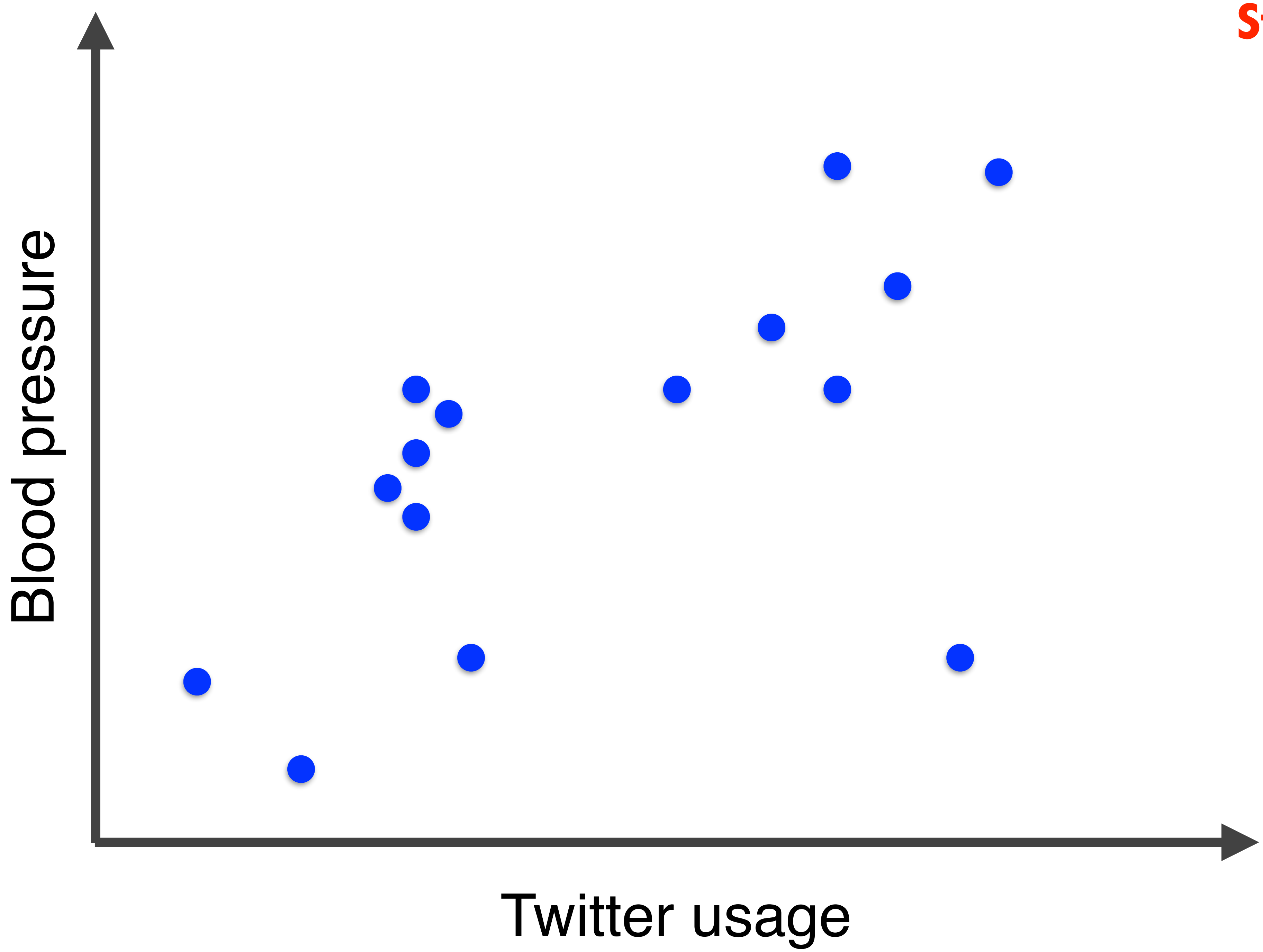
Prio: Private, Robust, and Efficient Computation of Aggregate Statistics

Henry Corrigan-Gibbs and Dan Boneh
Stanford University

NSDI 2017

Today: Non-private aggregation



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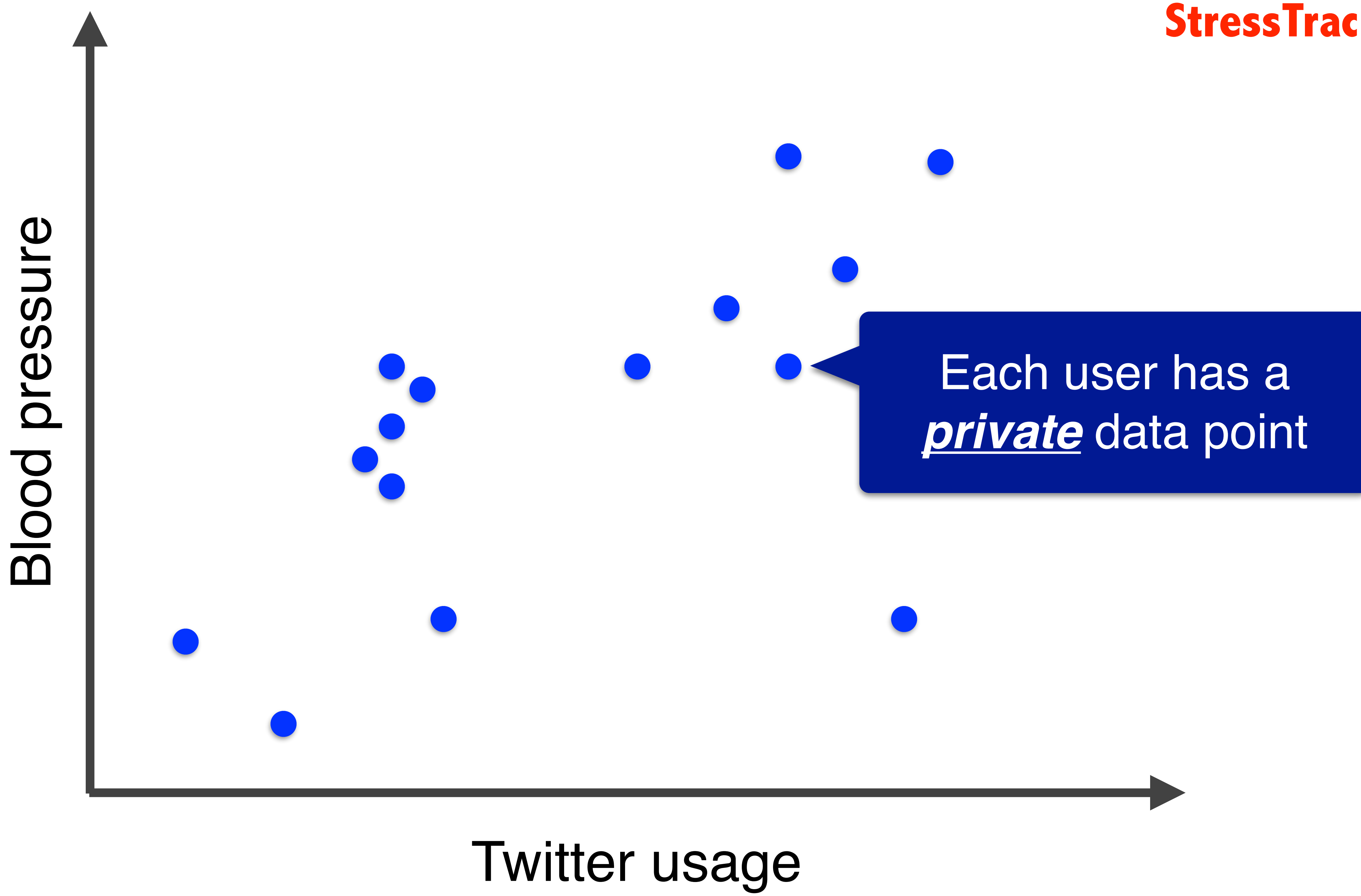

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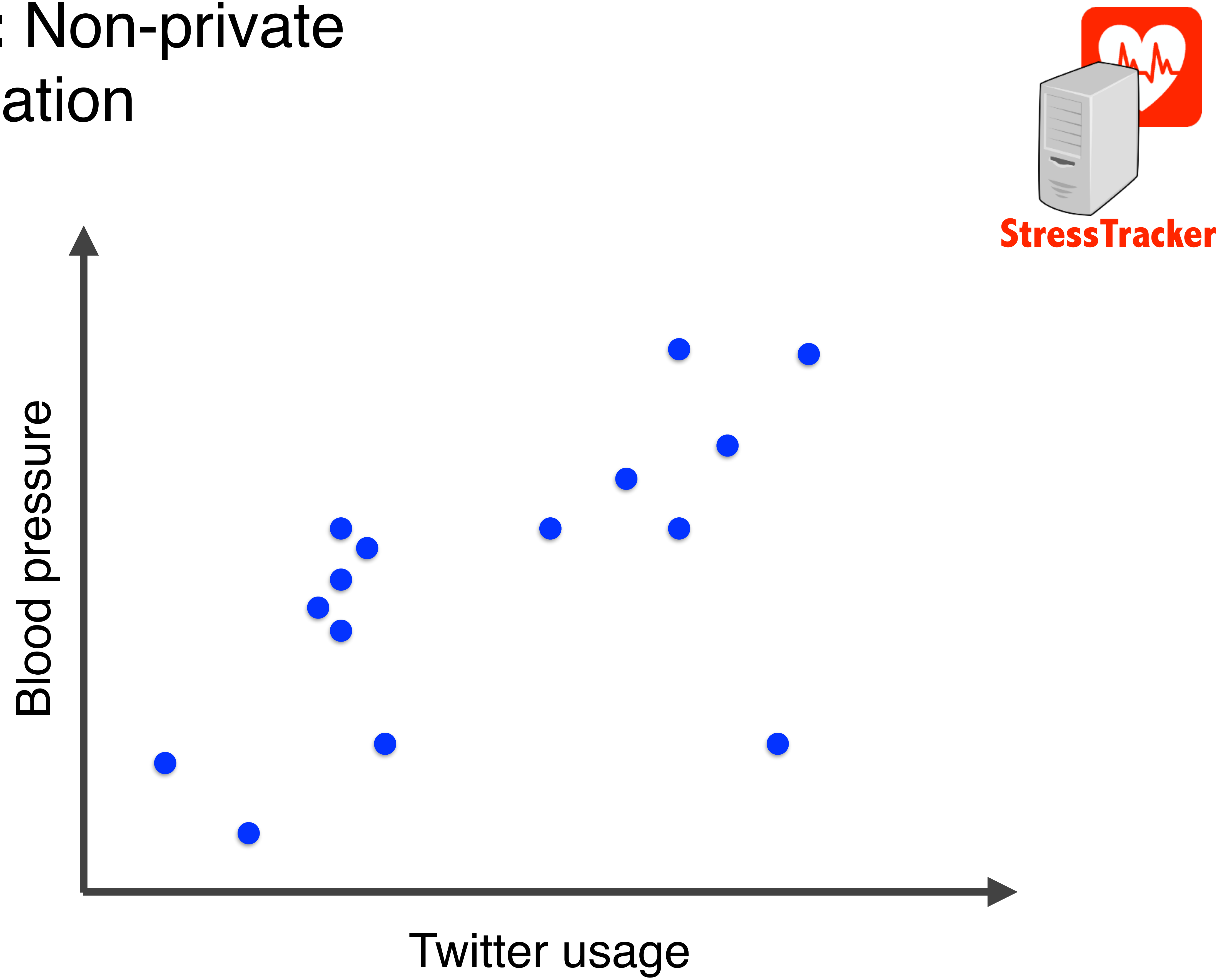

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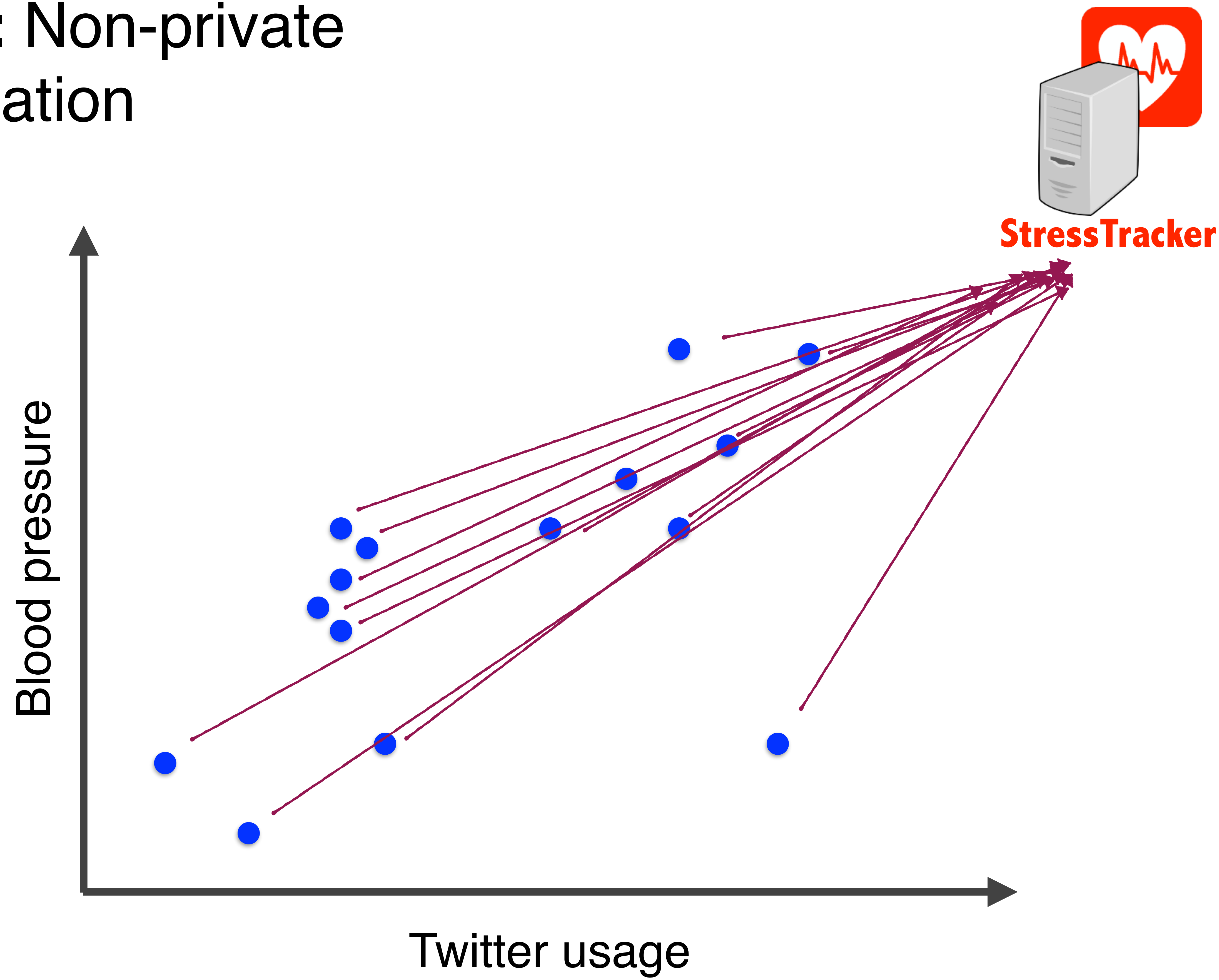

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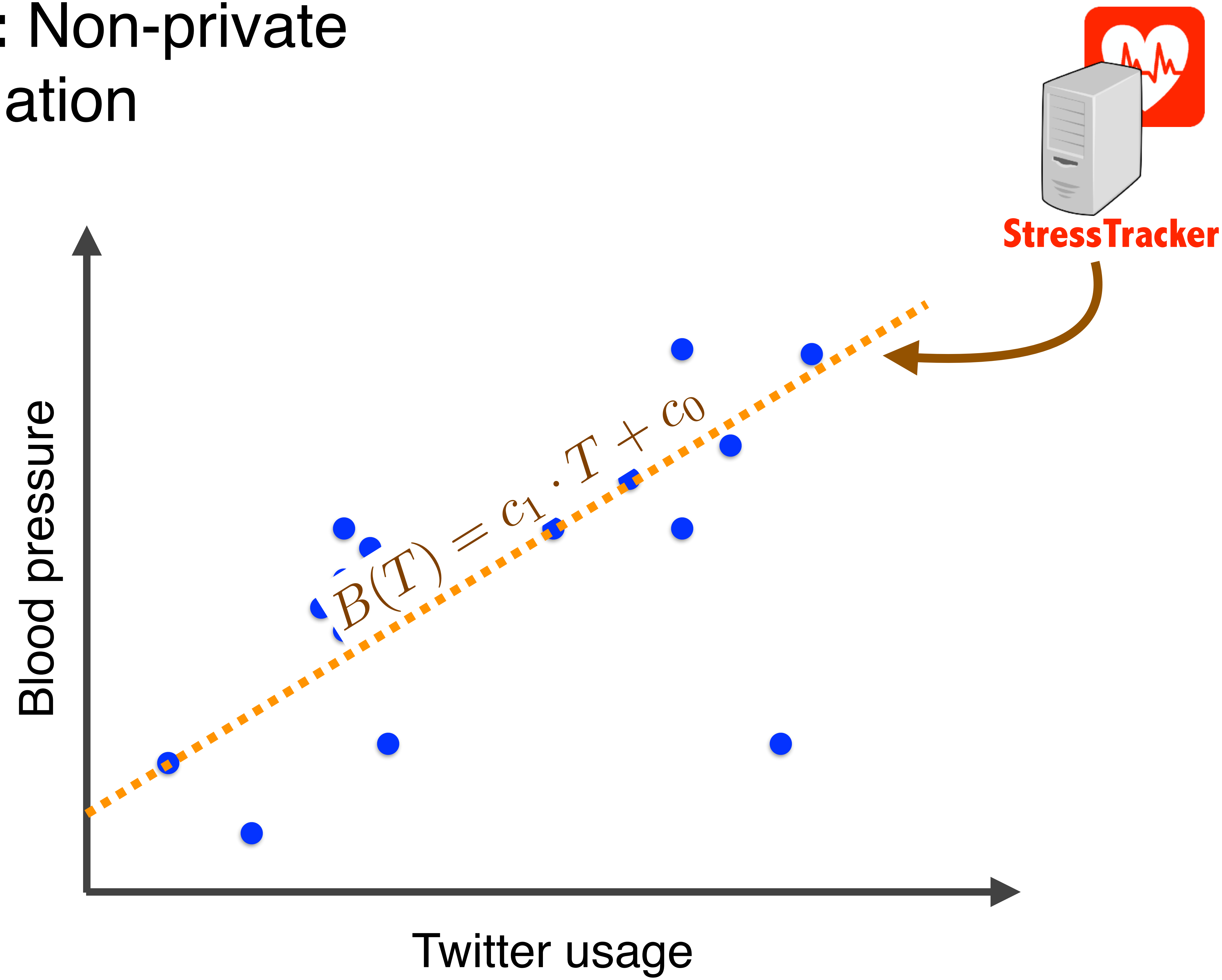

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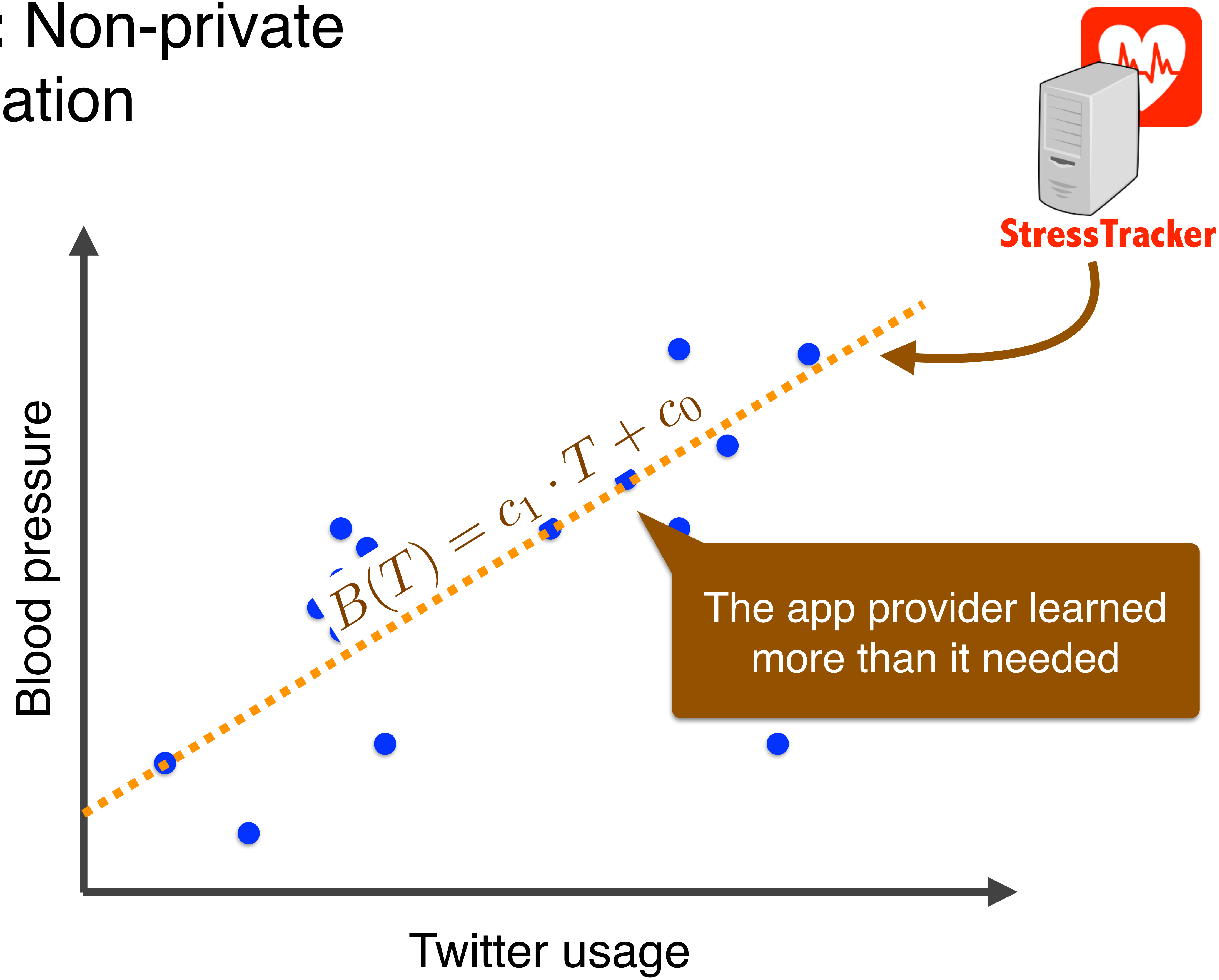

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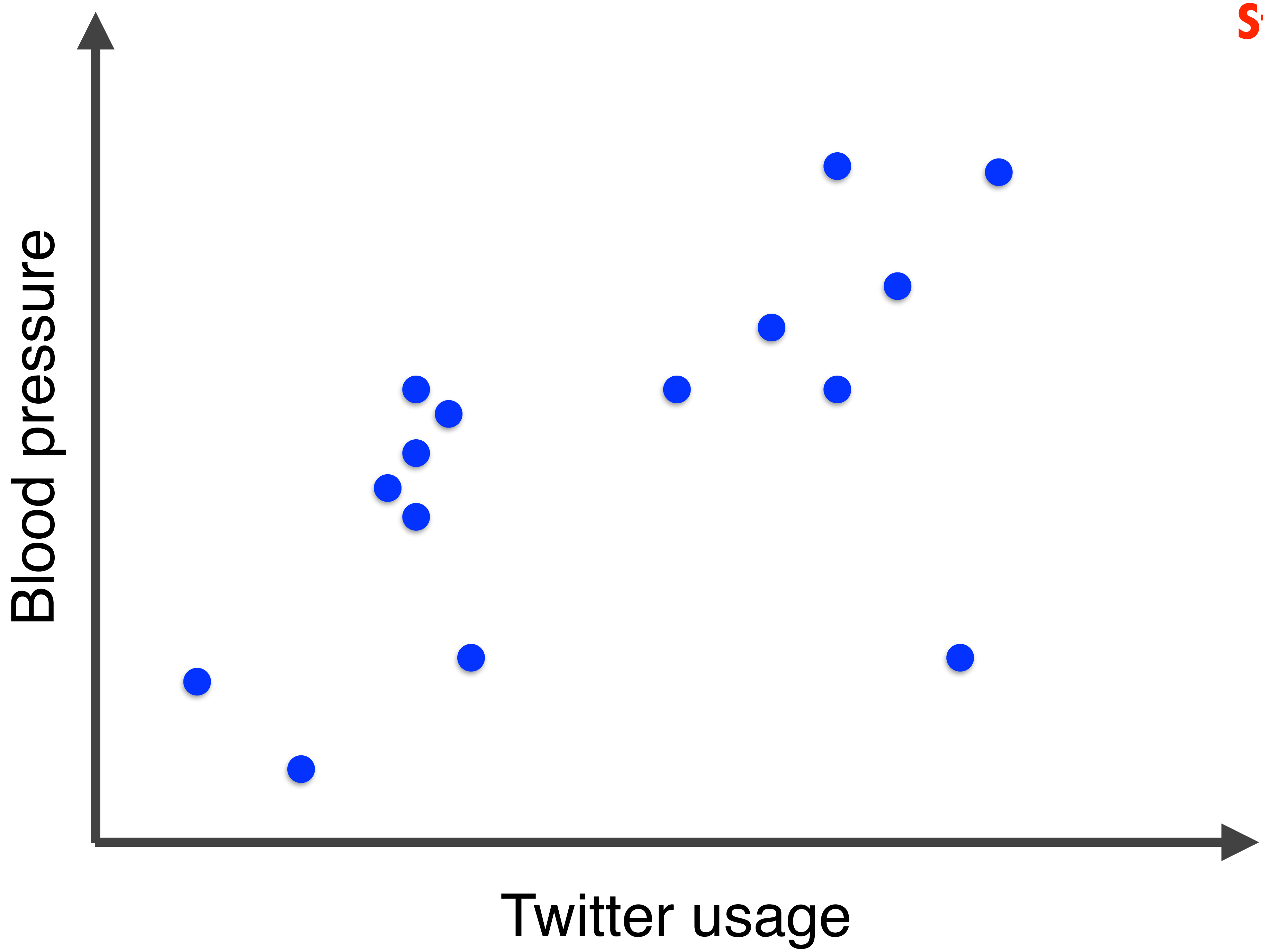

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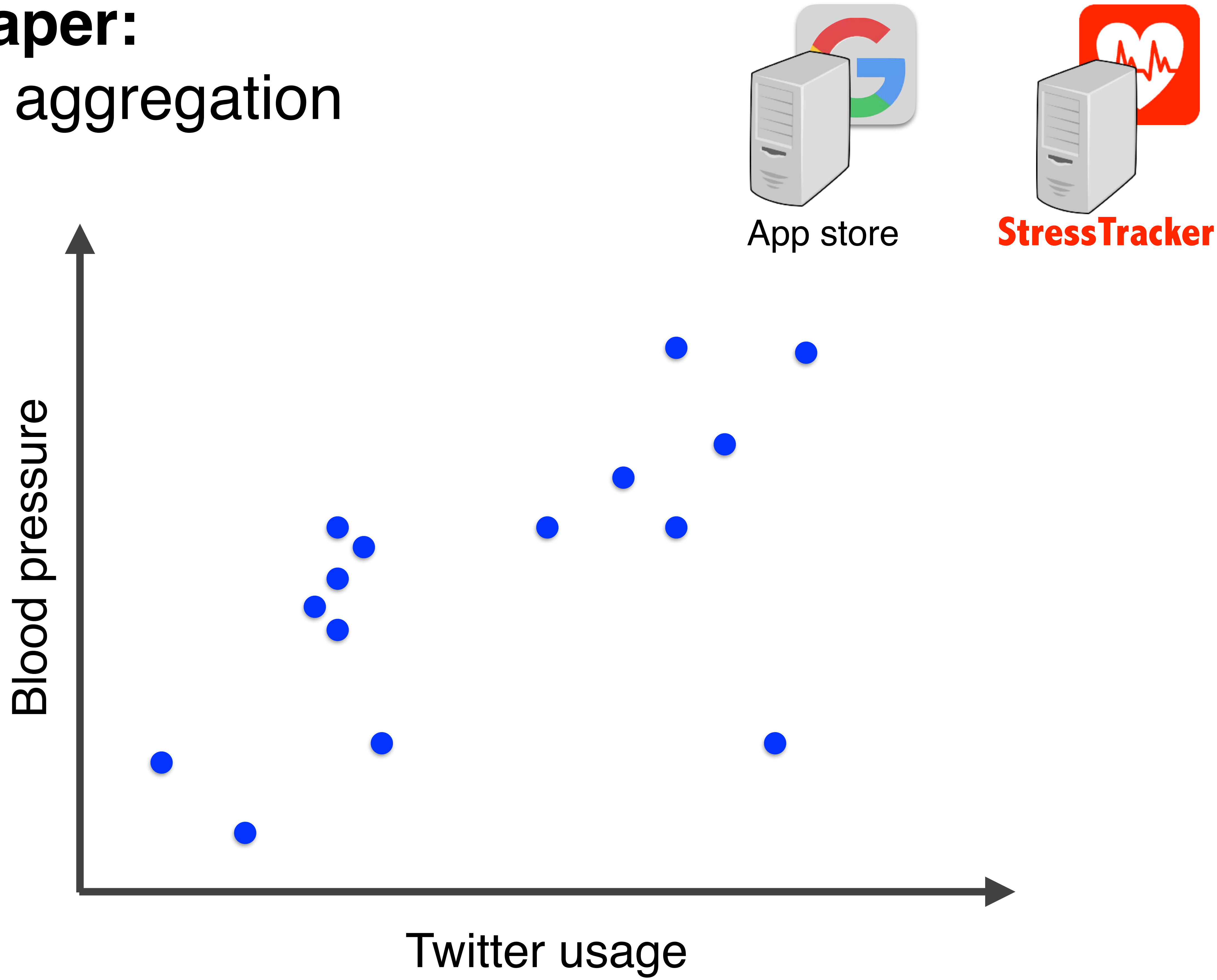

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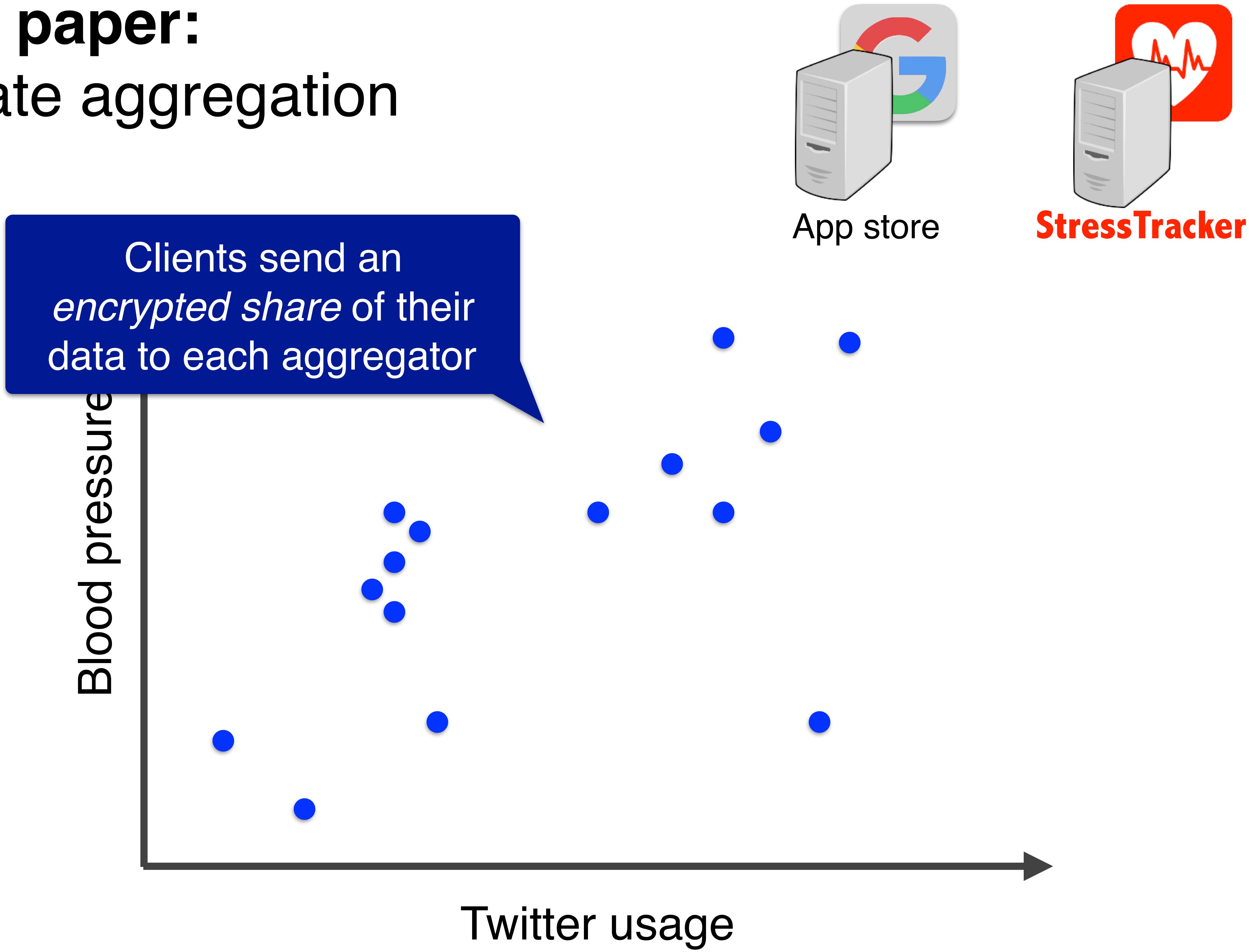

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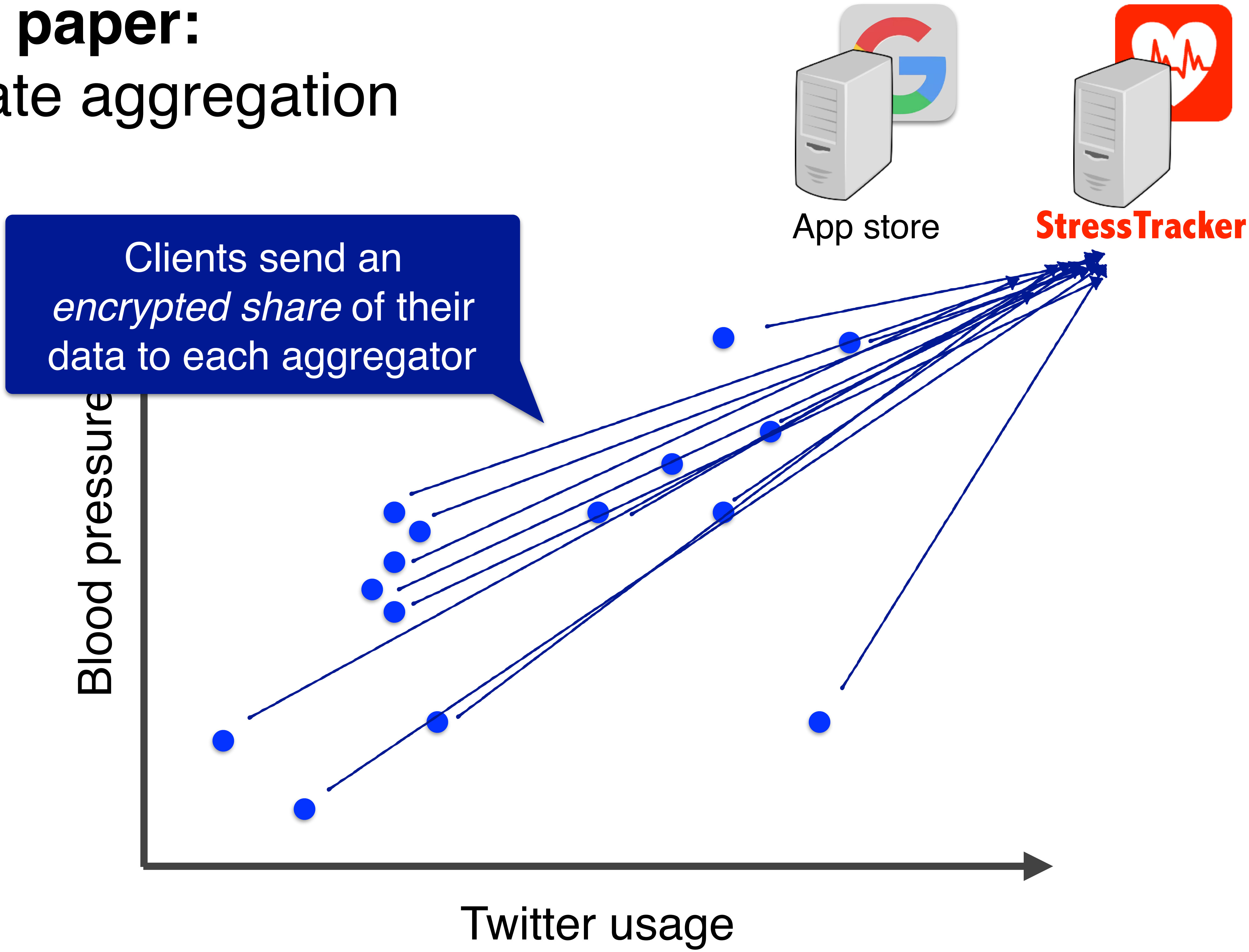

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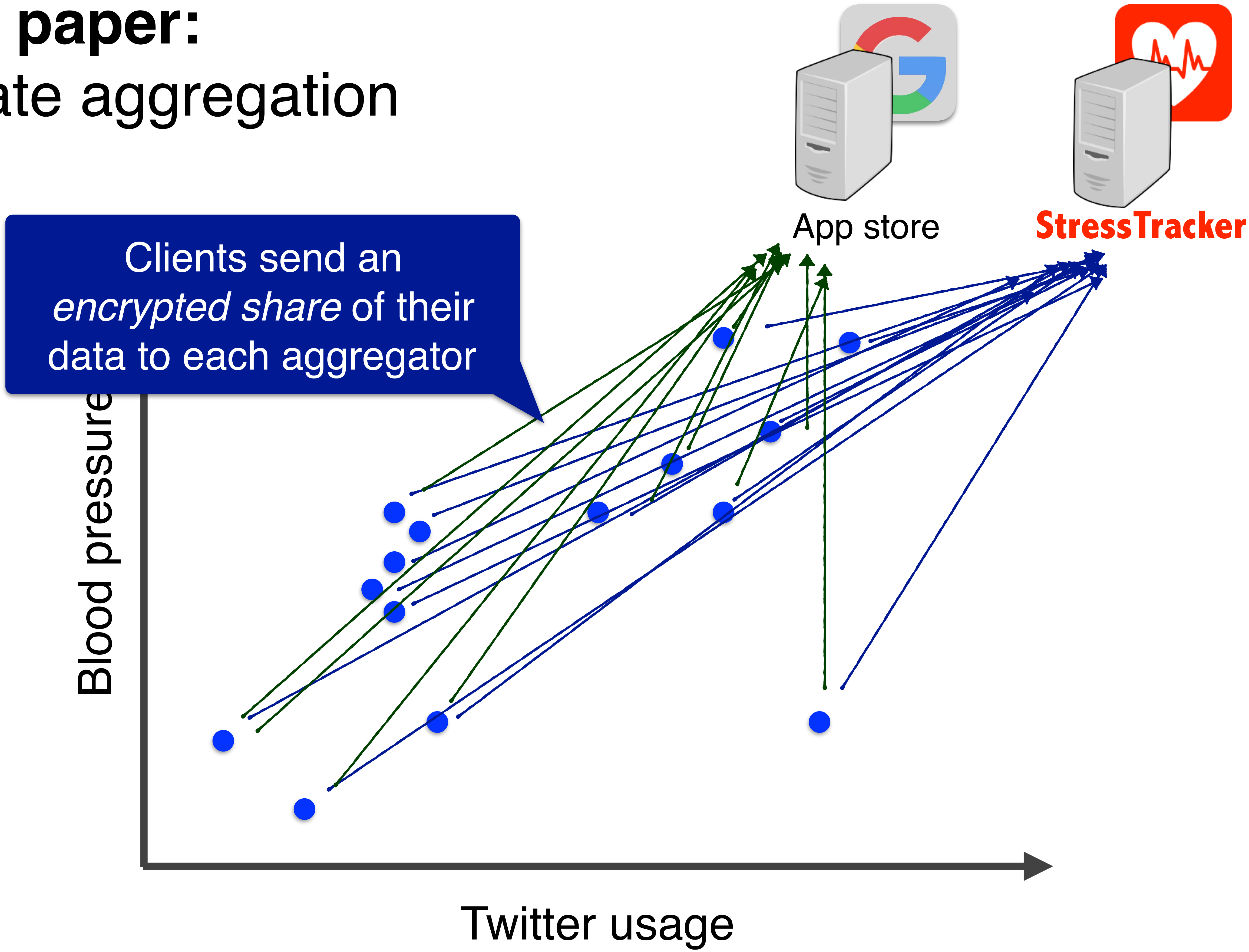

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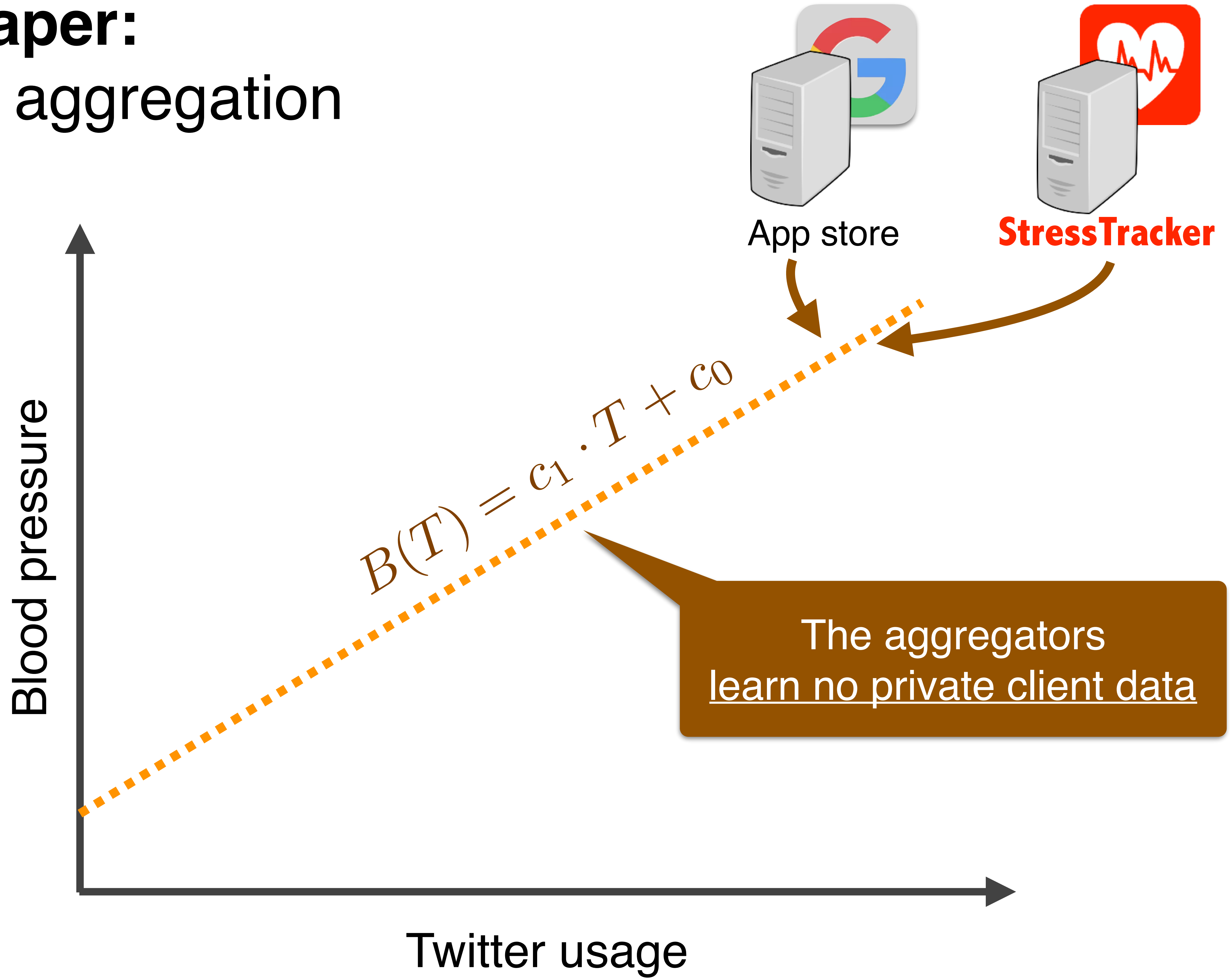
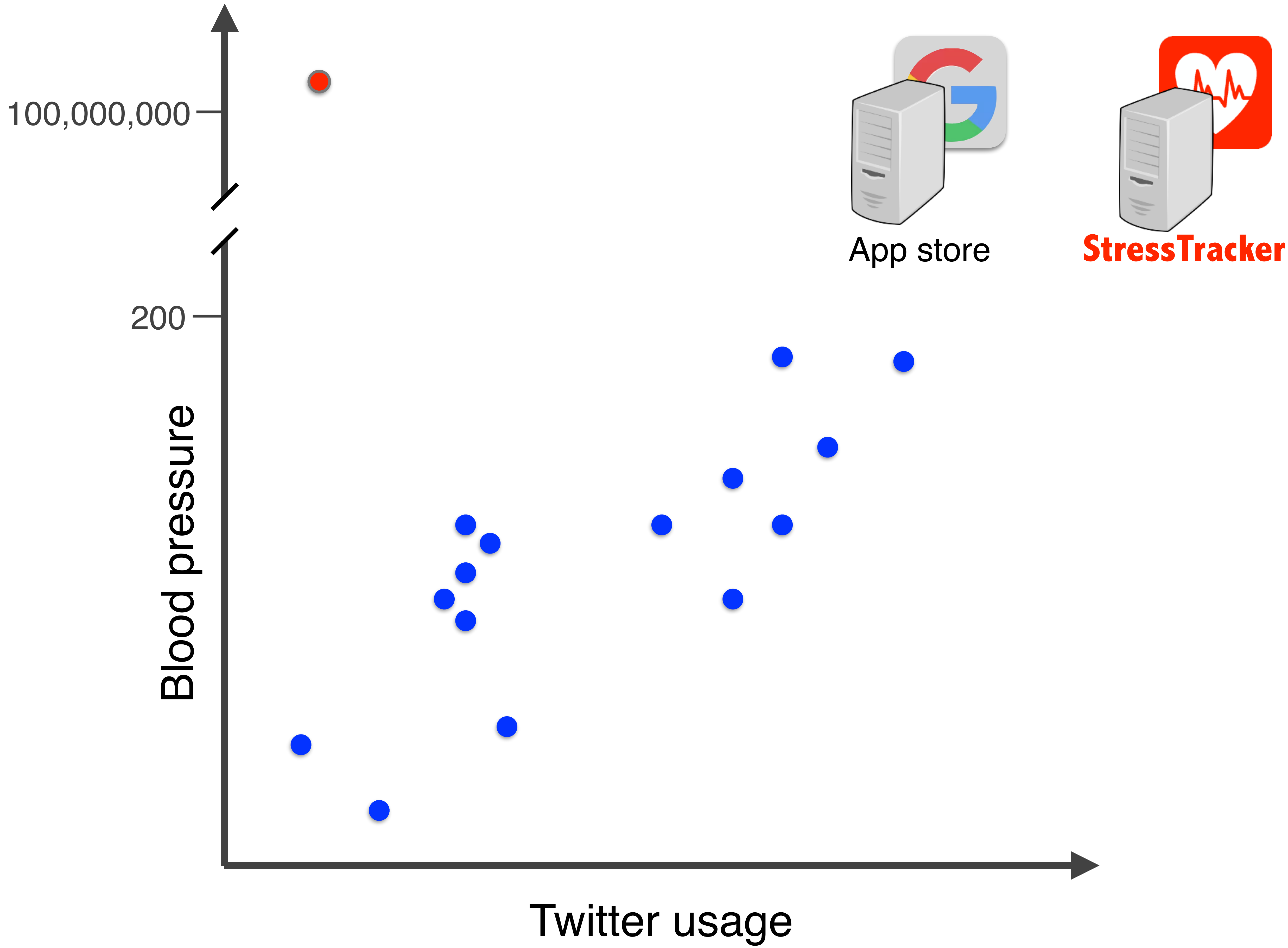


Private aggregation

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
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Twitter usage
App store
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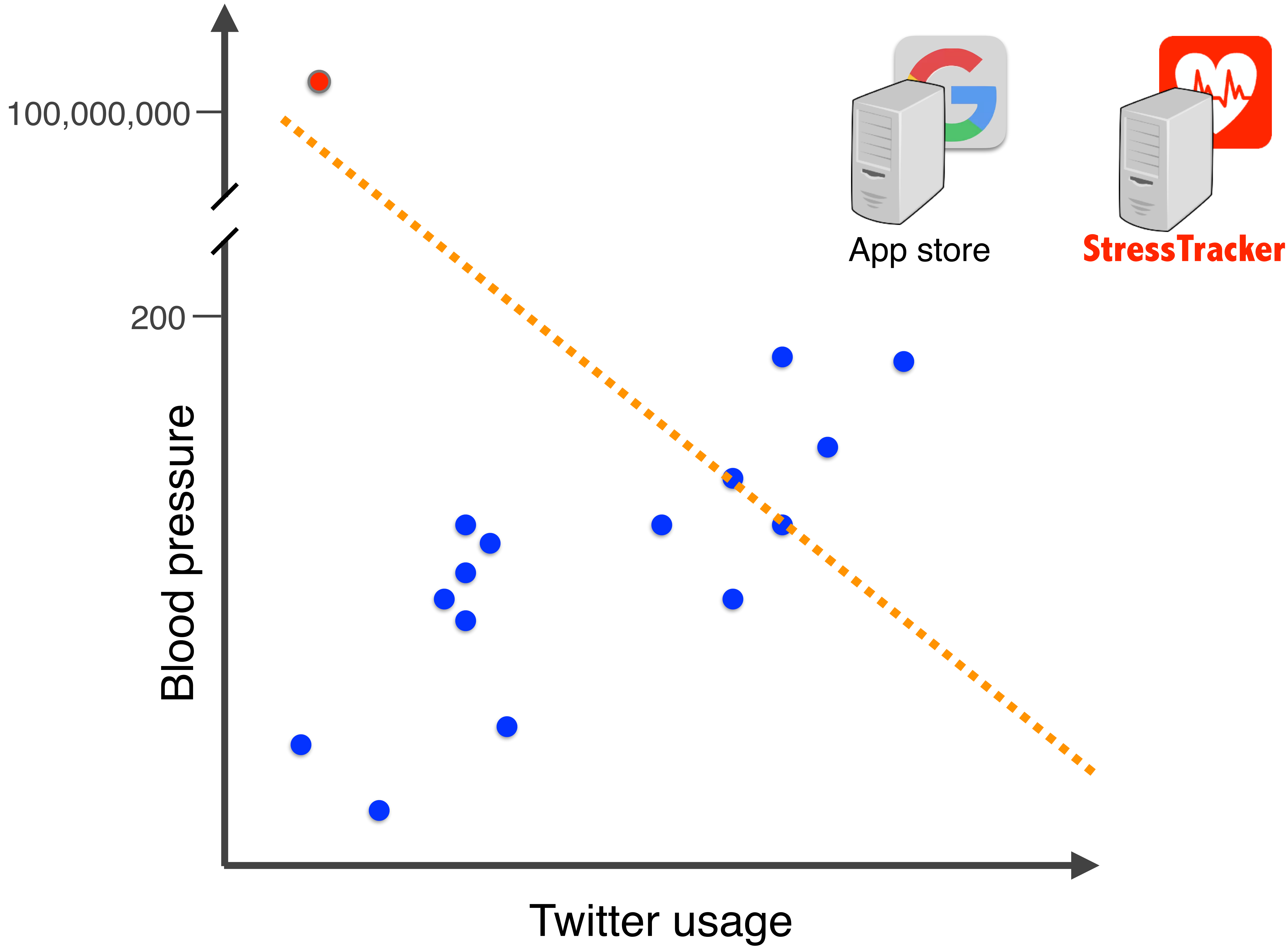
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Private aggregation

1. **Exact correctness** — If <u>all servers</u> are honest, servers learn $f(\cdot)$
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Prio is the first system to achieve all four.

Private aggregation

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…and Prio supports a wide range of aggregation functions f(·)

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

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
- Encodings for <u>complex</u> aggregates

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- Every device i holds a value x_i
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  without learning any users' private value x_i.

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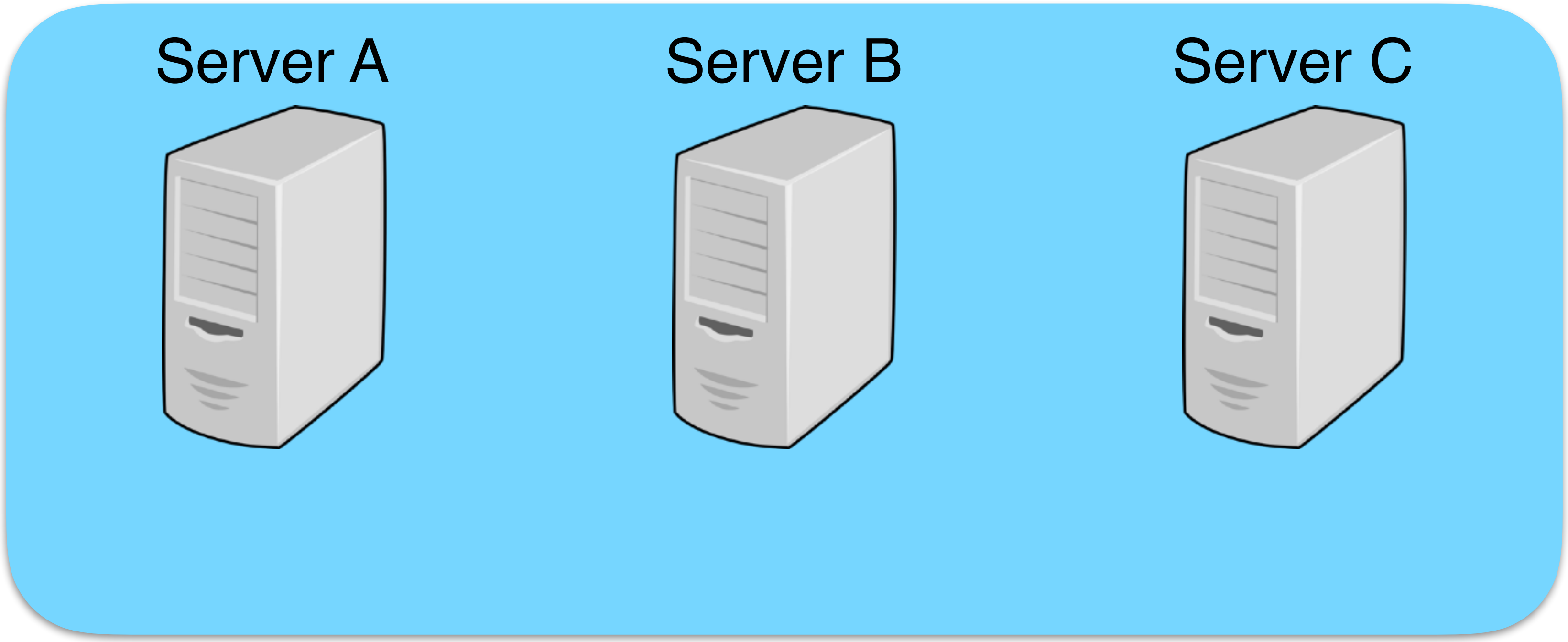
Example: Privately measuring traffic congestion.

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

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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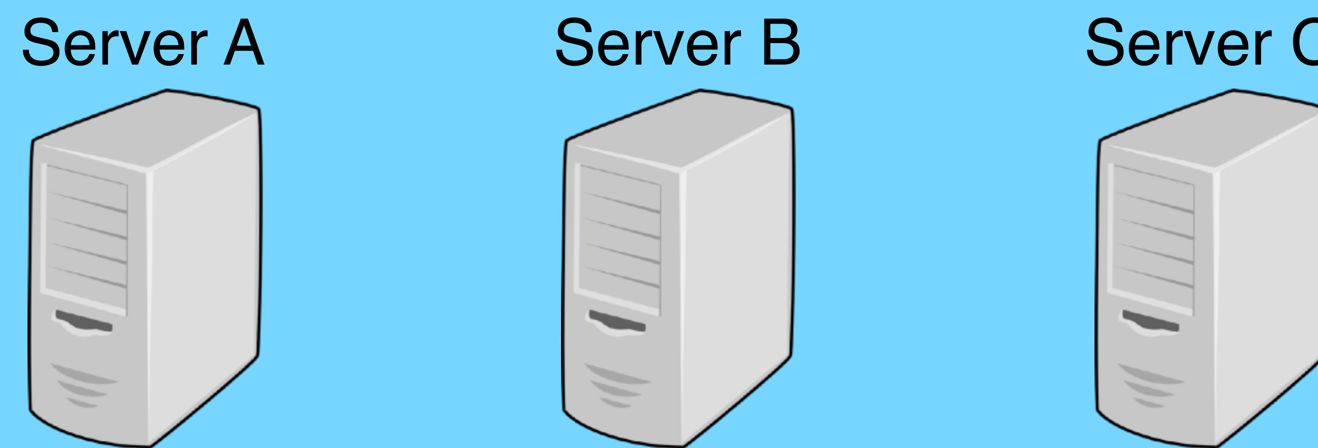

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Equivalently: that at least one server is honest.

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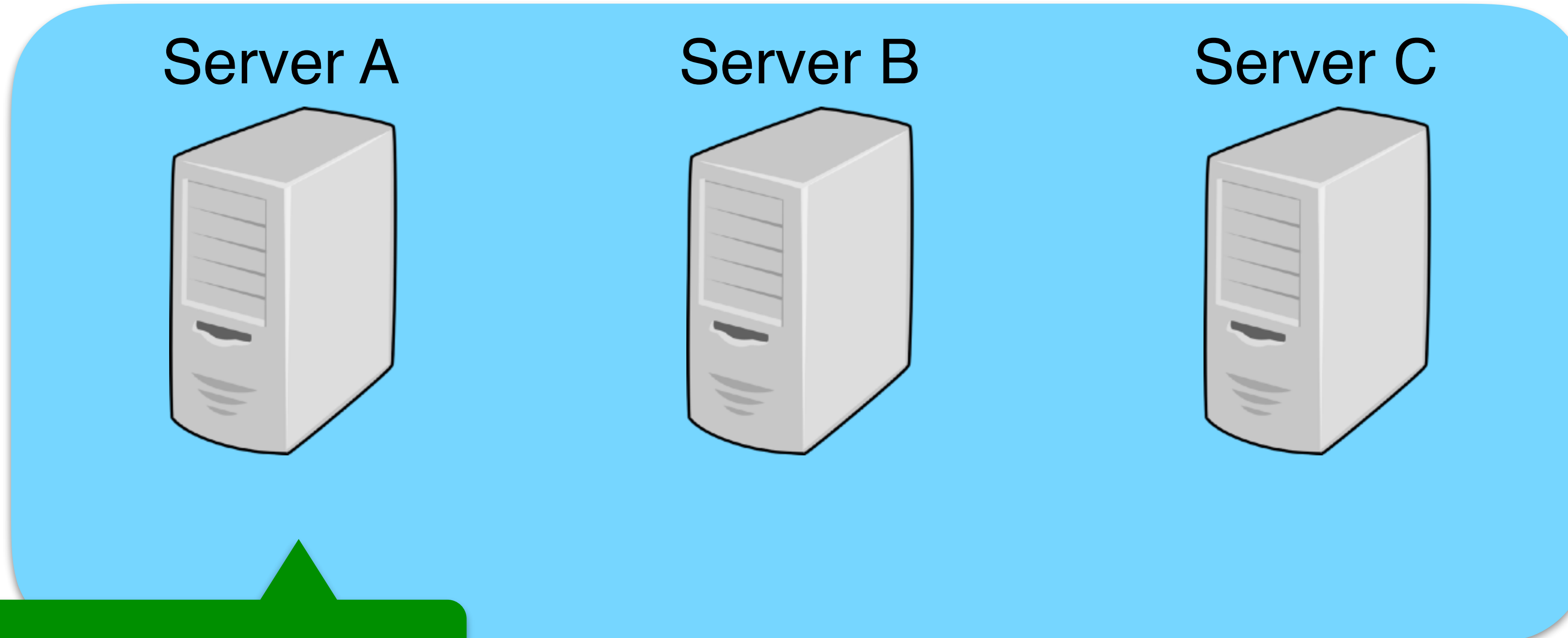

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App store

App

StressTracker

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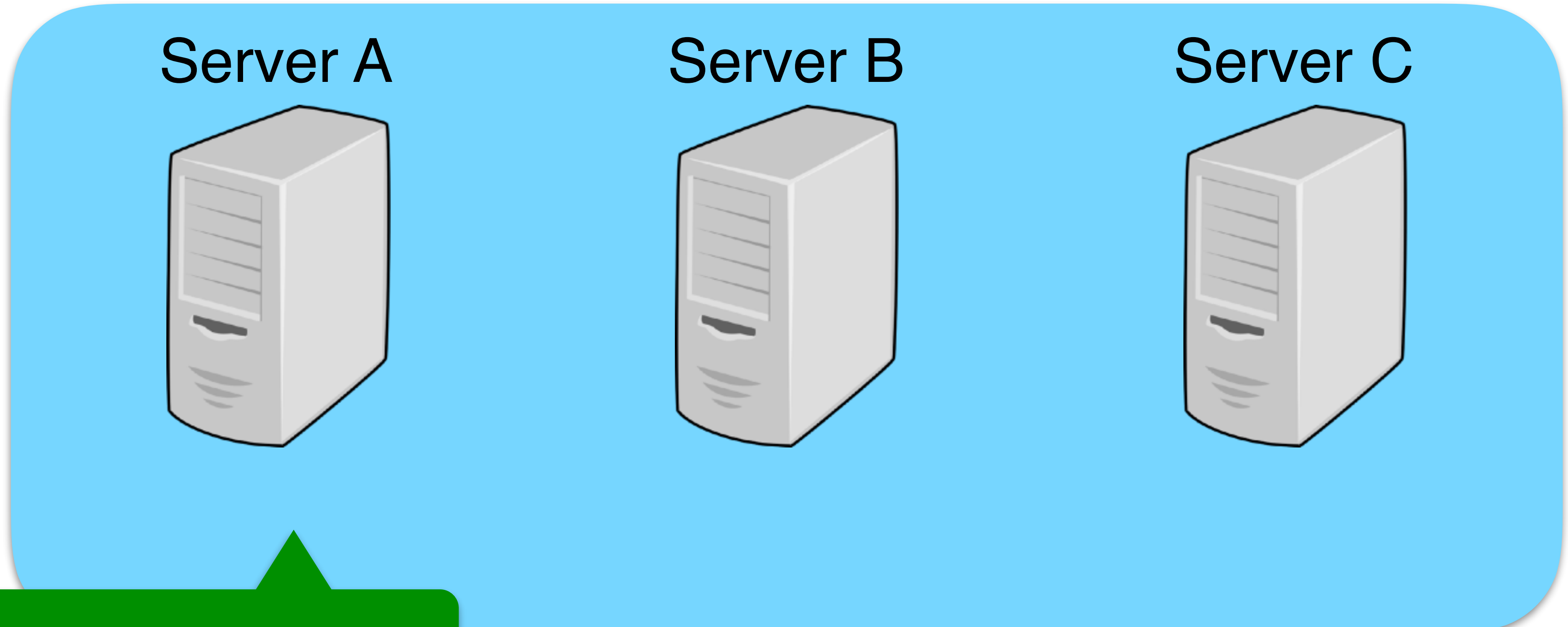

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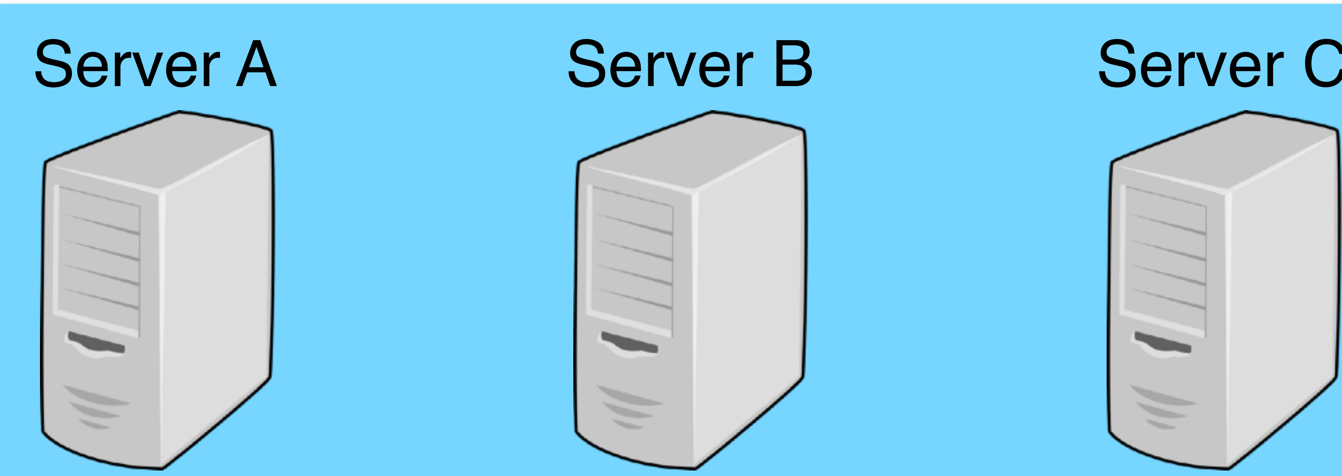

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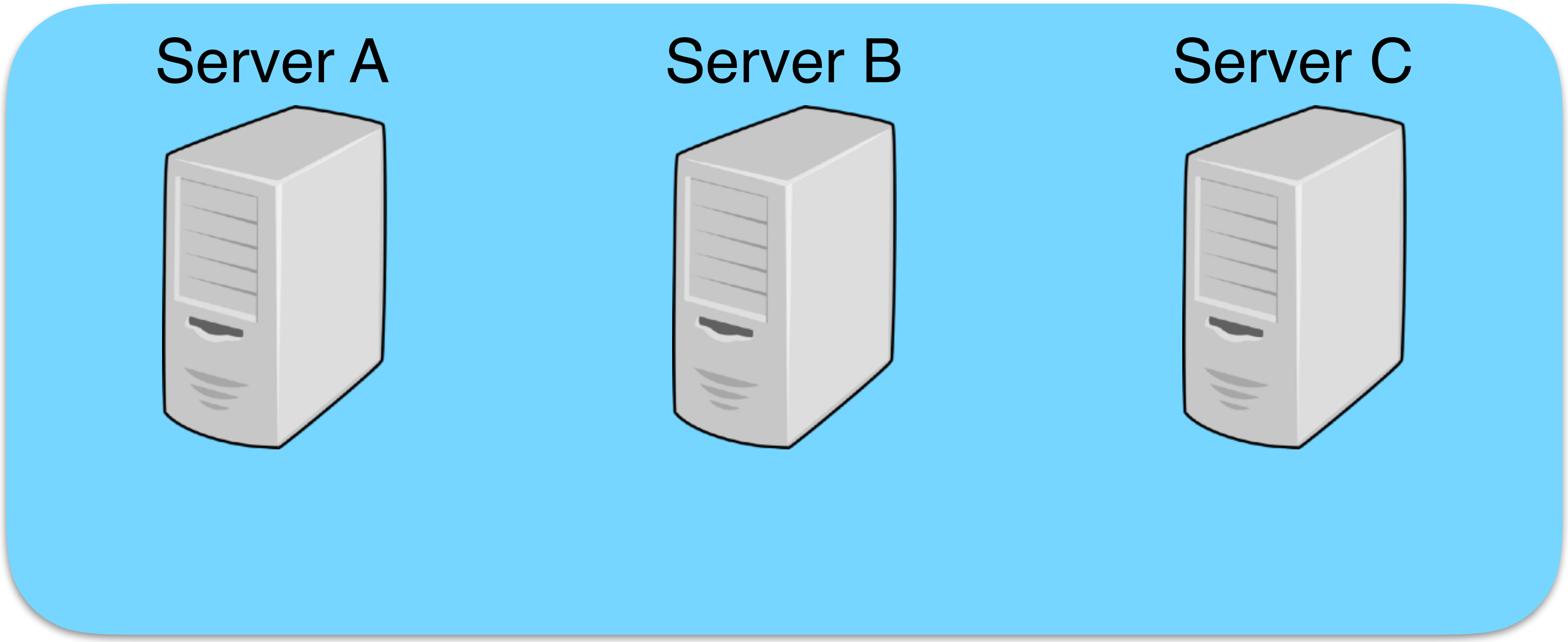

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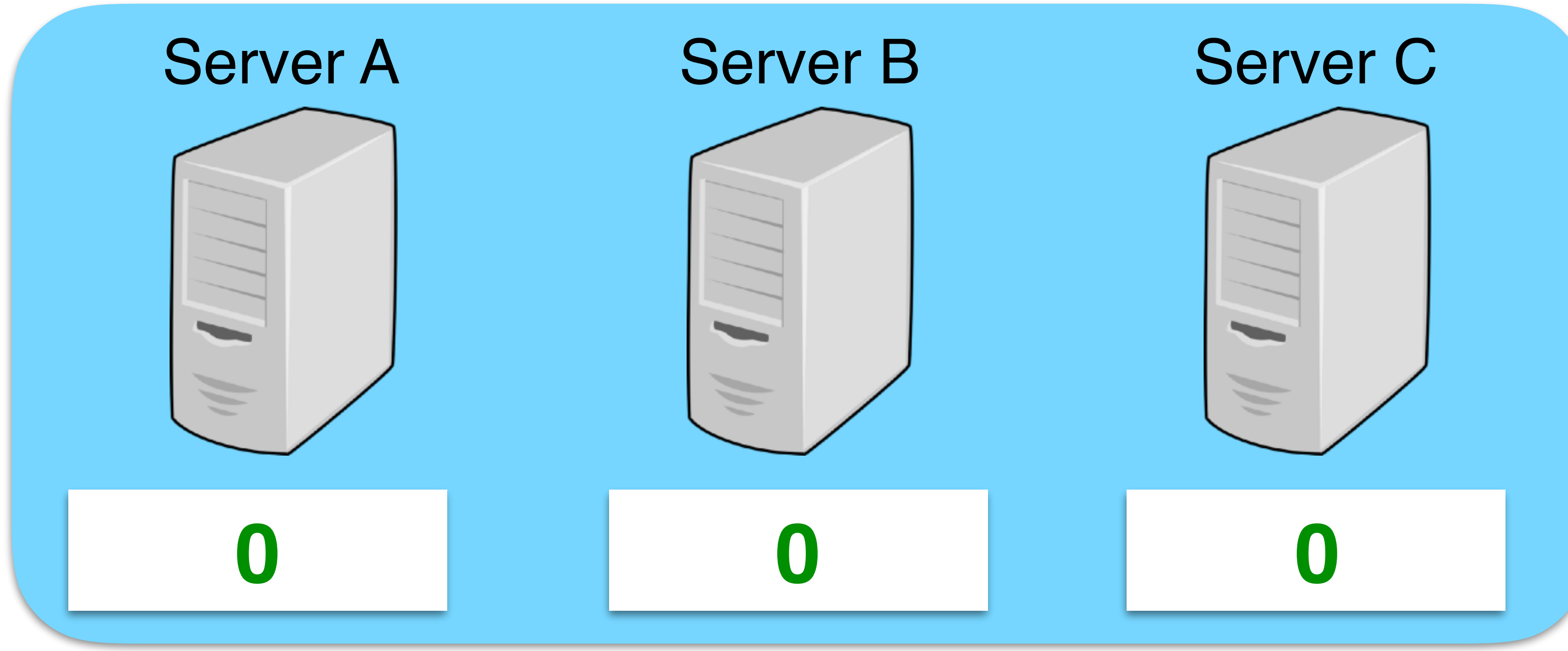

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<u>Secret sharing</u>

Pick three random "shares" that sum to 1.

$1 = 15 + (-12) + (-2) \pmod{31}$

Need all three shares to recover the shared value.

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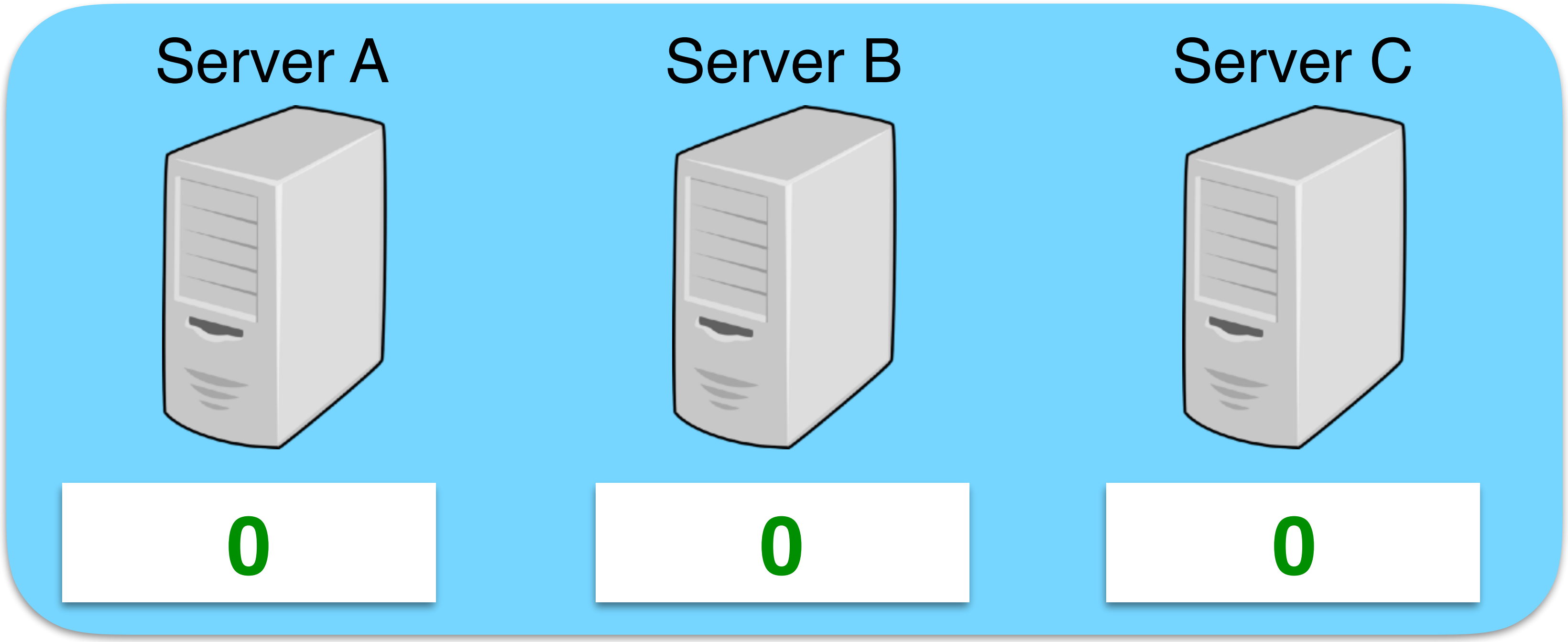

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In real system, we use a “big” prime

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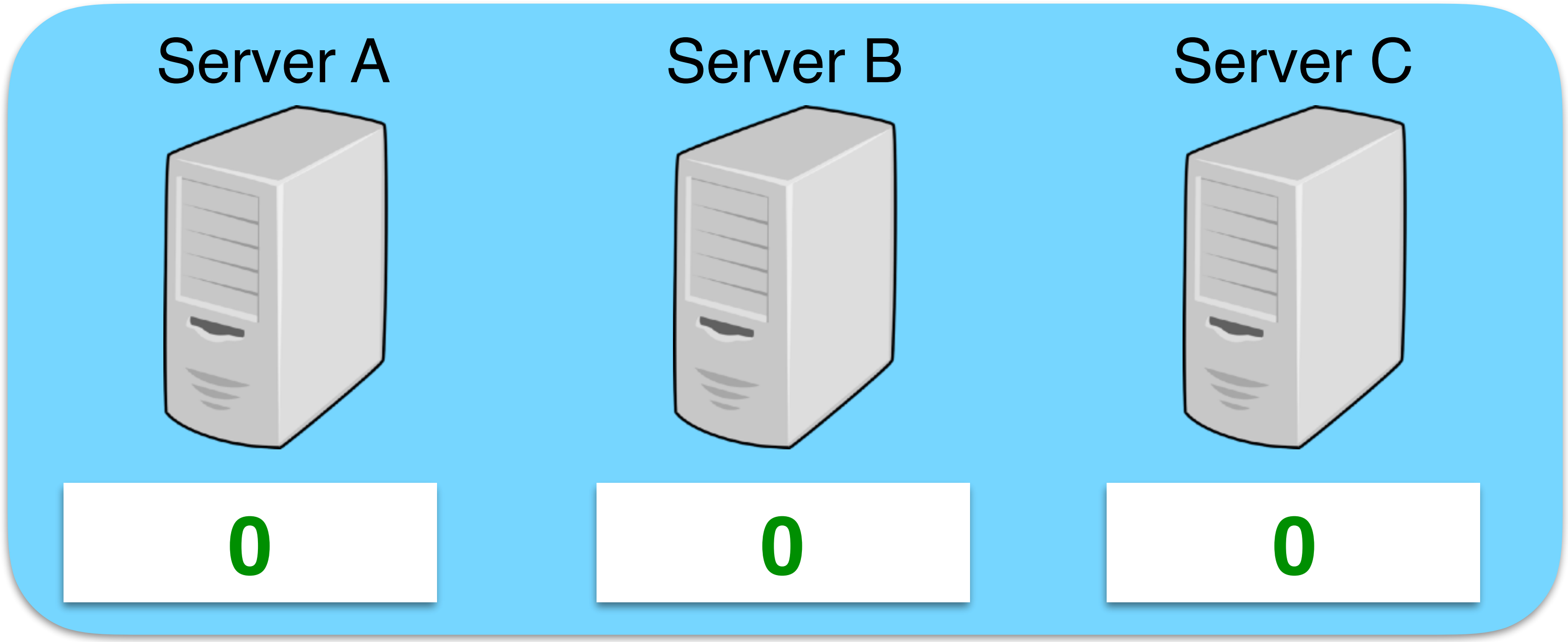

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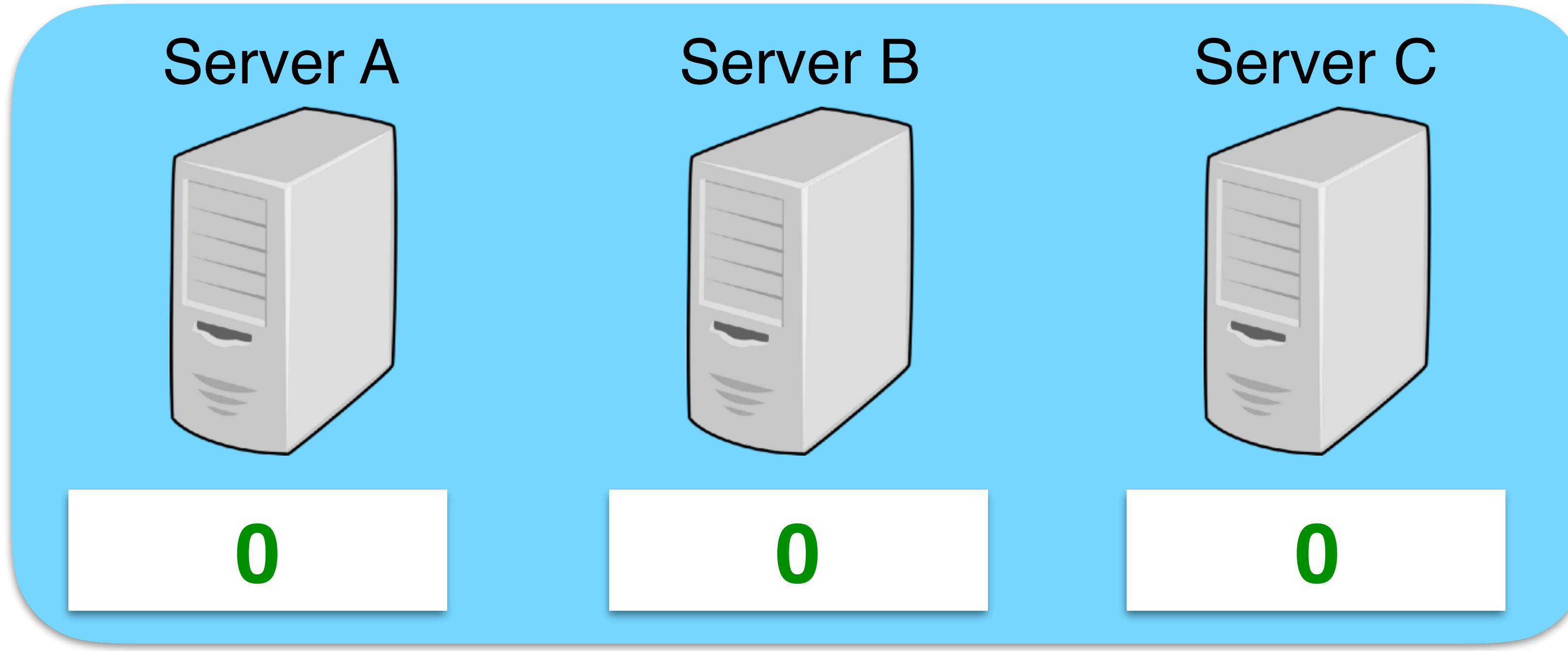

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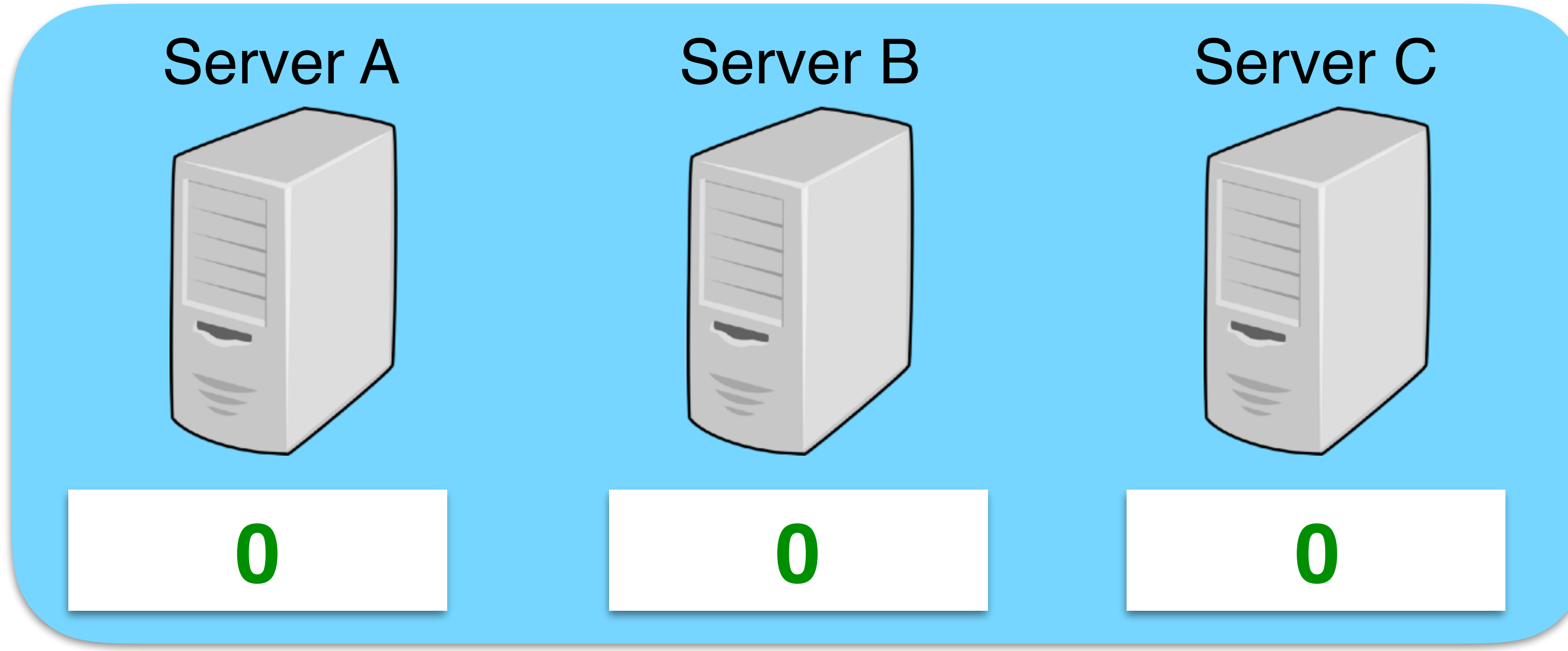

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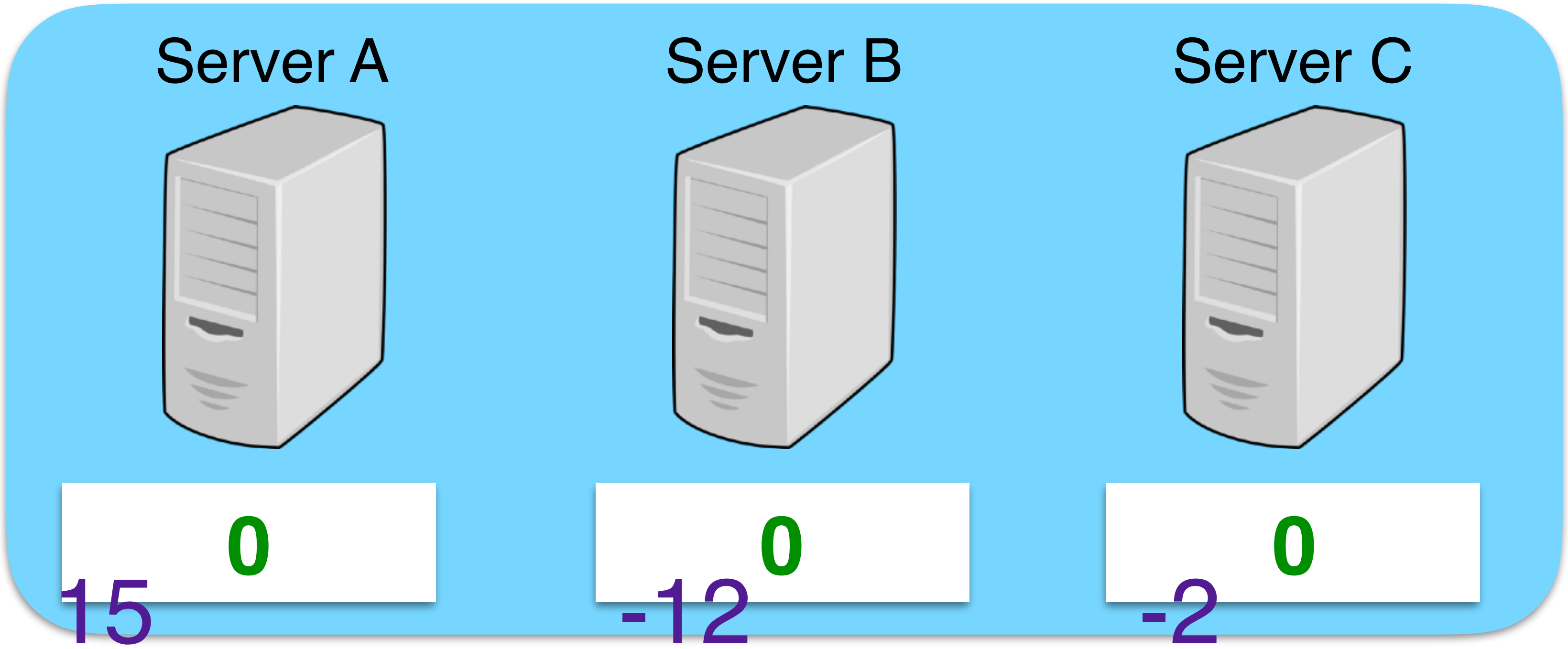

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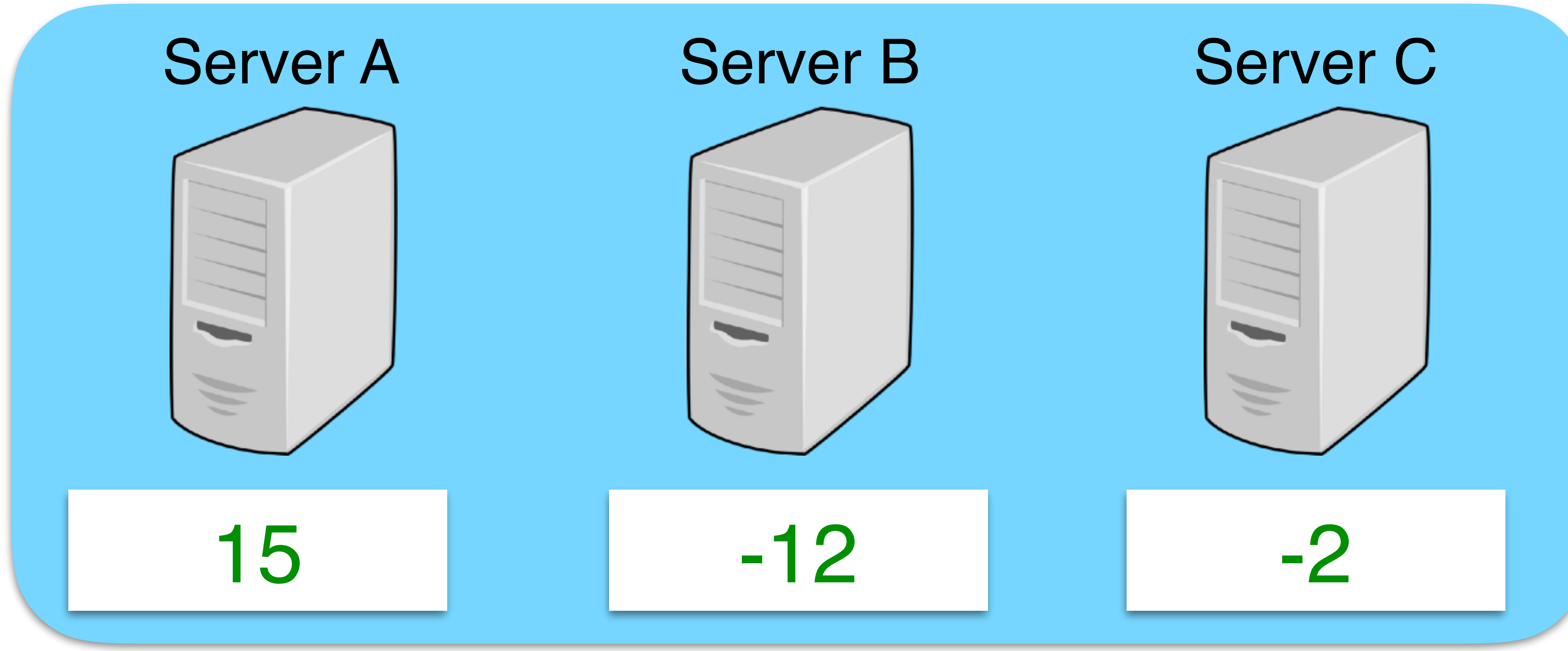

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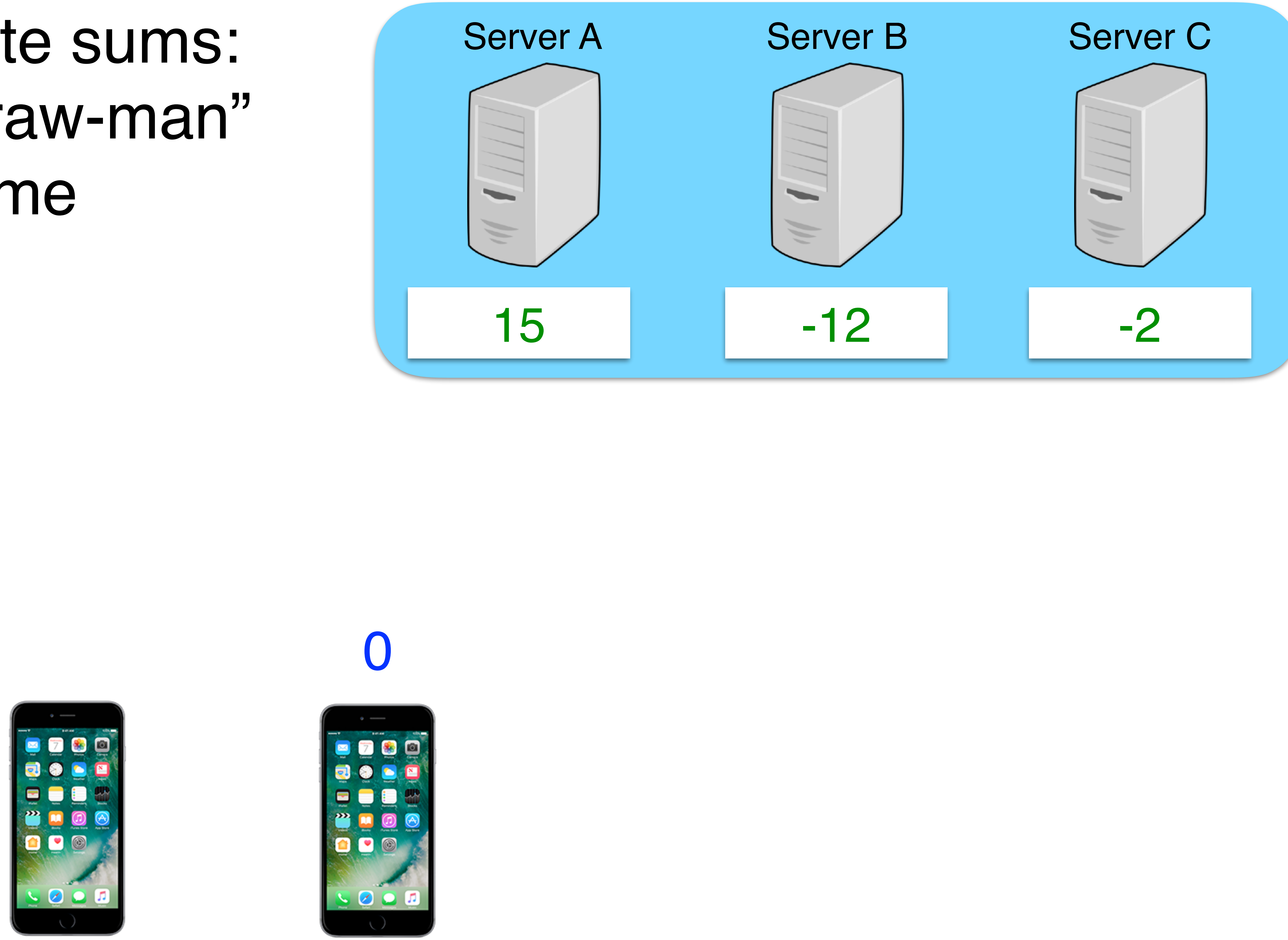

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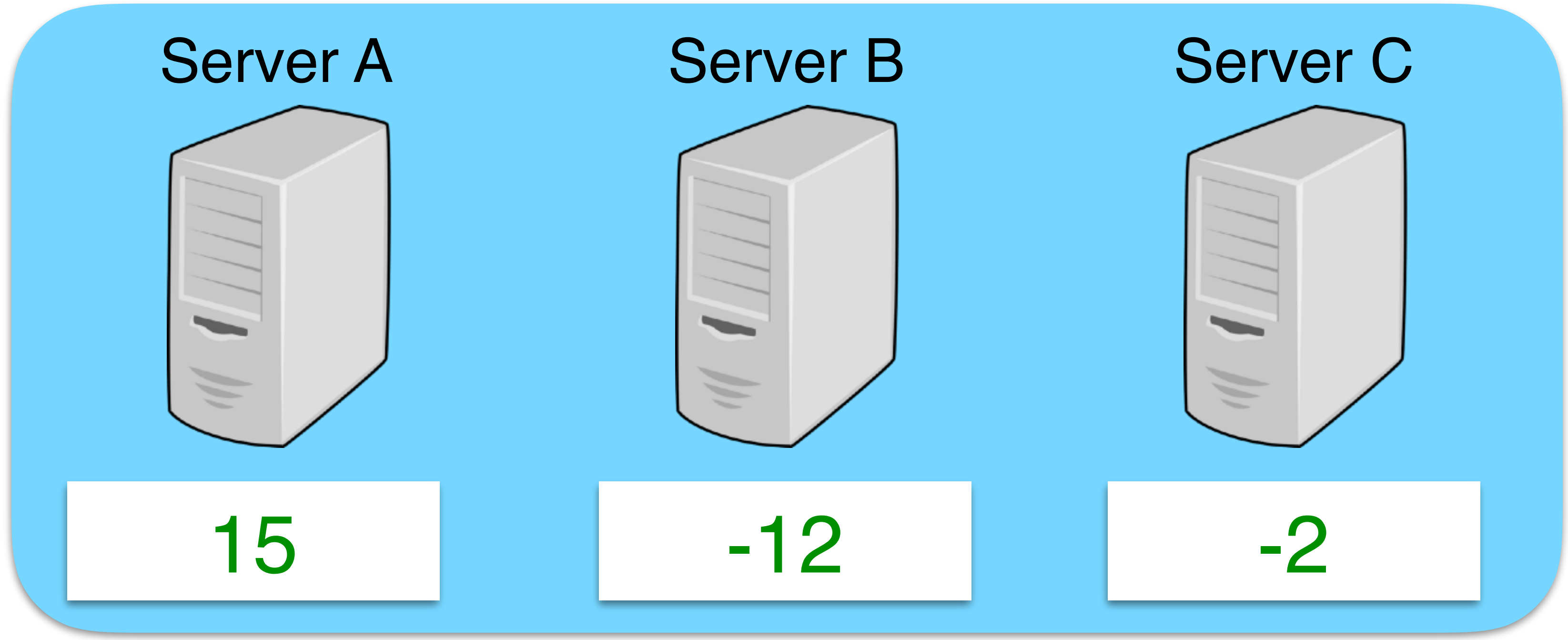

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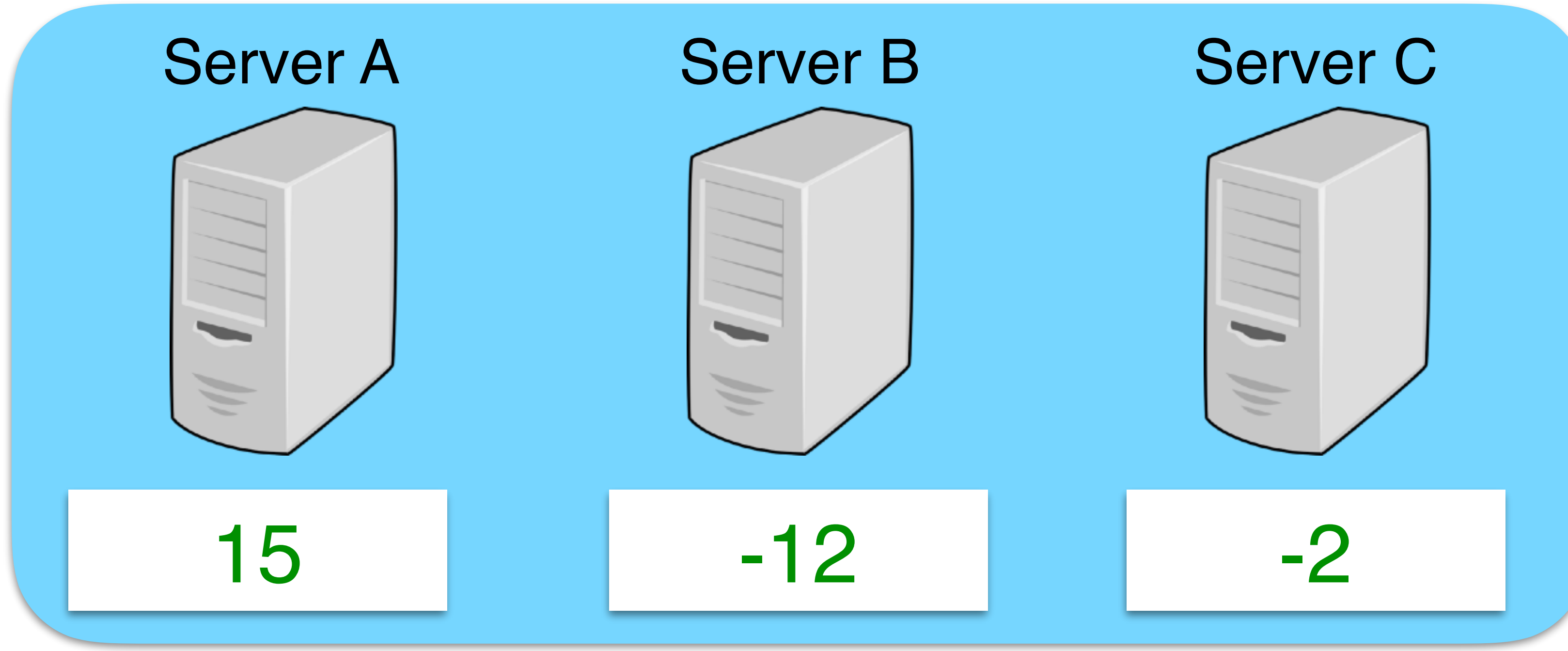

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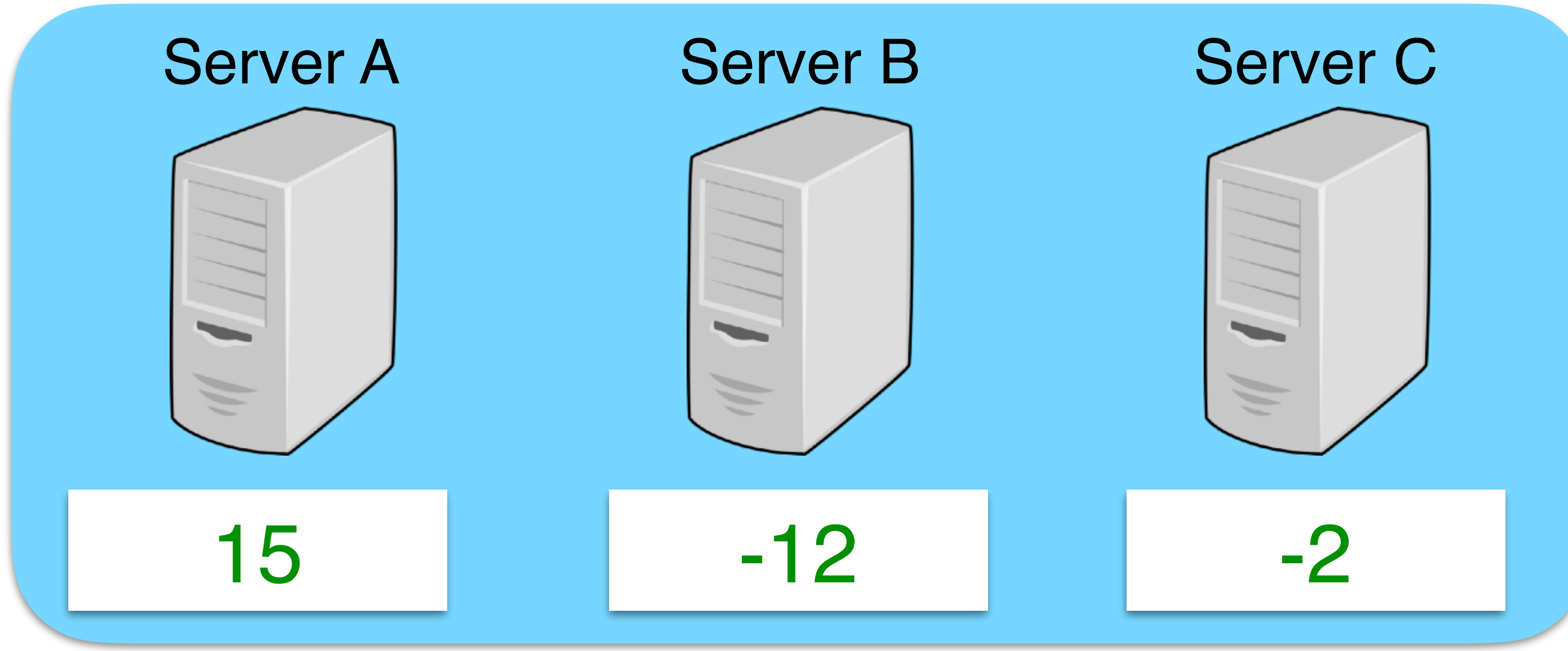

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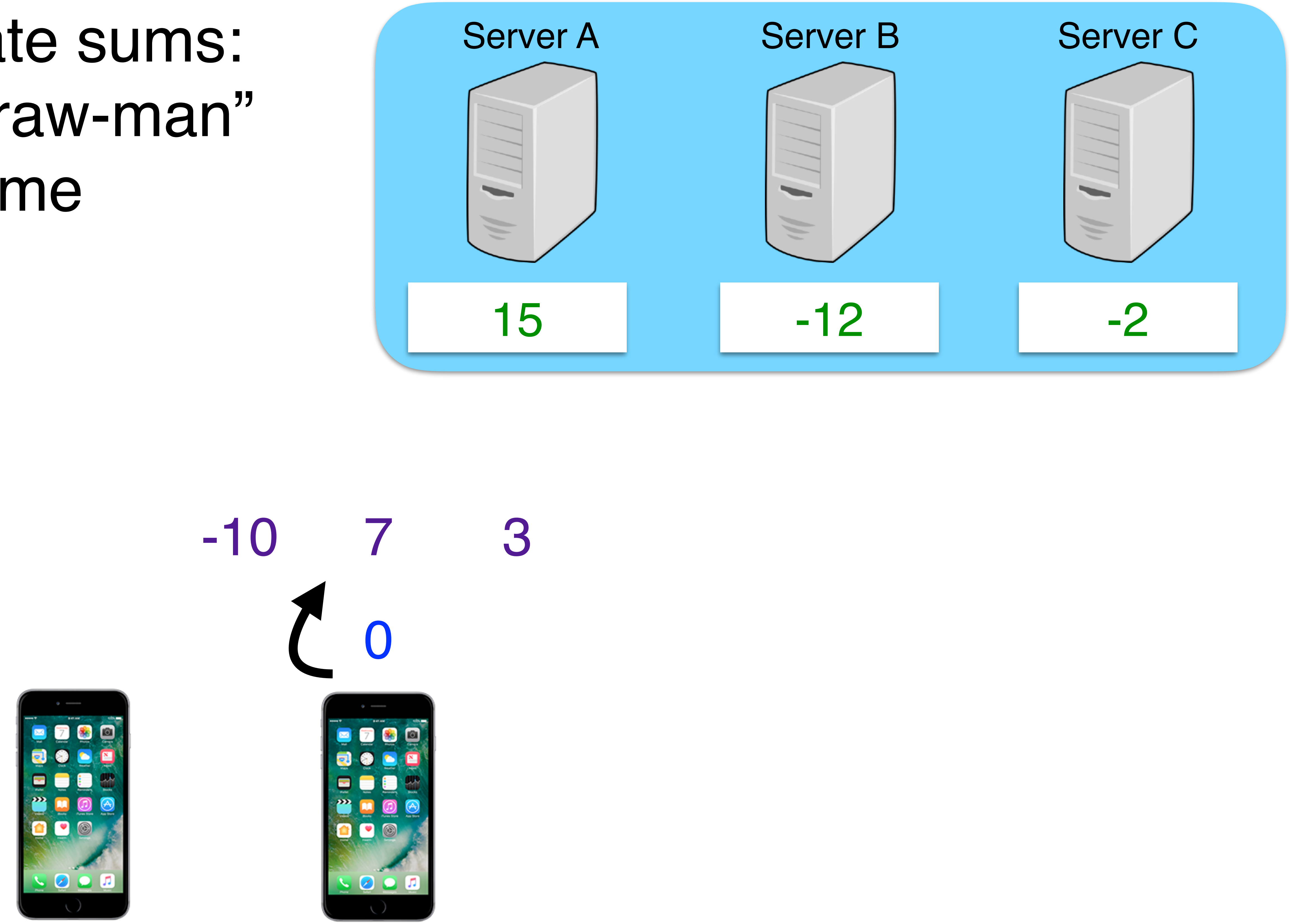

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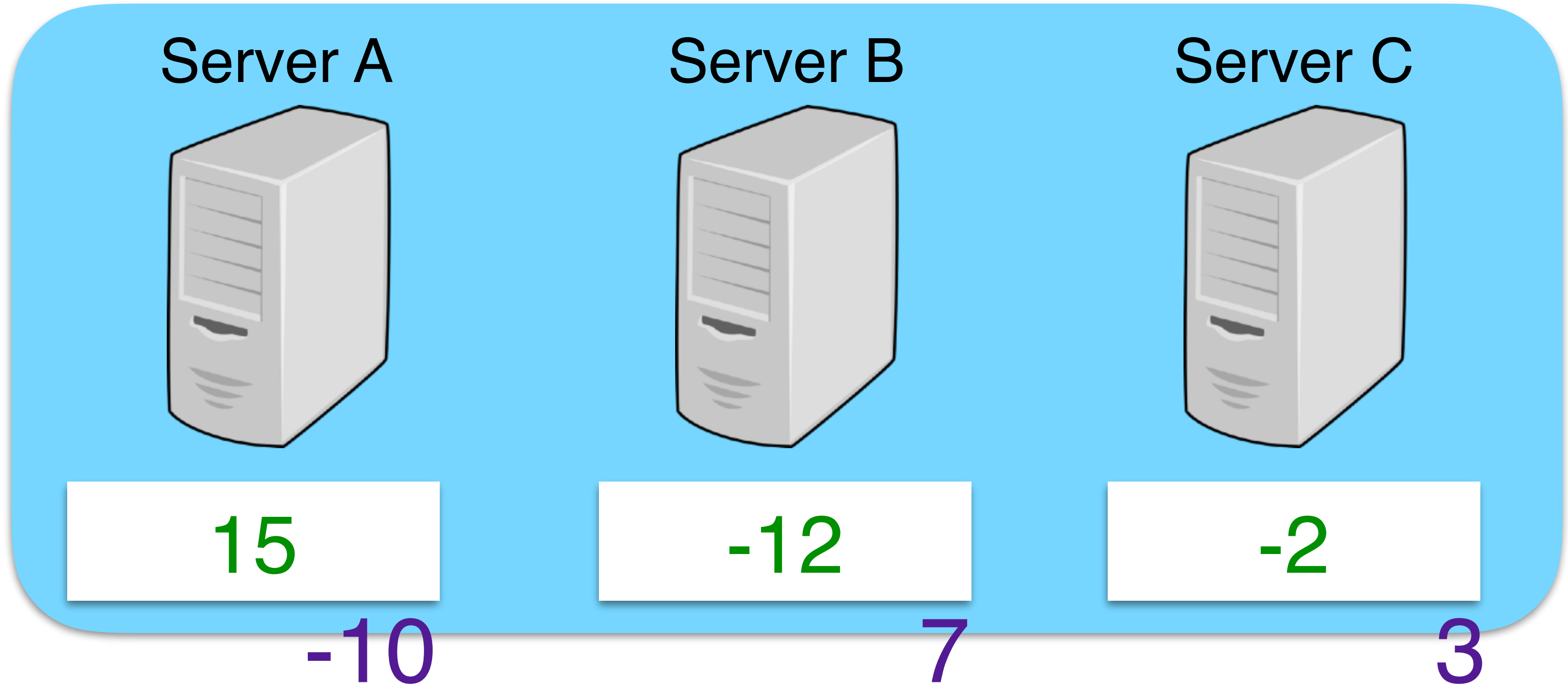

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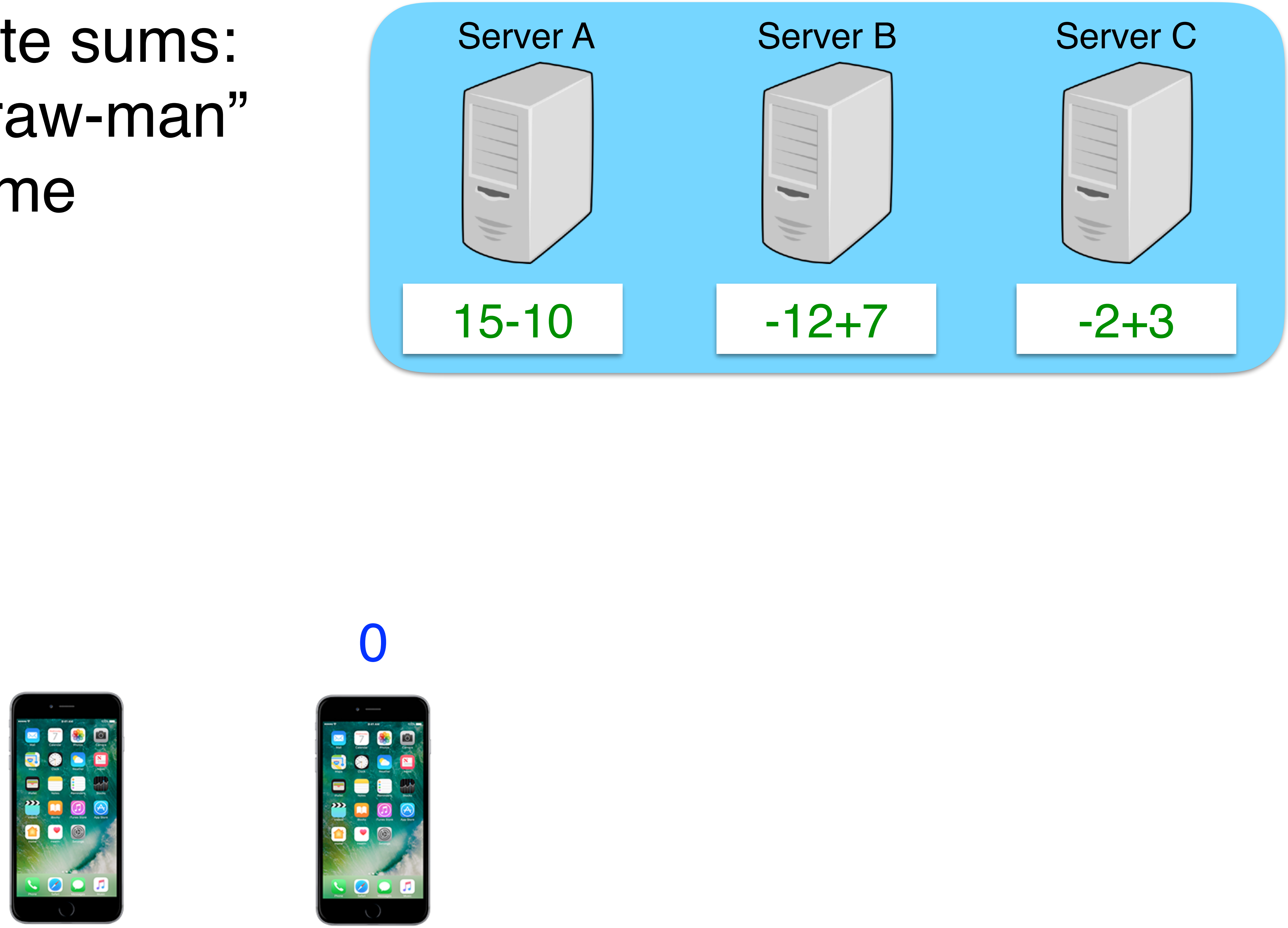

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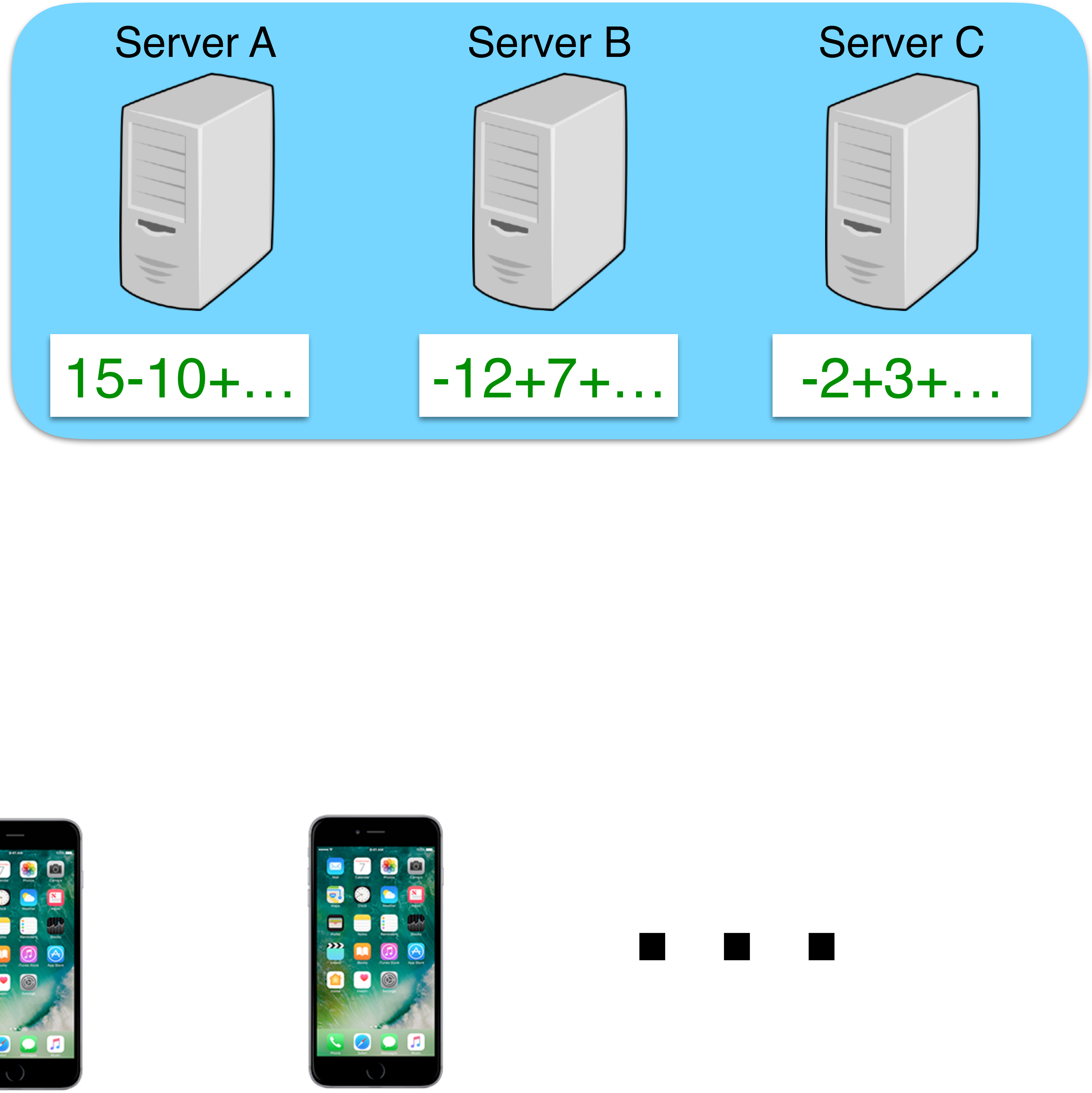

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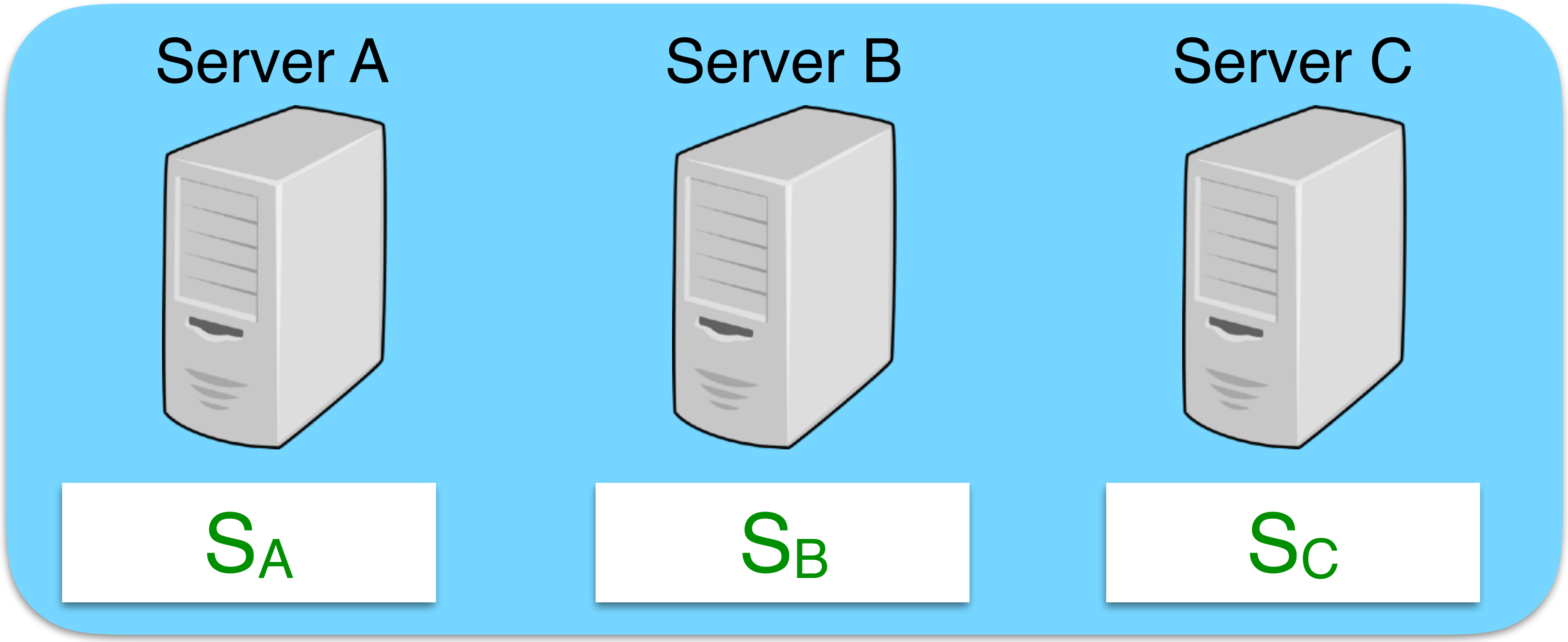

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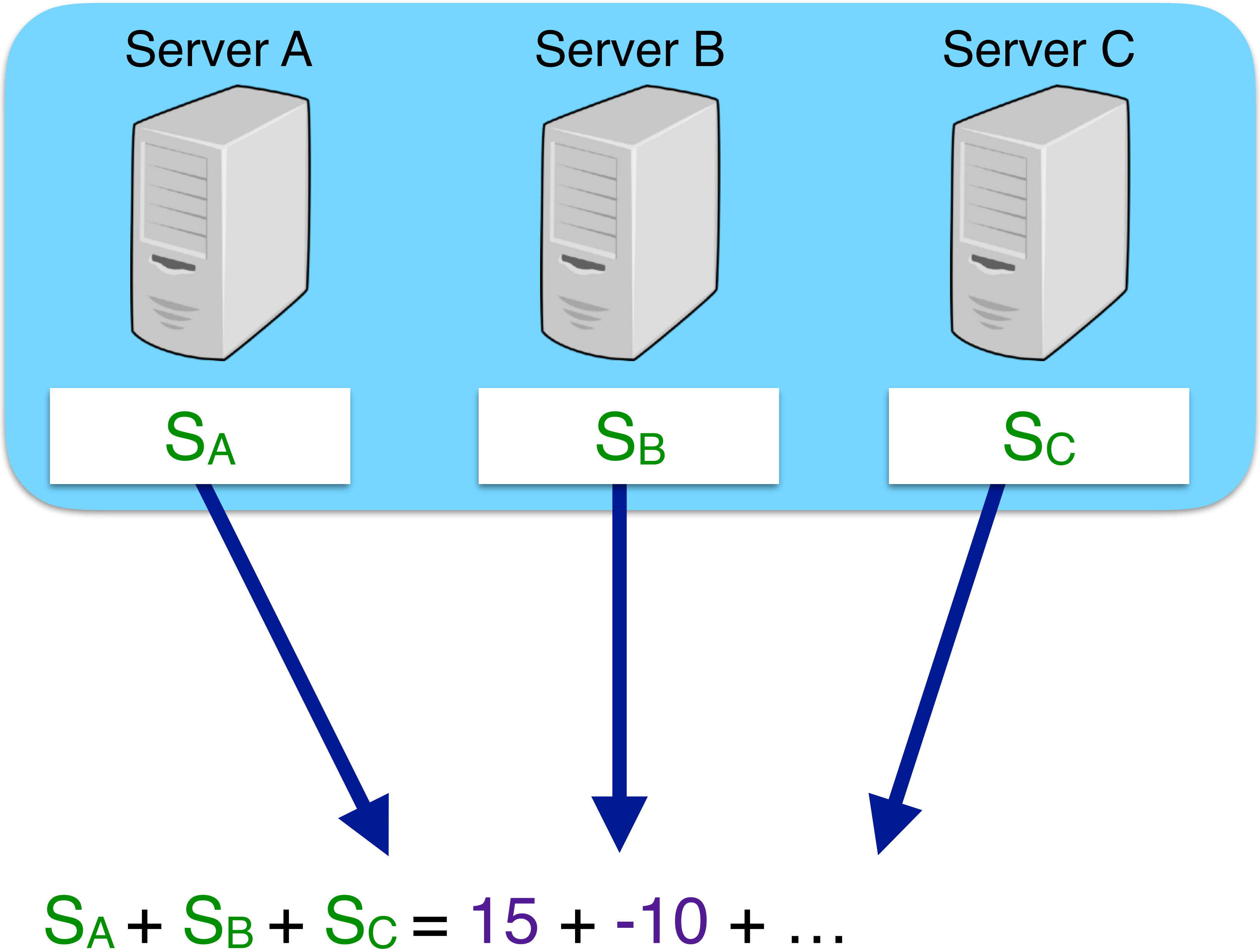

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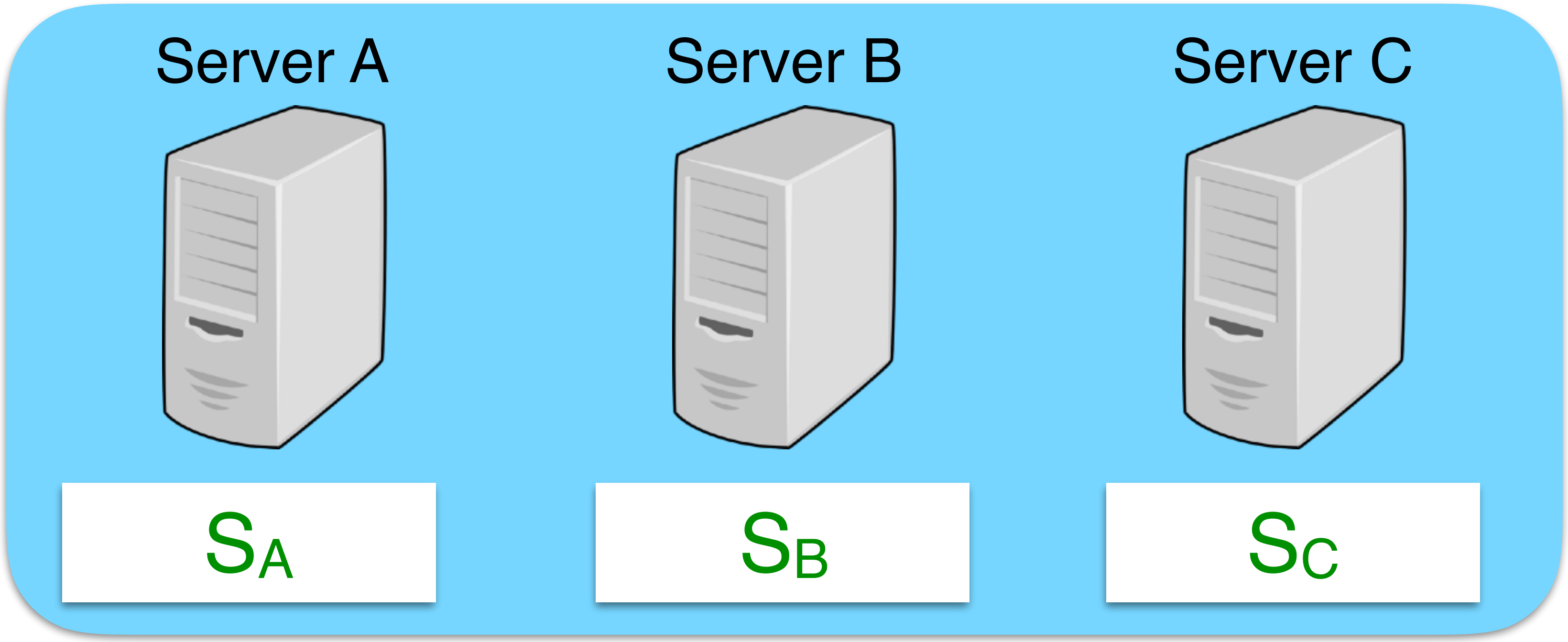

$S_A + S_B + S_C = 15 + -10 + \ldots$

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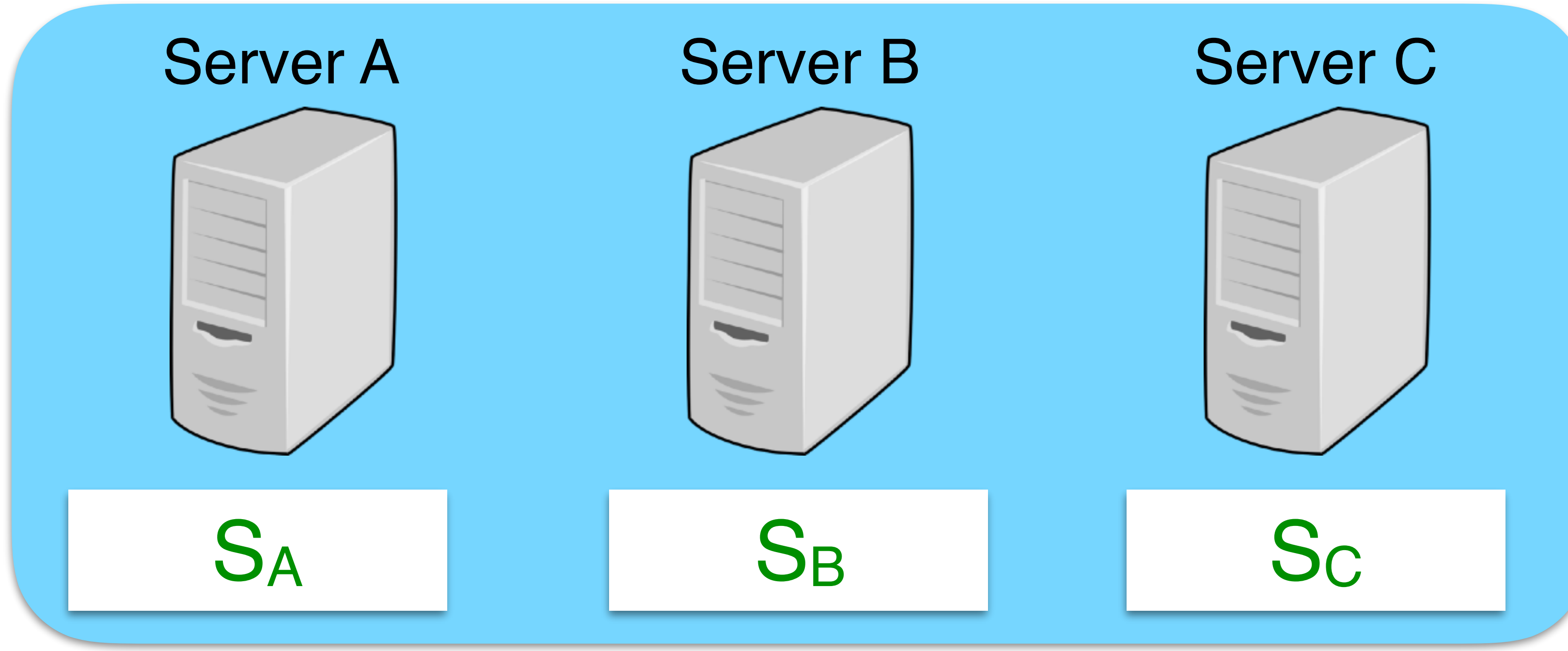

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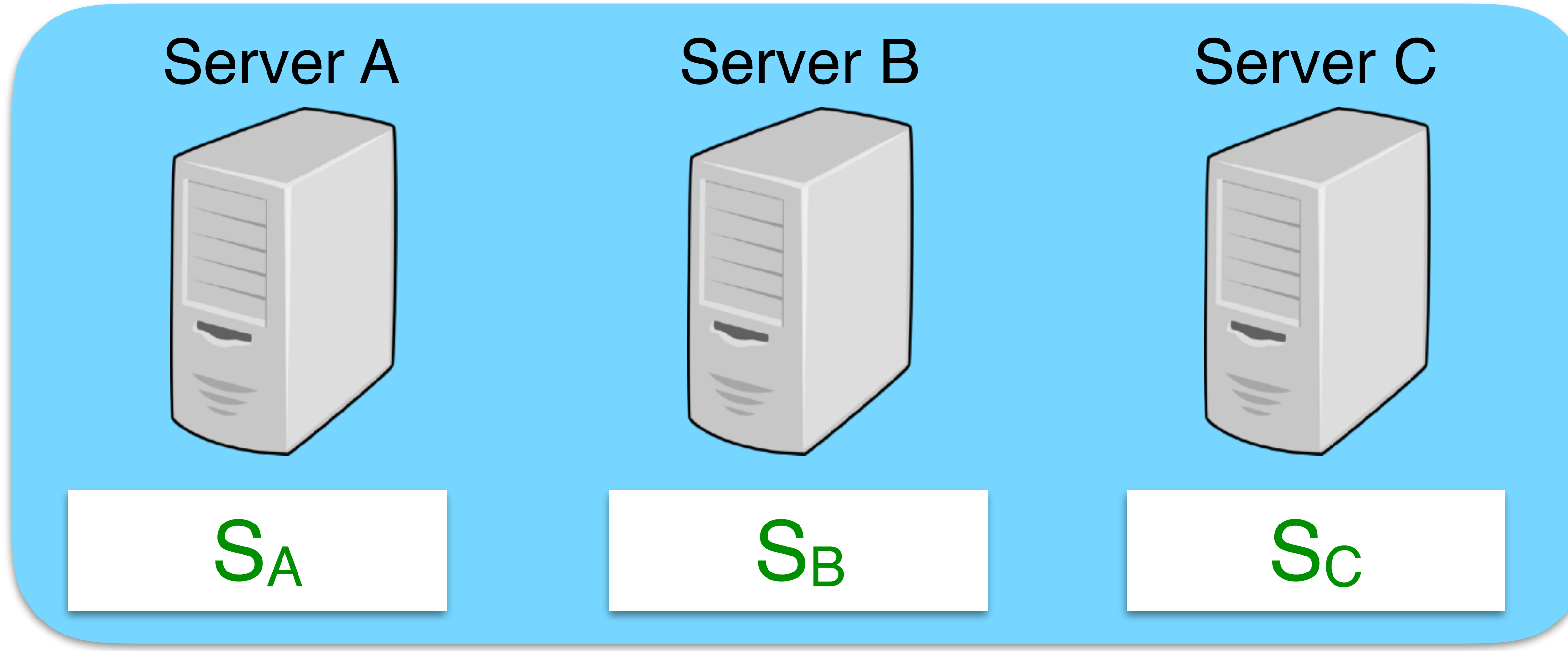

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Servers learn the sum of client values and learn *nothing else*.

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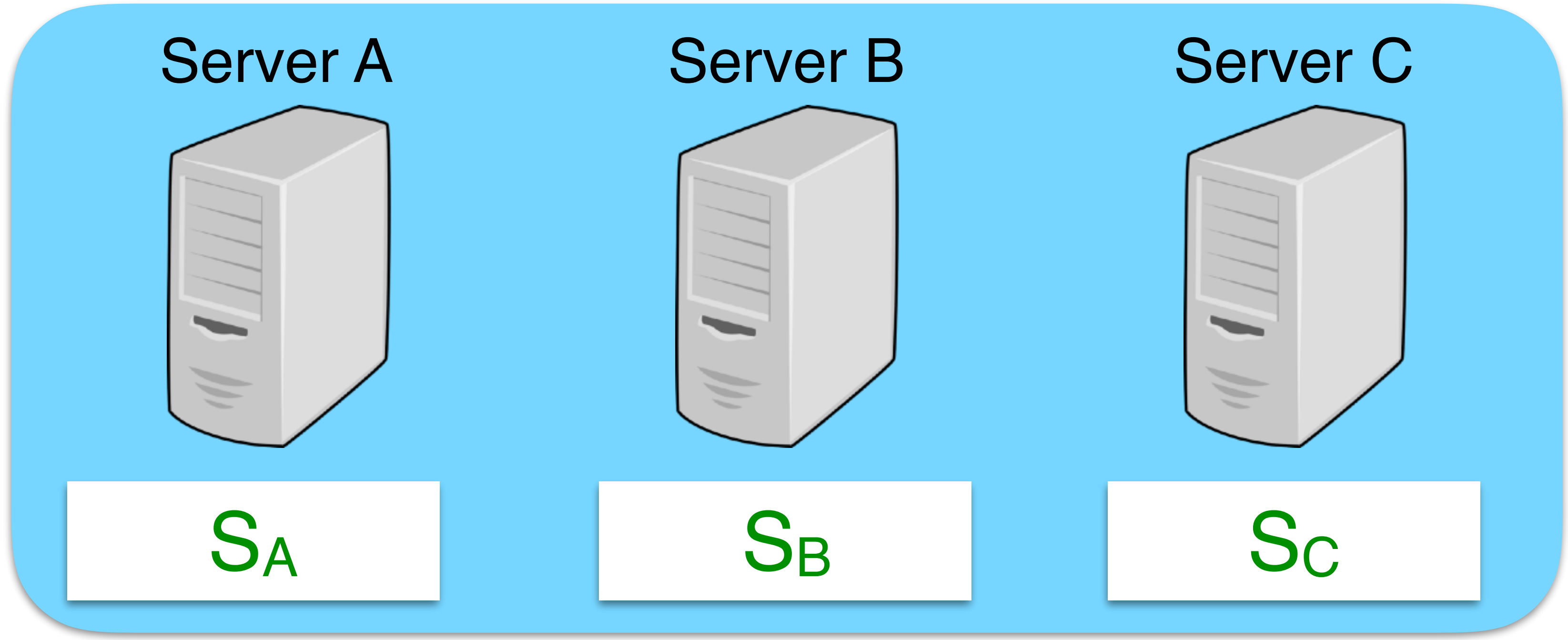

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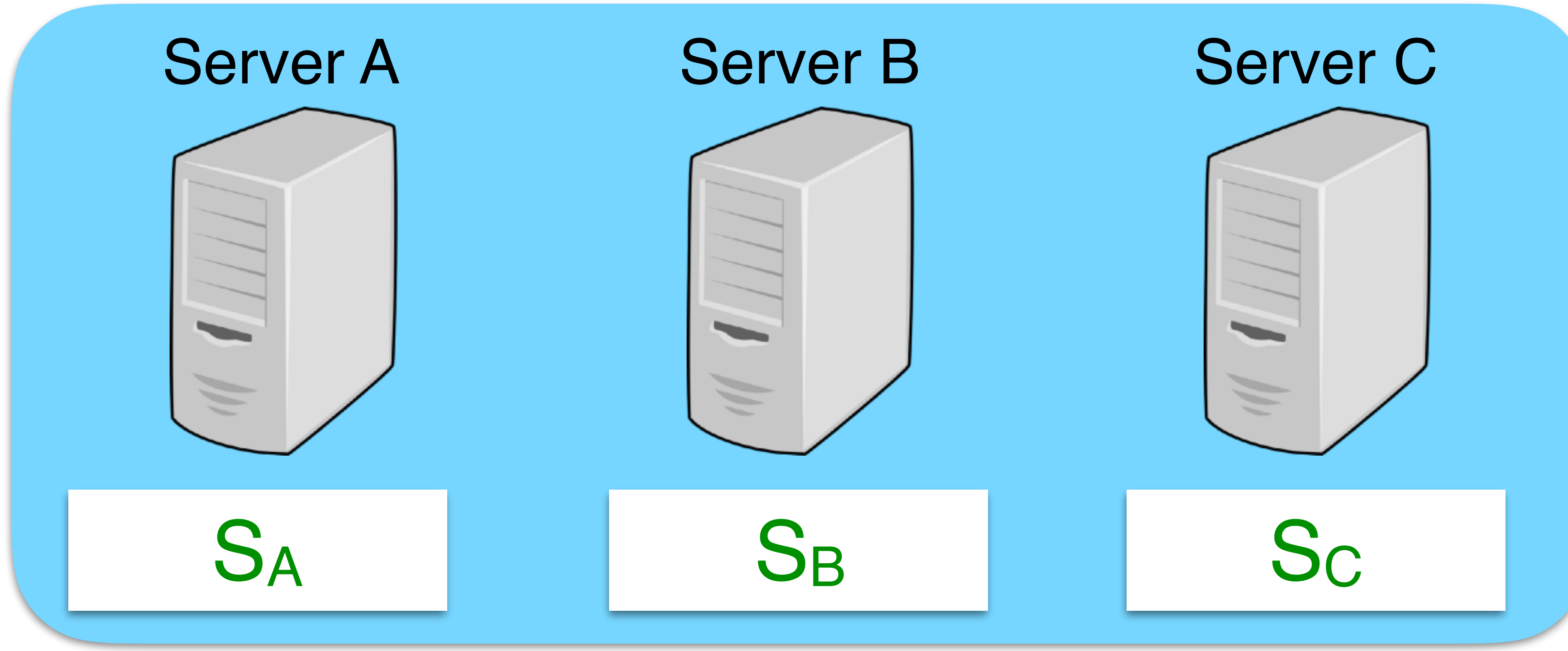

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Learn that three phones are on the Bay Bridge—don't know which three

Computing private sums

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Robustness: ???

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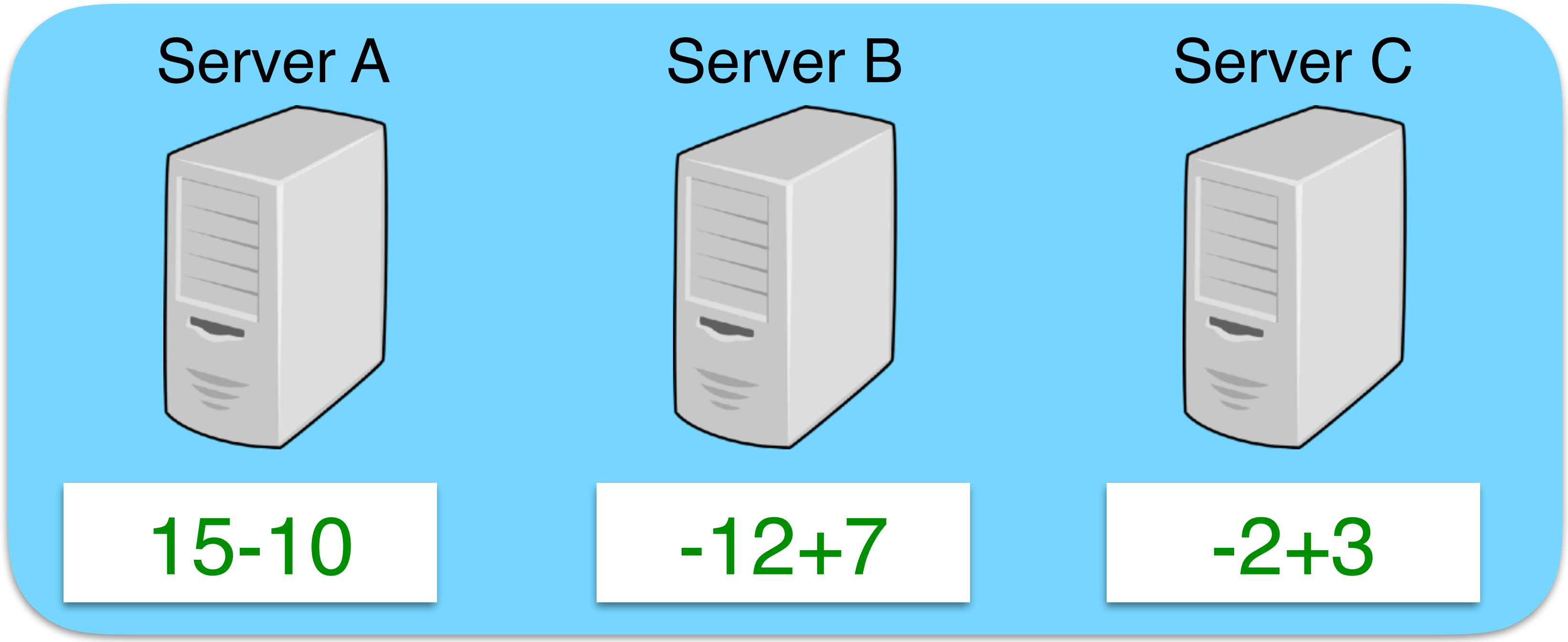

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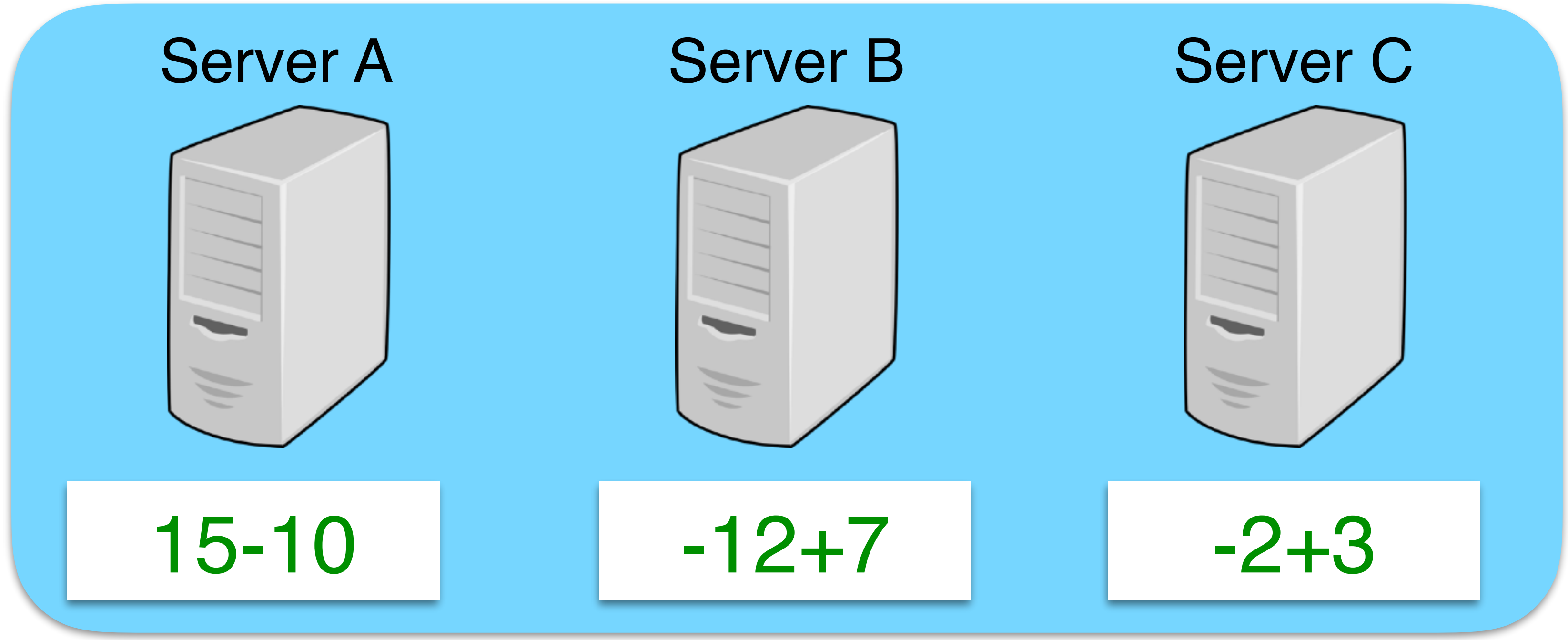

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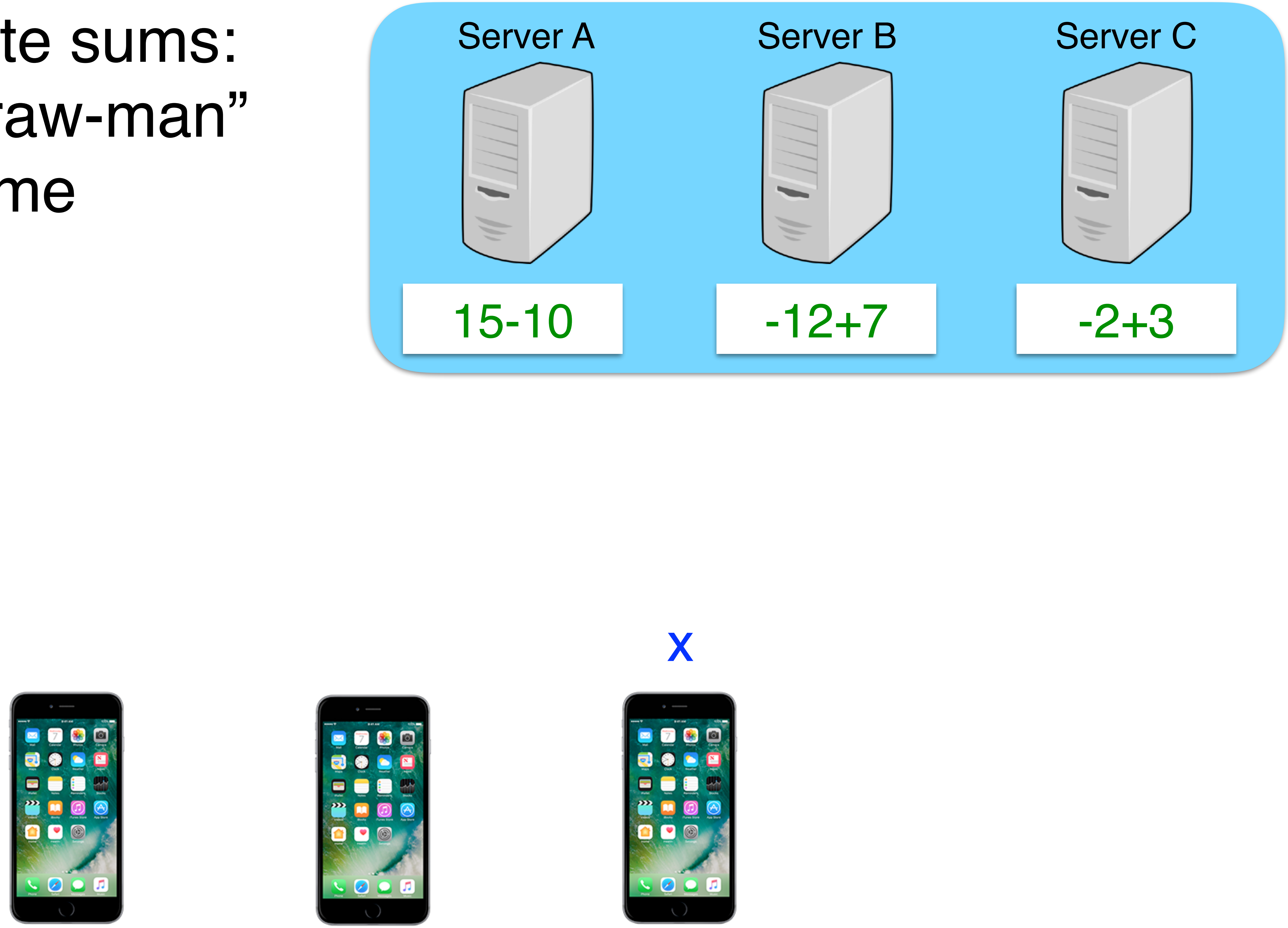

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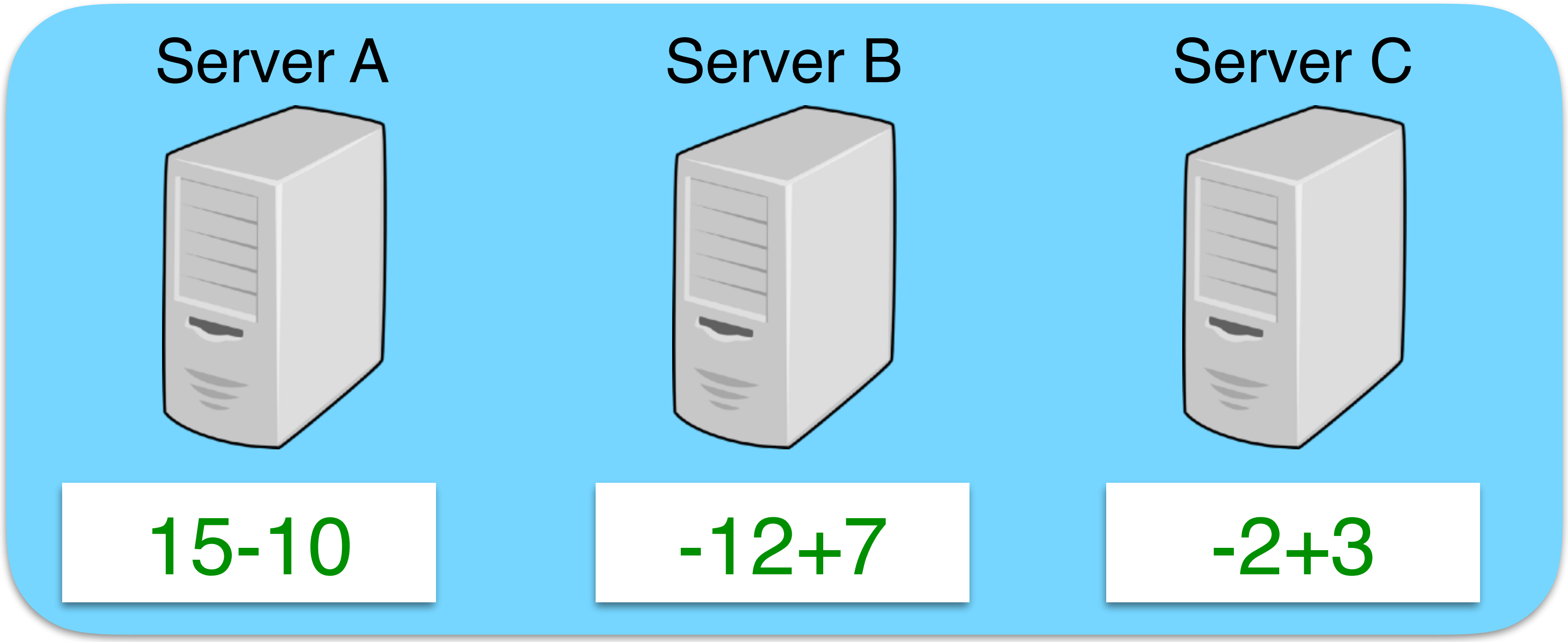

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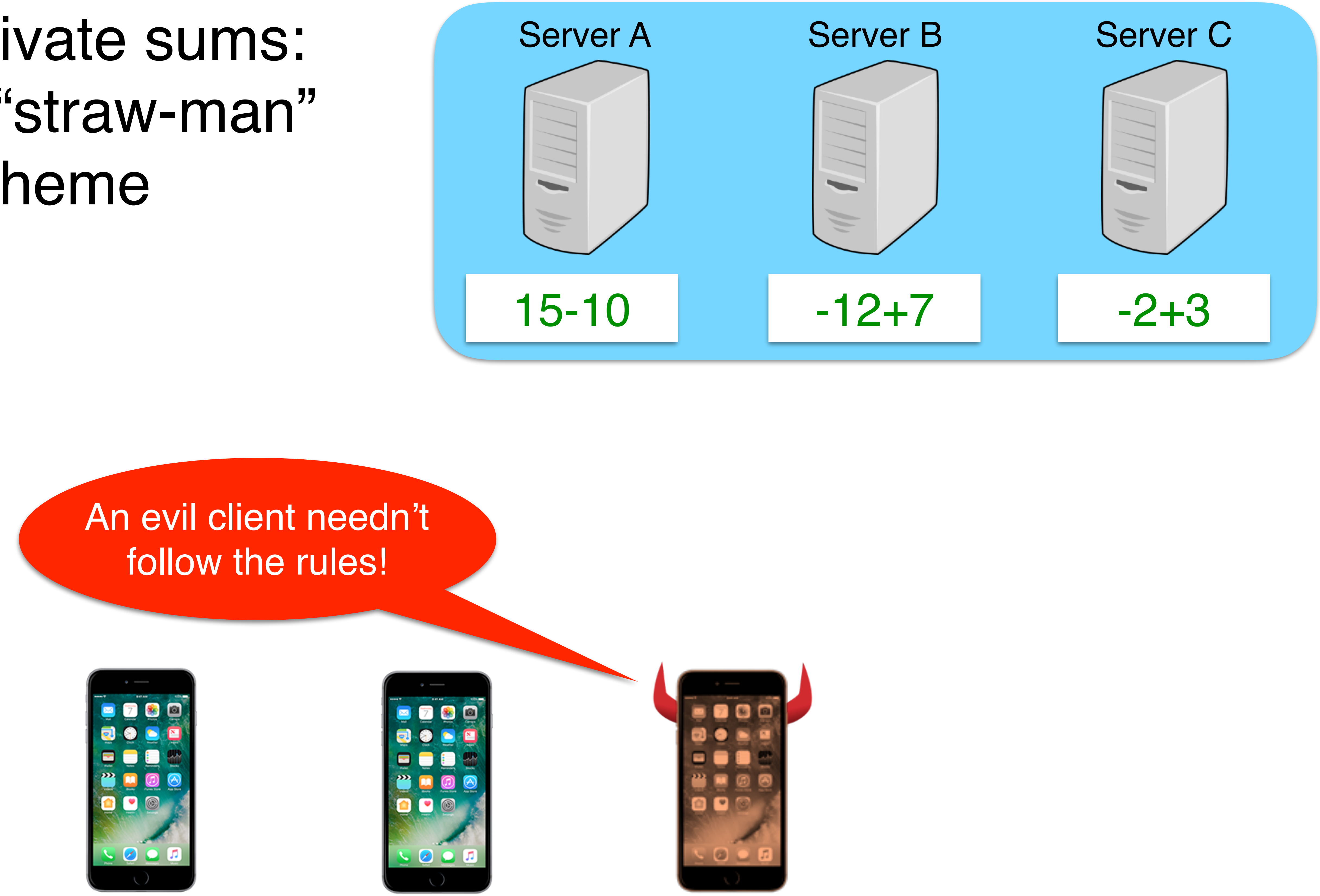

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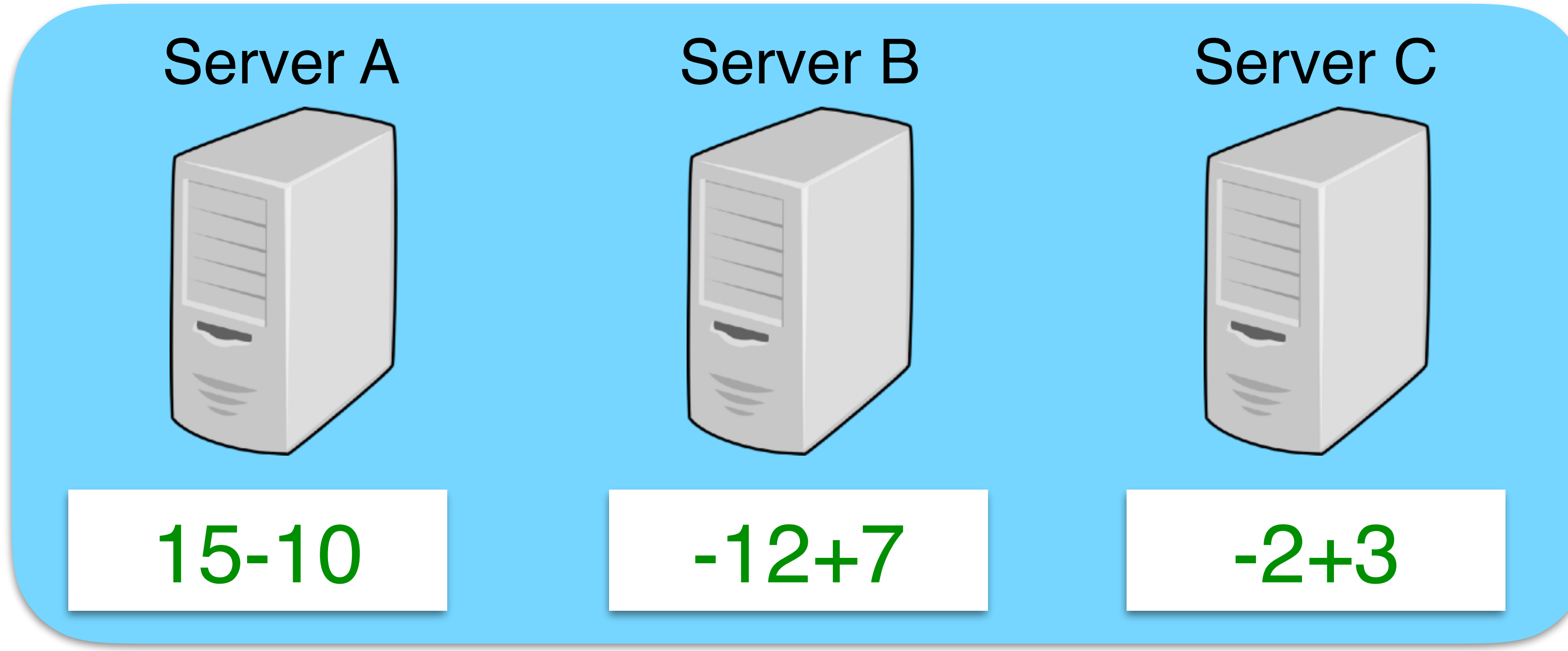

An evil client needn’t follow the rules!

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

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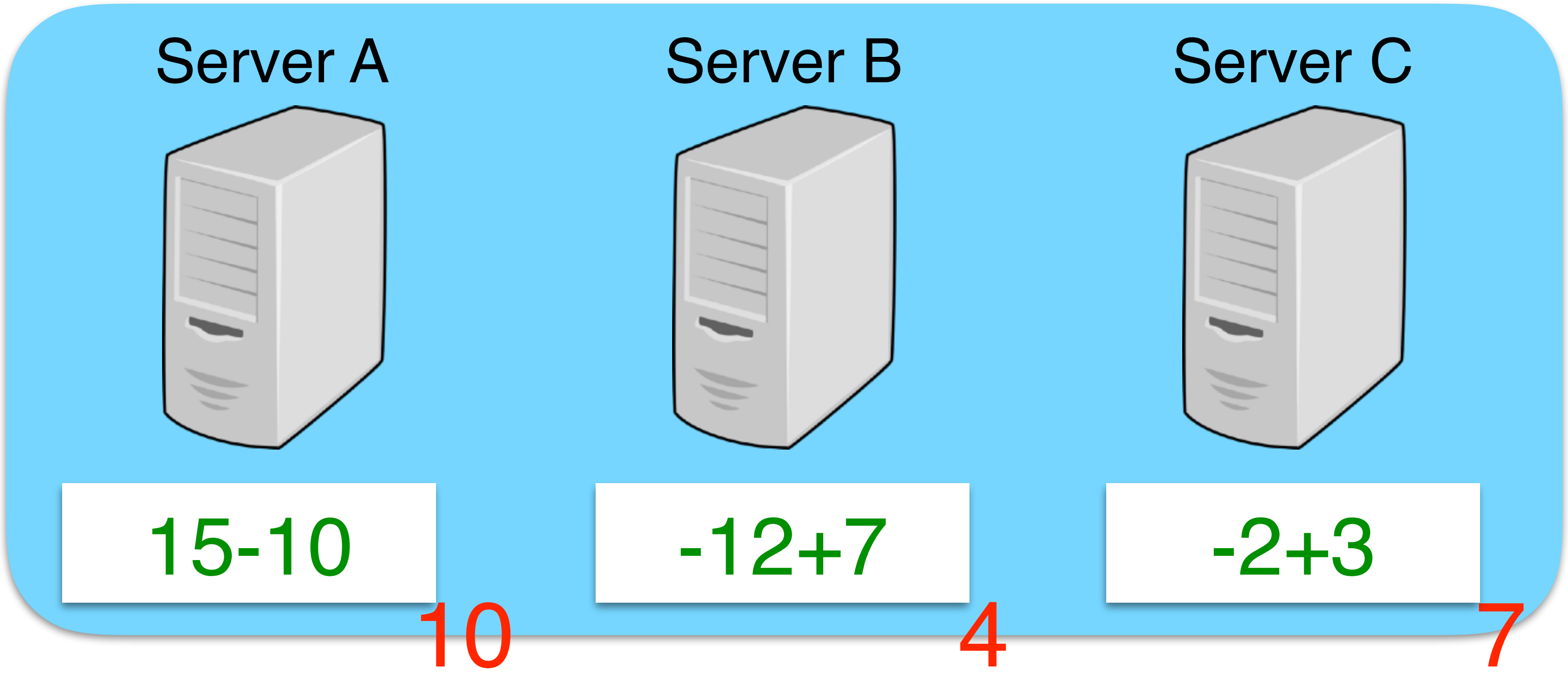

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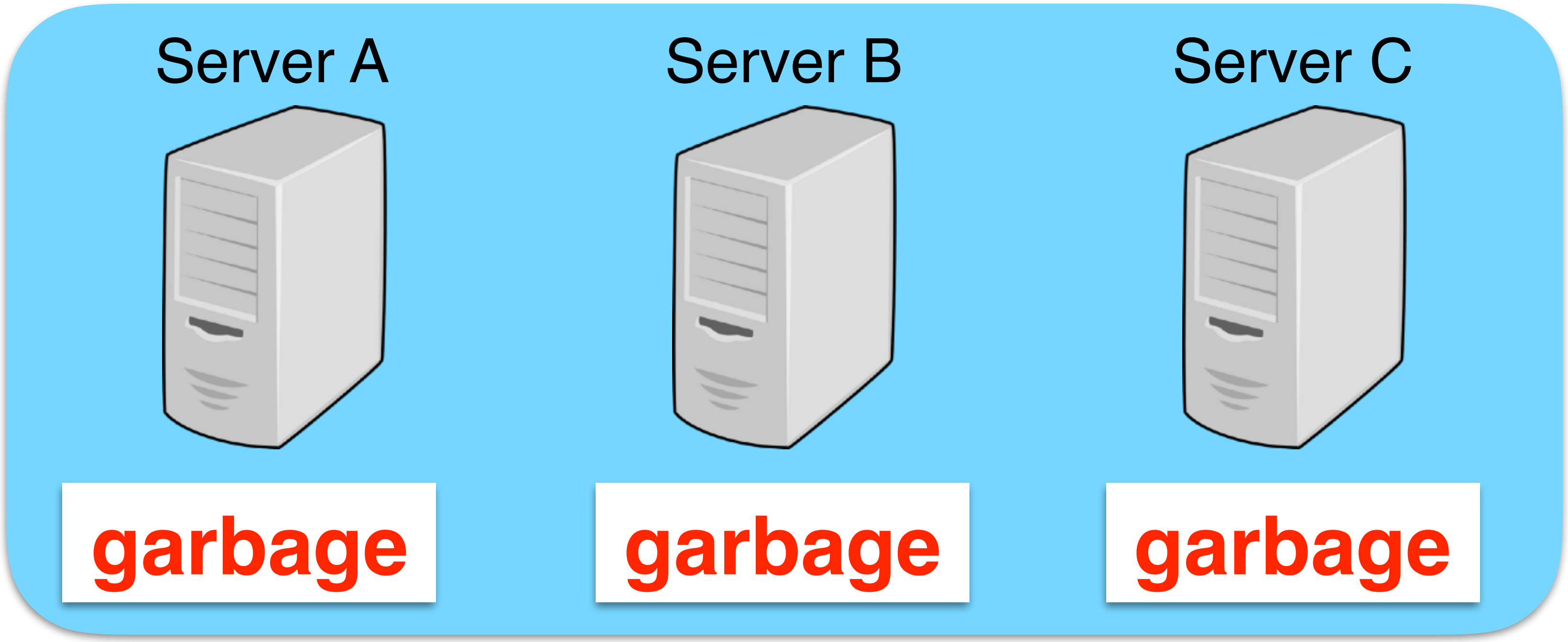

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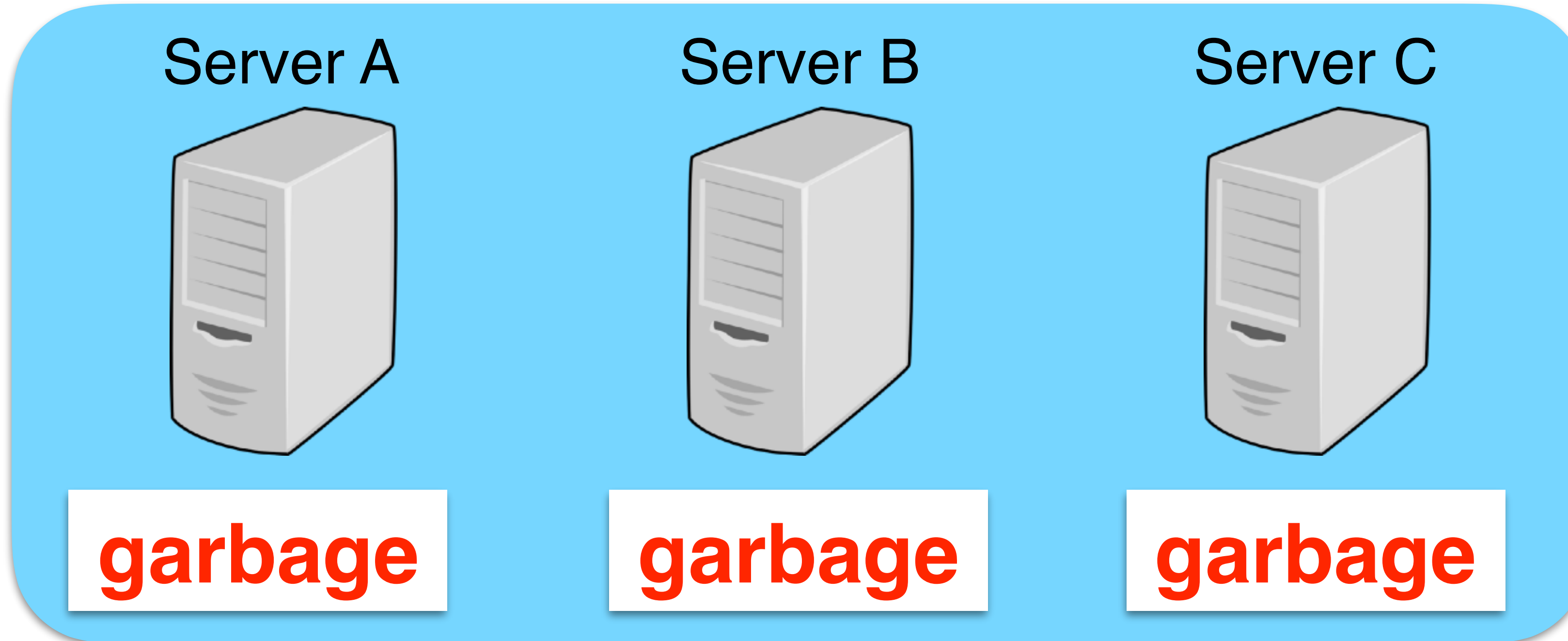

A single bad client **can undetectably corrupt** the sum

Users have **incentives** to cheat

Typical defenses (NIZKs) are costly

Outline

- Background: The private aggregation problem
- **A straw-man solution for private sums**
- Providing robustness with SNIPs
- Evaluation
- Encodings for <u>complex</u> aggregates

Outline

- Background: The private aggregation problem
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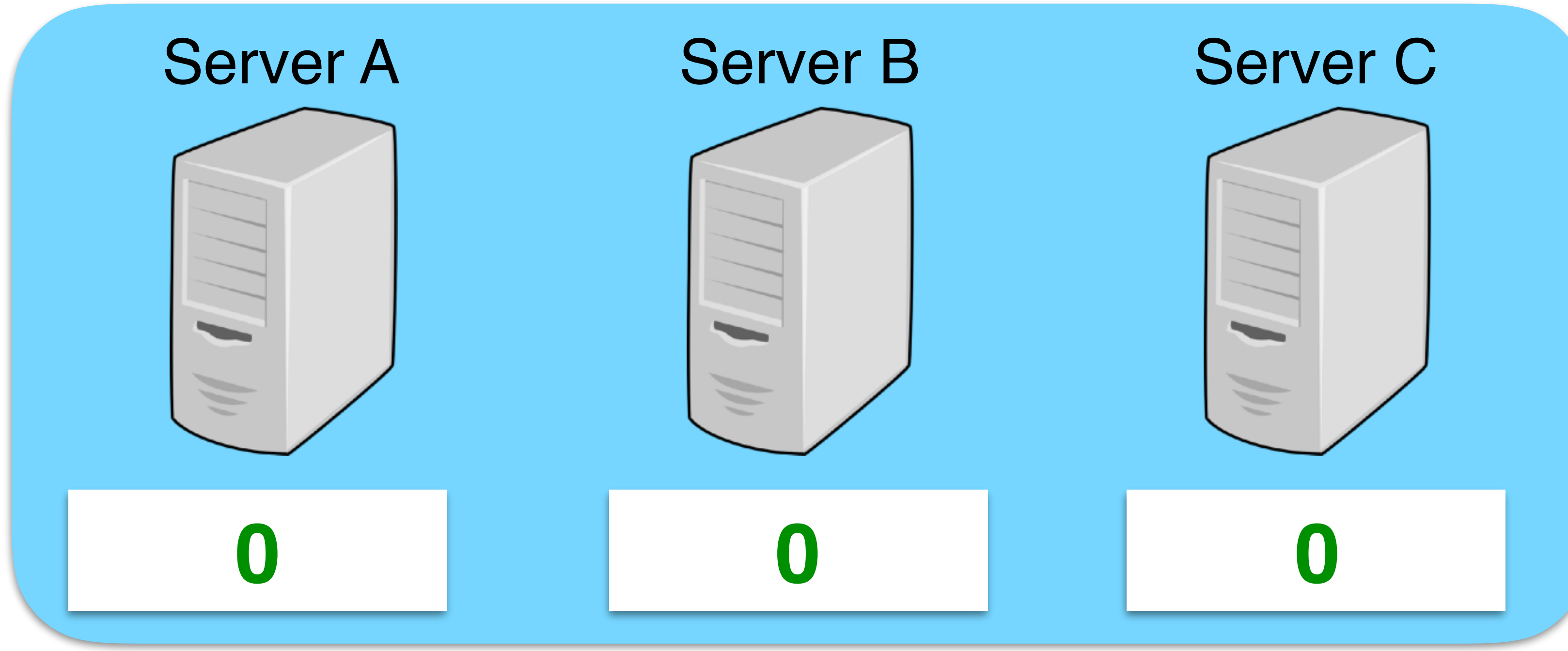
Contribution 1
Secret-shared non-interactive proofs (SNIPs)



$x = 1$

Contribution 1
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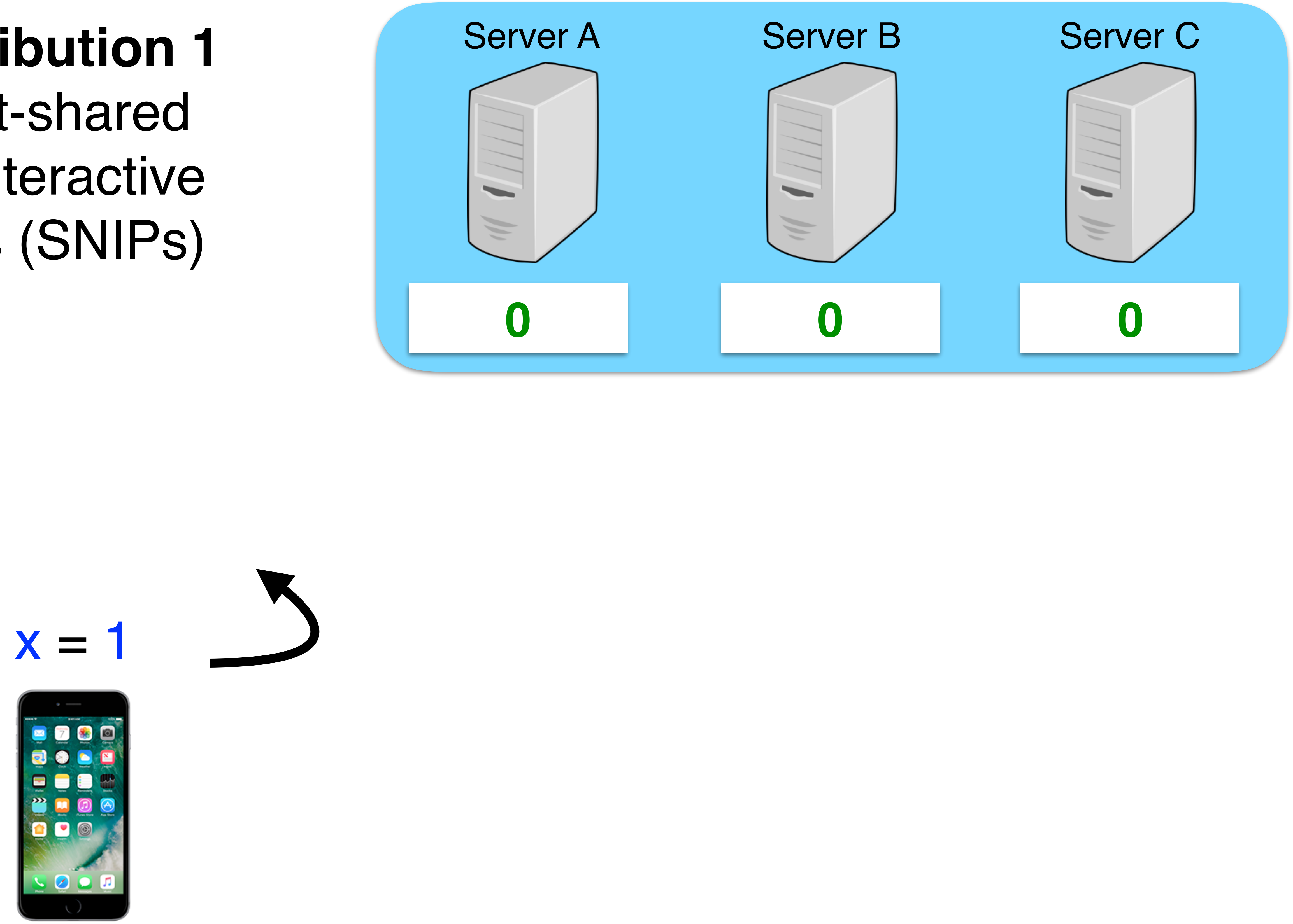

Contribution 1
Secret-shared
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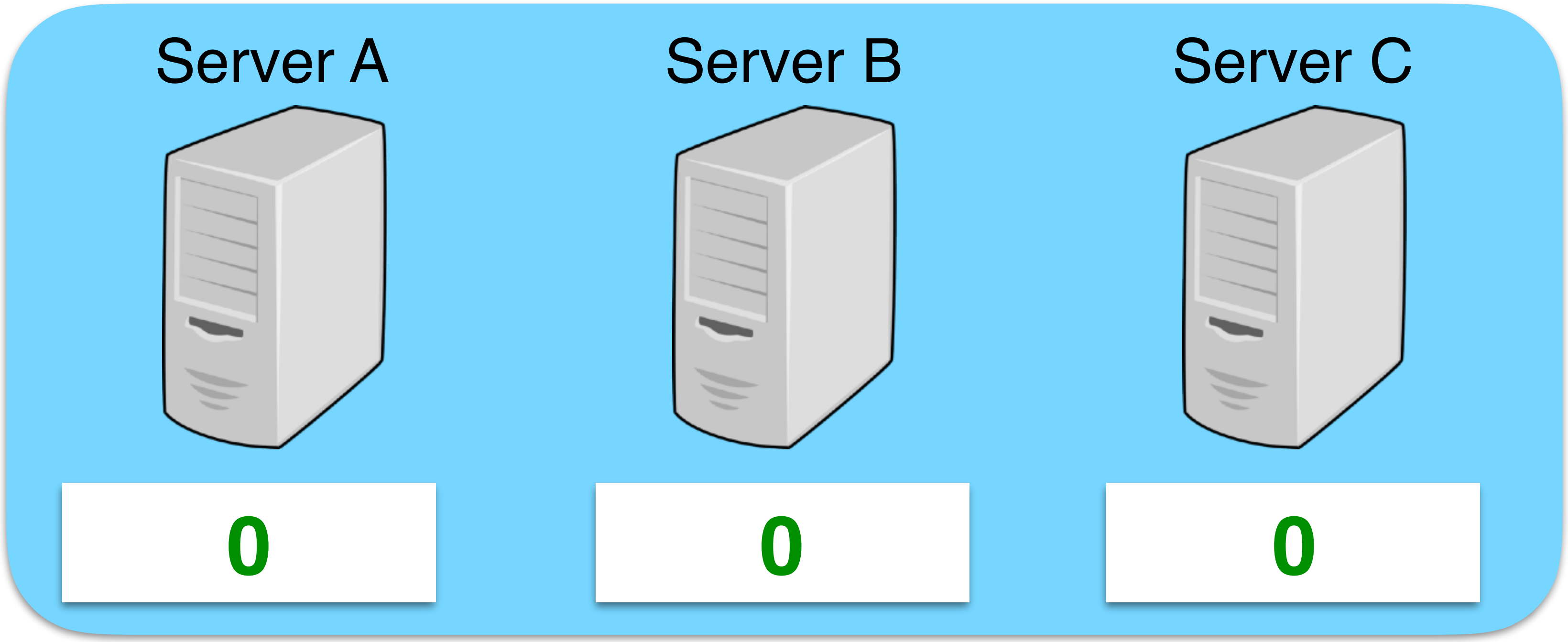

$15 + (-12) + (-2) = 1$

$x = 1$

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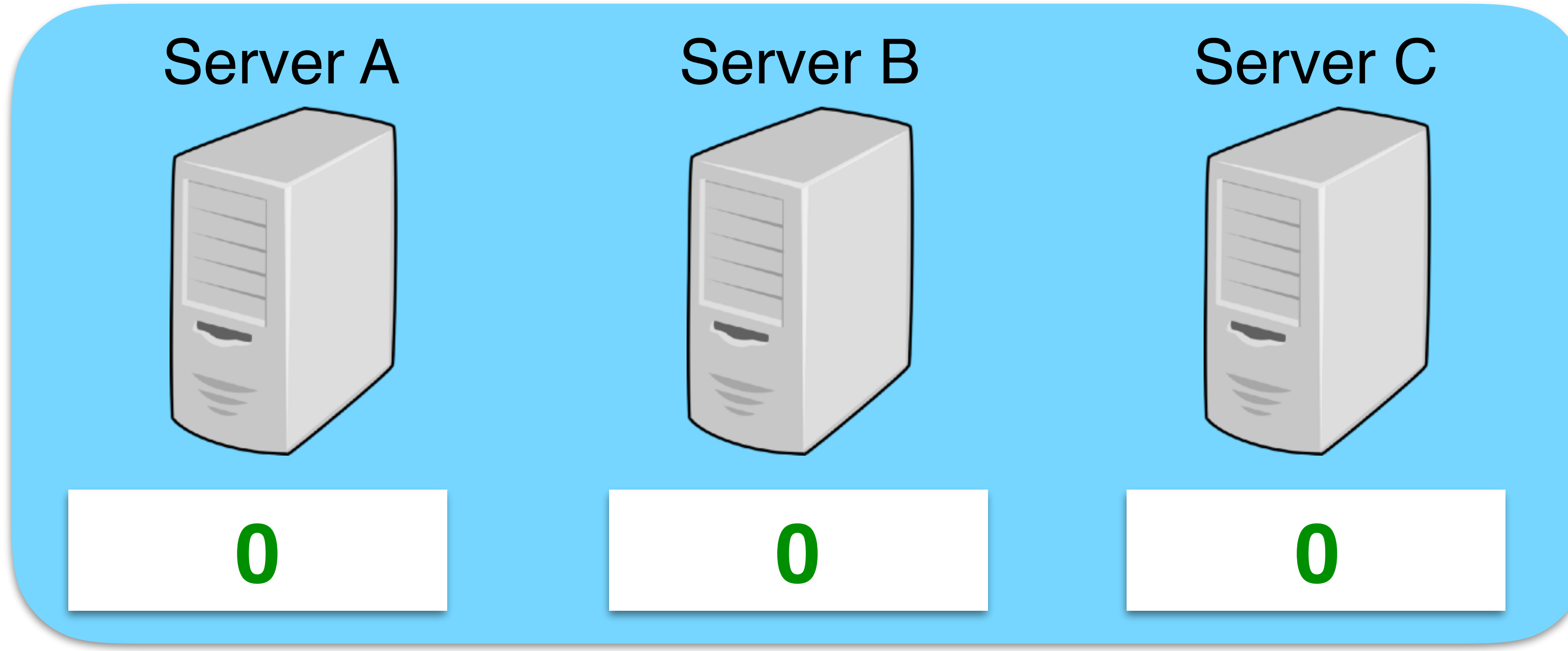

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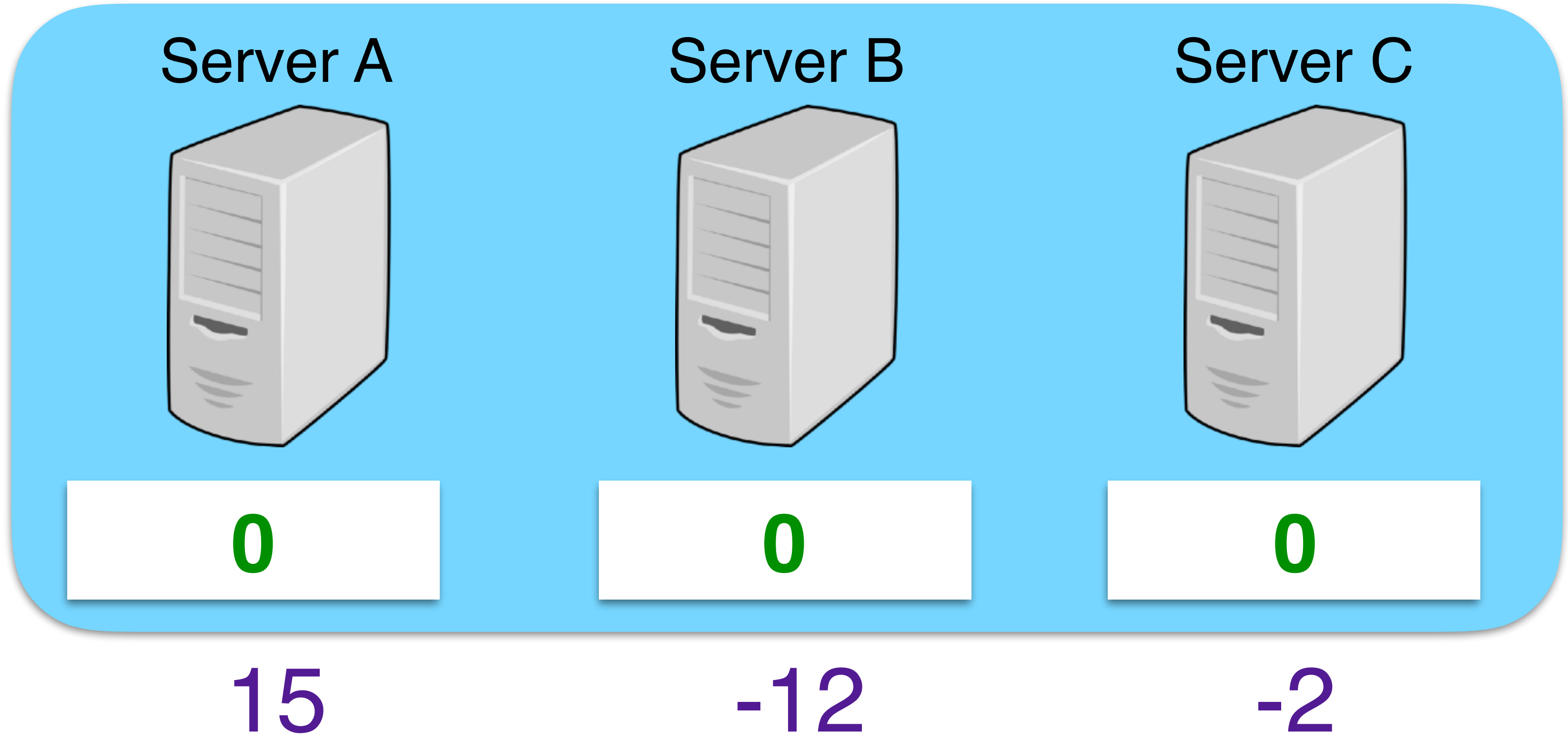

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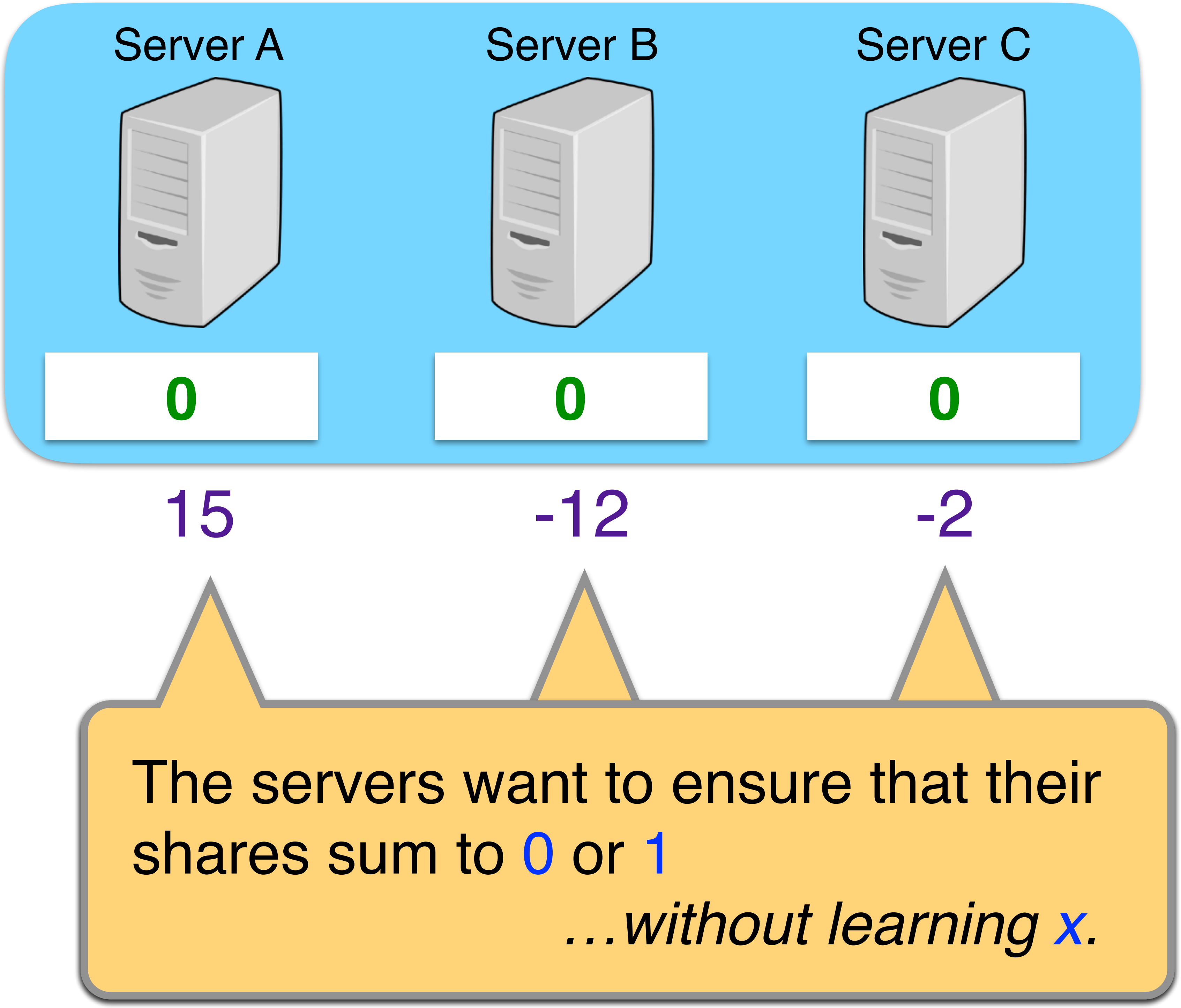

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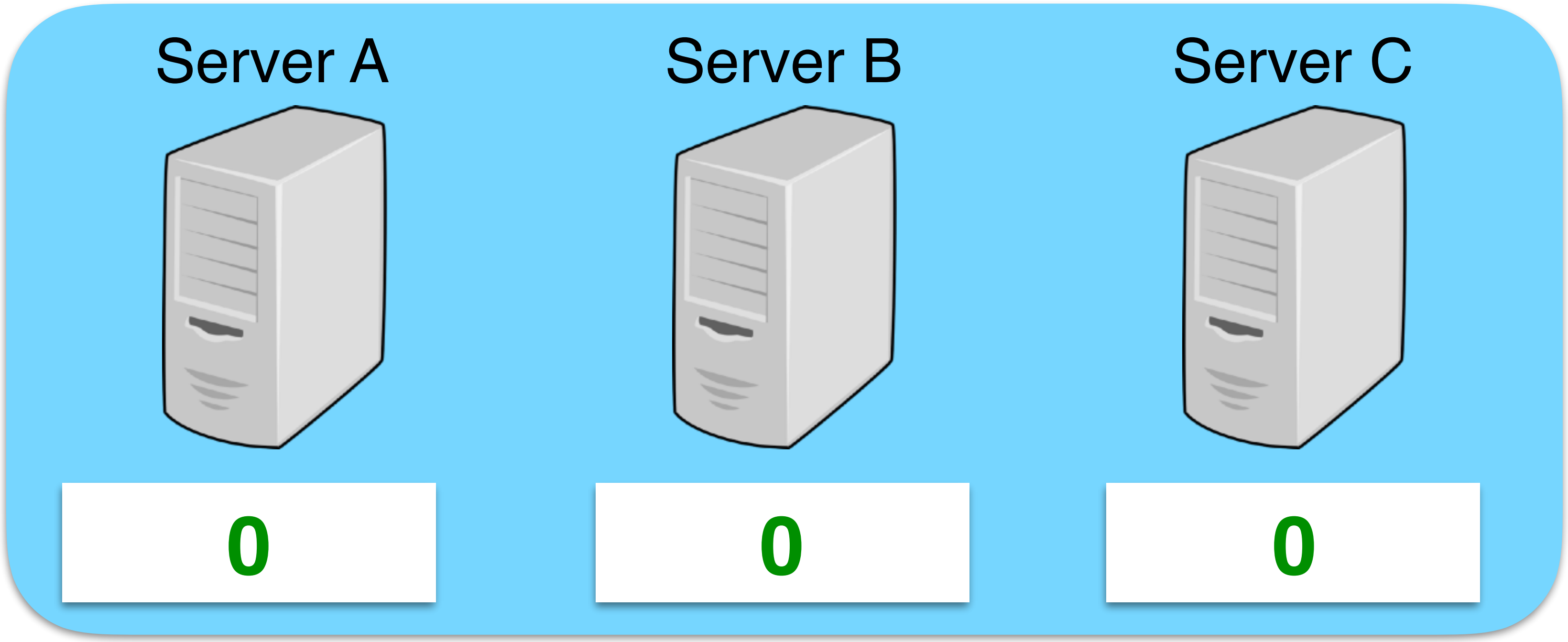


x_a x_b x_c

$x = 1$

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

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

Server A Server B Server C

0 0 0

x_a x_b x_c

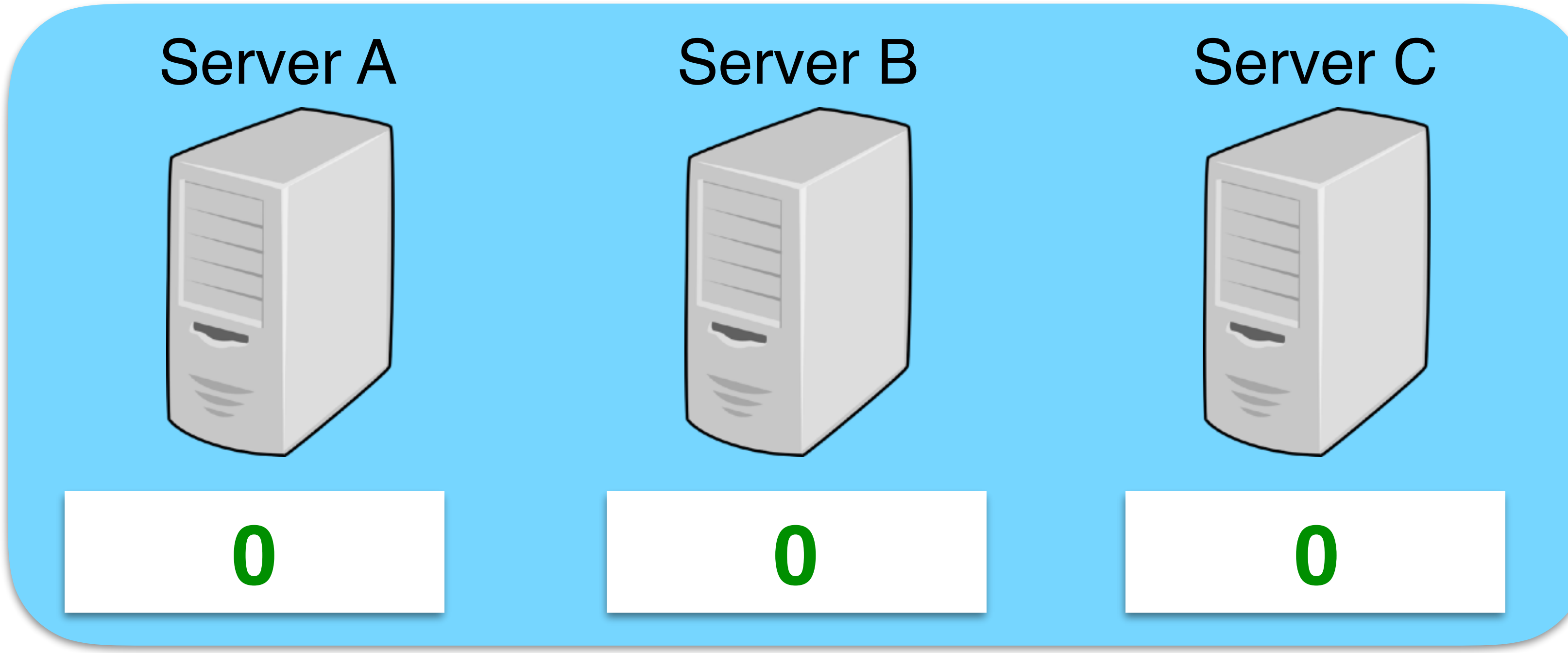
$x = 1$

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

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

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



x_a x_b x_c

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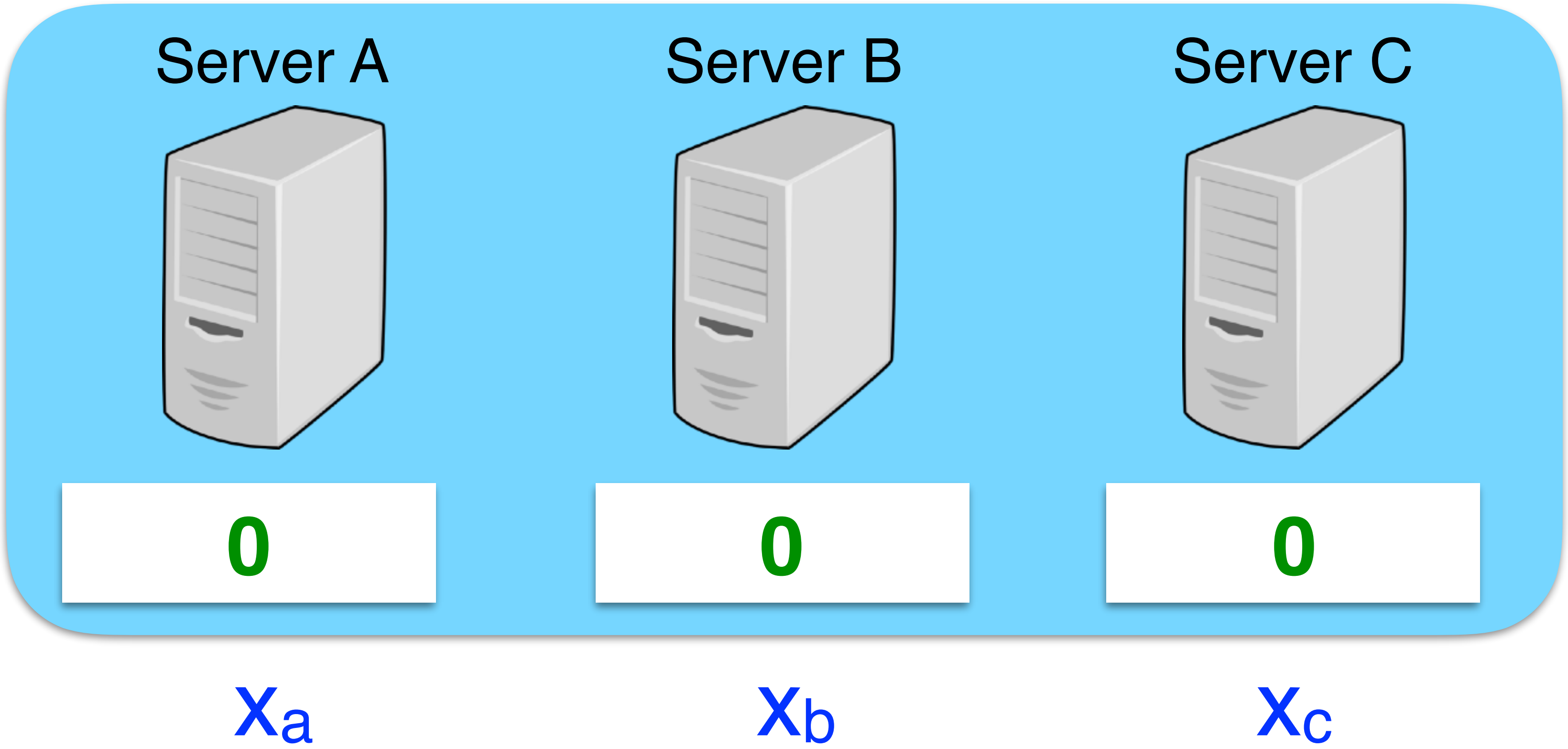

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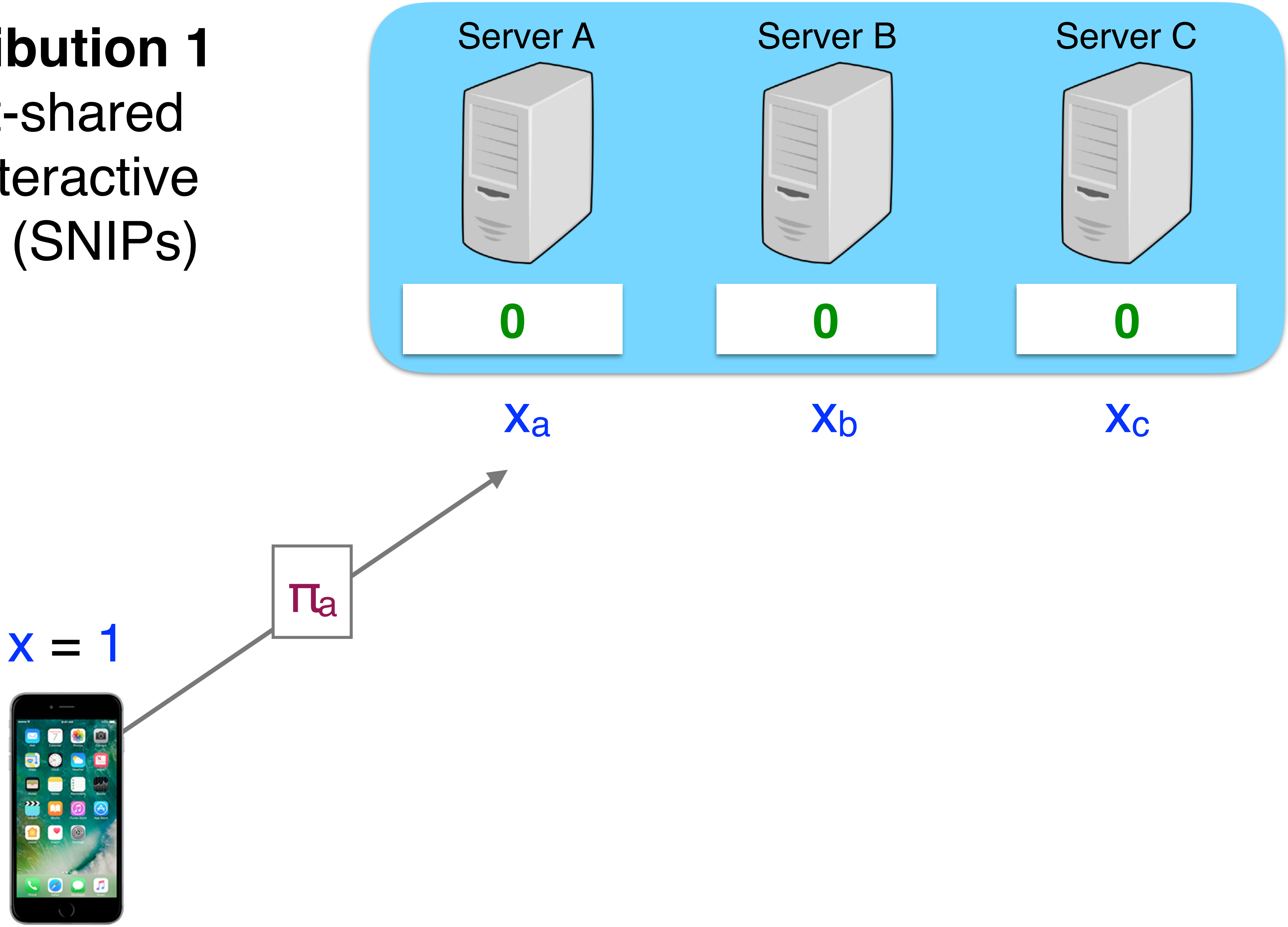

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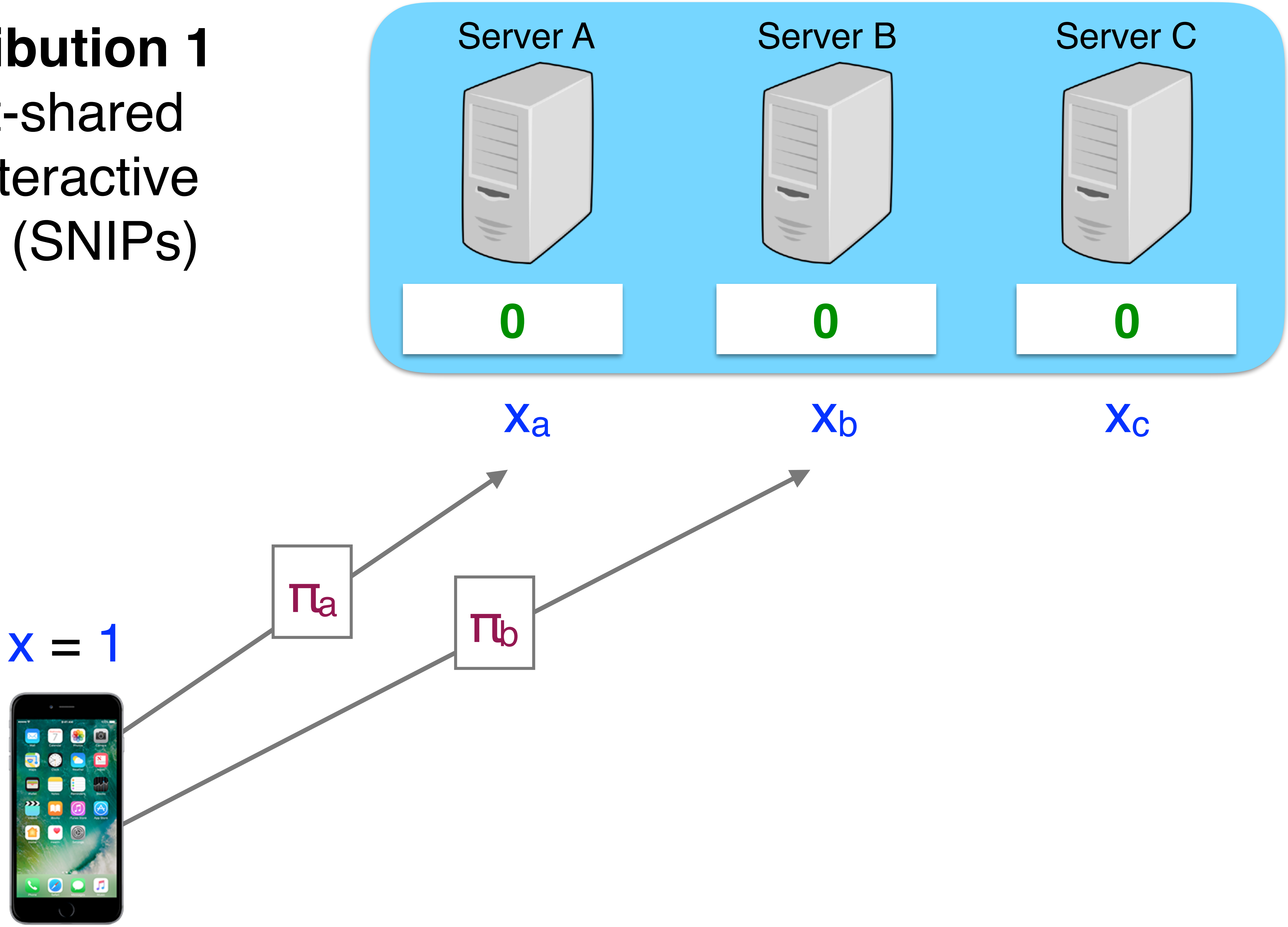

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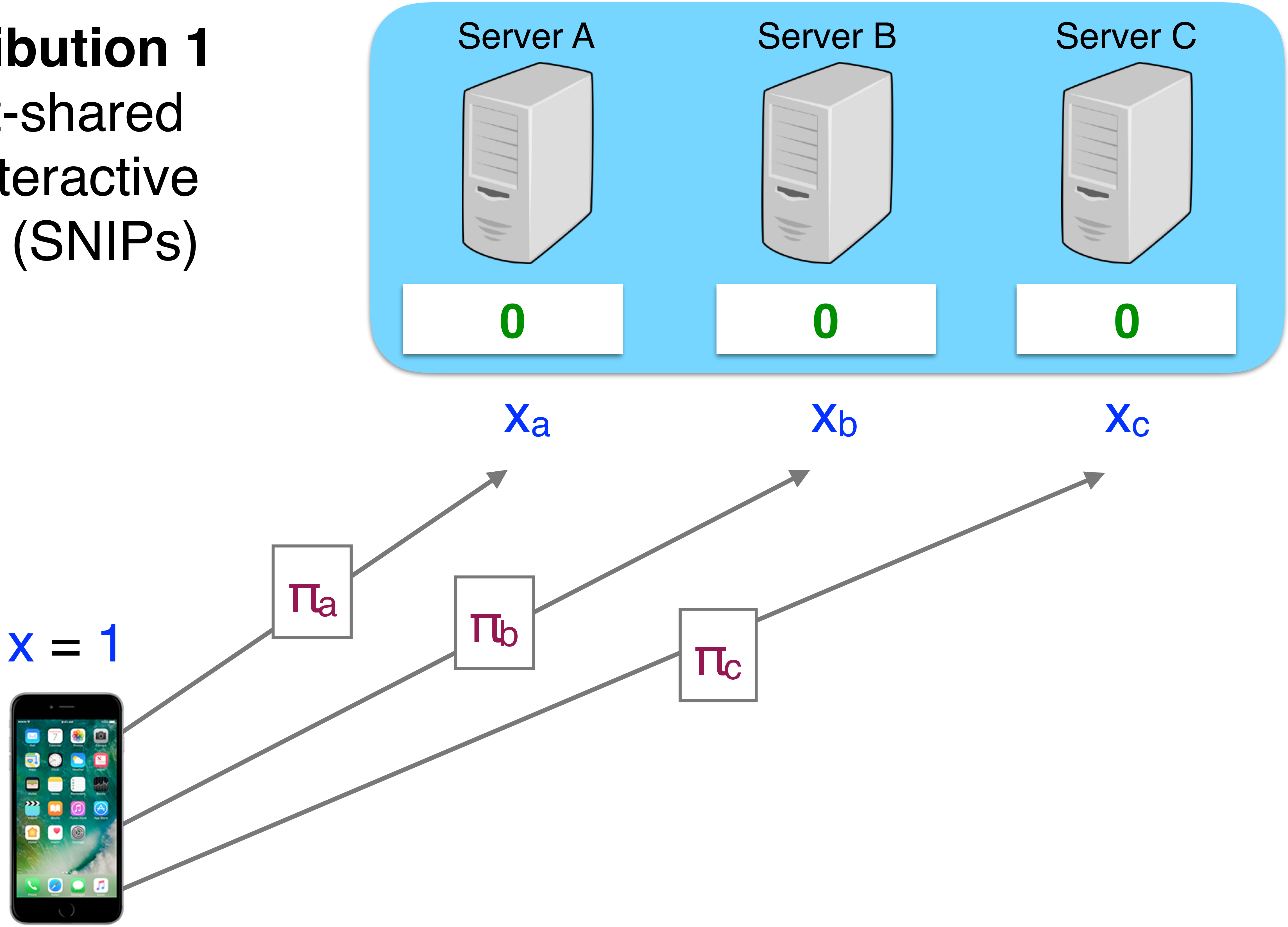

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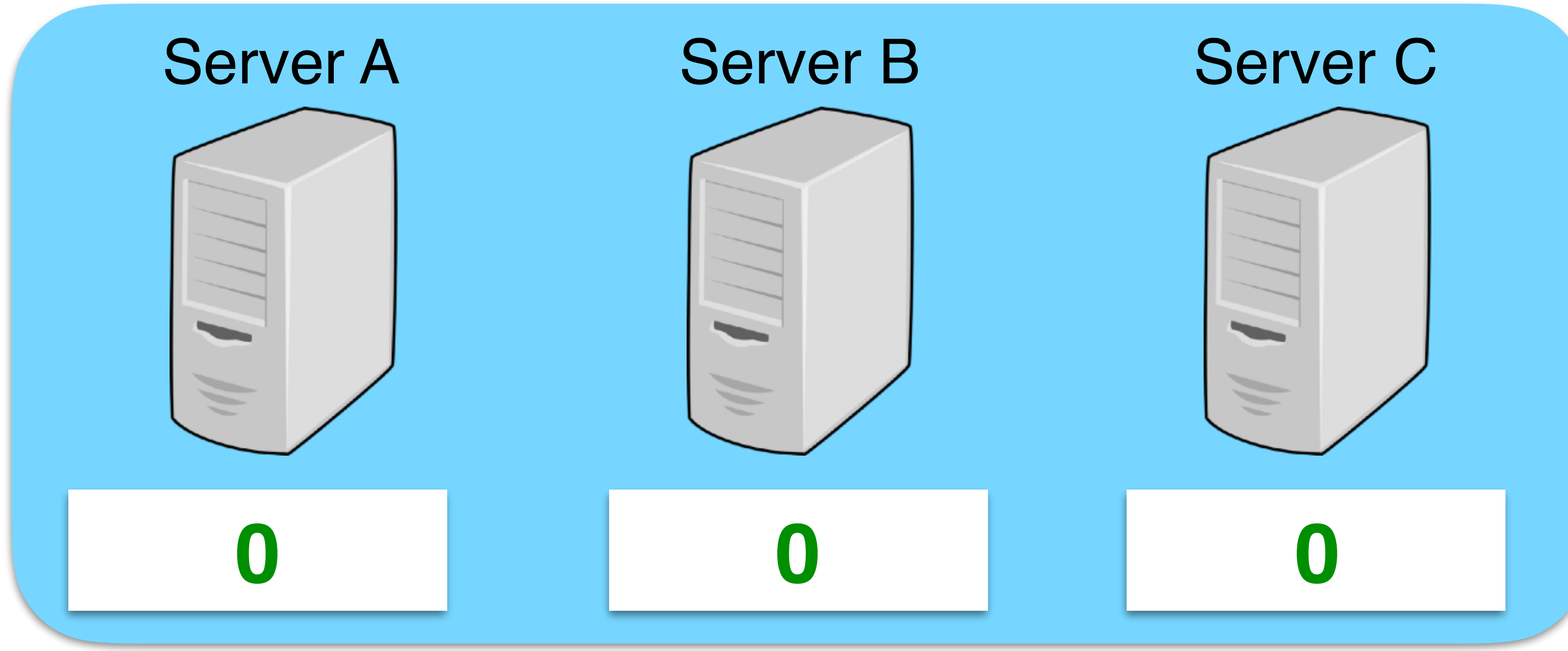
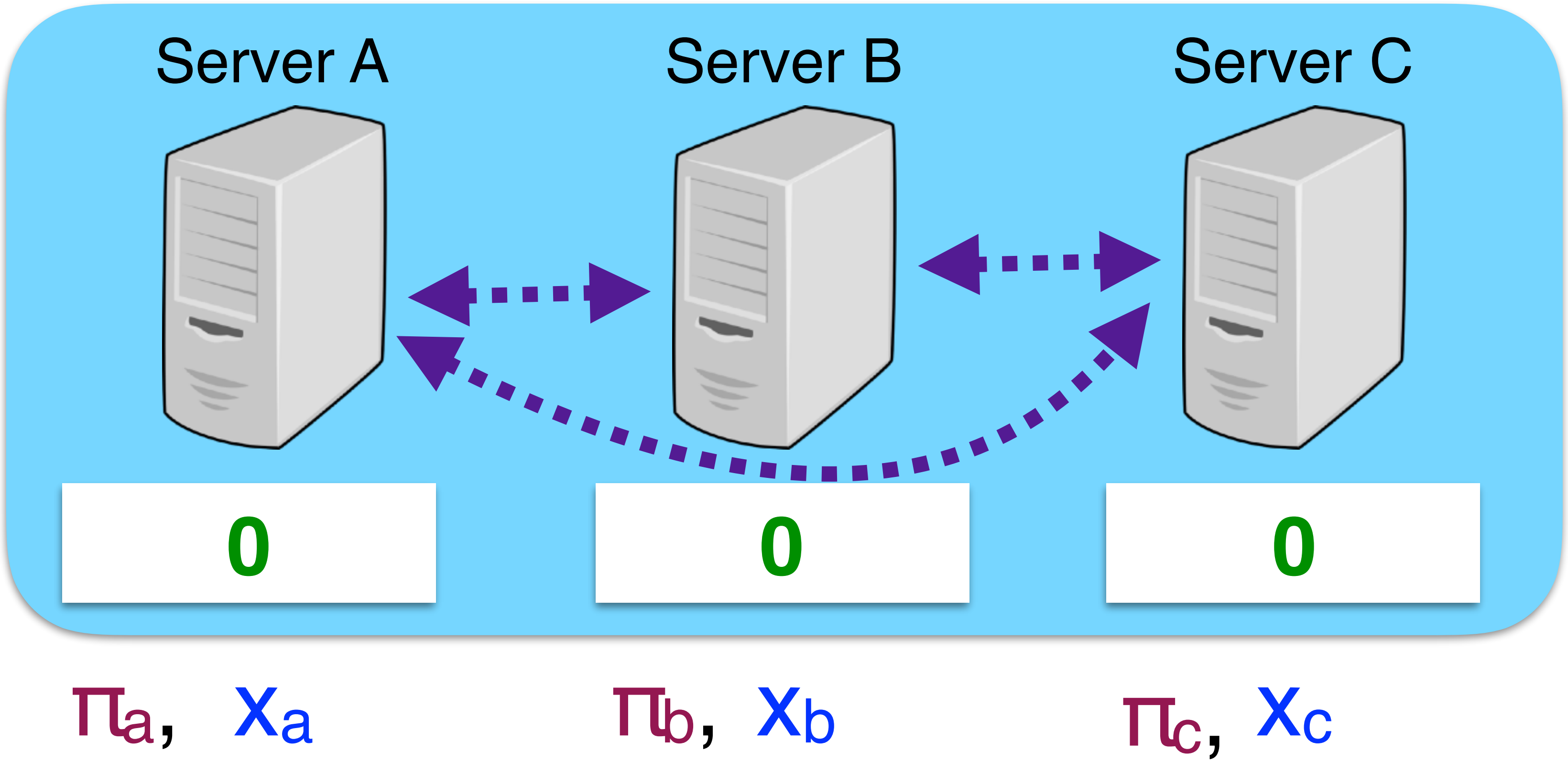


π_a, x_a π_b, x_b π_c, x_c

$x = 1$

Contribution 1

Secret-shared non-interactive proofs (SNIPs)



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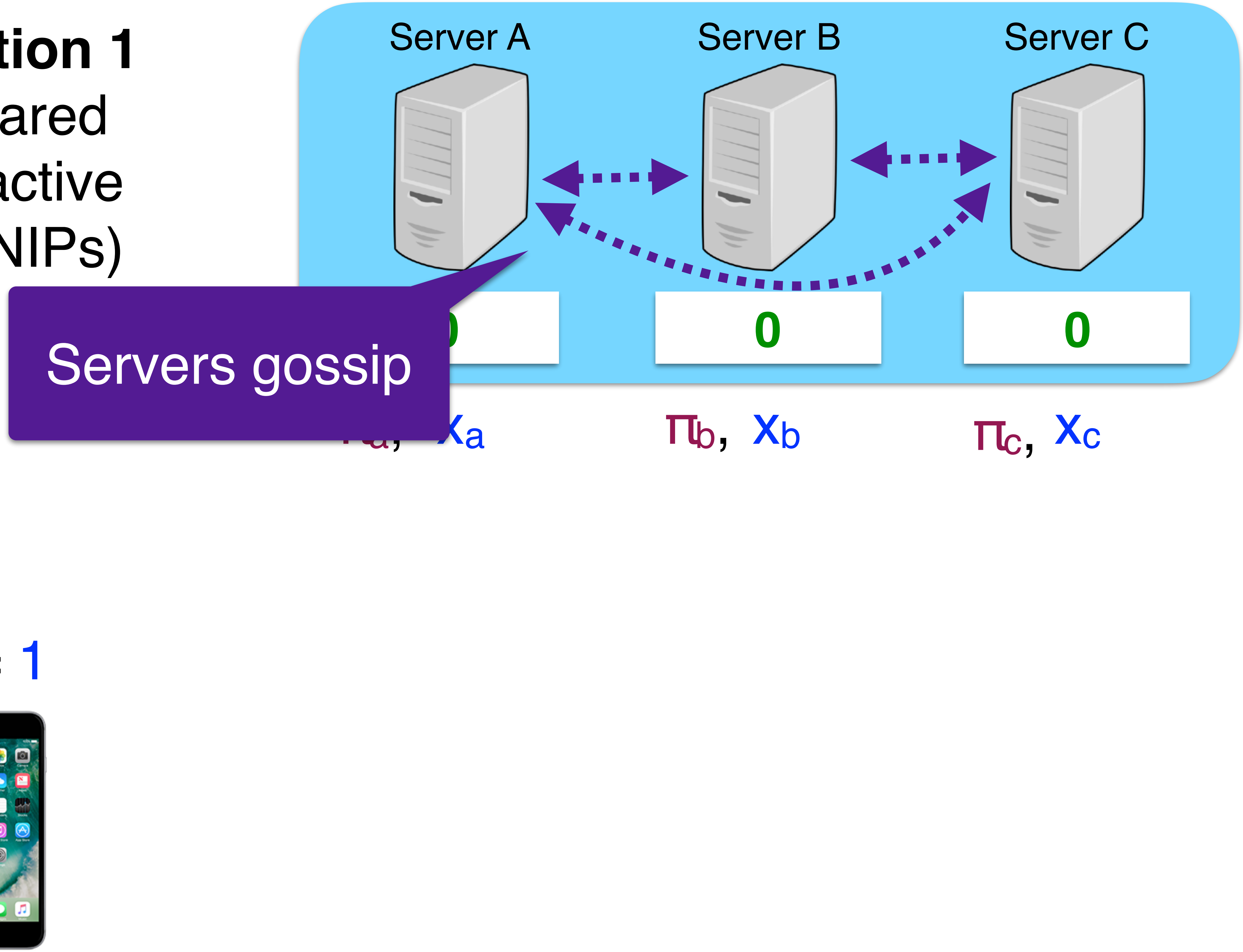

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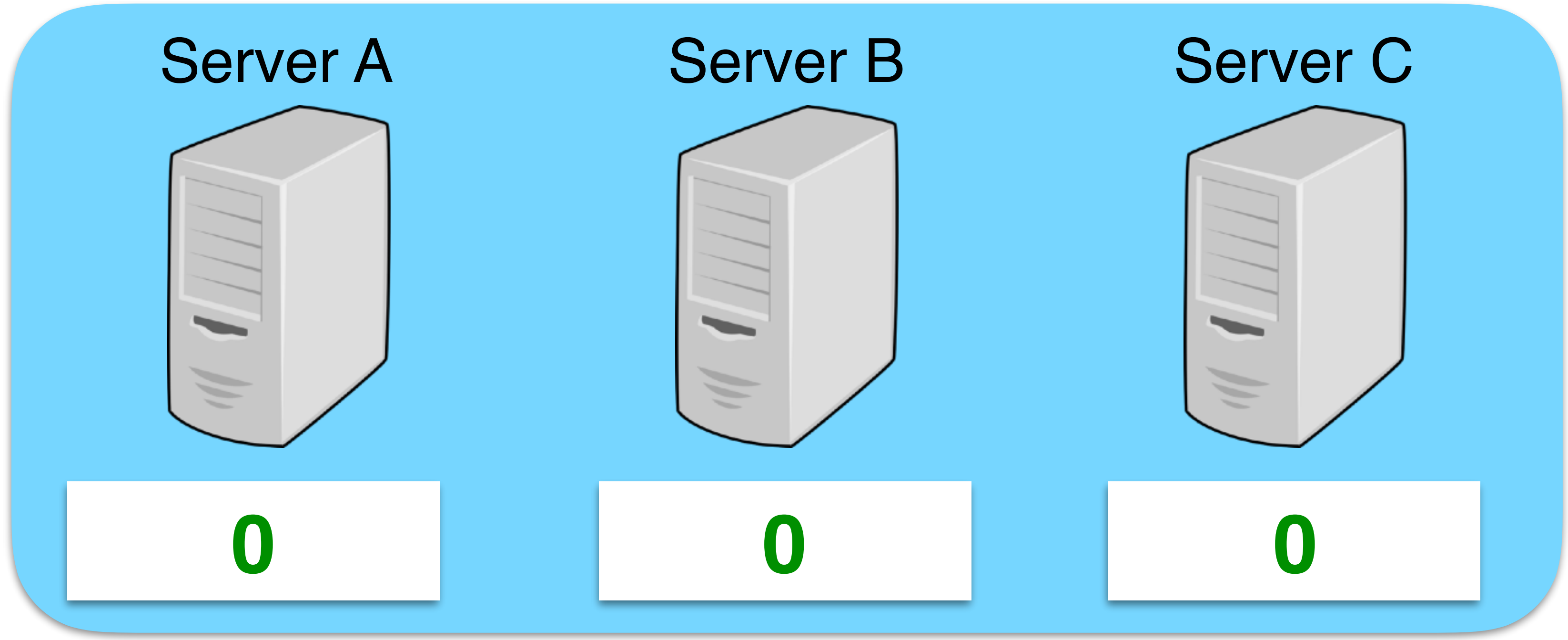

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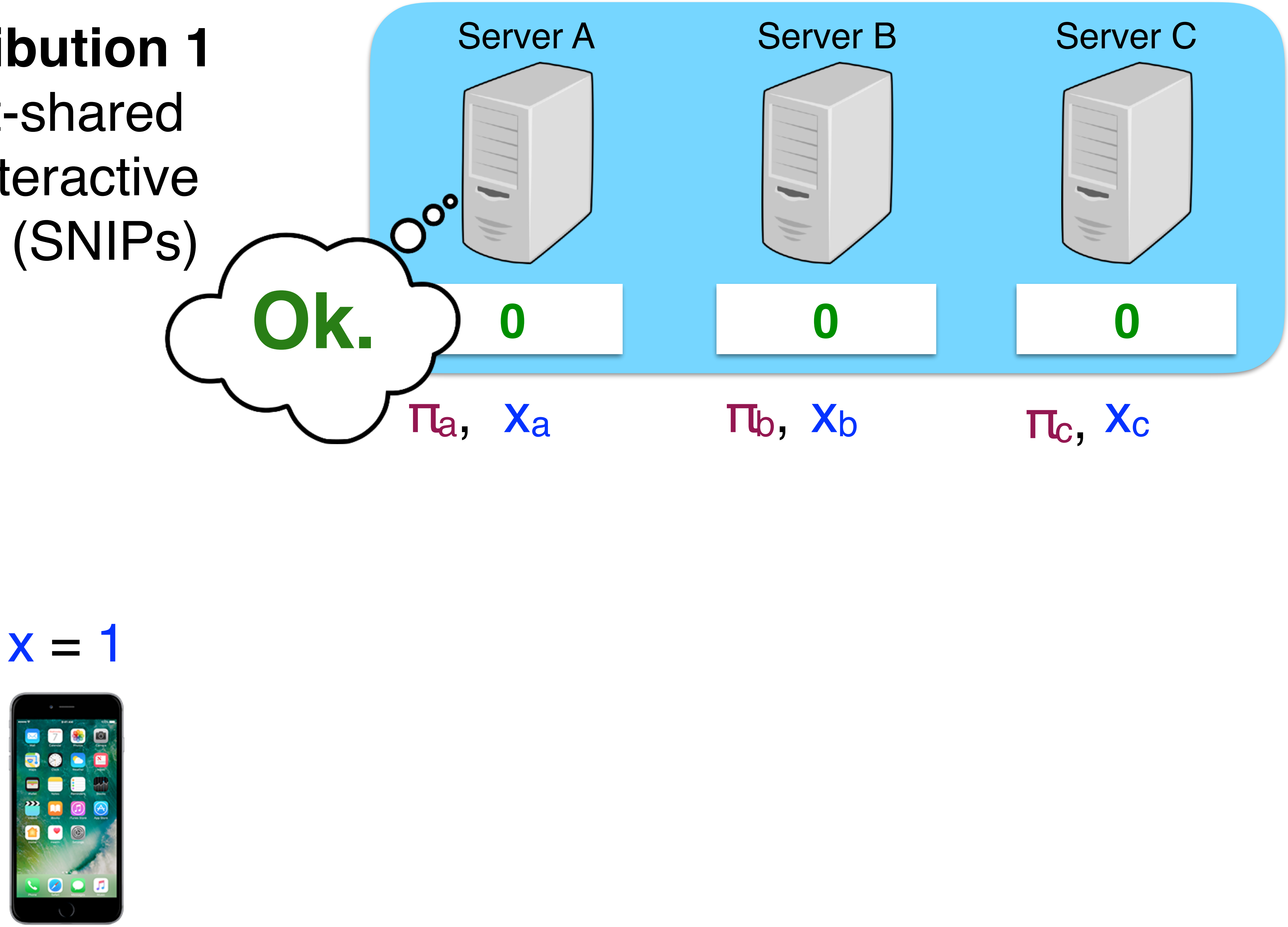

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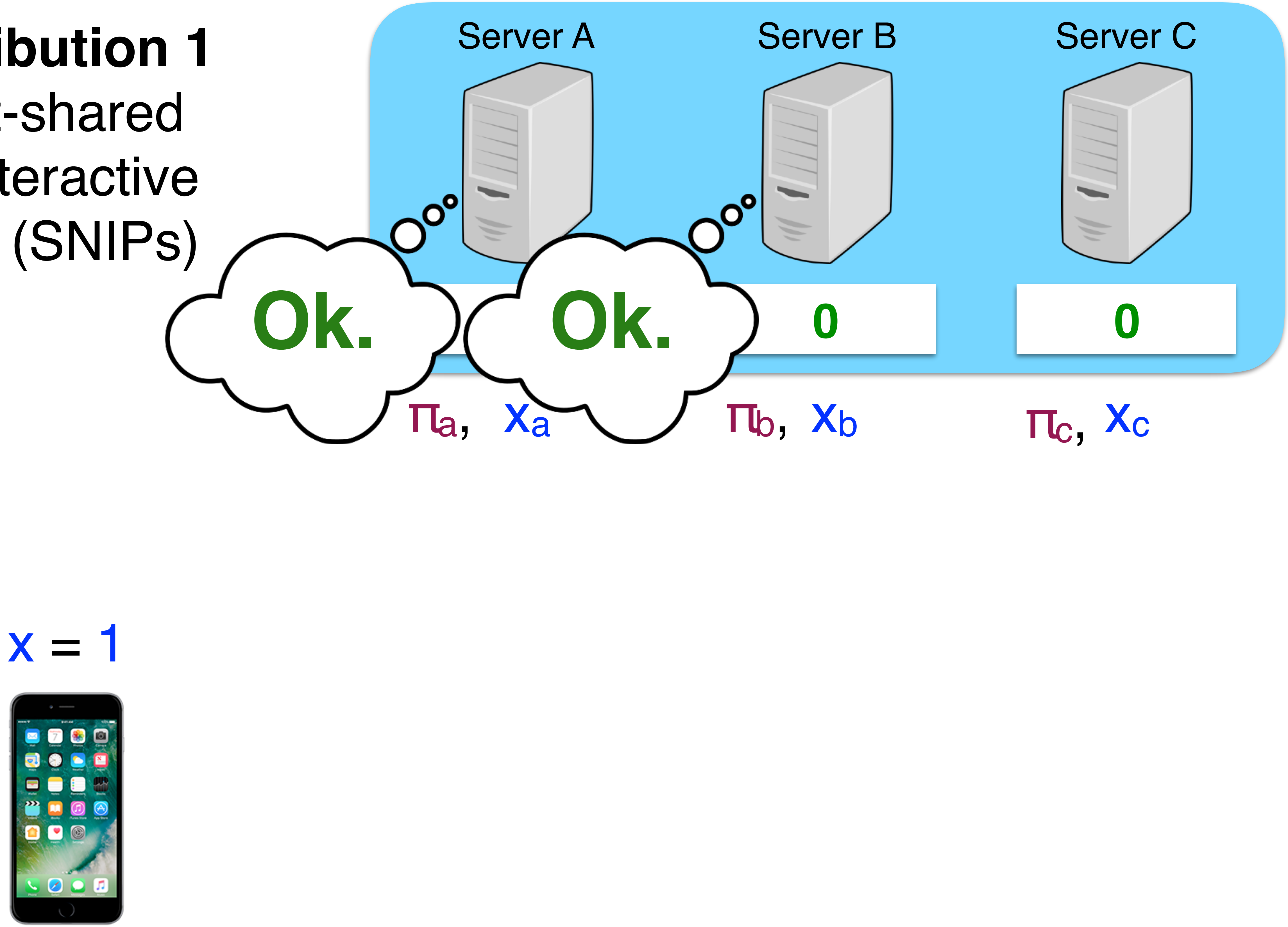

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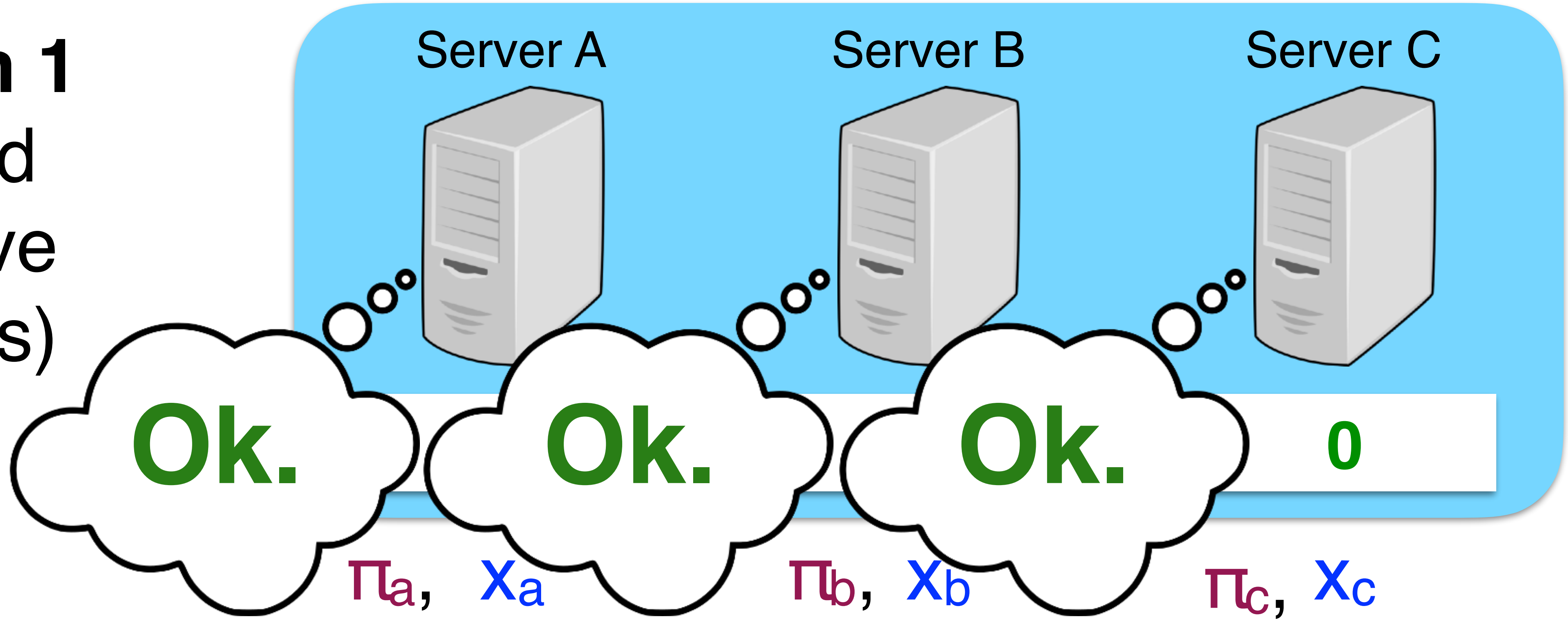

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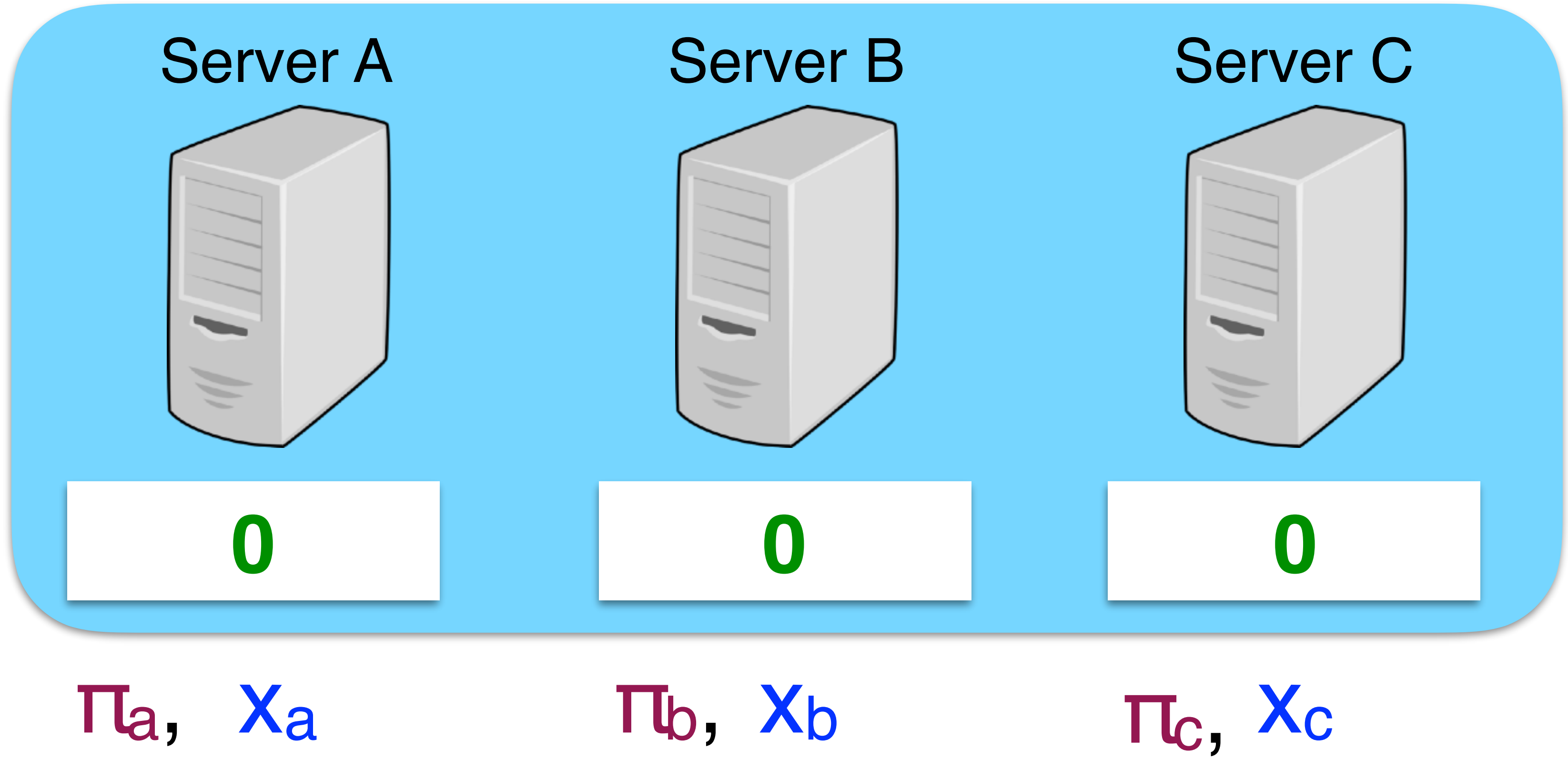

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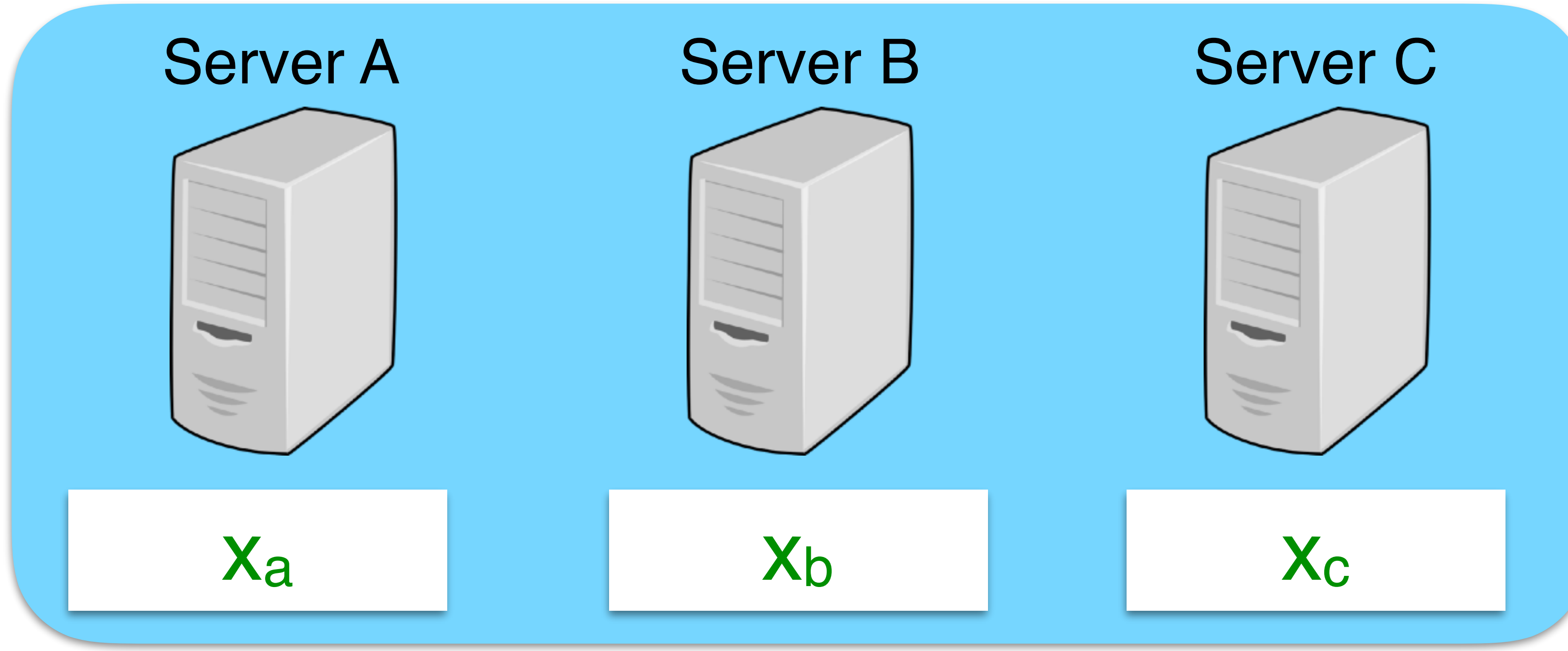

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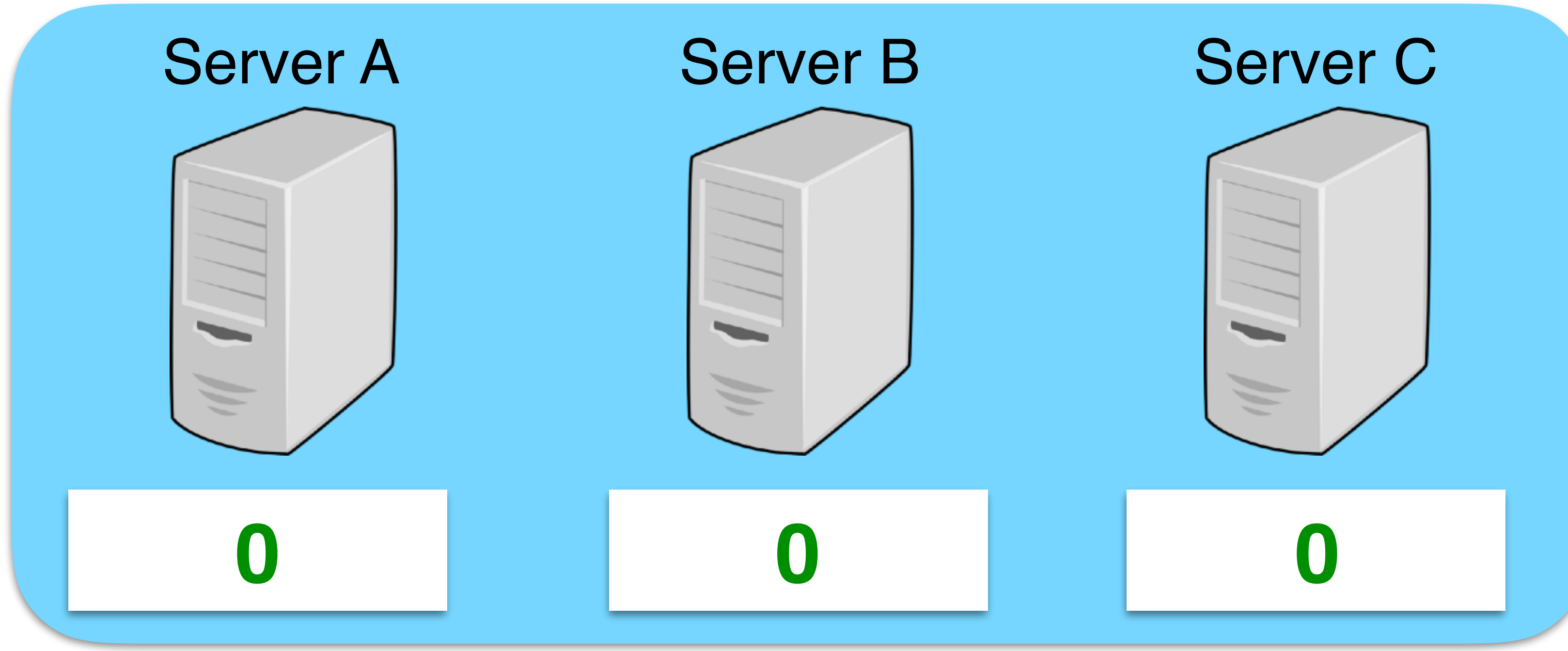

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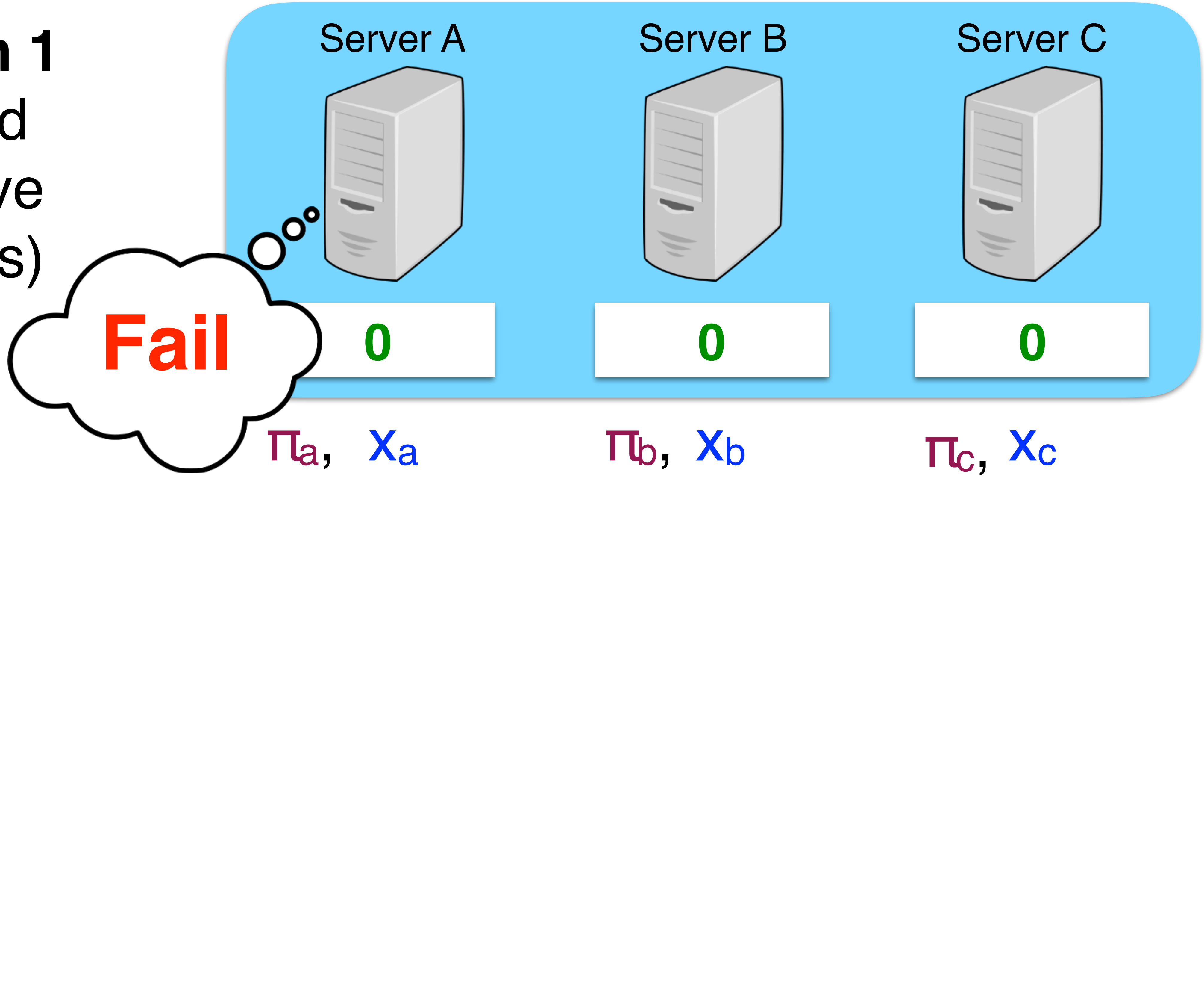

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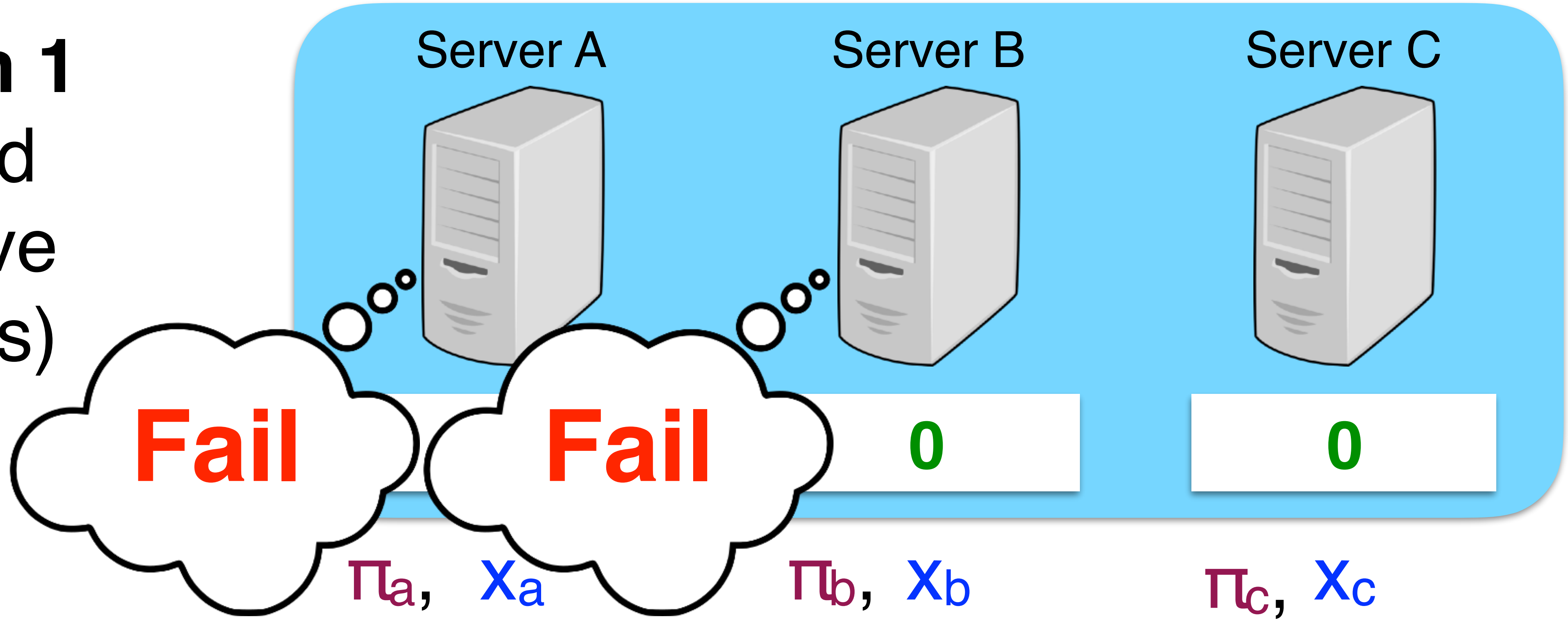

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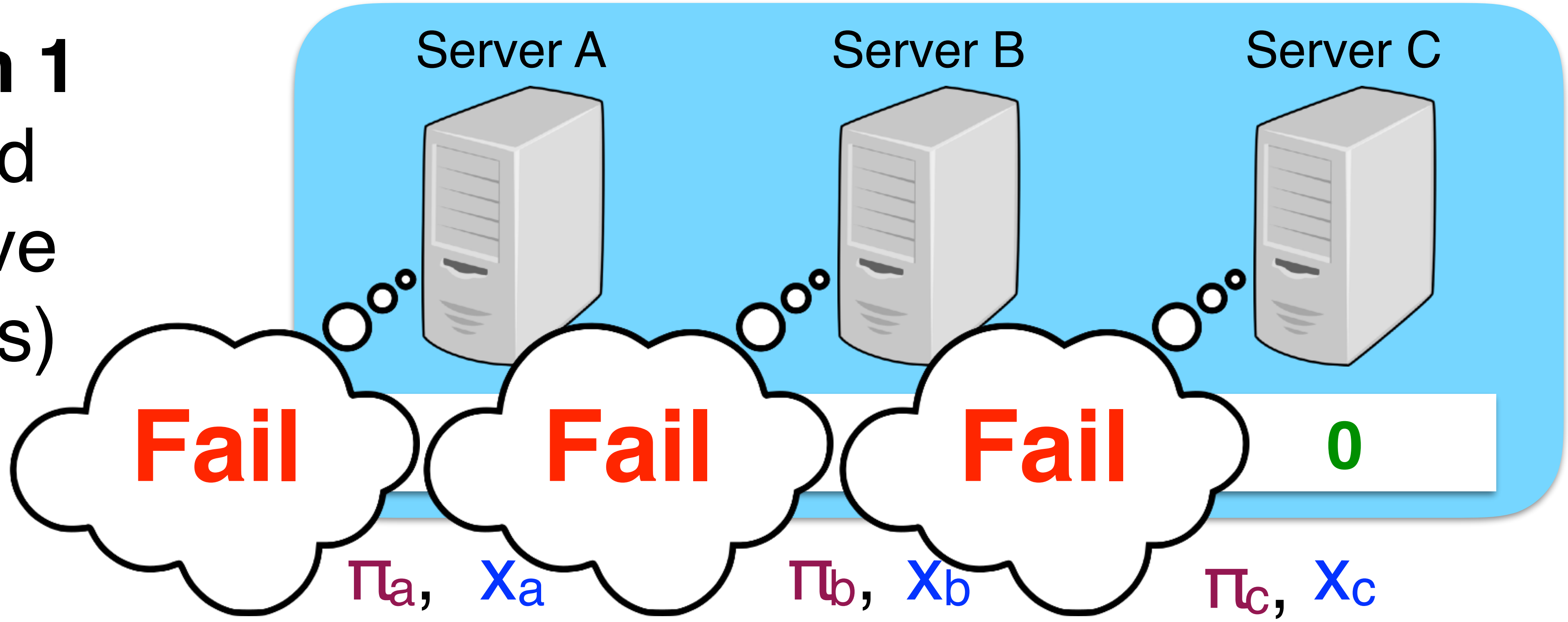

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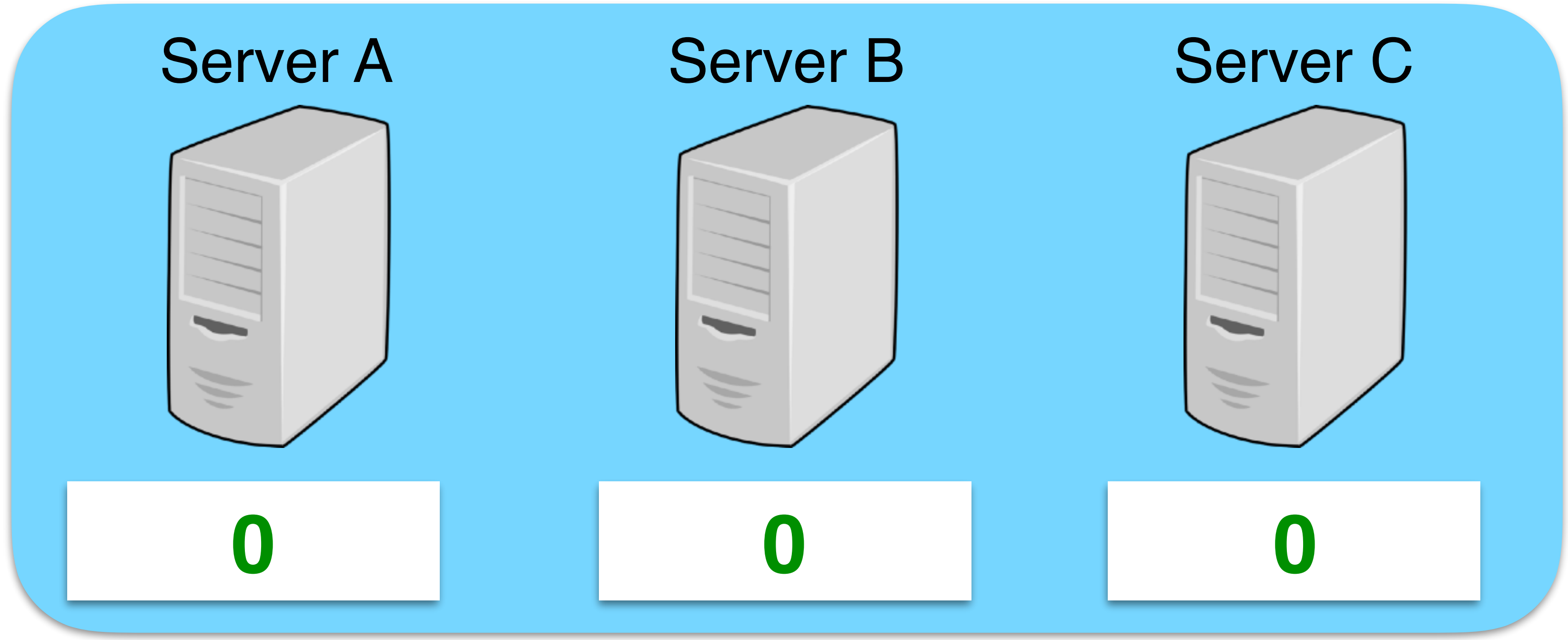

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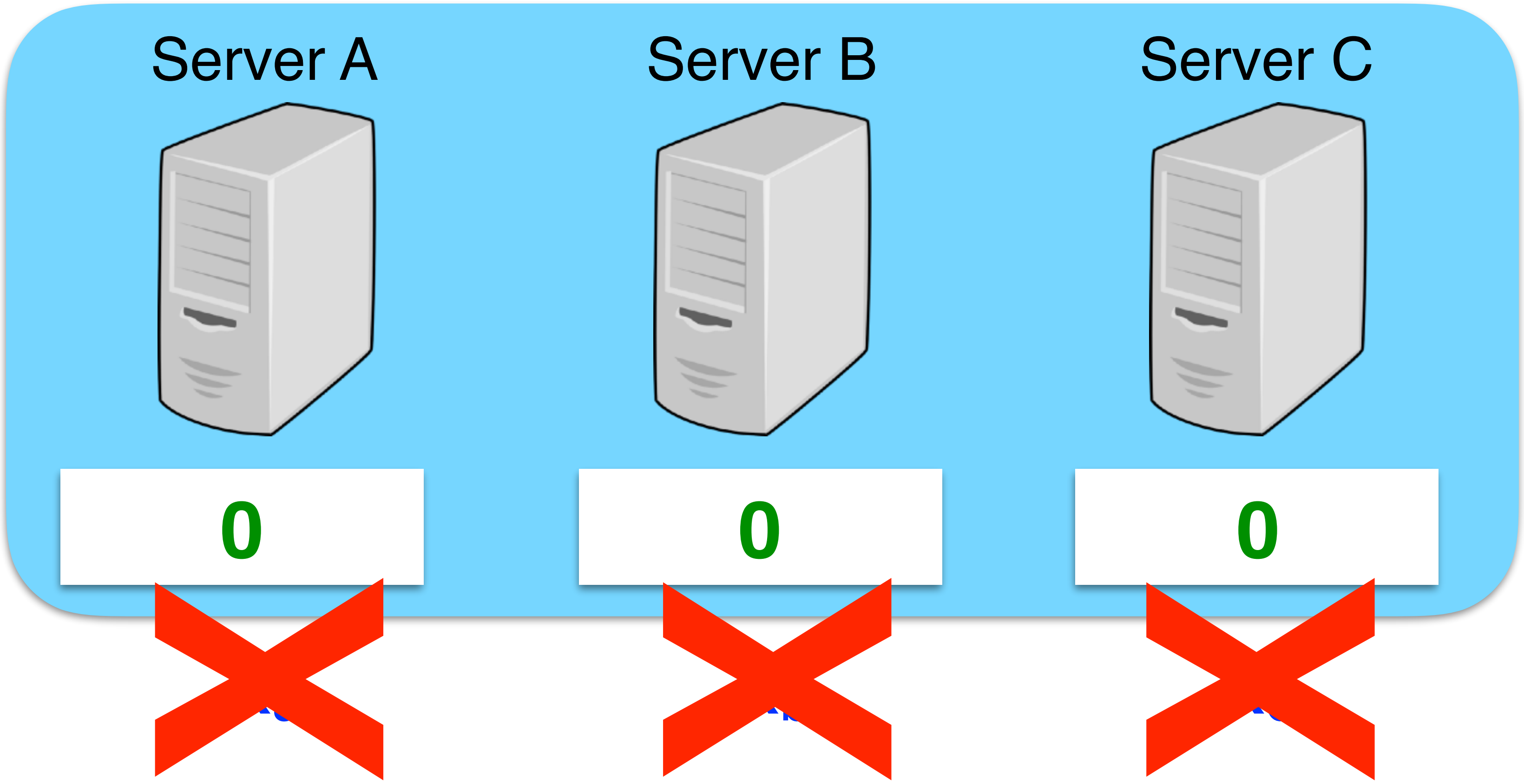
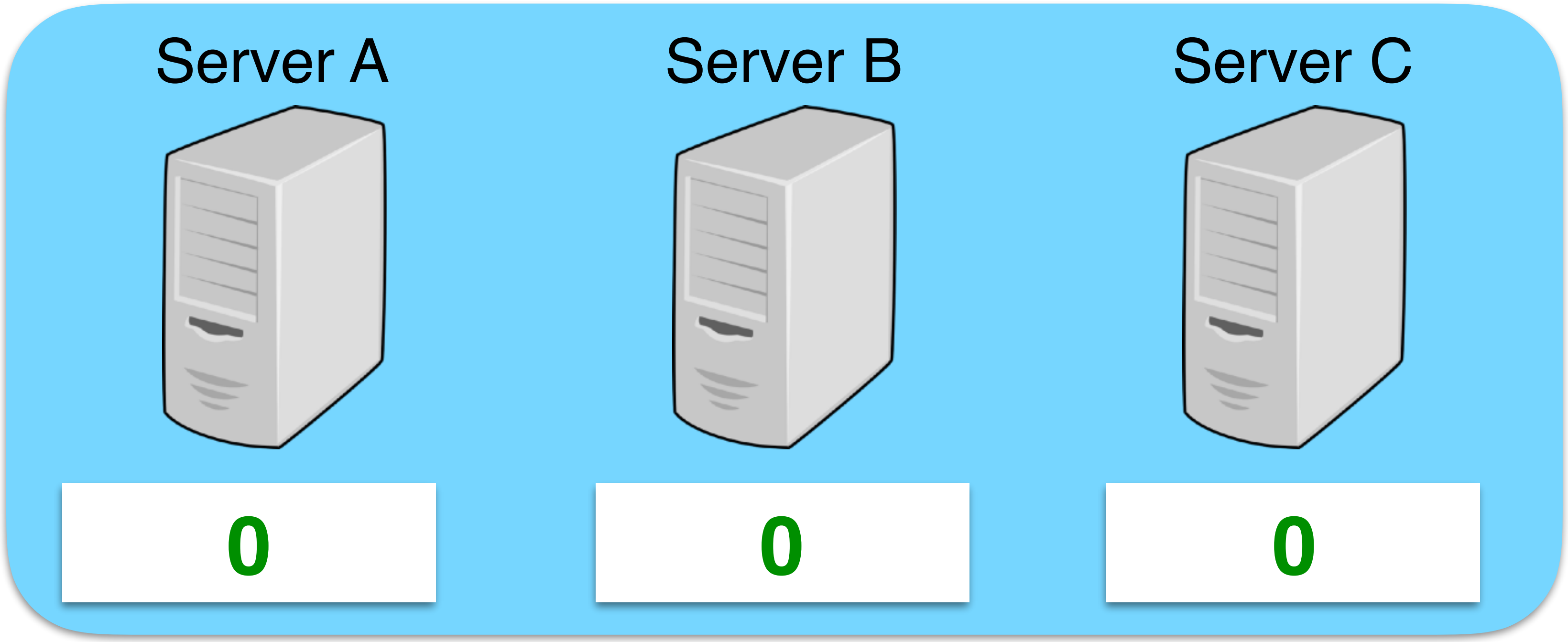


- Prio servers *detect and reject malformed client submissions*
- In this example, each client can influence the aggregate statistic by +/- 1, at most

How SNIPs work

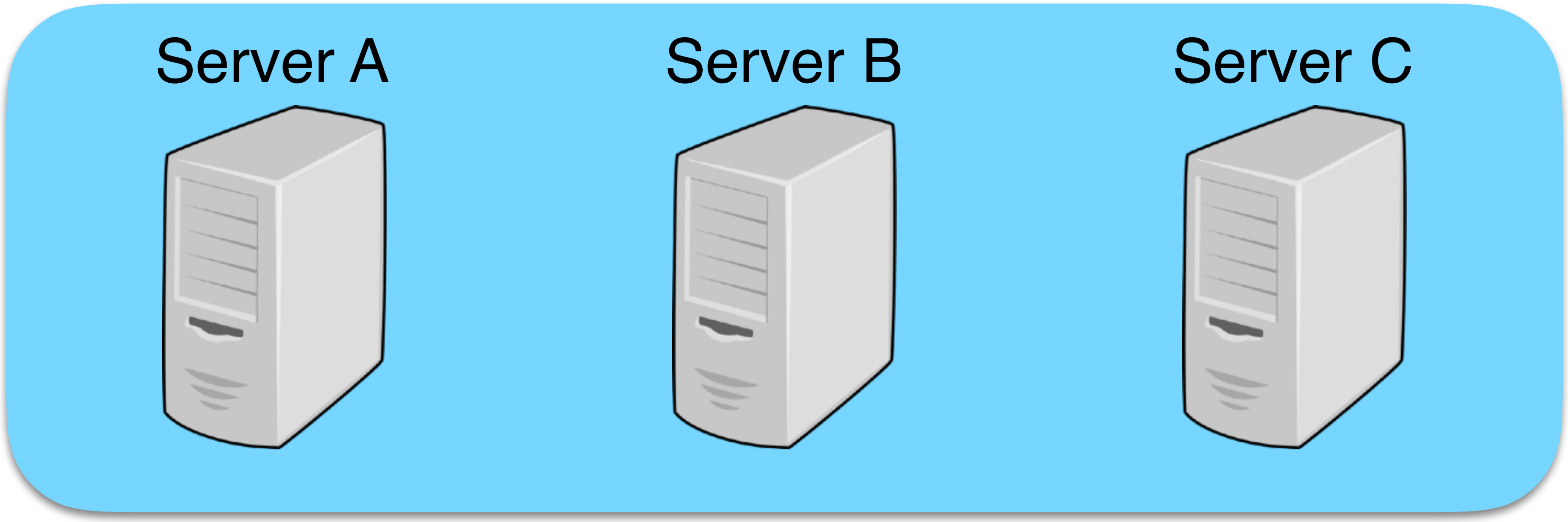


x_a x_b x_c

The servers want to ensure that
$\text{Valid}(x) = \text{Valid}(x_a + x_b + x_c) = 1$
...without learning x.

$x = 1$

How SNIPs work



x_a x_b x_c

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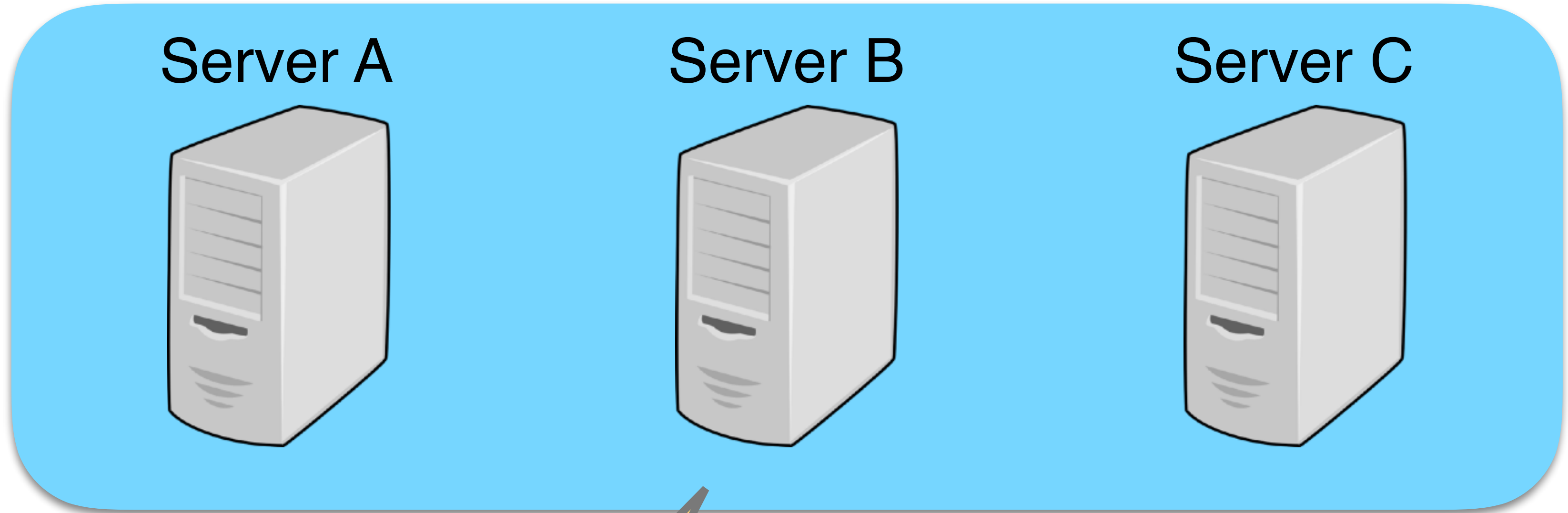
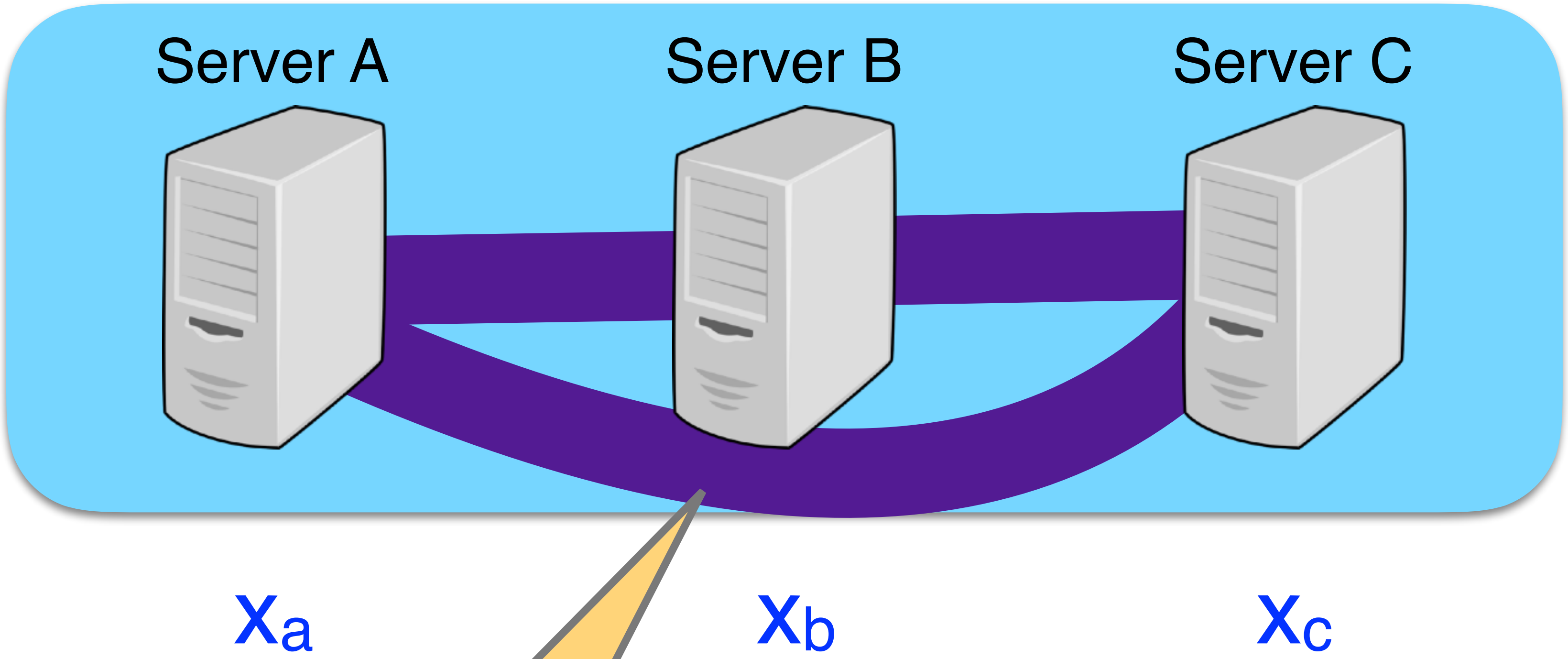


x_a x_b x_c

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

[GMW87], [BGW88]

How SNIPs work



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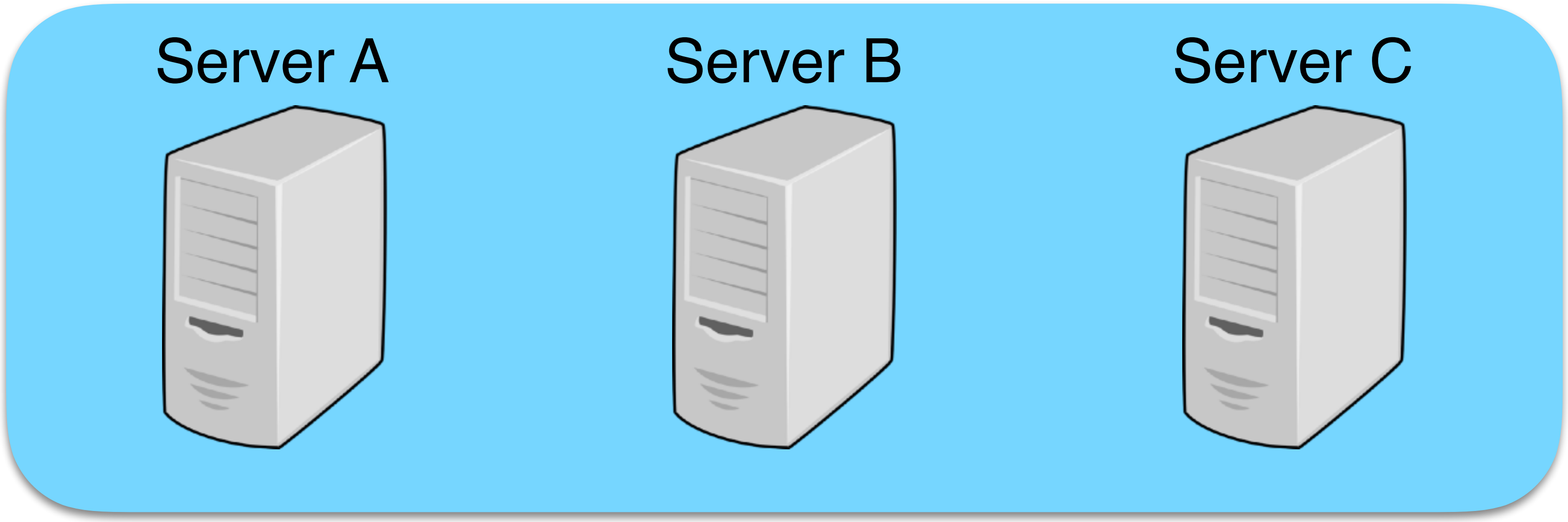

x_a x_b x_c

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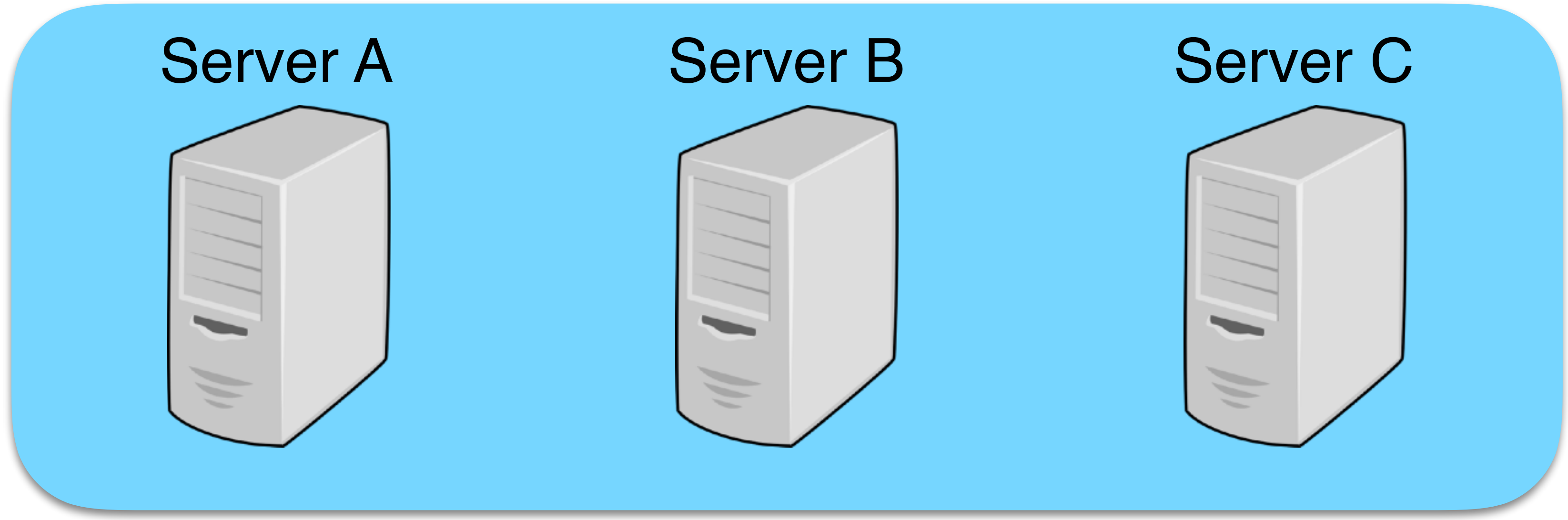
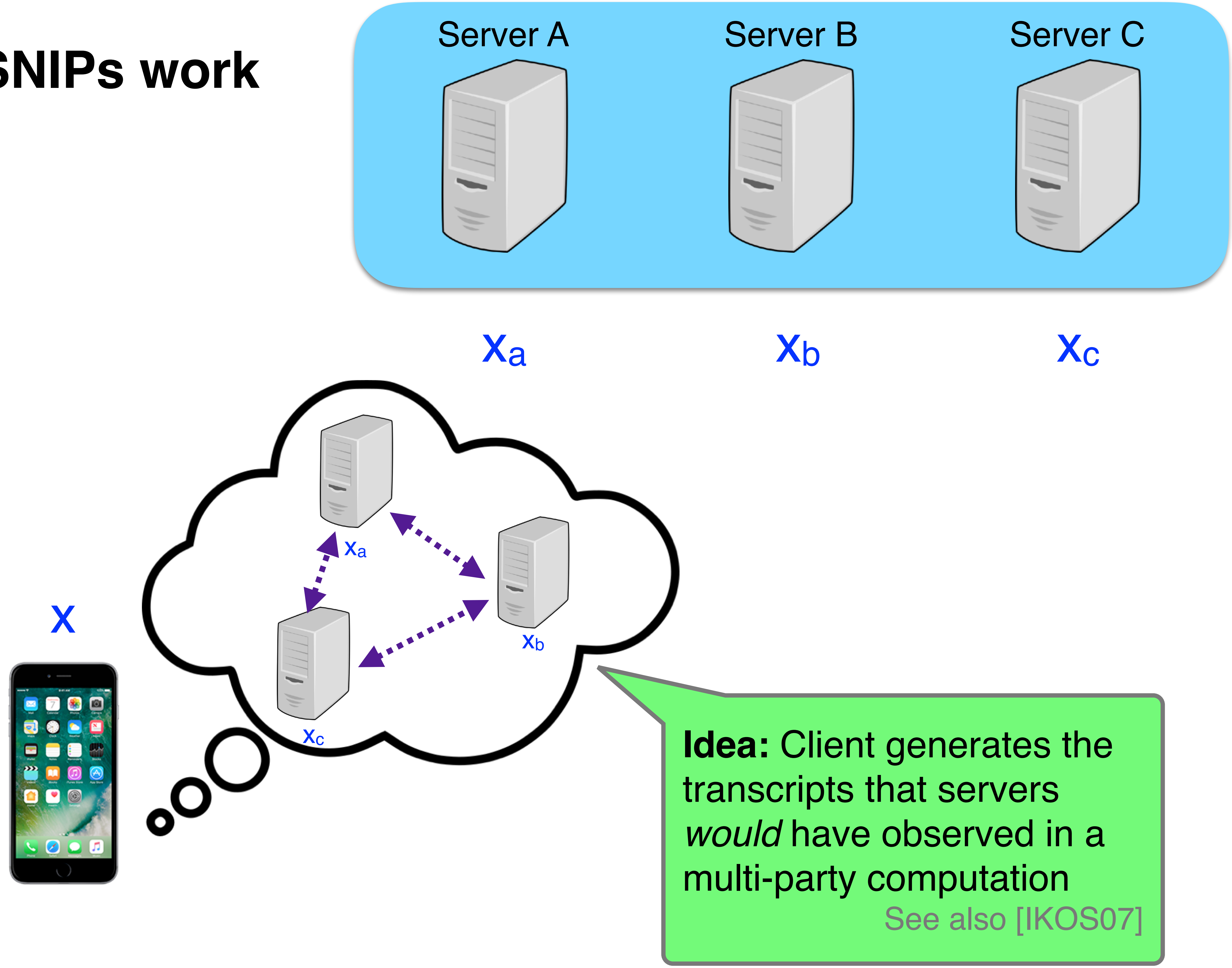


x_a x_b x_c

x

How SNIPs work



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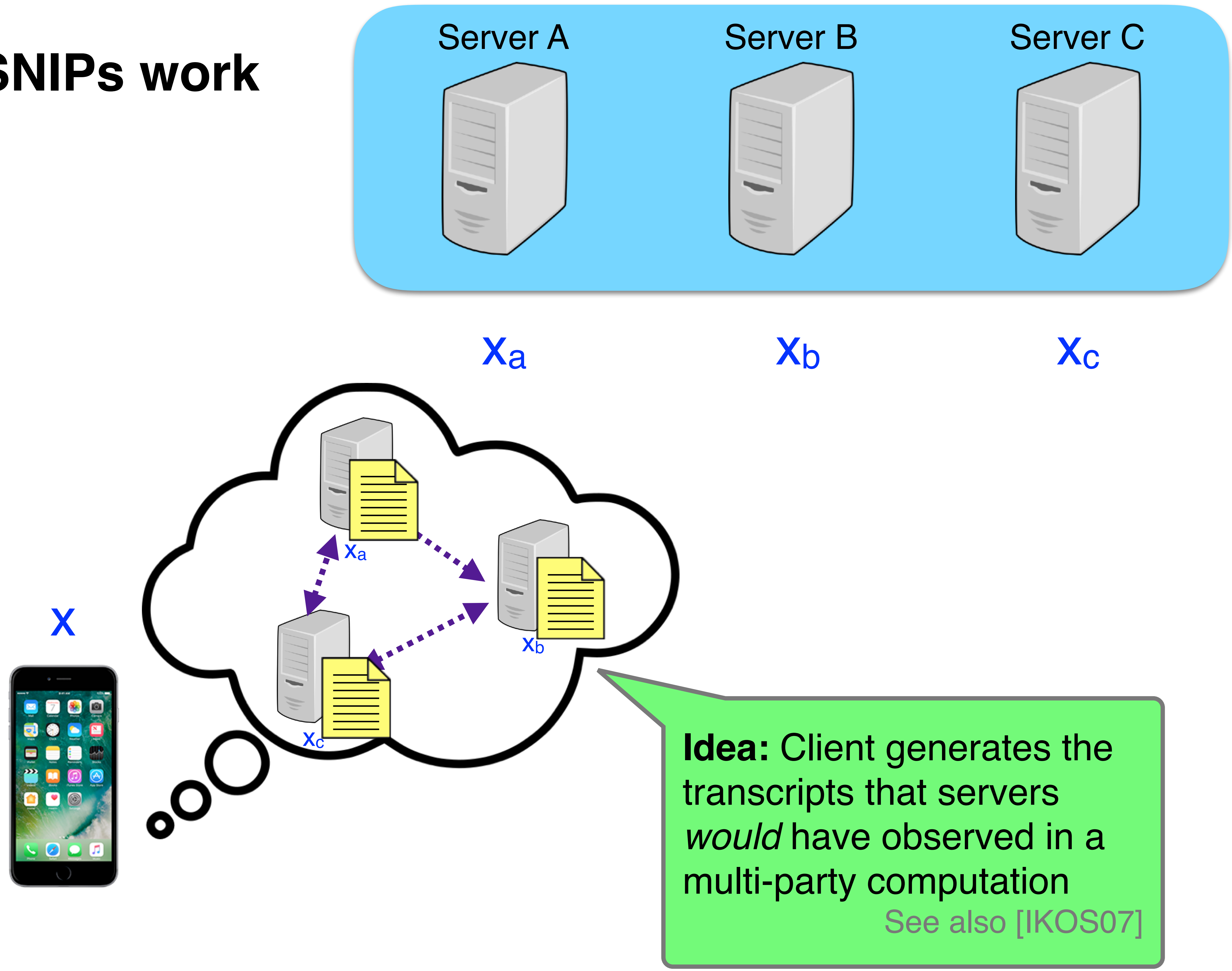

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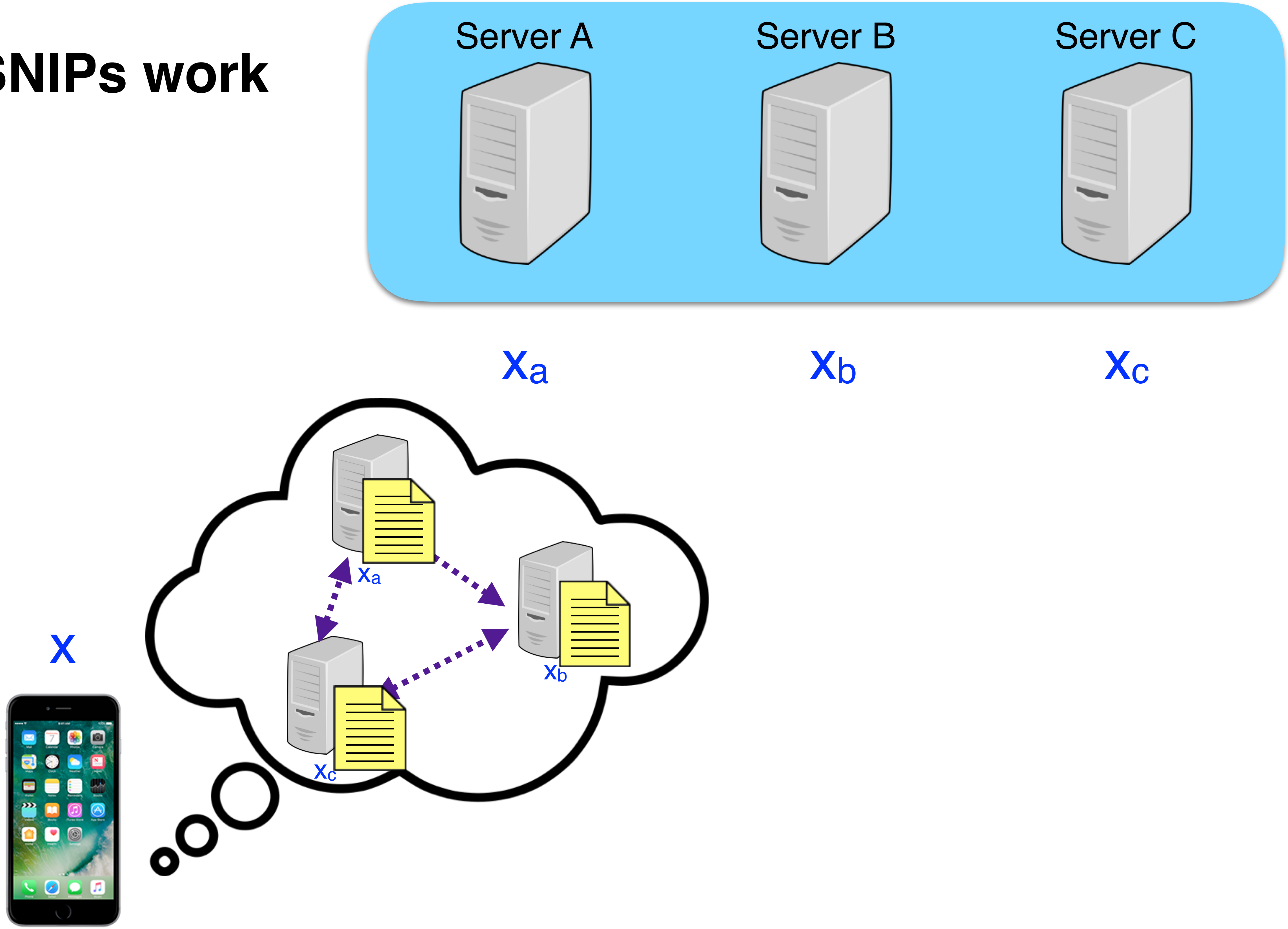

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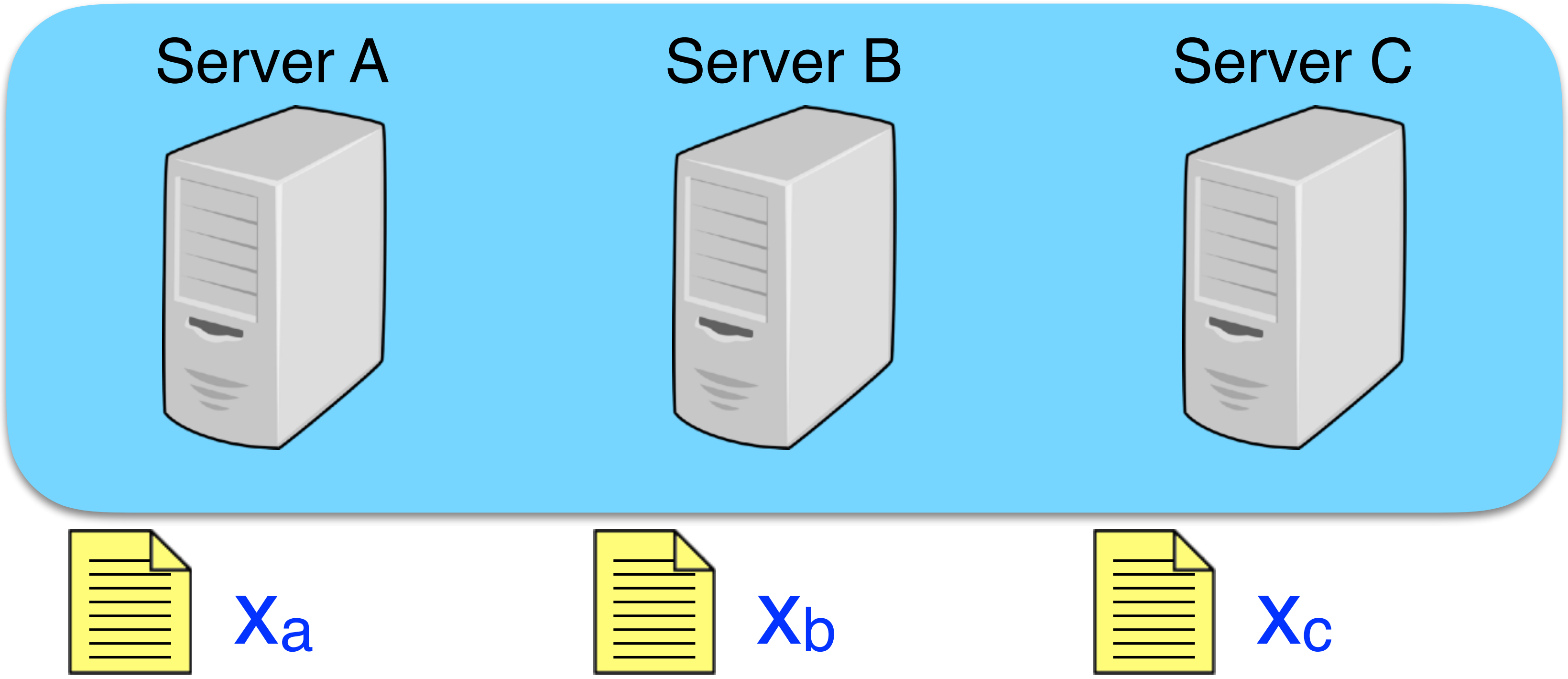

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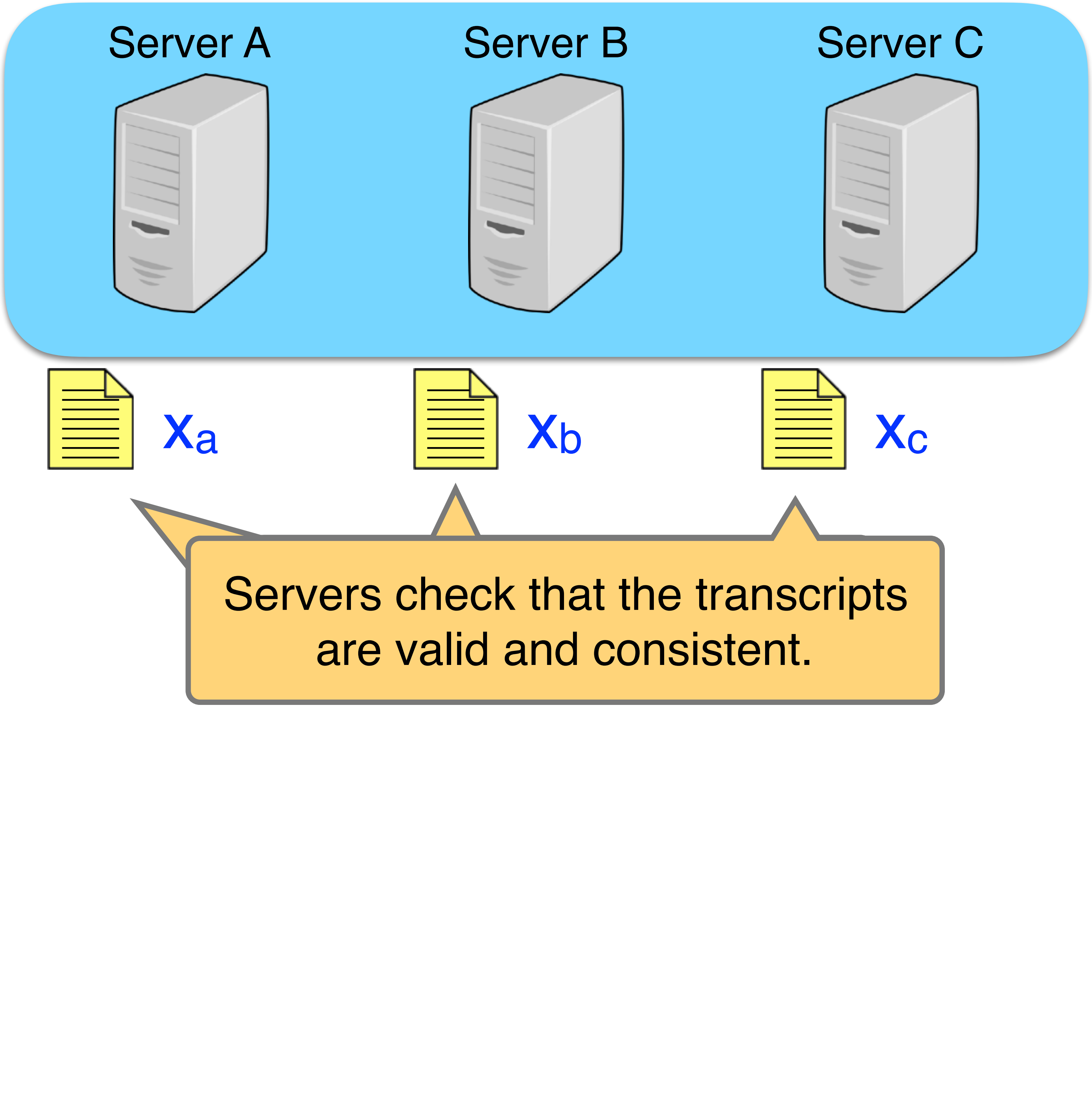

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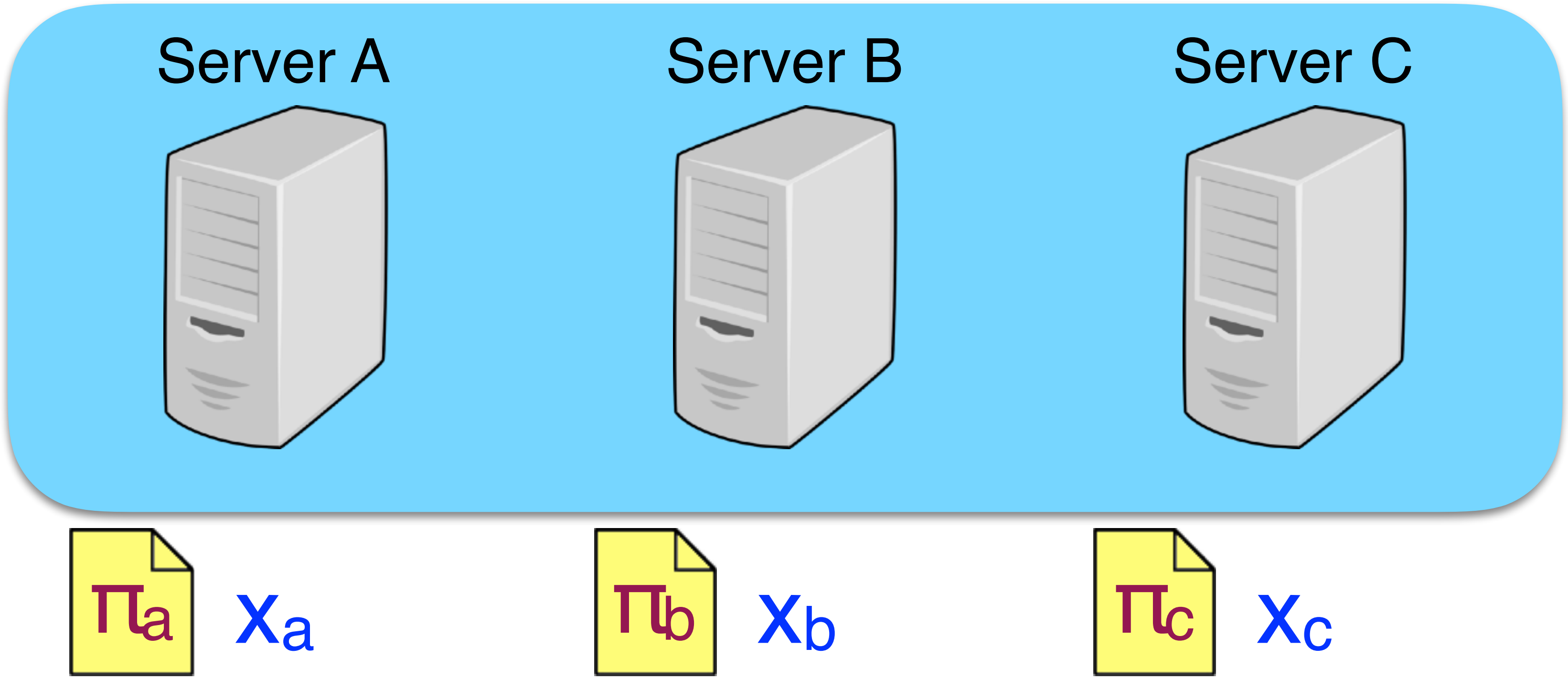
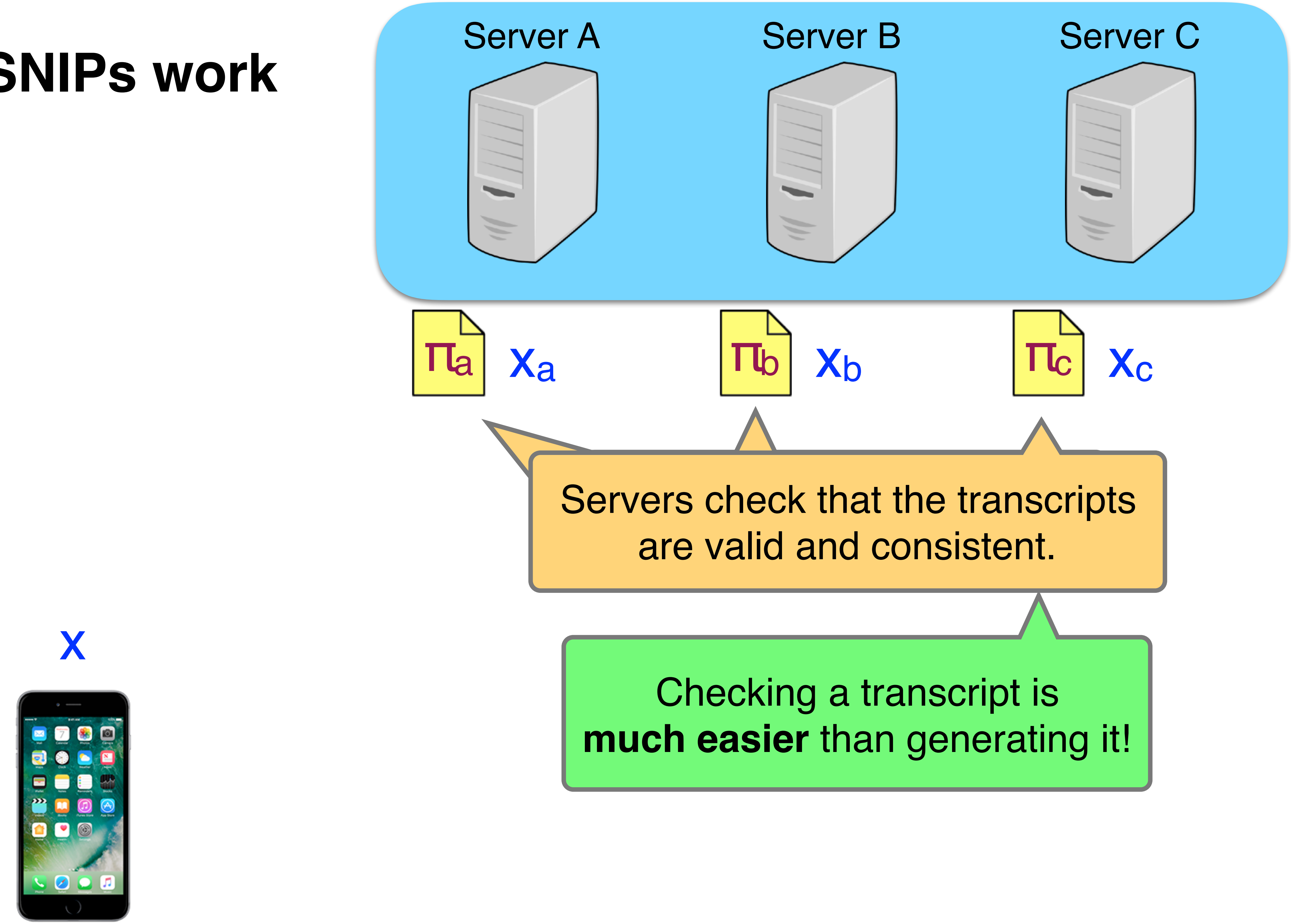


Servers check that the transcripts are valid and consistent.

How SNIPs work



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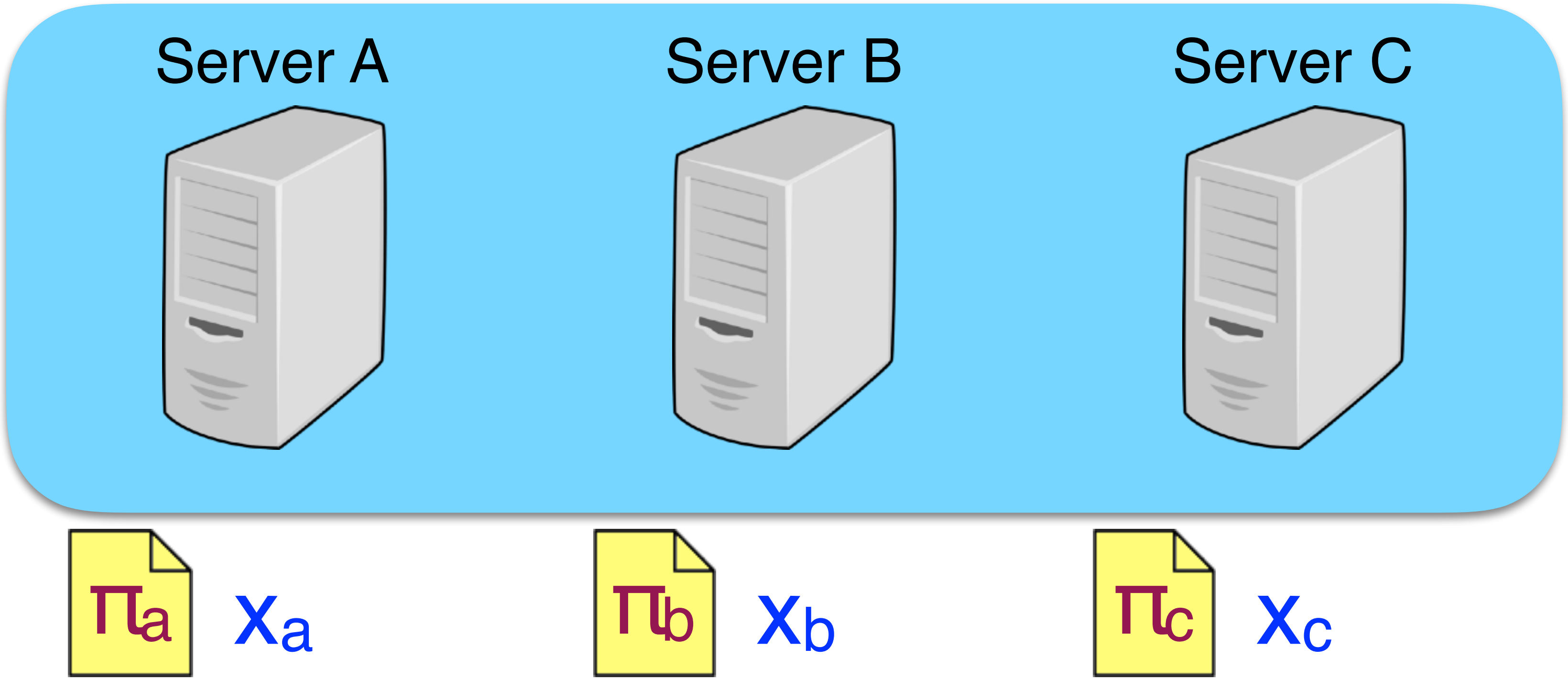

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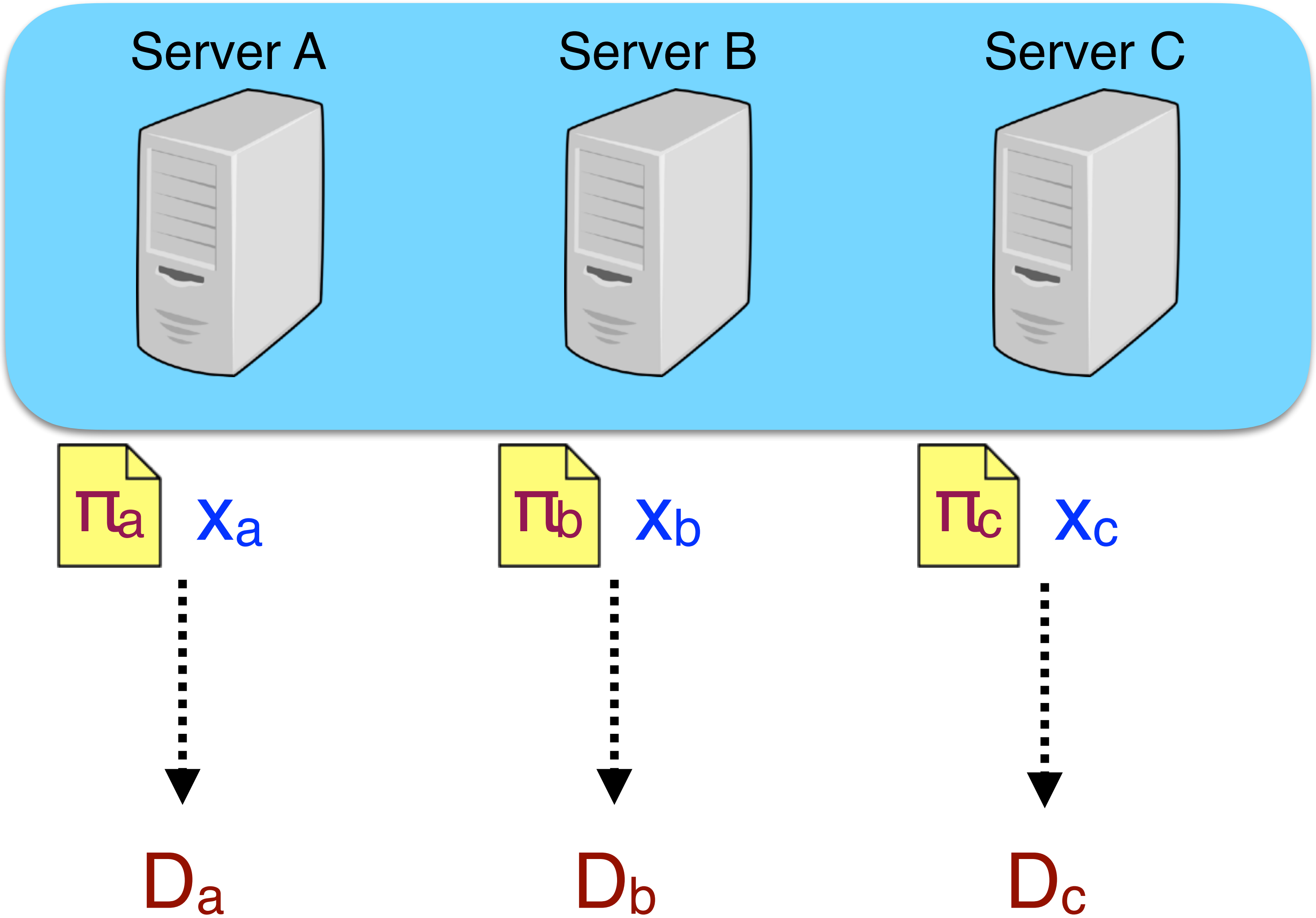

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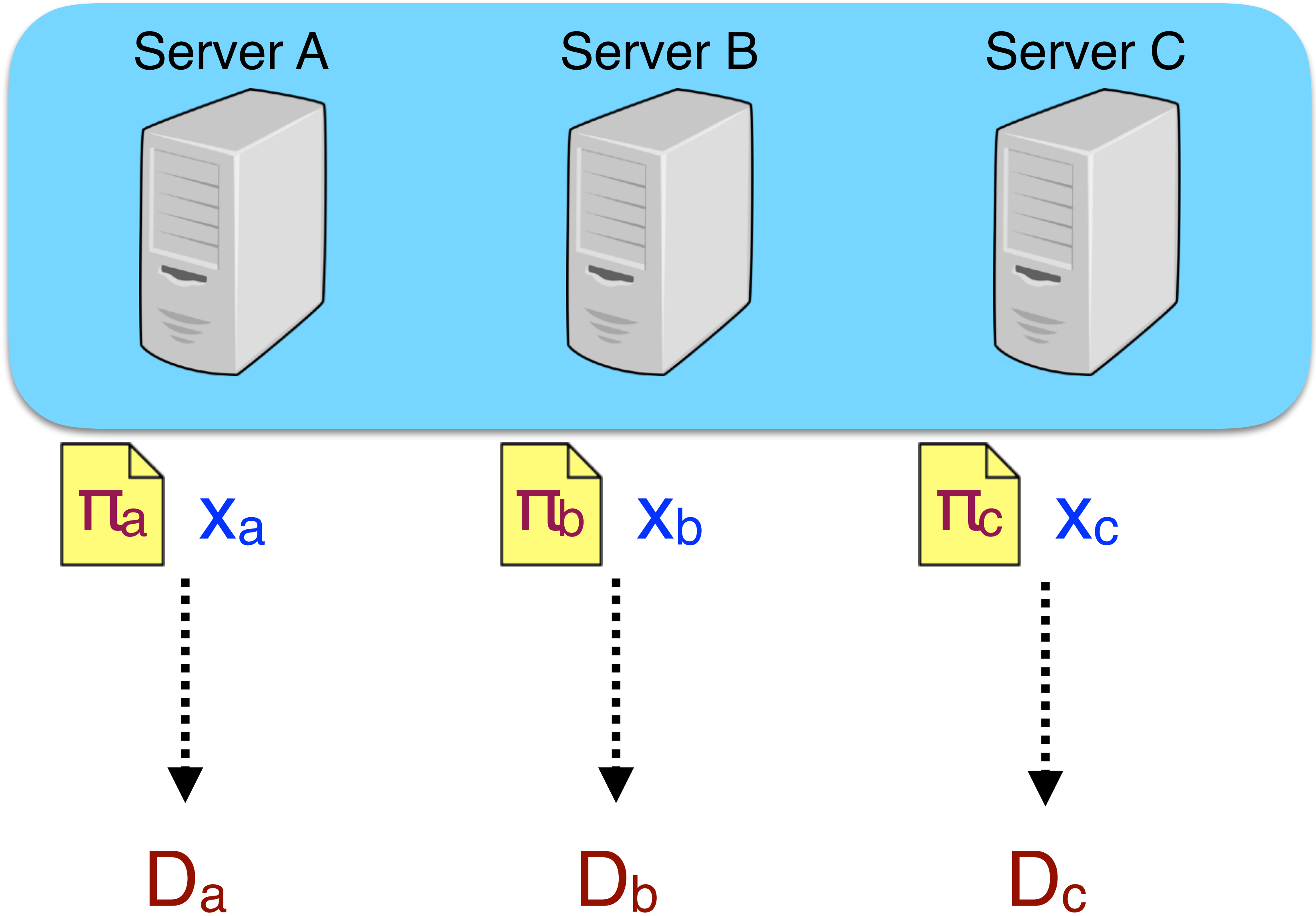
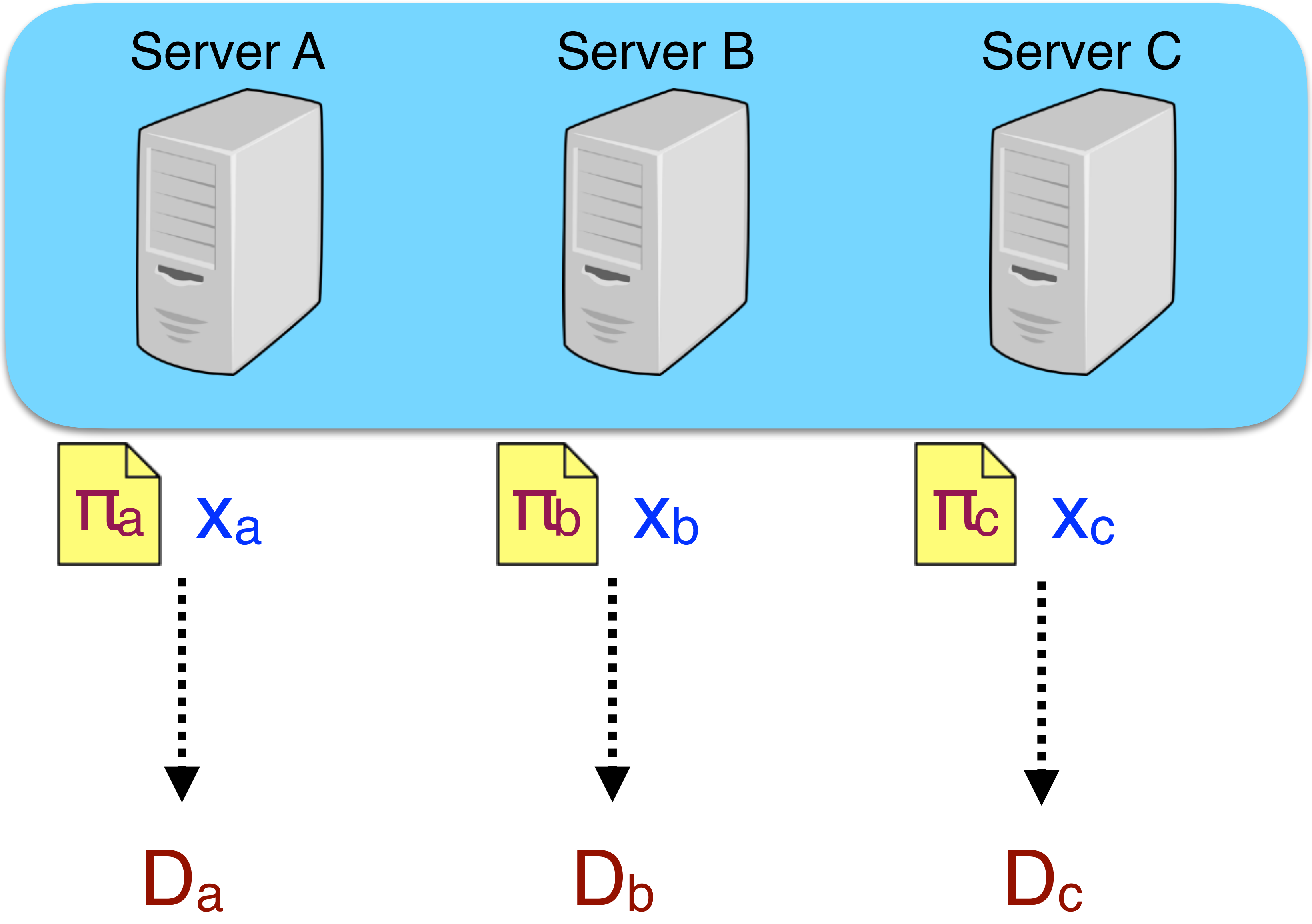


“Randomized digest” of the transcript

How SNIPs work



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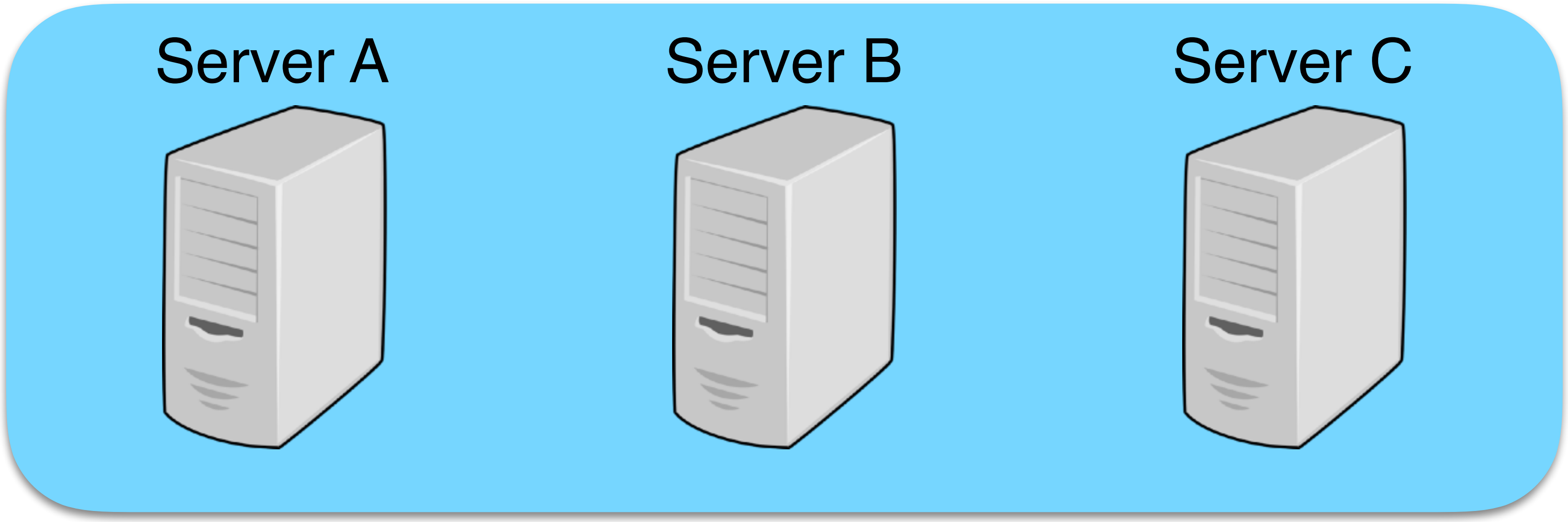
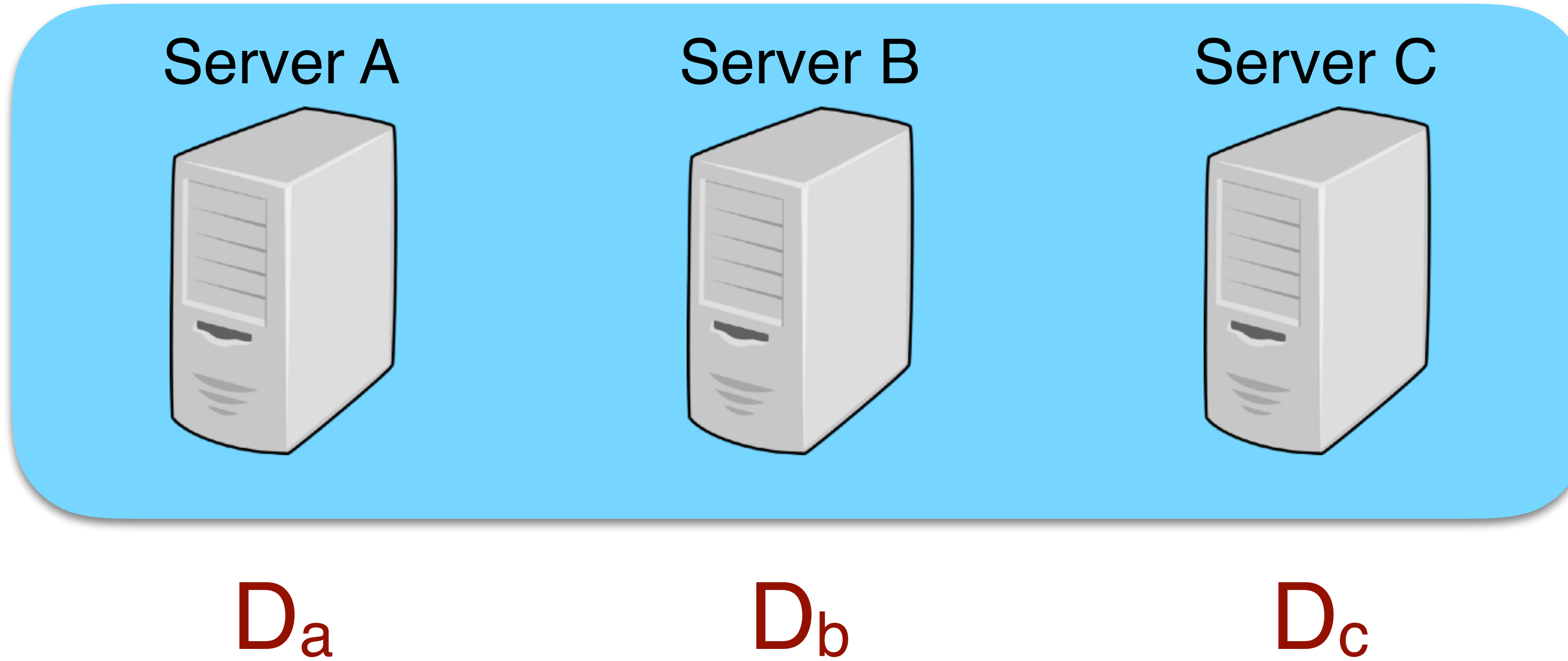


D_a D_b D_c

[BFO12]

How SNIPs work



[BFO12]

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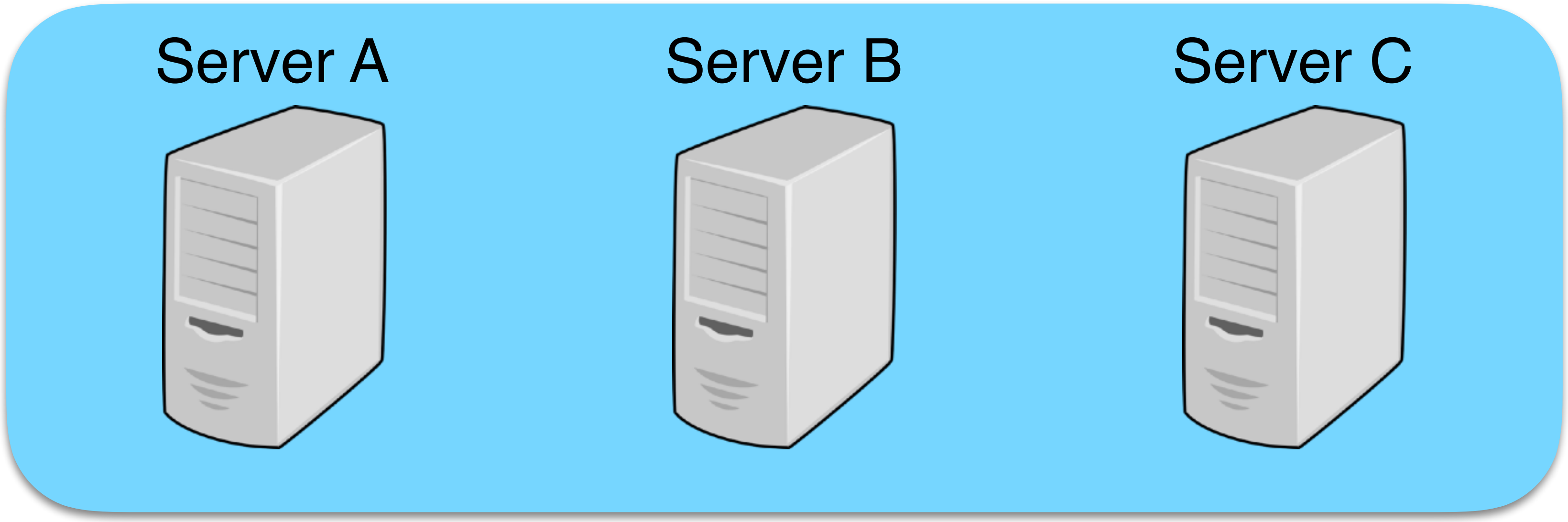


D_a D_b D_c

- 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

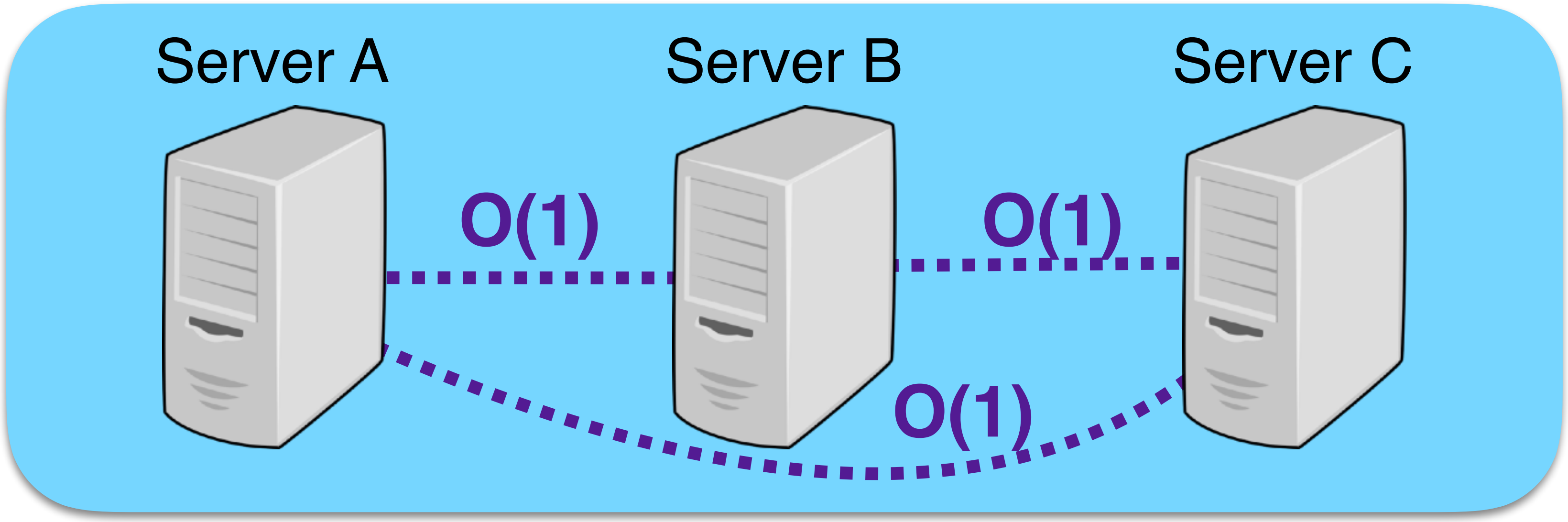
Servers run lightweight multi-party computation to check that

$$D_a + D_b + D_c = 0$$

If so, servers accept x is valid.

[BFO12]

How SNIPs work



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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	Server	**Communication** C-to-S	S-to-S	**Slow-down**
Dishonest-maj. MPC [CLOS02], [DPSZ12], …	0	$\Theta(M)$	0	$\Theta(M)$	5,000x at server
Commits + NIZKs [FS86], [CP92], [CS97], …	$\Theta(M)$	$\Theta(M)$	$\Theta(M)$	$\Theta(M)$	50x at server
Commits + SNARKs [GGPR13], [BCGTV13], …	$\Theta(M)$	$O(1)$	$O(1)$	$O(1)$	500x at client

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
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	Public-key ops. Server	Communication C-to-S	Communication S-to-S	Slow-down
Dishonest-maj. MPC [CLOS02], [DPSZ12], …	0	Θ(M)	0	Θ(M)	5,000x at server
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

For specific Valid() circuits, it is possible to eliminate this cost [BGI16]

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
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

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- **Providing robustness with SNIPs**
- Evaluation
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Evaluation

- 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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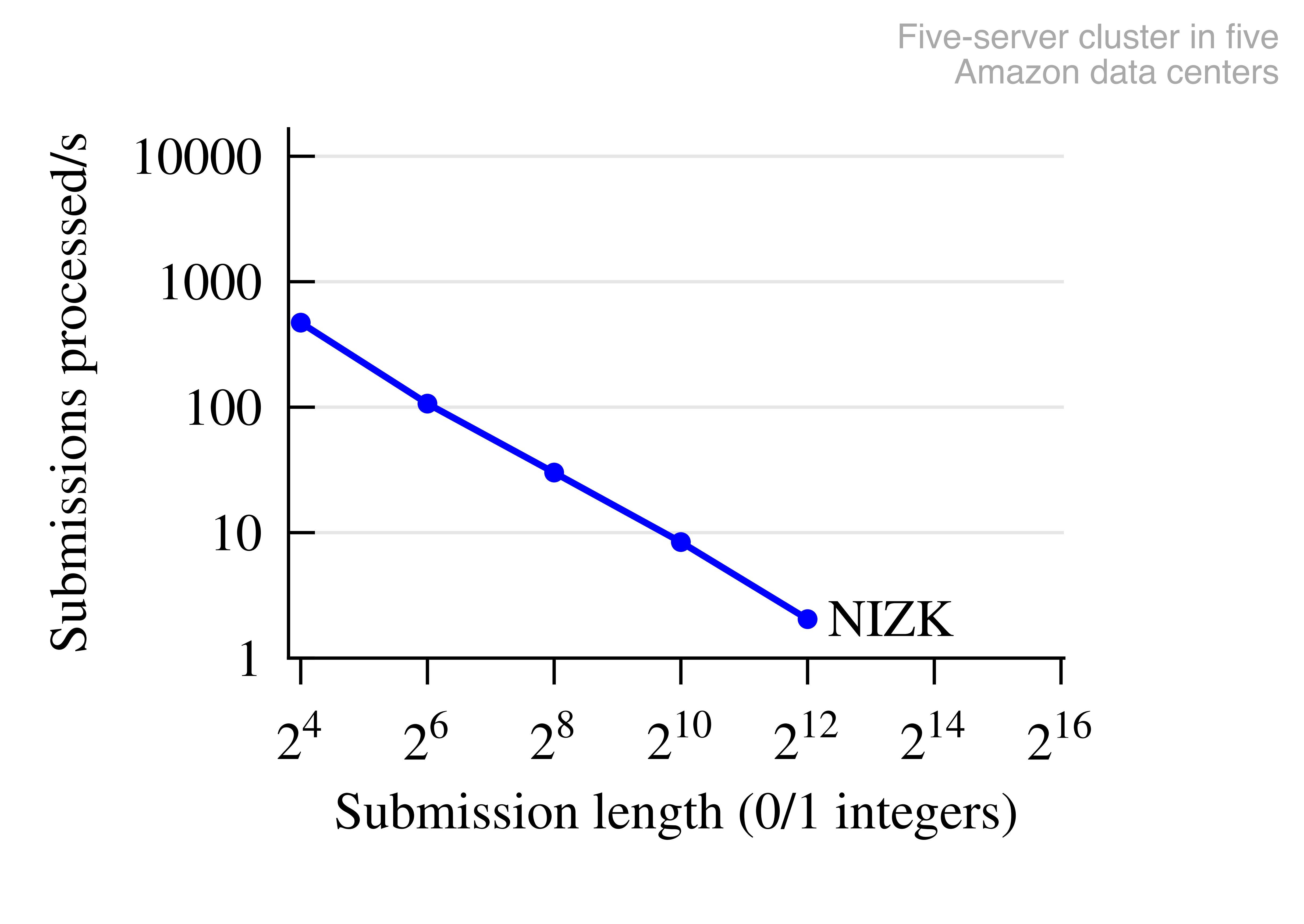
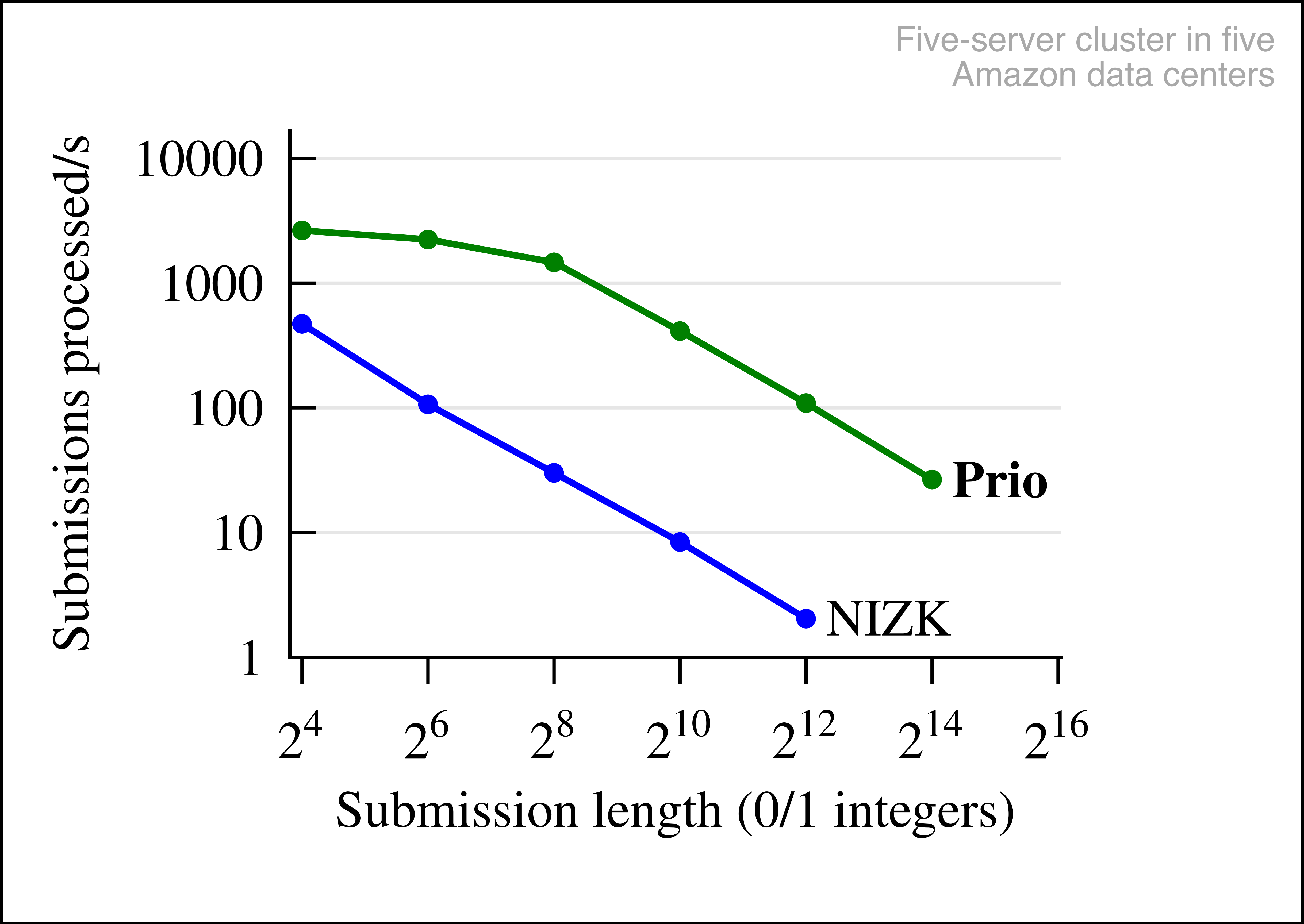
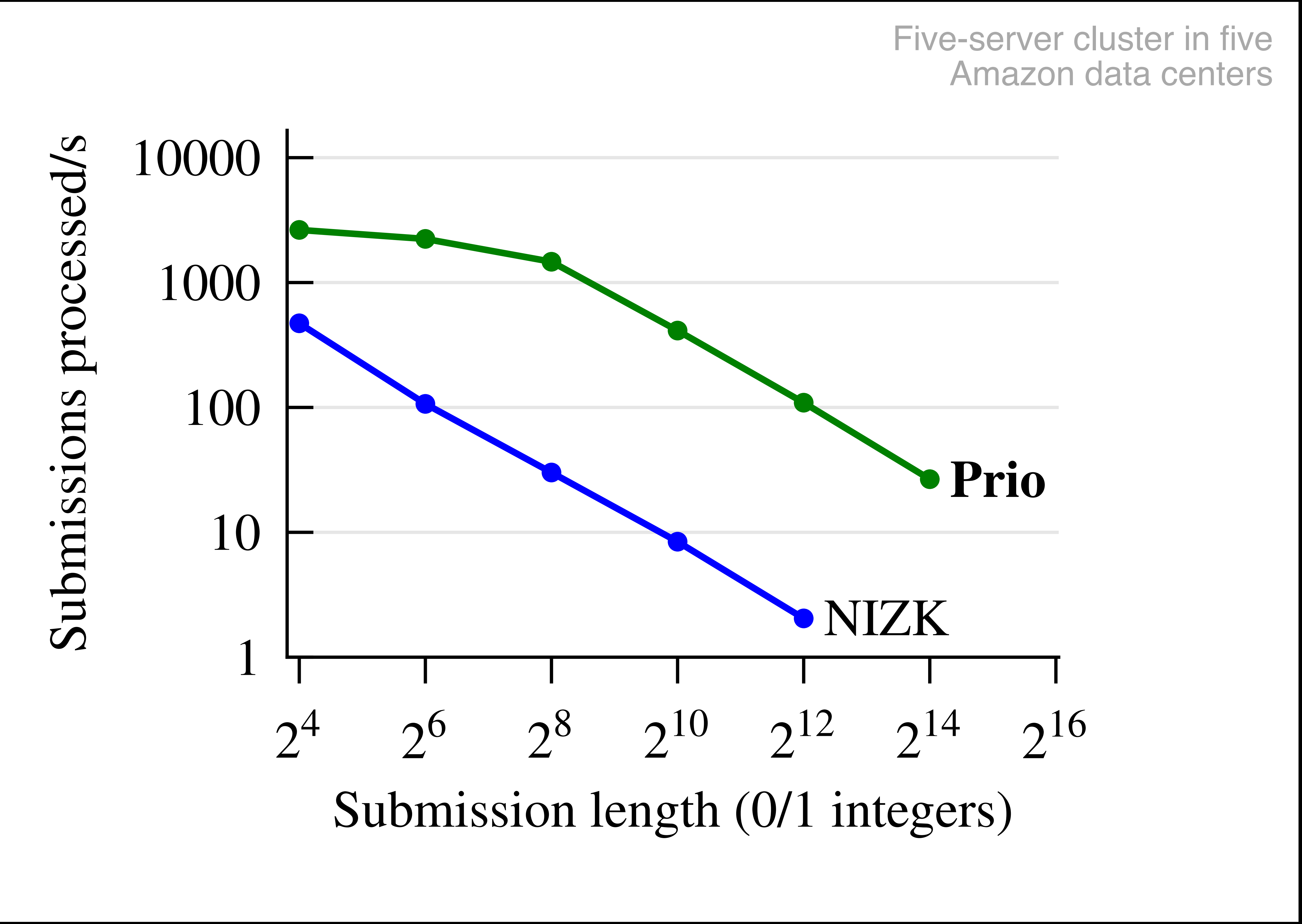
five servers


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
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
2^6
2^8
2^{10}
2^{12}
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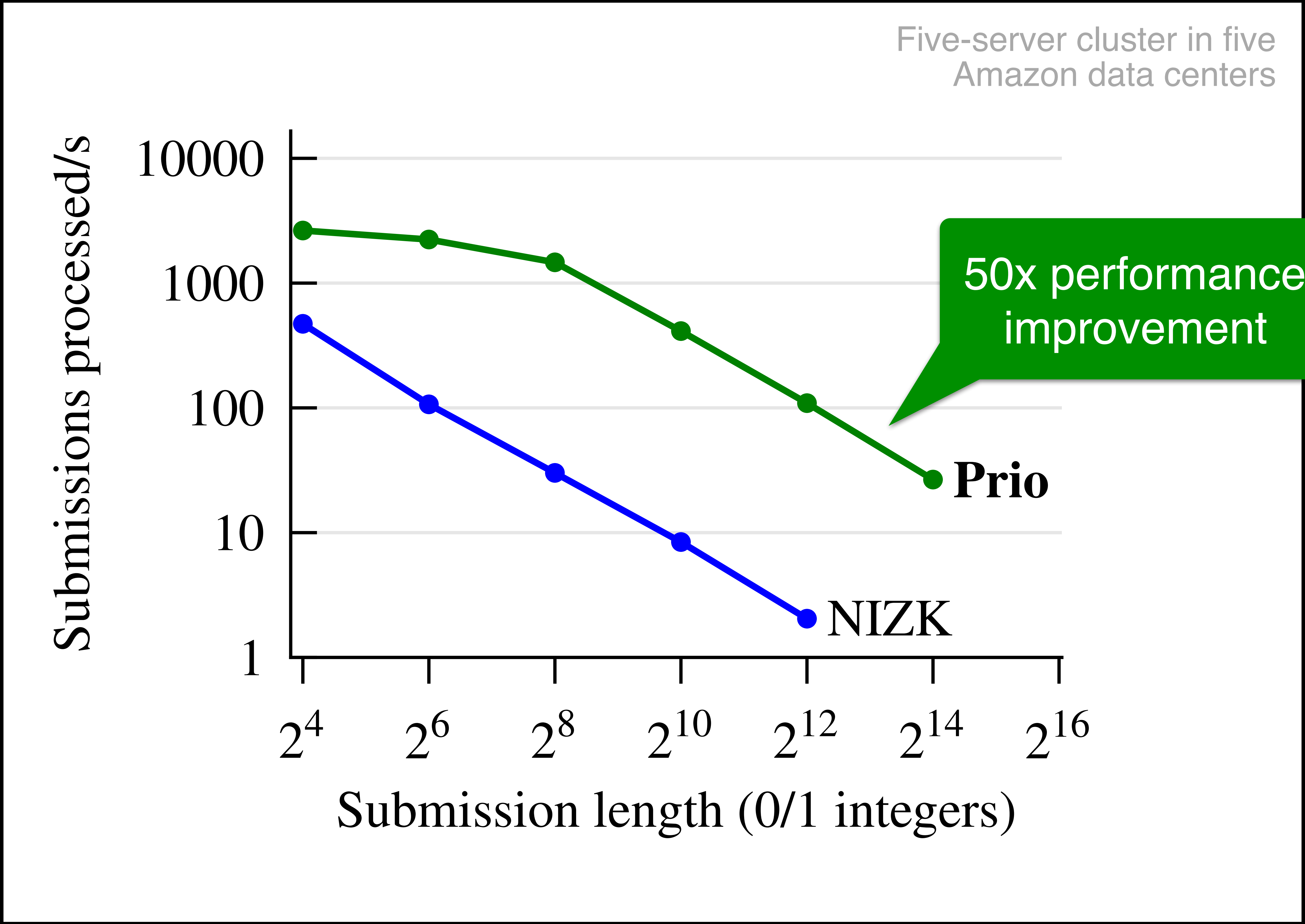
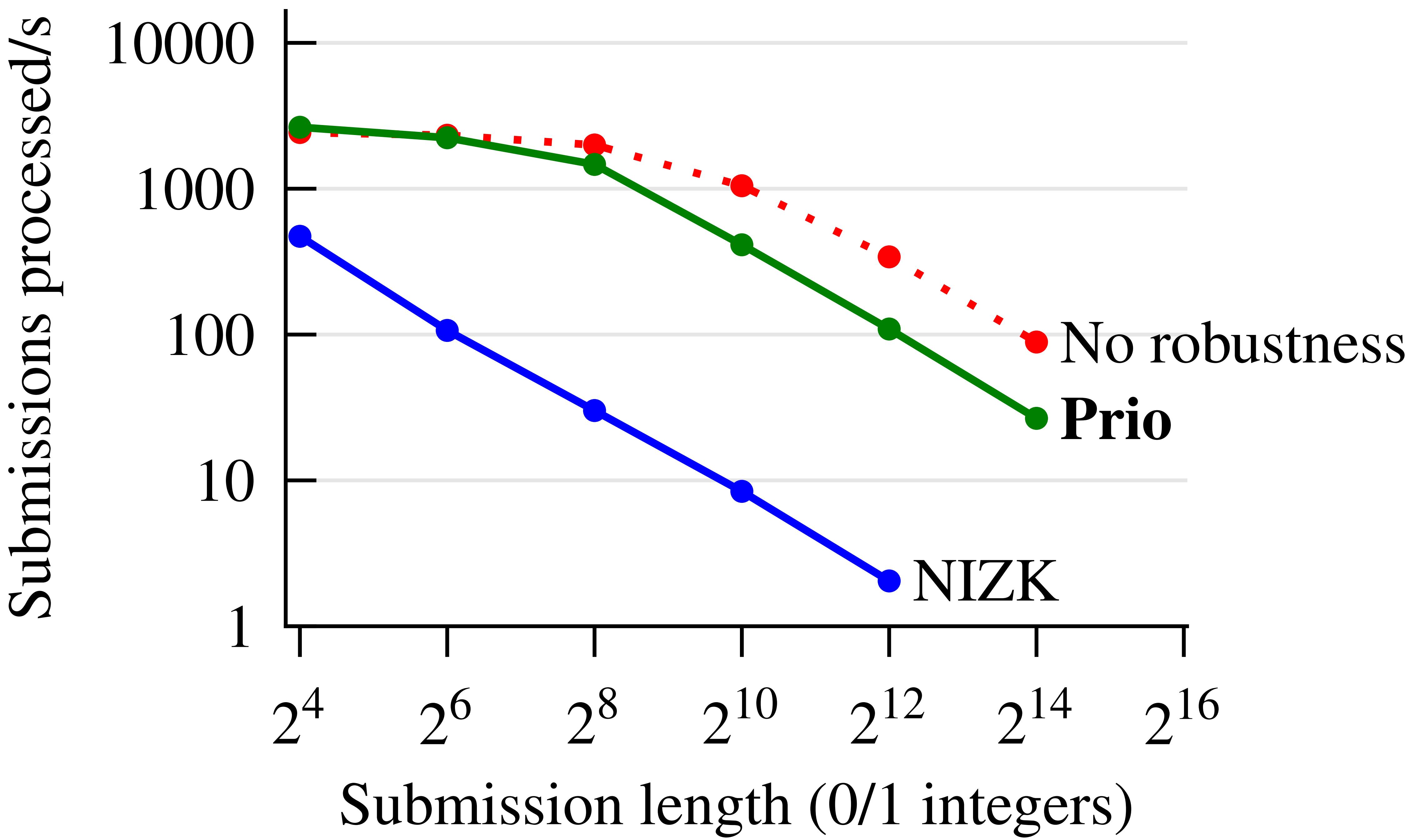
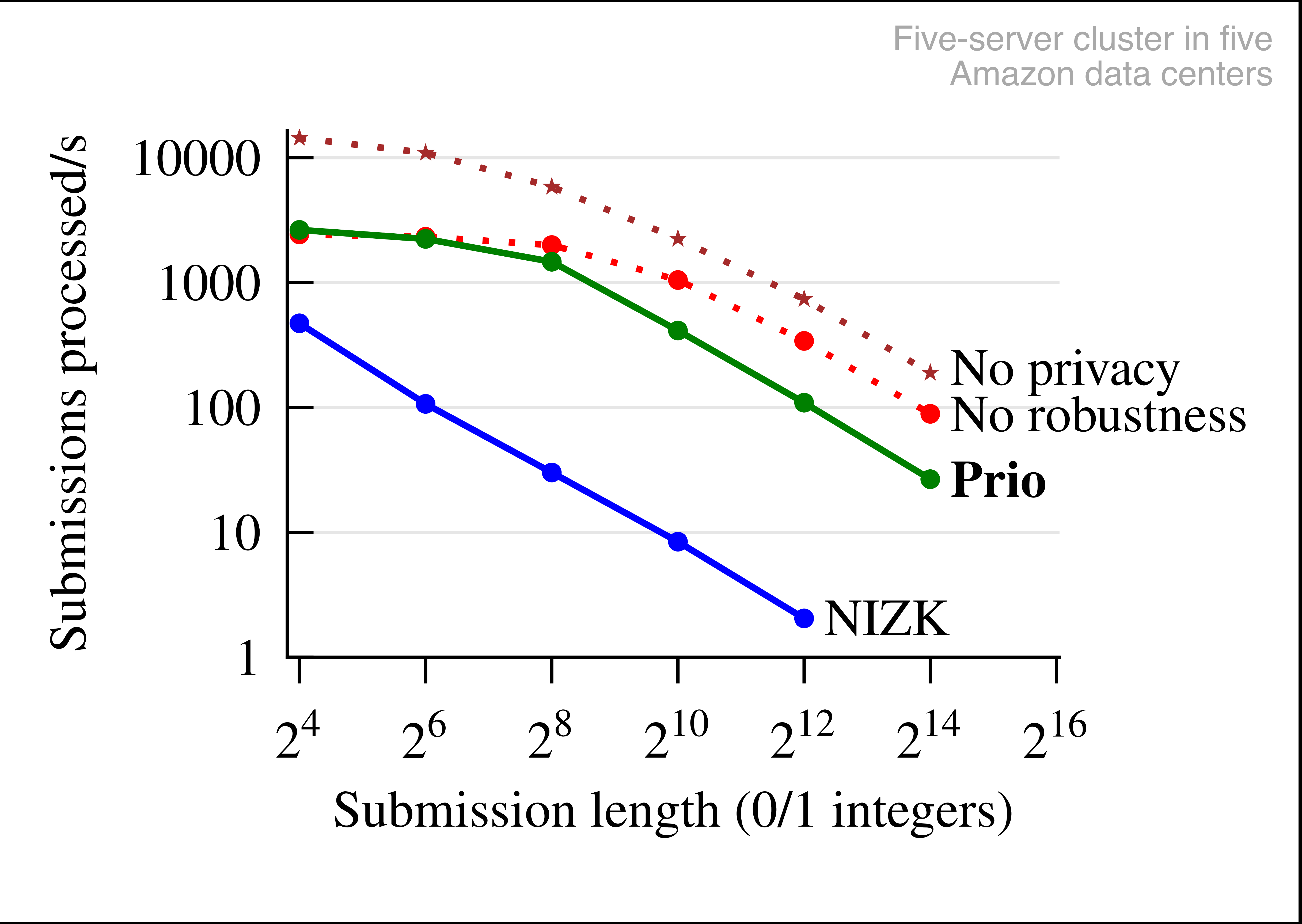
Submission length (0/1 integers)



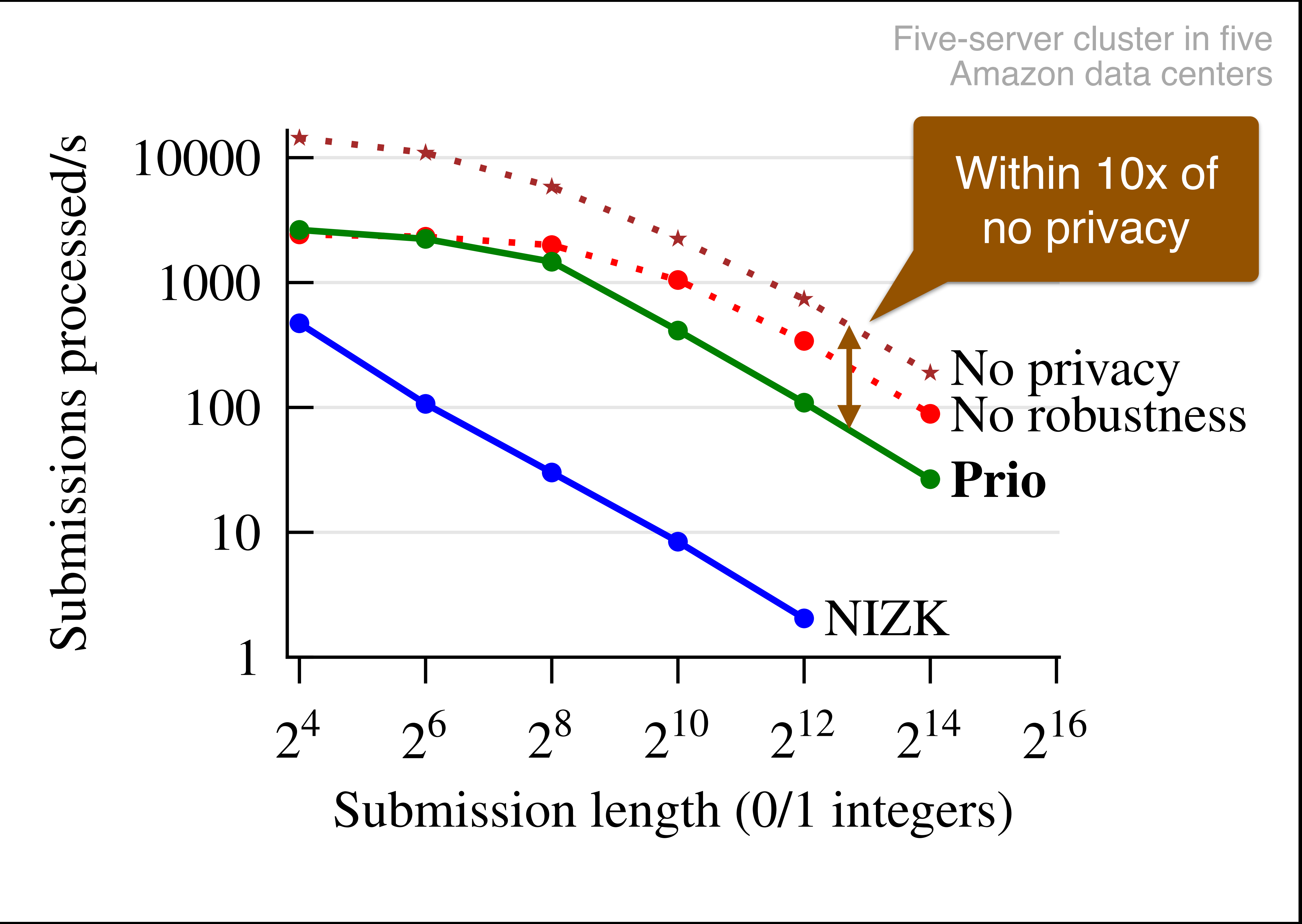
Five-server cluster in five
Amazon data centers
Submissions processed/s
10000
1000
100
10
1
50x performance
improvement
Prio
NIZK
2^4
2^6
2^8
2^{10}
2^{12}
2^{14}
2^{16}
Submission length (0/1 integers)

Five-server cluster in five
Amazon data centers

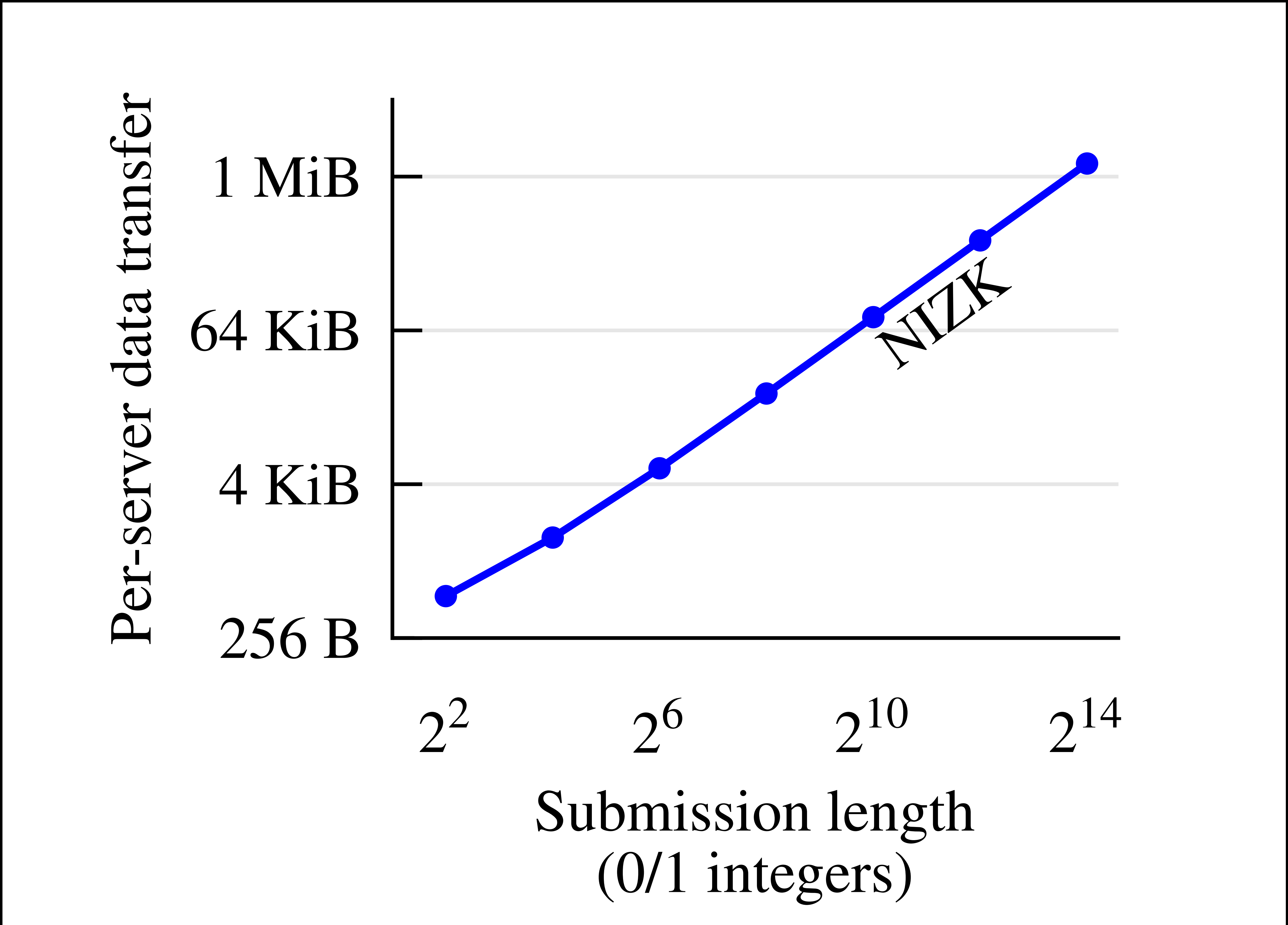

Submissions processed/s
10000
1000
100
10
1
No robustness
Prio
NIZK
2^4
2^6
2^8
2^10
2^12
2^14
2^16
Submission length (0/1 integers)



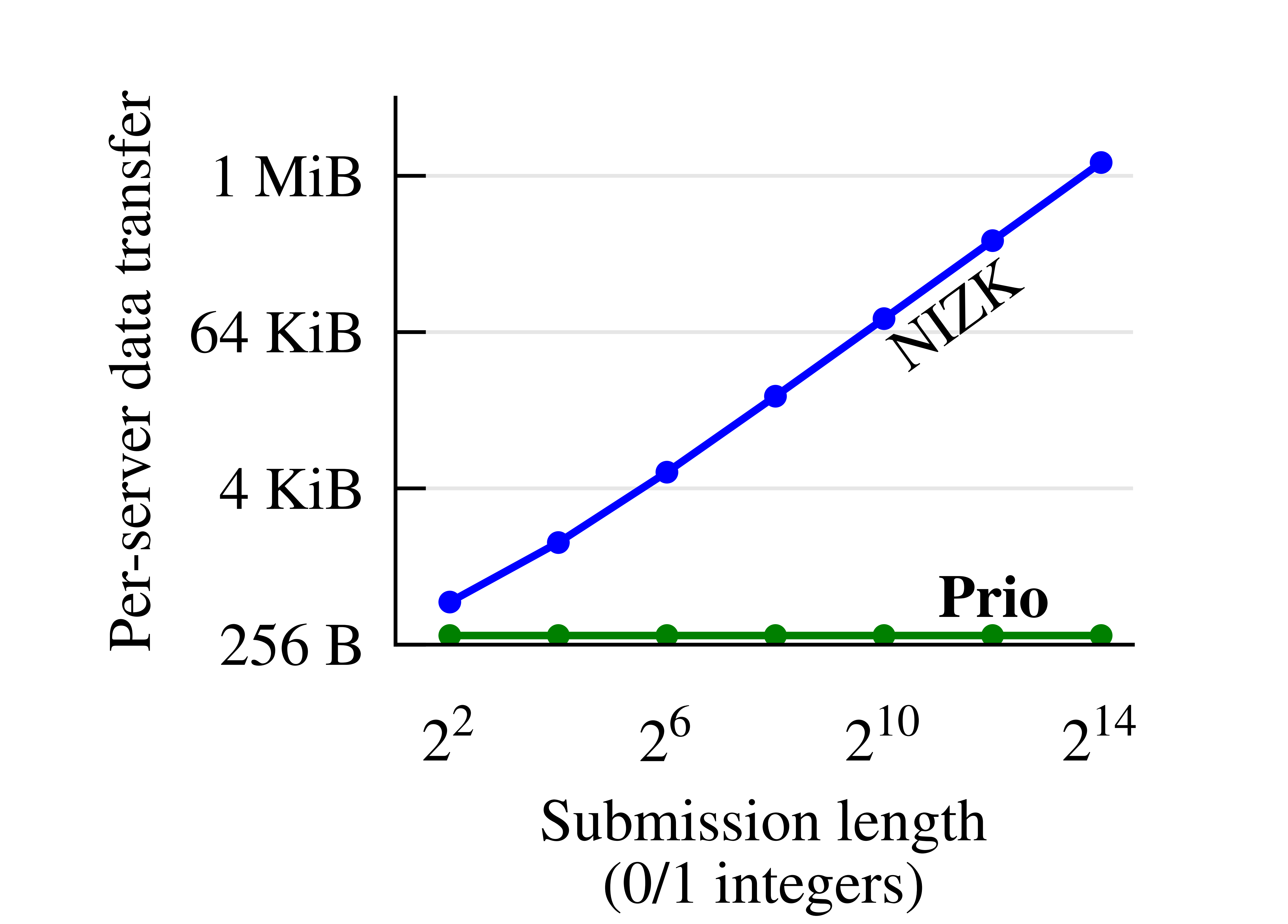
Five-server cluster in five
Amazon data centers
Submissions processed/s
10000
1000
100
10
1
No privacy
No robustness
Prio
NIZK
2^4
2^6
2^8
2^{10}
2^{12}
2^{14}
2^{16}
Submission length (0/1 integers)



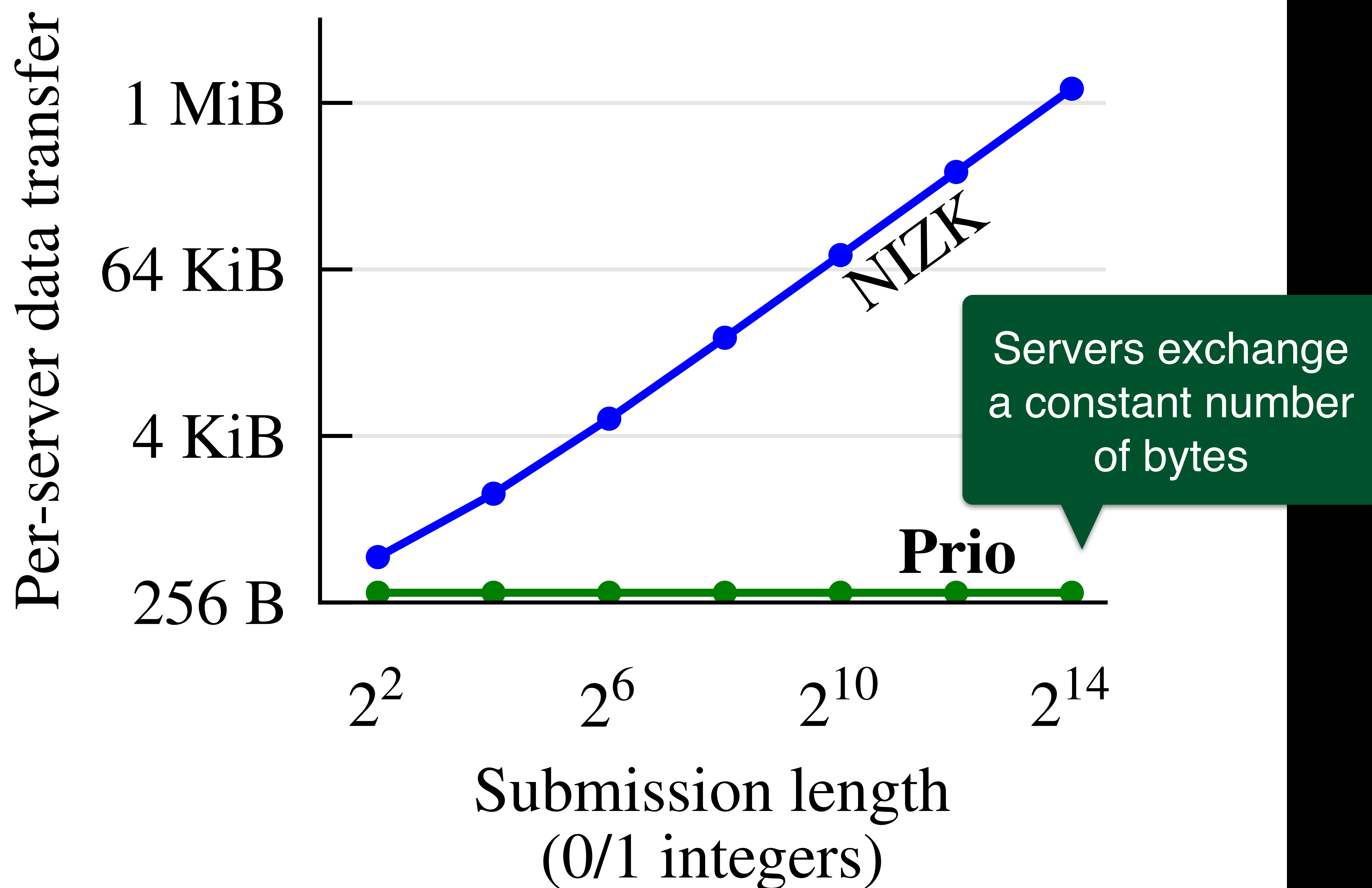
Five-server cluster in five
Amazon data centers
Within 10x of
no privacy
Submissions processed/s
10000
1000
100
10
1
No privacy
No robustness
Prio
NIZK
2^4
2^6
2^8
2^{10}
2^{12}
2^{14}
2^{16}
Submission length (0/1 integers)



Per-server data transfer
1 MiB
64 KiB
4 KiB
256 B
NIZK
2^2
2^6
2^10
2^14
Submission length
(0/1 integers)



Per-server data transfer
1 MiB
64 KiB
4 KiB
256 B
NIZK
Prio
2^2
2^6
2^{10}
2^{14}
Submission length
(0/1 integers)



Per-server data transfer
1 MiB
64 KiB
4 KiB
256 B
NIZK
Prio
Servers exchange a constant number of bytes
2^2
2^6
2^{10}
2^{14}
Submission length (0/1 integers)

Outline

- Background: The private aggregation problem
- A straw-man solution for private sums
- Providing robustness with SNIPs
- **Evaluation**
- Encodings for complex aggregates

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Known techniques: Complex statistics

If you can compute private sums, you can compute many other interesting aggregates using known techniques

[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
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SNIP-friendly encodings for these statistics

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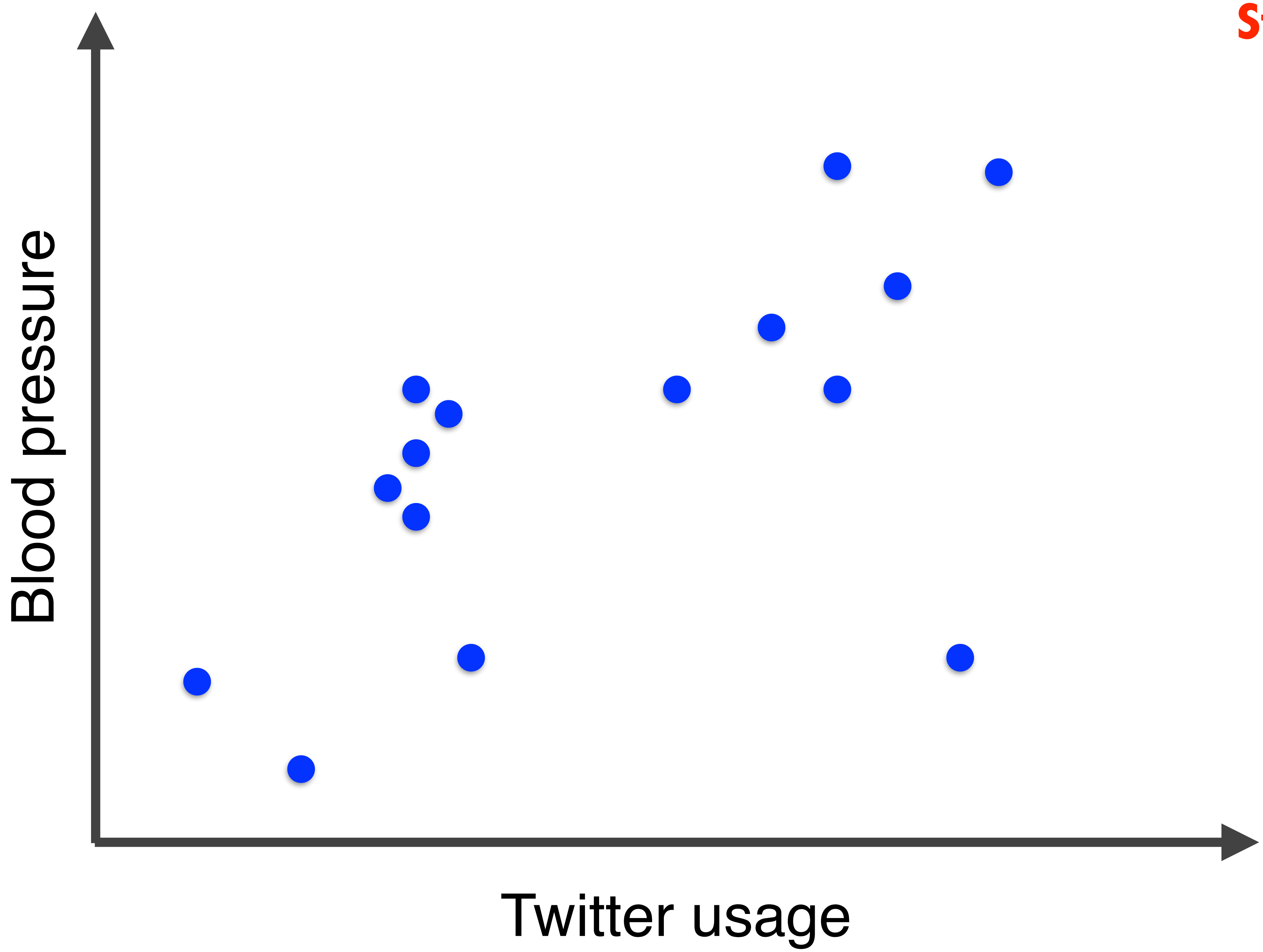
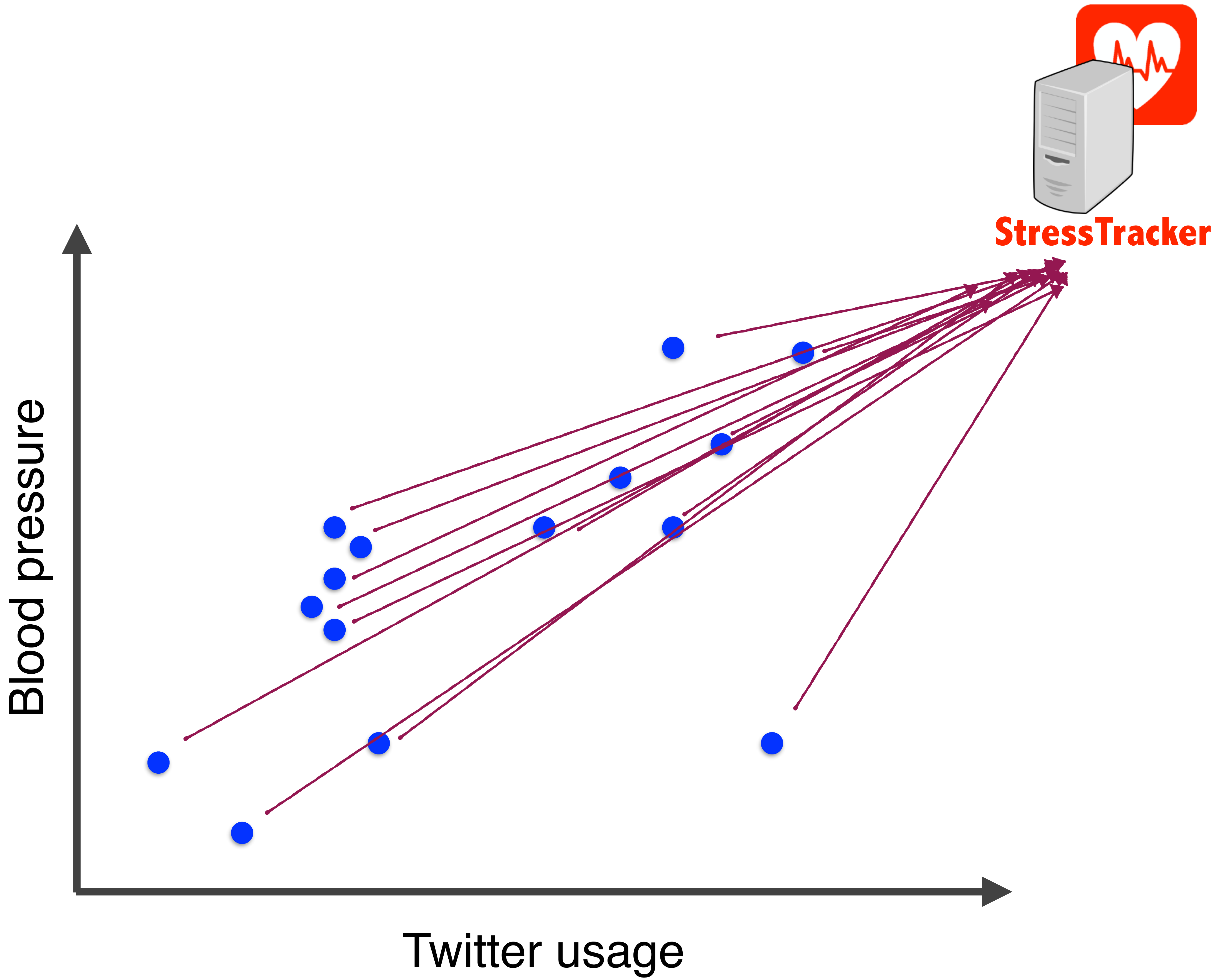
See the paper for the details

Today

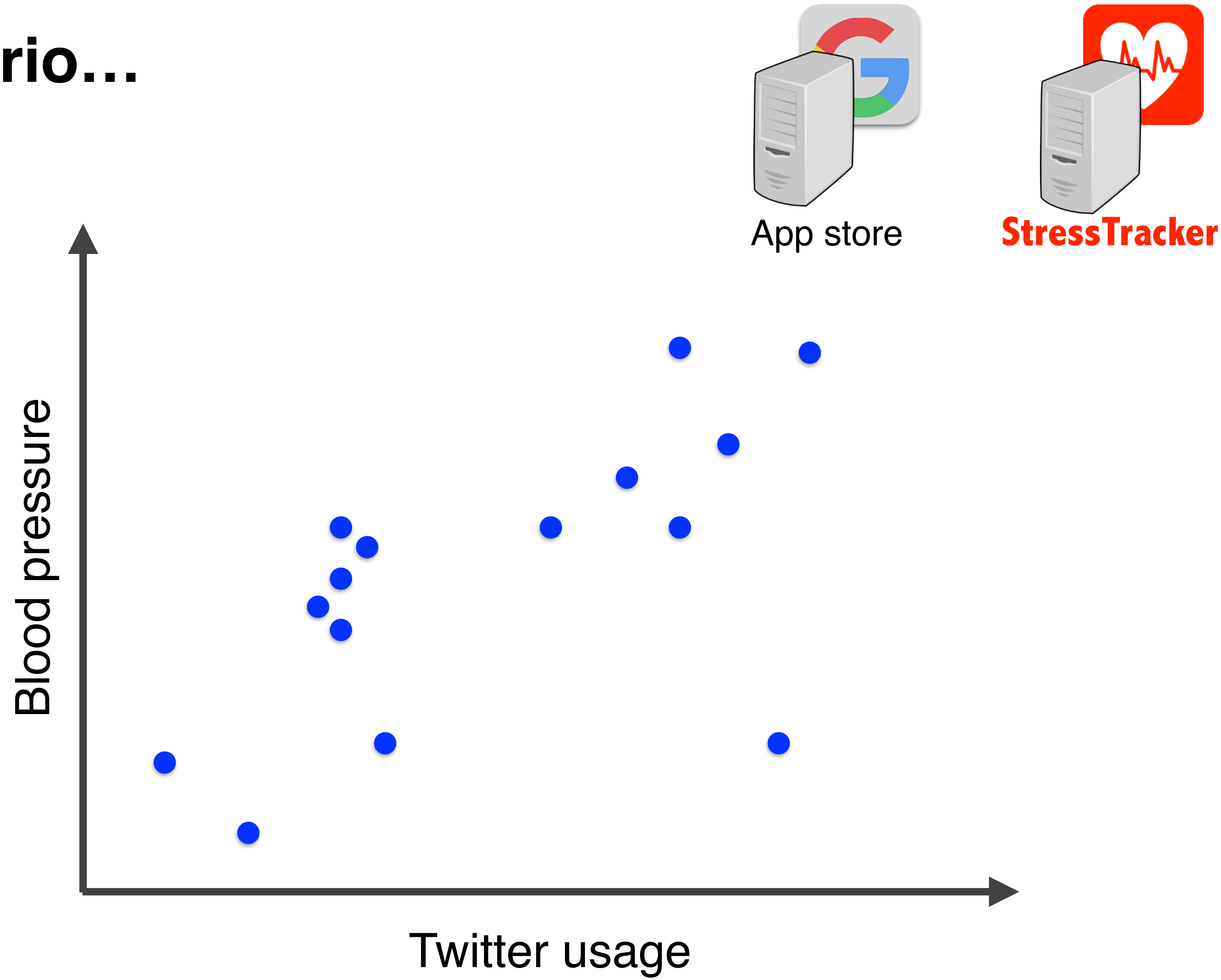
StressTracker



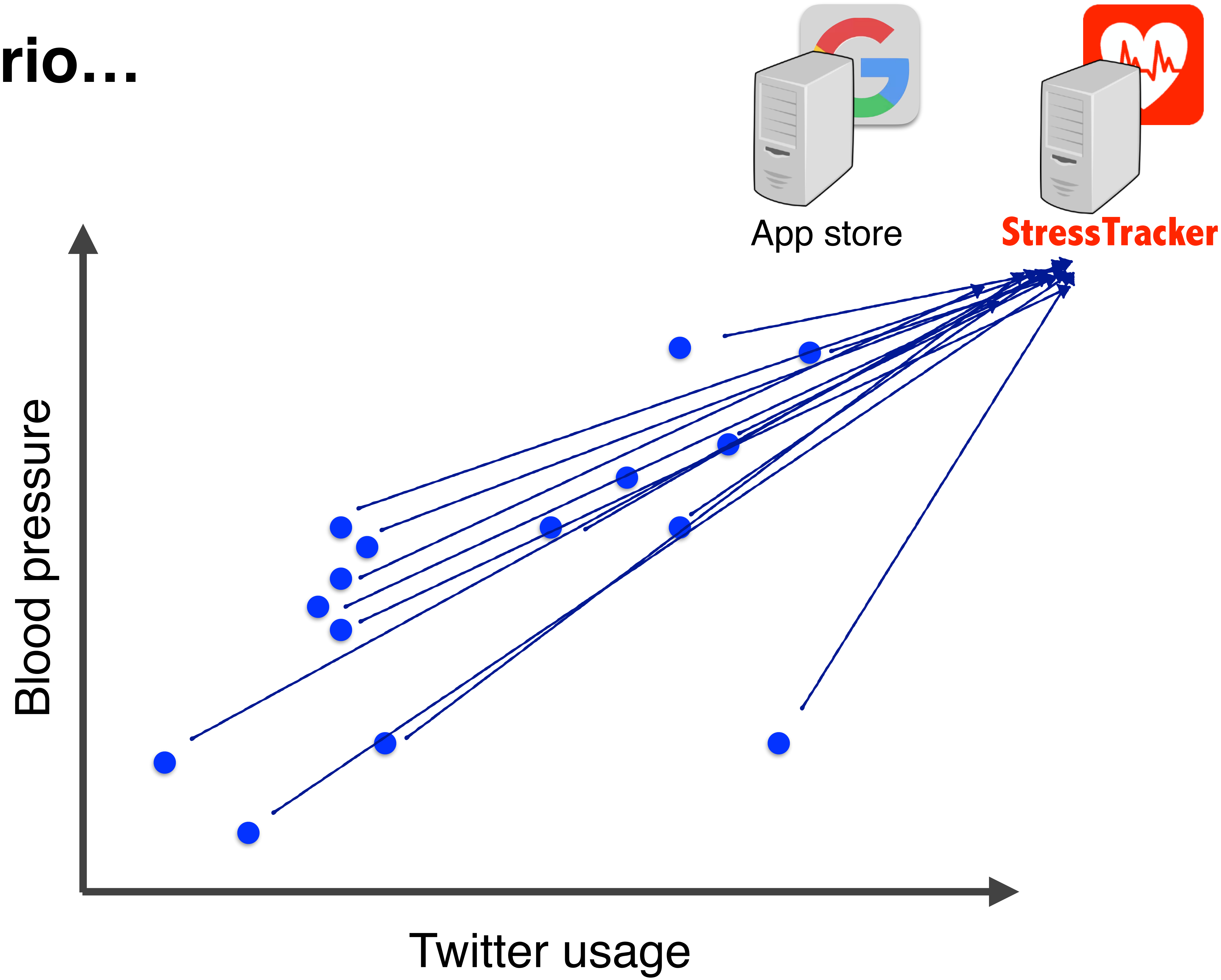
Today



With Prio…



With Prio…



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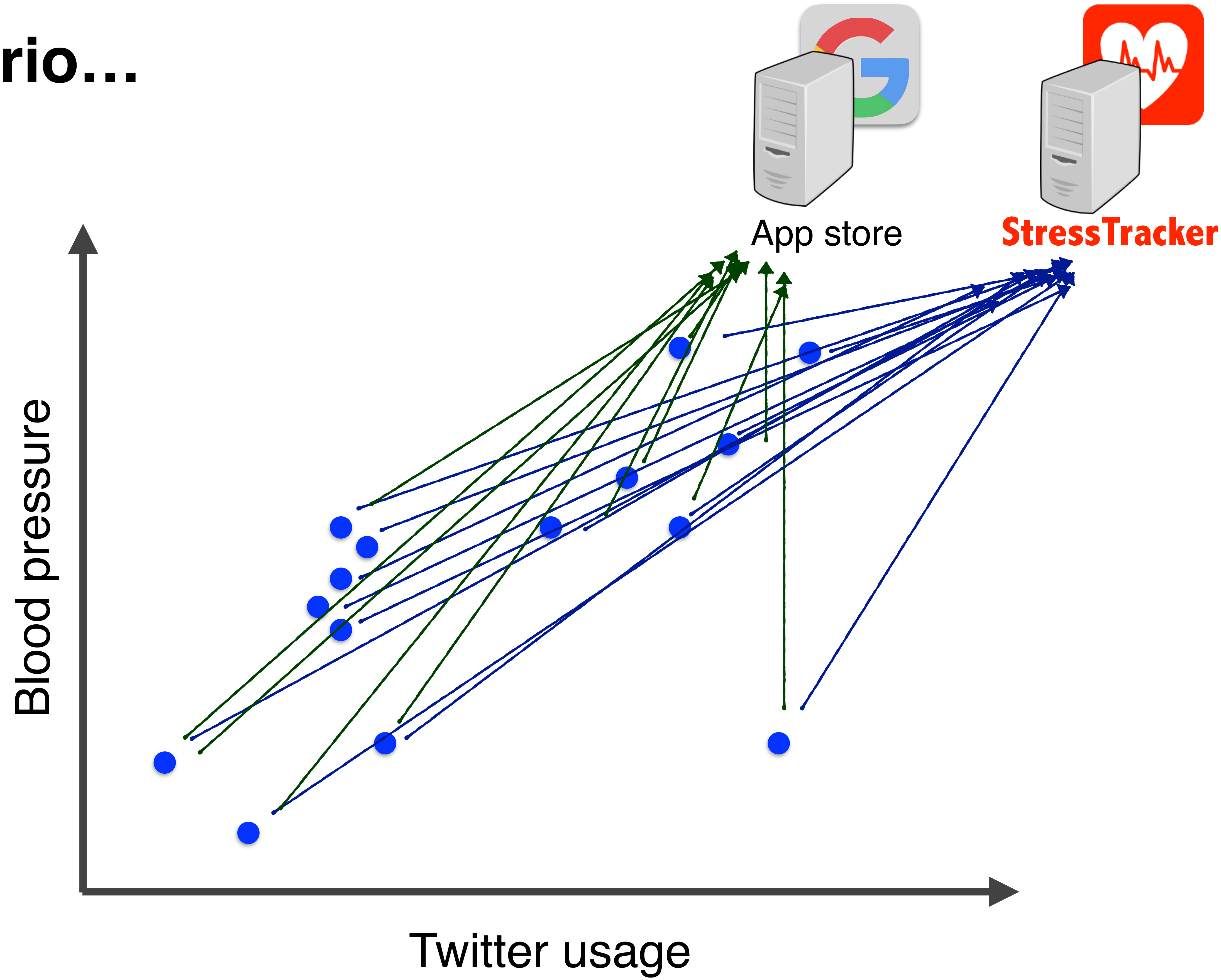

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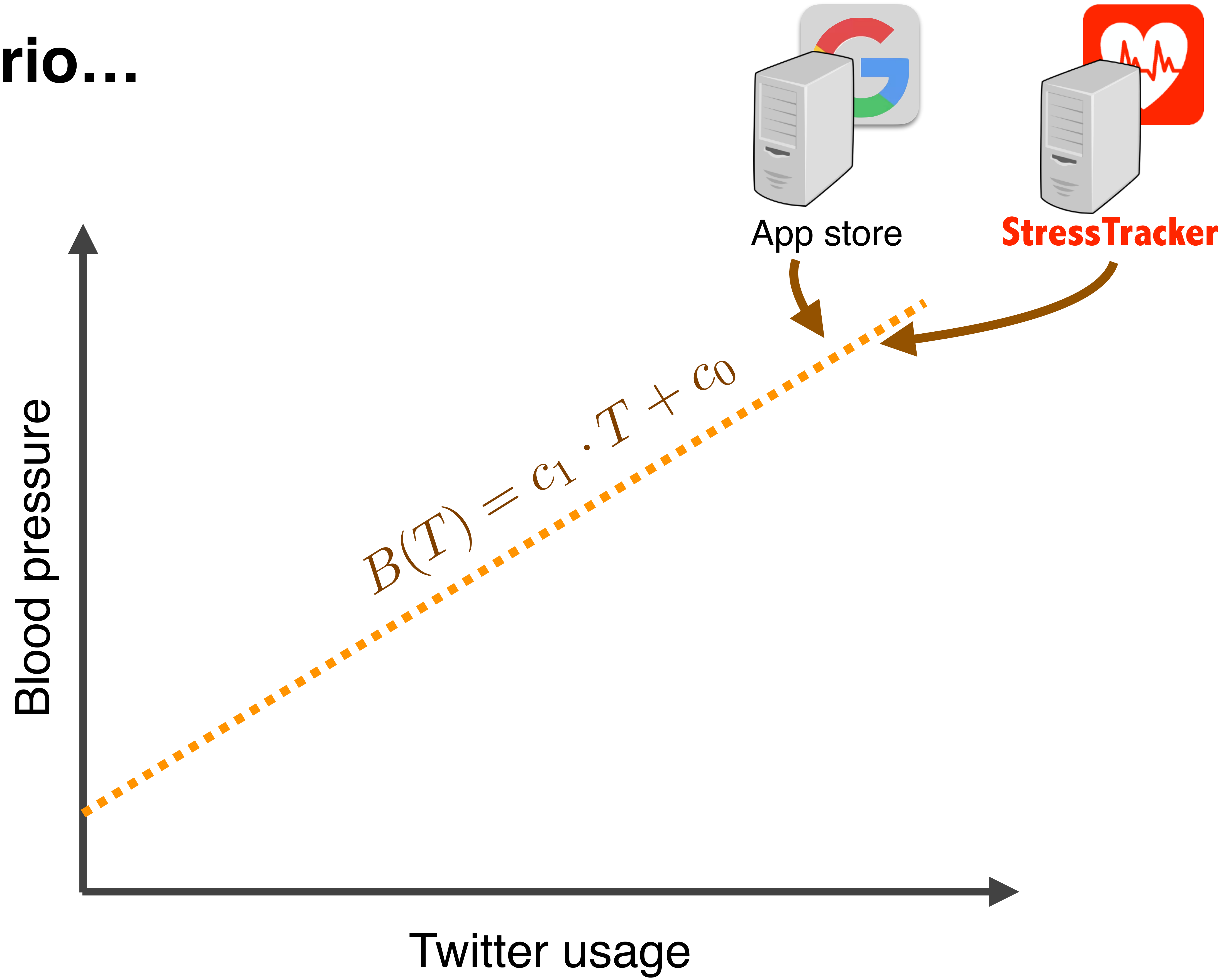

App store
StressTracker
$B(T) = c_1 \cdot T + c_0$
Blood pressure
Twitter usage

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!

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

Henry Corrigan-Gibbs
henrycg@cs.stanford.edu

Example Encoding: Average and Variance

[PrivStats11]

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- Each of N clients holds a value x_i
- Servers want the AVG and VAR of the x_is.

Each client i encodes her value x as the pair

$$(x, y) = (x, x^2)$$

Simple to check that the encoding is valid:

$$\text{Valid}(x, y) = (x^2 - y)$$ [outputs zero if valid]

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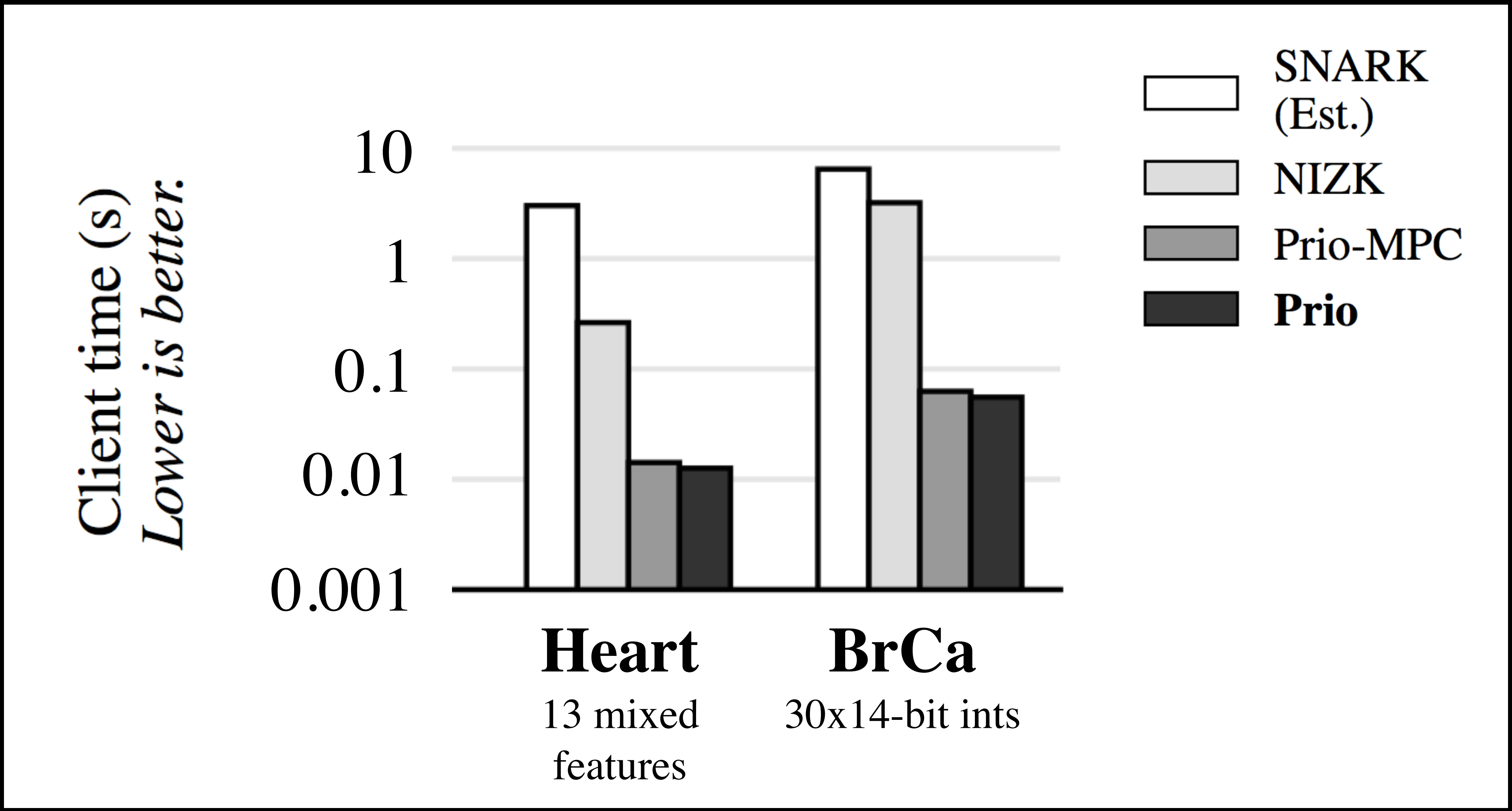
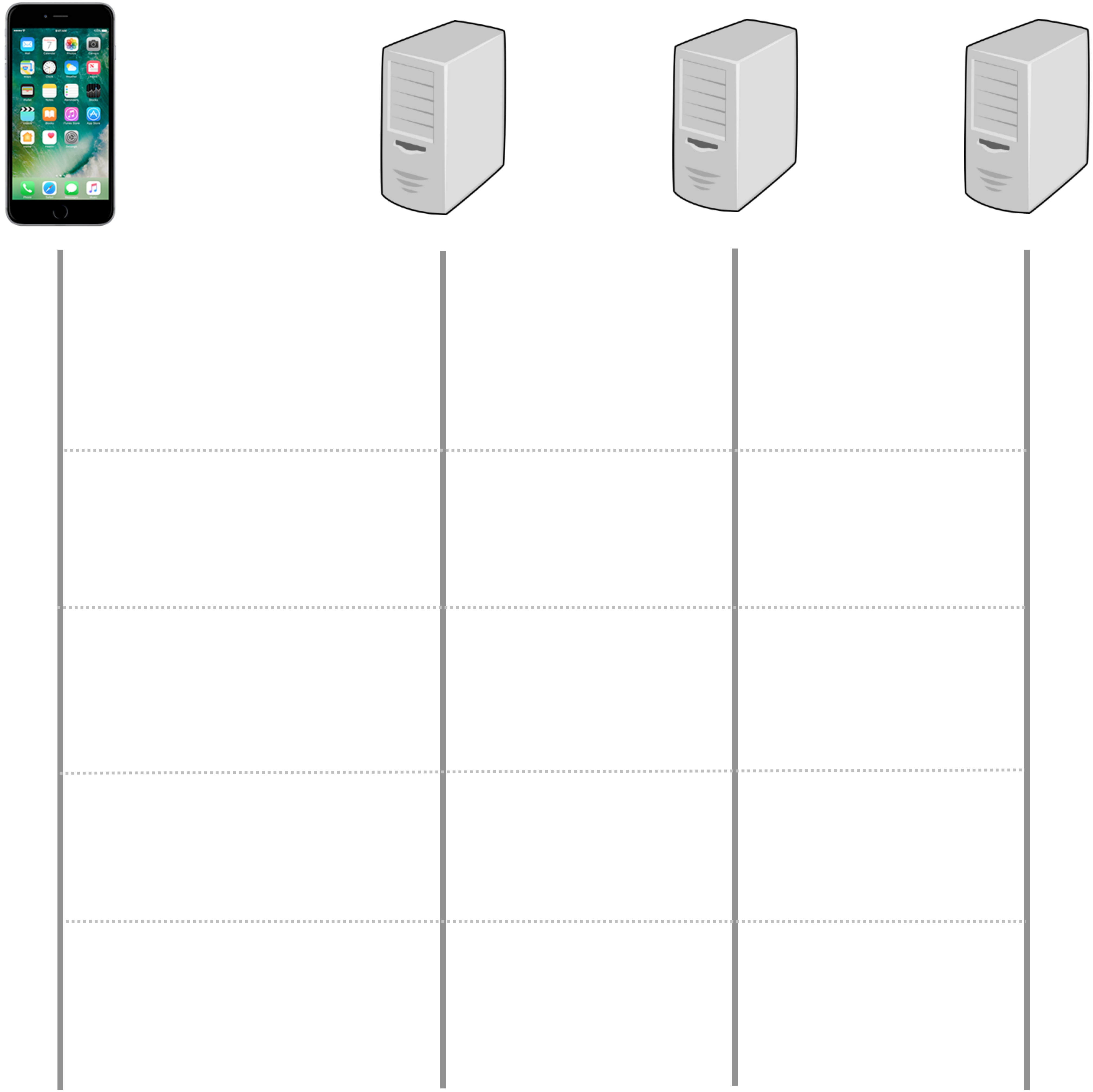
Then recover the statistics:

$$\begin{aligned} \text{AVG}(X) &= (\textstyle\sum_i x_i) \;/\; N \\ \text{AVG}(X^2) &= (\textstyle\sum_i y_i) \;/\; N \quad = (\textstyle\sum_i x_i^2) \;/\; N \\ \text{VAR}(X) &= \text{AVG}(X^2) - \text{AVG}(X)^2 \end{aligned}$$



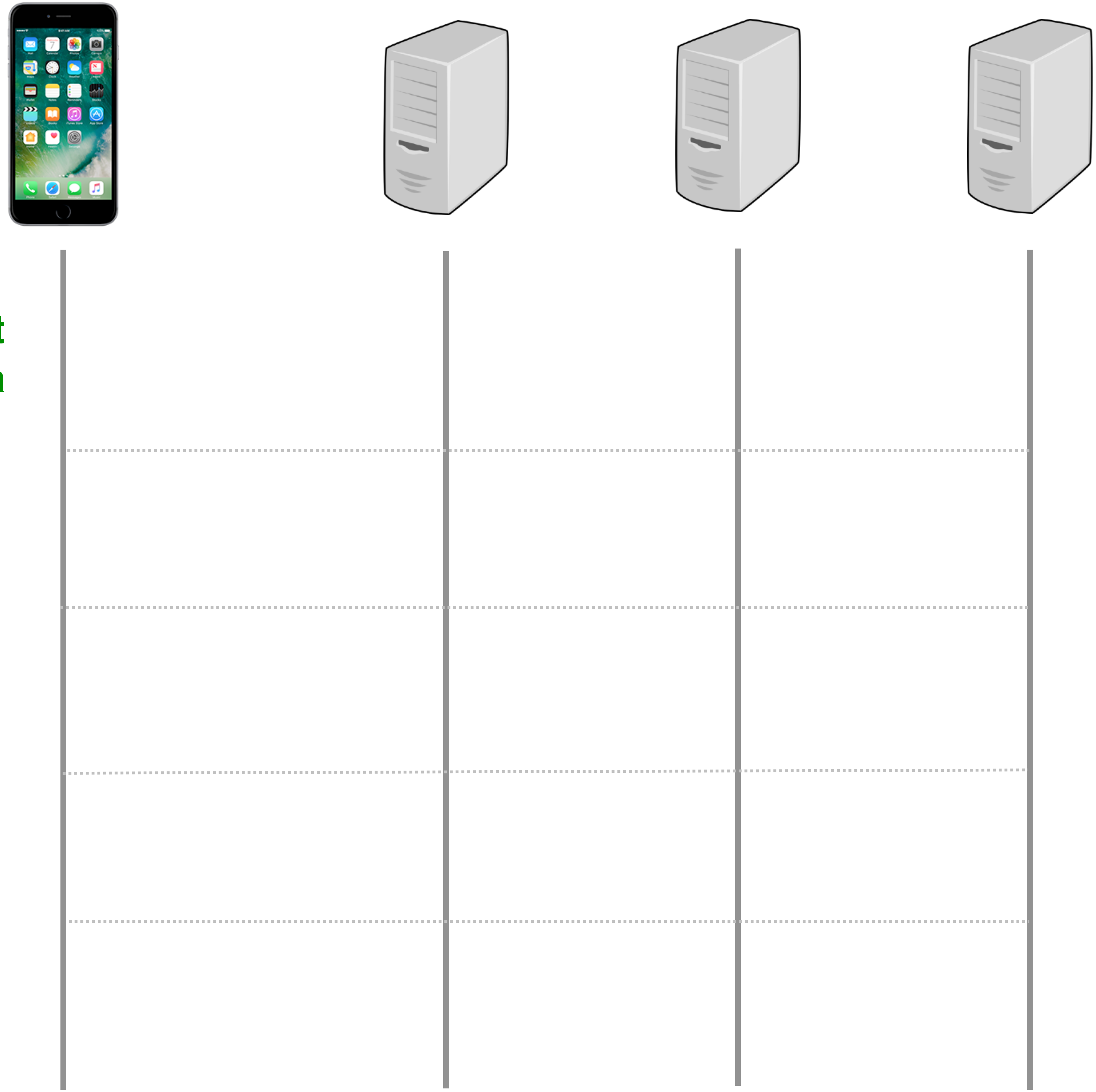
Client time (s)
Lower is better.
10
1
0.1
0.01
0.001
Heart
13 mixed features
BrCa
30x14-bit ints
SNARK (Est.)
NIZK
Prio-MPC
Prio

Using 128-bit integers

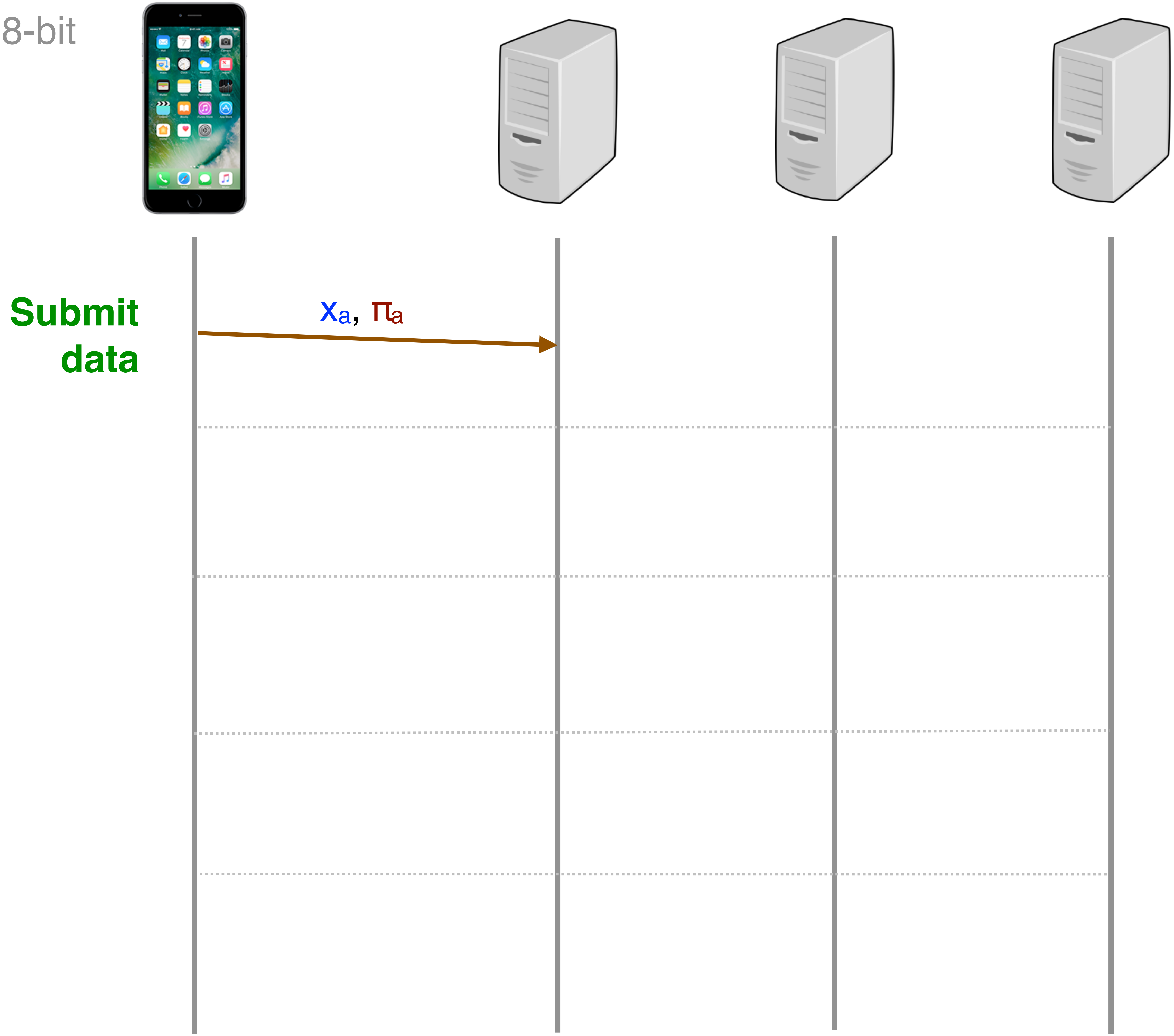


Using 128-bit integers

Submit data



Using 128-bit integers



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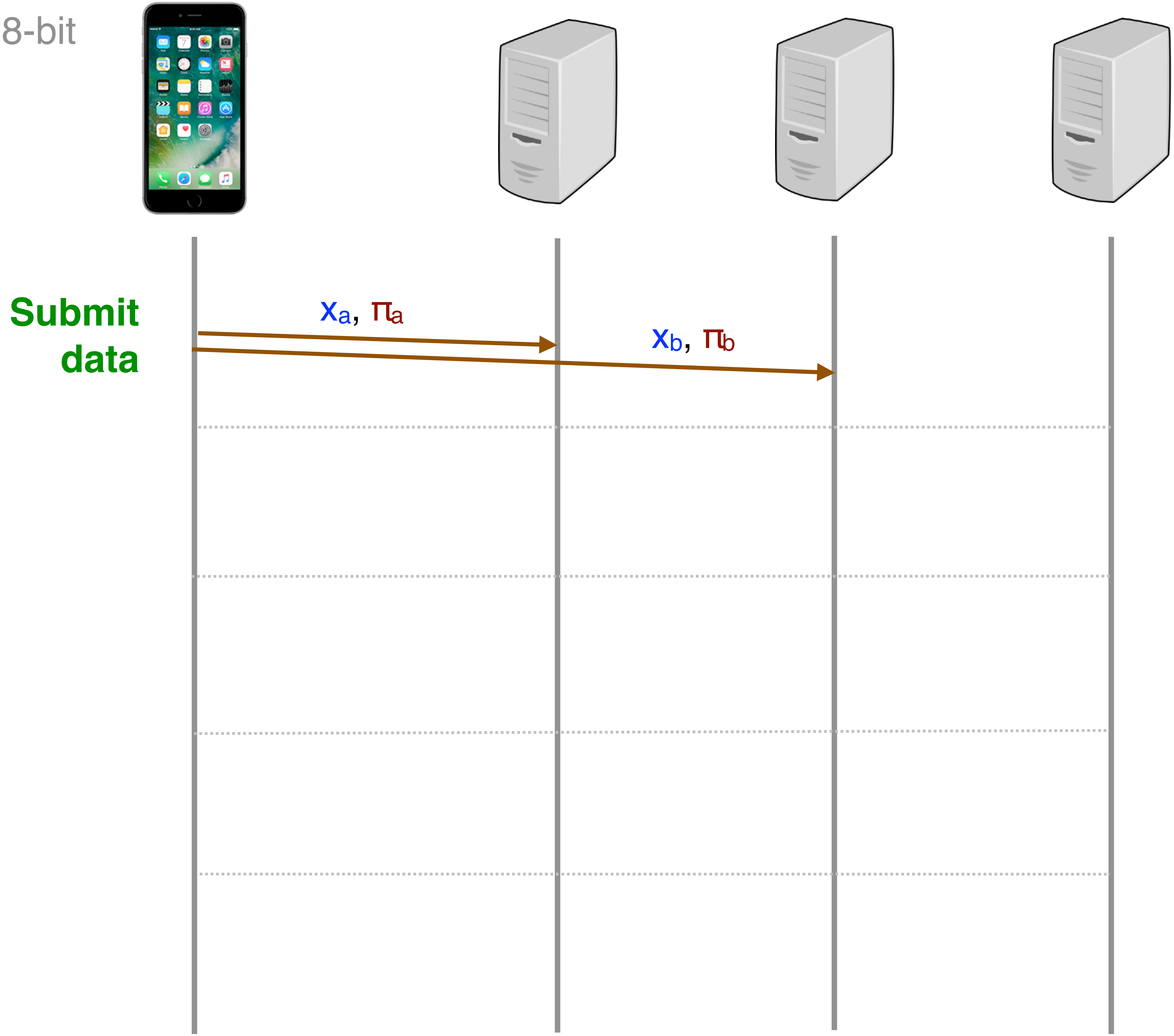

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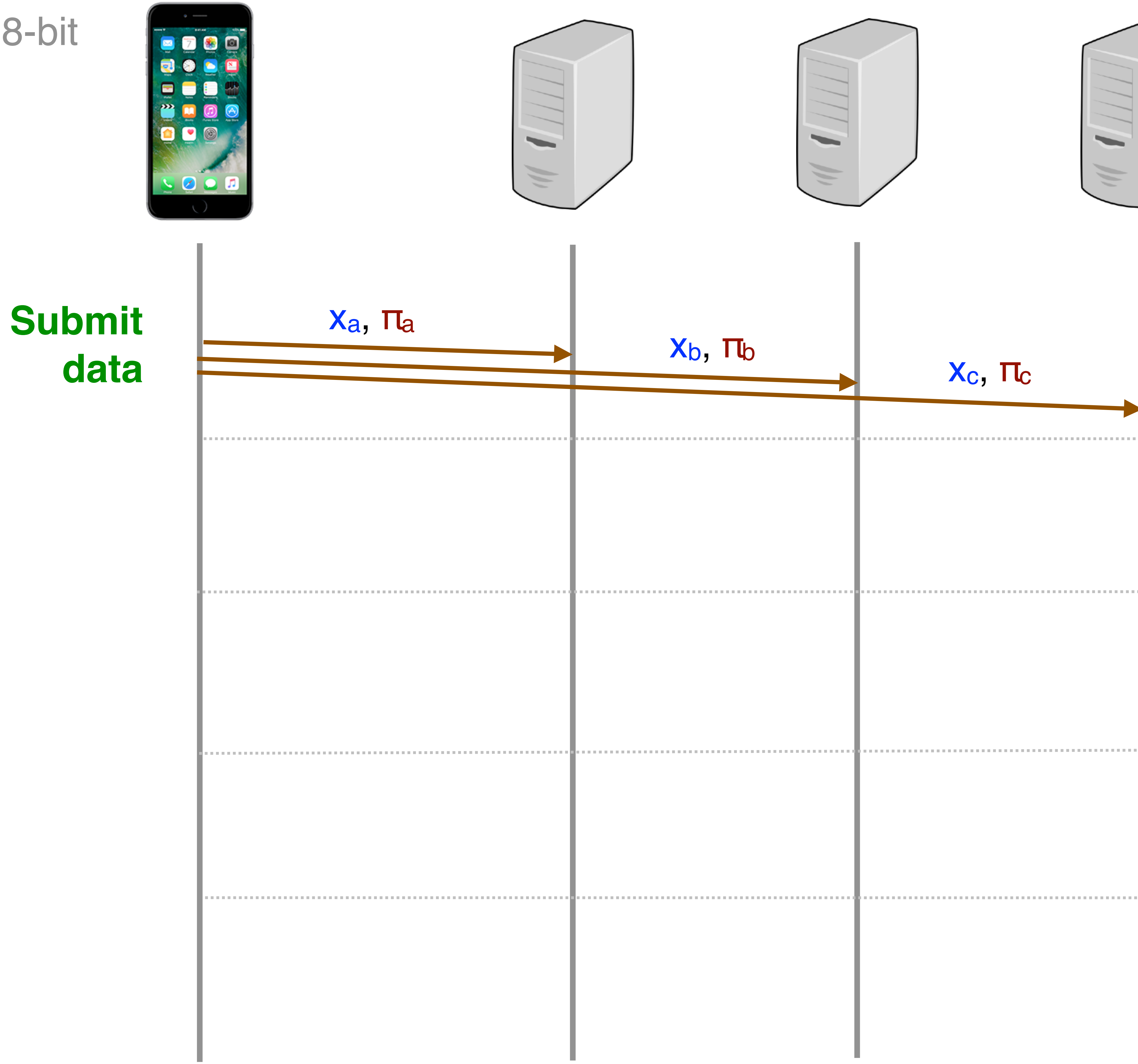

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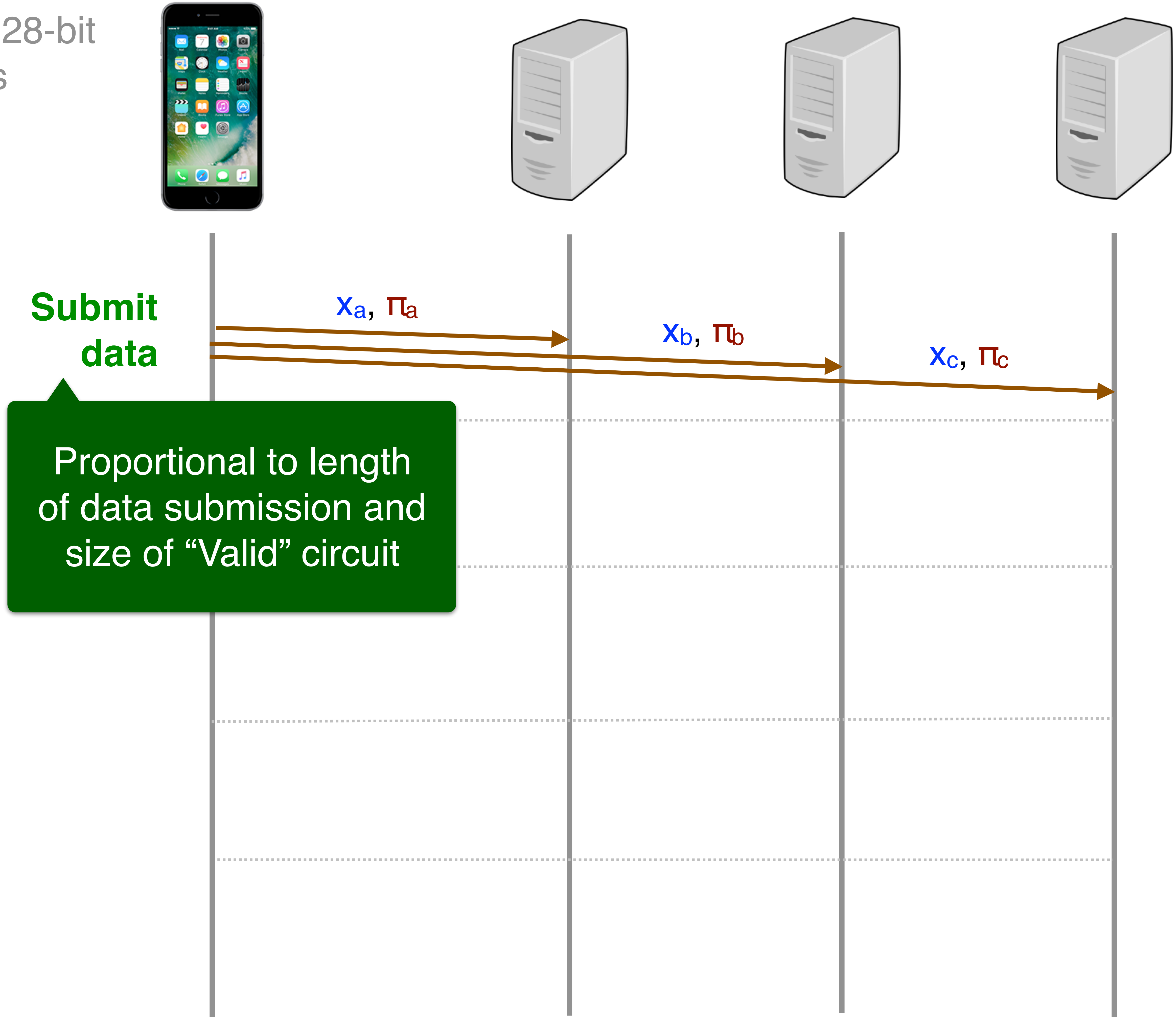

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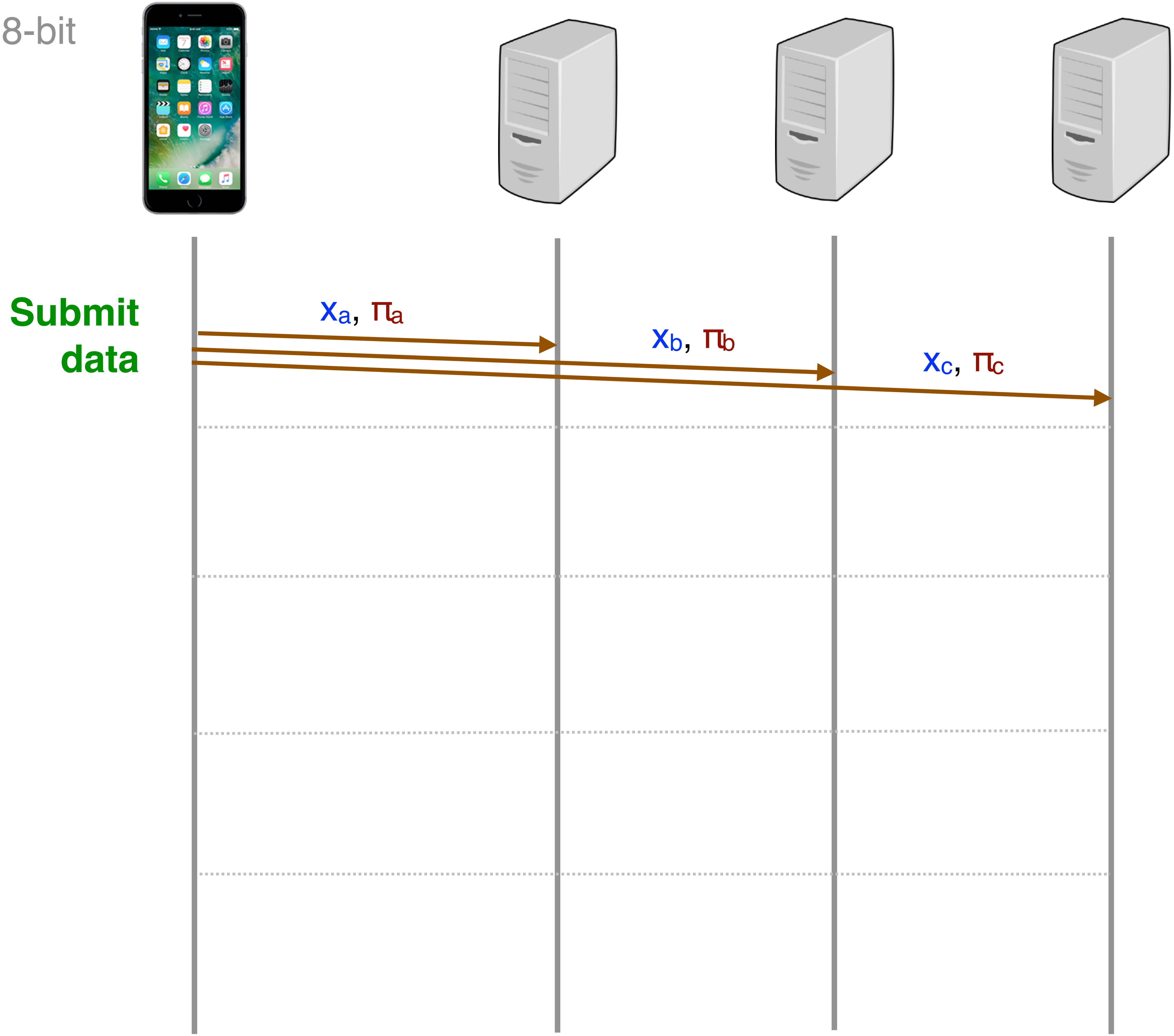

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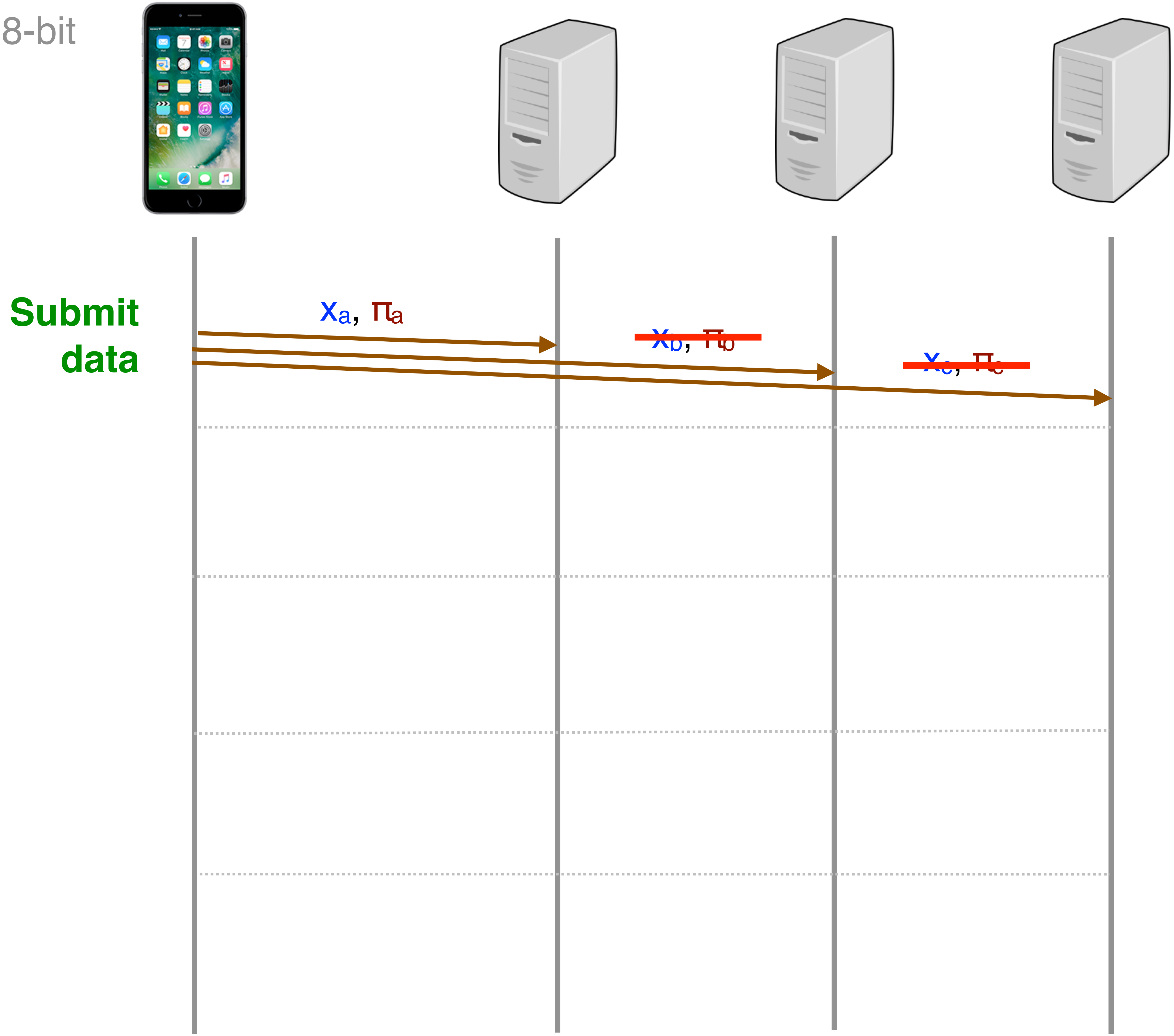

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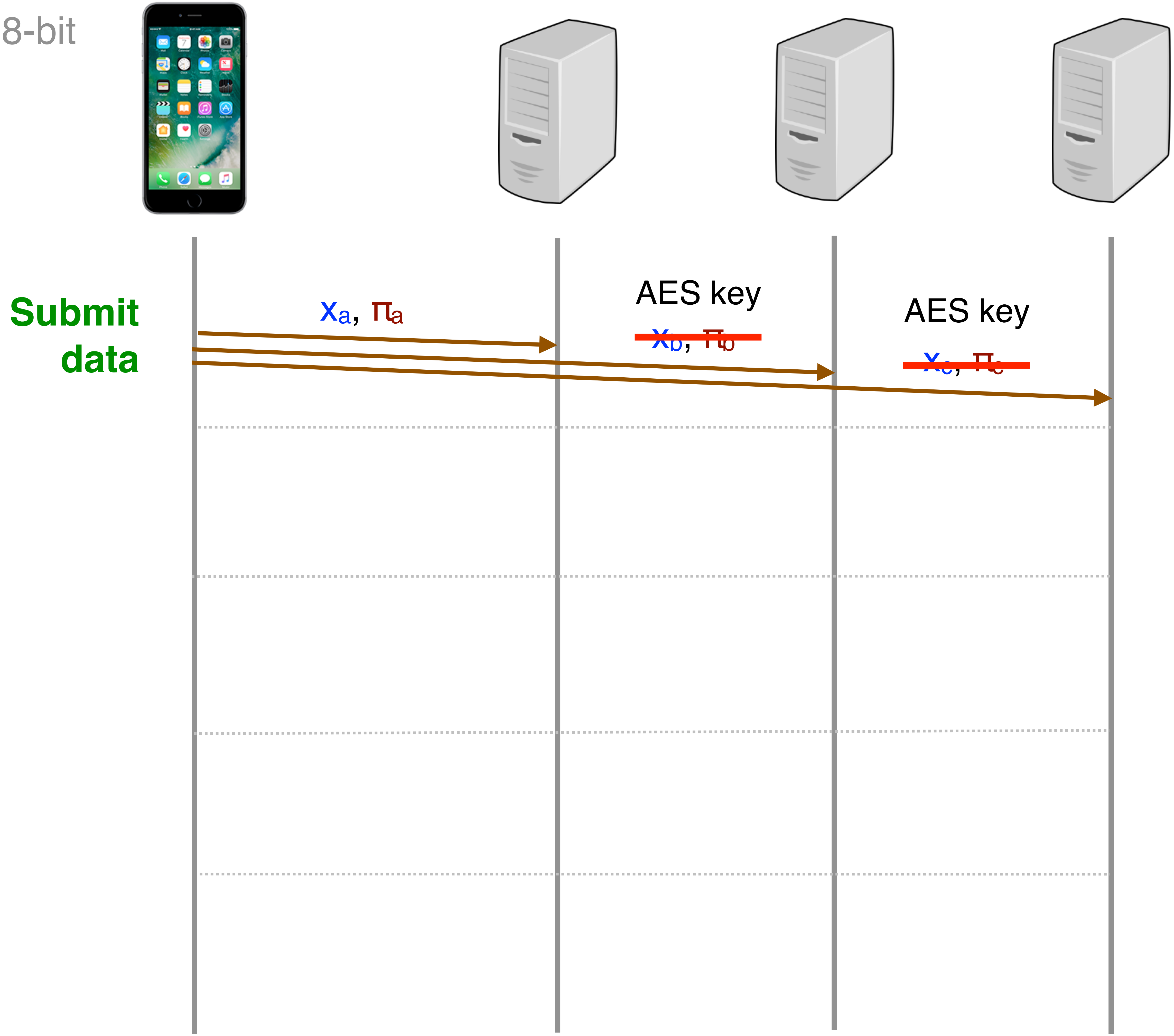

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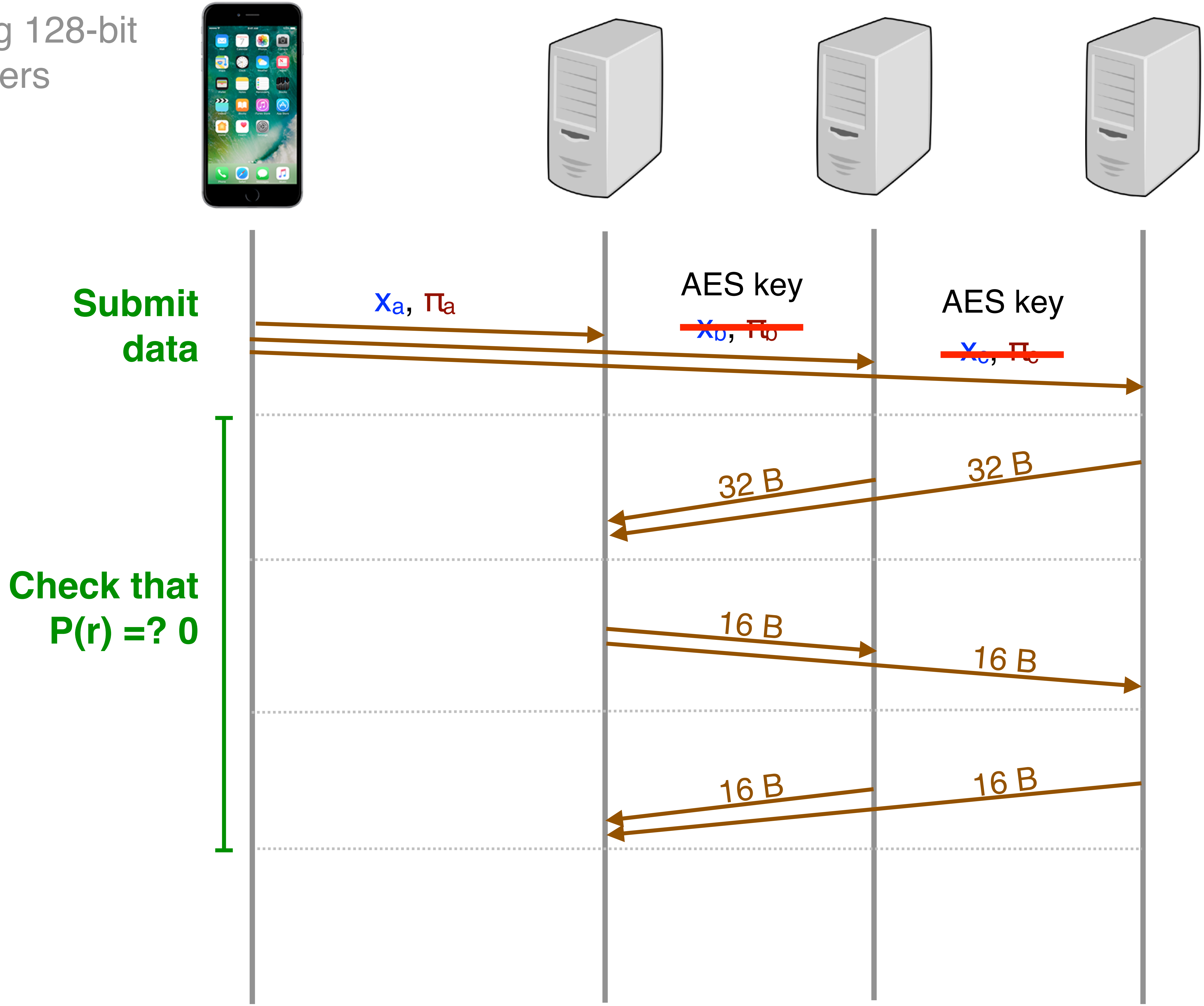

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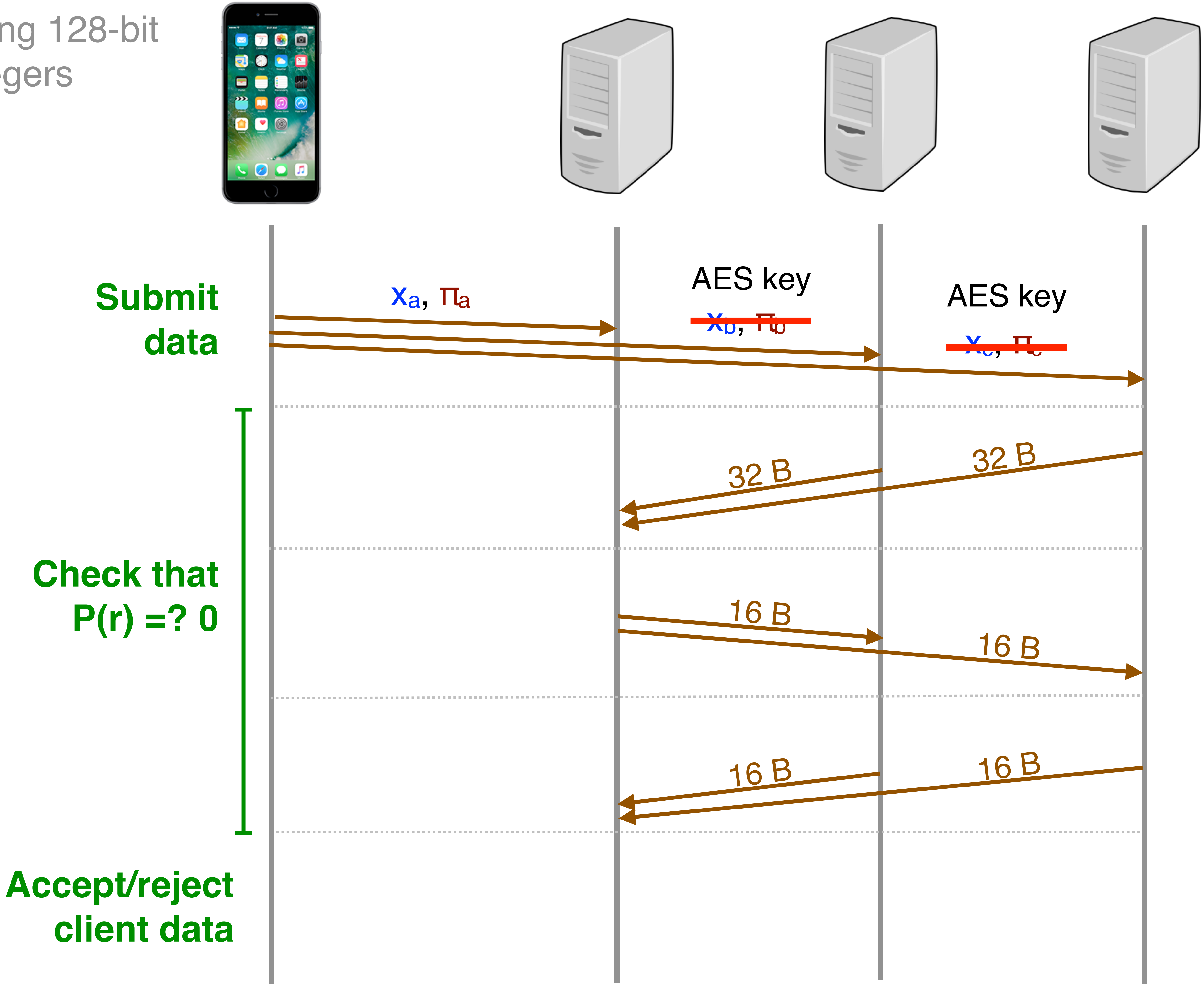

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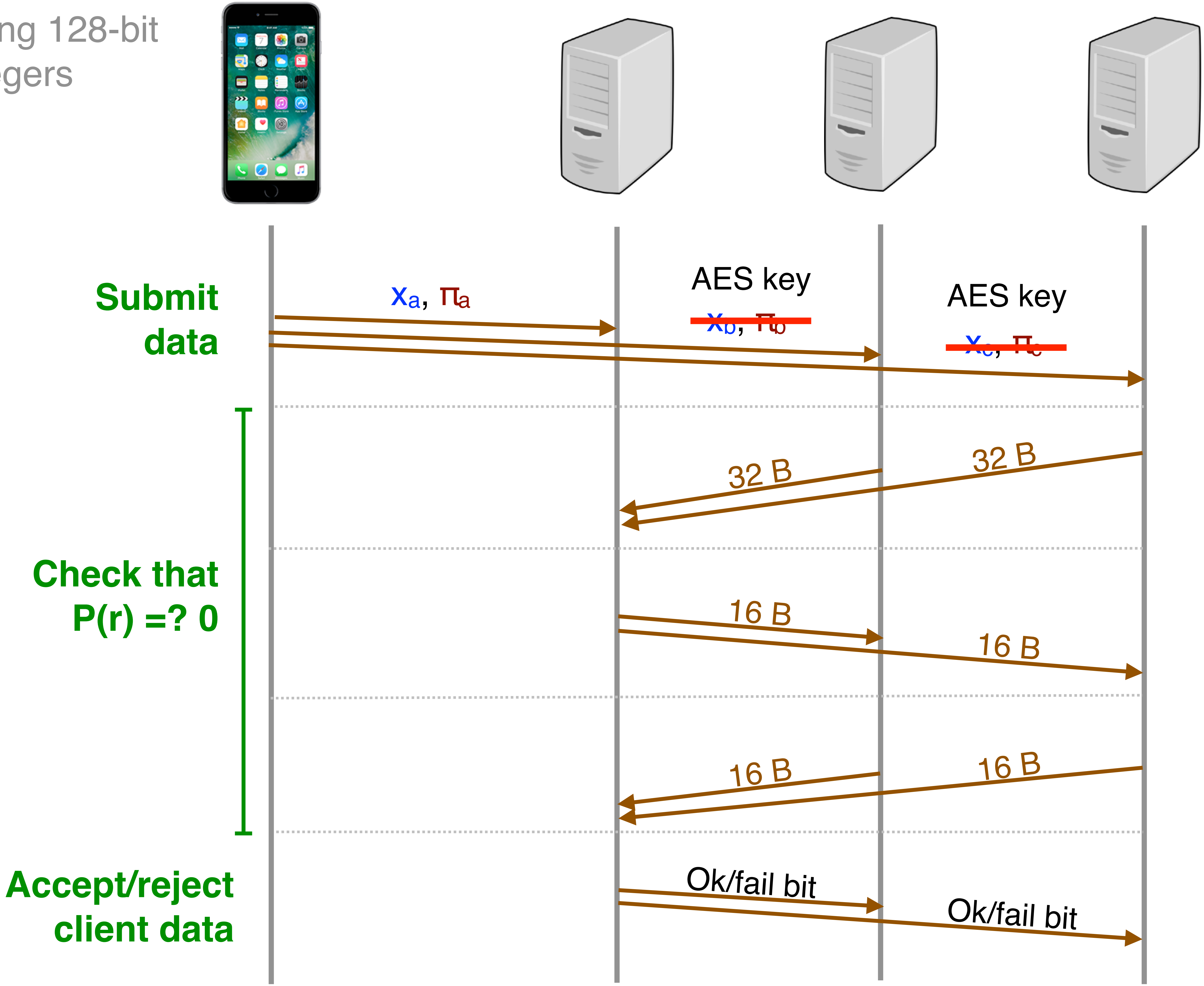

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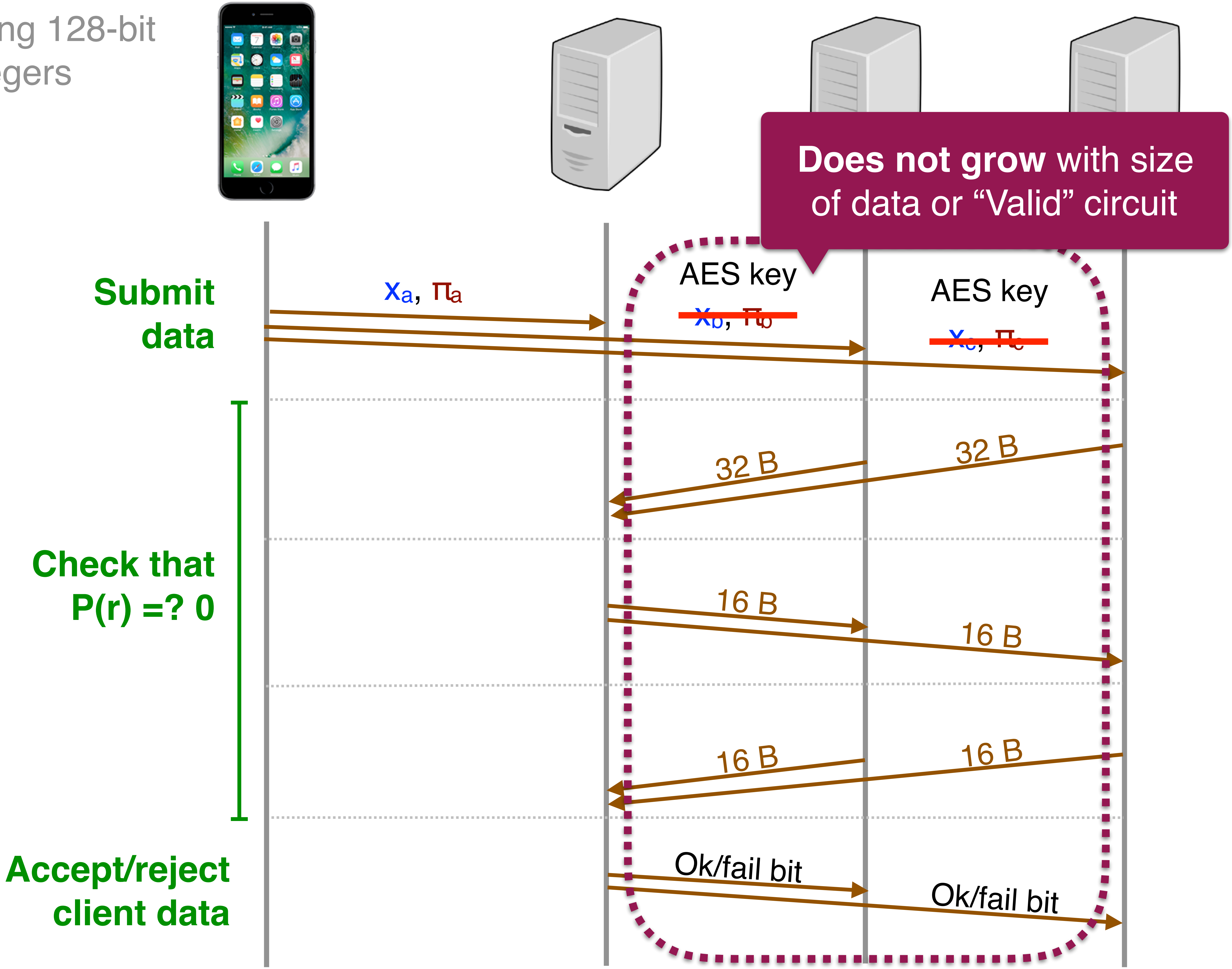

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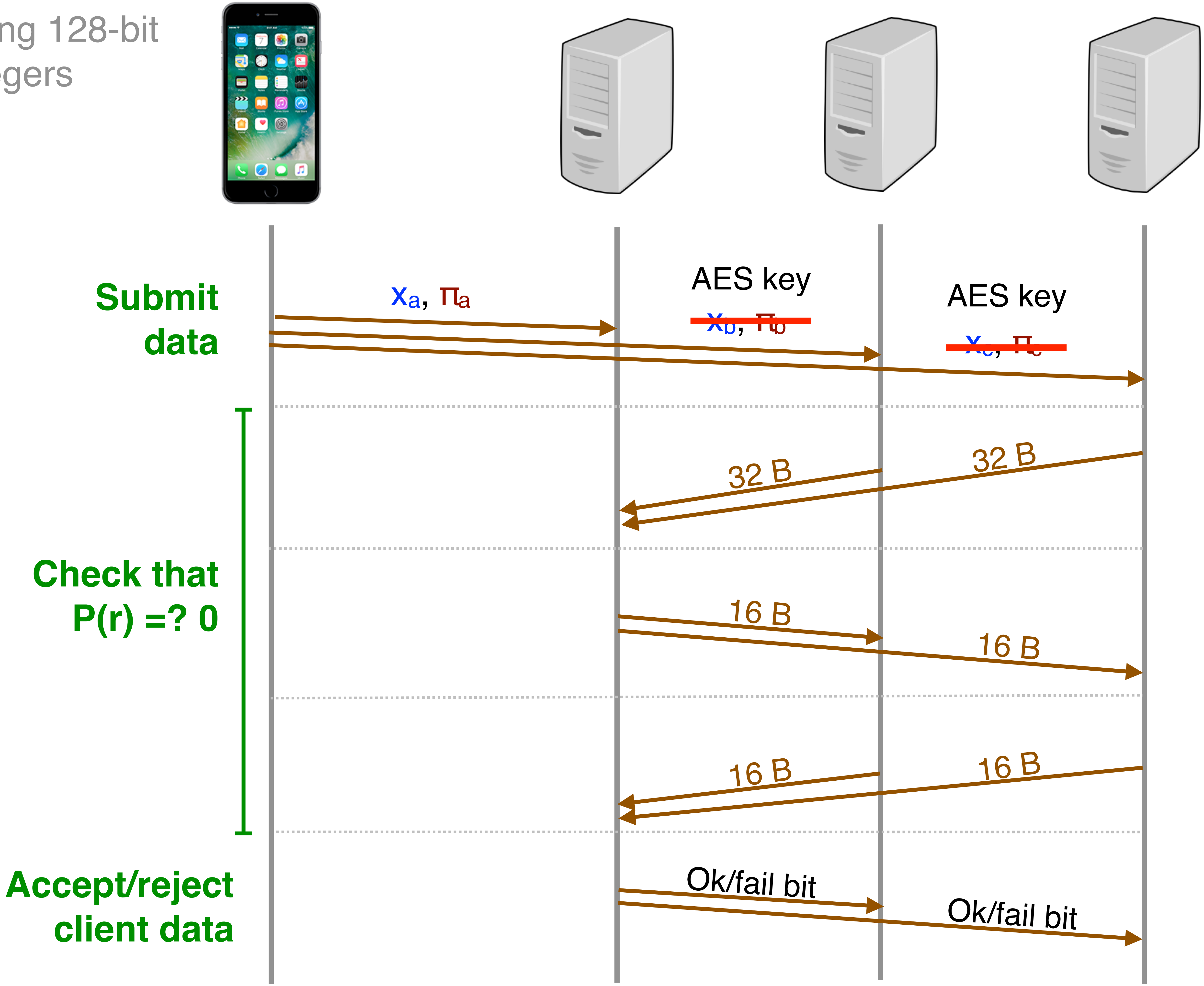

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$$(x, y) = (x, x^2, b_3, b_2, b_1, b_0)$$

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To test validity of the encoding, check that:

$$\mathrm{Valid}(x, y) = \begin{cases} (x^2 - y) = 0 & \text{— y is } x^2 \\ x - \sum_j 2^j b_j = 0 & \text{— b's are the bits of x} \\ b_j \cdot (b_j - 1) = 0 & \text{— b's are 0/1 values} \end{cases}$$