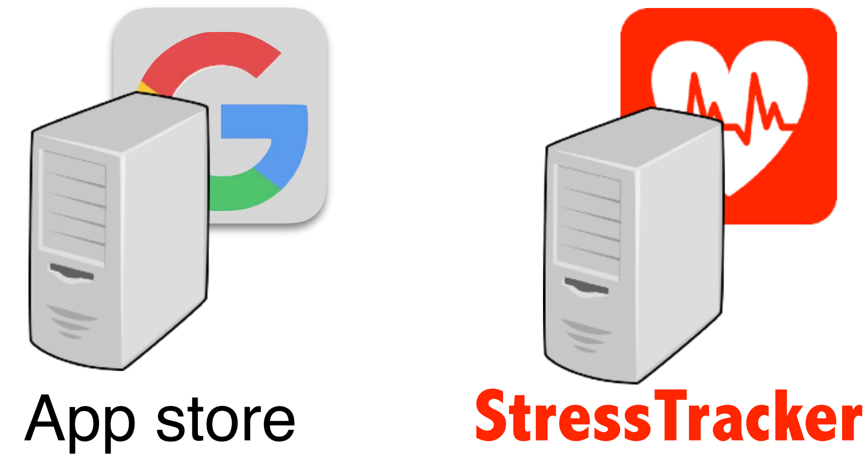
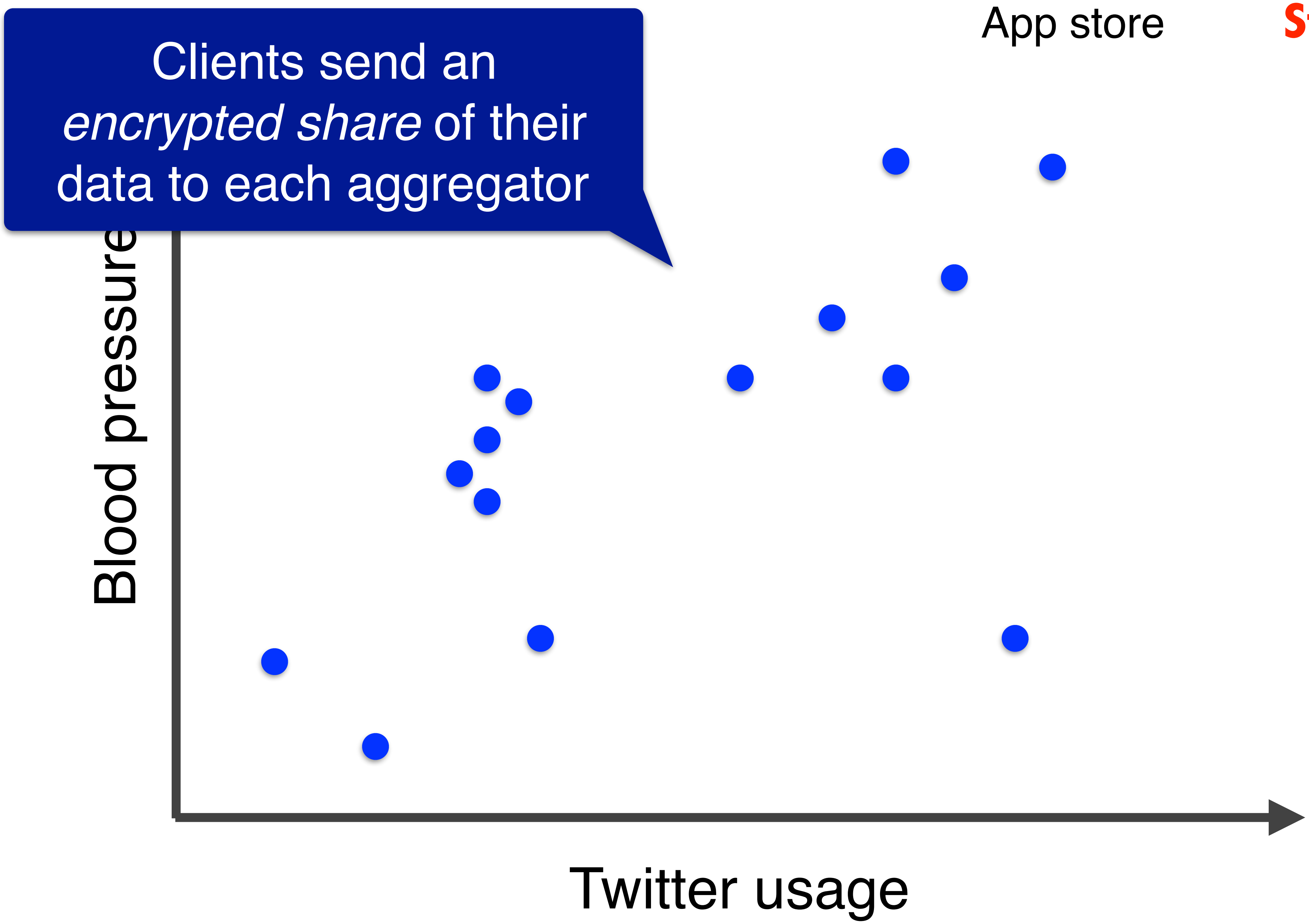
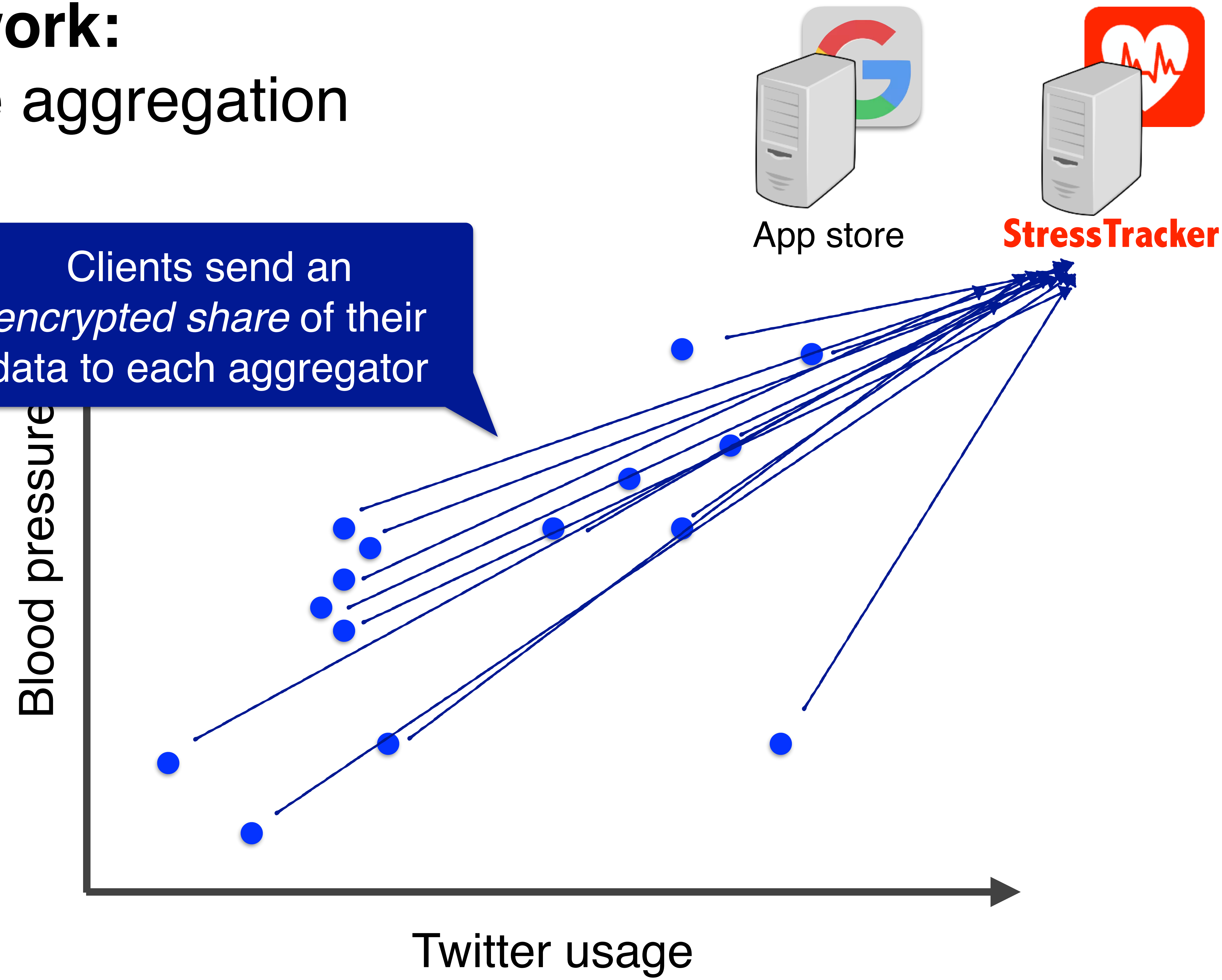




This work:
Private aggregation

Clients send an *encrypted share* of their data to each aggregator



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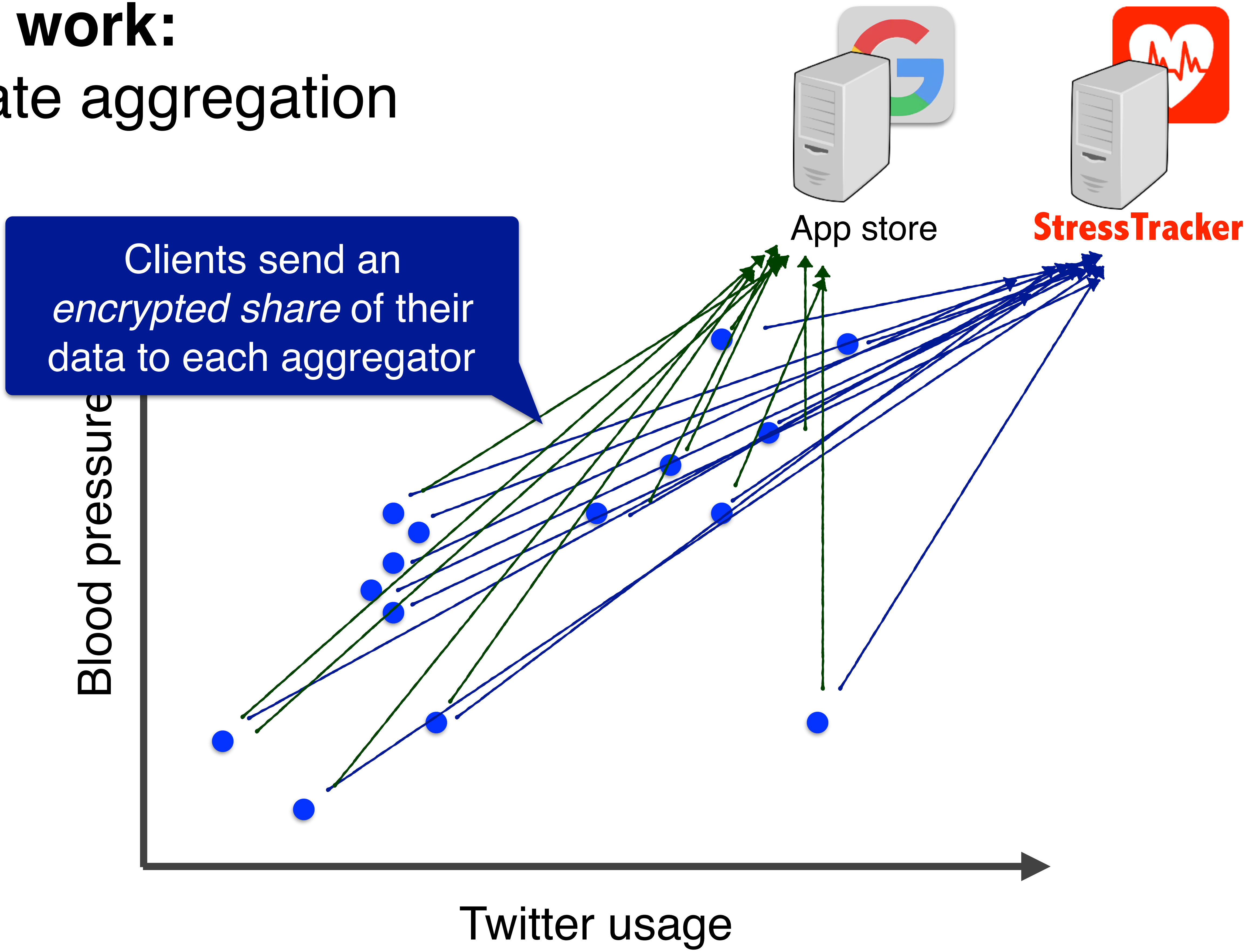

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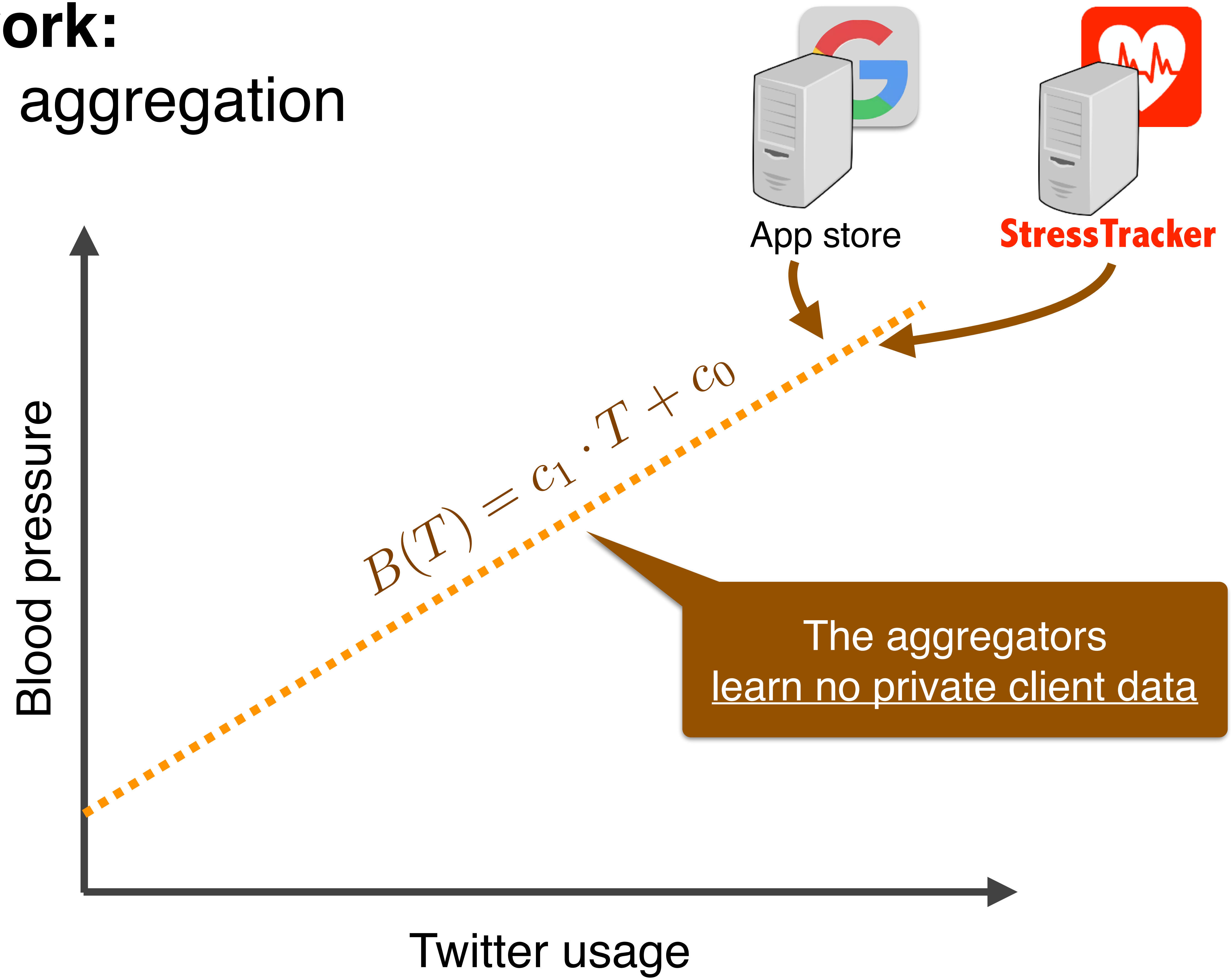
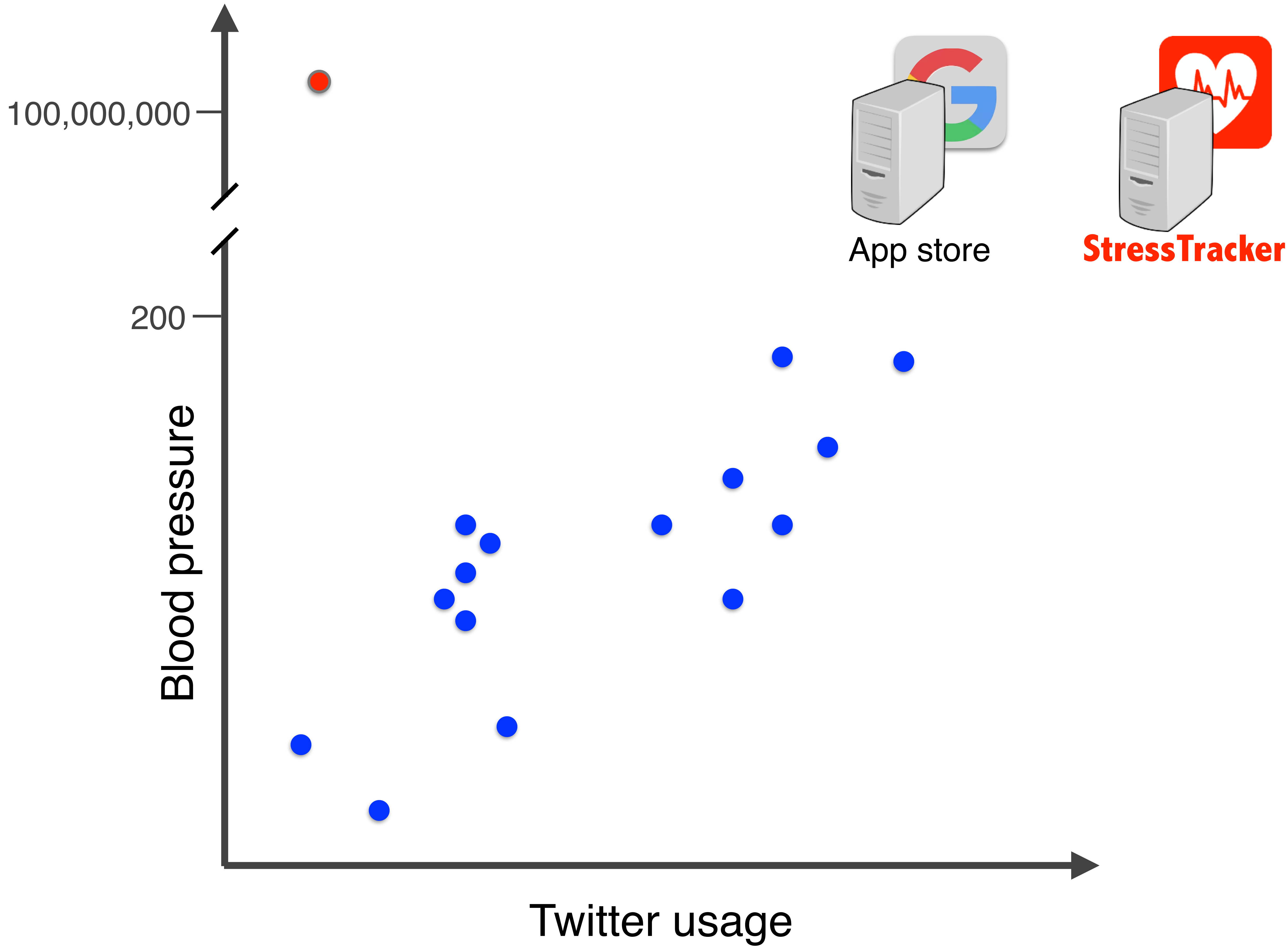
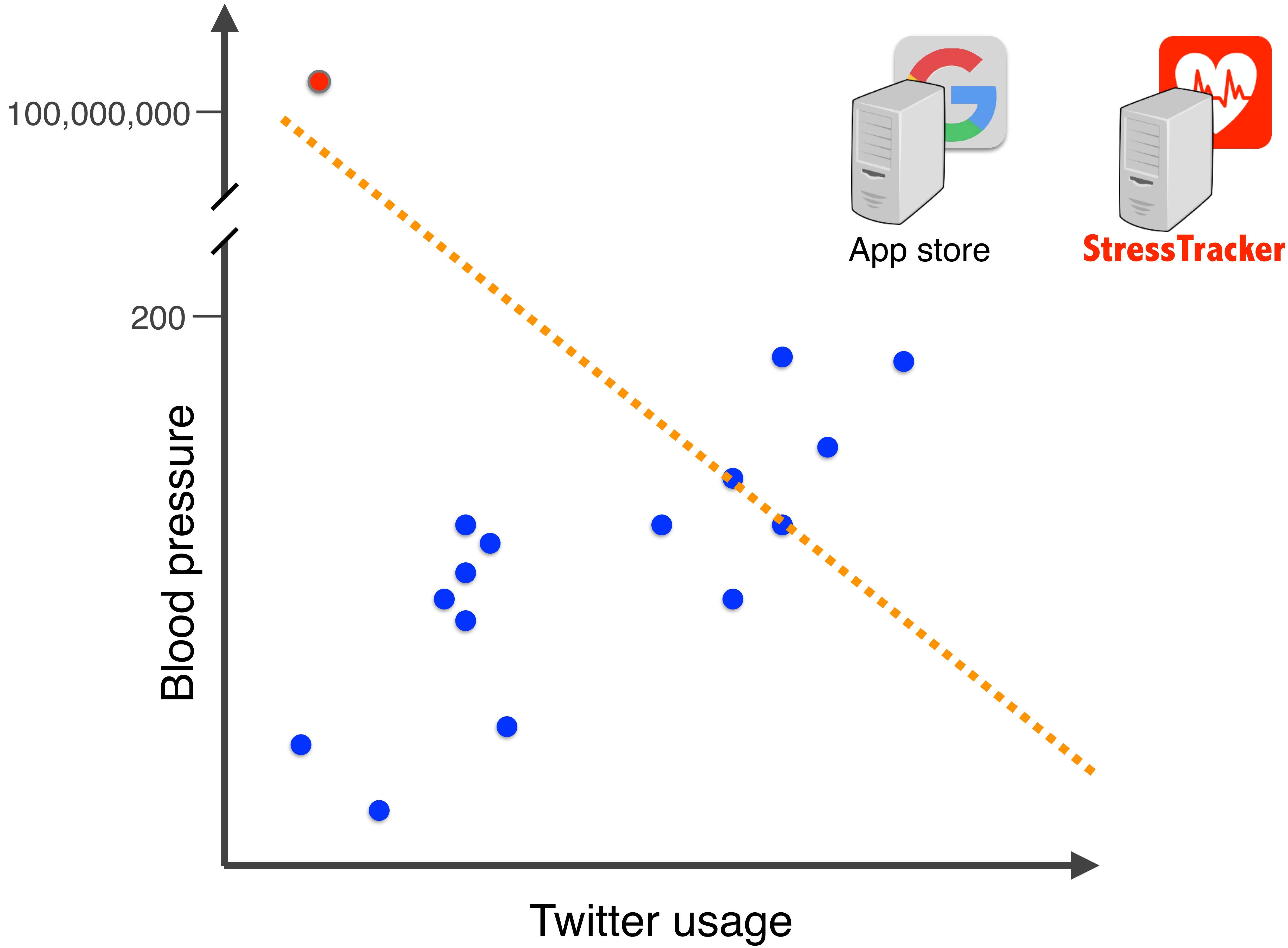


Private aggregation

1. **Exact correctness** — If all servers are honest, servers learn $f(\cdot)$
2. **Privacy** — If one server is honest, servers learn only* $f(\cdot)$
3. **Robustness** — Malicious clients have bounded influence
4. **Efficiency** — No public-key crypto (apart from TLS)
   1000s of submissions per second


100,000,000
200
Blood pressure
Twitter usage
App store
StressTracker



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Contributions

1. **Secret-shared non-interactive proofs (SNIPs)**
   – Client proves that its encoded submission is well-formed
   – We do not need the power of traditional “heavy” crypto tools

2. **Aggregatable encodings**
   Can compute sums privately $\implies$ Can compute $f(\cdot)$ privately
   …for many f’s of interest

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   Can compute sums privately $\Longrightarrow$ Can compute $f(\cdot)$ privately
   …for many f’s of interest

See the paper

Related systems

- Additively homomorphic encryption
  P4P (2010), Private stream aggregation (2011), Grid aggregation (2011), PDDP (2012), SplitX (2013), PrivEx (2014), PrivCount (2016), Succinct sketches (2016), …
- Multi-party computation [GMW87], [BGW88]
  FairPlay (2004), Brickell-Shmatikov (2006), FairplayMP (2008), SEPIA (2010), Private matrix factorization (2013), JustGarble (2013), …
- Anonymous credentials/tokens
  VPriv (2009), PrivStats (2011), ANONIZE (2014), …
- Randomized response [W65], [DMNS06], [D06]
  RAPPOR (2014, 2016), …

Prio is the first system to achieve
exact correctness, privacy, robustness, efficiency.

Outline

- **Background: The private aggregation problem**
- A straw-man solution for private sums
- Providing robustness with SNIPs
- Evaluation
- Discussion: Real-world considerations

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- We want to compute

$$f(x_1, \ldots, x_N) = x_1 + \ldots + x_N$$

without learning any users' private value x_i.

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without learning any users' private value x_i.

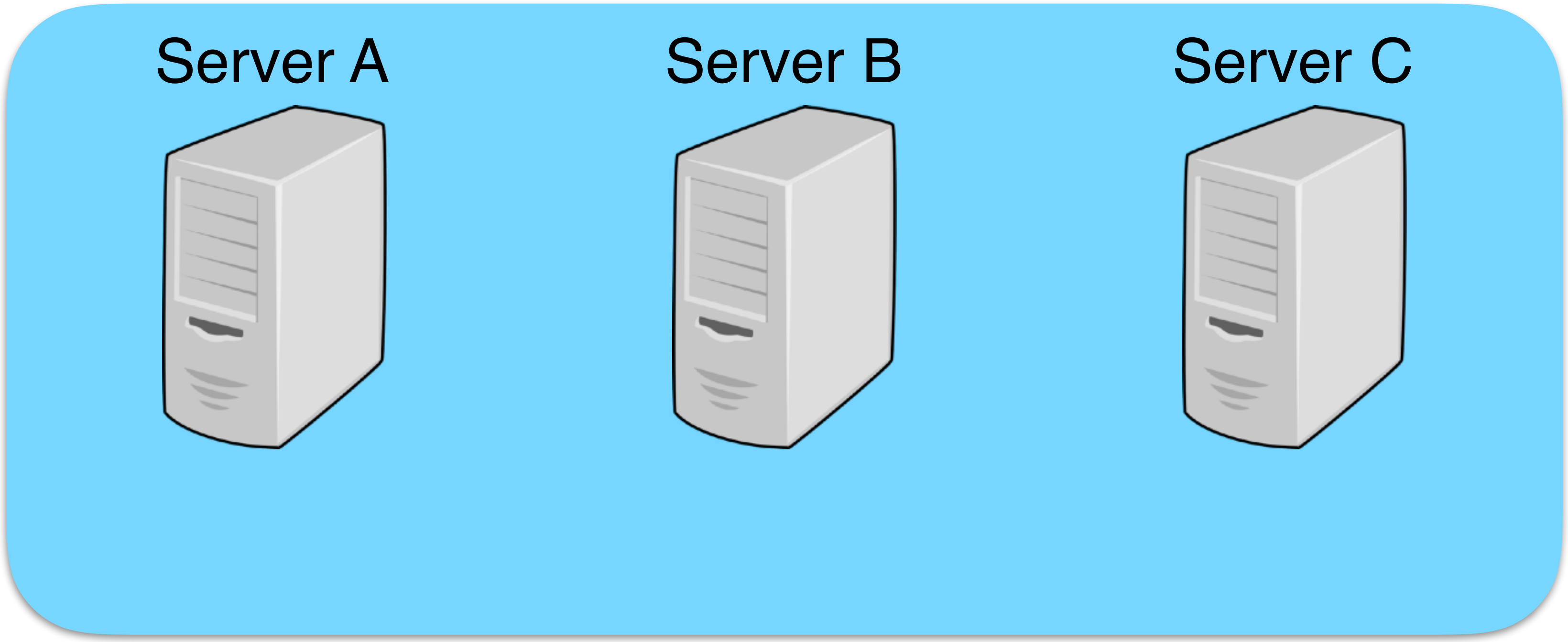
Example: Privately measuring traffic congestion.

$$x_i \quad = 1 \qquad \text{if user } i \text{ is on the Bay Bridge}$$
$$\quad\;\; = 0 \qquad \text{otherwise}$$

The sum $x_1 + \ldots + x_N$ yields the number of app users on the Bay Bridge.

Private sums: A “straw-man” scheme

[Chaum88], [BGW88], …
[KDK11] [DFKZ13] [PrivEx14] …



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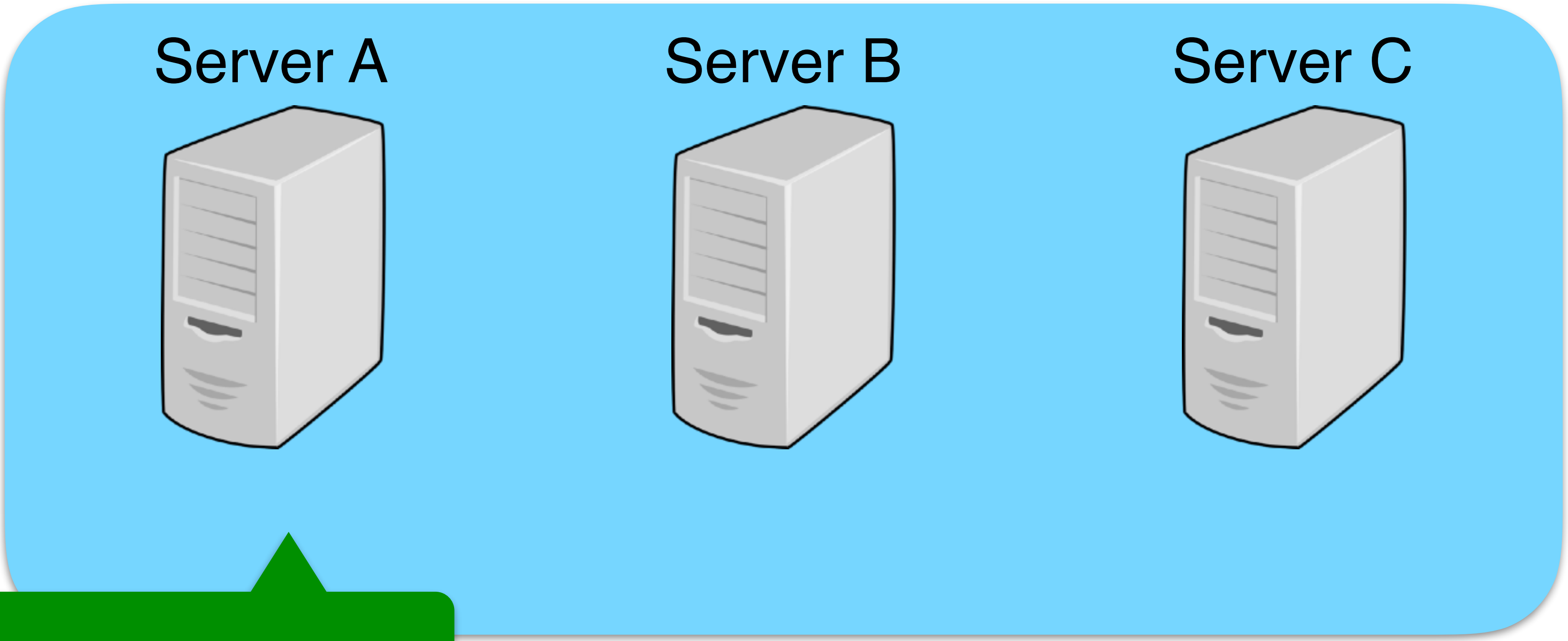

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Equivalently: that at least one server is honest.

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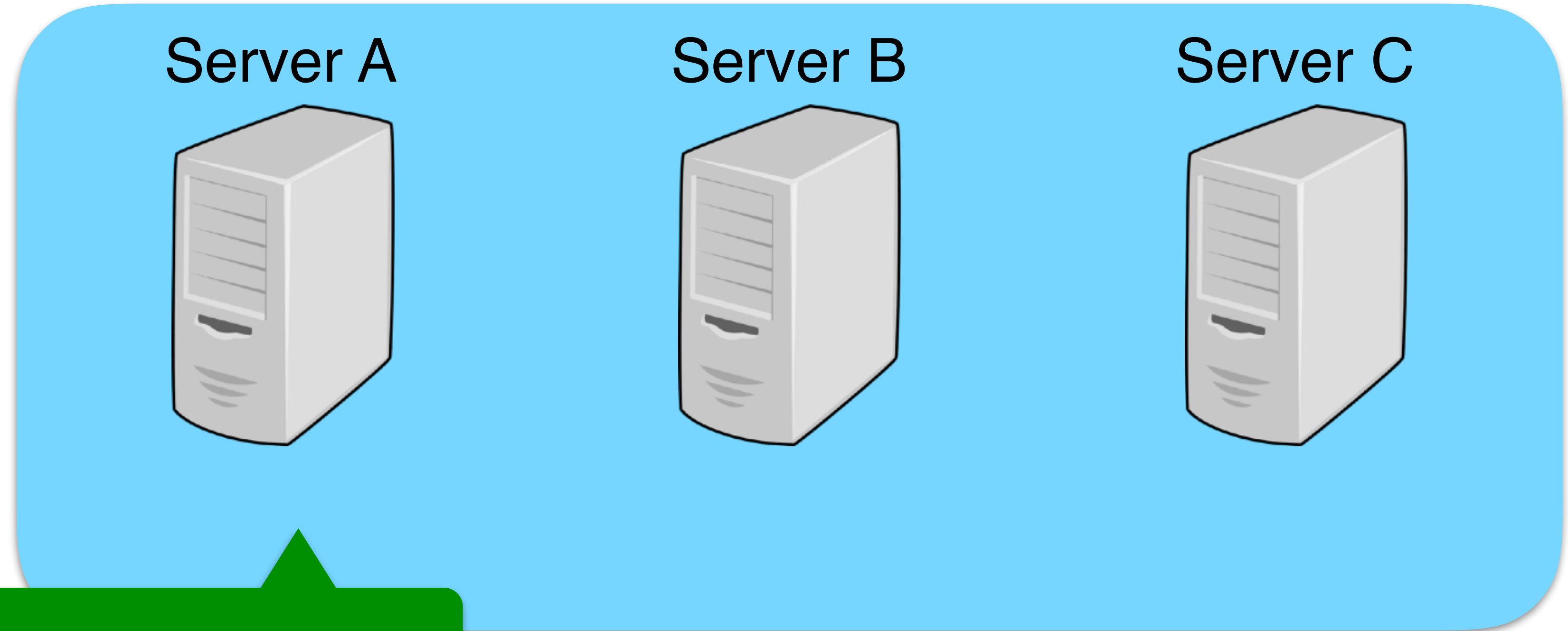

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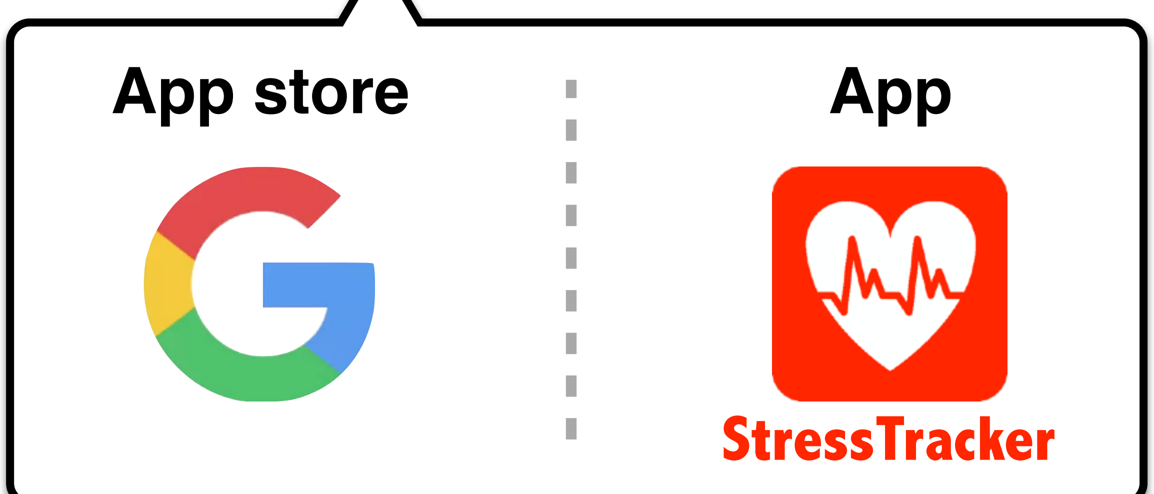

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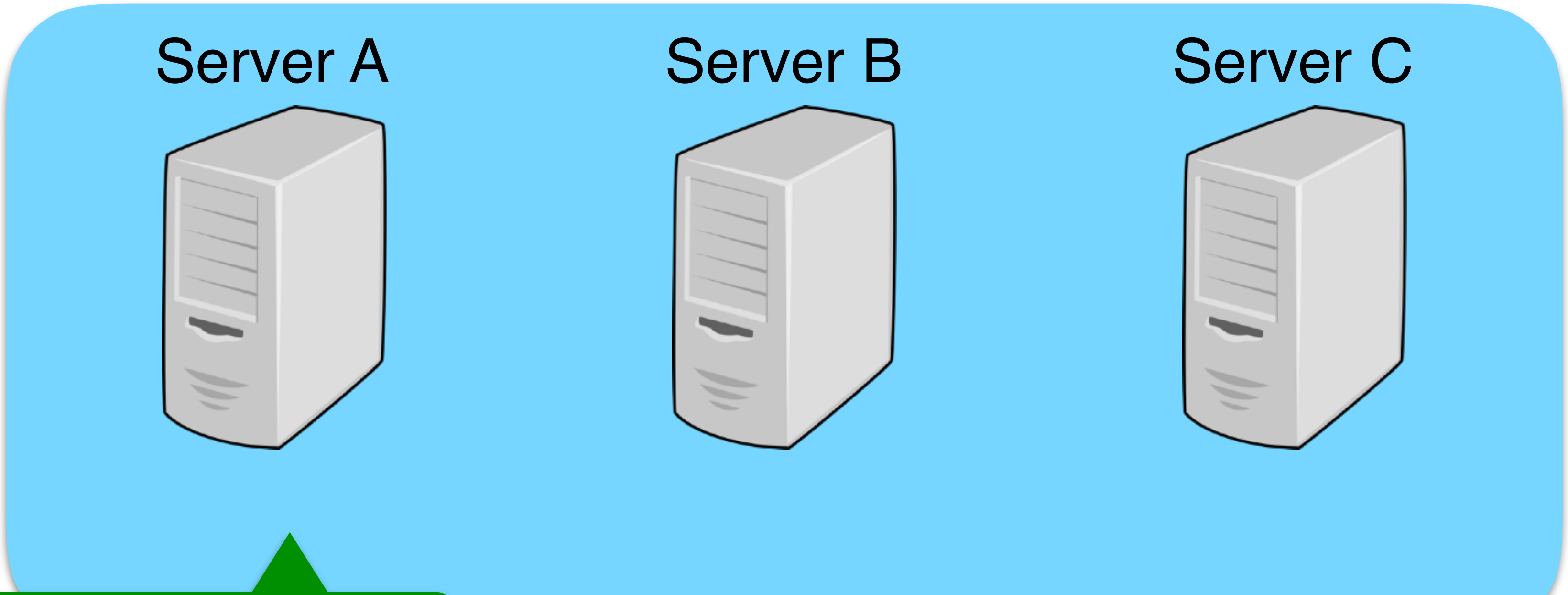

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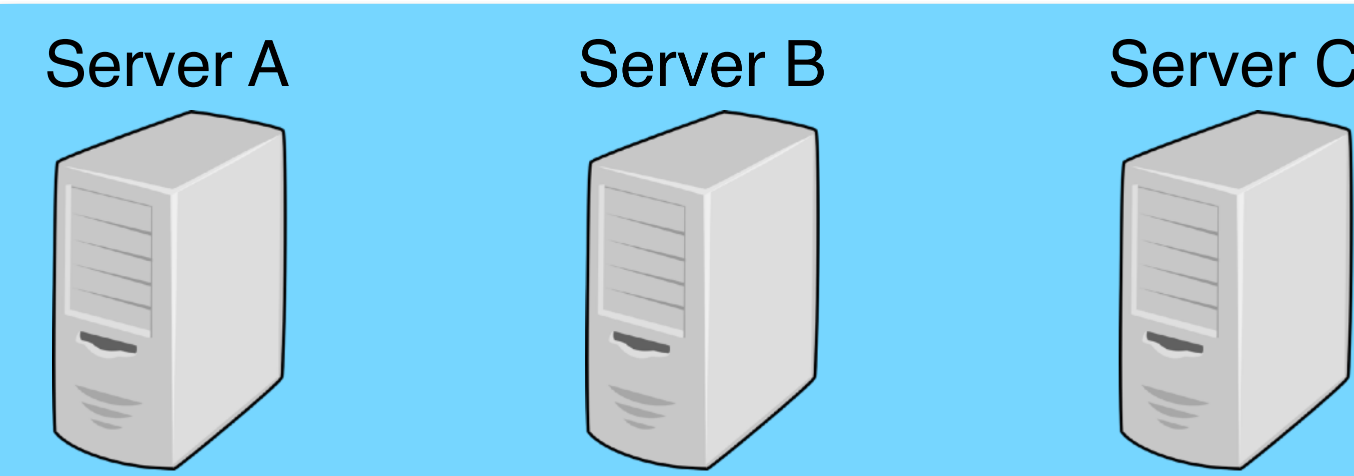

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Spain **Germany** **Iceland**

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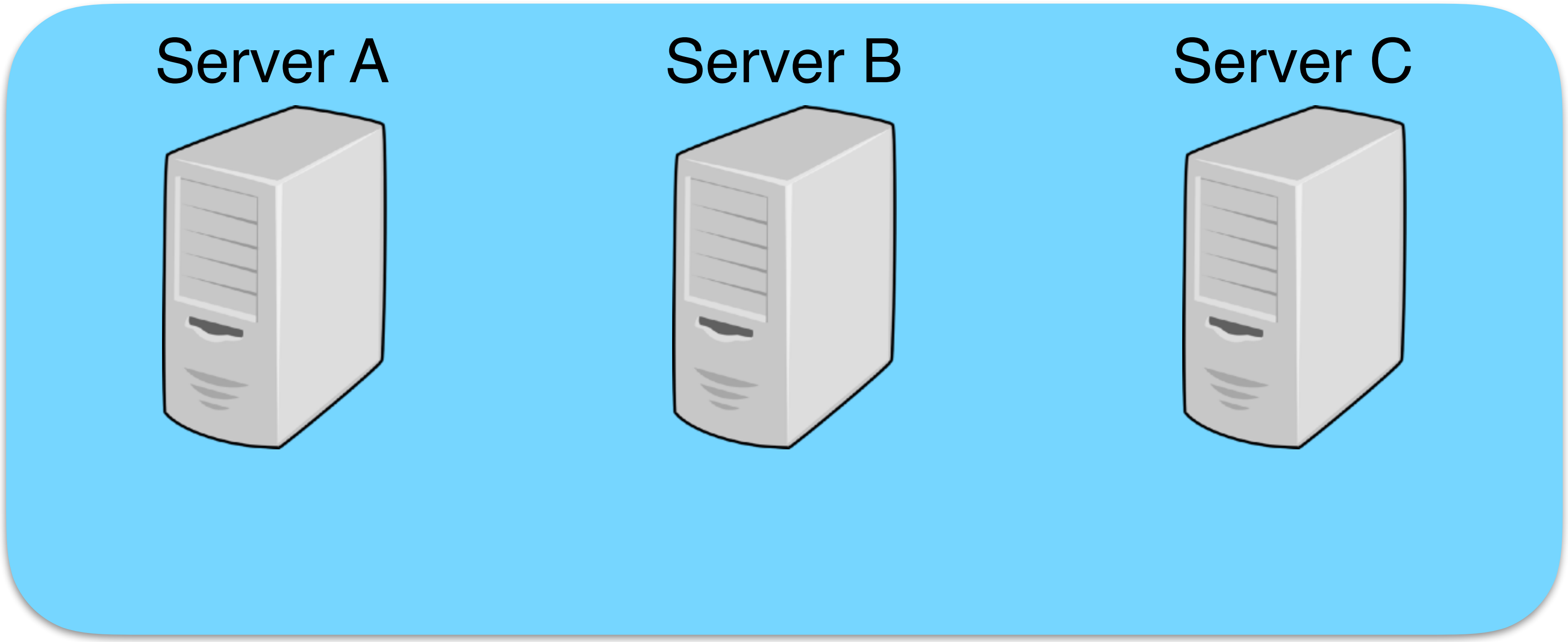

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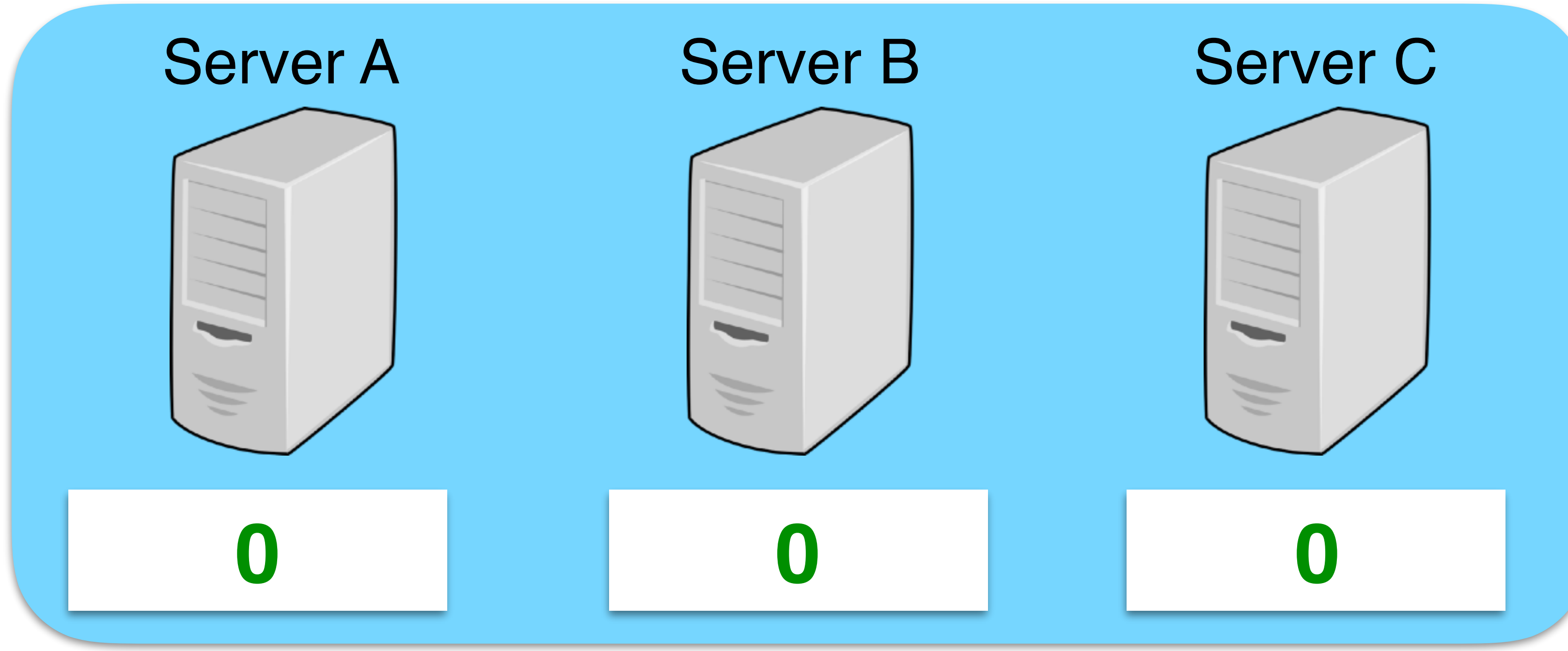

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<u>Secret sharing</u>

Pick three random “shares” that sum to 1.

1 = 15 + (-12) + (- 2) (mod 31)

Need all three shares to recover the shared value.

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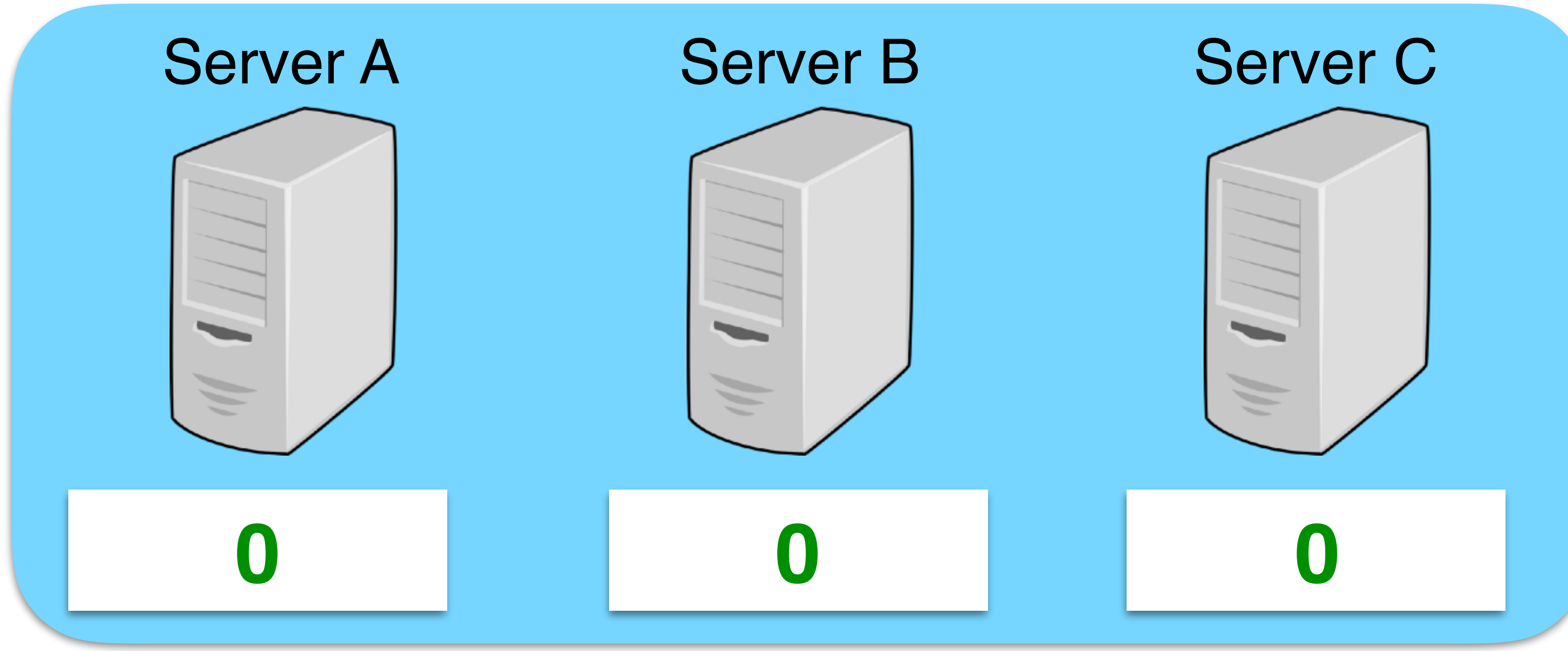

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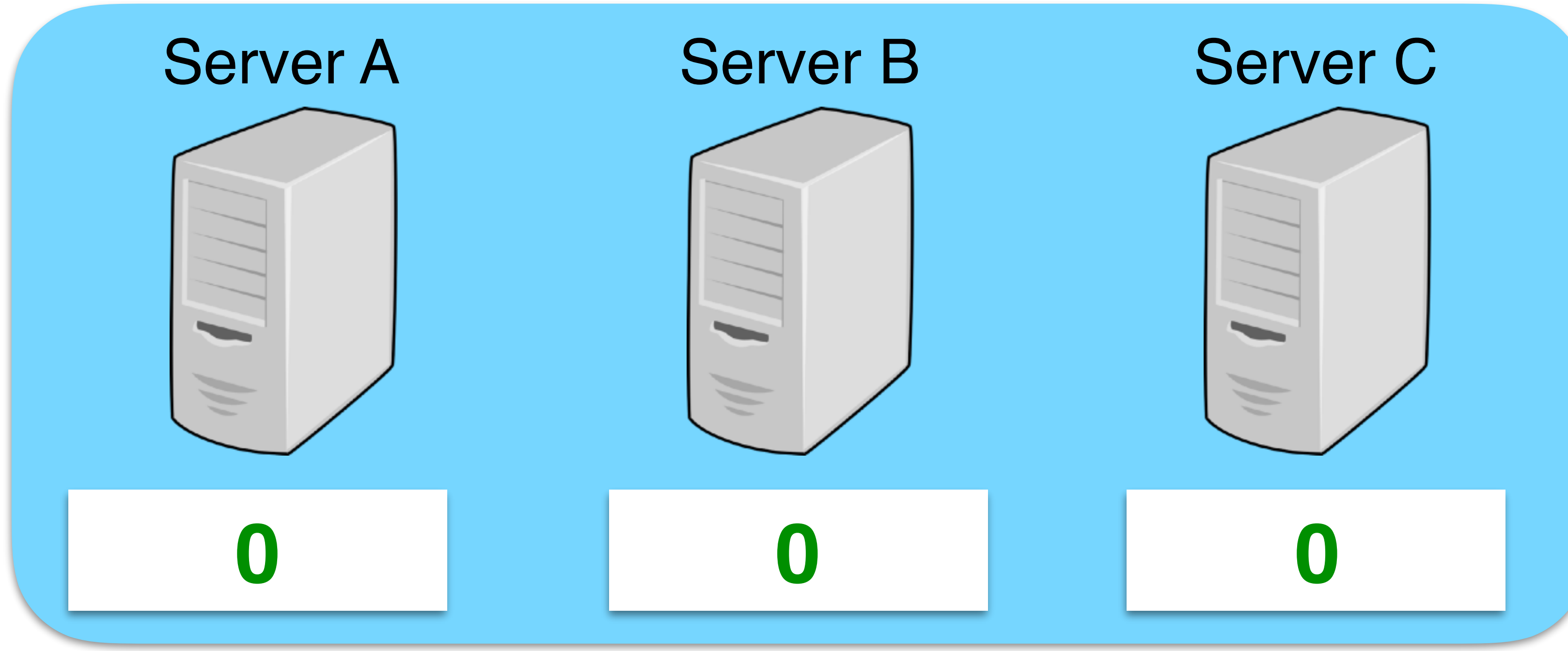

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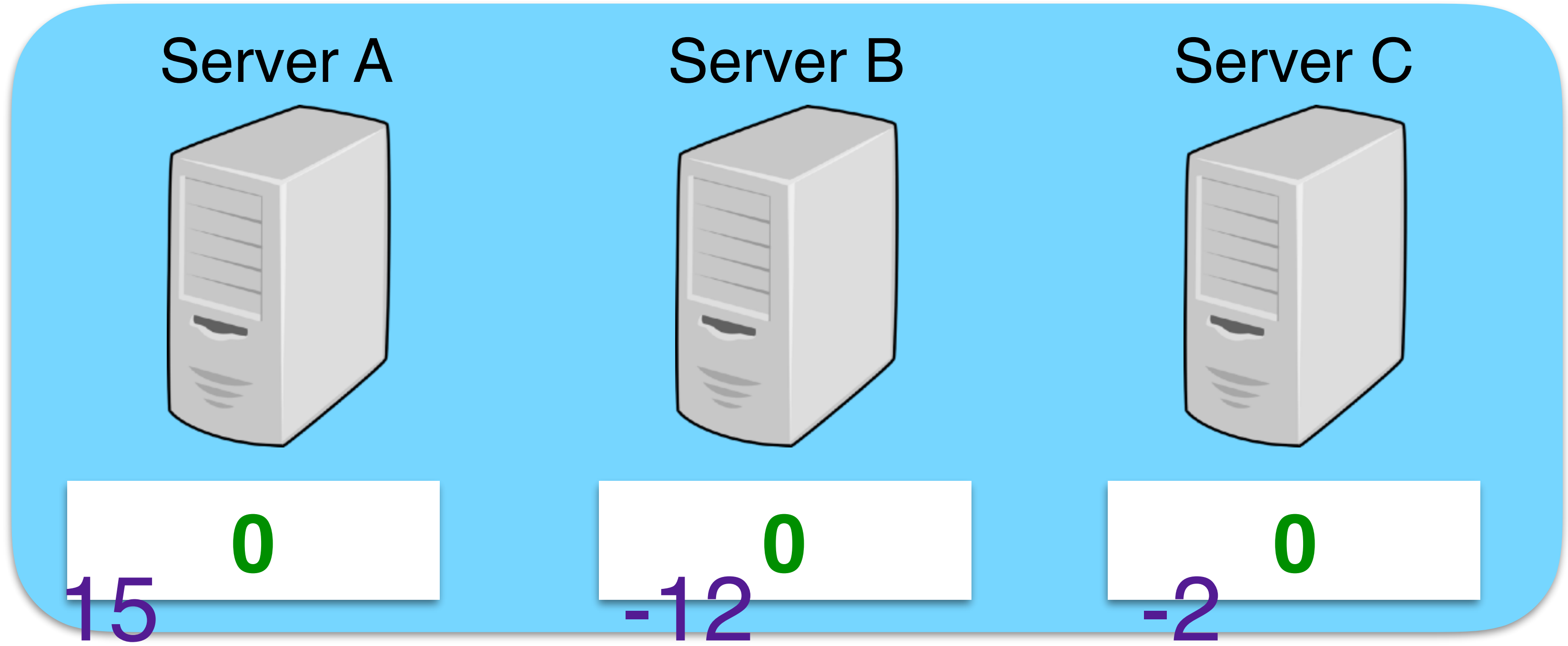

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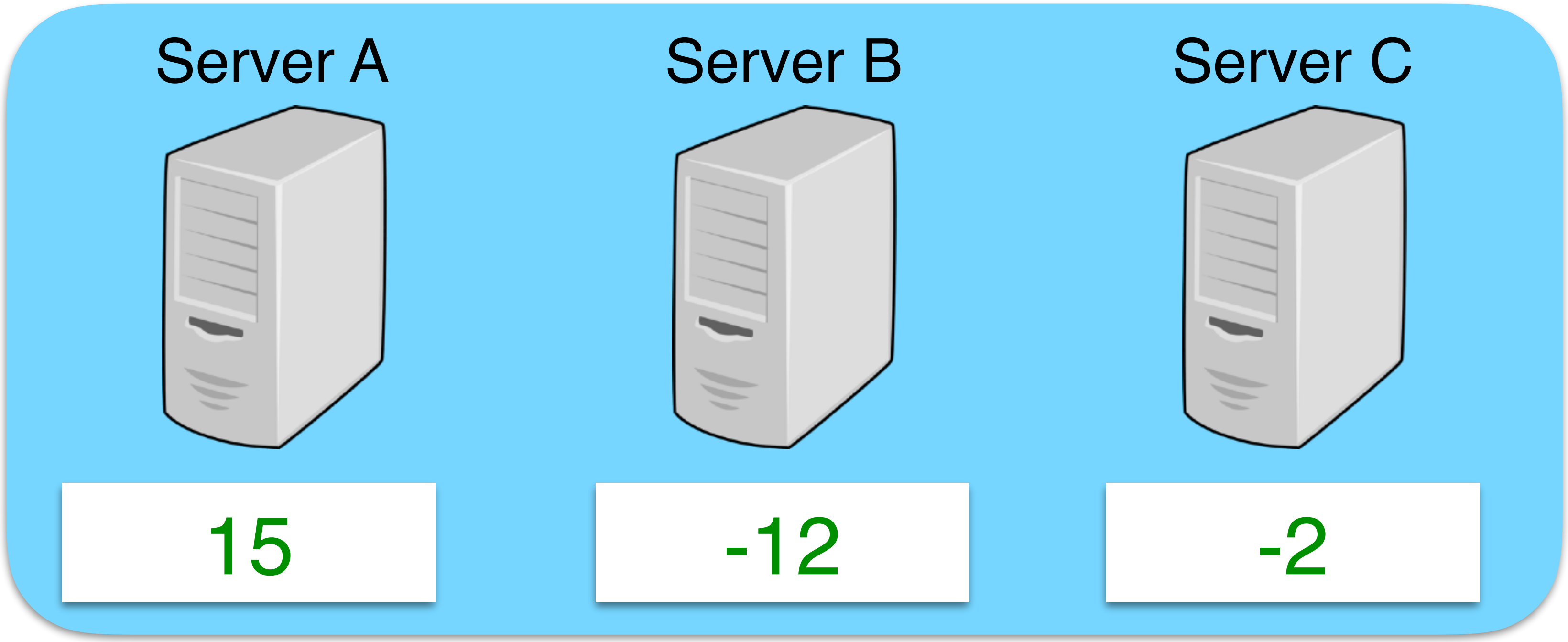

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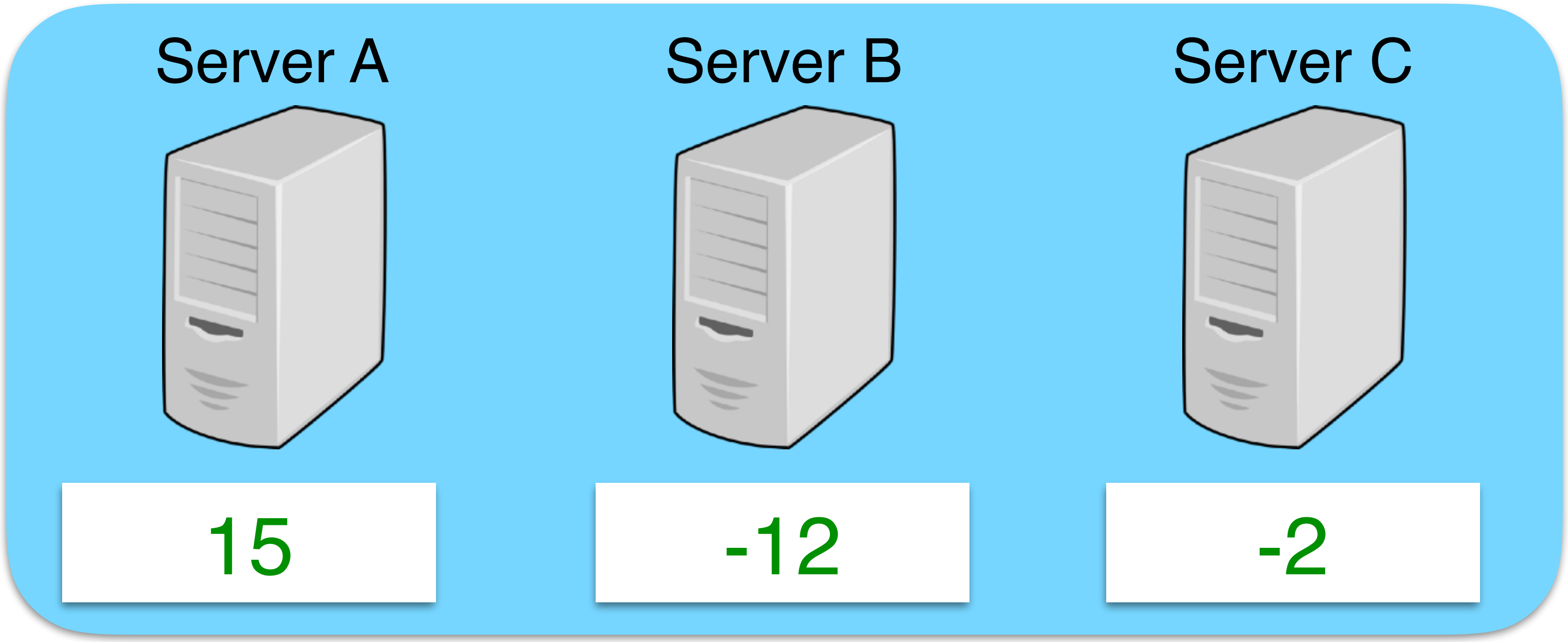

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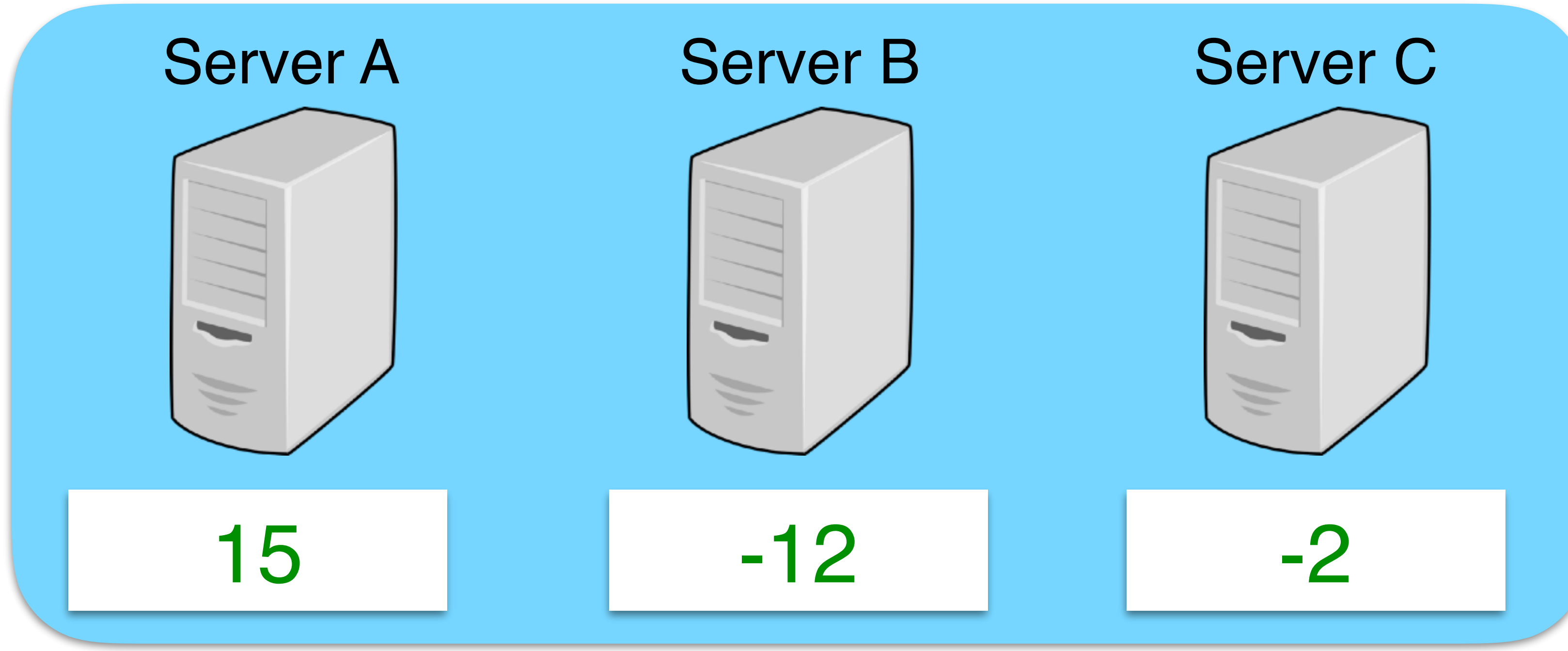

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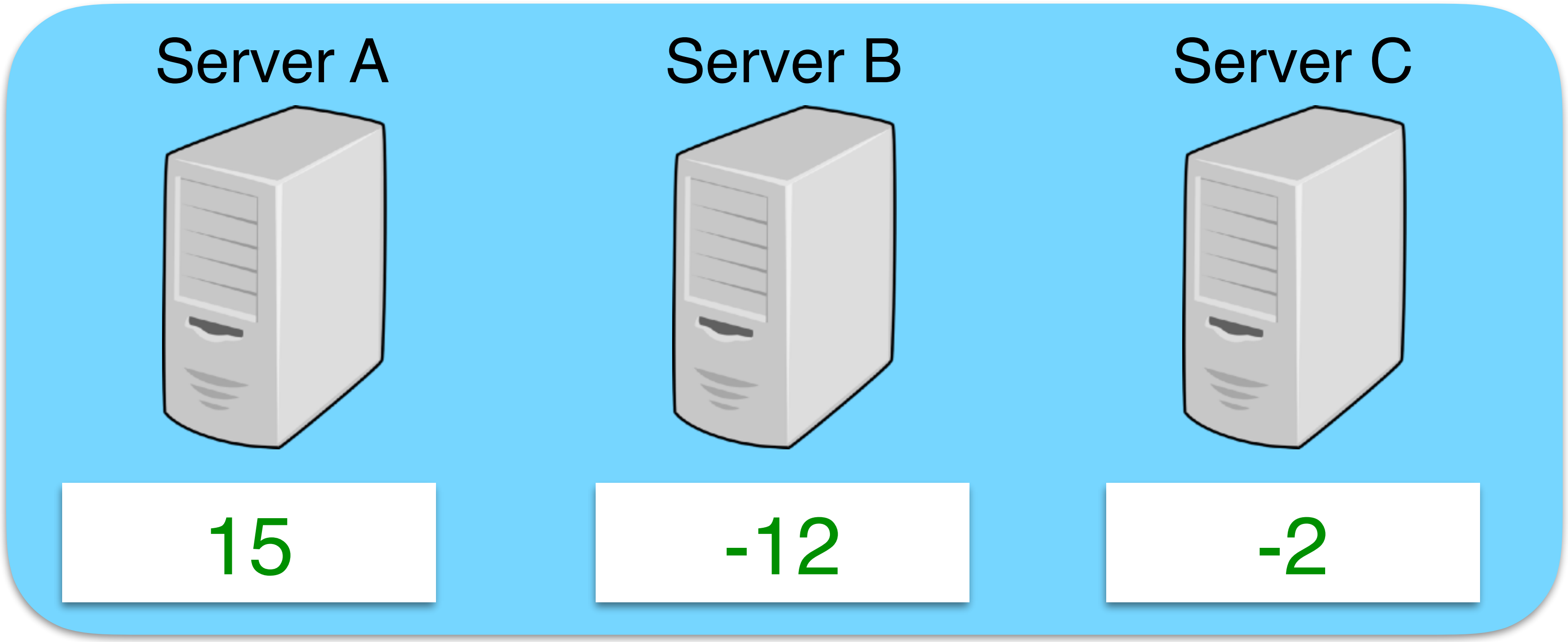

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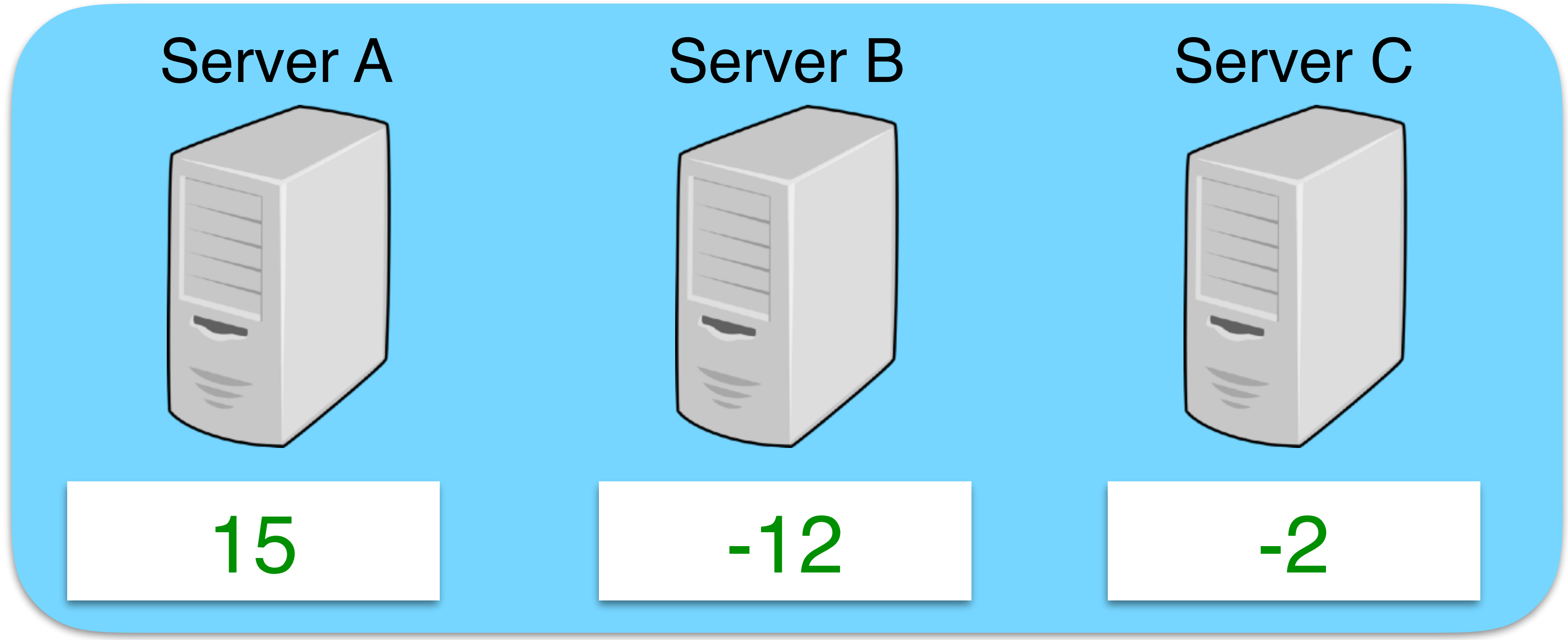

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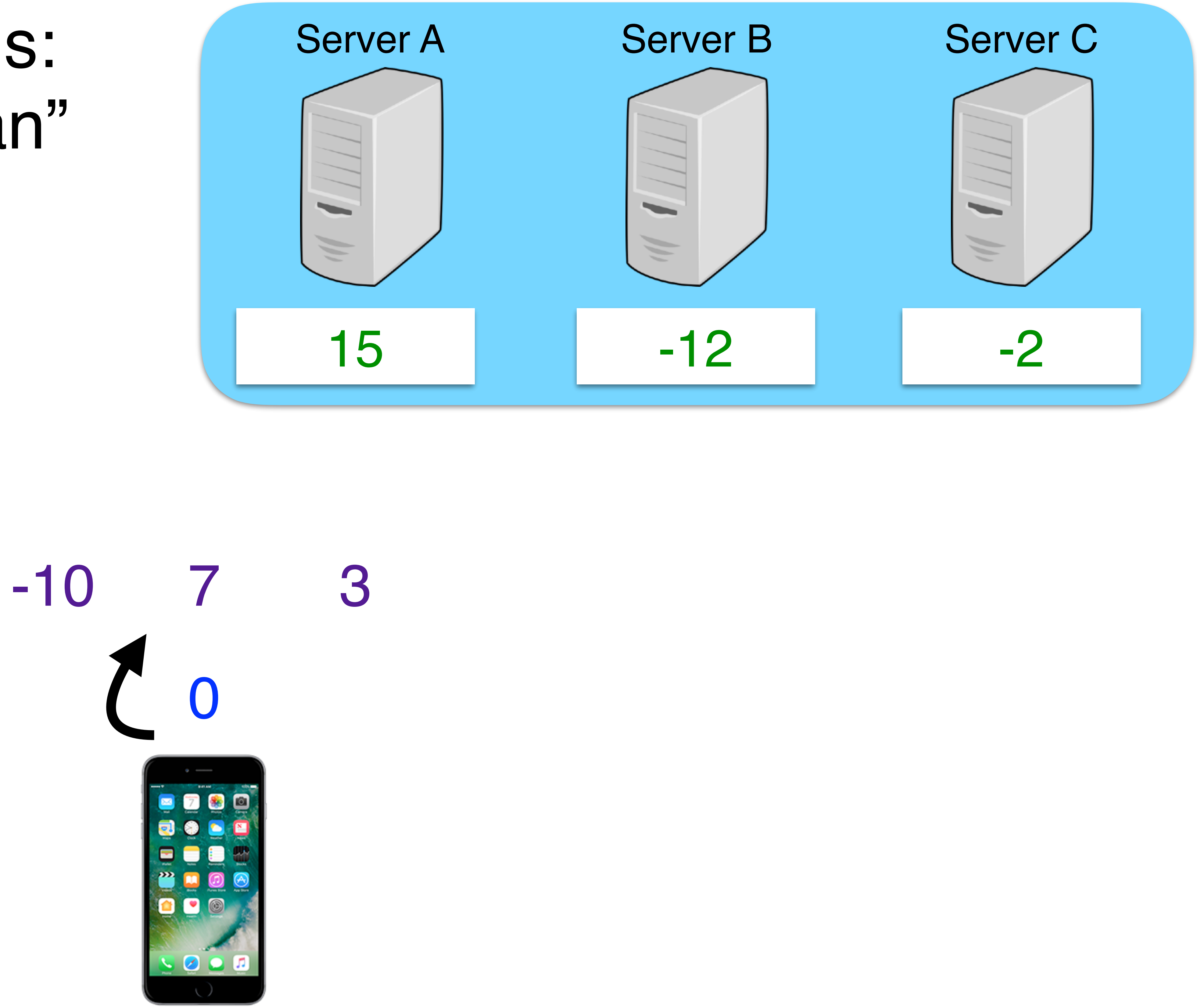

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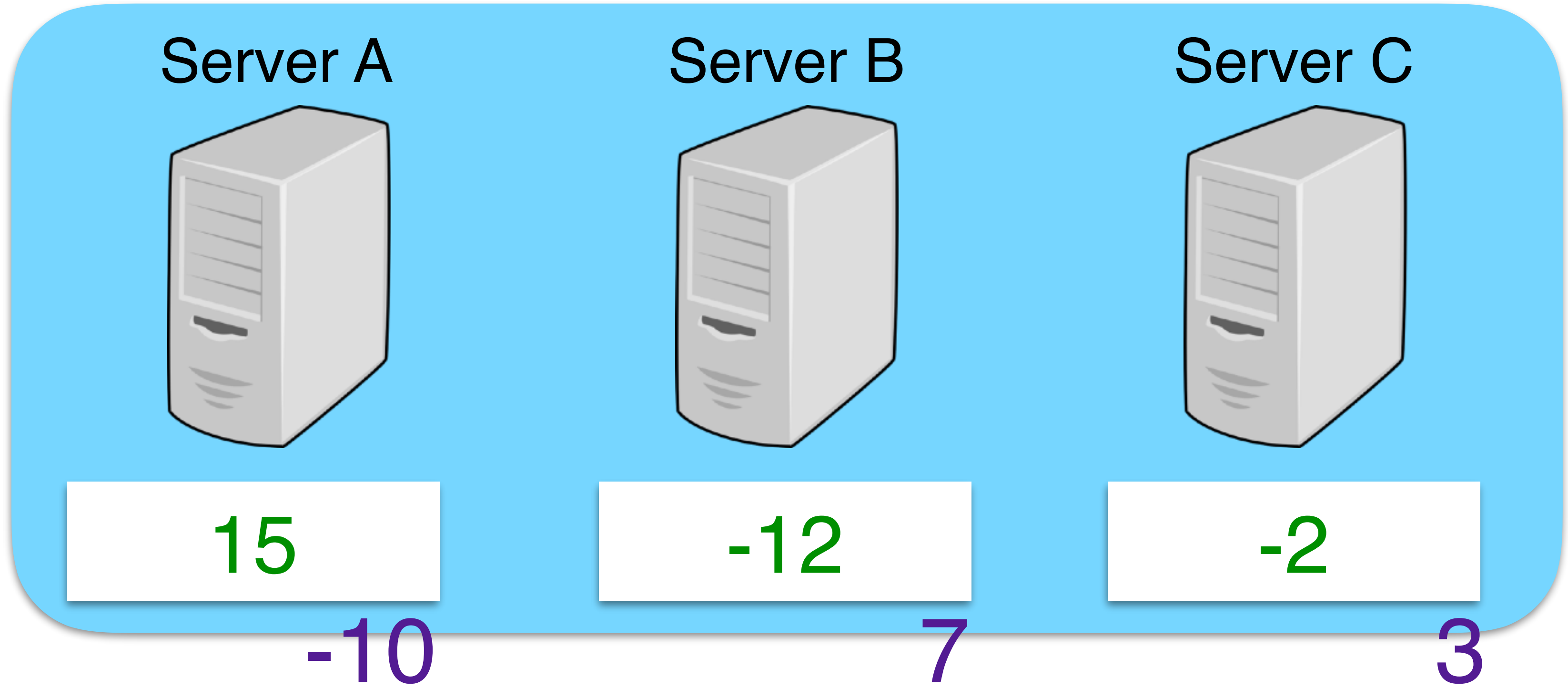

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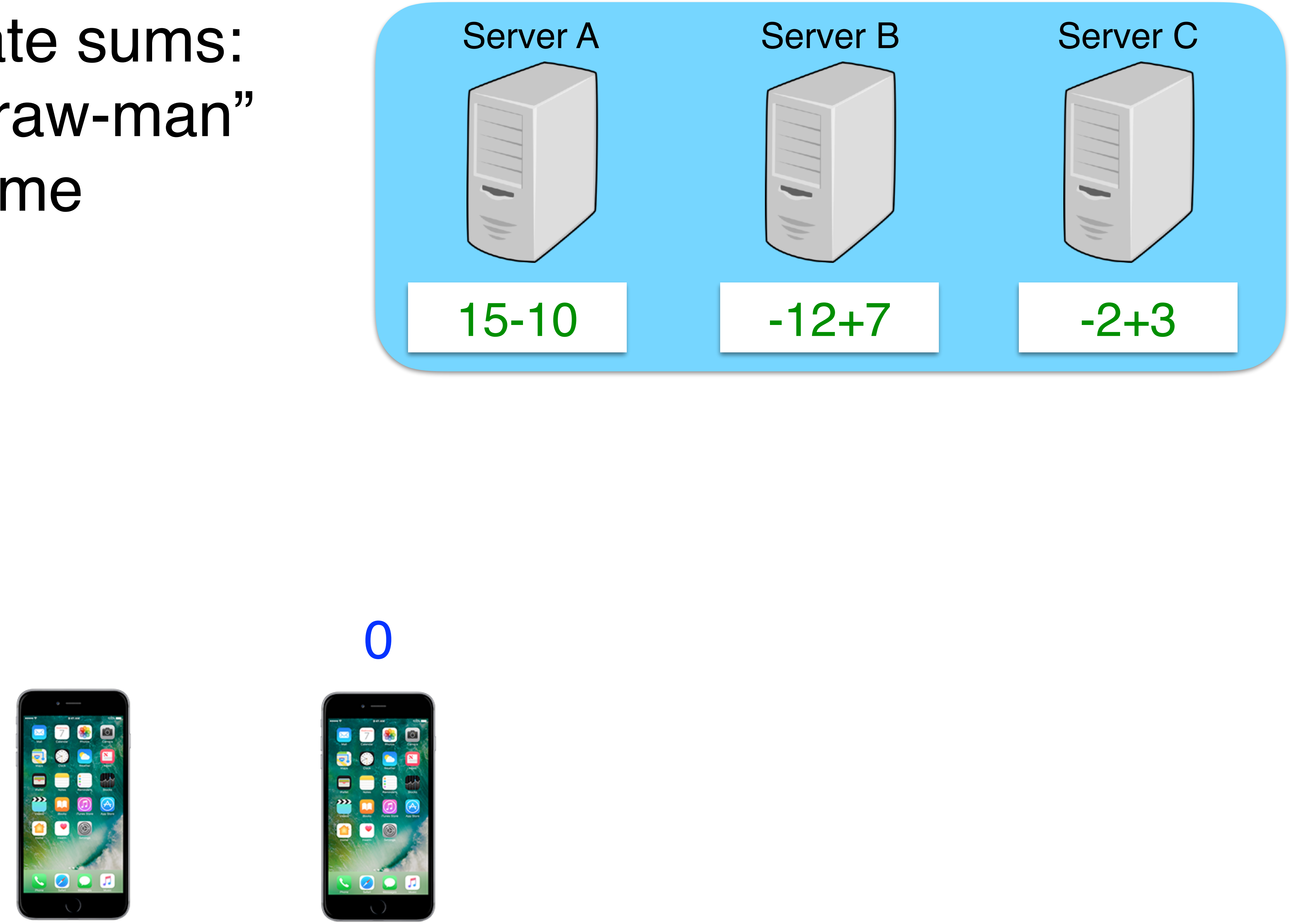

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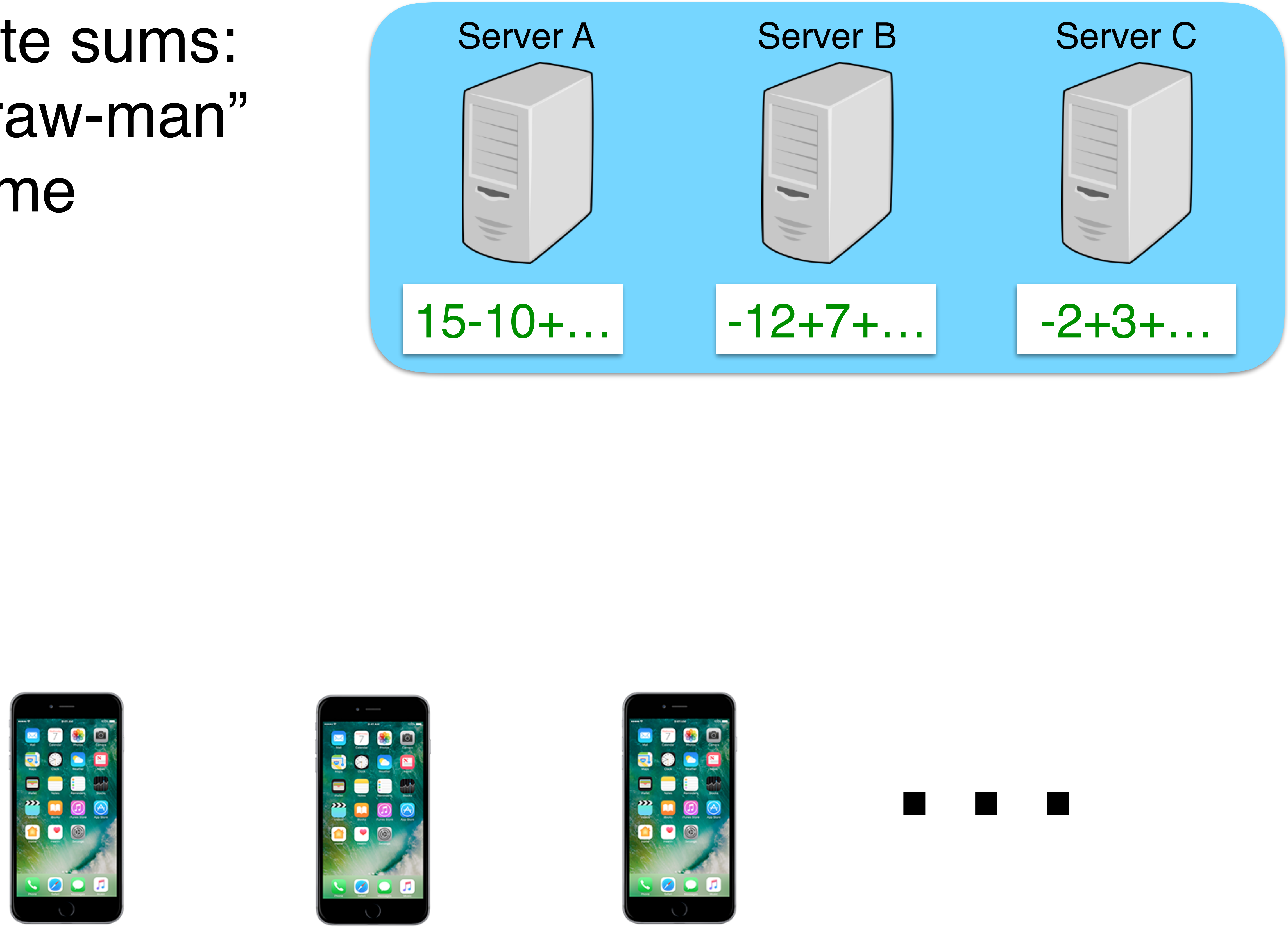

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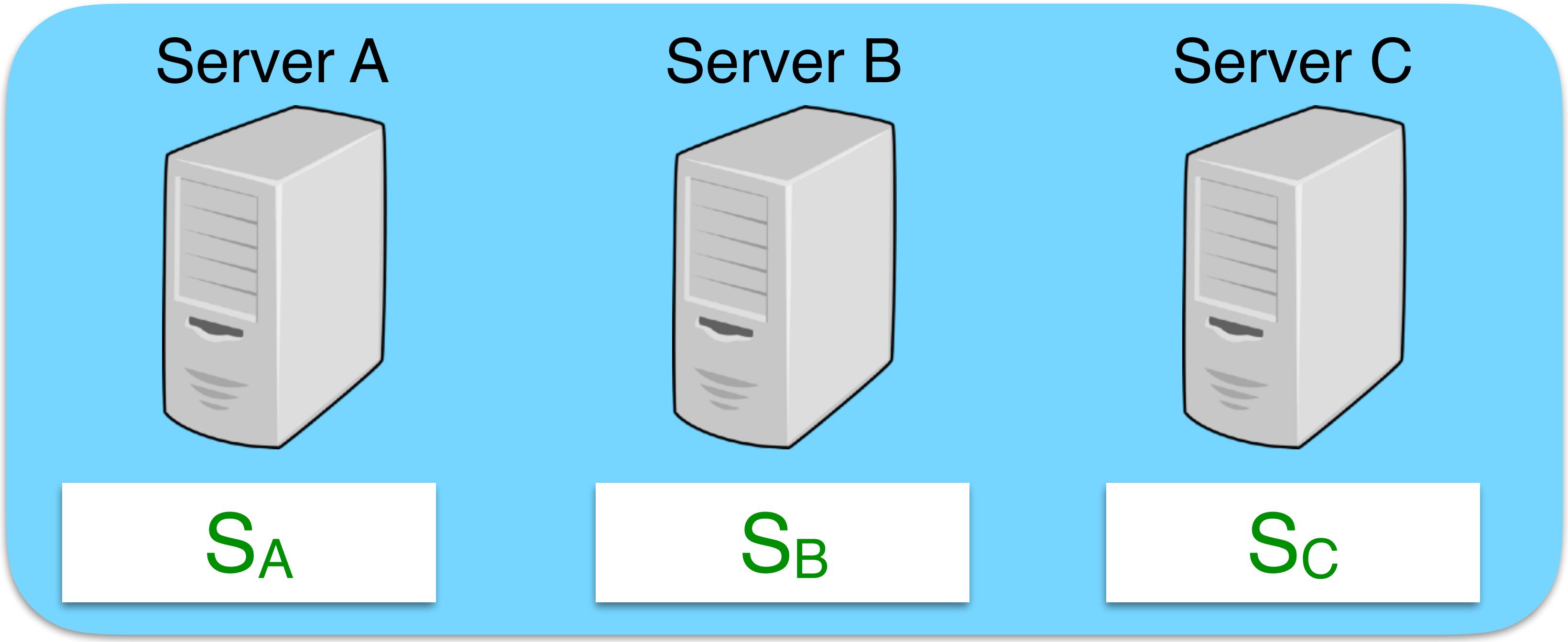

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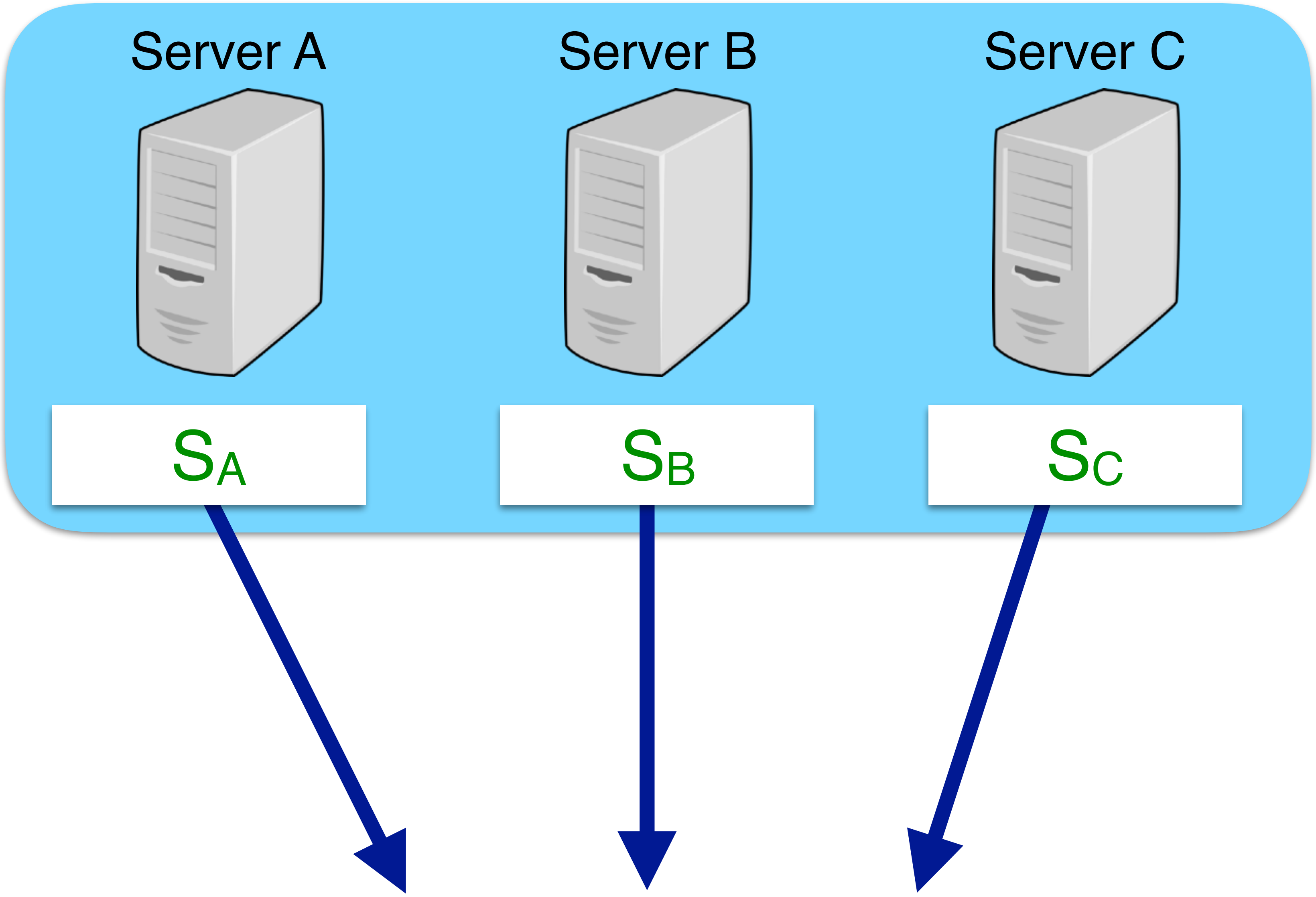

$S_A + S_B + S_C = 15 + -10 + \ldots$

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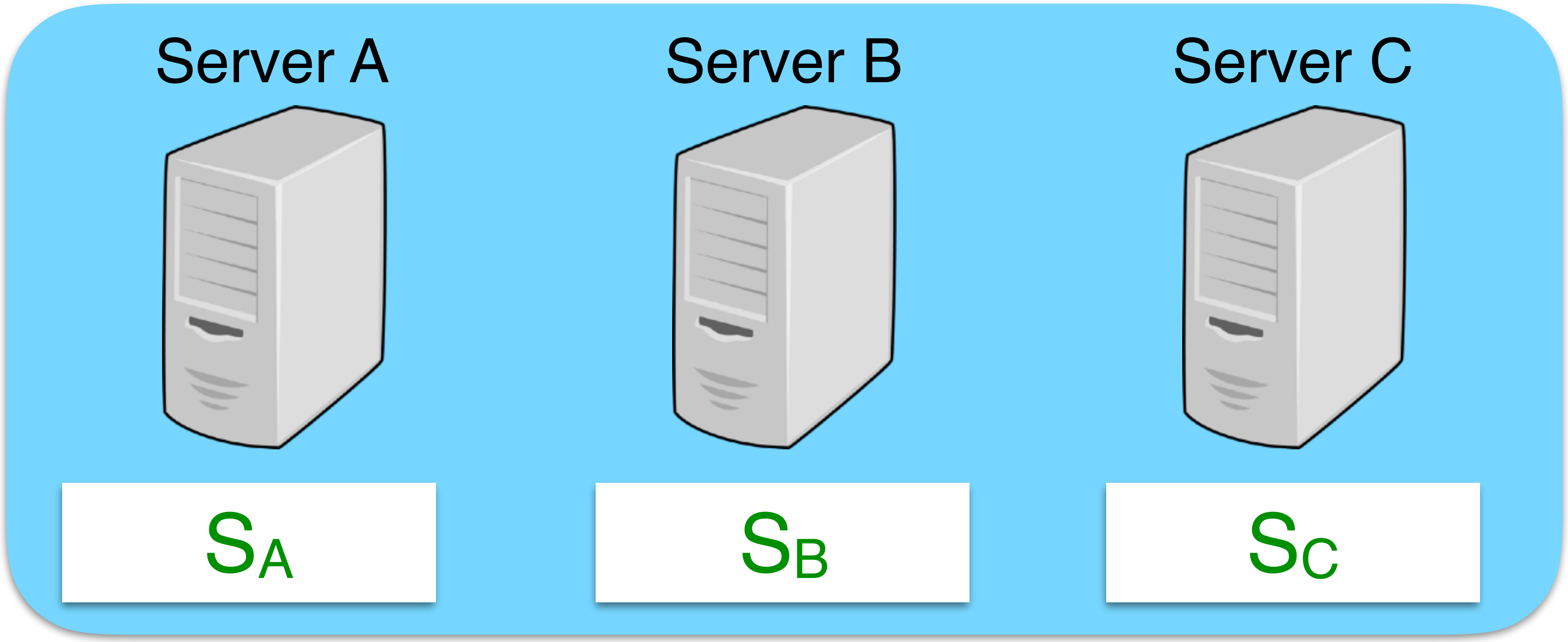

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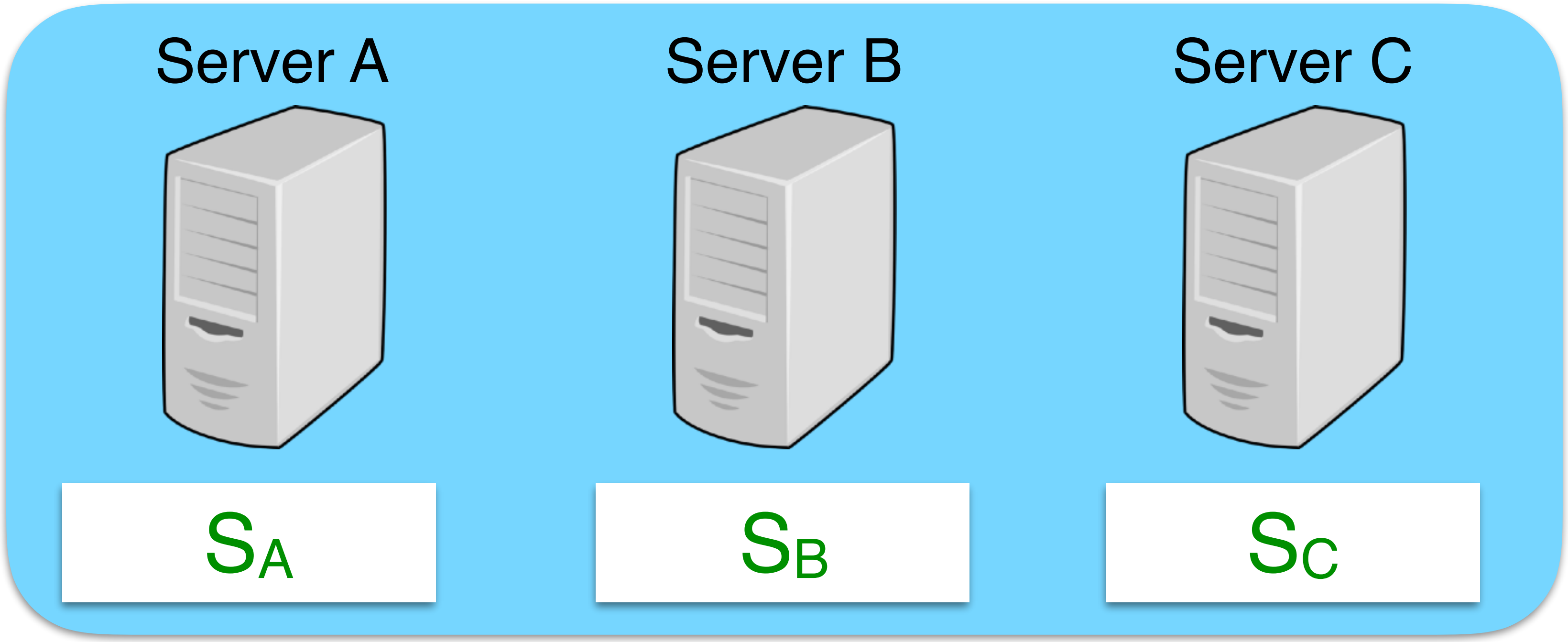

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&= 1 + 0 + \ldots + 1
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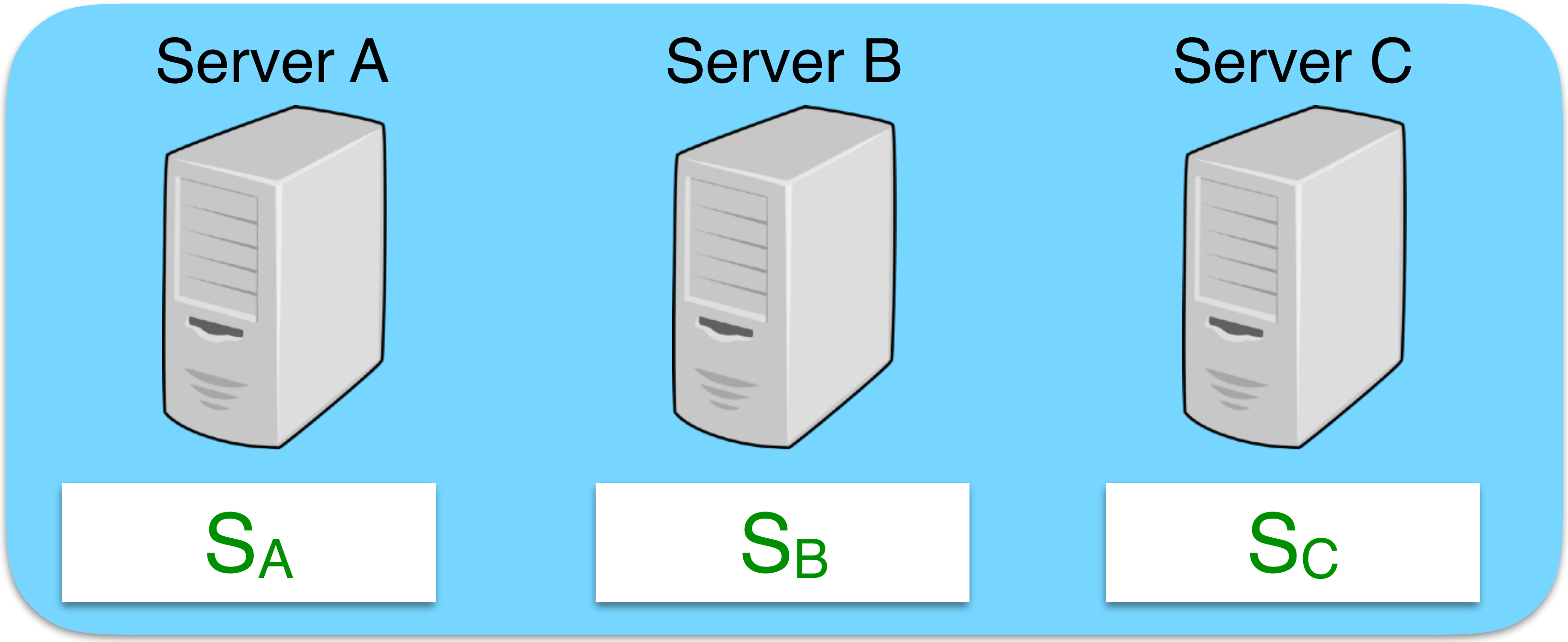

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$= 1 + 0 + \ldots + 1$

Servers learn the sum of client values and learn *nothing else*.

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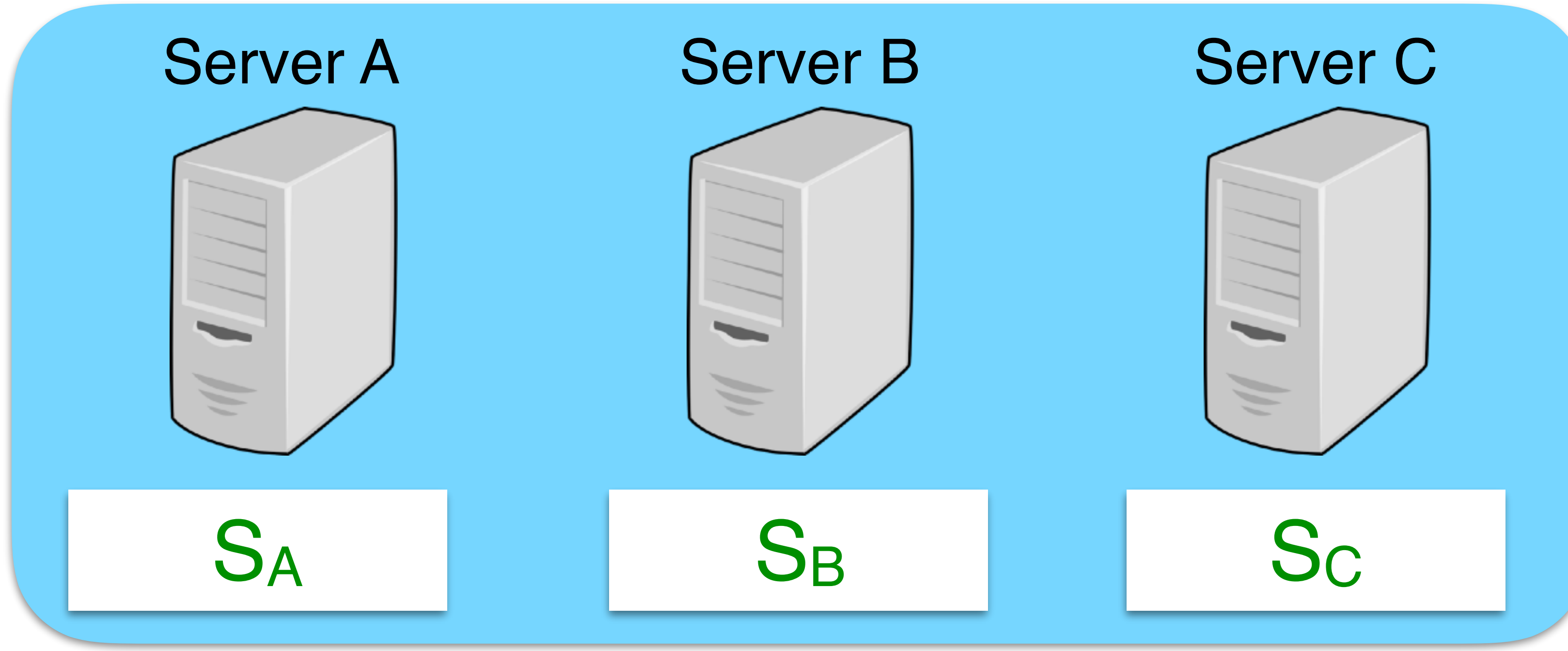

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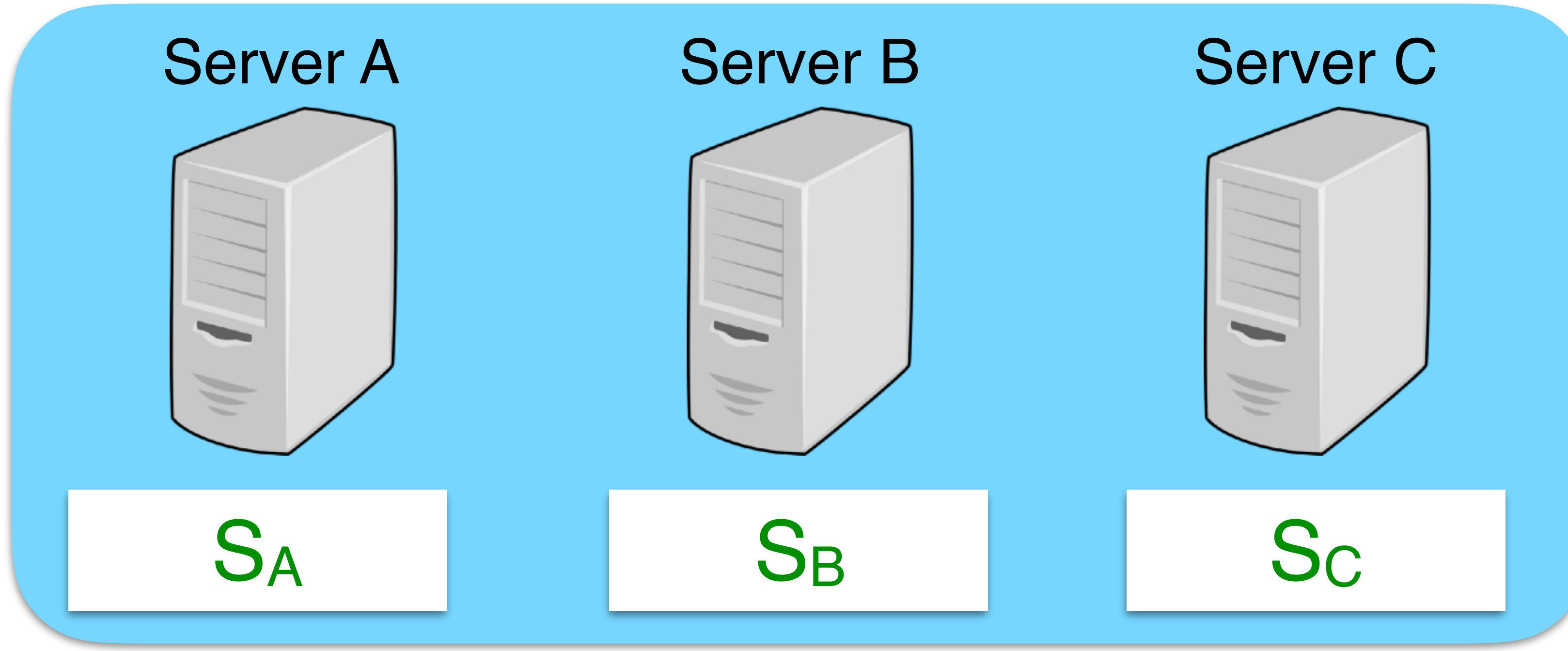

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$$= 1 + 0 + \ldots + 1$$

Learn that three phones are on the Bay Bridge—don’t know which three

Computing private sums

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Exact correctness: If everyone follows the protocol, servers compute the sum of all x_is.

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Robustness: ???

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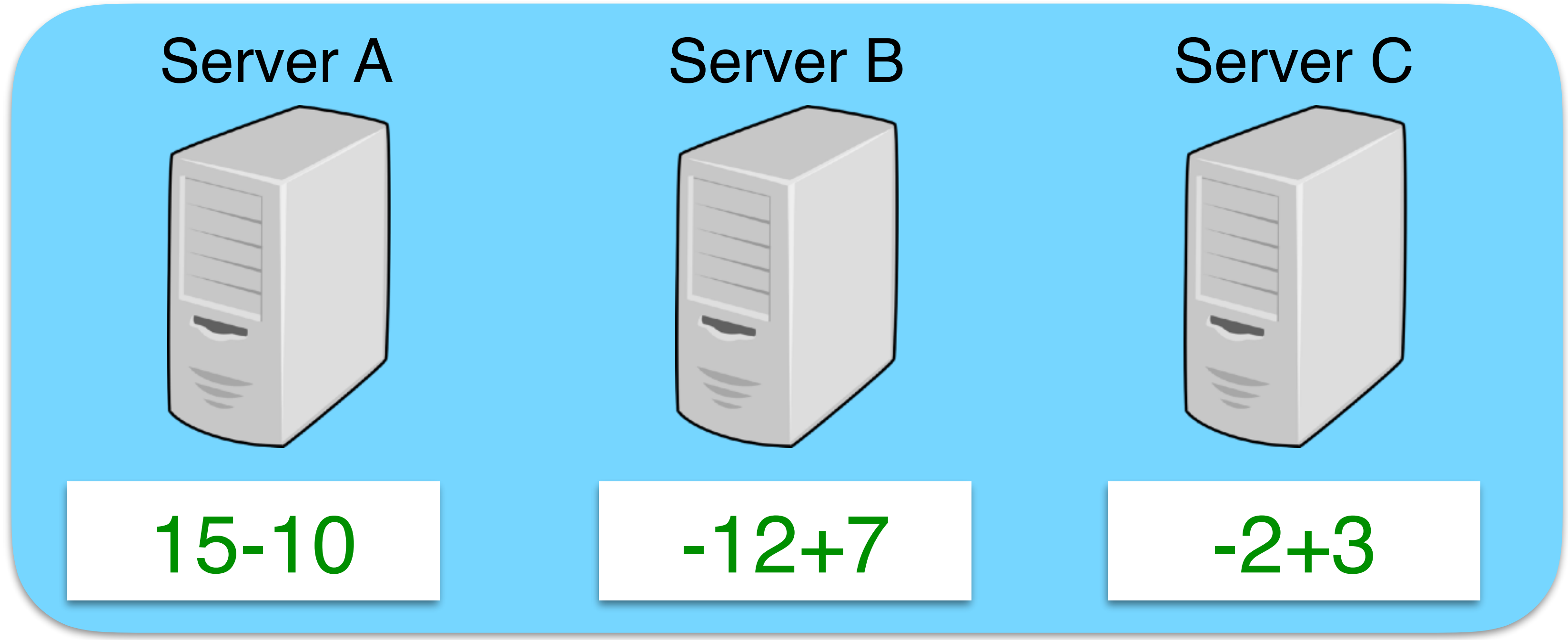

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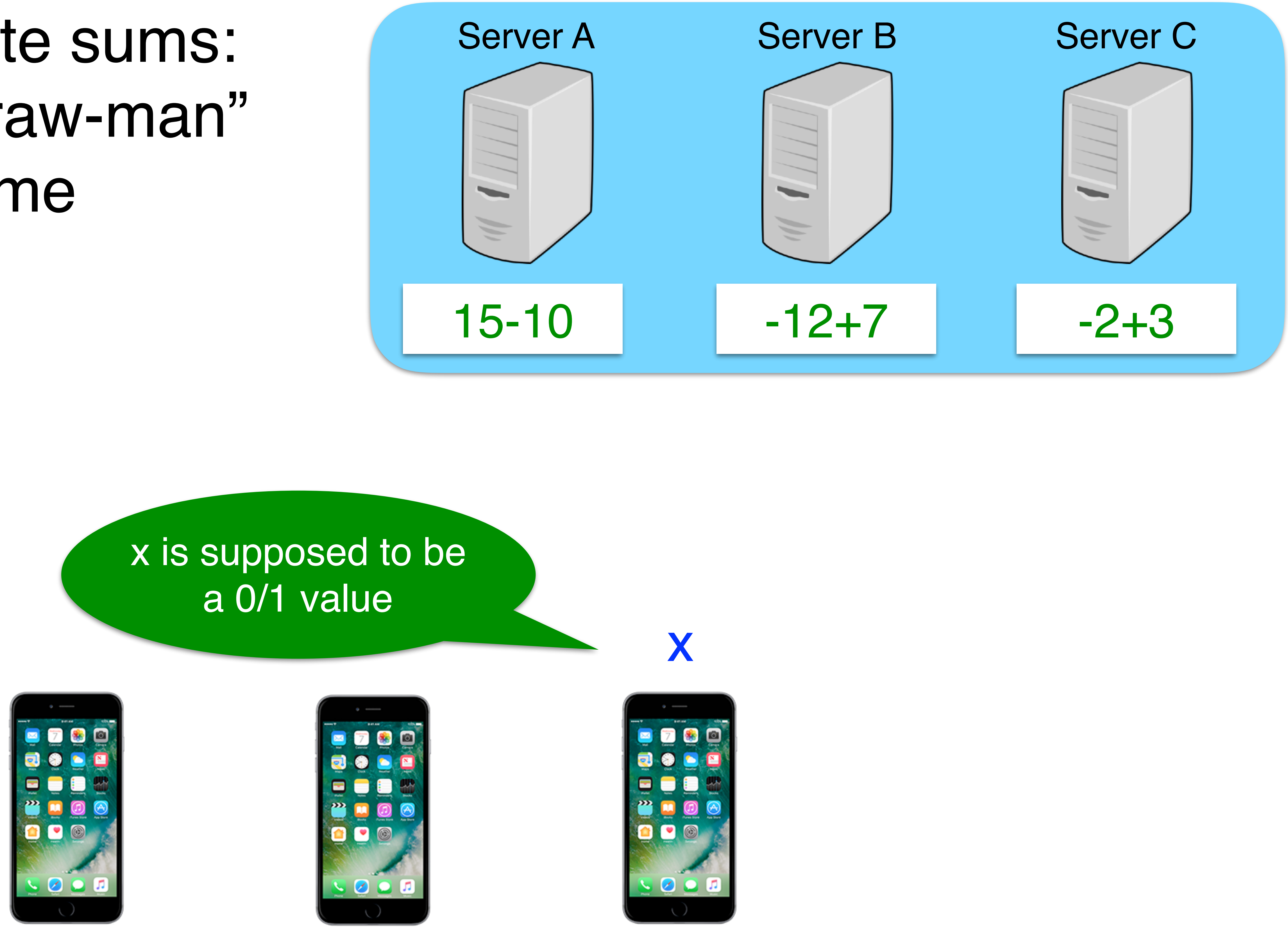

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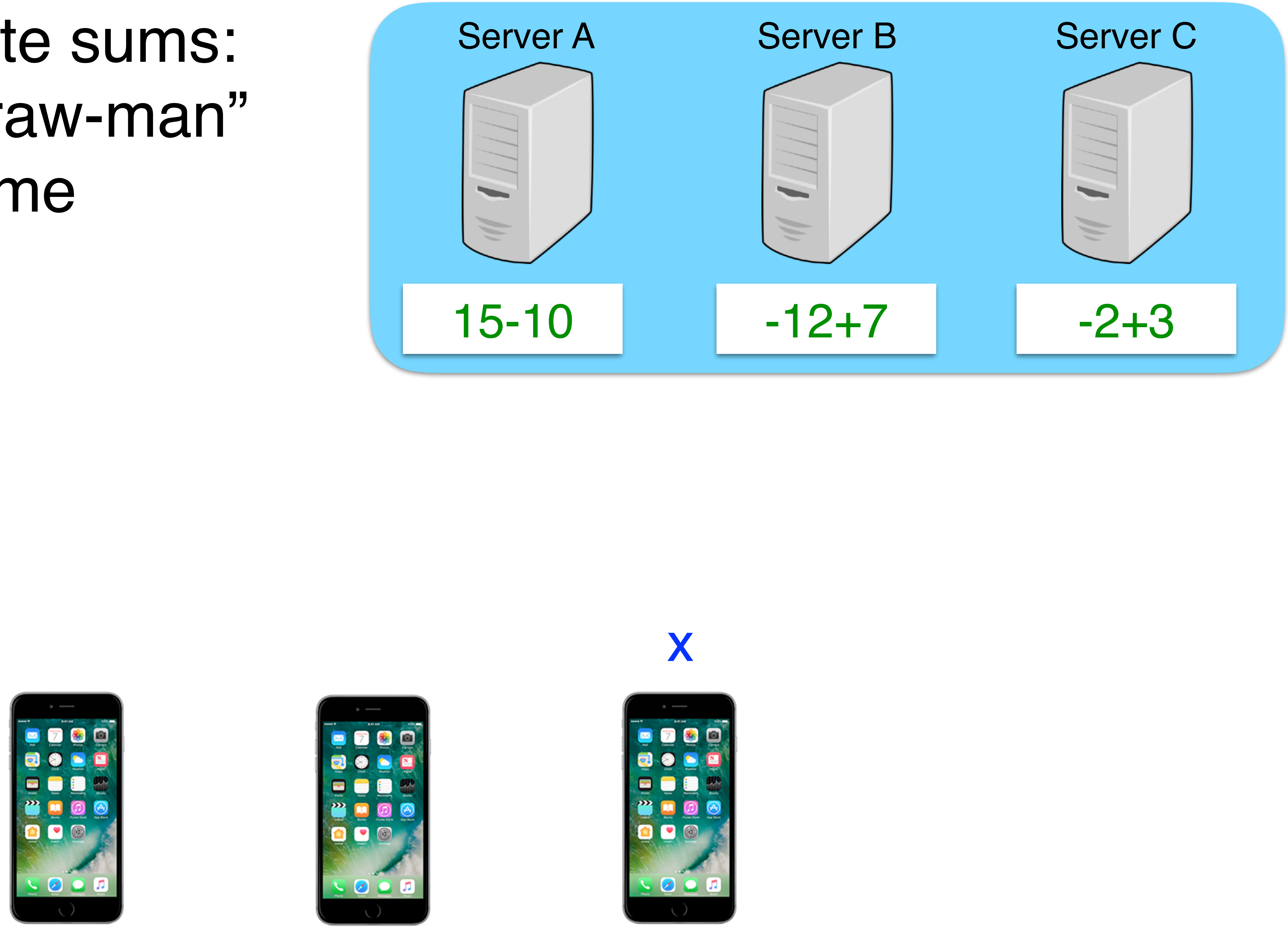

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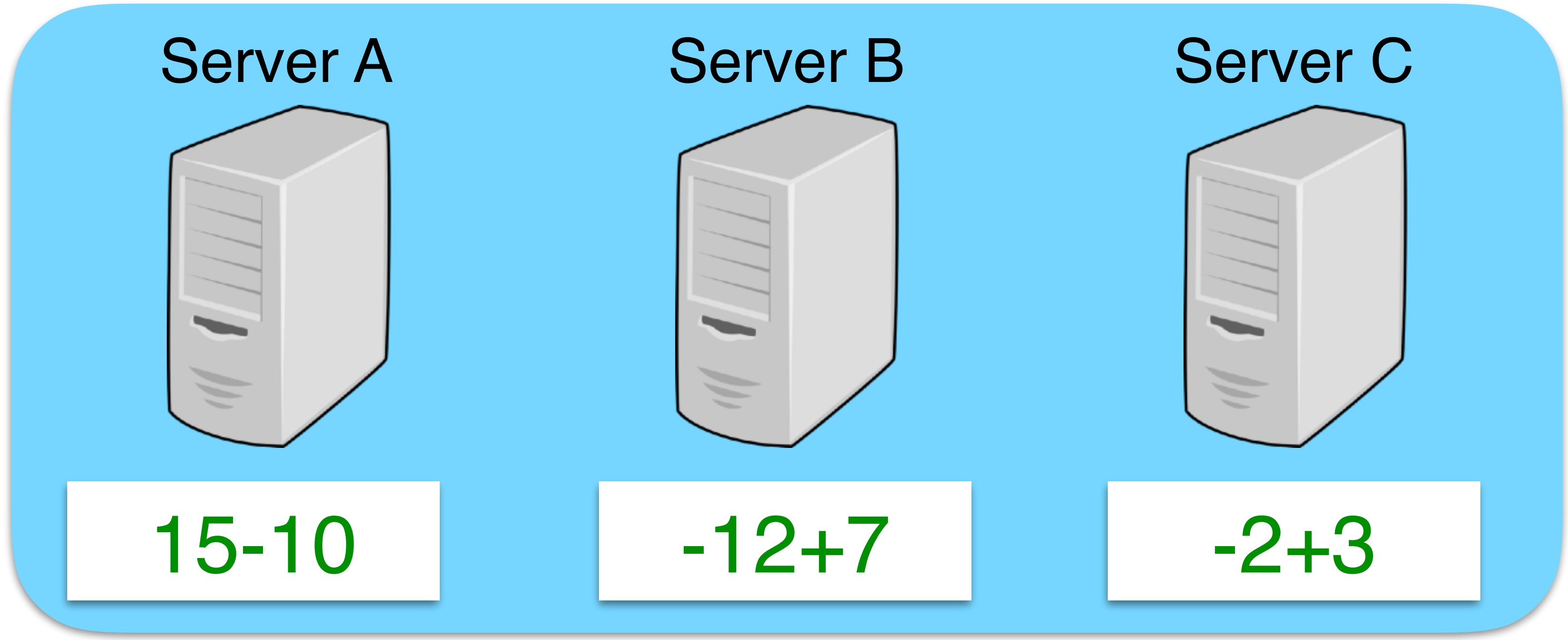

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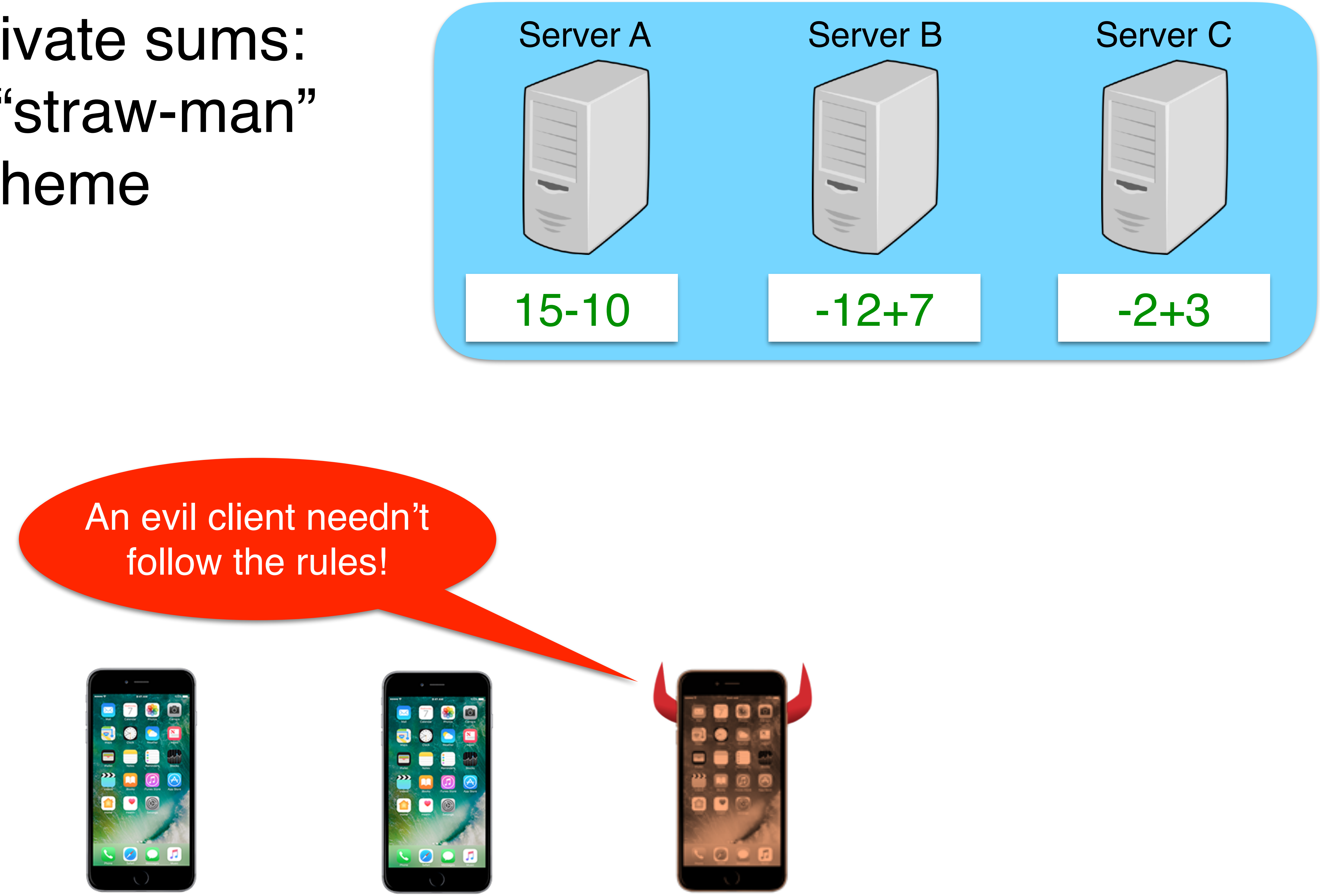

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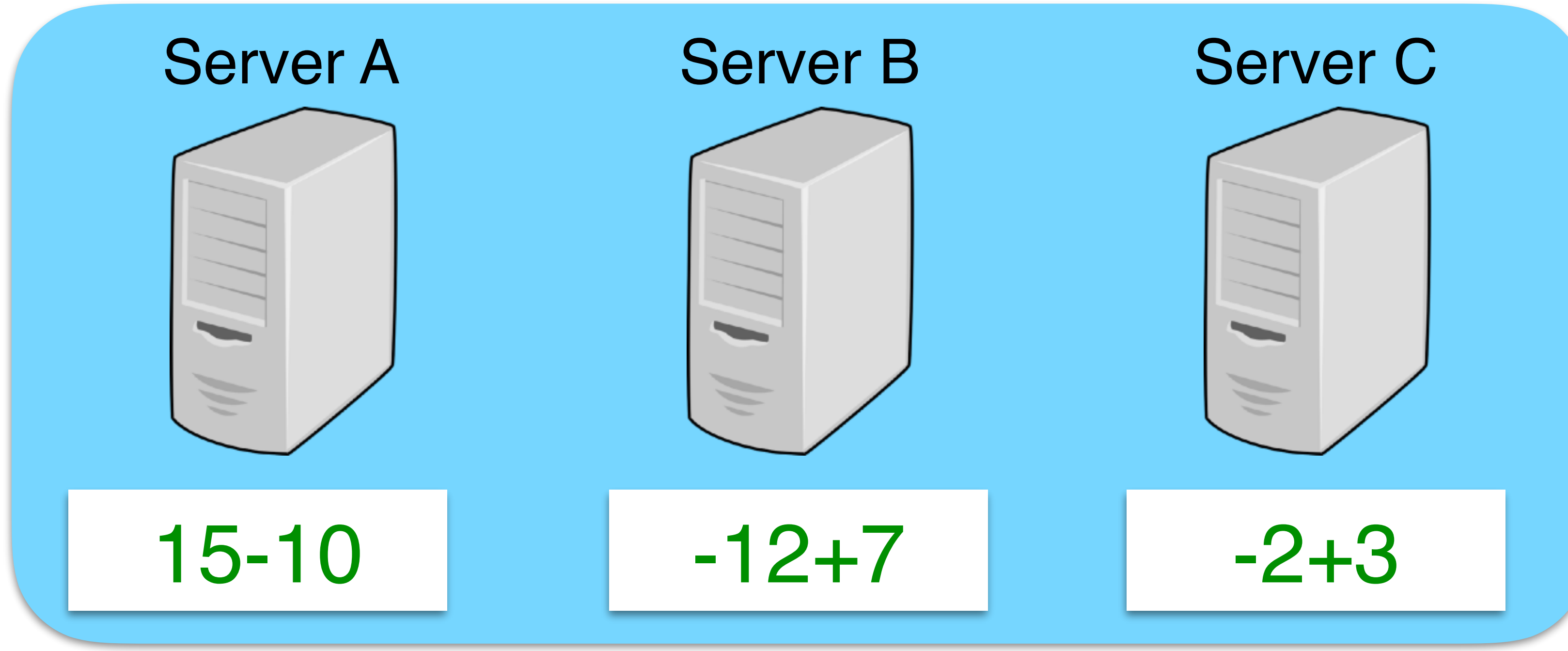

An evil client needn’t follow the rules!

$$10 + 4 + 7 = \mathbf{21}$$

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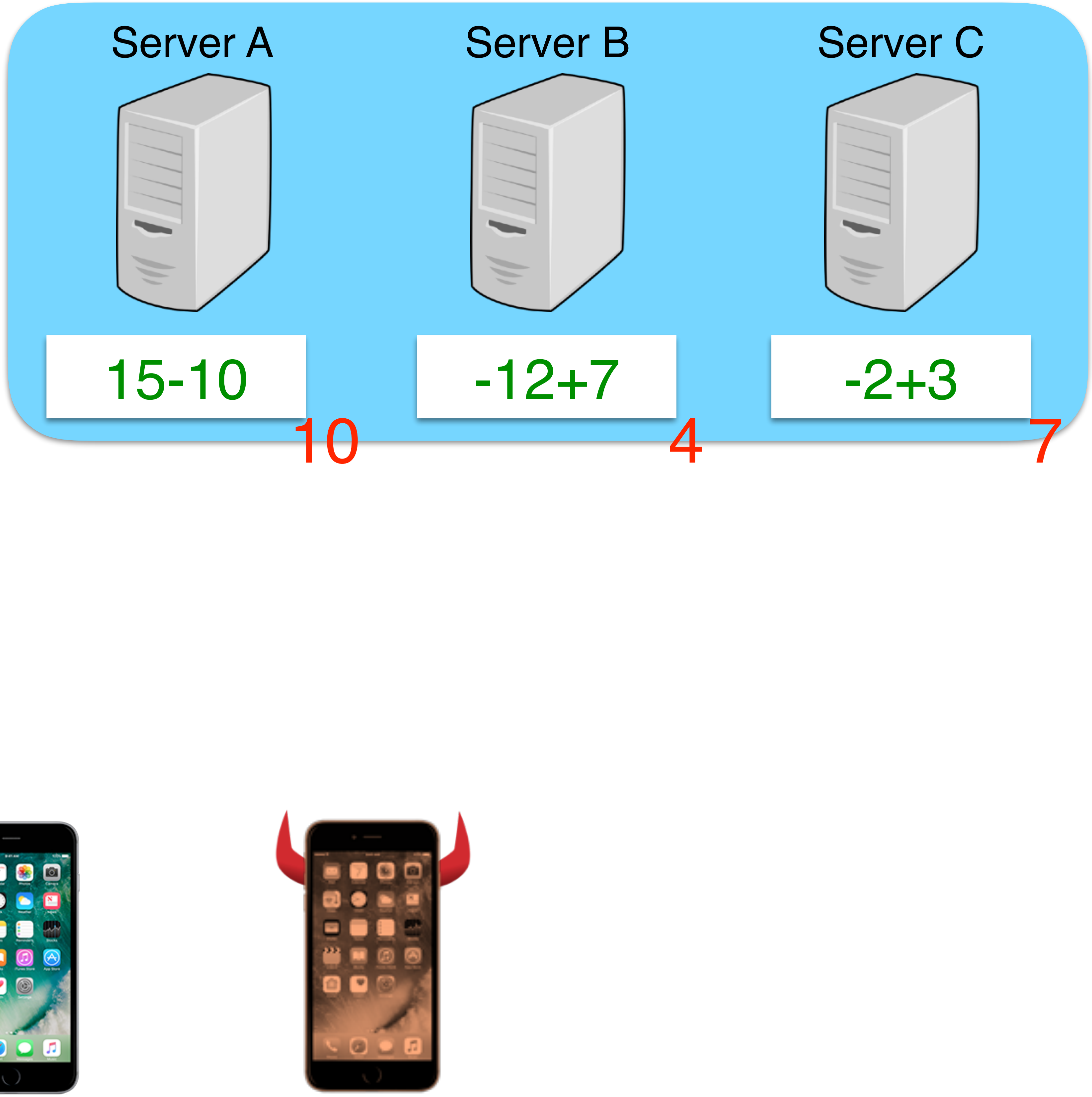

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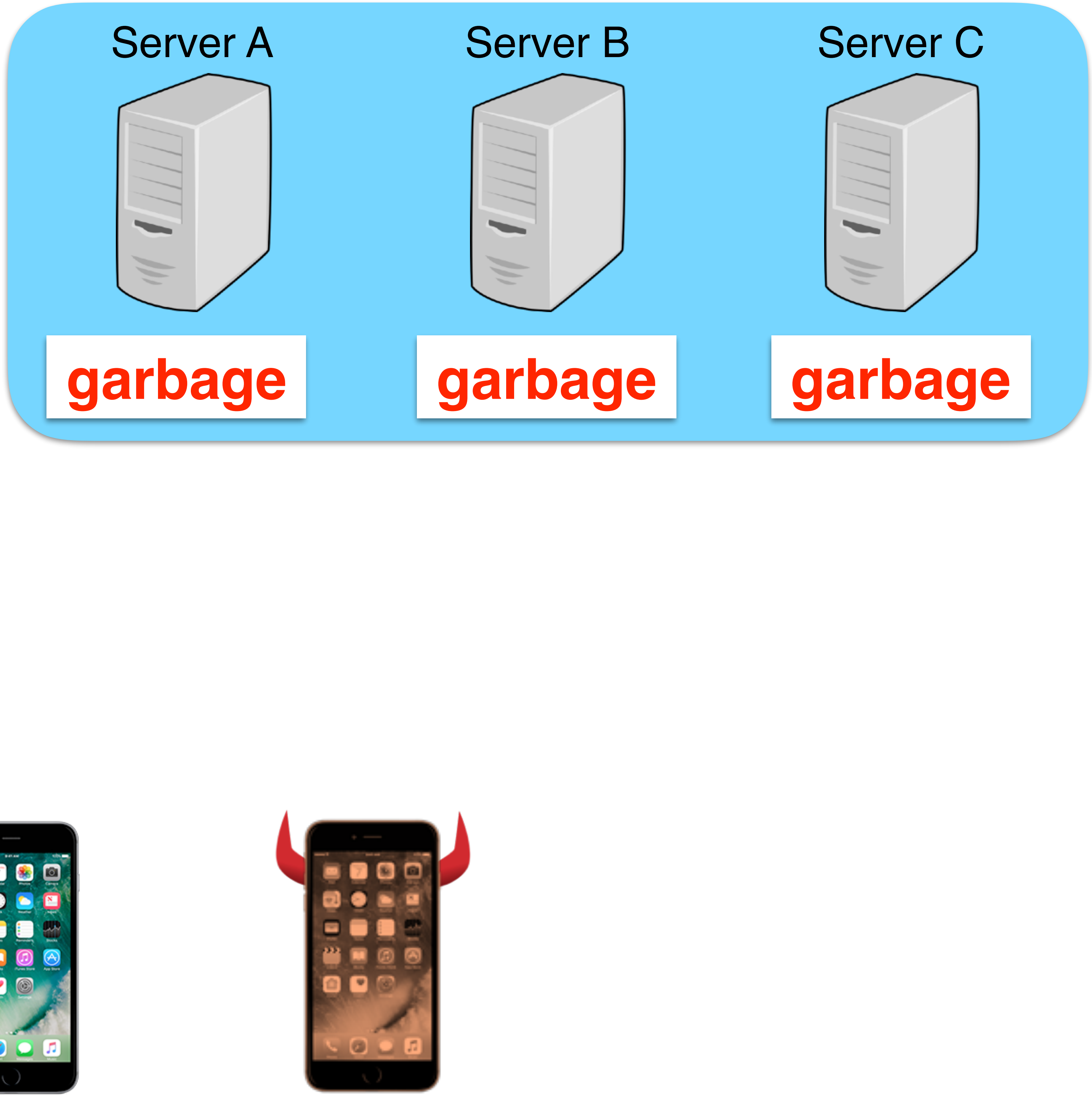

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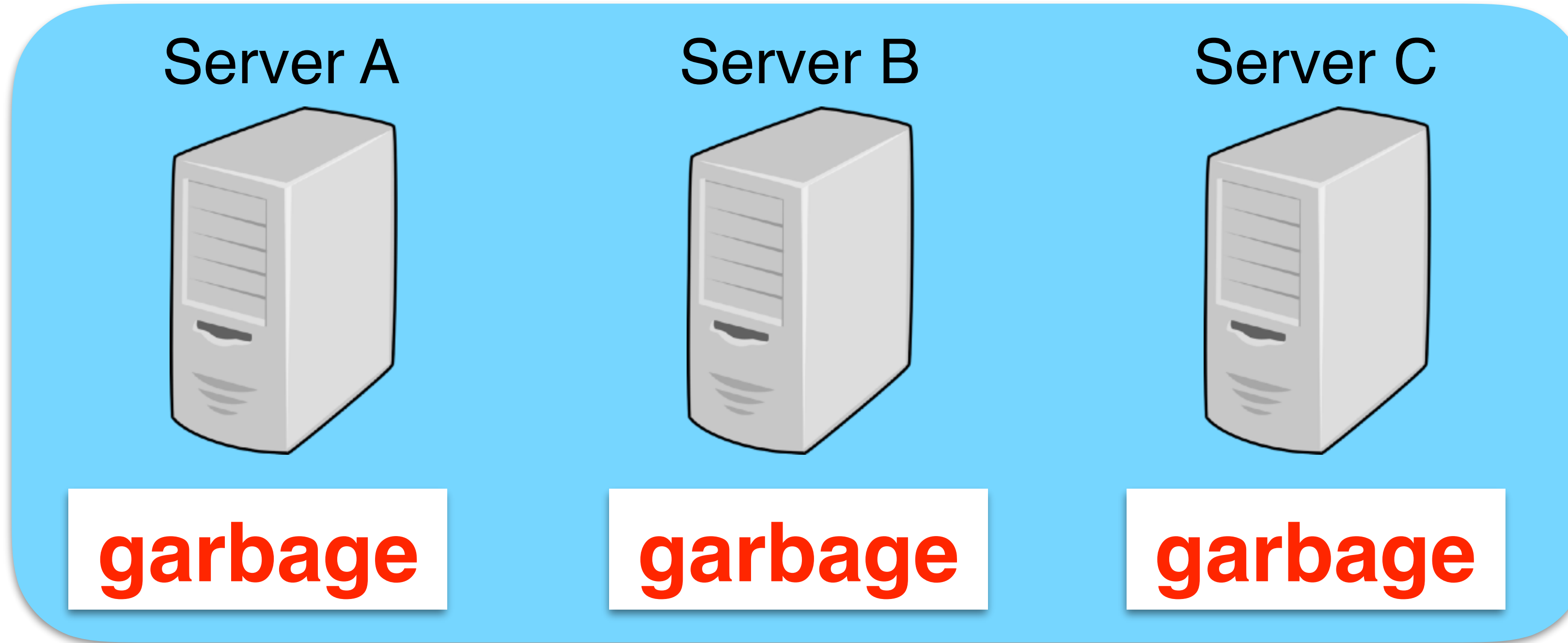

A single bad client **can undetectably corrupt** the sum

Users have **incentives** to cheat

Typical defenses (NIZKs) are costly

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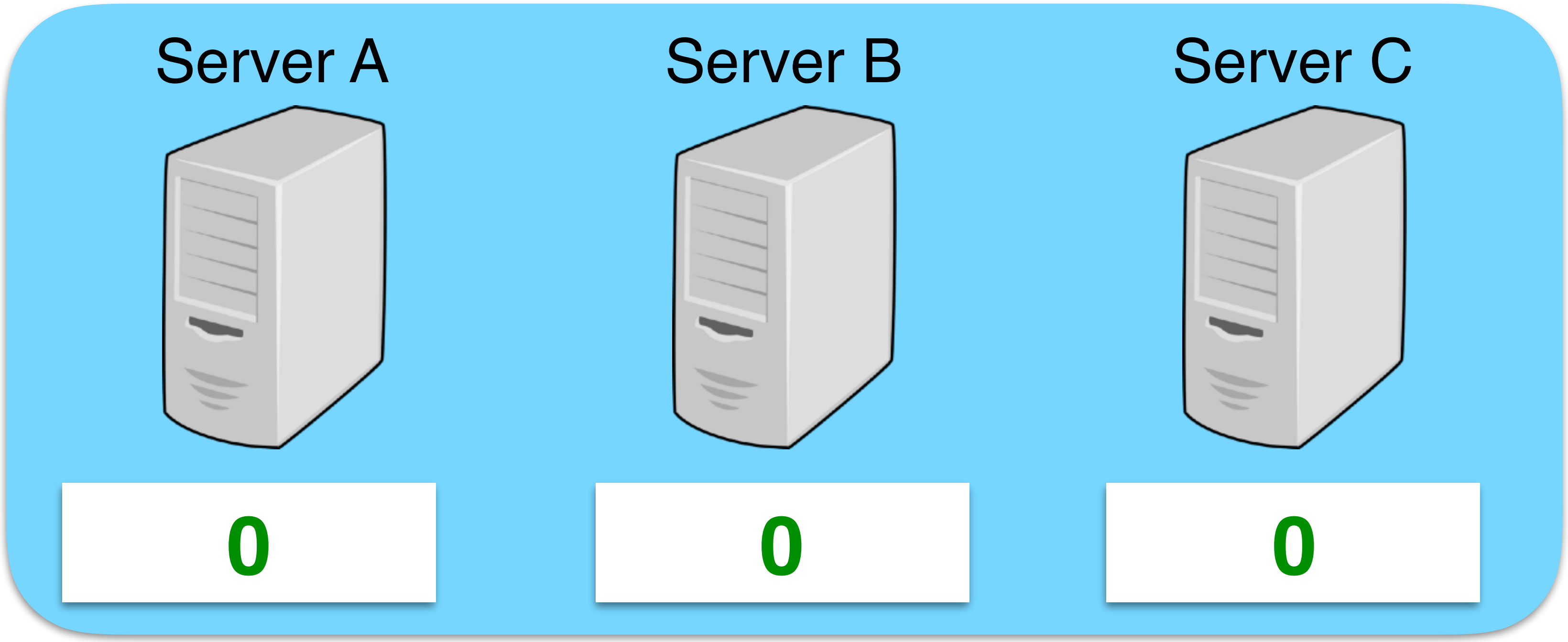
- Discussion: Real-world considerations

Outline

- Background: The private aggregation problem
- A straw-man solution for private sums
- **Providing robustness with SNIPs**
- Evaluation
- Discussion: Real-world considerations

Contribution 1
Secret-shared non-interactive proofs (SNIPs)



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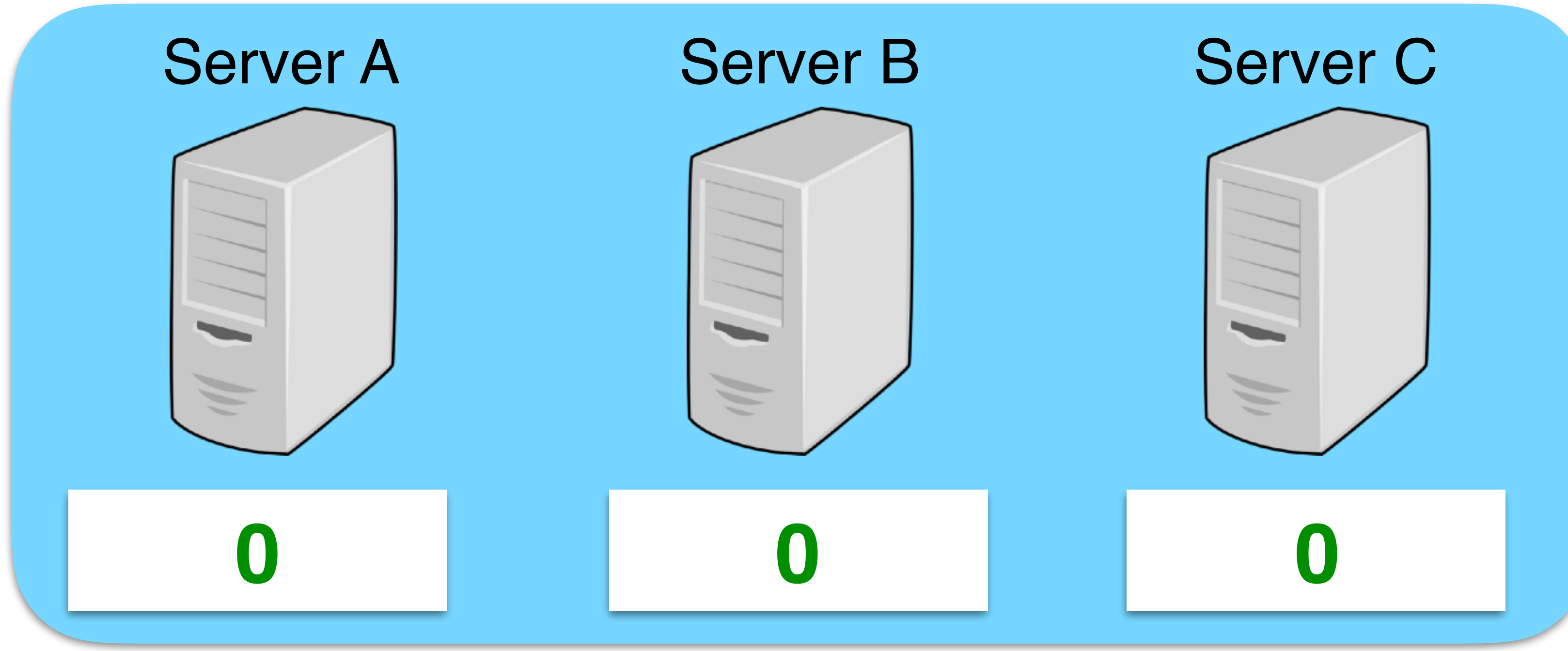

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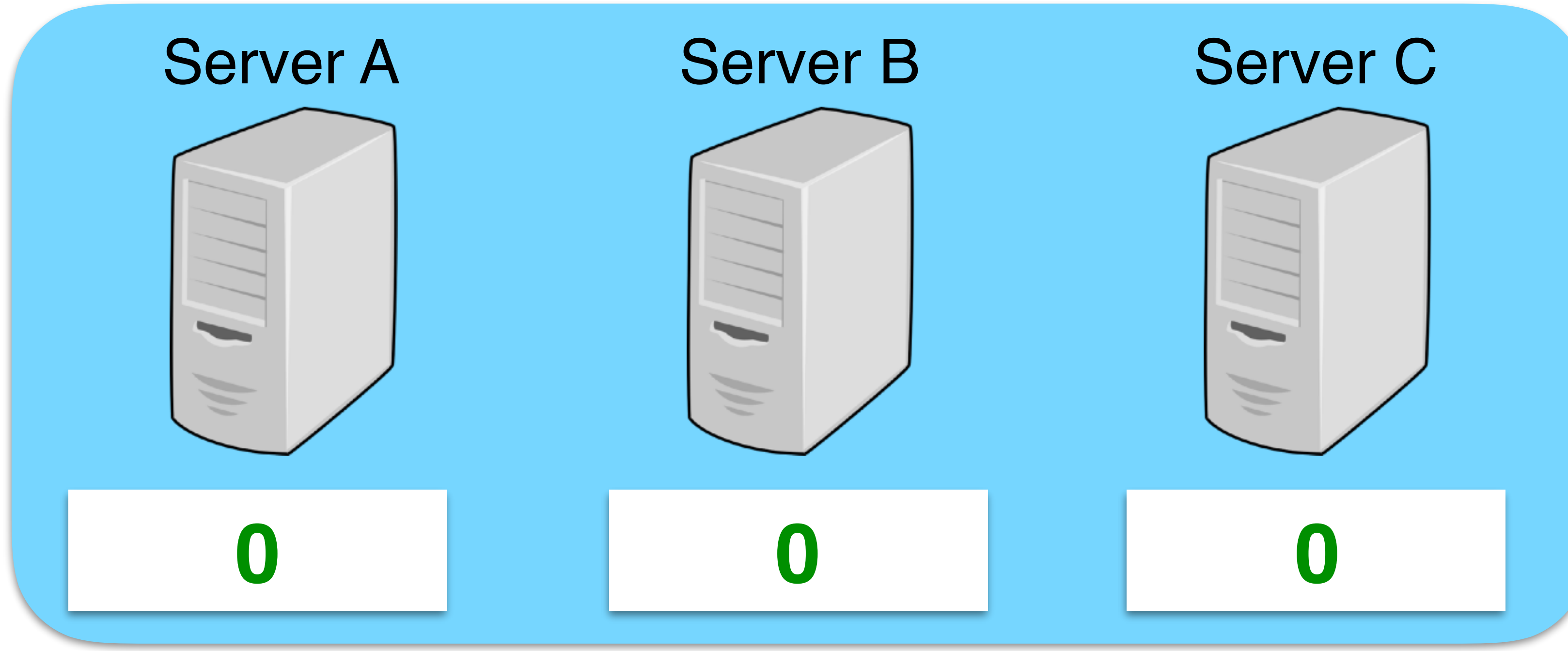

$$15 + (-12) + (-2) = 1$$

$x = 1$

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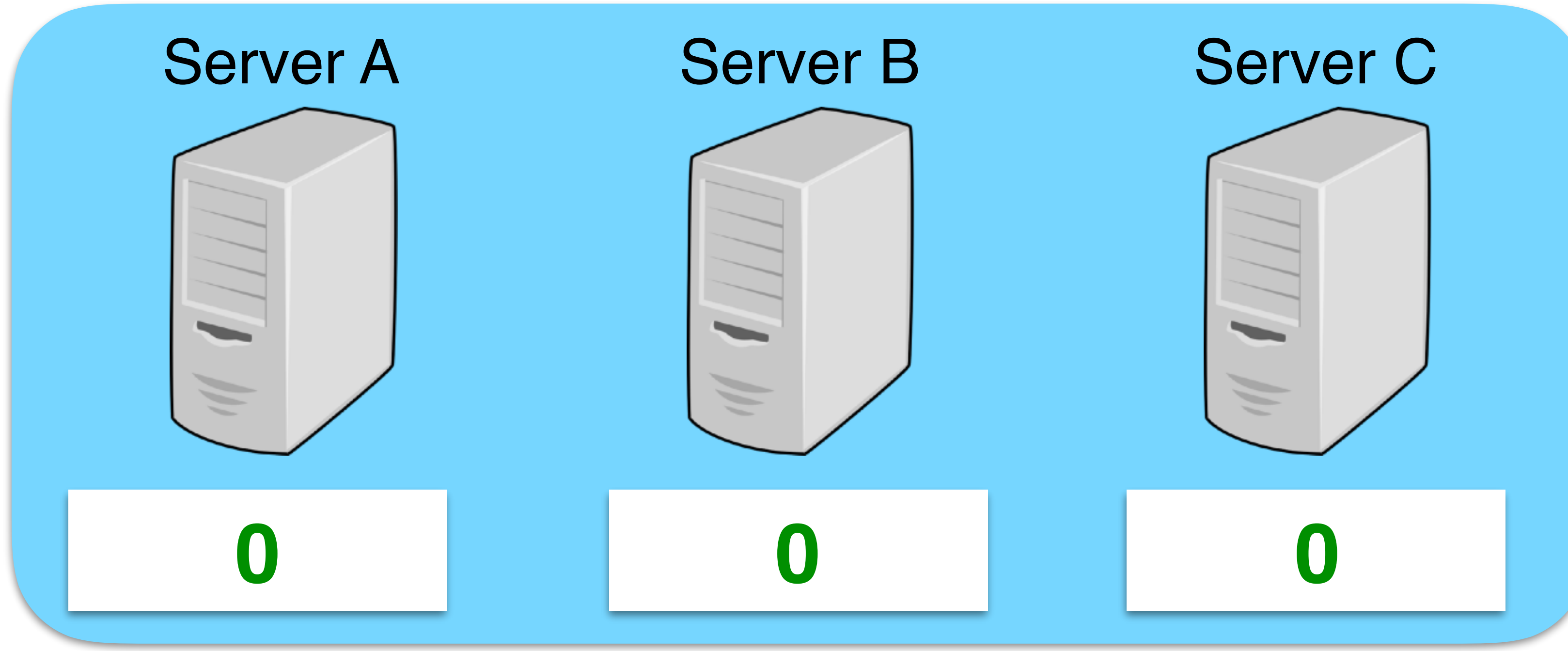

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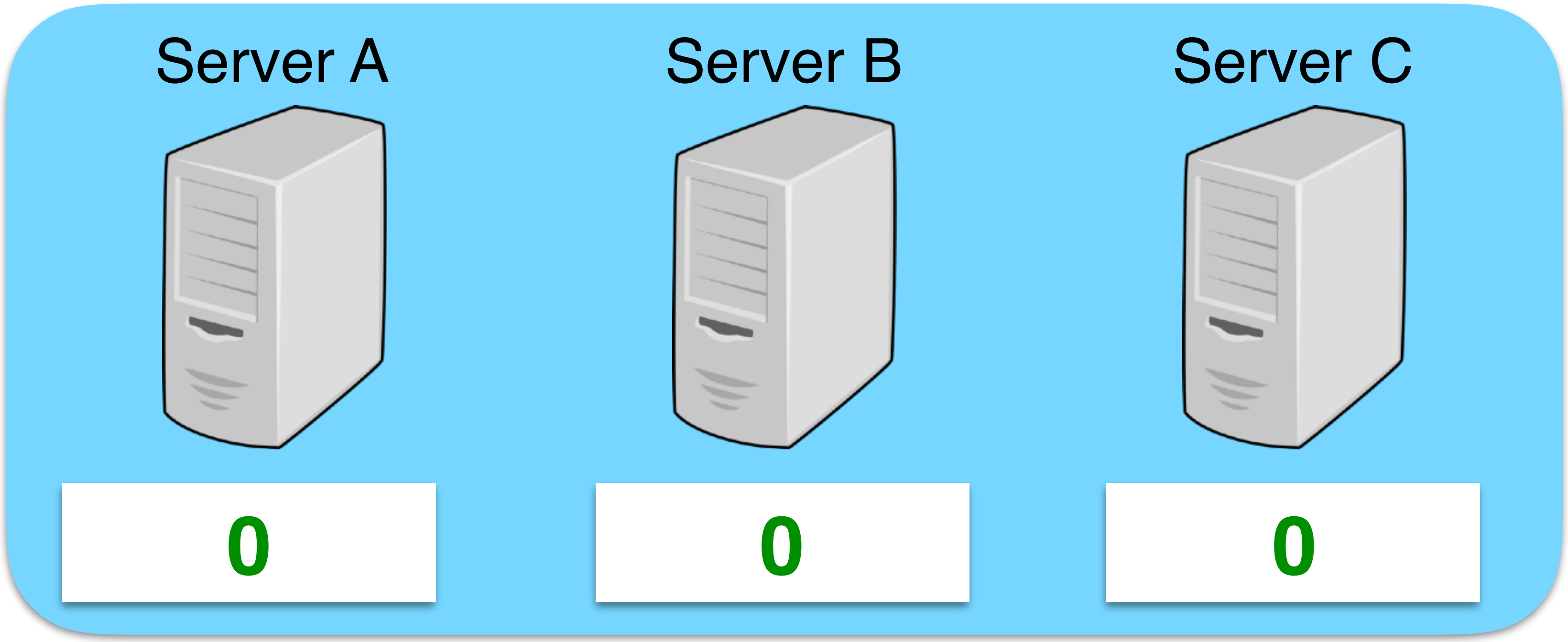

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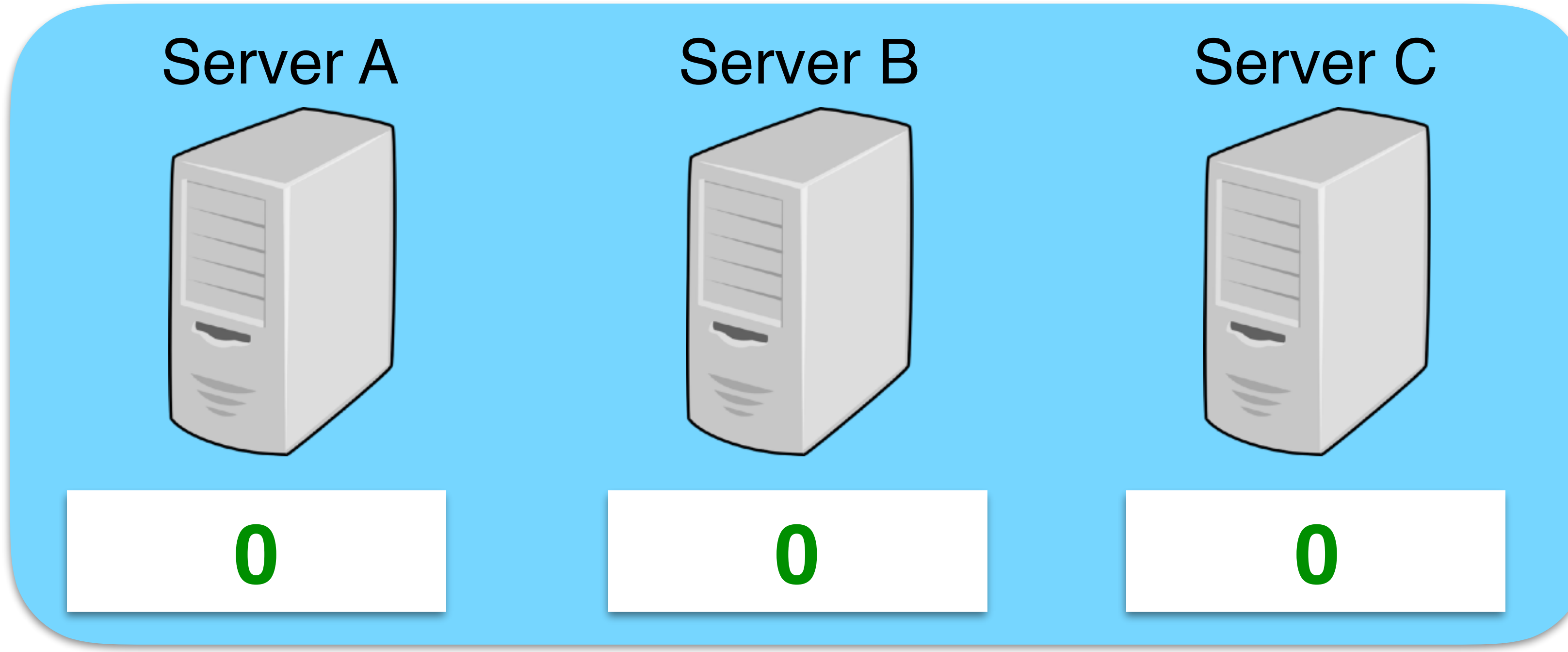

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In this example, the servers want to ensure that their shares sum to 0 or 1

…without learning x.

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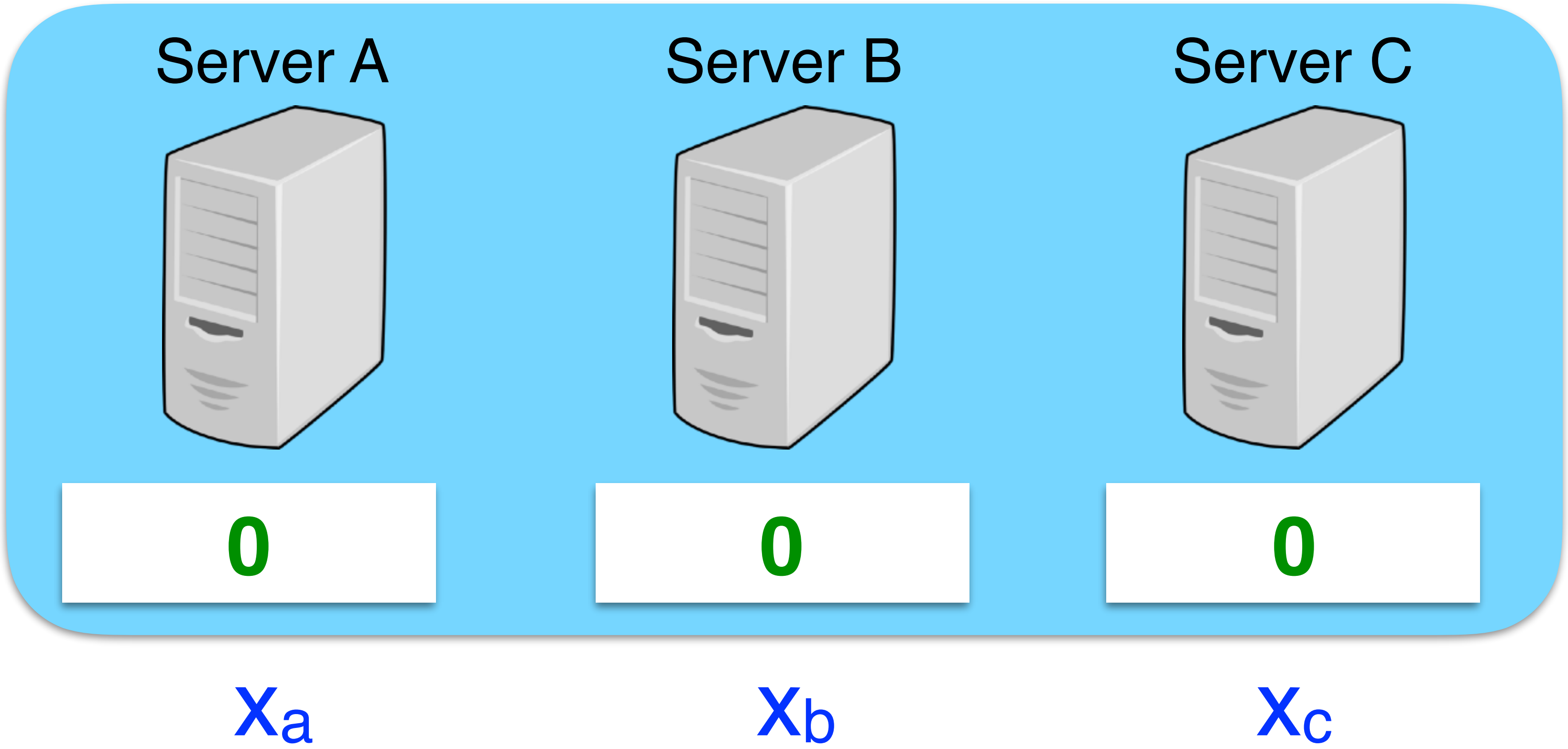

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More generally, servers

- hold shares of the client's private value x
- hold an <u>arbitrary</u> public predicate Valid(·)
  – expressed as an arithmetic circuit
- want to test if "Valid(x)" holds, without leaking x

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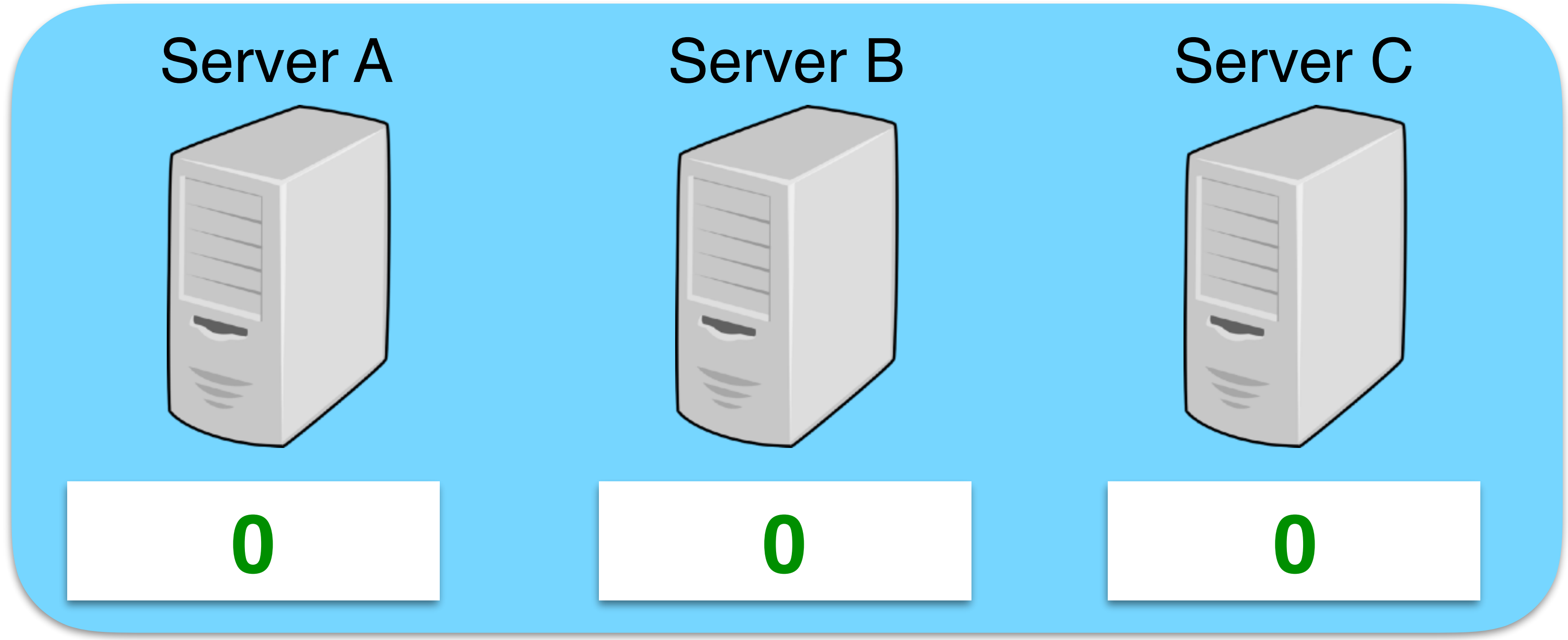

x_a x_b x_c

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For our running example:
Valid(x) = “$x \in \{0,1\}$”

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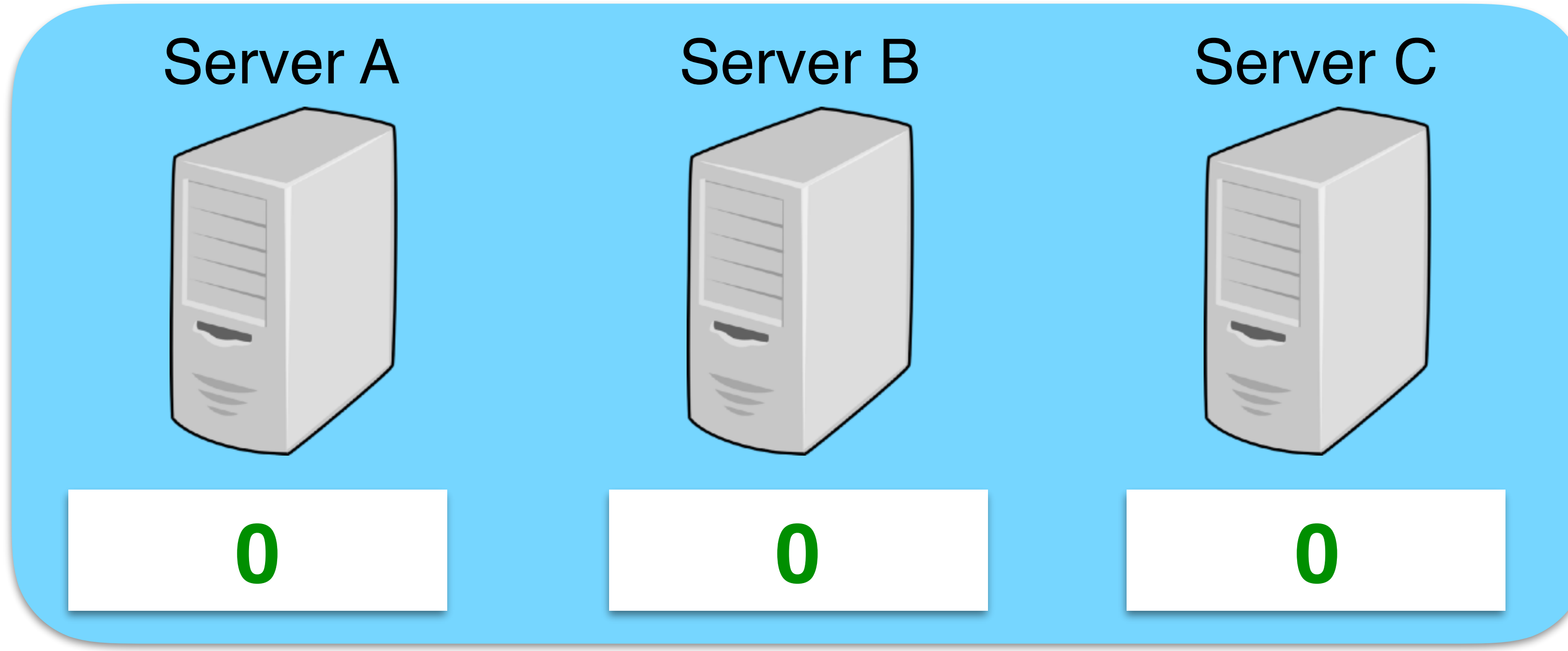

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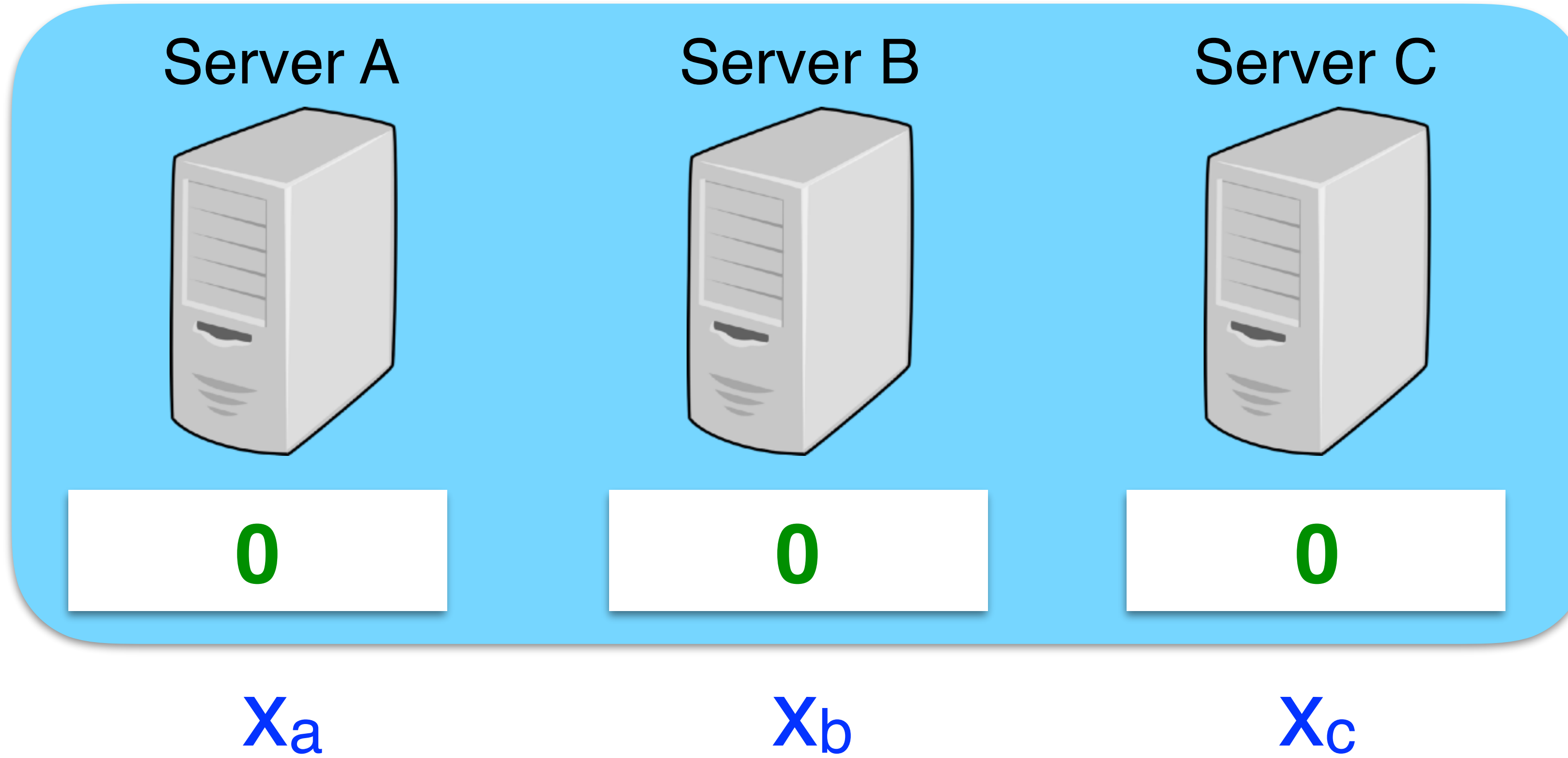

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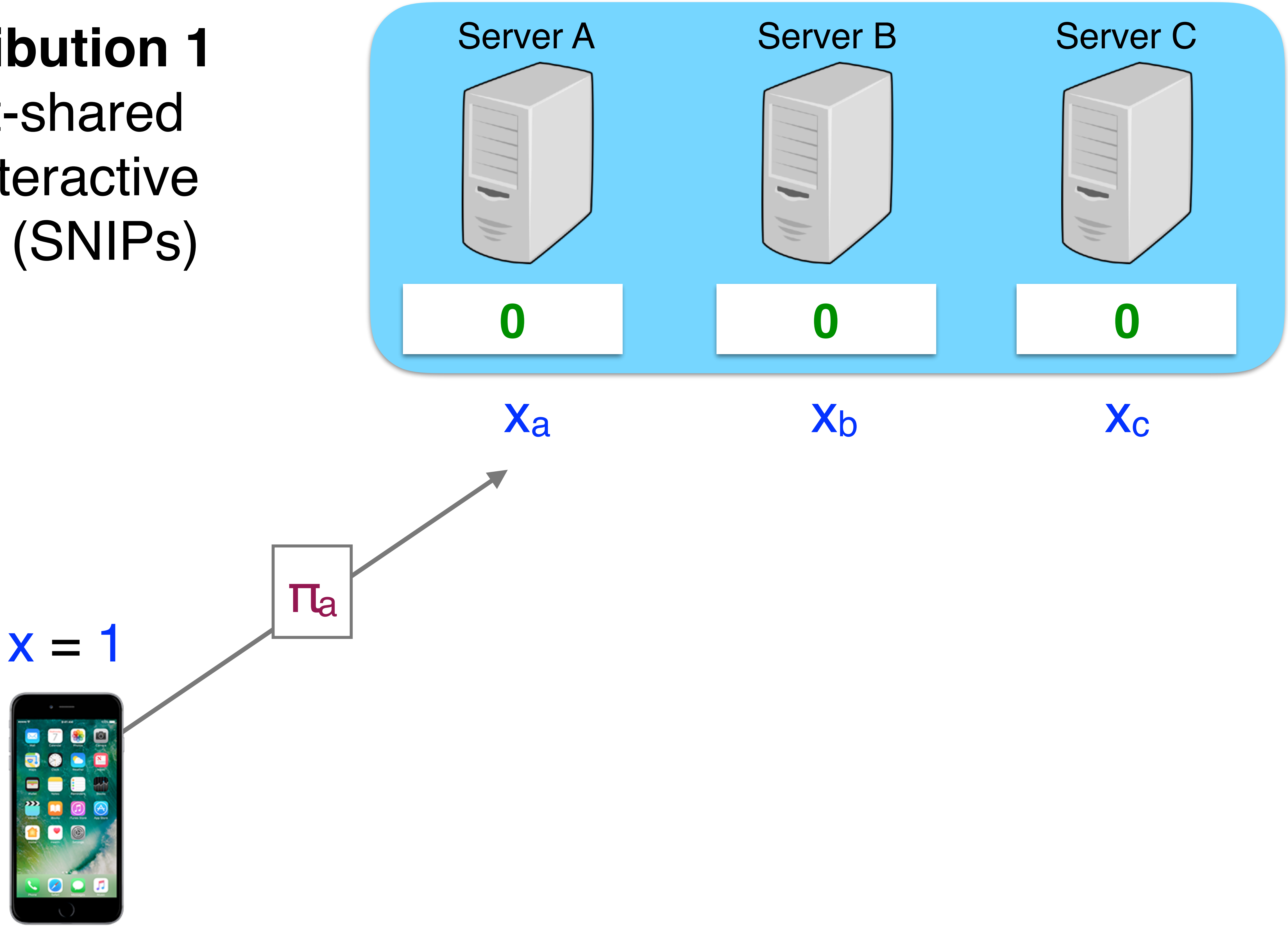

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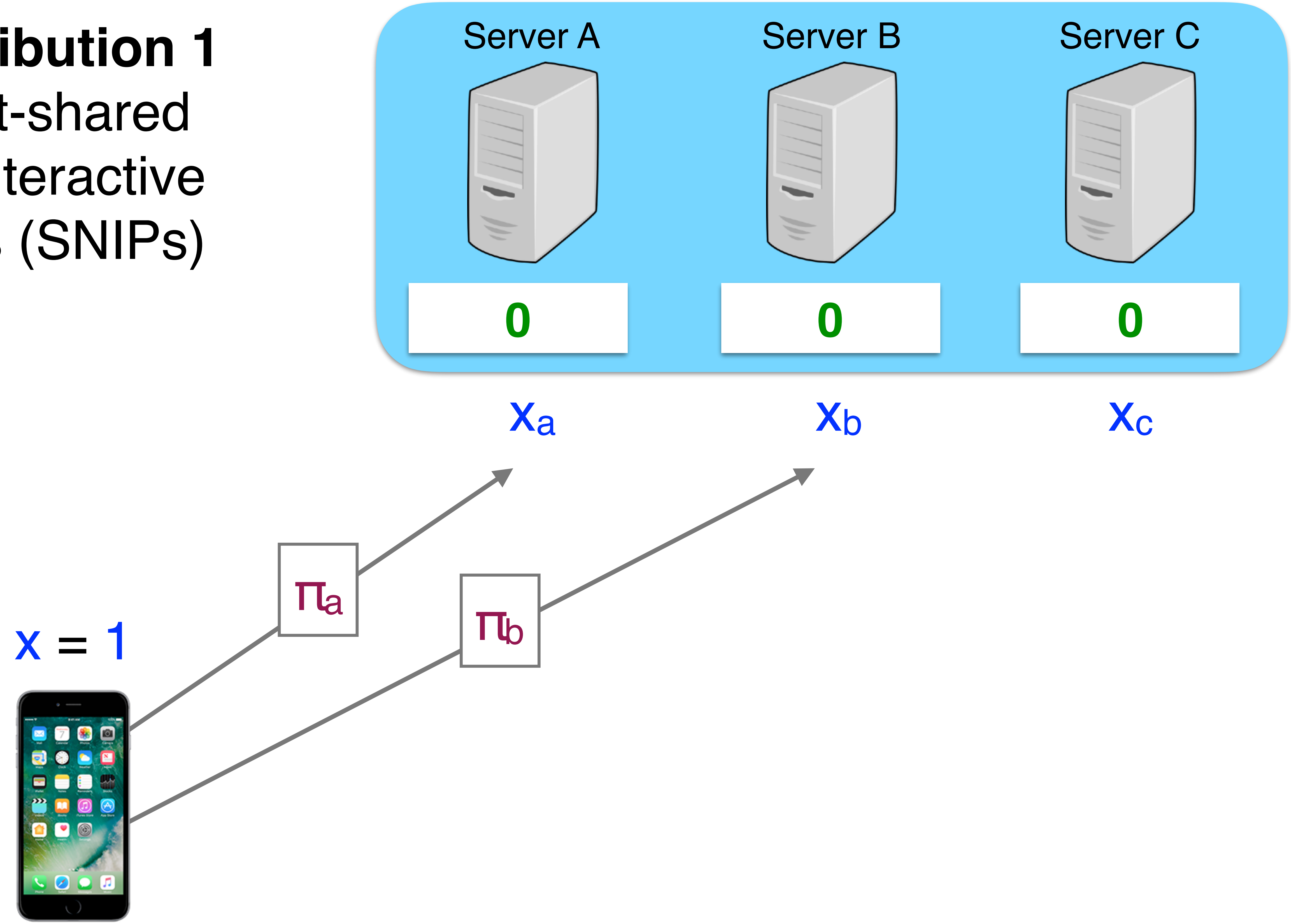

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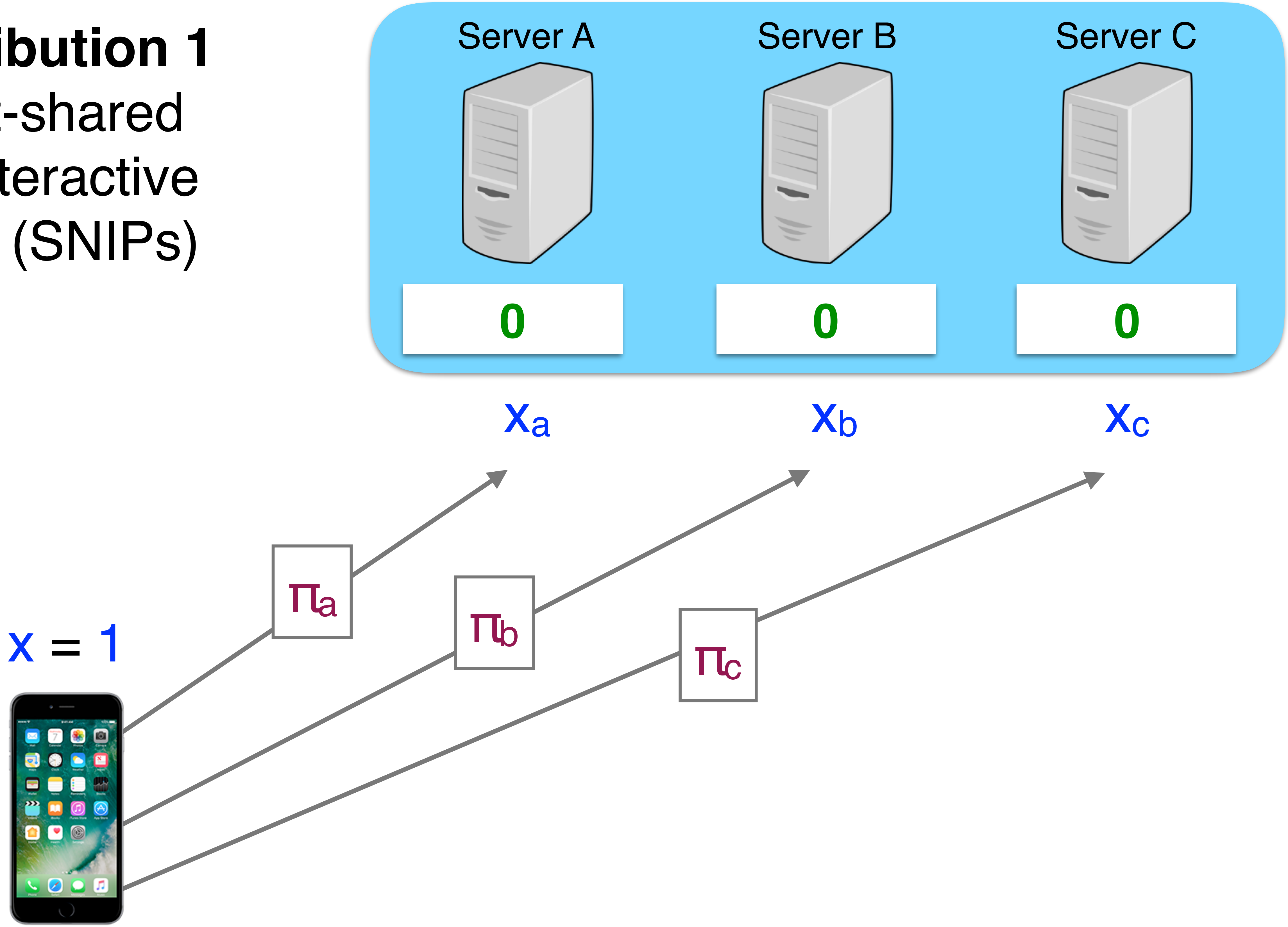

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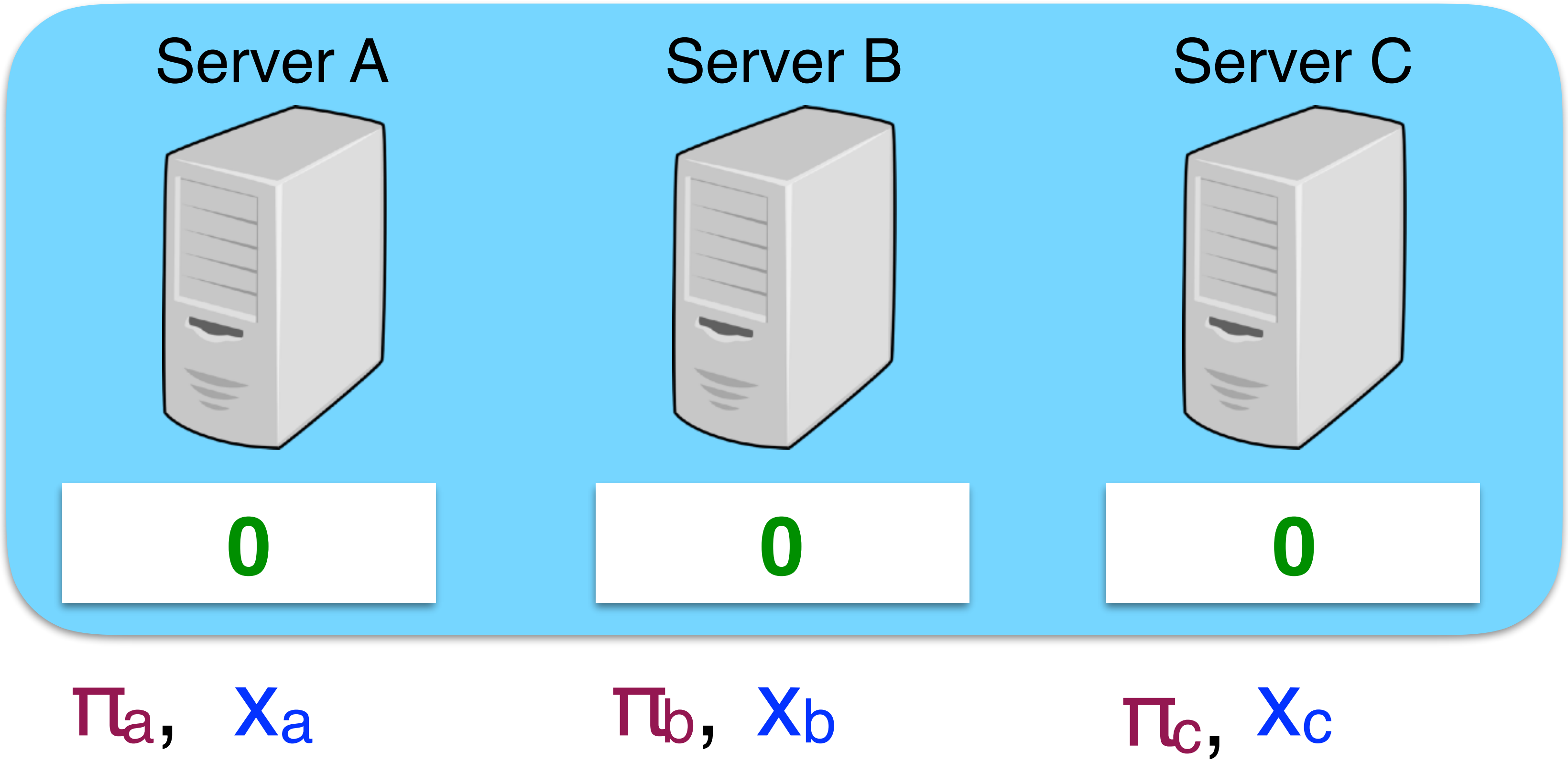

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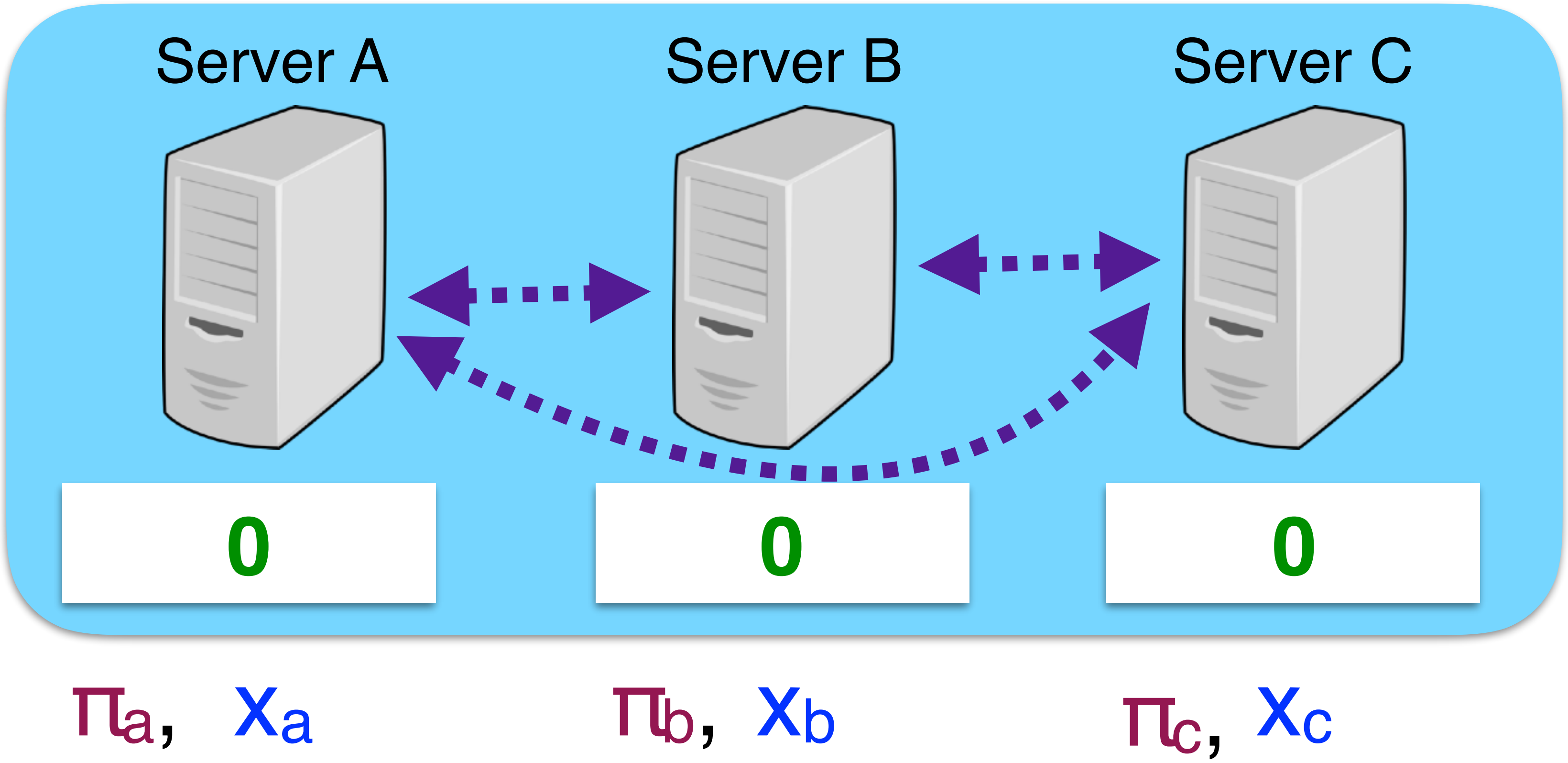

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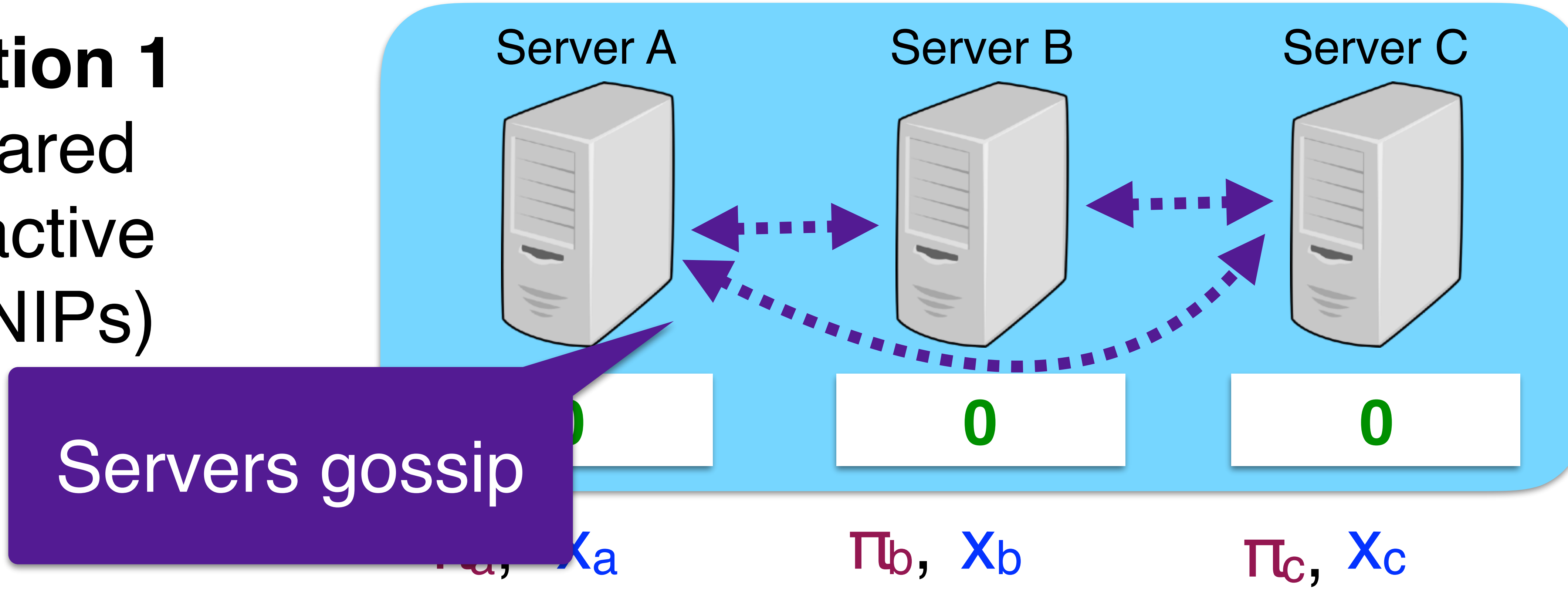

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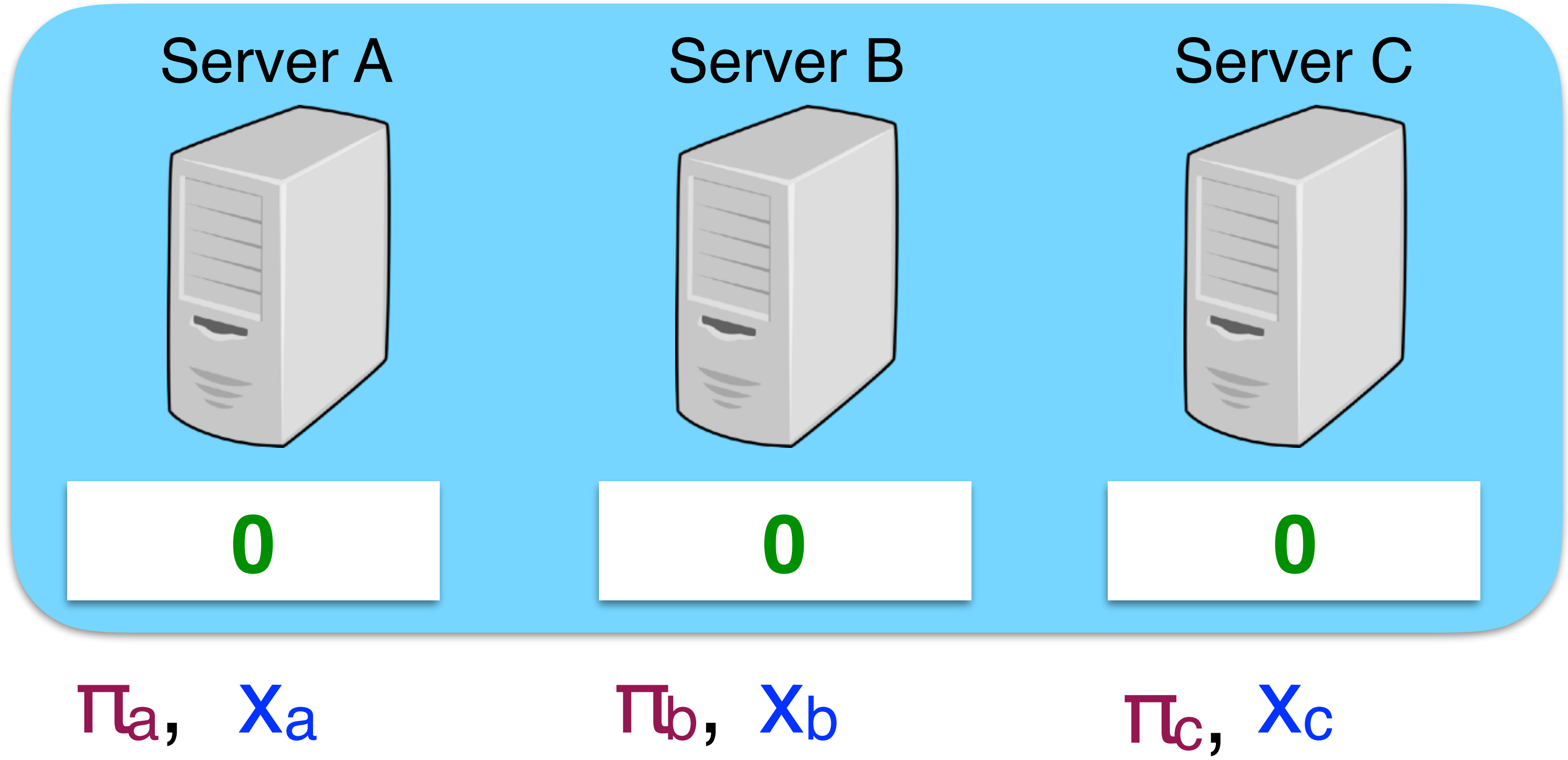

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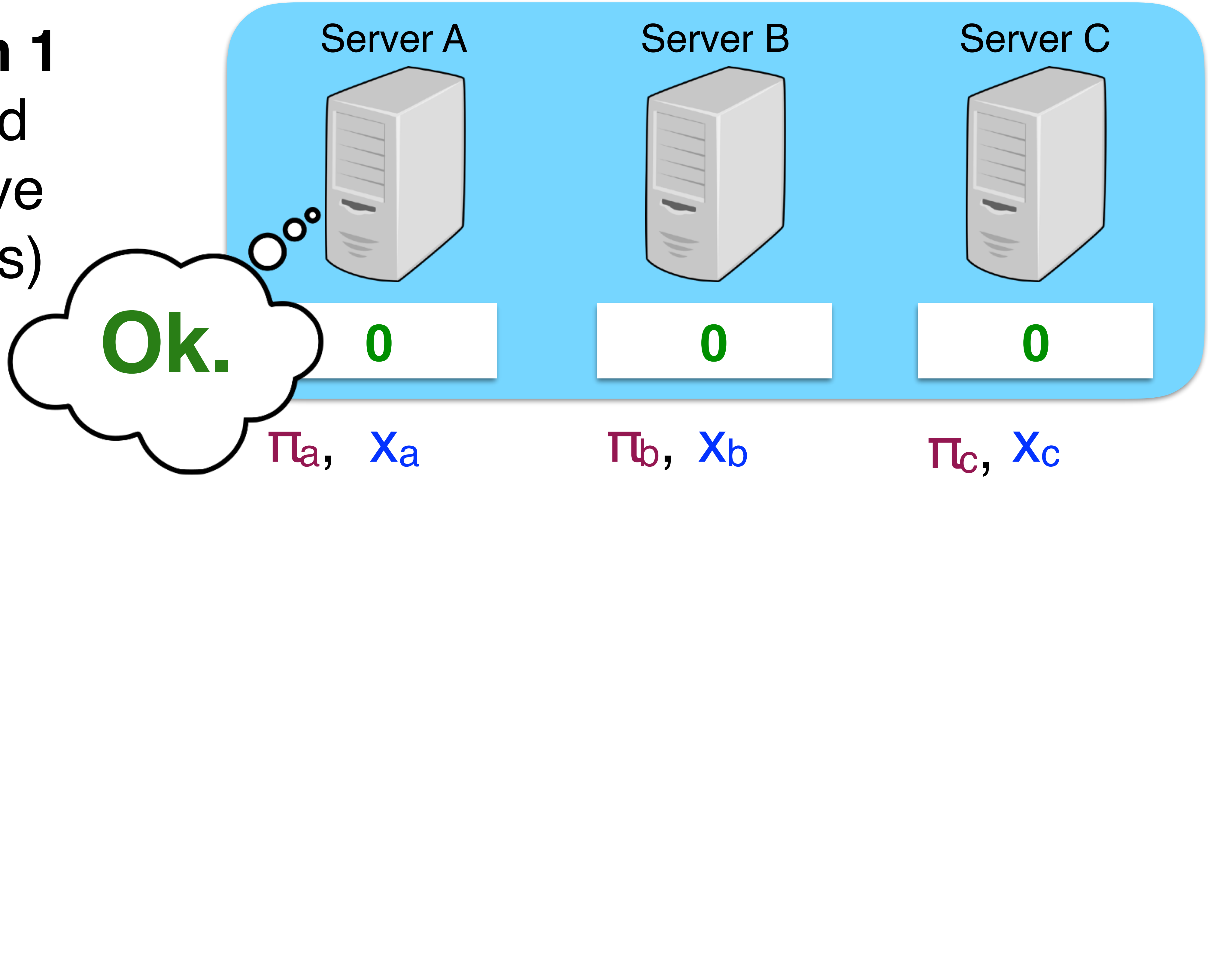

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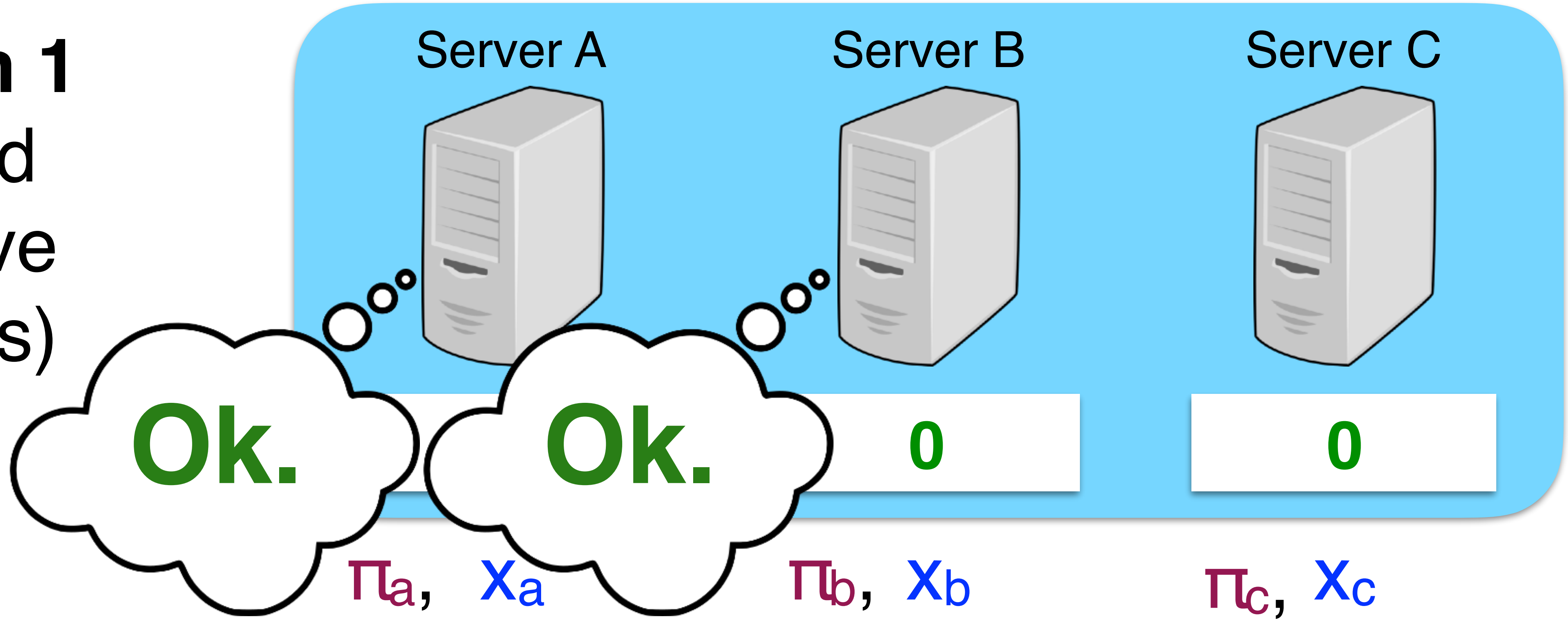

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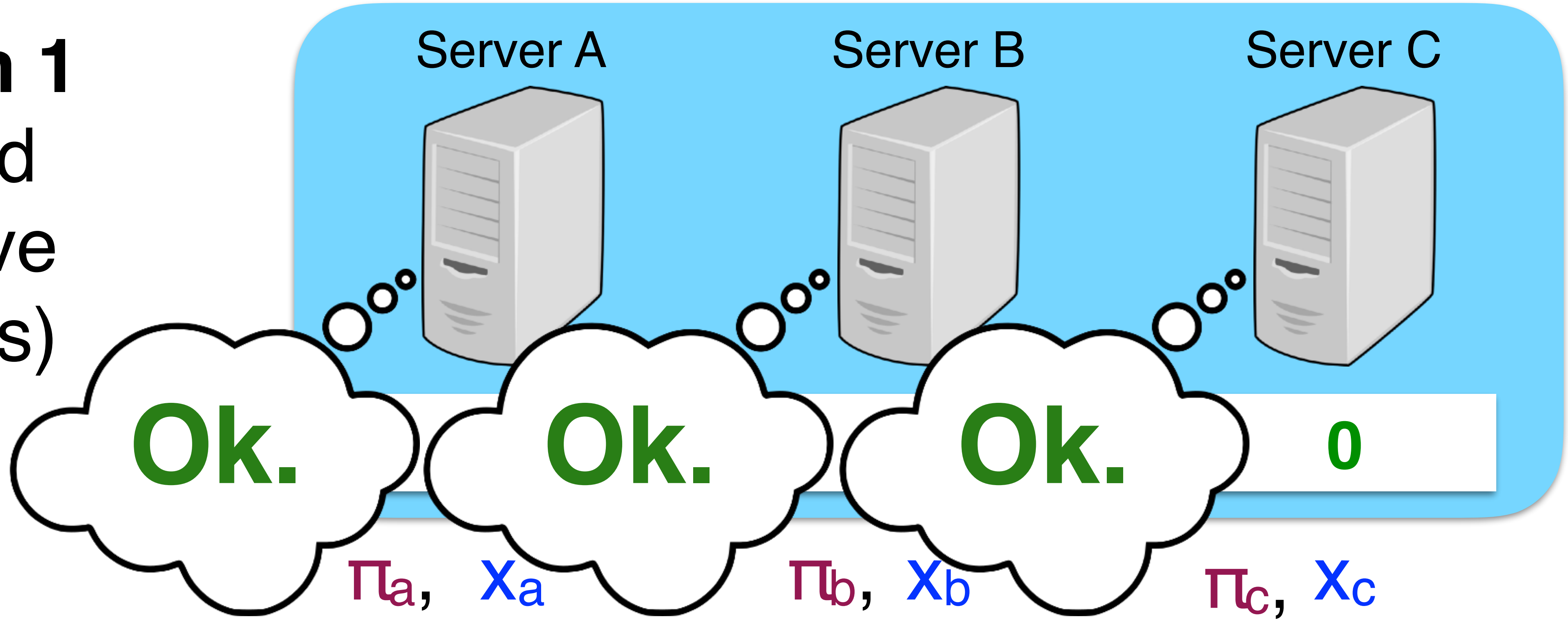

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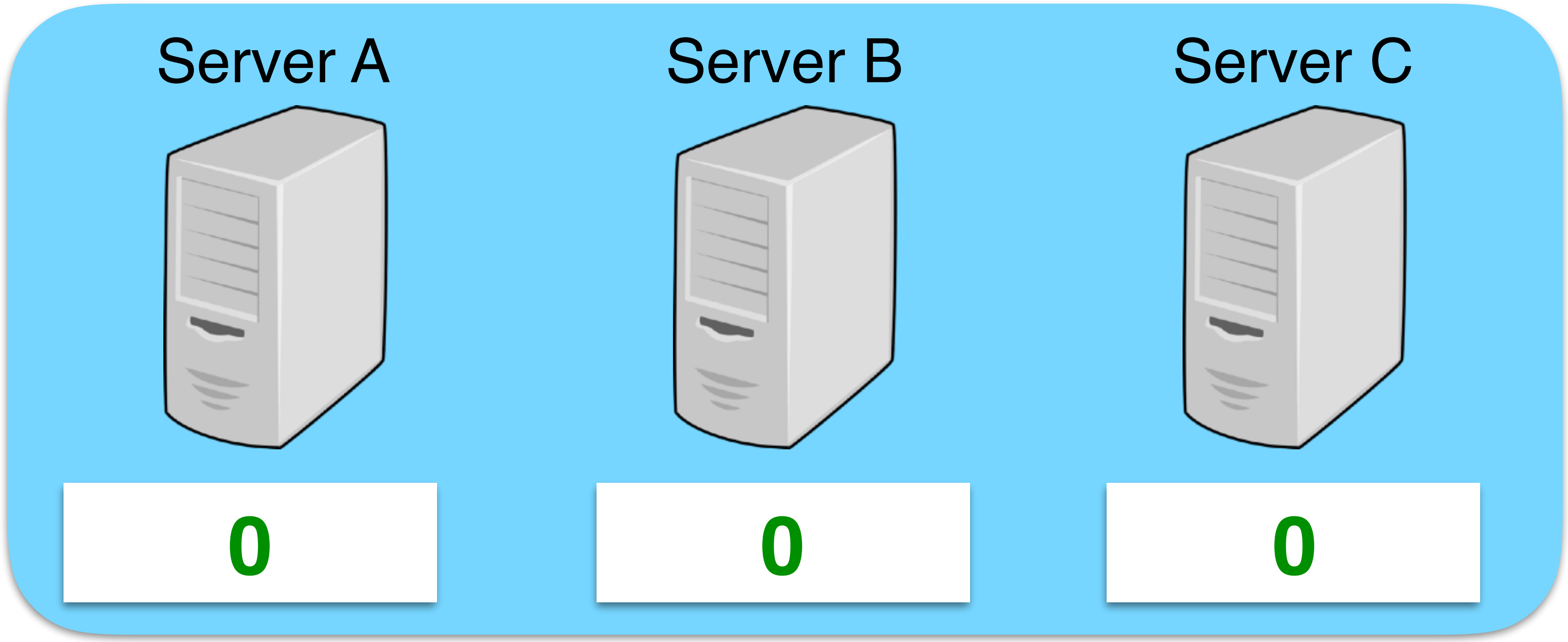

π_a, x_a π_b, x_b π_c, x_c

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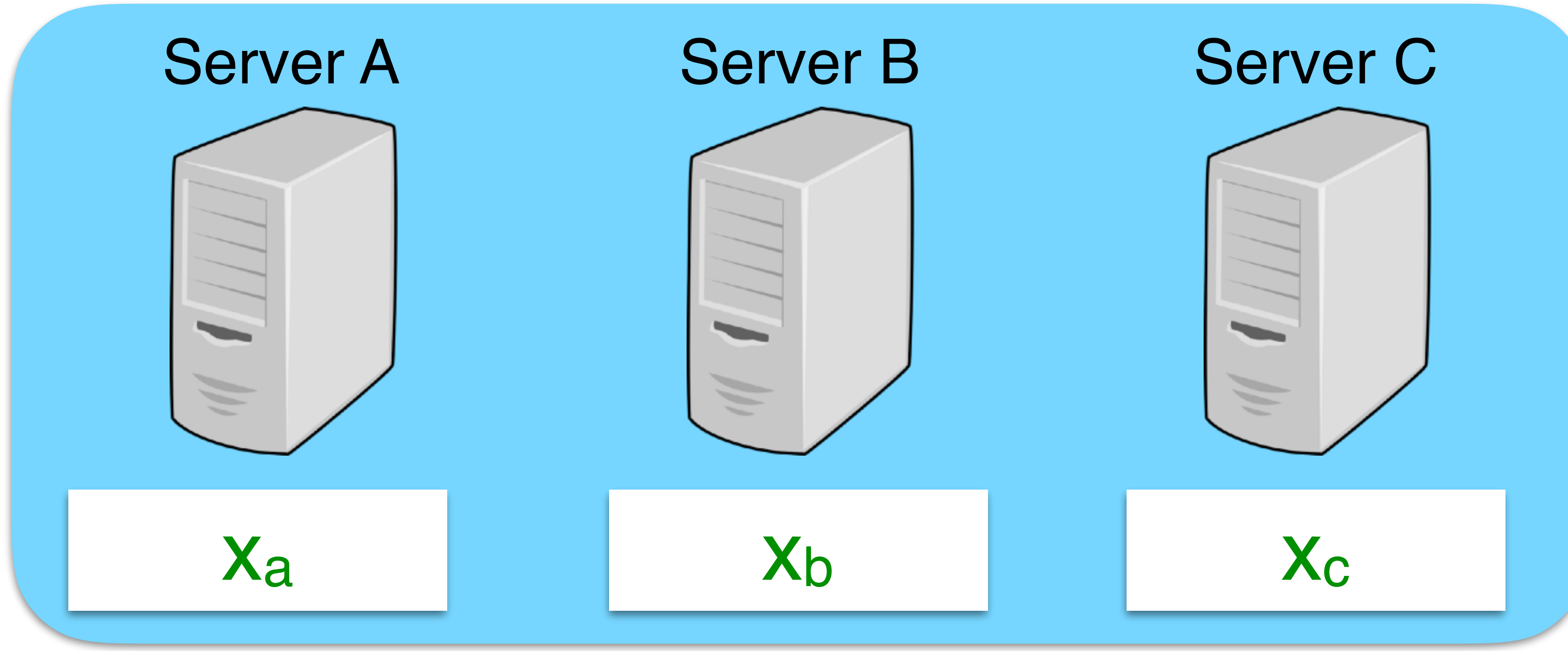

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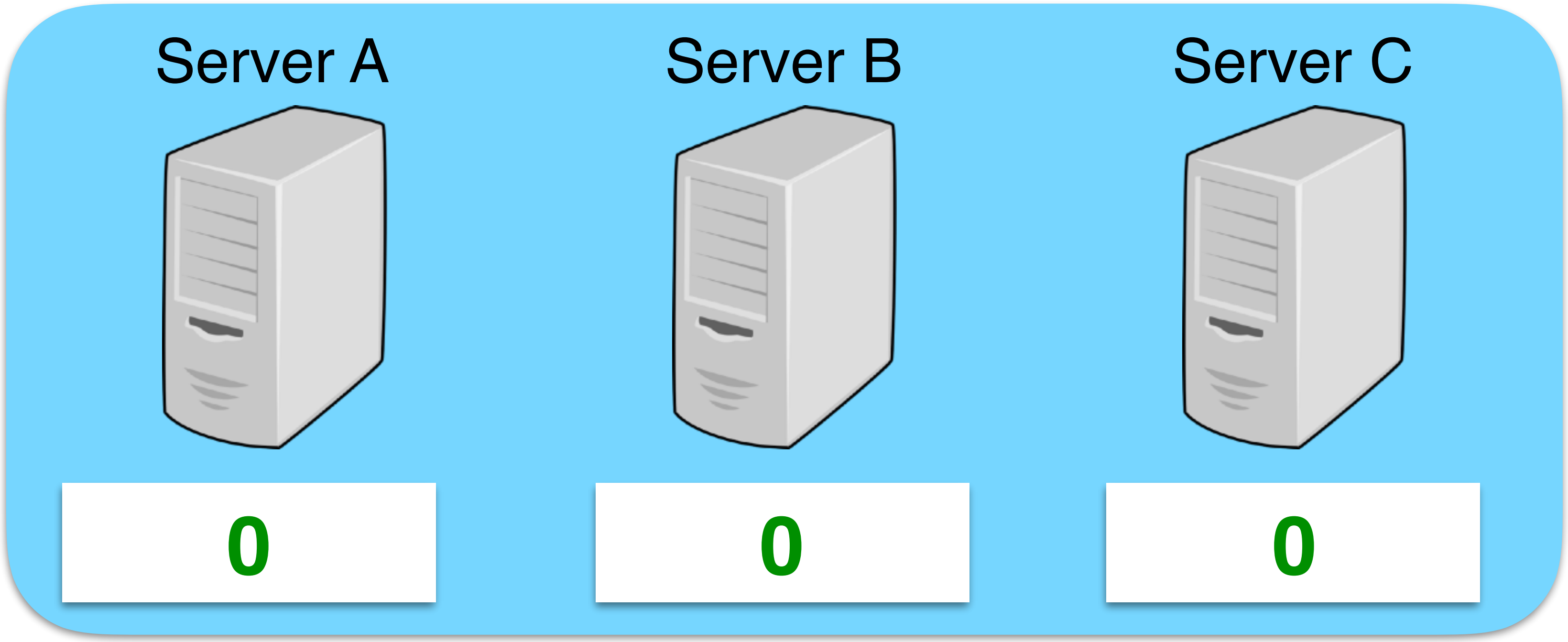

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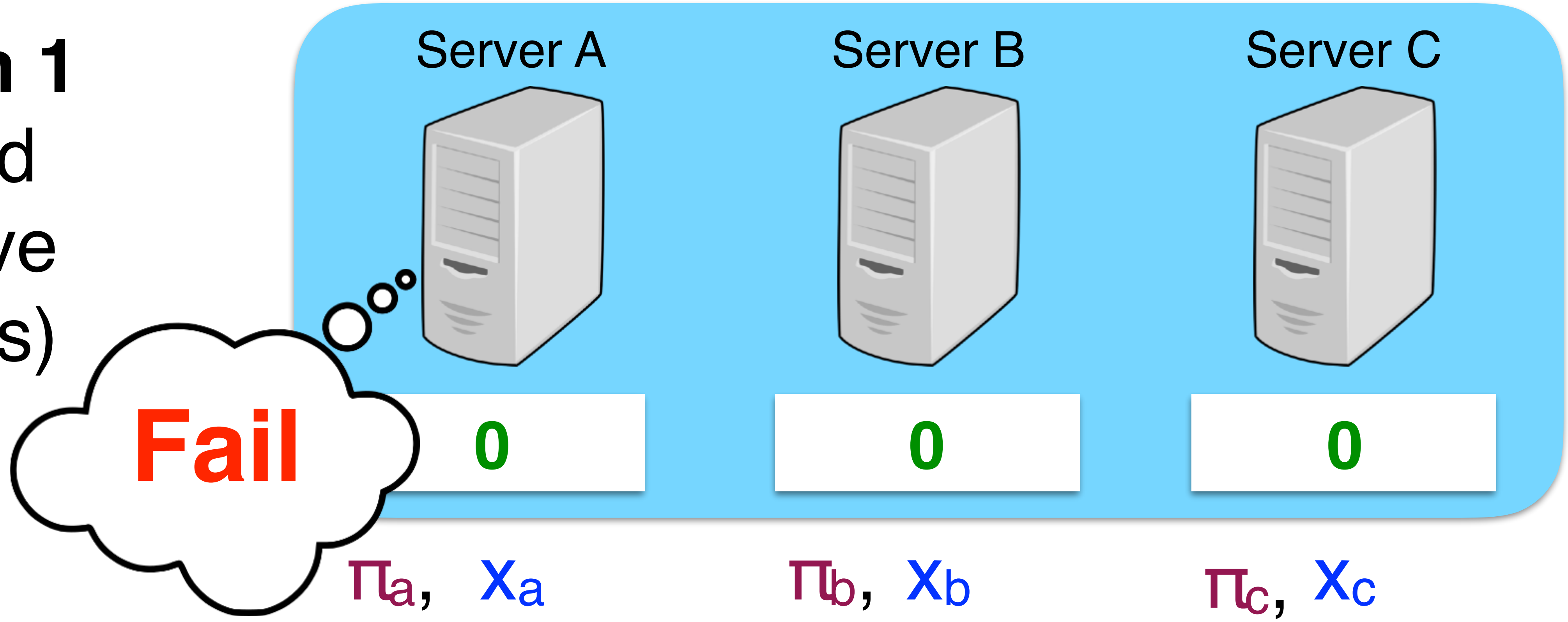

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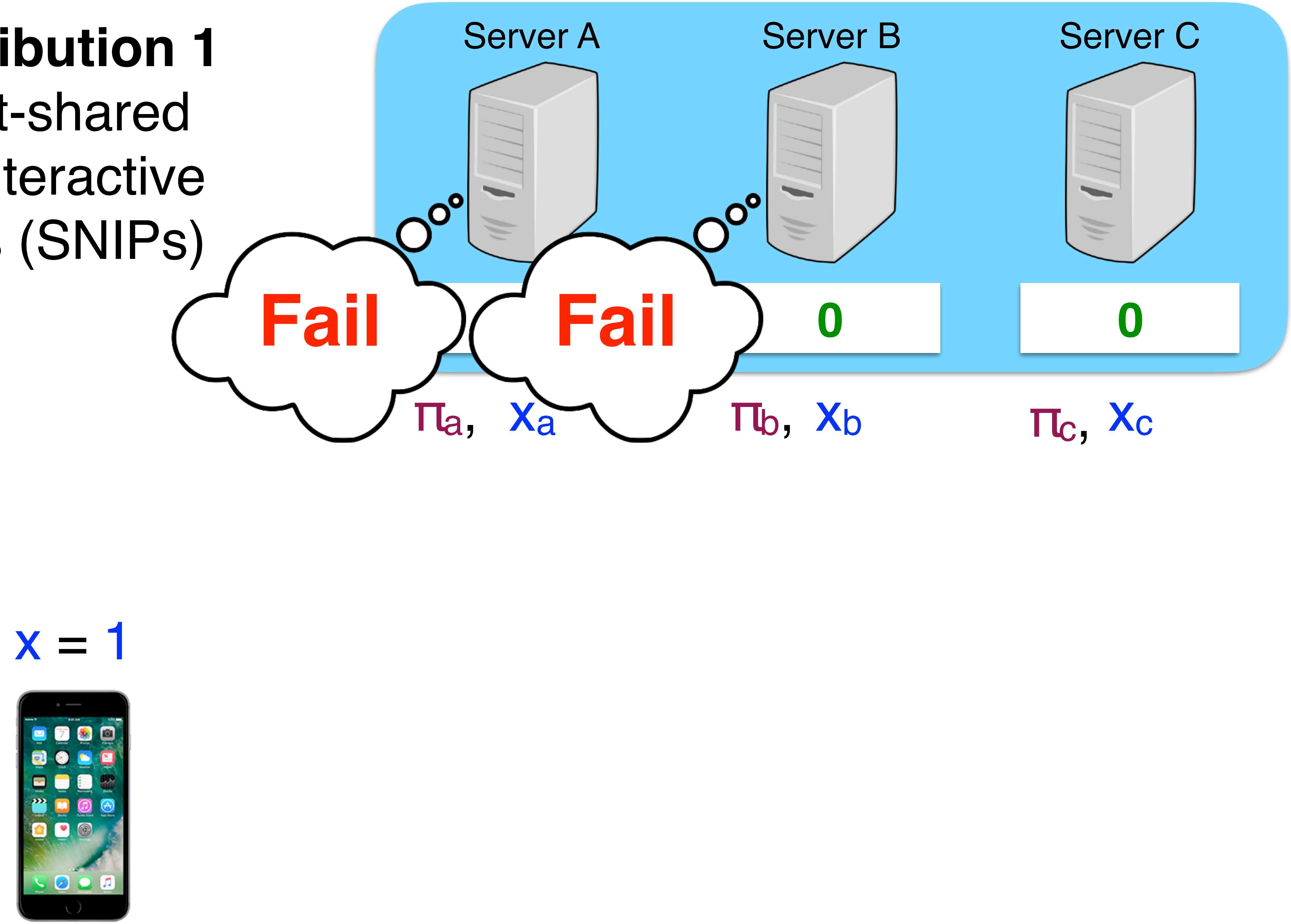

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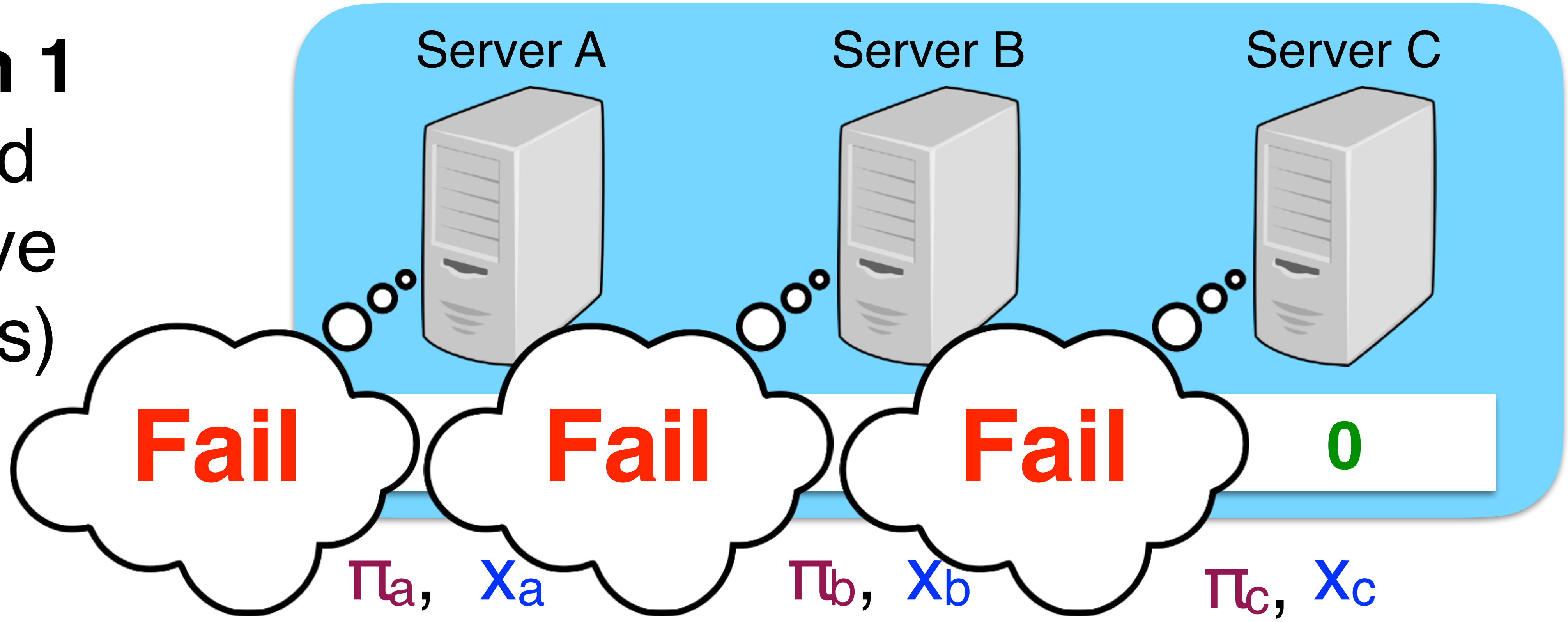

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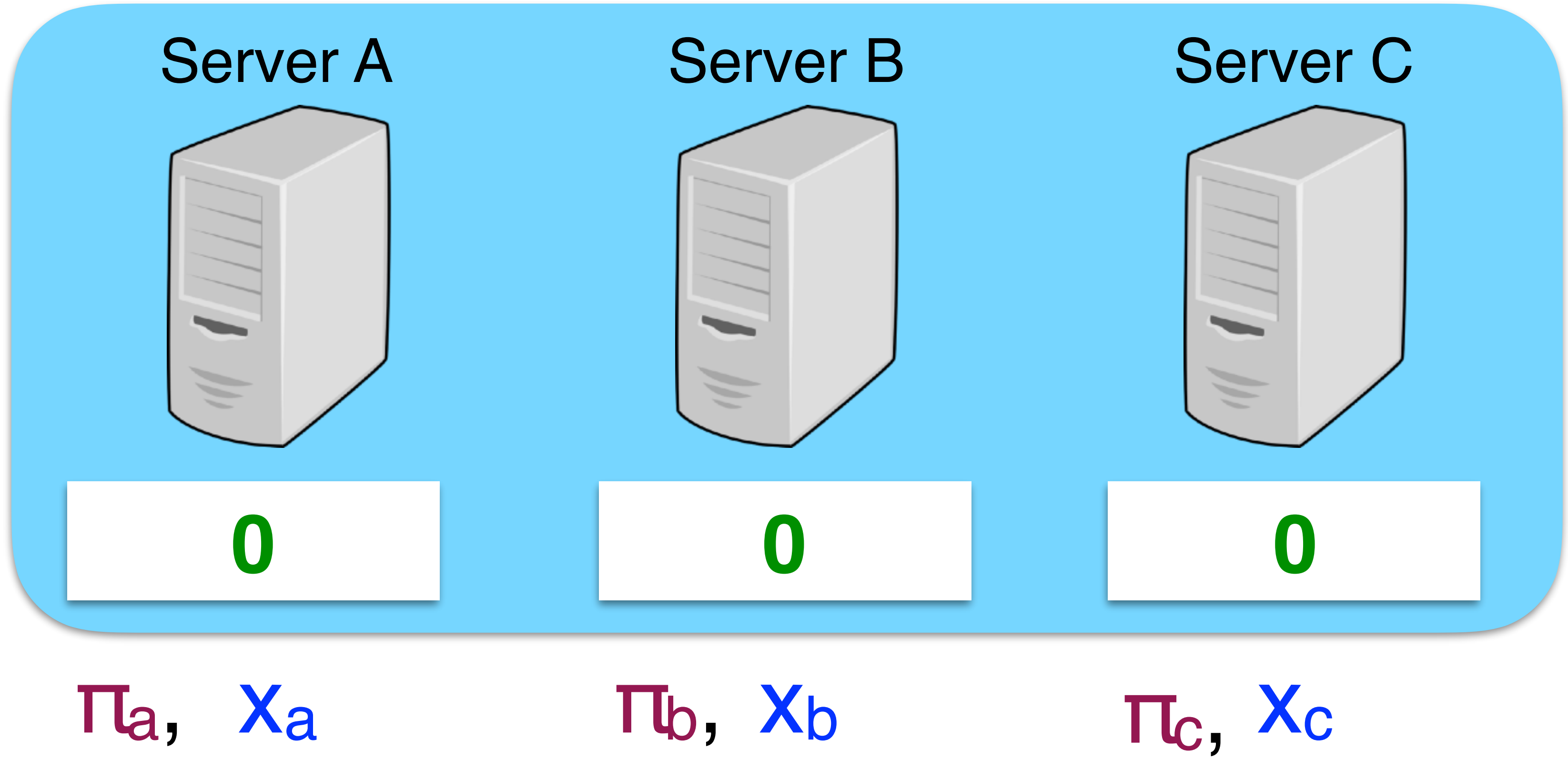

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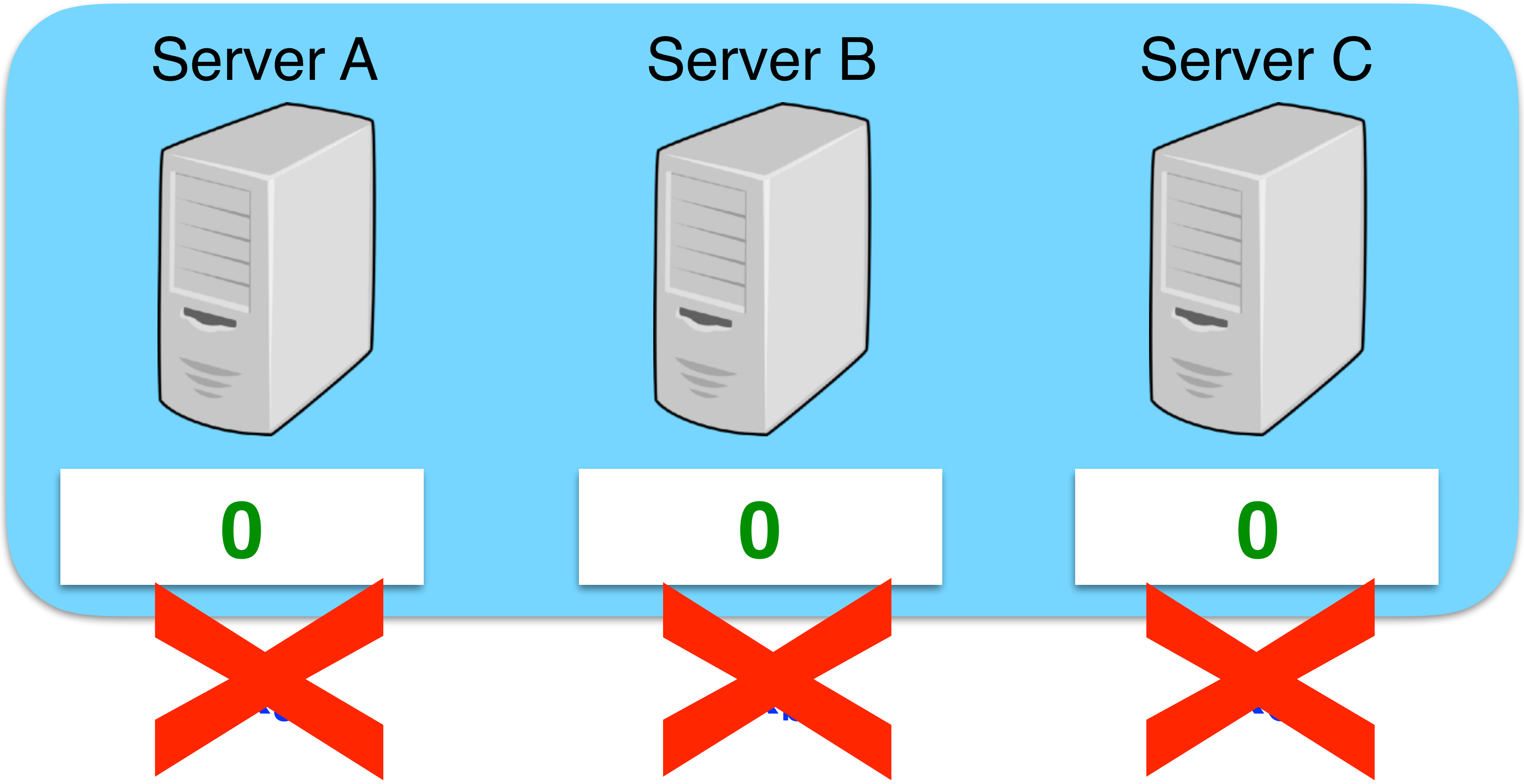
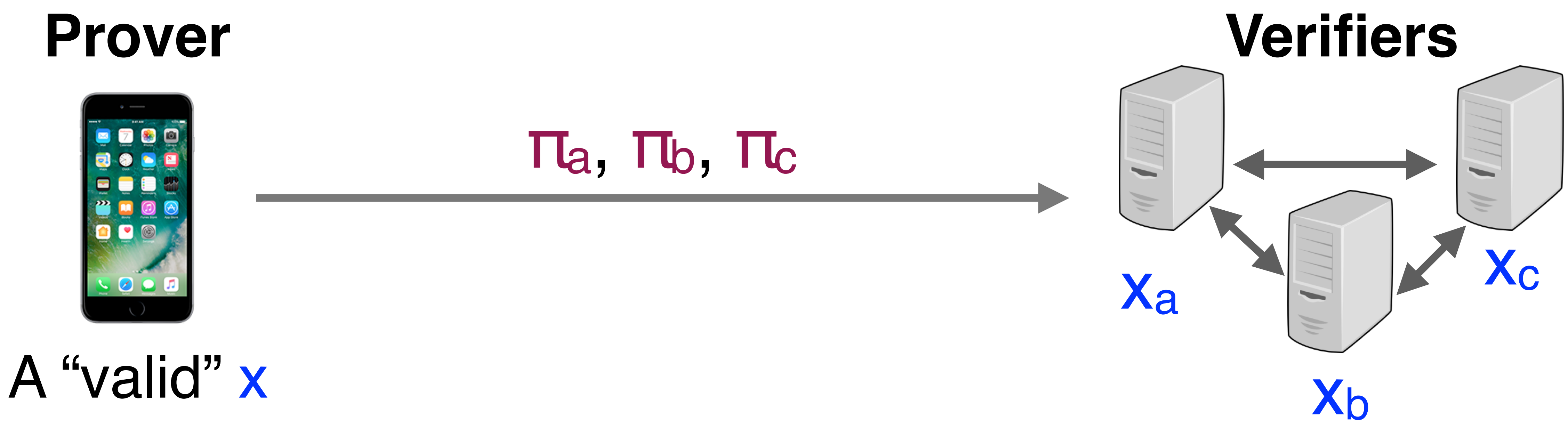


x = 1

- Prio servers *detect and reject malformed client submissions*
- In this example, each client can influence the aggregate statistic by +/- 1, at most

We need a proof system



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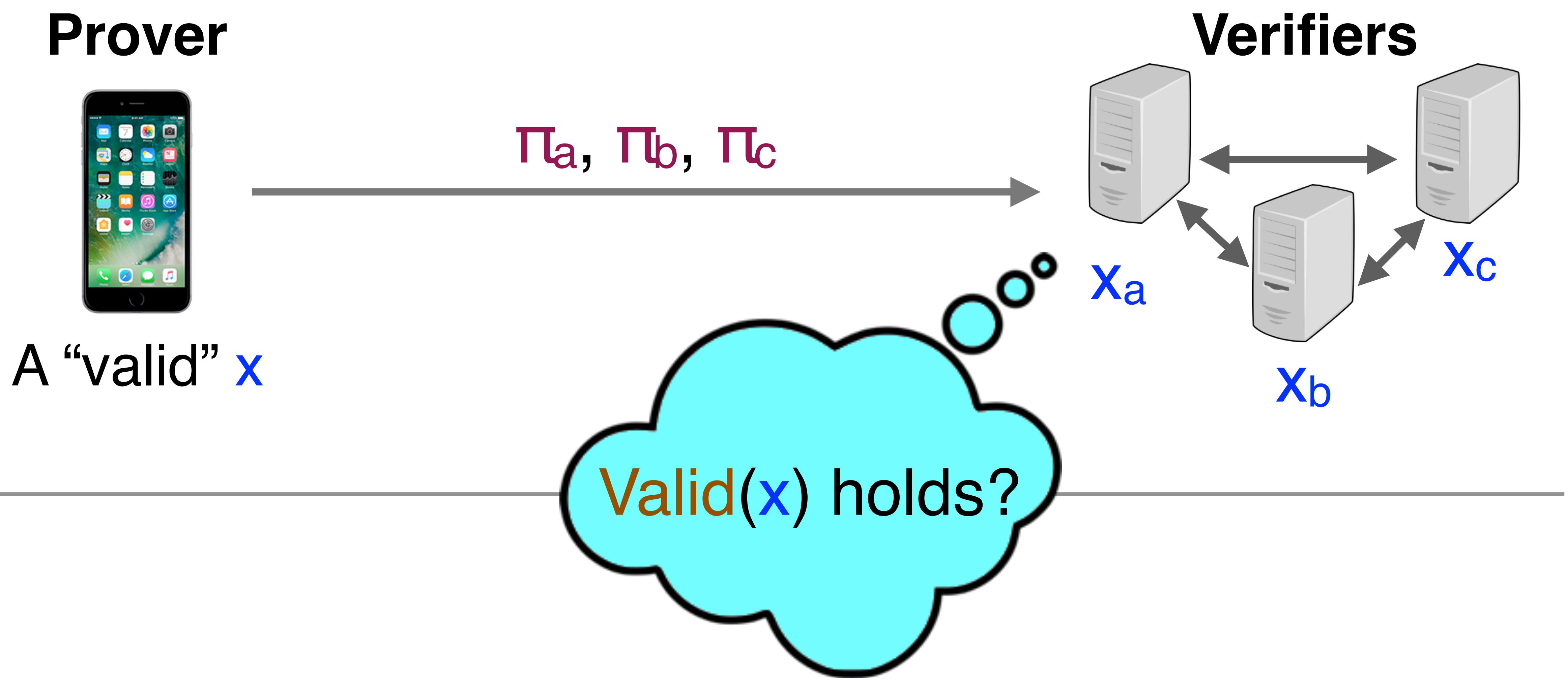

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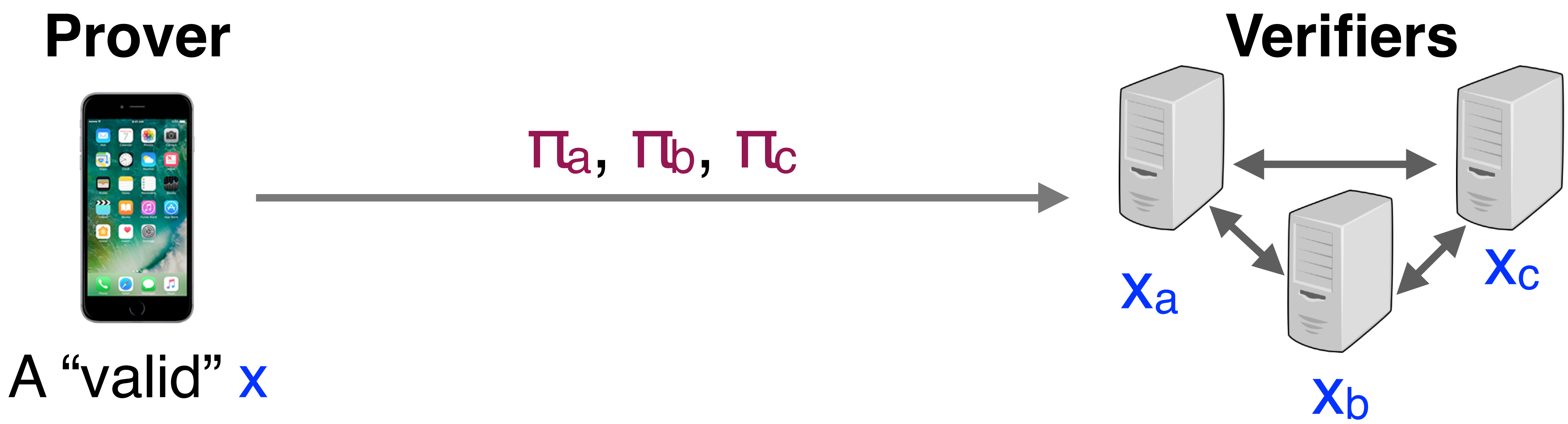

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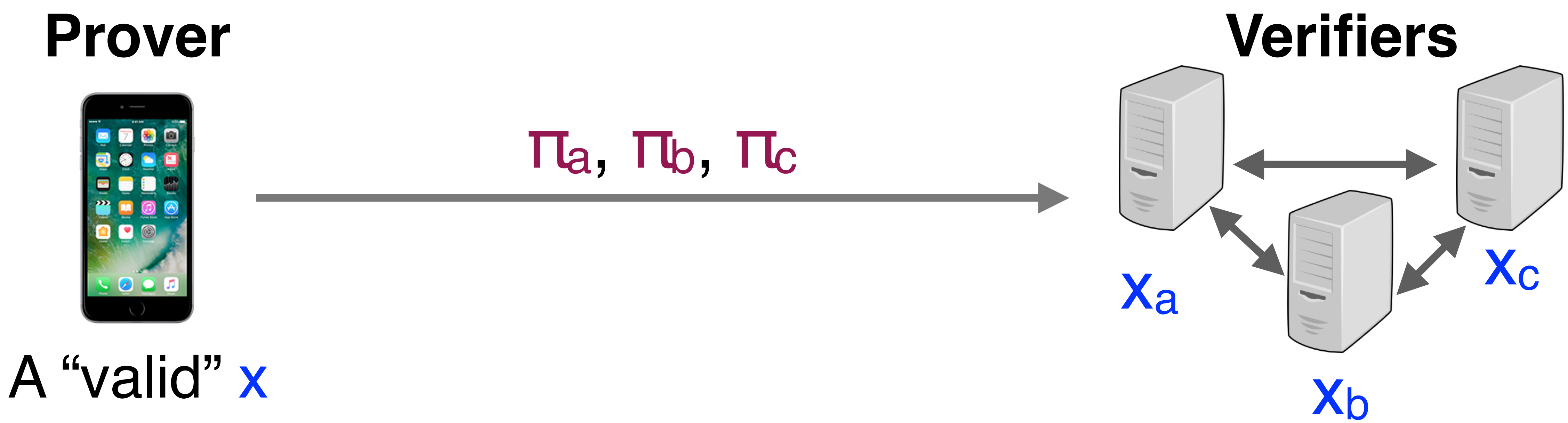

Completeness.	Honest prover convinces honest verifiers.
Soundness.	Dishonest prover rarely convinces honest verifiers.
Zero knowledge.	Any proper subset of the verifiers learns nothing about x, except that x is valid.

Traditional techniques

- Non-interactive proofs in ROM
  [FS86], [BFM88], [BDMP91], [CP92], [CS97], [M00], …
- zkSNARKs and KOE-based proofs
  [G10], [L12], [GGPR13], [BCGTV13], [PGHR13], …
- Multi-party computation
  [Y82], [GMW87], [BGW88], [CCD88], [CLOS02], [DPSZ12], [DKLPSS13], …

In our setting, SNIPs are a more efficient solution.

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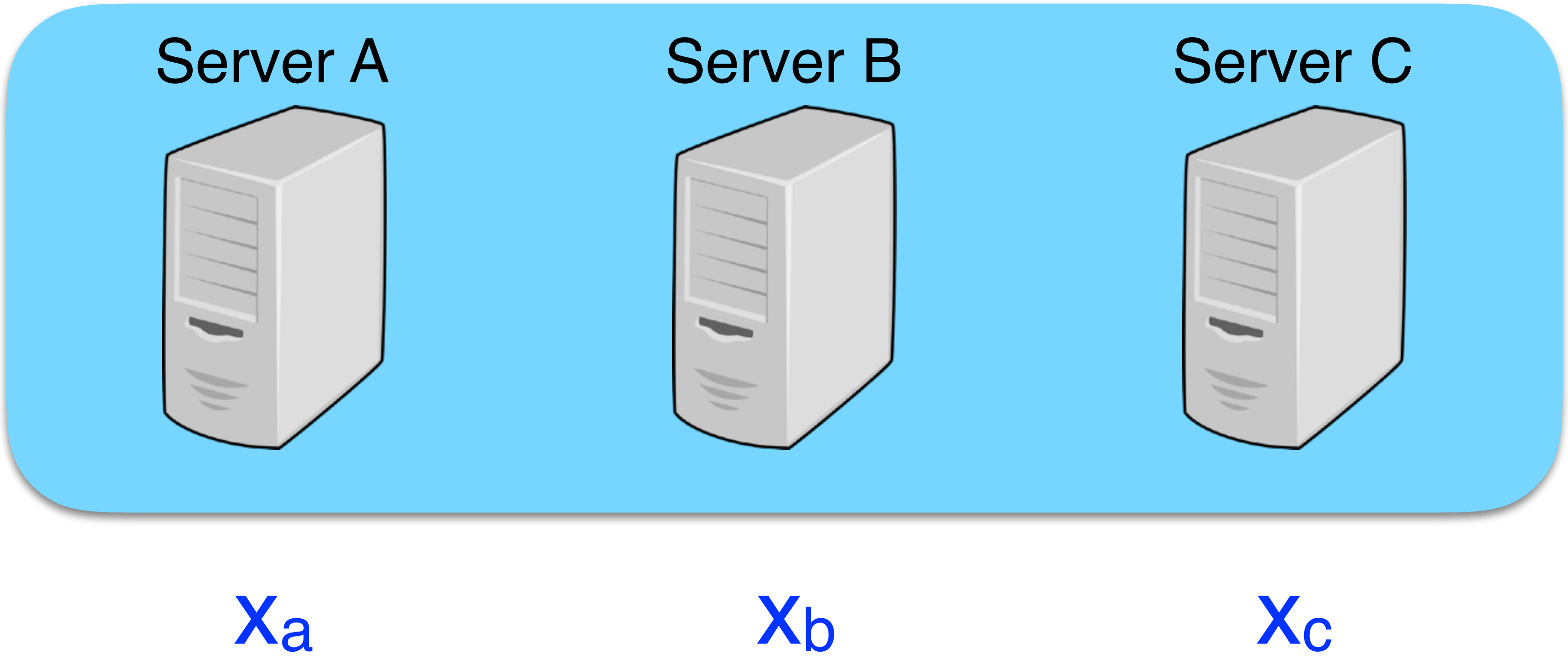

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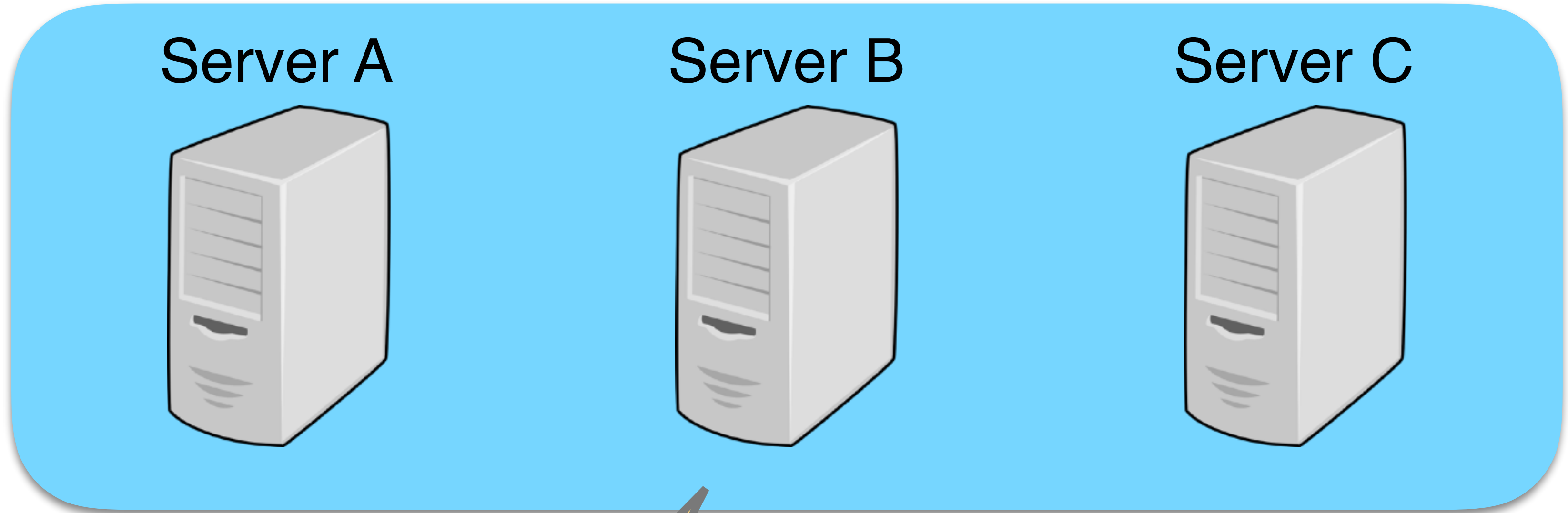

x_a x_b x_c

Could run **secure multiparty computation** to check that Valid(x) = 1.

[GMW87], [BGW88]

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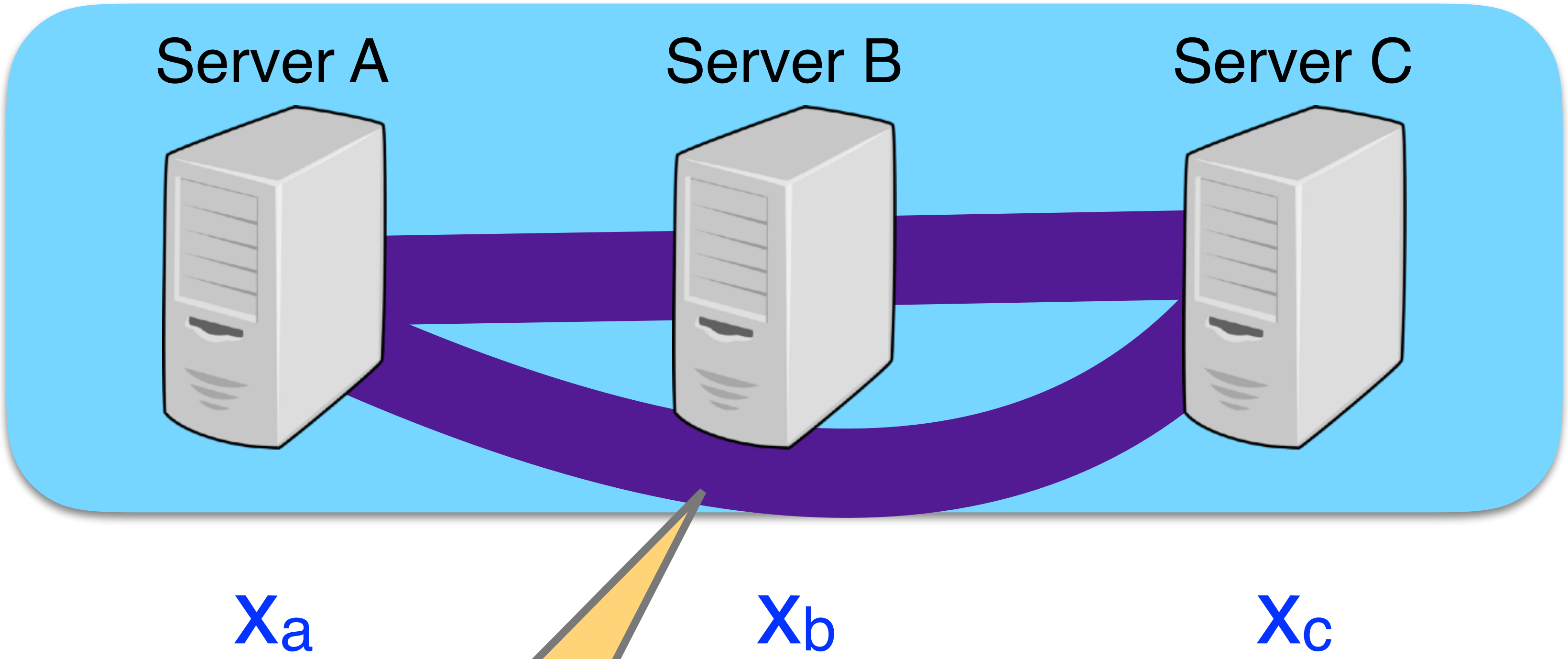

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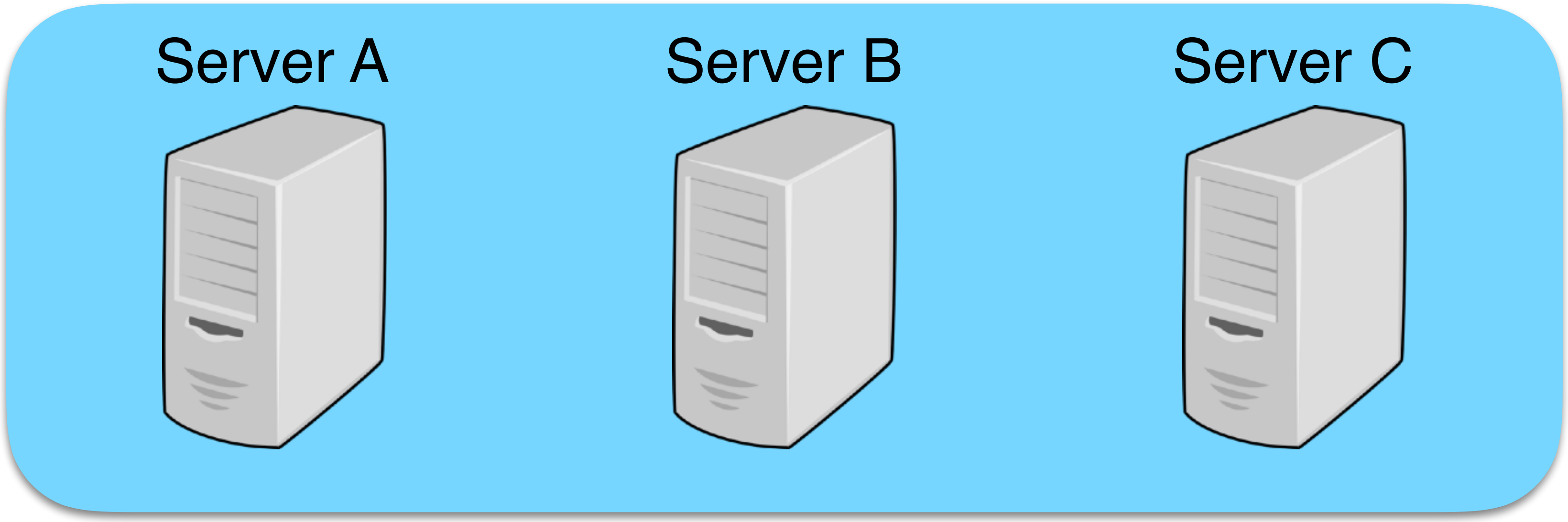

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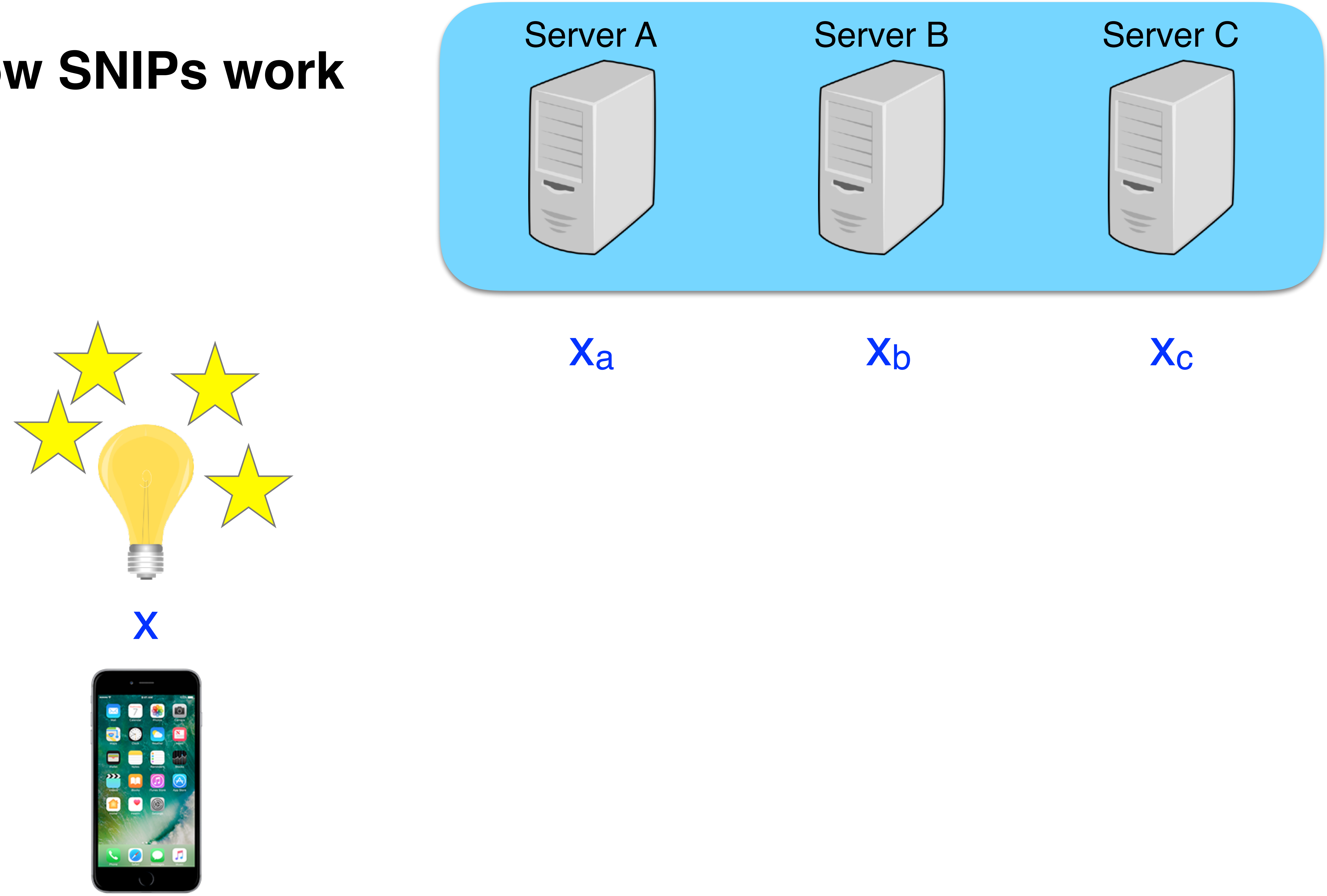

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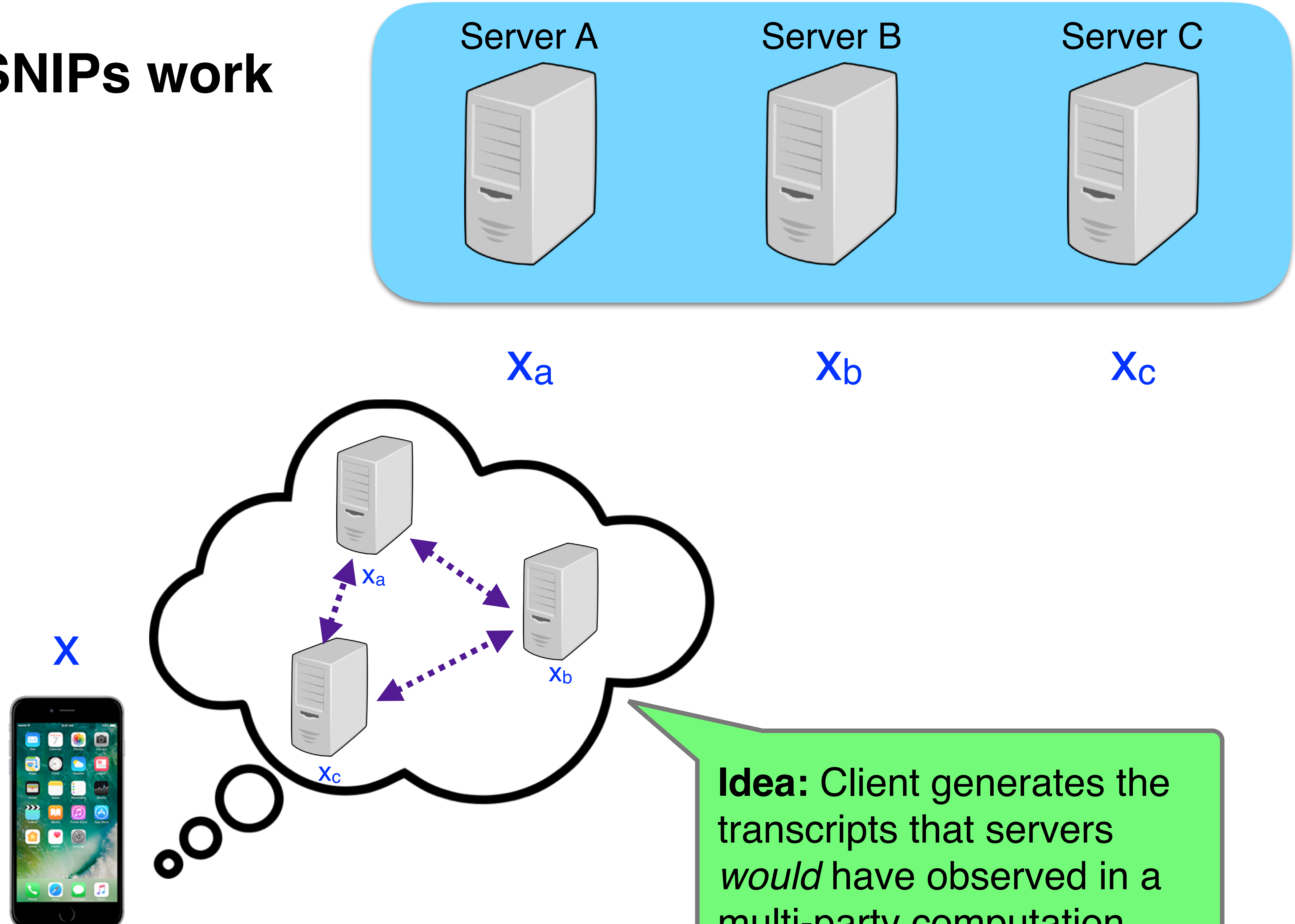

Idea: Client generates the transcripts that servers *would* have observed in a multi-party computation

See also [IKOS07]

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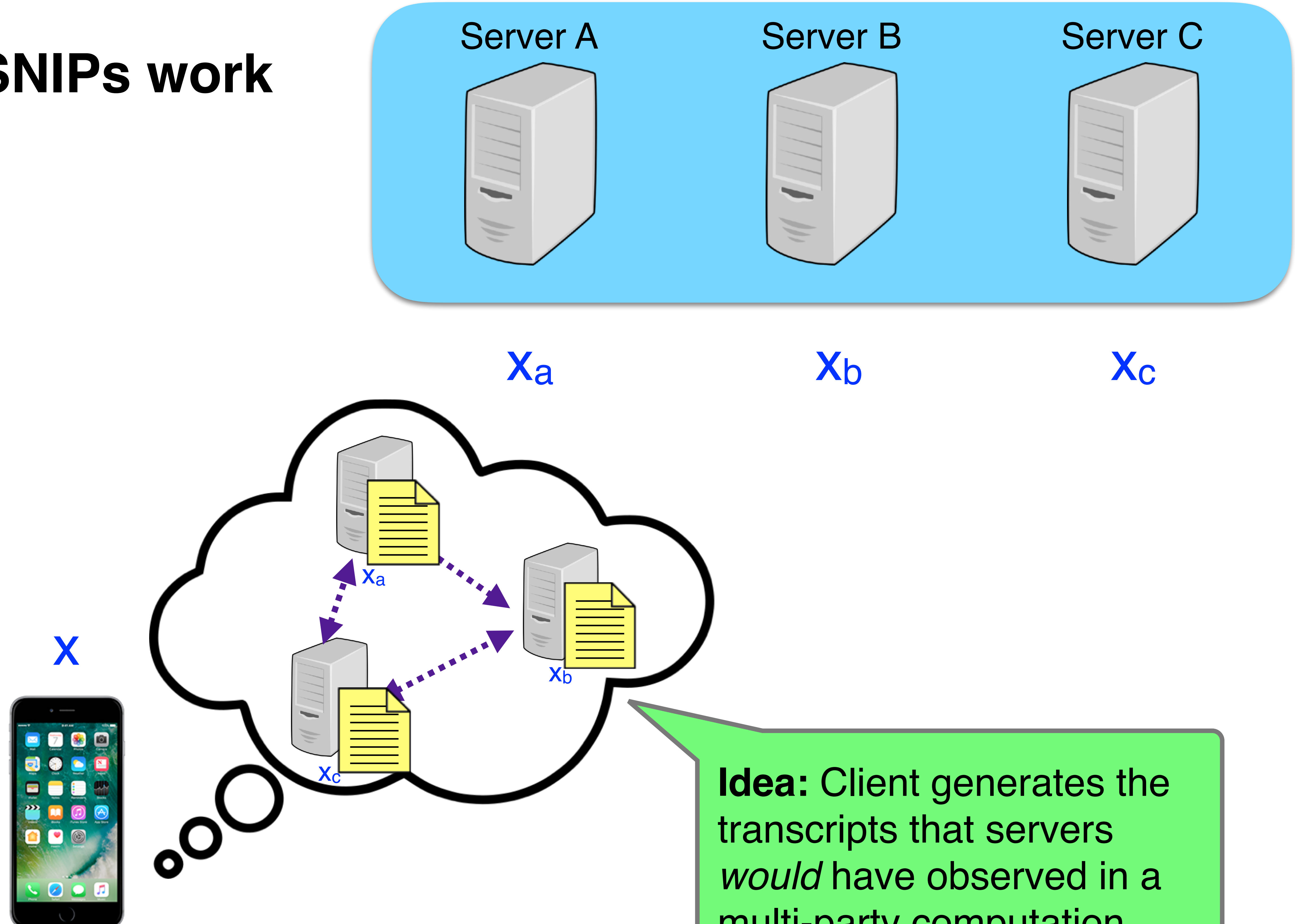

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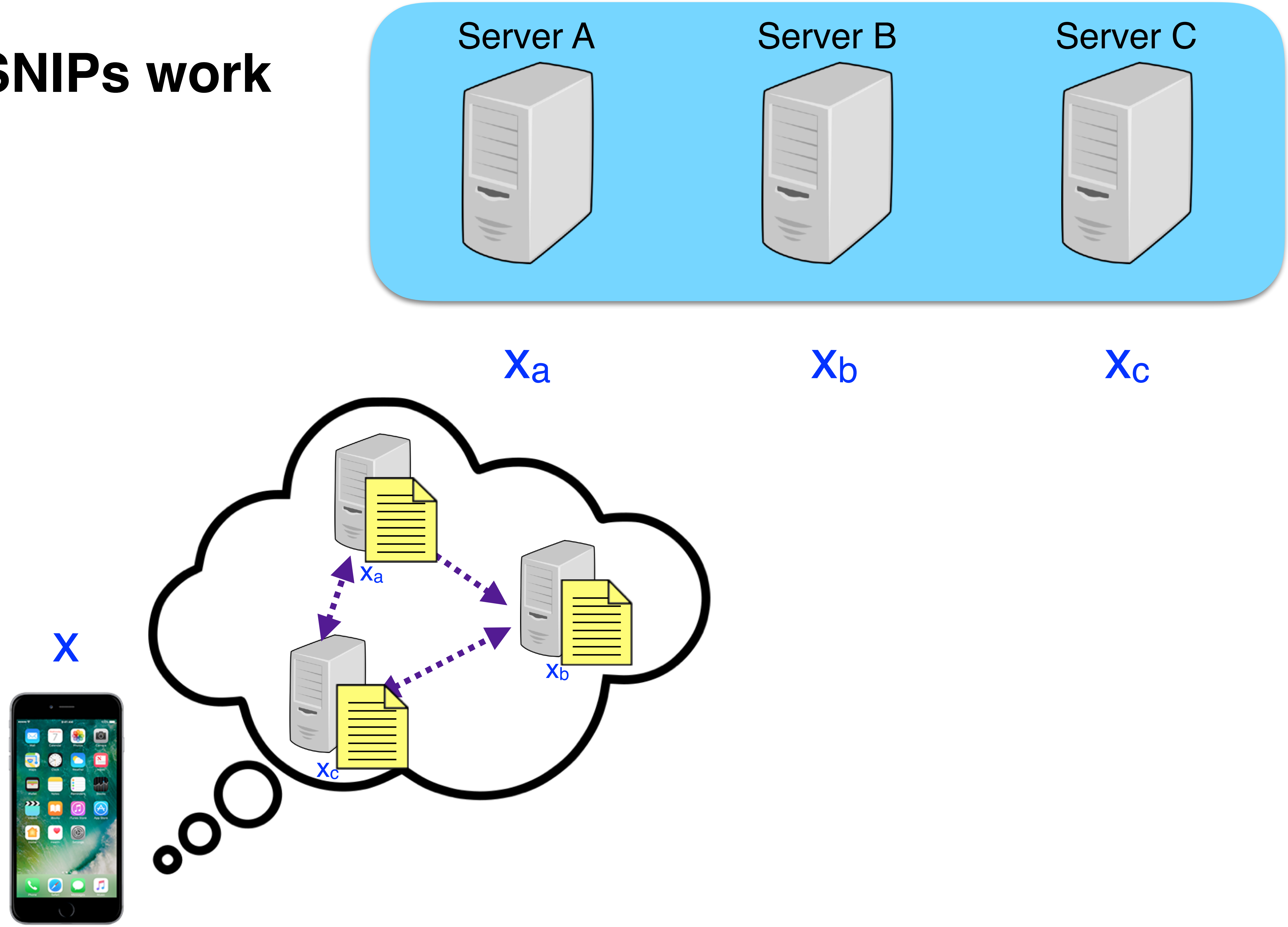

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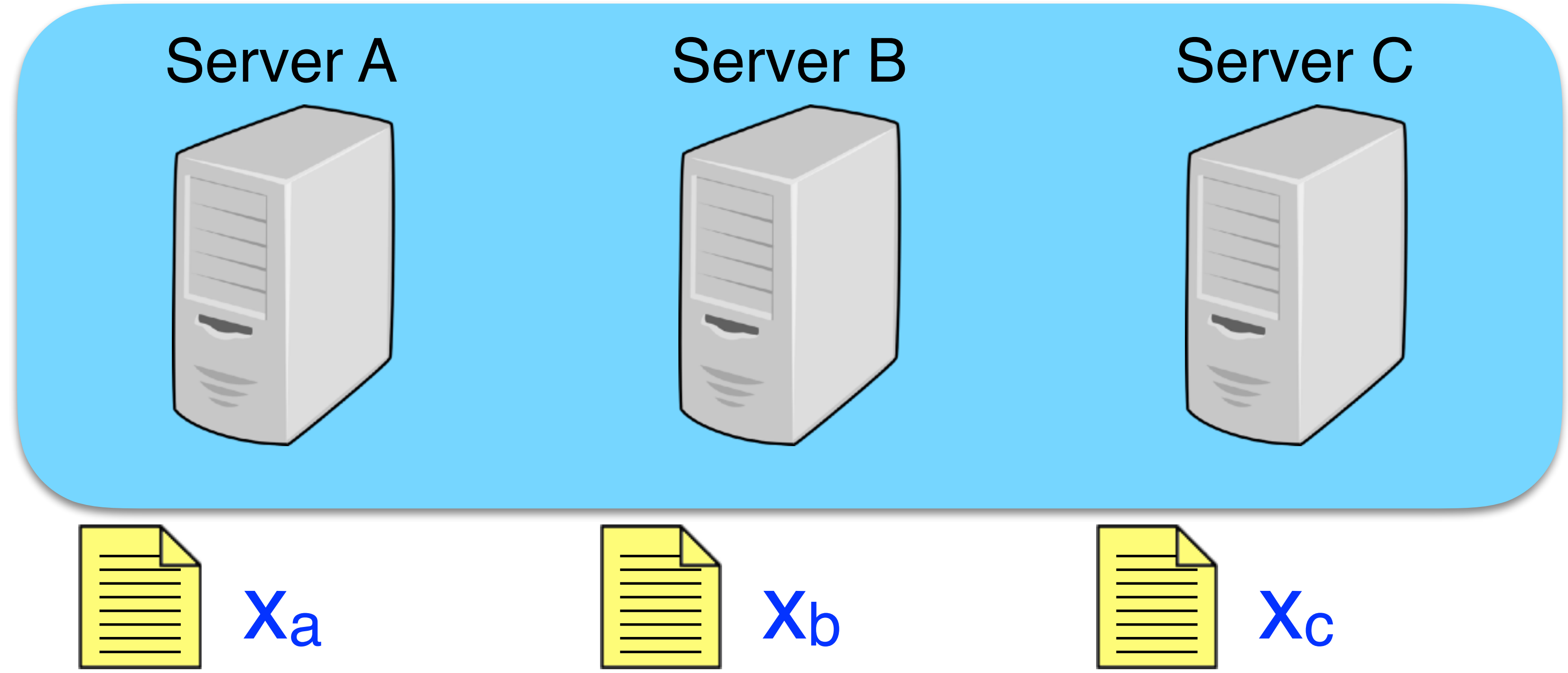

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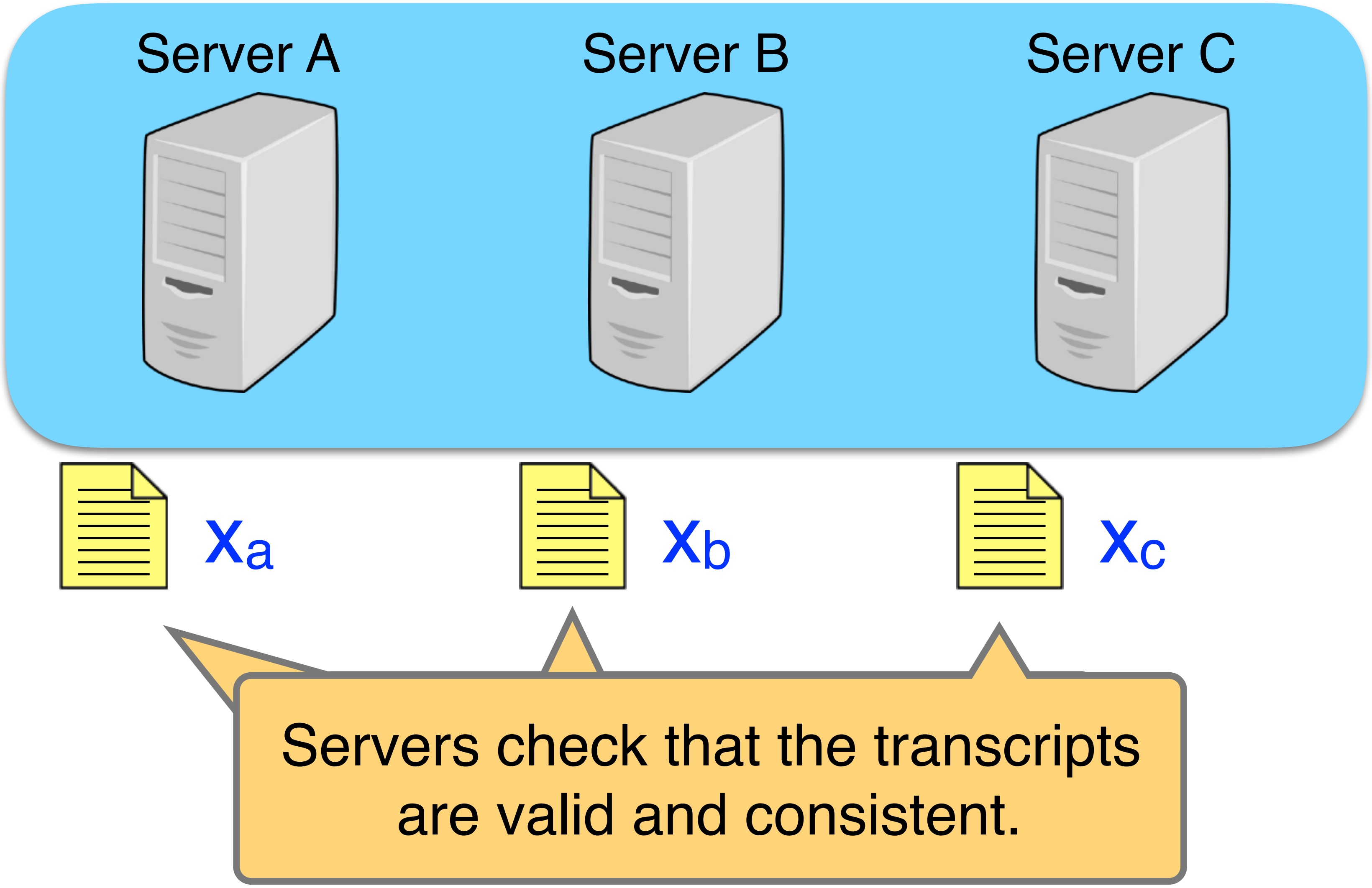

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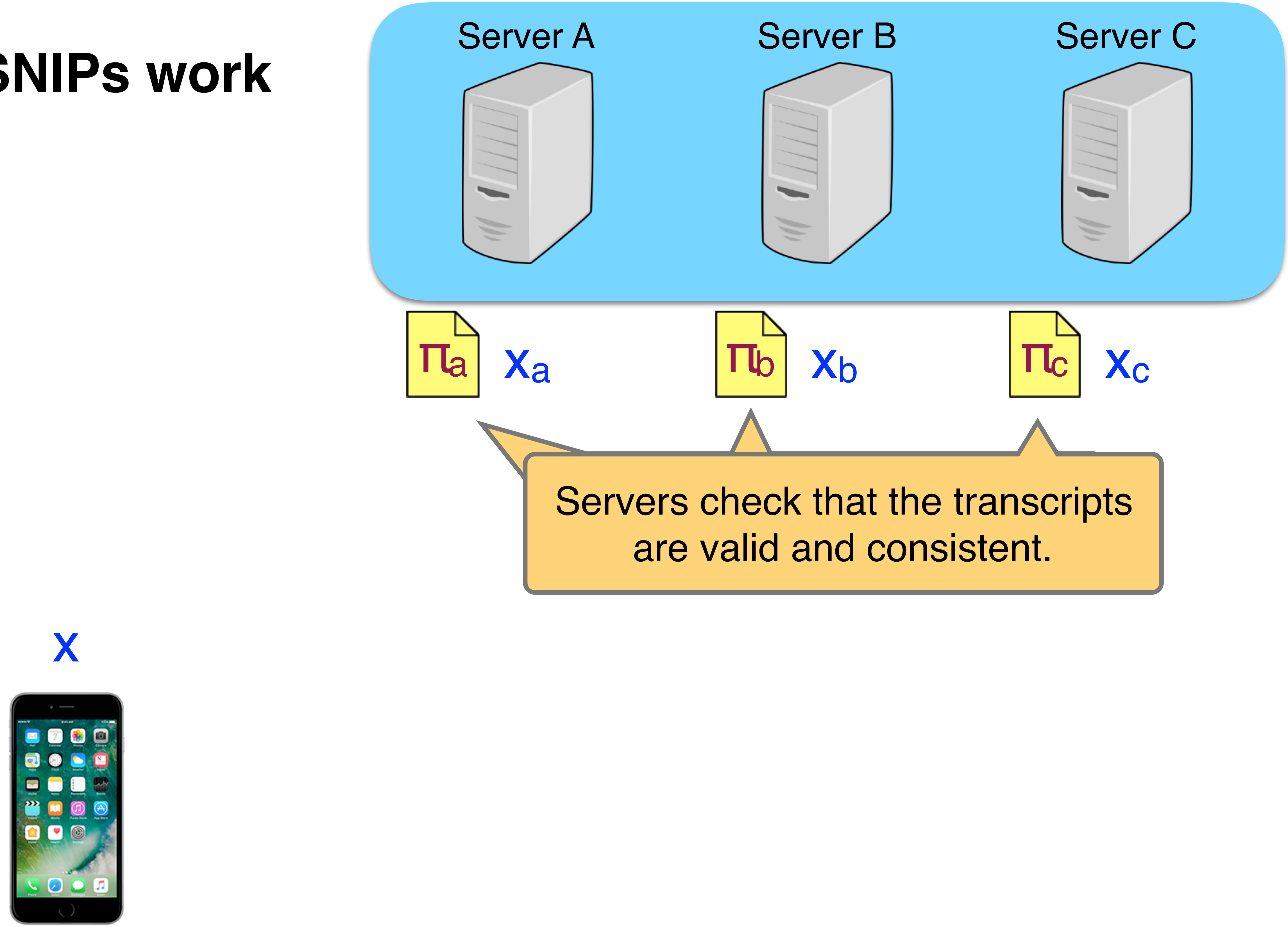

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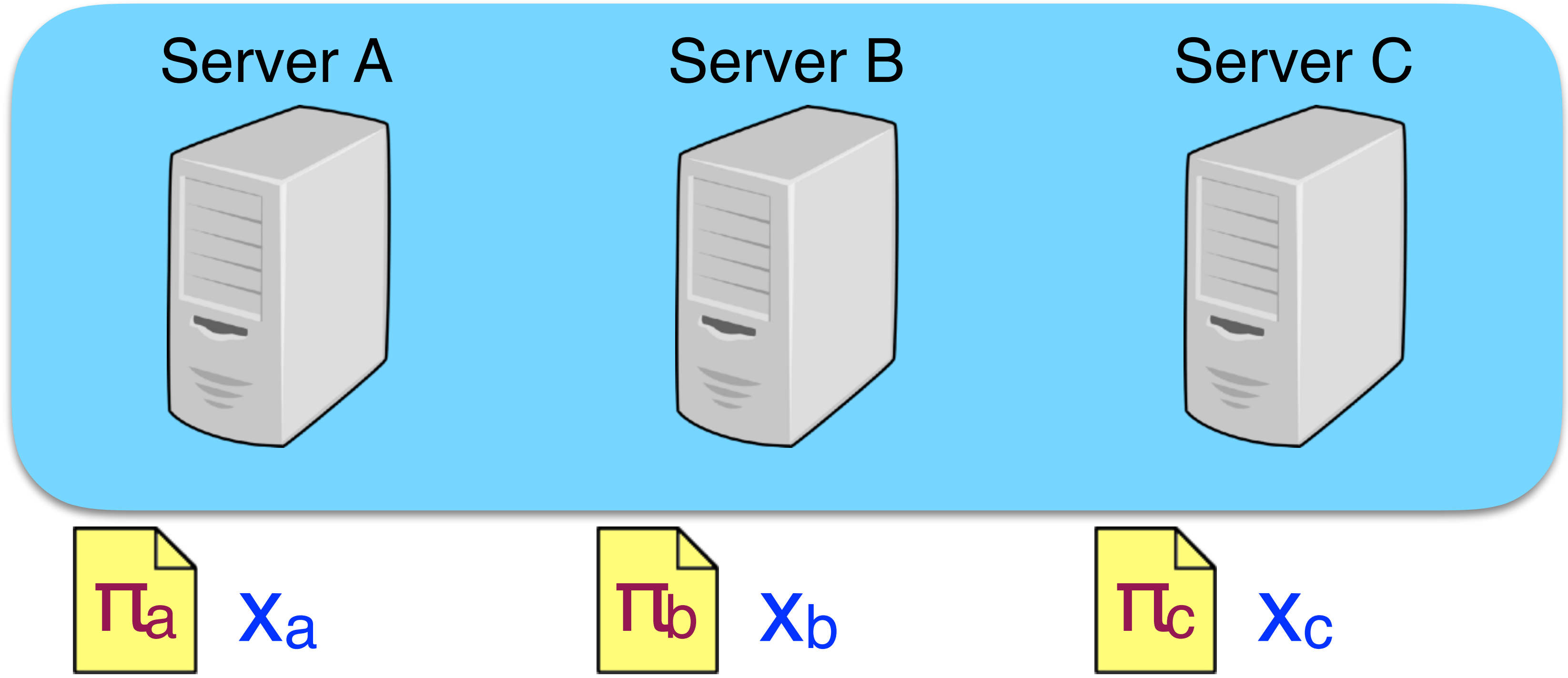
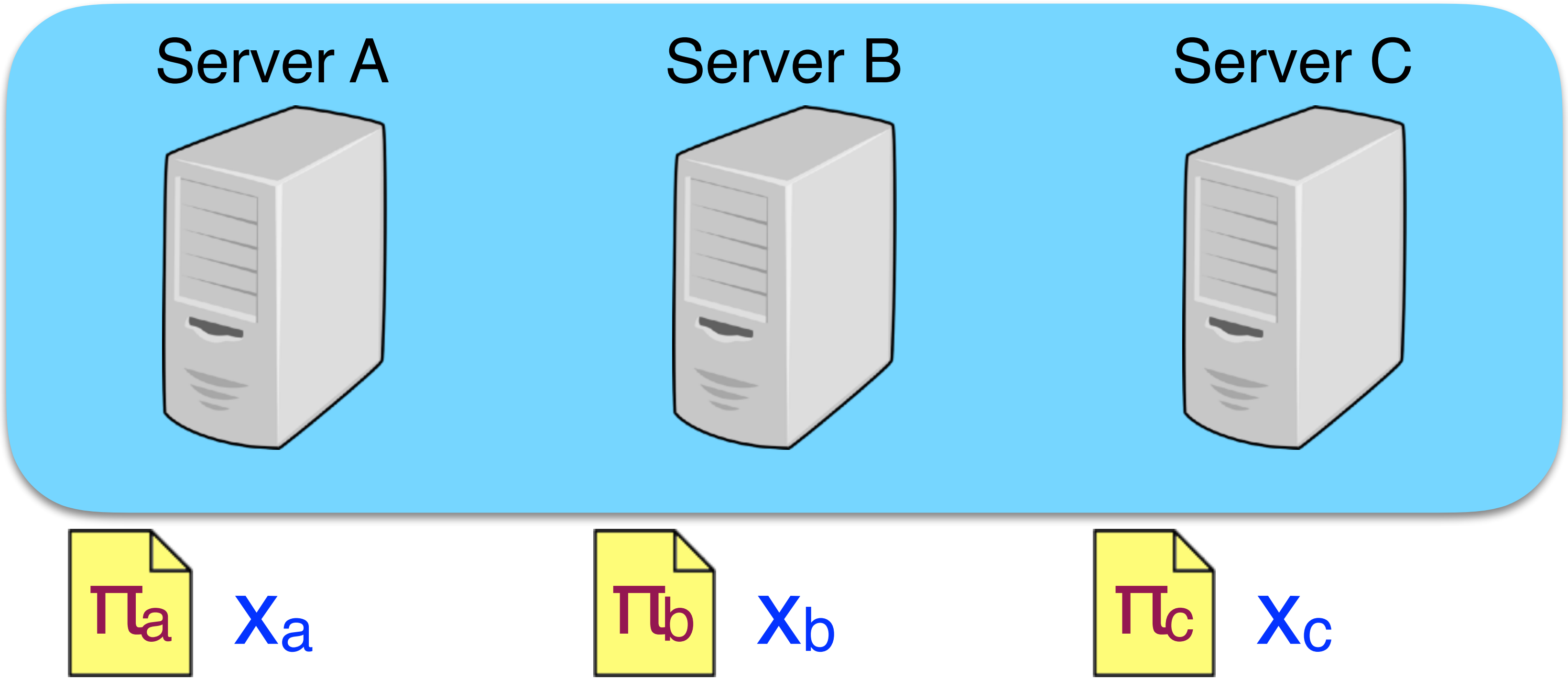


Servers check that the transcripts are valid and consistent.

Checking a transcript is **much easier** than generating it!

x

How SNIPs work



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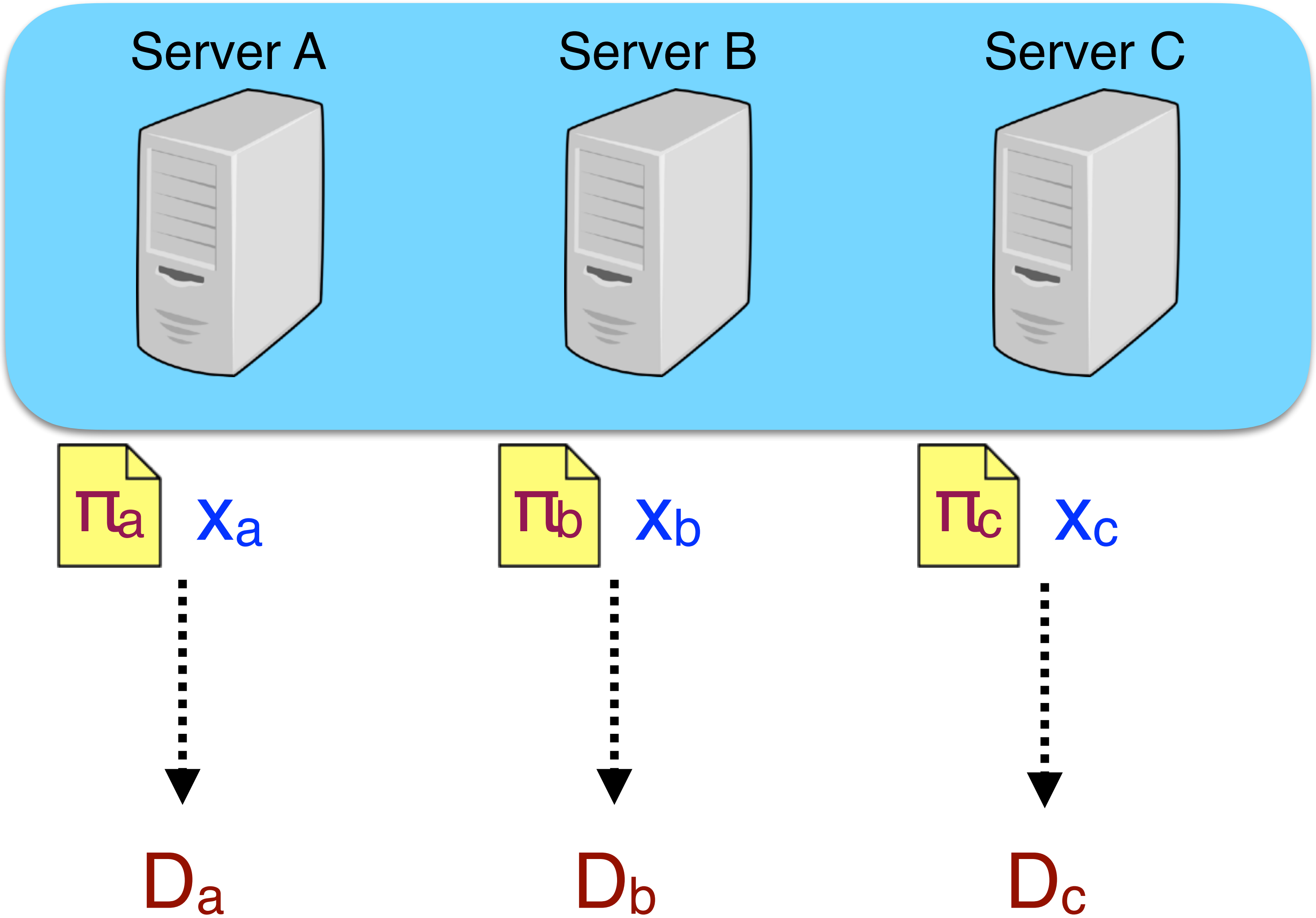

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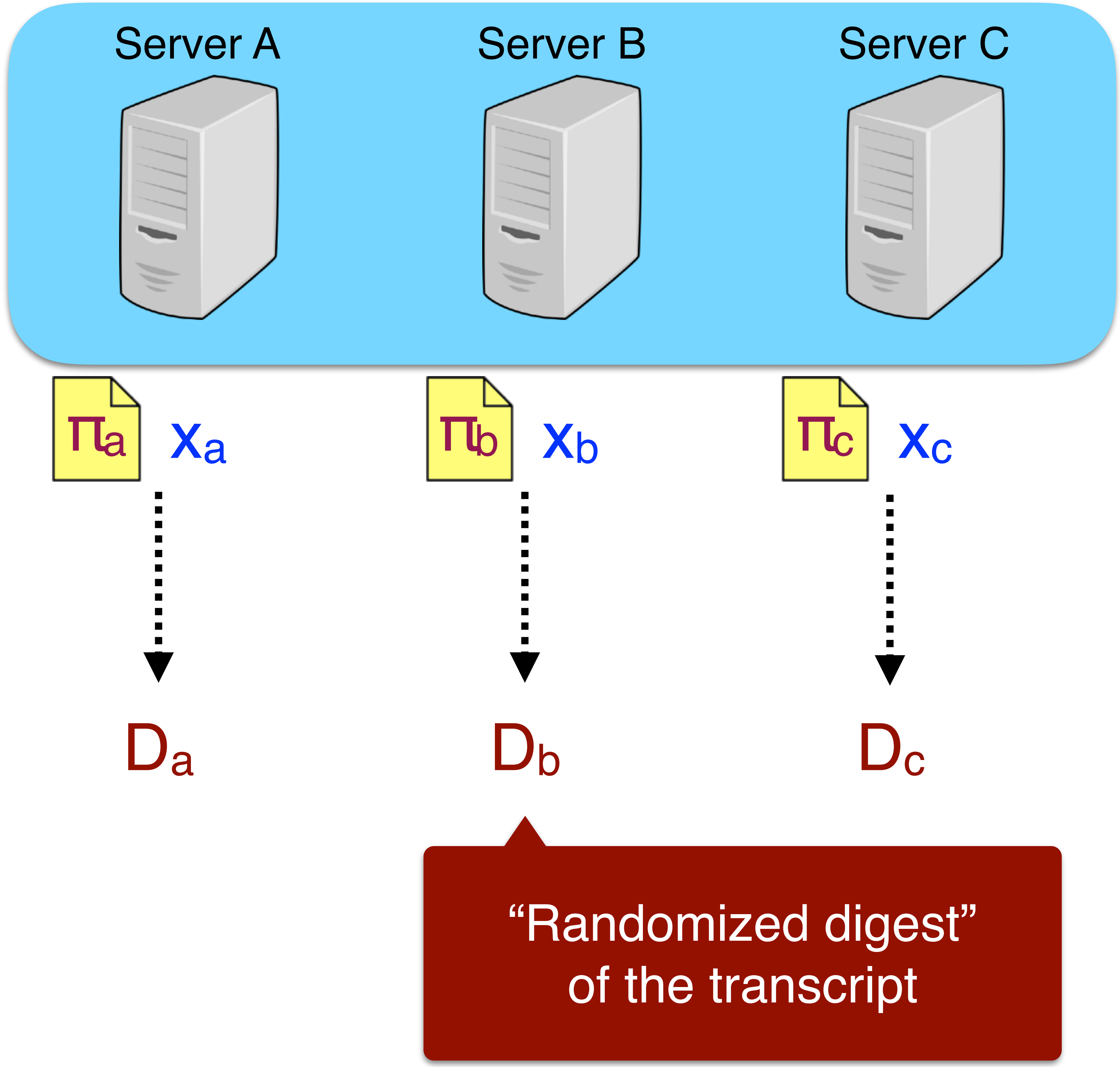

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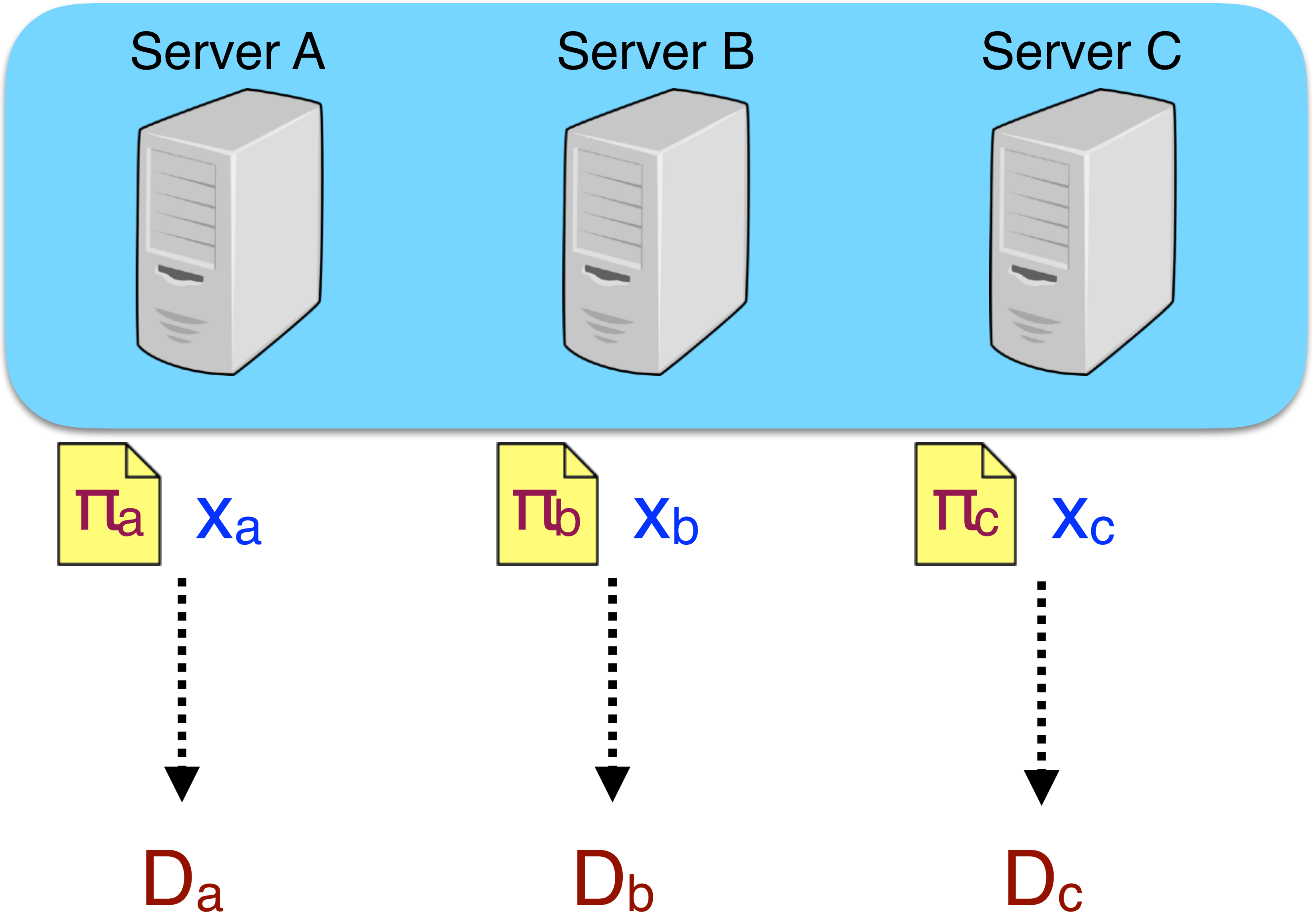

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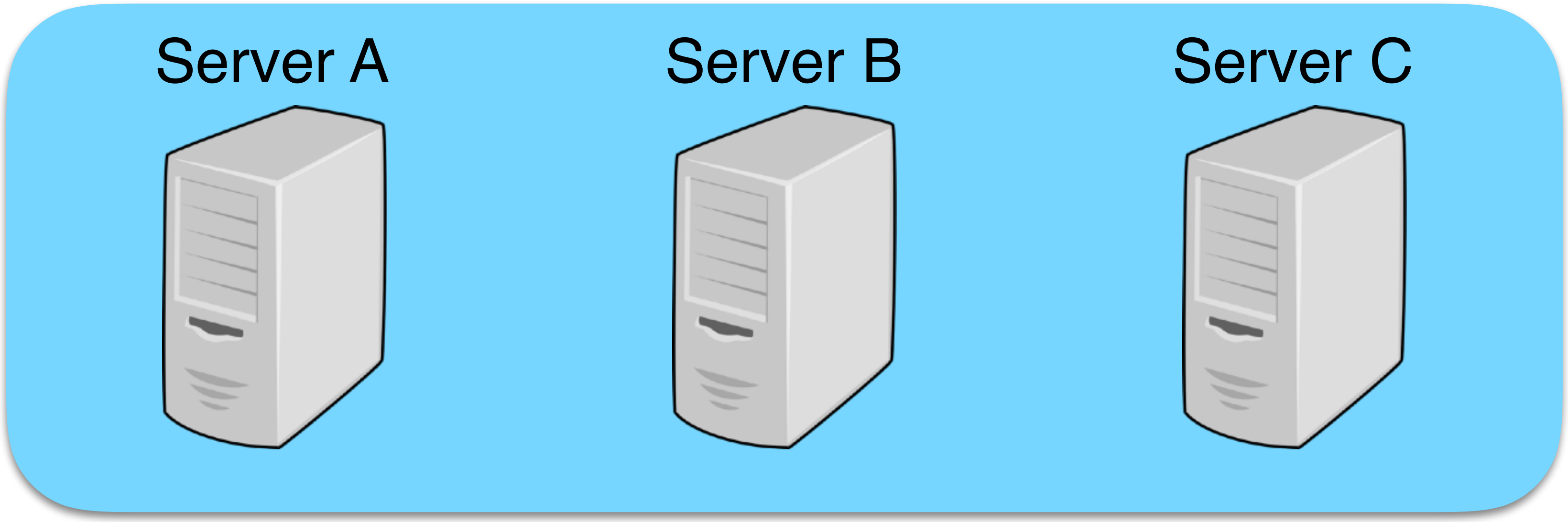

D_a D_b D_c

[BFO12]

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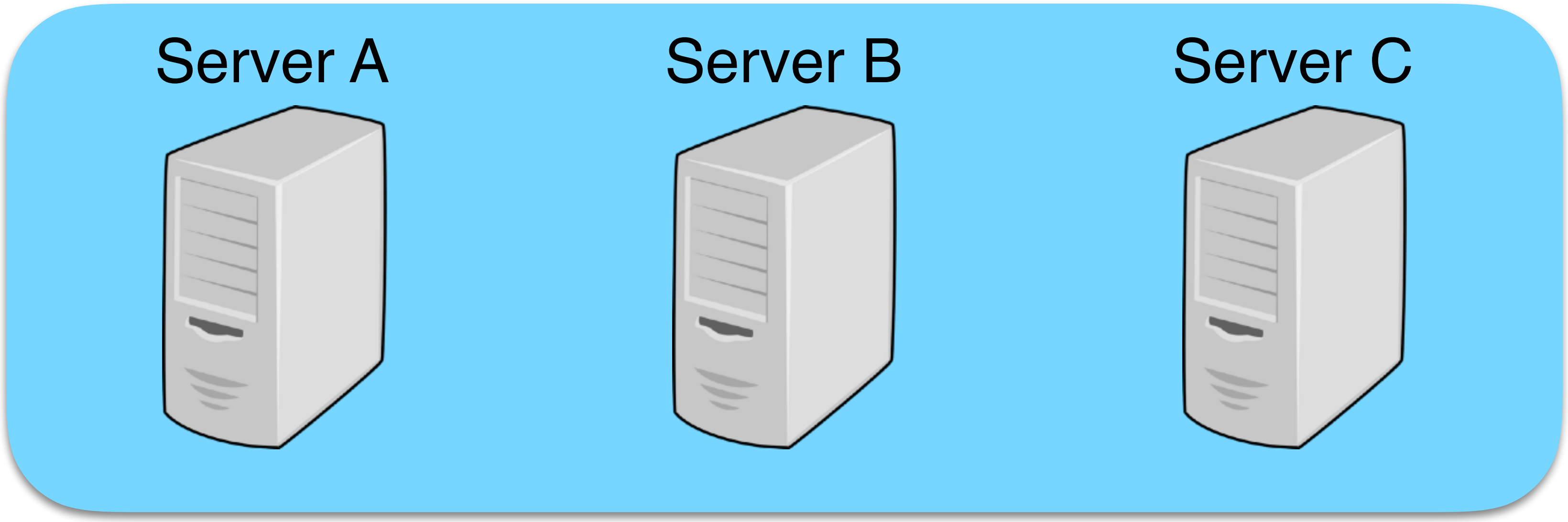

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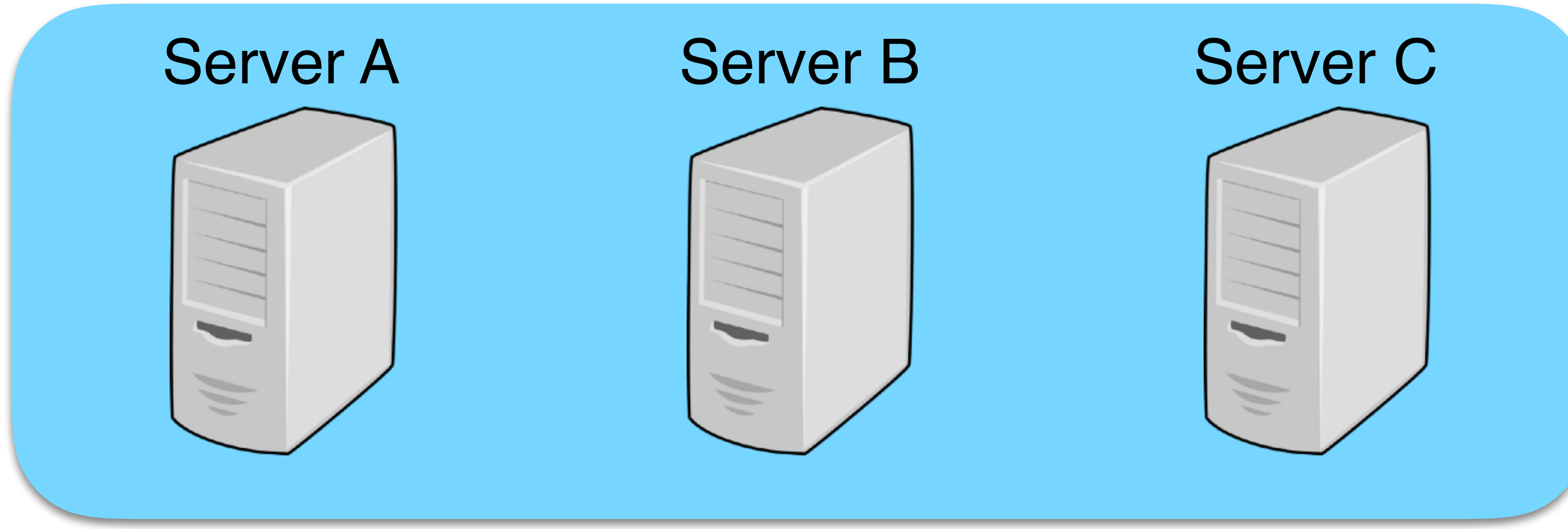

D_a D_b D_c

- If x is valid, $D_a + D_b + D_c = 0$
- If x is invalid, $D_a + D_b + D_c \neq 0$ with high probability

Servers run lightweight multi-party computation to check that

$$D_a + D_b + D_c = 0$$

If so, servers accept x is valid.

[BFO12]

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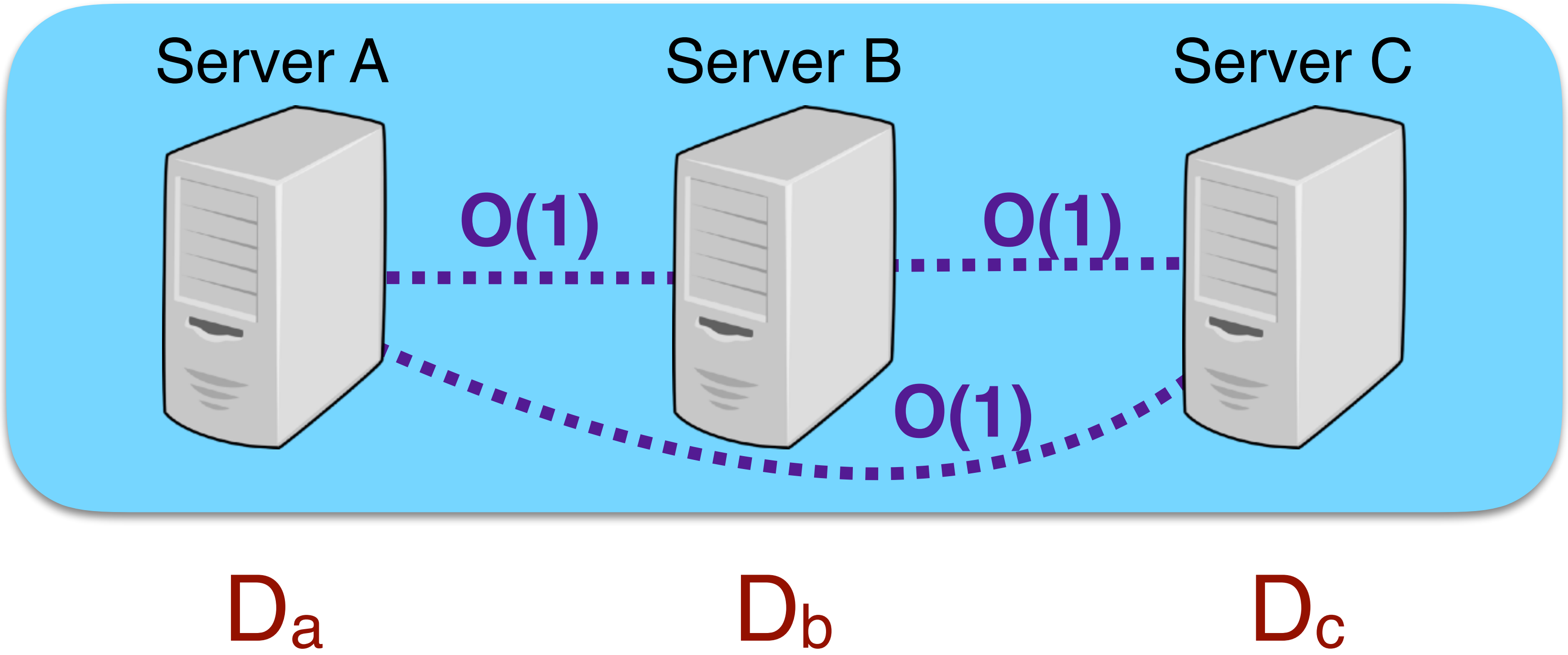

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[BFO12]

M = # of multiplication gates in Valid(·) circuit	**Public-key ops.**		**Communication**		**Slow-down**
	Client	Server	C-to-S	S-to-S	

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Dishonest-maj. MPC [CLOS02], [DPSZ12], …	0	Θ(M)	0	Θ(M)	5,000x at server

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Commits + NIZKs [FS86], [CP92], [CS97], …	Θ(M)	Θ(M)	Θ(M)	Θ(M)	50x at server

M = # of multiplication gates in Valid(·) circuit	**Public-key ops.** Client	**Public-key ops.** Server	**Communication** C-to-S	**Communication** S-to-S	**Slow-down**
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Commits + NIZKs [FS86], [CP92], [CS97], …	Θ(M)	Θ(M)	Θ(M)	Θ(M)	50x at server
Commits + SNARKs [GGPR13], [BCGTV13], …	Θ(M)	O(1)	O(1)	O(1)	500x at client

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Commits + NIZKs [FS86], [CP92], [CS97], …	Θ(M)	Θ(M)	Θ(M)	Θ(M)	50x at server
Commits + SNARKs [GGPR13], [BCGTV13], …	Θ(M)	O(1)	O(1)	O(1)	500x at client
This work: SNIPs	0	0	Θ(M)	O(1)	1x

M = # of multiplication gates in Valid(·) circuit	**Public-key ops.** Client	Server	**Communication** C-to-S	S-to-S	**Slow-down**
Dishonest-maj. MPC [CLOS02], [DPSZ12], …	0	Θ(M)	0	Θ(M)	5,000x at server
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For specific Valid() circuits, it is possible to eliminate this cost [BGI16]

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Dishonest-maj. MPC [CLOS02], [DPSZ12], …	0	$\Theta(M)$	0	$\Theta(M)$	5,000x at server
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From sums to more complex aggregates

If you can compute private sums, you can compute many other interesting aggregates

[PrivStats11], [KDK11], [DFKZ13], [PrivEx14], [MDD16], …

- Average
- Variance
- Standard deviation
- Most popular (approx)
- “Heavy hitters” (approx)
- Min and max (approx)
- Quality of arbitrary regression model (R^2)
- Least-squares regression
- Stochastic gradient descent [Bonawitz et al. 2016]

Outline

- Background: The private aggregation problem
- A straw-man solution for private sums
- **Providing robustness with SNIPs**
- Evaluation
- Discussion: Real-world considerations

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- Implemented Prio in Go
  (see optimizations described in paper)
- Five-server cluster in EC2
- System collects the sum of “N” 0/1 values

Four variants

1. No privacy
2. No robustness (“straw man”)
3. Prio (privacy + robustness)
4. NIZK (privacy + robustness)

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E.g., for privately measuring telemetry data.

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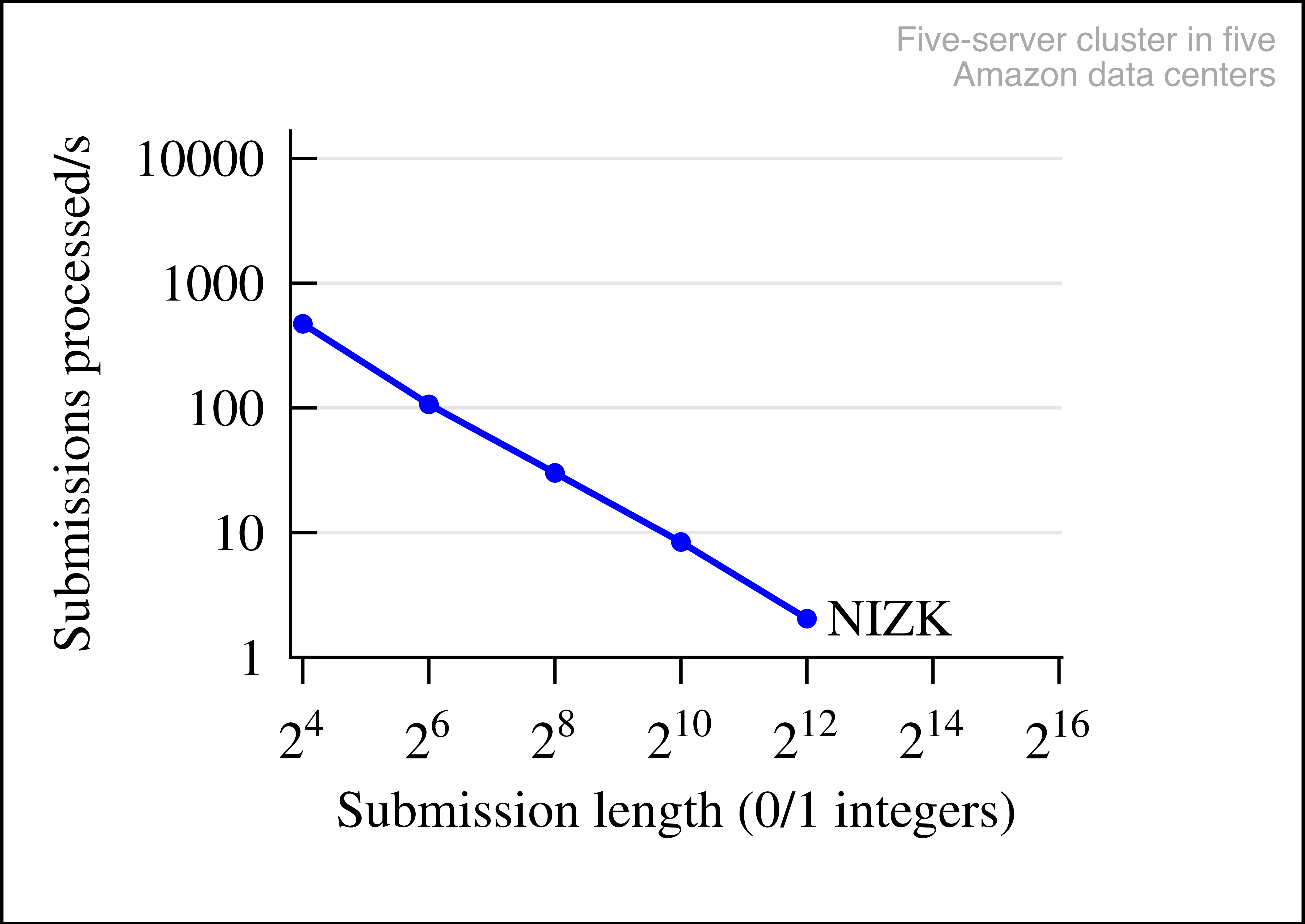
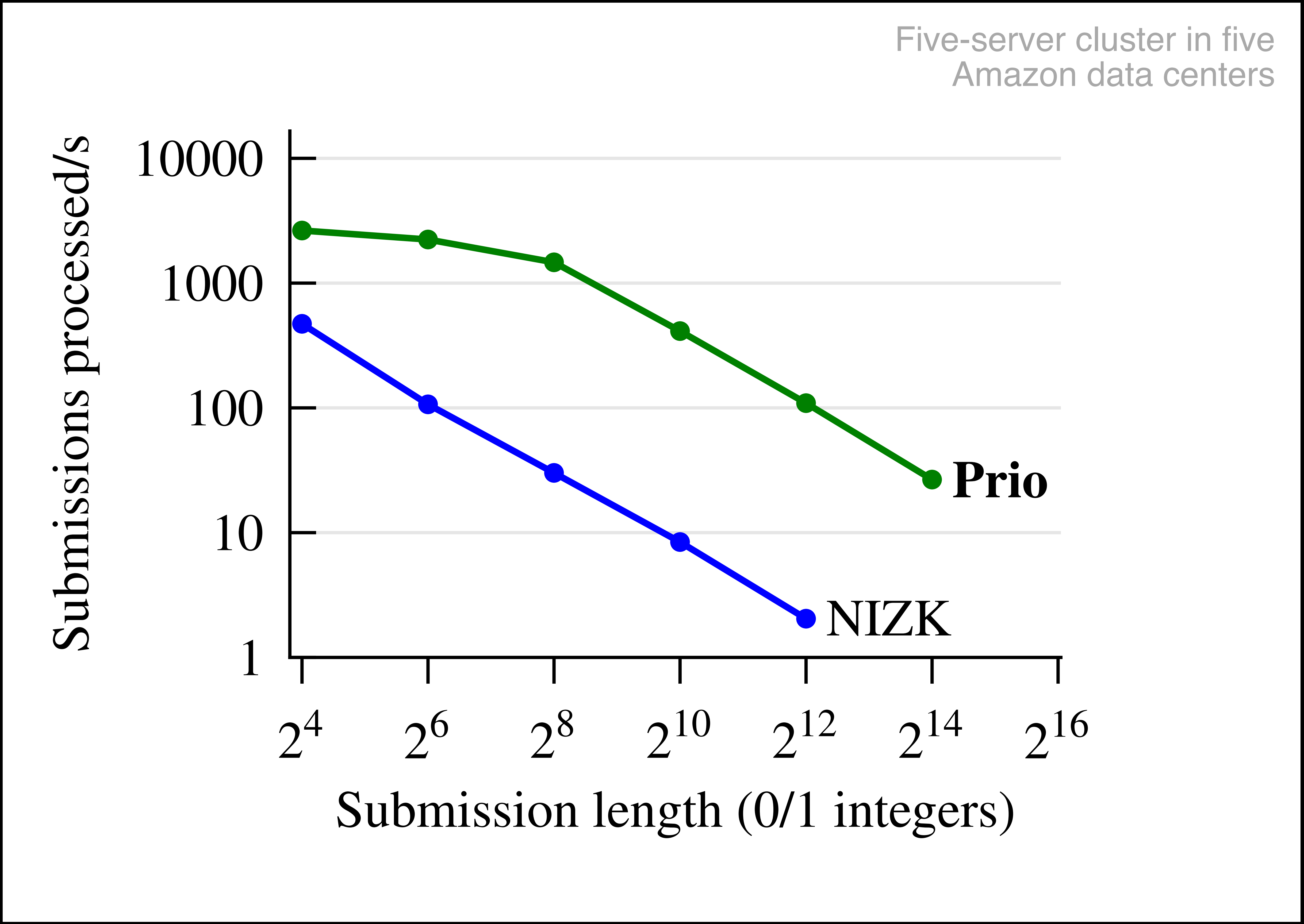
one server

five servers


Five-server cluster in five
Amazon data centers
Submissions processed/s
10000
1000
100
10
1
NIZK
2^4
2^6
2^8
2^{10}
2^{12}
2^{14}
2^{16}
Submission length (0/1 integers)



Five-server cluster in five
Amazon data centers
Submissions processed/s
10000
1000
100
10
1
Prio
NIZK
2^4
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2^8
2^{10}
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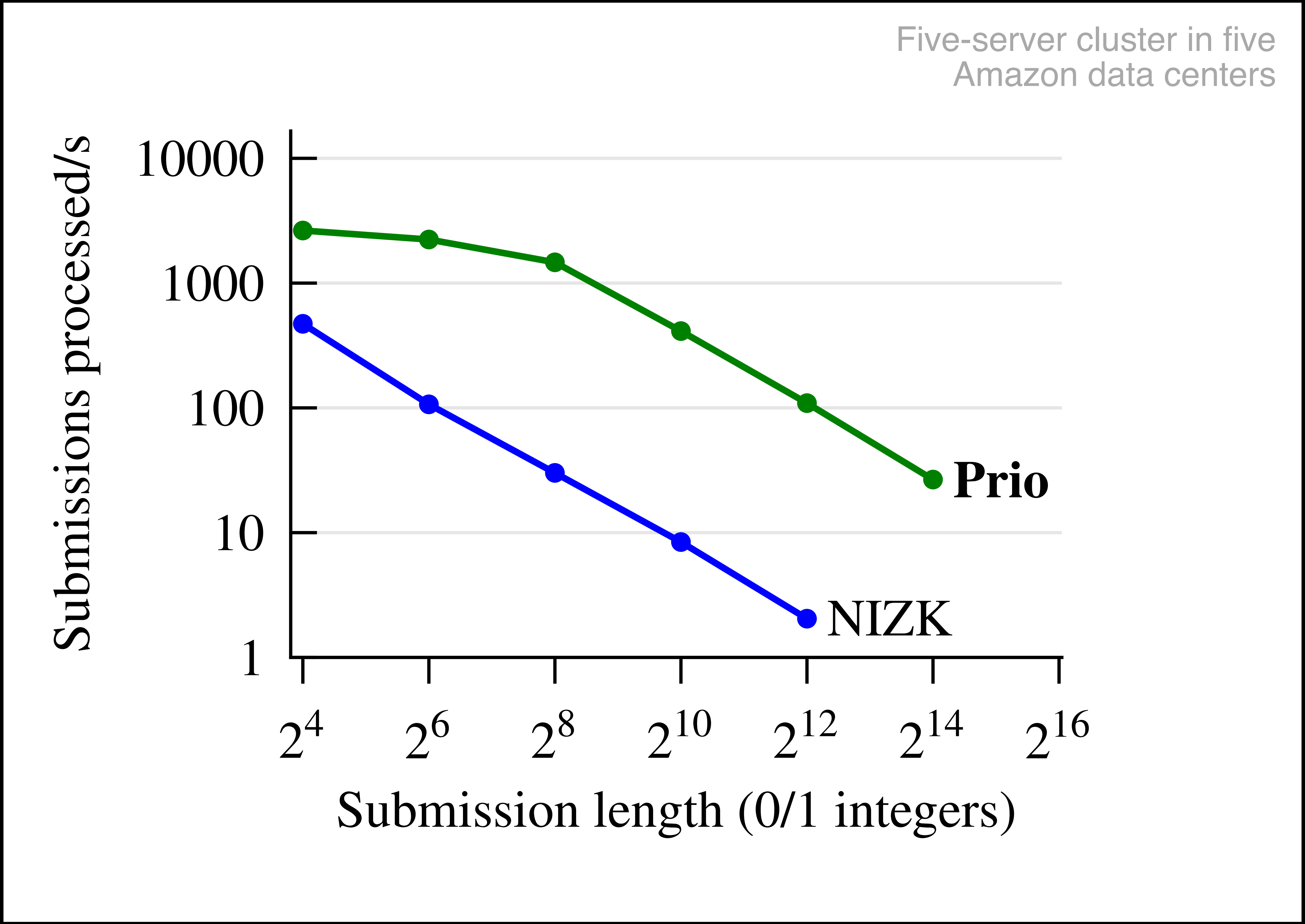
Five-server cluster in five
Amazon data centers
Submissions processed/s
10000
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10
1
2^{4}
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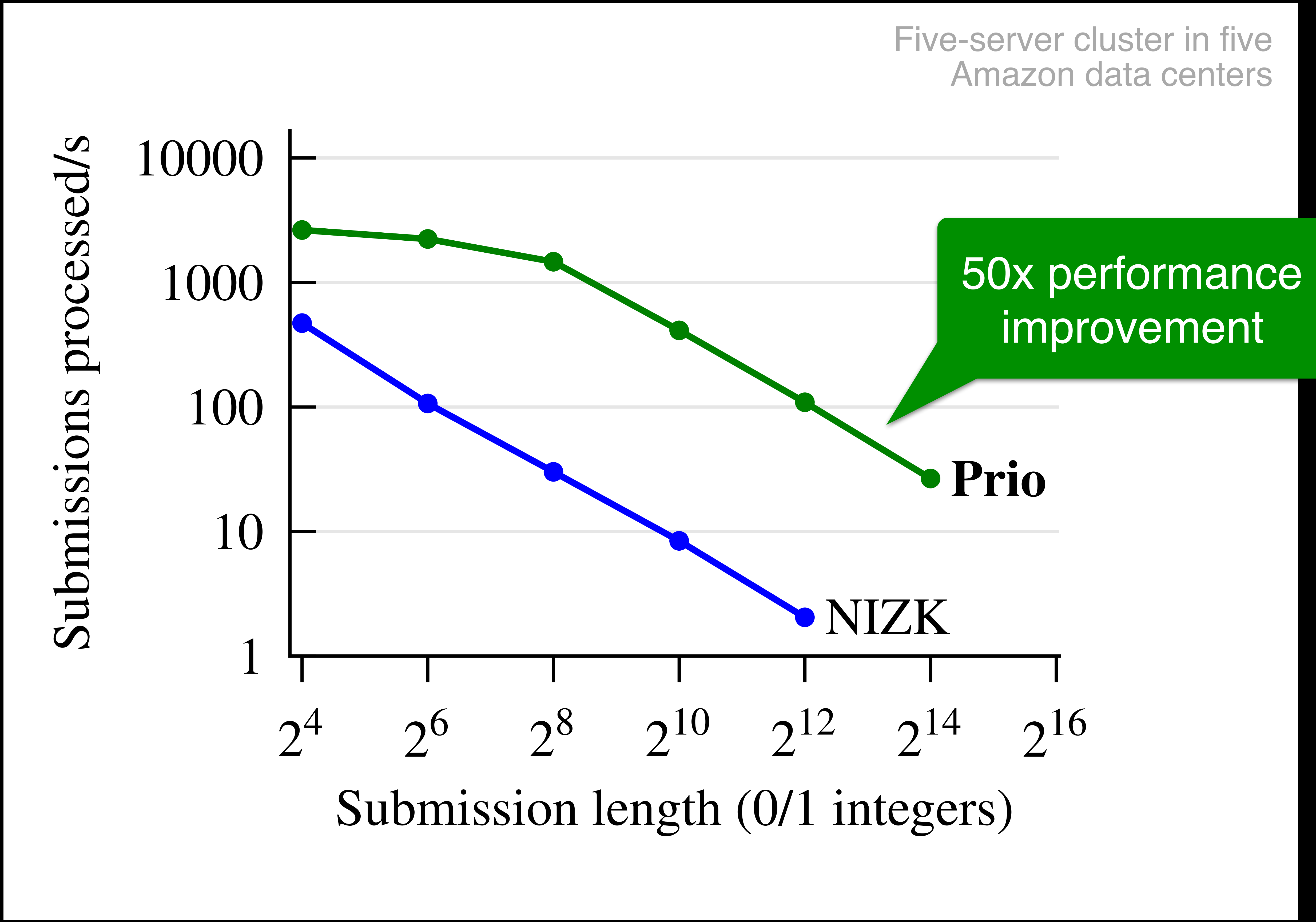
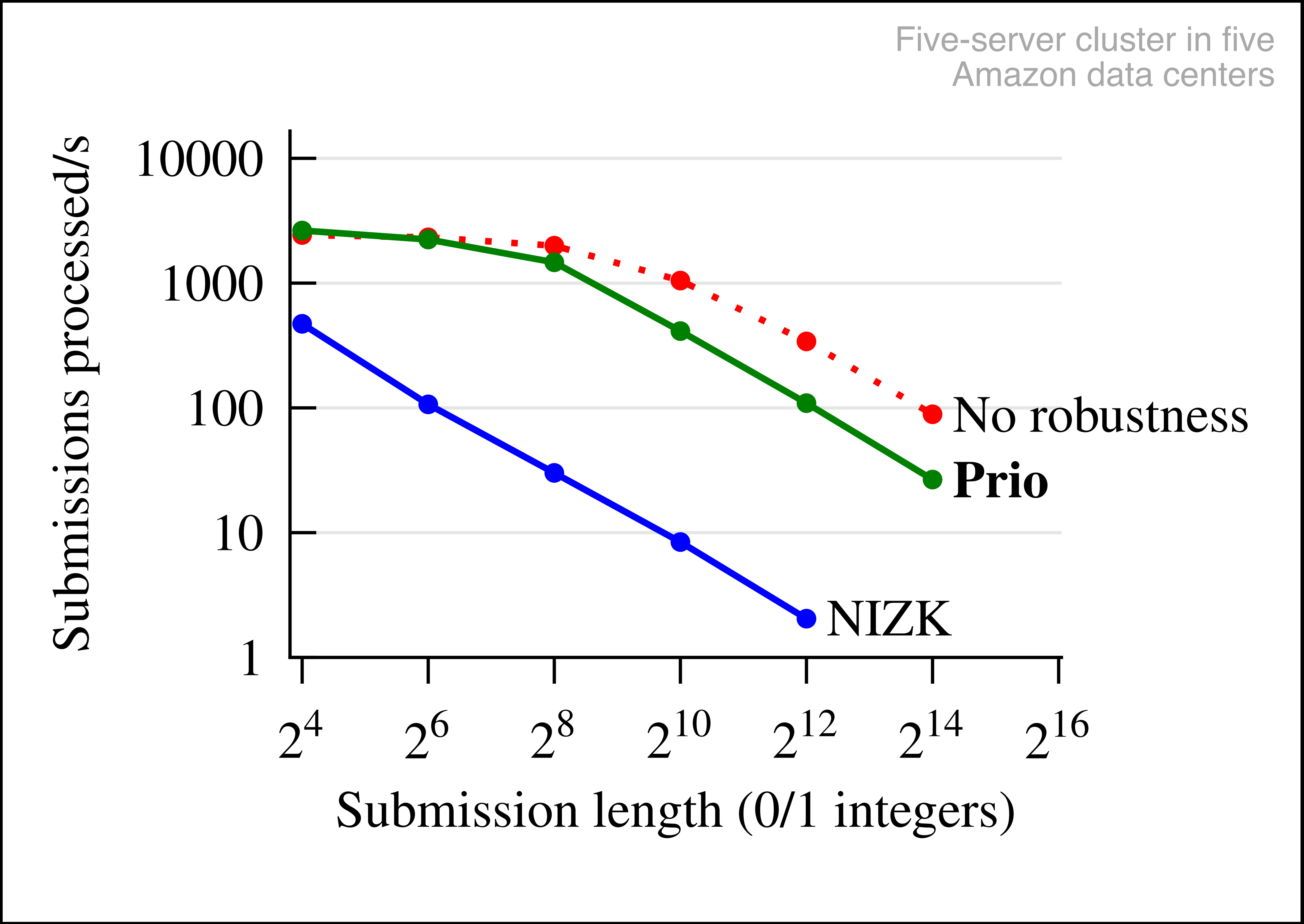
Prio
NIZK


Five-server cluster in five
Amazon data centers
Submissions processed/s
10000
1000
100
10
1
50x performance
improvement
Prio
NIZK
2^4
2^6
2^8
2^{10}
2^{12}
2^{14}
2^{16}
Submission length (0/1 integers)



Five-server cluster in five
Amazon data centers
Submissions processed/s
10000
1000
100
10
1
No robustness
Prio
NIZK
2^4
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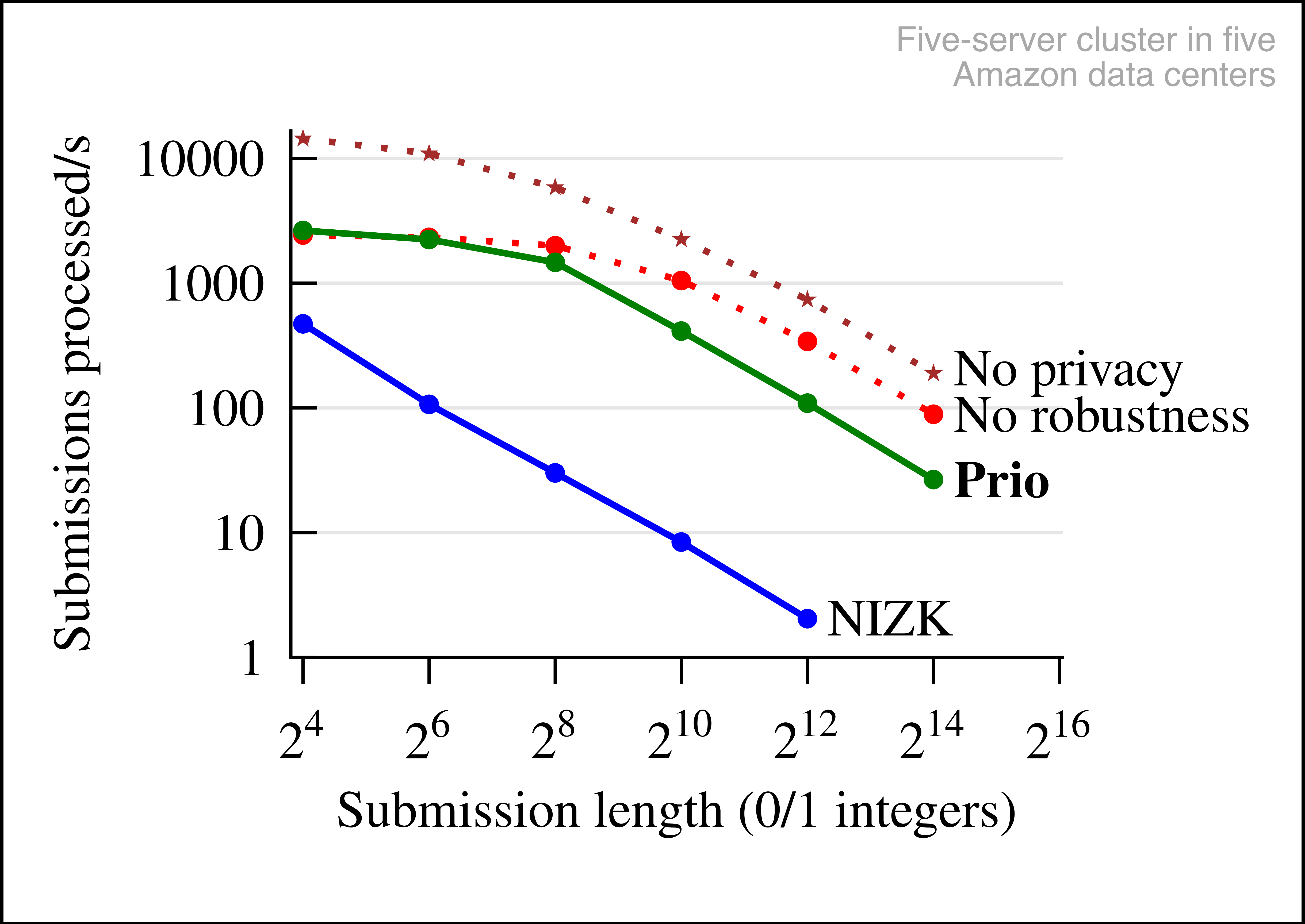

Five-server cluster in five
Amazon data centers
Submissions processed/s
10000
1000
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10
1
2^4
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2^{10}
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2^{14}
2^{16}
Submission length (0/1 integers)
No privacy
No robustness
Prio
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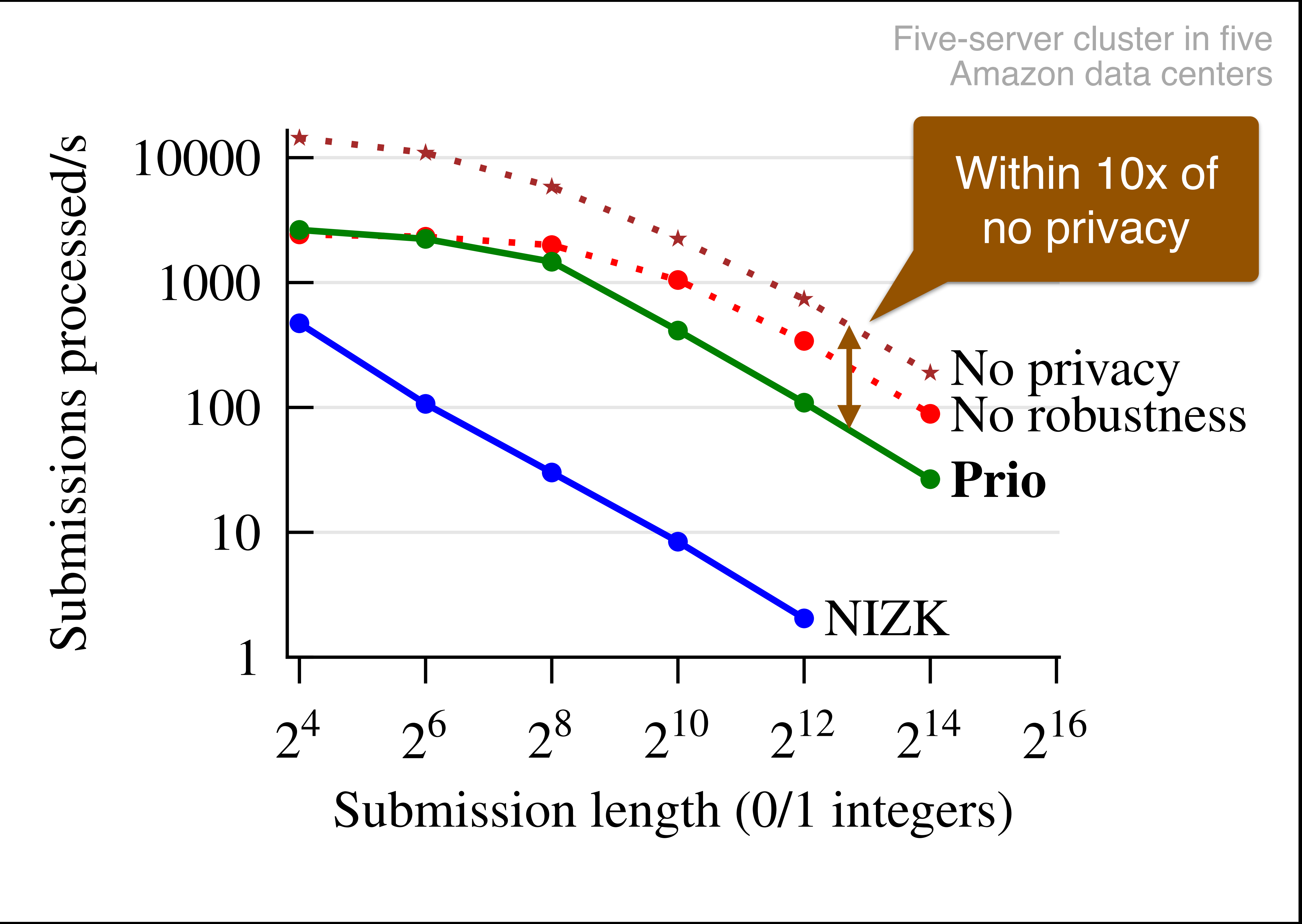

Five-server cluster in five
Amazon data centers
Within 10x of
no privacy
Submissions processed/s
10000
1000
100
10
1
No privacy
No robustness
Prio
NIZK
2^4
2^6
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2^{16}
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Real-world considerations: Technical

Every company we spoke with said:

- Server resources are cheap, client resources are not
- Client <u>bandwidth usage</u> is the important quantity to minimize
- Need some defense against faulty/disruptive clients
- Privately collecting popular URLs is the interesting application
  - Existing solutions are good, but not great

Areas of vehement disagreement between companies:

- Non-colluding servers—realistic?
- Does SGX obviate the need for these cryptographic protocols?

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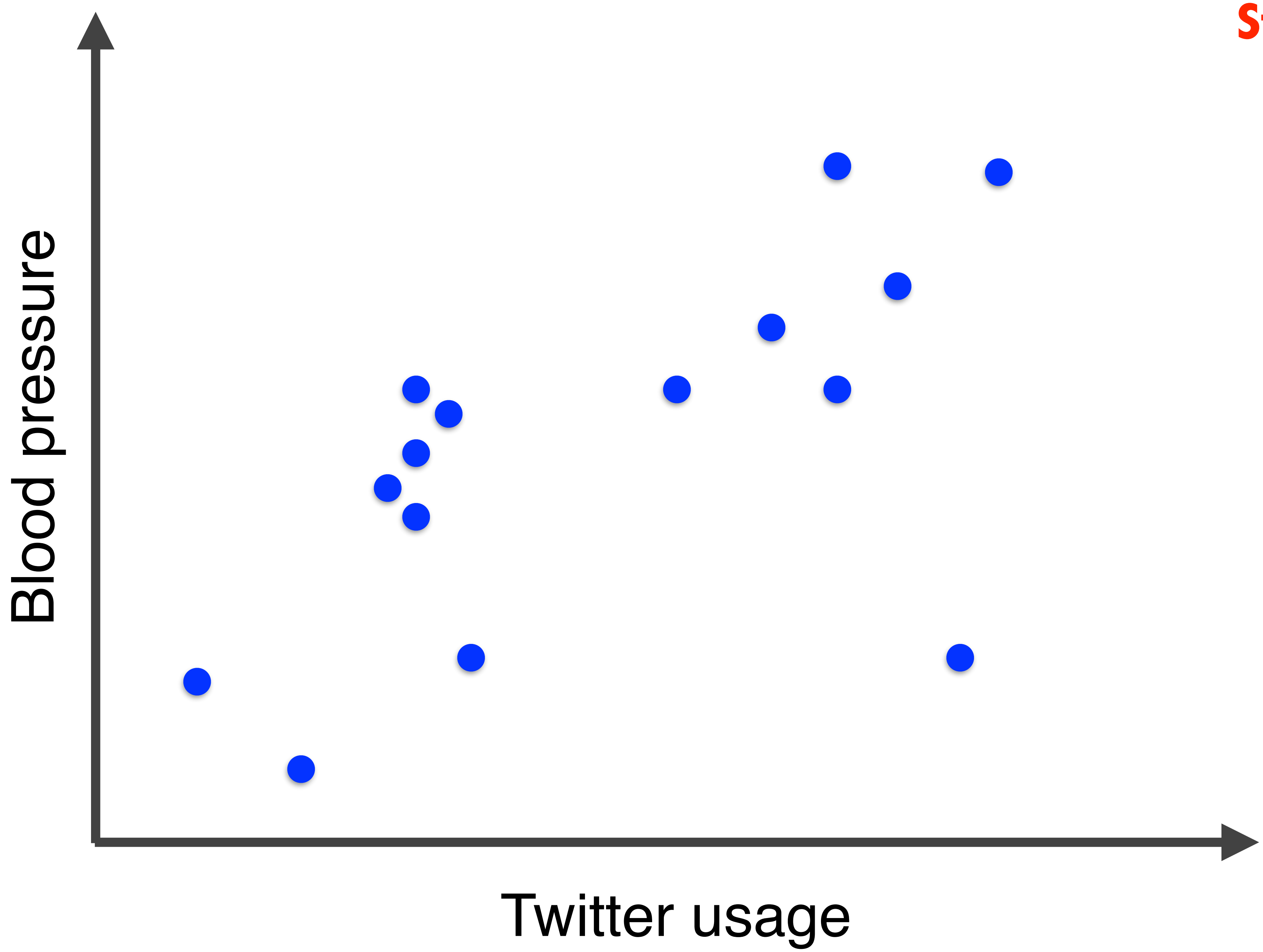
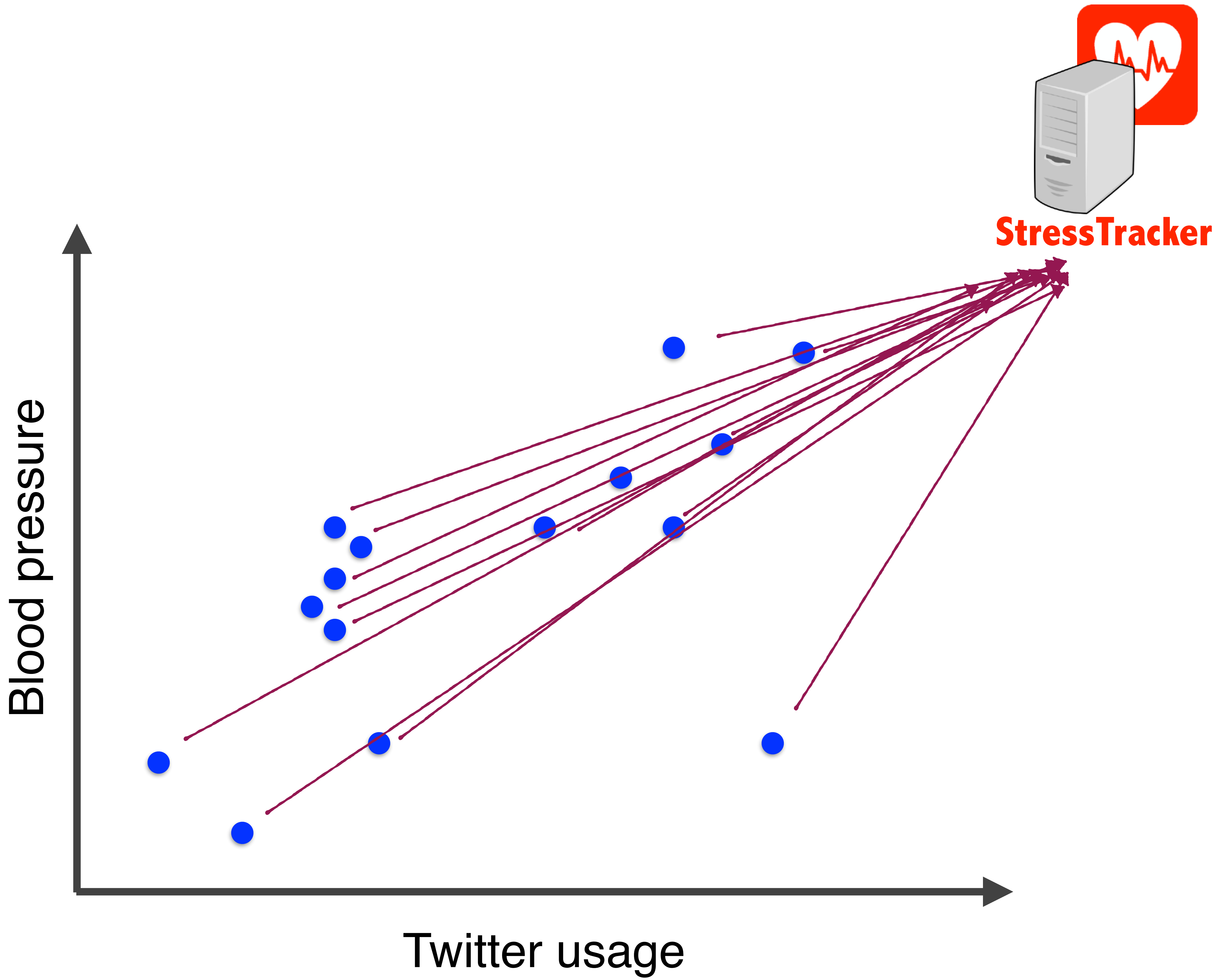
- **???**

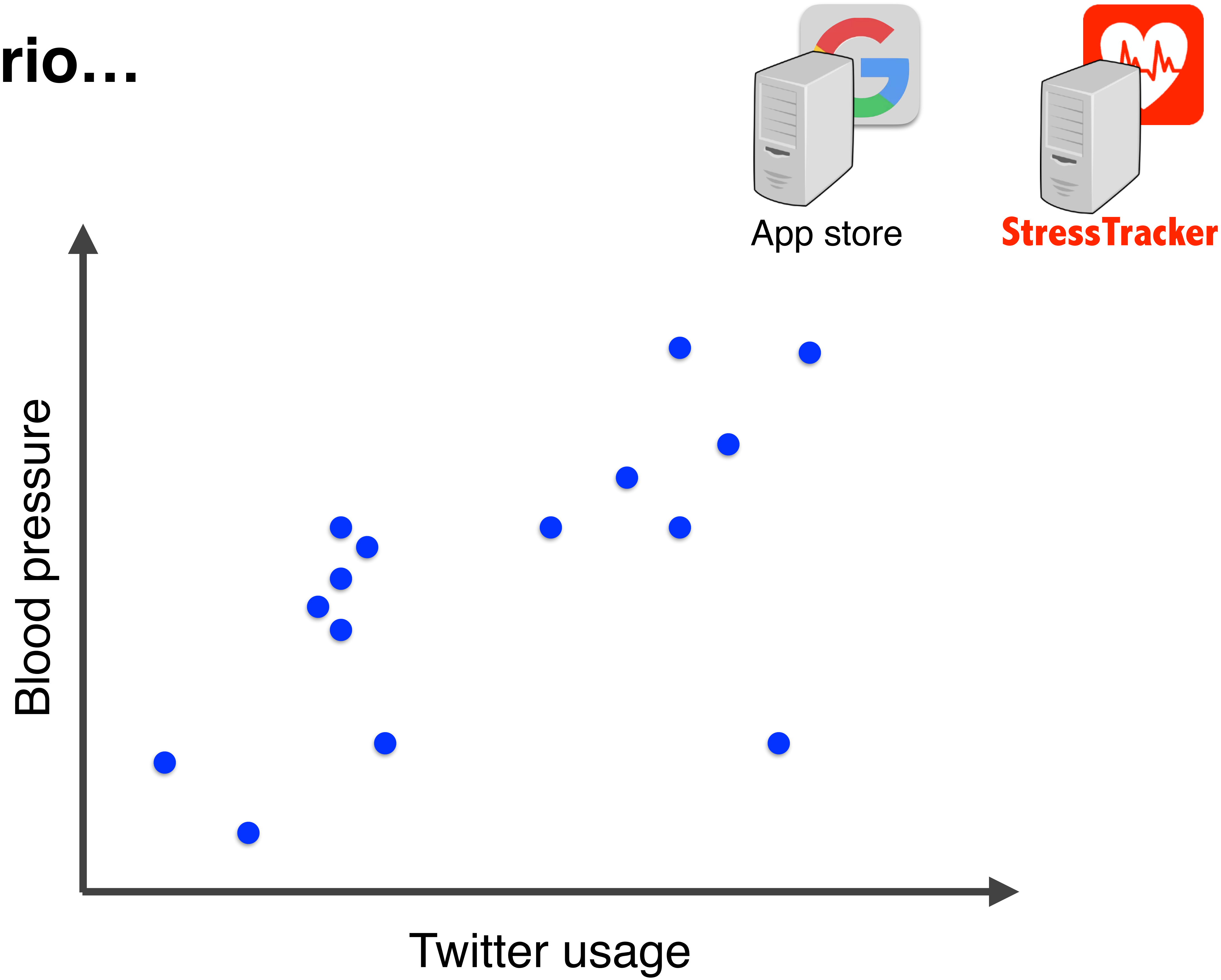
Today



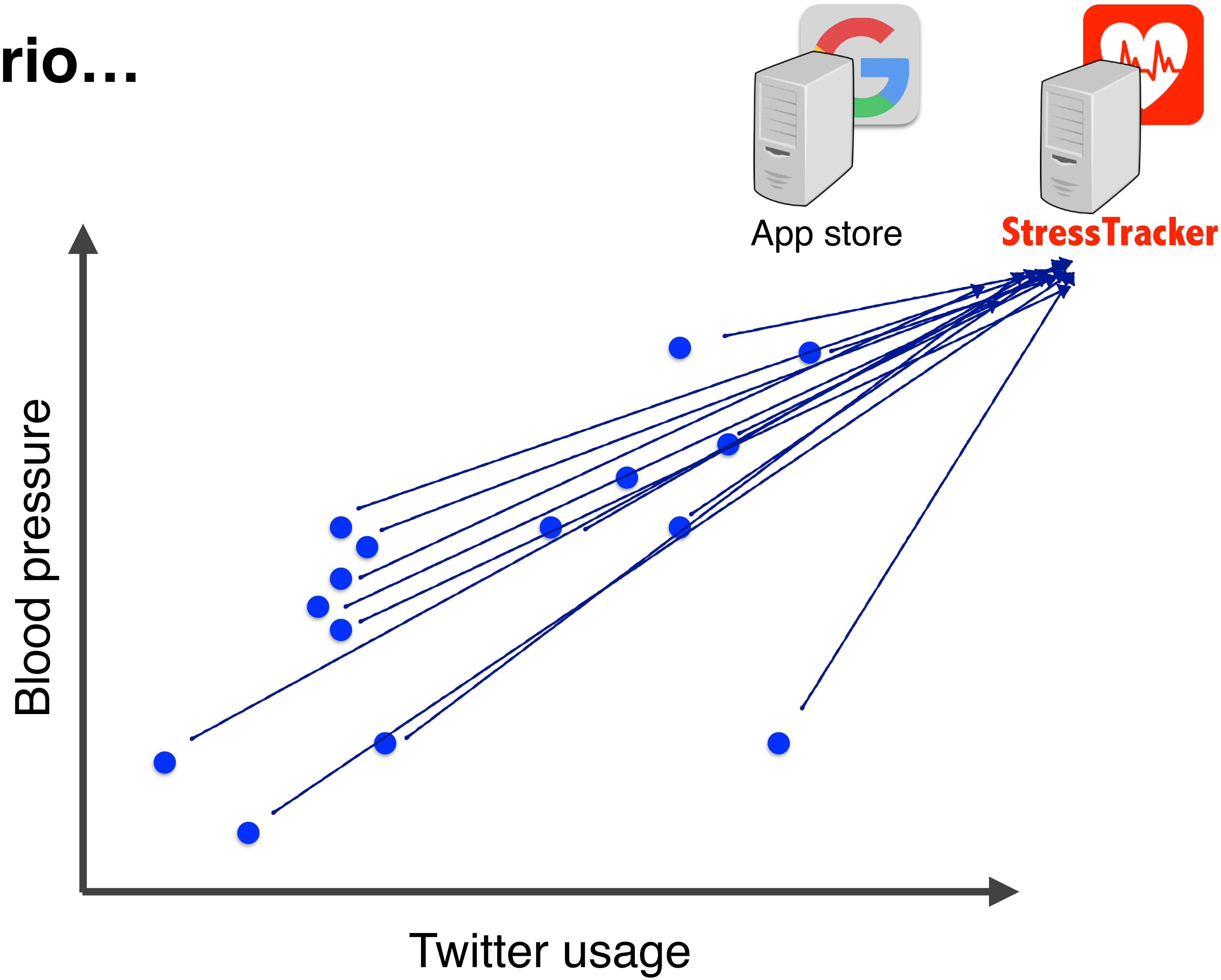
Today



With Prio…



With Prio…



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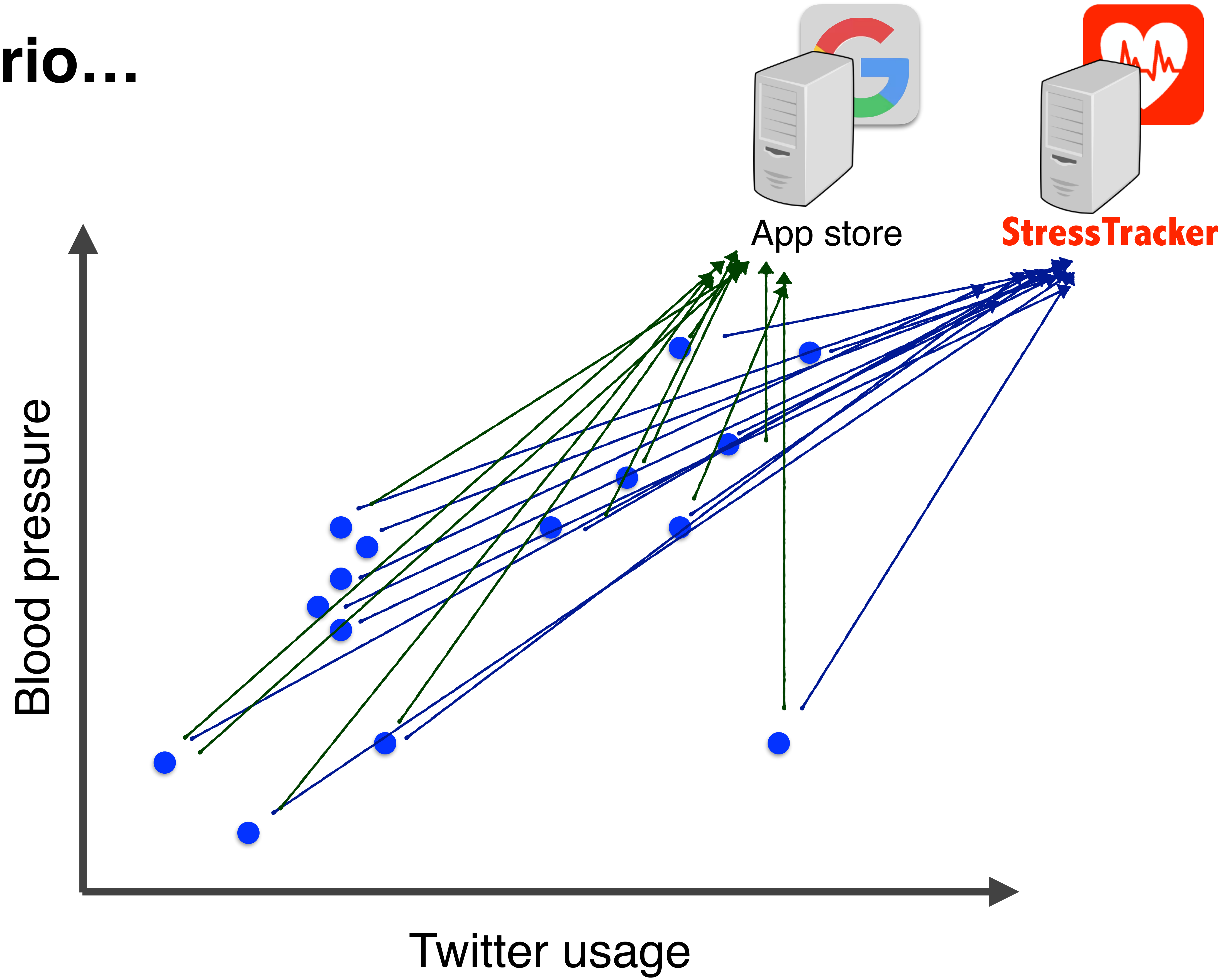

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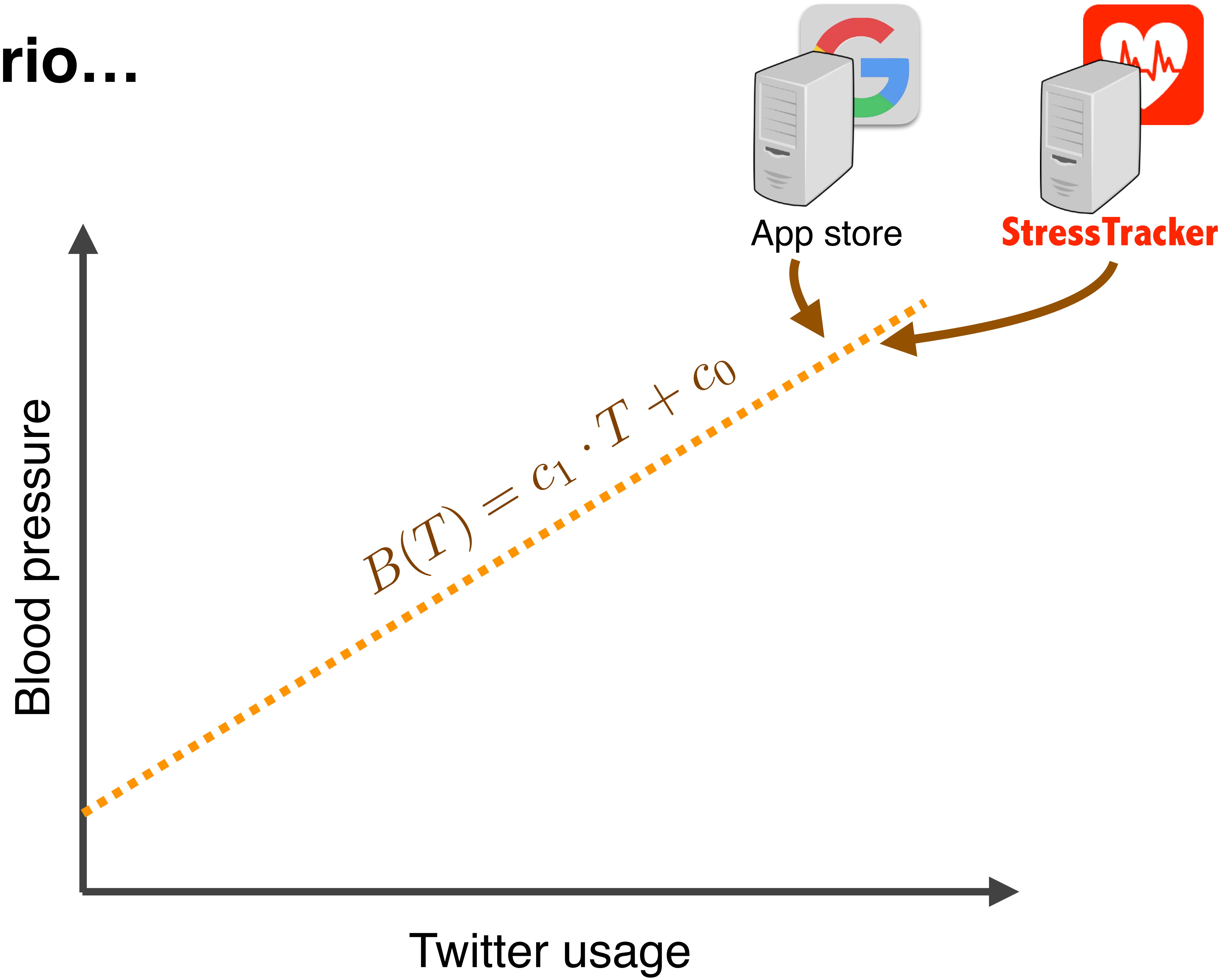

App store
StressTracker
$B(T) = c_1 \cdot T + c_0$
Blood pressure
Twitter usage

Conclusions

- Wholesale collection of sensitive user data puts our security at risk.
- Prio is the first system for aggregation that provides:
  - **exact correctness**,
  - **privacy**,
  - **robustness**, and
  - **efficiency**.
- To do so, Prio uses SNIPs and aggregatable encodings.
- These techniques together bring private aggregation closer to practical.

Thank you!

Henry Corrigan-Gibbs
henrycg@cs.stanford.edu

https://crypto.stanford.edu/prio/