SPHINCS: practical stateless hash-based signatures

D. J. Bernstein, D. Hopwood, A. Hülsing,
T. Lange, R. Niederhagen, L. Papachristodoulou,
P. Schwabe, and Z. Wilcox O'Hearn

Technische Universiteit
Eindhoven
University of Technology

Where innovation starts

Digital Signatures are Important!

Software updates

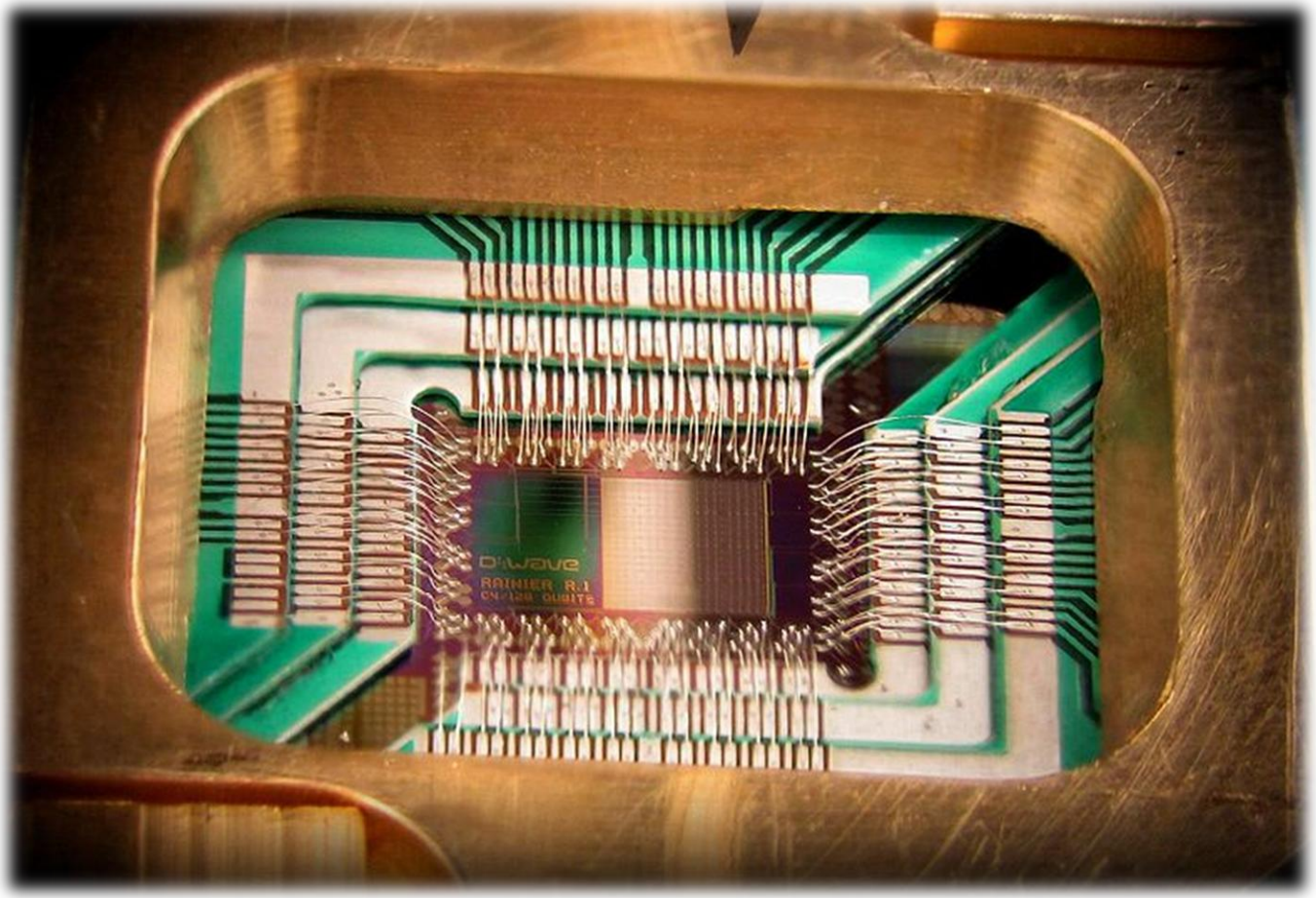
amazon

E-Commerce

ebay™

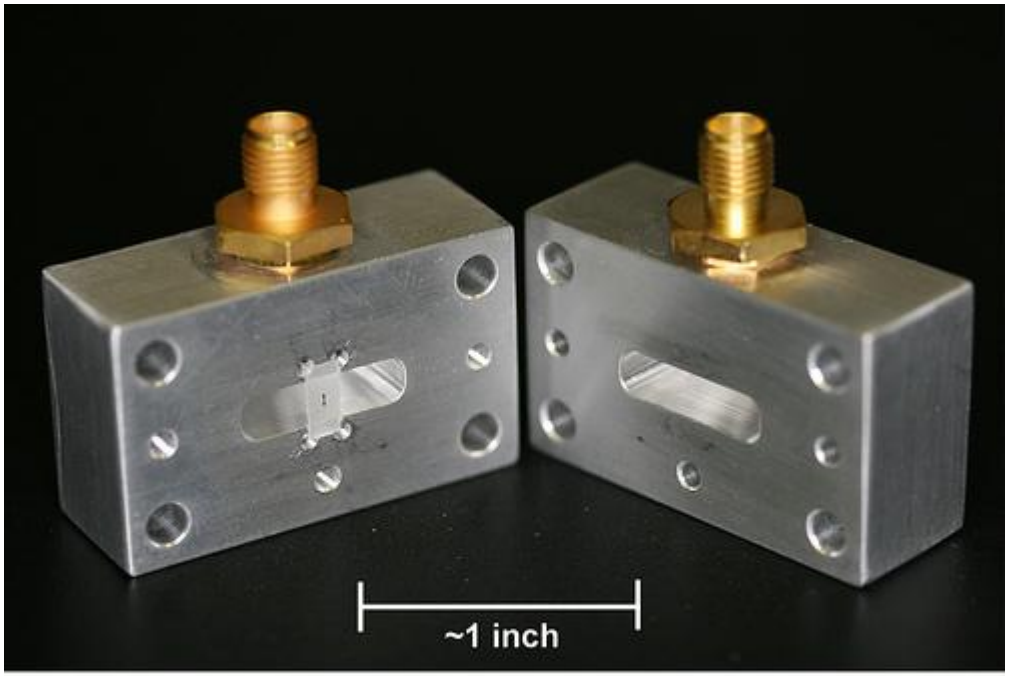
… and many others

What if…



Problem?

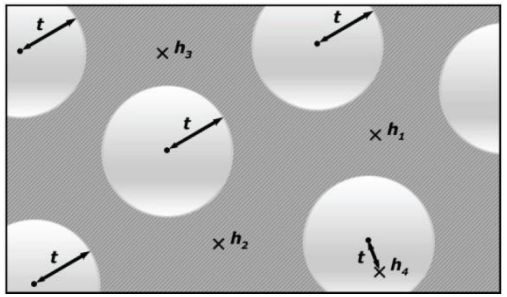
IBM 2012: ***„…optimism about superconducting qubits and the possibilities for a future quantum computer are rapidely growing***.“



Post-Quantum Signatures

Lattice, MQ, Coding

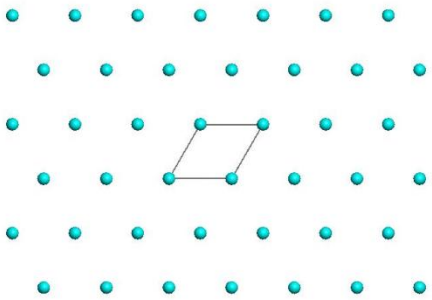
- Signature and/or key sizes
- Runtimes
- Secure parameters



$$y_1 = x_1^2 + x_1x_2 + x_1x_4 + x_3$$

$$y_2 = x_3^2 + x_2x_3 + x_2x_4 + x_1 + 1$$

$$y_3 = \ldots$$



Hash-based Signature Schemes [Mer89]

- Post quantum
- Only secure hash function
- Security well understood
- Fast
- Stateful

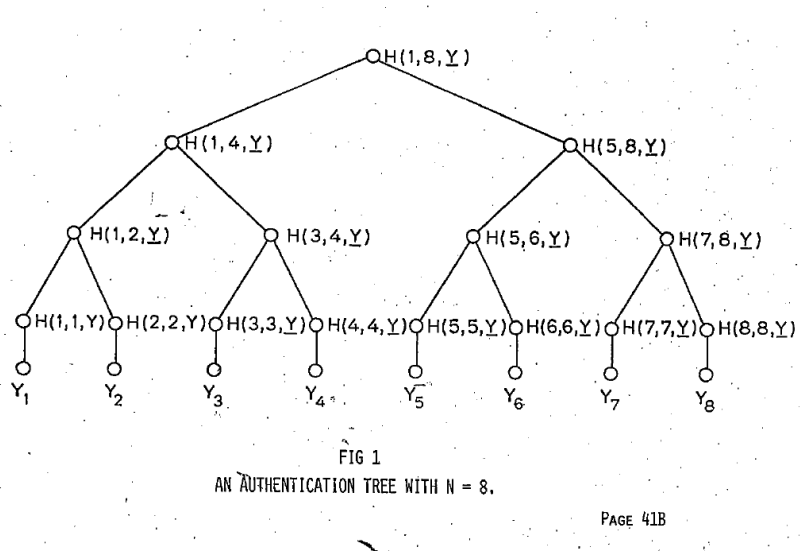
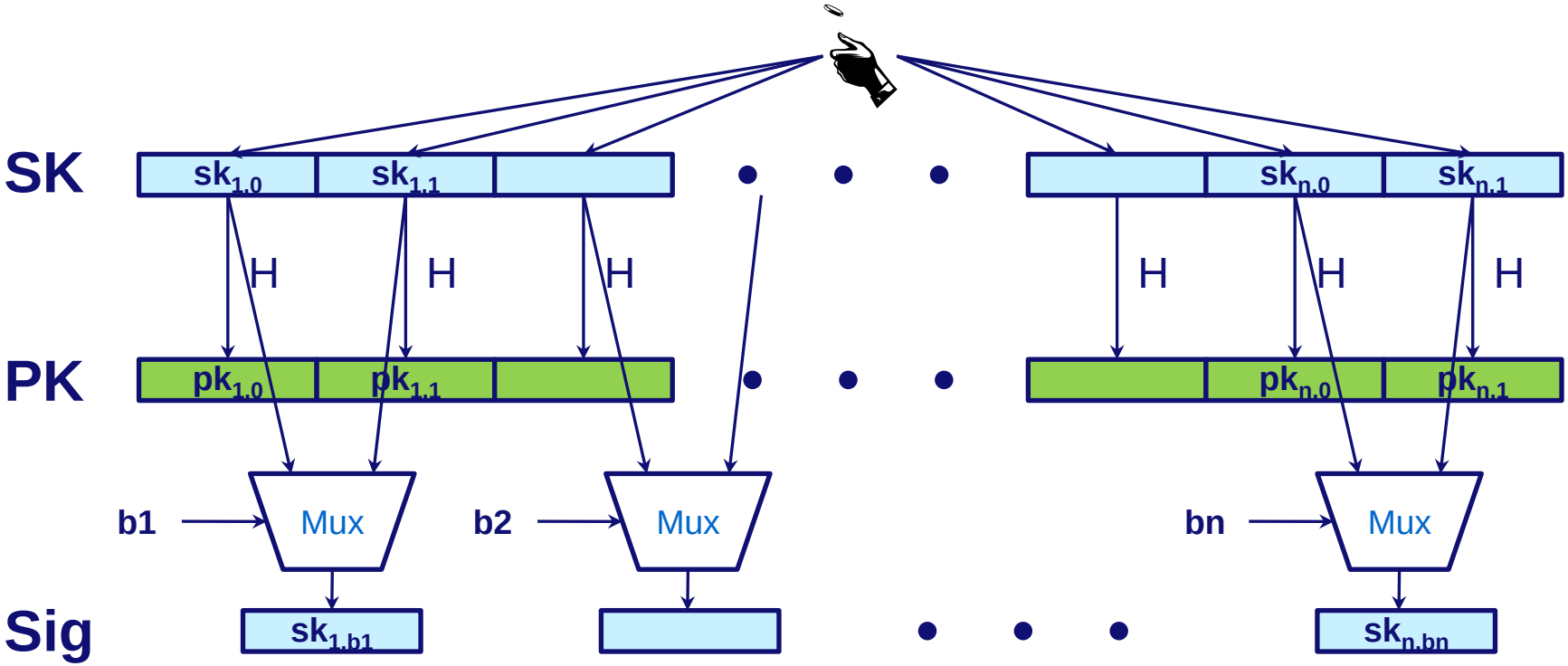


FIG 1
AN AUTHENTICATION TREE WITH N = 8.

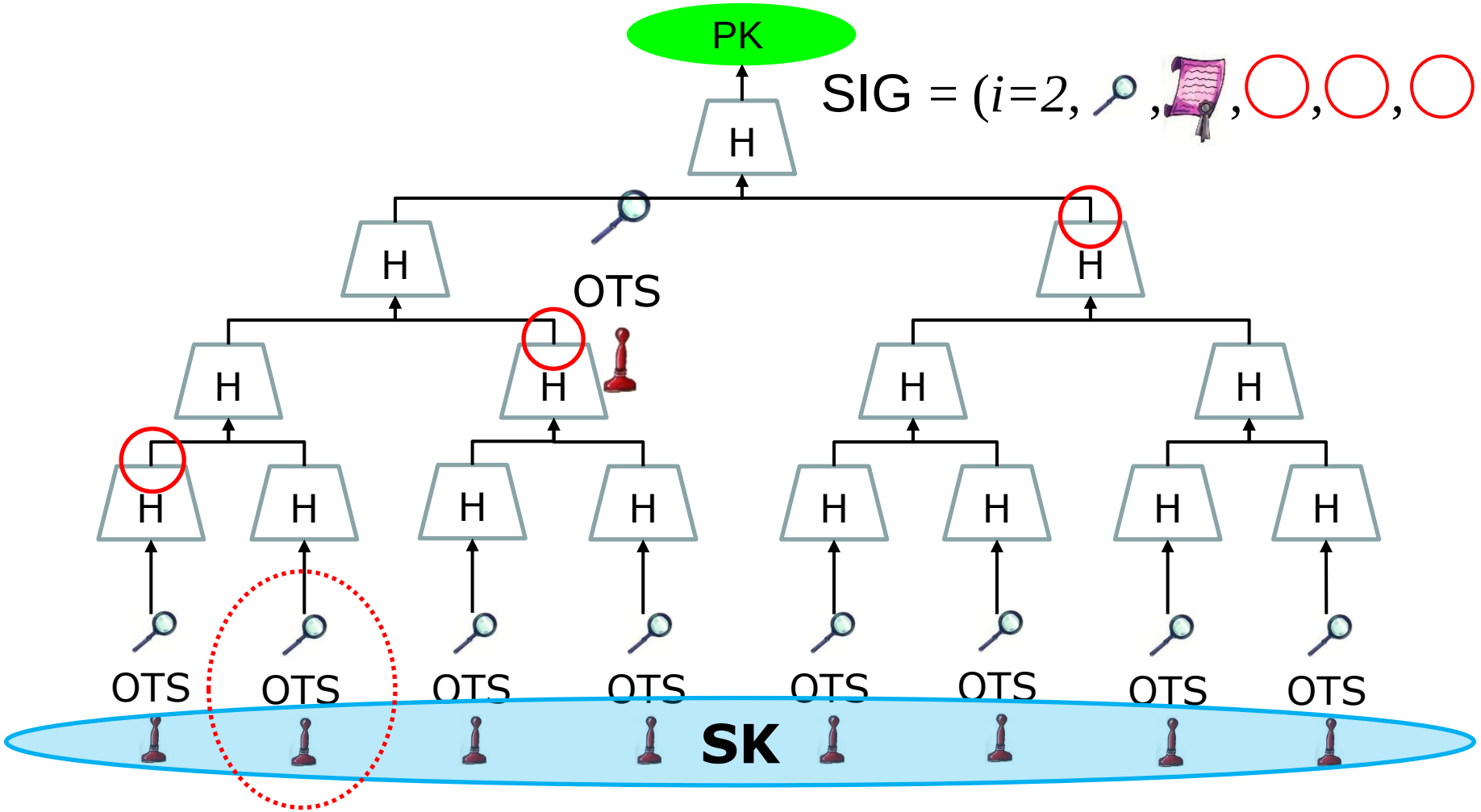
PAGE 41B

Lamport-Diffie OTS [Lam79]

Message M = b1,…,bn, OWF H * **= n bit**



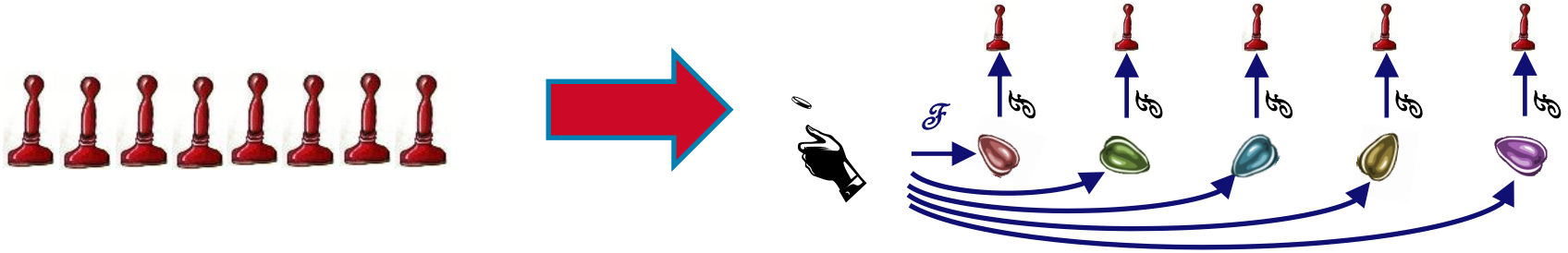
Merkle's Hash-based Signatures



Known Improvements [BGD+06]

- Pseudorandom Key Generation:

  SK $2^h n \rightarrow n$

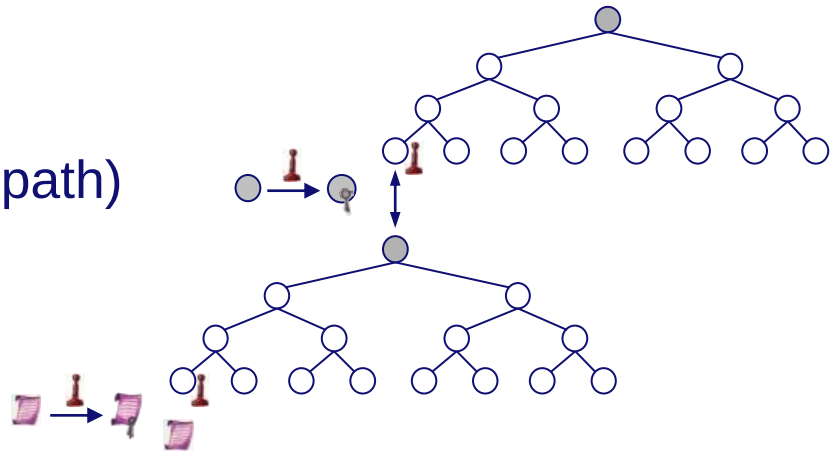


- Hypertree:

  Key generation

  (== Building Trees on one path)

  $\mathcal{O}(2^h) \rightarrow \mathcal{O}(d2^{h/d})$

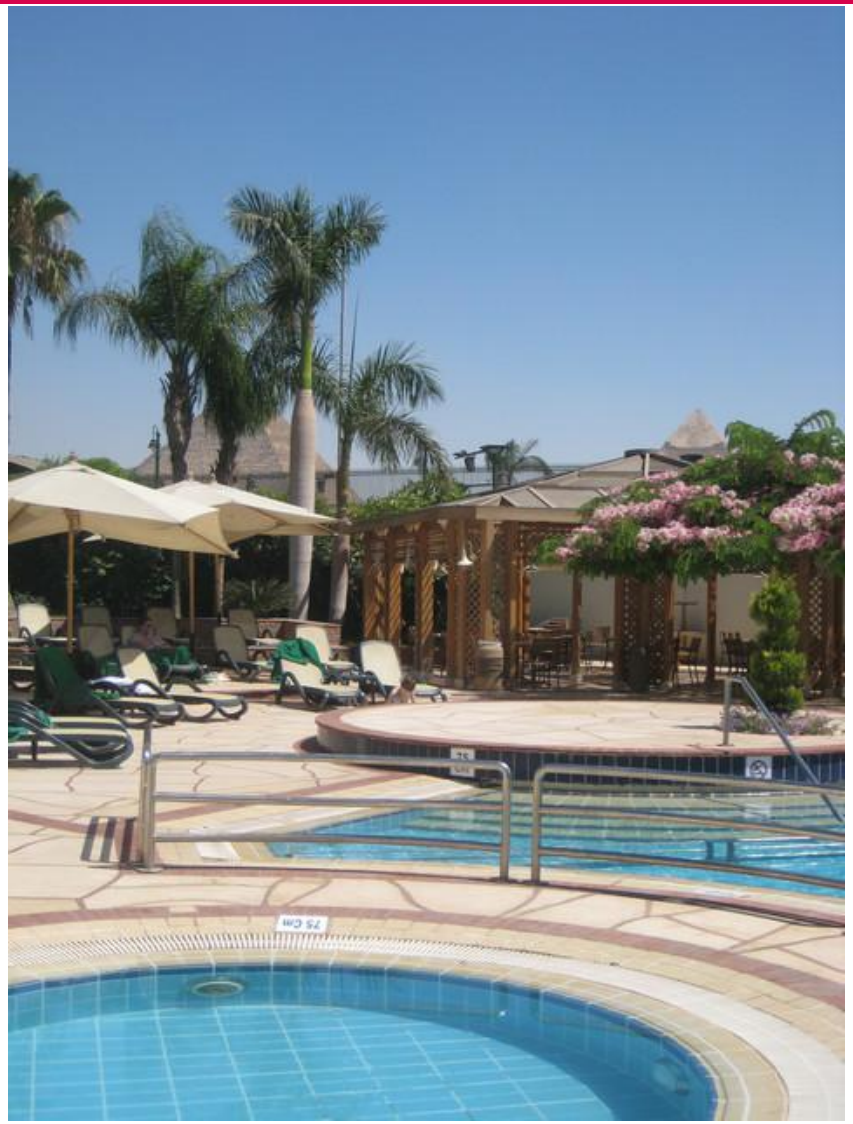


Known Improvements, cont'd

- **Winternitz OTS [Mer'89, …, BDE+11,Hül13]**
  - **Smaller Sigs**
  - **Minimum Security Assumptions**

- **Minimum Security Assumptions / Collision-Resilient Scheme [BDH11]**
  - **XMSS requires only PRF & SPR**

SPHINCS: Stateless Practical Hash-based Incredibly Nice Cryptographic Signatures



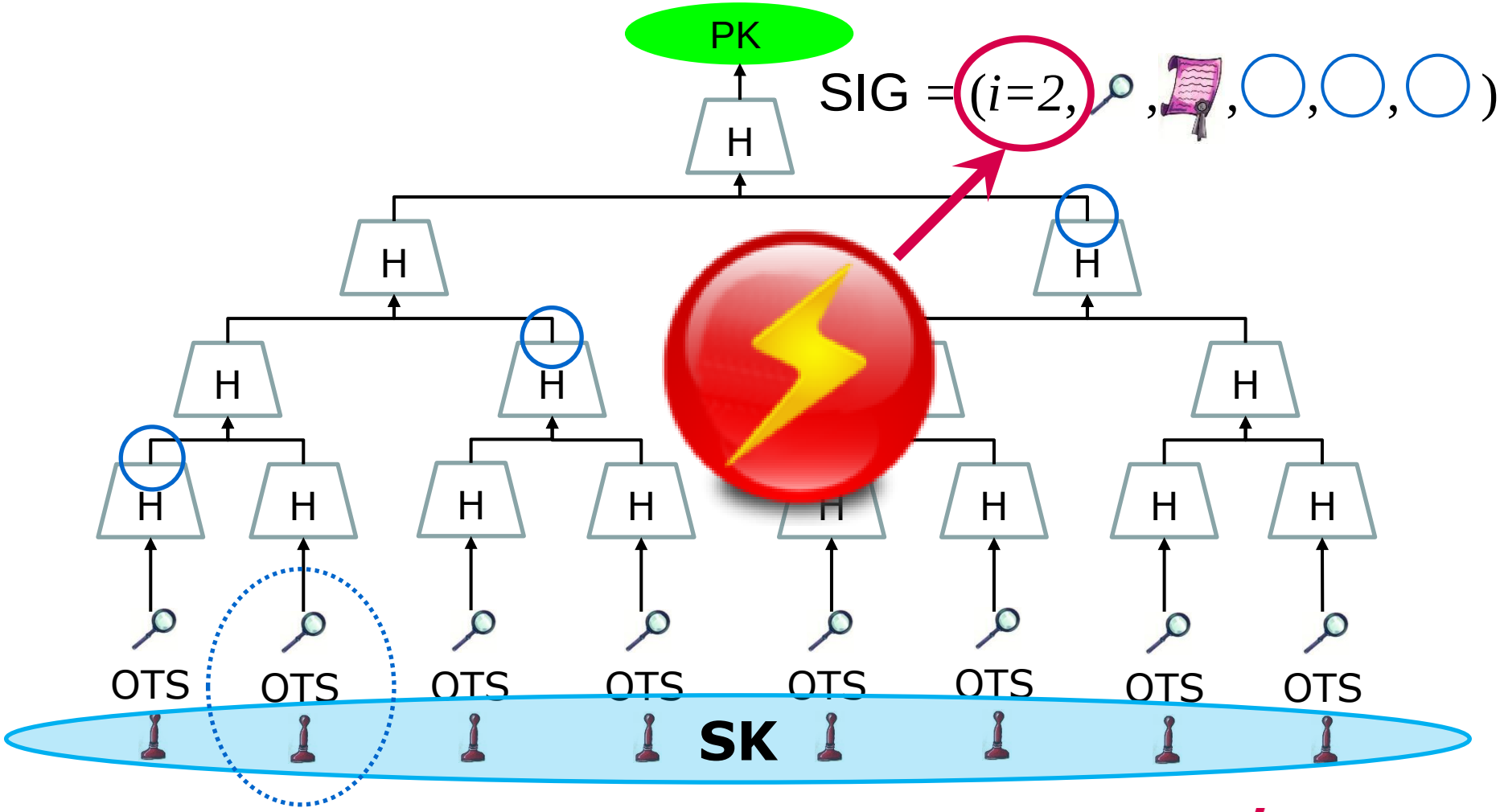
Goals

- **Stateless**
- **128bit Quantum Security**
- **Practical Speed**
- **Practical Signature Size**

How to Eliminate the State

Trial & Error:

- **Run MSS without State**



Approach 1: Goldreich

i = Integer.getValue(Hash(Message));

- **128bit Quantum Sec.**

  → n = 256 bit Hash [Ber09]

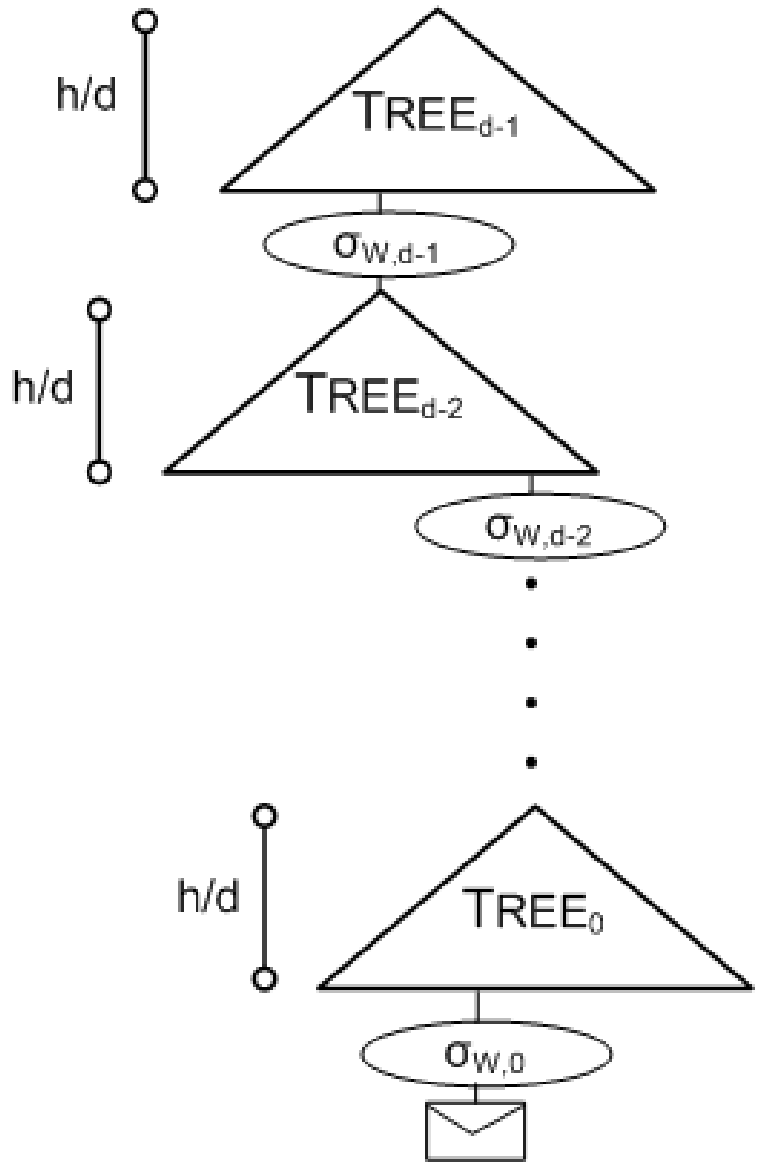
  → #Indices = 2^{256}

  → $h = n = 256$

- **h depends on n!**

Approach 1, cont'd

- **d > 1, otherwise**
  t_{Sign} = exp(n)



Approach 1, cont'd

i = Integer.getValue(Hash(Message));

- $h = n = 256$
- Impossible to make this efficient:
  - $t_{Sign} \approx d2^{n/d} (t_{Hash} + t_{OTS\_KeyGen}) \approx d2^{n/d} n\, t_{Hash}$
  - $|Sig| \approx d\, |OTS\_Sig|$ (+ n^2, if $d<n$) $\approx dn^2$
- E.g. $d = n / \log n$:
  - $t_{Sign} \approx n^3 / \log n\, t_{Hash}$; $|Sig| \approx n^3 / \log n$
- Goldreich: d = n
  - $t_{Sign} \approx 2n^2\, t_{Hash}$; $|Sig| \approx n^3$
  - $|Sig| > 1MB$ for $n = 256$

Approach 2: Random Index

$$I \leftarrow_{\$} U_{\#Indices}$$

- 128bit Quantum Sec.
  - → Sampled by Signer
    - → #Indices determined by collision prob.
    - → #Indices = 2^{256}
    - → $h = 256$
- Impossible to make this efficient, again… BUT
  - h independent of n
  - Statistical collision probability NOT collision resistance

Sphincs

- Approach 2 + Few-Time Signature Scheme (FTS)

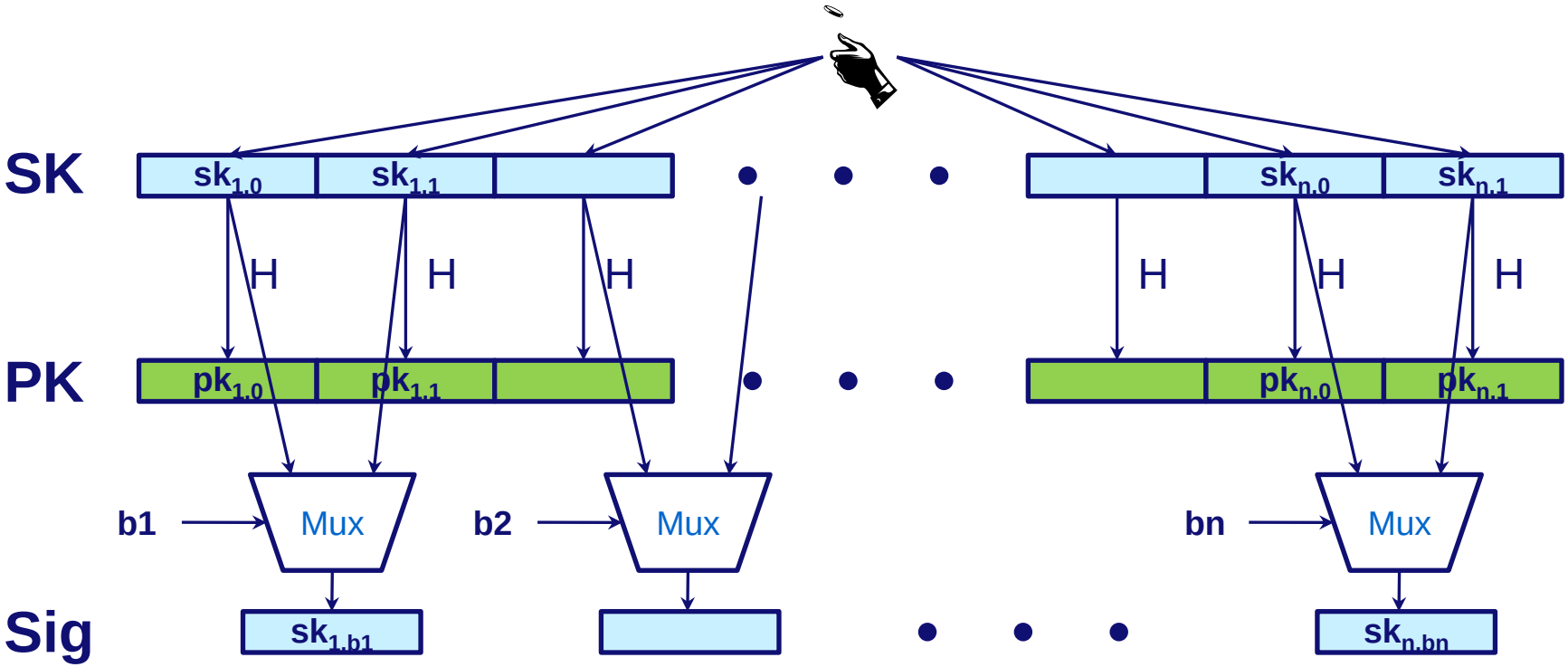
- Next: Introduce new FTS
  HORS with Trees (HORST)

- Preview: Allows h = 60 for any n
  - $t_{Sign} \approx d2^{60/d}\ (t_{Hash} + t_{OTS\_KeyGen}) \approx d2^{60/d} n\ t_{Hash}$
  - $|Sig| \approx d\ |OTS\_Sig|\ (+ n^2, \text{ if } d<n) \approx dn^2$
  - E.g. $d = 12$:
    - $t_{Sign} \approx 384n\ t_{Hash}$; $|Sig| \approx 12n^2$ (without HORST)

Few-Time Signature Schemes

Recap LD-OTS

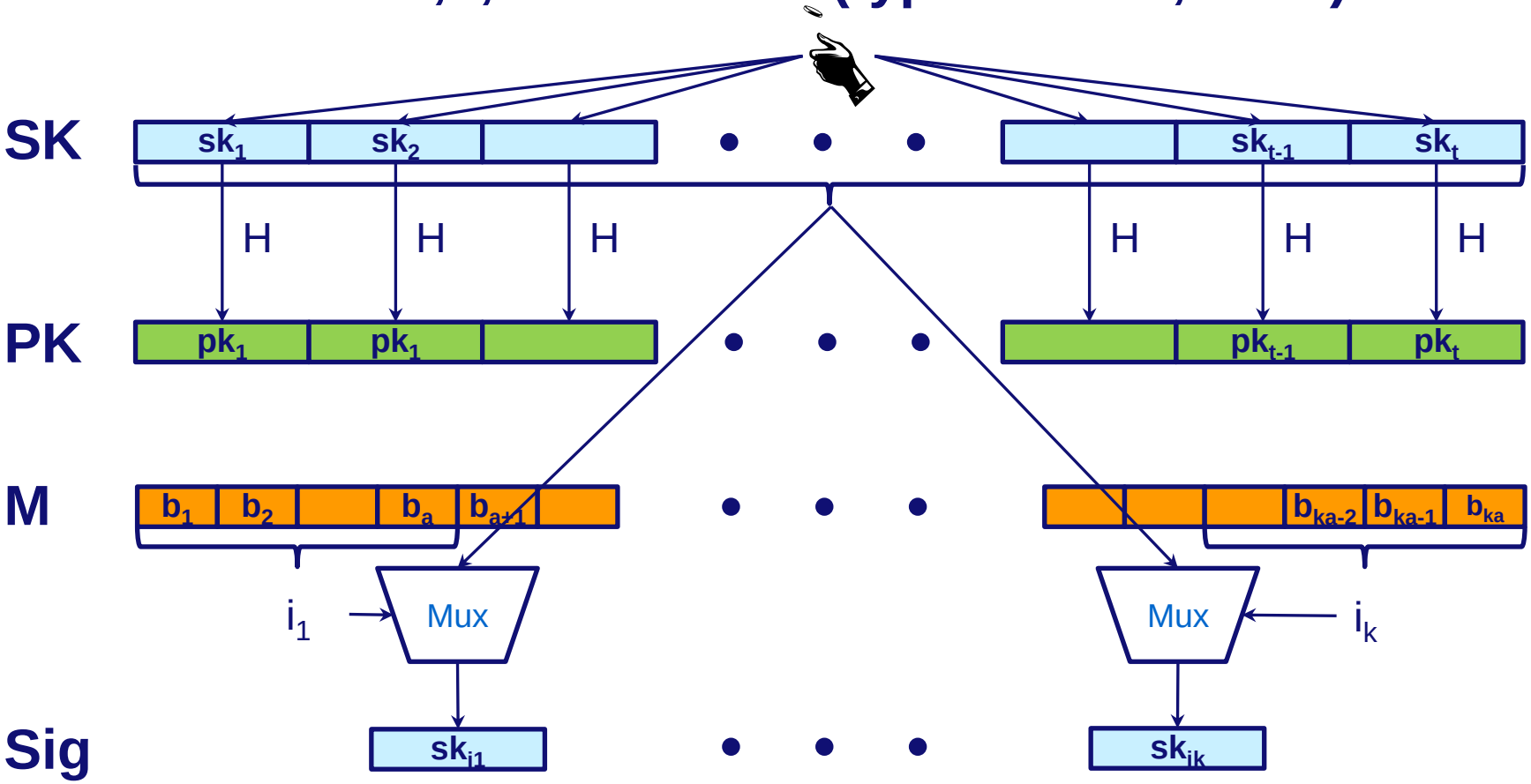
Message M = b1,…,bn, OWF H ***** **= n bit**



HORS [RR02]

Message M = $b_1,\ldots,b_m$, OWF H *** = n bit**

Parameters $t=2^a$,k, with m = ka (typical a=16, k=32)



HORS Security

- Message M = Hash(msg)
- M mapped to k element index set $M^i \in \{1,..,t\}^k$
- Each signature publishes k out of t secrets
- Either break one-wayness or…

- r-Subset-Resilience: After seeing index sets M^i_j for r messages msg_j, $1 <= j <= r$, hard to find $msg_{r+1} \neq msg_j$ such that $M^i_{r+1} \in \cup_{1<=j<=r} M^i_j$.

- Best generic attack: $Succ_{r\text{-}SSR}(A,q) = q(rk / t)^k$

→ Security shrinks with each signature!

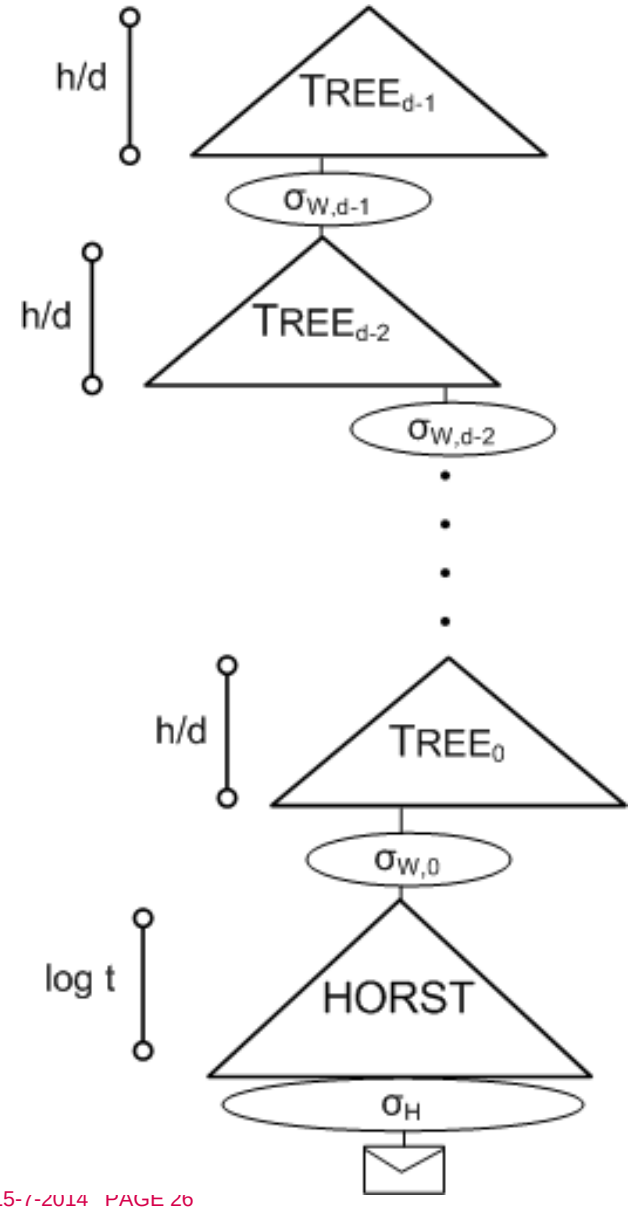
HORST

- **Using HORS with MSS requires adding PK (tn) to MSS signature.**

- **HORST: Build a Merkle Tree on top of PK**
  - **PK = Root**
  - **Publish Authentication Paths for HORS signature values**
  - **PK can be computed from Sig**
  - **With optimizations: $tn \rightarrow (k(\log t - x + 1) + 2^x)n$**
    - **E.g. SPHINCS-256: 2 MB → 16 KB**

SPHINCS

SPHINCS Signature



SPHINCS Key Ideas

- Use HORST key pairs to sign messages
- Authenticate HORST key pairs using hypertree (of MSS trees)
- Use random index

- Select h,k,t,m such that

$$\text{sum}_{r \in [0,\infty)}(\Pr[\text{r-times index collision}] * \text{Succ}_{\text{r-SSR}}(A)) = \text{negl}(n)$$

SPHINCS-256

Table 1: SPHINCS-256 parameters and functions for the 128-bit post-quantum security level and resulting signature and key sizes.

Parameter	Value	Meaning
n	256	bitlength of hashes in HORST and WOTS
m	512	bitlength of the message hash
h	60	height of the hyper tree
d	12	layers of the hyper tree
w	16	Winternitz parameter used for WOTS signatures
t	2^{16}	number of secret-key elements of HORST
k	32	number of revealed secret-key elements per HORST signature
Functions		
Hash $\mathcal{H}$:	$\mathcal{H}(R, M) = \text{BLAKE-512}(R\|\|M)$	
PRF $\mathcal{F}_a$:	$\mathcal{F}_a(A, K) = \text{BLAKE-256}(K\|\|A)$	
PRF $\mathcal{F}$:	$\mathcal{F}(M, K) = \text{BLAKE-512}(K\|\|M)$	
PRG G_λ:	$\text{G}_\lambda(\text{SEED}) = \text{ChaCha12}_{\text{SEED}}(0)_{0,\ldots,\lambda-1}$	
Hash F:	$\text{F}(M_1) = \text{CHOP}(\pi_{ChaCha}(M_1\|\|C), 256)$	
Hash H:	$\text{H}(M_1\|\|M_2) = \text{CHOP}\left(\pi_{ChaCha}\left(\pi_{ChaCha}\left(M_1\|\|C\right) \oplus \left(M_2\|\|0^{256}\right)\right), 256\right)$	
Sizes		
Signature size:	41000 bytes	
Public-key size:	1056 bytes	
Private-key size:	1088 bytes	

SPHINCS-256 Speed

- **Key generation: 3,051,562 cycles**
- **Verification: 1,369,060 cycles**
- **Signature: 47,466,005 cycles**

- **Still hundreds of messages per second on a modern 4-core 3.5GHz Intel CPU (13ms / Sig)**

In Paper (online soon)

- **Standard model security reduction without collision resistance**
- **Complexity of generic quantum attacks**
- **Efficient fixed-input length hashing**
- **Optimized implementation**

Conclusion

- **Stateless Hash-based Signatures**
- **Performance like RSA or BLISS? No!**
- **First stateless signature scheme with post-quantum secure parameters**
- **Practical Speed and Sizes**

Thank you!

Questions?