Attaques par fautes sur SLH-DSA

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JAIF 2024

Post Quantum Cryptography

Quantum computers vs cryptography

	Primitive	Vs classical computers	Vs quantum computers
Symmetric crypto	AES	Very hard	Hard
	SHA	Very hard	Hard
Asymmetric crypto	RSA	Very hard	Easy
	ECC	Very hard	Easy

Post-quantum cryptography aims to replace RSA/ECC:

- Lattices
- Codes
- Isogenies
- Hash-based
- Multivariate
- …

NIST standardisation

Dec. 2016

NIST Call for proposals

Dec. 2017

Round 1
69 candidates

Jan. 2019

Round 2
26 candidates

July 2020

Round 3
15 candidates

July 2022

Standards announced
- ML-KEM
- ML-DSA
- SLH-DSA
- FN-DSA

Aug. 2024

Standards published
- FIPS 203
- FIPS 204
- FIPS 205

The simplest hash-based signature

Main idea is to use *hash chains*

sk						**pk**

$$s1 \rightarrow H(s1) \rightarrow H^2(s1) \rightarrow \dots \rightarrow H^{N-1}(s1) \rightarrow H^N(s1) = p1$$

$$s2 \rightarrow H(s2) \rightarrow H^2(s2) \rightarrow \dots \rightarrow H^{N-1}(s2) \rightarrow H^N(s2) = p2$$

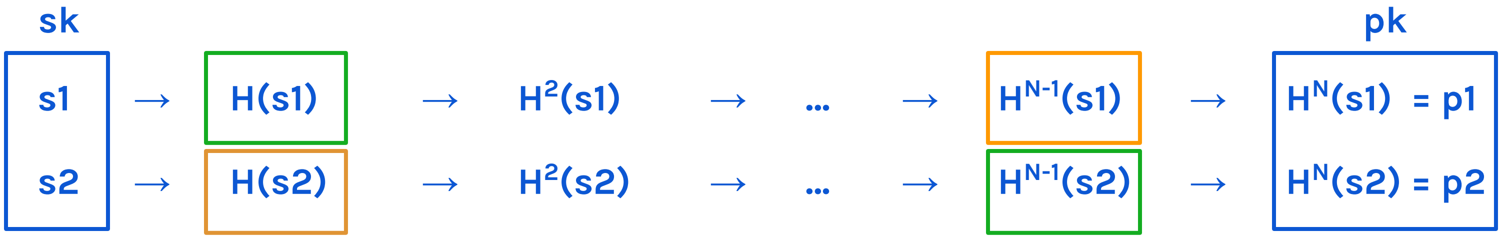
Signing key: sk = (s1, s2) two 256-bit values
Verification key: pk = (p1, p2)
Signature of m: sig = (sig1, sig2) = (H^m(s1), H^{N-m}(s2))
Verification: Check that (H^{N-m}(sig1), H^m(sig2)) = (p1, p2)

Observation 1: pk is a convoluted hash commitment of sk, sig partially opens this commitment

Observation 2: From any valid signature, we can recover the public key

Observation 3: This is a *one-time* signature (OTS). Asking two or more signatures breaks the scheme

Attacks on the simplest hash-based signature



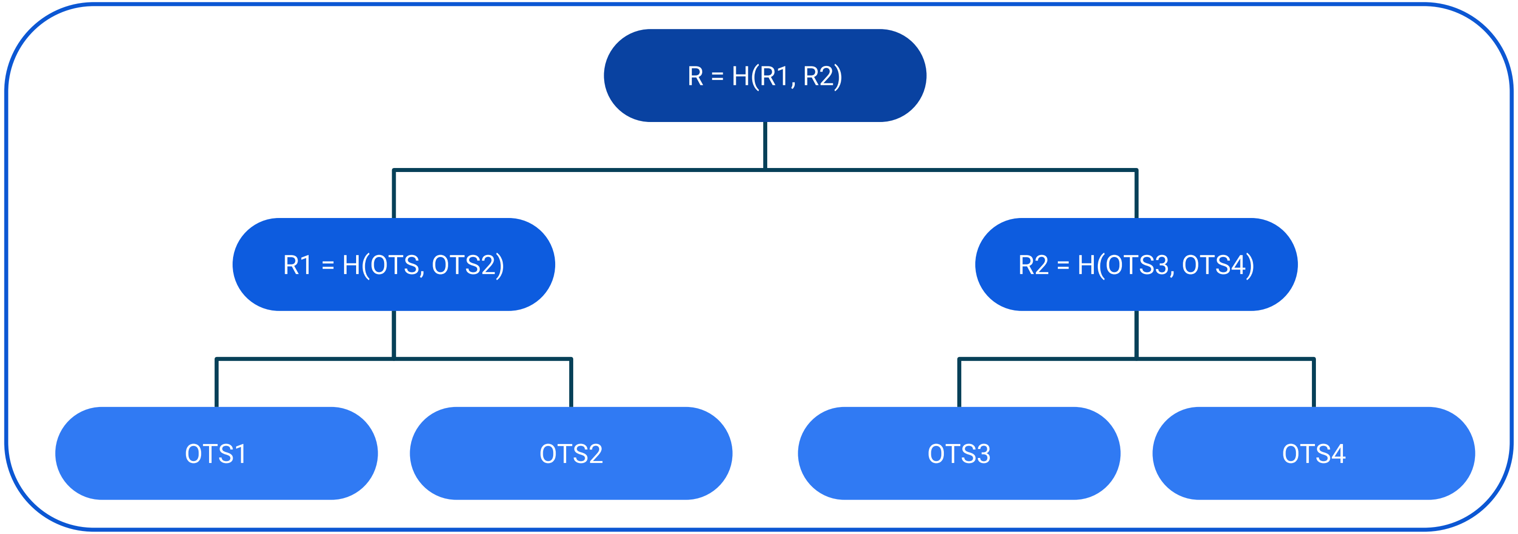
Black box attack (two signatures):

1. Ask two signatures (for **msg2** < **msg1**)
2. We can forge a signature for *any* **msg2** < **msg** < **msg1**

Fault injection attack (random fault):

1. Ask for a signature of **msg1 = N** and fault the counter **msg1 (→ msg2)** when computing $H^{msg1}(s2)$
2. We can forge a signature for any message **msg2** < **msg** < **msg1 = N**

Merkle trees: from one-time to few-time



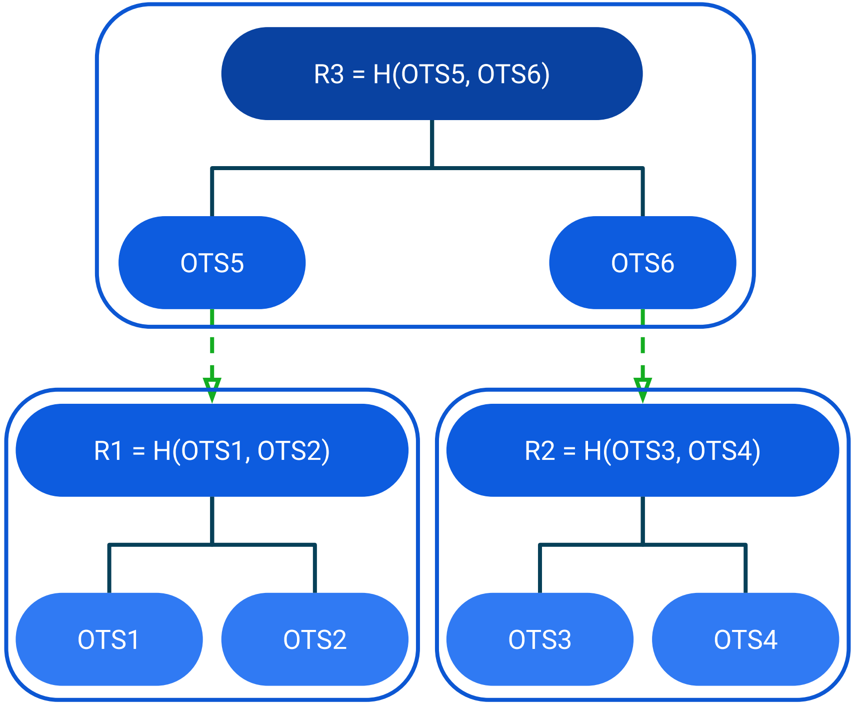
Merkle trees: allows to sign N times using N OTS

- **Signature:** 1 signature = { 1 OTS signature } + { log N hashes (= the co-path of the OTS used) }
- **Limitation:**
  - Generating pk = R costs O(N) hashes, so N cannot be too large
  - Requires a stateful counter ⟶ bad for deployment, bad against FIA!

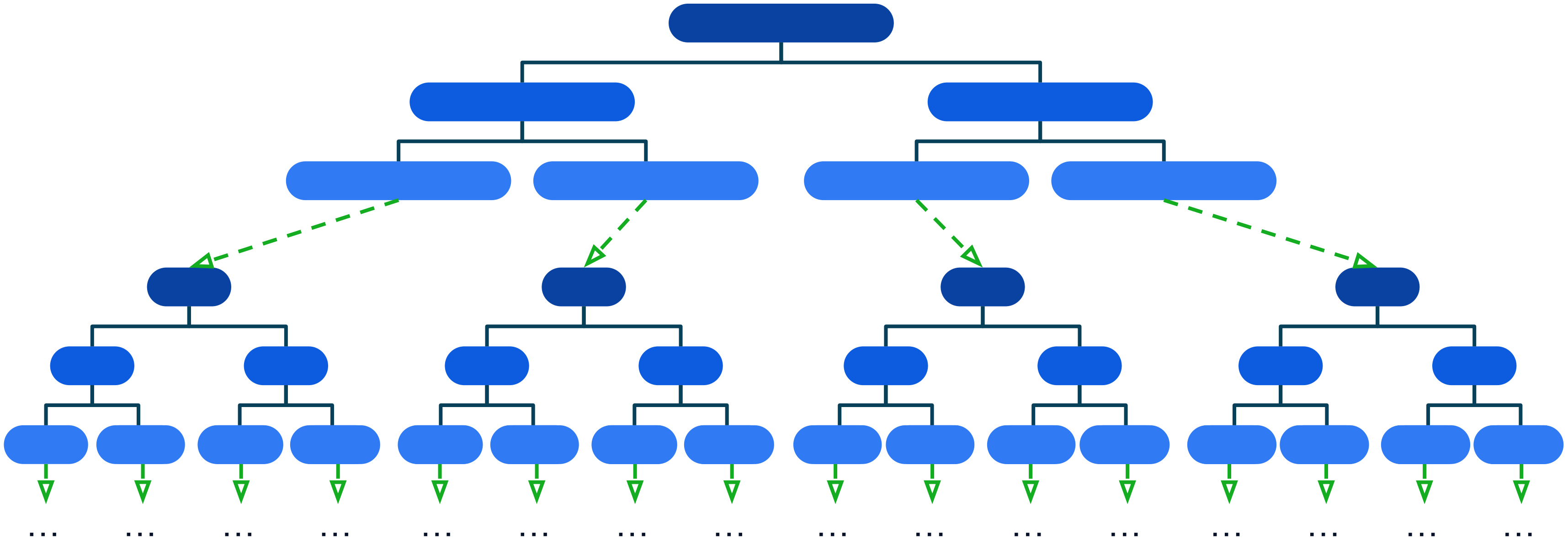
Goldreich trees: *stateless* few-time signatures

Goldreich trees:

- **Principle:**
  - N Merkle trees, each of depth 1
  - Each OTS signs the root of the Merkle tree below it
- **Signature:** 1 signature = { log N hashes } + { log N OTS signatures }
- **Advantages:**
  - Generating pk = R2 takes time O(1), so scales for arbitrarily large N
  - Can be made *stateless* when n → ∞
- **Fault attacks?**
  - Fault the OTS
  - Fault the Merkle tree recomputation



SPHINCS+: Merkle + Goldreich + optimizations



SPHINCS+: a huge Goldreich “hyper-tree”, with each Merkle tree having many levels

1. The specific OTS used in SPHINCS+ is **WOTS+**
2. The bottom-most OTS are actually few-time signatures (specifically **FORS**)
3. 3 security levels (128/192/256), 2 variants (short/fast). *Stateless.*

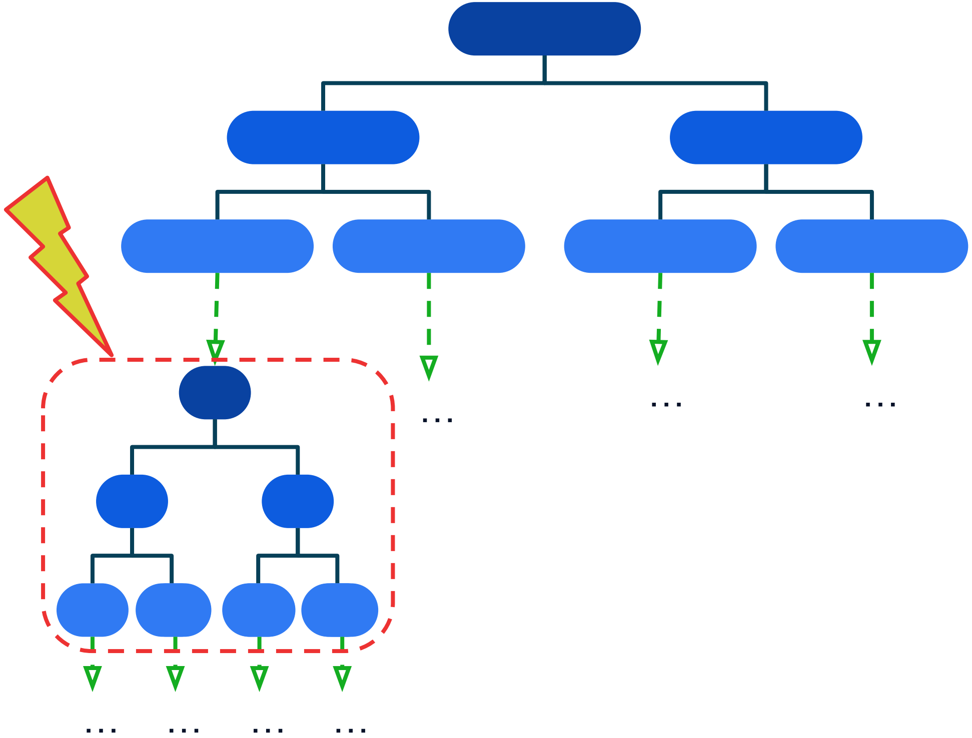
Fault injection on SPHINCS+ (Castelnovi et al, 2018)

Main idea: make a top-level OTS sign 2 ≠ values

1. Ask two signatures of msg
    - SPHINCS+ is deterministic → the "signing path" is always the same
2. **First signature:** no fault
3. **Second signature:** fault the computation of the second-level Merkle tree
4. **The same OTS signs two ≠ values → we break the unforgeability of this OTS**

How to exploit this: Tree grafting 🌲

1. Generate a partial signature (up to second-level Merkle tree M) for any msg*
2. Sign M using the faulted OTS
3. We now have a forged signature



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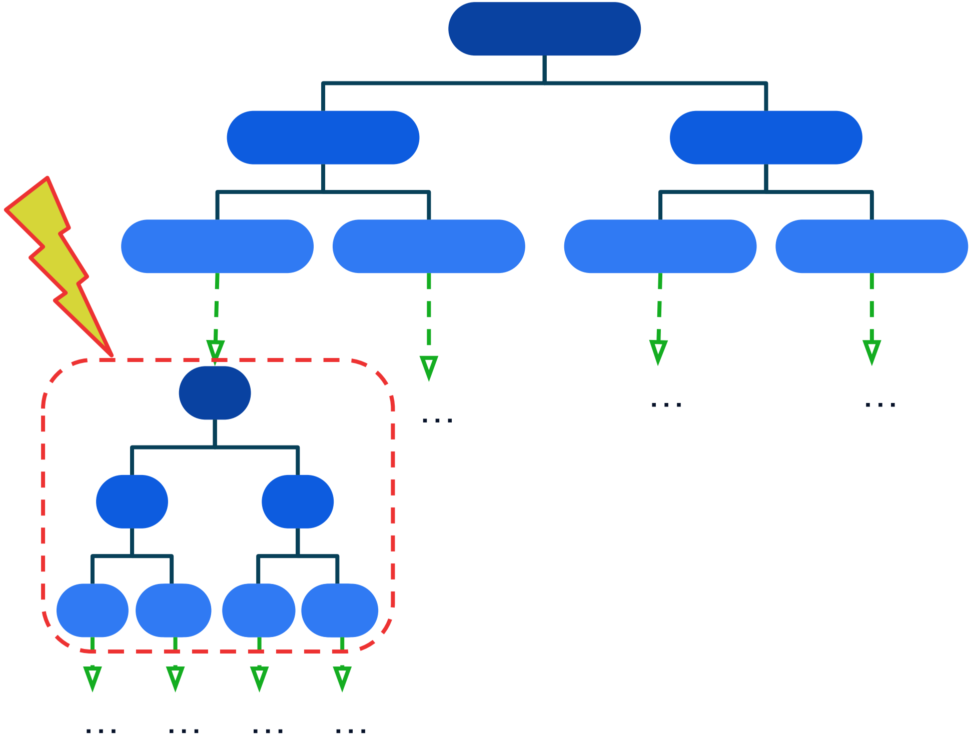
Bonus:

- **One fault**
- **Low required precision**
- **Faulted signatures are valid**



Countermeasures

Aim at preventing triggering twice the same WOTS+ instance on different messages

Pb: SLH-DSA is STATELESS, so we need to add some shenanigans in memory to ensure that

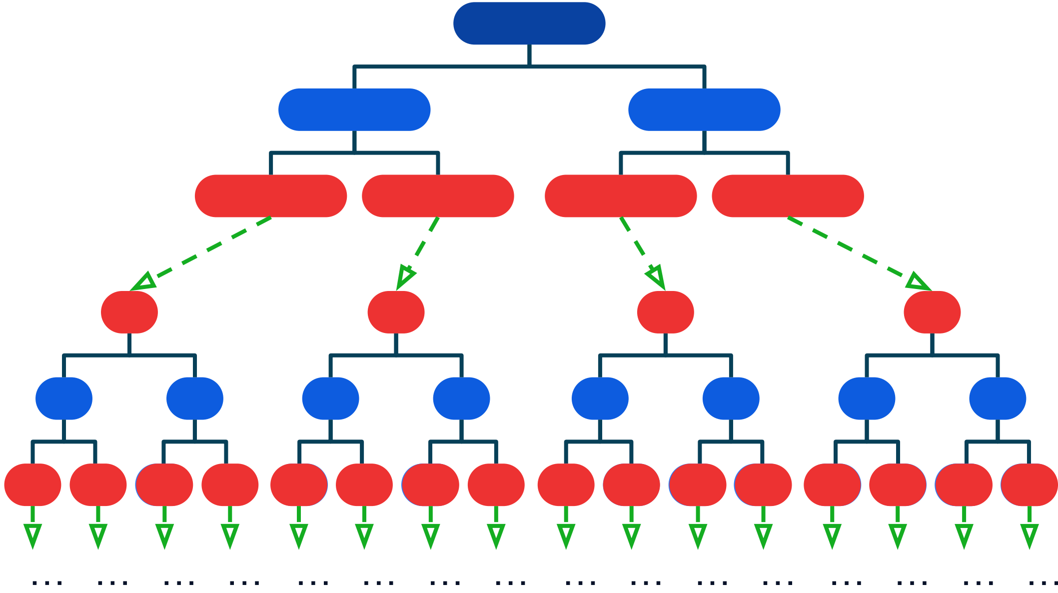
Idea (Genêt 2023): cache the OTS operations

Shortcoming: there are a LOT of them, we need to make some choice

Caching layers (Genêt CHES 2023)

Inspired by Gravity-SPHINCS:
[static] cache all WOTS+ in the top layers

Define the nb c of layers that can be cached depending on available memory



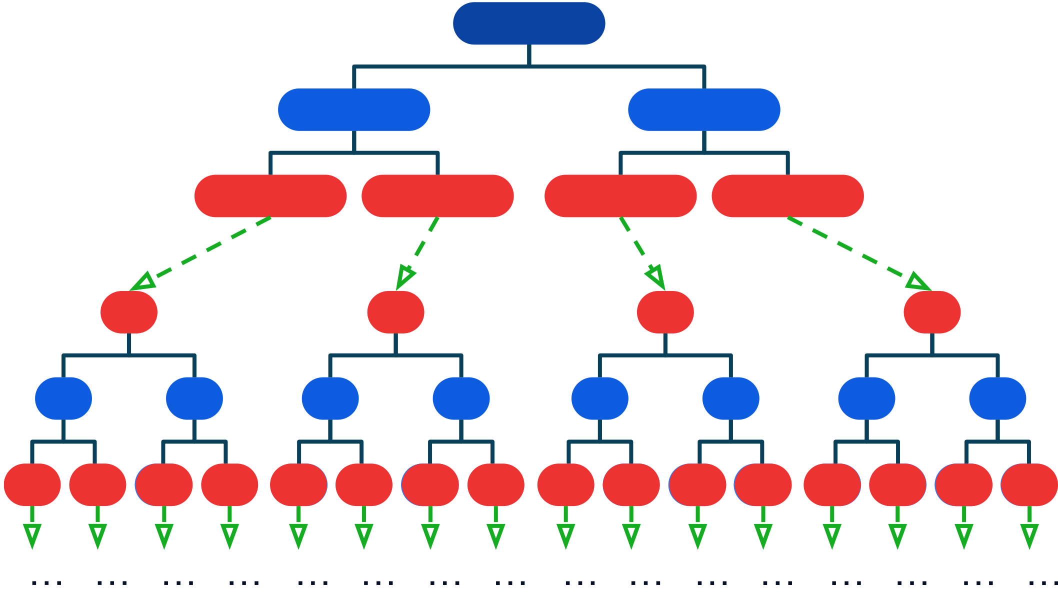
Caching layers (Genêt CHES 2023)

Table 9: Analysis of the layer caching countermeasure for all SPHINCS$^+$ parameter sets.

	$\mathbb{P}$(Expl.)						
$c =$	1	2	3	4	…	$d-1$	d
128s	0.8972	0.8591	0.8179	0.7733	…	0.6141	0.0000
128f	0.9505	0.9335	0.9158	0.8975	…	0.5076	0.0000
192s	0.9287	0.9034	0.8767	0.8486	…	0.7539	0.0000
192f	0.9420	0.9218	0.9007	0.8787	…	0.2625	0.0000
256s	0.8711	0.8216	0.7670	0.7066	…	0.4784	0.0000
256f	0.9327	0.9090	0.8840	0.8578	…	0.3864	0.0000

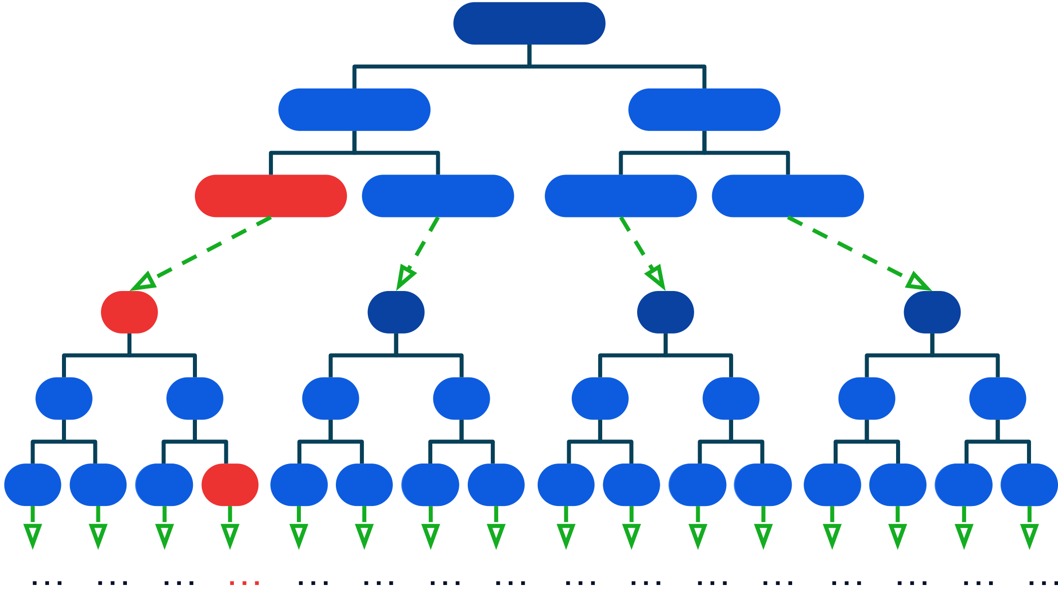
Table 10: Analysis of the layer caching countermeasure for all SPHINCS$^+$ parameter sets.

	Memory (bytes)					
$c =$	1	2	3	4	…	d
128s	1.43×10^5	3.68×10^7	9.43×10^9	2.41×10^{12}	…	1.04×10^{22}
128f	4.48×10^3	4.03×10^4	3.27×10^5	2.62×10^6	…	7.38×10^{20}
192s	3.13×10^5	8.05×10^7	2.06×10^{10}	5.28×10^{12}	…	2.27×10^{22}
192f	9.79×10^3	8.81×10^4	7.15×10^5	5.73×10^6	…	1.03×10^{23}
256s	5.49×10^5	1.41×10^8	3.61×10^{10}	9.24×10^{12}	…	3.97×10^{22}
256f	3.43×10^4	5.83×10^5	9.36×10^6	1.50×10^8	…	6.75×10^{23}



Caching branches (Genêt CHES 2023)

[Dynamic] cache all WOTS+ operations occurring during computation



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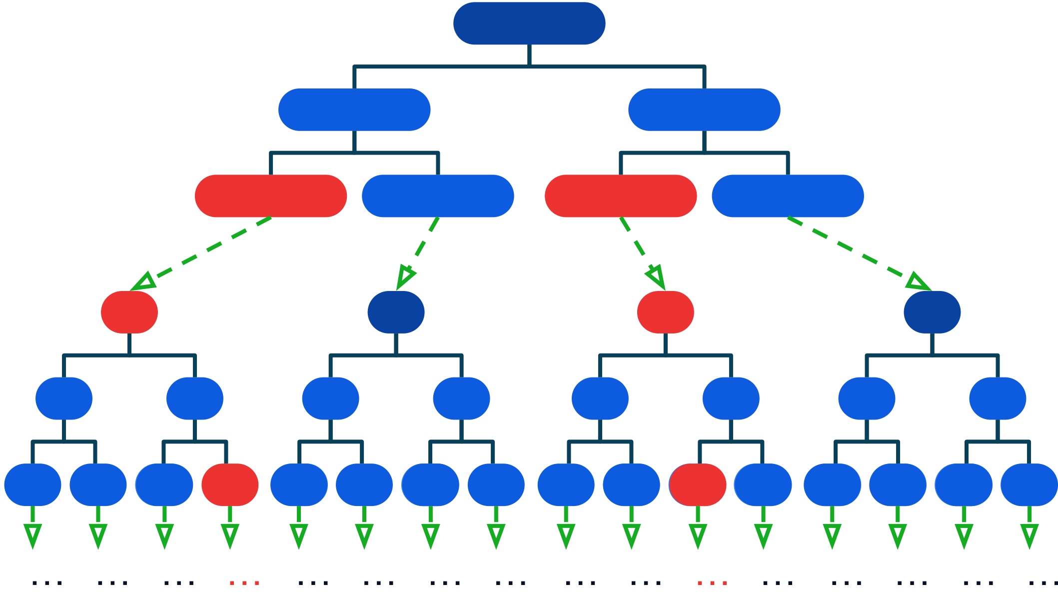


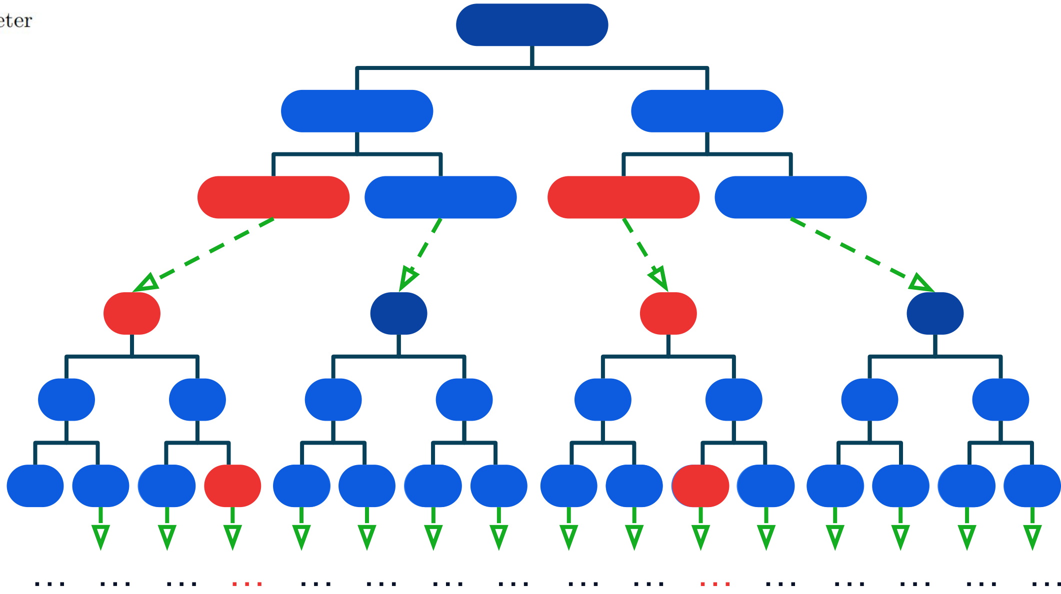
Caching branches (Genêt CHES 2023)

Table 11: Analysis of the branch caching countermeasure for all SPHINCS$^+$ parameter sets. The numbers b are rounded up to the next integer.

	$\mathbb{P}$(Expl.)					
$b =$	$(2/3)2^{h'}$	$(2/3)2^{2h'}$	$(2/3)2^{3h'}$	$(2/3)2^{4h'}$	...	$(2/3)2^{dh'}$
128s	0.9292	0.9238	0.9174	0.9098	...	0.3172
128f	0.9647	0.9634	0.9620	0.9605	...	0.3219
192s	0.9511	0.9485	0.9457	0.9425	...	0.3249
192f	0.9585	0.9568	0.9549	0.9528	...	0.3052
256s	0.9111	0.9023	0.8917	0.8785	...	0.3068
256f	0.9530	0.9507	0.9481	0.9453	...	0.3130

Table 13: Analysis of the branch caching countermeasure for all SPHINCS$^+$ parameter sets. The numbers b are rounded up to the next integer.

	Memory (bytes)					
$b =$	$(2/3)2^{h'}$	$(2/3)2^{2h'}$	$(2/3)2^{3h'}$	$(2/3)2^{4h'}$	...	$(2/3)2^{dh'}$
128s	8.14×10^5	1.82×10^8	4.00×10^{10}	8.53×10^{12}	...	7.36×10^{21}
128f	7.14×10^4	4.91×10^5	3.71×10^6	2.80×10^7	...	5.55×10^{20}
192s	1.74×10^6	3.90×10^8	8.56×10^{10}	1.83×10^{13}	...	1.58×10^{22}
192f	1.68×10^5	1.16×10^6	8.81×10^6	6.69×10^7	...	7.62×10^{22}
256s	3.02×10^6	6.77×10^8	1.49×10^{11}	3.17×10^{13}	...	2.74×10^{22}
256f	4.13×10^5	6.08×10^6	9.12×10^7	1.36×10^9	...	4.79×10^{23}

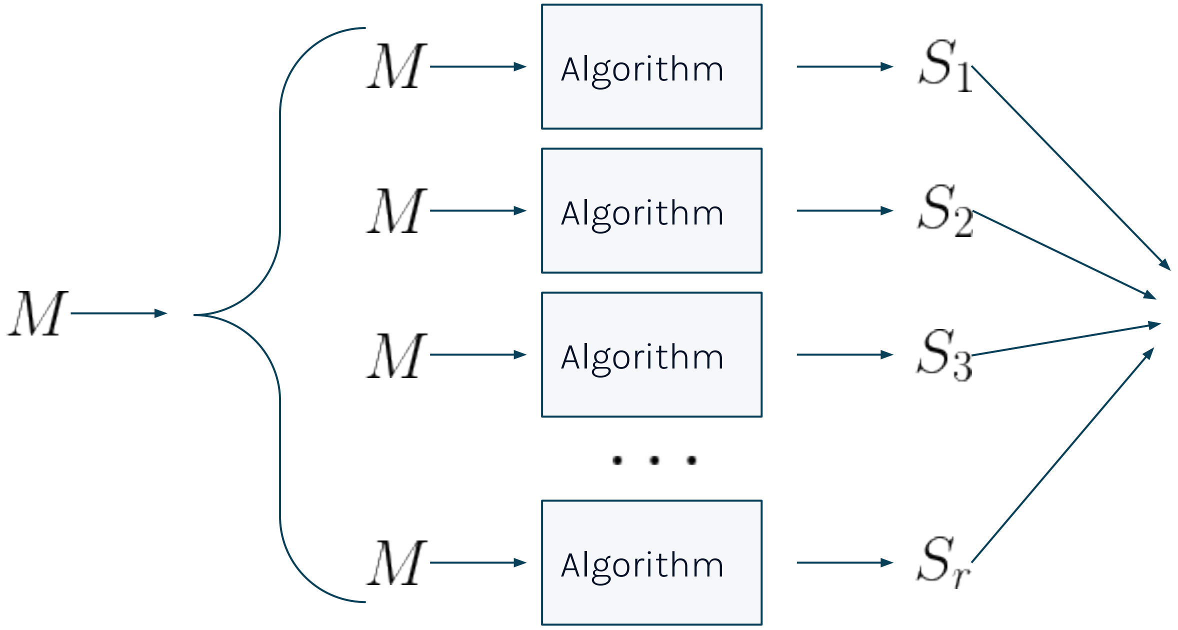


Caching strategies are too costly

“Since the threat of a fault can never be completely eliminated, the current best solution to protect the signature scheme against accidental and intentional faults is through redundancy; an observation that is shared by others”

“In conclusion, the results of this paper urge all real-world deployments of SPHINCS+ to come with redundancy checks, even if the use case is not prone to faults”

Best countermeasure yet: redundancy



$$(S_1 = S_2 = S_3 = \cdots = S_r)?$$

(provided secure checks, sanitized inputs, constants…)

Secure up to r-1 faults.

Attacker model

Attacker has a scope: they can recognize patterns on operations, but not their operands
=> can distinguish the operations based on the nb of input words

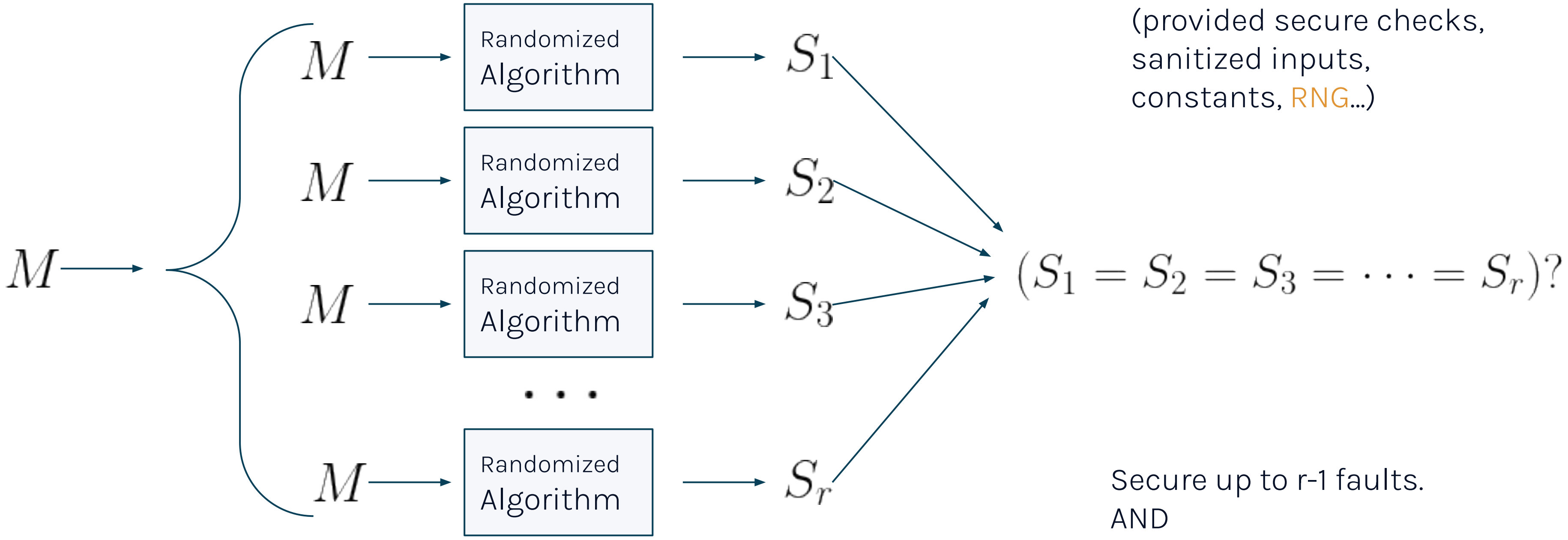
	F	**H**	**PRF**	$T_{\texttt{len}}$
Key Generation	$2^{h/d}w\texttt{len}$	$2^{h/d}-1$	$2^{h/d}\texttt{len}$	$2^{h/d}$
Signing	$kt+d(2^{h/d})w\texttt{len}$	$k(t-1)+d(2^{h/d}-1)$	$kt+d(2^{h/d})\texttt{len}$	$d2^{h/d}$
Verification	$k+dw\texttt{len}$	$k\log t+h$	–	d

Attacker model

Attacker has a scope: they can recognize patterns on operations, but not their operands
=> can distinguish the operations based on the nb of input words

Comparisons are protected: the attacker needs to perturbate the SLH-DSA execution
=> must inject twice the same fault (consider no collision)

Redundancy + randomization



(provided secure checks, sanitized inputs, constants, RNG…)

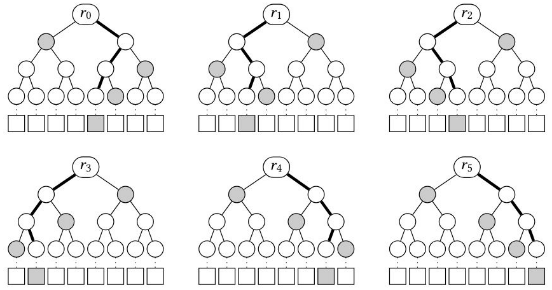
Secure up to r-1 faults.
AND
Probably secure to > r-1 faults.

Randomization

Execute operations in a random order (eg., 16 sboxes in AES => 16! possible orders).

In SLH-DSA, many operations can be performed in parallel:

- at every level of the FORS (leaves)



Randomization

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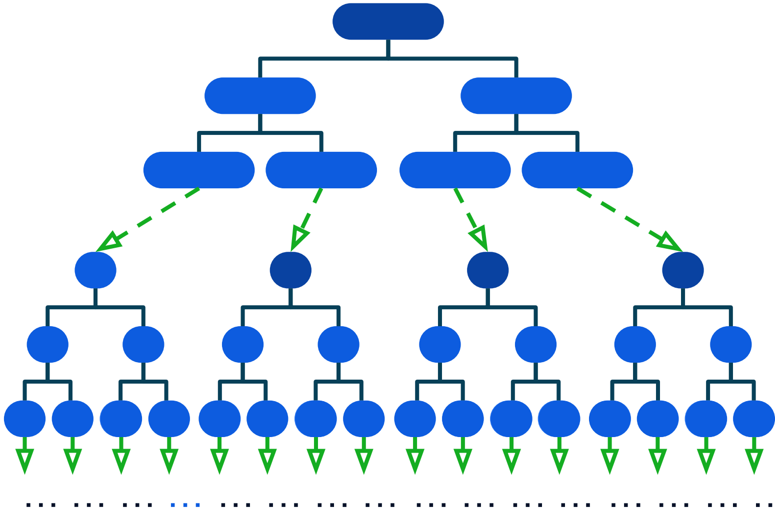
- at every level of the hypertree



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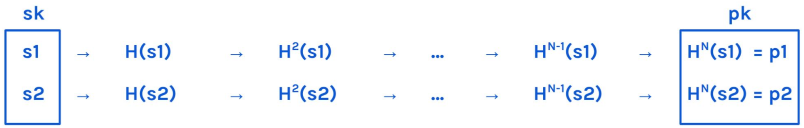
- at every step of a WOTS chain



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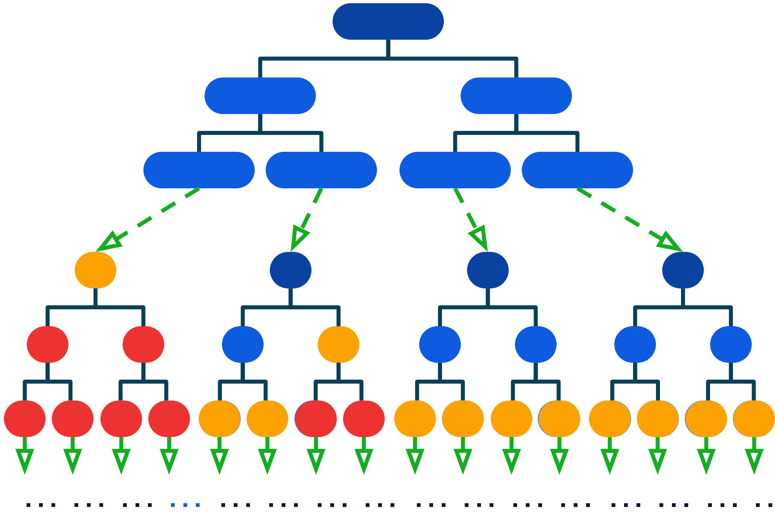
- (possible optimizations)



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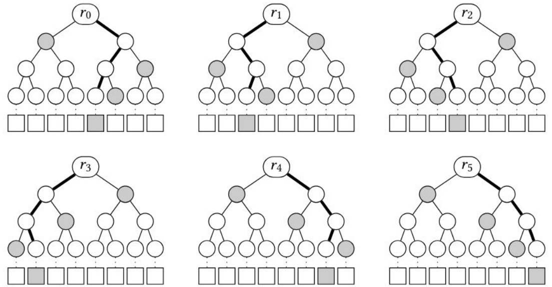


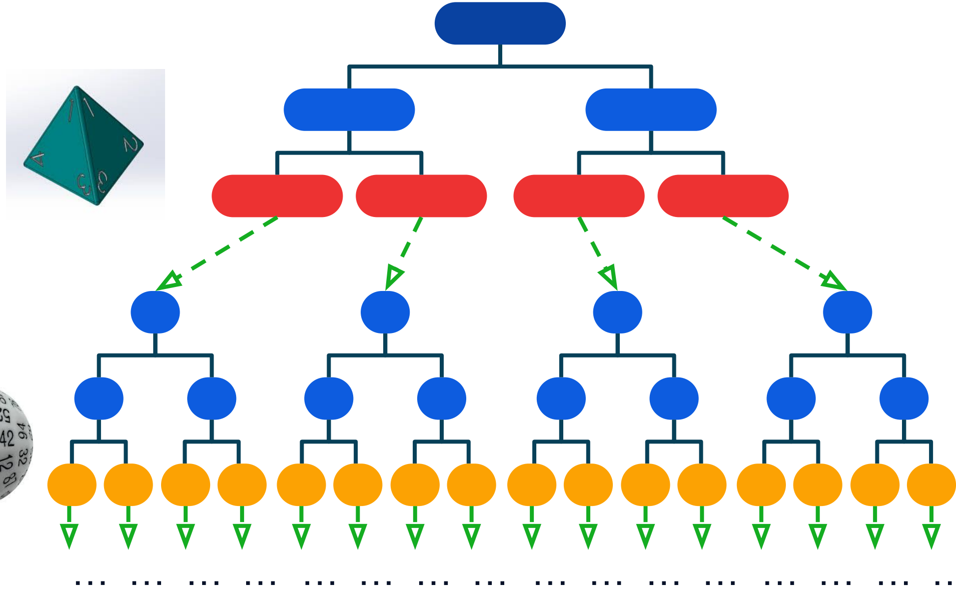
(k*t)! possible orders (eg 14*2^12)! for SLH-DSA-128s.

Decaying entropy

Climbing in each subtree lowers the number of possible orders, up to the root, where no randomness can occur.

Depending on the constraints:

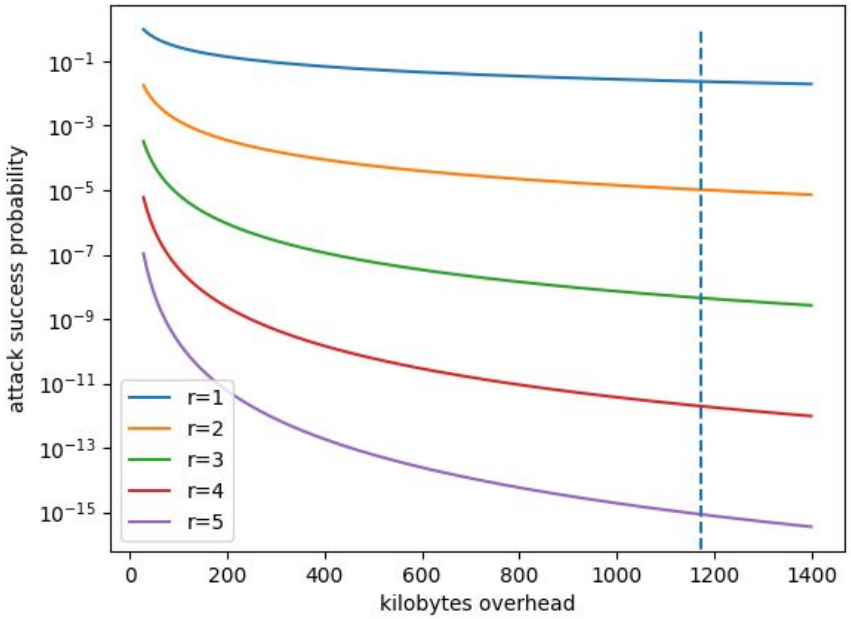
- add dummy operations
  artificially raise entropy and decreases success probability
- locally duplicate the operation
  perfect security but need to be carefully made (eg duplicate inputs)



Security (no dummies): proba of success

128s	r=1	r=2	r=3	r=4	r=5
PRF	1.00e+00	5.47e-06	2.99e-11	1.64e-16	8.96e-22
F-FORS	1.00e+00	1.74e-05	3.04e-10	5.30e-15	9.25e-20
F-i	1.00e+00	7.97e-06	6.36e-11	5.07e-16	4.04e-21
Tlen	8.57e-01	2.39e-04	6.67e-08	1.86e-11	5.19e-15
H0	9.52e-01	4.54e-02	2.16e-03	1.03e-04	4.90e-06
Hmax	1.00e+00	6.98e-05	4.87e-09	3.39e-13	2.37e-17

Asymptotic security (dummies on most sensitive pool)



Quick PoC

Ran simulations on open source “sloth” implementation (https://github.com/slh-dsa/sloth), slightly modified to get:

- compiled in -O0, r executions and final comparison
- compiled in -O0, r executions and final comparison w randomization of F leaves

Implementation allows for easy and immediate randomization of 14*12 operations (modifying a bit more would allow for much better, but time constraints…)

gdb scripting to stuck at 0 the same register at the exact same time:

- redundancy => 100% success rate
- redundancy + randomization:
    - r=2 => 55 successes on 10k (p=0.0055, expected 0.0059)
    - r=3 => 2 successes on 200k (p=0.00001, expected 0.0000354)

Conclusion

PQ algorithms are coming into embedded devices and they need fault countermeasures.

SLH-DSA is particularly vulnerable and it is not easy to protect.

For multiple faults, we may leverage SLH-DSA structure to gain entropy to get “probable” security.