Cryptographic Engineering

An example of post-quantum crypto

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- Ephemeral ECDH on ≈ 256-bit curve to compute shared key
- Use EdDSA signatures for public-key authentication
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- RSA signatures, DSA signatures
- Stream cipher, e.g., Salsa20
- Other authenticators, e.g., GHASH, Poly1305...

The end of crypto as we know it. . .

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  - **Hash-based signatures:** only signatures (e.g., XMSS)
- Less efficient (in time or space), than ECC
- For most of those: underlying problems not as well studied as, e.g., factoring or ECDLP
- Even less studied: attacks by quantum computers

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- If *all* hash functions are insecure, we're in bigger trouble anyway

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- 16 KB private and public key, 8 KB signature

Merkle Trees

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- Idea: Put a binary hash tree on top of all public keys:
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  - All other nodes are hashes of their two child nodes

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- Signature is the one-time signature plus *authentication path*

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A first analysis

- Let's fix 2^{32} signatures (≈ 4 Bio.)
- Key generation needs to compute the whole tree ($2^{33} - 1$ hashes)
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- Signature size: ≈ 25 KB
  - 8 KB Lamport Signature
  - 16 KB Lamport public key
  - $32 \cdot 32 = 1024$ bytes authentication path
  - 4 bytes for the index of the leaf node

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  - **We need to remember the state!**

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- This is not even compatible with the *definition* of cryptographic signatures

ELIMINATE
THE STATE

Goldreich's approach

- Goldreich, 1986: stateless hash-based signatures
- Idea: Use binary tree as in Merkle, but
  - make the tree huge (e.g., height $h = 256$), such that one can pick leaves *at random*;
  - each node corresponds to an OTS key pair;
  - leaf nodes are used to sign messages;
  - non-leaf nodes are used to sign the hash of the public keys of the two child nodes.
- All OTS secret keys are generated from a seed

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  - $256 \cdot 24\,$KB for Lamport signatures and public keys
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  - $256 \cdot 24$ KB for Lamport signatures and public keys
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  - 32 bytes for the index of the leaf node
- Total size of 6 MB
- More efficient OTS helps, but still very large signatures

SPHINCS

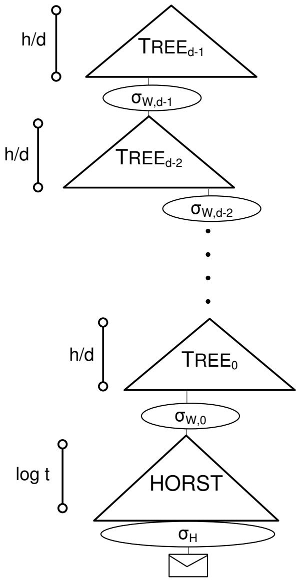
- Bernstein, Hopwood, Hülsing, Lange, Niederhagen, Papachristodoulou, Schneider, Schwabe, and Wilcox-O'Hearn, 2015:

  SPHINCS – Stateless, practical, hash-based, incredibly nice cryptographic signatures

SPHINCS

A high-level view on SPHINCS

- Use a "hyper-tree" of total height h
- Each tree has height h/d
- Inside the tree use Merkle approach
- Between trees use Goldreich approach



A high-level view on SPHINCS

- Use a "hyper-tree" of total height h
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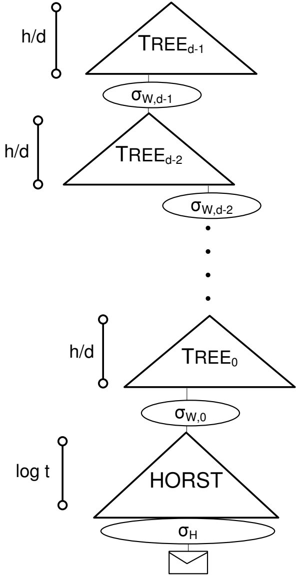
- Inside the tree use Merkle approach
- Between trees use Goldreich approach
- Sign messages with a *few-time* signature scheme
- Significantly reduce total tree height



A zoom into SPHINCS

- We propose SPHINCS-256 for 128 bits of security
- In the following, only consider (slightly simplified) SPHINCS-256:
  - 12 trees of height 5 each
  - Use **WOTS** as one-time-signature scheme
  - Use **HORST** (HORS with tree) as few-time signature scheme
  - Fix $n = 256$ as bitlength of hashes in WOTS and HORST
  - Fix $m = 512$ as size of the message hash (BLAKE-512 hash function)
  - Use ChaCha12 as pseudorandom generator
- SPHINCS-256 really uses WOTS$^+$ instead of WOTS
- Some more modifications required for security proofs

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- Similar trick in Ed25519 signatures (this is not specific to hash-based signatures!)

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  - Signature consists of k parts $(sk_{m_i}, \mathrm{Auth}_{m_i})$
  - Auth_{m_i} is the authentication path in the Merkle tree

HORST

- Idea in SPHINCS: use a *few-time* signature scheme to sign the message digest
- HORST uses two parameters: $k = 32$ and $t = 2^{16}$
- Need that $k \cdot \log_2 t$ equals the length of the message hash
- HORS(T) secret key: t 256-bit pseudorandom values $(sk_0, \ldots, sk_{t-1})$
- HORS public key: $H(sk_0), \ldots, H(sk_{t-1})$
- HORST public key: root of a Merkle tree on top of the HORS public key
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- Each signature reveals $k = 32$ out of 2^{16} secret-key pieces
- Can sign several times before an attacker has a good chance of having enough pieces

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- Signing needs to compute 32 authentication paths
- Can compute the whole tree, extract required nodes
- Can also use more memory-friendly algorithm, extract nodes on the fly

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- Note: SPHINCS does not sign the hash of the public key, but the root of an L-tree on top of the WOTS public key
- An L-tree is a binary tree where nodes without siblings get promoted

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- WOTS signature size: $32 \cdot 67 = 2144$ bytes

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- The performance of SPHINCS-256 is largely determined by
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- The same permutation is used in Blake-512

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- Total cost:
  $65536 + 65536 + 131070 + 12 \cdot (32160 + 4224 + 62) = 699494$ ChaCha12 permutations
- This ignores (neglible) cost for 12 WOTS signatures

Target architecture

- Intel Haswell processors featuring AVX2
- 16 vector registers of length 256 bits each
- Supports arithmetic on vector of integers
- Particularly interesting: arithmetic on 8×32-bit integers

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- 8 way parallel computation of F: 420 Haswell cycles
- 8 way parallel computation of H: 836 Haswell cycles

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- Handle the small tree on top non-vectorized (neglible)

Results

- SPHINCS-256 is slightly more complex (random bitmasks all over the place)
- Results for full SPHINCS-256 on Intel Haswell (Xeon E3-1275):
  - **Keygen:** $3\,237\,260$ cycles
  - **Signing:** $51\,636\,372$ cycles
  - **Verification:** $1\,451\,004$ cycles
- Sizes for SPHINCS-256:
  - **Public Key:** 1056 bytes
  - **Secret Key:** 1088 bytes
  - **Signature:** 41000 bytes
- For more details see http://sphincs.cr.yp.to