Single-Server Private Outsourcing of zk-SNARKs (IEEE S&P 2026)

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dd May 2026

ZKPROOF
Paving the path to adoption

8th Workshop

Rome, Italy
9-10 May 2026

Zero-Knowledge Succinct ARGuments of Knowledge

R public relation

x public instance

w private witness

R public relation

x public instance

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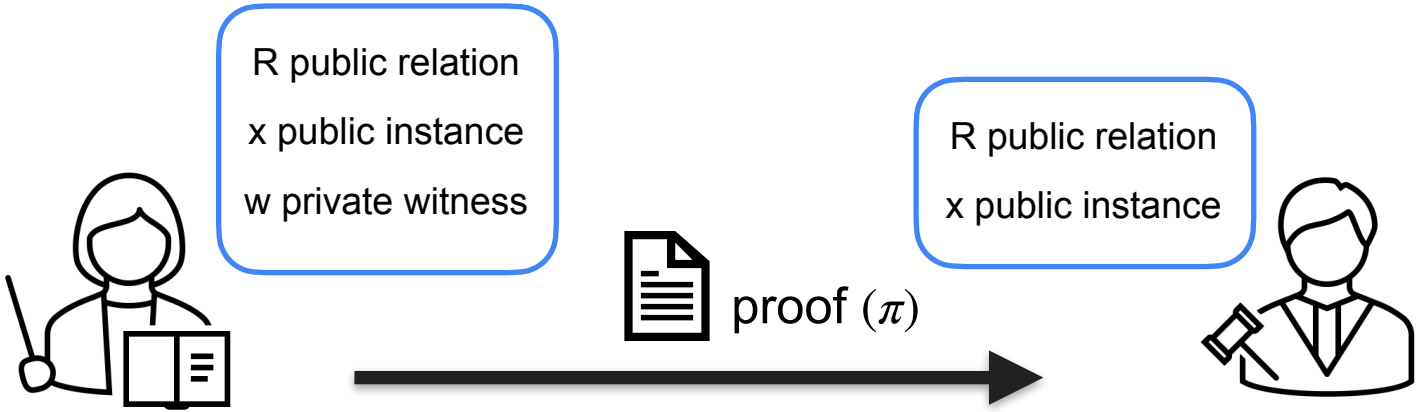

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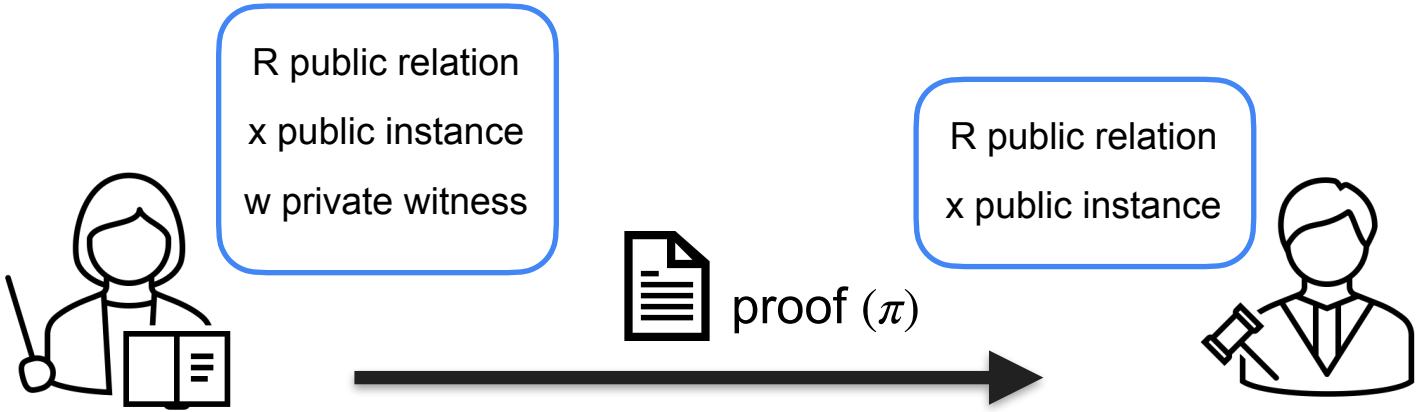

Completeness. For every $(x, w) \in R$, it holds that Pr[Verify(x, π)] $= 1$

Knowledge Soundness.If Verify$(x, \pi) = 1$, then the prover must know w.

Zero-Knowledge. π reveals nothing about the underlying witness w.

Sunccinctness. size of π is sublinear in w.

Many Real-World Applications

Espresso

Aleo

STARKWARE

Aztec

zk-creds: Flexible Anonymous Credentials from zkSNARKs and Existing Identity Infrastructure

Michael Rosenberg*[1], Jacob White†[2], Christina Garman[2], and Ian Miers[1]

ZEXE: Enabling Decentralized Private Computation

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Efficient Proofs of Software Exploitability for Real-world Processors

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What's Not There Yet?

High prover cost

Prover is 1000 × slower than native computation.

computing SHA256 hash of 100KB takes 1ms; however, proving this takes up to 20 min

Groth16, on a laptop

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Many applications require generating proof for millions of arithmetic constraints.

zk-login, proof of training, auditable key transparency, etc.

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Many applications require generating proof for millions of arithmetic constraints.

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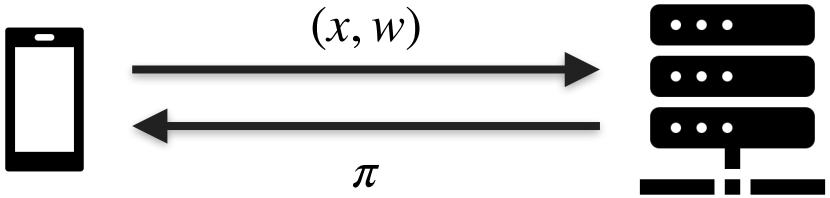
Can we outsource proof generation to more powerful servers to lower the prover's workload and latency?

Outsourcing zk-SNARK prover



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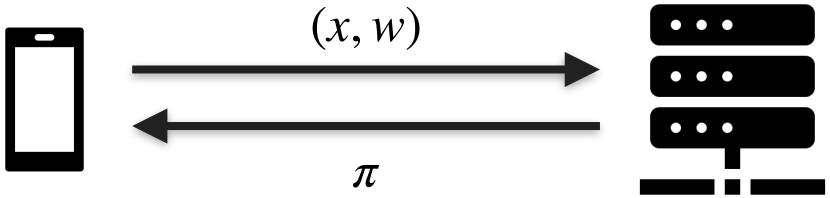

A cluster of servers can generate the proof 100x faster [Wu+18].

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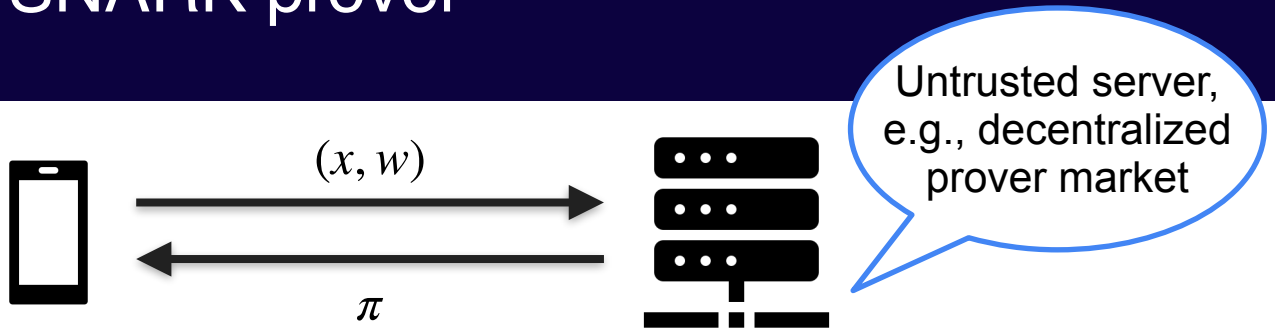

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The problem: Exposing secrets to the servers; not ideal for privacy-preserving applications

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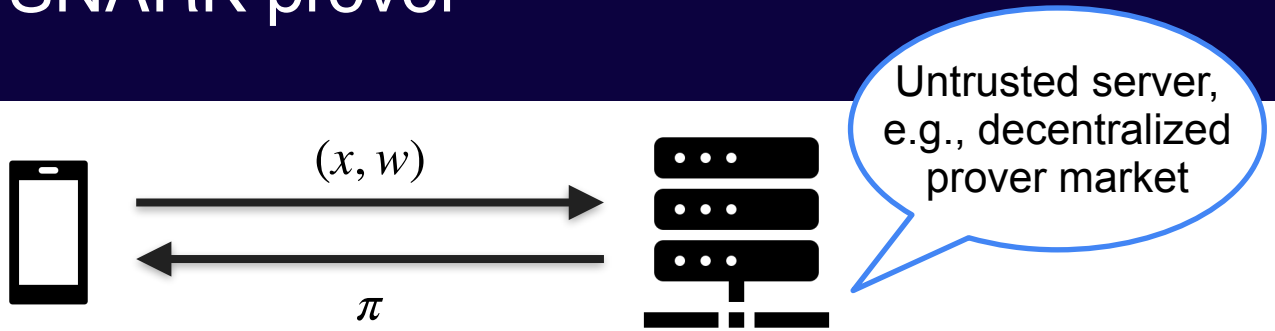

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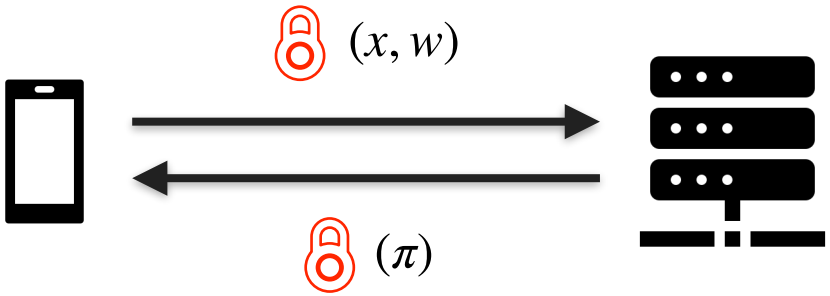
Ideally: (1) do not reveal the witness (2) unlinkablity

Private Outsourcing of zk-SNARKs Prover



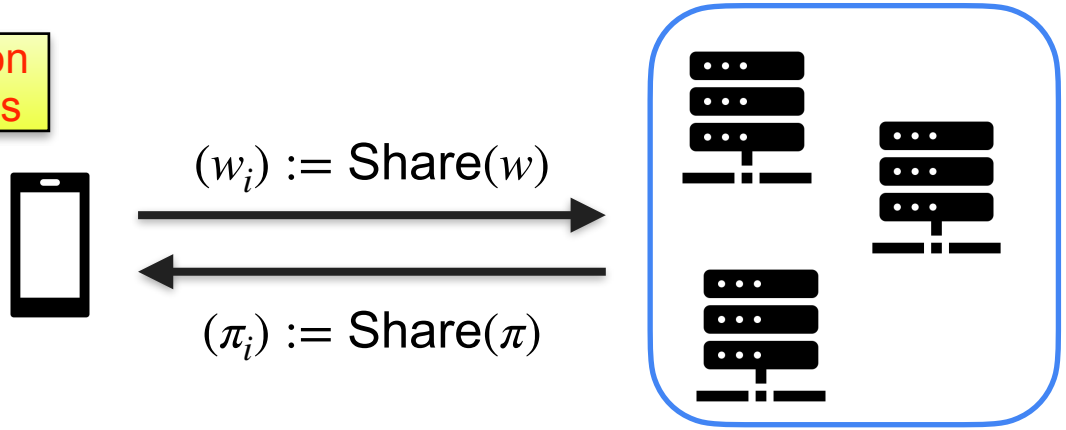
Generic approaches to computation over private data:

i) Fully Homomorphic Encryption (FHE)

ii) Secure Multi-Party Computation via secret sharing (MPC)

Private Outsourcing of zk-SNARKs via MPC

Client only does construction and reconstruction of shares



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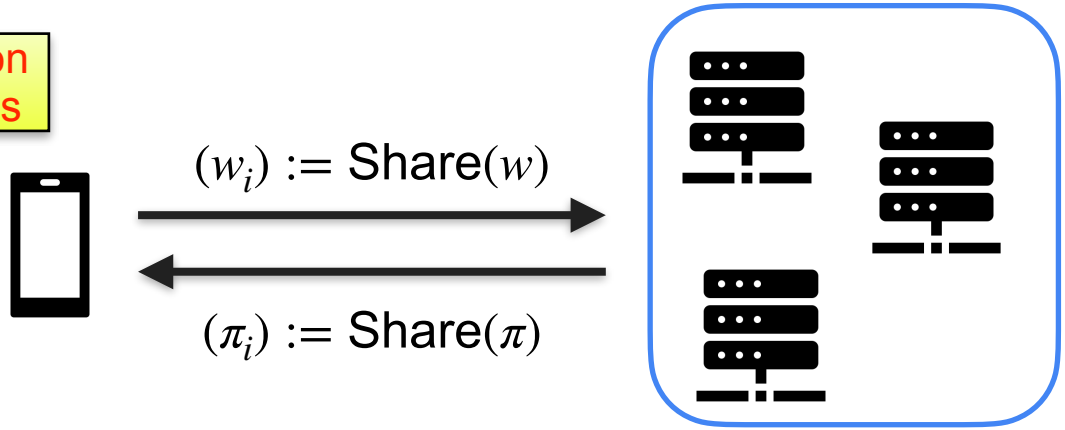
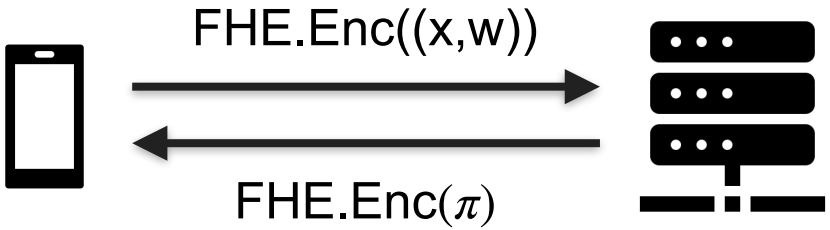


[GGJ+23, CLMZ24]: Similar to non-private schemes, low latency and efficient client.

The key limitation: non-collusion assumption

Private Outsourcing of zk-SNARKs via FHE



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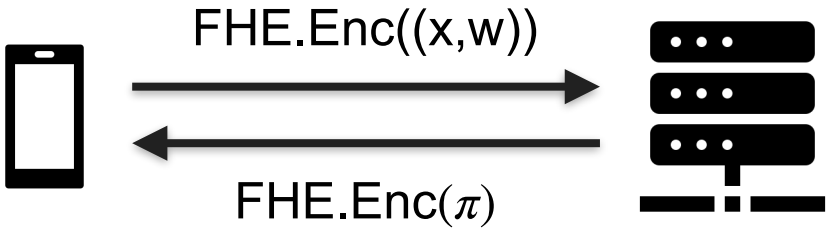

Generic FHE incurs 10,000x slowdown

[GGW24]: Single-server, minimal interctive and efficient client

Main Barrier: Latency overhead, e.g., 10x in [GGW24] for (adapted) FRI-based zk-SNARKs

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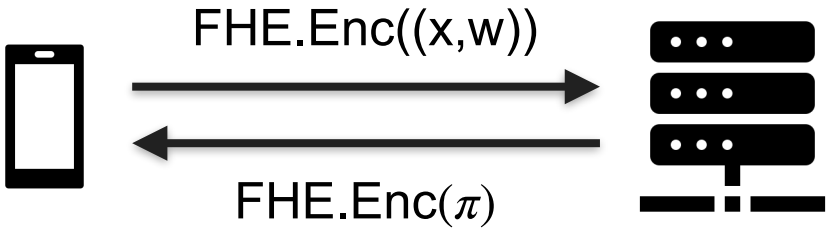

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No malicious security and unlinkablity

Comparison with Prior Work

Scheme	# of servers	Improved latency	Unlinkability	Malicious security	Instantiations
co-SNARKs [52]	≥ 2	✗	✗	✓	Groth16; Marlin; Plonk; Fractal
EOS [21]	≥ 2	✓	✗	✗	Marlin
ZKSaaS [33]	≥ 8	✓	✗	✗	Groth16; Plonk; Marlin
DFS [38]	≥ 2	✓	✗	✓	Marlin*
Siniel [64]	≥ 2	✓	✗	✓	Marlin
Liu et al. [46]	≥ 8	✓	✗	✓	HyperPlonk
Fang et al. [28]	≥ 2	✓	✗	✓	Plonk*
Blind FRI [35, 32]	1	✗	✗	✗	Fractal*
This paper	1	✓	✓	✓	Nova; Groth16; Plonk

* Delegation-specific adaptations.

Table 1: Private delegation schemes. Number of servers assumes the scheme tolerates at least one corrupted server. Although EOS claims malicious security, an attack is known [38].

Our Contribution

- Server-aided zk-SNARKs: single-server framework for private outsourcing of zk-SNARKs, which supports latency reduction, malicious security, unlinkability and group-based zk-SNARKs.
- EMSM (encrypted multi-scalar multiplication): we construction EMSM from LPN assumption with lightweight cryptographic overhead.

What is Multi-Scalar Multiplication (MSM)?

$$\text{MSM}(\vec{g}, \vec{z}) = \prod_{i \in [n]} g_i^{z_i} \text{ such that } g_i \in \mathbb{G}, z_i \in \mathbb{F}$$

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The computation bottleneck for group-based zk-SNARKs.For a circuit with 1 million constraints: MSM is **97%** percent of computation with Nova and **91%** with groth16

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Use linear structure of MSM to fully outsource it to the server, and instead, the client does field operations

Dual Learning Parity with Noice (LPN)

Dual LPN

$(\mathbf{H}, \mathbf{H}\vec{e}) \approx_c (\mathbf{H}, \vec{b})$ such that $\vec{b} \leftarrow \mathbb{F}^n$

the noise is sparse, $\vec{e} \leftarrow \text{Bern}_p$

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the noise is sparse, $\vec{e} \leftarrow \text{Bern}_p$

The noise vector has only a constant number of non-zeros.

Building EMSM from Dual-LPN

Fix the bases $\vec{g}$ then $\text{MSM}(\vec{g}, \vec{z} + \vec{r}) = \text{MSM}(\vec{g}, \vec{z}) + \text{MSM}(\vec{g}, \vec{r})$

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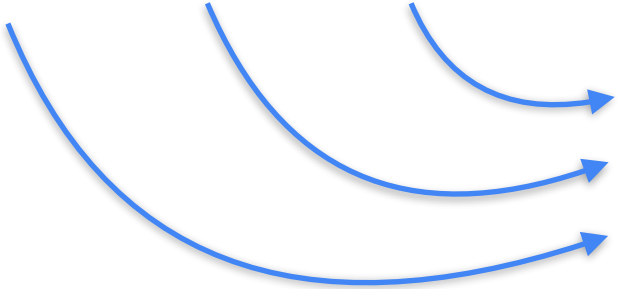

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Client want to outsource this to the server

The server computes this for the client

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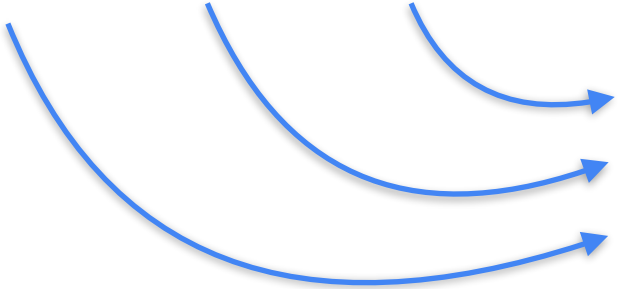

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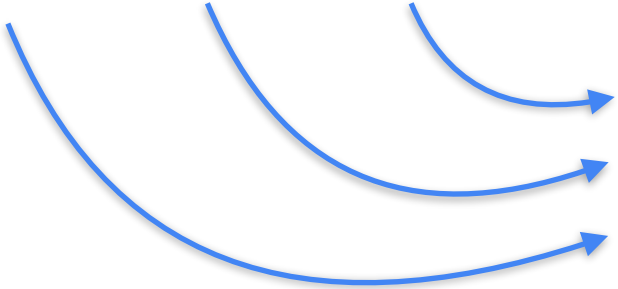

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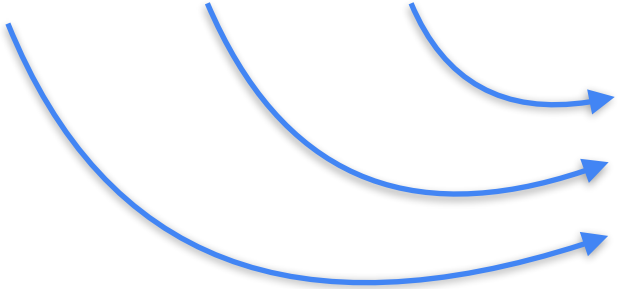

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However if H has no structure, it requires quadric group operations, it can take days for an MSM of size on million

Concrete Instantiation

We instantiate dual-LPN with RAA codes [DJM98, BCF+25]

The generator matrix: $\mathbf{H} = \mathbf{F}_r \cdot \mathbf{M}_{\sigma_1} \cdot \mathbf{A} \cdot \mathbf{M}_{\sigma_2} \cdot \mathbf{A} \in \mathbb{F}^{n \times N}$ where N=nr, such that:

1) $\mathbf{F}_r$: r-repetition matrix, repeats each entry of input r times.

2) $\mathbf{M}_\sigma$: permutation matrix, corresponding to a matrix $\sigma : [N] \to [N]$

3) $\mathbf{A}$: an accumulation matrix, i.e., upper triangle with all 1 non-zero entries.

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The preprocessing requires only $12 \cdot n\ \mathbb{G}_{\text{EXP}}$ for the setup. This setup is untrusted and can be used many times.

Security of the RAA Code

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- We propose an empirical analysis over arbitrary finite fields.

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Distance of RAA Codes over Large Finite Fields (with Applications in zkSNARKs and PCGs)

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Server-Aided zk-SNARKs via EMSM

- At a high-level, the prover does the field operations locally and outsources the MSMs.
- This simple idea yields efficient server-aided zk-SNARK for many group-based schemes: Groth16, Plonk, Nova, Sonic, HyperNova, KZH-Fold, etc.
- The prover for these schemes only does field operation and only a constant number of group operations.

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Field addition is 10000x cheaper than group exponentiation

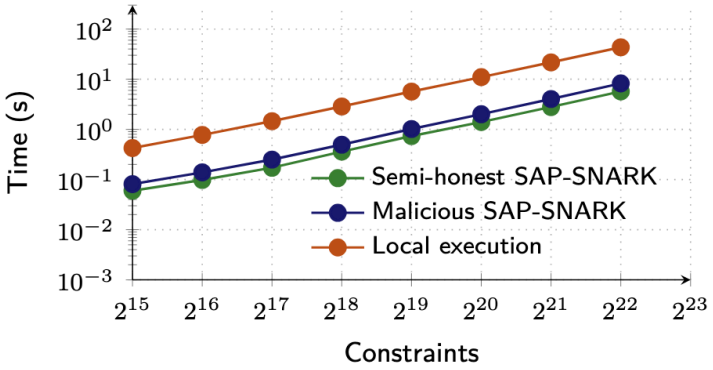
Security against Malicious Server

The client chooses a random $c \in \mathbb{F}$ and outsources MSM$(\vec{g}, \vec{z})$ and MSM$(\vec{g}, c \cdot \vec{z})$

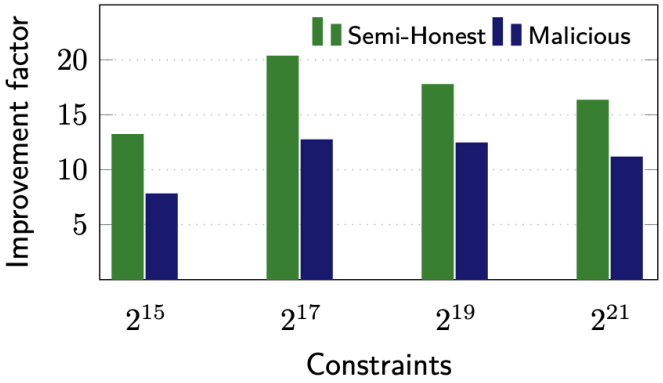
Given MSM$(\vec{g}, \vec{z})$ and MSM$(\vec{g}, c \cdot \vec{z})$, the client checks that $\implies$ $c \cdot \text{MSM}(\vec{g}, \vec{z}) = \text{MSM}(\vec{g}, c \cdot \vec{z})$

Performance of Server-Aided Nova

Lowers the client's active computation by up 20x and latency by 10x



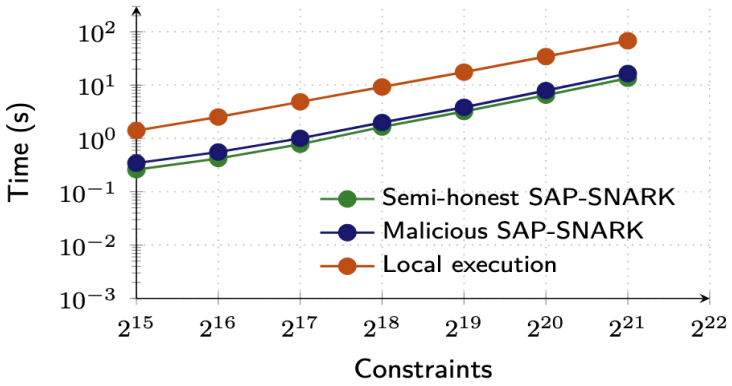
(a) Latency of proof generation (log-log scale).



(b) Improvement in the client's active runtime.

Performance of Server-Aided Groth16

Lowers the client's active computation by up 10x and latency by 6x



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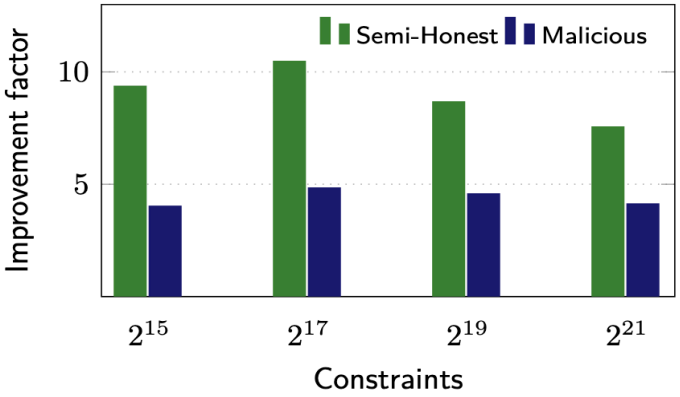

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Conclusion and Future Work

- We introduce server-aided zk-SNARKs for popular group-based zk-SNARKs such as Plonk, Nova and Groth16.
- The techniques of EMSM and analysis of RAA code over large fields might be of independent interest.

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Future Work: Memory improvement for the client side

ZKPROOF

Paving the path to adoption

Thank you!

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Questions?