# Differential Fault Attacks on Deterministic Lattice Signatures

**Leon Groot Bruinderink[1], Peter Pessl[2]**
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- Signatures and nonce reuse...
  - solution: determinism, $n = \text{Hash}(M, K)$
  - EdDSA, Deterministic ECDSA

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  - nonce-reuse for “different” messages [PSS$^+$17, ABF$^+$18]
- ...but what about lattices?

# Our Contribution

- Extend DFA to deterministic lattice signatures
  - Dilithium, qTESLA$^{(*)}$

- Closer look at peculiarities of lattices
  - rejection-sampling technique
  - key compression
  - efficient exploitation of partial nonce reuse

# Dilithium Lattice Signatures

- Module-LWE assumption with base ring $\mathcal{R}_q = \mathbb{Z}_q[x]/(x^{256} + 1)$
- Key generation
  - "small" keys $(\mathbf{s}_1, \mathbf{s}_2) \in \mathcal{R}_q^l \times \mathcal{R}_q^k$
  - random public $\mathbf{A} \in \mathcal{R}_q^{k \times \ell}$
  - public key $\mathbf{t} = \mathbf{A}\mathbf{s}_1 + \mathbf{s}_2$
- Determinism to protect against bad randomness

# Dilithium - Framework

**Input:** Message $M$, private key $sk = (\mathbf{A}, K, \mathbf{s}_1, \mathbf{s}_2)$

**while** $\mathbf{z} = \perp$ **do**

  $\mathbf{y} := \text{DeterministicSample}(K || M || \kappa{+}{+})$

  $\mathbf{w} := \mathbf{Ay}$; $\mathbf{w}_1 := \text{HighBits}(\mathbf{w})$

  $c := \text{H}(M || \mathbf{w}_1)$

  $\mathbf{z} := \mathbf{y} + c\mathbf{s}_1$

  **if** $\|\mathbf{z}\|_\infty \geq \gamma_1 - \beta$ or $\text{Reject}(\mathbf{w}, c\mathbf{s}_2)$ or … **then** $\mathbf{z} := \perp$

**return** $(\mathbf{z}, c)$

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5: $\quad \mathbf{z} := \mathbf{y} + c\mathbf{s}_1$ ▷ only if we can change something else!
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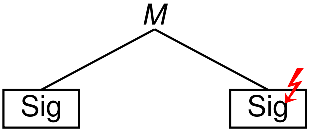
# Attack Intuition

- Sign same $M$ twice
  1. no fault: $(\mathbf{z}, c)$
  2. fault s.t. same $\mathbf{y}$ but different $c$: $(\mathbf{z}', c')$



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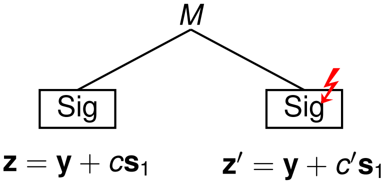

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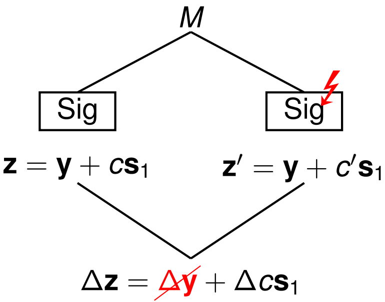

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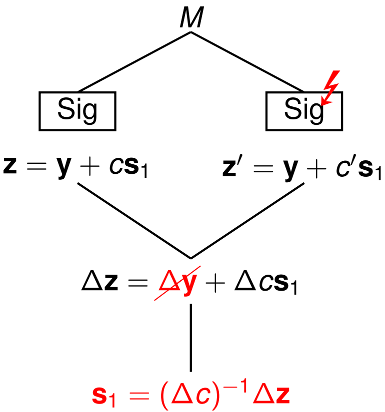

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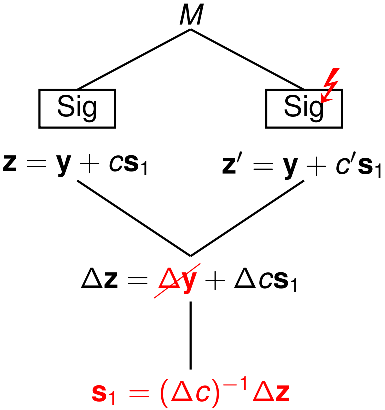

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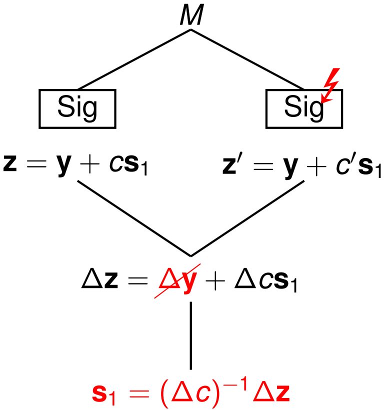
- . . . wasn't there something else?



# Rejection hurts...

- $\mathbf{y} := \text{DeterministicSample}(K||M||\kappa{+}{+})$
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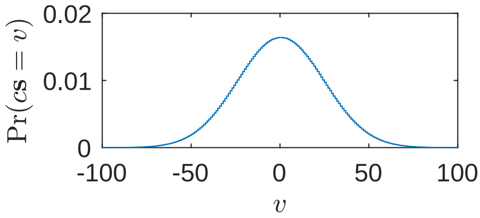
- Faults influence intermediates used in rejection conditions
  - fault position determines success probability
- 5 fault scenarios (concrete positions)

# Faulting the Hash: fH

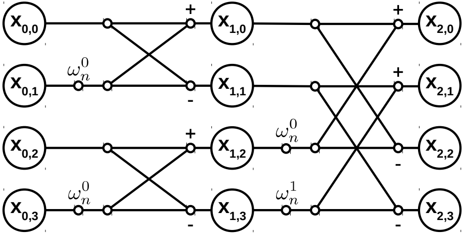
- Target: $c := \mathrm{H}(M||\mathbf{w}_1)$
- Observation: $\|\mathbf{y}\| \gg \|c\mathbf{s}_1\|$
  - $\mathbf{z} = \mathbf{y} + c\mathbf{s}_1 \approx \mathbf{y}$
  - in other words $\mathbf{z} \approx \mathbf{z}'$
- Success probability: 91%

$y \in [\pm 523\,776]$



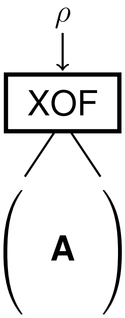
# Faulting Polynomial Multiplication: fW

- Target: $\mathbf{w} := \mathbf{Ay}$
  - $c := \mathrm{H}(M \| \mathrm{HighBits}(\mathbf{w}))$
- Multiplication using NTT
  - fault early $\rightarrow$ many output coefficients affected
- Success probability: $25 - 90\%$
  - but a “larger” target



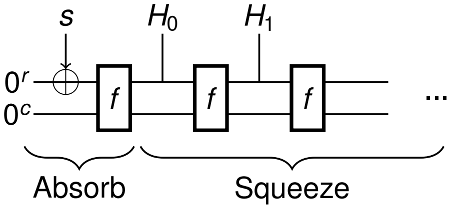
# Faulting the Public Key: $fA_E$, $fA_\rho$

- Target: loading of **A**
  - $c := H(M \| \text{HighBits}(\mathbf{Ay}))$
- **A** generated from seed $\rho$
  - attack $\rho$ or expansion
- Success probability: $25 - 54\%$
  - but potentially permanent



# Faulting the Nonce: fY

- Target: $\mathbf{y} := \text{DeterministicSample}(K||M||\kappa{+}{+})$
  - $c := \text{H}(M||\text{HighBits}(\mathbf{Ay}))$
- but then no nonce-reuse anymore...
  - target partial reuse: $\mathbf{y} \approx \mathbf{y}'$
- Sampling uses SHAKE XOF
  - fault Keccak-$f$ application in squeeze
  - previous XOF output unchanged



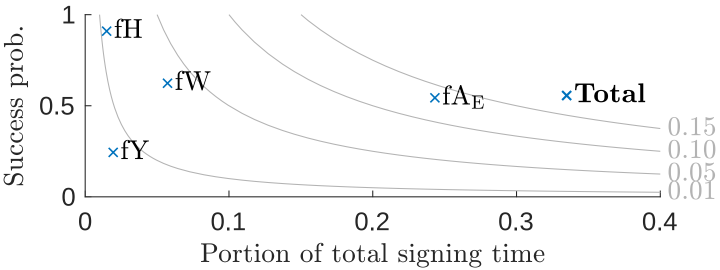
# Efficient Exploitation of Partial Reuse

- First $n - v$ coefficients are 0
  - brute-force still infeasible
- Key recovery as a lattice problem
  - $\mathbf{t} = (\Delta c)^{-1}\Delta\mathbf{z} = (\Delta c)^{-1}\Delta\mathbf{y} + \mathbf{s}_1$
  - vector close to $\mathbf{t}$ in the lattice generated by $(\Delta c)^{-1}$
- Can fault last 2 (from 5) Keccak-*f* permutations
  - recovery runtime: $< 1$ minute
  - success probability: 24%

$$\Delta\mathbf{y} = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ \Delta y_v \\ \Delta y_{v+1} \\ \vdots \\ \Delta y_{n-1} \end{pmatrix}$$

# Experimental Verification

- Clock glitches @ ARM Cortex M4
  - single random fault



# Countermeasures

| | $fA_\rho$ | $fA_E$ | fY | fW | fH | Runtime |
|---|---|---|---|---|---|---|
| Double computation | ✗ | ✓ | ✓ | ✓ | ✓ | +100% |
| Verification-after-sign | ✓ | ✓ | ✗ | ✓ | ✓ | +25% |
| Additional randomness | ✓ | ✓ | ✓ | ✓ | ✓ | +0% |

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| Verification-after-sign | ✓ | ✓ | ✗ | ✓ | ✓ | $+25\%$ |
| Additional randomness | ✓ | ✓ | ✓ | ✓ | ✓ | $+0\%$ |

- Additional randomness: $\mathbf{y} := \text{DeterministicSample}(K||M||\kappa{+}{+}||r)$
  - protects against faults, bad randomness, and DPA-recovery of $K$ [SHS16]
  - qTESLA: recent update, countermeasure now mandatory [BAA+17]
  - Dilithium: not compatible with proof… [KLS18]

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