KZH-Fold: Accountable Voting from Sublinear Accumulation

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dd May 2026

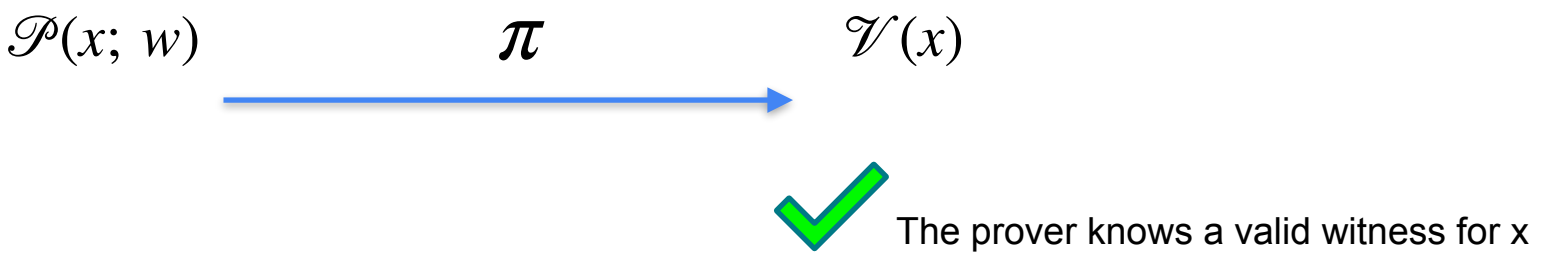
ZKPROOF
Paving the path to adoption

8th Workshop

Rome, Italy
9-10 May 2026

NARK (Non-interactive Argument of Knowledge)

What is a NARK (Non-interactive Argument of Knowledge)?



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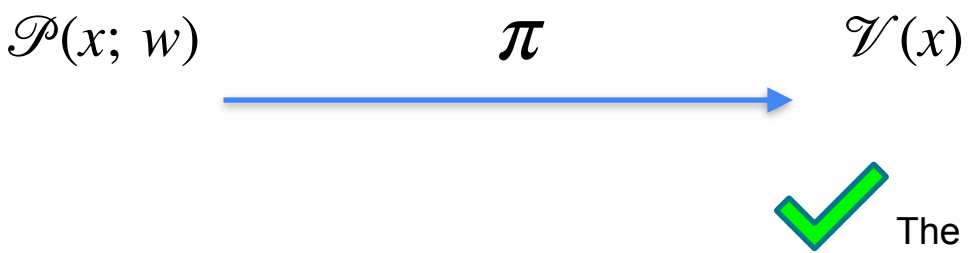

The prover knows a valid witness for x

Completeness: If (x; w) is valid the verifier always accepts

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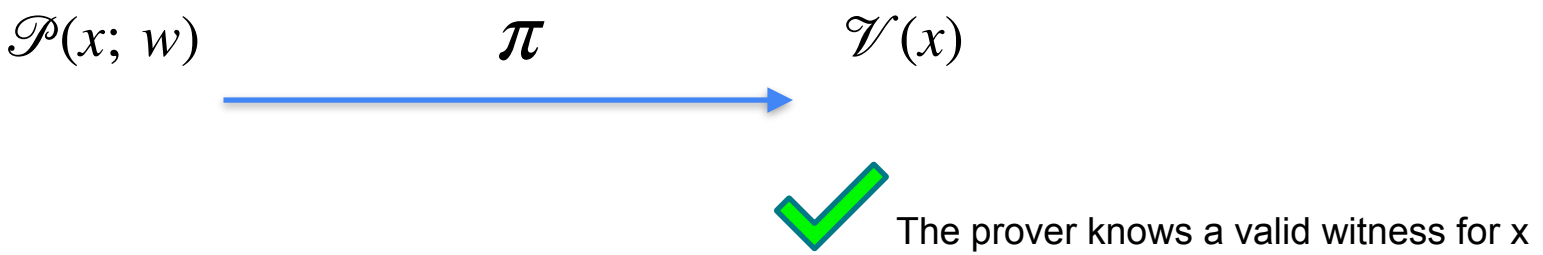

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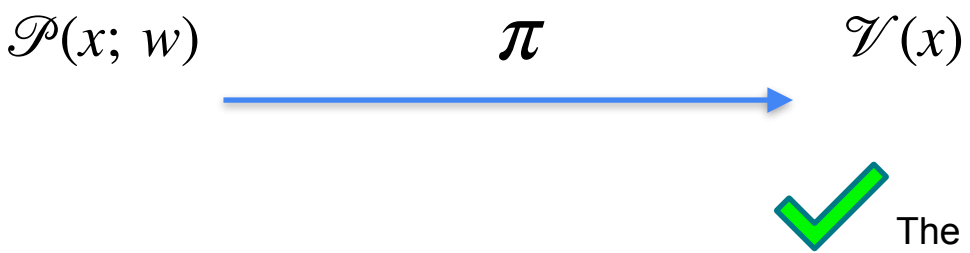

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Completeness: If (x; w) is valid the verifier always accepts

Knowledge-soundness: If the verifier accepts, then the prover must “know” a valid witness.

Succinct: It’s called a SNARK if the size of the proof is sublinear in the size of w

Accumulation Scheme

Accumulation Scheme [BCLMS21; KST21; KP22; BC23]

Let $\mathscr{L}$ and $\mathscr{L}_{\mathsf{acc}}$ be two NP languages. $(x_{\mathsf{acc}}, w_{\mathsf{acc}}) \in \mathscr{L}_{\mathsf{acc}}, (x, w) \in \mathscr{L}$

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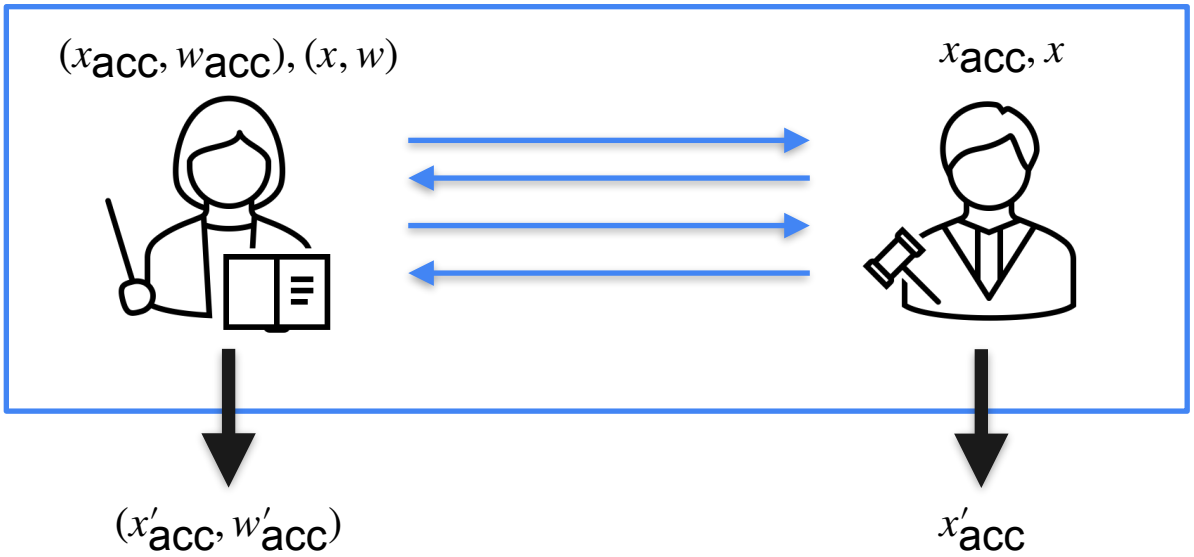

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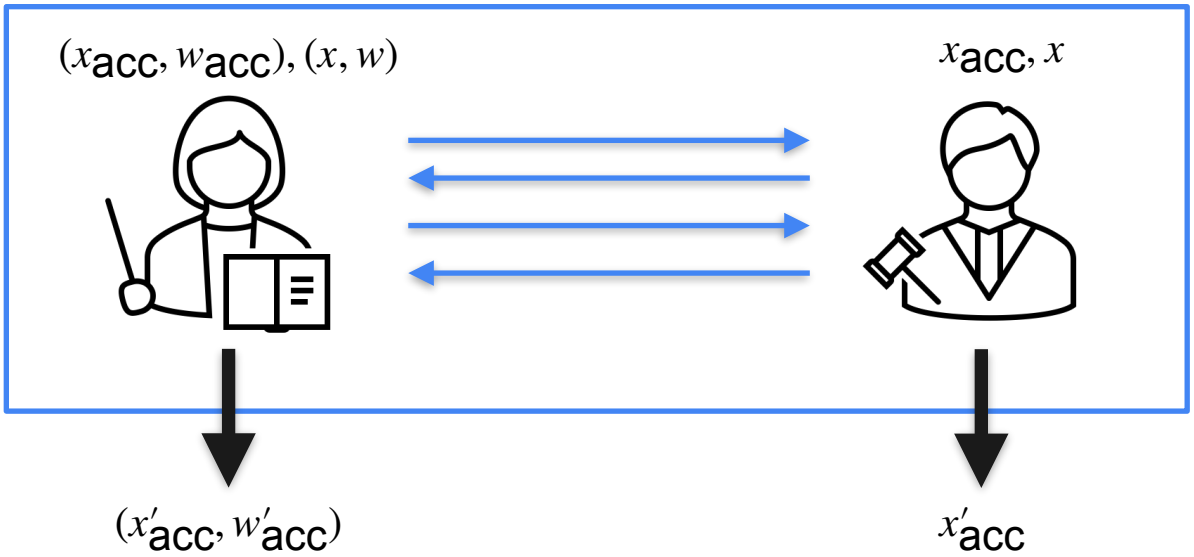

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$\iff (x'_{\mathsf{acc}}, w'_{\mathsf{acc}}) \in \mathscr{L}_{\mathsf{acc}}$

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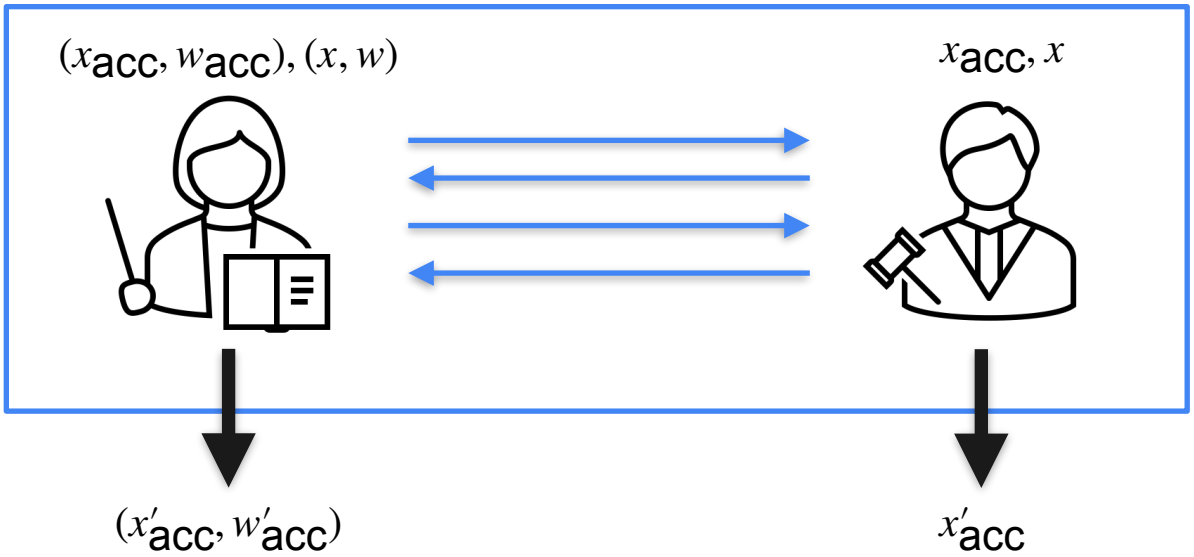

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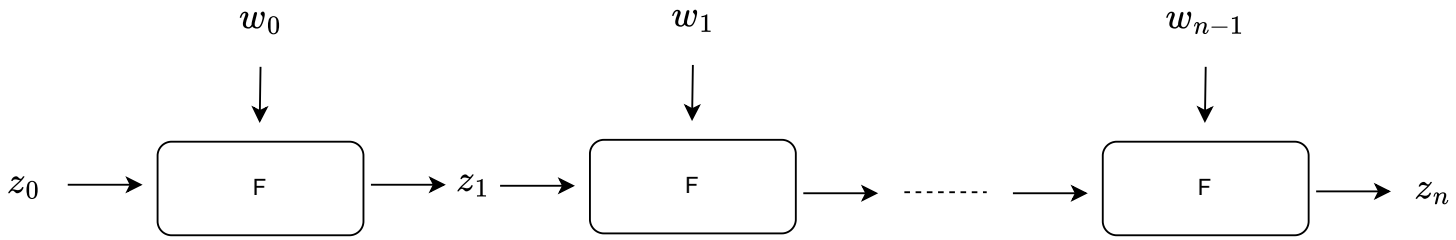
$\iff (x'_{\mathsf{acc}}, w'_{\mathsf{acc}}) \in \mathscr{L}_{\mathsf{acc}}$

It reduces check two NP instances into one

Incremental Verifiable Computation (IVC)

What is Incremental Verifiable Computation (IVC)?

IVC is used to prove correctness of iterative computations such as the following:



IVC has n steps and every step proves the evaluation of F at step i

Proof-Carrying Data (PCD)

Generalization of IVC from straight-line to DAGs (directed acyclic graphs).

PCD enables distributed and parallel computation.

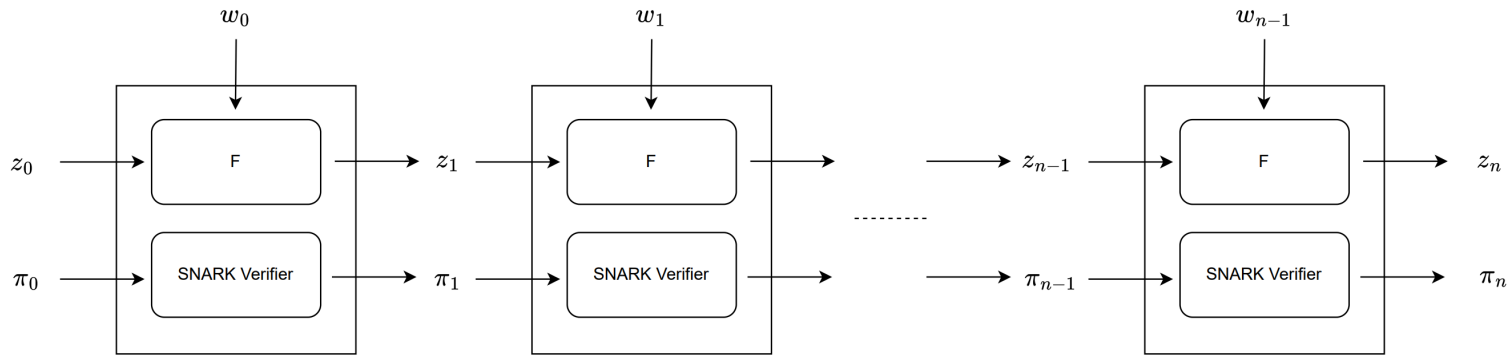
Used in distributed proving, distributed signature aggregation, secure aggregation, etc

How to build IVC/PCD? (Traditional approach :D)

Build an augmented circuit:

1) Subcircuit F

2) SNARK verifier subcircuit (recursive overhead)

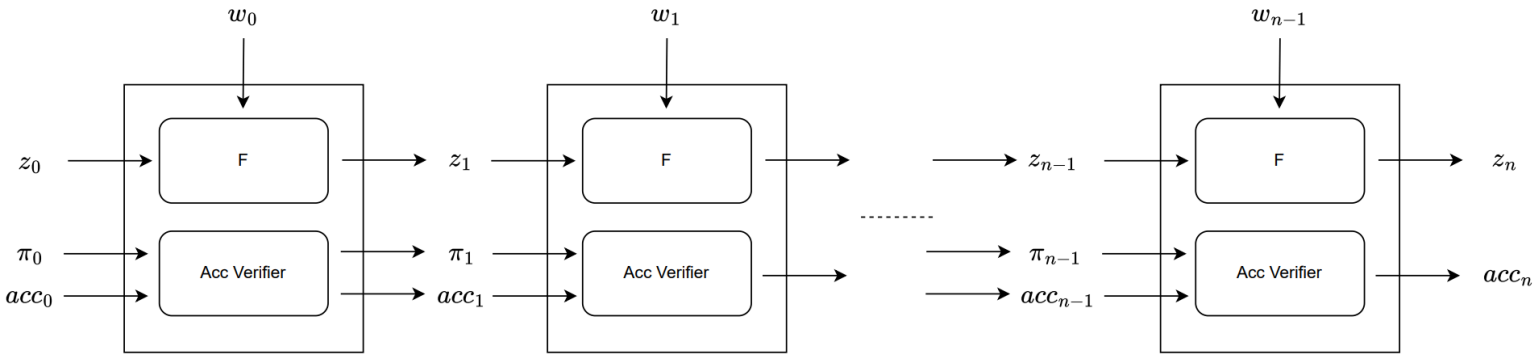


IVC/PCD Construction from Accumulation Schemes [Halo]

The SNARK verifier in the circuit is quite expensive!

Observation: Defer checking the step proves to the last step via accumulation schemes.

How to build IVC/PCD from accumulation schemes?



$\pi_1, \pi_2, \ldots, \pi_n \implies$ Accumulate them into acc_n and check acc_n.

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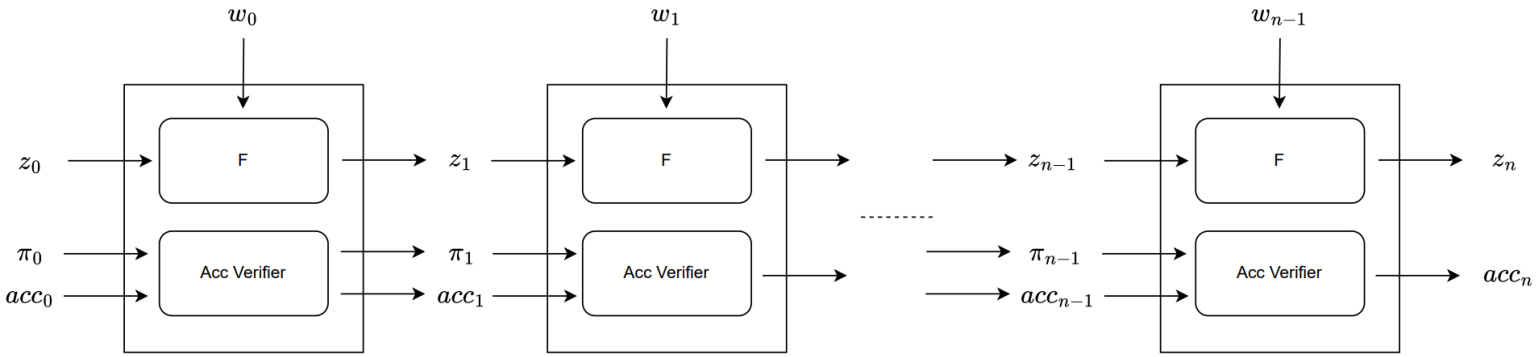

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Acc verifier is more efficient than the SNARK verifier in the circuit

BCLMS Compiler

BCLMS Compiler: NARK + NARK Verifier Accumulation $\implies$ IVC

- IVC proof = $|\text{acc}|$
- IVC verifier = $\text{Decider}_{\text{acc}}$
- IVC prover = $\text{Prover}_{\text{NARK}}$ (for augmented circuit) + $\text{Prover}_{\text{acc}}$

Long Line of Work On Accumulation Schemes

Proof-Carrying Data from Accumulation Schemes

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Proof-Carrying Data without Succinct Arguments

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HyperNova: Recursive arguments for customizable constraint systems

Abhiram Kothapalli
Carnegie Mellon University

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Microsoft Research

LatticeFold+: Faster, Simpler, Shorter Lattice-Based Folding for Succinct Proof Systems

Dan Boneh and Binyi Chen

Stanford University

LatticeFold: A Lattice-based Folding Scheme and its Applications to Succinct Proof Systems

Dan Boneh and Binyi Chen

Stanford University

Nova: Recursive Zero-Knowledge Arguments from Folding Schemes

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PROTOSTAR: Generic Efficient Accumulation/Folding for Special-sound Protocols

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NeutronNova: Folding everything that reduces to zero-check

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Accumulation without Homomorphism

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Long Line of Work On Accumulation Schemes

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HyperNova: Recursive arguments for customizable constraint systems

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The focus of all these papers is to reduce the recursive overhead, and build "prover" efficient IVC/PCD

LatticeFold+: Faster, Simpler, Shorter
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Zero-Knowledge Arguments
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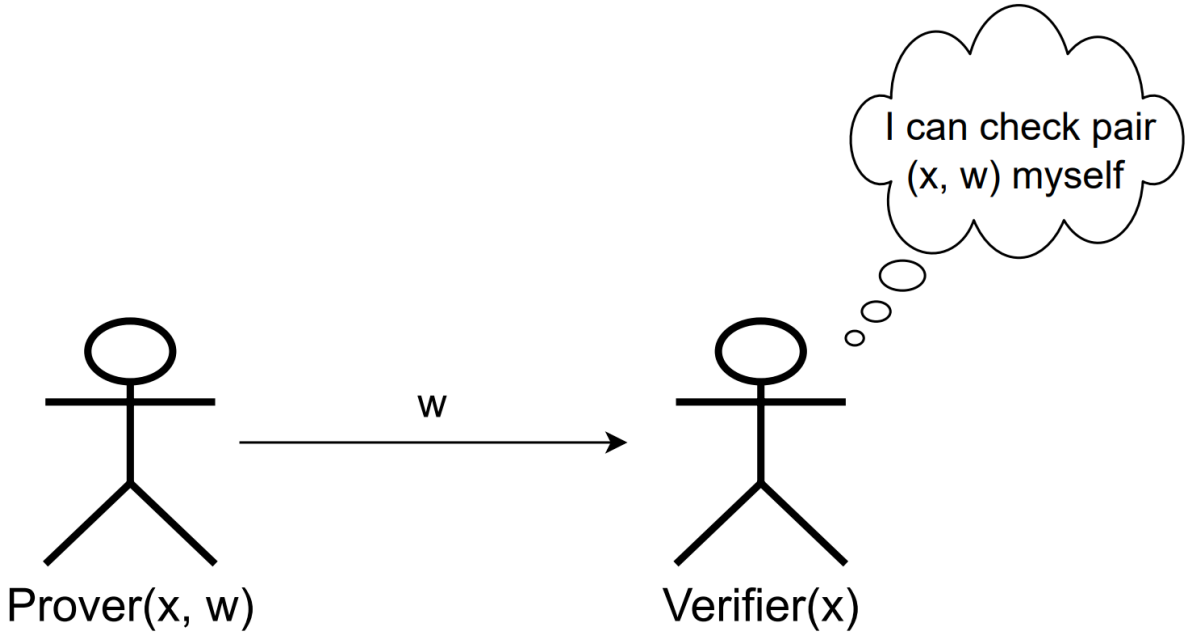
Nova: IVC/PCD with efficient prover

Example of Nova: What is a trivial NARK?



Nova: Accumulation Scheme for Trivial R1CS NARK

Nova accumulator for (relaxed) R1CS: (n =instance+witness size of R1CS)

- Accumulator size: $O(n)$
- Accumulator prover time: $O(n)$
- Accumulator decider time: $O(n)$
- Verifier circuit: $O(1)$, 2 or 3 scalar multiplications

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For a circuit of 1 million constraints ==>
1) the accumulator size = IVC proof size = 80 MB
2) Decider time = IVC verifier time = 4s

Nova / MicroNova solution ==> run an additional zkSNARK at the end (24x prover overhead, no longer incremental)

IVC/PCD With Linear-Sized Proof and Verifier

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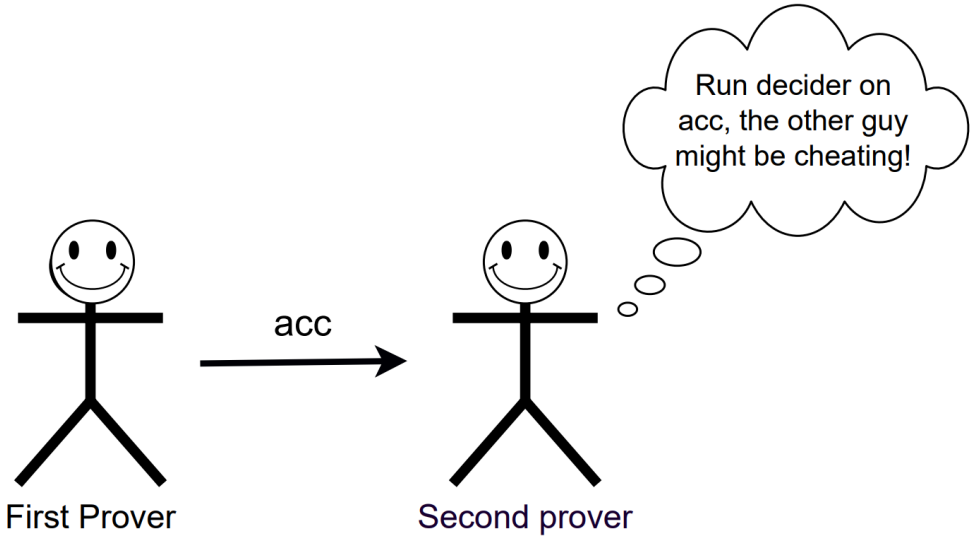
This holds for Nova, Hypernova, Protostar, NeutronNova, KiloNova, ProtoGalaxy, Lattice-Fold, Lattice-Fold+, hash-based such as Arc etc

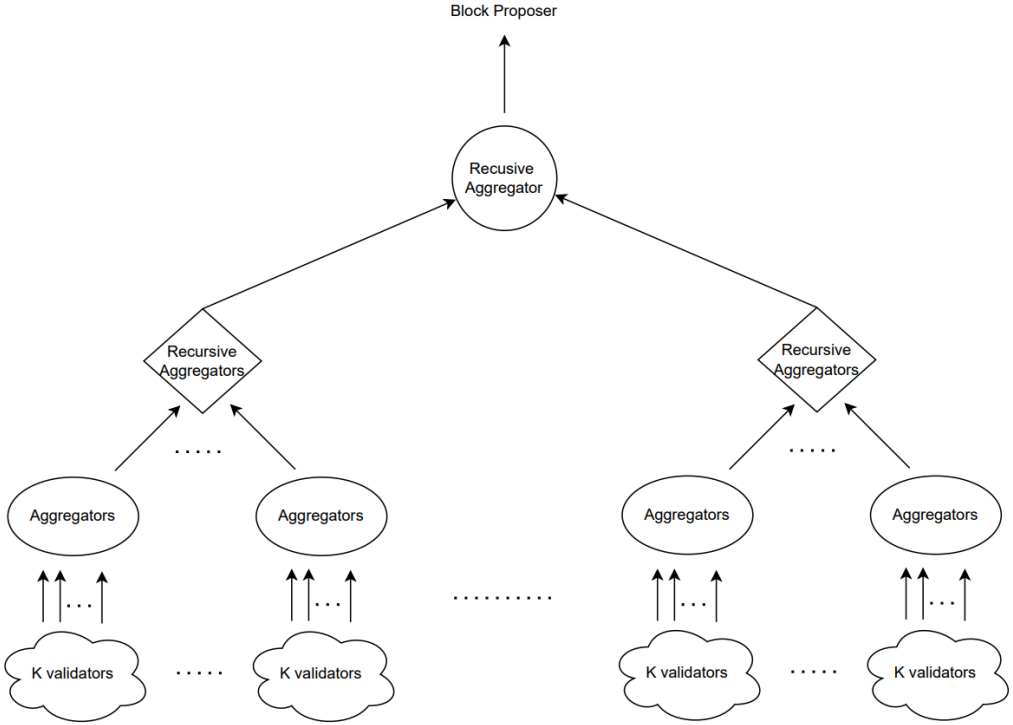
Main Motivation of KZH-Fold: IVC/PCD with Sublinear Proofs

Distributed Proving with IVC / PCD

Different prover do the different proving steps.



Applications of Distributed Proving (Signature Aggregation)



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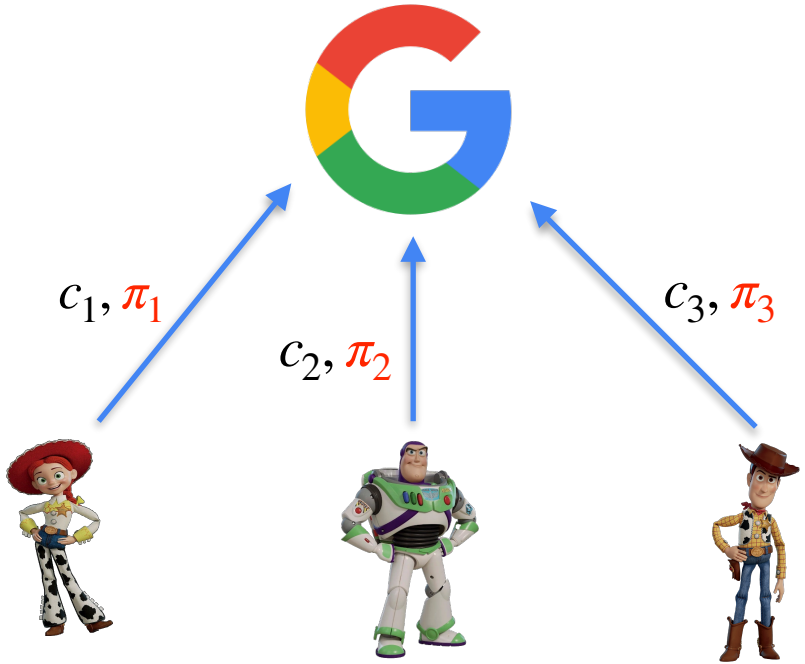

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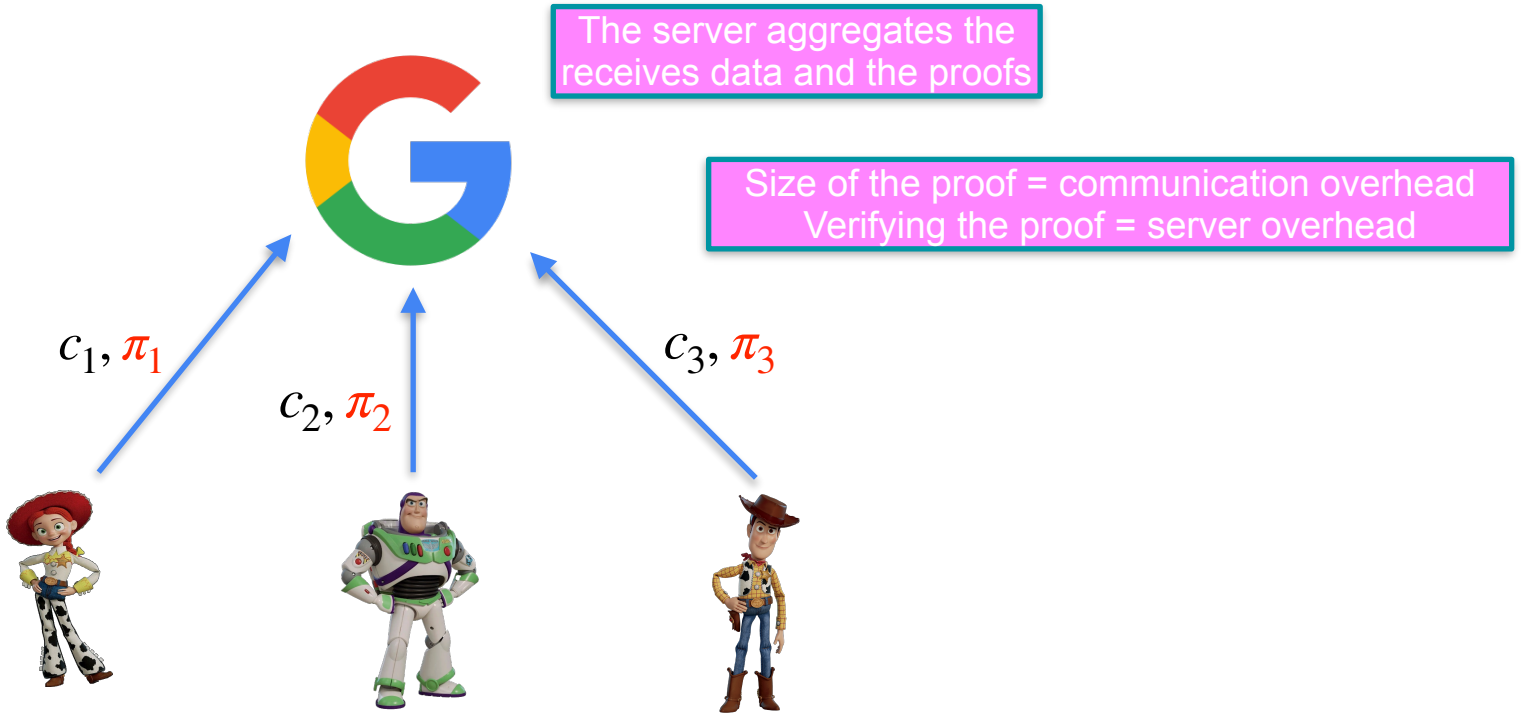
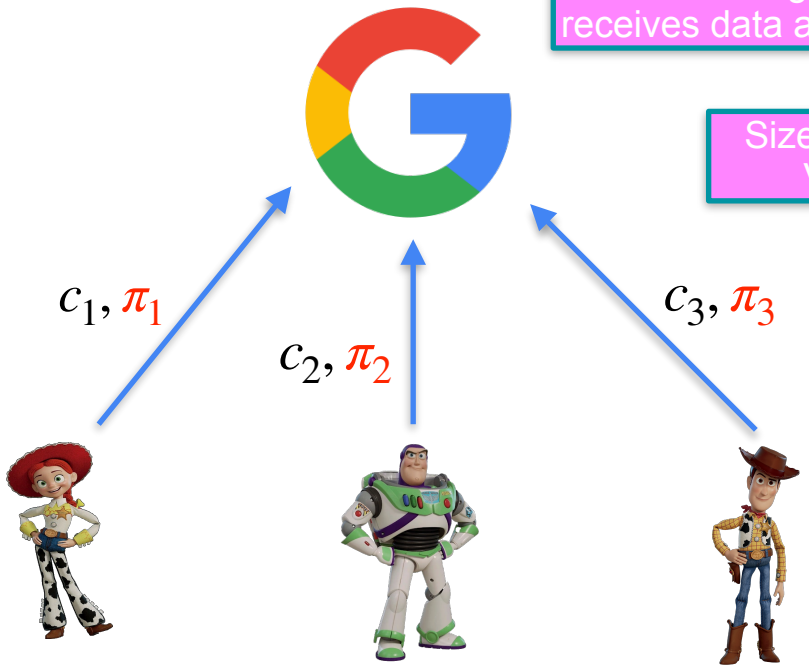


Application of Distributed Proving (Secure Data Aggregation)

The server aggregates the receives data and the proofs

Size of the proof = communication overhead
Verifying the proof = server overhead



WillowFold: Secure Aggregation with a Lightweight Committee

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Sublinear Accumulation: Key to IVC/PCD with Sublinear Proofs

Sublinear Accumulation Scheme

Let “decider” be the NP verification function of $\mathscr{L}_{\text{acc}}$

We call an accumulation scheme sublinear if:

1) $|\mathscr{L}_{acc}| \in o(|\mathscr{L}|)$

2) $\text{decider}_{\mathscr{L}_{\text{acc}}} \in o(\text{verifier}_{\mathscr{L}})$

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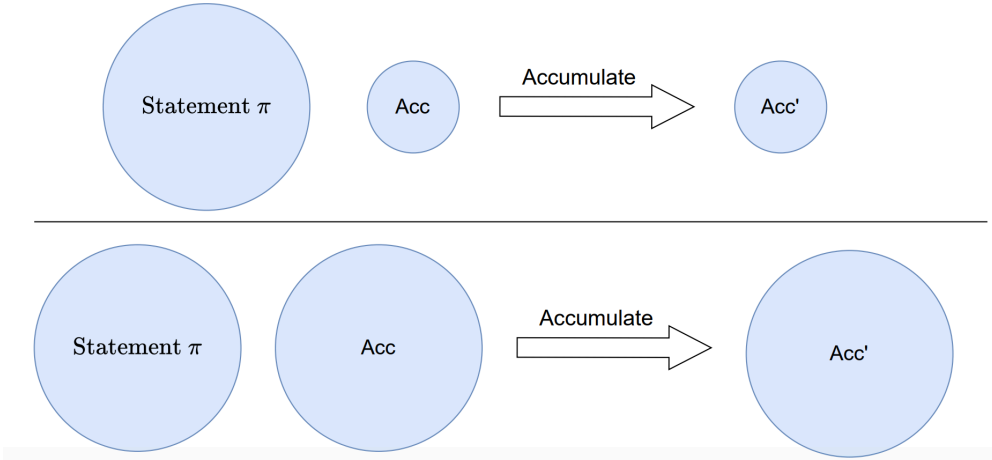

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BCLMS Compiler: NARK + NARK Verifier Accumulation $\implies$ IVC

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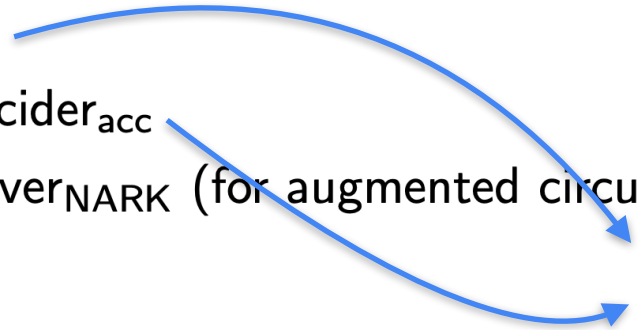

If NARK is the original function F ==> these are sublinear in the size of the original function F

Sublinear accumulator => sublinear IVC

Contributions

1) Build KZH-Fold, i.e., a sublinear accumulation scheme

1) KZH-Fold is based on KZH, a PCS with sublinear opening

---

3) New approach to designing non-uniform IVC/PCD (first efficient N-PCD)

Our Goal

- IVC with sublinear proof/decider $\iff$ Sublinear accumulation.
- PCS with sublinear predicate $\implies$ Sublinear accumulation.

Starting Point: Hyrax

Reminder: Hyrax is a polynomial commitment scheme with $\sqrt{n}$ opening and commitment size.

Overview of Hyrax

Given a Pedersen setup $(g_1, g_2, \ldots, g_m)$, commit to rows of the coefficient matrix:

$$\begin{bmatrix} t_{11} & t_{12} & \cdots & t_{1m} \\ t_{21} & t_{22} & \cdots & t_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ t_{k1} & t_{k2} & \cdots & t_{km} \end{bmatrix} \begin{matrix} \Longrightarrow c_1 \\ \Longrightarrow c_2 \\ \vdots \\ \Longrightarrow c_k \end{matrix}$$

Commitment size is $O(\sqrt{n}) \Rightarrow$ homomorphism/acc verifier is $O(\sqrt{n})$

Starting Point: Hyrax

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Sublinear opening ==> sublinear accumulation scheme

Square-root size commitment ==> High recusive overhead (square root group operations in the circuit)

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Our goal: make the commitment one group element

How to Build KZH? KZH = KZG + Hyrax

KZH2: Overview

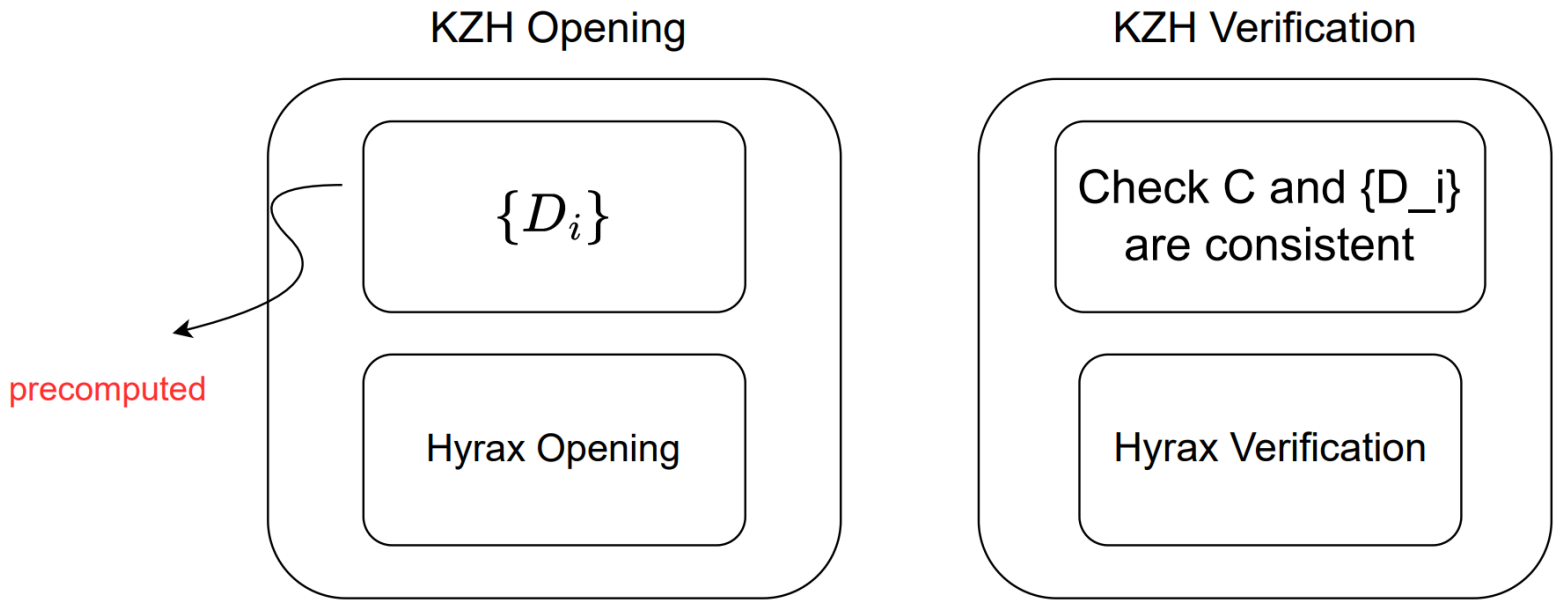
Commitment phase of KZH: (with SRS)

1. C: commit to the whole matrix in $1\mathbb{G}$ element, using a universal-SRS.
2. $\{D_i\}$: Commit to each row using $g_1, \ldots, g_m$.

$$\underbrace{\begin{bmatrix} t_{11} & t_{12} & \cdots & t_{1m} \\ t_{21} & t_{22} & \cdots & t_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ t_{k1} & t_{k2} & \cdots & t_{km} \end{bmatrix}}_{C} \begin{array}{l} \Longrightarrow D_1 \\ \Longrightarrow D_2 \\ \vdots \\ \Longrightarrow D_k \end{array}$$

Prove via pairing C and $\{D_i\}$ correspond to the same matrix.

KZH2: Overview



Efficiency of KZH2

For a multilinear polynomial $f(\vec{X})$ with on boolean hypercube of size ℓ:

- commitment time $=$ $O(\ell)$ group operations.
- Proof size $= \sqrt{\ell}\ \mathbb{G}_1 + \sqrt{\ell}\ \mathbb{F}$
- Opening time $= \ell\ \mathbb{F}$ [1]
- Verifier time $= \sqrt{\ell}$ pairing $+$ MSM$(2\sqrt{\ell}) + \sqrt{\ell}\ \mathbb{F}$.

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The opening cost is optimal: just polynomial evaluation and no group operations

KZH-k: An overview of efficiency

We extend KZH matrix construction to tensors of higher degree $\Longrightarrow$
Lower verifier cost at the cost of higher opening.

- Commitment cost: $O(k \cdot \ell)$
- Opening cost: $O(\ell^{1/2})$ via pre-processing
- Verifier cost: $O(k \cdot \ell^{1/k})$

KZH-log(ℓ)

We extend KZH matrix construction to tensors of higher degree $\Longrightarrow$
Lower verifier cost at the cost of higher opening.

- Commitment cost: $O(\log \ell \cdot \ell)$
- Opening cost: $O(\ell^{1/2})$ via pre-processing
- Verifier cost: $O(\log \ell)$

Comparison of KZH-k vs Prior Work

Scheme	Supports	Opening time	Proof size	Verifier time
KZH	Multilinear	$n^{\frac{1}{2}}\,\mathbb{G}_1$	$2n^{\frac{1}{2}}\mathbb{G}_1$	$n^{\frac{1}{2}}\ \mathrm{P} + 2 \cdot \mathrm{MSM}(n^{\frac{1}{2}})$
KZH-$\log(n)$	Multilinear	$n^{\frac{1}{2}}\,\mathbb{G}_1$	$2\log(n)\,\mathbb{G}_1$	$2\log(n)\ \mathrm{P}$
[PST13]	Multivariate	$\mathrm{MSM}(n)$	$\log(n)\,\mathbb{G}_1$	$\log(n)\ \mathrm{P}$
[KZG10]	Univariate	$\mathrm{MSM}(n)$	$1\mathbb{G}_1$	$2\ \mathrm{P}$
[Lee21]	Multilinear	$n^{\frac{1}{2}}\ P$	$3\log(n)\,\mathbb{G}_T$	$\log(n)\,\mathbb{G}_T,\ \mathrm{P}$

Other properties that make KZH unique.

KZH offers free opening for points in the boolean hypercube $\implies$ an efficient VC instantiation

KZH offers cheap zk $\implies$ $O(k \cdot N^{\frac{1}{k}})$

Free opening at Boolean points

HydraProofs: Optimally Computing All Proofs in a Vector Commitment
(with applications to efficient zkSNARKs over data from multiple users)

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Square root proof size

Does not support zero-knowledge

Free opening at Boolean points

IronDict:
Transparent Dictionaries from Polynomial Commitments

Hossein Hafezi[†1], Alireza Shirzad[†2], Benedikt Bünz[3], and Joseph Bonneau[4]

[1,3,4]New York University
[2]University of Pennsylvania

USENIX Security 2026

Aegon: Scalable and Self-Auditable Key Transparency

Hossein Hafezi
University of Cambridge

Alireza Shirzad
University of Pennsylvania

Benedikt Bünz
NYU

Kevin Lewi
Meta

Dillon George
Meta

Joseph Bonneau
NYU

KZH-Fold: Sublinear Accumulation Scheme for KZH

Goal

- Just to review: building IVC/PCD with sublinear proof requires a sublinear accumulation scheme
- We have built a PCS with sublinear proof, next we build an polynomial accumulation (PA) scheme for it.
- We'll later see how to compiler PIOP+PA into IVC/PCD.

KZH-Fold: Accumulation Scheme for KZH Verifier

The verifier function for KZH= degree 2 scalar multiplications + degree 1 pairing check $\overset{\text{Protostar compiler}}{\Longrightarrow}$

- Accumulator size. $O(\ell^{\frac{1}{2}})$
- Decider complexity. $O(\ell^{\frac{1}{2}})$
- Prover complexity. $O(\ell)$
- Verifier complexity. $3-4$ $\mathbb{G}_1$ scalar multiplications + $O(1)$ $\mathbb{F}$

KZH-k fold:

- $O(k \cdot \ell^{1/k})$ decider and accumulator size
- $k+1$ scalar multiplication in recursive circuit.

Comparing KZH-Fold with Prior Work

Scheme	Recursive Overhead	Decider	—acc—
Nova	2 group ops	$\mathrm{MSM}(n)$	$O(n)$
KZH2-fold	3 group ops	$n^{\frac{1}{2}}$ P	$O(n^{\frac{1}{2}})$
KZH-k fold	$k+1$ group ops	$k \cdot n^{\frac{1}{k}}$ P	$O(k \cdot n^{\frac{1}{k}})$
Halo	$O(\log n)$ group ops	$\mathrm{MSM}(n)$	$O(\log n)$

How to achieve IVC/PCD from PA?

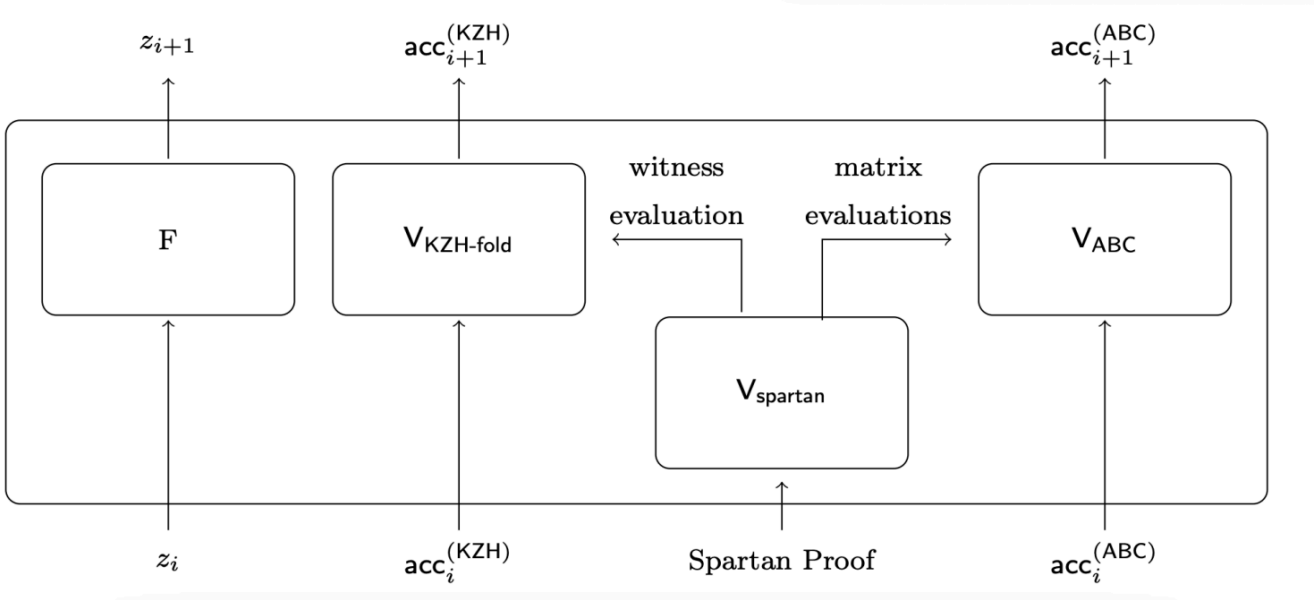
- BCLMS Compiler: NARK + NARK verifier accumulation ==> IVC/PCD
  - SNARK + SNARK verifier accumulation ==> Sublinear IVC/PCD
- NARK = PIOP + PCS
  - SNARK = $\mathscr{V}_{\mathsf{PIOP}}$ and $\mathscr{V}_{\mathsf{PCS}}$ are both succinct.
- Accumulation for $\mathscr{V}_{\mathsf{PIOP}}$ and $\mathscr{V}_{\mathsf{PCS}} \equiv$ Accumulation for $\mathscr{V}_{\mathsf{SNARK}}$

How to achieve IVC/PCD from PA?

PIOP (Spartan) + PCS (KZH) = SNARK (Spartan+KZH)

Spartan verifier accumulator + KZH-Fold = Spartan+KZH verifier accumulation

IVC circuit of Spartan+KZH-Fold



Comparison of Nova vs Spartan+KZH-Fold

Scheme	**Prover**	**Verifier**	$\|\text{Acc}\|$	**# Constraints**
Spartan+KZH-fold	16.5 s	135 ms	37 KB	$2^{21} \approx 2097k$
Nova	4.8 s	5.6 s	80.8 MB	1185k

Table: Spartan+KZH-Fold vs Nova for Circuit With 2000 Poseidon Hashes

New Paradigm in Design of Non-Uniform IVC/PCD

What is Non-Uniform IVC/PCD?

Standard IVC/PCD: repetitive computation of a function F

What is we have multiple function?!

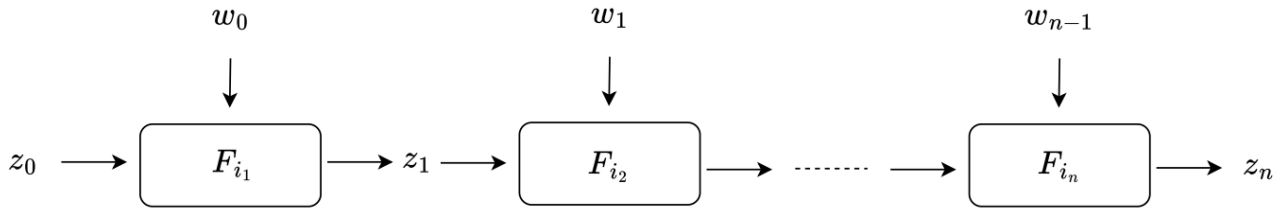
What is Non-Uniform IVC/PCD?

Standard IVC/PCD: repetitive computation of a function F

What is we have multiple function?!

Step function F can be one of multiple predefined instructions F_1, ..., F_k

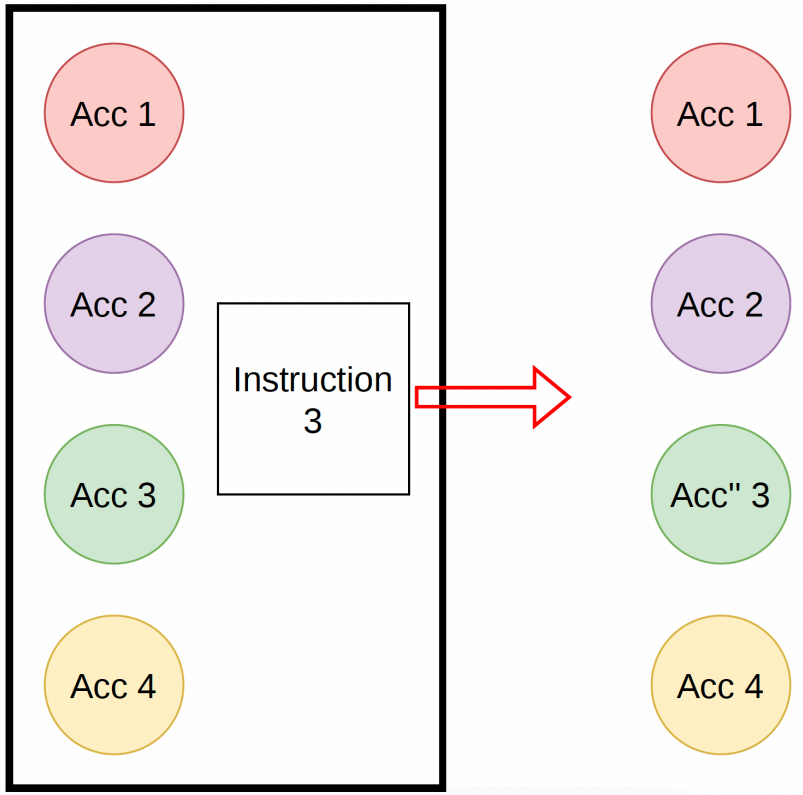
- Motivation: Verifiable CPU



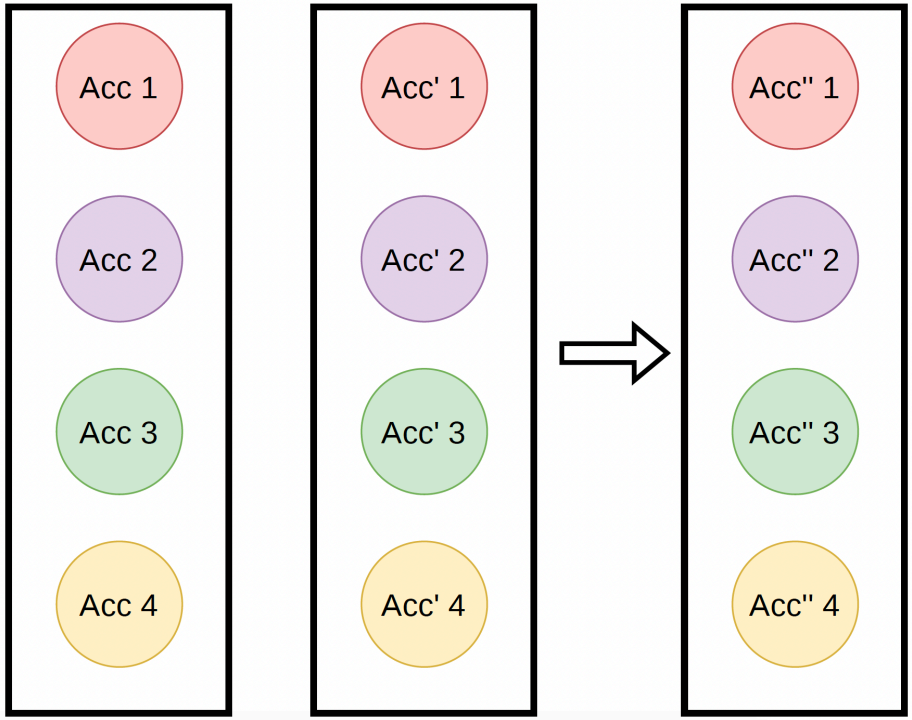
SuperNova: the State-of-the-Art for N-IVC

- Keep m different accumulators corresponding to m instructions.
- When a new instruction is received, accumulate with the corresponding and the remaining are untouched.

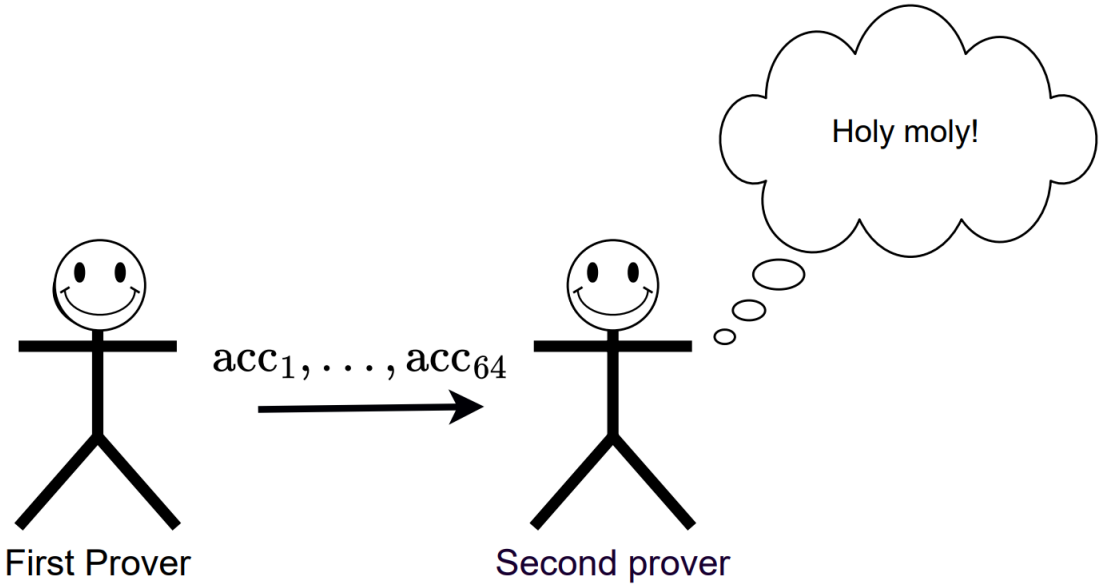
SuperNova: Previous State-of-the-Art



Why it doesn’t work for PCD



Distributed Proving of a zkVM with (Non-Uniform) IVC / PCD



- N-IVC/N-PCD with SuperNova $\Longrightarrow$ One accumulator per instruction

N-IVC/N-PCD from Polynomial Accumulation

High-level idea:

- PCS accumulation $\Longrightarrow$ more flexible than circuit accumulation
- Polynomials of different degrees can be accumulated.

Comparison to Supernova:

- directly accumulates circuit $\Longrightarrow$ one running accumulator for each instruction.

N-IVC/N-PCD from Polynomial Accumulation

F_i is translated into number of polynomial constraints via PIOP.

These polynomial are accumulated via polynomial accumulation

N-IVC/N-PCD from Polynomial Accumulation

F_i is translated into number of polynomial constraints via PIOP.

These polynomial are accumulated via polynomial accumulation

PIOP returns polynomial and polynomials are homogenous constraints

Comparison of N-IVC/N-PCD from PA+PIOP With Prior Work

Scheme	Prover Time	Verifier Time	Witness Size
SuperNova	$O(\sum \lvert F_i \rvert)\mathbb{G}$	$O(\sum \lvert F_i \rvert)\mathbb{G}$	$O(\sum_i \lvert F_i \rvert)$
Protostar	$O(\sum \lvert F_i \rvert)\mathbb{G}$	$O(\sum \lvert F_i \rvert)\mathbb{G}$	$O(\sum_i \lvert F_i \rvert)$
KiloNova	$O(\sum \lvert F_i \rvert)\mathbb{G}$	$O(\sum \lvert F_i \rvert)\mathbb{G}$	$O(\sum_i \lvert F_i \rvert)$
Spartan+PA	$\mathcal{P}_{\text{acc}}(\max_i \lvert F_i \rvert) + \sum_i \log \lvert F_i \rvert$	$\mathcal{D}_{\text{acc}}(\max_i \lvert F_i \rvert) + O(\sum_i \lvert F_i \rvert)\mathbb{F}$	$O(\lvert acc \rvert + \sum \log_i \lvert F_i \rvert)$

PA=KZH-Fold:

- Prover time: $O(\max_i \lvert F_i \rvert) + \sum_i \log \lvert F_i \rvert$
- Verifier time: $O(\sqrt{\max_i \lvert F_i \rvert}) + O(\sum_i \lvert F_i \rvert)\mathbb{F}$
- Witness size: $\sqrt{\max_i \lvert F_i \rvert} + \sum \log_i \lvert F_i \rvert$

ZKPROOF

Paving the path to adoption

Thank you!

ZKPROOF

Paving the path to adoption

Questions?