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Code-based digital signatures: state of the art and open challenges

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September 12, 2022

The NIST post-quantum standardization process

- In 2016 **NIST** has initiated a process for the development and standardization of one or more post-quantum public-key cryptographic algorithms.
  - 69 submissions in the 1° round
  - 26 admitted to the 2° round
  - 7 finalists and 8 alternates in the 3° round

Selected for standardization

Public-Key Encryption/KEMs:
- CRYSTALS-KYBER

Digital Signatures:
- CRYSTALS-Dilithium
- Falcon
- SPHINCS+

- PKE/KEMs admitted to the 4° round: BIKE, Classic McEliece, HQC, SIKE
- Just a few days after its admission to the fourth round, SIKE has been attacked[1].
- Rainbow has been the subject of a destructive key recovery attack although it had been admitted to the third round[2].

[1] https://eprint.iacr.org/2022/975
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Post-quantum digital signatures

- **Dustin Moody**, NIST PQC team, 5 July 2022:

  ...NIST also plans to issue a new Call for Proposals for public-key (quantum-resistant) digital signature algorithms by the end of summer 2022. NIST is primarily looking to diversify its signature portfolio, so signature schemes that are not based on structured lattices are of greatest interest. NIST would like submissions for signature schemes that have short signatures and fast verification (e.g., UOV). Submissions in response to this call will be due by June 1, 2023.

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Linear codes

- A linear code $\mathscr{C} \subseteq \mathbb{F}_q^n$ of length n and dimension k is a linear k-dimensional subspace of $\mathbb{F}_q^n$.

- Code parameters:
  - n: code length;
  - k: code dimension;
  - $r = n - k$: code redundancy;
  - $R = k/n$: code rate.
- Representations of a linear code:
  - generator matrix $\mathbf{G} \in \mathbb{F}_q^{k \times n}$, s.t. $\mathscr{C} = \{\mathbf{u}\mathbf{G} | \mathbf{u} \in \mathbb{F}_q^k\}$;
  - parity-check matrix $\mathbf{H} \in \mathbb{F}_q^{r \times n}$, s.t. $\mathscr{C} = \{\mathbf{c} \in \mathbb{F}_q^n | \mathbf{H}\mathbf{c}^\top = \mathbf{0}_r\}$.
- Hamming weight: $\mathrm{wt}(\mathbf{a}) = |\{i \text{ s.t. } a_i \neq 0\}|$.

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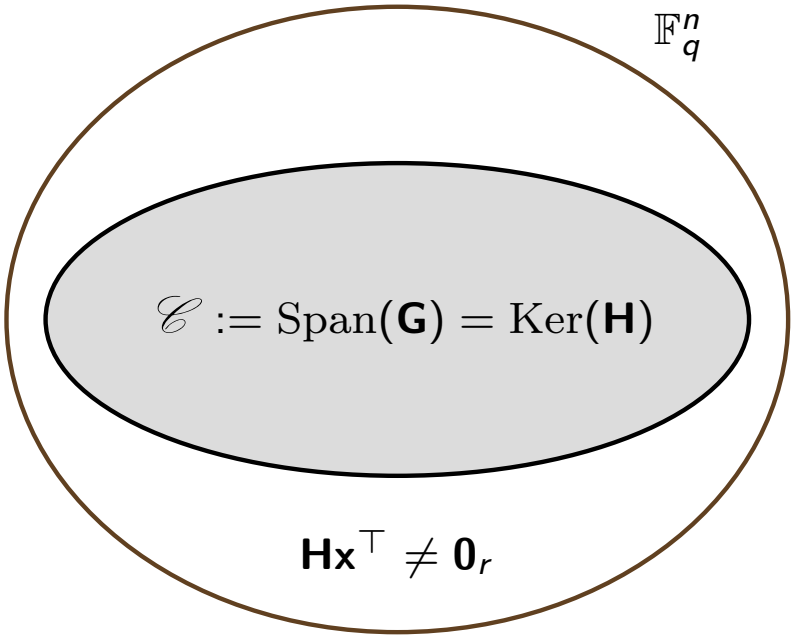

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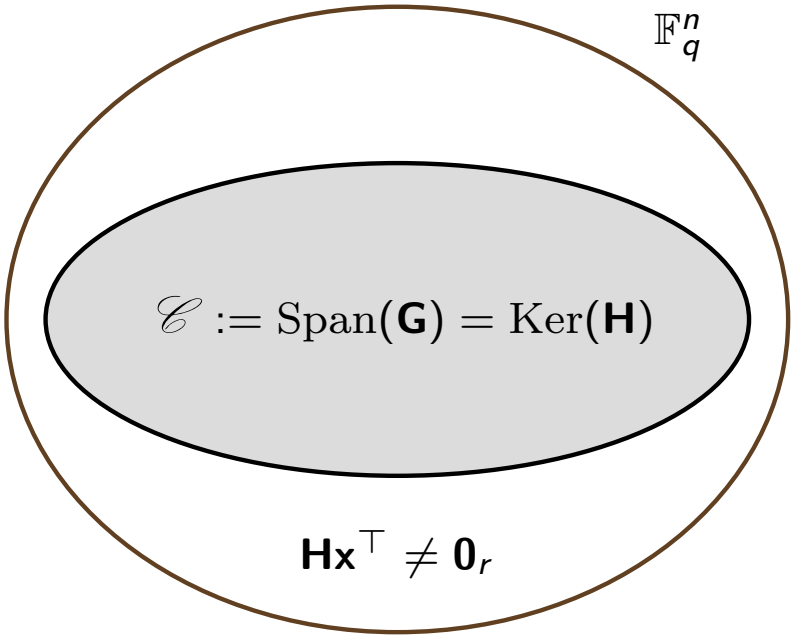

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Syndrome Decoding Problem

- **Syndrome Decoding Problem (SDP)**: given an arbitrary parity-check matrix $\mathbf{H} \in \mathbb{F}_q^{r \times n}$ and $\mathbf{s} \in \mathbb{F}_q^r$, find $\mathbf{e}$ with weight $\leq t$ such that $\mathbf{s} = \mathbf{H}\mathbf{e}^\top$.
- For the Hamming metric, SDP is NP-hard.
- For the binary case (i.e., $q = 2$), when t is sub-linear in n the best solver is Information Set Decoding (ISD), with running time

$$T_{ISD} = \mathcal{O}\left(2^{t \cdot \alpha(R)}\right), \quad \alpha(R) = -\log_2(1-R)$$

- Quantum solver: Grover + ISD, complexity is still exponential in t:

$$\widetilde{T}_{ISD} = \mathcal{O}\left(2^{t \cdot \frac{\alpha(R)}{2}}\right)$$

Other choices are possible

SDP is hard also for different metrics (rank, Lee ...) and/or weight constraints (large weight ...).

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Quantum vs signatures

- Quantum computers will endanger many widespread signature schemes (like DSA and RSA signatures).
- Only a few replacements are available up to now (lattice-based and hash-based signatures).
- Code-based digital signatures are quantum-safe...
- But finding efficient code-based solutions is still a challenge!

Two main approaches to code-based signatures

- Hash-and-sign
- Derived from identification schemes

- G. Kabatianskii, E. Krouk, B. Smeets, "A digital signature scheme based on random error-correcting codes", in IMA International Conference on Cryptography and Coding (pp. 161–167). Springer, Berlin, Heidelberg, 1997.
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Hash-and-sign code-based signatures

- Natural approach to code-based signatures:
  - **Secret key**: error correcting code $\mathscr{C}$;
  - **Public key**: disguised parity-check matrix **H** of $\mathscr{C}$.
  - **Signature generation**: compute **s** = Hash(m) and decode **s** into low weight vector **e**;
  - **Signature verification**: check that **e** has low weight and $\mathbf{He}^\top$ = Hash(m).

- However, finding a decodable syndrome is not easy!
  - Number of possible syndromes: $N_s = q^r$.
  - Every two vectors with weight $\leq t$ have distinct syndromes.
  - Number of decodable syndromes: $N_d = \sum_{i=1}^{t} \binom{n}{i}(q-1)^i$.
  - Probability to pick a decodable syndrome is N_d/N_s: normally, $N_s \gg N_d$.

- Example with Goppa codes: $q = 2$, $r = mt$, $n = 2^m \Rightarrow N_s = n^t$.
  $N_d \approx \frac{n^t}{t!}$.
  Probability of picking a decodable syndrome $= \frac{N_d}{N_s} \approx \frac{1}{t!}$.
- However, small t requires large k: public key size increases.
- Small t and large k imply high code rate: Goppa code distinguishers become efficient.

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Hash-and-sign code-based signatures

- Natural approach to code-based signatures:
  - **Secret key**: error correcting code $\mathscr{C}$;
  - **Public key**: disguised parity-check matrix **H** of $\mathscr{C}$.
  - **Signature generation**: compute $\mathbf{s} = \text{Hash(m)}$ and decode **s** into low weight vector **e**;
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- However, finding a decodable syndrome is not easy!
  - Number of possible syndromes: $N_s = q^r$.
  - Every two vectors with weight $\leq t$ have distinct syndromes.
  - Number of decodable syndromes: $N_d = \sum_{i=1}^{t} \binom{n}{i}(q-1)^i$.
  - Probability to pick a decodable syndrome is N_d/N_s: normally, $N_s \gg N_d$.

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Evolution of hash-and-sign code-based signatures

- **1997**: Kabatianskii-Krouk-Smeets (KKS) scheme
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  - has a very large region of weak parameters
- **2001**: Courtois-Finiasz-Sendrier (CFS) scheme
  - uses high rate Goppa codes
  - very large public-keys and long signature times
  - security issues due to distinguishers for high rate Goppa codes
- **2013**: Baldi-Bianchi-Chiaraluce-Rosenthal-Schipani (BBCRS) scheme
  - based on low density generator matrix (LDGM) codes
  - very small keys, no decoding required
  - statistical attacks exploiting key leakage due to correlations
- **2018**: Debris-Alazard-Sendrier-Tillich: Wave scheme
  - exploits the hardness of decoding large-weight errors over $\mathbb{F}_q$
  - based on generalized $(U; U + V)$ codes
  - requires information-set decoding for signature generation (slow)
  - public key size in the order of 4 MB for 128-bit security

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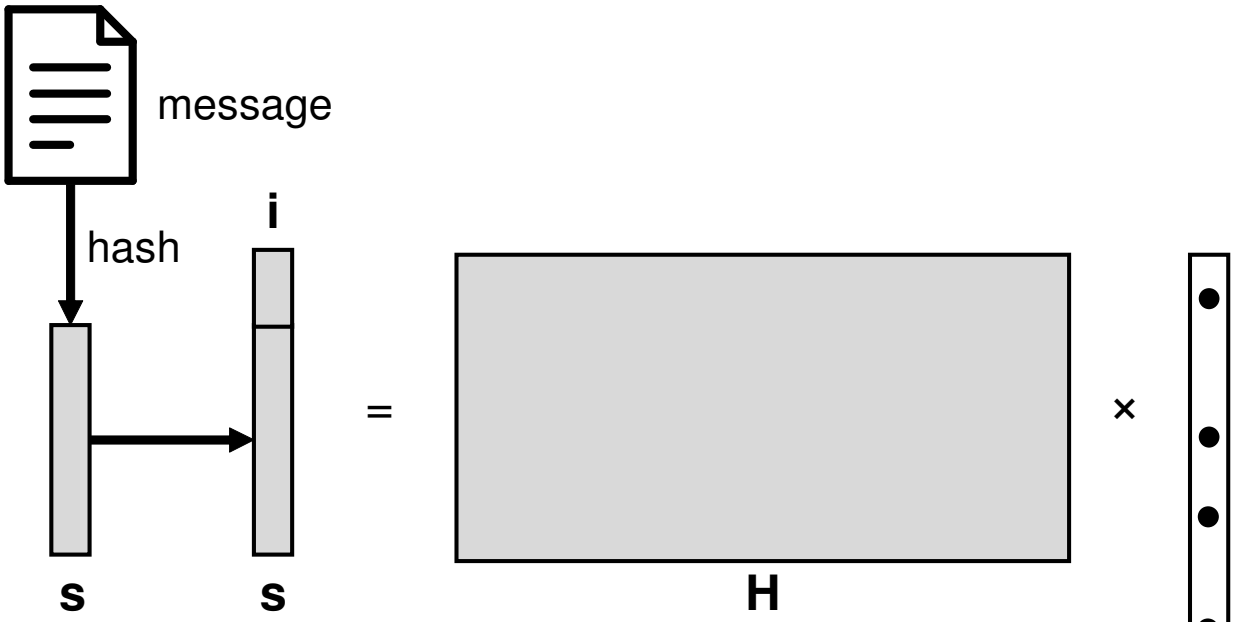
CFS



- Private key: $\{\mathbf{V}, \mathbf{H}, \mathbf{P}\}$
- Public key: $\mathbf{H}' = \mathbf{V} \cdot \mathbf{H} \cdot \mathbf{P}$
- Vary the syndrome by appending a counter $\mathbf{i}$
- $\mathbf{e}$ found through decoding of $[\mathbf{i}|\mathbf{s}]$
- Signature: $\mathbf{e}' = \mathbf{e} \cdot \mathbf{P}$
- Verification: $[\mathbf{i}|\mathbf{s}] \stackrel{?}{=} \mathbf{H}' \cdot \mathbf{e}'^T$

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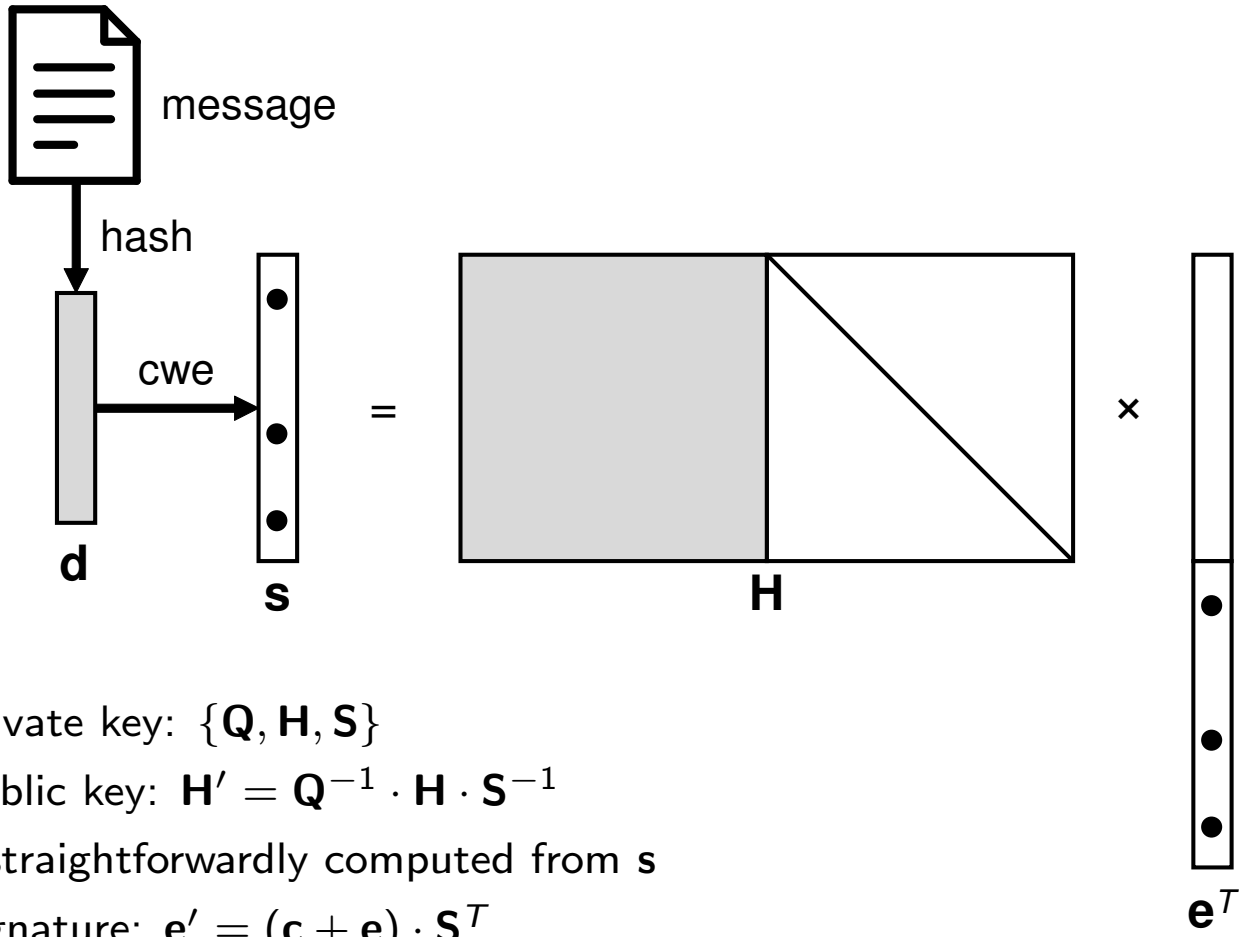
BBCRS (PQCrypto 2013)



- Private key: $\{\mathbf{Q}, \mathbf{H}, \mathbf{S}\}$
- Public key: $\mathbf{H}' = \mathbf{Q}^{-1} \cdot \mathbf{H} \cdot \mathbf{S}^{-1}$
- $\mathbf{e}$ straightforwardly computed from $\mathbf{s}$
- Signature: $\mathbf{e}' = (\mathbf{c} + \mathbf{e}) \cdot \mathbf{S}^T$
- Verification: $\mathbf{s} \stackrel{?}{=} \mathbf{H}' \cdot \mathbf{e}'^T$

▶ M. Baldi, M. Bianchi, F. Chiaraluce, J. Rosenthal, D. Schipani, "Using LDGM Codes and Sparse Syndromes to Achieve Digital Signatures," Proc. PQCrypto 2013, vol. 7932 of Springer LNCS, pp. 1–15, 2013.

BBCRS - rationale

- The sparsity of $\mathbf{s}$ and the systematic form of $\mathbf{H}$ allow trivially deriving a sparse $\mathbf{e}$ without decoding
- The random codeword $\mathbf{c}$ adds noise to $\mathbf{e}$ and makes the signature stochastic
- If $\mathbf{S}$ is sparse then the signature $(\mathbf{c} + \mathbf{e}) \cdot \mathbf{S}^T$ is sparse too

Pro

Very fast signature generation (no decoding)

Con

To make the decoding problem hard for low-weight vectors we need sparse signatures and hence:

- a sparse codeword $\mathbf{c}$ (easy to find using LDGM codes)
- a sparse $\mathbf{S}$

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BBCRS - cryptanalysis

- In the BBCRS scheme all the components of the signature $(\mathbf{c} + \mathbf{e}) \cdot \mathbf{S}^T$ are sparse and binary
- The signature is obtained as the sum of a few rows of $\mathbf{S}^T$
- As a result, the structure of each row of $\mathbf{S}^T$ is still visible in the signature

Attack

- Collect many signatures (100'000)
- Look at correlations (covariance) between pairs of signature entries
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▶ A. Phesso, JP. Tillich, "An Efficient Attack on a Code-Based Signature Scheme," Proc. PQCrypto 2016, vol. 9606 of Springer LNCS, pp. 86–103, 2016.

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From BBCRS to SPANSE

How to avoid the attack against BBCRS?

- Restrict to one-time use (at least for the moment ☺)
- Possibly avoid sparsity of signatures, but how?
  - Replace the sparse binary $\mathbf{S}$ with a dense one over $\mathbb{F}_q$
  - Rely on the hardness of large-weight vector decoding over $\mathbb{F}_q$

Zero-concentrated S

$\mathbf{S}$ no longer sparse, but dense with the constraint of having small-valued entries taken from $\mathbb{F}_q$.

- d_i: fraction of entries equal to $i, i = 0, 1, 2, \ldots, q-1$, in each row of $\mathbf{S}$.
- $d(x) = \sum_{i=0}^{q-1} d_i x^i$, with $\sum_{i=0}^{q-1} d_i = 1$: polynomial describing the density of the symbols of $\mathbb{F}_q$ in each row of $\mathbf{S}$.
- If $d(x)$ has decreasing coefficients we say it is zero-concentrated.
- The matrix $\mathbf{Q}$ is no longer needed to disguise the secret key, because of the density of $\mathbf{S}$, and can be replaced with a simple permutation matrix $\mathbf{P}$.

▶ M. Baldi, F. Chiaraluce, P. Santini, " SPANSE: combining sparsity with density for efficient one-time code-based digital signatures," CoRR, abs/2205.12887, https://arxiv.org/abs/2205.12887.

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Security level and key size

- Public key size: $K_s = 2436.6$ kB
- Number of different signatures: $N_s = 2^{263.9}$
- Number of different codewords: $N_c = 2^{133.8}$
- ISD work factor: 2^{132}
- PGE+SS work factor: $2^{131.6}$

Another approach to code-based signatures

Hash-and-sign code-based digital signatures

- Classic approach (McEliece)
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- Key recovery attacks may target such a hidden structure

Code-based signatures derived from ID schemes

- Alternative approach
- Start from an interactive identification scheme
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Identification schemes

Phase 1

The prover randomly generates a pair $(\mathsf{sk}, \mathsf{pk})$

Phase 2

The prover exchanges messages with the verifier, who is only equipped with pk, with the goal of demonstrating knowledge of sk

Decision

The verifier decides whether to accept the prover or not

Properties:

1. zero-knowledge: no information about the secret key is revealed during the identification process
2. completeness: an honest prover always gets accepted
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- Single round interaction between prover and verifier:

- The honest prover can always reply correctly, an adversary is able to reply with some **cheating probability** δ. With N rounds, the cheating probability gets reduced to δ^N.

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Prepare commitment c		
	$\xrightarrow{c}$	
	$\longleftarrow$ Exchange additional messages $\longrightarrow$	
		Choose random challenge b
	$\xleftarrow{b}$	
Compute reply f		
	$\xrightarrow{f}$	
		Verify validity of f

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Code-based identification schemes

- **Stern**'s scheme:
  - random binary codes
  - 3 passes
  - cheating probability $= 2/3$
- **Veron**'s scheme:
  - dual version of Stern's scheme
  - lower communication cost
- **CVE** scheme:
  - random codes over $\mathbb{F}_q$
  - 5 passes
  - cheating probability $= \frac{q-1}{2q}$
- **AGS** scheme:
  - random binary quasi-cyclic codes
  - 5 passes
  - cheating probability $\approx 1/2$
  - compression of communications

- J. Stern, "A new identification scheme based on syndrome decoding," in Advances in Cryptology - CRYPTO' 93, D. R. Stinson, Ed. Springer Berlin Heidelberg, 1994, pp. 13–21.
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Signatures from identification schemes

- Identification schemes can be rendered non-interactive
- The **Fiat-Shamir** transformation obtains a signature scheme as the transcript of one execution of a 3-pass identification scheme
- This requires fixing the list of challenges by deriving them from some sort of seed
- **Dagdelen et al.** generalize this approach to n-pass identification schemes, including 5-pass code-based identification schemes
- The resulting signature scheme has very compact keys
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Examples of signatures from ID schemes

- Security level: $\lambda = 128$ bits
- Cheating probability: 2^{-128}
- Signature size = communication cost of the underlying identification scheme

	CVE	AGS	R-CVE
Number of rounds	129	128	135
Public key size (bits)	832	1574	305
Average signature size (kB)	43.263	41.040	23.201
Max signature size (kB)	51.261	56.992	22.484

- These schemes follow the classical approach and can be optimized with several modern tricks (e.g., MPC-in-the-head, seed trees), which do not affect security.
- They allow further reductions of the signature size.

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Identification schemes based on code equivalence

- **Code Equivalence Problem (CEP)**: given $\mathscr{C}$ and $\mathscr{C}'$, find an isometry τ such that $\mathscr{C}' = \tau(\mathscr{C})$.
- Hard-to-solve instances exist:
  - permutations and self dual codes;
  - monomials and random codes over $\mathbb{F}_q$ with $q \geq 5$.
- LESS: first cryptographic scheme based on code equivalence:
  - 3-pass code-based ID scheme;
  - soundness error is $1/2$;
- LESS-FM: follow-up, improved version of LESS:
  - updated and secure parameters;
  - optimized underlying ID scheme;
  - tunable features (e.g., 5.3 kB signatures with 20.5 kB public keys, or 10.4 kB signatures with 11.6 kB publick keys).
- Possibility of advanced functionalities, such as ring signatures.

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Conclusion

- New post-quantum digital signature schemes are needed
- Lattice-based solutions apparently are the first choice, but diversity is required
- Code-based signatures are post-quantum
- Two main approaches: hash-and-sign and identification-based
- Some promising schemes already exists
- Research is needed to make them (at least) as efficient as lattice-based ones

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