Post-Quantum Zero-Knowledge and Signatures from Symmetric-Key Primitives

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Overview

Digital Signatures in a post-quantum world

- RSA and DLOG based schemes insecure

New schemes

- based on new structured hardness assumptions (lattices, codes, isogenies, etc.)
- based on symmetric primitives: Hash-based signatures

Other alternatives only relying on symmetric primitives?

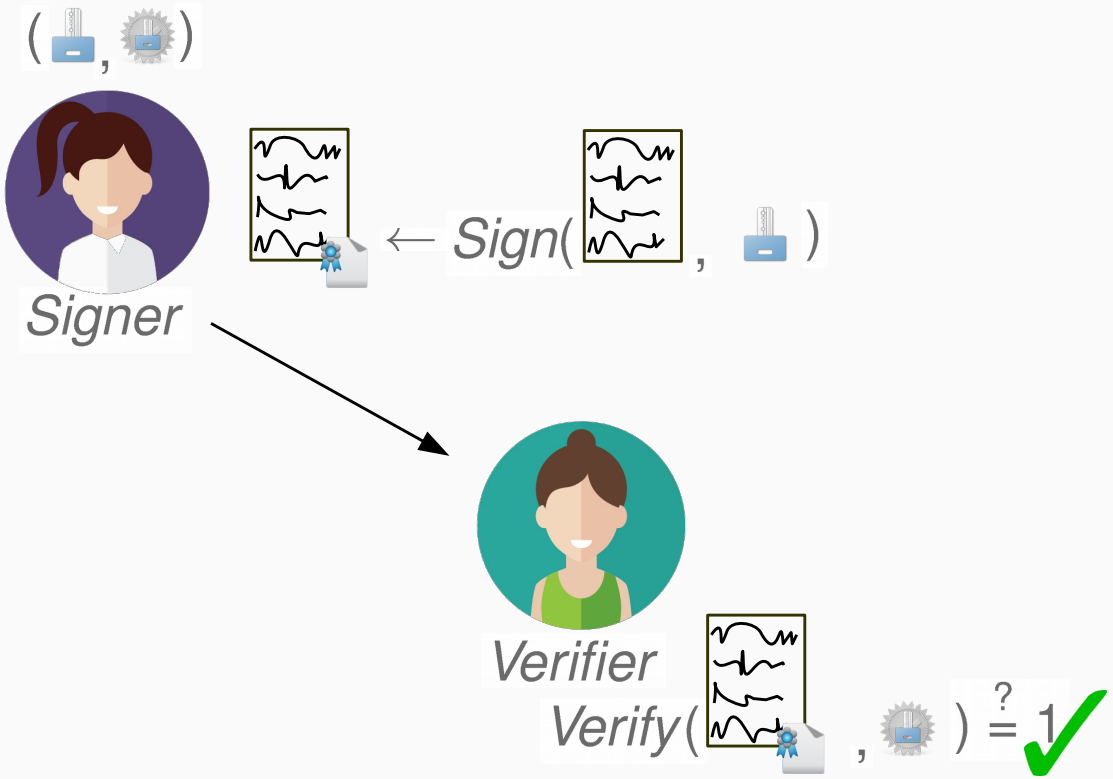
High-level View

Recent years progress in two areas

- Symmetric-key primitives with few multiplications
- Practical ZK-Proof systems over general circuits

New signature schemes based on these advances

Digital Signatures

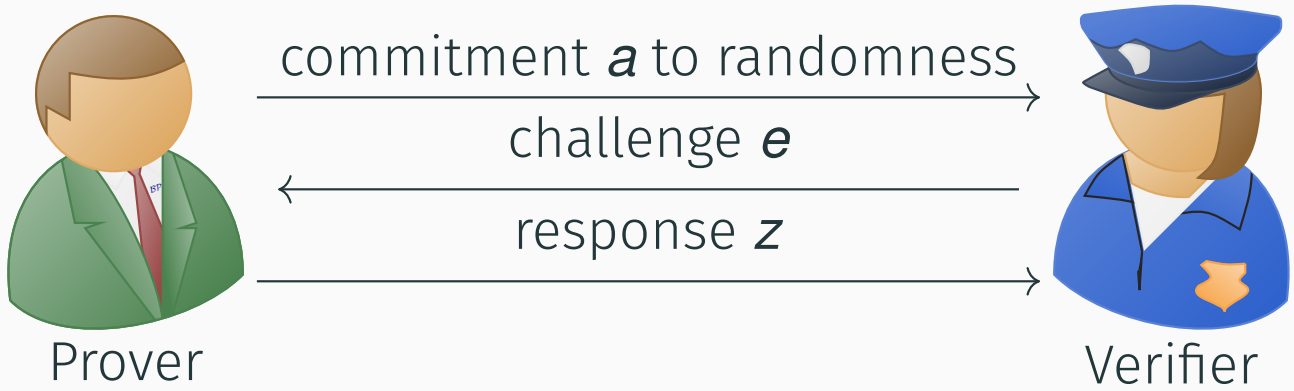


Existential Unforgeability under Chosen-Message Attacks

- Adversary may see signatures on arbitrary messages
- Still intractable to output signature for new message

Σ-Protocols

Three move protocol:



- Important that e unpredictable before sending a
- aka (Interactive) Honest-Verifier Zero-Knowledge Proofs

Non-interactive variant via Fiat-Shamir [FS86] transform

Digital Signatures from Σ-Protocols

Well known methodology

One-way function $f_k : D \to R$ with $k \in K$

- $sk \xleftarrow{R} K$
- $y \leftarrow f_{sk}(x)$, $pk \leftarrow (x, y)$

Signature

- Σ-protocol to prove knowledge of sk so that $y = f_{sk}(x)$
- Use Fiat-Shamir transform to bind message to proof $e \leftarrow H(a \| m)$

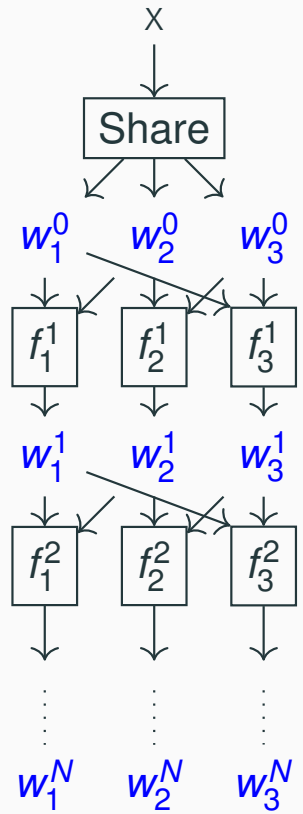
ZKBoo [GMO16]

Efficient Σ-protocols for arithmetic circuits

- generalization, simplification, + implementation of "MPC-in-the-head" [IKOS07]

Idea

1. (2,3)-decompose circuit into three shares
2. Revealing 2 parts reveals no information
3. Evaluate decomposed circuit per share
4. Commit to each evaluation
5. Challenger requests to open 2 of 3
6. Verifies consistency



Efficiency

- Heavily depends on #multiplications

ZKB++

Improved version of ZKBoo:

- Remove redundant information from views
- Remove redundant checks
- Proof size reduction to less than half the size
- But without extra computational cost

Optimizations

Optimization 1: Share Function and Input Shares

- Use PRNGs R_i keyed with k_i
- Share as $x_1 \leftarrow R_1(0)$, $x_2 \leftarrow R_2(0)$ and $x_3 \leftarrow x - x_1 - x_2$
- x_1 and x_2 deterministically computable by the verifier from k_1 and k_2
- Only need to include k_i in View_1 and View_2
- Expected proof size reduction: $4r \cdot |x|/3$ bits

Optimizations (cont.)

Optimization 2: Not Including Commitments

- For opened views, verifier can re-compute commitment
- Only one commitment needs to be sent
- View e as a "commitment to the commitments"
- Proof size reduction: $2r \cdot |c|$ bits

Optimizations (cont.)

Optimization 3: Not Including the Output Shares

- Output shares y_i for opened views can be re-computed
- Third output share reconstructable from y and re-computed output shares
- Unnecessary to include any output shares in proof
- Proof size reduction: $3r \cdot |y|$ bits

Optimizations (cont.)

Optimization 4: No Additional Randomness for Commitments

- First input to the commitment is seed k_i
- Protocol input to commitment doubles as randomization values
- No additional randomness for commitments necessary
- ROM is needed here, but we already need it for non-interactivity

Optimizations (cont.)

Optimization 5: Not Including View_e

- Verifier can re-compute View_e given k_e, k_{e+1} and wire values of View_{e+1}
- By binding of the commitment, commitment verifies only if View_e re-computed correctly
- Only need to store input wires of View_e
- Proof size reduction: $r \cdot |\mathsf{View}|$ bits

LowMC [ARS+15, ARS+16]

Substitution-permutation-network design

- Very lightweight S-box with one AND gate per bit
- S-box layer is only partial
- Very expensive affine layer with $n/2$ XOR gates per bit.
- Allows selection of instances minimizing, e.g.
  - ANDdepth,
  - number of ANDs, or
  - ANDs / bit

Blocksize n	**S-boxes** m	**Keysize** k	**Data** d	**ANDdepth** r	**# of ANDs**	**ANDs/bit**
256	2	256	256	232	**1392**	5.44
512	66	256	256	**18**	3564	6.96
1024	10	256	256	103	3090	**3.02**

Table 1: LowMC parameters for 128-bit PQ-security

Fish

Fish:

- Turn ZKB++ and OWF into signature scheme
- via Fiat-Shamir Transform
- Instantiate OWF with LowMC v2
- $\Rightarrow$ EUF-CMA security in the ROM

Security in QROM

Proving Fiat-Shamir transform secure in QROM faces problems

- Proof requires rewinding
- Unclear how to translate

Use Unruh Transform [Unr15]

Take random permutation G and random oracle H

- Produce multiple proofs $(c_i, G(resp_{i,1}), \ldots, G(resp_{i,n}))$
- Hash all of them with H
- Use the result of hashing to indicate which response of each c_i should be revealed

Picnic

Picnic:

- Turn ZKB++ and OWF into signature scheme
- via Unruh Transform
- Instantiate OWF with LowMC v2
- $\Rightarrow$ EUF-CMA security in the QROM

Unruh Transform incurs overhead in signature size

- But careful tweaking reduces overhead to factor 1.6

Signature Size

- Recall: OWF $f_k : D \to R$, $sk \xleftarrow{R} K$, $pk \leftarrow (x, f_{sk}(x))$
- Security parameter κ

OWF represented by arithmetic circuit with

- ring size λ
- multiplication count a

Signature size: $|\sigma| = c_1 + c_2 \cdot (c_3 + \lambda \cdot a)$ where c_i are polynomial in κ

OWF with few multiplications?

Build OWF from

name	security	$\lambda \cdot a$	
AES	128	5440	$\mathbb{F}_2$ approach
AES	128	4000?	$\mathbb{F}_{2^4}$ approach
AES	256	7616	$\mathbb{F}_2$ approach
SHA-2	256	> 25000	
SHA-3	256	38400	
Noekeon	128	2048	
Trivium	80	1536	
PRINCE		1920	
Fantomas	128	2112	
LowMC v2	128	< 800	
LowMC v2	256	< 1400	
Kreyvium	128	1536	
FLIP	128	> 100000	
MIMC	128	10337	
MIMC	256	41349	

Signature Size Comparison

name	security	$\lvert\sigma\rvert$
AES	128	339998
AES	256	473149
SHA-2	256	1331629
SHA-3	256	2158573
LowMC v2	256	108013

Example of Exploration of Variation of LowMC Instances

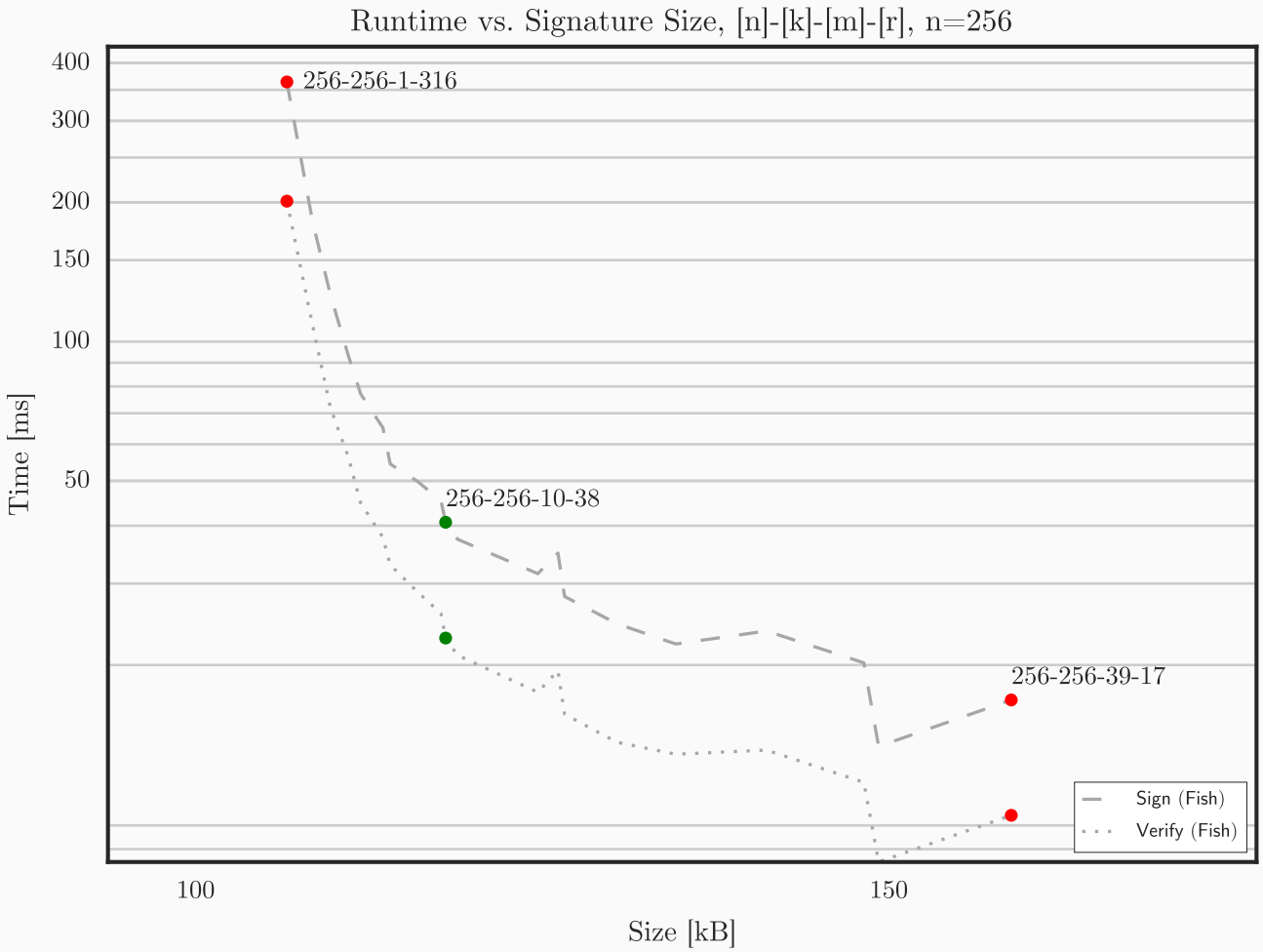


Figure 1: Measurements for instance selection (128-bit PQ-security).

Comparison with other recent proposals

Scheme	Gen	Sign	Verify	$\lvert sk \rvert$	$\lvert pk \rvert$	$\lvert \sigma \rvert$	M
Fish-10-38	0.01	29.73	17.46	32	32/64	116K	ROM
Picnic-10-38	0.01	31.31	16.30	32	32/64	191K	QROM
MQ 5pass	1.0	7.2	5.0	32	74	40K	ROM
SPHINCS-256	0.8	1.0	0.6	1K	1K	40K	SM
BLISS-I	44	0.1	0.1	2K	7K	5.6K	ROM
Ring-TESLA	17K	0.1	0.1	12K	8K	1.5K	ROM
TESLA-768	49K	0.6	0.4	3.1M	4M	2.3K	(Q)ROM
FS-Véron	n/a	n/a	n/a	32	160	$\geq$ 126K	ROM
SIDHp751	16	7K	5K	48	768	138K	QROM

Table 2: Timings (ms) and key/signature sizes (bytes)

Conclusion

ZKB++: Improved ZK proofs for arithmetic circuits

Fish/ Picnic: Two new efficient post-quantum signature schemes in ROM and QROM

Applications beyond signatures: NIZK proof system for arithmetic circuits in post-quantum setting

Outlook and Future Work

- Alternative symmetric primitives with few multiplications
  - Something new with even less multiplications than LowMC?
  - 256-bit secure variant of Trivium/Kreyvium?
- More LowMC cryptanalysis
  - More aggressive LowMC parameters with very low allowable data complexity, e.g. only 2 plaintexts.
- Analysis regarding side-channels
- Unruh Transform with constant overhead?

Thank you.

- Preprint will soon appear on eprint.
  - Merge of `https://ia.cr/2016/1085` and `https://ia.cr/2016/1110`.

Supported by: prisma cloud, CryptoAction, PQCRYPTO ICT-645622

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