NTNU | Norwegian University of Science and Technology

PRIO: PRIVATE, ROBUST, AND SCALABLE COMPUTATION OF AGGREGATE STATISTICS

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Key Contributions

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- Introduction of Secret-Shared Non-Interactive Proofs (SNIPs).

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- Introduction of Secret-Shared Non-Interactive Proofs (SNIPs).
- Presentation of affine-aggregatable encodings, unifying many data-encoding techniques for private aggregation.
- Demonstration of combining these encodings with SNIPs to ensure robustness and privacy in large-scale data collection.

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The Problem

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- This collection are vulnerable to data manipulation by malicious clients

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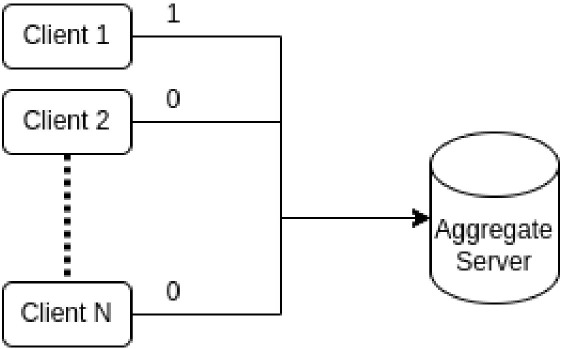

Prio’s Solution

Overview

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- Manages to achieve: privacy and robustness against faulty and malicious clients

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Prio's Solution

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- Manages to achieve: privacy and robustness against faulty and malicious clients
- Prio is also scalable
- Achieves this with the use of a novel technique: secret-shared non-interactive proofs (SNIPs)

Applications for Prio

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- Machine Learning

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- Health/fitness tracking

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- Machine Learning
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- Web browsing data collection
- Essentially in every scenario where aggregate data is valuable, but user privacy is just as important

Efficiency of Prio

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- Prio has a minimal slowdown compared to non-private systems

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- Prio has a minimal slowdown compared to non-private systems
- It also has a significant performance advantage over systems using conventional ZK approaches

Efficiency of Prio

Comparison

Type	Prio	Prio (non-robust)	NIZK
Client-side cost	50x slowdown	N/A	50-100x vs. (compared to Prio)
Server-side cost	1-2x slowdown	5-15x slowdown	267x slowdown
Overall system	5.7x slowdown	N/A	N/A

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Results:

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Experiment

Case: Privately collect responses to a survey with 434 true/false questions.

Results:

- Client: 26ms computation
- Servers: 2ms computation per submission

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What are SNIPs?

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- Cryptographic tools that allow a client to prove to a set of servers that a submitted value is correct and within expected parameters, without revealing the actual value.

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- Cryptographic tools that allow a client to prove to a set of servers that a submitted value is correct and within expected parameters, without revealing the actual value.
- Designed to work in a distributed setting where multiple servers collaboratively verify the correctness of client submissions.

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So what is the difference?

- SNIPs are tailored for efficiency in client/server settings.
- SNIPs are specifically designed for data aggregation settings, while NIZKs have a broader range of applications.
- SNIPs generally use a combination of polynomial identity tests and secret sharing, and are usualyl focused on information theoretic security.

SNIPs in Prio (simplified)

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Setup

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- Client evaluates $Valid(x)$ on input x to know the value of every wire in the circuit

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- Let M be the number of multiplication gates for the circuit $Valid$
- $2M << |\mathbb{F}|$

Client Evaluation

- Client evaluates $Valid(x)$ on input x to know the value of every wire in the circuit
- Client uses wires to construct polynomials f, g, h which encodes values on input and output wires of the M gates.

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Polynomial Construction

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- Then $\deg(f) \leq M - 1, \deg(f) \leq M - 1, \deg(h) \leq 2M - 2$

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- Define $h = f \cdot g$
- Then $\deg(f) \leq M - 1, \deg(f) \leq M - 1, \deg(h) \leq 2M - 2$
- Since $h(t) = f(t) \cdot g(t)$, then $h(t)$ equals the output wire of the t-th gate.

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Client's Computation

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- The client then splits the coefficients of h in s parts and sends the i-th share to the i-th server
- This way, only one honest server is needed to achieve information theoretic security (they each also only get x_i)

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Consistency Checking

- Each server holds share x_i and h_i.

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- From this, the servers produce shares f_i, g_i without communicating with each other.
- If clients and servers all act honestly, then correctness is obvious

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- Then, with certainty: $\hat{h} \neq \hat{f} \cdot \hat{g}$
- Since $\hat{h}(t_0) \neq h(t_0) = f(t_0) \cdot g(t_0) = \hat{f}(t_0) \cdot \hat{g}(t_0)$, then $\hat{h} \neq \hat{f} \cdot \hat{g}$ for the least t_0 s.t. $\hat{h}(t_0) \neq h(t_0)$

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Polynomial Identity Test

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- Each server evaluates their share by calculating $\sigma_i = f_i(r) \cdot g_i(r) - h_i(r)$

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- Servers publish σ_i and ensure $\sum_i \sigma_i = 0$, if not reject

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- From a trusted dealer, each server receives one-time-use shares $(a_i, b_i, c_i) \in \mathbb{F}^3$ s.t. $a \cdot b = c \in \mathbb{F}$, then using the Beaver MPC multiplication protocol.

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- In this setting, the client generates a, b, c and splits into shares a_i, b_i, c_i for each of the servers.
- This saves computation time/resources.

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Beavers MPC Protocol

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- Using the triples (a_i, b_i, c_i) and f_i, g_i, to compute:

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- $d_i = f_i(\tau) - a_i, e_i = g_i(\tau) - b_i$ where τ is the last multiplication gate of the circuit C.

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- Using the triples (a_i, b_i, c_i) and f_i, g_i, to compute:
- $d_i = f_i(\tau) - a_i, e_i = g_i(\tau) - b_i$ where τ is the last multiplication gate of the circuit C.
- Each server broadcasts d_i, e_i
- Each server calculates $\rho_i = de/s + db_i + ea_i + c_i$.

SNIPs in Prio (simplified)

Beaver MPC Protocol Correctness

$$\begin{aligned}
\sum_i \rho_i &= \sum_i (de/s + db_i + ea_i + c_i) \\
&= de + db + ea + c \\
&= (f(\tau) - a)(g(\tau) - b) + (f(\tau) - a)b + (g(\tau) - b)a + c \\
&= f(\tau)g(\tau) - ag(\tau) + ag(\tau) - ab + c \\
&= f(\tau)g(\tau) - ab + c \\
&= f(\tau)g(\tau) && = h(\tau)
\end{aligned}$$

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Output Verification

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- Servers publish output shares after the circuit

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- Servers publish output shares after the circuit
- Sum up shares to confirm $Valid(x) = 1$

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Security

- Correctness follows construction.
- A malicious client must cheat the polynomial identity test with probability $(2M-2)/|\mathbb{F}|$.
- Completeness nor soundness holds in the presence of malicious servers.
- Malicious servers can mount selective DoS attacks against clients
- As long as at least one server is honest, dishonest servers learn nothing about the clients data.

SNIPs in Prio (simplified)

Efficiency

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- Computation cost for each server is not much more than to evaluate the $Valid$ circuit.
- Client-to-server communication cost grows linearly with the size of the $Valid$ circuit.
- The authors note an interesting challenge to try to reduce the communication cost without needing expensive asymm. cryptography.

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- Each client holds a one-bit integer x_i.
- The servers wants to compute $\sum_i x_i$.
- We have s servers.

Simple Prio

Upload

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- Each client i splits its private value x_i into s shares

Simple Prio

Upload

- Each client i splits its private value x_i into s shares
- Then sends this share $[x_i]_j$, $j \in [s]$ to each corresponding server j.

Simple Prio

Aggregate

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- Each server j holds an accumulator value $A_j \in \mathbb{F}_p$

Simple Prio

Aggregate

- Each server j holds an accumulator value $A_j \in \mathbb{F}_p$
- And updates this $A_j \leftarrow A_j + [x_i]_j \in \mathbb{F}_p$ each time it receives a new value.

Simple Prio

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- Computing $\sum_j A_j \in \mathbb{F}_p$ yields $\sum_i x_i$.

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Our Setting

- Each client i holds a value $x_i \in D$, where D is some set of data values.
- The servers holds an aggregation function $f : D^n \to A$.
- The servers goal is to evaluate $f(x_1, \ldots, x_n)$ without learning $x_i \forall i$.

Affine-Aggregatable Encodings (AFEs)

What do AFEs do?

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What do AFEs do?

- Gives an efficient way to encode data values x_i s.t. it is possible to compute $f(x_1, \ldots, x_n)$ given only the sum of the encodings of $x_1, \ldots, x_n$.

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- $\mathsf{Encode}(x)$: maps an input $x \in D$ to its encoding in $\mathbb{F}^k$

- $\mathsf{Valid}(y)$: returns true iff $y \in \mathbb{F}^k$ is a valid encoding of some data item in D.

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- An AFE have 3 (efficient) algorithms:
- $\mathsf{Encode}(x)$: maps an input $x \in D$ to its encoding in $\mathbb{F}^k$
- $\mathsf{Valid}(y)$: returns true iff $y \in \mathbb{F}^k$ is a valid encoding of some data item in D.
- $\mathsf{Decode}(\sigma)$: Takes $\sigma = \sum_{i=1}^{n} Trunc_{k'}(\mathsf{Encode}(x_i)) \in \mathbb{F}^k$ and outputs $f(x_1, \ldots, x_n)$

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Implementation

- The prototype is only 5700 lines of Go and 620 lines of C (for FLINT)
- Code is available on `https://crypto.stanford.edu/prio/`.

Questions?