Weak Fiat-Shamir Attacks on Modern Proof Systems

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Real World Cryptography 2024

Proof Systems and Applications

Proof Systems and Applications

Zcash is cash for the new age.

Monero Means Money

Private, decentralized cryptocurrency that keeps your finances confidential and secure.

polygon 2.0

The Value Layer of the Internet

STARKWARE

STARK Proof Pioneers

Bringing scalability, security, and privacy to a blockchain near you

Filecoin is a decentralized storage network designed to store humanity's most important information.

Regulated And Decentralized Finance

Espresso helps rollups:

Ethereum's First zkRollup Layer 2

Ethereum, ncrypted

AN INTENT-CENTRIC PROTOCOL FOR COMPOSABLE PRIVACY, DECENTRALIZED COUNTERPARTY DISCOVERY, SOLVING, AND ATOMIC MULTI-CHAIN SETTLEMENT

Aleo

era

ztec is a first-of-its-kind hybrid zkRollup supporting both public and ivate smart contract execution.

The Native zkEVM Scal Solution for Ethereu

Scroll is a zkEVM-based zkRollup on Ethereum that ena native compatibility for existing Ethereum applications an

Mina is building the p security layer for web knowledge proofs.

The ZK Coprocessor for Ethereum

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Do implementations of proof systems match their theoretical security?

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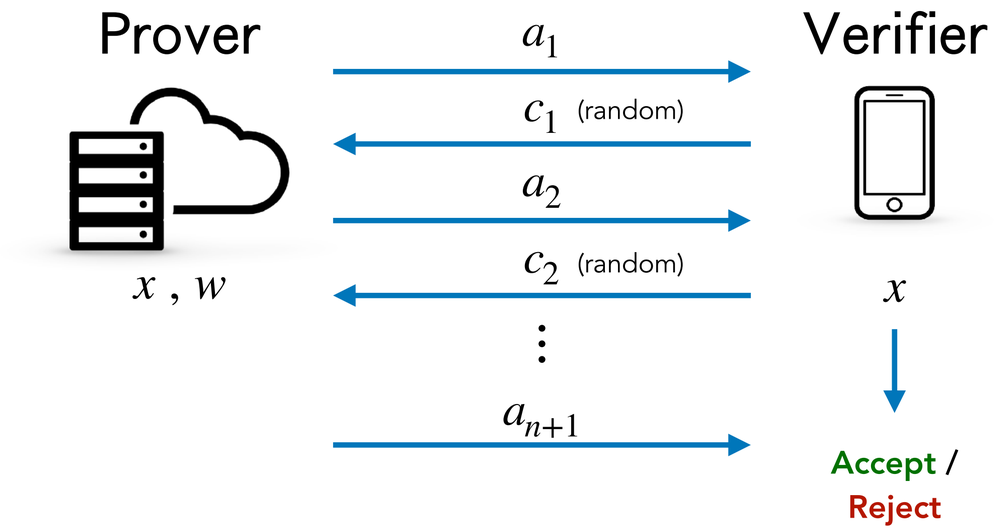

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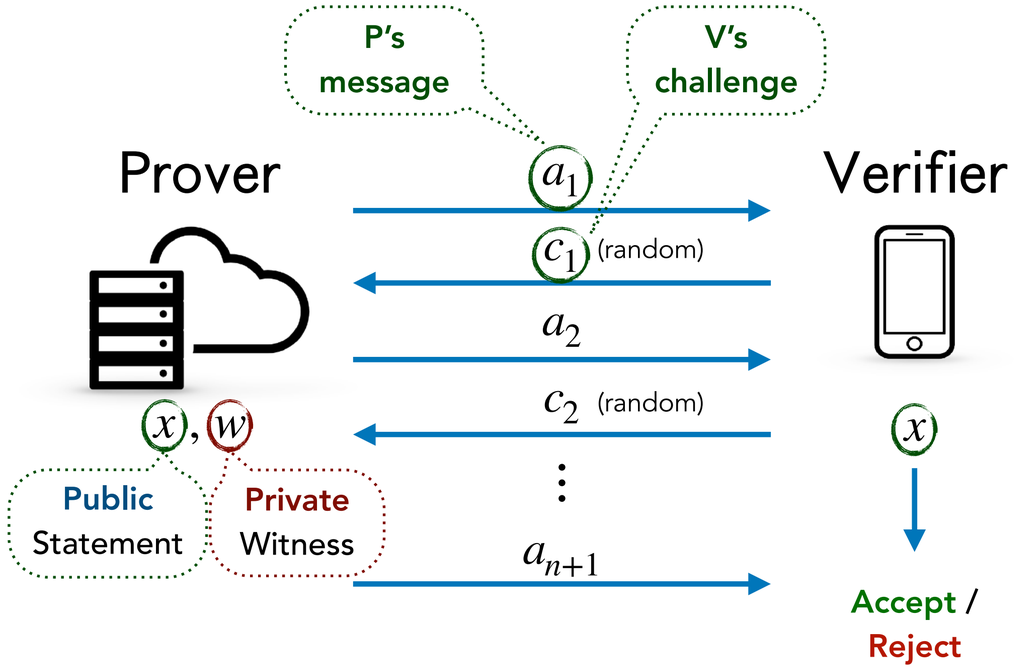

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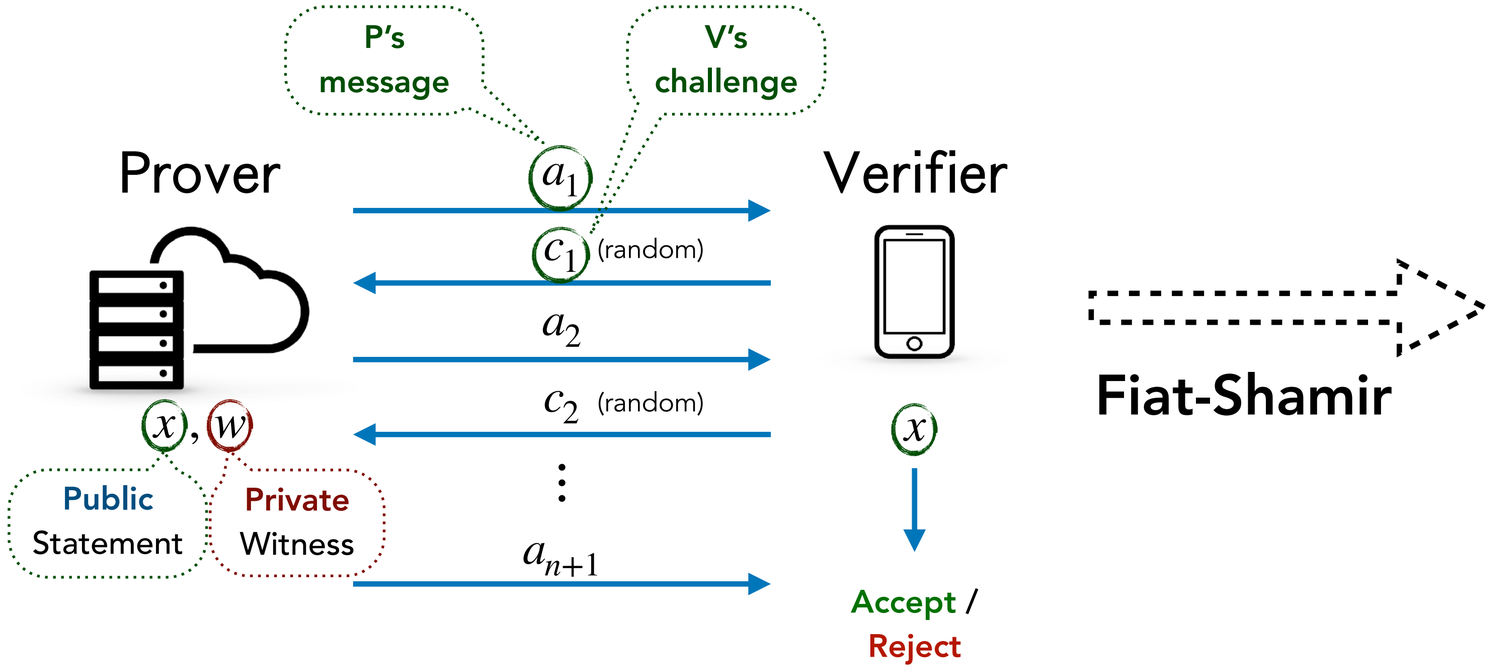

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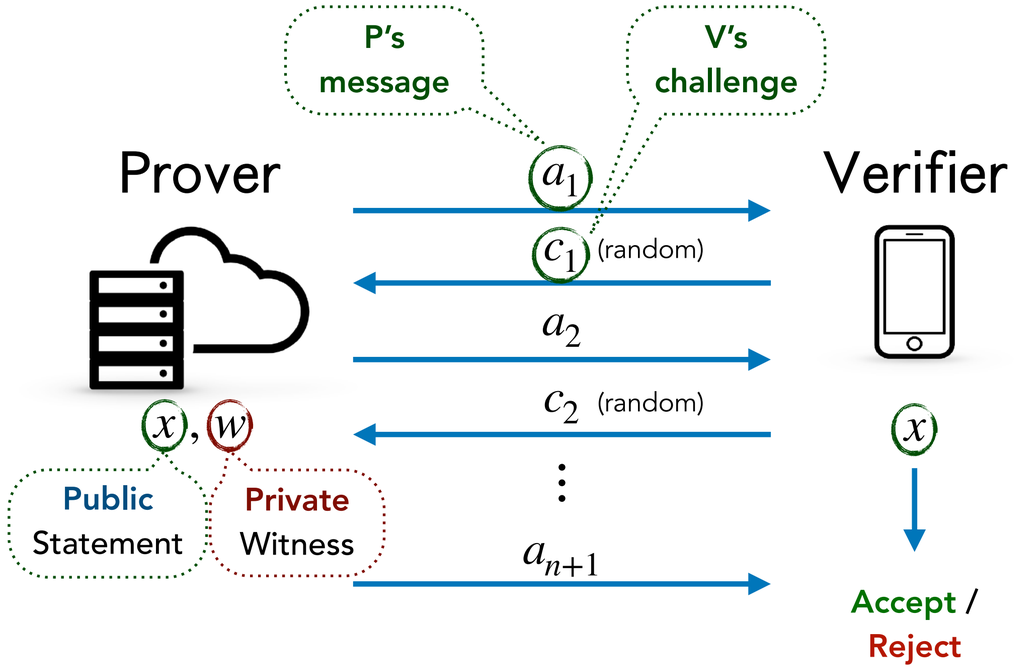

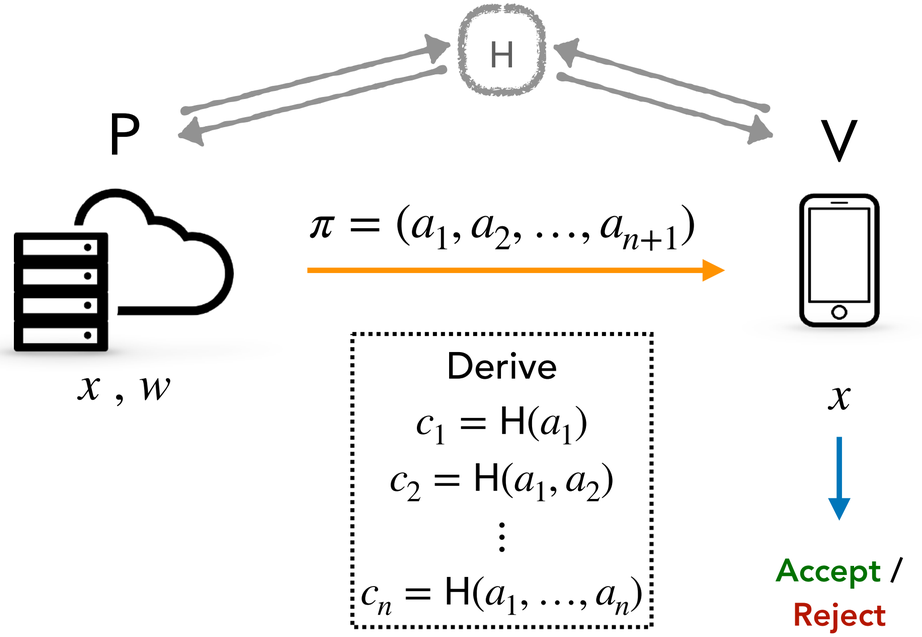

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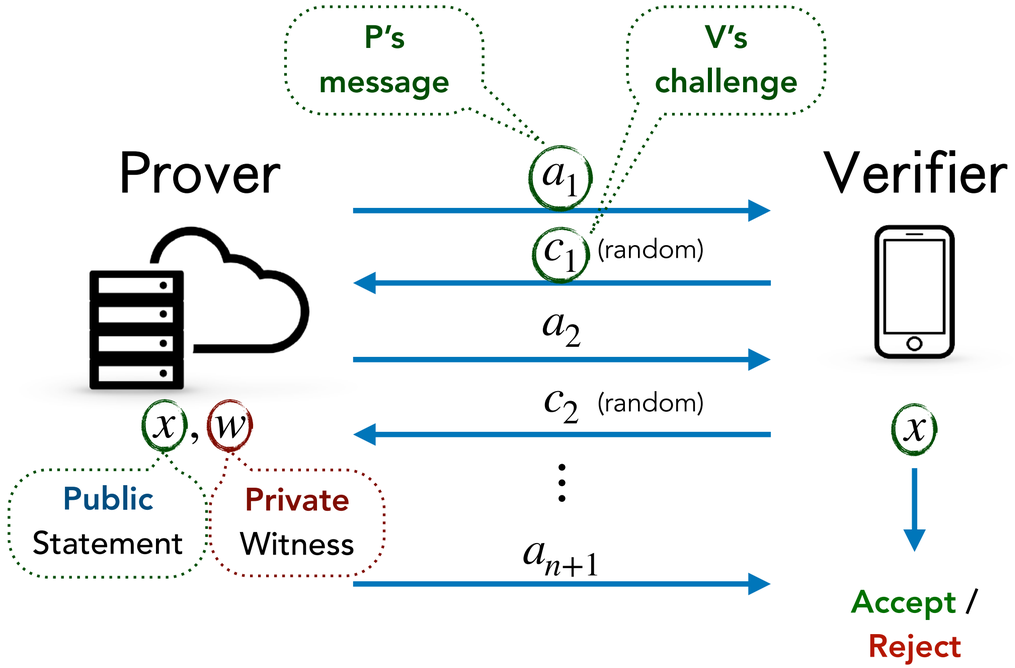
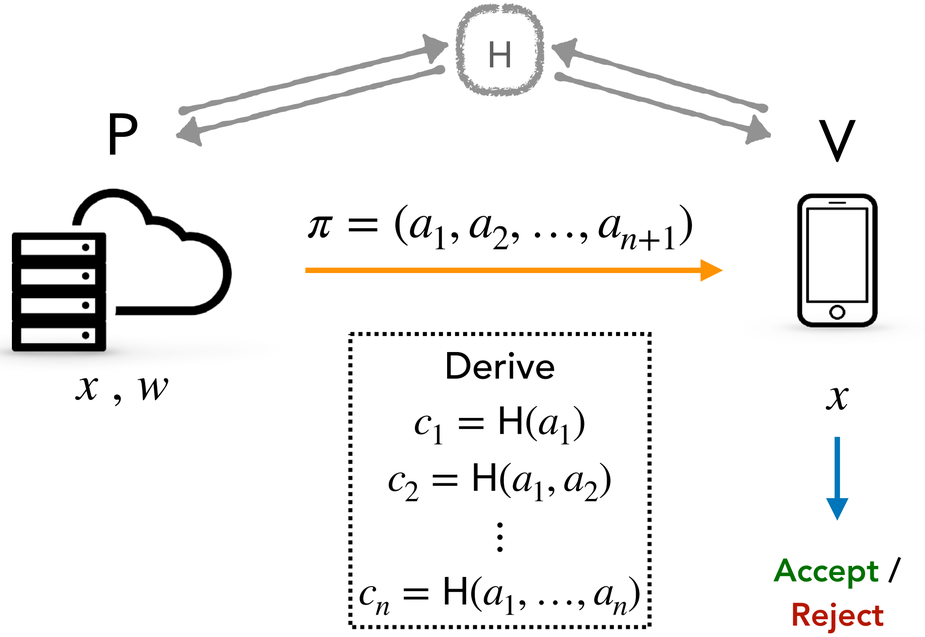


Fiat-Shamir



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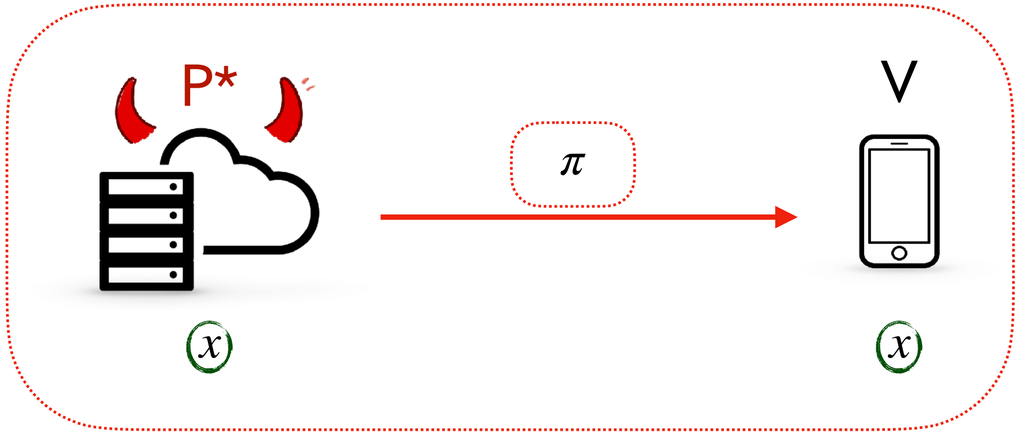

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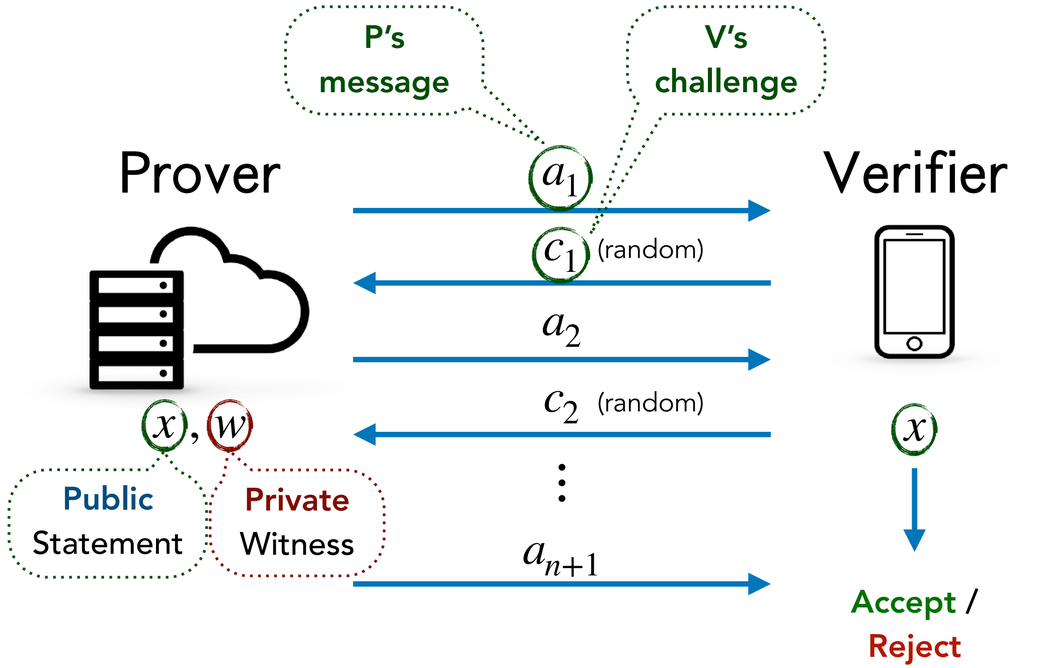

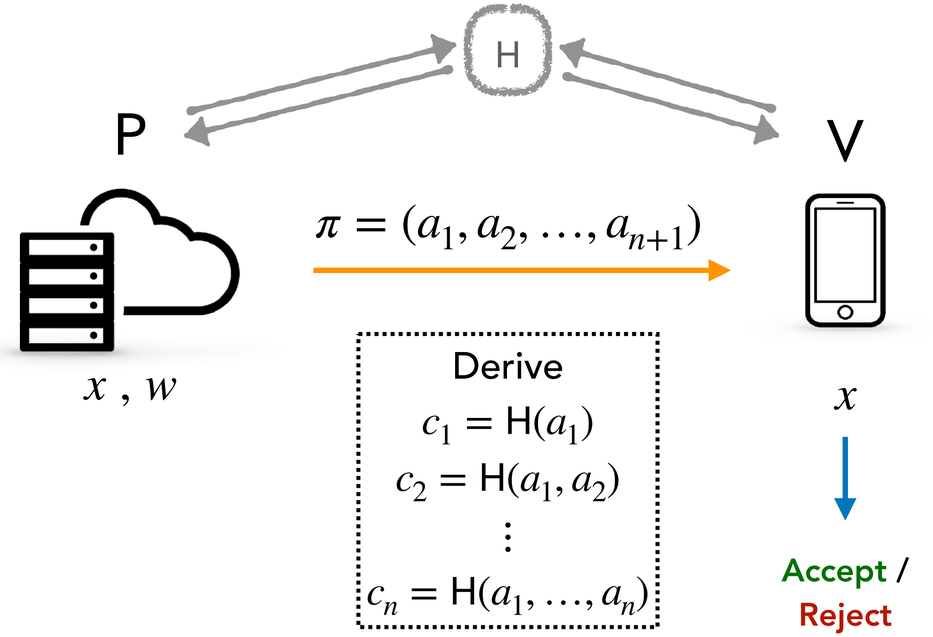

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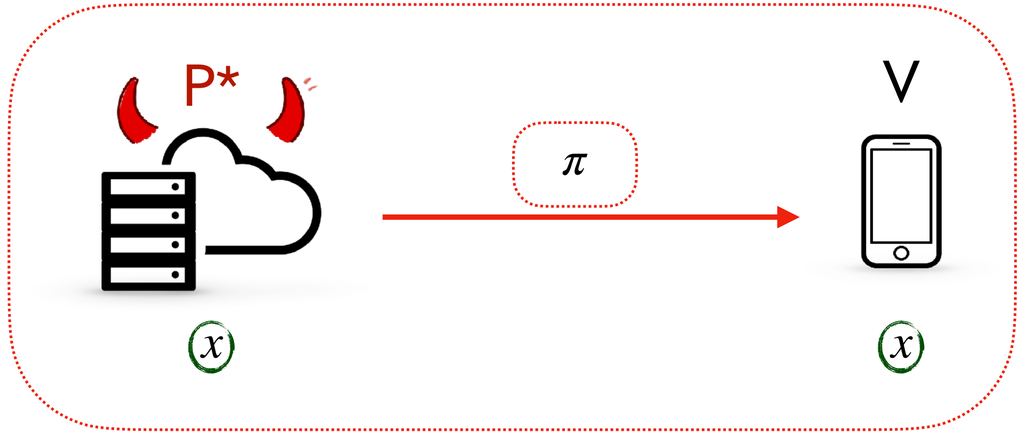

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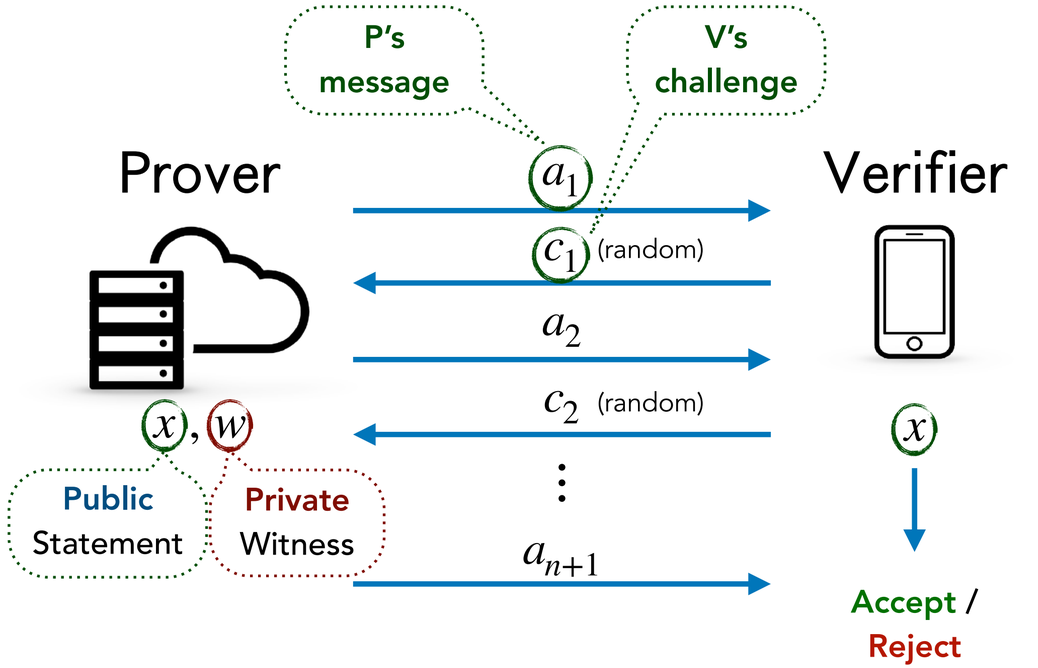

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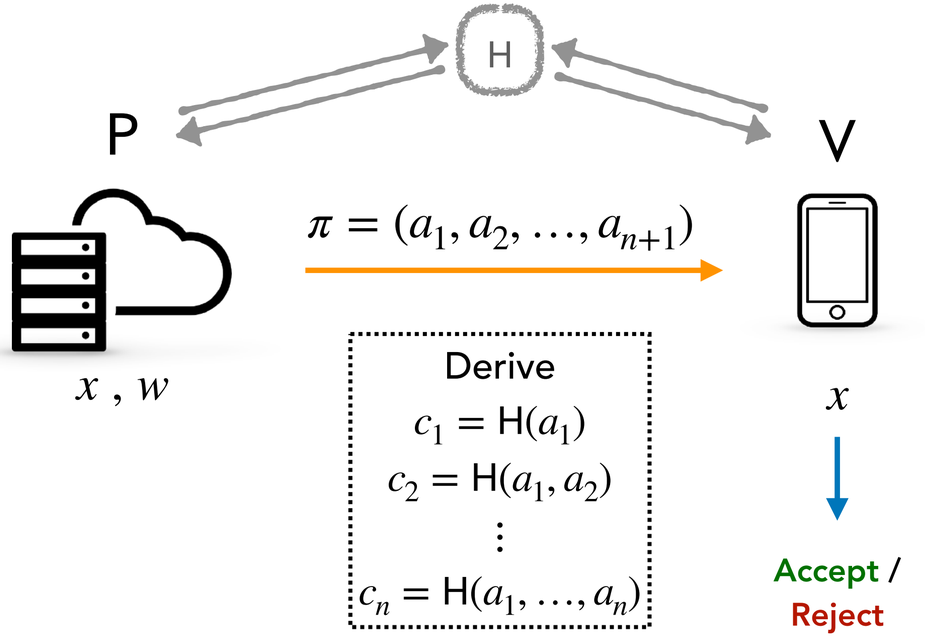

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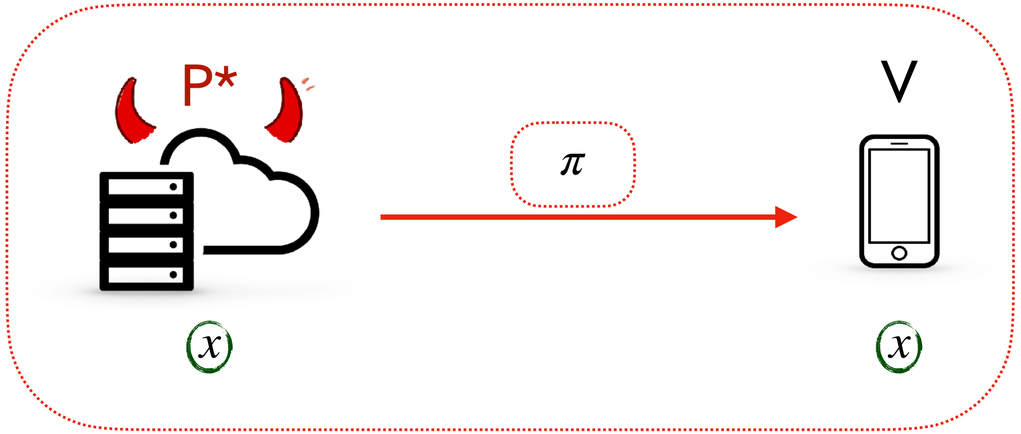

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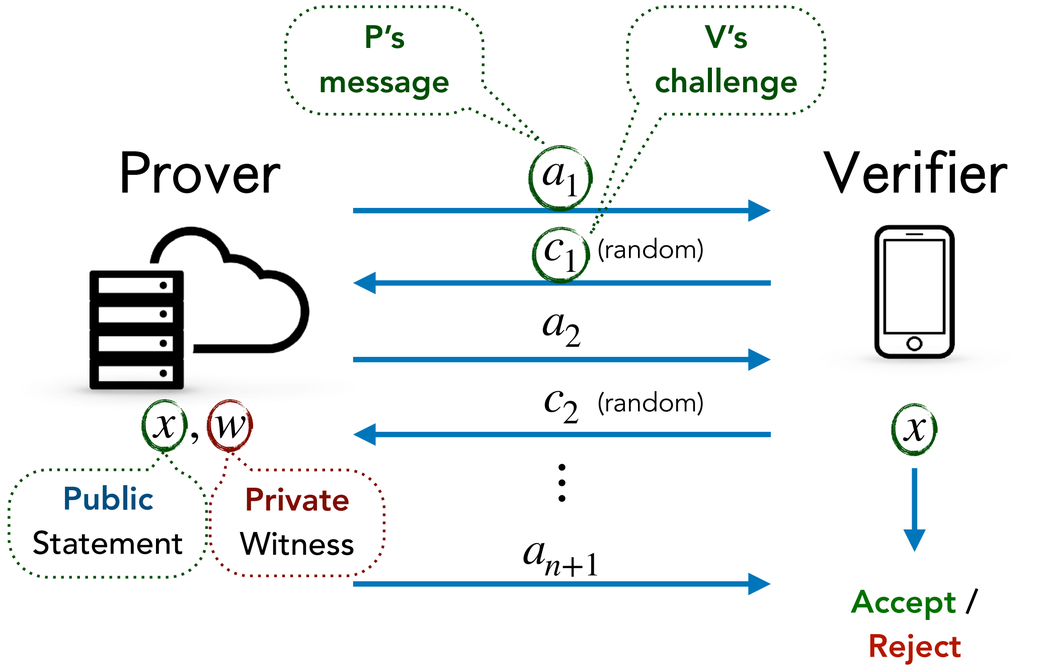

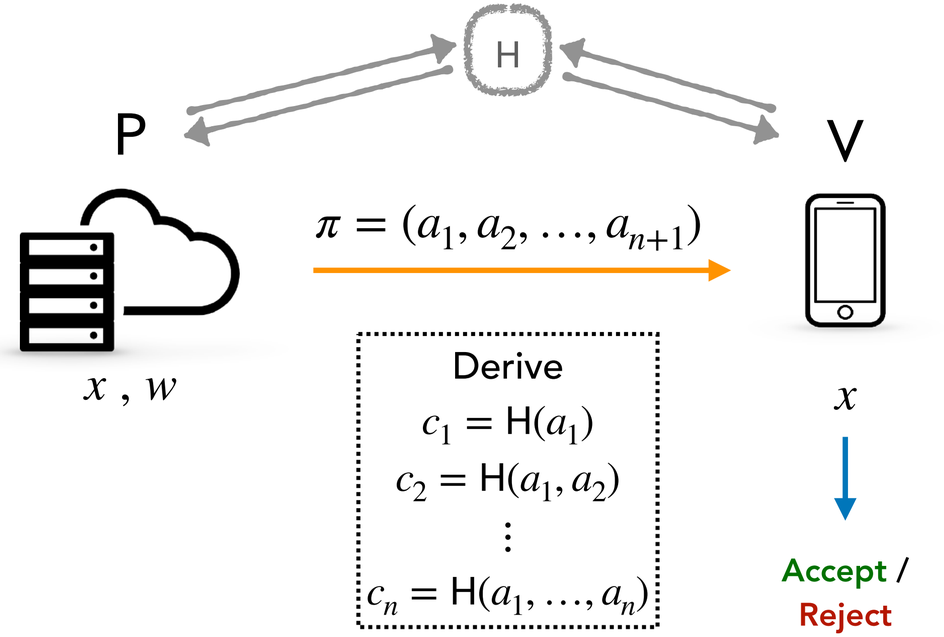

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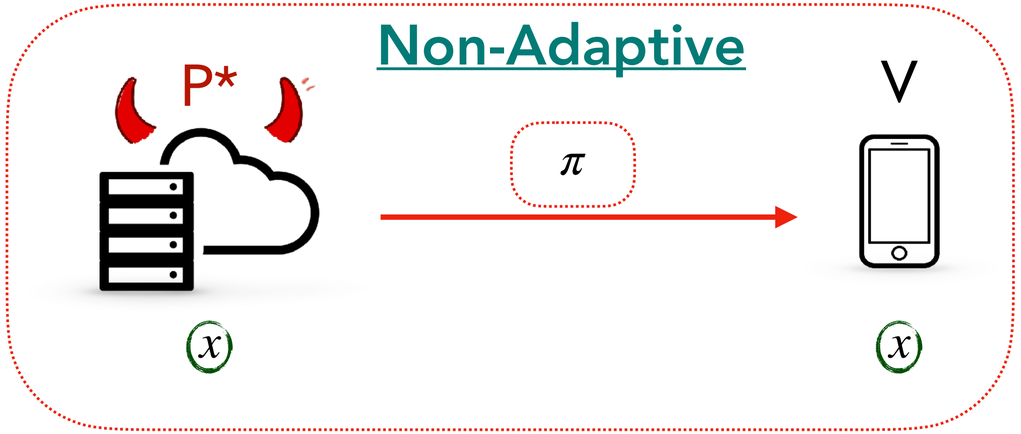
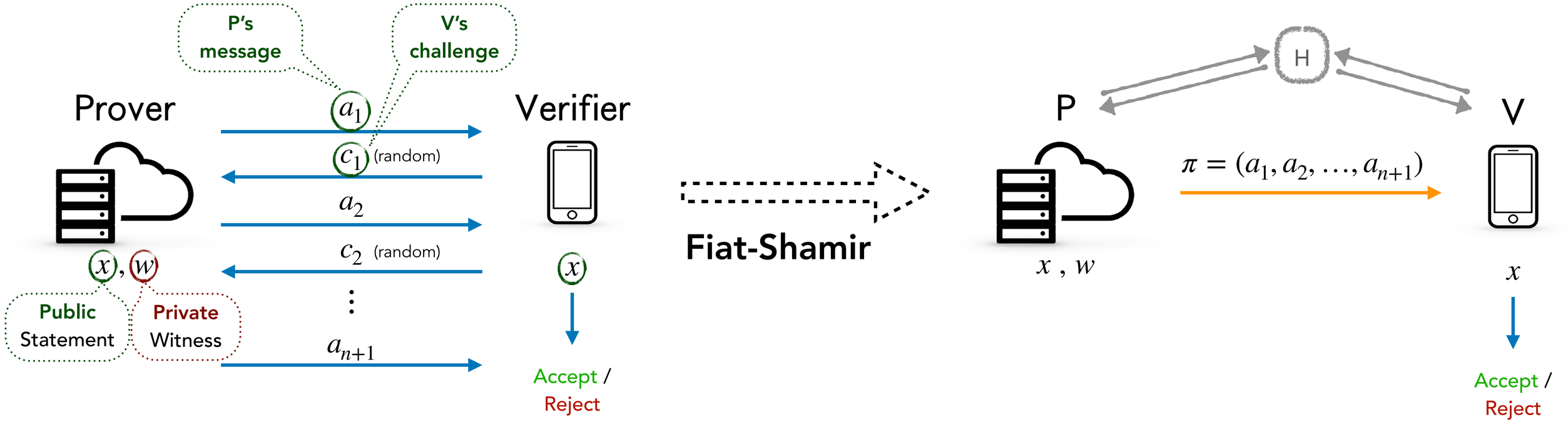


Strong Fiat-Shamir for Adaptive Security



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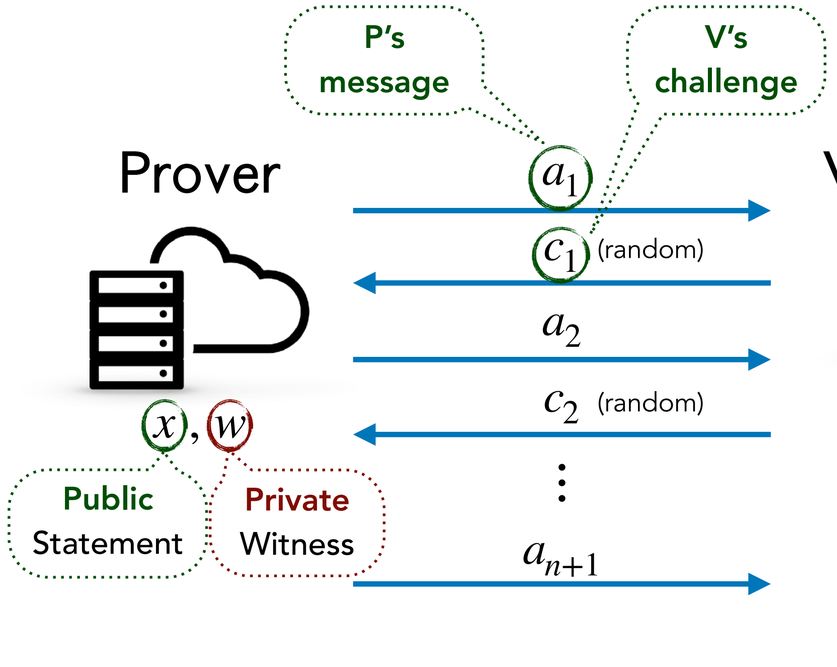

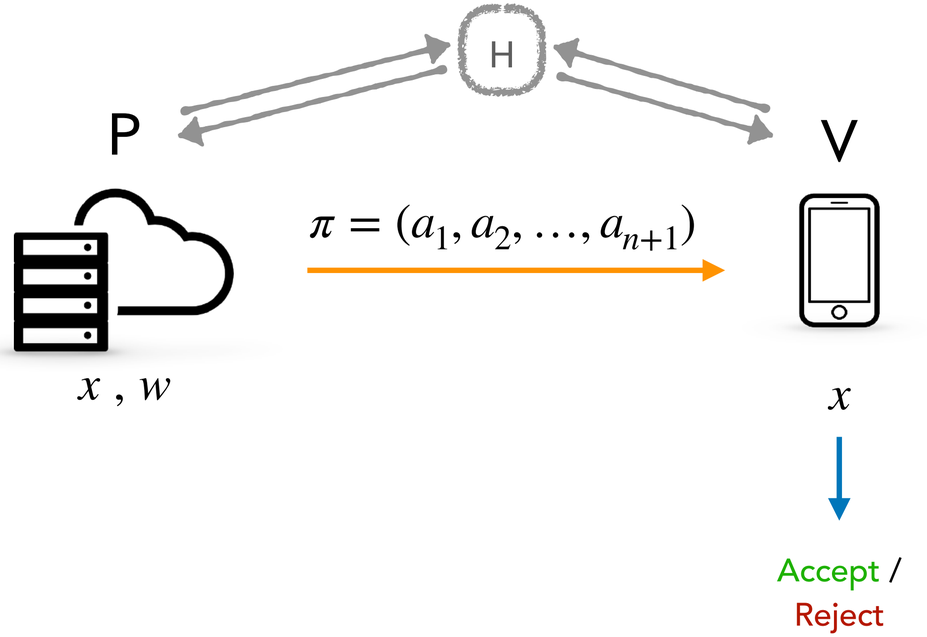

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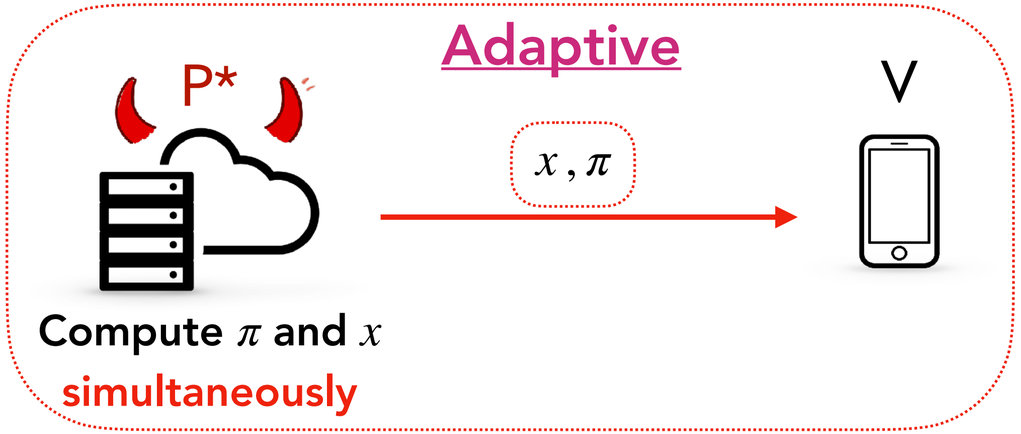

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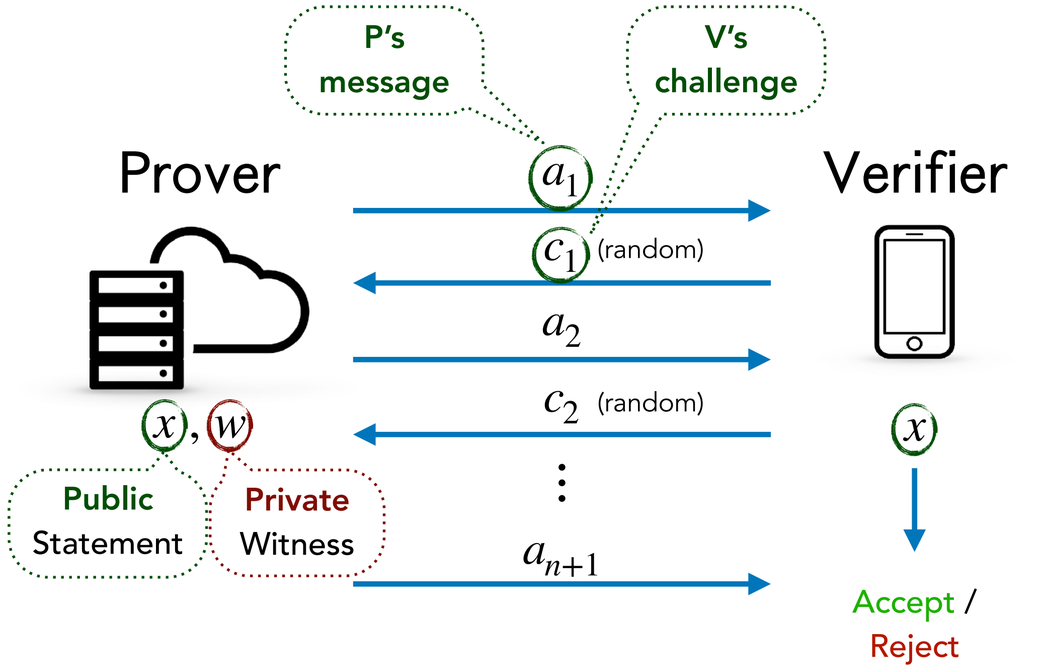

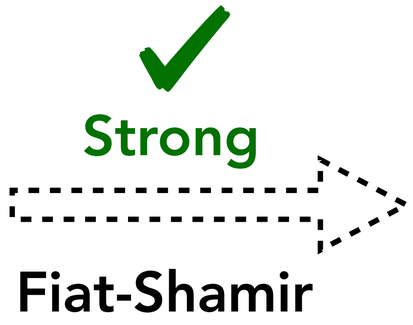

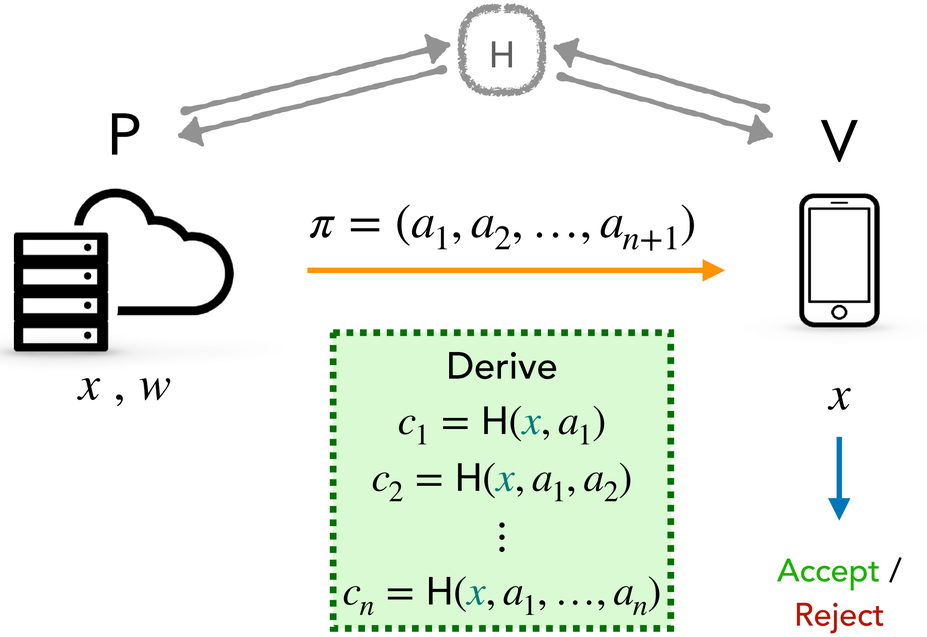

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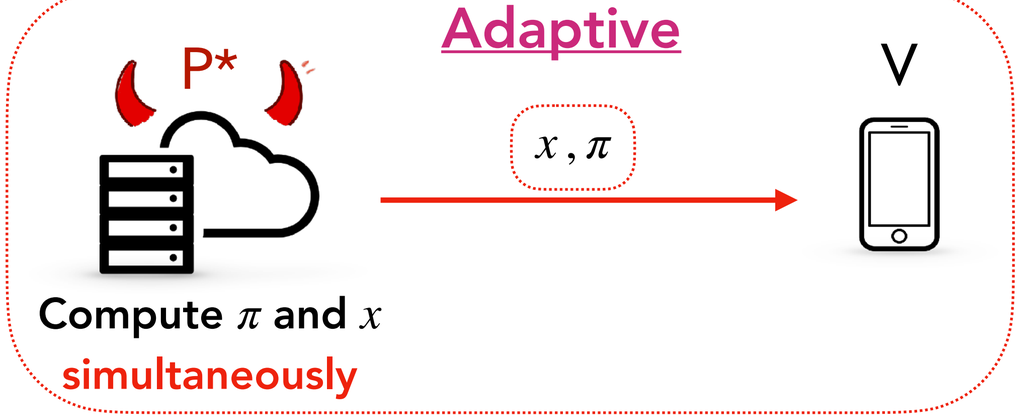

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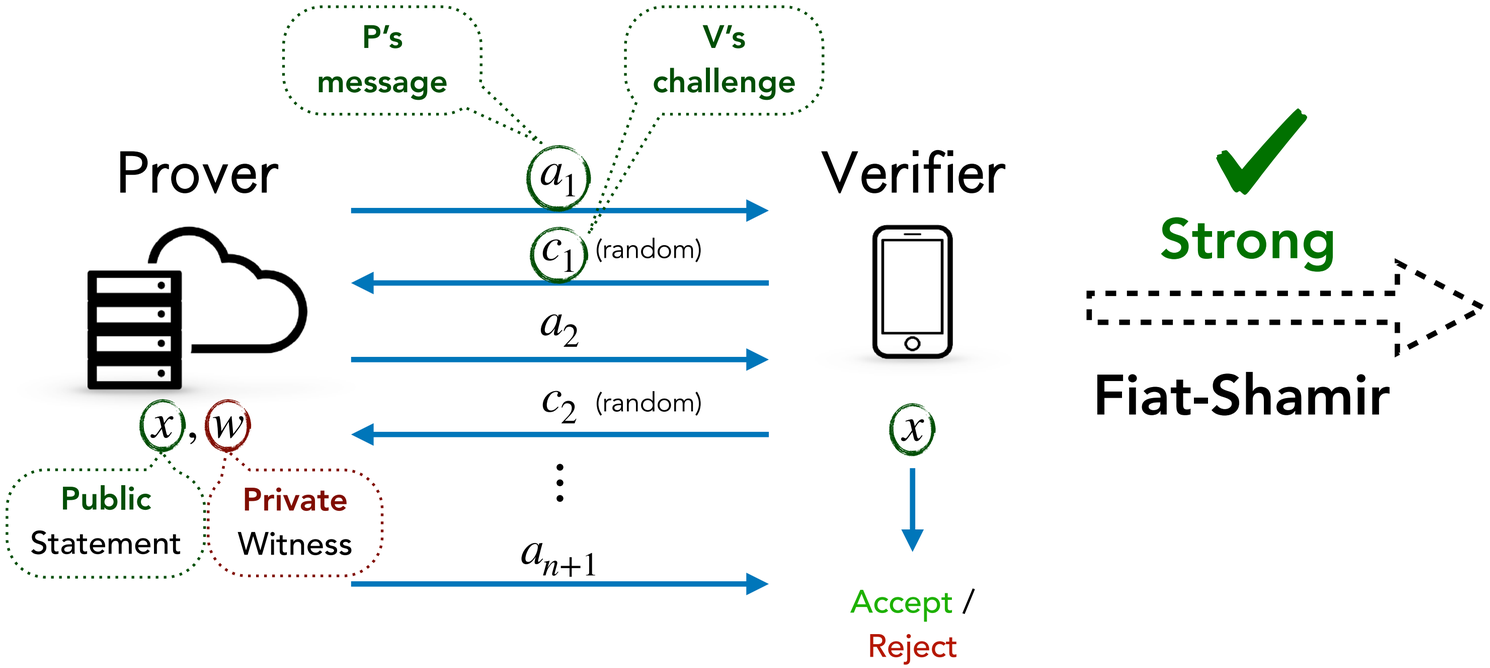

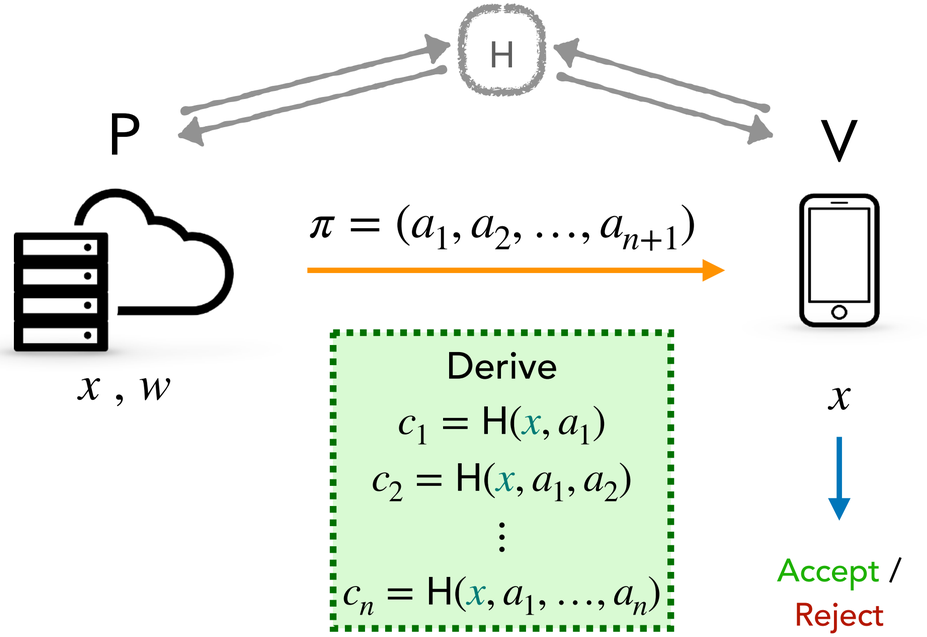

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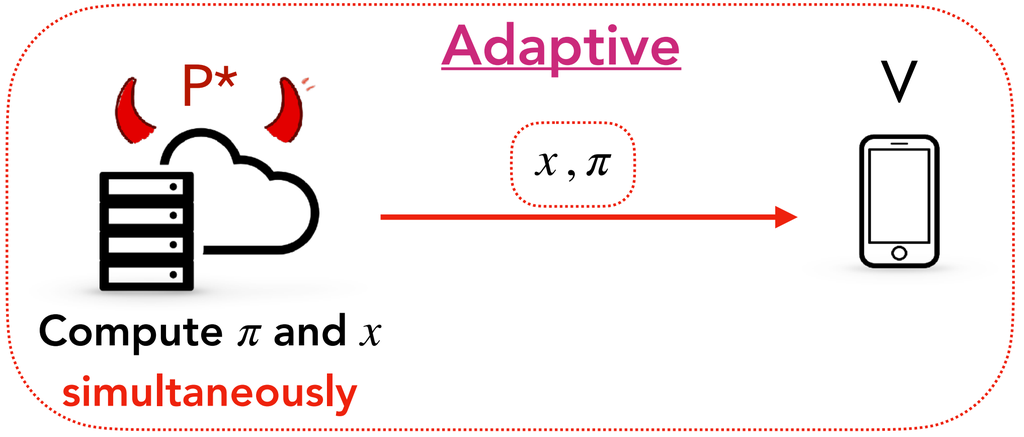
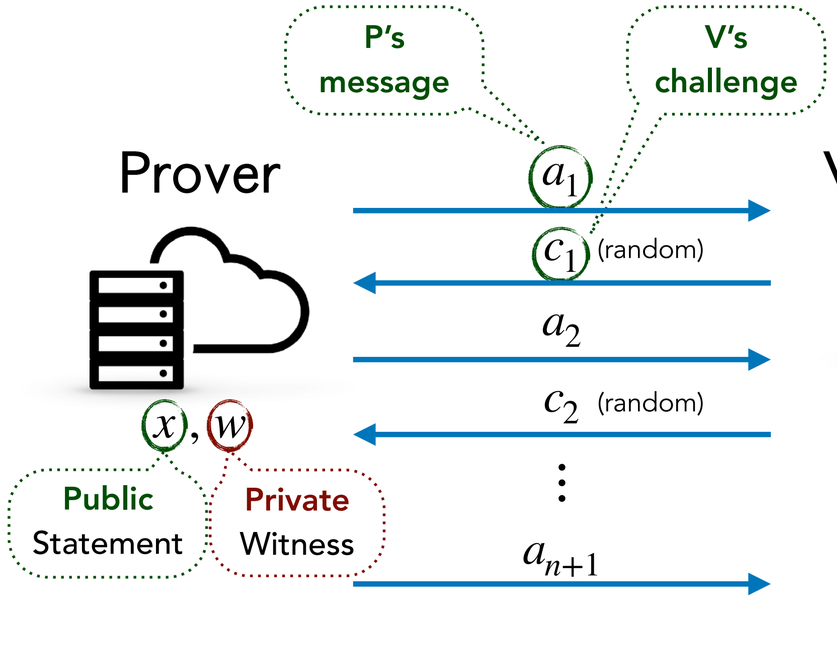
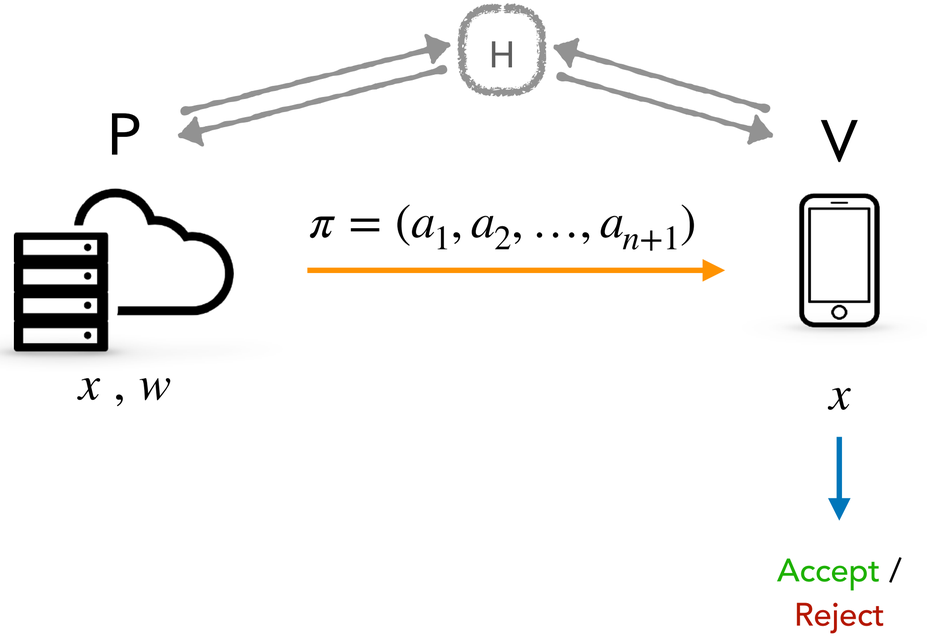


Weak Fiat-Shamir and Attacks





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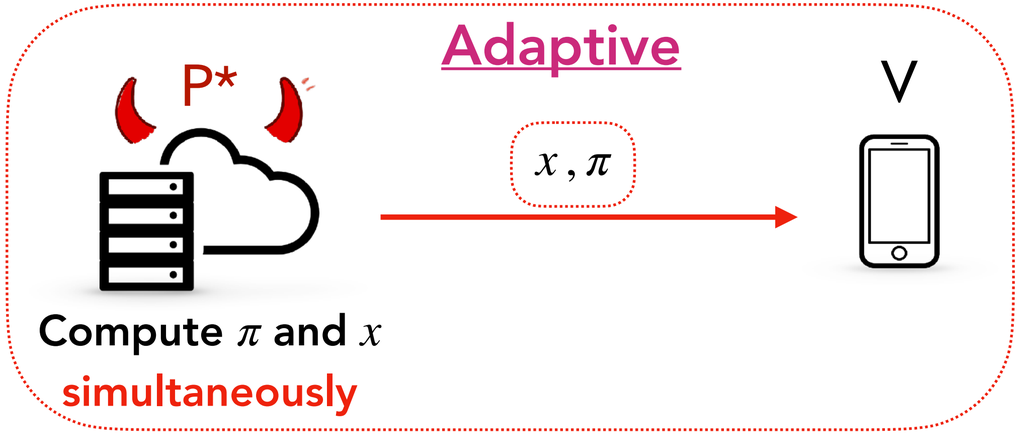

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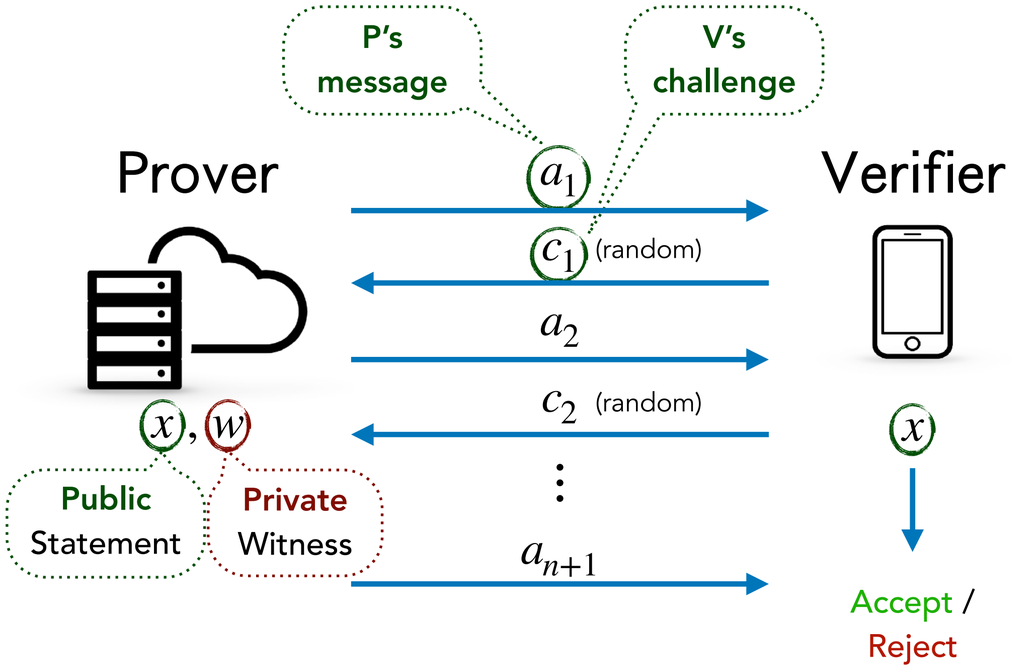

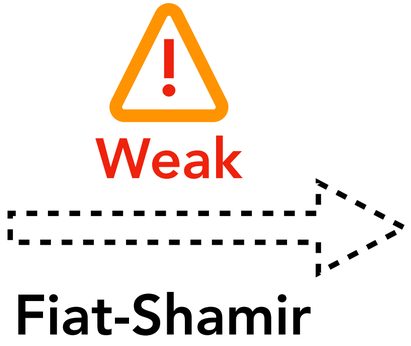

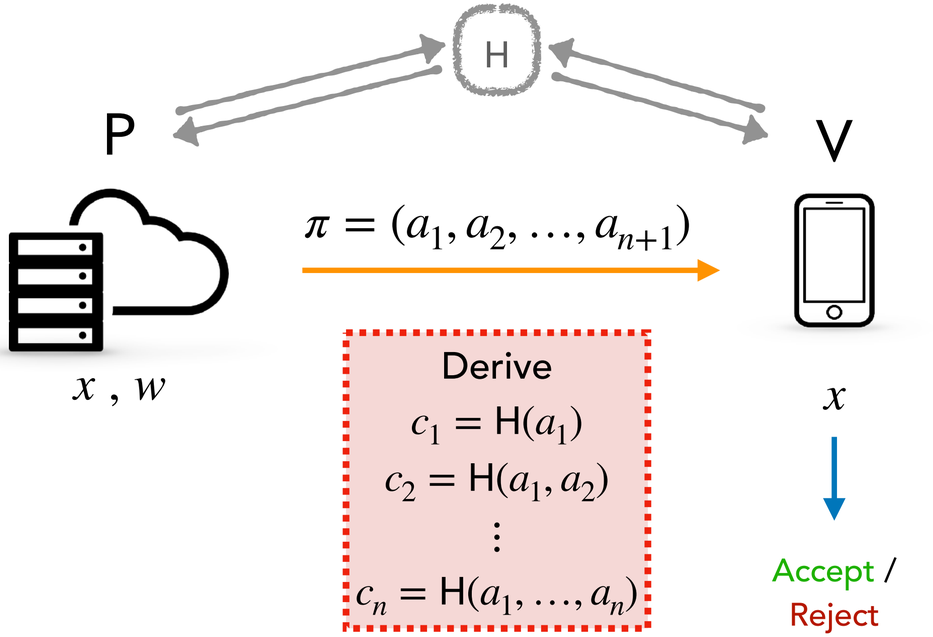

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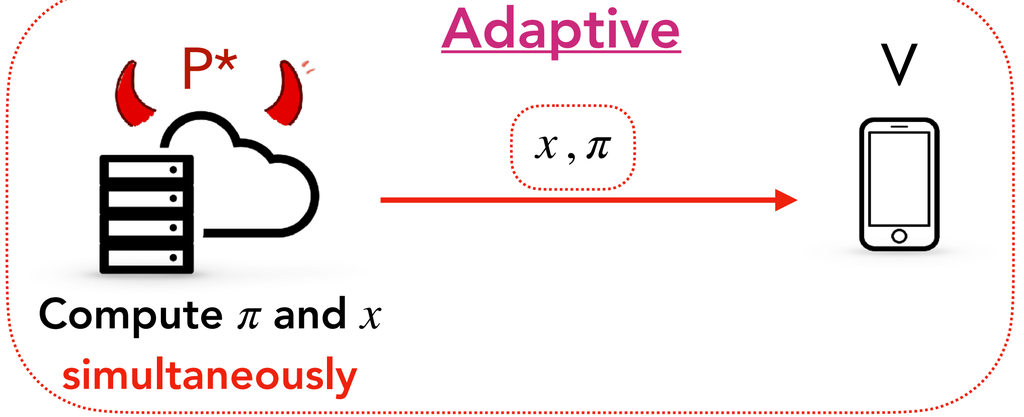

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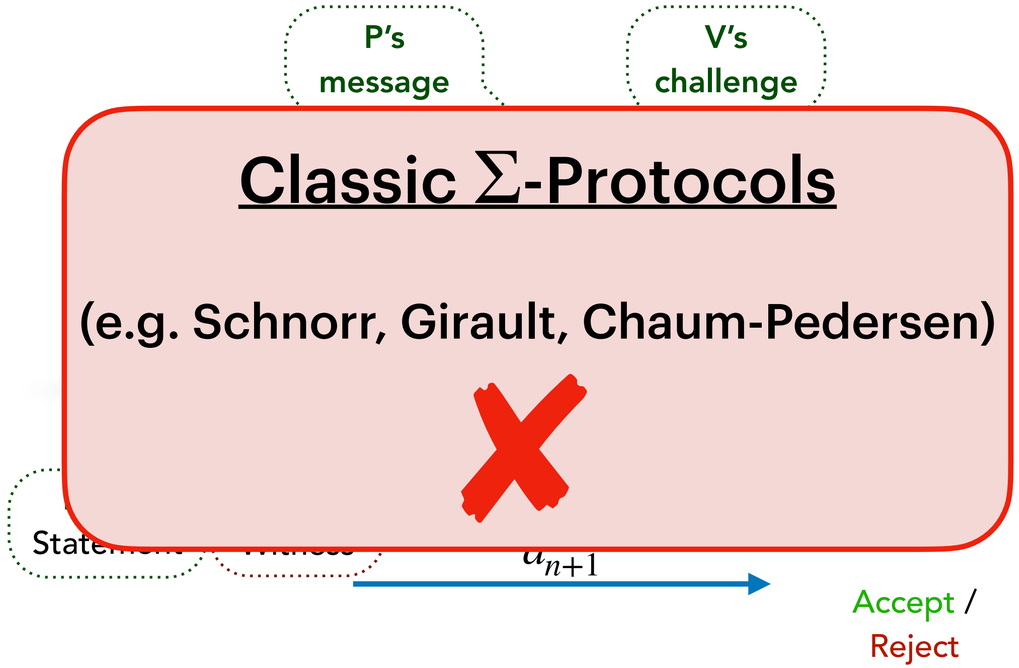

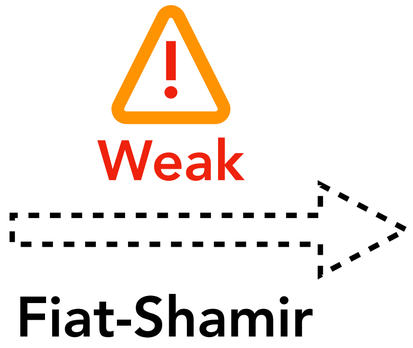

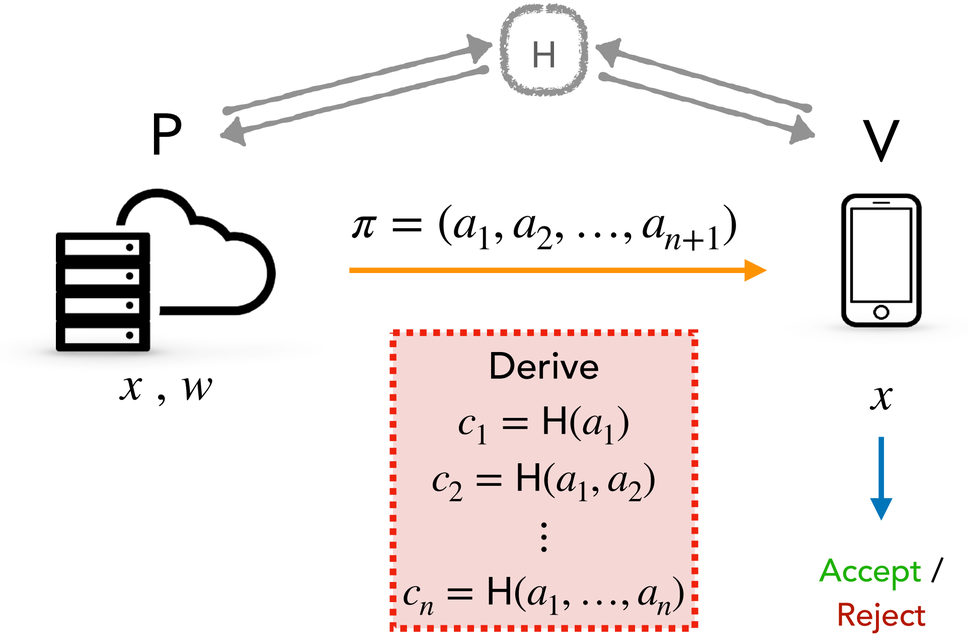

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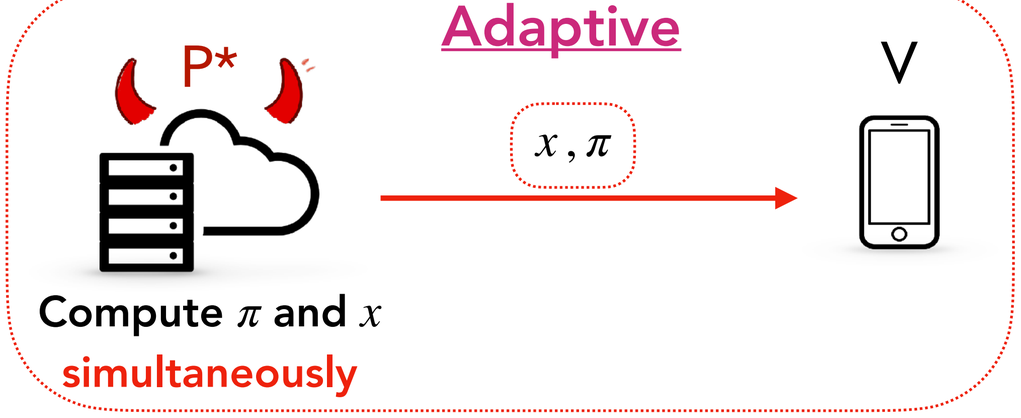


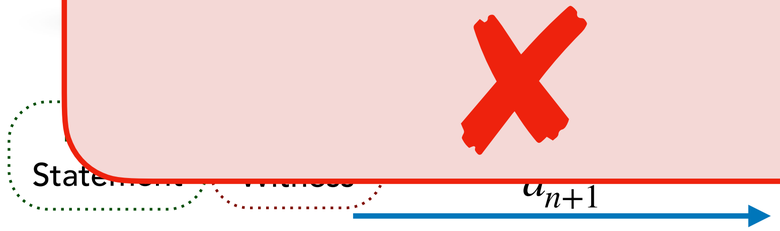
Weak Fiat-Shamir and Attacks

P's message

V's challenge

Classic Σ-Protocols

(e.g. Schnorr, Girault, Chaum-Pedersen)

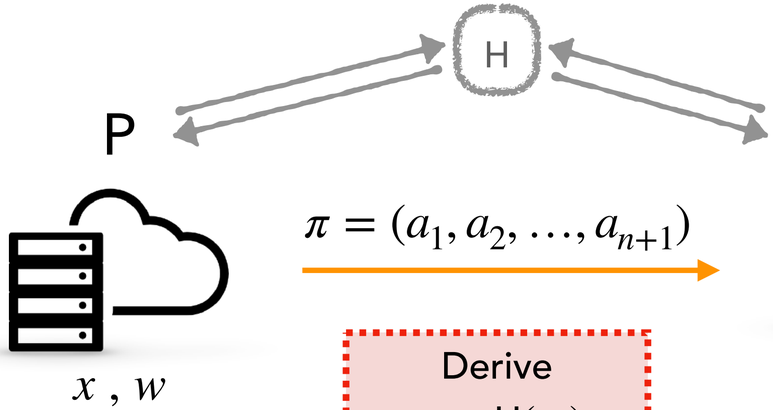


a_{n+1}

Accept /

Weak

Fiat-Shamir



How not to Prove Yourself:
Pitfalls of the Fiat-Shamir Heuristic and Applications to Helios

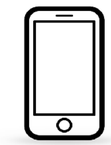
David Bernhard[1], Olivier Pereira[2], and Bogdan Warinschi[1]

n

How not to prove your election outcome

Thomas Haines*, Sarah Jamie Lewis†, Olivier Pereira‡, and Vanessa Teague§

Adaptive



x , π

Compute π and x simultaneously

Weak Fiat-Shamir and Attacks

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(e.g. Schnorr, Girault, Chaum-Pedersen)

✗

Weak

Fiat-Shamir

H

Modern Proof Systems

(e.g. Bulletproofs, Plonk, Spartan)

?

$c_n = \mathsf{H}(a_1, \ldots, a_n)$

Accept / Reject

a_{n+1}

Accept /

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(e.g. Bulletproofs, Plonk, Spartan)

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1. *Are modern proof systems insecure under weak Fiat-Shamir?*

Weak Fiat-Shamir and Attacks

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1. *Are modern proof systems insecure under weak Fiat-Shamir?*
2. *Are these vulnerabilities present in implementations?*

Weak Fiat-Shamir and Attacks

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1. *Are modern proof systems insecure under weak Fiat-Shamir?*
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3. *Do they lead to attacks on larger/surrounding protocols?*

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1. *Are modern proof systems insecure under weak Fiat-Shamir?*
2. *Are these vulnerabilities present in implementations?*
3. *Do they lead to attacks on larger/surrounding protocols?*
4. *What are the consequences of these attacks?*

Our Contributions

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1. **Survey** of **75+** implementations:

   36 weak F-S vulnerabilities across

   12 different proof systems.

Proof System	Codebase	Weak F-S?
Bulletproofs [22]	bp-go [88]	✓
	bulletproof-js [2]	✓
	simple-bulletproof-js [84]	✓
	BulletproofSwift [20]	✓
	python-bulletproofs [79]	✓
	adjoint-bulletproofs [3]	✓
	zkSen [99]	✓
	incognito-chain [52]	✓♦
	encoins-bulletproofs [33]	✓♦
	ZenGo-X [97]	✓♦
	zkrp [53]	✓♦
	ckb-zkp [82]	✓♦
	bulletproofsrb [21]	✓♦
	monero [69]	✗
	dalek-bulletproofs [29]	✗
	secp256k1-zkp [76]	✗
	bulletproofs-ocaml [75]	✗
	tari-project [86]	✗
	Litecoin [60]	✗
	Grin [44]	✗
Bulletproofs variant [40]	dalek-bulletproofs [29]	✓♦
	cpp-lwevss [61]	✗
Sonic [62]	ebfull-sonic [18]	✓
	lx-sonic [59]	✓
	iohk-sonic [54]	✗
	adjoint-sonic [4]	✗
Schnorr [80]	noknow-python [7]	✓

Proof System	Codebase	Weak F-S?
Plonk [37]	anoma-plonkup [6]	✓
	gnark [17]	✓♦
	dusk-network [31]	✓♦
	snarkjs [50]	✓♦
	ZK-Garage [98]	✓♦
	plonky [68]	✗
	ckb-zkp [82]	✗
	halo2 [94]	✗
	o1-labs [72]	✗
	jellyfish [34]	✗
	matter-labs [63]	✗
	aztec-connect [8]	✗
Wesolowski's VDF [91]	0xProject [1]	✓
	Chia [70]	✓
	Harmony [47]	✓
	POA Network [71]	✓
	IOTA Ledger [55]	✓
	master-thesis-ELTE [48]	✓
Hyrax [90]	ckb-zkp [82]	✓♦
	hyraxZK [49]	✗
Spartan [83]	Spartan [65]	✓♦
	ckb-zkp [82]	✓♦
Libra [92]	ckb-zkp [82]	✓♦
Brakedown [43]	Brakedown [19]	✓
Nova [58]	Nova [64]	✓♦
Gemini [16]	arkworks-gemini [38]	✓♦
Girault [42]	zk-paillier [96]	✓♦

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vulnerable

patched

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	adjoint-bulletproofs [3]	✓
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	encoins-bulletproofs [33]	✓♦
	ZenGo-X [97]	✓♦
	zkrp [53]	✓♦
	ckb-zkp [82]	✓♦
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	secp256k1-zkp [76]	✗
	bulletproofs-ocaml [75]	✗
	tari-project [86]	✗
	Litecoin [60]	✗
	Grin [44]	✗
Bulletproofs variant [40]	dalek-bulletproofs [29]	✓♦
	cpp-lwevss [61]	✗
Sonic [62]	ebfull-sonic [18]	✓
	lx-sonic [59]	✓
	iohk-sonic [54]	✗
	adjoint-sonic [4]	✗
Schnorr [80]	noknow-python [7]	✓

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IEEE S&P Distinguished Paper Award!

Weak Fiat-Shamir Attacks

(as easy as solving a linear equation)

Template for Weak F-S Attacks

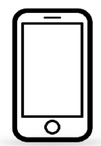
Template for Weak F-S Attacks

Schnorr with Weak F-S

Relation:

$$\left\{ \left((\mathbb{G}, g, p), X, x \right) : X = g^x \right\}$$

(X, x)



X

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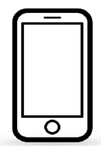

X

$$a \xleftarrow{R} \mathbb{F}_p$$

$$A := g^a$$

$$c := H(A) \in \mathbb{F}_p$$

$$z := a + cx$$

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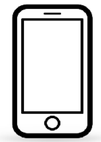
P

(X, x)



V

X

$a \xleftarrow{R} \mathbb{F}_p$

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$z := a + cx$

$\pi := (A, z)$ →

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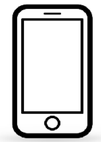

V

X

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$z := a + cx$

$\pi := (A, z)$

$c := H(A) \in \mathbb{F}_p$

Check that

$g^z \stackrel{?}{=} A \cdot X^c$

Template for Weak F-S Attacks

Attack Strategy

Schnorr with Weak F-S

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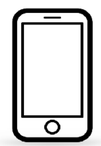

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$A := g^a$

$c := H(A) \in \mathbb{F}_p$

$z := a + cx$

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Check that

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Schnorr with Weak F-S

Relation:

$$\left\{ \left((\mathbb{G}, g, p), X, x \right) : X = g^x \right\}$$

$\pi := (A, z)$

$c := H(A) \in \mathbb{F}_p$

Check that

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Attack Strategy

1. **Identify** the public input(s) that are ***not*** included in Fiat-Shamir,

Schnorr with Weak F-S

Relation:

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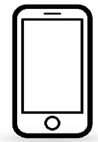

$\pi := (A, z)$ →

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Template for Weak F-S Attacks

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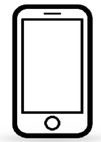
1. **Identify** the **public input(s)** that are ***not*** included in Fiat-Shamir,

Schnorr with Weak F-S

Relation:

$$\left\{ \left((\mathbb{G}, g, p), X, x \right) : X = g^x \right\}$$



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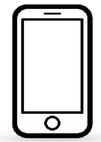

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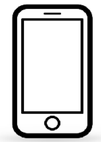

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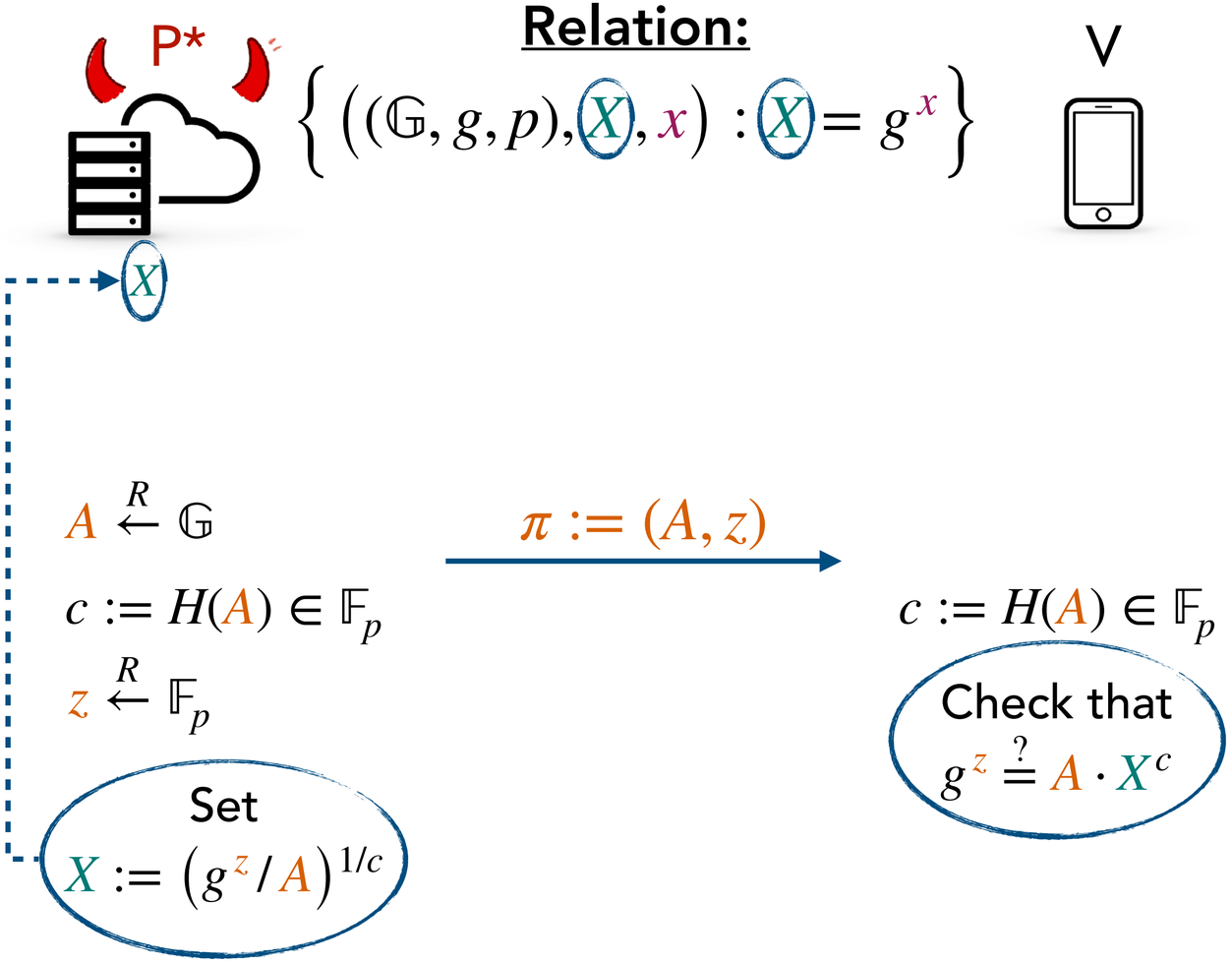

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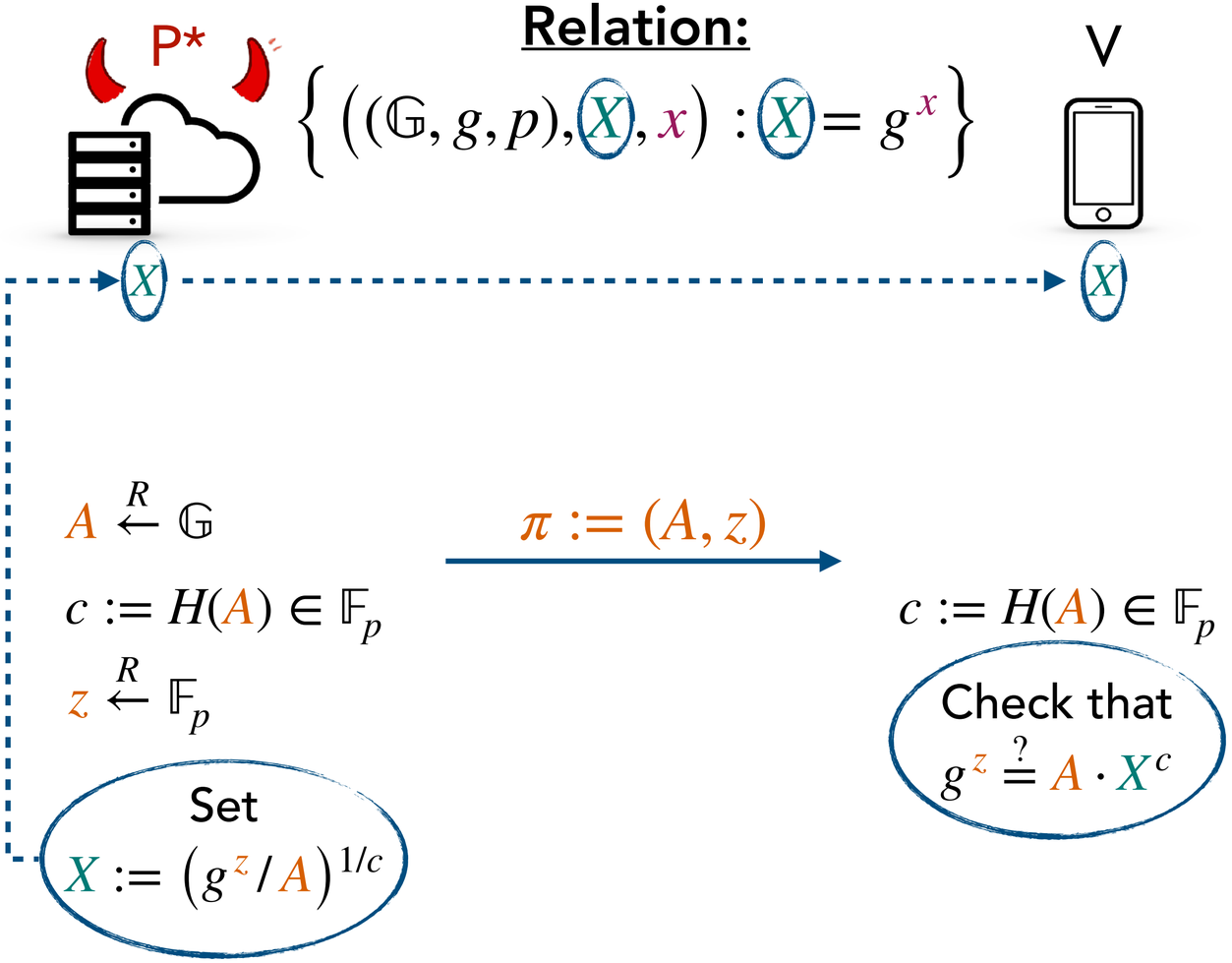

Weak Fiat-Shamir Attack on Plonk

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Constraint System: general (fan-in 2) arithmetic circuits

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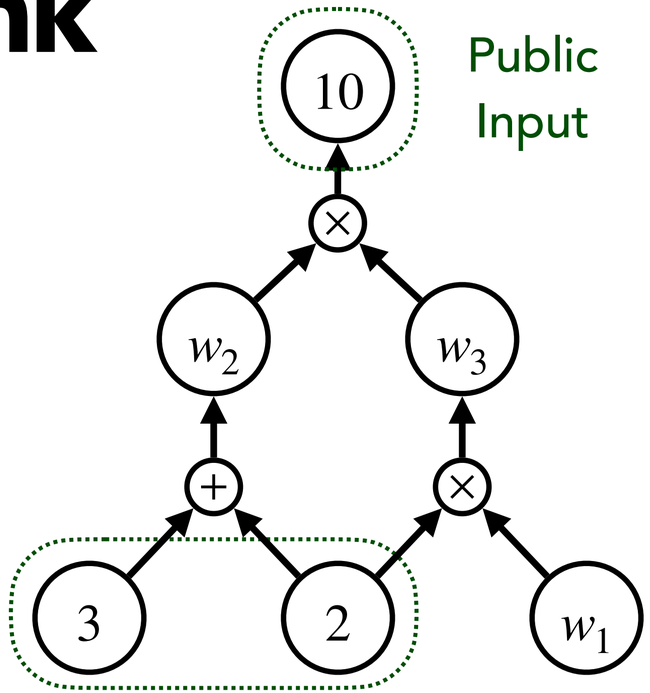

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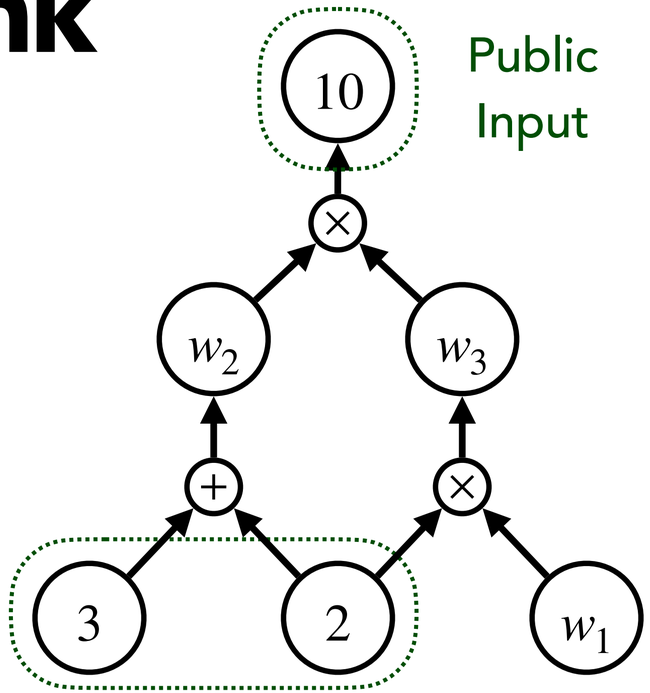

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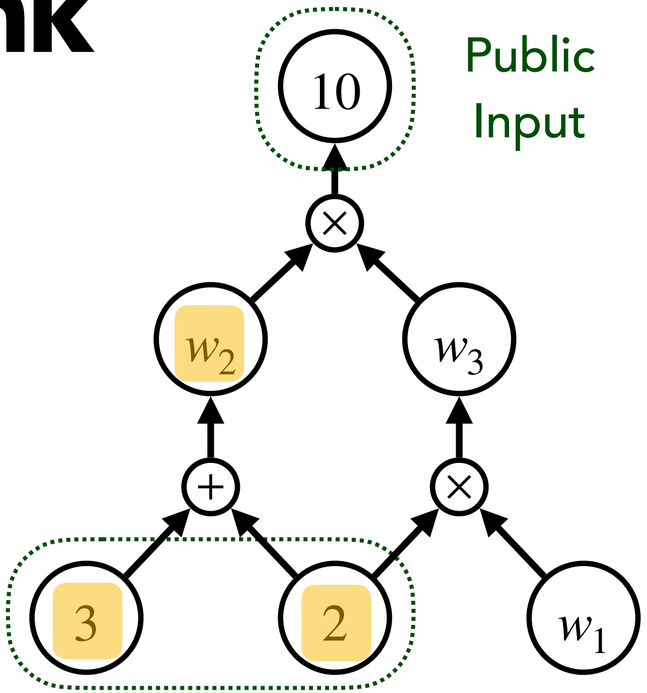

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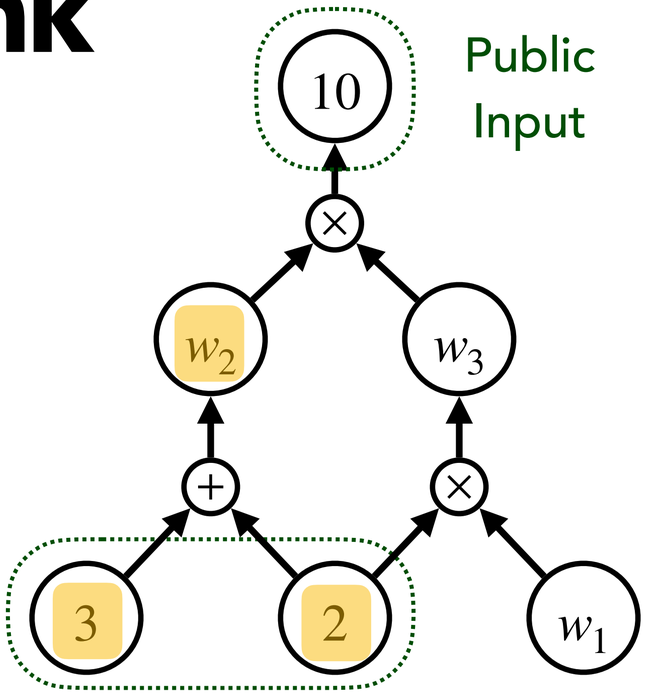

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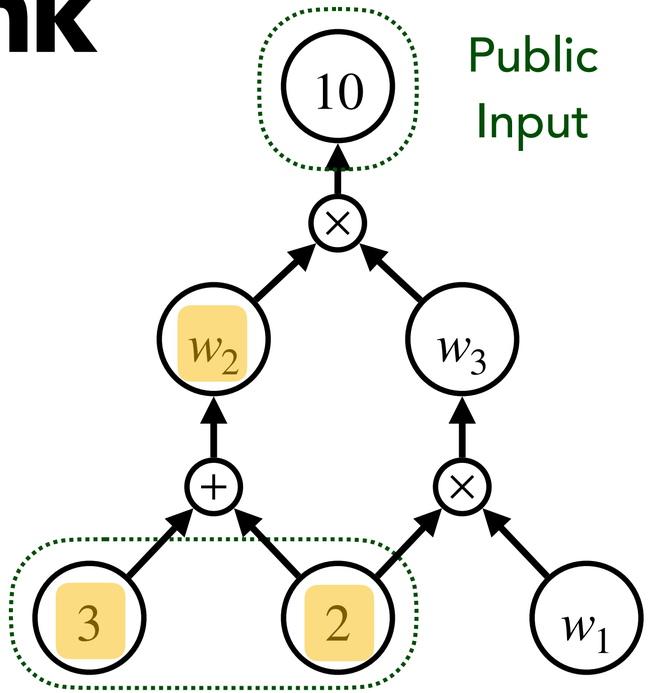

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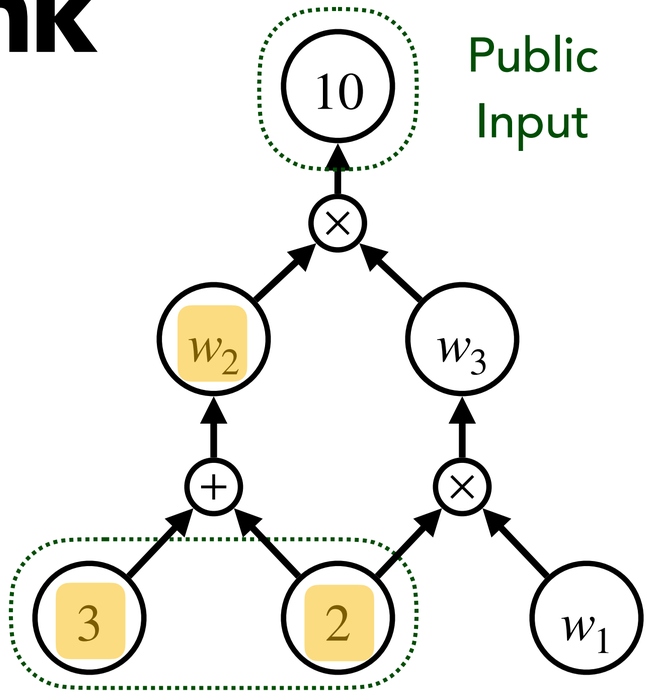

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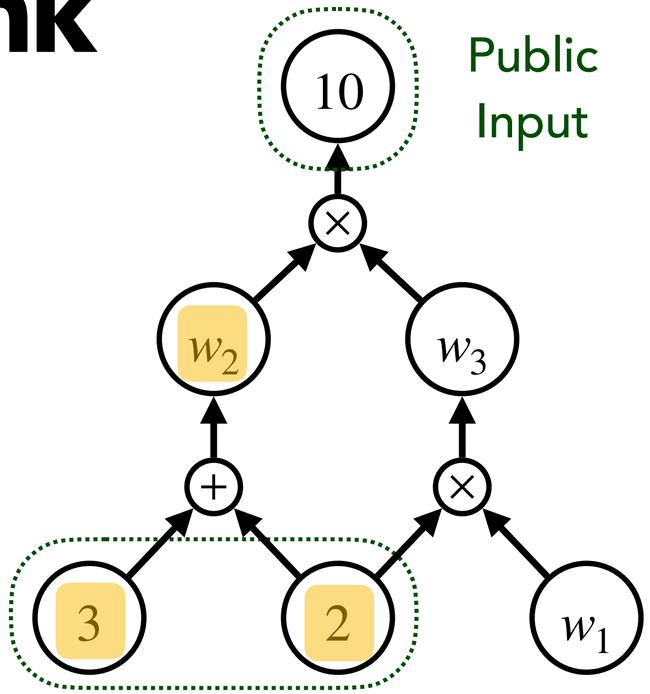

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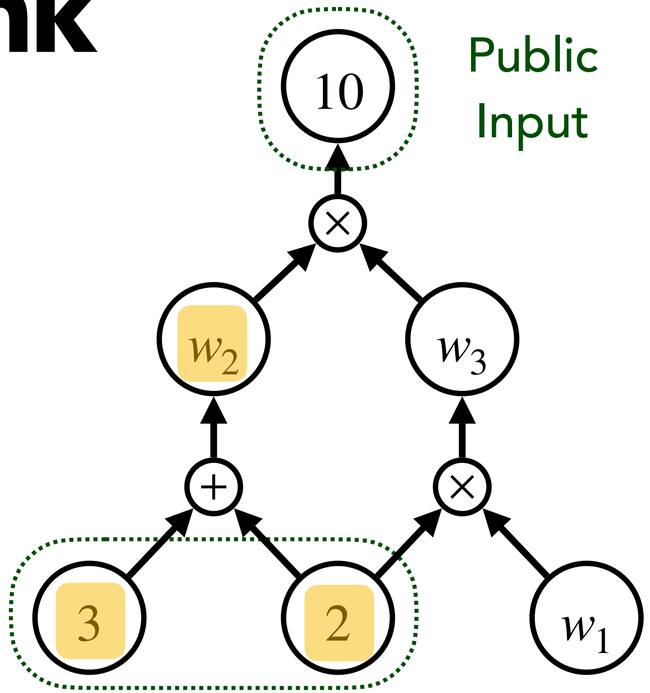

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Verification Equation:

Batching Challenge

Evaluation Point

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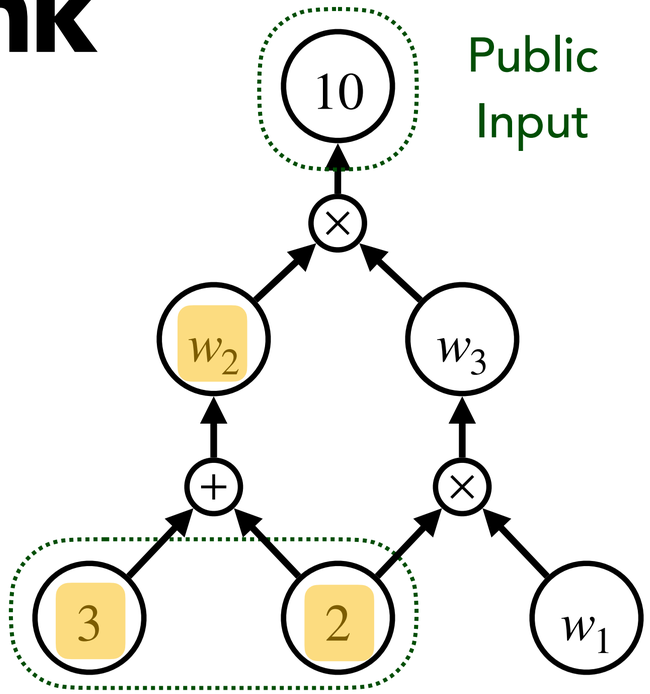

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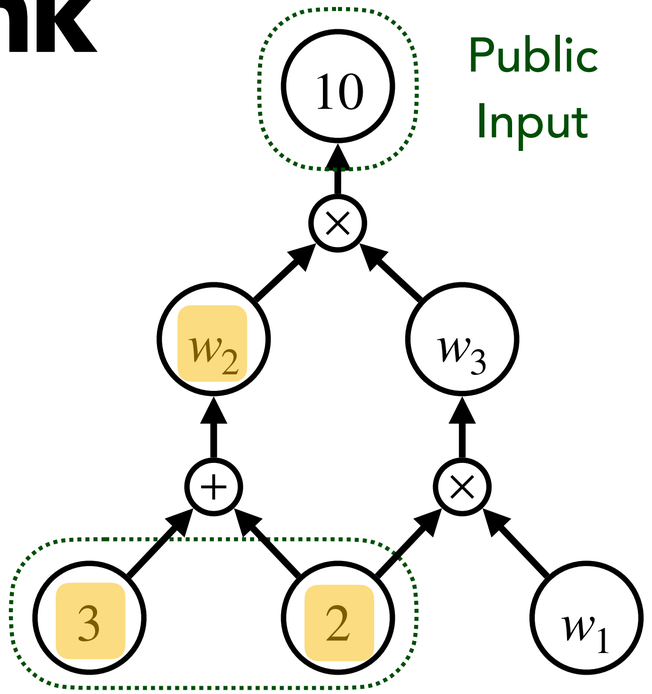
Batching Challenge: α

Evaluation Point: ζ

Weak Fiat-Shamir Attack on Plonk



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(Fixed) Scalars

Batching Challenge

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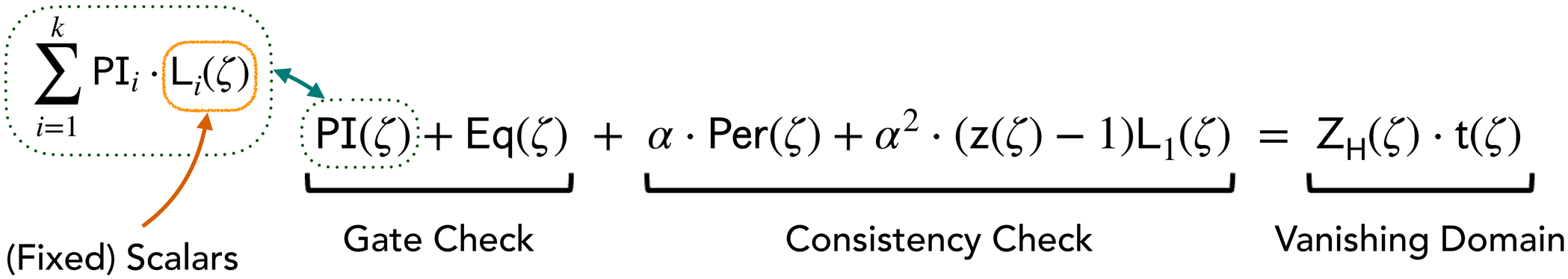

Weak F-S Attack: When PI is not part of hash computation (for deriving α, ζ)

Weak Fiat-Shamir Attack on Plonk

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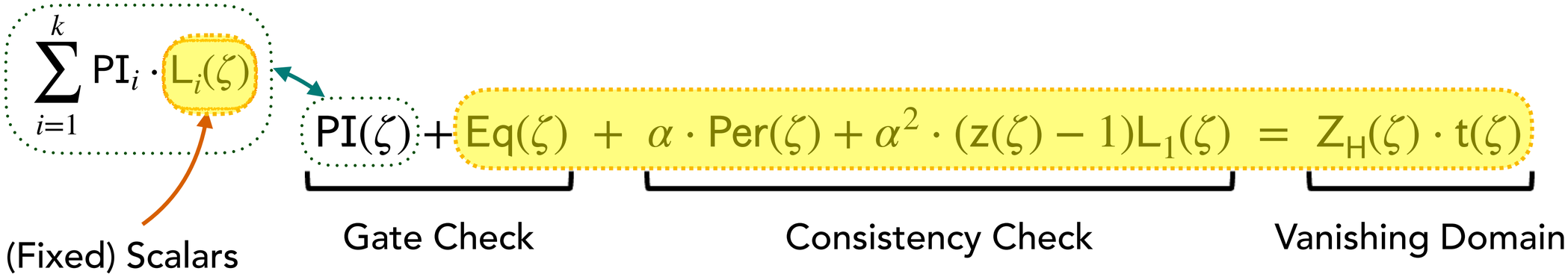

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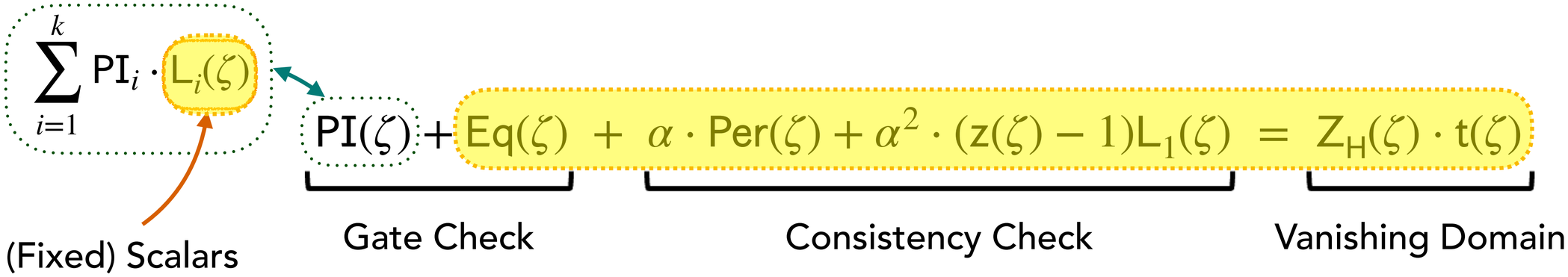

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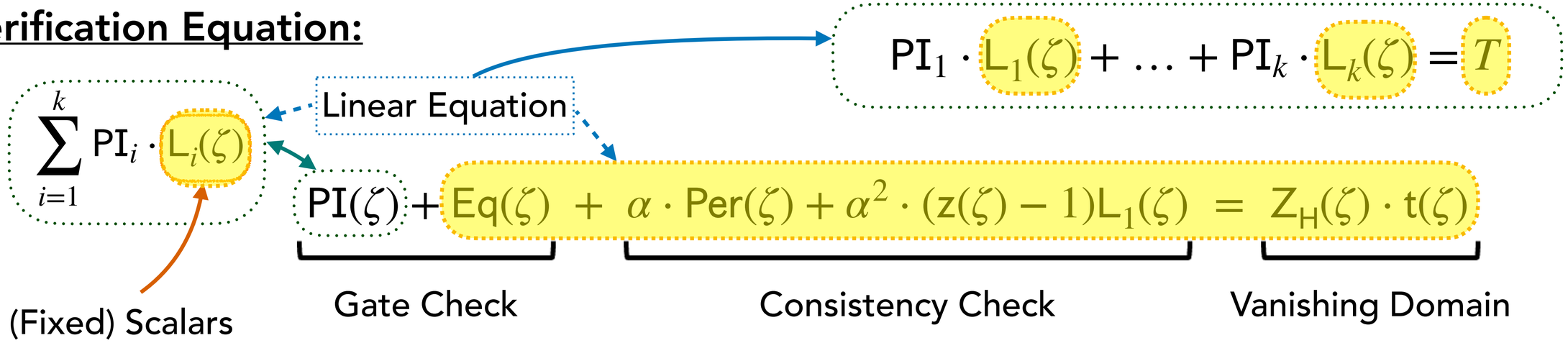

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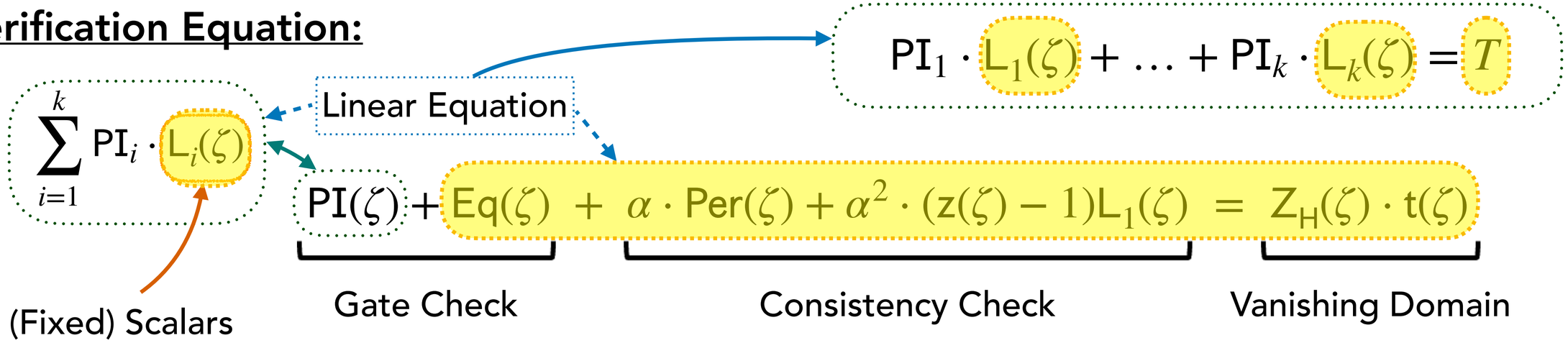

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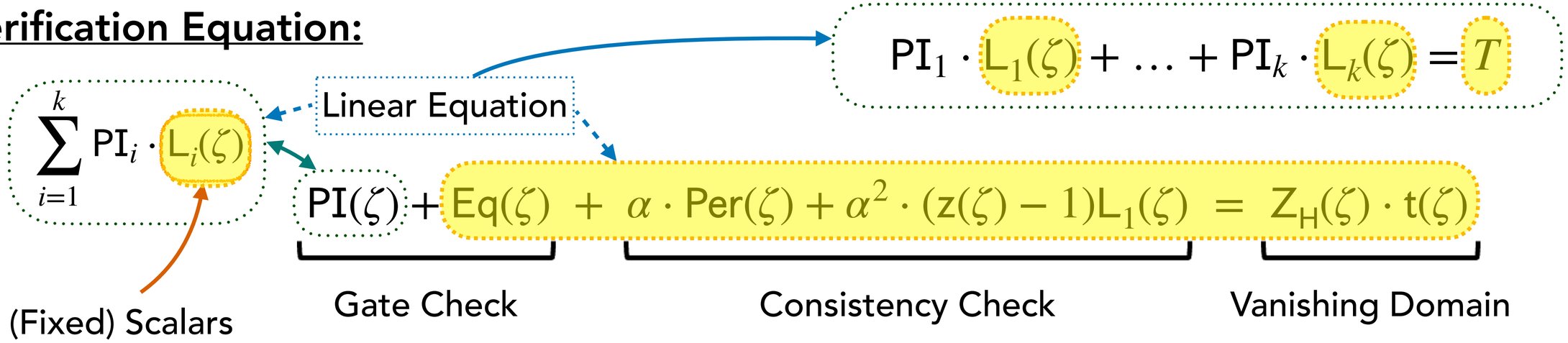

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In Contrast: For **strong** Fiat-Shamir, changing PI will also change α, ζ.

Weak Fiat-Shamir Attacks

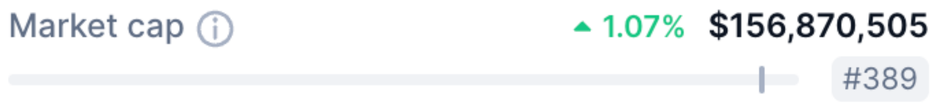
Practical Impacts

(unlimited money printing on blockchains)

Case Study: Dusk Network

DUSK

Regulated And Decentralized Finance.



(as of March 11, 2024)

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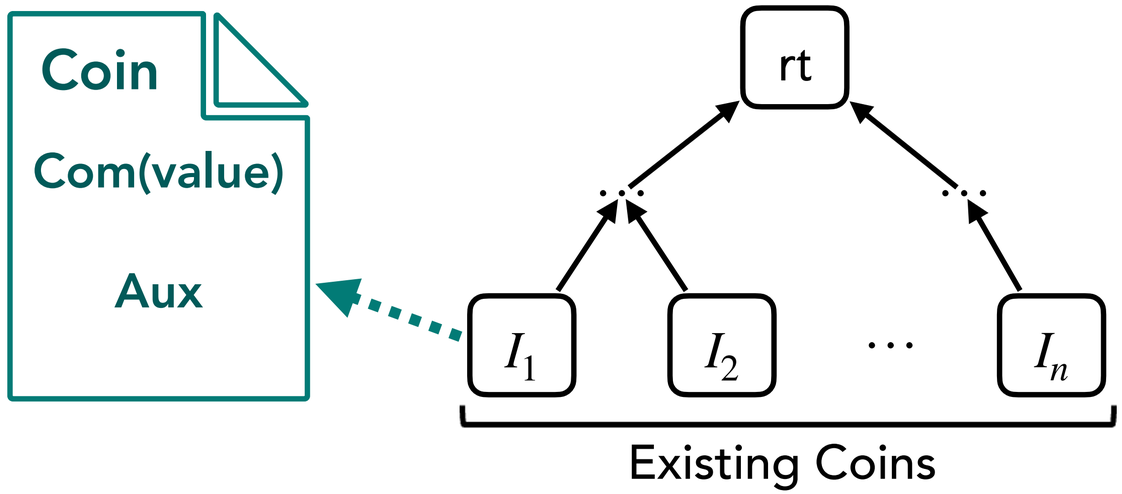
Transaction Model (simplified):



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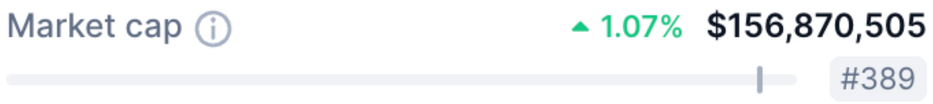

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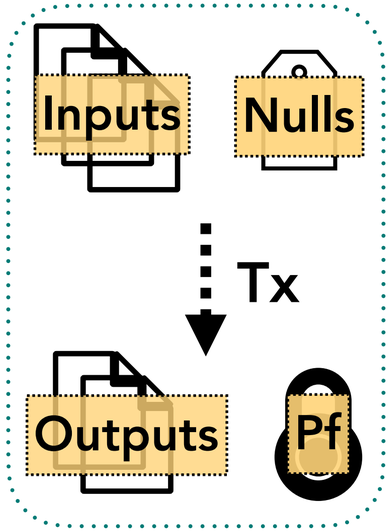
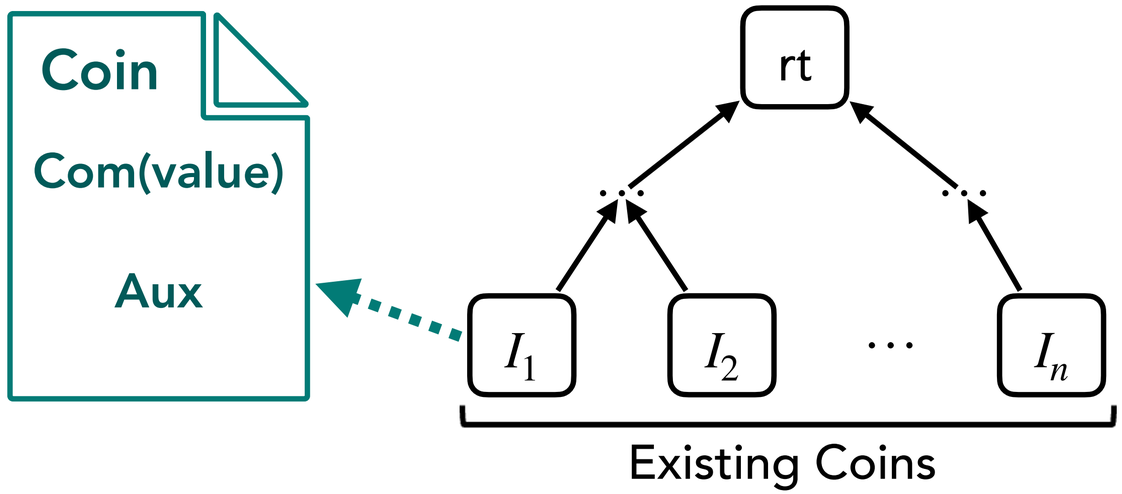
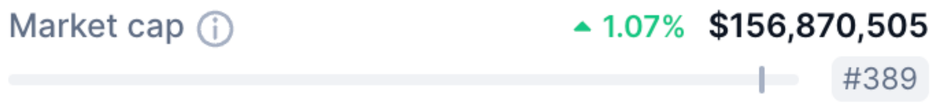




DUSK

Regulated And Decentralized Finance.



(as of March 11, 2024)

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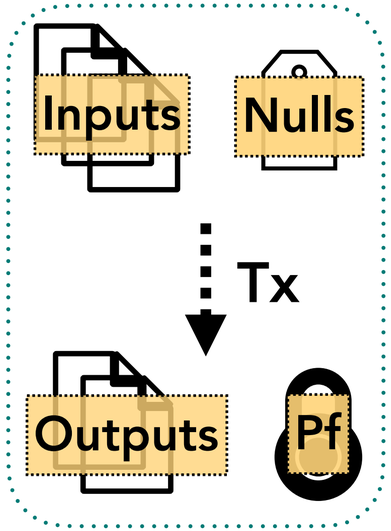

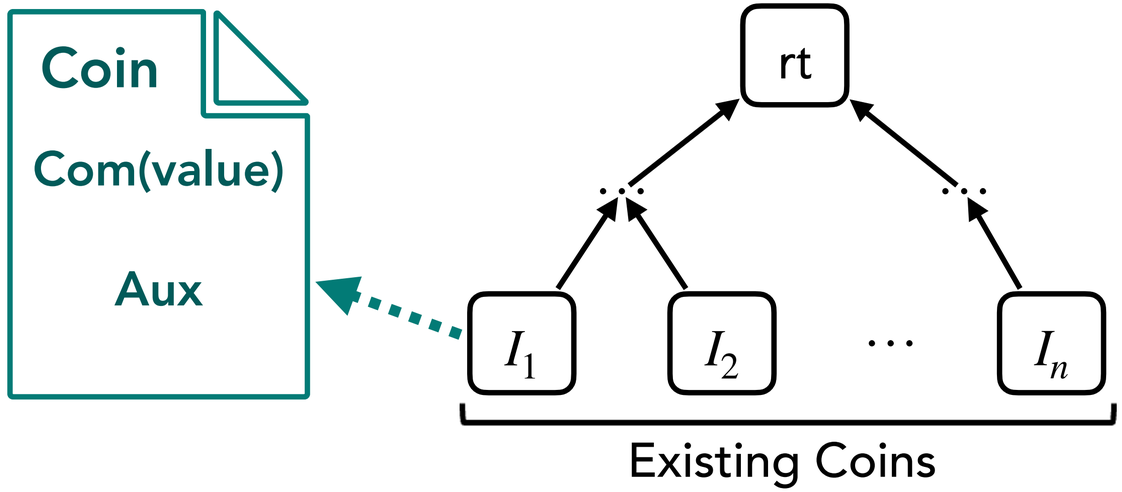

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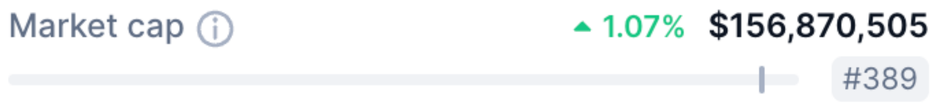

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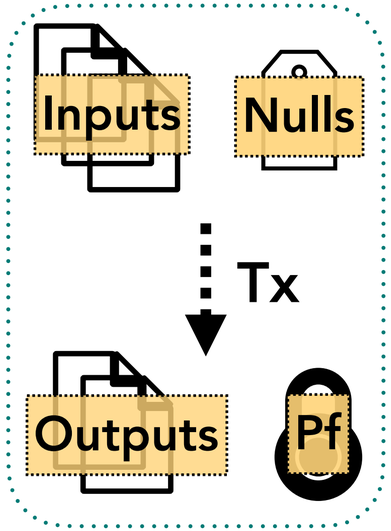

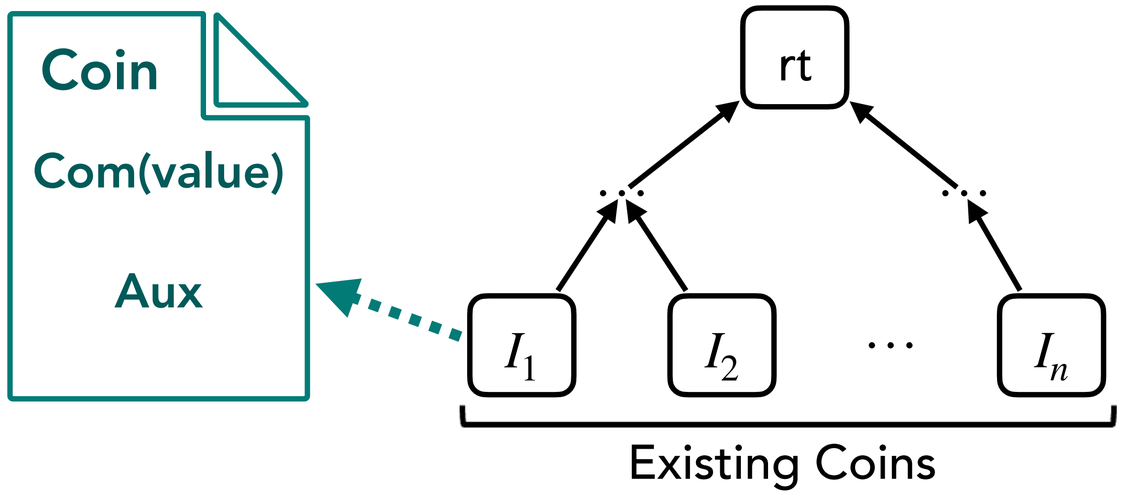

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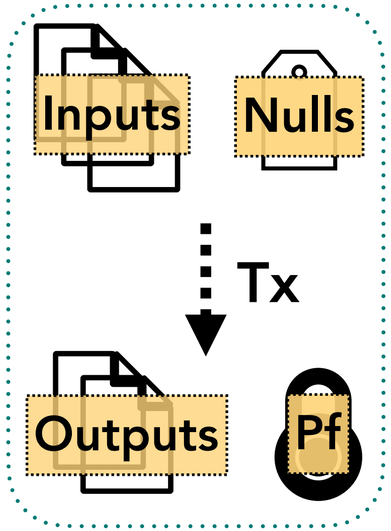

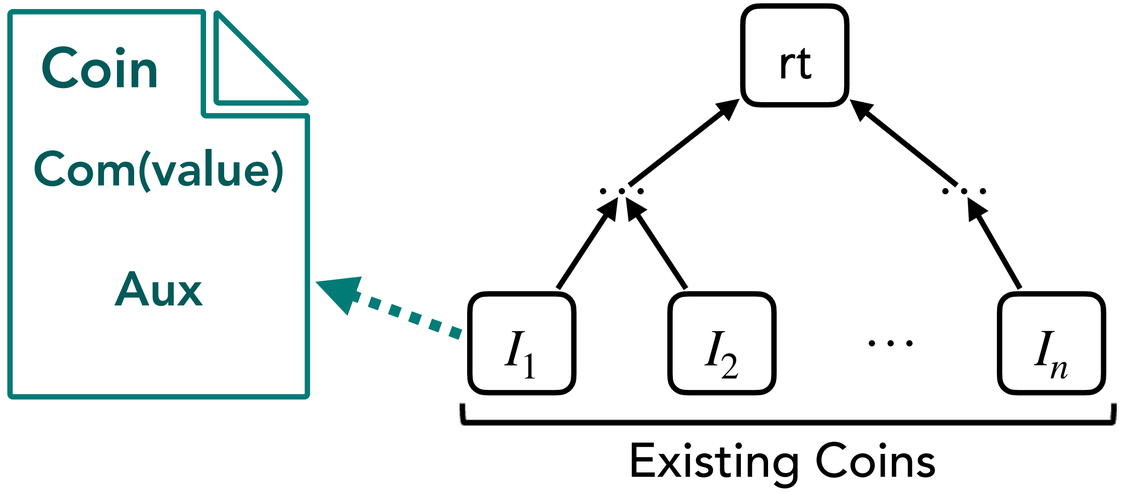

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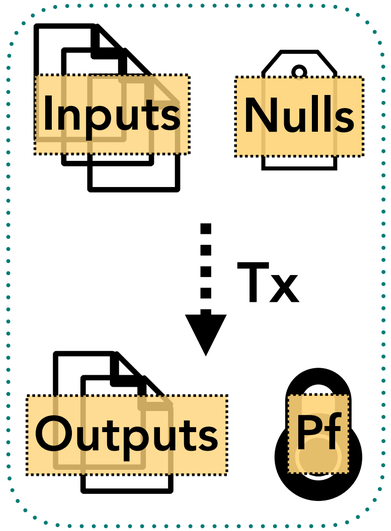

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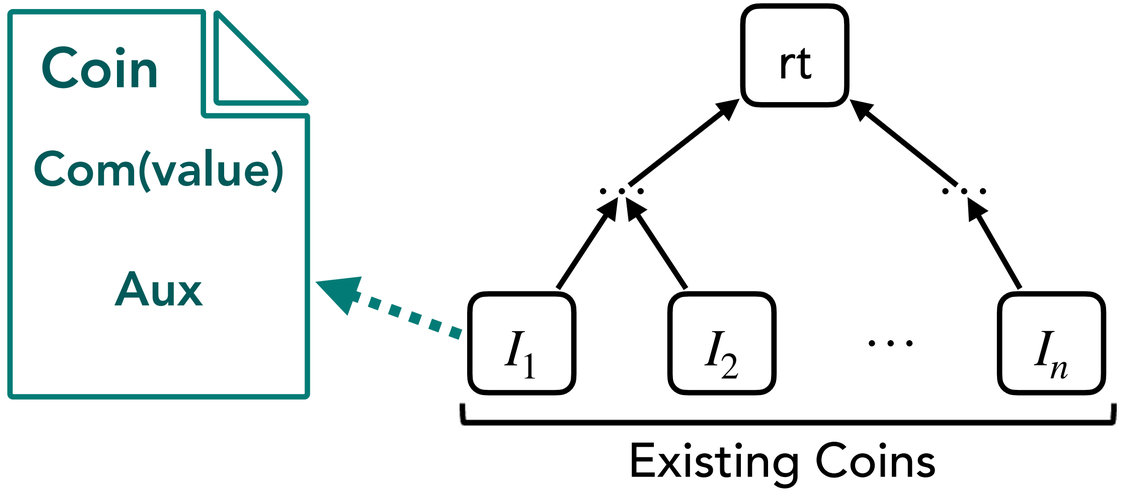

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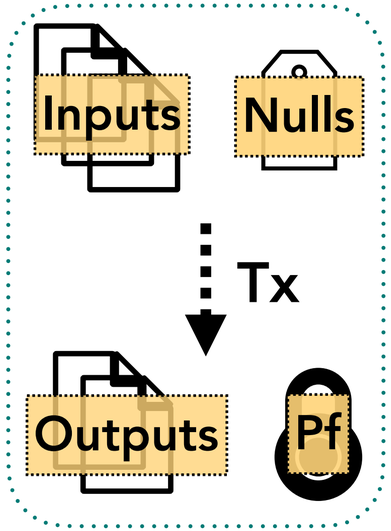

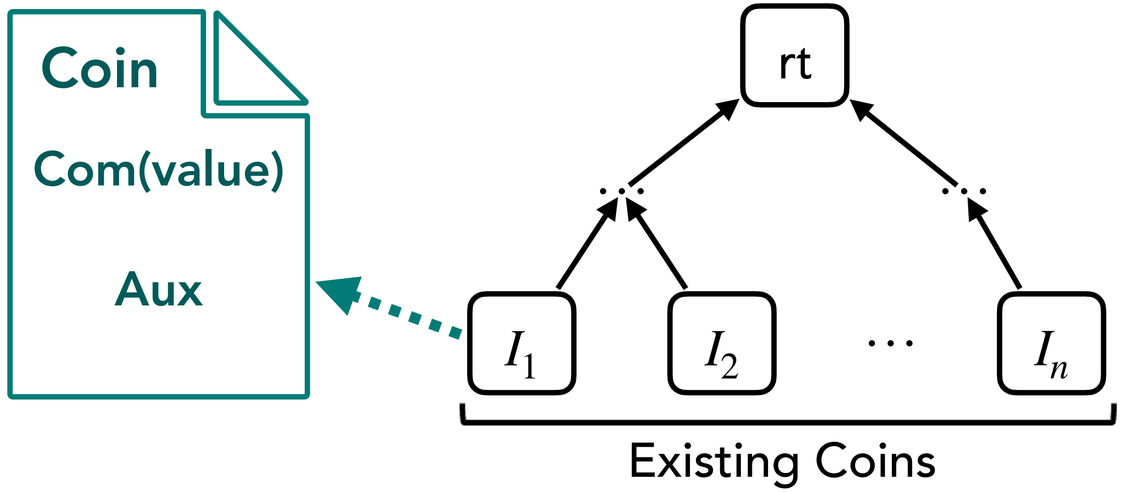

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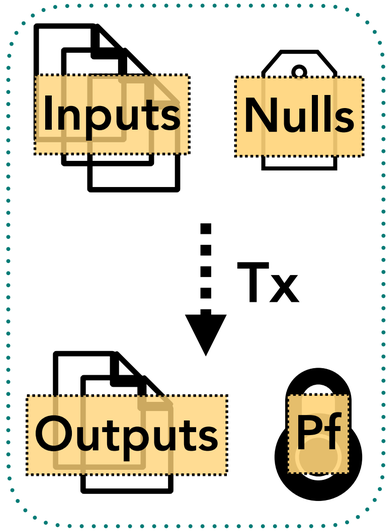

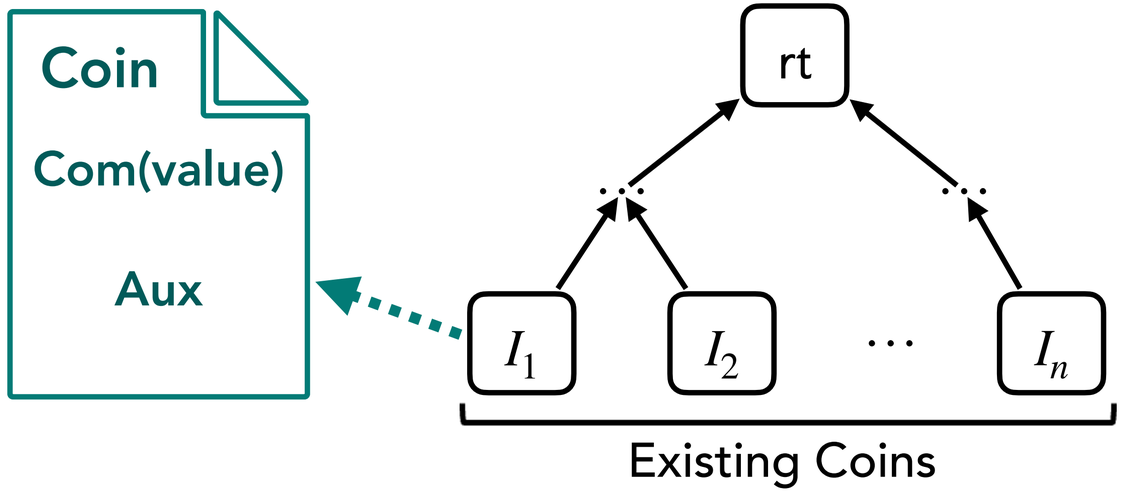

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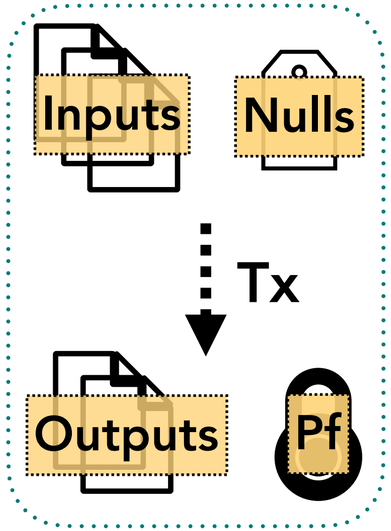

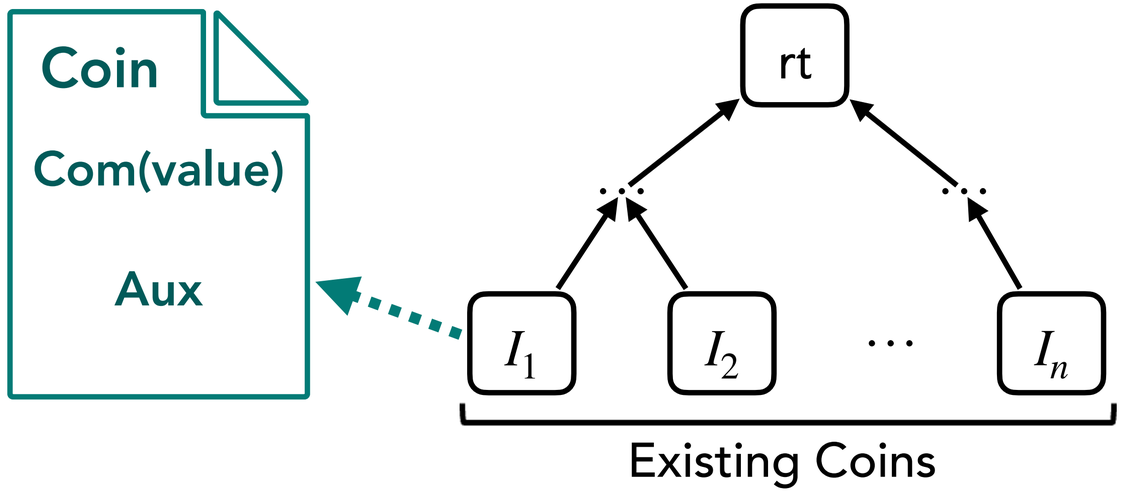

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Case Study: Dusk Network

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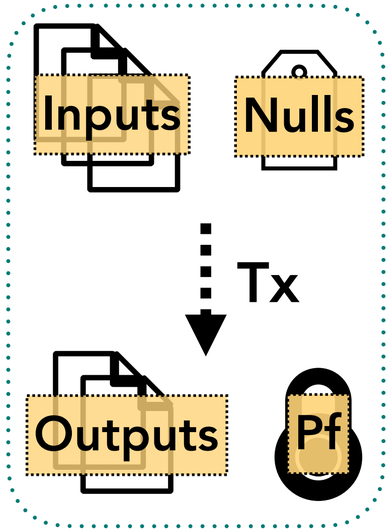

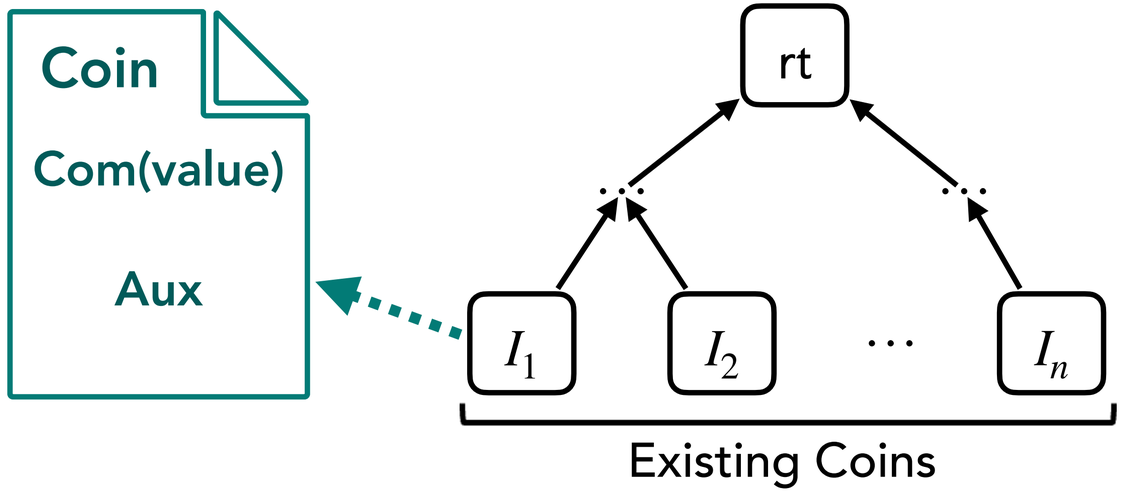

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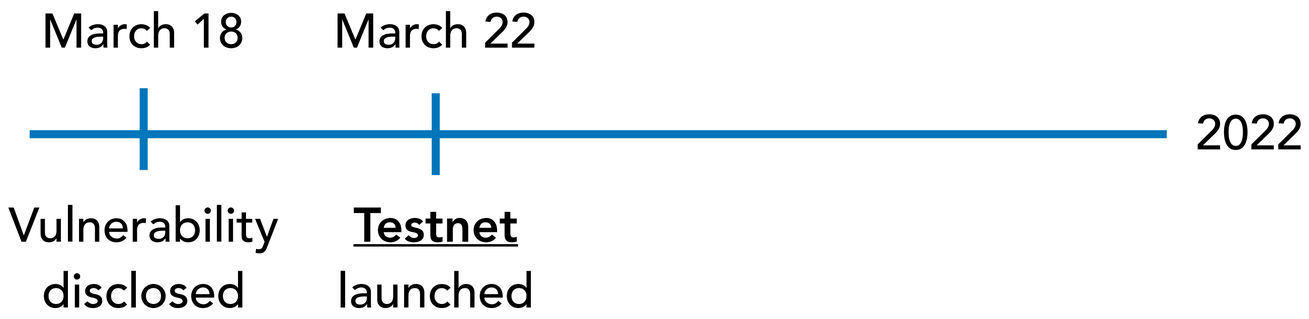

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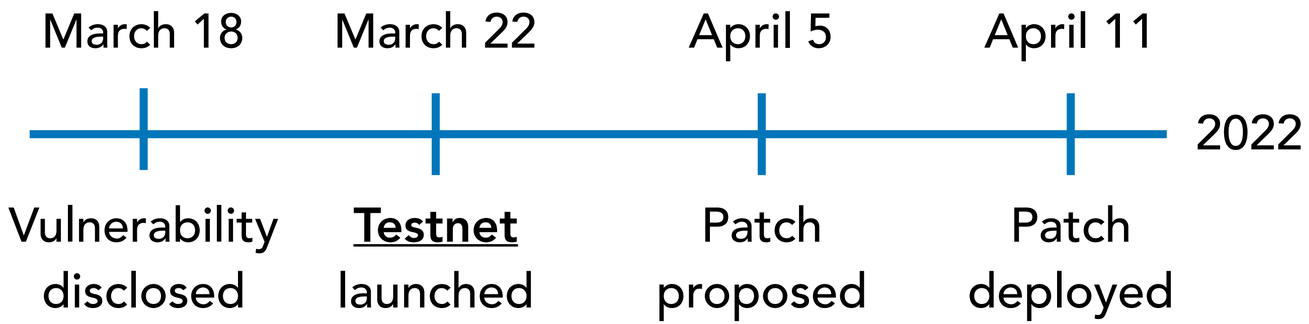

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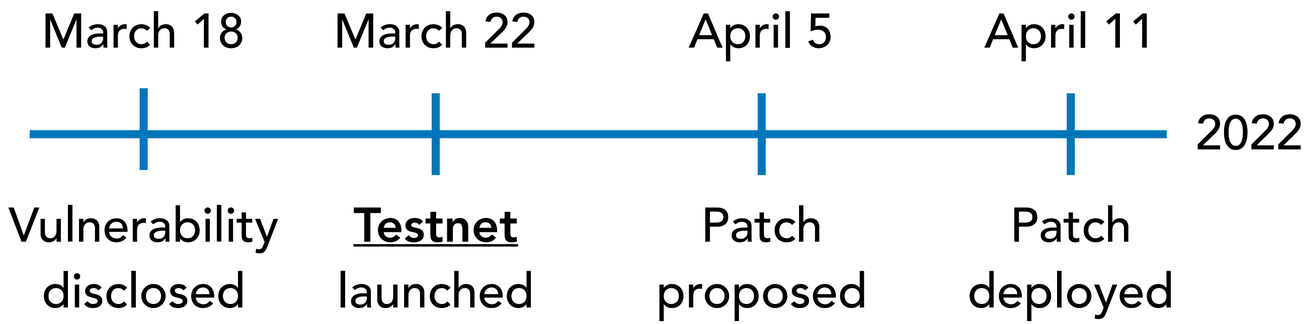

Apr 12, 2022 - Mels Dees

PLONK Critical Vulnerability Successfully Remediated

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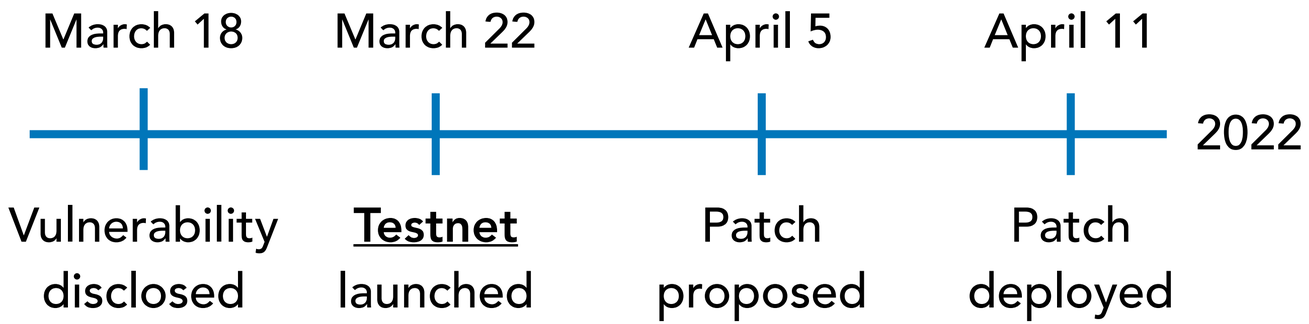

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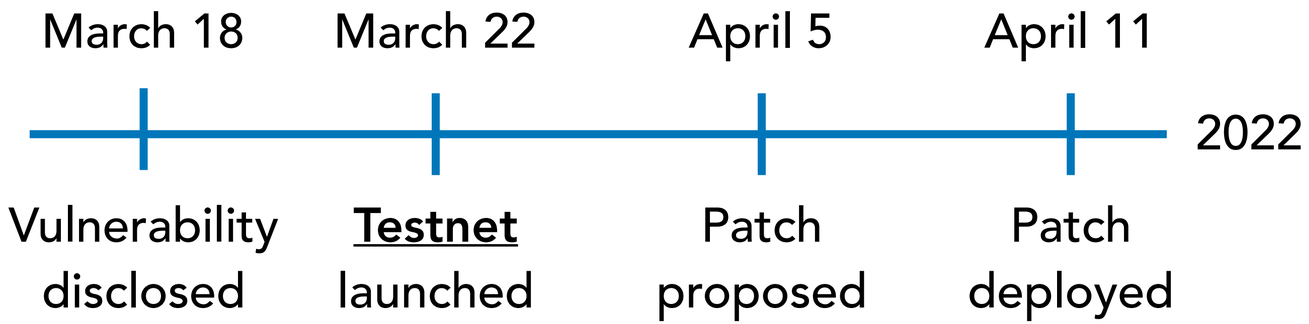

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Case Study: Incognito Chain

Incognito

$250M+	+6M	100+	16
Volume shielded	Anonymous transactions	Coins supported	Bridges supported

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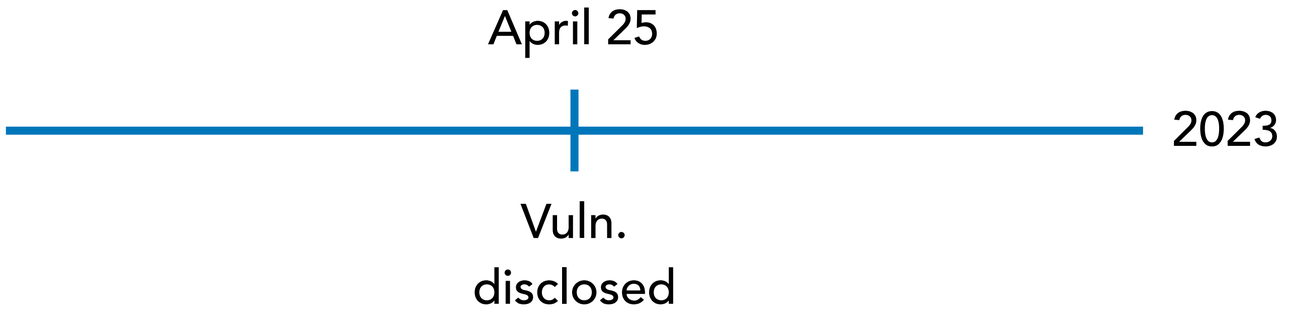

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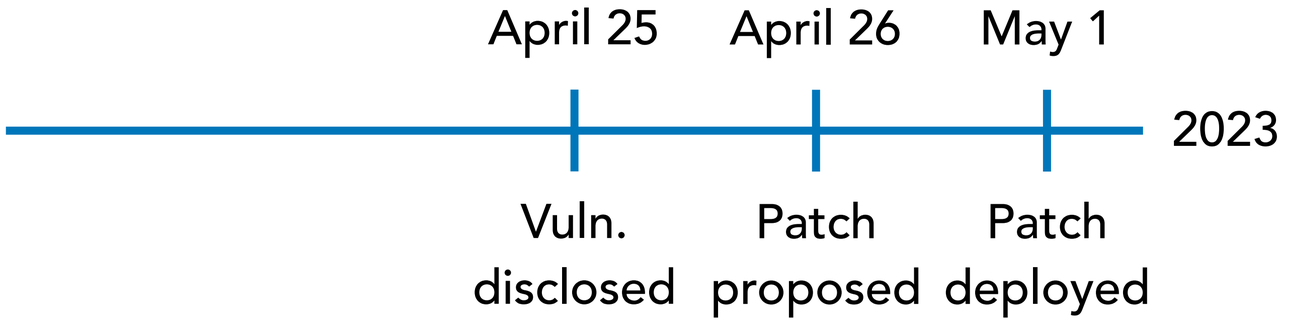

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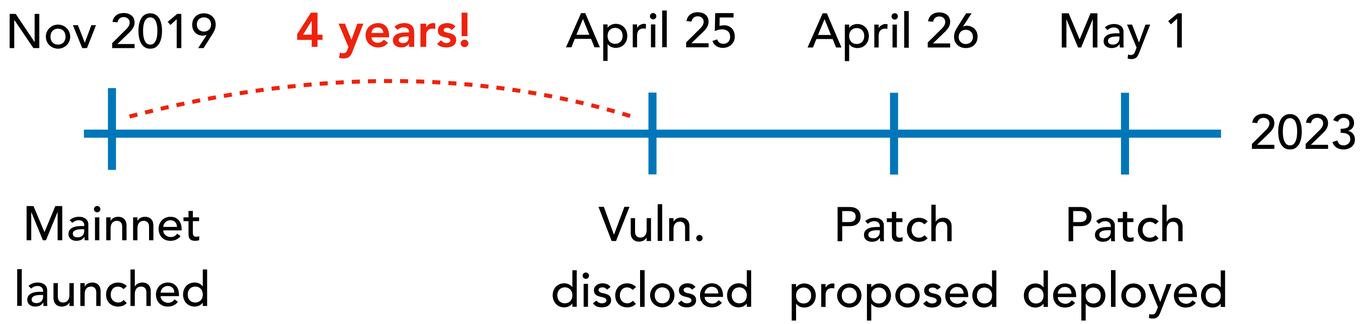

Weak Fiat-Shamir Attacks

Practical Impacts

Why is Weak F-S so widespread?

(and how to prevent it?)

Insufficient Coverage of “correct” Fiat-Shamir

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How is Fiat-Shamir presented in academic papers?

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Removing interaction. Our construction can be made non-interactive in the random oracle model using Fiat—Shamir heuristic [28]. Though GKR protocol is not constant round, recent results [14, 22] show that

as well. Finally, public-coin interactive arguments may be cryptographically compiled into SNARKs using the Fiat-Shamir transform.

subsequent step, the argument can be made non-interactive via the Fiat–Shamir transformation, and thereby obtain a preprocessing SNARG with universal SRS.

lenges are random field elements. In practice we assume that the Fiat-Shamir heuristic would be applied in order to obtain a non-

We apply the Fiat–Shamir heuristic to the protocol from Section 5 to obtain a non-interactive argument of knowledge that is secure in the random oracle model

The above SNARK is obtained via a popular paradigm that combines a polynomial IOP and a polynomial commitment scheme in order to obtain an interactive argument, and then relies on the Fiat–Shamir paradigm

Hyrax-I is a public-coin protocol, we apply the Fiat-Shamir heuristic [45] to produce a zkSNARK that we call Hyrax whose

Finally, since our protocol is public coin, it can be made non-interactive in the random oracle model using the Fiat-Shamir transform [55], thereby obtaining a family

be made non-interactive in the random oracle model using the Fiat-Shamir transform [FS86], and be instantiated (heuristically) in the plain model using a

witness-extended emulation. Applying the Fiat-Shamir transform [FS86] to the public-coin interactive argument results in the claimed SNARK for $\mathcal{R}_{\text{R1CS}}$.[14]

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Plonk:

Compute quotient challenge $\alpha \in \mathbb{F}_p$:

$$\alpha = H([a]_1, [b]_1, [c]_1, [z]_1)$$

(December 2019)

We describe the protocol below as a non-interactive protocol using the Fiat-Shamir hueristic. For this purpose we always denote by transcript the concatenation of the common preprocessed input, and public input, and the proof elements written by the prover up to a certain point in time. We use transcript for obtaining random challenges via

(March 2020)

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$\Longrightarrow$ (some) do not get it right on the first try!

Plonk:

challenges are replaced by hashes of the transcript up to that point. For instance $y = \mathsf{H}(A, S)$ and $z = \mathsf{H}(A, S, y)$

(July 2018)

Bulletproofs:

random challenges are replaced by hashes of the transcript up to that point, including the statement itself. For example, one could set $y = \mathsf{H}(\mathsf{st}, A, S)$ and $z = \mathsf{H}(A, S, y)$, where st is the statement.

(April 2022)

(in response to our FrozenHeart disclosure)

How to Prevent Weak Fiat-Shamir?

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Merlin prevents some F-S issues

Merlin: composable proof transcripts for public-coin arguments of knowledge

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let log = BigInt::parse_bytes(b"187777970837149957259676149979333086l5", 10).unwrap();
let modulus = &BigInt::from(2u32).pow(127) - BigInt::from(1u32);

// Random exponent
let mut rng = rand::thread_rng();
let randomizer_exp = rng.gen_bigint(256) % (&modulus - BigInt::from(1u32));
let randomizer = base.modpow(&randomizer_exp, &modulus);
💡
// Update transcript — order of addition matters!
transcript.append_message("modulus", &modulus);
transcript.append_message("base", &base);
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- No detection of missing, duplicated, or incorrect inputs
- No enforcement of ordering for inputs & challenges
- Unclear boundaries for protocol stages
- Limited auditability, i.e., “the code is the spec”

Preventing Weak F-S with Decree

Improving on Merlin with Decree

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Long-term: Standardization of Fiat-Shamir

ZKPROOF ZKDocs

Summary & Future Directions

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Takeaways:

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Read our paper
(ePrint 2023/691)

IEEE S&P Distinguished Paper Award!

Thank You! Questions?