Using Zero-Knowledge Proofs to Fight Disinformation

Trisha Datta and Dan Boneh

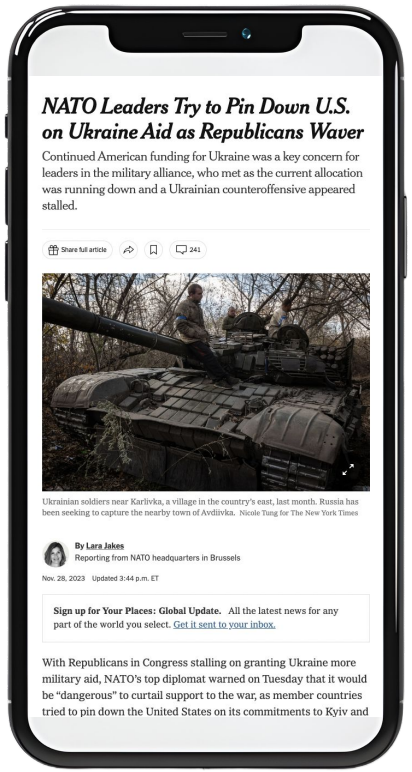
Stanford University

Image Provenance Verification

- Want to verify **when** and **where** photos were taken

Image Provenance Verification

- Want to verify **when** and **where** photos were taken
- Important for news articles



NATO Leaders Try to Pin Down U.S. on Ukraine Aid as Republicans Waver

Continued American funding for Ukraine was a key concern for leaders in the military alliance, who met as the current allocation was running down and a Ukrainian counteroffensive appeared stalled.

Share full article 241

Ukrainian soldiers near Karlivka, a village in the country's east, last month. Russia has been seeking to capture the nearby town of Avdiivka. Nicole Tung for The New York Times

By Lara Jakes
Reporting from NATO headquarters in Brussels

Nov. 28, 2023 Updated 3:44 p.m. ET

Sign up for Your Places: Global Update. All the latest news for any part of the world you select. Get it sent to your inbox.

With Republicans in Congress stalling on granting Ukraine more military aid, NATO's top diplomat warned on Tuesday that it would be "dangerous" to curtail support to the war, as member countries tried to pin down the United States on its commitments to Kyiv and

Image Provenance Verification

- Want to verify **when** and **where** photos were taken
- Important for news articles

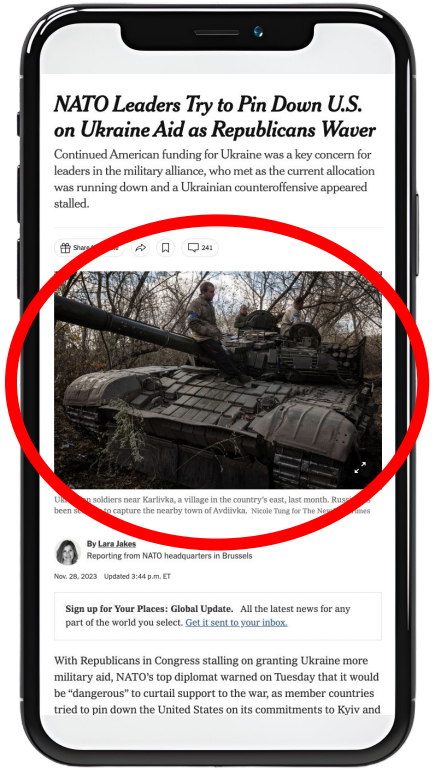
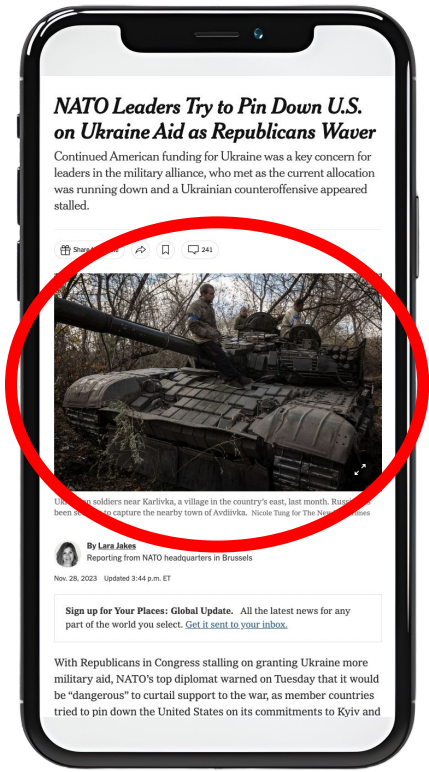


Image Provenance Verification

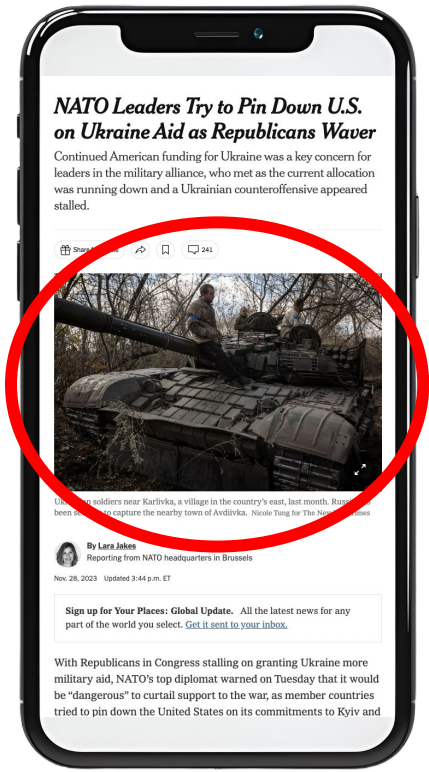
- Want to verify **when** and **where** photos were taken
- Important for news articles



Ukrainian soldiers near Karlivka, a village in the country's east, last month.

Image Provenance Verification

- Want to verify **when** and **where** photos were taken
- Important for news articles



Ukrainian soldiers near Karlivka, a village in the country's east, last month.

Ukraine conflict: Many misleading images have been shared online

By Alistair Coleman & Shayan Sardarizadeh
BBC Monitoring

24 February 2022

Ukraine conflict: Many misleading images have been shared online

By Alistair Cole
BBC Monitorin

24 February 202

Fact-checking videos and pictures from Ukraine

Since Russia's attacks on Ukraine began, we have seen several videos and pictures go viral that are actually fake posts.

Ukraine conflict: Many misleading images have been shared online

By Alistair Cole
BBC Monitorin

24 February 202

Fact-checking videos and pictures from Ukraine

Since Rus
and pictu

False social media posts are hindering earthquake relief efforts in Turkey. You can help stop that

Ukraine conflict: Many misleading images have been shared online

By Alistair Cole
BBC Monitorin

24 February 202

Fact-checking videos and pictures from Ukraine

Since Rus
and pictu

False social media posts are hindering earthquake relief efforts in Turkey. You can help sto

THE NEWS / UKRAINE

BBC Breakfast uses old footage of Russian parade rehearsal to show invasion of Ukraine

C2PA: A Content Provenance Standard

Sony Unlocks In-Camera Forgery-Proof Technology

04 Aug, 2022

embedded certified signing key sk_1

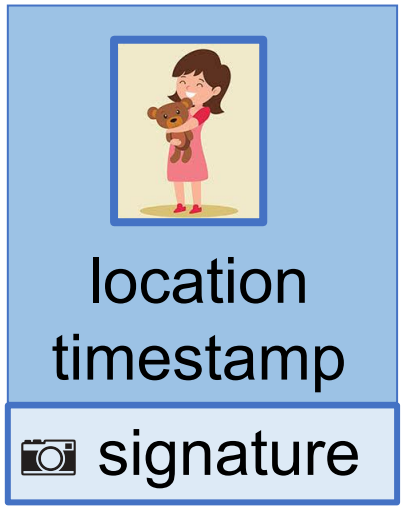
Adobe BBC intel Microsoft PUBLICIS GROUPE SONY Truepic

C2PA: A Content Provenance Standard

Sony Unlocks In-Camera Forgery-Proof Technology

04 Aug, 2022

embedded certified signing key sk_1



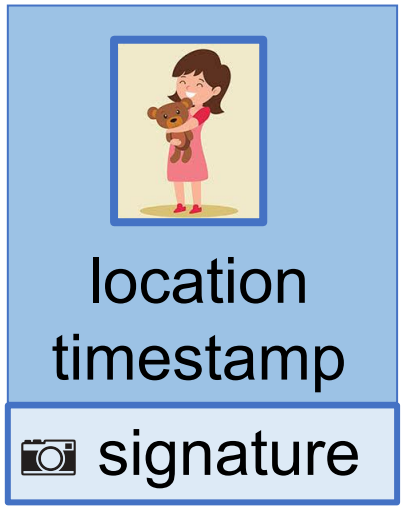
Adobe BBC intel Microsoft PUBLICIS GROUPE SONY Truepic

C2PA: A Content Provenance Standard

Sony Unlocks In-Camera Forgery-Proof Technology

04 Aug, 2022

embedded certified signing key sk_1



Adobe BBC intel Microsoft PUBLICIS GROUPE SONY Truepic

C2PA: A Content Provenance Standard

Sony Unlocks In-Camera Forgery-Proof Technology

04 Aug, 2022

embedded certified signing key sk_1

location
timestamp
signature

C2PA

verify metadata by checking signature

Adobe BBC intel Microsoft PUBLICIS GROUPE SONY Truepic

C2PA: A Content Provenance Standard

Sony Unlocks In-Camera Forgery-Proof Technology

04 Aug, 2022

See Rivadeneira, "Harms Modelling in the C2PA," 2022 for security analysis of C2PA

embedded certified signing key sk_1

location
timestamp
signature

C2PA

verify metadata by checking signature

Adobe BBC intel Microsoft PUBLICIS GROUPE SONY Truepic

A Problem: Post-Processing

- Newspapers often process photos before publication
  - At minimum, need to resize (90 MB $\longrightarrow$ 8 MB)
  - Allowable operations from the *Associated Press:*

    cropping, grayscale, …

A Problem: Post-Processing

- Newspapers often process photos before publication
  - At minimum, need to resize (90 MB $\longrightarrow$ 8 MB)
  - Allowable operations from the *Associated Press:*

    cropping, grayscale, …

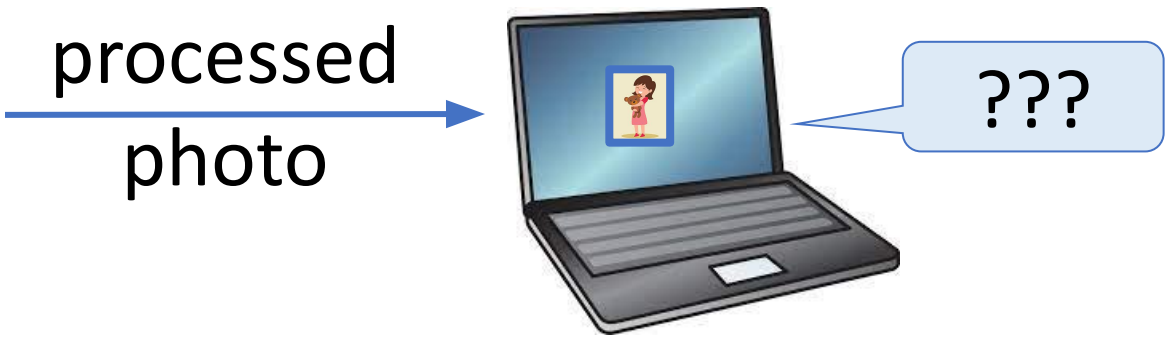
Problem: browser cannot verify the C2PA signature of a processed photo

A Problem: Post-Processing

- Newspapers often process photos before publication
  - At minimum, need to resize (90 MB ⟶ 8 MB)
  - Allowable operations from the *Associated Press:*

    cropping, grayscale, …

Problem: browser cannot verify the C2PA signature of a processed photo

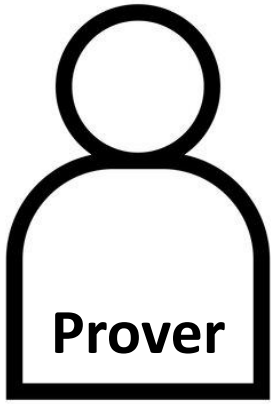


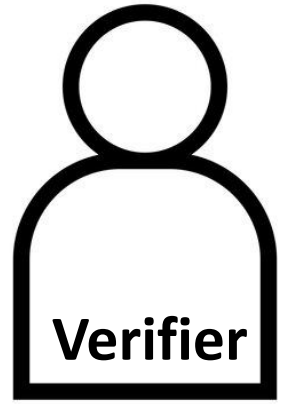
Proposed Solution: ZK-SNARKs!

- ZK-SNARK: efficiently verifiable statement about a secret witness

Proposed Solution: ZK-SNARKs!

- ZK-SNARK: efficiently verifiable statement about a secret witness



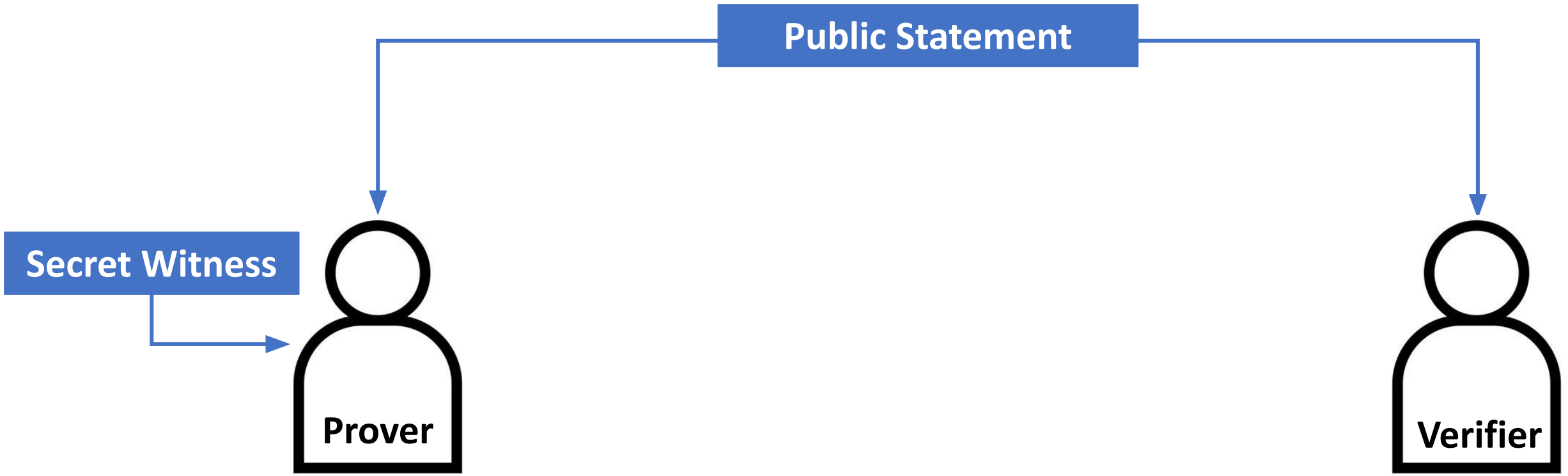


Proposed Solution: ZK-SNARKs!

- ZK-SNARK: efficiently verifiable statement about a secret witness

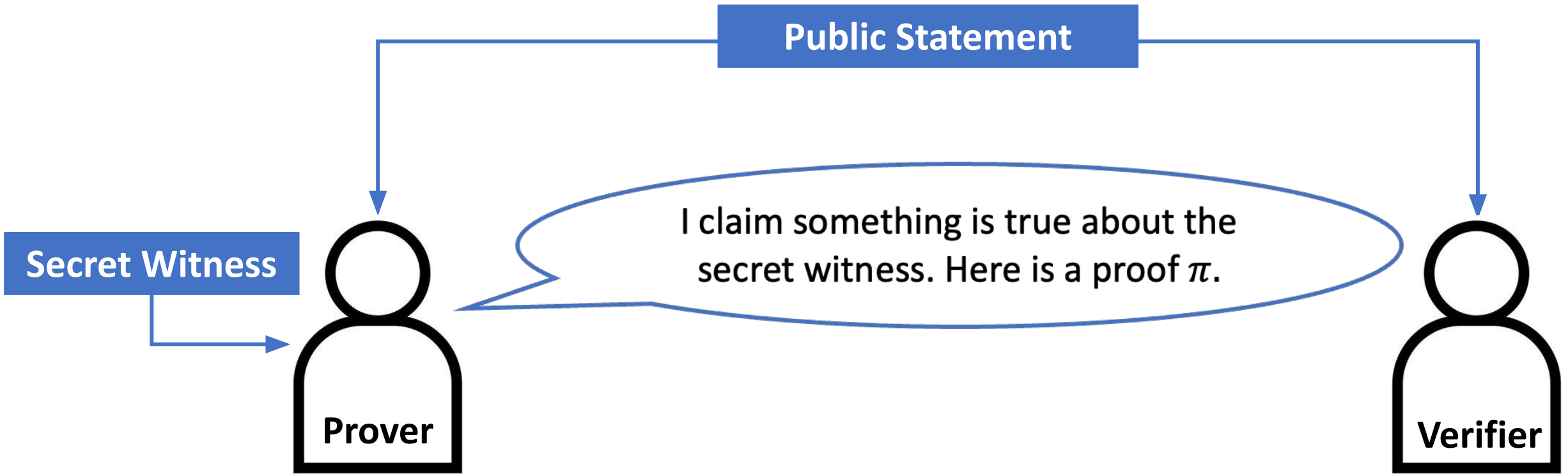
Proposed Solution: ZK-SNARKs!

- ZK-SNARK: efficiently verifiable statement about a secret witness



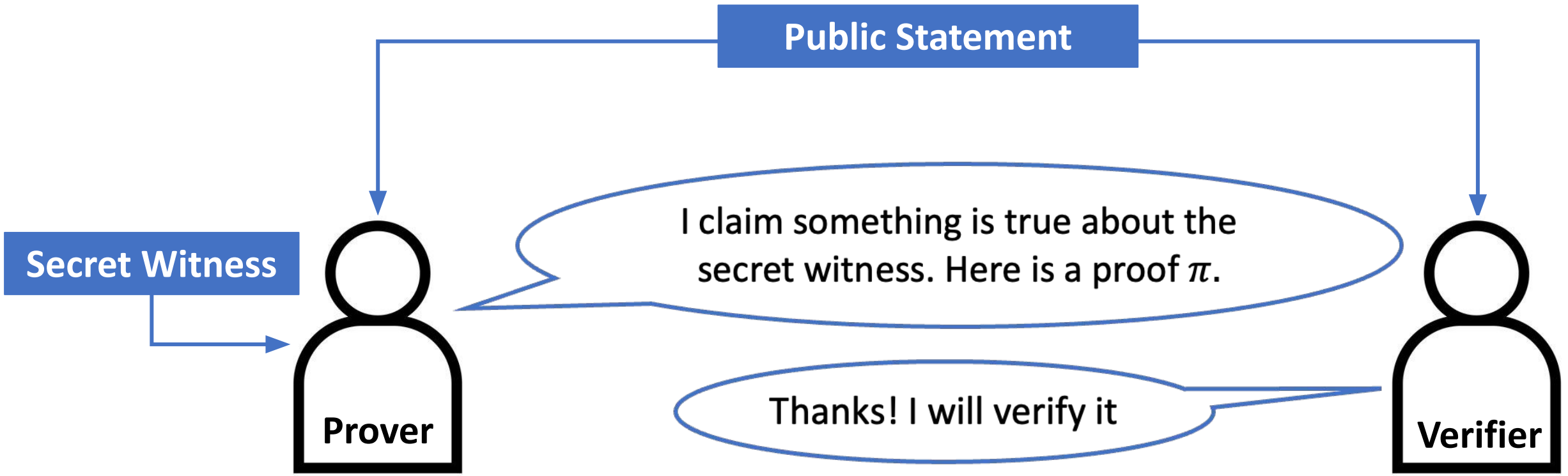
Proposed Solution: ZK-SNARKs!

- ZK-SNARK: efficiently verifiable statement about a secret witness



Proposed Solution: ZK-SNARKs!

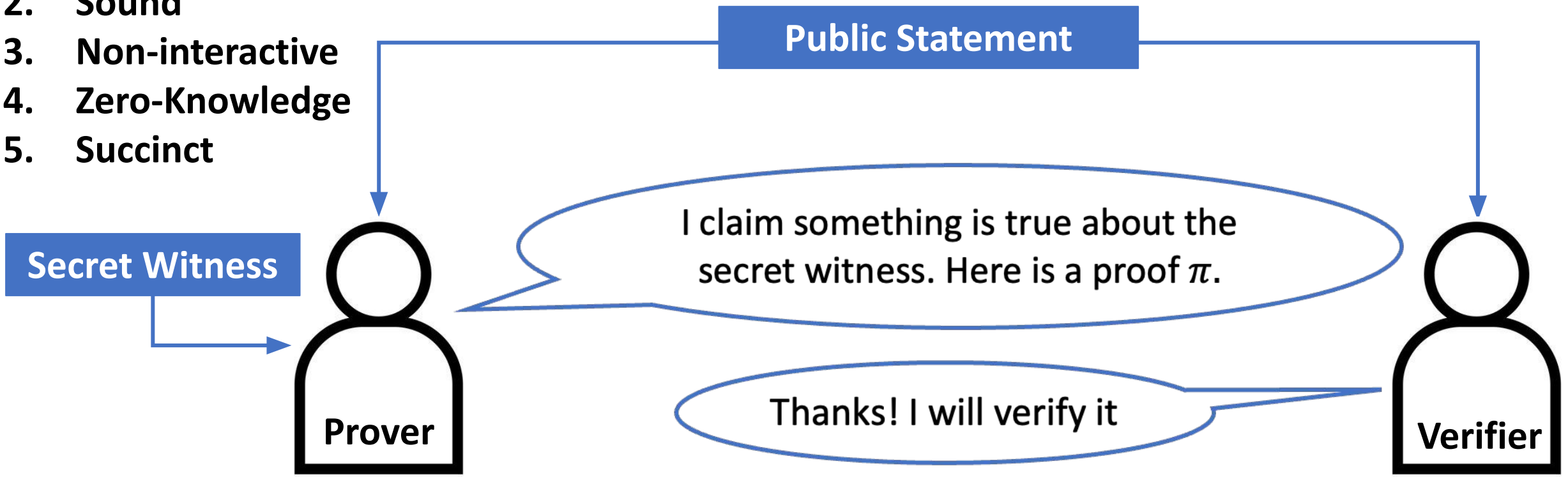
- ZK-SNARK: efficiently verifiable statement about a secret witness



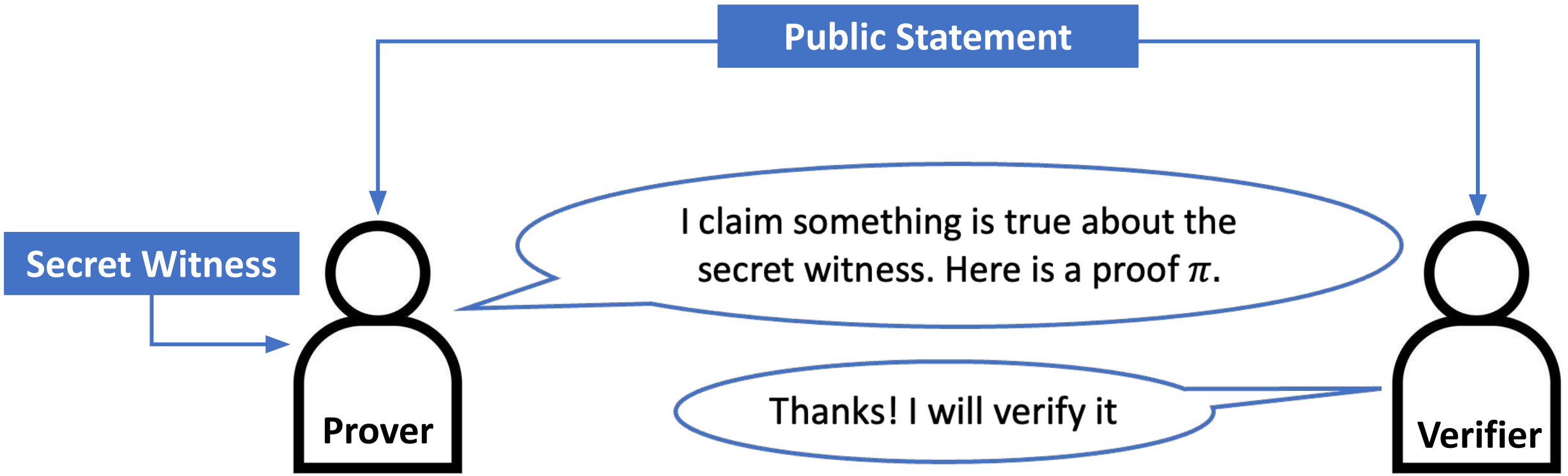
Proposed Solution: ZK-SNARKs!

- ZK-SNARK: efficiently verifiable statement about a secret witness

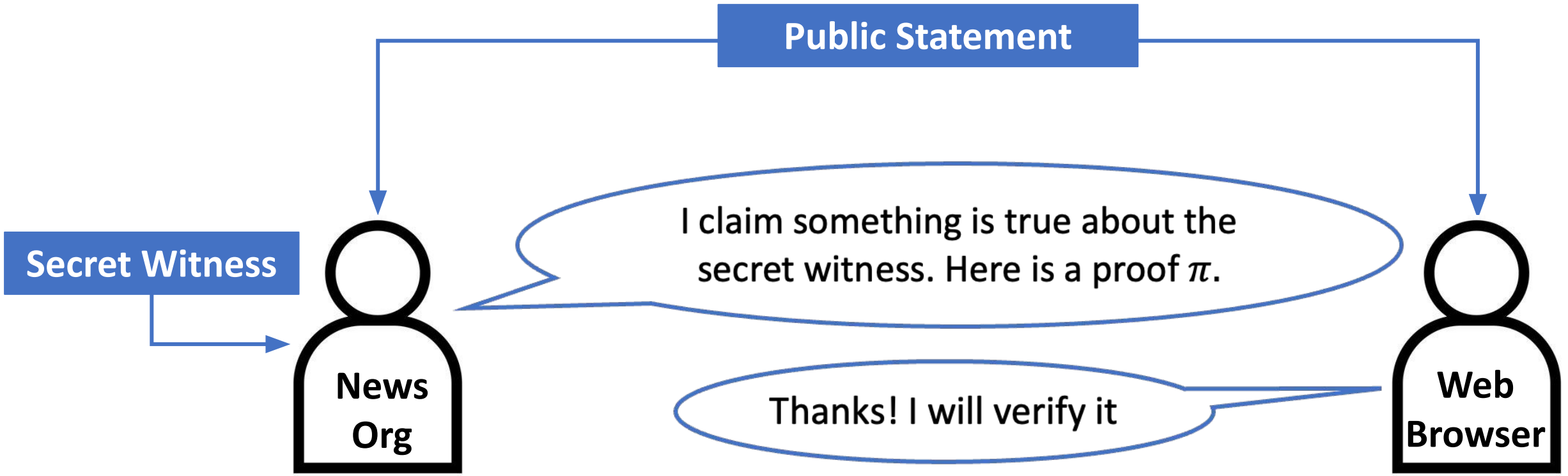
1. **Complete**
2. **Sound**
3. **Non-interactive**
4. **Zero-Knowledge**
5. **Succinct**



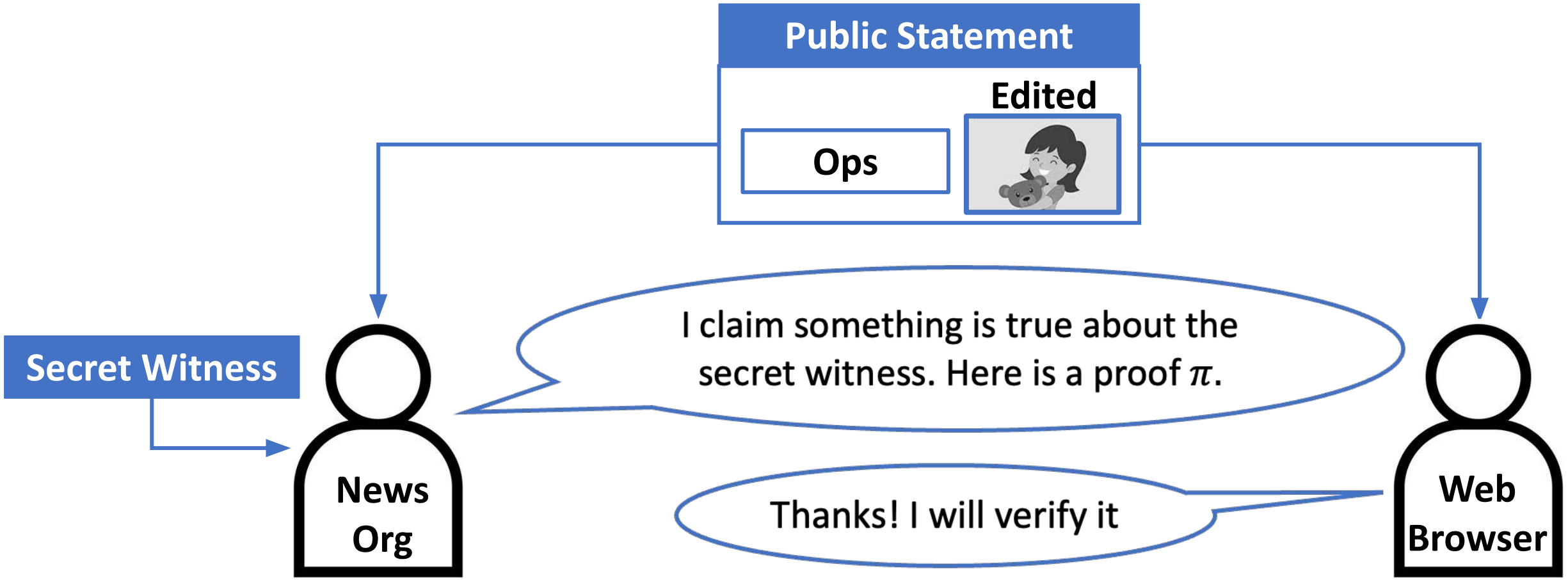
Proposed Solution: ZK-SNARKs!



Proposed Solution: ZK-SNARKs!

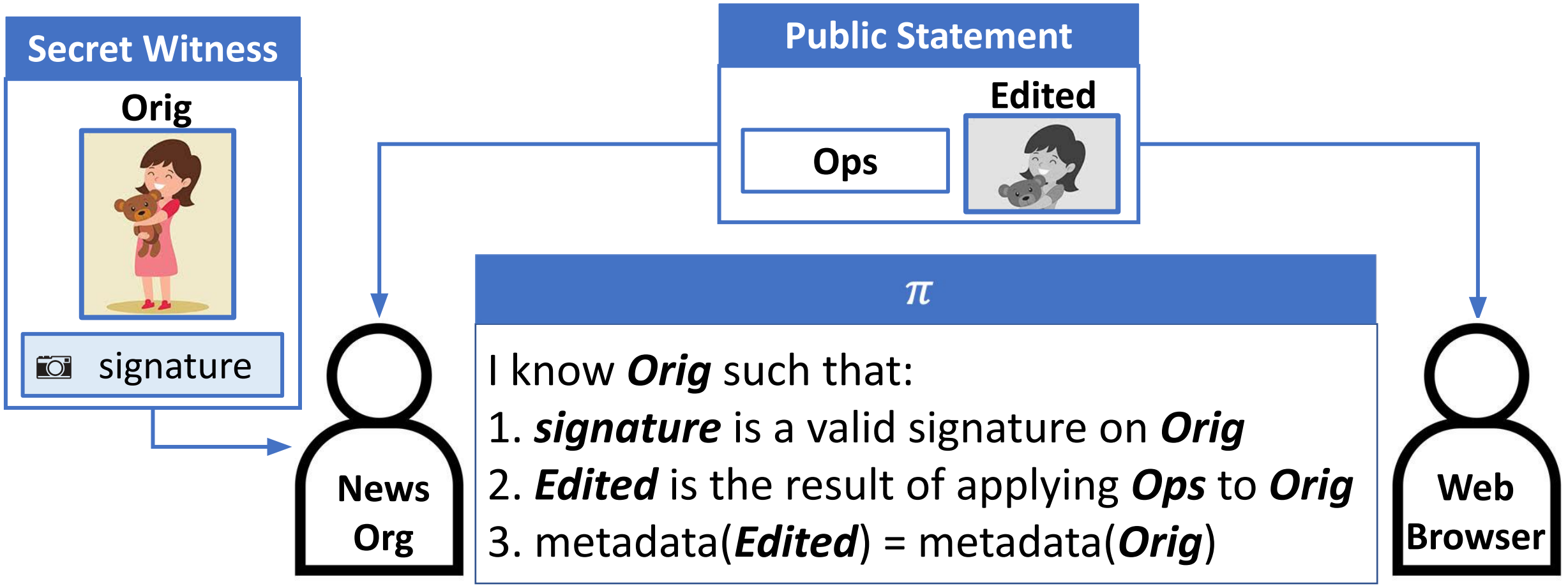


Proposed Solution: ZK-SNARKs!



Proposed Solution: ZK-SNARKs!

Proposed Solution: ZK-SNARKs!



Proposed Solution: ZK-SNARKs!

We rely on all properties of ZK-SNARKs!

Secret Witness

Orig

signature

Public Statement

Edited

Ops

News Org

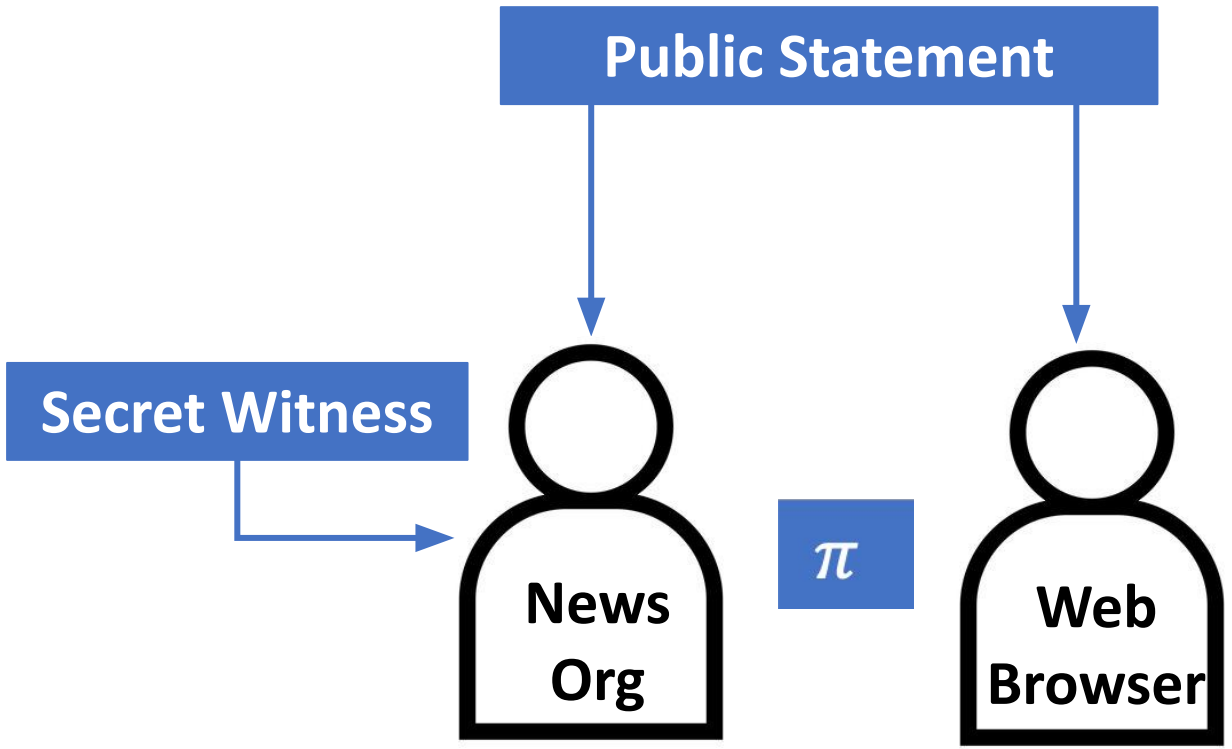
π

I know ***Orig*** such that:

1. ***signature*** is a valid signature on ***Orig***
2. ***Edited*** is the result of applying ***Ops*** to ***Orig***
3. metadata(***Edited***) = metadata(***Orig***)

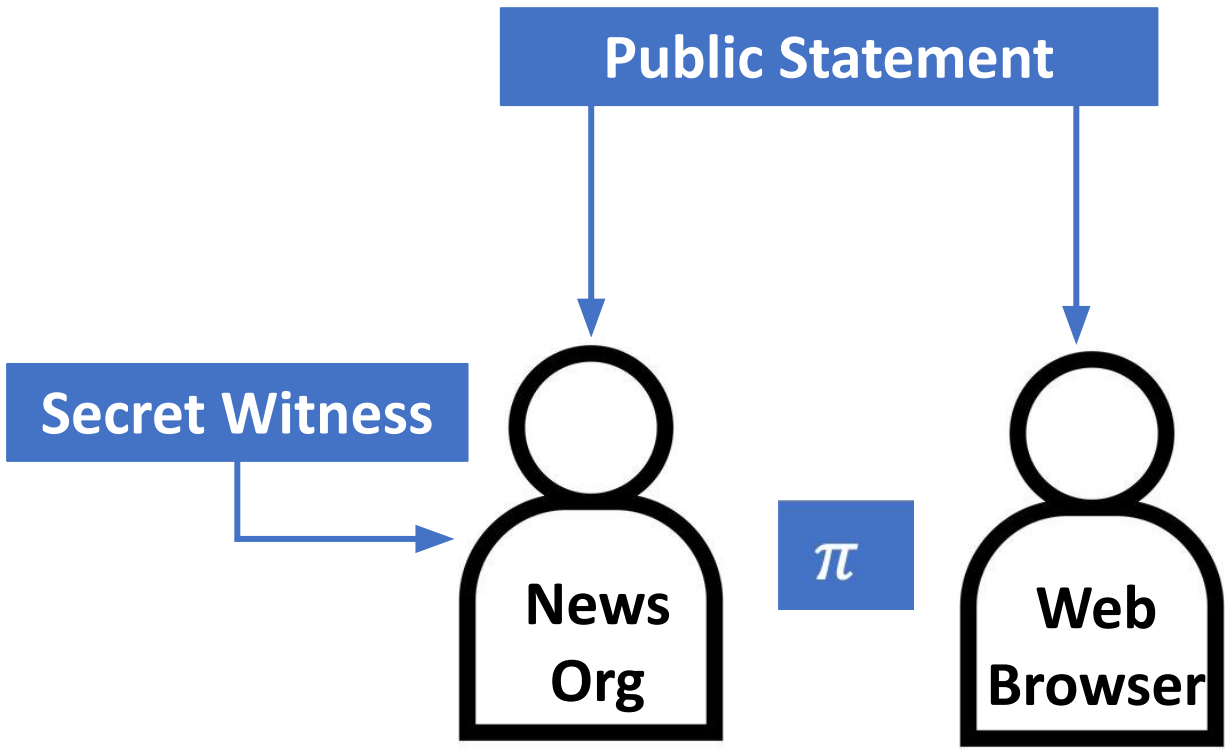
Web Browser

Proposed Solution: ZK-SNARKs!



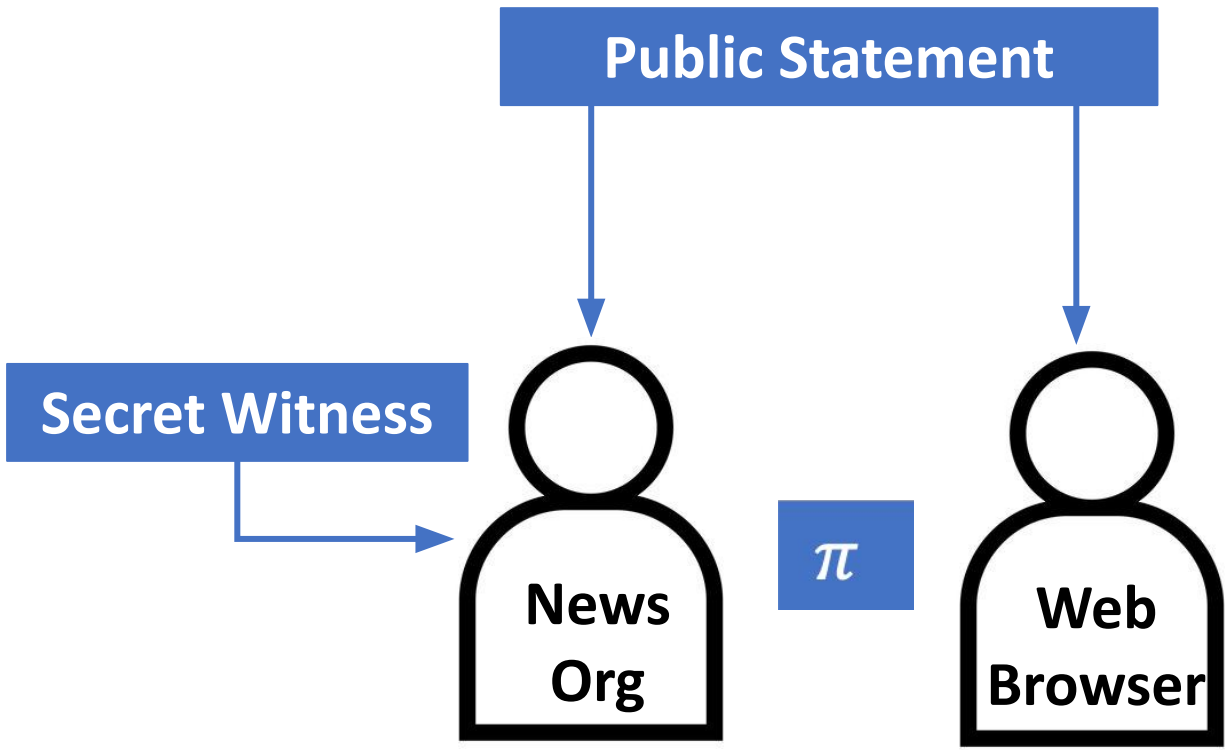
1. **Complete/Sound:** verifier doesn't need to trust prover

Proposed Solution: ZK-SNARKs!



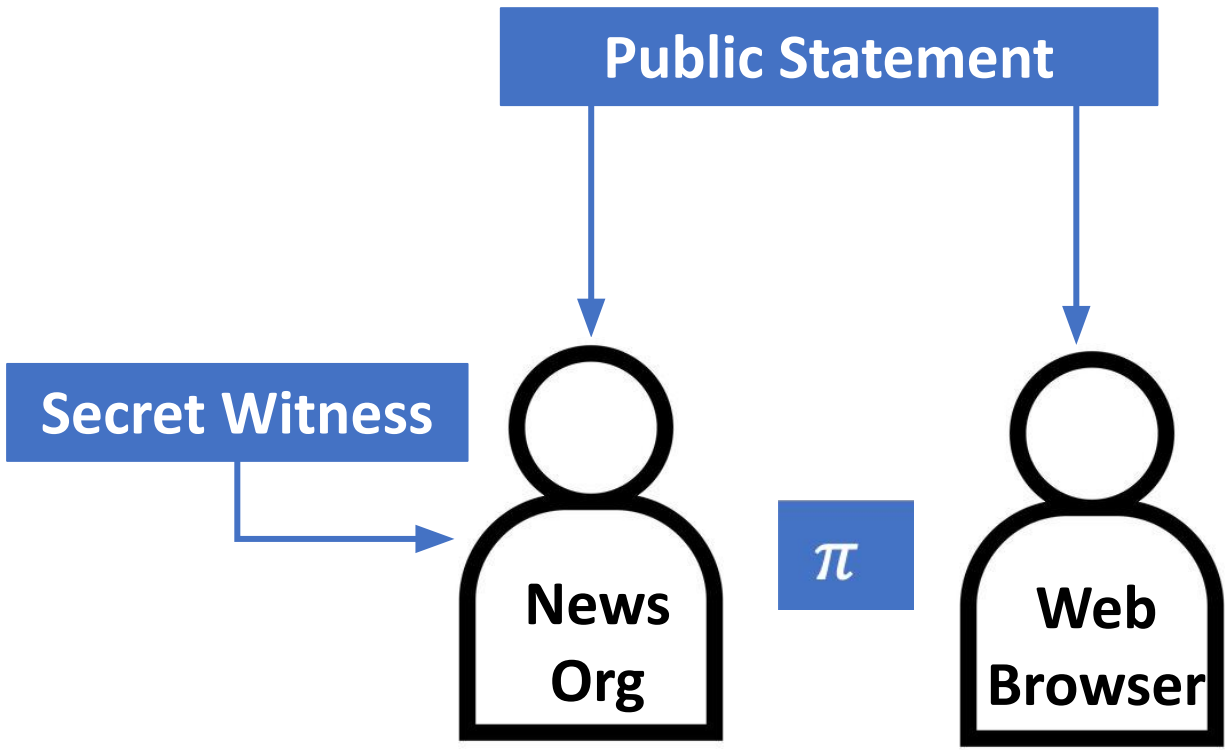
1. **Complete/Sound:** verifier doesn't need to trust prover
2. **Non-interactive:** interactivity would entail unique proofs for each browser

Proposed Solution: ZK-SNARKs!



1. **Complete/Sound:** verifier doesn't need to trust prover
2. **Non-interactive:** interactivity would entail unique proofs for each browser
3. **Zero-Knowledge:** useful for ops such as cropping

Proposed Solution: ZK-SNARKs!



1. **Complete/Sound:** verifier doesn't need to trust prover
2. **Non-interactive:** interactivity would entail unique proofs for each browser
3. **Zero-Knowledge:** useful for ops such as cropping
4. **Succinct:** web browser can efficiently verify proof

Verifying Signatures in a SNARK Prover

π
I know ***Orig*** such that: 1. ***signature*** is a valid signature on ***Orig*** 2. ***Edited*** is the result of applying ***Ops*** to ***Orig*** 3. metadata(***Edited***) = metadata(***Orig***)

Verifying Signatures in a SNARK Prover

π
I know ***Orig*** such that: 1. ***signature*** is a valid signature on ***Orig*** 2. ***Edited*** is the result of applying ***Ops*** to ***Orig*** 3. metadata(***Edited***) = metadata(***Orig***)

?

Proofs for Post-Processing Ops

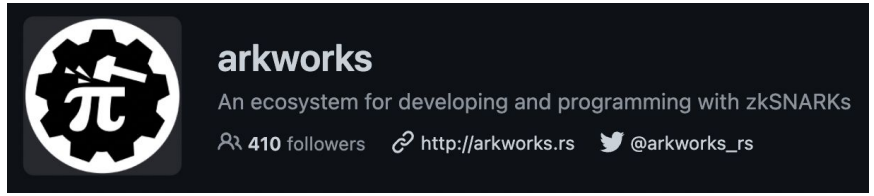
- PhotoProof (Naveh and Tromer, 2016): a few minutes to generate photo editing proofs for 128 x 128 pixel image

Proofs for Post-Processing Ops

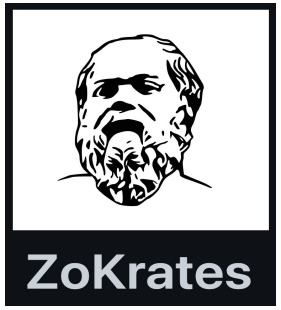
- PhotoProof (Naveh and Tromer, 2016): a few minutes to generate photo editing proofs for 128 x 128 pixel image
- New tools enable faster development!

==> circom
CIRCUIT COMPILER

halo2 crates.io v0.1.0-beta.2



gnark
A fast zk-SNARK library that offers a high-level API to design circuits



The Noir Programming Language

Performance for Post-Processing Ops Proofs

For resizing, cropping, grayscale ops on images of about 6000 x 4000 pixels (~30MP) using Circom:

- Proof generation time: <1 second
- Witness generation time: <4 minutes

by newspaper once per image

- Verification time: 2 ms
- Proof size: <1 KB

by browser

Verifying Signatures in a SNARK Prover

π
I know ***Orig*** such that: 1. ***signature*** is a valid signature on ***Orig*** 2. ***Edited*** is the result of applying ***Ops*** to ***Orig*** 3. metadata(***Edited***) = metadata(***Orig***)

Verifying Signatures in a SNARK Prover

π
I know ***Orig*** such that: 1. ***signature*** is a valid signature on ***Orig*** ? 2. ***Edited*** is the result of applying ***Ops*** to ***Orig*** ✓ 3. metadata(***Edited***) = metadata(***Orig***)

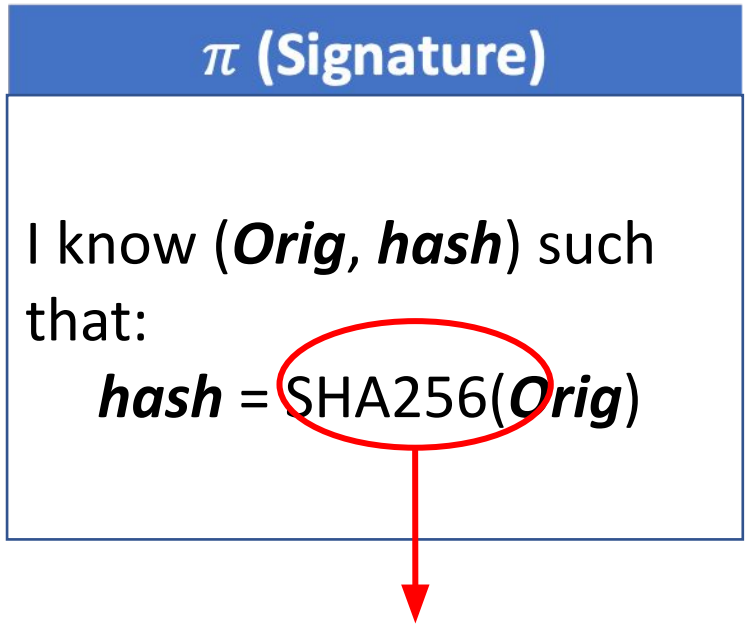
Verifying Signatures in a SNARK Prover

Attempt 1

π (Signature)
I know (***Orig***, ***hash***) such that: ***hash*** = SHA256(***Orig***)

Verifying Signatures in a SNARK Prover

Attempt 1



Verifying Signatures in a SNARK Prover

Attempt 1

π (Signature)

I know (***Orig***, ***hash***) such that:

hash = SHA256(***Orig***)

Too slow for 30 MP!

Attempt 2

π (Signature)

I know (***Orig***, ***hash***) such that:

hash = Poseidon(***Orig***)

Verifying Signatures in a SNARK Prover

Attempt 1

π (Signature)

I know (***Orig***, ***hash***) such that:

hash = SHA256(***Orig***)

Too slow for 30 MP!

Attempt 2

π (Signature)

I know (***Orig***, ***hash***) such that:

hash = Poseidon(***Orig***)

SNARK-friendly hash

Verifying Signatures in a SNARK Prover

Attempt 1

π (Signature)

I know (***Orig***, ***hash***) such that:

hash = SHA256(***Orig***)

Too slow for 30 MP!

Attempt 2

π (Signature)

I know (***Orig***, ***hash***) such that:

hash = Poseidon(***Orig***)

SNARK-friendly hash …but still too slow for 30MP!

Verifying Signatures in a SNARK Prover

Attempt 1

π (Signature)

I know (***Orig***, ***hash***) such that:

hash = SHA256(***Orig***)

Too slow for 30 MP!

Attempt 2

π (Signature)

I know (***Orig***, ***hash***) such that:

hash = Poseidon(***Orig***)

SNARK-friendly hash …but still too slow for 30MP!

Attempt 3

π (Signature)

I know (***Orig***, ***hash***) such that:

hash = Poseidon(LatticeHash(***Orig***))

Verifying Signatures in a SNARK Prover

Attempt 1

π (Signature)

I know (***Orig***, ***hash***) such that:

hash = SHA256(***Orig***)

Too slow for 30 MP!

Attempt 2

π (Signature)

I know (***Orig***, ***hash***) such that:

hash = Poseidon(***Orig***)

SNARK-friendly hash …but still too slow for 30MP!

Attempt 3

π (Signature)

I know (***Orig***, ***hash***) such that:

hash = Poseidon(LatticeHash(***Orig***))

Verifying Signatures in a SNARK Prover

Poseidon hash of lattice hash [GGH'96 , SCMPGLW'08]

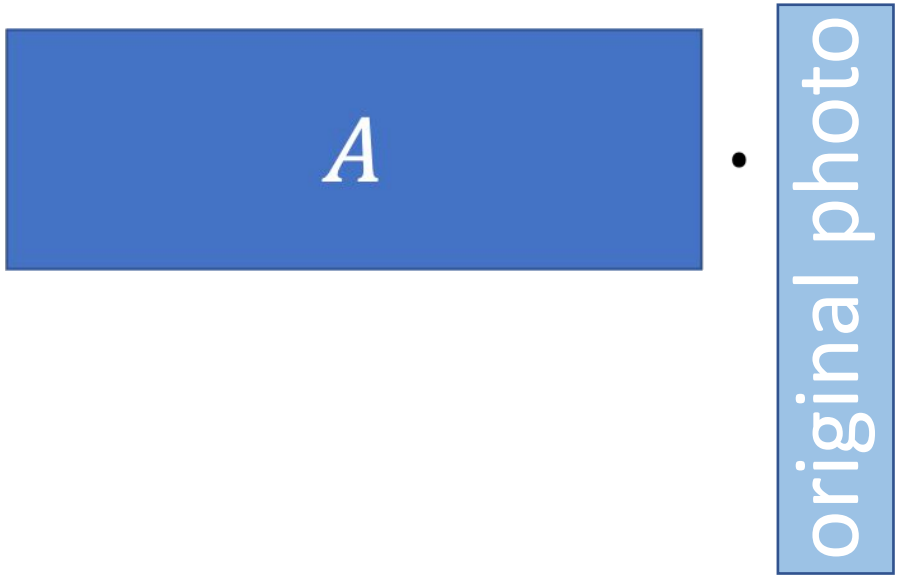
Verifying Signatures in a SNARK Prover

Poseidon hash of lattice hash [GGH'96 , SCMPGLW'08]

- A is random matrix from finite field $\mathbb{F}_q$

Verifying Signatures in a SNARK Prover

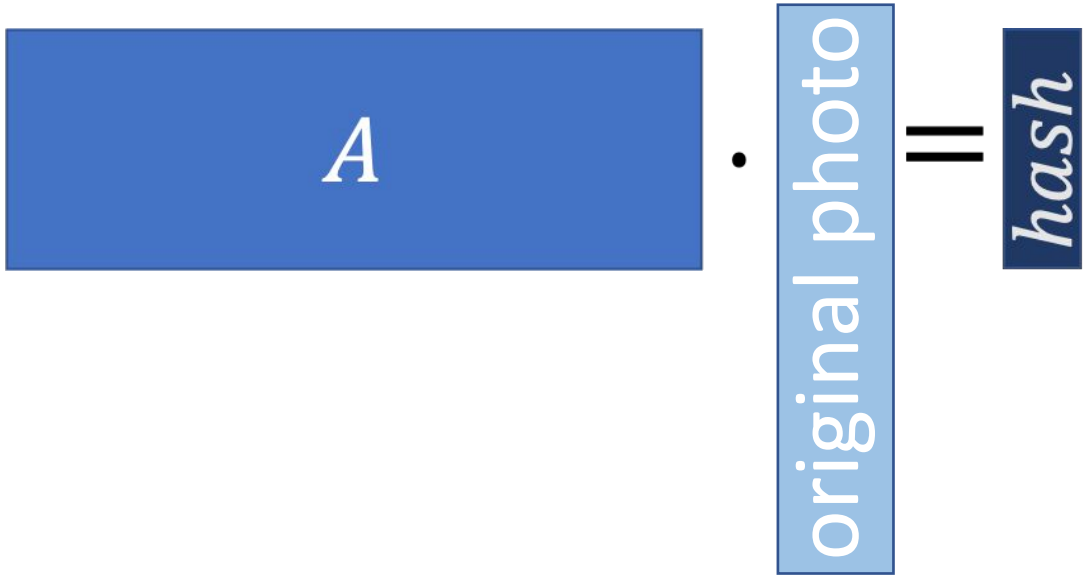
Poseidon hash of lattice hash [GGH'96 , SCMPGLW'08]



- A is random matrix from finite field $\mathbb{F}_q$
- $\vec{x}$ is low norm vector in $\mathbb{F}_q$ representing the input

Verifying Signatures in a SNARK Prover

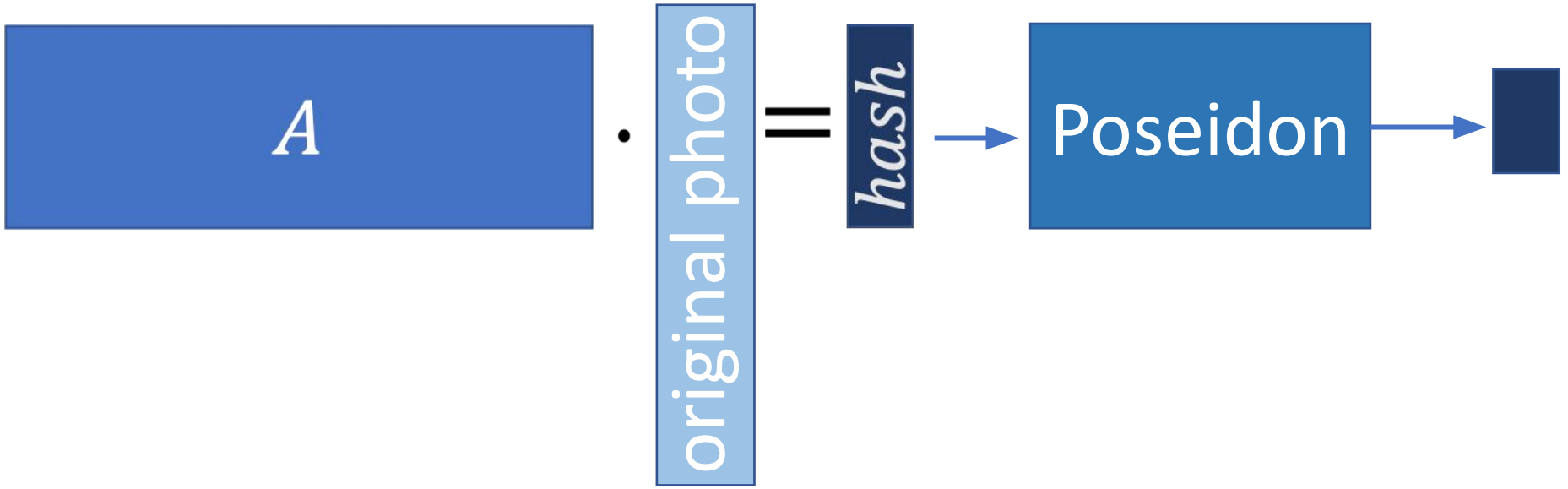
Poseidon hash of lattice hash [GGH'96 , SCMPGLW'08]



- A is random matrix from finite field $\mathbb{F}_q$
- $\vec{x}$ is low norm vector in $\mathbb{F}_q$ representing the input

Verifying Signatures in a SNARK Prover

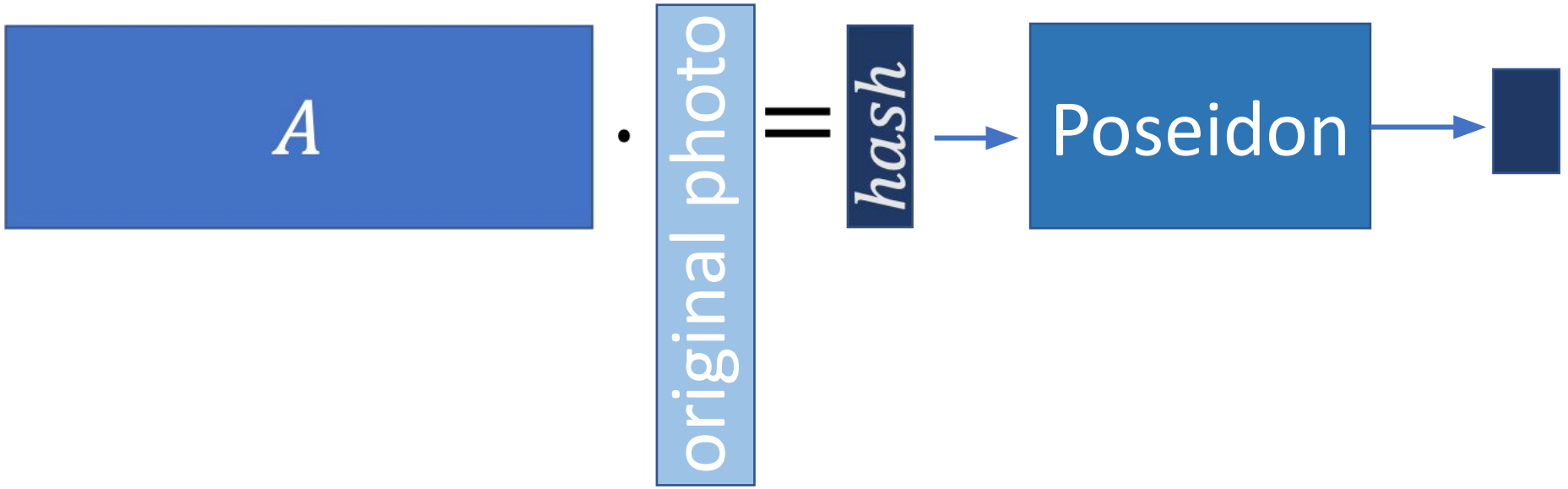
Poseidon hash of lattice hash [GGH'96 , SCMPGLW'08]



- A is random matrix from finite field $\mathbb{F}_q$
- $\vec{x}$ is low norm vector in $\mathbb{F}_q$ representing the input

Verifying Signatures in a SNARK Prover

Poseidon hash of lattice hash [GGH'96 , SCMPGLW'08]



- Collision-resistant assuming SIS ⟶ prover must prove original photo representation is low norm

Verifying Signatures in a SNARK Prover

To prove $\vec{x}$ is low norm,

i.e., $\vec{x} \in \{0, 1, \dots, R-1\}^n$:

***[BCGJM'18, GWC'19, GW'20]

Verifying Signatures in a SNARK Prover

To prove $\vec{x}$ is low norm,

i.e., $\vec{x} \in \{0, 1, \ldots, R-1\}^n$:

$R = 4$

$\vec{x}$ | 2 | 0 | 2 |

***[BCGJM'18, GWC'19, GW'20]

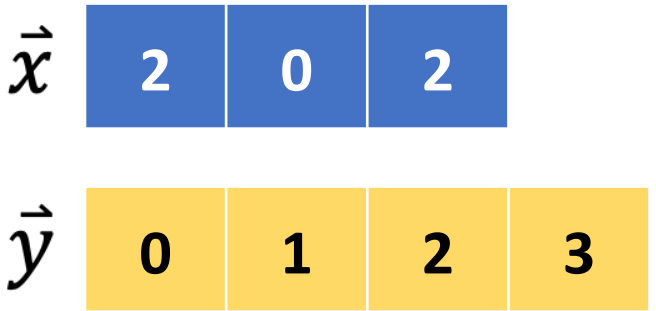
Verifying Signatures in a SNARK Prover

To prove $\vec{x}$ is low norm,

i.e., $\vec{x} \in \{0, 1, \dots, R-1\}^n$:

- $\vec{y} := [0, 1, \dots, R-1]$

$R = 4$



***[BCGJM'18, GWC'19, GW'20]

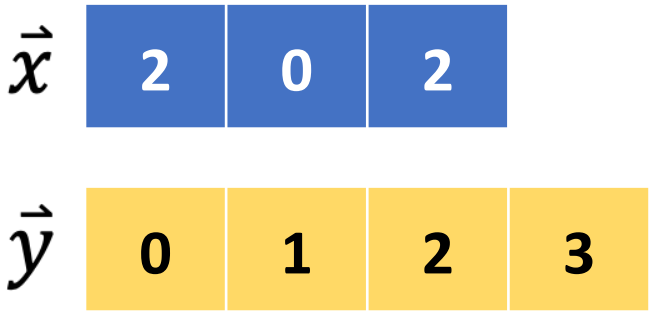
Verifying Signatures in a SNARK Prover

To prove $\vec{x}$ is low norm,

i.e., $\vec{x} \in \{0, 1, \dots, R-1\}^n$:

- $\vec{y} := [0, 1, \dots, R-1]$
- $\vec{z} := sort(\vec{x} \,||\vec{y})$

$R = 4$



***[BCGJM'18, GWC'19, GW'20]

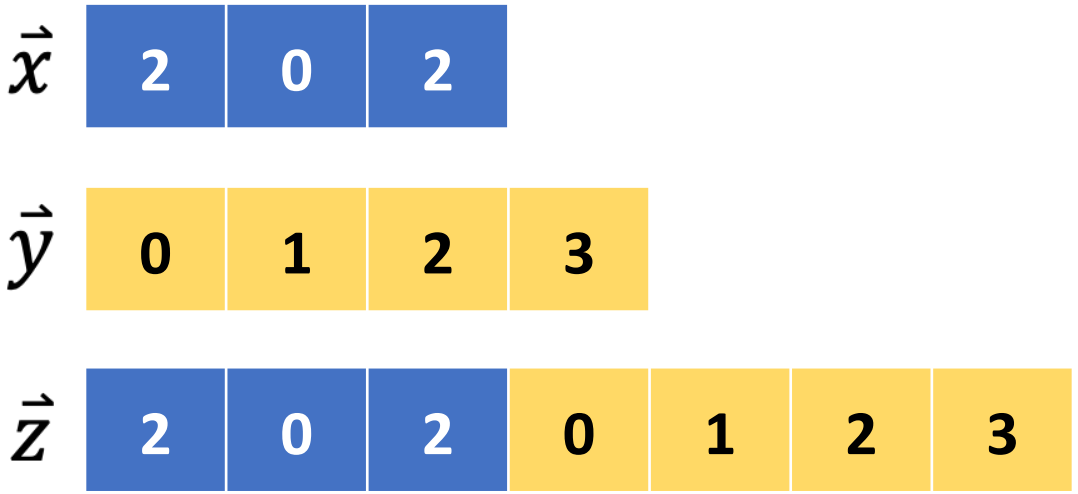
Verifying Signatures in a SNARK Prover

To prove $\vec{x}$ is low norm,

i.e., $\vec{x} \in \{0, 1, \dots, R-1\}^n$:

- $\vec{y} := [0, 1, \dots, R-1]$
- $\vec{z} := sort(\vec{x} \,||\vec{y})$

$R = 4$



***[BCGJM'18, GWC'19, GW'20]

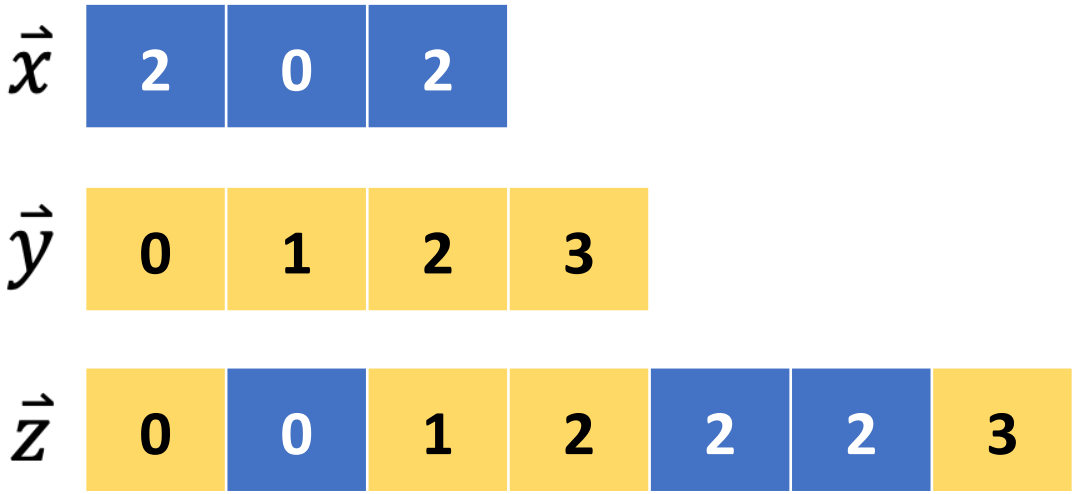
Verifying Signatures in a SNARK Prover

To prove $\vec{x}$ is low norm,

i.e., $\vec{x} \in \{0, 1, \dots, R-1\}^n$:

- $\vec{y} := [0, 1, \dots, R-1]$
- $\vec{z} := sort(\vec{x} \,||\vec{y})$

$R = 4$



***[BCGJM'18, GWC'19, GW'20]

Verifying Signatures in a SNARK Prover

To prove $\vec{x}$ is low norm,

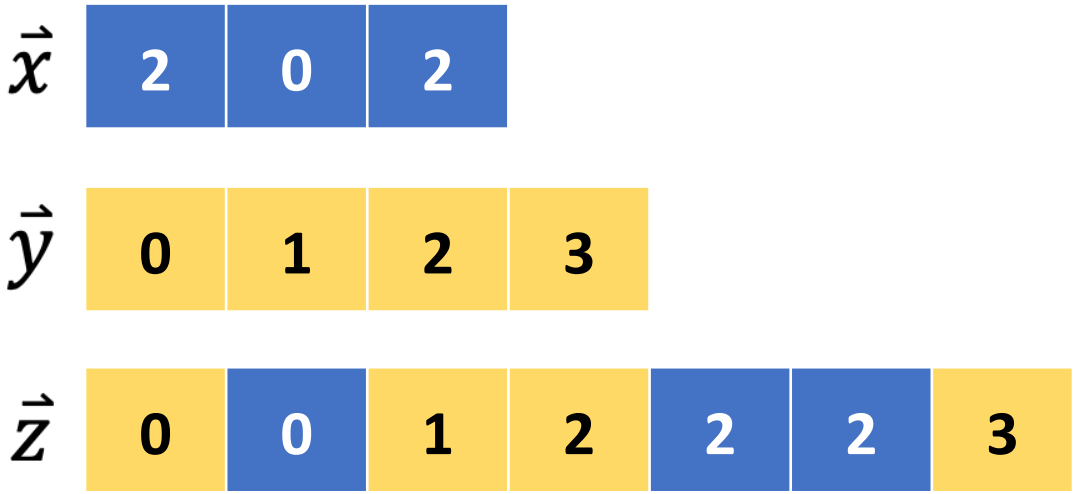
i.e., $\vec{x} \in \{0, 1, \dots, R-1\}^n$:

- $\vec{y} := [0, 1, \dots, R-1]$
- $\vec{z} := sort(\vec{x} \,||\vec{y})$

Must show:

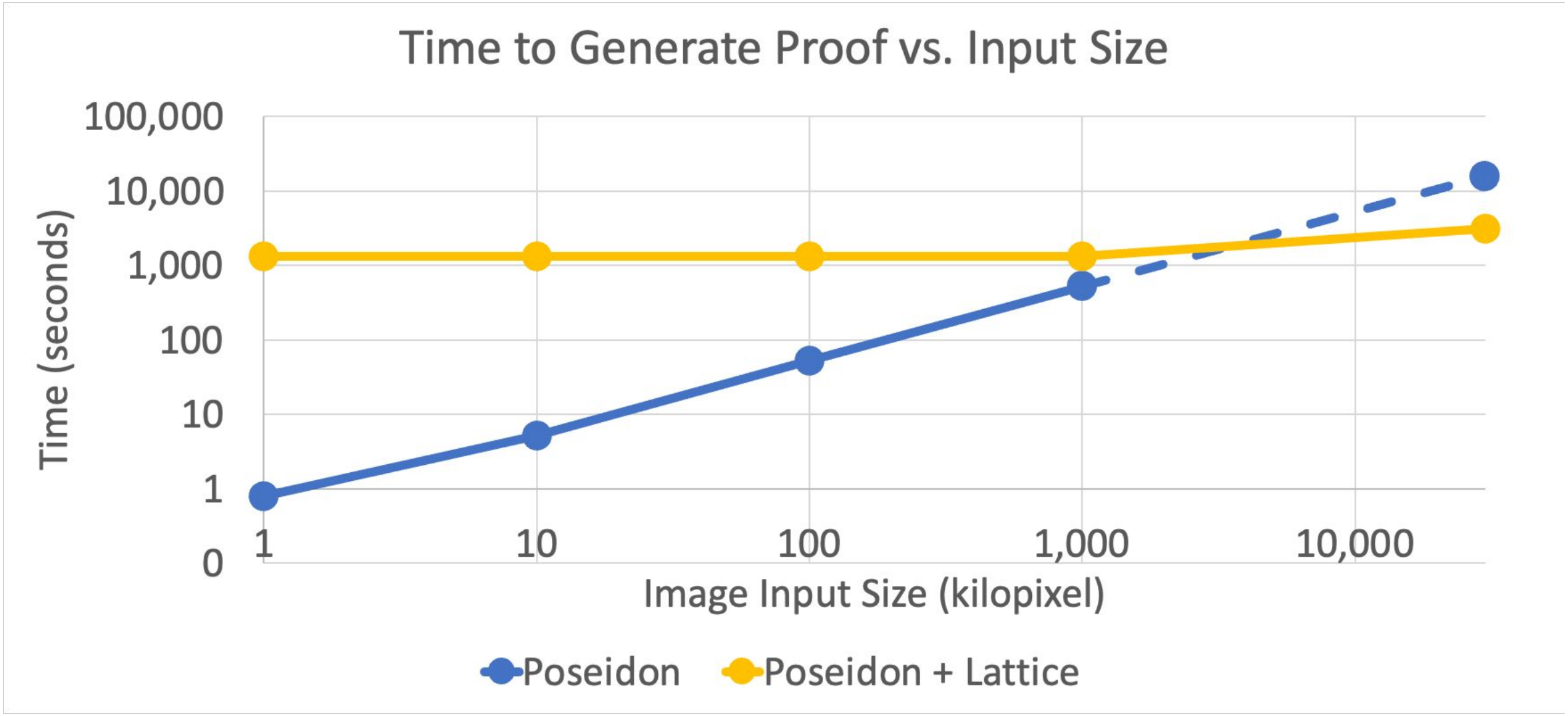
- $\vec{z}$ is permutation of $\vec{x}$ and $\vec{y}$
- $\vec{z}[i+1] - \vec{z}[i] \in \{0, 1\}$

$R = 4$

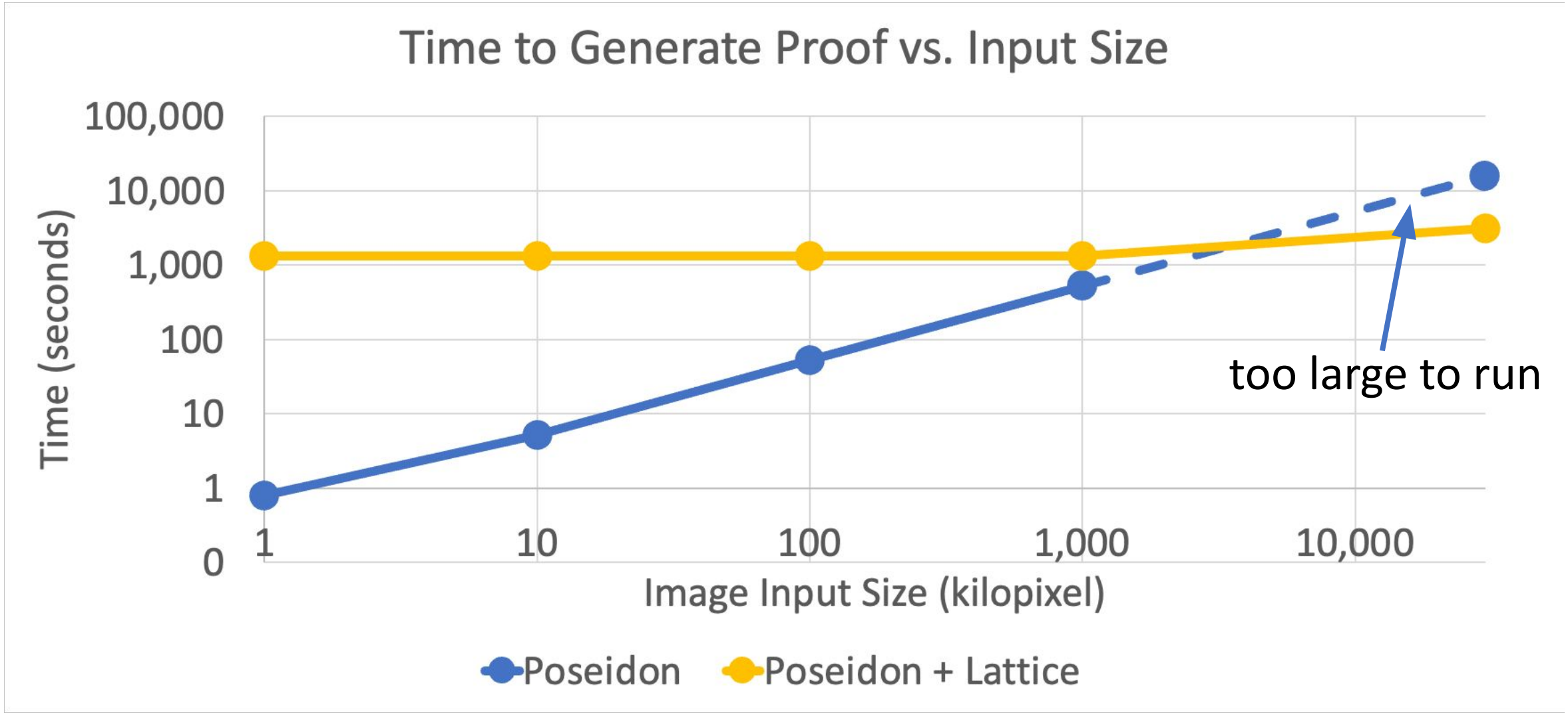


***[BCGJM'18, GWC'19, GW'20]

Performance Results for Proving Signatures



Performance Results for Proving Signatures



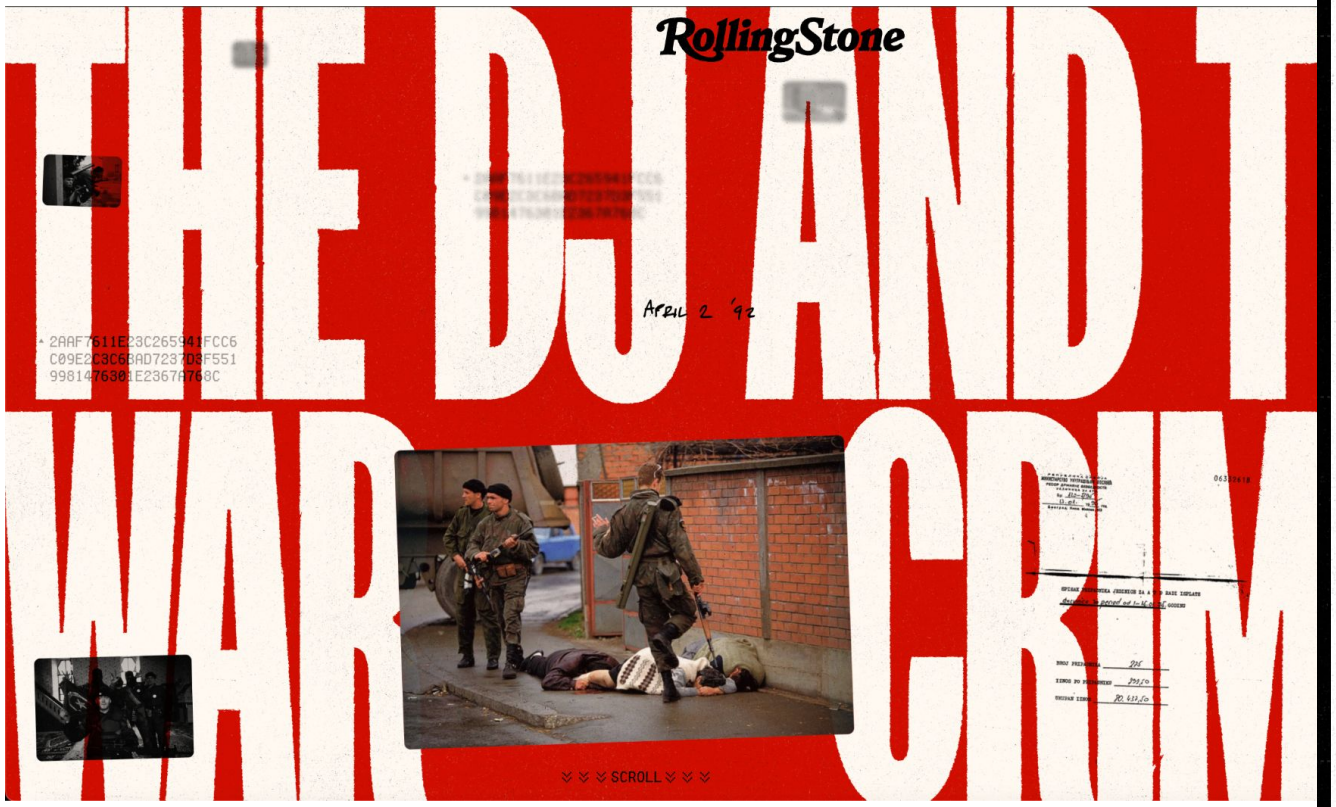
Verifying Signatures in a SNARK Prover

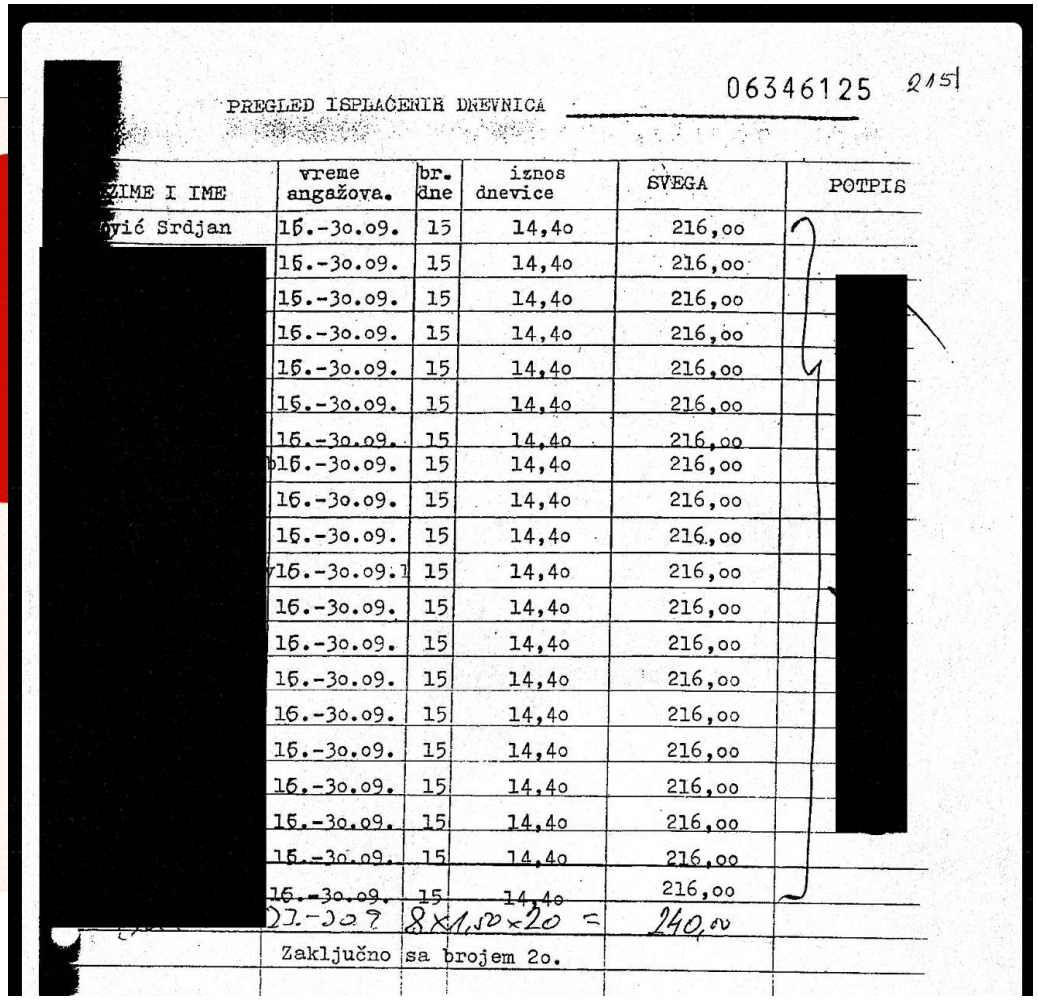
π
I know ***Orig*** such that: 1. ***signature*** is a valid signature on ***Orig*** ✓ 2. ***Edited*** is the result of applying ***Ops*** to ***Orig*** ✓ 3. metadata(***Edited***) = metadata(***Orig***)

Real World Example: Redaction Proofs

***Joint work with Starling Lab (https://rb.gy/vcc3wu)

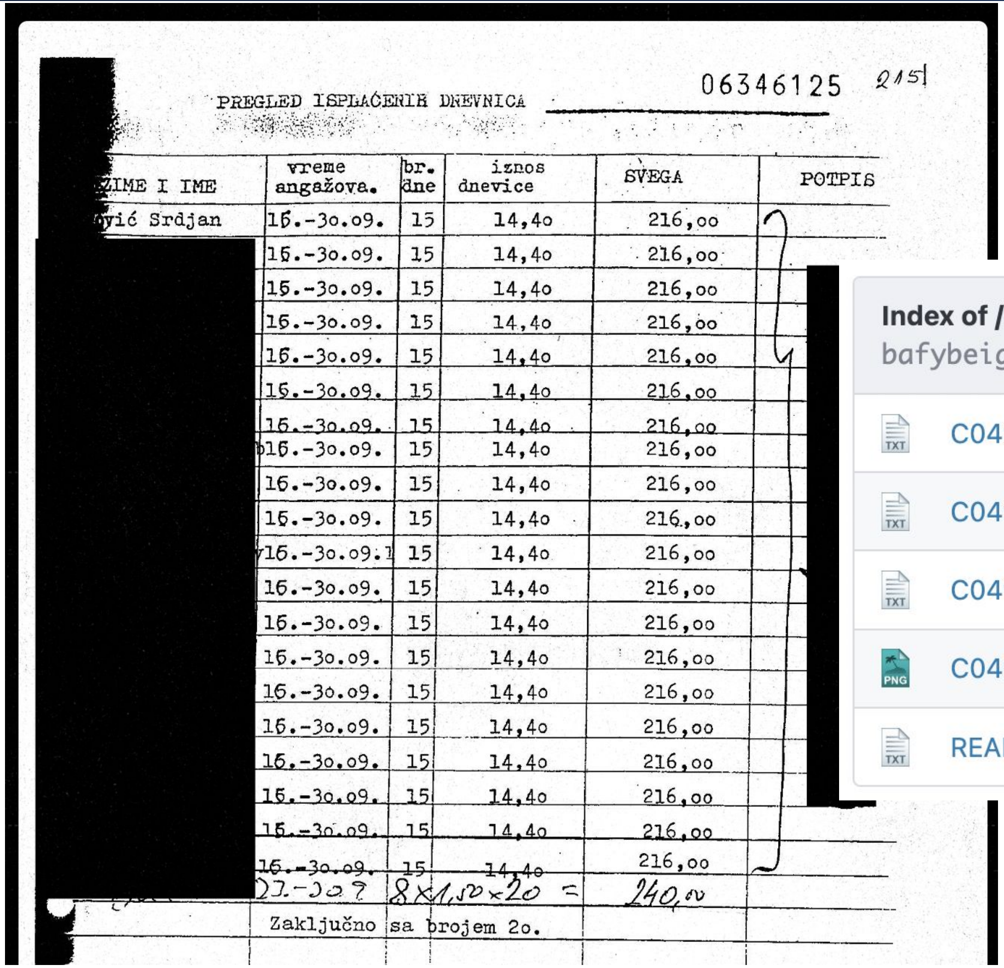
Real World Example: Redaction Proofs





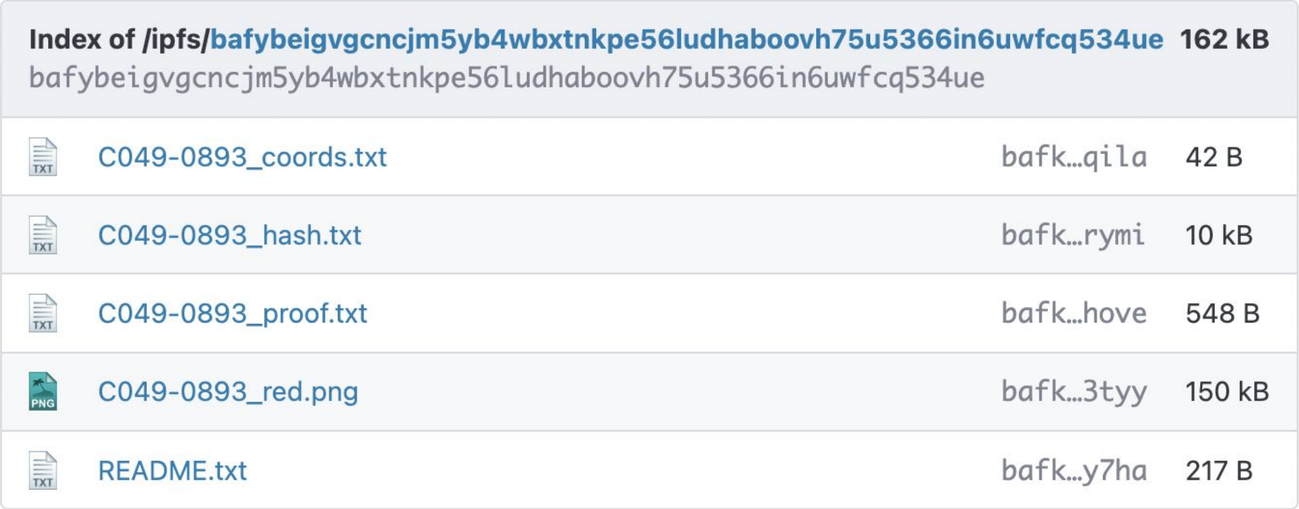
***Joint work with Starling Lab (https://rb.gy/vcc3wu)

Real World Example: Redaction Proofs



PREGLED ISPLAĆENIH DNEVNICA 06346125 2151

[redacted]ZIME I IME	vreme angažova.	br. dne	iznos dnevice	SVEGA	POTPIS
[redacted] Srdjan	16.-30.09.	15	14,40	216,00	
[redacted]	16.-30.09.	15	14,40	216,00	
[redacted]	16.-30.09.	15	14,40	216,00	
[redacted]	16.-30.09.	15	14,40	216,00	
[redacted]	16.-30.09.	15	14,40	216,00	
[redacted]	16.-30.09.	15	14,40	216,00	
[redacted]	16.-30.09.	15	14,40	216,00	
[redacted]	16.-30.09.	15	14,40	216,00	
[redacted]	16.-30.09.	15	14,40	216,00	
[redacted]	16.-30.09.	15	14,40	216,00	
[redacted]	16.-30.09.	15	14,40	216,00	
[redacted]	16.-30.09.	15	14,40	216,00	
[redacted]	16.-30.09.	15	14,40	216,00	
[redacted]	16.-30.09.	15	14,40	216,00	
[redacted]	16.-30.09.	15	14,40	216,00	
[redacted]	16.-30.09.	15	14,40	216,00	
[redacted]	16.-30.09.	15	14,40	216,00	
[redacted]	16.-30.09.	15	14,40	216,00	
[redacted]	16.-30.09.	15	14,40	216,00	
[redacted]	16.-30.09.	15	14,40	216,00	
[redacted]	22.-30.9	8x1,50x20 =		240,00	
	Zaključno	sa brojem 2o.			



***Joint work with Starling Lab (https://rb.gy/vcc3wu)

Conclusions

- Proof systems have greatly improved due to their need in blockchains ⇒ non-blockchain applications benefit
- Proofs about large images (4000 × 6000) can be done in reasonable time
- Applicable to C2PA for image authenticity
  - If keys extracted, all bets are off ⇒ could rely on hardware enclaves
- Open problem: ZK proofs for videos?