Practical Forward Secure Signatures using Minimal Security Assumptions

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Digital Signatures are Important!

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Software updates

amazon

E-Commerce

ebay™

… and many others

Forward Secure Signatures
[And97]

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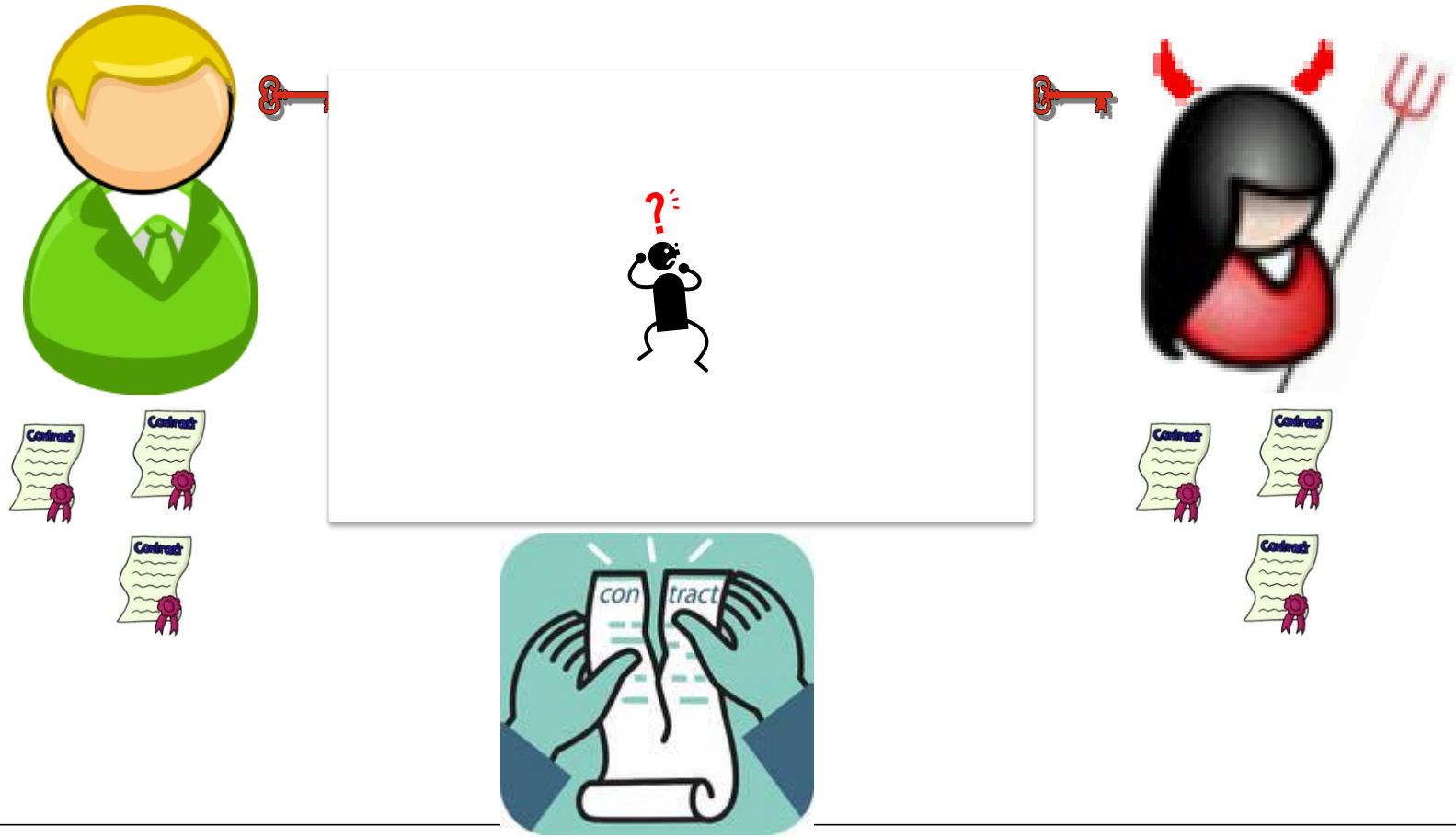
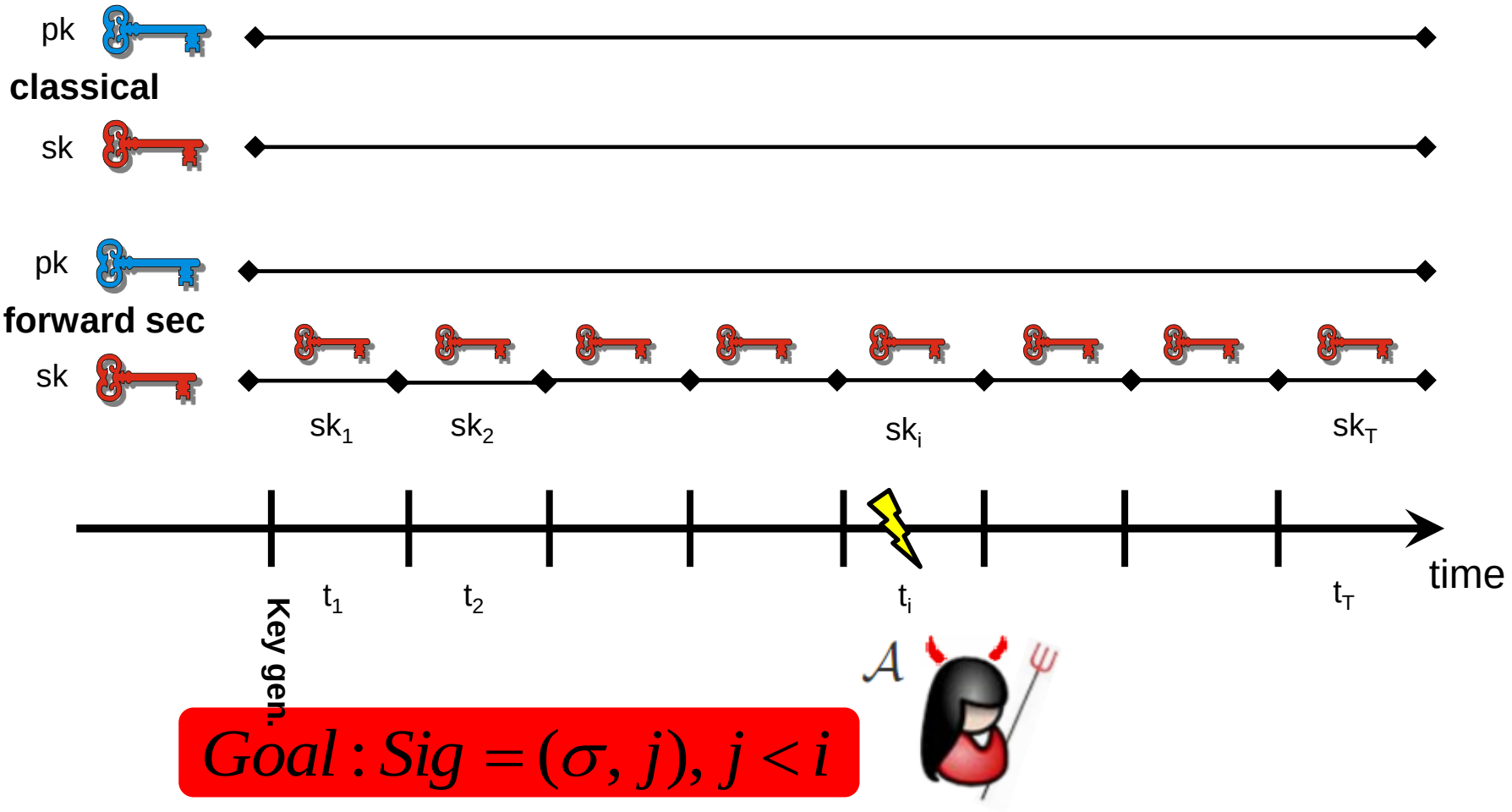


Forward Secure Signatures



What if…

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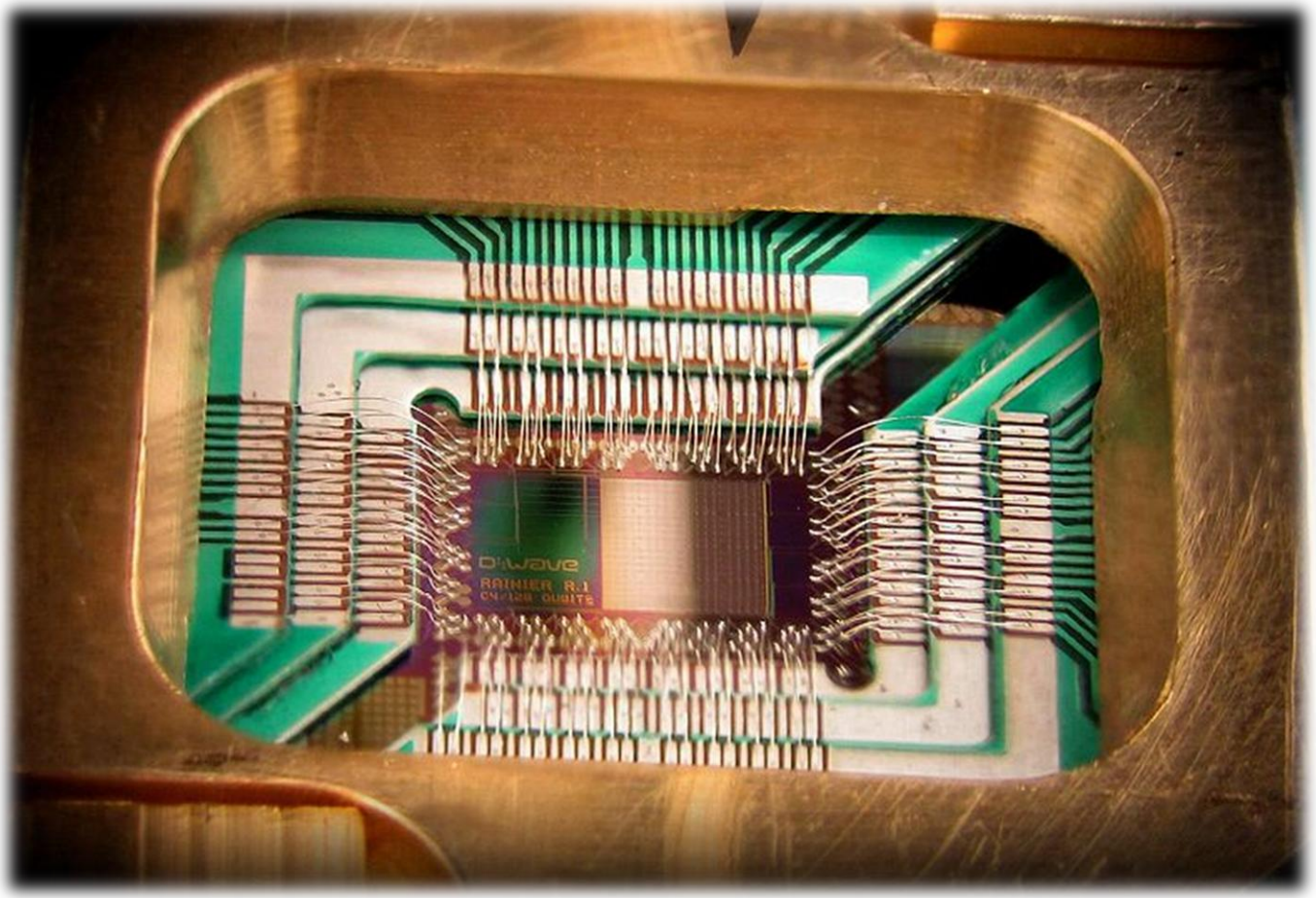

Post-Quantum Signatures

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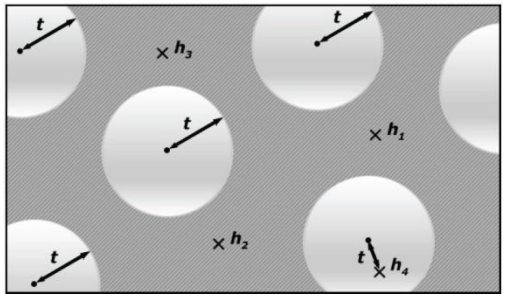
Lattice, MQ, Coding

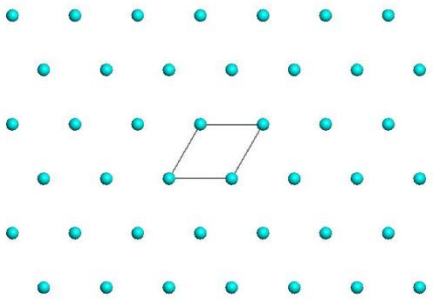
- Signature and/or key sizes
- Runtimes
- Secure parameters
- no forward secure signatures



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

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

$$y_3 = \ldots$$



Hash-based Signature Schemes
[Mer89]

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- Post quantum
- Only secure hash function
- Security well understood
- Fast
- Forward secure (inefficient)

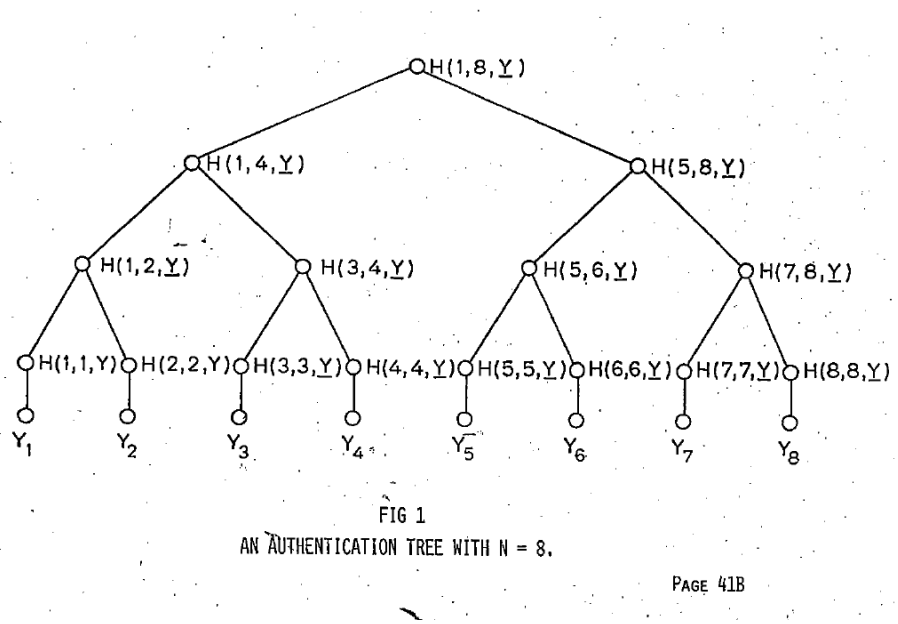

FIG 1
AN AUTHENTICATION TREE WITH N = 8.

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Cryptographic Hash Functions

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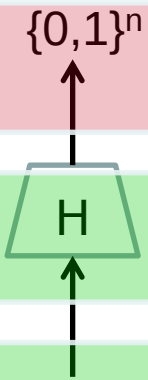
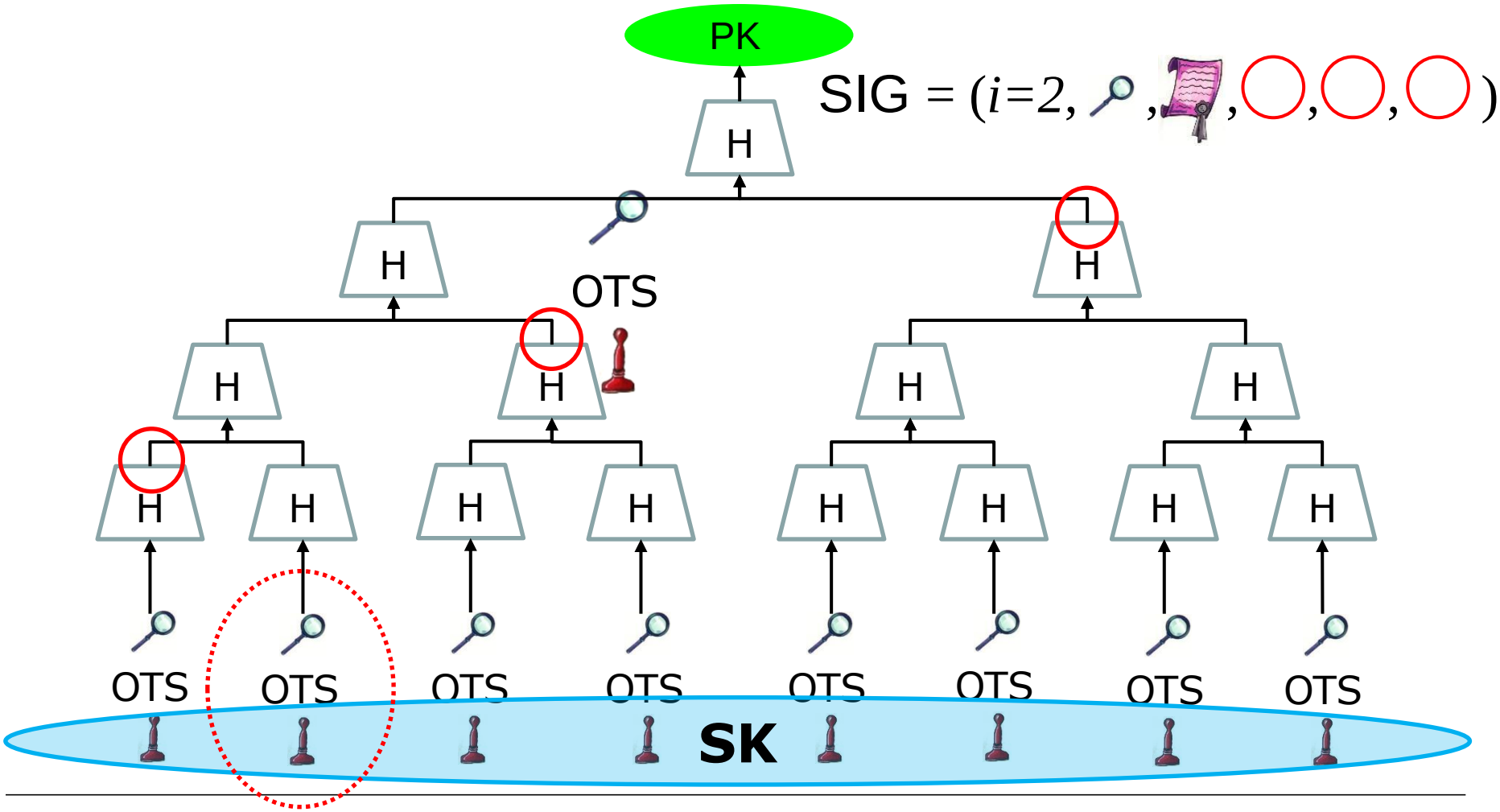
$$\mathcal{H}_n = \{H_K : \{0,1\}^m \rightarrow \{0,1\}^n \mid K \in \{0,1\}^{n'}\}$$

Collision Resistance (CR)	• Cryptomania • AC $\mathcal{O}(2^{n/2})$
Second-preimage Resistance (SPR)	• Minicrypt • AC $\mathcal{O}(2^n)$
One-wayness	• Minicrypt • AC $\mathcal{O}(2^n)$
Undetectability (UD)	• Minicrypt • AC $\mathcal{O}(2^n)$
Pseudorandomness (PRF)	• Minicrypt • AC $\mathcal{O}(2^n)$



Hash-based Signatures



Challenges & Achievements

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Minimal security assumptions XOR Efficient

Forward secure XOR Efficient

Large signatures

No full smartcard implementation

Efficient

Minimal security assumptions

„Small signatures"

Forward secure

Full smartcard implementation

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New Variants of the Winternitz One Time Signature Scheme

OTS

Winternitz OTS (WOTS)
[Mer89; EGM96]

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SIG = (i,  ,  , ◯, ◯, ◯)

|  | = |  | = m * | ◯ |

1.  = f()

2. Trade-off between runtime and signature size

|  | ~ m/log w * | ◯ |

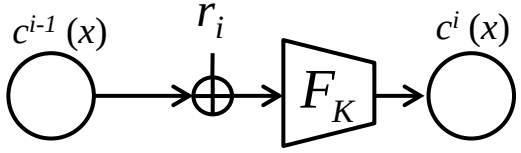
WOTS
Function Chain

Function family: $\mathcal{F}_n = \{F_K : \{0,1\}^n \rightarrow \{0,1\}^n \mid K \in \{0,1\}^{n'}\}$

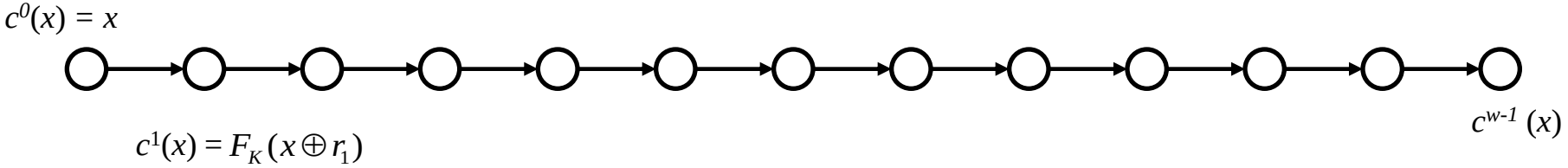
Formerly: $c^i(x) = F_K(c^{i-1}(x)) = \underbrace{F_K \circ F_K \circ \ldots \circ F_K(x)}_{i-times}, K \in \{0,1\}^{n'}$

WOTS+

For $w \geq 2$ select $\mathcal{R} = (r_1, \ldots, r_{w-1}) \in \{0,1\}^{n \times w-1}, K \in \{0,1\}^{n'}$



$$c^i(x) = F_K(c^{i-1}(x) \oplus r_i)$$



WOTS+
[Hül13]

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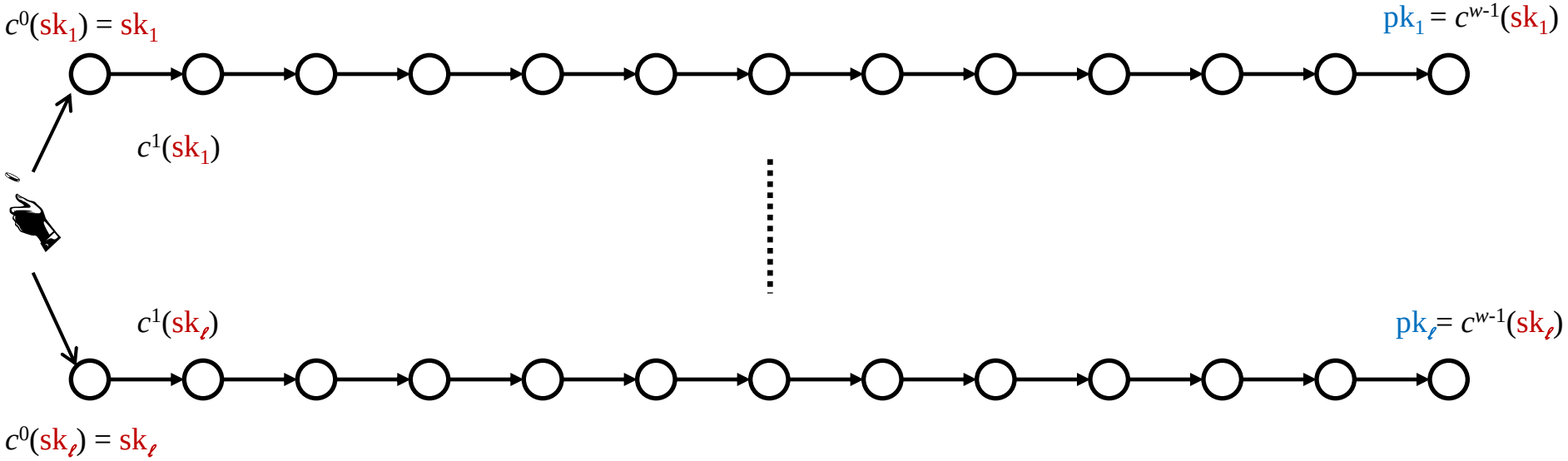
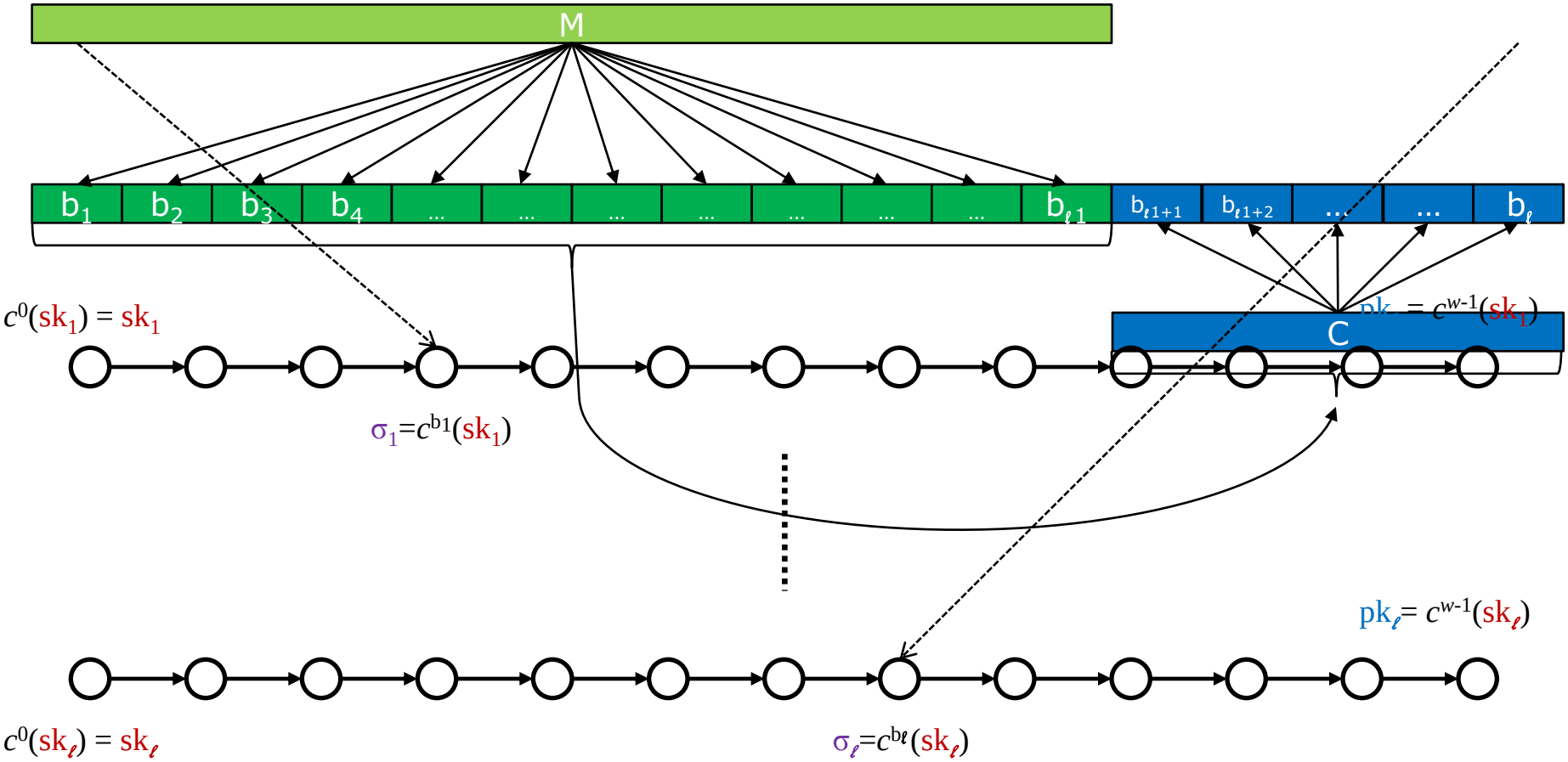
Winternitz parameter w, security parameter n, message length m, function family $\mathcal{F}_n = \{F_K : \{0,1\}^n \to \{0,1\}^n \mid K \in \{0,1\}^{n'}\}$

Key Generation: Compute ℓ, sample K, sample $\mathcal{R}$



WOTS+ Signature generation



Main result

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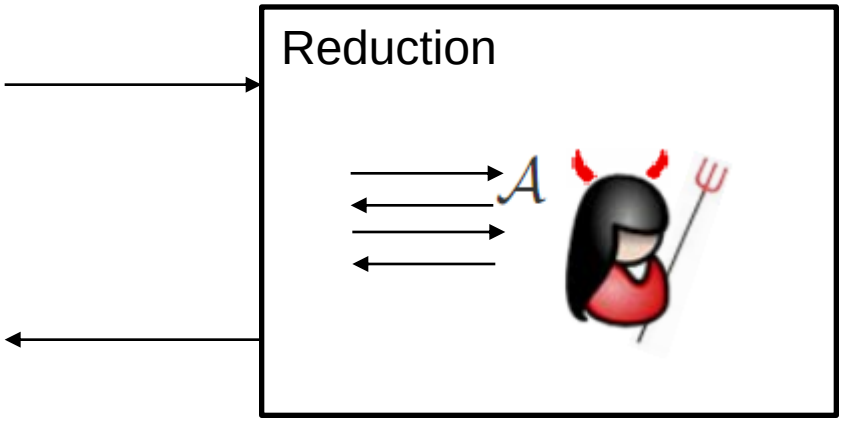
Theorem 3.9 (informally):

W-OTS$^+$ is strongly unforgeable under chosen message attacks if $\mathcal{F}$ is a 2nd-preimage resistant, undetectable one-way function family

Security Proof



Intuition

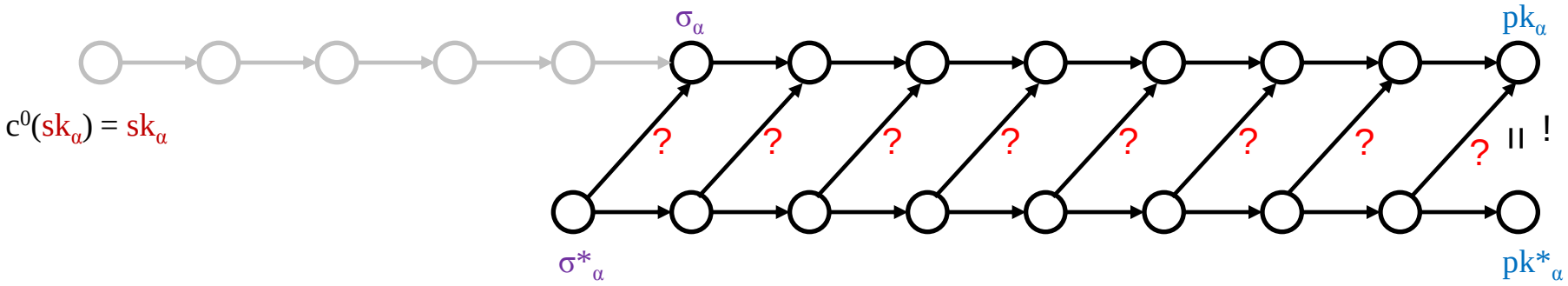
Oracle Response: $(\sigma, M);$ $M \rightarrow (b_1, \ldots, b_\ell)$

Forgery: $(\sigma^*, M^*);$ $M^* \rightarrow (b_1^*, \ldots, b_\ell^*)$

Observations:

1. Checksum: $\exists \alpha \in \{1,..,l\}\, s.th.\ b_\alpha^* < b_\alpha$
2. Verification $c^{w-1-b\alpha^*}(\sigma^*_\alpha) = pk_\alpha = c^{w-1-b\alpha}(\sigma_\alpha)$

➡ "quasi-inversion"



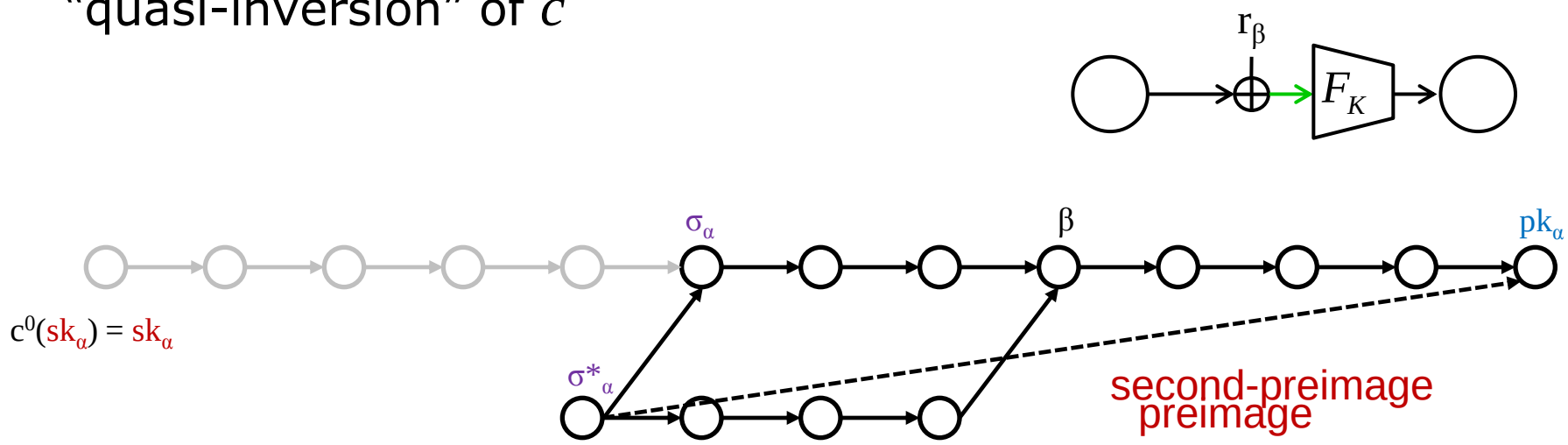
Intuition, cont'd

Oracle Response: (σ, M); $M \rightarrow (b_1, \ldots, b_\ell)$

Forgery: (σ^*, M^*); $M^* \rightarrow (b_1^*, \ldots, b_\ell^*)$

Given:

"quasi-inversion" of c



Result

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Old [DSS05]	WOTS$ [BDEHR11]	WOTS+ [Hül13]
CR, UD, OW $\mathcal{F}_n$	PRF $\mathcal{F}_n$	SPR, UD, OW $\mathcal{F}_n$
Cryptomania	Minicrypt	Conj. Minicrypt
|Sig| = ℓ *2b	|Sig| = ℓ *(b+w)	|Sig| = ℓ *(b+log w)

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XMSS

XMSS
[BDH11]

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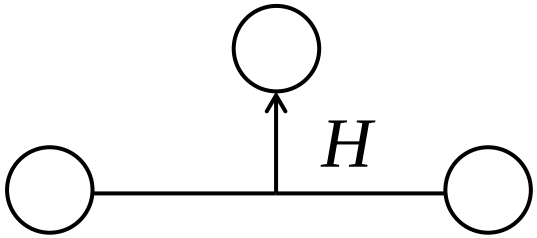
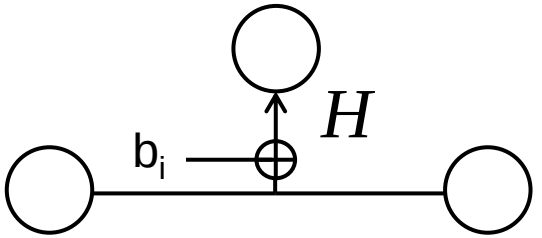
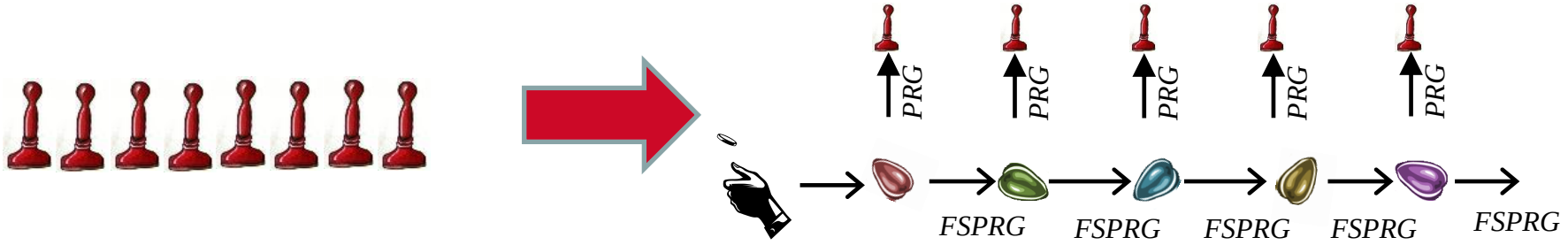
Lamport-Diffie / WOTS → WOTS$^+$ / WOTS$^{\$}$

Tree construction
[DOTV08]





Pseudorandom key generation



Result

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SPR-MSS [DOTV08]	GMSS (Single Tree) [BDK+07]	XMSS [BDH11]
Minicrypt	Cryptomania	Minicrypt
FSS	Not FSS	FSS
$\|SK\| = 2^{h+1}bm + TTA$	$\|SK\| = b + TTA$	$\|SK\| = b + TTA$
$\|SIG\| \sim 2bm + hb$	$\|SIG\| \sim 2b(m/\log w) + h2b$	$\|SIG\| \sim b(m/\log w) + hb$

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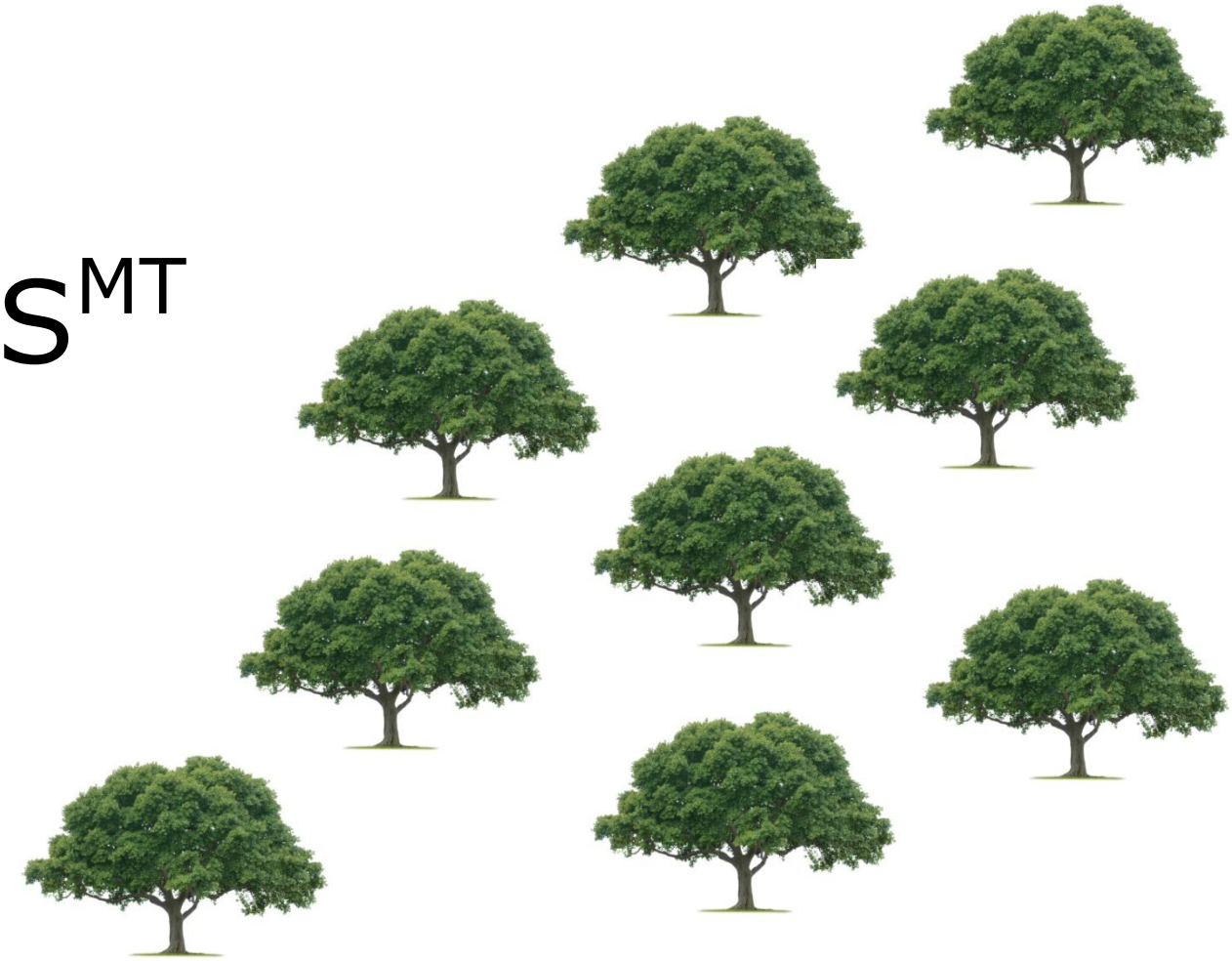
Chapter 5
XMSS^{MT}



Tree Chaining
[BGD+06,BDK+07]

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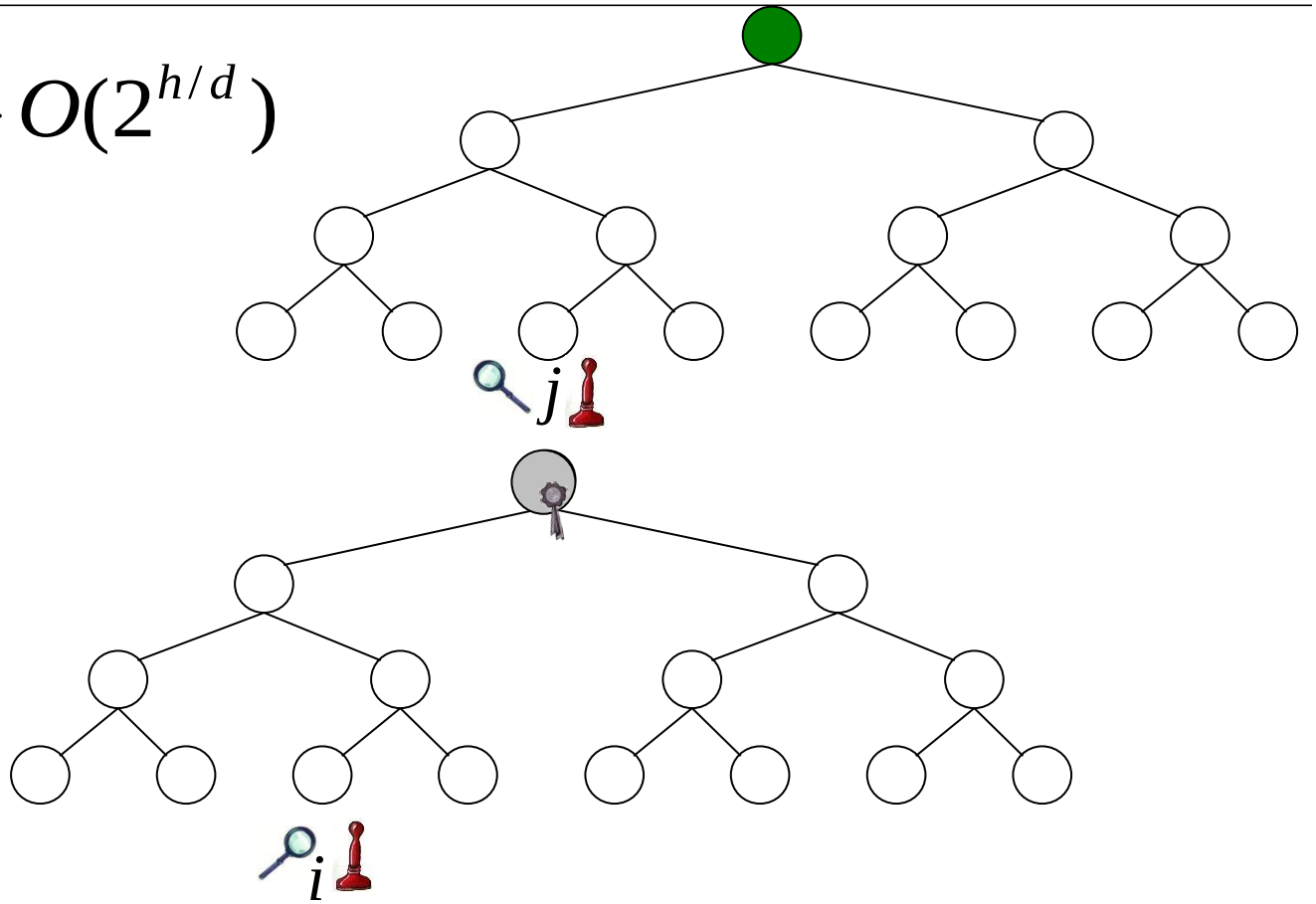
$$t_{KG} : O(2^h) \rightarrow O(2^{h/d})$$



Improved distributed signature generation [HBB12,HRB13]

Result

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GMSS
[BDK+07]

Cryptomania

Not FSS

$t_{SIG} = h/2 = \Sigma\, h_i/2$

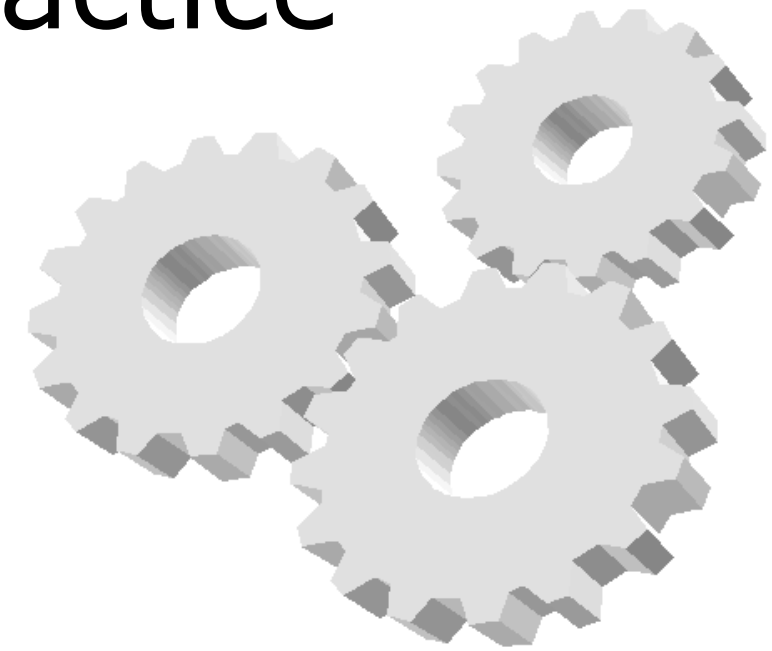
XMSS^{MT}
[HBB12,HRB13]

Minicrypt

FSS

$t_{SIG} = h_0/2$

XMSS* in Practice



XMSS Implementations
C Implementation

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C Implementation, using OpenSSL [BDH2011]

	Sign (ms)	Verify (ms)	Signature (bit)	Public Key (bit)	Secret Key (byte)	Bit Security	Comment
XMSS-SHA-2	35.60	1.98	**16,672**	13,600	3,364	157	h = 20, w = 64,
XMSS-AES-NI	**0.52**	**0.07**	19,616	7,328	1,684	84	h = 20, w = 4
XMSS-AES	1.06	0.11	19,616	7,328	1,684	84	h = 20, w = 4
RSA 2048	**3.08**	**0.09**	≤ 2,048	≤ 4,096	≤ 512	87	

Intel(R) Core(TM) i5-2520M CPU @ 2.50GHz with Intel AES-NI

XMSS Implementations
Smartcard Implementation

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	Sign (ms)	Verify (ms)	Keygen (ms)	Signature (byte)	Public Key (byte)	Secret Key (byte)	Bit Sec.	Comment
XMSS	**134**	23	**925,400**	2,388	800	2,448	92	H = 16, w = 4
XMSS$^+$	**106**	25	**5,600**	3,476	544	3,760	94	H = 16, w = 4
RSA 2048	190	7	11,000	≤ 256	≤ 512	≤ 512	87	

Infineon SLE78 16Bit-CPU@33MHz, 8KB RAM, TRNG, sym. & asym. co-processor

NVM: Card 16.5 million write cycles/ sector,
XMSS$^+$ < 5 million write cycles (h=20)

[HBB12]

Conclusion

Conclusion

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- Efficient
- Minimal security assumptions
- „Small signatures"
- Forward secure
- Full smartcard implementation

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Main Drawback: State

Easy Migration?

- Interfaces
- Key Management

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Thank you!
Questions?