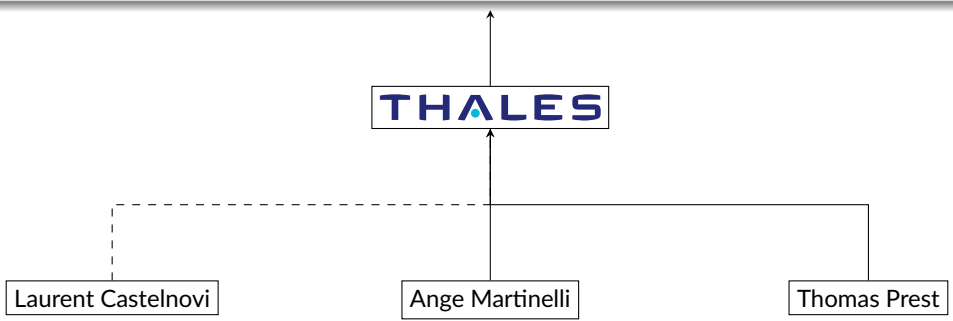
Grafting Trees: a Fault Attack against the SPHINCS framework



Introduction

Hash-based signatures:

- Signatures based on the collision or preimage resistance of hash functions
- Optimal from a security perspective [Rom90]
- Post quantum: two proposals to NIST's CFP [AE17, BDE+17]

Obvious question: do they resist to fault attacks?

- Short answer: No.
- This talk: a fault attack against schemes of the SPHINCS family:
  - The original SPHINCS [BHH+15]
  - Gravity-SPHINCS [AE17]
  - SPHINCS+ [BDE+17]

Let's fault stuff! 

Outline of this talk

One-time signatures (OTS) from hash functions

A toy example:

- $\mathsf{sk} = (s_1, s_2) \in \{0,1\}^{256\times 2}$
- $\mathsf{pk} = (p_1, p_2) = (\mathsf{H}^N(s_1), \mathsf{H}^N(s_2))$
- $\mathsf{Sign}(\mathsf{m} \in \{0, \dots, N\})$:

$$\mathsf{sig}(\mathsf{m}) = (\sigma_1, \sigma_2) = (\mathsf{H}^{\mathsf{m}}(s_1), \mathsf{H}^{N-\mathsf{m}}(s_2)) \tag{1}$$

- $\mathsf{Verify}(\mathsf{m}, \mathsf{sig})$: accept if and only if $\left(\mathsf{H}^{N-\mathsf{m}}(\sigma_1), \mathsf{H}^{\mathsf{m}}(\sigma_2)\right) = \mathsf{pk}$
- one signature $\Rightarrow$ existentially unforgeable
- two signatures $\Rightarrow$ existential forgery for a proportion $\approx \frac{|\mathsf{m}_1 - \mathsf{m}_2|}{N}$ of the messages

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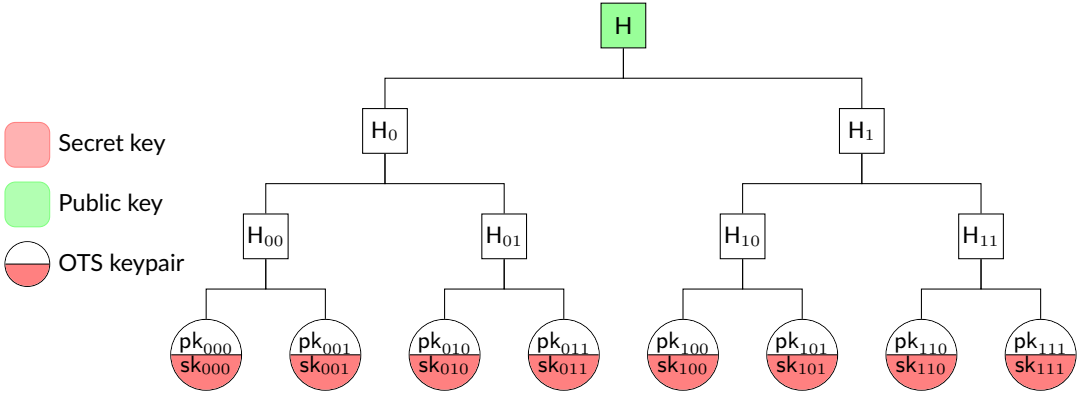
For WOTS(+), the OTS used in schemes of the SPHINCS family:

- one signature $\Rightarrow$ existentially unforgeable
- two signatures $\Rightarrow$ existential forgery for a proportion 2^{-34} of the messages

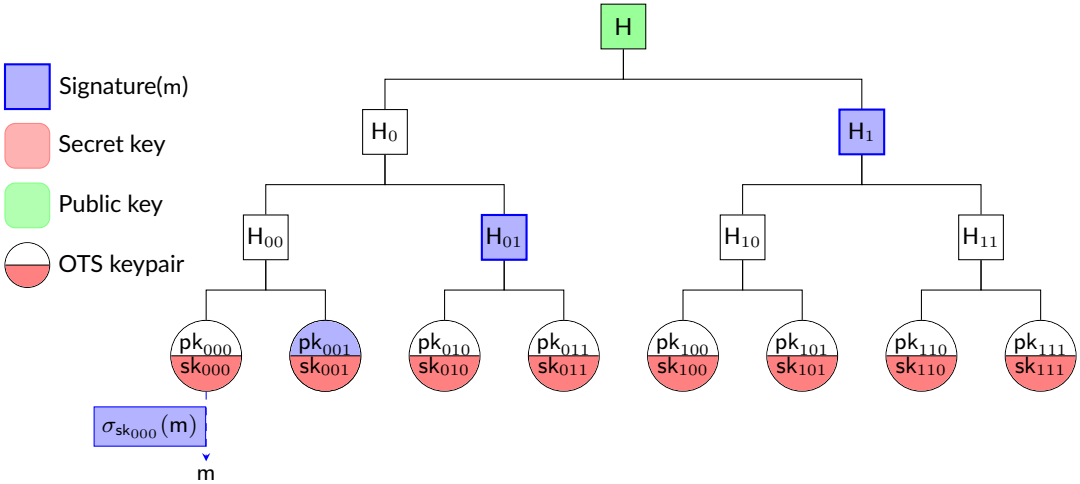
Feature common to all hash-based signatures:

From a valid signature, one can recover the public key.

Merkle's construction [Mer90]



Merkle's construction [Mer90]



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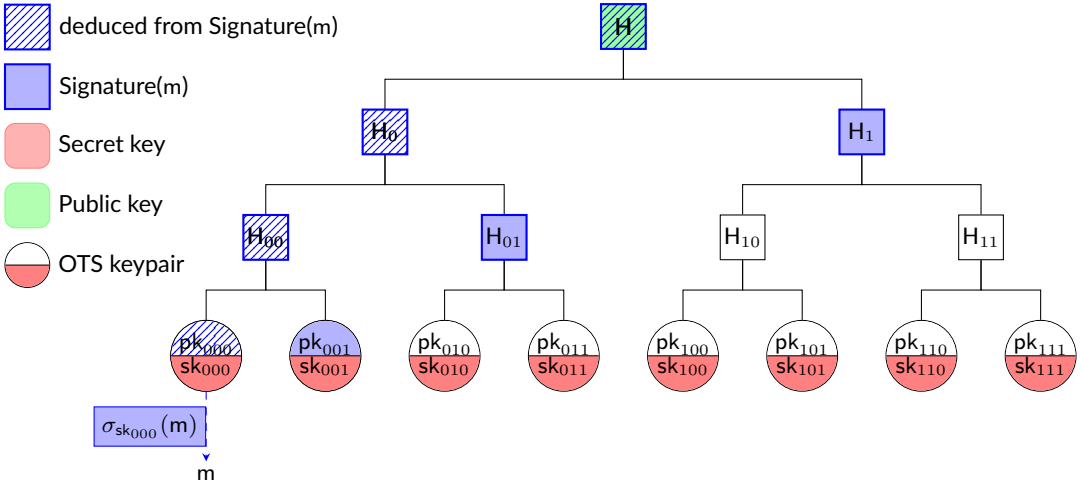
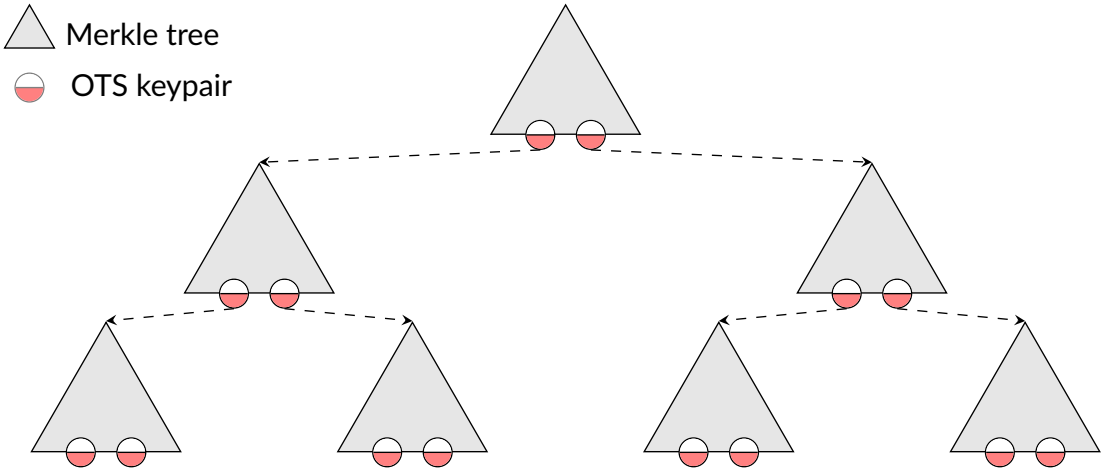
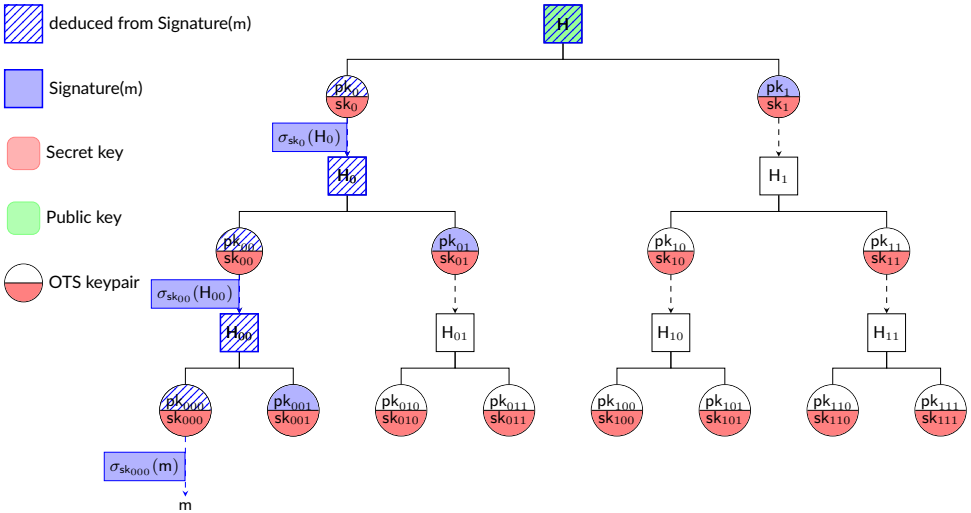


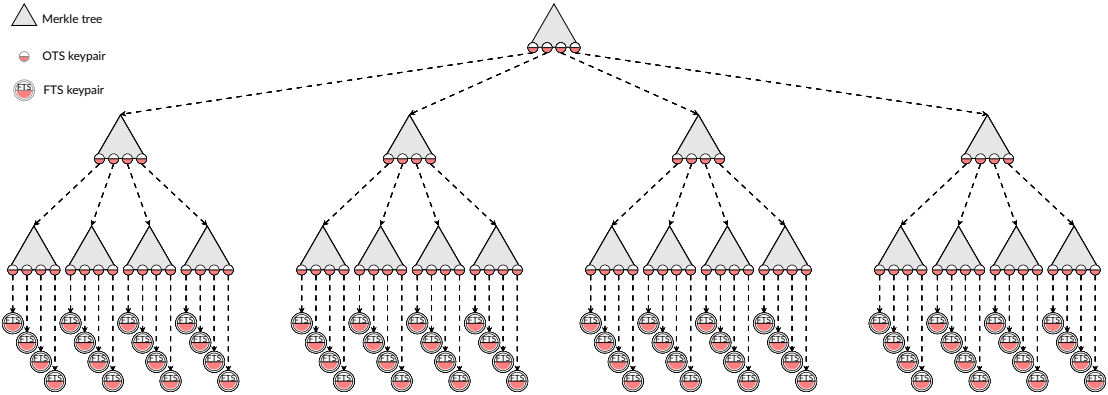
Goldreich's construction (abstract) [Gol86]



Goldreich's construction (detailed)



The SPHINCS framework



- Common to SPHINCS [BHH+15], Gravity-SPHINCS [AE17] and SPHINCS+ [BDE+17]
- Typical parameters: layers = 8, height of each Merkle tree = 8, total height = 64

Outline of the attack

Observations useful for our attack:

- In all hash-based signatures:

$$[\text{a valid signature } \sigma_{\mathsf{sk}}(\mathsf{m})] \Rightarrow [\text{one can recover } \mathsf{pk}]$$

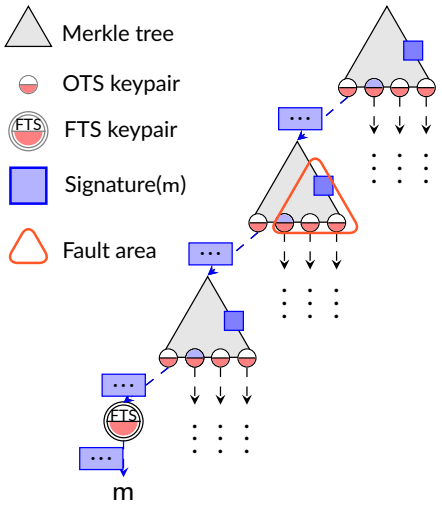
- For the OTS used in SPHINCS:

$$[2 \text{ signatures}] \Rightarrow [\text{one can forge for 1 message over } 2^{34}]$$

Outline of our attack:

1. *Faulting step.* We provoke a fault to make an OTS sign two different values
2. *Grafting step.* We use the compromised OTS to obtain an universal forgery

The faulting step



The faulting step:

- One normal sig(m), one faulted sig(m)
- Target the Merkle tree just below the top
- We may fault any computation ”below” the authentication path

Regular vs faulted signature:

- Two $\neq$ values are computed for the root of the faulted Merkle tree
- The top OTS signs two $\neq$ values

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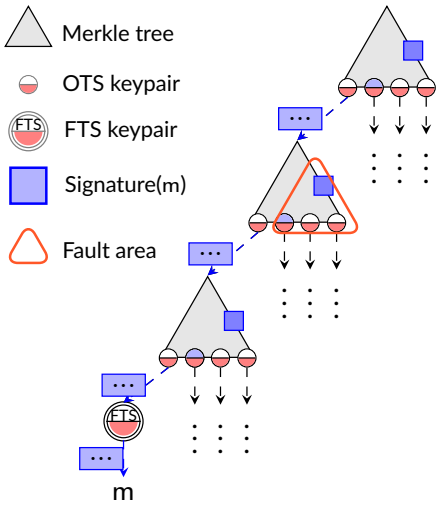

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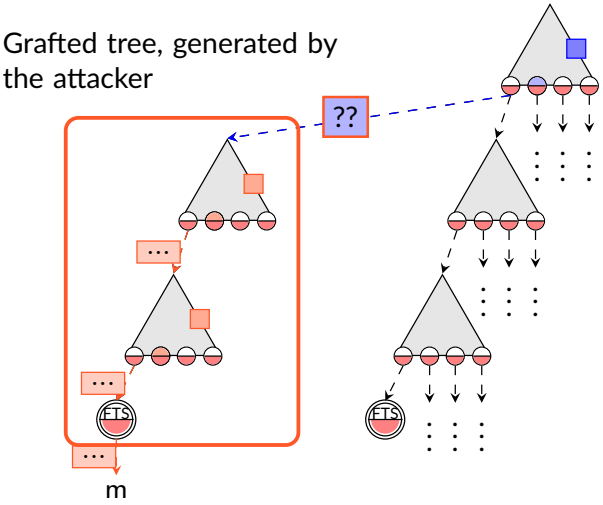
Features of this fault:

- One fault
- Little precision required
- Stealthy

The grafting step



Goal of the attacker:

- Sign his own tree with the compromised OTS

Naïve approach:

- Generate trees until a suitable one is found
- Time: $2^{34}\times$ (generate a tree)

Adaptive approach:

- Only modify the top of the grafted tree
- Time: $2^{34}+$ (generate a tree)

Specifics of each scheme and countermeasures

Selection of the FTS index:

1. SPHINCS: $\mathsf{idx} \leftarrow \mathsf{H}(r, \mathsf{m})$, where r is private
   $\Rightarrow$ very easy
2. Gravity-SPHINCS: $\mathsf{idx} \leftarrow \mathsf{H}(r, \mathsf{m})$, where $r \leftarrow \mathsf{H}(\mathsf{sk}, \mathsf{m})$
   $\Rightarrow$ easy
3. SPHINCS$^+$: $\mathsf{idx} \leftarrow \mathsf{H}(r, \mathsf{pk}, \mathsf{m})$, where $r \leftarrow \mathsf{H}(\mathsf{sk}, \$, \mathsf{m})$
   $\Rightarrow$ no control on the FTS index anymore, but still easy

Height of the top Merkle tree:

1. SPHINCS and SPHINCS$^+$: no more than 8
2. Gravity-SPHINCS: 20

Countermeasures:

1. Generic: redundancy
2. Specific: ?

Conclusion

Key takeaways:

1. A fault attack on schemes of the SPHINCS family
2. Universal forgery with one fault
3. Fault model is very weak:
   1. little to no control on the time of the fault
   2. little to no control on the precision of the fault
   3. independent of underlying hash function(s)
4. Stealthy
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Related works:

- This work was based on Laurent Castelnovi's Master thesis [Cas17]
- Independently studied by Genêt [Gen17] and Kannwischer [Kan17]

https://eprint.iacr.org/2018/102

Thanks!


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