SPHINCS: practical stateless hash-based signatures

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Where innovation starts

Digital Signatures are Important!

Software updates

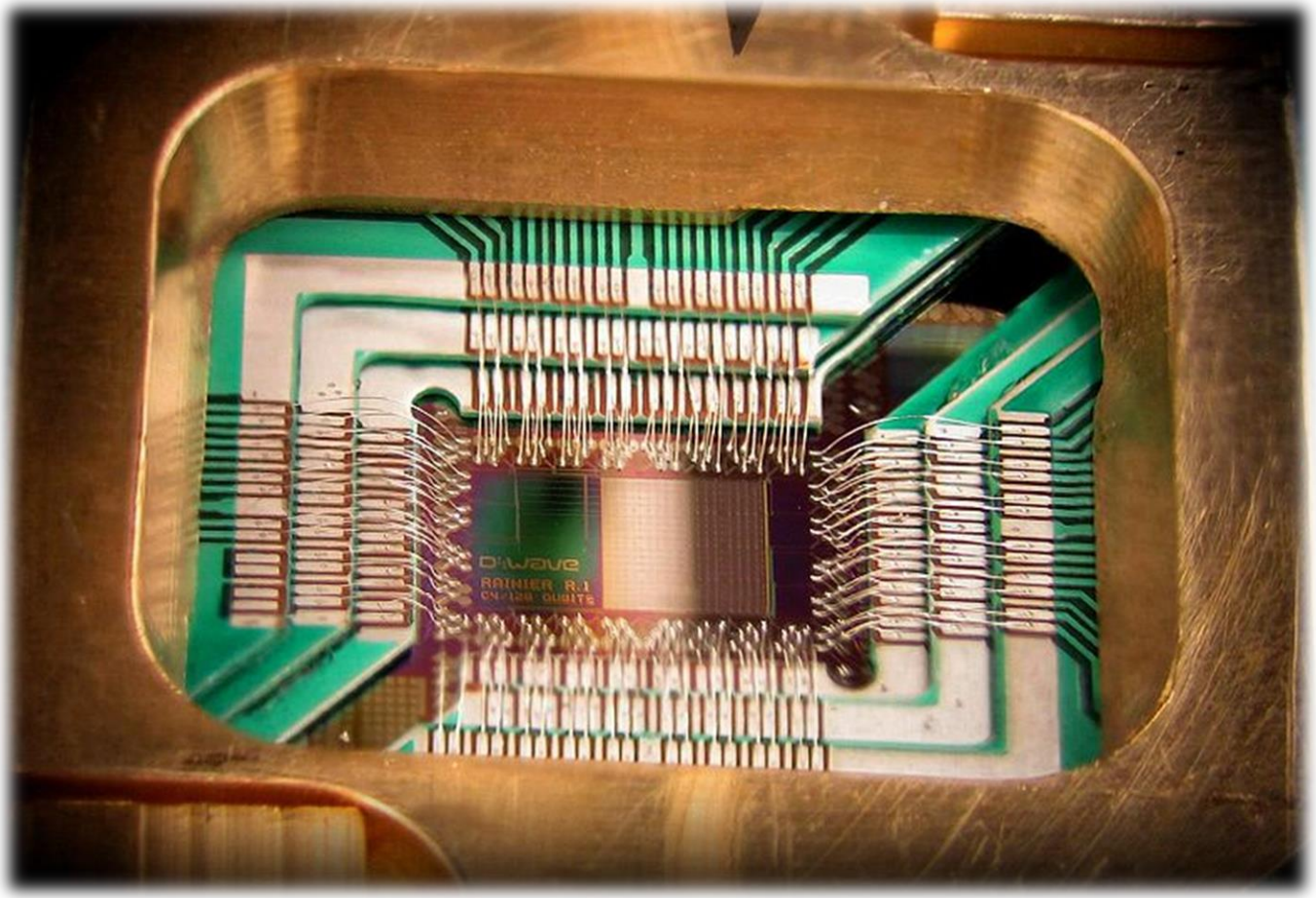
amazon

E-Commerce

ebay™

… and many others

What if…



Problem?

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

„Want to factor a 2000-bit number?

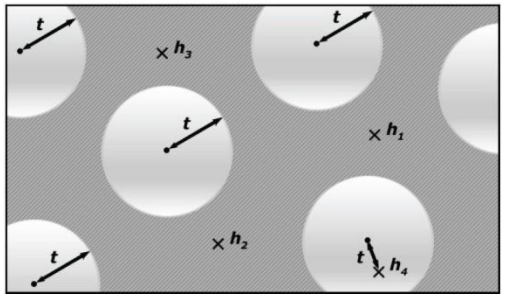
- ***Quantum computer runtime = 24h***
- ***Number of physical qubits required = 500M***
- ***Power required ~ dedicated nuclear power plant***
- ***Lead time ~5 (research) + 10 (development) years***
- ***Dollar required ~1 billion (CERN ~ 10 billion)“***

Matteo Mariantoni, PQ-Crypto 2014

Post-Quantum Signatures

Lattice, MQ, Coding

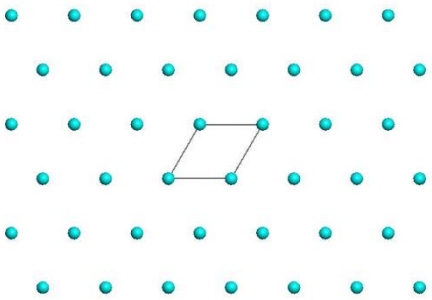
- Signature and/or key sizes
- Runtimes
- Secure parameters



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

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

$$y_3 = \ldots$$



Hash-based Signature Schemes [Mer89]

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

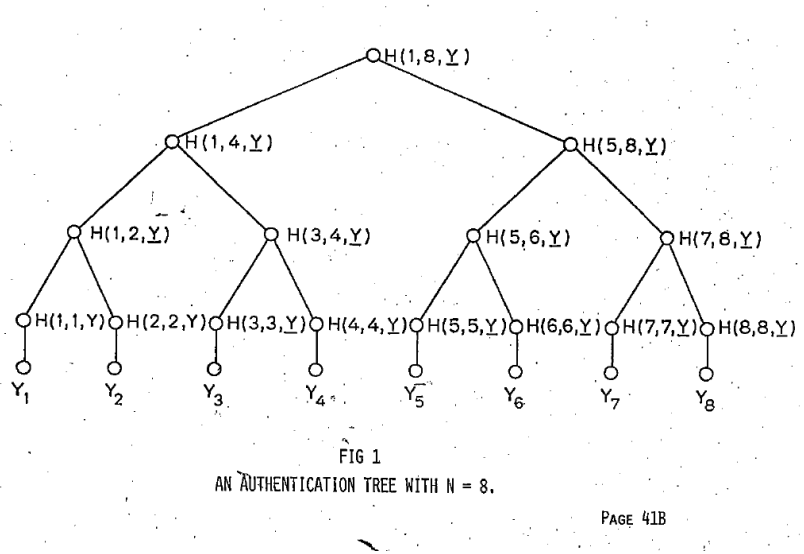
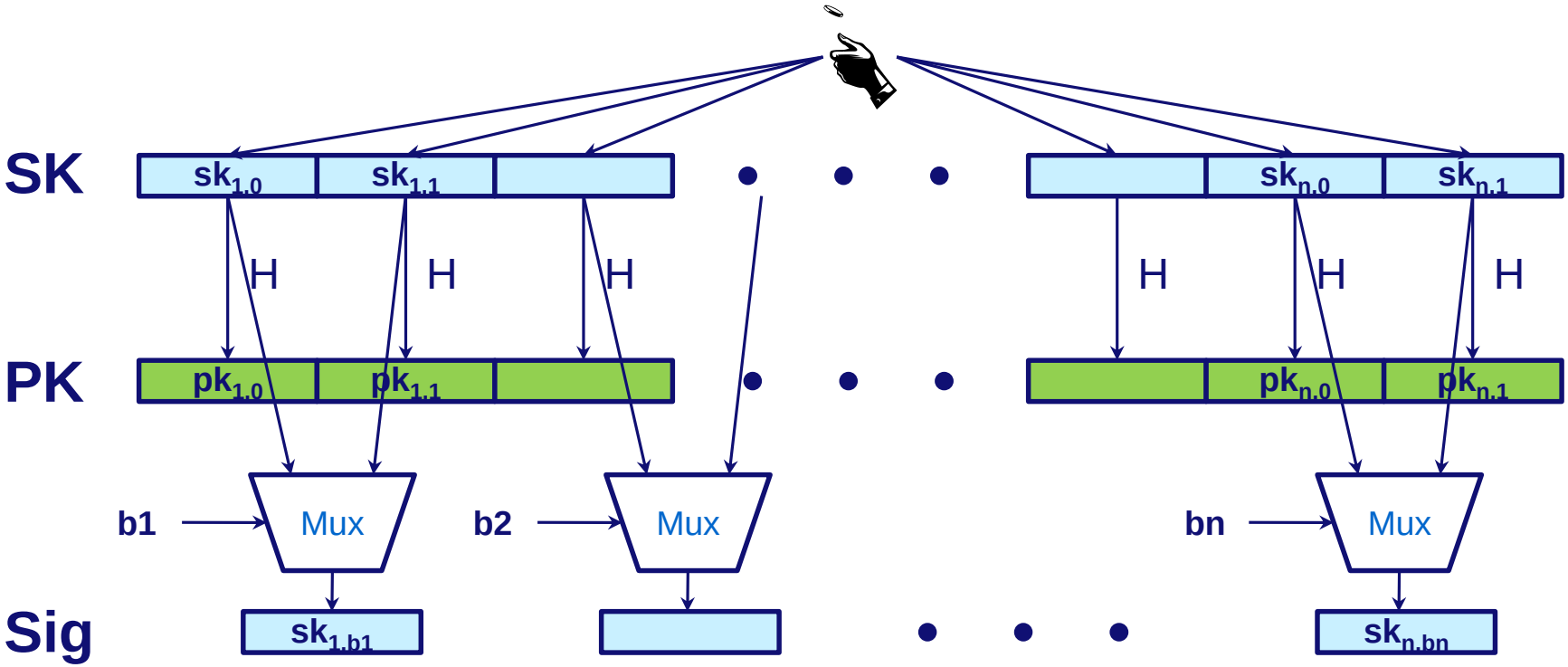


FIG 1
AN AUTHENTICATION TREE WITH N = 8.

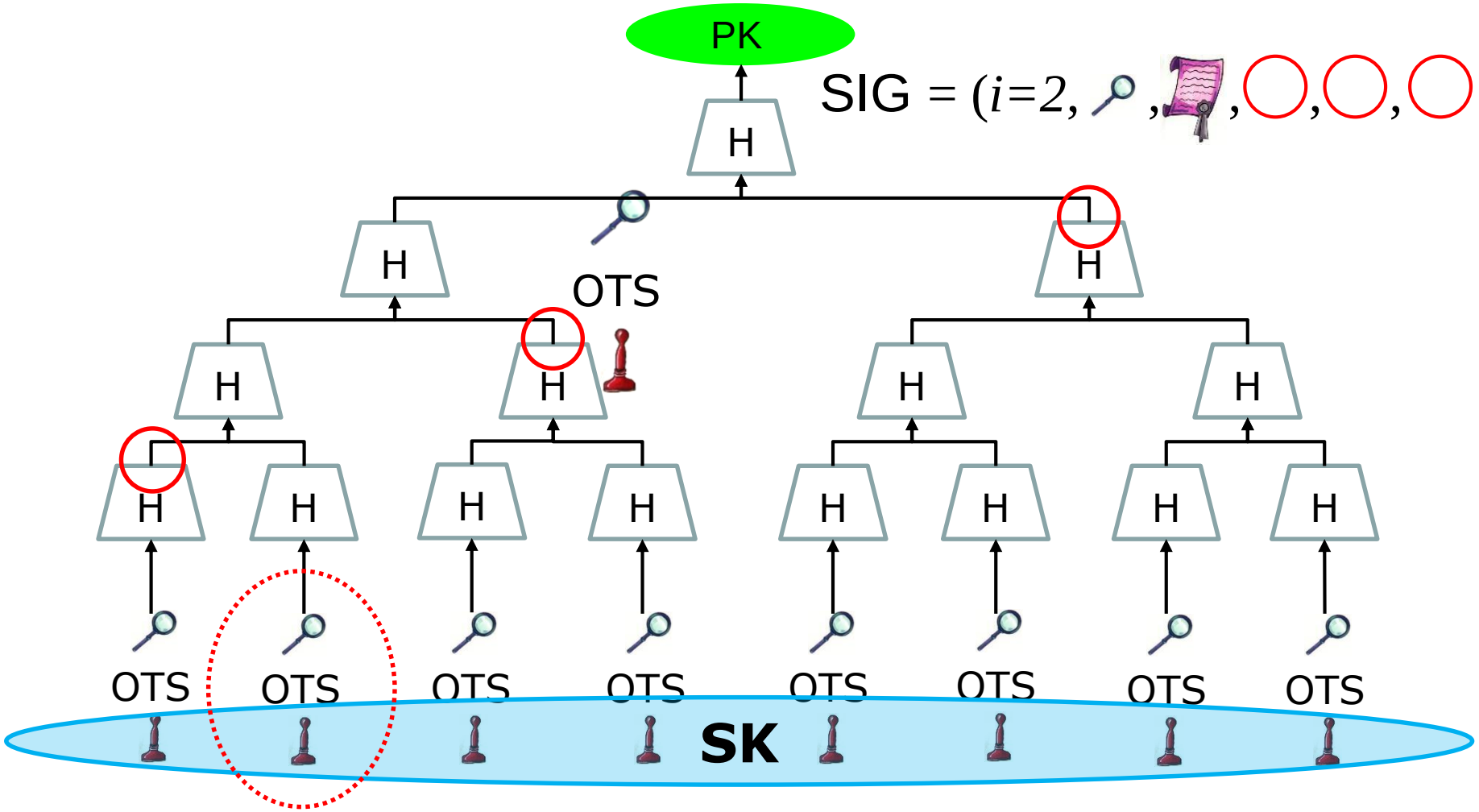
PAGE 41B

Lamport-Diffie OTS [Lam79]

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



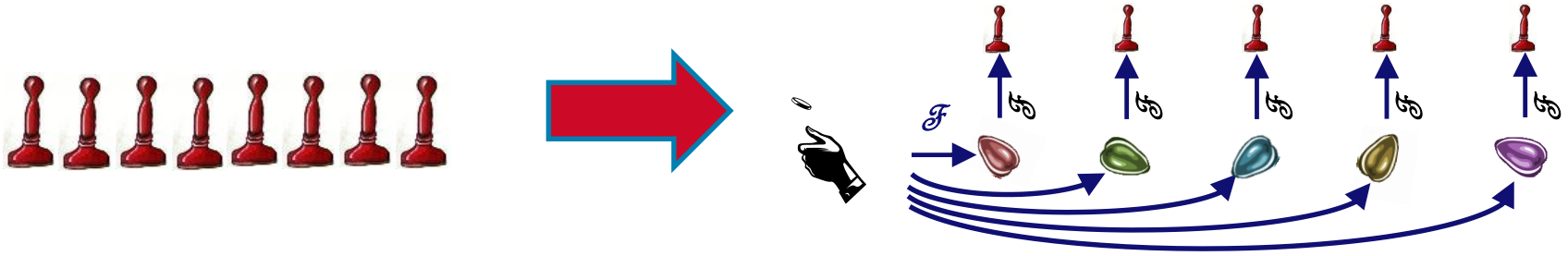
Merkle's Hash-based Signatures



Known Improvements [BGD+06]

- Pseudorandom Key Generation:

  SK $2^h n \to n$

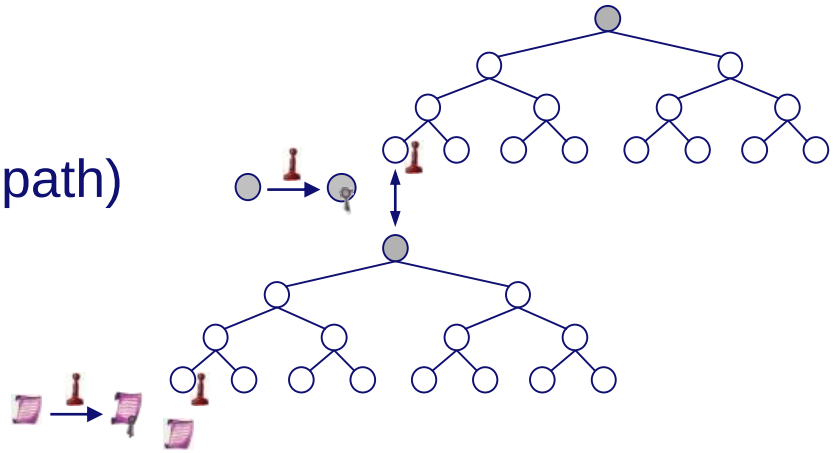


- Hypertree:

  Key generation

  (== Building Trees on one path)

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



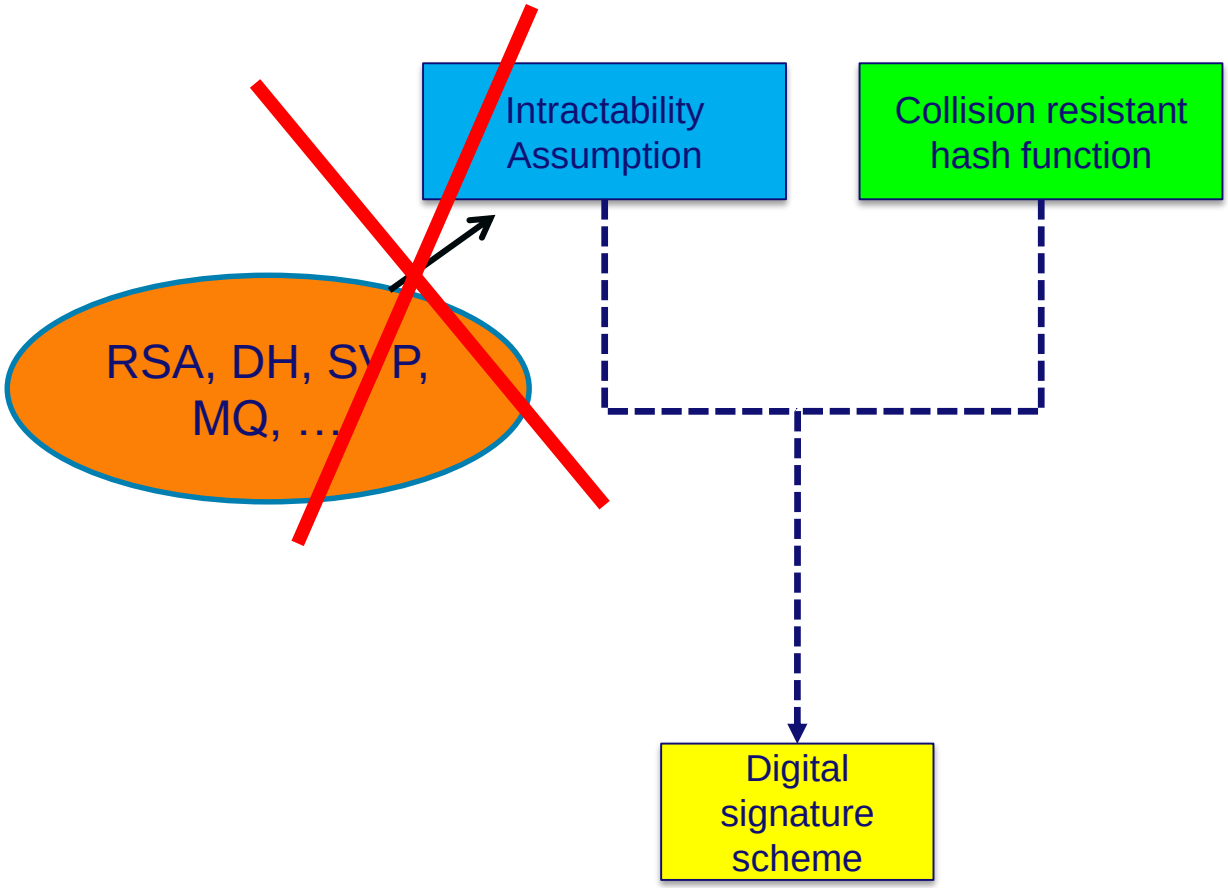
Known Improvements, cont'd

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

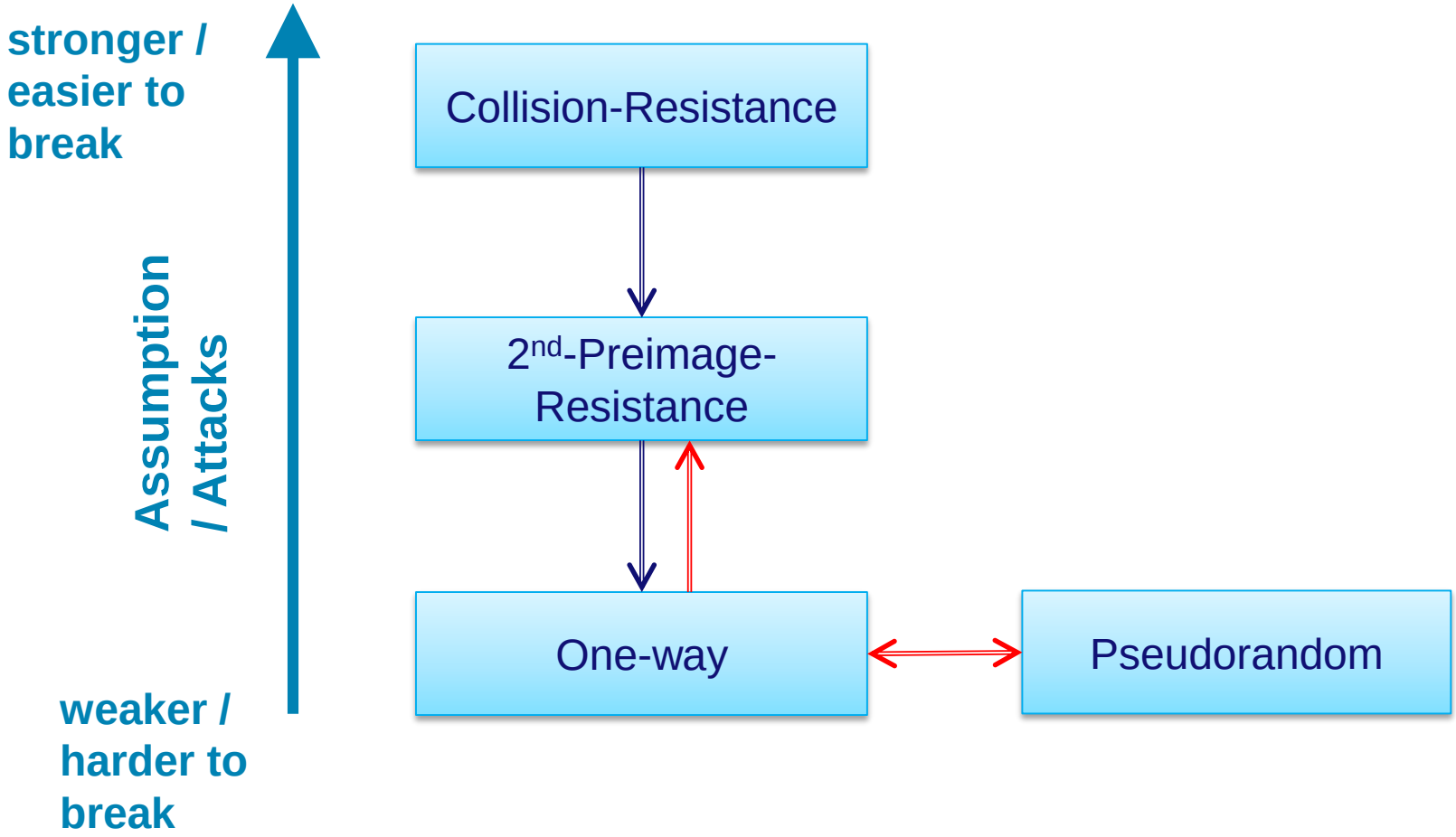
- **Minimum Security Assumptions / Collision-Resilient Scheme [BDH11]**
  - **XMSS requires only PRF & SPR**

Advantages of Hash-based Signatures

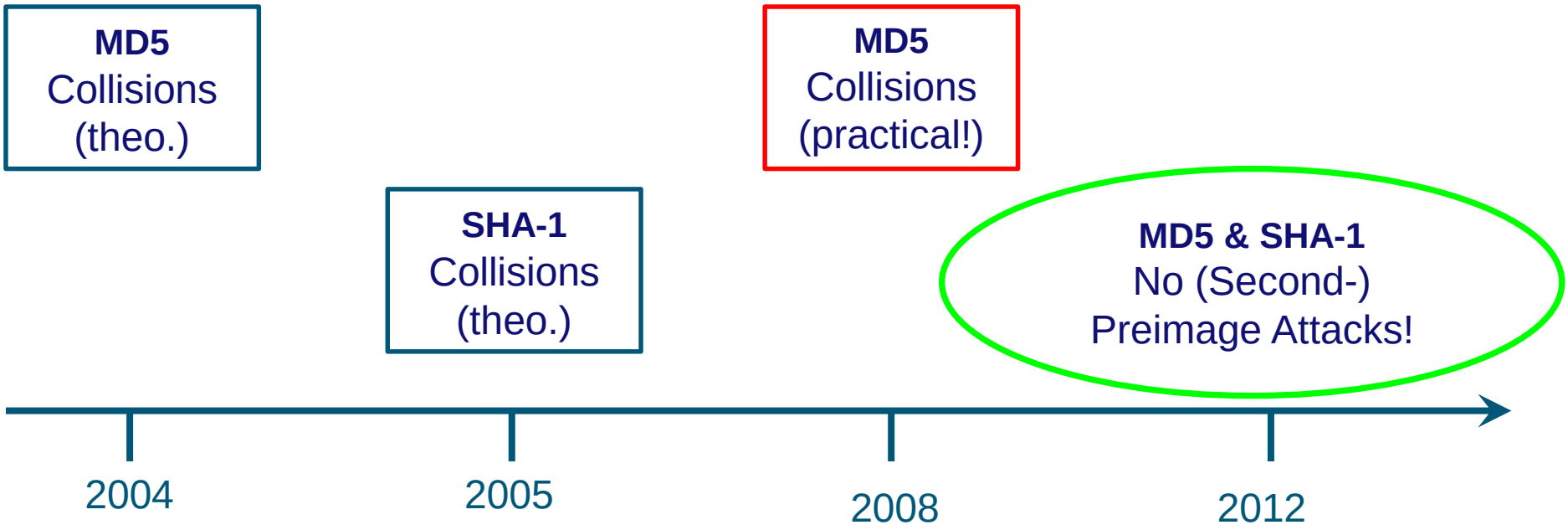
RSA – DSA – EC-DSA...



Early Warning System
Hash-function properties



Early Warning System
Attacks on Hash Functions



Easy Redundancy

Hash-Combiner

- Collision-Resistance / 2nd-Preimage-Resistance:

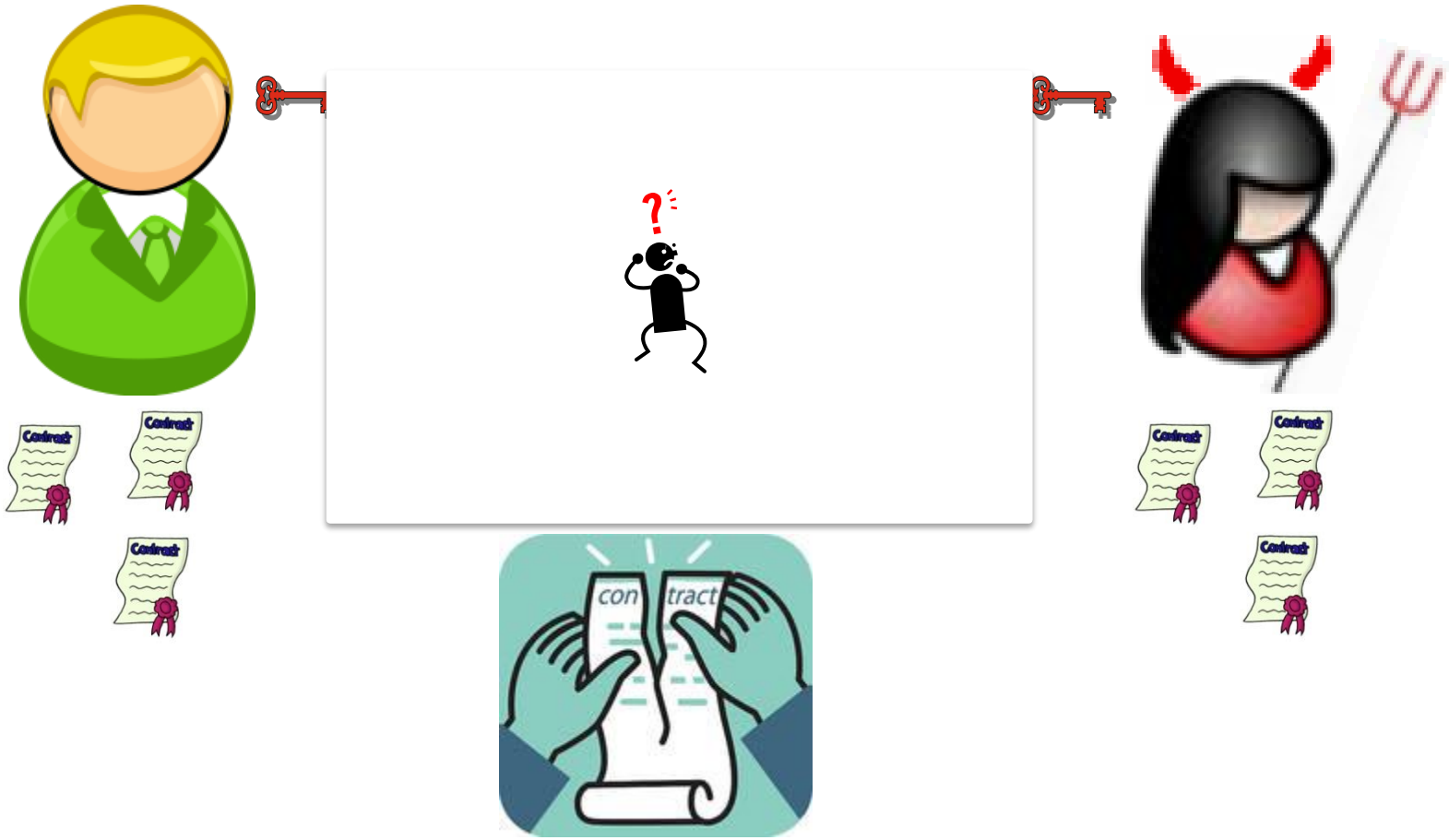
$$h_k(x) = g_k(x) \| f_k(x)$$

- PRF:

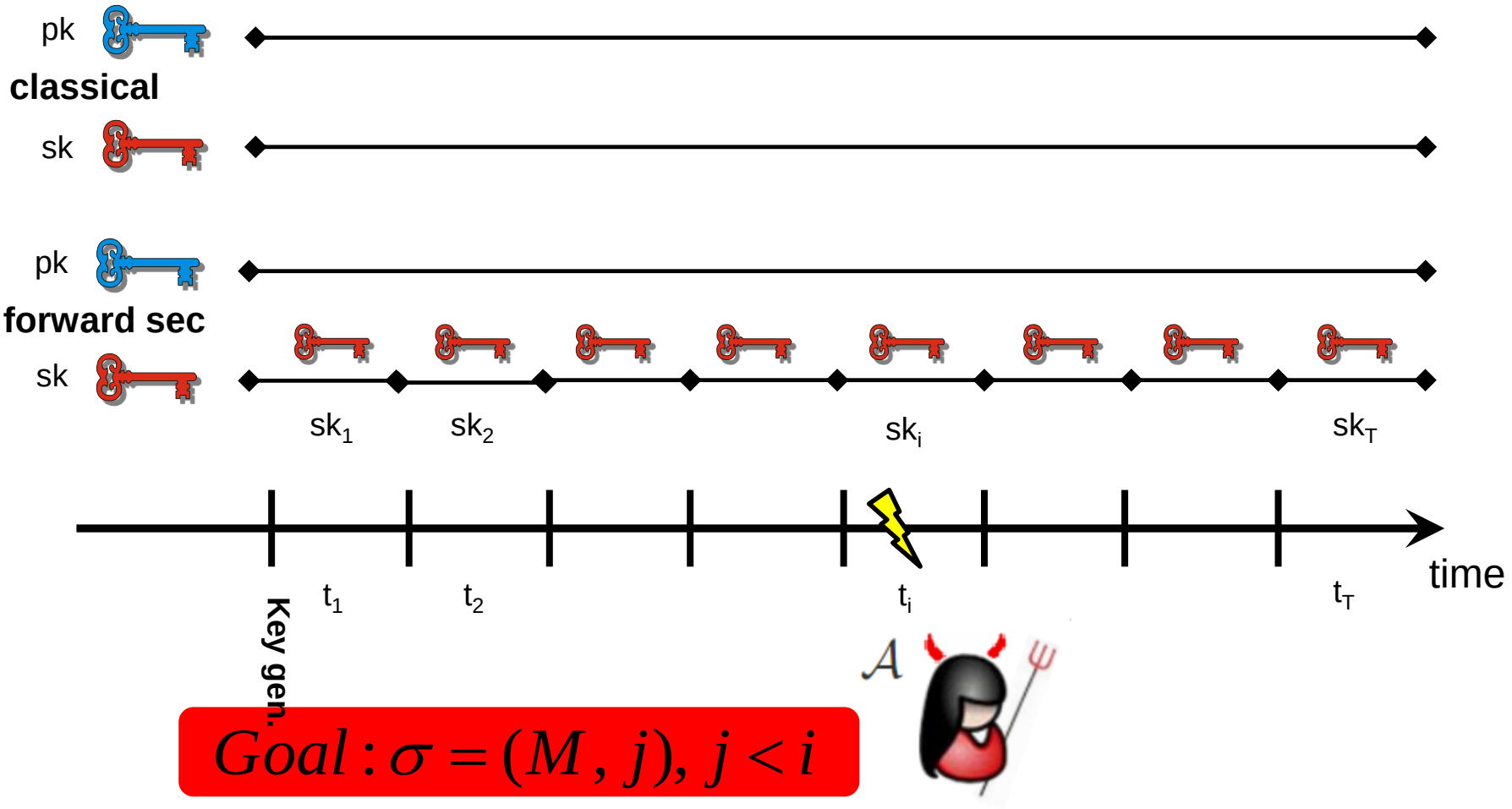
$$h_k(x) = g_k(x) \oplus f_k(x)$$

- **No sudden break**
- **Replaces double signature**
- **Signature size only grows by h*n**
- **Runtime ~ doubled**

Forward Security



Forward Security - cont'd



$$Goal : \sigma = (M, j), j < i$$

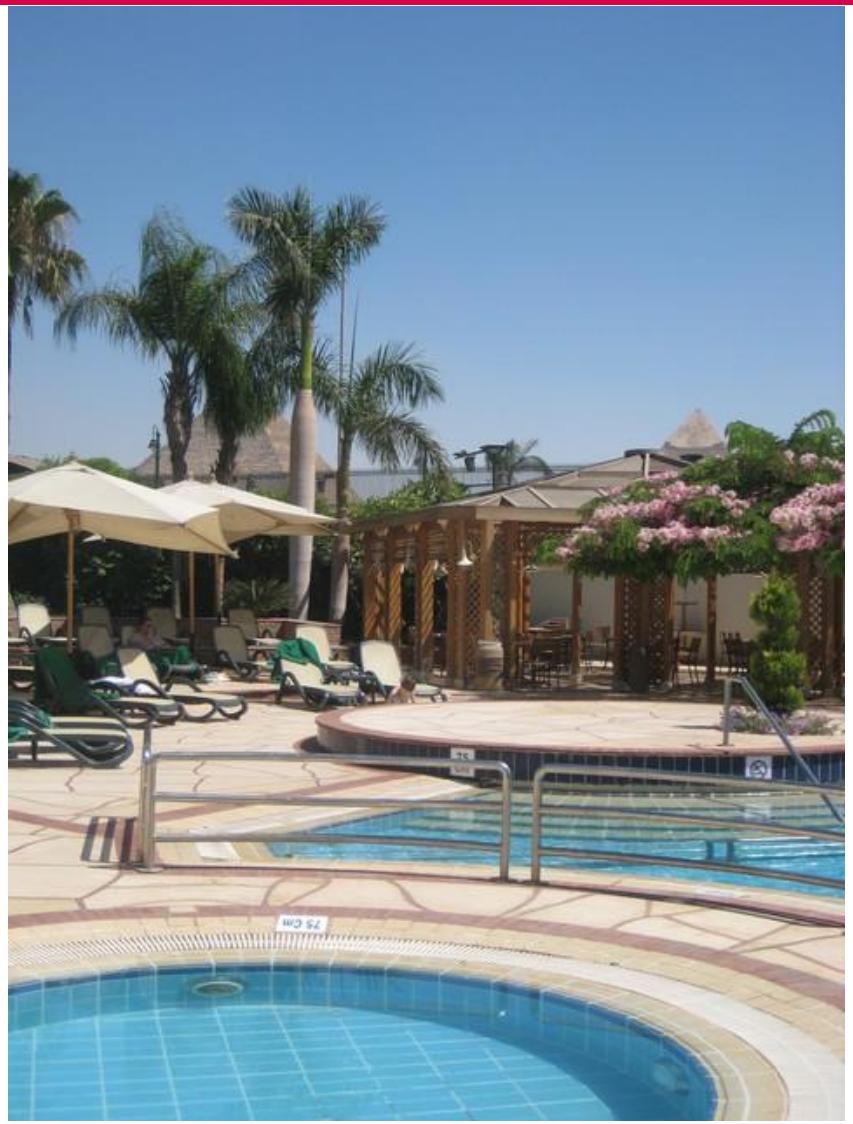
Long-Standing Problem: Statefulness

- No problem in many cases.
  - Qualified signatures,
  - Keys on smartcard, ...
- Necessary for forward-security!

But:

- Key back-ups undermine security
- Parallel use of key problematic
  - Multi-threading scenarios,
  - Load balancing...
- Do not fit standard API

SPHINCS: Stateless Practical Hash-based Incredibly Nice Cryptographic Signatures



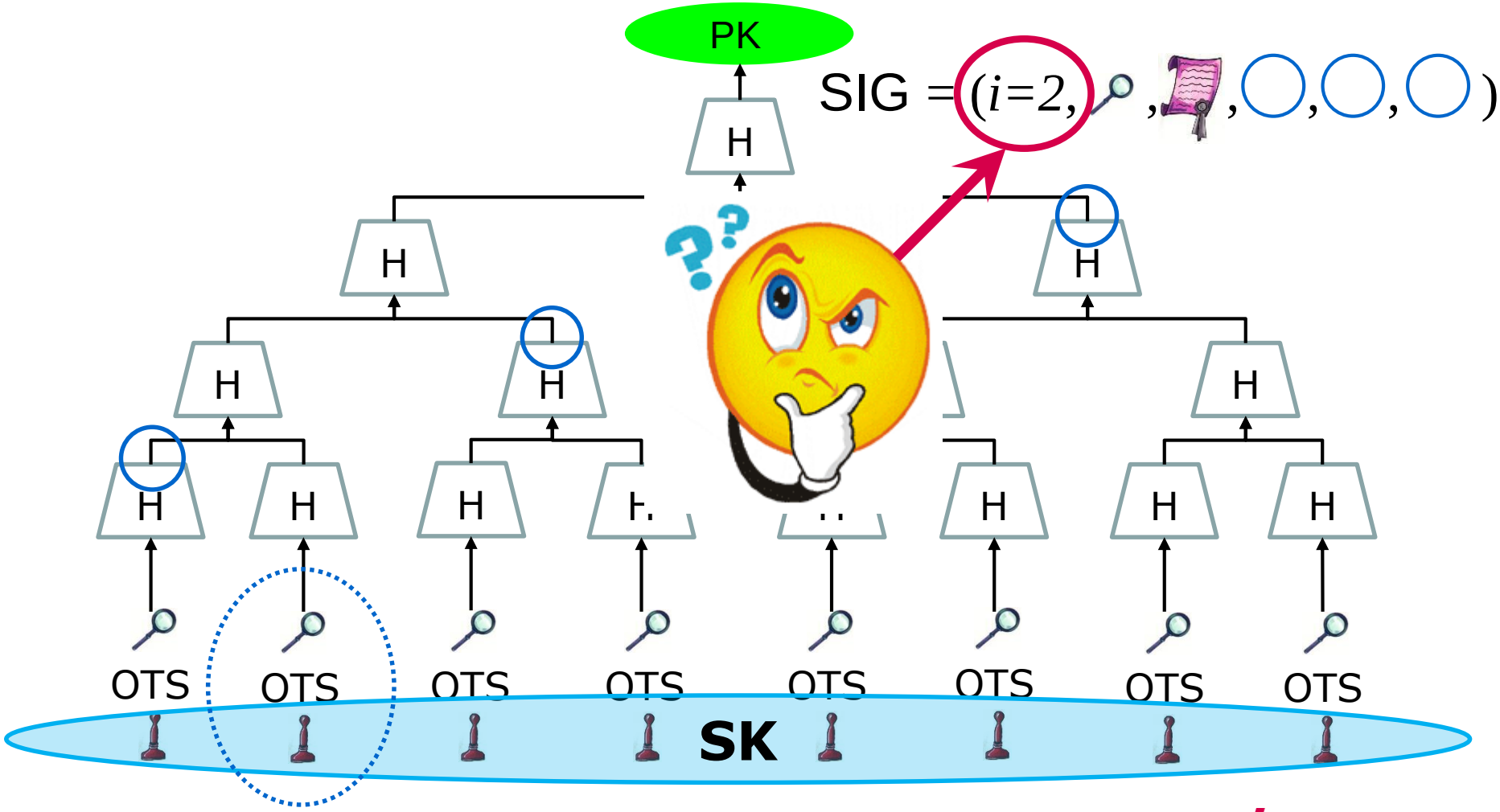
Goals

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

How to Eliminate the State

Straight Forward

- **Run MSS without State**



Approach 1: Message Hash

i = Hash(Message);

- 128bit Quantum Sec.

  $\rightarrow n = 256$ bit Hash [Ber09]

  $\rightarrow$ #Indices = 2^{256}

  $\rightarrow h = n = 256$

- h depends on n!
- Best we can do:

  $t_{Sign} \approx n^3 / \log n \; t_{Hash} = 2M \; t_{Hash} \approx 15$ min*

  $|Sig| \approx n^3 / \log n > 256$ kb

* (OpenSSL SHA2)

Approach 2: Random Index

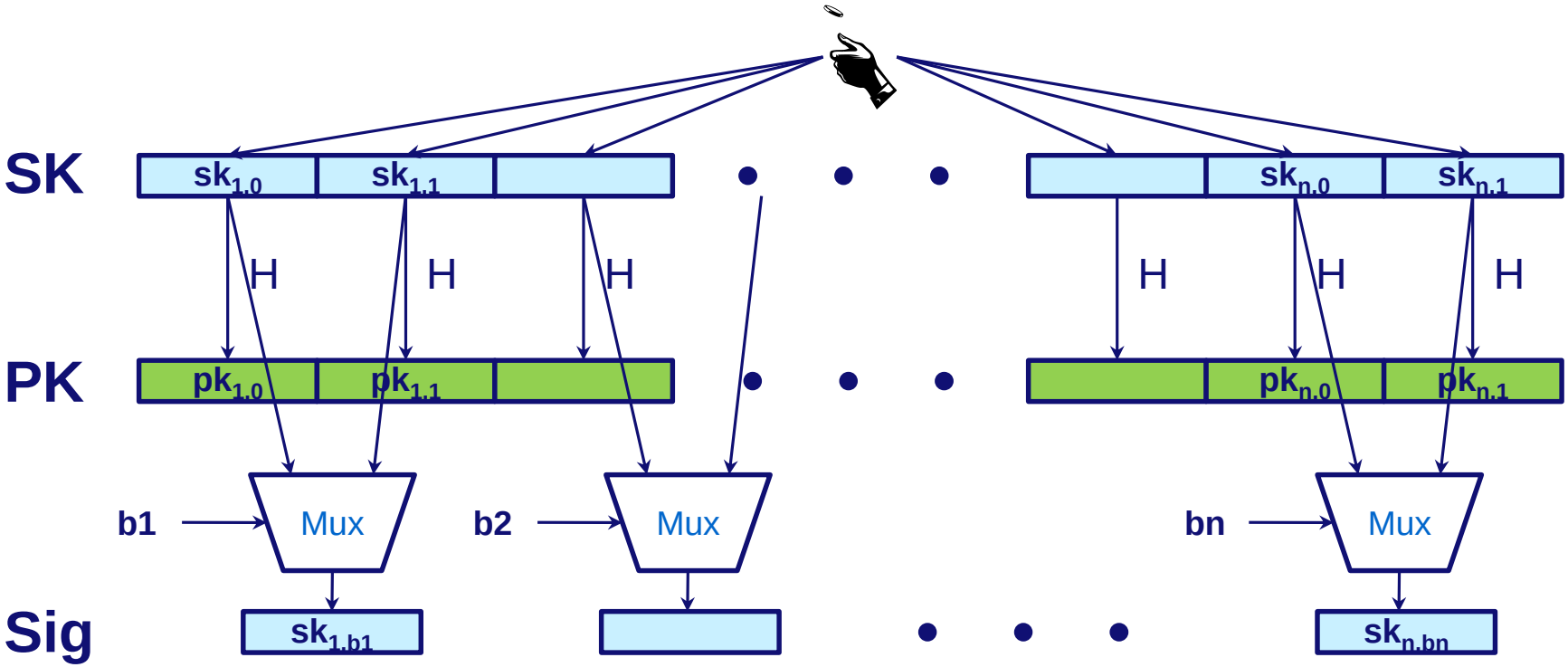
$$I \leftarrow_{\$} U_{\#Indices}$$

- 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

Few-Time Signature Schemes

Recap LD-OTS

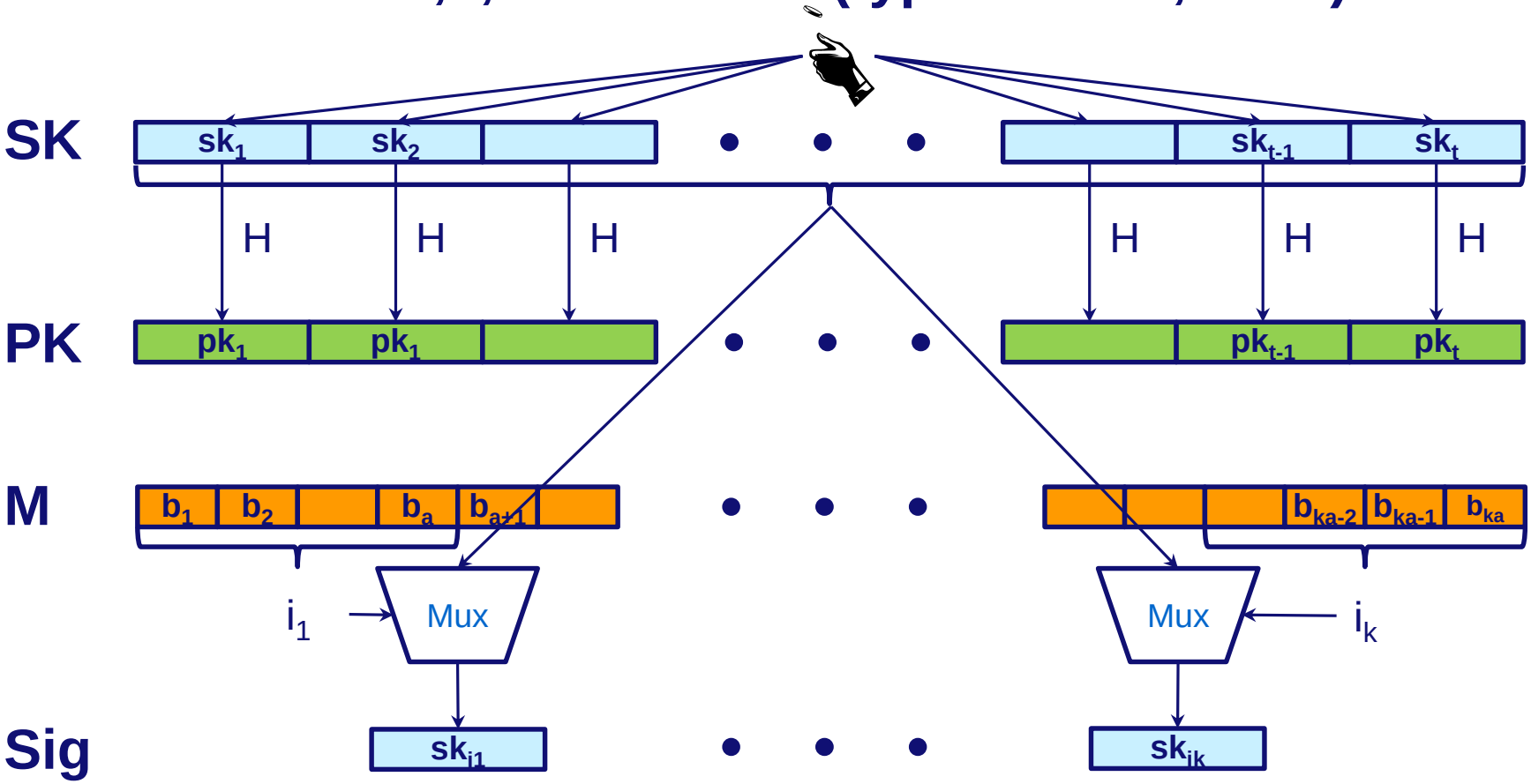
Message M = b1,…,bn, OWF H ***** **= n bit**



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!

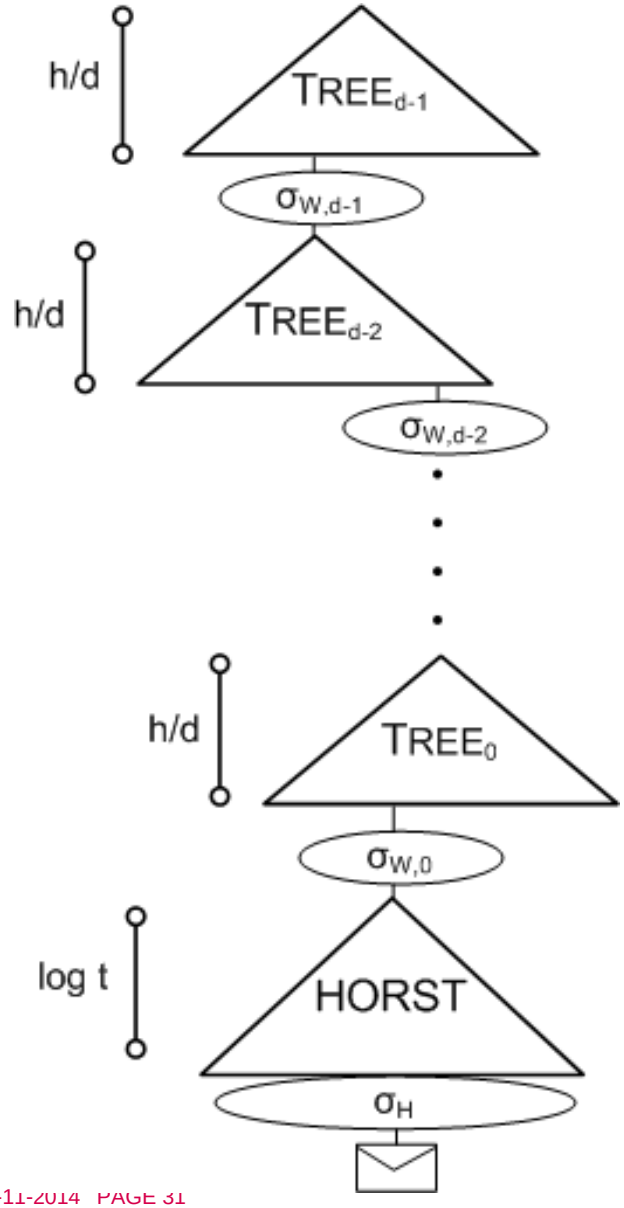
HORST

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

- **HORST: Build a Merkle Tree on top of HORS-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 Parameters 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)**

- **Remember: Straight Forward**

$$t_{Sign} \approx 15 \text{ min}^*$$
$$|Sig| > 256 \text{ kb}$$

In Paper (http://eprint.iacr.org/2014/795)

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

Conclusion

- **If you can live with a state: Go for XMSS.**

- **Otherwise:**
  - **Go for Sphincs-256!**
  - **First stateless signature scheme with post-quantum secure parameters**
  - **Practical Speed and Sizes**

Thank you!

Questions?