Side-channel protections for Picnic signatures

CHES 2021

Diego F. Aranha[1] Sebastian Berndt[2] Thomas Eisenbarth[2] Okan Seker[2]
Akira Takahashi[1] Luca Wilke[2] Greg Zaverucha[3]

[1]Aarhus University, Denmark

[2]University of Lübeck, Germany

[3]Microsoft Research, USA

Background & Motivation: NIST PQC Standardization Round 3

Finalists

- CRYSTALS-DILITHIUM
- Falcon
- Rainbow

Alternates

- GeMSS
- Picnic
- SPHINCS+

- Side-channel resilience is becoming more relevant
- Little study on side-channel resilience of **Picnic**/MPC-in-the-head paradigm

Picnic & side-channel security

- Fiat–Shamir-type signature from **MPC-in-the-head** ZKP [IKOS07]

☺ No number-theoretic assumptions
  - Block cipher
  - Hash function (modeled as RO)

☺ Various parameters

Picnic1

☹ Known to be vulnerable to DPA [GSE20]

☹ Existing countermeasure breaks interoperability with verification [SBWE20]

☹ Also increases signature size

Picnic3

- Follows MPC-in-the-head with **preprocessing** paradigm [KKW18]
- More compact signature
- No side-channel evaluation yet

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Our goal

- Side-channel evaluation of Picnic3 / MPC-in-the-head with preprocessing
- Maintain **interoperability** and **signature size** while applying masking countermeasures

This work

- Side-channel vulnerabilities of unprotected **Picnic3**
  - Attack I extends [GSE20]
  - Attack II is new
- Generic approach to mask ZKP using MPCitH with **preprocessing**
  - Proof for t-probing security
  - Supported by **`maskVerif`** formal verification tool [BBC+19]
  - Possible to trade-off **provable security** for **lower masking overhead**
- First-order masked implementation of **Picnic3** & **SHA-3**
- Practical electromagnetic (EM) leakage analysis

Side-channel Attacks on Picnic3

Zero-knowledge proof using the MPC-in-the-head [IKOS07, GMO16]

Prover$(sk = sk_1 + sk_2 + sk_3)$

Verifier$(pk = (f, x))$
s.t. $f(sk) = x$

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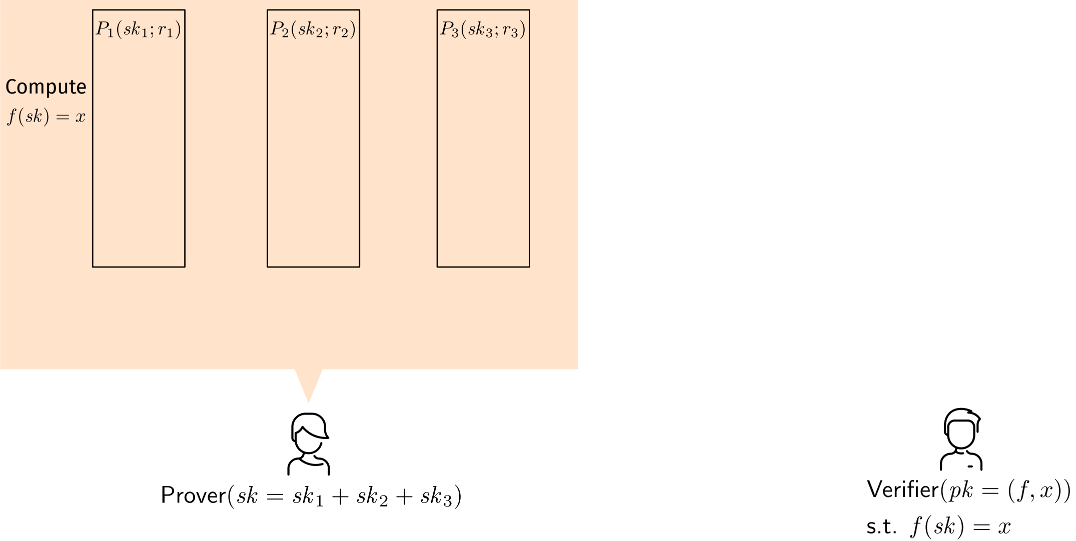

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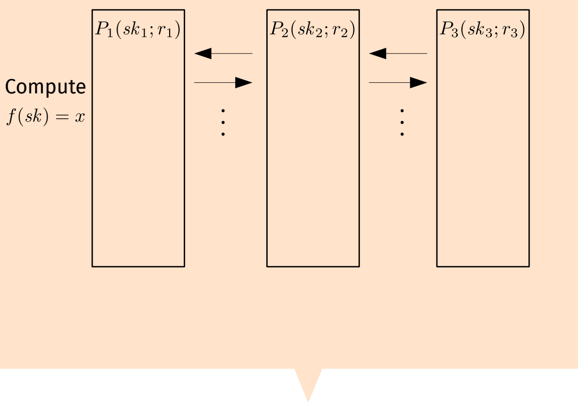

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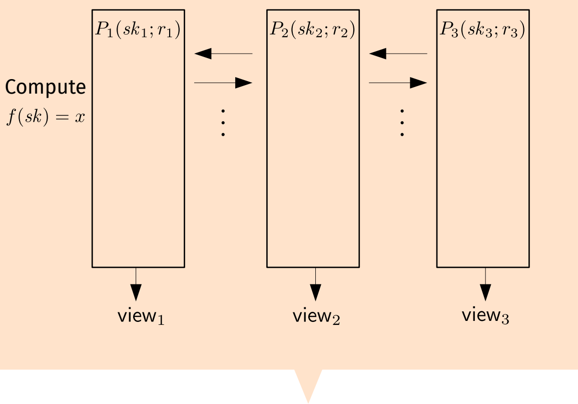

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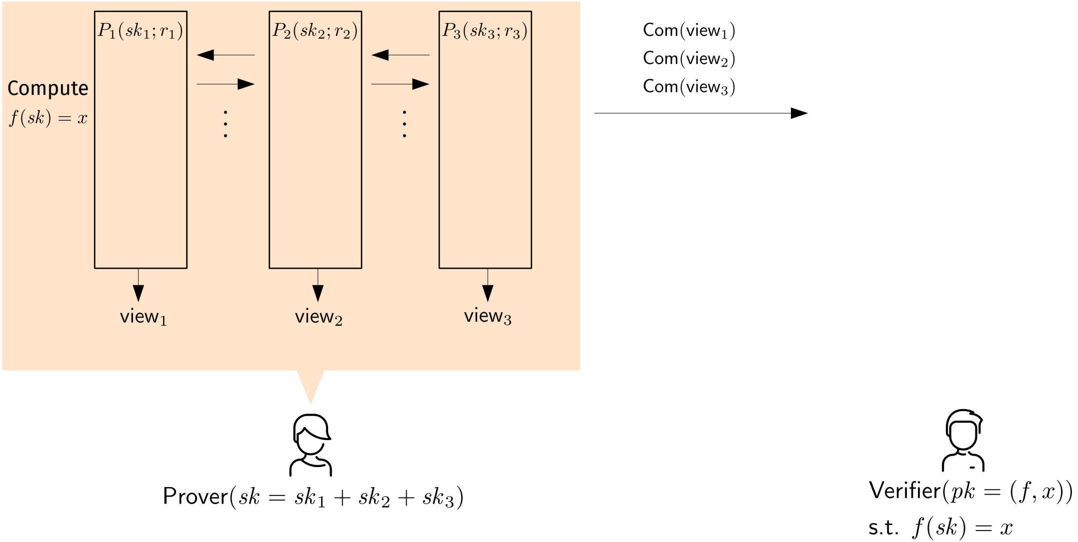

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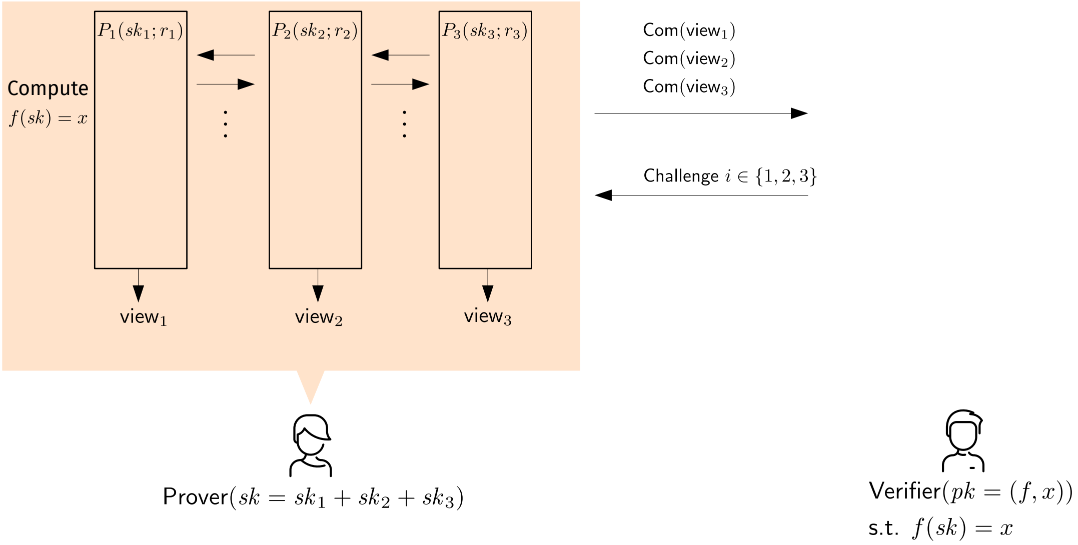

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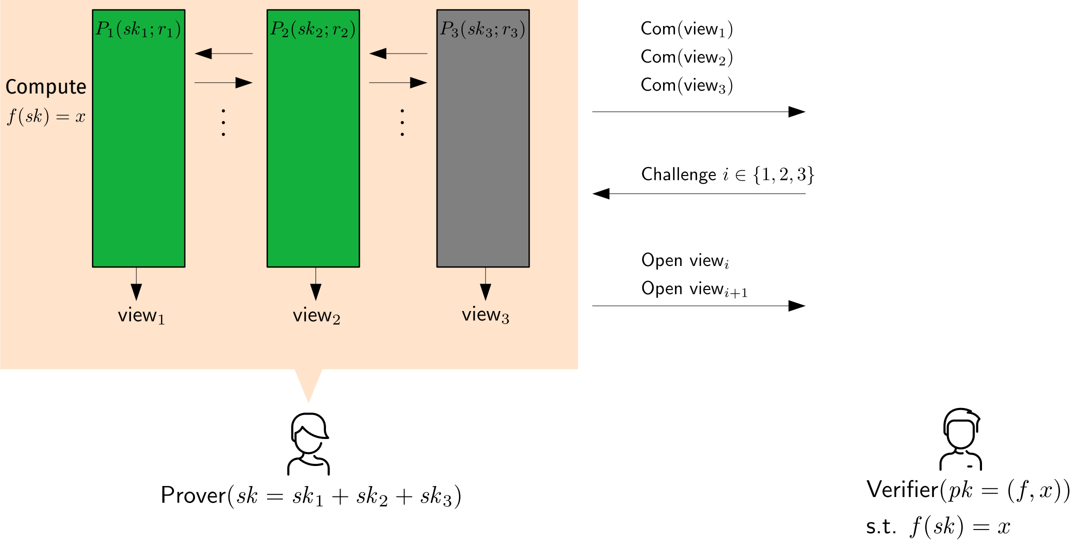

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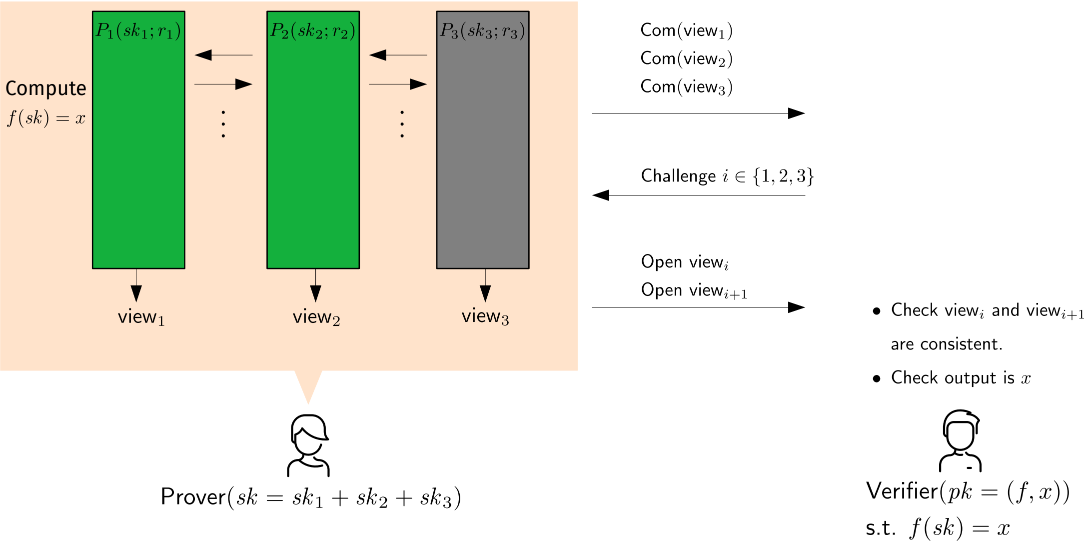

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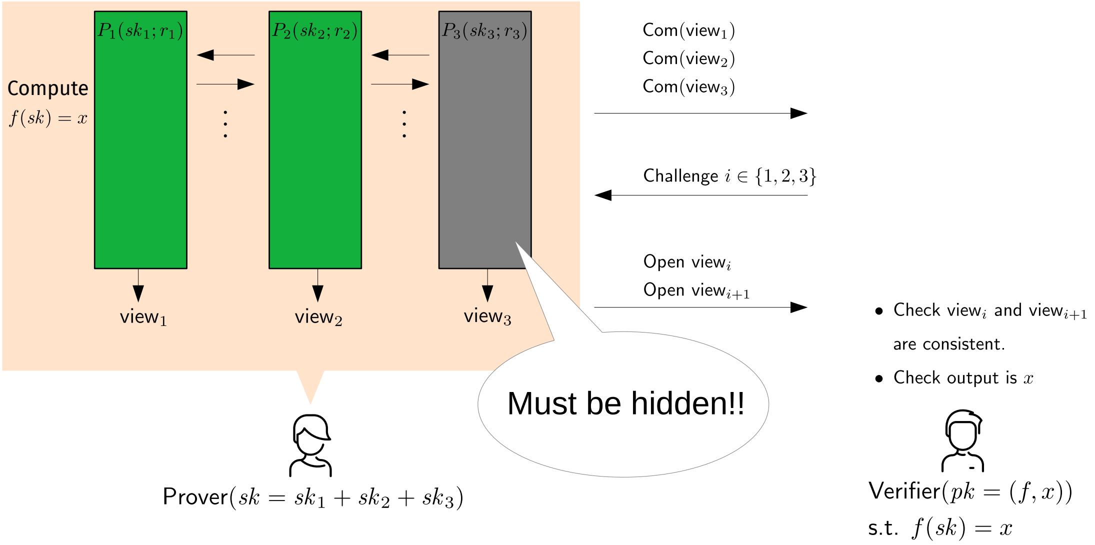

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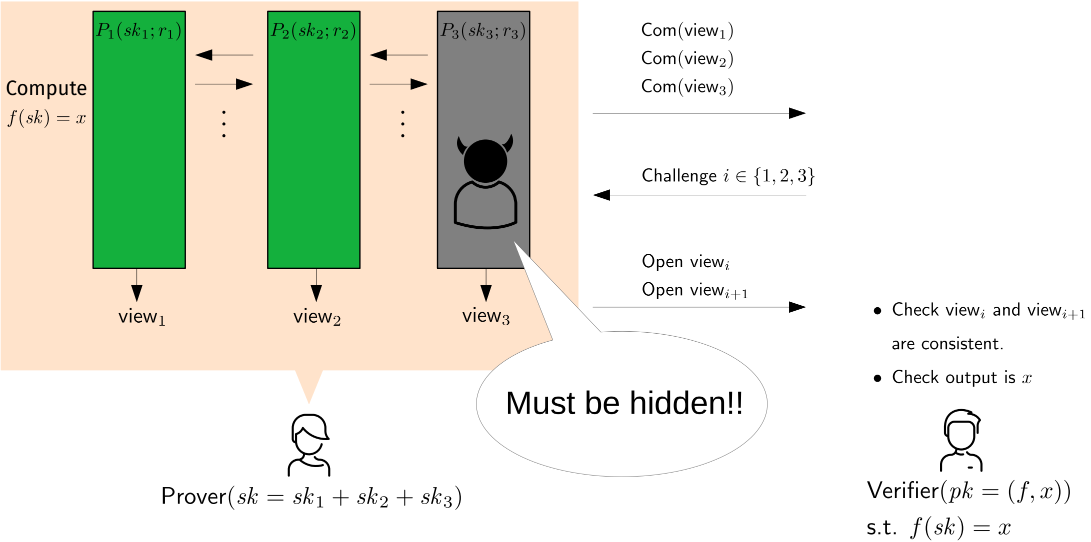

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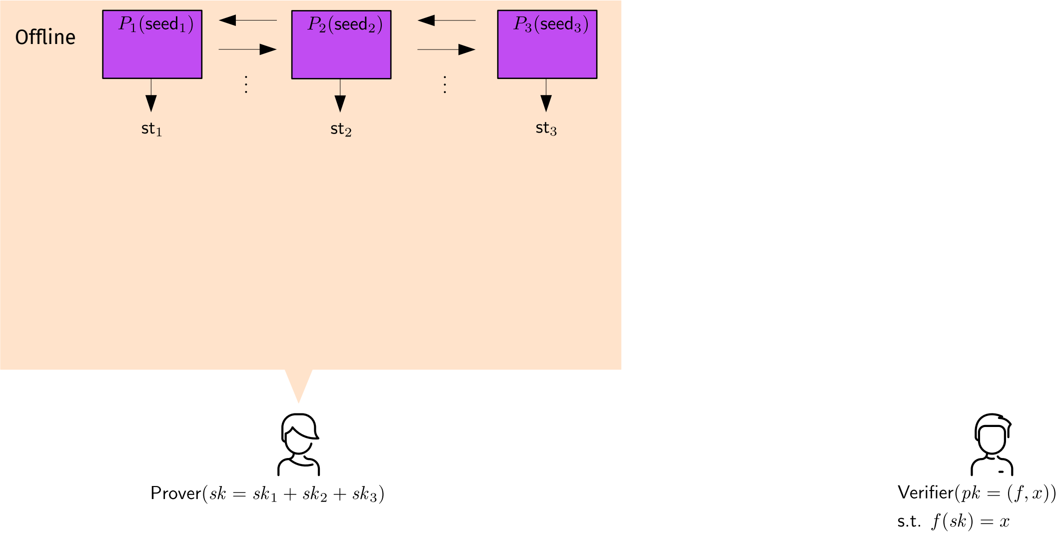

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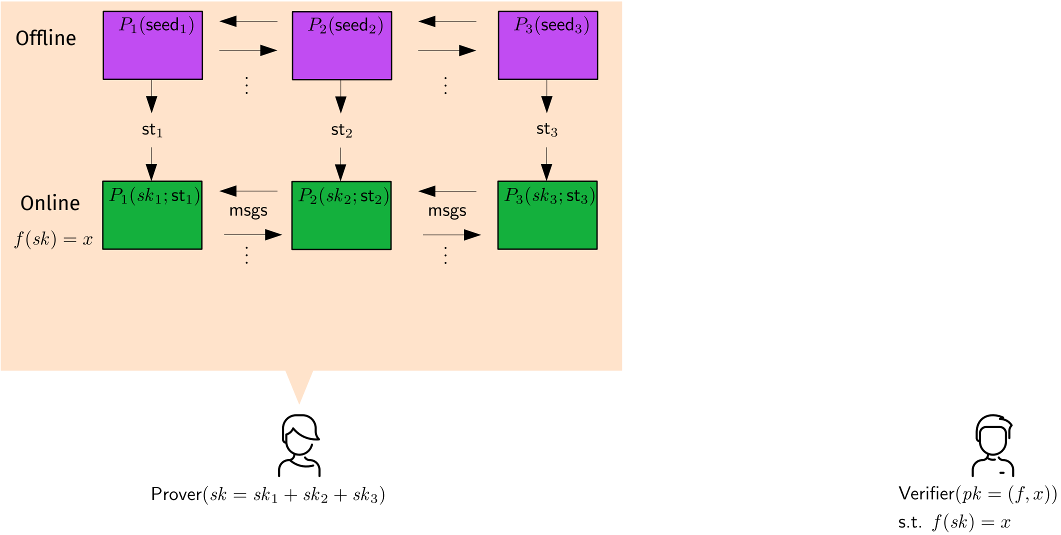

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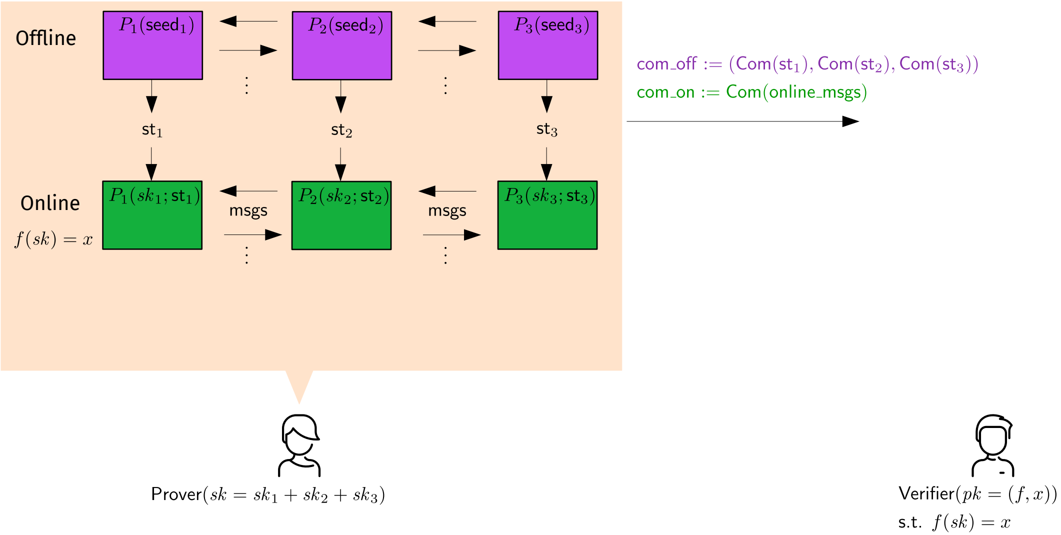

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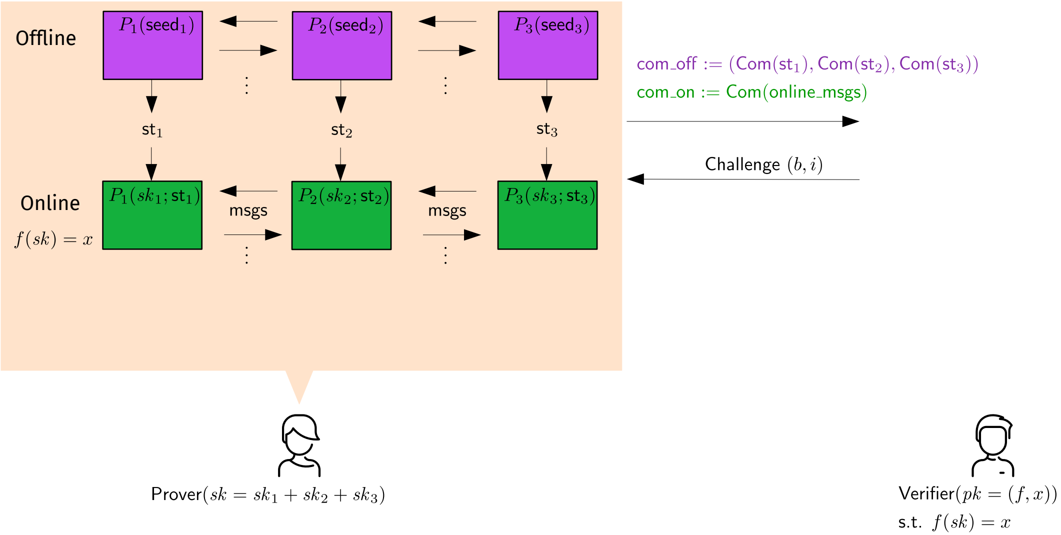

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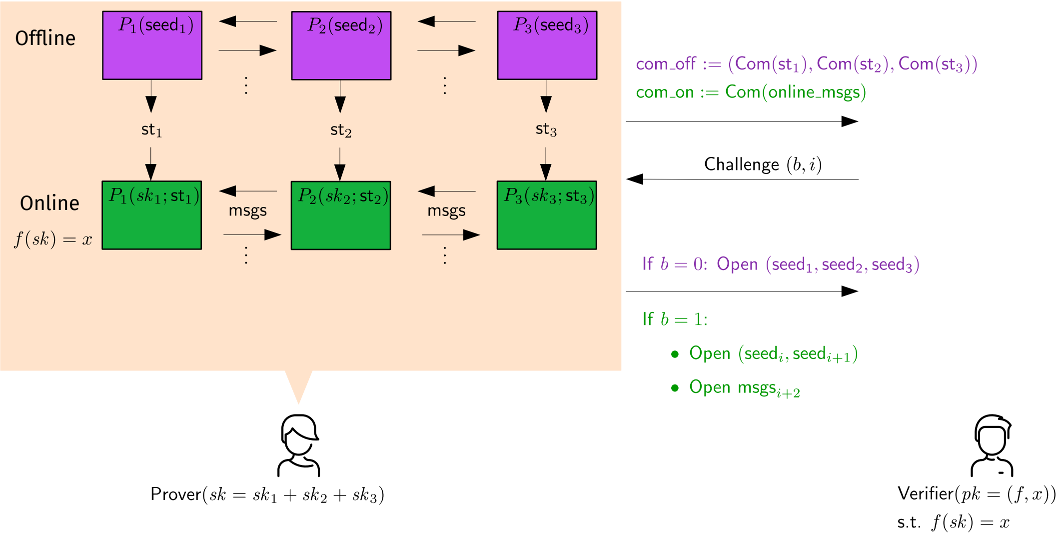

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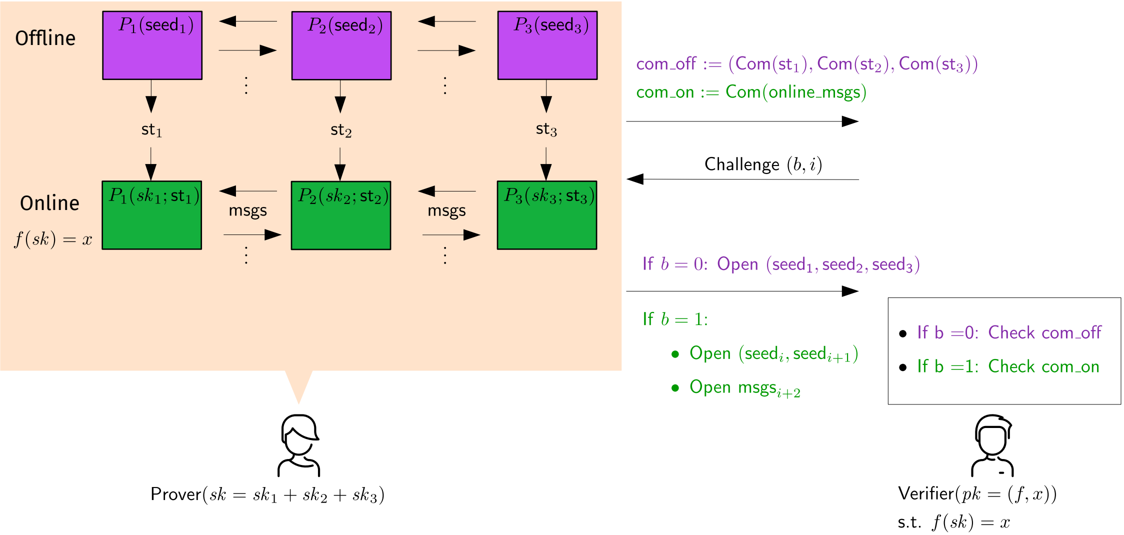

Why preprocessing? – Multiplication with Beaver triples

Inputs $:[x] = (x_1, \ldots, x_N)$ and $[y] = (y_1, \ldots, y_N)$

Output $:[z] = (z_1, \ldots, z_N)$ such that $z = xy$

Offline

- Generate many random triples $([\lambda^x], [\lambda^y], [\lambda^{xy}])$ with $\lambda^{xy} = \lambda^x \lambda^y$
- Easy in MPCitH:

$$\lambda_N^{xy} := \left(\sum_{i=1}^{N} \lambda_i^x\right)\left(\sum_{i=1}^{N} \lambda_i^y\right) - \sum_{i=1}^{N-1} \lambda_i^{xy}$$

Online

- Observation: $xy = ((x + \lambda^x) - \lambda^x)((y + \lambda^y) - \lambda^y)$
- Reconstruct $\hat{x} := x + \lambda^x$ and $\hat{y} := y + \lambda^y$
- Compute

$$[z] = \hat{x}\hat{y} - \hat{x}[\lambda^y] - \hat{y}[\lambda^x] - [\lambda^{xy}]$$

No non-linear operations in the online phase!

WARNING: New attack surface arises..

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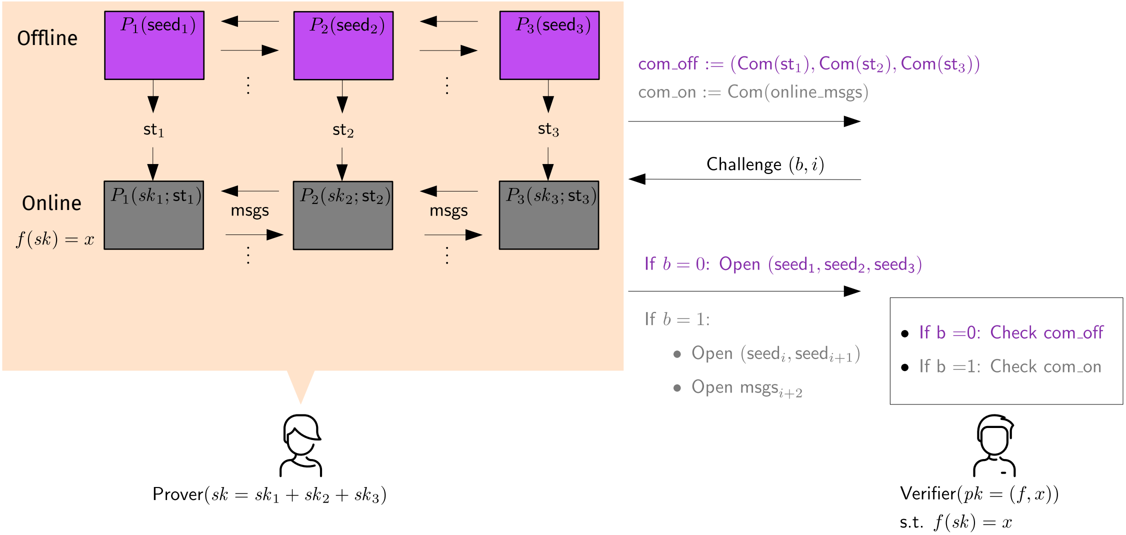

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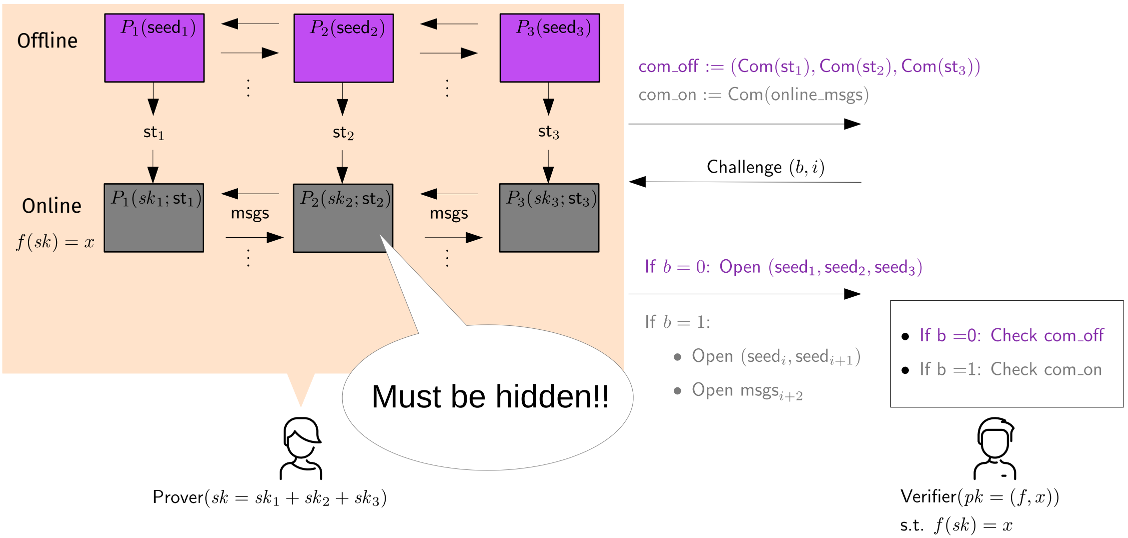

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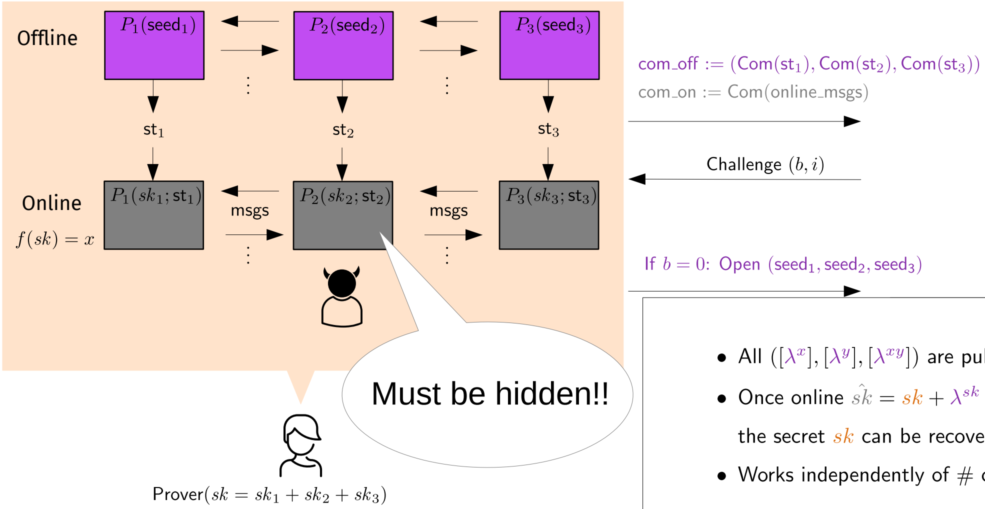

- All $([\lambda^x], [\lambda^y], [\lambda^{xy}])$ are public
- Once online $\hat{sk} = sk + \lambda^{sk}$ is probed, the secret sk can be recovered!!
- Works independently of # of parties!

Masking Picnic3

Our approach: Masking inside each party

Compute
$f(sk) = x$

$P_1(sk_{1,1} + sk_{1,2}; r_{1,1} + r_{1,2})$

$P_2(sk_{2,1} + sk_{2,2}; r_{2,1} + r_{2,2})$

$P_3(sk_{3,1} + sk_{3,2}; r_{3,1} + r_{3,2})$

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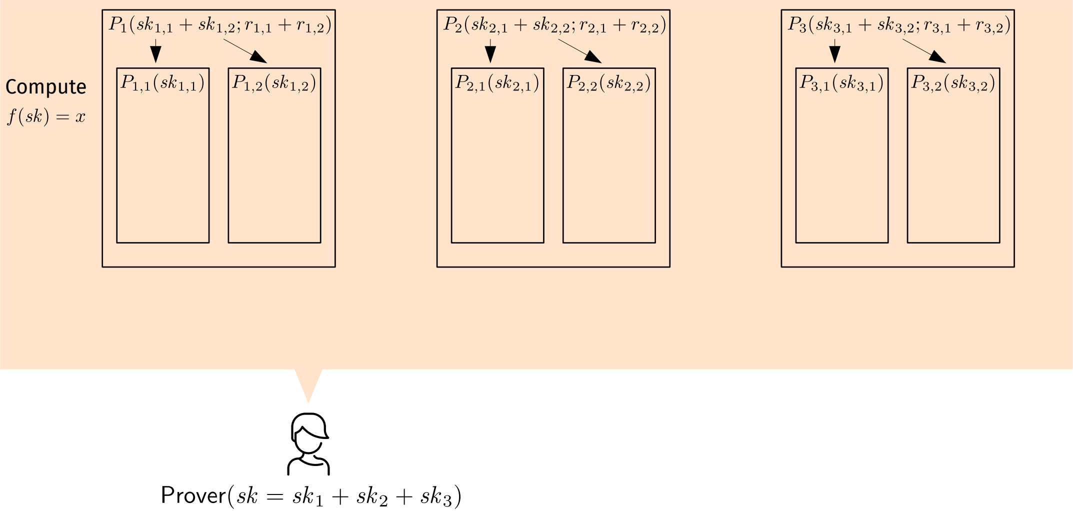

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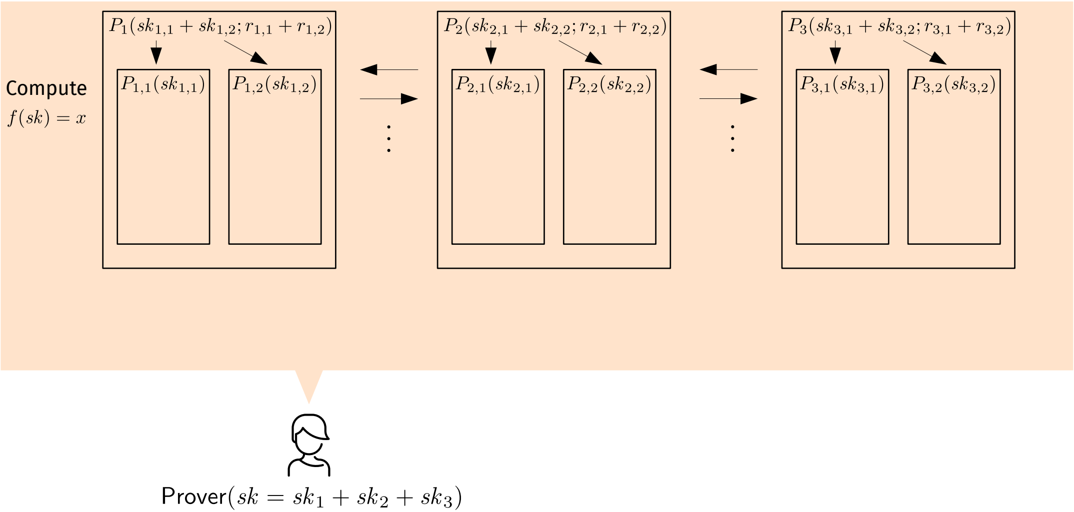

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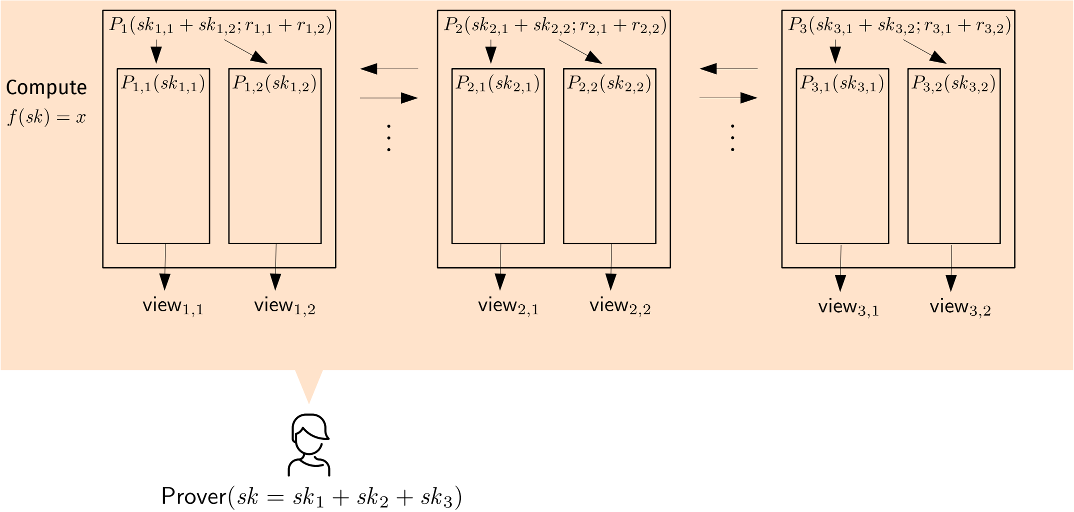

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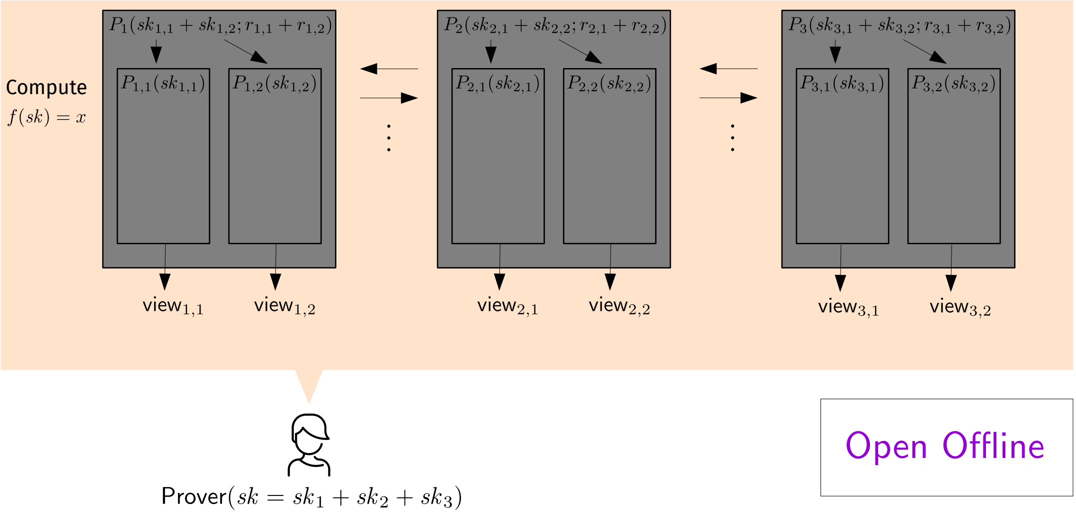

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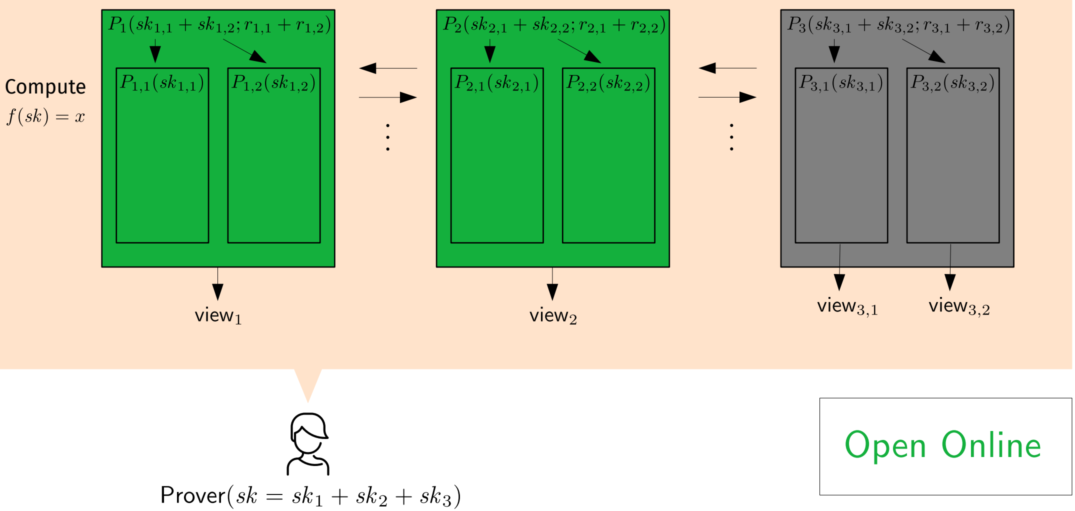

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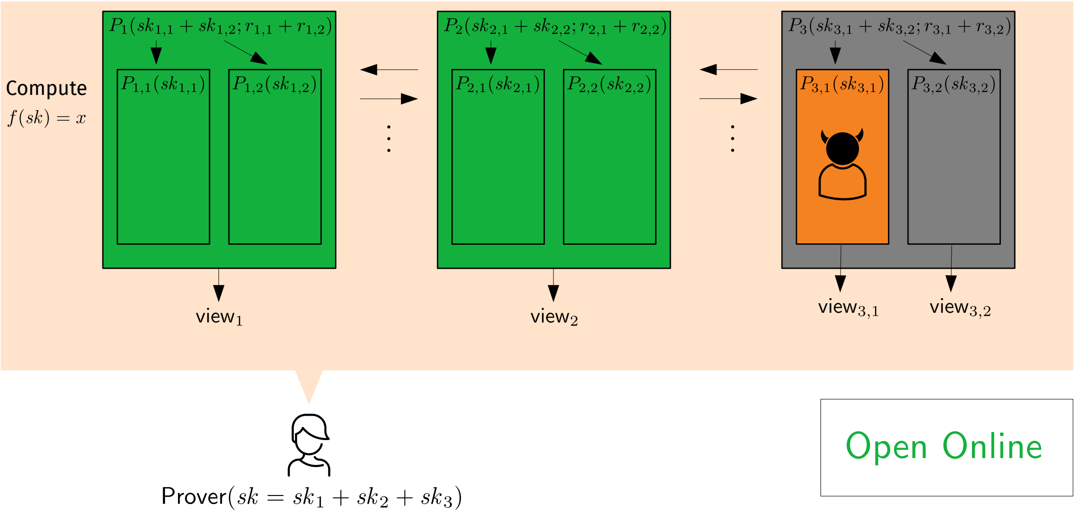

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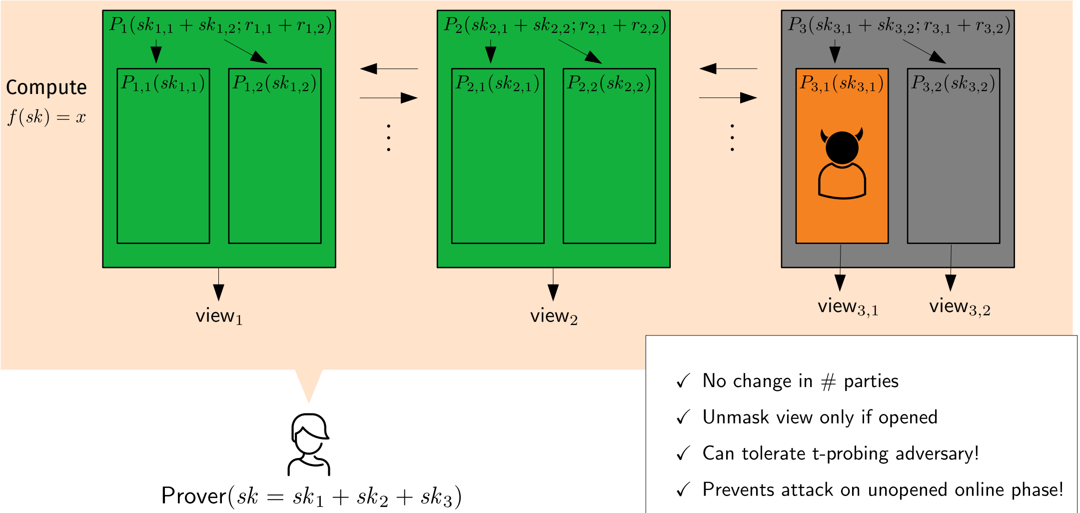

- ✓ No change in # parties
- ✓ Unmask view only if opened
- ✓ Can tolerate t-probing adversary!
- ✓ Prevents attack on unopened online phase!

Masking SHA-3

Masking seed expansion

- $[\text{tapes}_i] \leftarrow \text{SHA-3}([\text{seed}_i])$

Masking commitments

- $[\text{com\_off}_i] \leftarrow \text{SHA-3}([\text{st}_i])$
- $[\text{com\_on}] \leftarrow \text{SHA-3}([\text{online\_msgs}])$

Masking everything is expensive..

Heuristic options

- Some hash inputs that are unique per signature are not sensitive by regarding SHA-3 as a random oracle and if attacker only probes t bits of input.
- Commitment outputs are not sensitive
- Unmask / selectively mask half of the SHA-3 computations (without formal t-probing security)
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Implementation & leakage analysis

Benchmarking for the First-order Protected Implementations

Picnic Masking	SHAKE Masking	Signing cycles	Hashing	Masking Overhead	Stack	Code	Random bytes(KB)
No	None	304	71%	1.00	32,460	121,349	0
Yes	None	460	50%	1.51	32,500	131,326	2,025
Yes	All-`SNI`	1663	86%	5.47	32,724	166,216	158,172
Yes	All-`DOM`	1289	81%	4.24	32,724	158,776	80,378
Yes	All-`IND`	856	72%	2.82	32,724	148.712	2,585
Yes	Selective	613	62%	2.01	32,460	148,712	2,025
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Table 1: Benchmarks in millions of Cortex-M4 cycles when $t = 1$.

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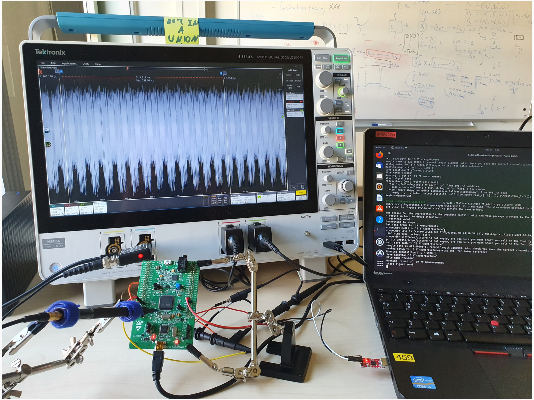

- Capture: Tektronix MSO 6
- Short traces at 3.125 GS/s and long traces at 625 MS/s sampling rate
- Target device: STM32F4 Discovery board, Arm Cortex M4, operated at 168 MHz
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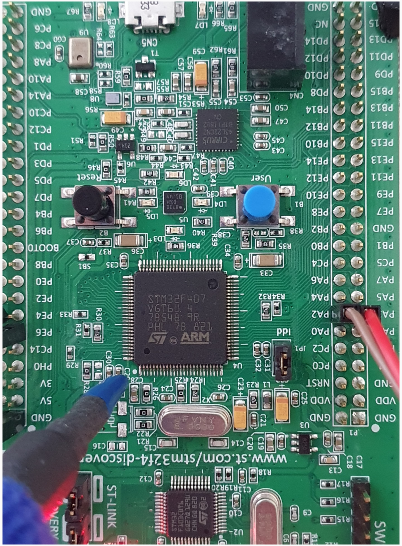

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Test Vector Leakage Assessment (TVLA)

A pass-fail test to decide if an implementation has exploitable leakage

- fixed-vs-random (FvR): to detect all possible first-order leakage.
- random-vs-random (RvR): to identify a specific exploitable leakage.

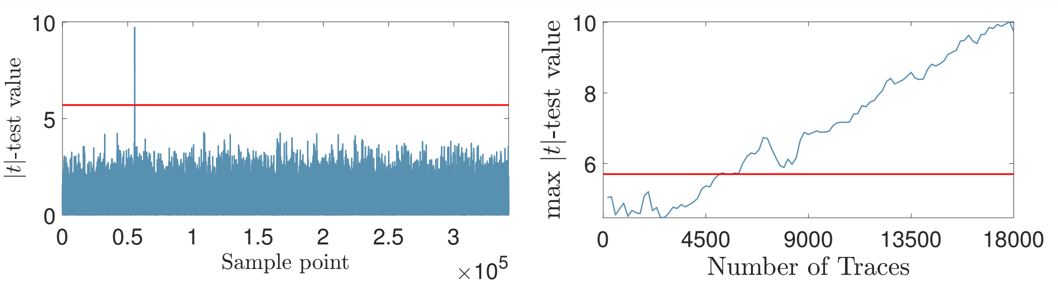
Goals

- Unprotected **Picnic3** is vulnerable (RvR)
- Protected **Picnic3** eliminates such vulnerabilities (FvR).

Attack I: Probing the opened online phase

$$\hat{x} = x + \lambda_1 + \cdots + \lambda_{N-1} + \lambda_N$$

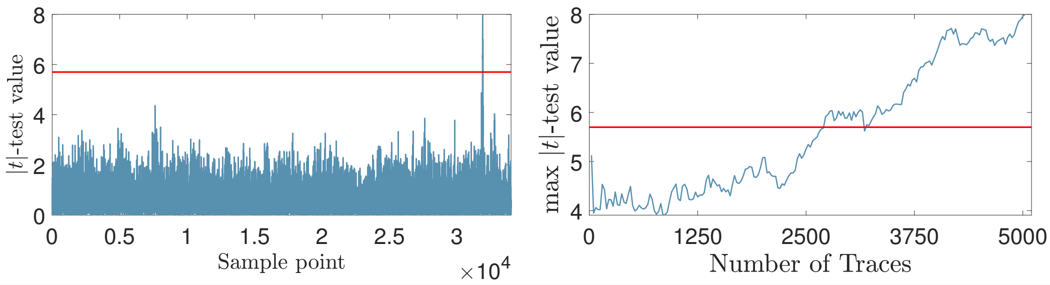
- Measurements from precomputation phase
- The leakage becomes clear after 6,000 traces.



Attack II: Probing the unopened online phase

$$\hat{x} = x + \lambda_1 + \cdots + \lambda_N$$

- Measurements from online simulation,
- The leakage becomes clear after 2,725 traces.



Leakage Analysis (FvR)

Masked SHA-3 (All-IND)

- 71 % of the calculation is hashing
- Fixing the mask value to a constant results in a leaking implementation with 2,000 traces.
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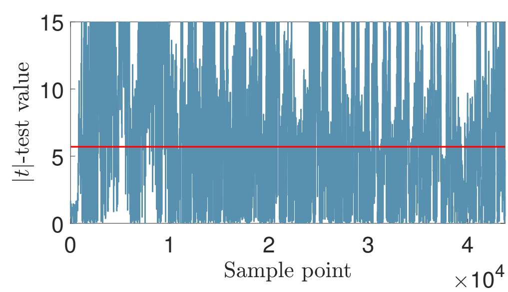

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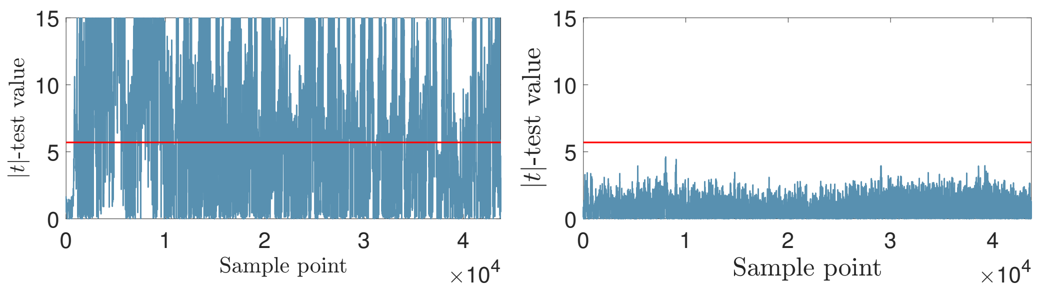

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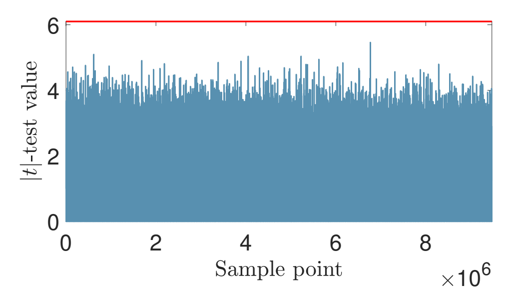
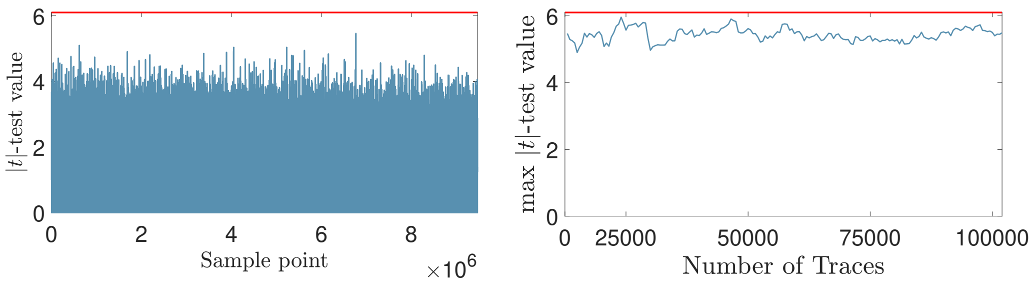


Leakage Analysis (FvR)

Masked Picnic3 (All-IND 4-round Masked SHA-3)

- Beginning of signature generation until the end of the first MPC instance
- Fixed vs Random *secret* key – fixed *message* – randomized *signature*.
- The $|t|$-value remains below threshold using 100,000 traces.
- Max $|t|$-value has a stable pattern.



Takeaways

- Side-channel attacks against MPCitH with preprocessing is a real threat: as our two attacks demonstrate
- Generic masking countermeasures without breaking interoperability / increasing signature size
- Application to **Picnic3**: an overhead in the range of 1.80-5.47.
- Masked implementation of SHA-3: optimized with M4 assembly and supports a range of options, from slower but SNI-secure, to our much faster options.

Thank you!

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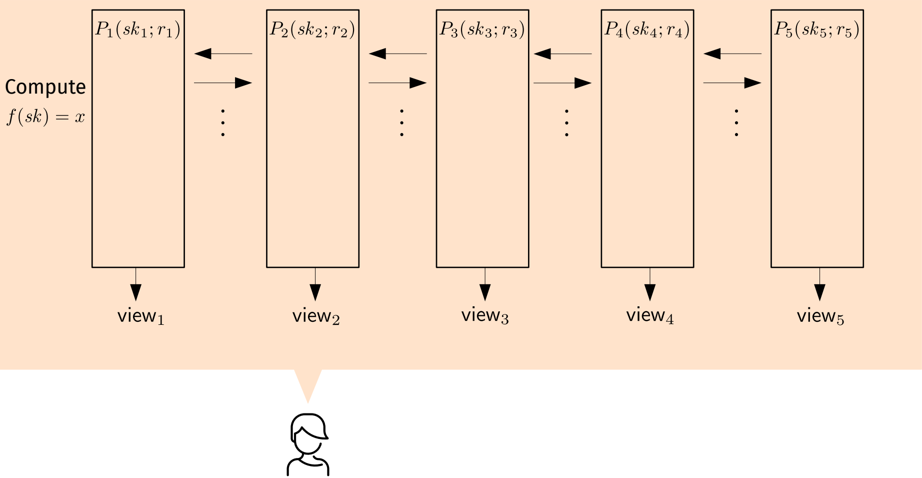
Previous countermeasure: SNI-in-the-head [SBWE20]



Prover$(sk = sk_1 + sk_2 + sk_3 + sk_4 + sk_5)$

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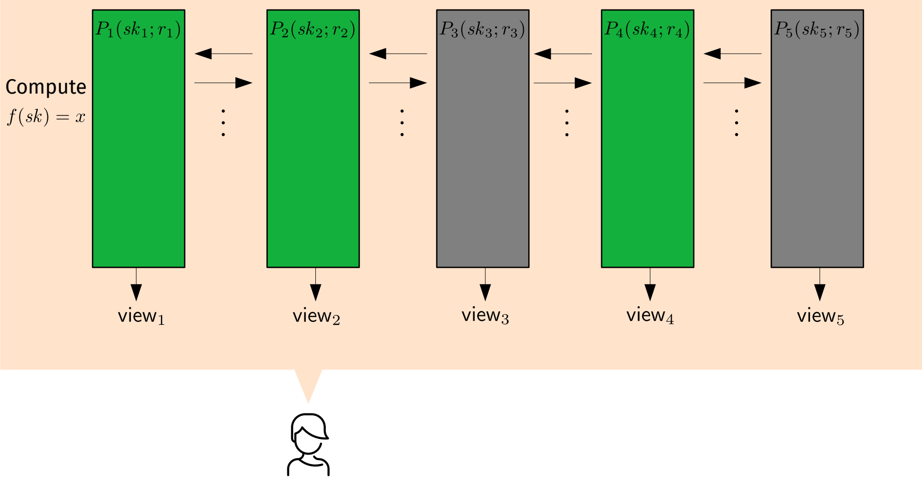

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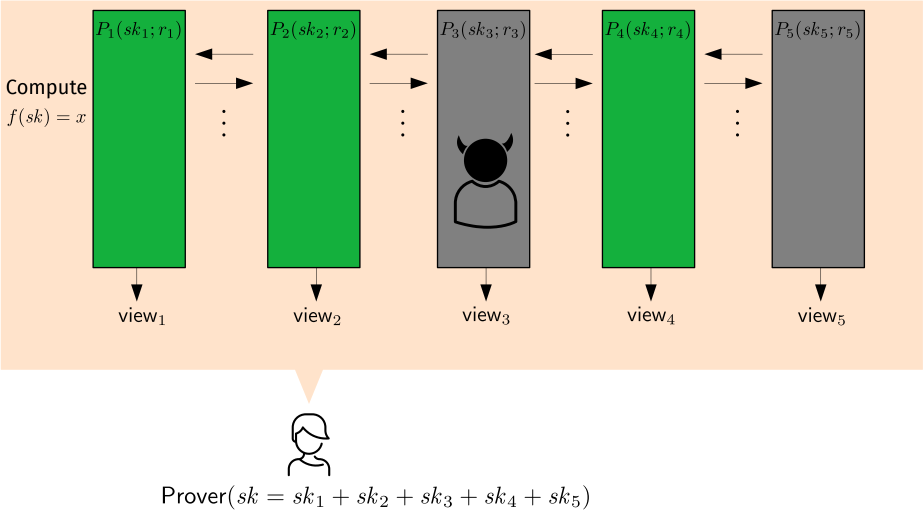

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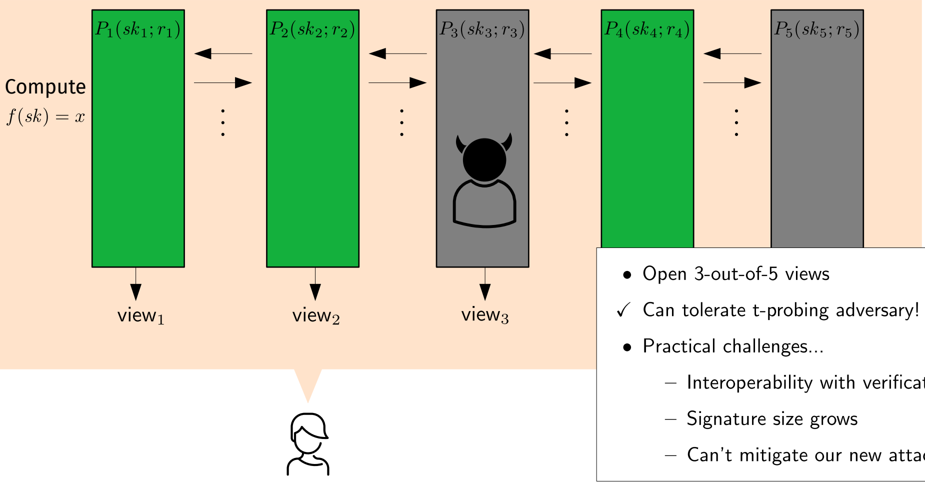

Prover$(sk = sk_1 + sk_2 + sk_3 + sk_4 + sk_5)$

- Open 3-out-of-5 views
- ✓ Can tolerate t-probing adversary!
- Practical challenges...
  - Interoperability with verification
  - Signature size grows
  - Can't mitigate our new attack on MPCitH-PP

Masking MPC

SNI-secure Masked Online Multiplication

- Mask $[\hat{x}] := [x + \lambda^x]$ and $[\hat{y}] := [y + \lambda^y]$
- Each P_i computes

$$[z_i] = \delta_{1,i}\mathsf{SMul}([\hat{x}], [\hat{y}]) - \mathsf{SMul}([\hat{x}], [\lambda_i^y]) - \mathsf{SMul}([\hat{y}], [\lambda_i^x]) - [\lambda_i^{xy}]$$

✓ **SMul**: Standard SNI secure masked multiplier [ISW03]

✓ Never unmask $[\hat{x}]$ and $[\hat{y}]$ until the online phase can be safely revealed

✓ Applies to **any** MPCitH-PP-style signatures

✓ Securely **composable** with other gadgets thanks to the SNI property

Heuristics overview

- NI/SNI secure gadgets
- Input-sensitive, half-masked
- Output-sensitive, half-masked
- Unmasked