Protecting privacy by splitting trust

Henry Corrigan-Gibbs
Stanford University

Based on joint work with: Dan Boneh, Elette Boyle, Emma Dauterman, Niv Gilboa, Yuval Ishai, Dima Kogan, David Mazières, and Dominic Rizzo.

We put a large amount of trust in a small number of entities.

Applications	 50% of U.S. medical patients
Libraries	OpenSSL 60% of web sites
OS	 Microsoft 80% of desktop OS
Hardware	 50% of crypto chips

These entities are
single points of privacy failure.

One breach...

One bug...

One backdoor...

These entities are

single points of privacy failure.

One breach...

One bug...

One backdoor...


The New York Times

All 3 Billion Yahoo Accounts Were Affected by 2013 Attack

These entities are

single points of privacy failure.

One breach...

One bug...

One backdoor...

These entities are

single points of privacy failure.

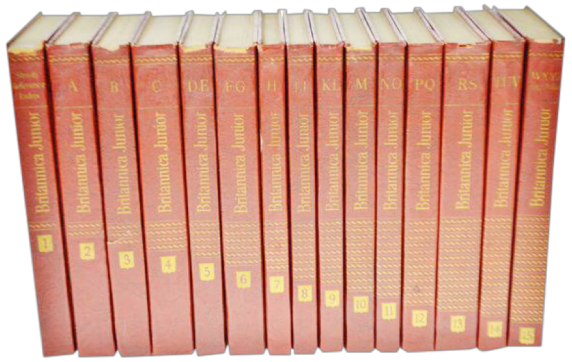
One breach...

One bug...

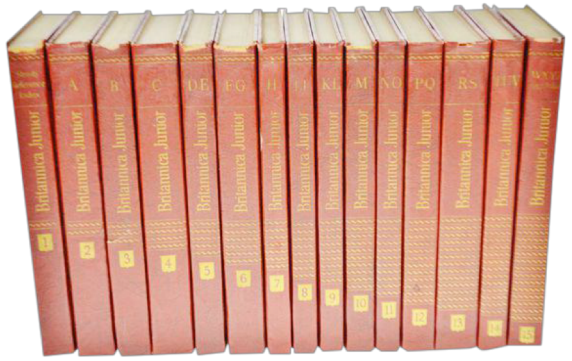
One backdoor...

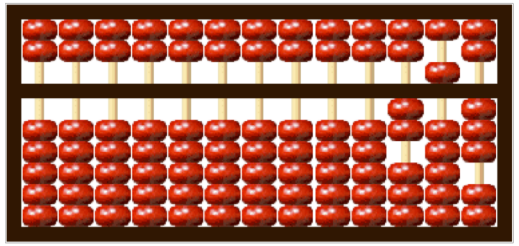
Solution? Don’t trust anyone.

Solution? Don’t trust anyone.

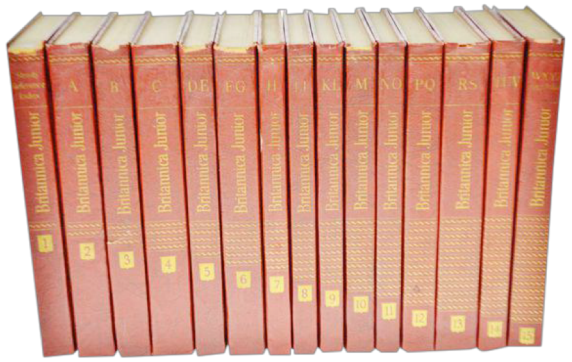


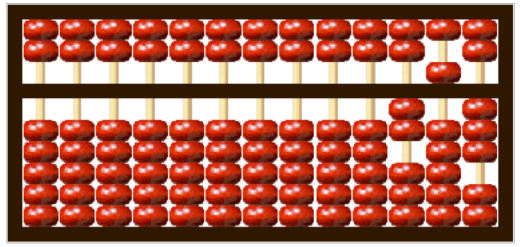
Solution? Don’t trust anyone.





Solution? Don’t trust anyone.

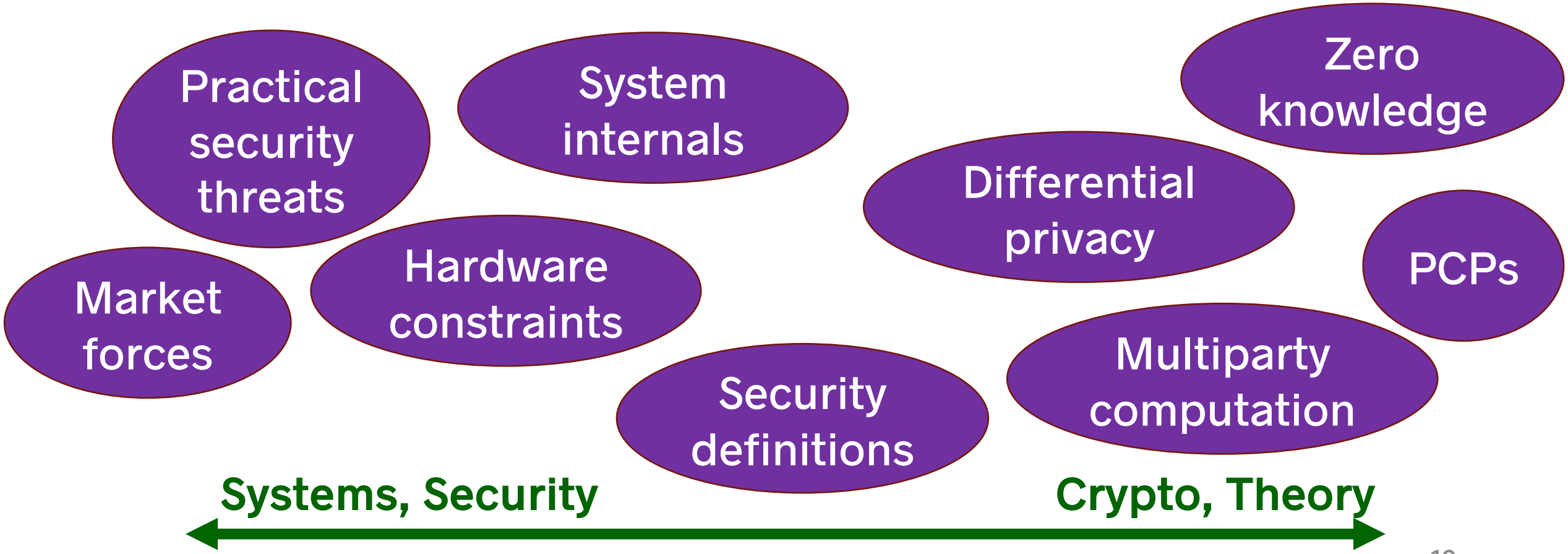




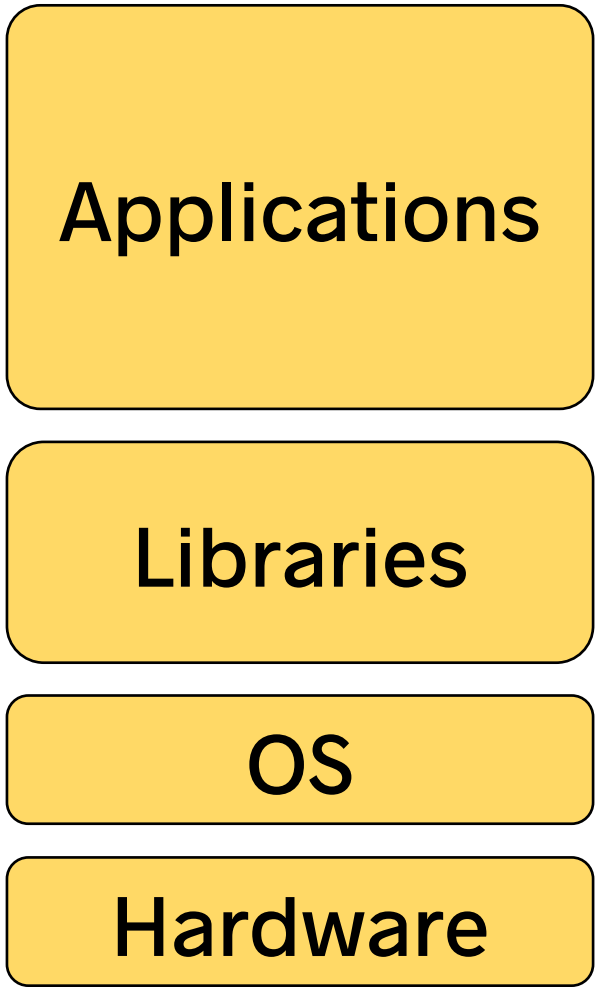
Classic idea:
Eliminate single points of failure by splitting trust

Challenge: Split trust to protect privacy, without sacrificing functionality

Combine ideas from systems, security, crypto to make it practical to split trust



Eliminate single points of privacy failure



Data-collection systems (NSDI '17)
Shipping in the Firefox browser

Messaging services (SOSP '17),
(IEEE S&P '15) (USENIX Sec. '13) (OSDI '12) (CCS '10)
S&P distinguished paper, PET award

Cryptographic standards
(Eurocrypt '18) (ECCC '18)
Best young researcher paper

Password storage (Asiacrypt '16)

Hardware components (IEEE S&P '19) (CCS '13)

Eliminate single points of privacy failure

Applications

Libraries

OS

Hardware

Data-collection systems (NSDI '17)
Shipping in the Firefox browser

Messaging services (SOSP '17),
(IEEE S&P '15) (USENIX Sec. '13) (OSDI '12) (CCS '10)
S&P distinguished paper, PET award

Cryptographic standards
(Eurocrypt '18) (ECCC '18)
Best young researcher paper

Password storage (Asiacrypt '16)

Hardware components (IEEE S&P '19) (CCS '13)

Eliminate single points of privacy failure

Applications

Libraries

OS

Hardware

Data-collection systems (NSDI '17)
Shipping in the Firefox browser

Messaging services (SOSP '17),
(IEEE S&P '15) (USENIX Sec. '13) (OSDI '12) (CCS '10)
S&P distinguished paper, PET award

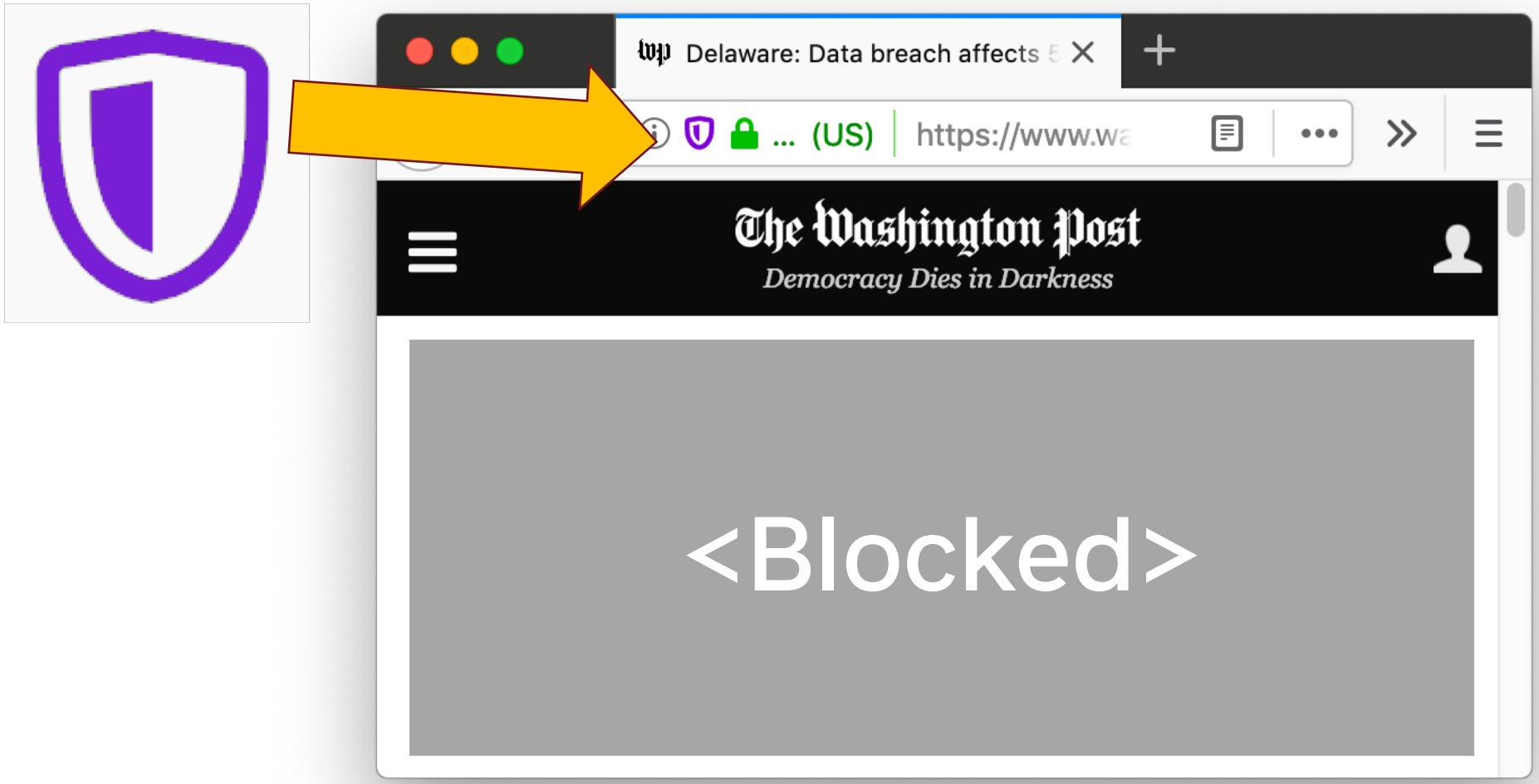
Cryptographic standards
(Eurocrypt '18) (ECCC '18)
Best young researcher paper

Password storage (Asiacrypt '16)

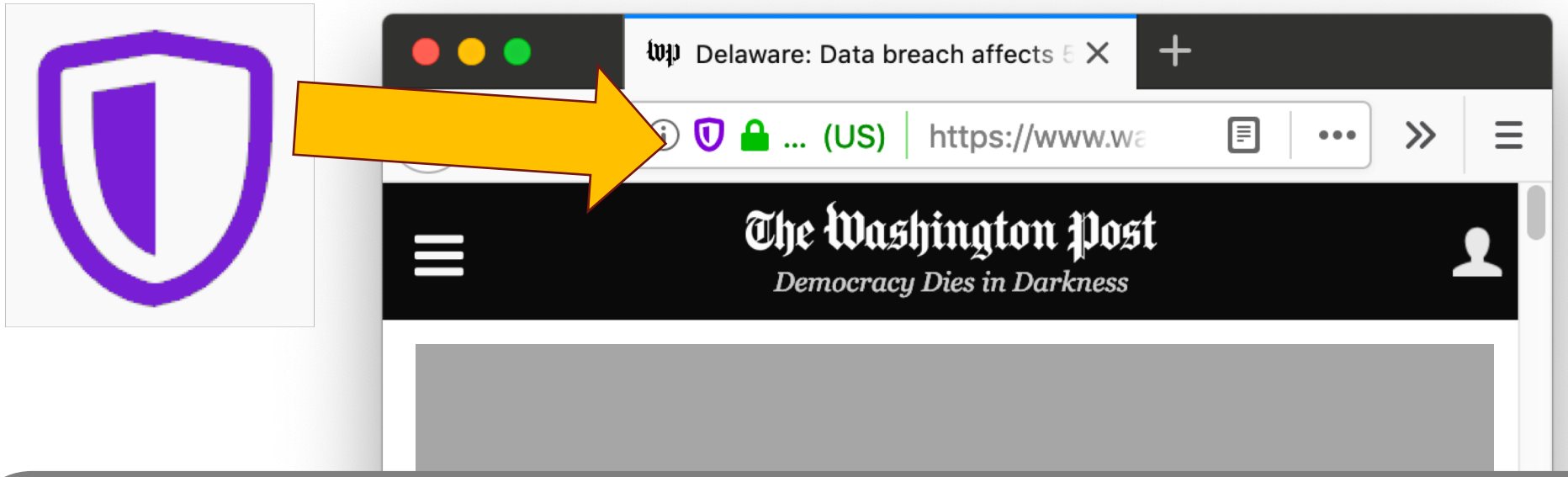
Hardware components (IEEE S&P '19) (CCS '13)

Running example:
Measuring effectiveness of content blocking

Running example:
Measuring effectiveness of content blocking



Running example:
Measuring effectiveness of content blocking

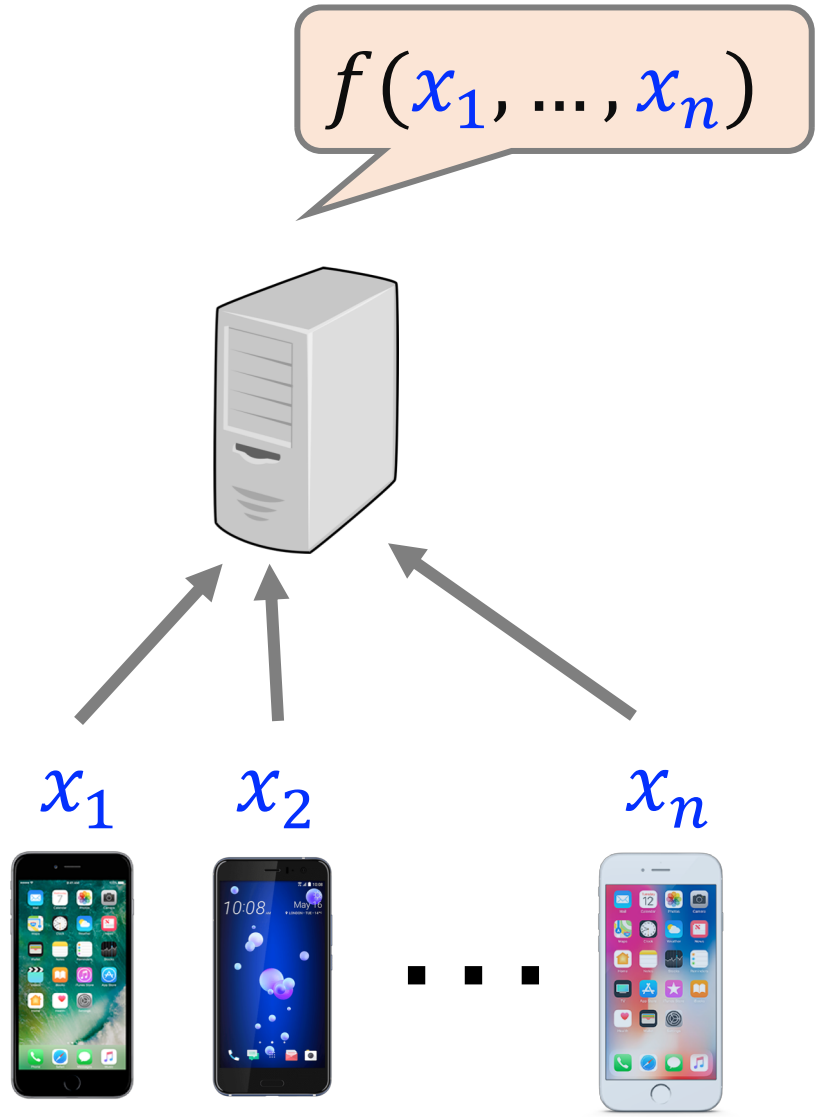


Mozilla wants to know:

“How many users disable content blocking on each of the top 500 websites?”

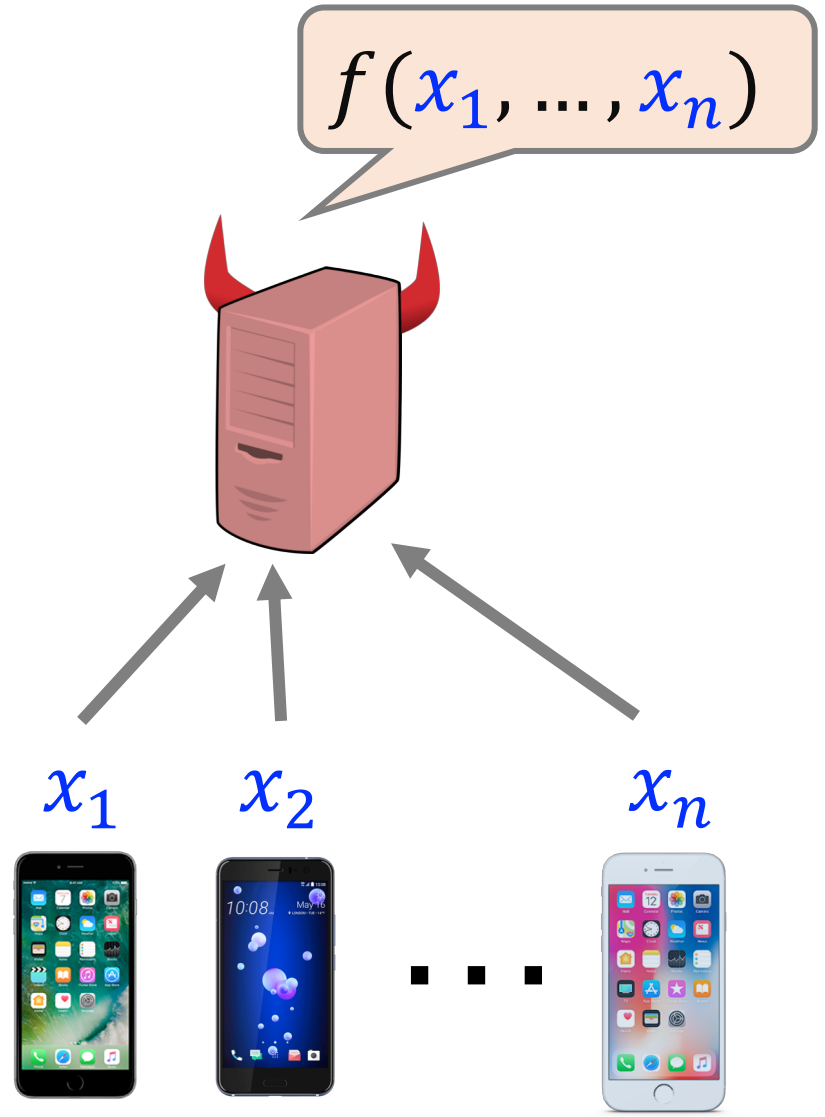
Manufacturers often
answer these questions
by collecting your sensitive data.

→ Single point of failure.



Manufacturers often
answer these questions
by collecting your sensitive data.

→ Single point of failure.



Mozilla’s previous attempt

Mozilla’s previous attempt

“I’ll have to file a complaint with the relevant Landes- and Bundesbeauftragten für Datenschutz”

Mozilla’s previous attempt

“I’ll have to file a complaint with the relevant Landes- and Bundesbeauftragten für Datenschutz”

“I wish you the worst of luck in your new venture to infringe even further upon the privacy of your users.”

Mozilla's previous attempt

"I'll have to file a complaint with the relevant Landes- and Bundesbeauftragten für Datenschutz"

"I wish you the worst of luck in your new venture to infringe even further upon the privacy of your users."

"Do the Mozilla thing, not the Google thing."

Prio: Aggregate data without the privacy risks

Built system: C–G and Boneh (NSDI 2017)
Follow-up theoretical work: Boneh, Boyle, C–G, Gilboa, and Ishai (preprint, 2019)

- Collect aggregate usage data **without seeing any single user's data**.
- New cryptography makes this system practical
  - Proofs on secret-shared data
- Our Prio code ships to 200m+ Firefox users
  - In pilot phase: Enabled by default in Nightly
  - Largest deployment of technology based on PCPs (probabilistically checkable proofs)

Running example:
Measuring effectiveness of content blocking

- User i has a bit $x_i^{\text{site.com}} \in \{0,1\}$
  - Bit is "1" iff user disabled content blocking on site.com
  - These x_is are **sensitive** – reveal user's browsing history

- For each site in Top 500, Mozilla wants the sum of users' bits:

How often content blocking breaks site.com $= \sum_{\text{users } i} x_i^{\text{site.com}}$

- Let's focus on one site... $x_i^{\text{~~site.com~~}}$
  - Each user i has a single bit x_i. Mozilla wants $\sum_i x_i$.

Prio: System goals

1. Correctness. If clients and servers are honest, servers learn $f(\cdot)$

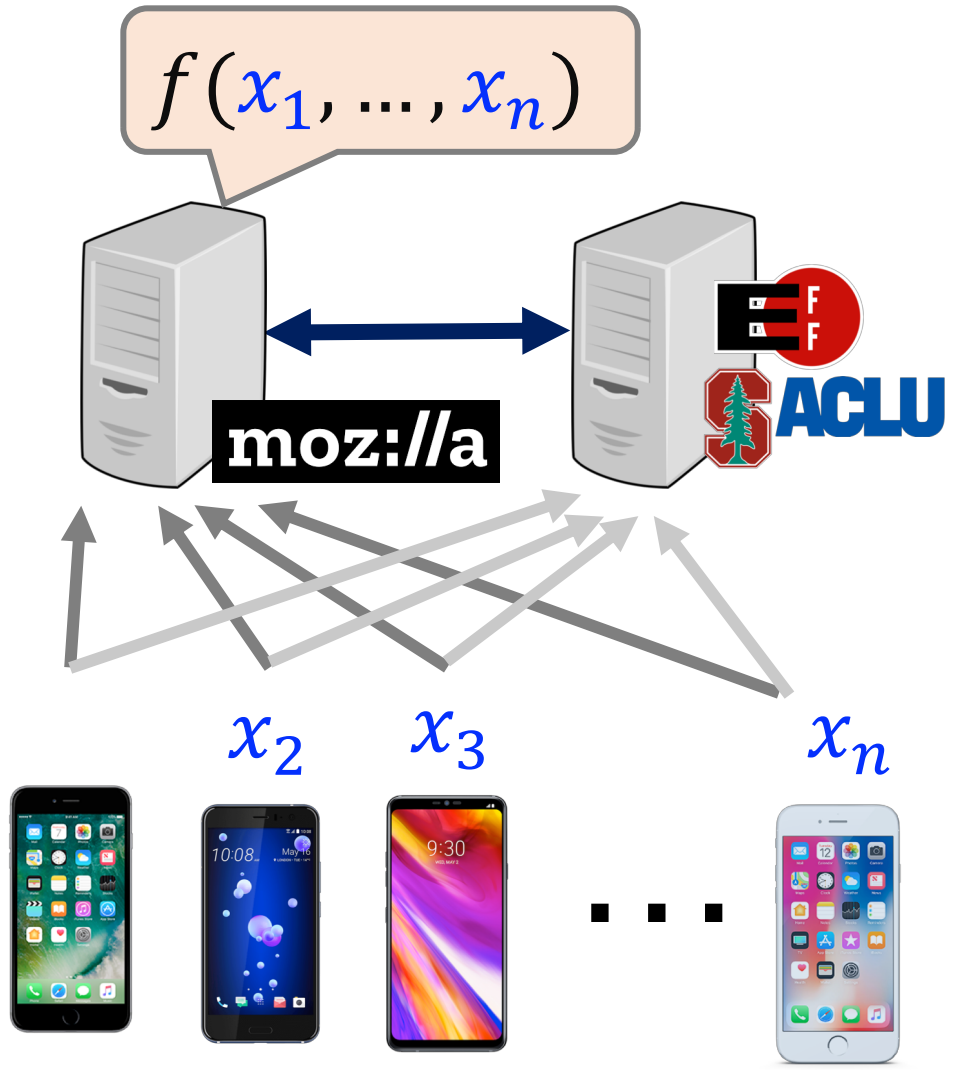
Extension: Maintain correctness in spite of server faults

2. f-Privacy. Attacker must compromise all servers to learn more than $f(\cdot)$

Extension: Differential privacy [DMNS06]

3. Disruption resistance. The worst that a malicious client can do is lie about her input.

4. Efficiency. Handle millions of submissions per server per hour



Prio: System goals

1. Correctness. If clients and servers are honest, servers learn $f(\cdot)$

Extension: Maintain correctness in spit

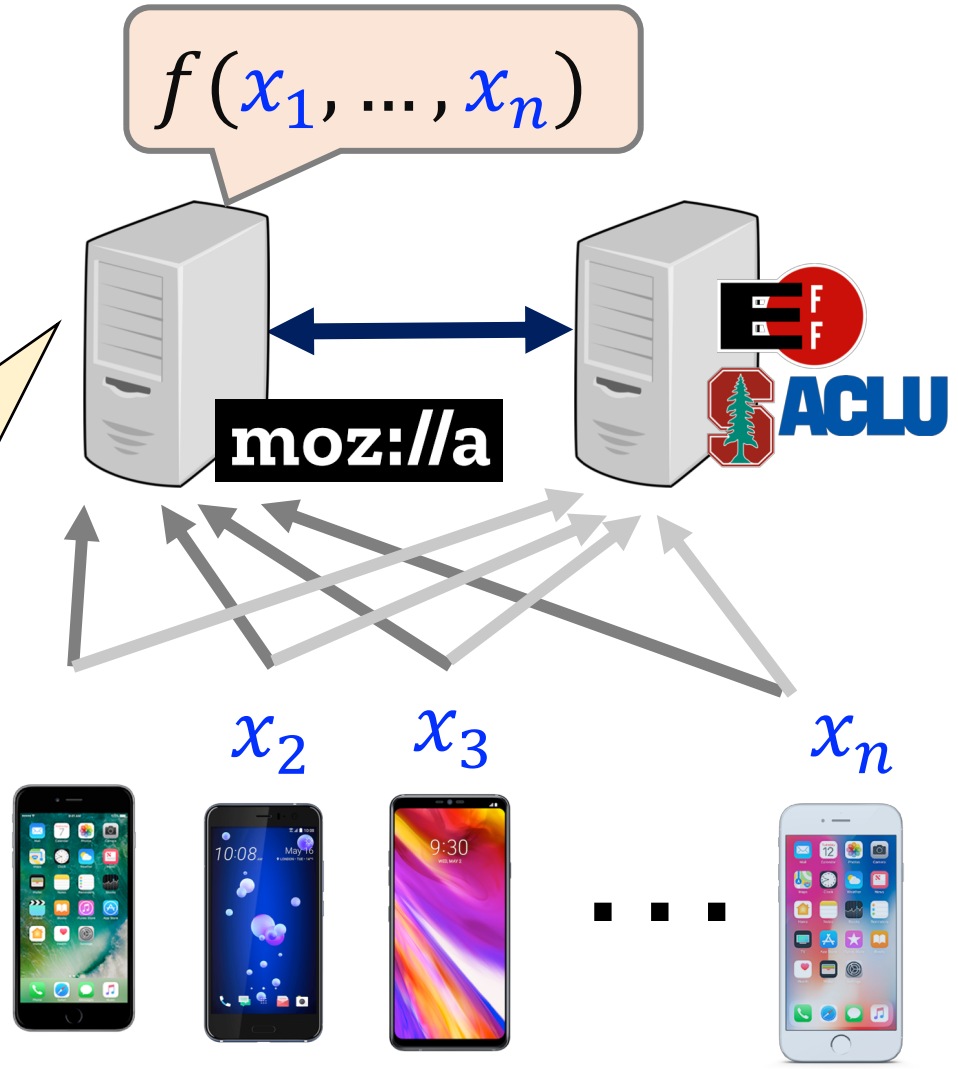
2. f-Privacy. A compromise a more than $f(\cdot)$

Extension: Diffe

3. Disruption The worst that can do is lie ab

4. Efficiency. Handle millions of submissions per server per hour

Split trust:
Attacker must compromise <u>all</u> servers to learn private data.



Prio: System goals

1. Correctness. If clients and servers are honest, servers learn $f(\cdot)$

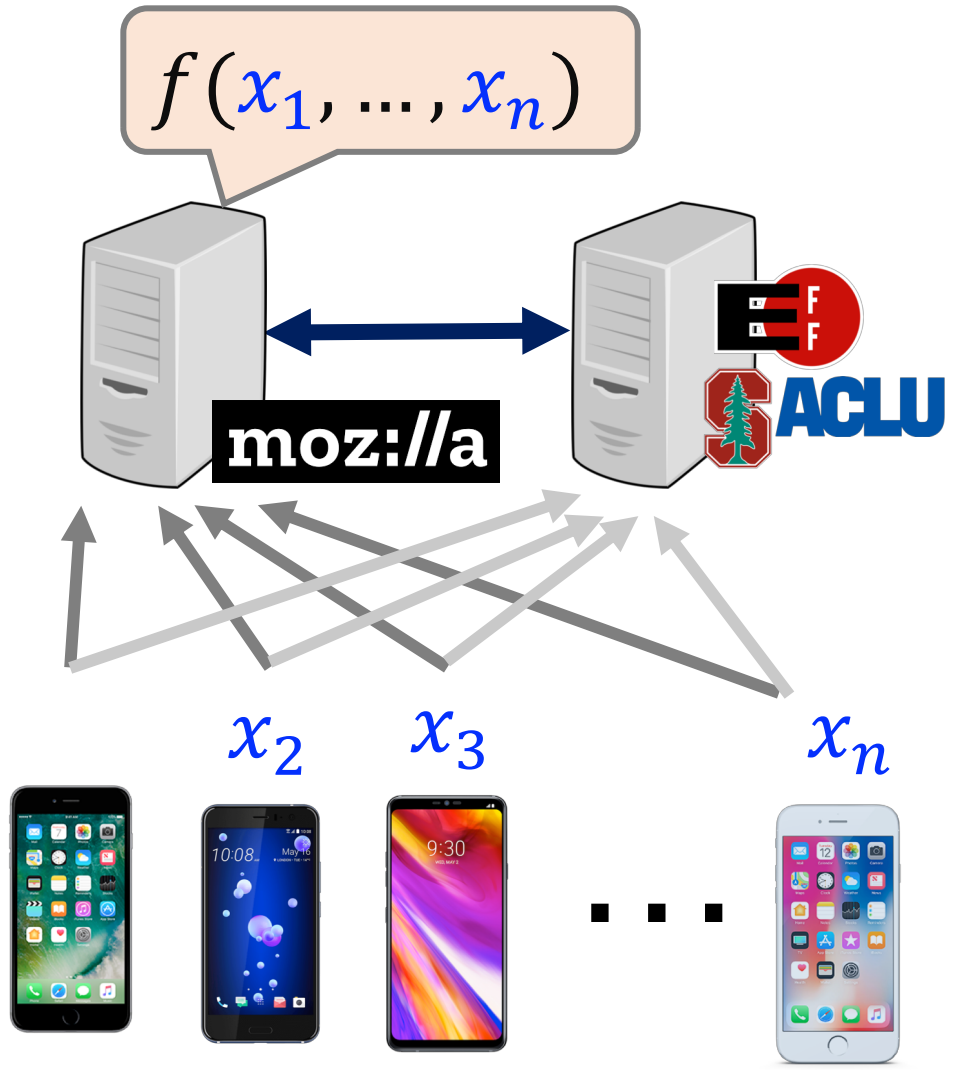
Extension: Maintain correctness in spite of server faults

2. f-Privacy. Attacker must compromise all servers to learn more than $f(\cdot)$

Extension: Differential privacy [DMNS06]

3. Disruption resistance. The worst that a malicious client can do is lie about her input.

4. Efficiency. Handle millions of submissions per server per hour



Prio: System goals

1. Correctness. If clients and servers are honest, servers learn $f(\cdot)$

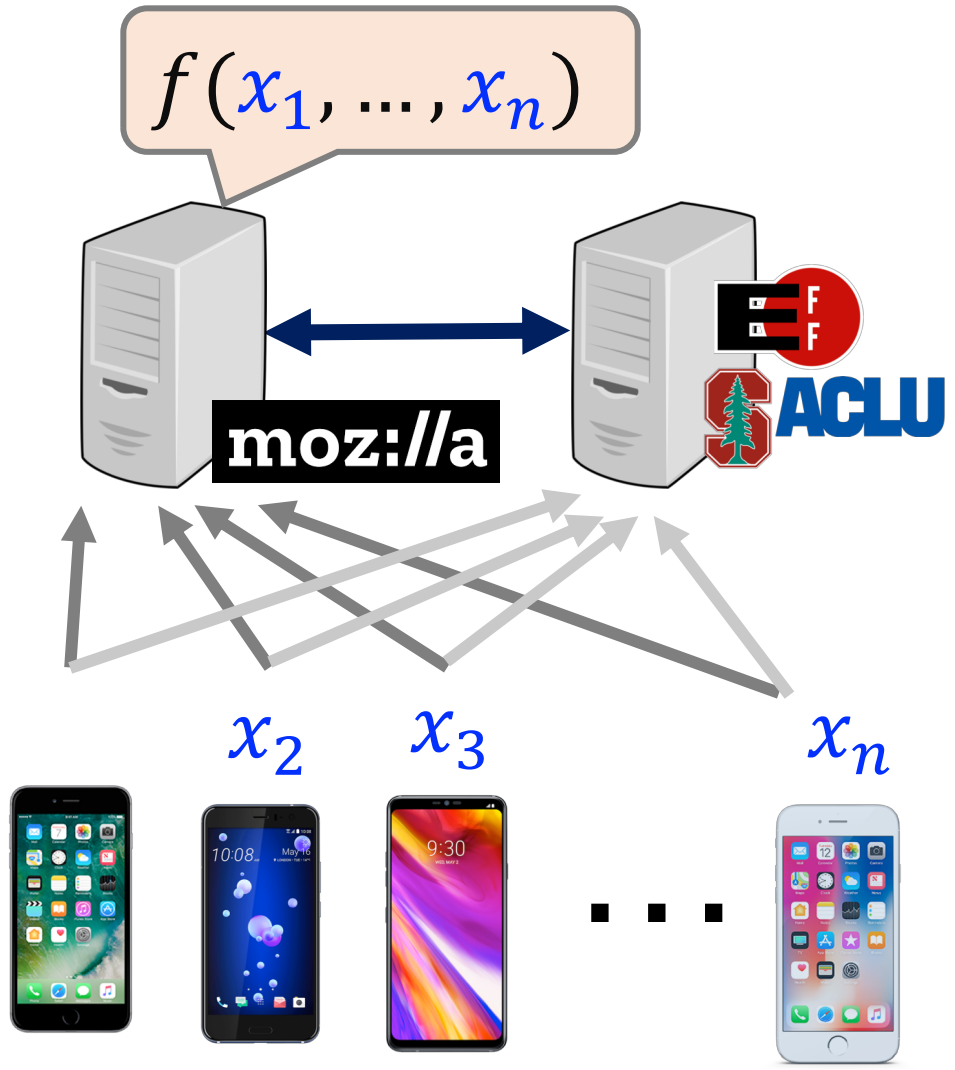
Extension: Maintain correctness in spite of server faults

2. f-Privacy. Attacker must compromise all servers to learn more than $f(\cdot)$

Extension: Differential privacy [DMNS06]

3. Disruption resistance. The worst that a malicious client can do is lie about her input.

4. Efficiency. Handle millions of submissions per server per hour



Prio: System goals

1. Correctness. If clients and servers are honest, servers learn $f(\cdot)$

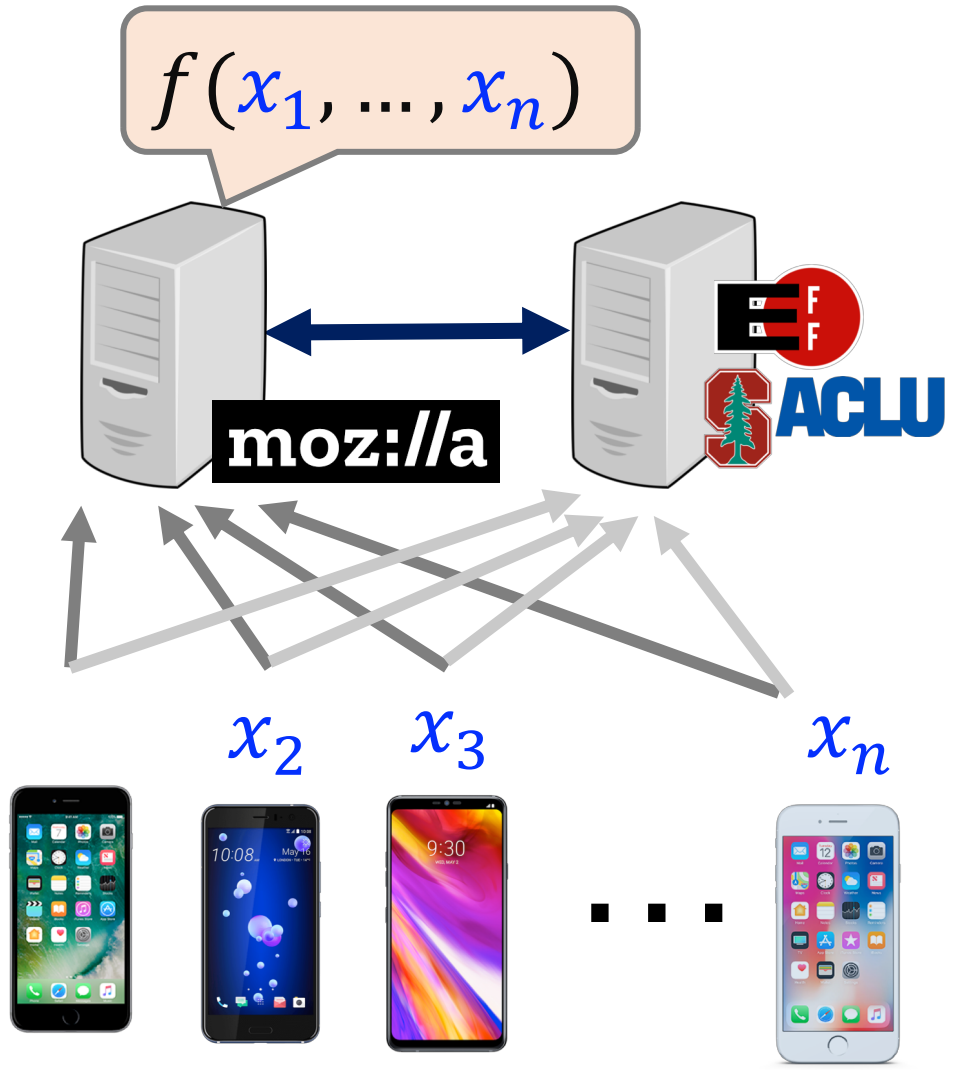
Extension: Maintain correctness in spite of server faults

2. f-Privacy. Attacker must compromise <u>all</u> servers to learn more than $f(\cdot)$

Extension: Differential privacy [DMNS06]

3. Disruption resistance.
The worst that a malicious client can do is lie about her input.

4. Efficiency. Handle millions of submissions per server per hour



Prio: System goals

1. Correctness. If clients and servers are honest, servers learn $f(\cdot)$

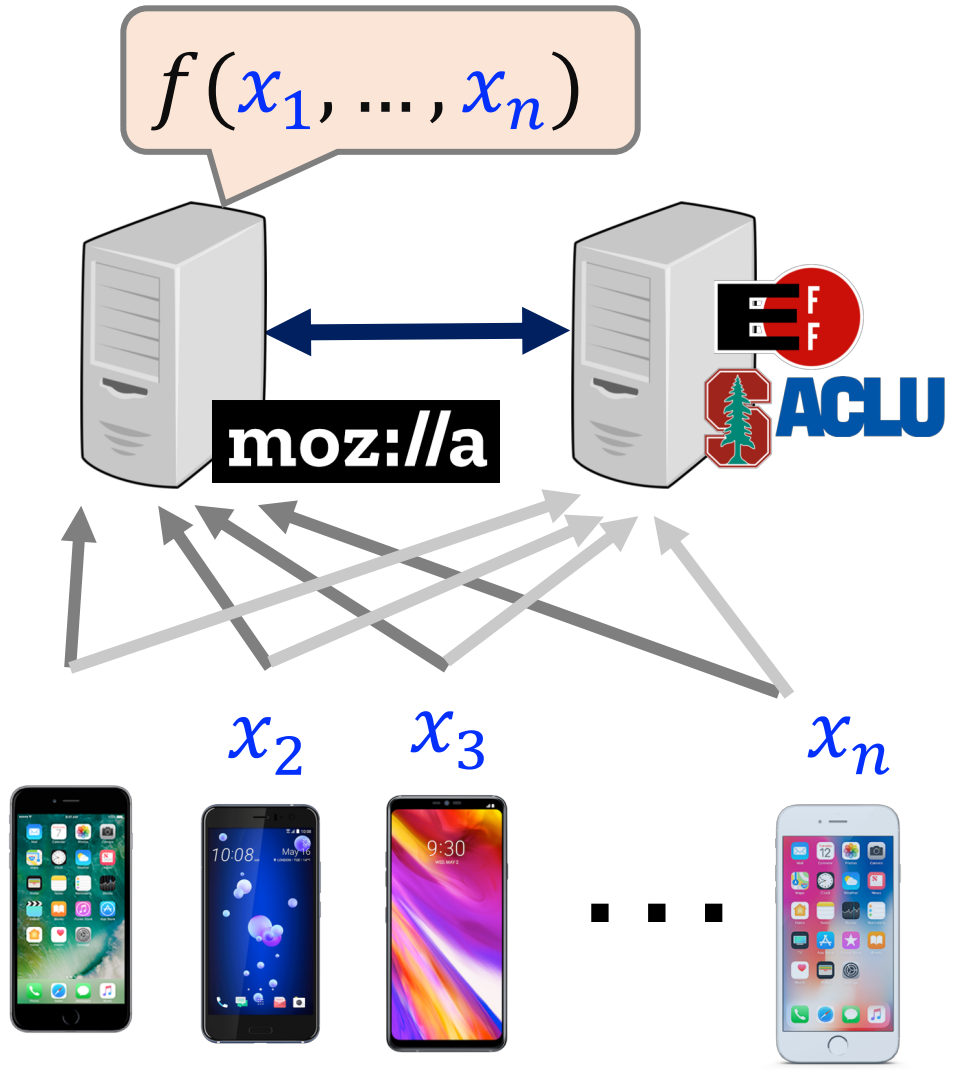
Extension: Maintain correctness in spite of server faults

2. f-Privacy. Attacker must compromise <u>all</u> servers to learn more than $f(\cdot)$

Extension: Differential privacy [DMNS06]

3. Disruption resistance.
The worst that a malicious client can do is lie about her input.

4. Efficiency. Handle millions of submissions per server per hour



Prio: System goals

1. Correctness. If clients and servers are honest, servers learn $f(\cdot)$

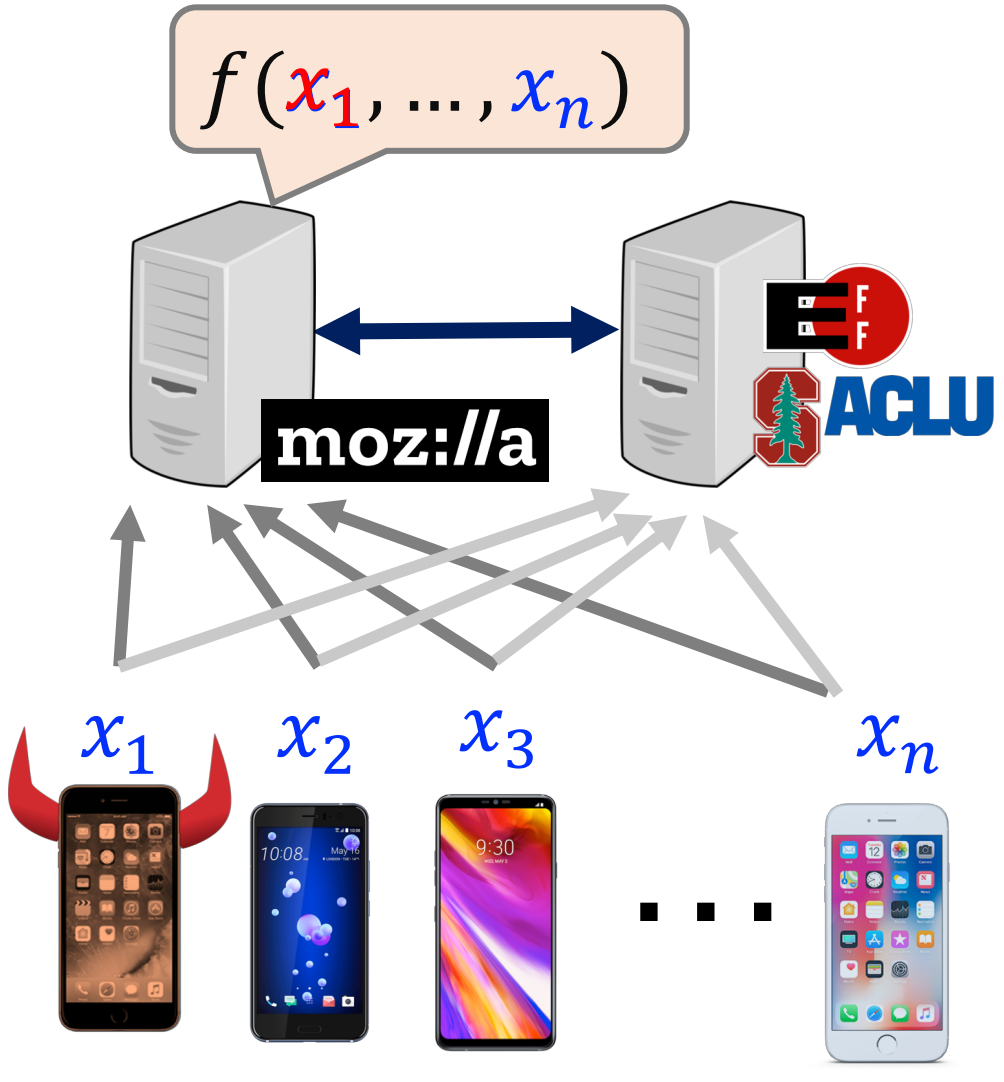
Extension: Maintain correctness in spite of server faults

2. f-Privacy. Attacker must compromise <u>all</u> servers to learn more than $f(\cdot)$

Extension: Differential privacy [DMNS06]

3. Disruption resistance. The worst that a malicious client can do is lie about her input.

4. Efficiency. Handle millions of submissions per server per hour



Prio: System goals

1. Correctness. If clients and servers are honest, servers learn $f(\cdot)$

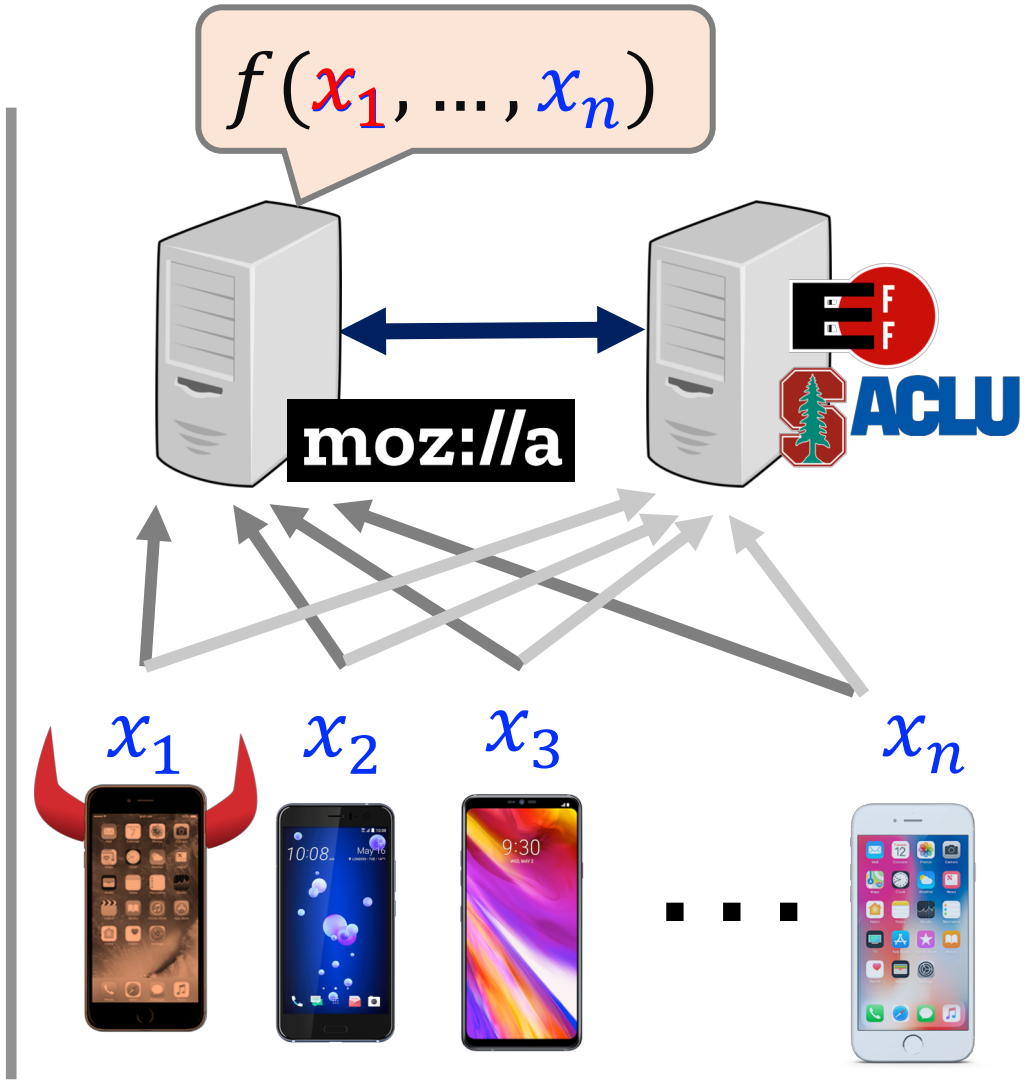
Extension: Maintain correctness in spite of server faults

2. f-Privacy. Attacker must compromise <u>all</u> servers to learn more than $f(\cdot)$

Extension: Differential privacy [DMNS06]

3. Disruption resistance. The worst that a malicious client can do is lie about her input.

4. Efficiency. Handle millions of submissions per server per hour



Prio: System g

Focus on sums, for now

1. Correctness. If clients and servers are honest, servers learn $f(\cdot)$

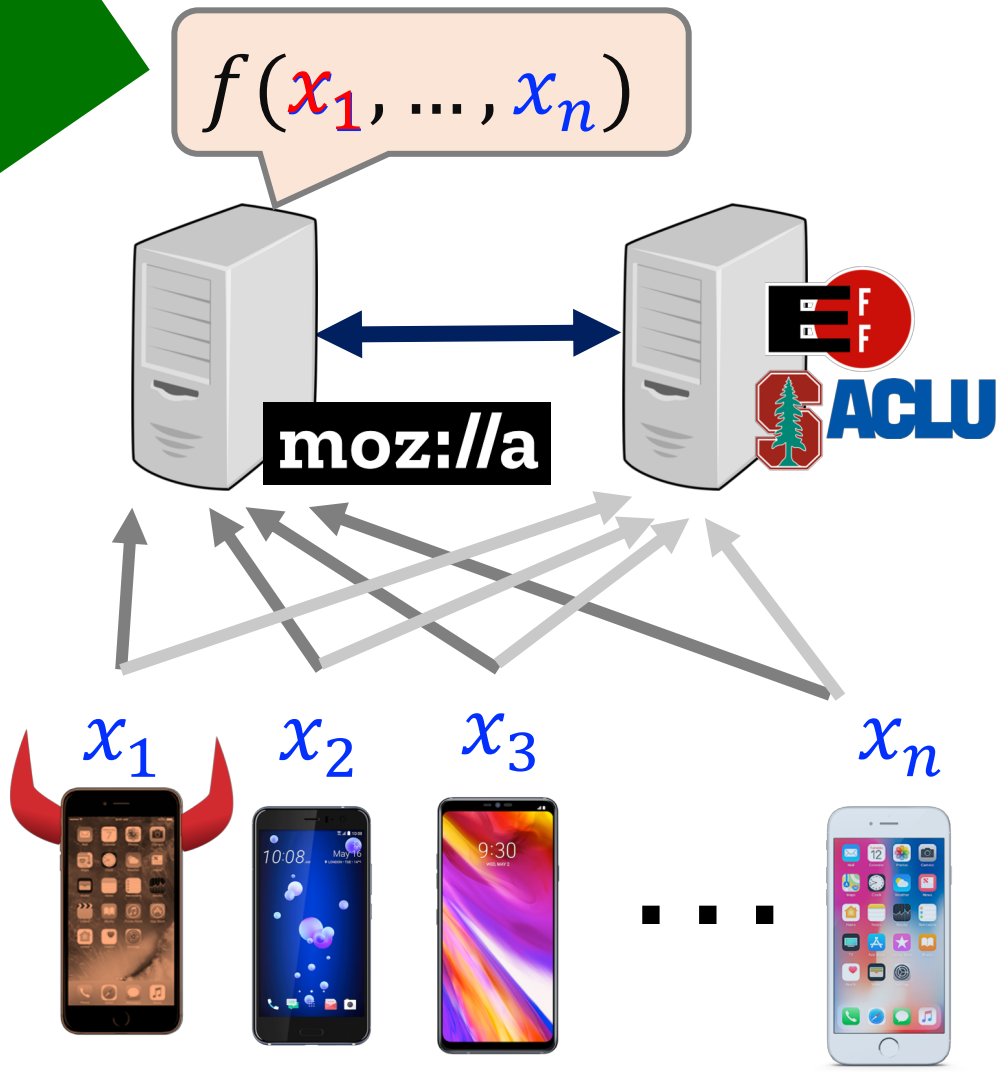
Extension: Maintain correctness in spite of server faults

2. f-Privacy. Attacker must compromise <u>all</u> servers to learn more than $f(\cdot)$

Extension: Differential privacy [DMNS06]

3. Disruption resistance. The worst that a malicious client can do is lie about her input.

4. Efficiency. Handle millions of submissions per server per hour



Relax correctness

Randomized response: [W65], [DMNS06], [DJW13], [BS15]
RAPPOR (2014, 2016), Wang et al. (2017),
Ding et al. (2017)...

Relax privacy model

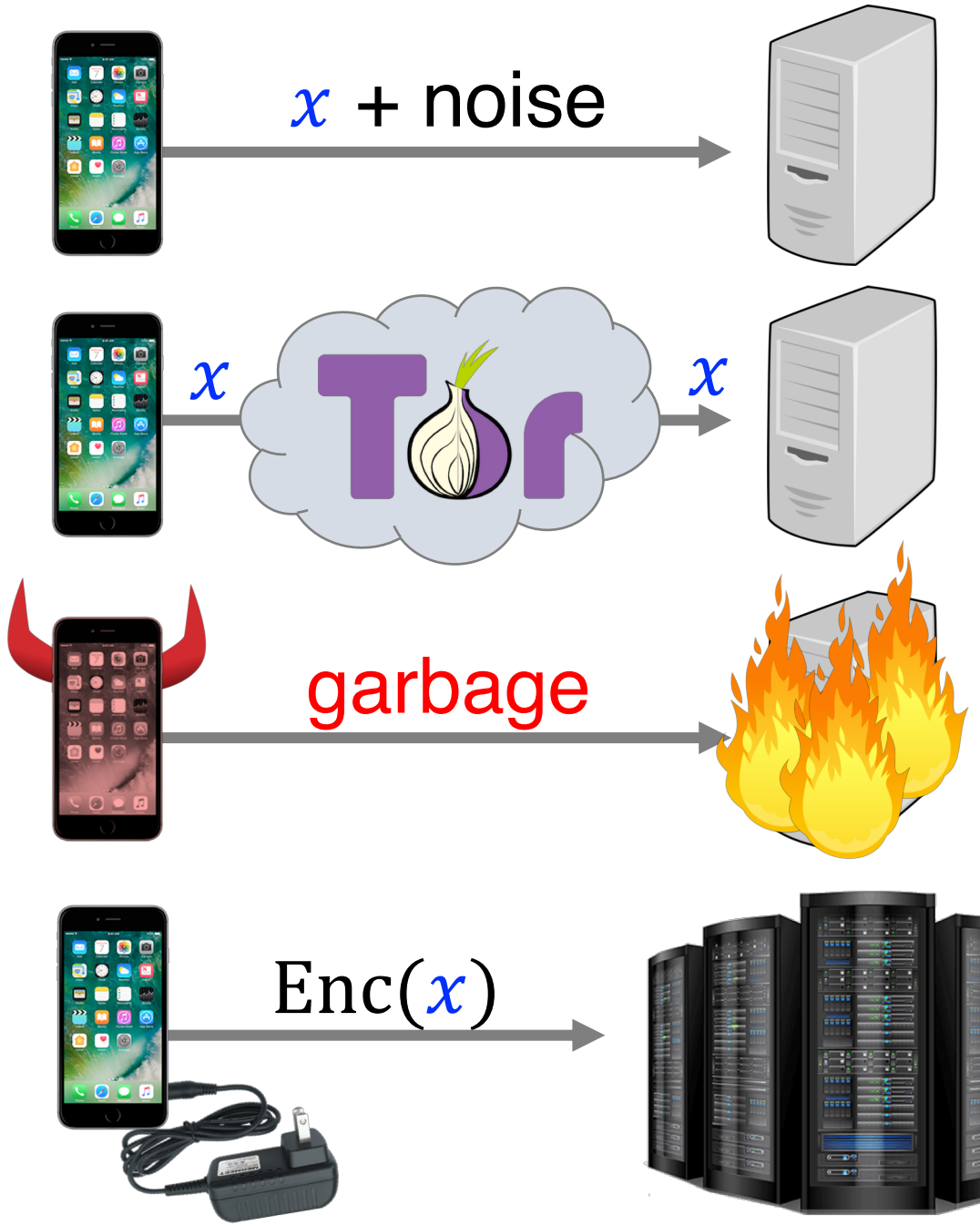
Tor: PrivStats (2011), ANONIZE (2014), ...
SGX: Prochlo (2017), SGX-BigMatrix (2017), ...
Honest but curious: PDDP (2012), SplitX (2013), ...

Relax disruption resistance

Private metering (2011), PrivEx-S2 (2014),
PrivCount (2016), Federated ML (2016, 2017), ...

Relax efficiency

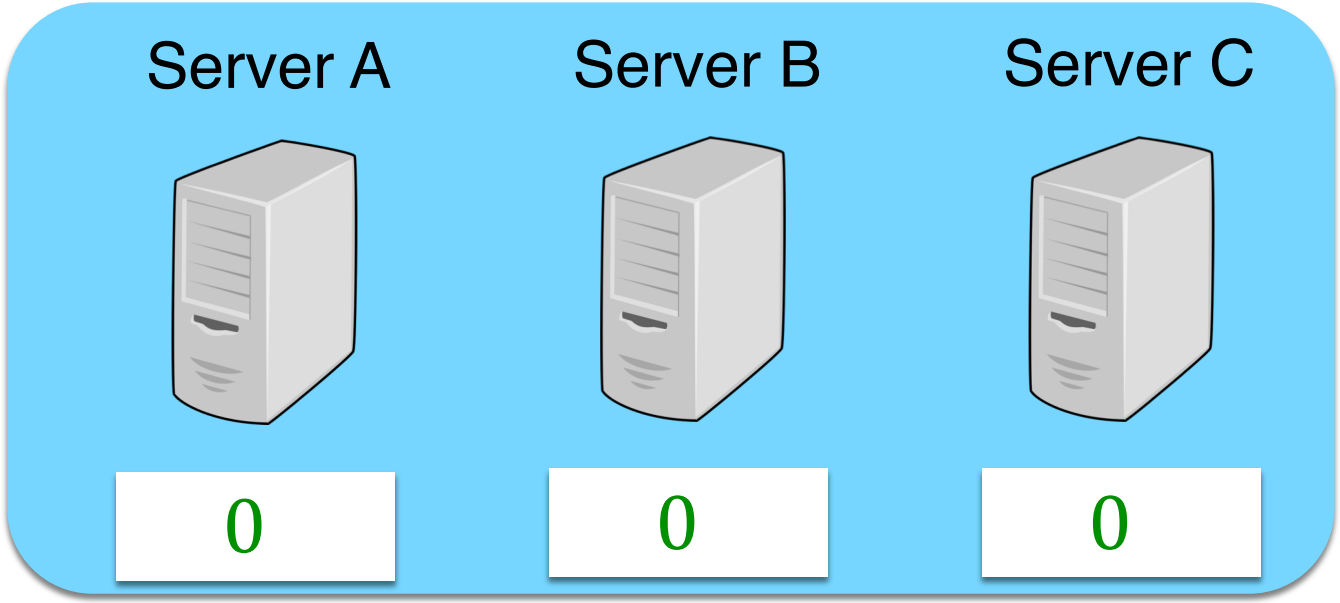
P4P (2010), Grid aggregation (2011), Haze (2013),
PrivEx-D2 (2014), Succinct sketches (2016), HisTorϵ (2017), ...
General MPC [GMW87], [BGW88]: FairPlay (2004), FairplayMP (2008), SEPIA (2010), Private matrix factorization (2013), Private ridge regression (2018), ...



Straw-man scheme

Private sums without disruption resistance

[C88], [BGW88], …
[KDK11] [DFKZ13] [PrivEx14] …

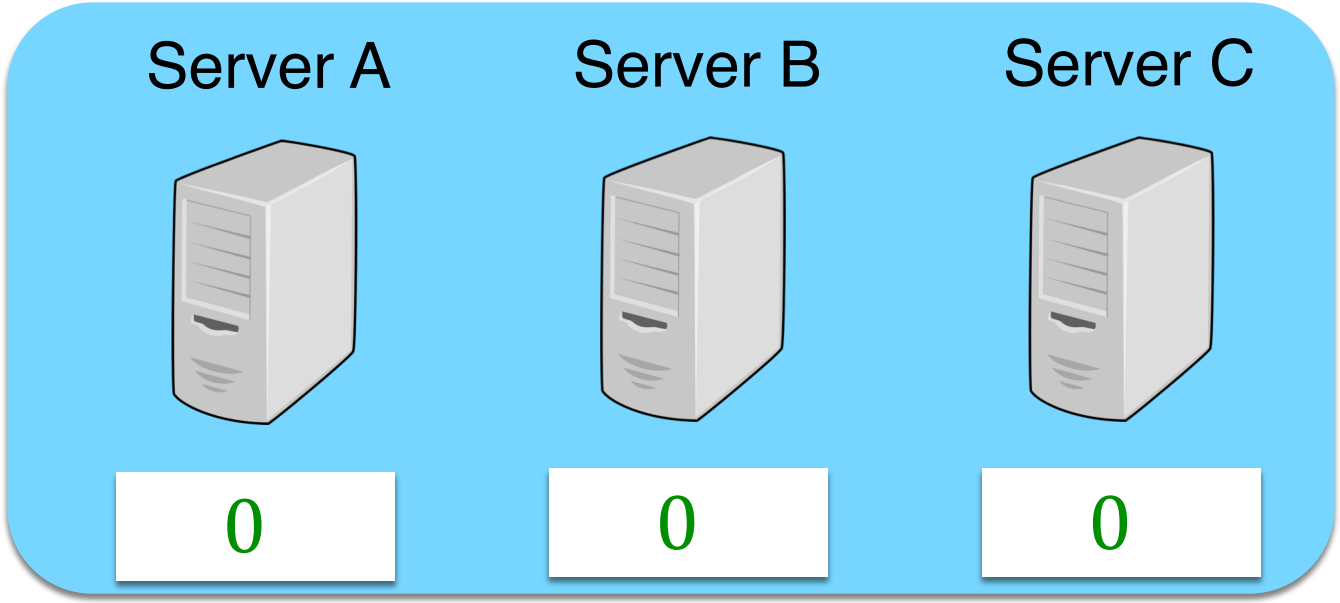


$x_1 = 1$

Straw-man scheme

Private sums without disruption resistance

[C88], [BGW88], …
[KDK11] [DFKZ13] [PrivEx14] …



$x_1 = 1$

Pick three random "shares" that sum to $x_1 = 1$.

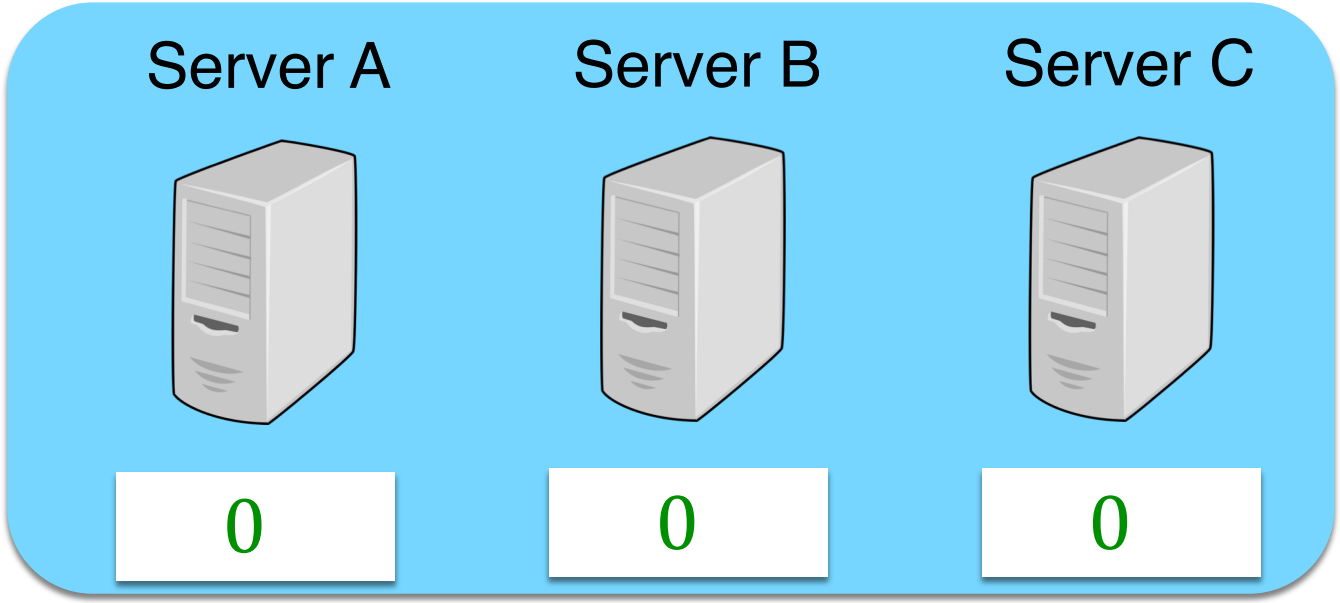
$$1 = 15 + (-12) + (-2) \pmod{p}$$

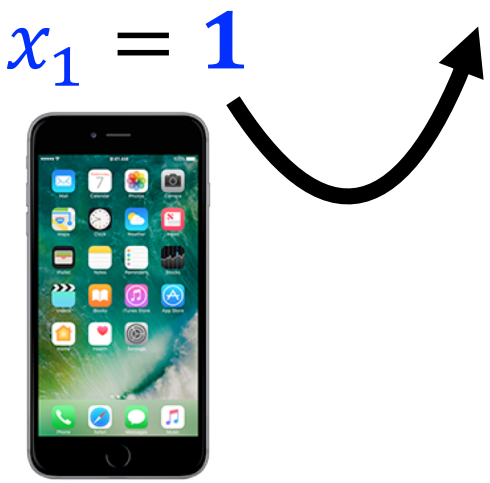
Send one share to each server.

Straw-man scheme

Private sums without disruption resistance

[C88], [BGW88], …
[KDK11] [DFKZ13] [PrivEx14] …





Pick three random "shares" that sum to $x_1 = 1$.

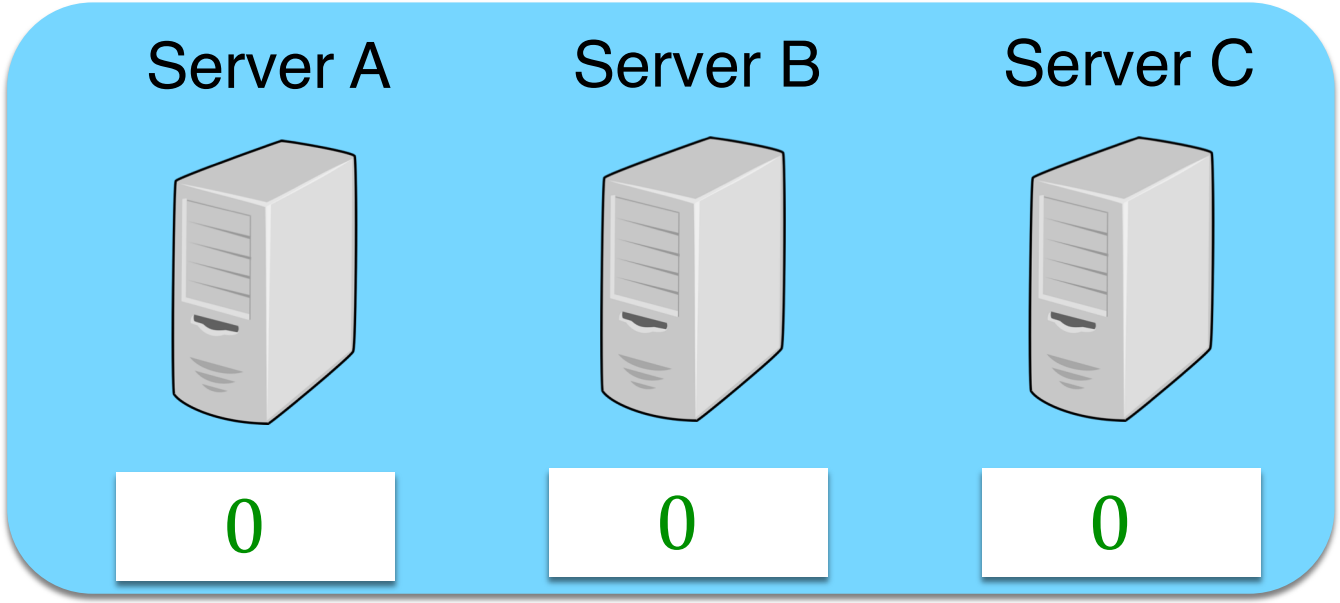
$$1 = 15 + (-12) + (-2) \pmod{p}$$

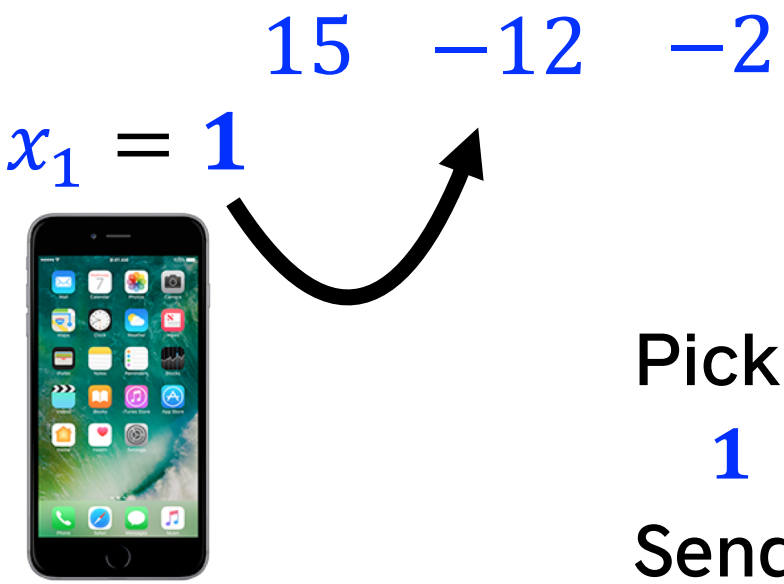
Send one share to each server.

Straw-man scheme

Private sums without disruption resistance

[C88], [BGW88], …
[KDK11] [DFKZ13] [PrivEx14] …





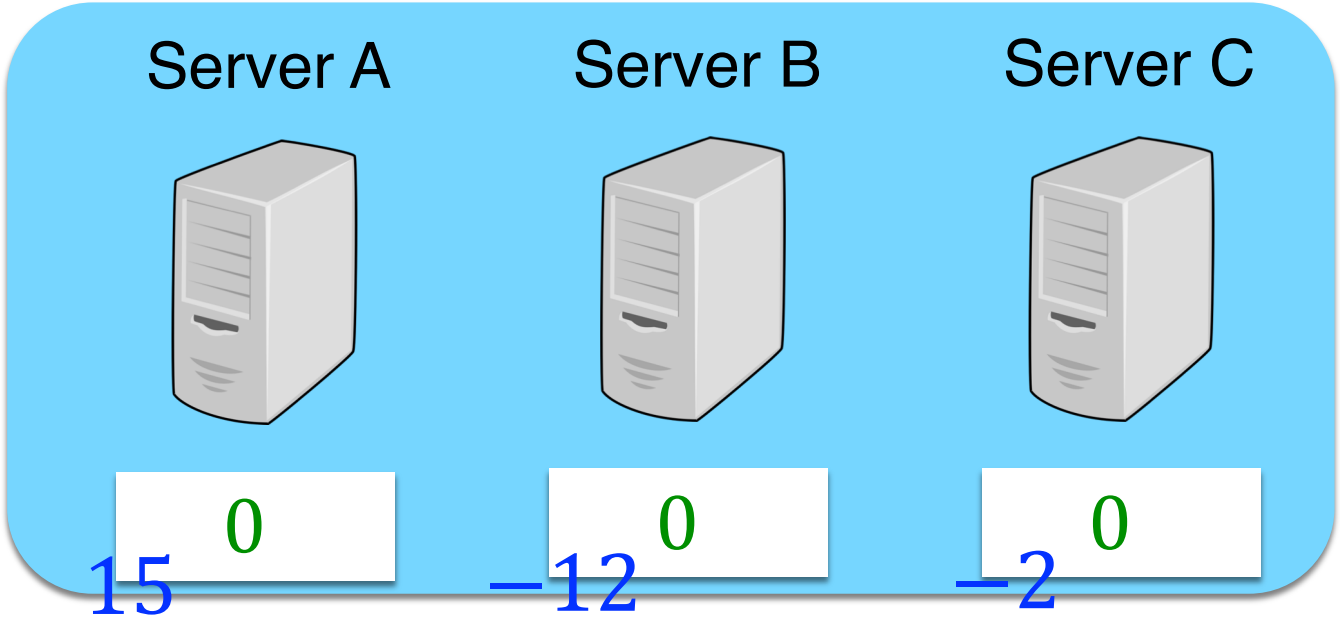
Pick three random "shares" that sum to $x_1 = 1$.

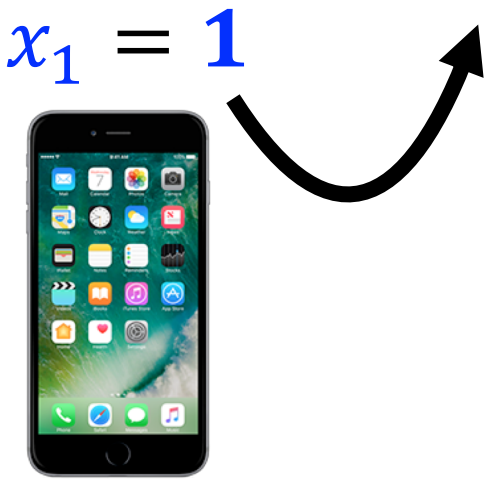
$$1 = 15 + (-12) + (-2) \pmod{p}$$

Send one share to each server.

Straw-man scheme

Private sums without disruption resistance



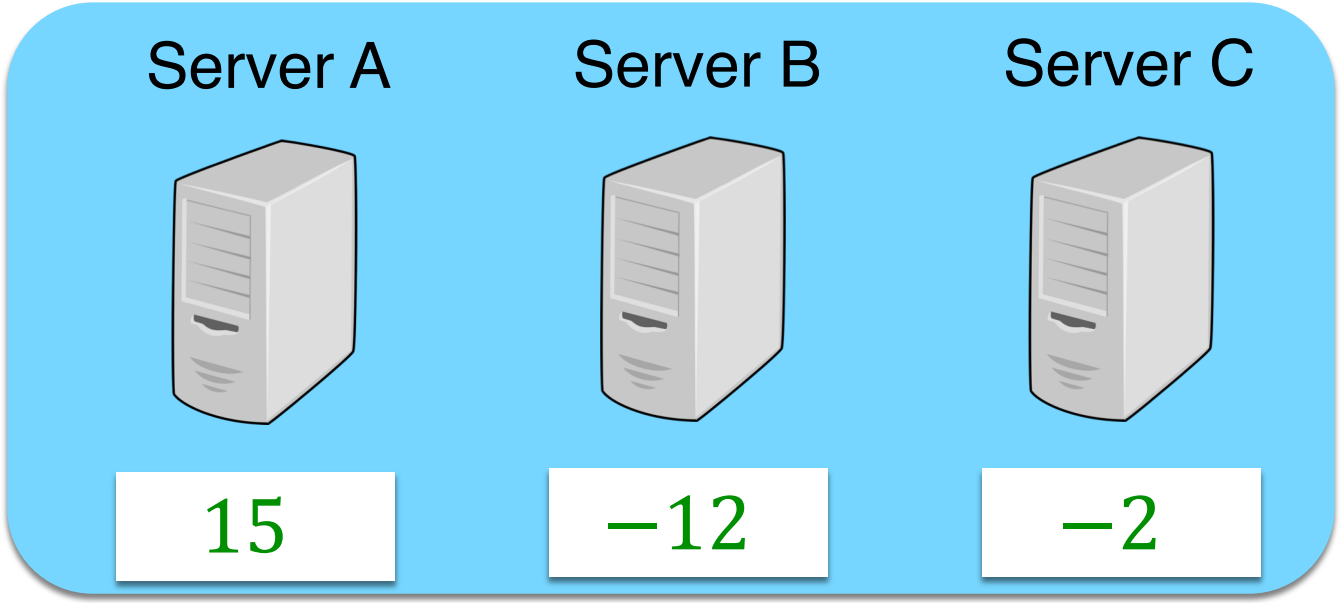


Pick three random "shares" that sum to $x_1 = 1$.

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

Send one share to each server.

Straw-man scheme
Private sums without disruption resistance



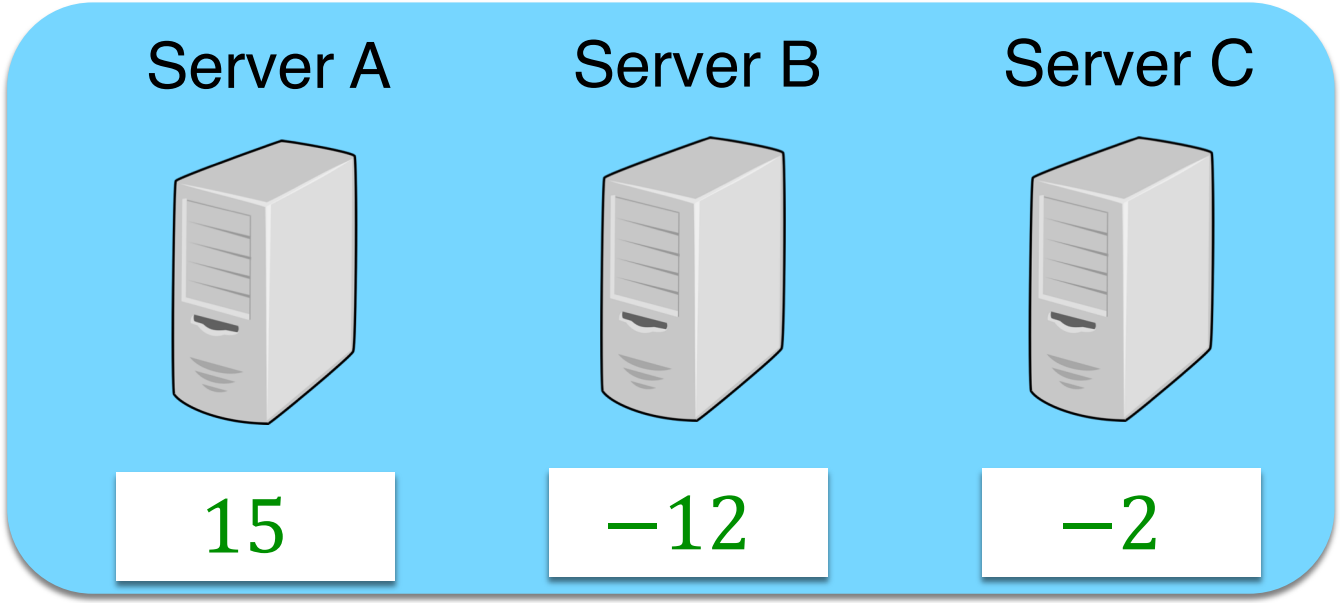
$x_1 = \mathbf{1}$

Pick three random "shares" that sum to $x_1 = \mathbf{1}$.

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

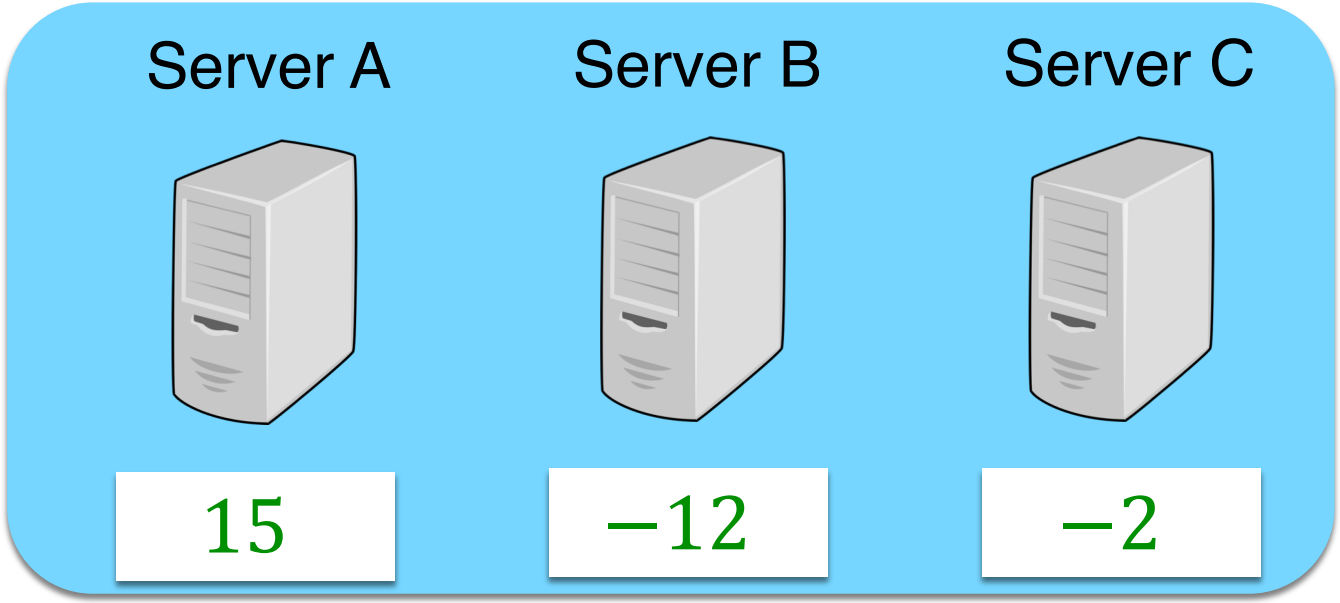
Send one share to each server.

Straw-man scheme
Private sums without disruption resistance



$x_2 = \mathbf{0}$

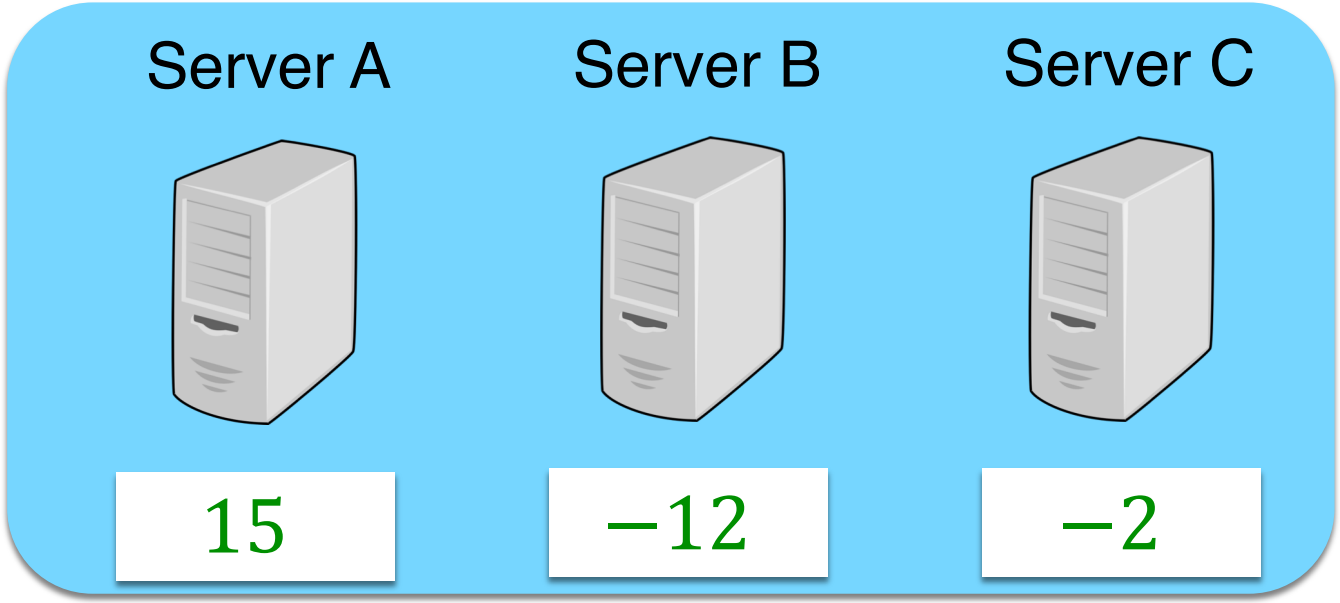
Straw-man scheme
Private sums without disruption resistance



$x_2 = \mathbf{0}$

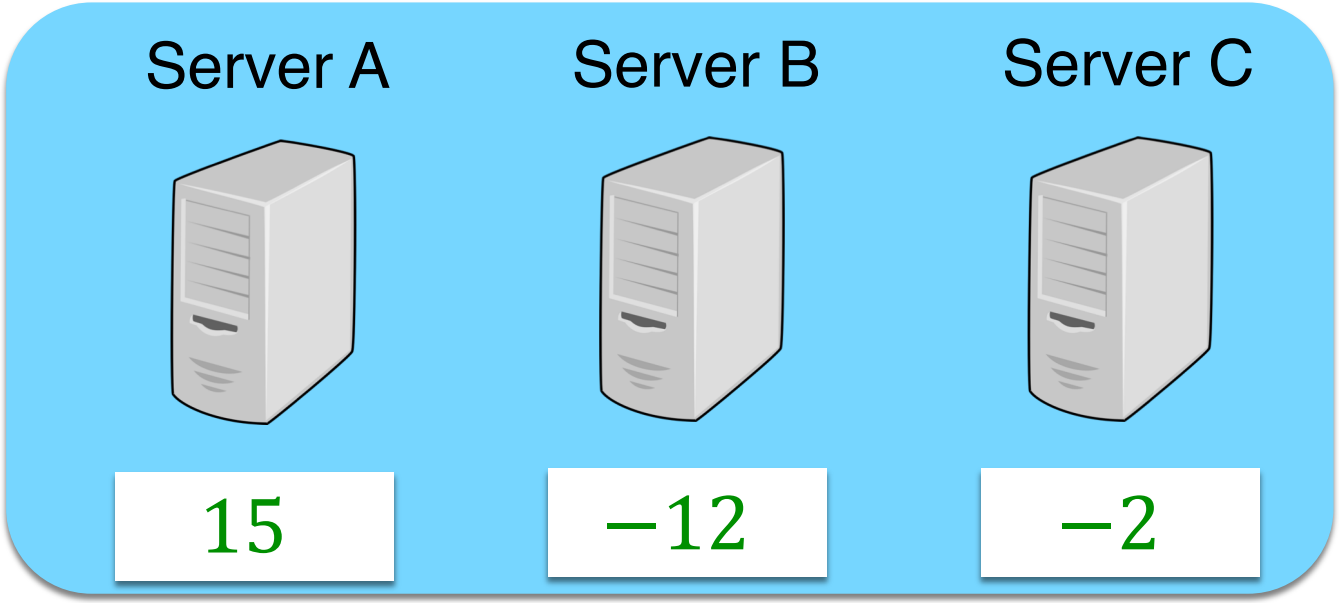
Straw-man scheme

Private sums without disruption resistance



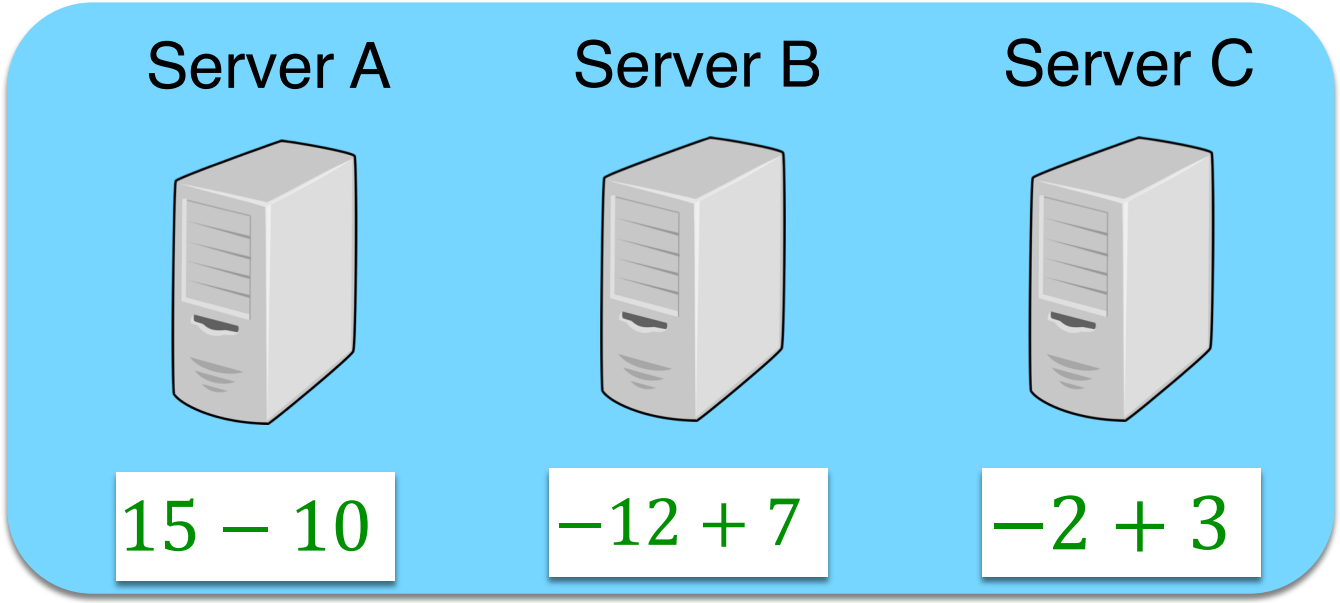
$$x_2 = \mathbf{0} = (-10) + 7 + 3$$

Straw-man scheme
Private sums without disruption resistance



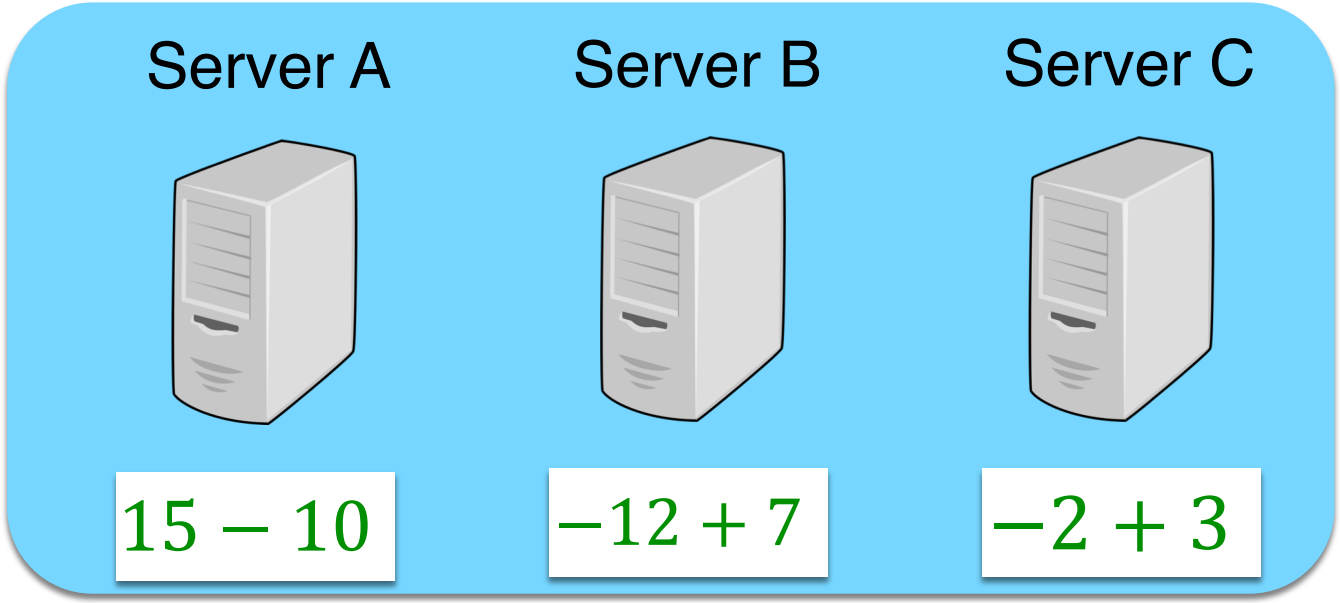
$x_2 = \mathbf{0}$ $\quad -10 \quad 7 \quad 3$

Straw-man scheme
Private sums without disruption resistance

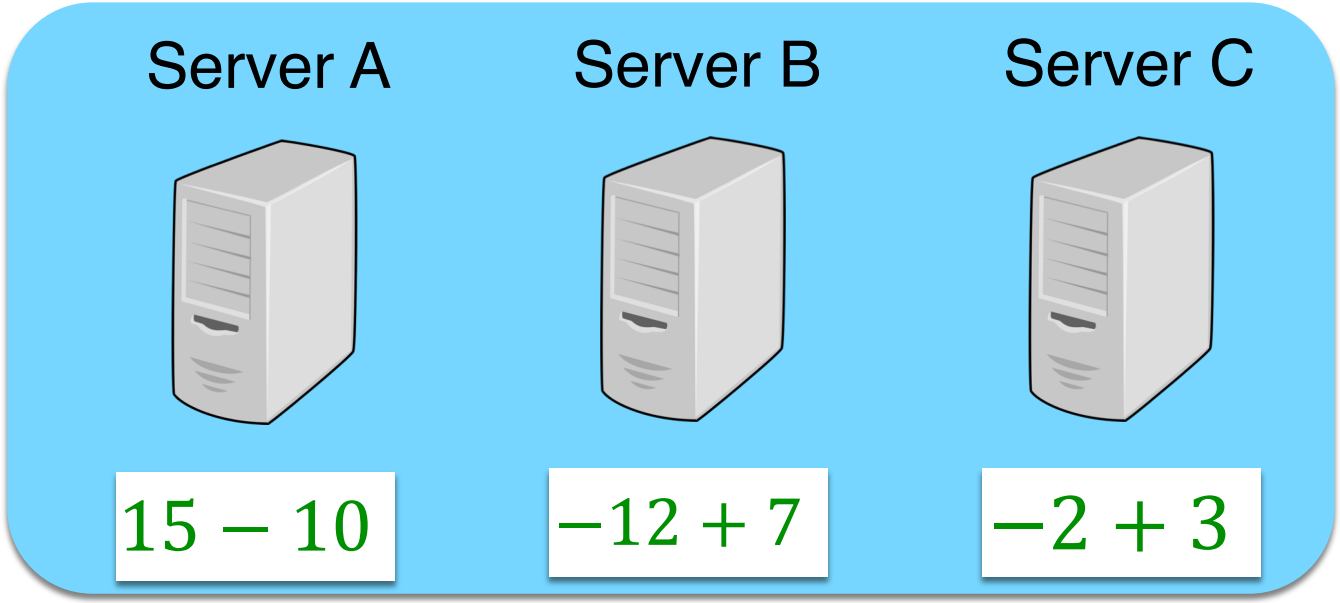


$x_2 = \mathbf{0}$

Straw-man scheme
Private sums without disruption resistance

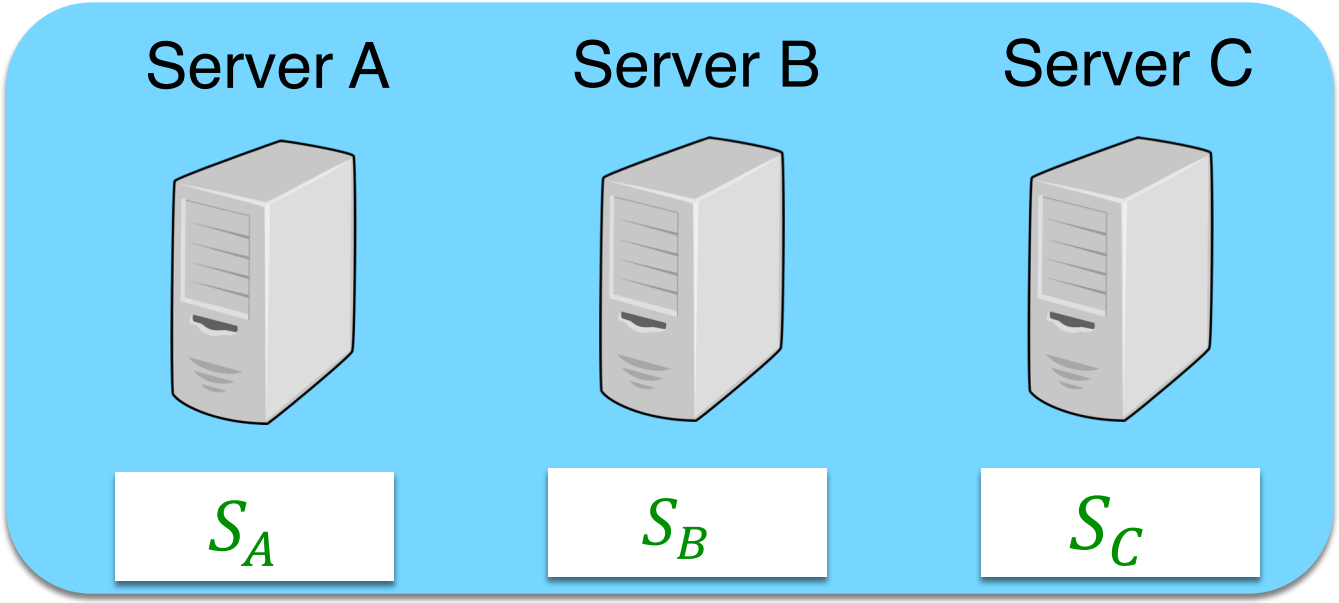


Straw-man scheme
Private sums without disruption resistance

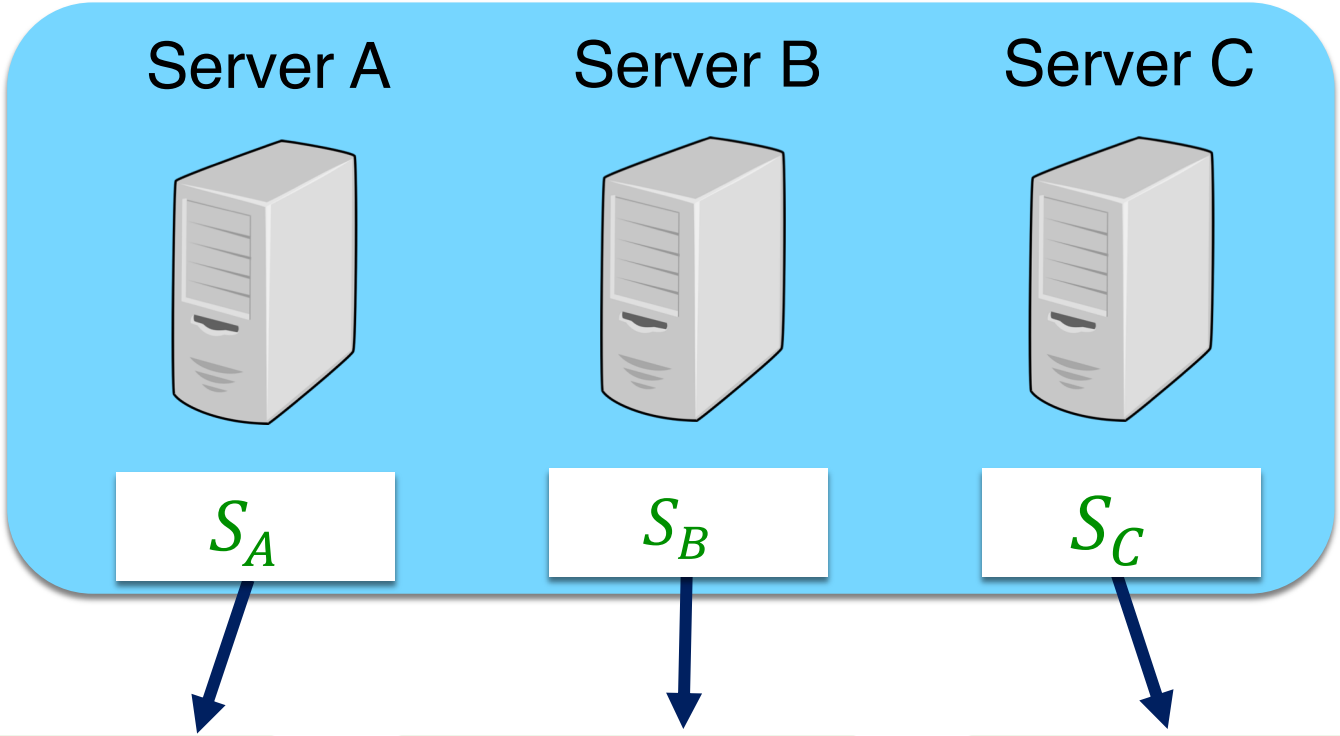


■ ■ ■

Straw-man scheme
Private sums without disruption resistance



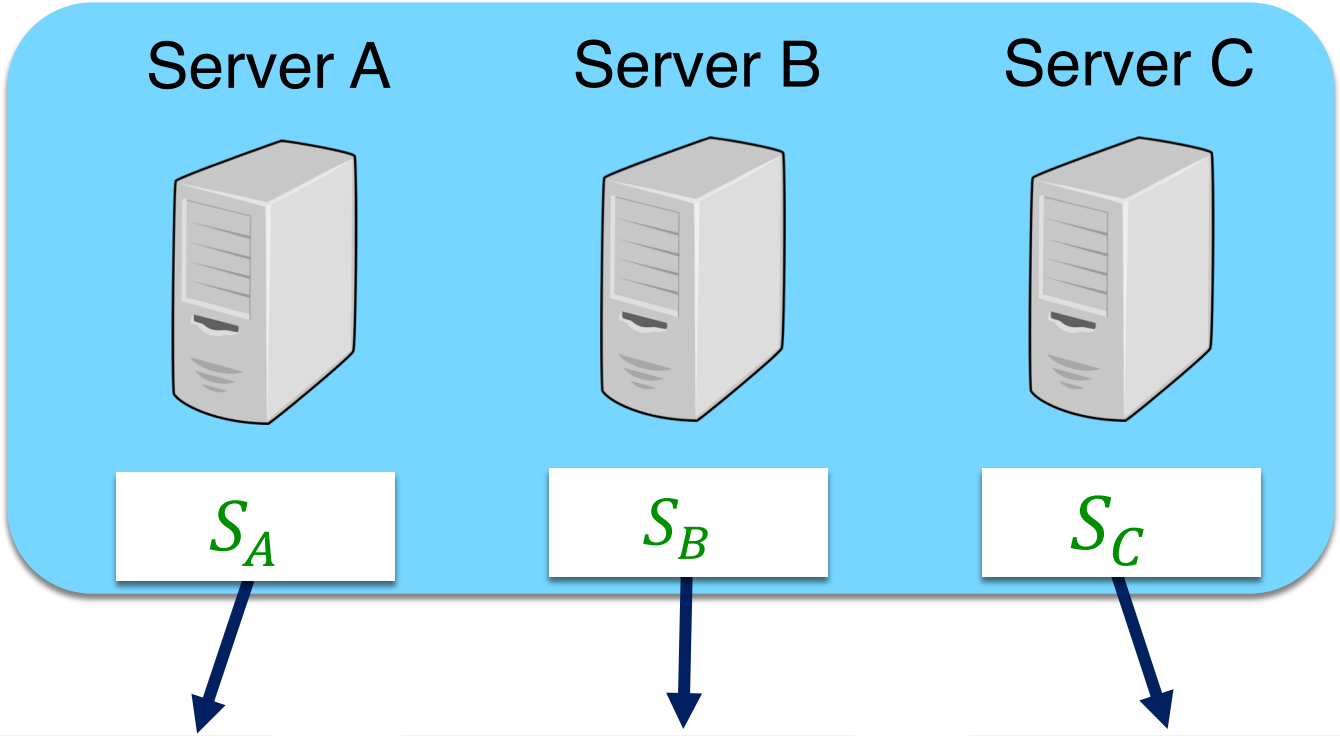
Straw-man scheme
Private sums without disruption resistance



$$(15 - 10 + \cdots) + (-12 + 7 + \cdots) + (-2 + 3 + \cdots)$$
$$= \quad x_1 + x_2 + x_3 + \cdots$$

Servers learn the sum of the clients' values and nothing else.

Straw-man scheme
Private sums without disruption resistance



$$(15 - 10 + \cdots) + (-12 + 7 + \cdots) + (-2 + 3 + \cdots)$$
$$= \quad x_1 + x_2 + x_3 + \cdots$$

e.g., 15 phones disabled content blocking on mysite.com, but <u>not</u> which phones

Servers learn the sum of the clients' values and <u>nothing else</u>.

Why this works: Shares are additive.

Say servers have shares of integers x_1 and x_2:

$$x_1 = [x_1]_A + [x_1]_B + [x_1]_C$$

$$x_2 = [x_2]_A + [x_2]_B + [x_2]_C$$

By adding, each server can compute a share of $x_1 + x_2$:

$$[x_1 + x_2]_A = [x_1]_A + [x_2]_A$$

Also, for a constant C, can compute a share of $C \cdot x$:

$$[C \cdot x]_A = C \cdot [x]_A$$

Will be useful later on...

Why this works: Shares are additive.

Say servers have shares of integers x_1 and x_2:

$$x_1 = [x_1]_A + [x_1]_B + [x_1]_C$$

$$x_2 = [x_2]_A + [x_2]_B + [x_2]_C$$

By adding, each server can compute a share of $x_1 + x_2$:

$$[x_1 + x_2]_A = [x_1]_A + [x_2]_A$$

Also, for a constant C, can compute a share of $C \cdot x$:

$$[C \cdot x]_A = C \cdot [x]_A$$

Will be useful later on...

Private sums: Straw-man scheme

Correctness. Servers learn the sum of the x_is

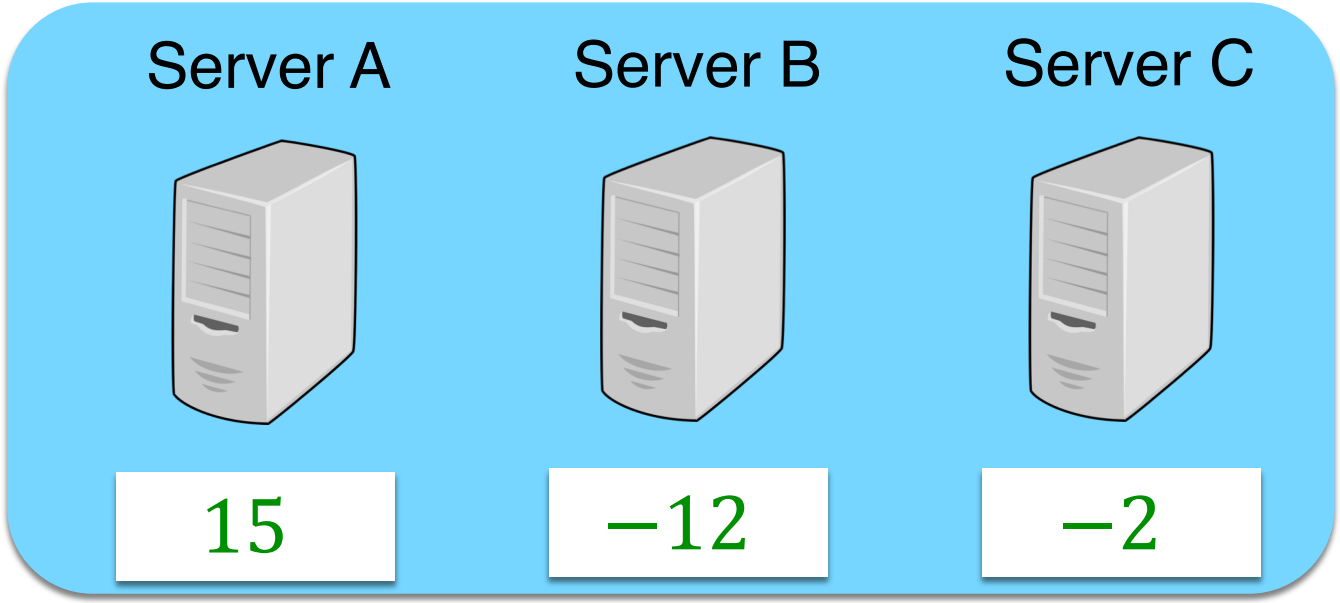
f-Privacy. Attacker must compromise <u>all</u> servers to learn more than sum of x_is

Efficiency. No heavy cryptographic operations

Disruption resistance. **One malicious client can corrupt the output.**

Straw-man scheme

One malicious client can corrupt output

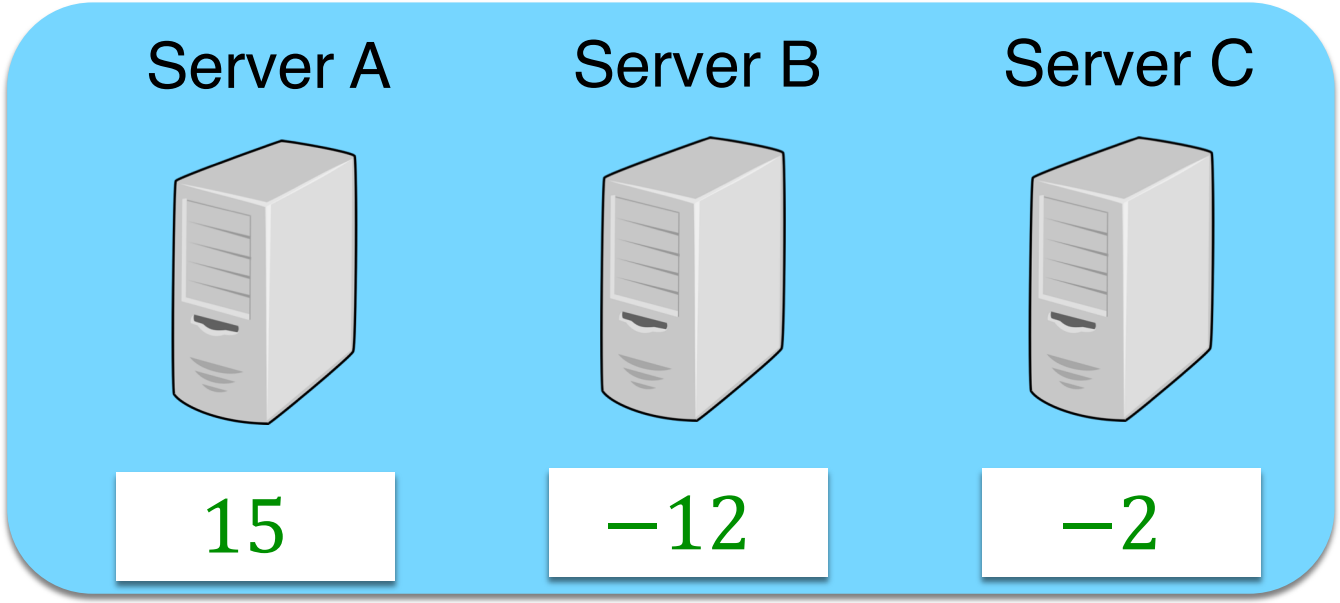


Evil ad network

Should be a value in the set $\{0,1\}$

Straw-man scheme

One malicious client can corrupt output



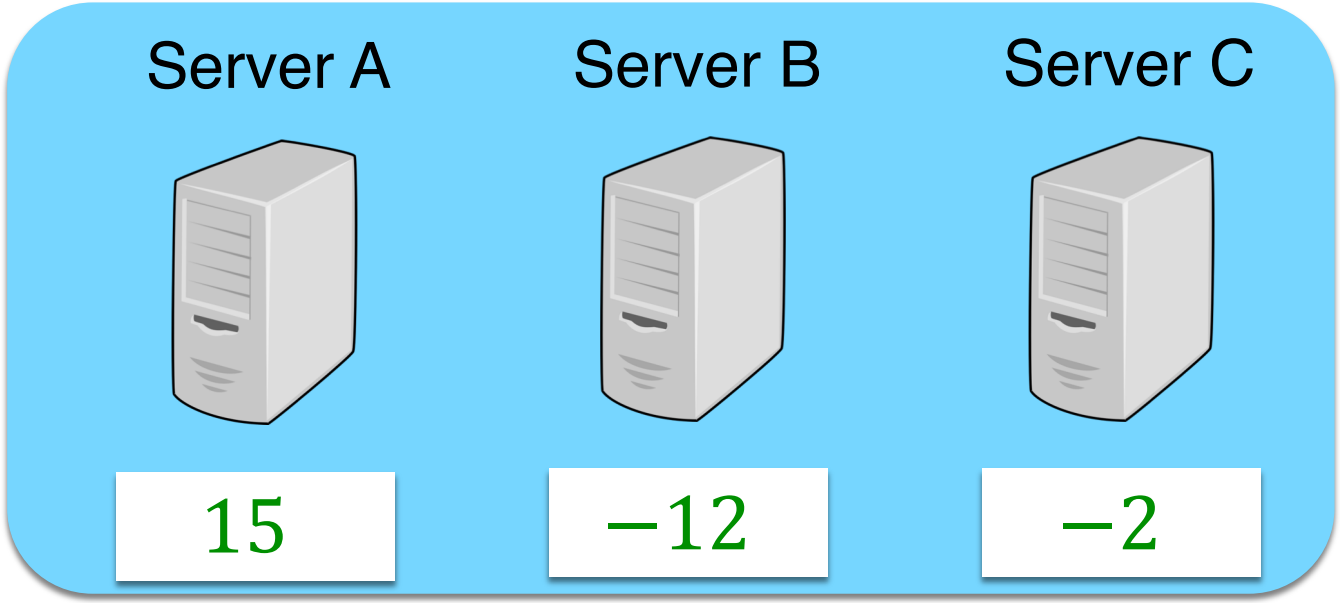
$x_2 = 53 = 19 + 16 + 18$

Evil ad network

Should be a value in the set $\{0,1\}$

Straw-man scheme

One malicious client can corrupt output



$x_2 = 53$ 19 16 18

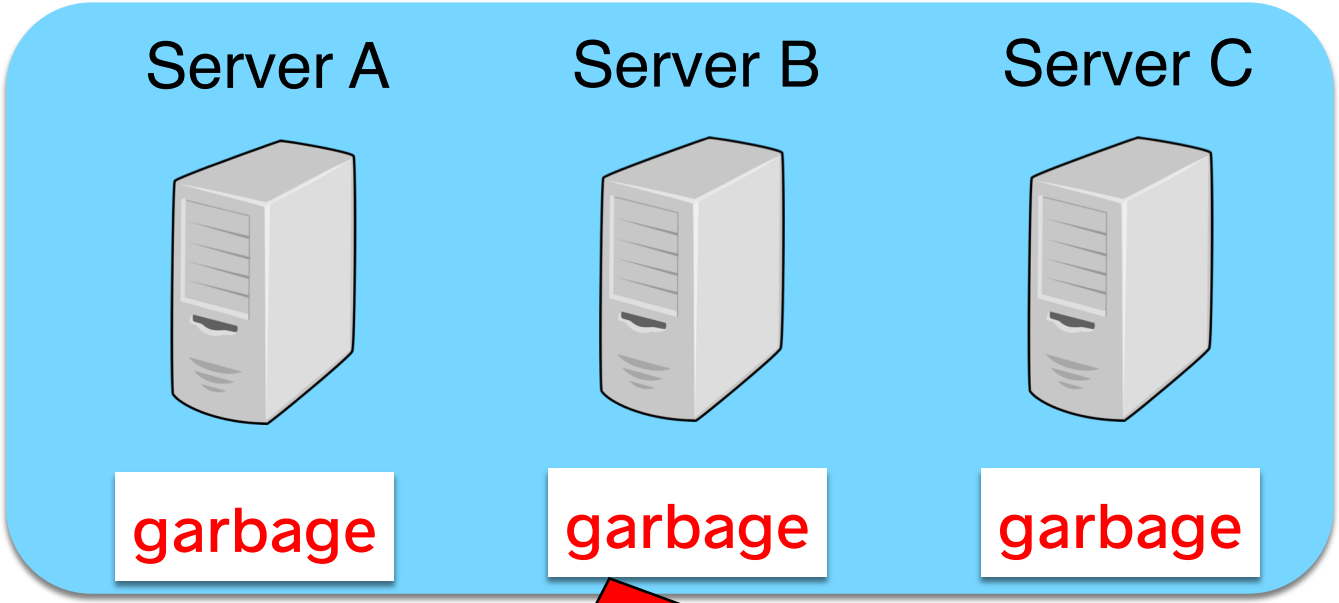
Should be a value in the set $\{0,1\}$

Evil ad network

Straw-man scheme

One malicious client can corrupt output

Evil ad network



Powerful but costly tools...

Multiparty computation

[GMW87], [BGW88]

Powerful but costly tools...

Multiparty computation

[GMW87], [BGW88]

Traditional zero-knowledge proofs

[GMR89]

Powerful but costly tools...

Multiparty computation

[GMW87], [BGW88]

Traditional zero-knowledge proofs

[GMR89]

New tool: Proof on secret-shared data

Techniques for providing disruption resistance

Testing that a length-n vector (e.g., data for n sites) consists of secret-shared 0/1 integers.

	Public-key ops.		Communication		Slow-down
	Client	Server	C-to-S	S-to-S	
Dishonest-maj. MPC	0	$\widetilde{\Theta}(n)$	0	$\widetilde{\Theta}(n)$	5,000× at server
General succinct zero knowledge	$\widetilde{\Theta}(n)$	$\tilde{O}(1)$	$\tilde{O}(1)$	$\tilde{O}(1)$	500× at client
General zero knowledge	$\widetilde{\Theta}(n)$	$\widetilde{\Theta}(n)$	$\widetilde{\Theta}(n)$	$\widetilde{\Theta}(n)$	50× at server

(Table hides log factors.)

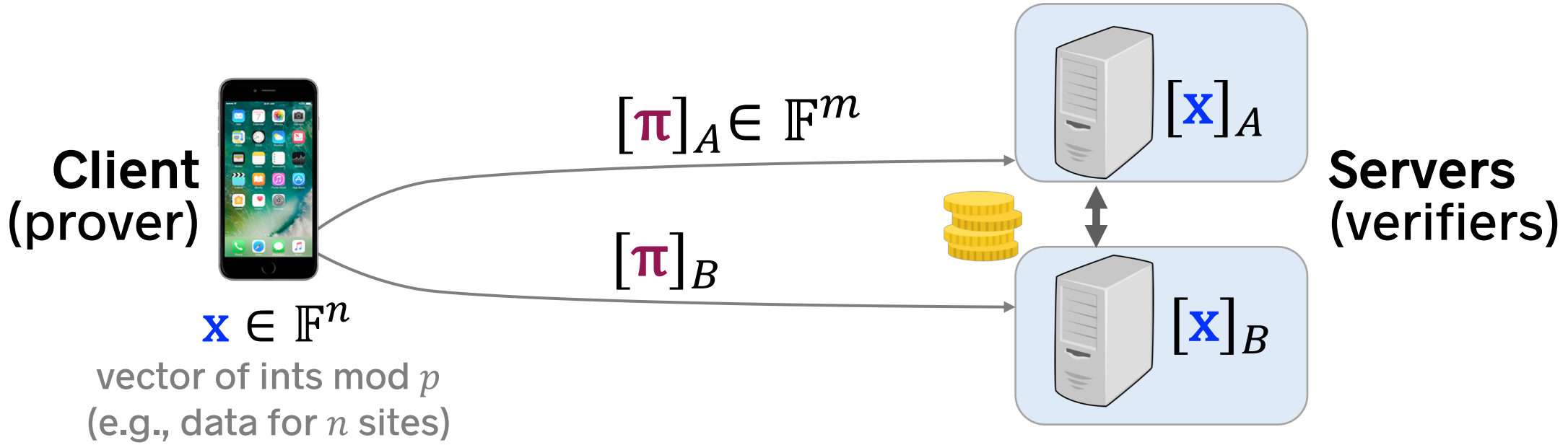
Techniques for providing disruption resistance

Testing that a length-n vector (e.g., data for n sites) consists of secret-shared 0/1 integers.

	Public-key ops.		Communication		Slow-down
	Client	Server	C-to-S	S-to-S	
Dishonest-maj. MPC	0	$\widetilde{\Theta}(n)$	0	$\widetilde{\Theta}(n)$	5,000× at server
General succinct zero knowledge	$\widetilde{\Theta}(n)$	$\tilde{O}(1)$	$\tilde{O}(1)$	$\tilde{O}(1)$	500× at client
General zero knowledge	$\widetilde{\Theta}(n)$	$\widetilde{\Theta}(n)$	$\widetilde{\Theta}(n)$	$\widetilde{\Theta}(n)$	50× at server
Prio (latest version)	0	0	$\tilde{O}(1)$	$\tilde{O}(1)$	1×

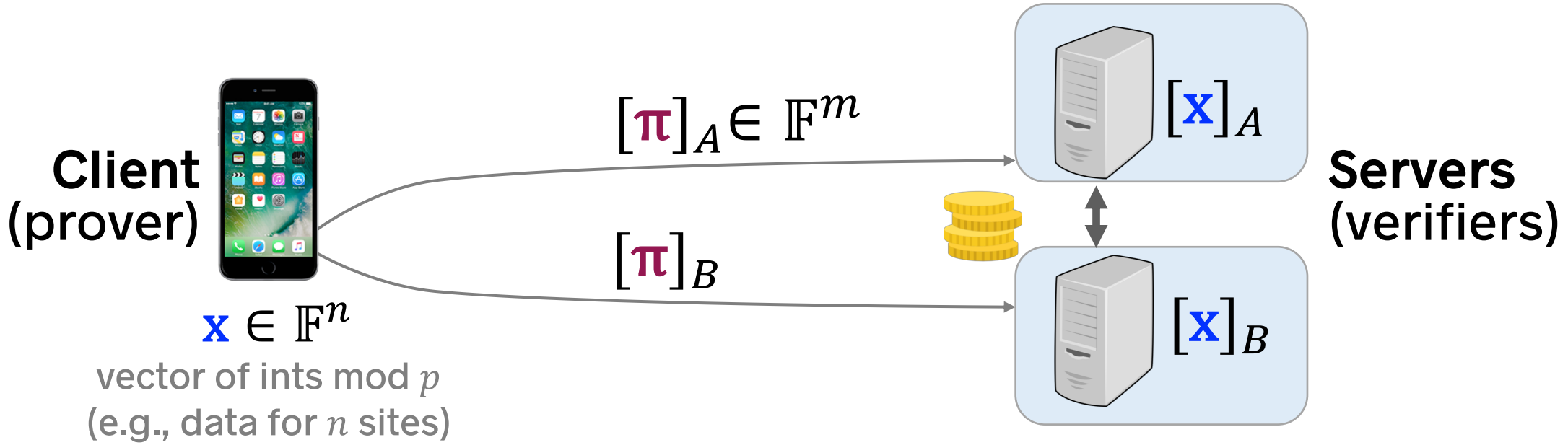
(Table hides log factors.)

Contribution: Proofs on secret-shared data



- Client sends proof to servers that $\mathbf{Valid}(\mathbf{x})$ holds
  - For our example, $\mathbf{Valid}(\mathbf{x}) =$ "$\mathbf{x} \in \{0,1\}^n$"
  - Servers exchange $O(1)$ bytes to check proof (e.g., 64 bytes)
- Prevents disruption in Prio
  - Servers detect and reject invalid client submissions

Contribution: Proofs on secret-shared data



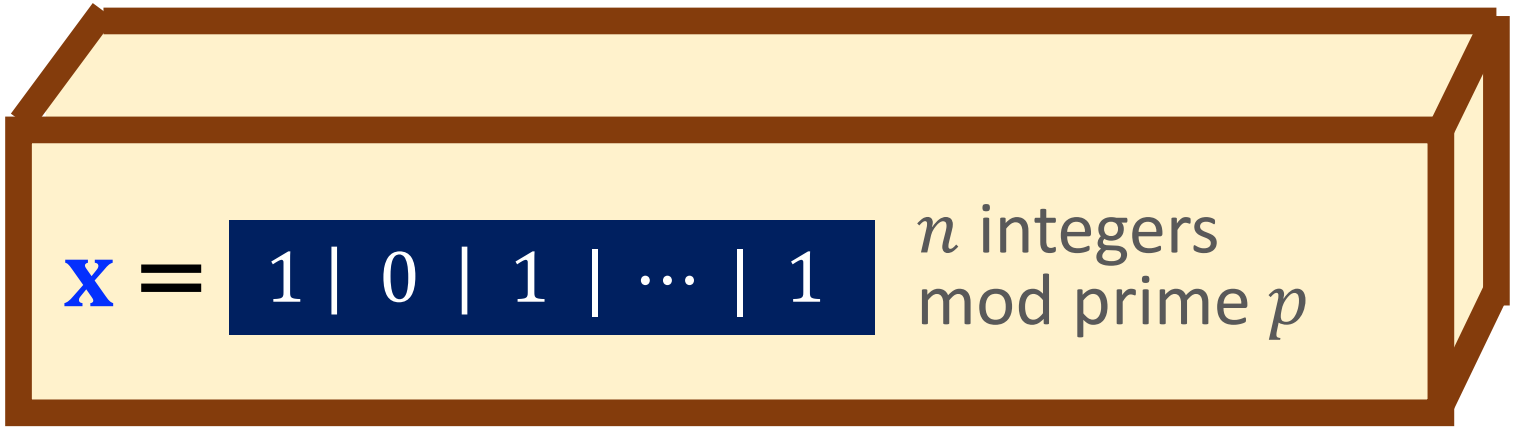
Complete. Honest servers accept valid $\mathbf{x}$s

Sound. Honest servers reject invalid $\mathbf{x}$s $(\Pr[\text{error}] \approx 2^{-128})$

Privacy preserving. Any proper subset of servers learns nothing about $\mathbf{x}$, apart from the fact that $\mathbf{x}$ is valid

Diversion:

The Box Game



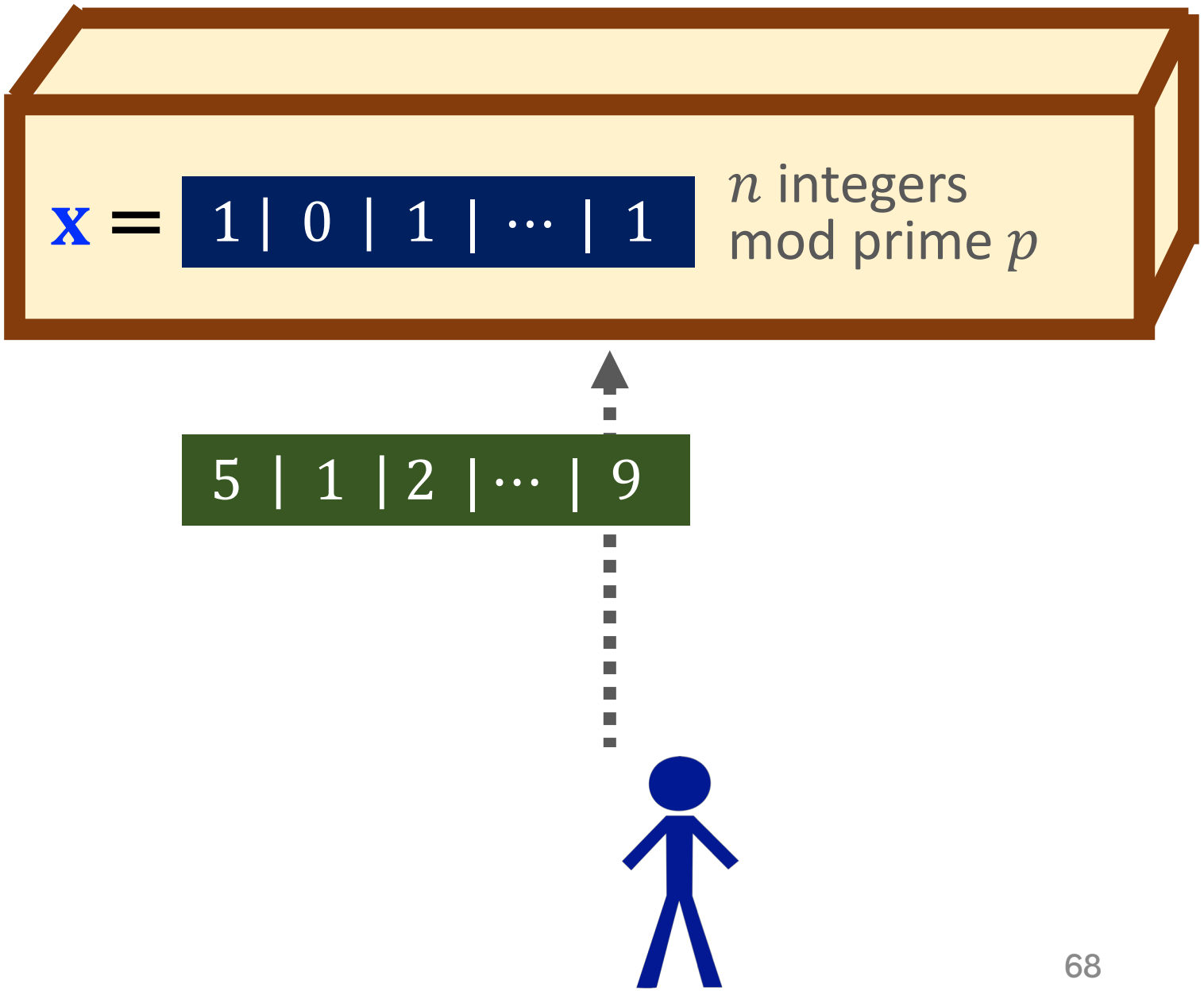
You must decide:
VALID or **INVALID**.

After asking **three** "linear questions" of the box.

Can you win?

Diversion:

The Box Game



You must decide:
VALID or **INVALID**.

After asking **three** “linear questions” of the box.

Can you win?

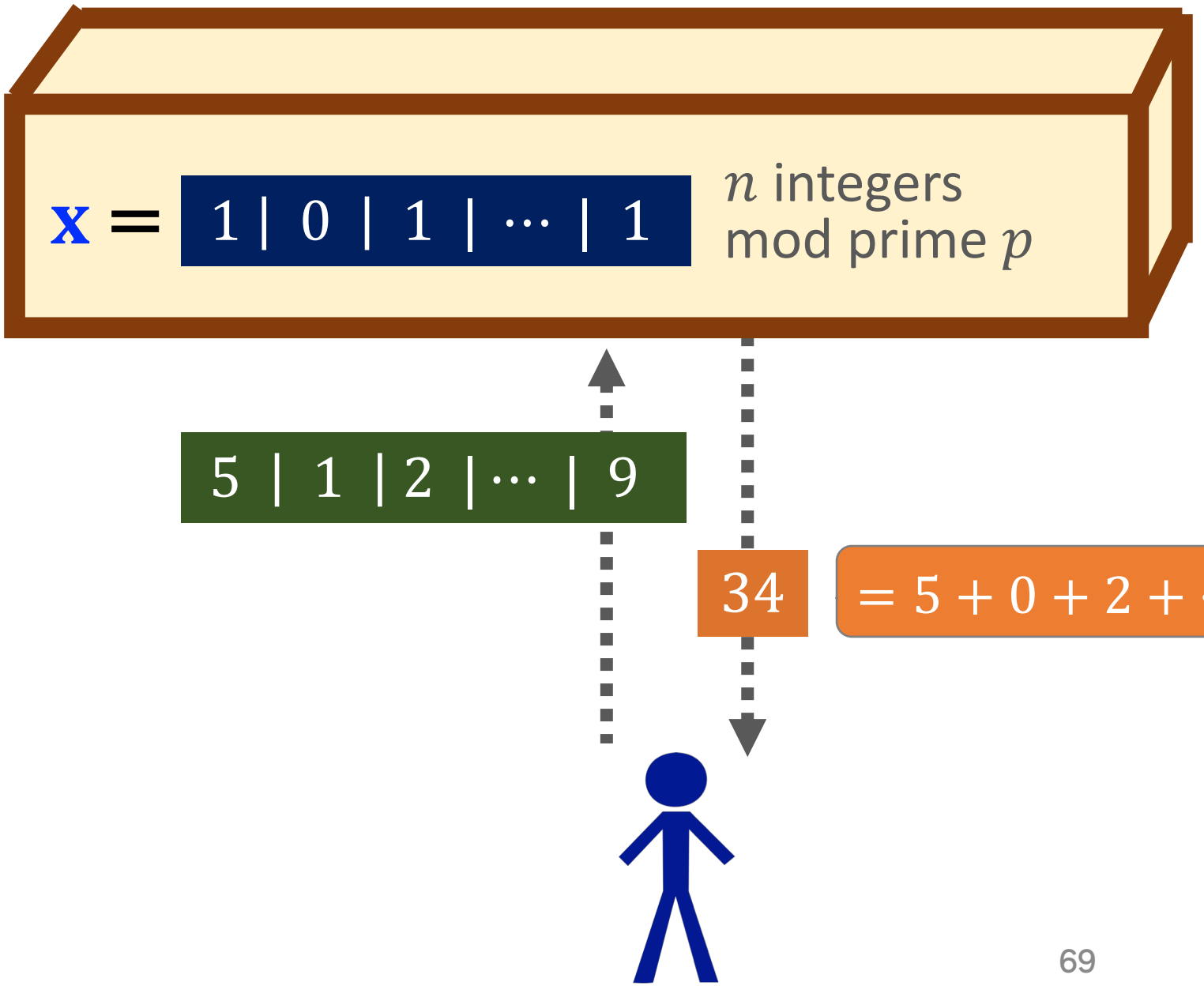
Diversion:

The Box Game

You must decide:
VALID or **INVALID**.

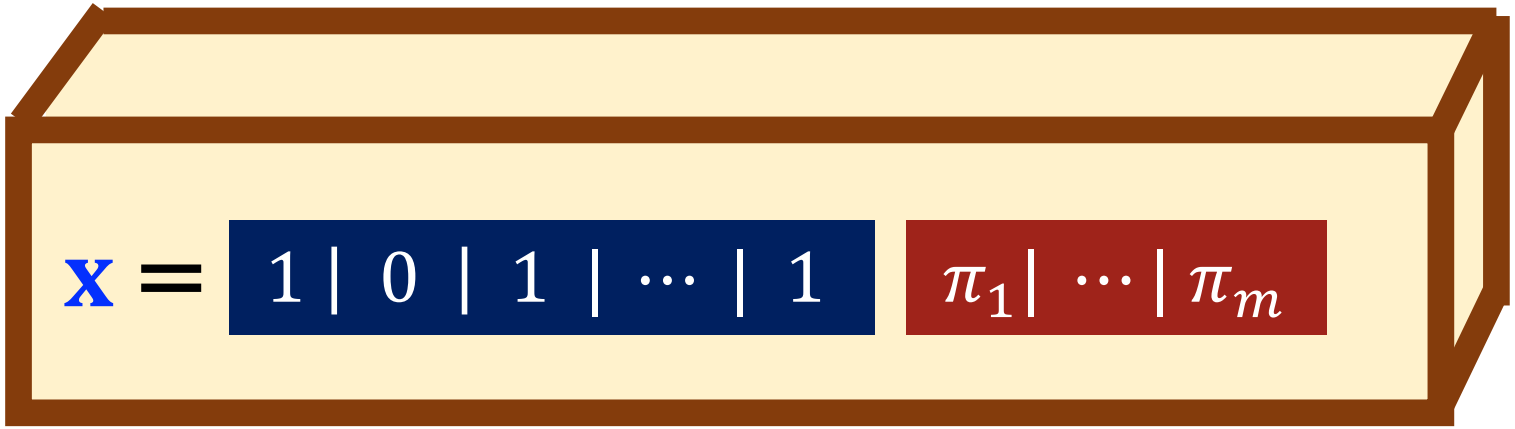
After asking **three** "linear questions" of the box.

Can you win?



Diversion:

The Box Game

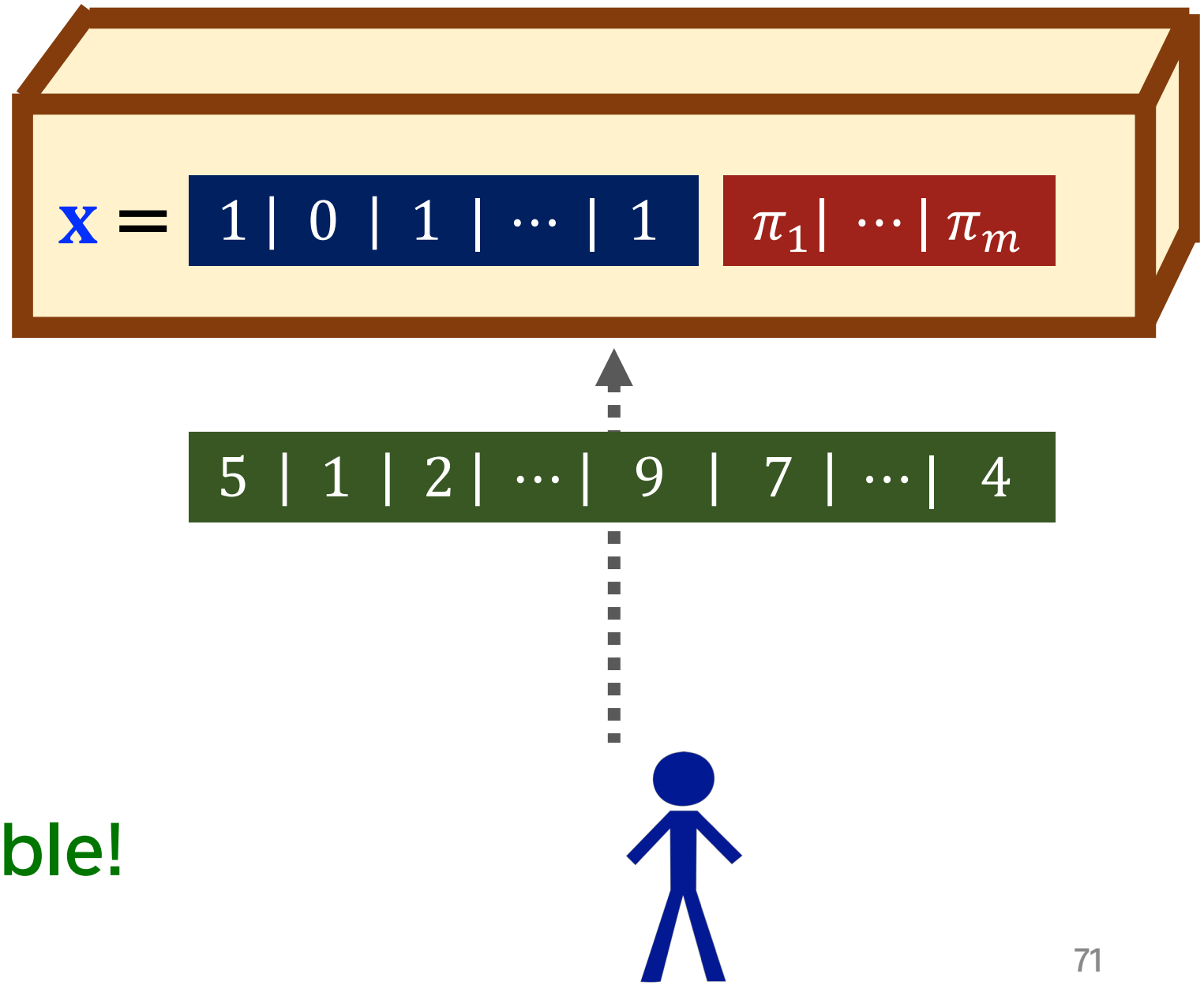


What if I can give you some help?

We show: It's possible!

Diversion:

The Box Game

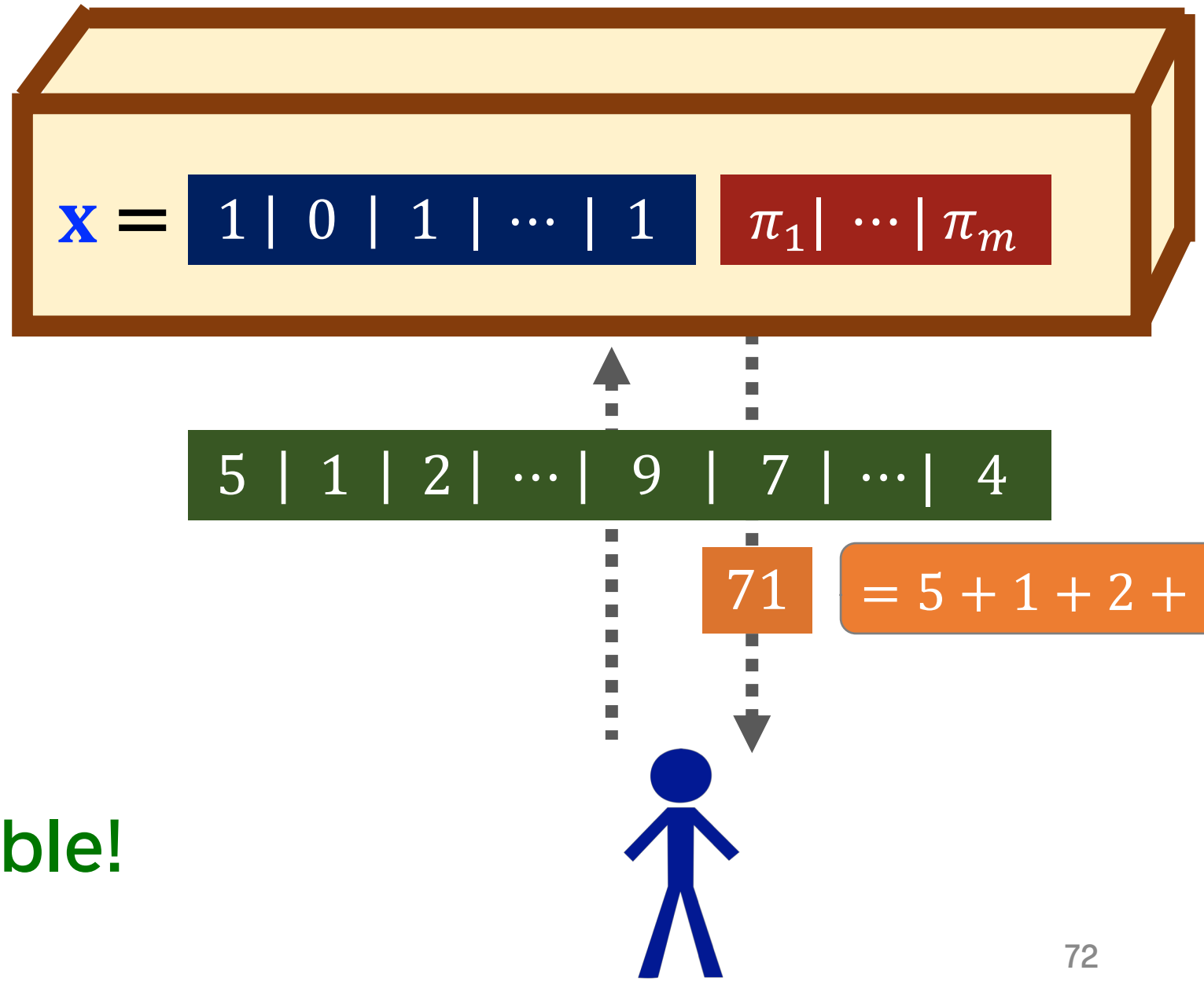


What if I can give you some help?

We show: It's possible!

Diversion:

The Box Game

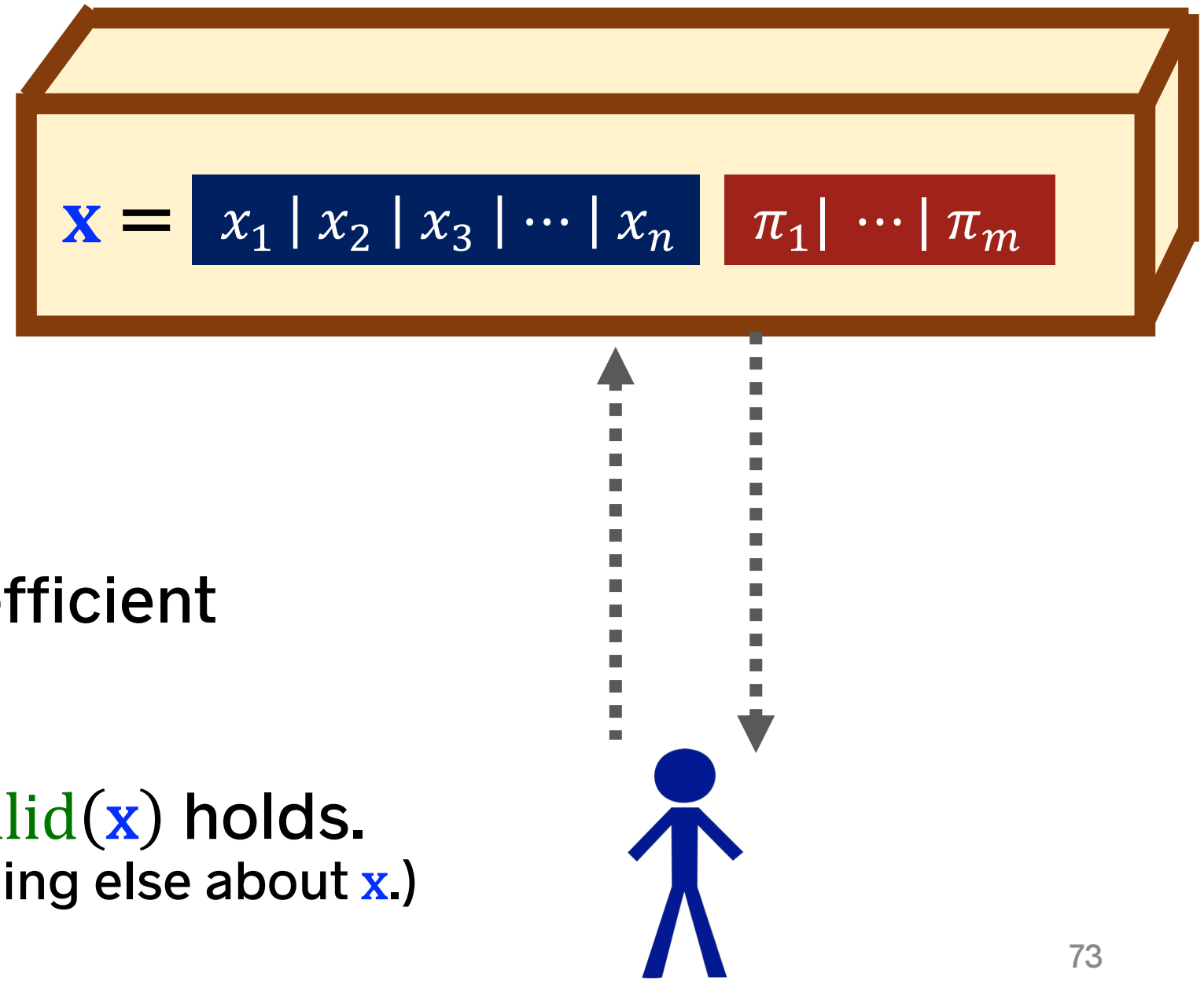


What if I can give you some help?

We show: It's possible!

Diversion:

The Box Game

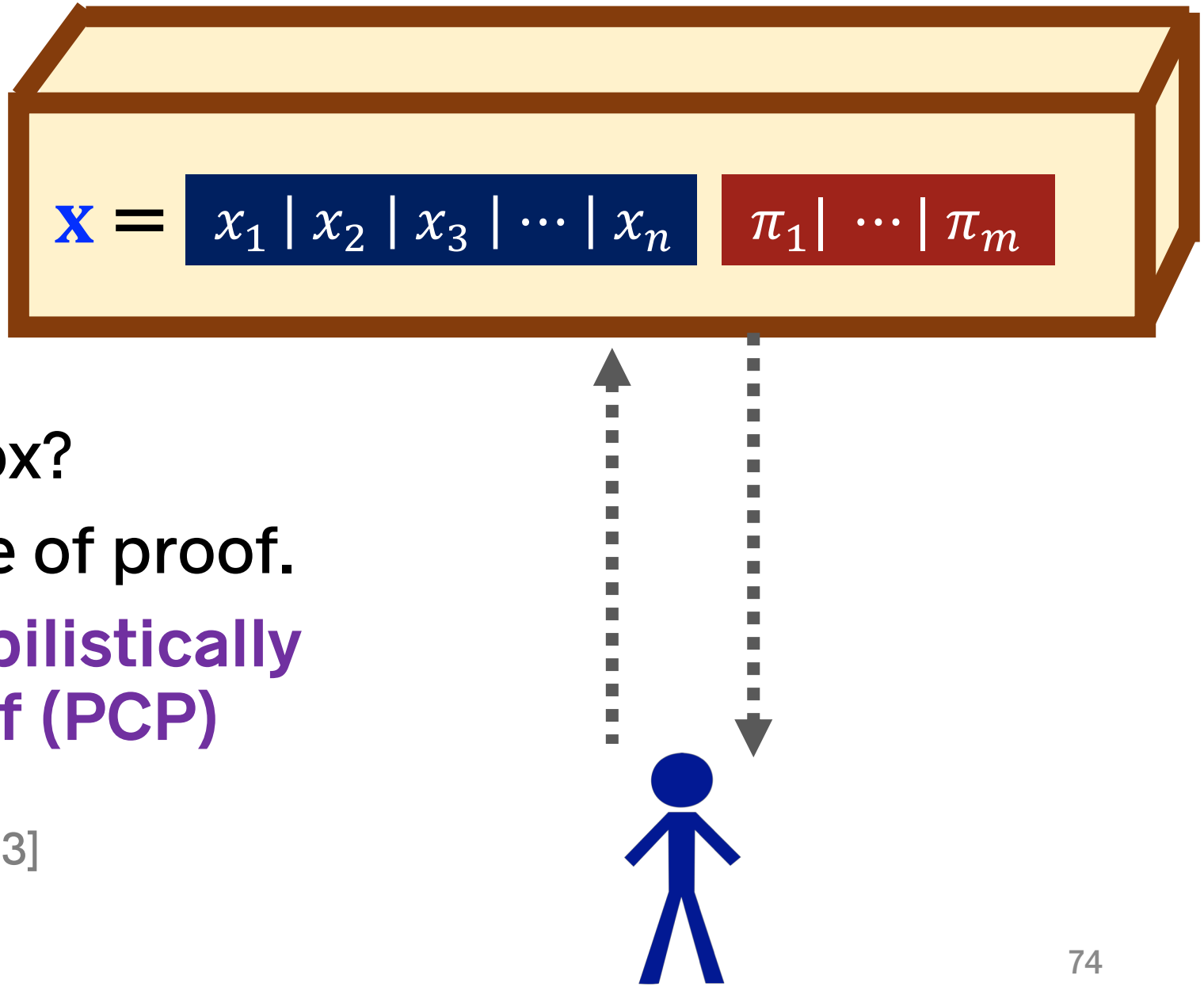


We show: For <u>any</u> efficient predicate $\mathrm{Valid}(\cdot)$...

...can check that $\mathrm{Valid}(\mathbf{x})$ holds.
(Without learning anything else about $\mathbf{x}$.)

Diversion:

The Box Game



And what is in the box?

Our work: A new type of proof.

Fully linear probabilistically checkable proof (PCP)

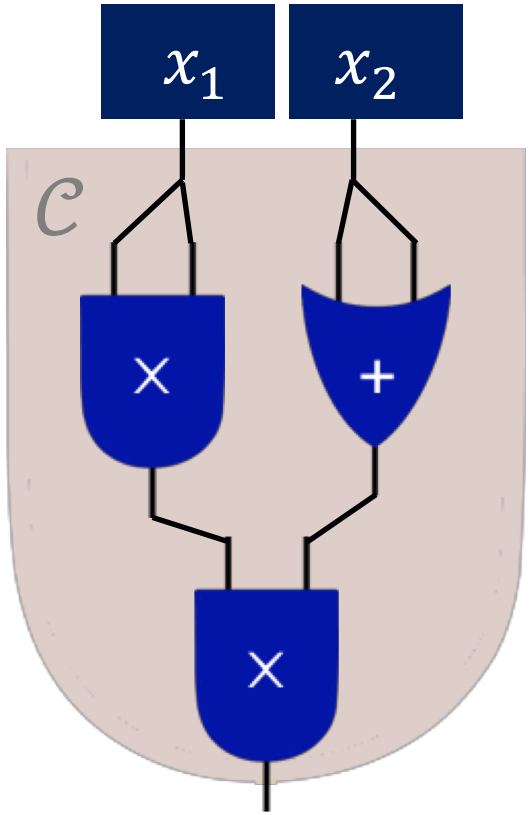
Linear PCPs: [IKO07], [BCIOP13]
PCPs: [AS92], [ALMSS92]

Can construct fully linear PCPs from plain linear PCPs

Linear PCPs: [IKO07], [GGPR13], [SBBVBPW13], [BCIOP13]

Rough idea:

- Take a circuit $\mathcal{C}$ computing the predicate **VALID**.
- Evaluate $\mathcal{C}$ on input $\mathbf{x}$.
- Proof is an error-correcting encoding of the internal wire values in $\mathcal{C}(\mathbf{x})$.
- Three linear questions are enough to check proof.



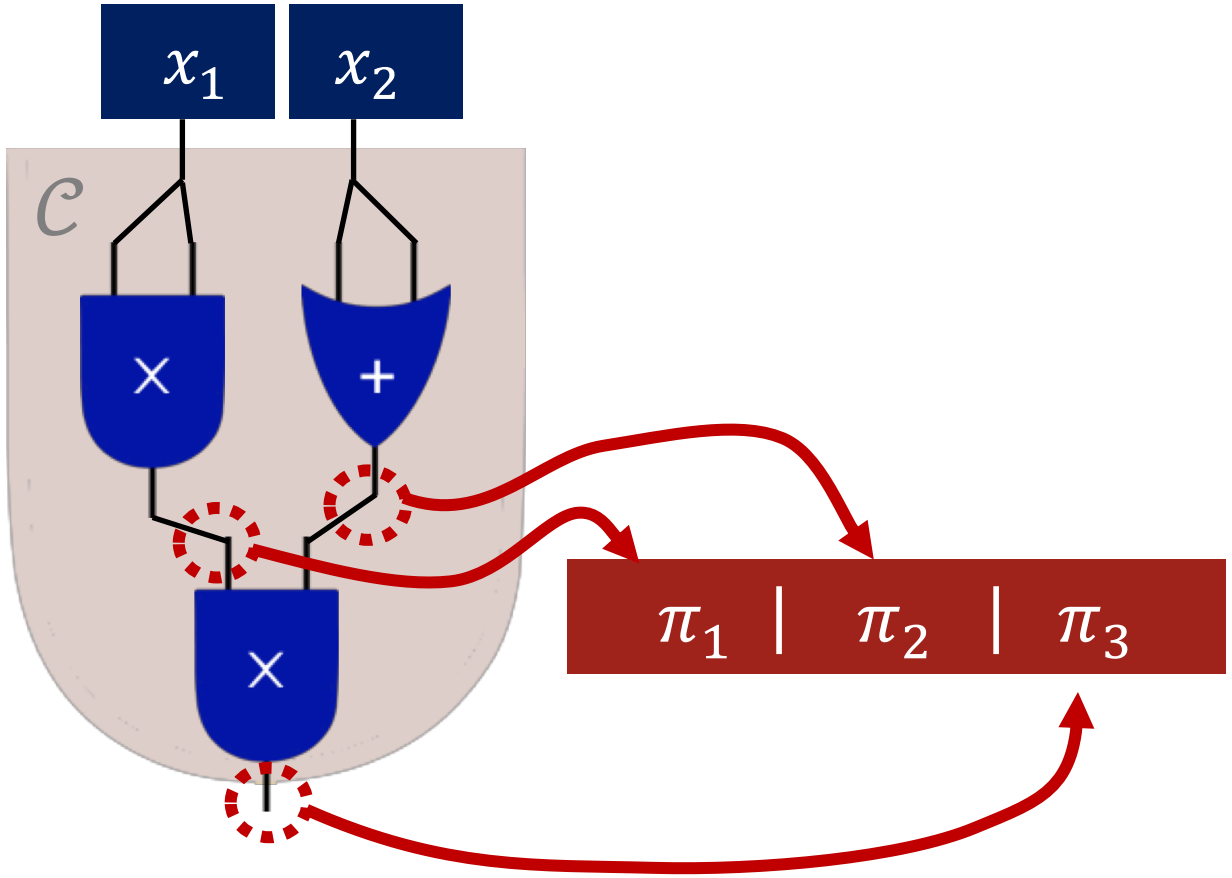
$\pi_1 \mid \pi_2 \mid \pi_3$

Can construct fully linear PCPs from plain linear PCPs

Linear PCPs: [IKO07], [GGPR13], [SBBVBPW13], [BCIOP13]

Rough idea:

- Take a circuit $\mathcal{C}$ computing the predicate **VALID**.
- Evaluate $\mathcal{C}$ on input $\mathbf{x}$.
- Proof is an error-correcting encoding of the internal wire values in $\mathcal{C}(\mathbf{x})$.
- Three linear questions are enough to check proof.

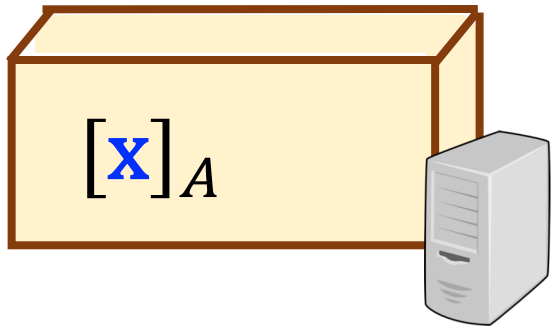


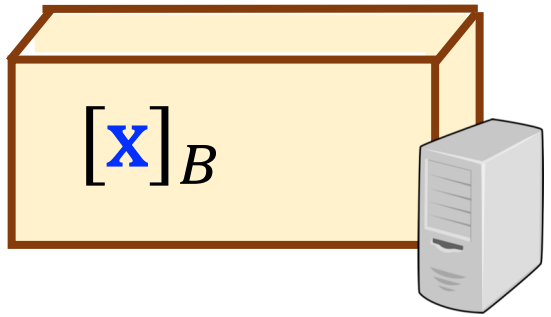
Our construction: Proof on secret-shared data from the Box Game

Servers

Client

Valid input $\mathbf{x}$.





Our construction: Proof on secret-shared data from the Box Game

Servers

Client

π

Valid input $\mathbf{x}$.

$[\mathbf{x}]_A$

$[\mathbf{x}]_B$

Our construction: Proof on secret-shared data from the Box Game

Servers

Client

$\pi = [\pi]_A + [\pi]_B$

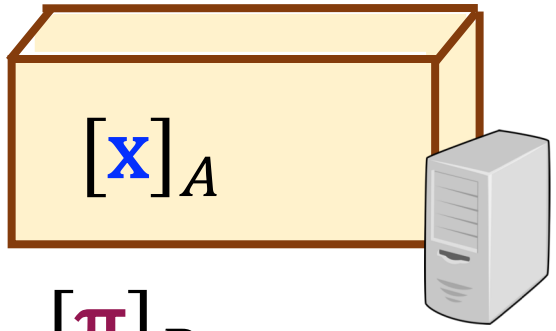
Valid input x.

$[x]_A$

$[x]_B$

Our construction: Proof on secret-shared data from the Box Game

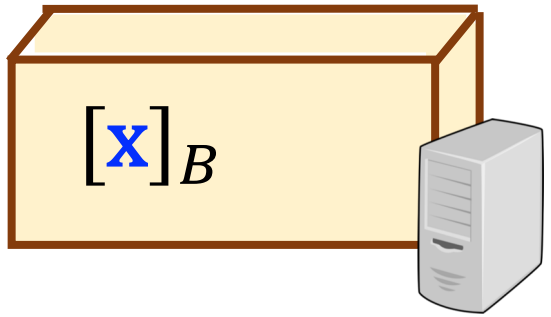
Servers



Client

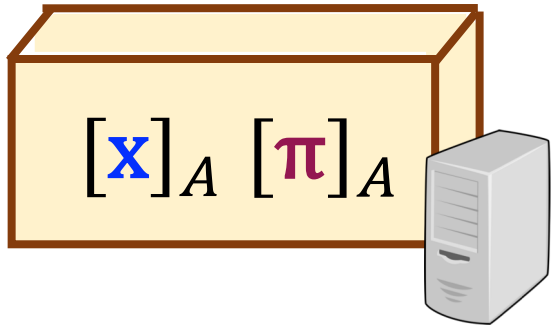
$[\pi]_A$ $[\pi]_B$

Valid input $\mathbf{x}$.



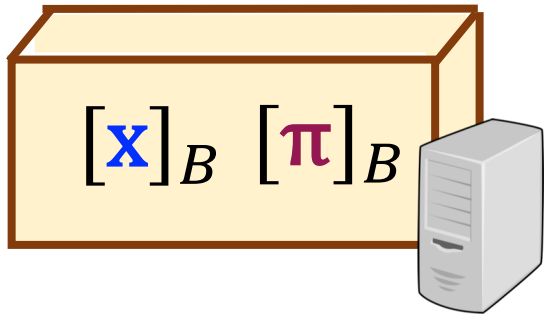
Our construction: Proof on secret-shared data from the Box Game

Servers



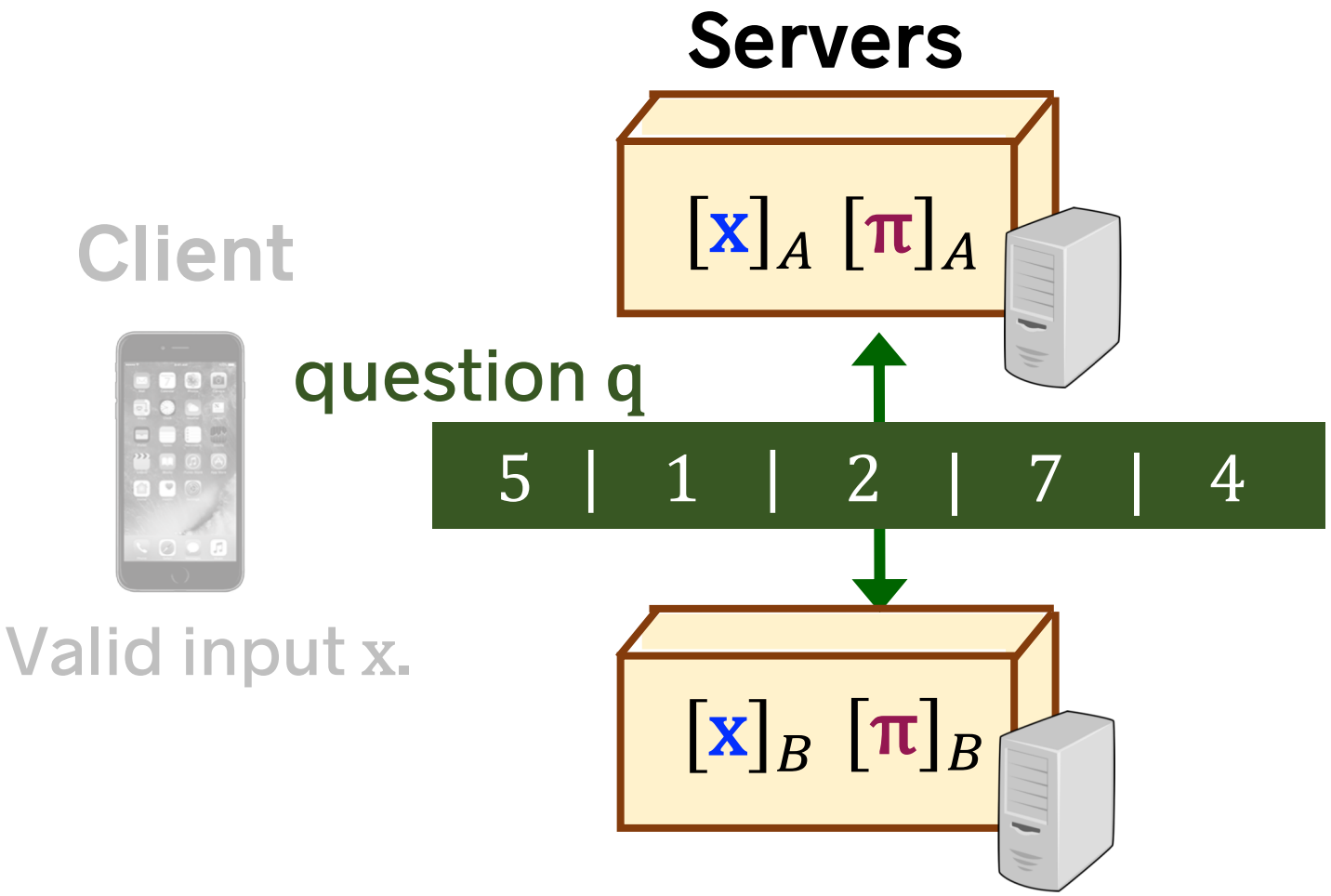
Client

Valid input $\mathbf{x}$.

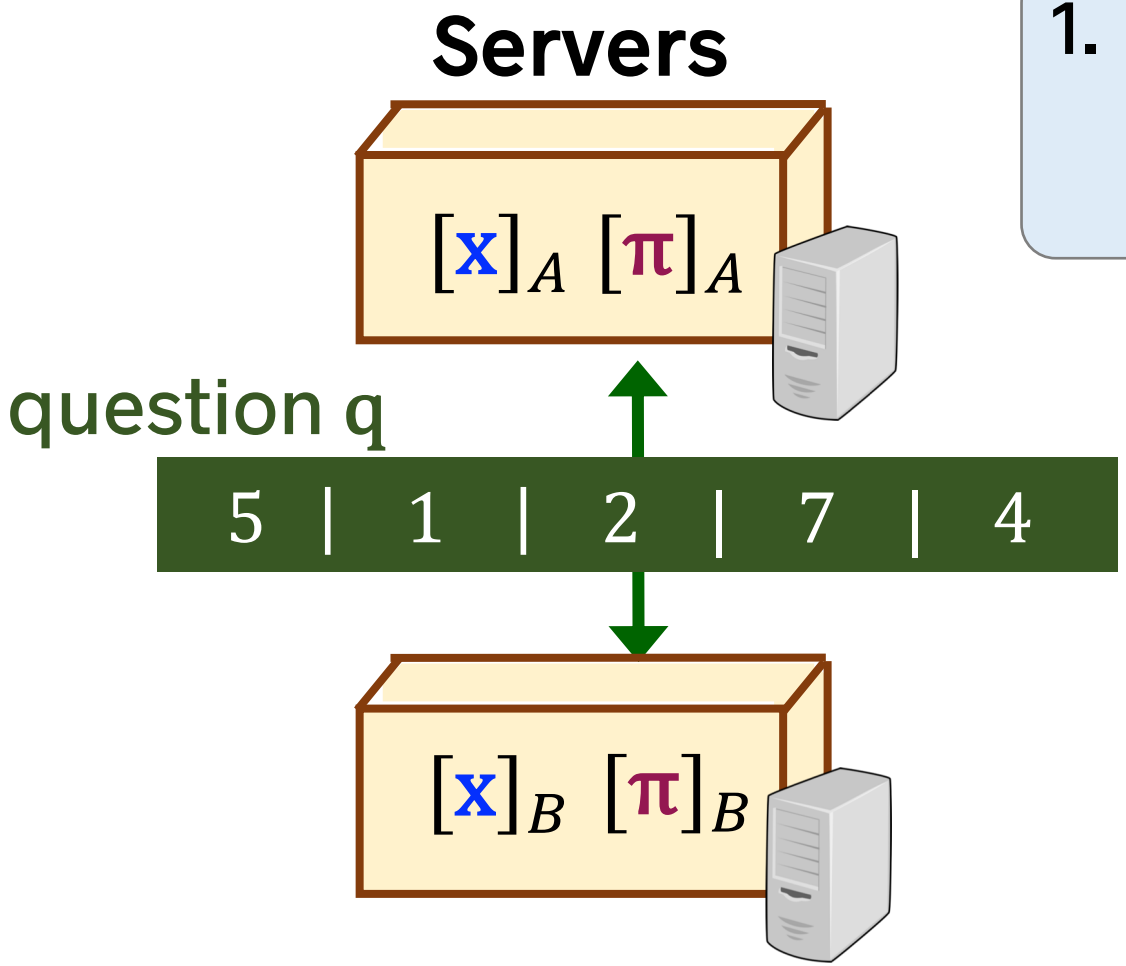


Our construction: Proof on secret-shared data from the Box Game

Servers use shared randomness to choose each question.

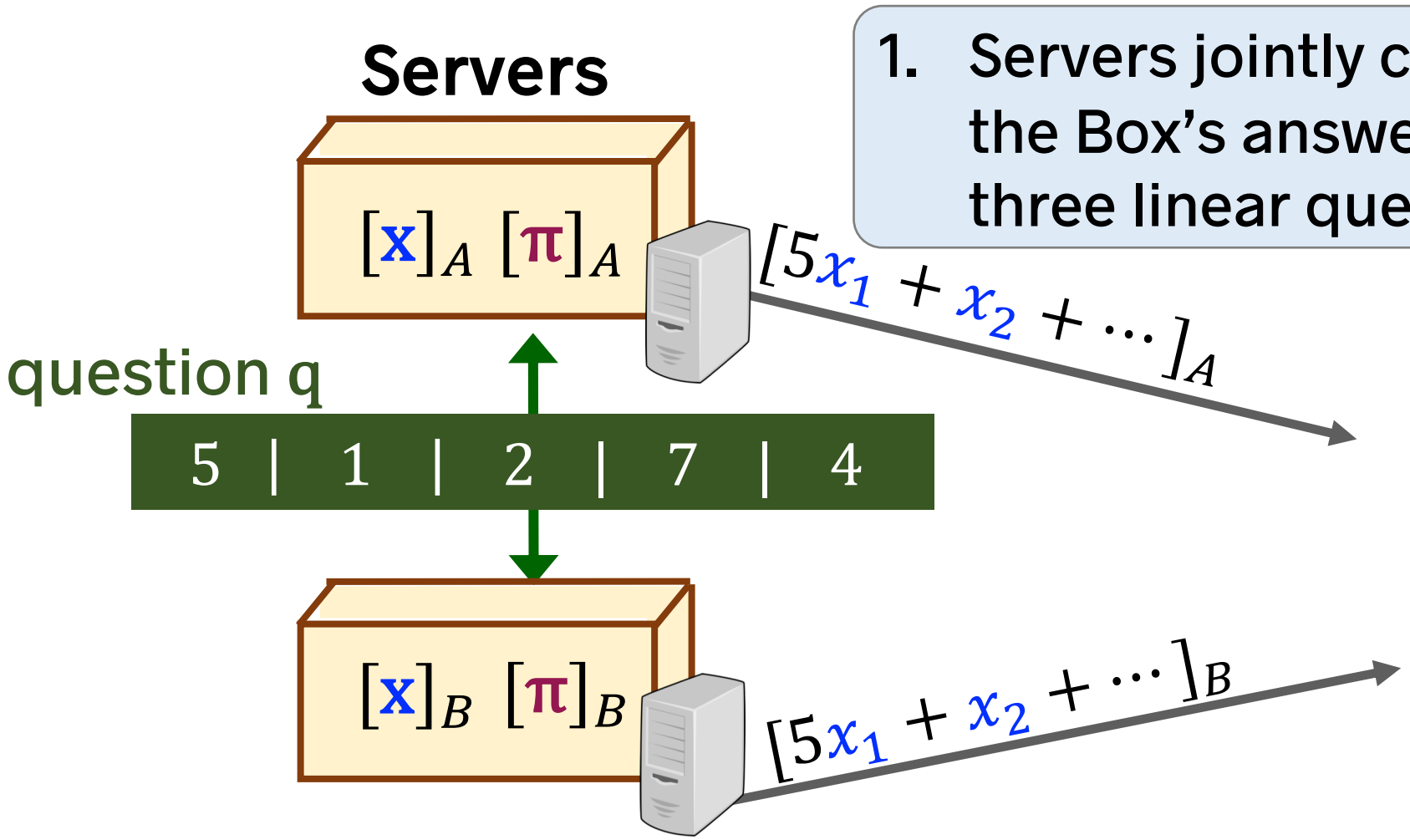


Our construction: Proof on secret-shared data from the Box Game



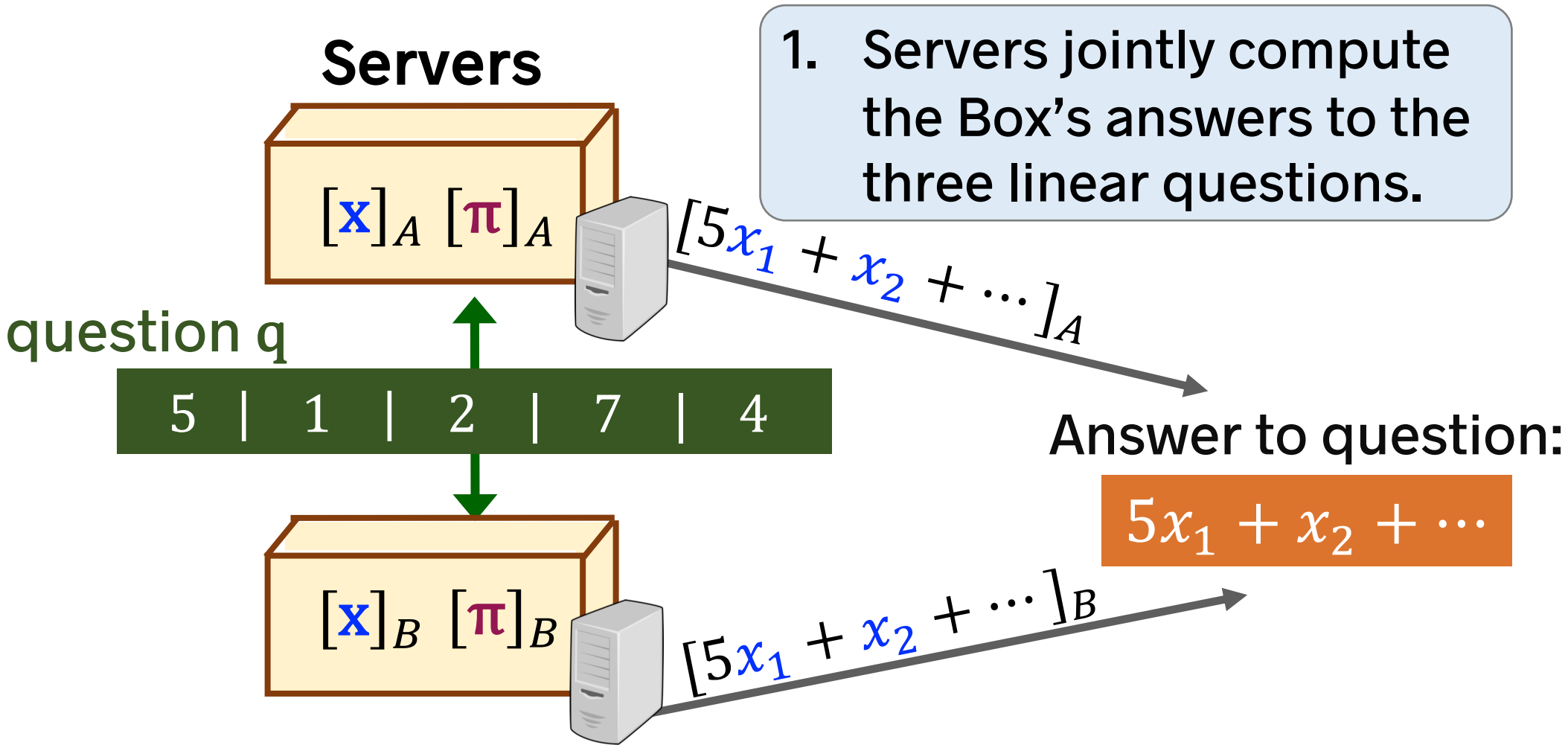
1. Servers jointly compute the Box's answers to the three linear questions.

Our construction: Proof on secret-shared data from the Box Game

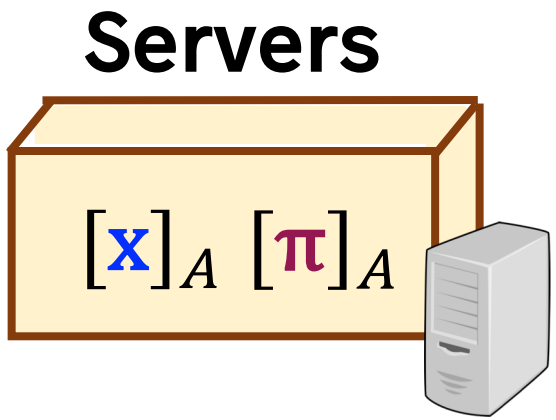


1. Servers jointly compute the Box's answers to the three linear questions.

Our construction: Proof on secret-shared data from the Box Game

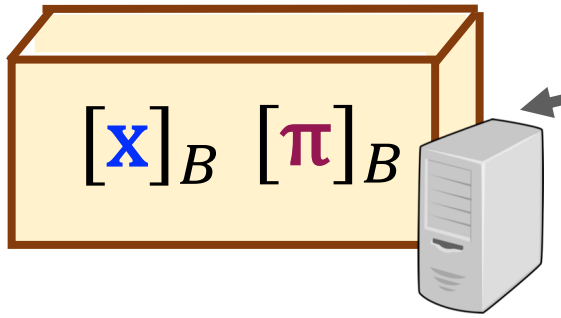


Our construction: Proof on secret-shared data from the Box Game



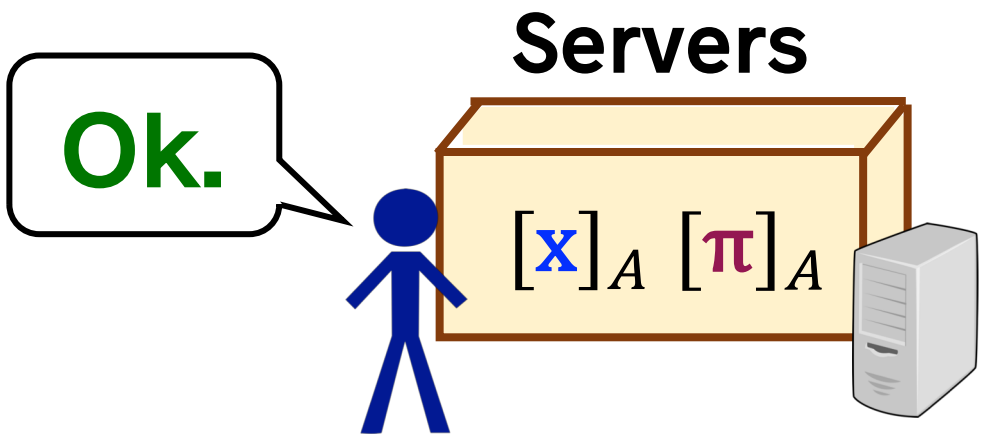
1. Servers jointly compute the Box's answers to the three linear questions.

a_1, a_2, a_3



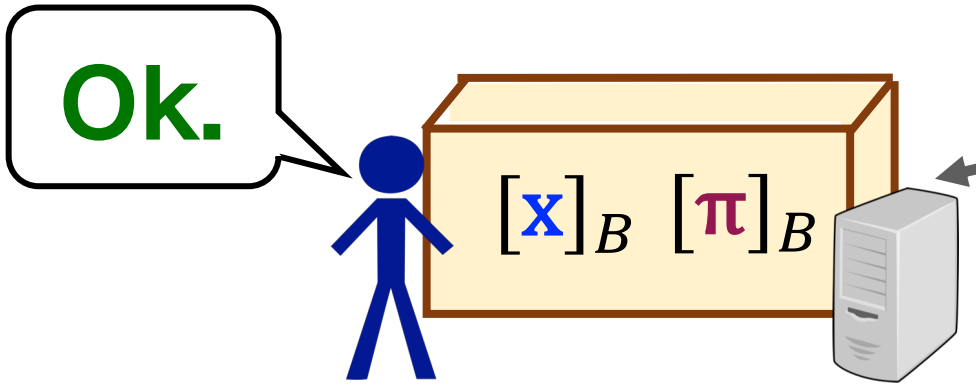
2. Servers each run the Box Game verifier on the answers.

Our construction: Proof on secret-shared data from the Box Game



1. Servers jointly compute the Box's answers to the three linear questions.

a_1, a_2, a_3



2. Servers each run the Box Game verifier on the answers.

Prio: Full system

✓ **Correctness.** Servers learn the sum of the x_is

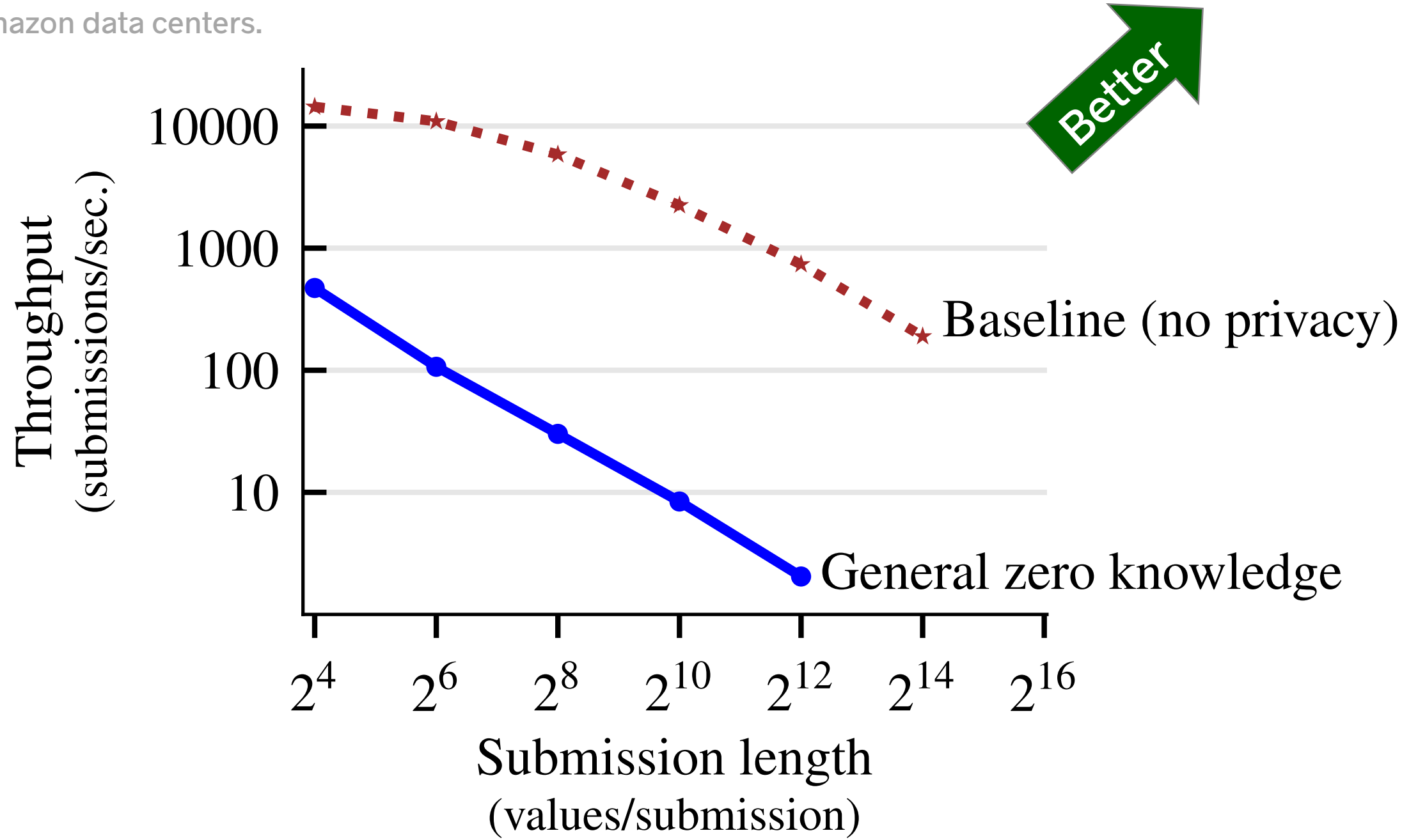
✓ **f-Privacy.** Attacker must compromise <u>all</u> servers to learn more than the sum of x_is

✓ **Efficiency.** No heavy cryptographic operations

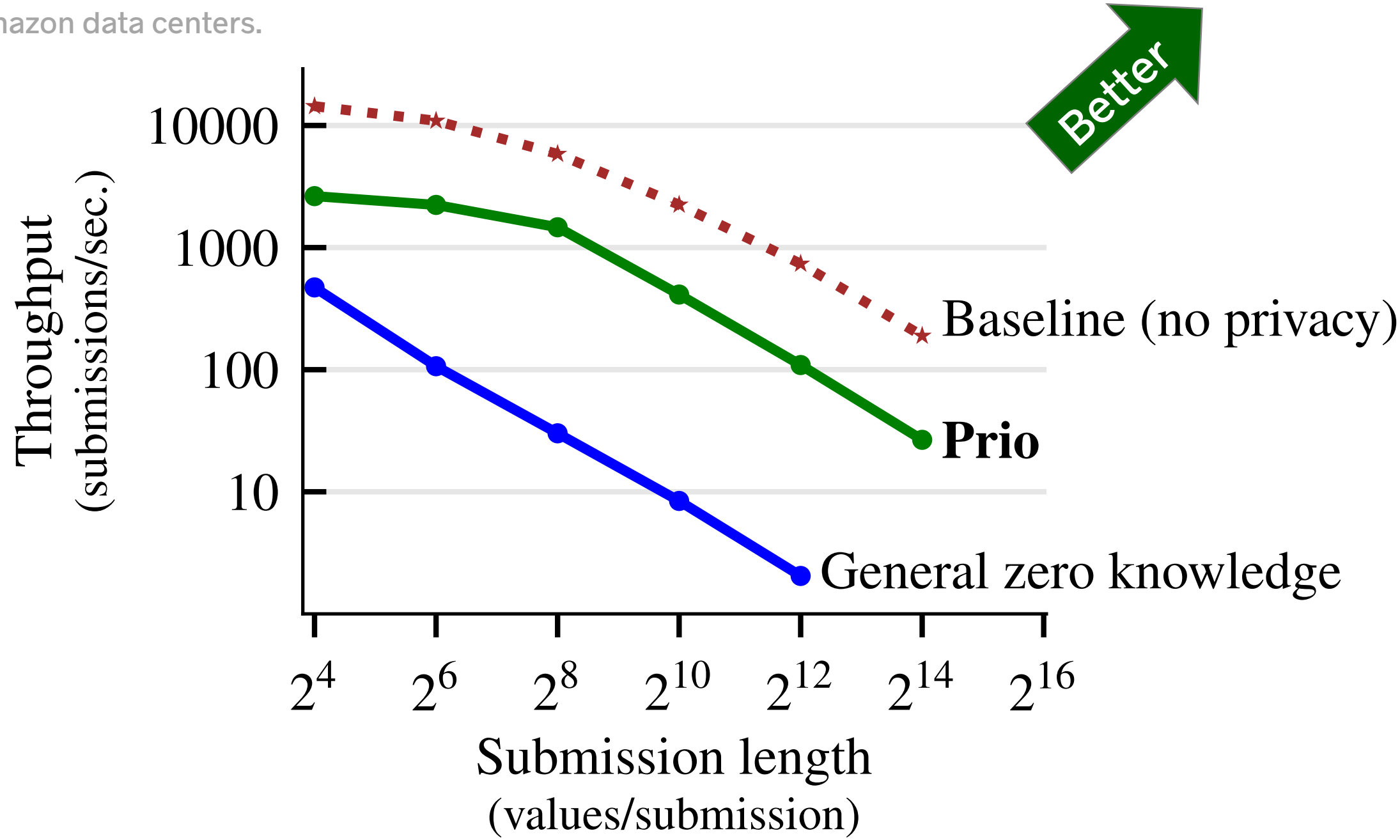
✓ **Disruption resistance.** Malicious clients have bounded influence

Using proofs on secret-shared data

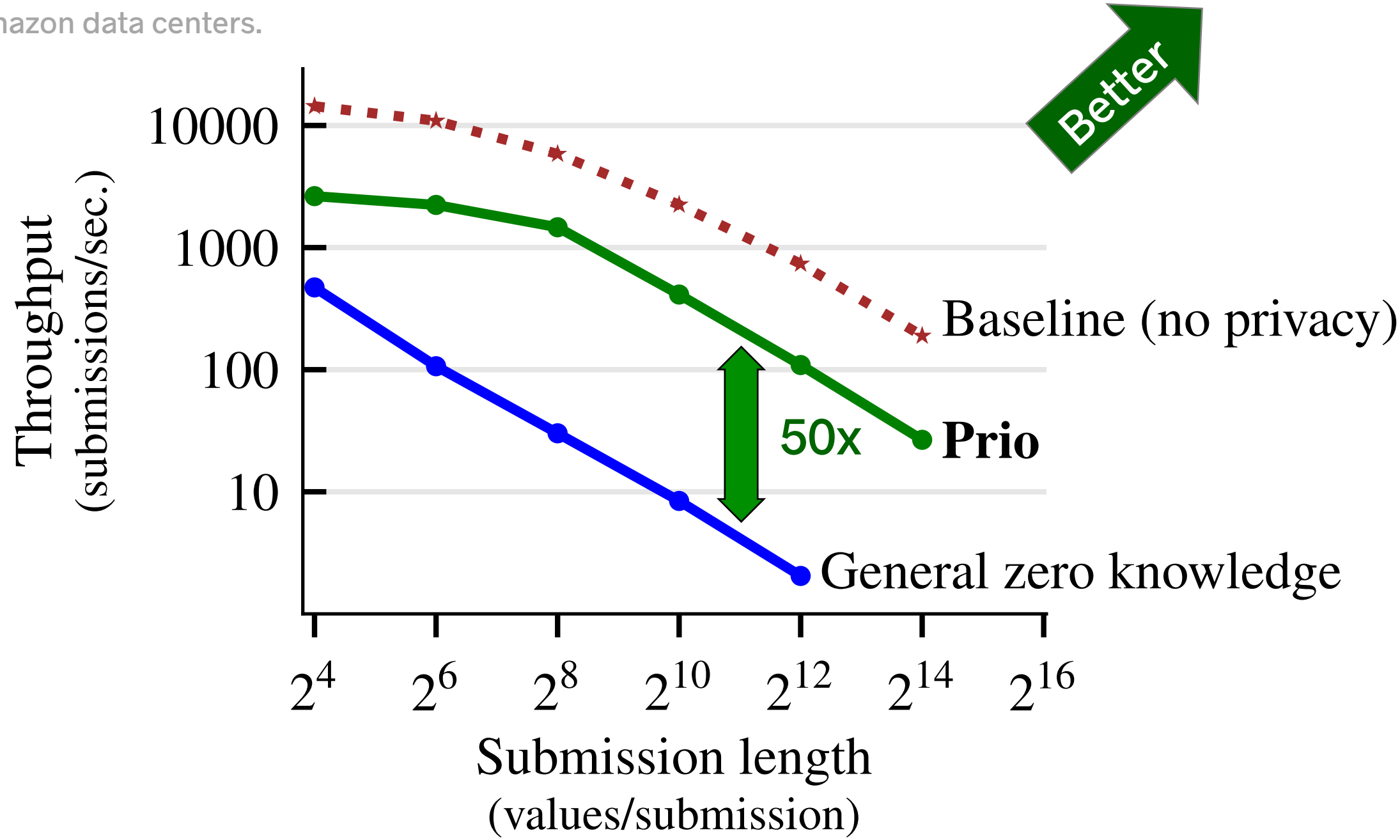
Five-server cluster in five Amazon data centers.



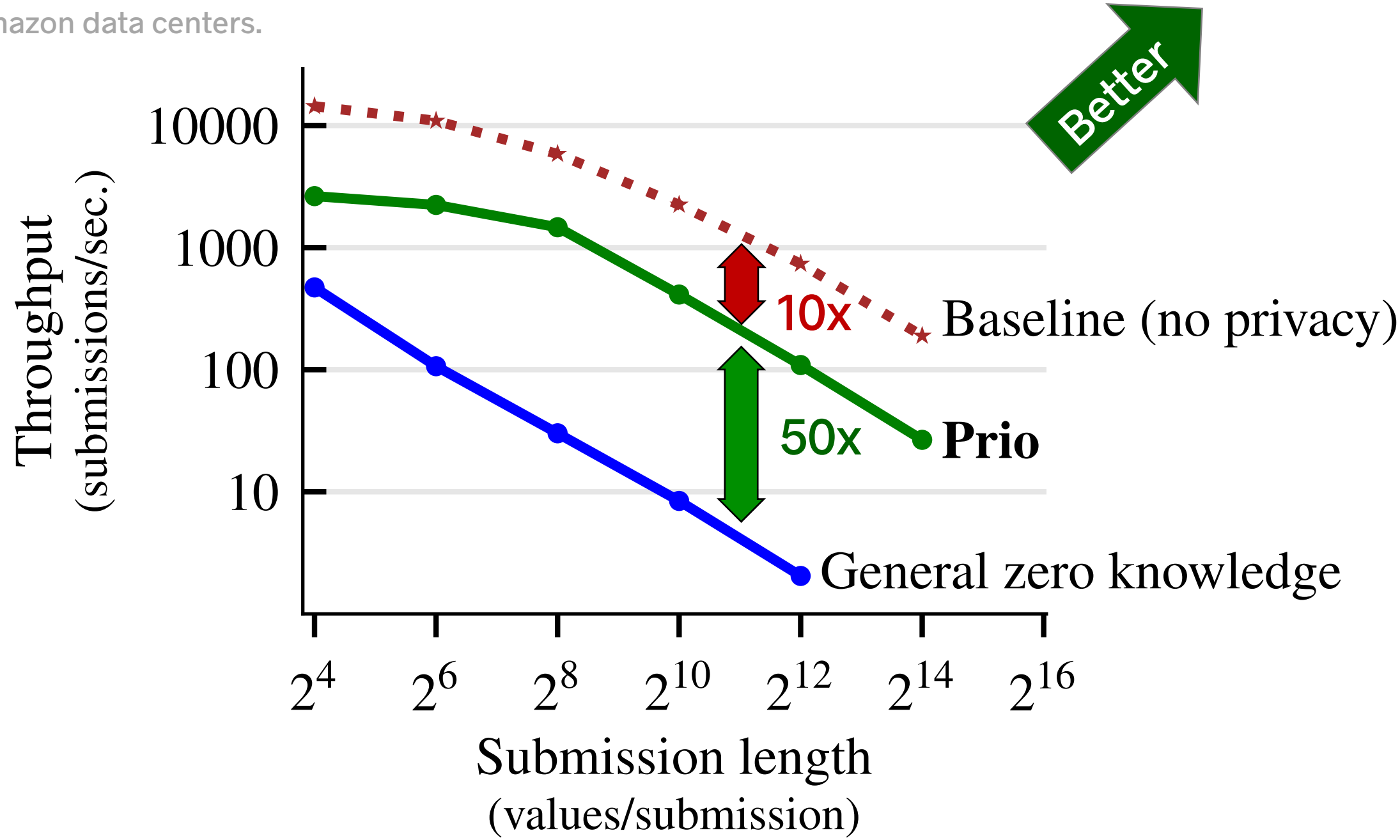
Five-server cluster in five Amazon data centers.



Five-server cluster in five Amazon data centers.



Five-server cluster in five Amazon data centers.



Firefox deployment

Uses a C library I wrote (`libprio`) that implements Prio

- `github.com/mozilla/libprio` - 3.5k LoC

Challenges

- Our code runs in the main event loop
- Interacting across three teams
- Browser idiosyncrasies

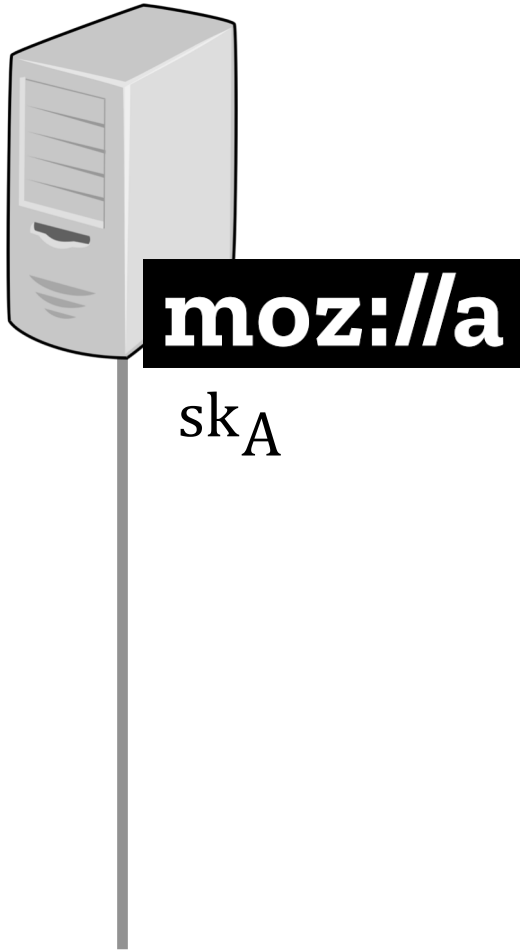
Pilot phase, 11/2018–now

- Ships to all Firefox users, enabled by default in the “Nightly” build
- Mozilla runs all servers, collects only non-sensitive information

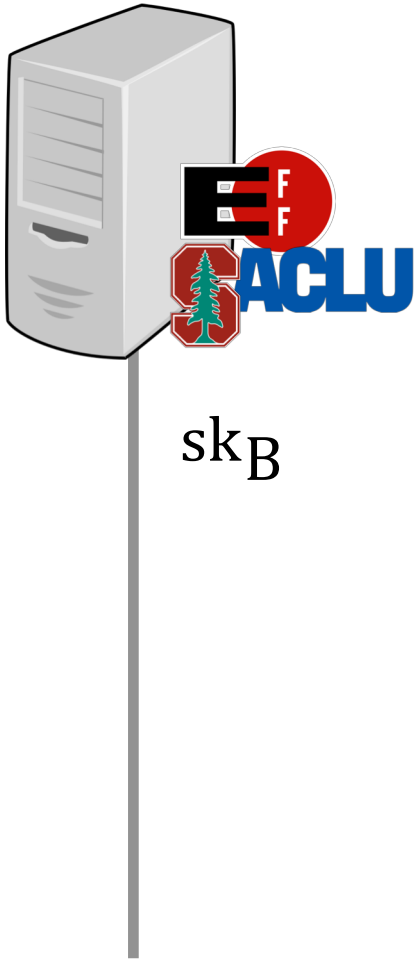
Next step: Move second server to external org.

Firefox deployment

pk_A, pk_B

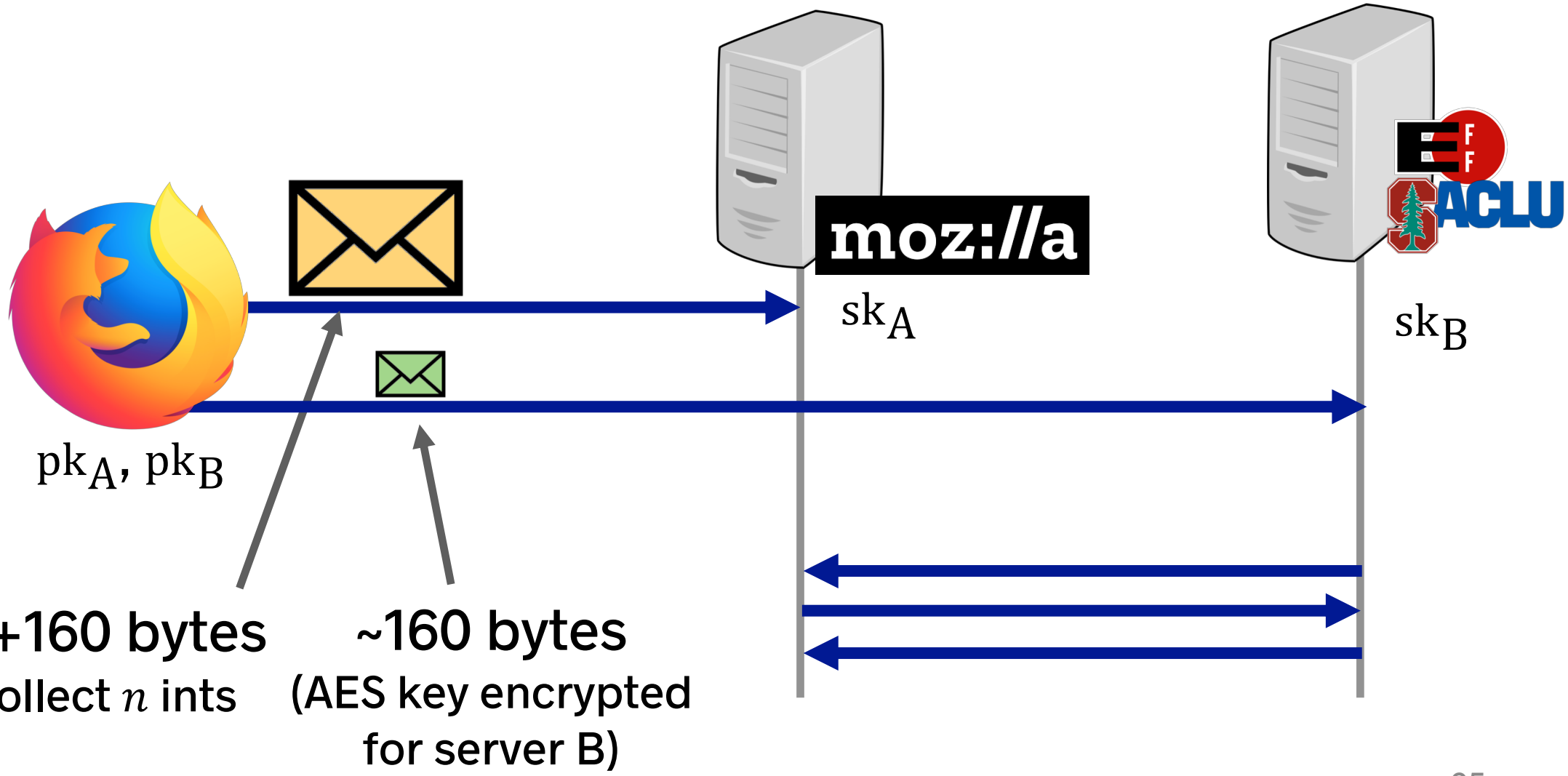


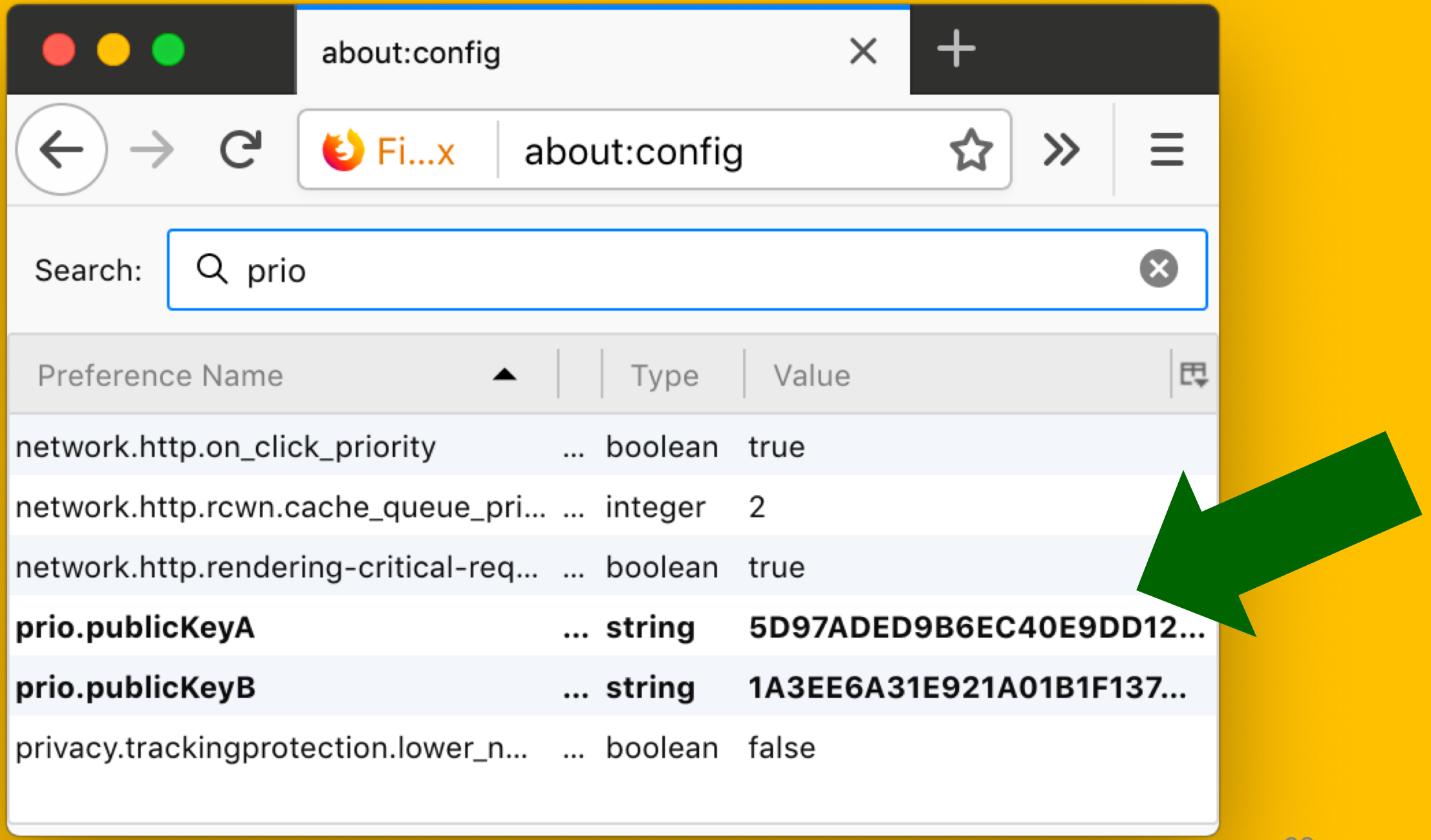
sk_A

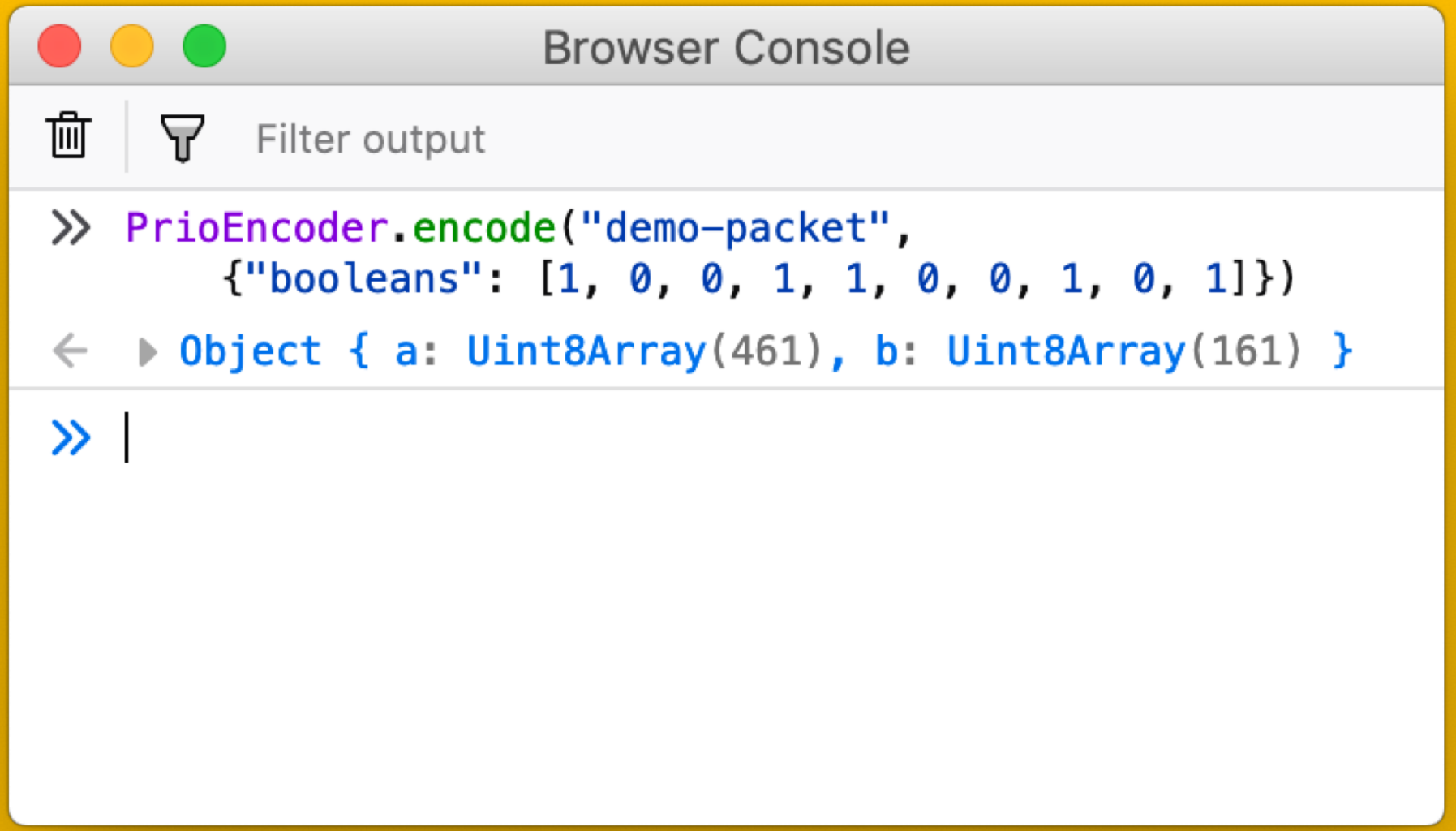


sk_B

Firefox deployment




about:config
Fi...x
about:config
Search:
prio
Preference Name
Type
Value
network.http.on_click_priority ... boolean true
network.http.rcwn.cache_queue_pri... ... integer 2
network.http.rendering-critical-req... ... boolean true
prio.publicKeyA ... string 5D97ADED9B6EC40E9DD12...
prio.publicKeyB ... string 1A3EE6A31E921A01B1F137...
privacy.trackingprotection.lower_n... ... boolean false


Browser Console
Filter output
PrioEncoder.encode("demo-packet",
{"booleans": [1, 0, 0, 1, 1, 0, 0, 1, 0, 1]})
Object { a: Uint8Array(461), b: Uint8Array(161) }

Testing Privacy-Preserving Telemetry with Prio

By Robert Helmer, Anthony Miyaguchi, Eric Rescorla

Posted on October 29, 2018 in Firefox and Privacy

Building a browser is hard; building a good browser inevitably requires gathering a lot of data to make sure that things that work in the lab work in the field. But as soon as you gather data, you have to make sure you protect user privacy. We're always looking at ways to improve the security of our data collection, and lately we've been experimenting with a really cool technique called Prio.

Prio supports a range of aggregation functions

- **Average**
- **Variance** [PBBL11]
- **Most popular** (approx.) [MDD16]
- **Min** and **max** (approx.)
- **Quality of arbitrary regression model** (R^2)
- **Least-squares regression**
- **Gradient descent step** [BIKMMPRSS17]

Prio supports a range of aggregation functions

- **Average**
- **Variance** [PBBL11]
- **Most popular** (approx.) [MDD16]
- **Min** and **max** (approx.)
- **Quality of arbitrary regression model** (R^2)
- **Least-squares regression**
- **Gradient descent step** [BIKMMPRSS17]

Encode integer x_i as (x_i^2, x_i).

$$\mathrm{Var}(X) = (\sum_i x_i^2) - (\sum_i x_i)^2$$

Prio applies more broadly...

Which PINs are most popular?

How congested is the Bay Bridge?

How much time does a user spend in each app? [DKY17]

Eliminate single points of privacy failure

Applications

Libraries

OS

Hardware

Data-collection systems (NSDI '17)
Shipping in the Firefox browser

Messaging services (SOSP '17),
(IEEE S&P '15) (USENIX Sec. '13) (OSDI '12) (CCS '10)
S&P distinguished paper, PET award

Cryptographic standards
(Eurocrypt '18) (ECCC '18)
Best young researcher paper

Password storage (Asiacrypt '16)

Hardware components (IEEE S&P '19) (CCS '13)

Eliminate single points of privacy failure

Applications

Libraries

OS

Hardware

Data-collection systems (NSDI '17)
Shipping in the Firefox browser

Messaging services (SOSP '17),
(IEEE S&P '15) (USENIX Sec. '13) (OSDI '12) (CCS '10)
S&P distinguished paper, PET award

Cryptographic standards
(Eurocrypt '18) (ECCC '18)
Best young researcher paper

Password storage (Asiacrypt '16)

Hardware components (IEEE S&P '19) (CCS '13)

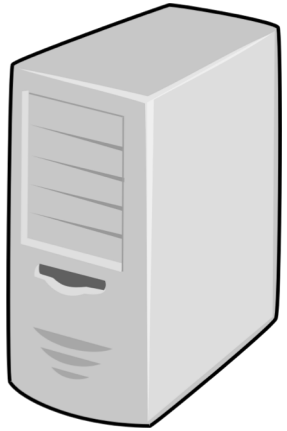
U2F hardware authentication tokens

- USB token that computes digital signatures
- To authenticate, provide password and signature
  - Protects against browser malware

Token

sk_{token}

Browser

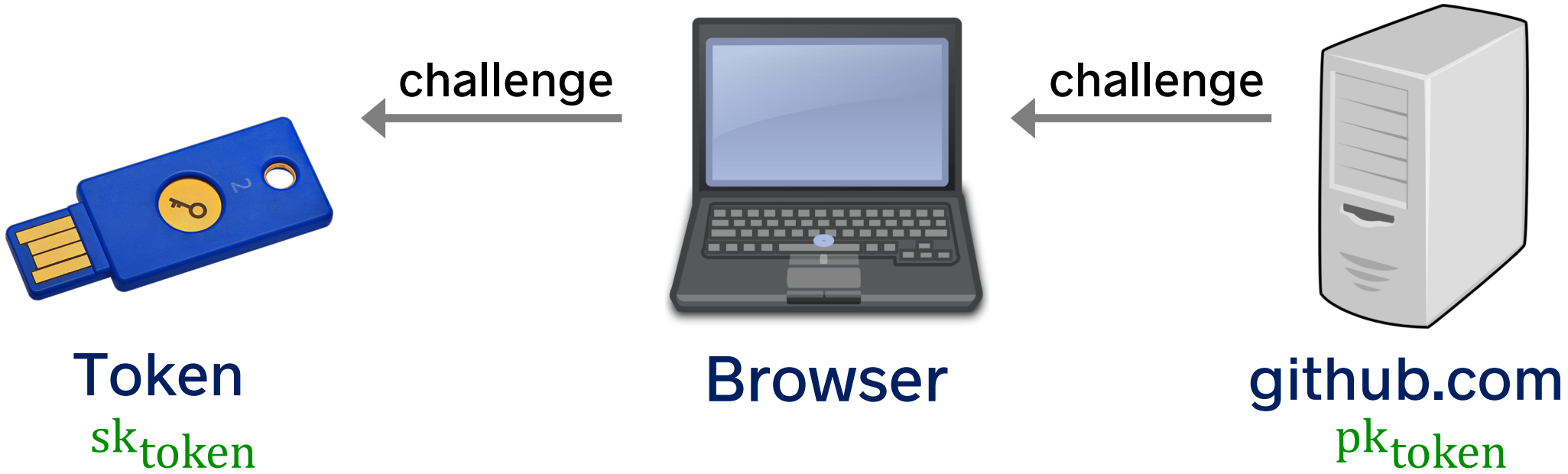


github.com

pk_{token}

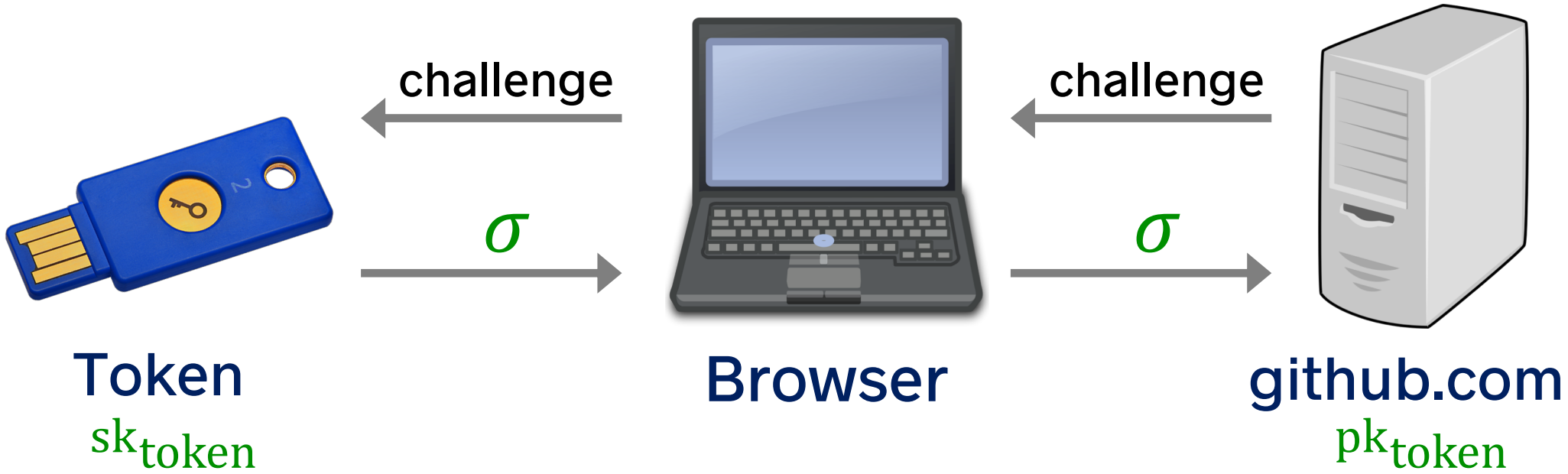
U2F hardware authentication tokens

- USB token that computes digital signatures
- To authenticate, provide password and signature
  - Protects against browser malware



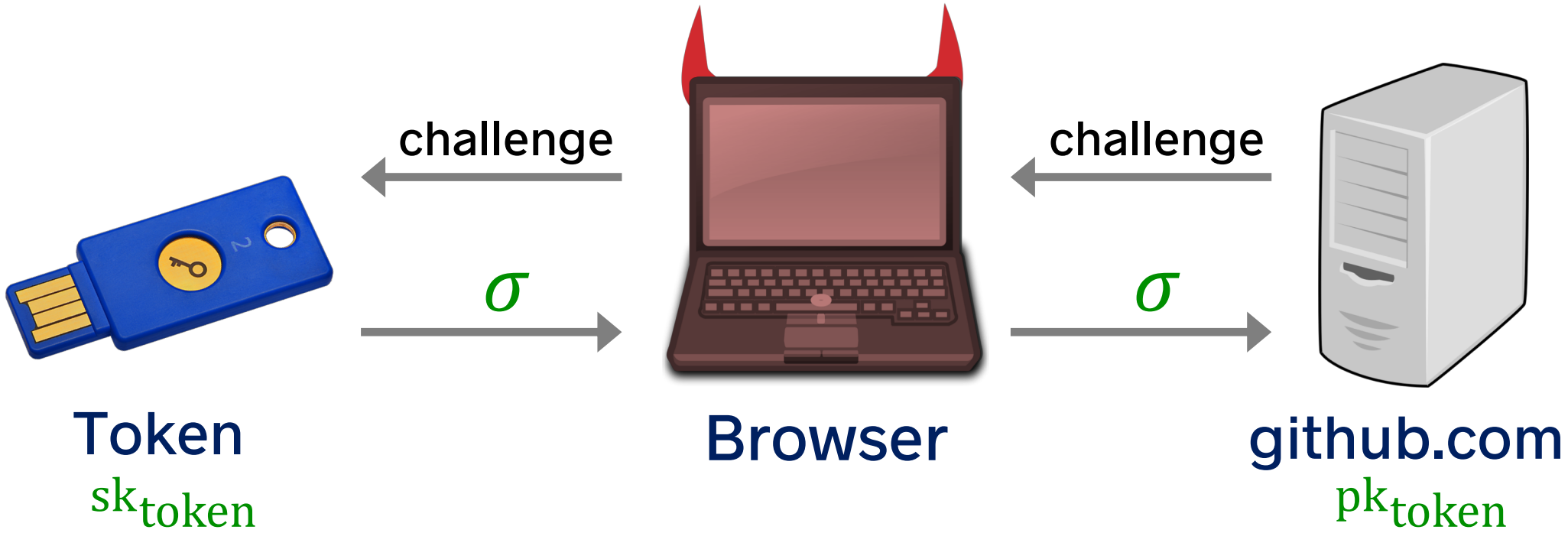
U2F hardware authentication tokens

- USB token that computes digital signatures
- To authenticate, provide password and signature
  - Protects against browser malware



U2F hardware authentication tokens

- USB token that computes digital signatures
- To authenticate, provide password and signature
  - Protects against browser malware



KrebsonSecurity
In-depth security news and investigation

23 JUL 18 Google: Security Keys Neutralized Employee Phishing

Google has not had any of its 85,000+ employees successfully phished on their work-related accounts since early 2017, when it began requiring all employees to use physical Security Keys in place of passwords and one-time codes, the company told KrebsOnSecurity.

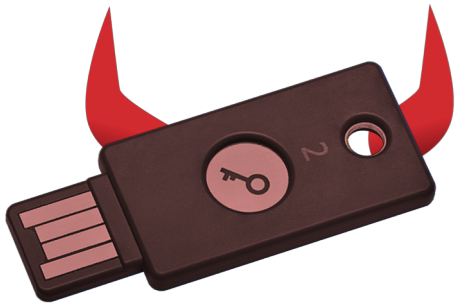
Security Keys are inexpensive USB-based devices that offer an alternative approach to two-factor authentication (2FA), which requires the user to log in to a Web site using something they know (the password) and something they have (e.g., a mobile device).

A Google spokesperson said Security Keys now form the basis of all account access at Google.

Opaque crypto hardware is a threat

[S84], [D88], [YY97], [ESJRZ14], [BPR14], [SWSHE15], [YHDAS16], ...

- Faulty token can use weak keys or weak randomness
  ⇒ Inadvertently leak your secret keys to evil.com
- Manufacturer is a single point of failure...

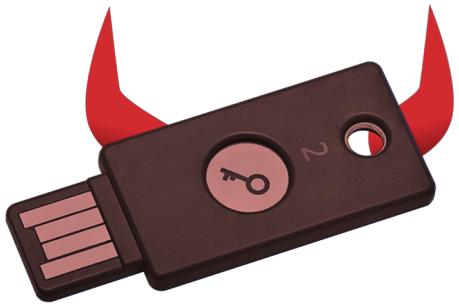


Token

Opaque crypto hardware is a threat

[S84], [D88], [YY97], [ESJRZ14], [BPR14], [SWSHE15], [YHDAS16], ...

- Faulty token can use weak keys or weak randomness
  ⇒ Inadvertently leak your secret keys to evil.com
- Manufacturer is a single point of failure...



Token

Flaw Found in an Online Encryption Method

By JOHN MARKOFF FEB. 14, 2012

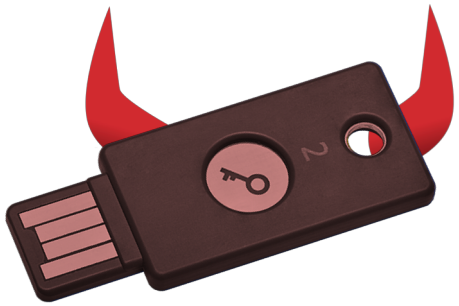
SAN FRANCISCO — A team of European and American mathematicians and cryptographers have discovered an unexpected weakness in the encryption system widely used worldwide for online shopping, banking, e-mail and other Internet services intended to remain private and secure.

[HDWH12], [LHABKW12]

Opaque crypto hardware is a threat

[S84], [D88], [YY97], [ESJRZ14], [BPR14], [SWSHE15], [YHDAS16], ...

- Faulty token can use weak keys or weak randomness
  ⇒ Inadvertently leak your secret keys to evil.com
- Manufacturer is a single point of failure...



Token

Flaw Found in an Online Encryption Method

By JOHN MARKOFF FEB. 14, 2012

SAN FRANCISCO — A team of European and American mathematicians and cryptographers have discovered an unexpected weakness in the encryption system widely used worldwide for online shopping, banking, e-mail and other Internet services intended to remain private and secure.

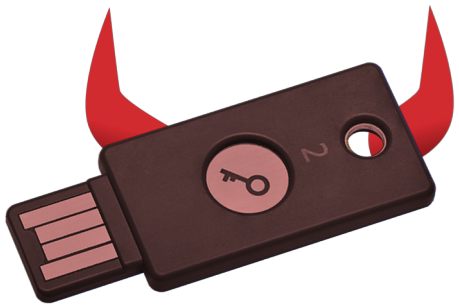
[HDWH12], [LHABKW12]

Protecting against randomness failures
C-G, Mu, Boneh, Ford (CCS 2013)

Opaque crypto hardware is a threat

[S84], [D88], [YY97], [ESJRZ14], [BPR14], [SWSHE15], [YHDAS16], ...

- Faulty token can use weak keys or weak randomness
  ⇒ Inadvertently leak your secret keys to evil.com
- Manufacturer is a single point of failure...



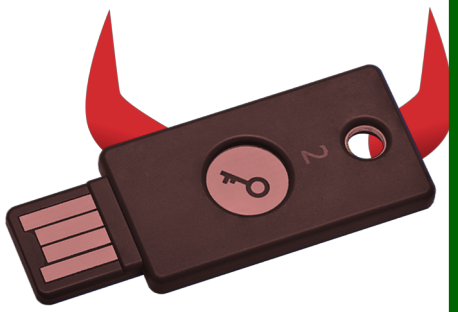
Token

[NSSKM17]

Opaque crypto hardware is a threat

[S84], [D88], [YY97], [ESJRZ14], [BPR14], [SWSHE15], [YHDAS16], ...

- Faulty token can use weak keys or weak randomness
  ⇒ Inadvertently leak your secret keys to evil.com
- Manufacturer is a single point of failure...



Token

→ A chance to use cryptographic ← hardware the right way.

[NSSKM17]

True2F: Protection against token faults

Dauterman, C-G, Boneh, Mazières, Rizzo (IEEE S&P 2019)

If token is correct:

Malicious browser learns nothing about the token's secret keys

⇒ Protects against browser compromise

If browser is correct:

Malicious website (evil.com) cannot distinguish the real token from an ideal token

⇒ Protects against faulty token

True2F: Protection against token faults

Dauterman, C-G, Boneh, Mazières, Rizzo (IEEE S&P 2019)

Idea: Split trust between browser and token.

Use new two-party protocols to implement each token operation.

[MS15, DMS16]

True2F: Design constraints

1. **Backwards-compatibility** with U2F-enabled sites

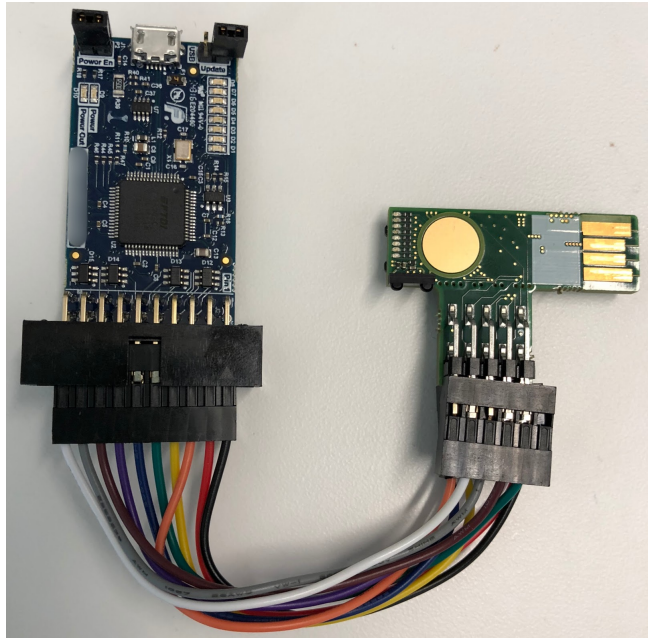
   Idea: Design new schemes for two-party key-generation and signing

2. **No changes** to U2F hardware (24 MHz chip, 512 KB flash)

   Idea: Token offloads compute and storage to browser, while checking browser's work

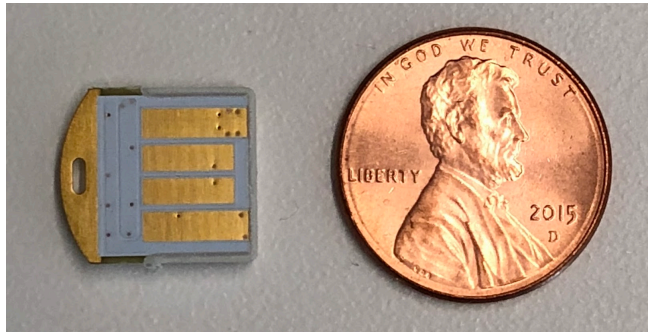
Evaluation

On Google's standard U2F hardware



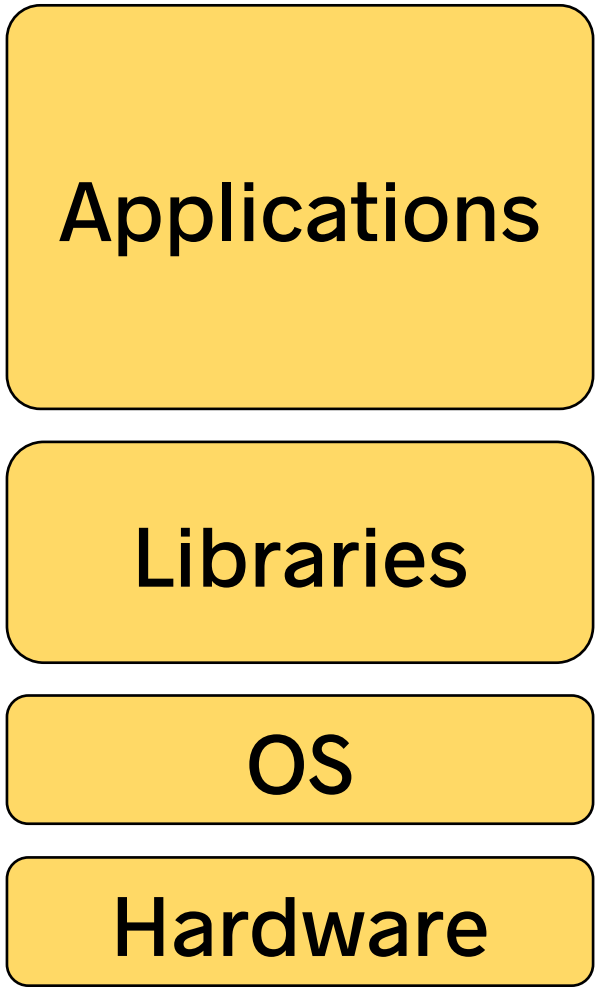
Authentication time

Naïve implementation	446 ms
True2F (optimized)	57 ms
U2F	23 ms



Ongoing: Effort to standardize True2F via the U2F standards body (FIDO alliance)

Eliminate single points of privacy failure



Data-collection systems (NSDI '17)
Shipping in the Firefox browser

Messaging services (SOSP '17),
(IEEE S&P '15) (USENIX Sec. '13) (OSDI '12) (CCS '10)
S&P distinguished paper, PET award

Cryptographic standards
(Eurocrypt '18) (ECCC '18)
Best young researcher paper

Password storage (Asiacrypt '16)

Hardware components (IEEE S&P '19) (CCS '13)

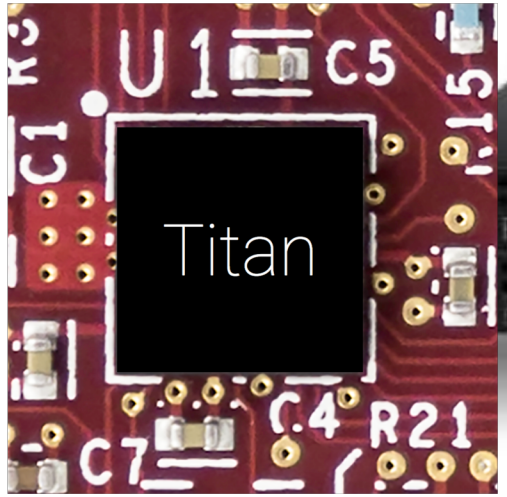
Future work

Applications

Libraries

OS

Hardware



Protecting against crypto hardware bugs

In the data center (HSMs), in the phone, ...

Future work

Applications

Libraries

OS

Hardware

Metadata-hiding messaging
at Internet scale

Future work

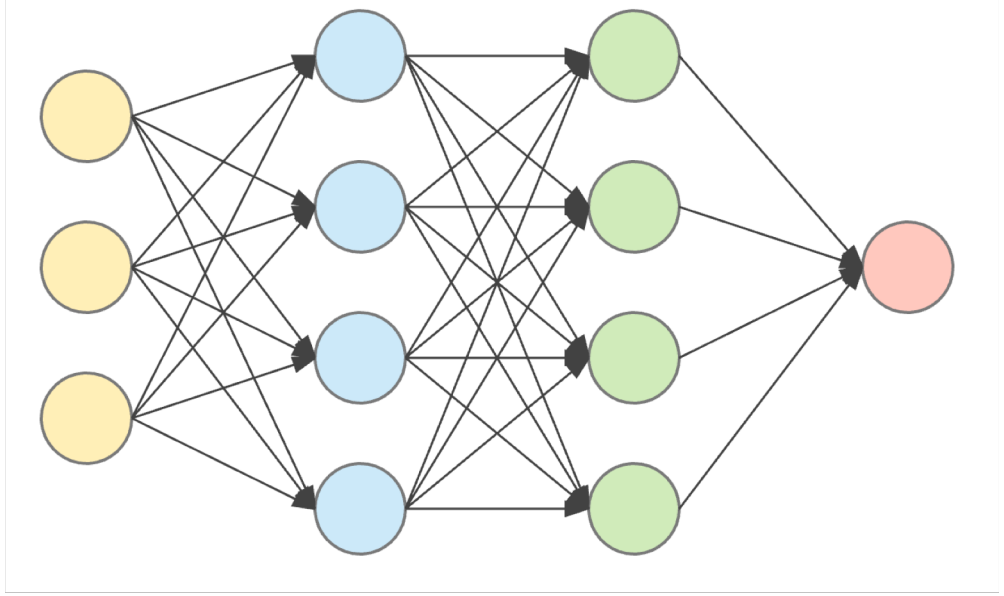
Applications

Libraries

OS

Hardware

Training sophisticated ML models
on private data



Conclusion

To use a computer system today is to surrender control.

- Of our most sensitive data
- Of our hardware
- Of our autonomy

Why do we accept this?

We have no other option.

Our systems should put the user back in charge.

It is feasible, e.g., by splitting trust.

We should expect more and get more.

Conclusion

To use a computer system today is to surrender control.

- Of our most sensitive data
- Of our hardware
- Of our autonomy

Why do we accept this?

We have no other option.

Our systems should put the user back in charge.

It is feasible, e.g., by splitting trust.

We should expect more and get more.

Thank you!