Differential Power Analysis of the Picnic Signature Scheme

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UNIVERSITÄT ZU LÜBECK
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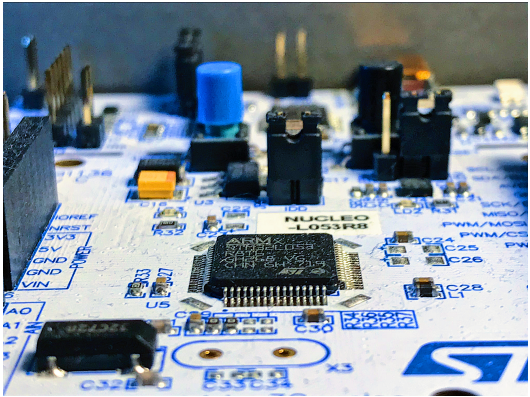
Physical Attacks on Embedded Devices



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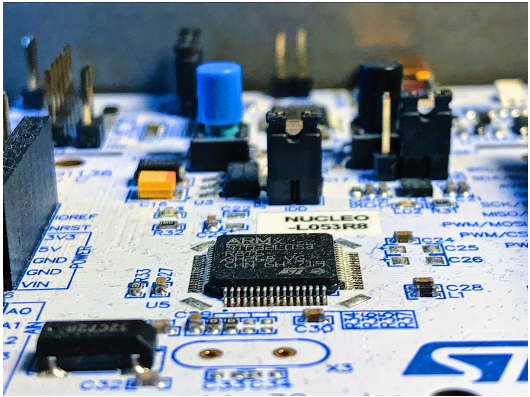

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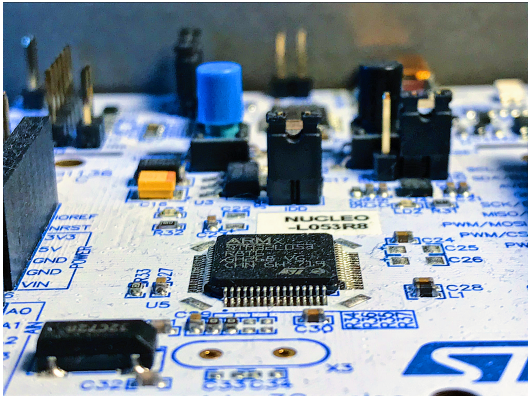

- Side Channel Attacks,
- Fault Injection,
- Timing,...

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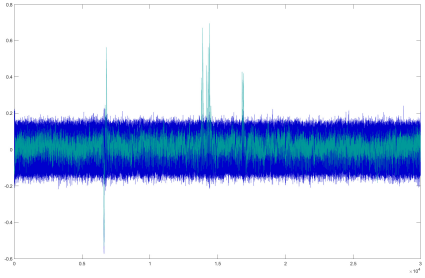

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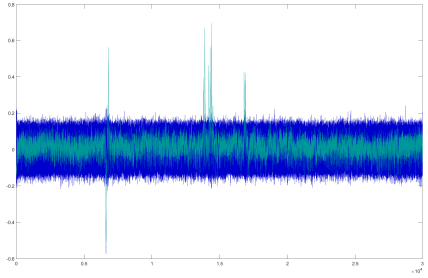

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The results have been known since 1998!

Post-Quantum Cryptography Standardization: Round 3

Finalists

- CRYSTALS-DILITHIUM
- Falcon
- Rainbow

Alternates

- GeMSS
- **Picnic**
- SPHINCS+

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Side-channel analysis on *protocol level* has a widespread attention.

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Side-channel analysis on *protocol level* has a widespread attention.

Picnic signature scheme

- Fiat–Shamir-type signature from **MPC-in-the-head** ZKP.
- ☺ No number-theoretic assumptions
  - Block cipher
  - Hash function (modeled as RO)
- ☺ Various parameters

Our Contribution

The applicability of DPA attacks to protocols relying on the MPC-in-the-head paradigm.

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- An attack on the Multiparty Computation of the `SboxLayer`

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A practical setup with a FRDM-K66F development board while monitoring electromagnetic emanation.

A novel algebraic key recovery part to reconstruct the key

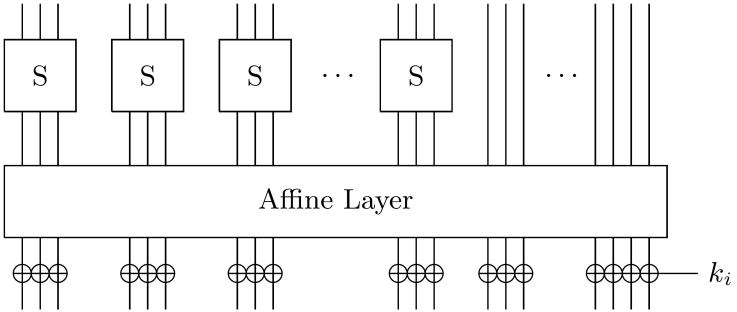
Table of Contents

LowMc Structure[1]

[1] Albrecht, M. R., Rechberger, C., Schneider, T., Tiessen, T., & Zohner, M. (2015, April). Ciphers for MPC and FHE. In Annual International Conference on the Theory and Applications of Cryptographic Techniques (pp. 430-454).

LowMc Structure[1]

- 4 main layers: `KeyAddition`, `ConstantAddition`, `LinearLayer` and `SboxLayer`
- With low AND depth suitable for Multi-part computations.
- Only 30-bit go into the Sbox Layer



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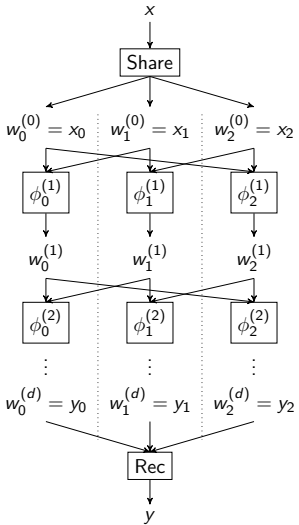

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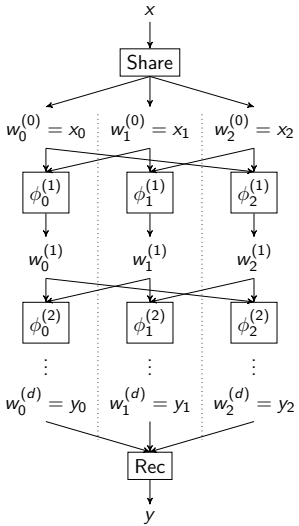

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- Consider the set of functions:

$$\mathcal{D} = \{\mathsf{Share}, \mathsf{Rec}\} \cup \{\phi(x)_1, \ldots\}$$

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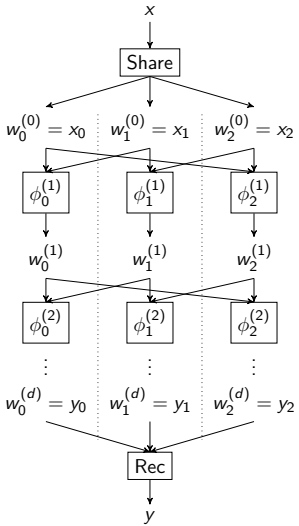

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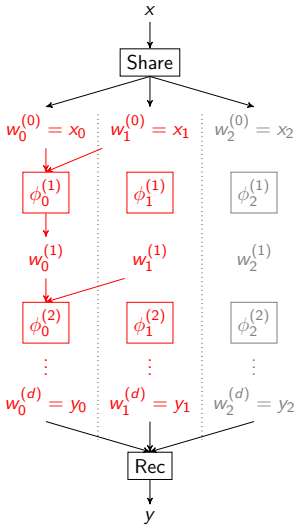

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- Revealing two branches will not leak any information.

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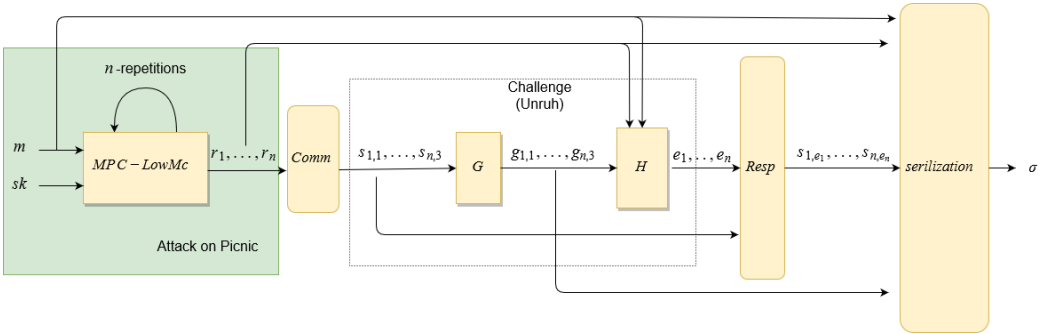

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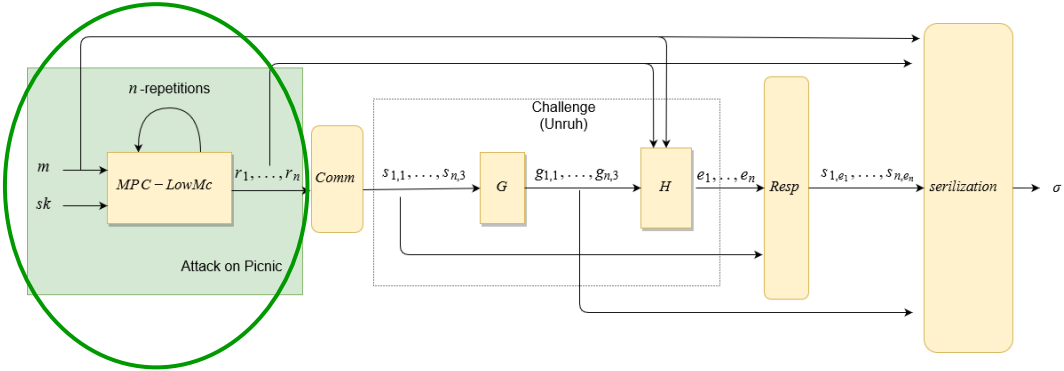

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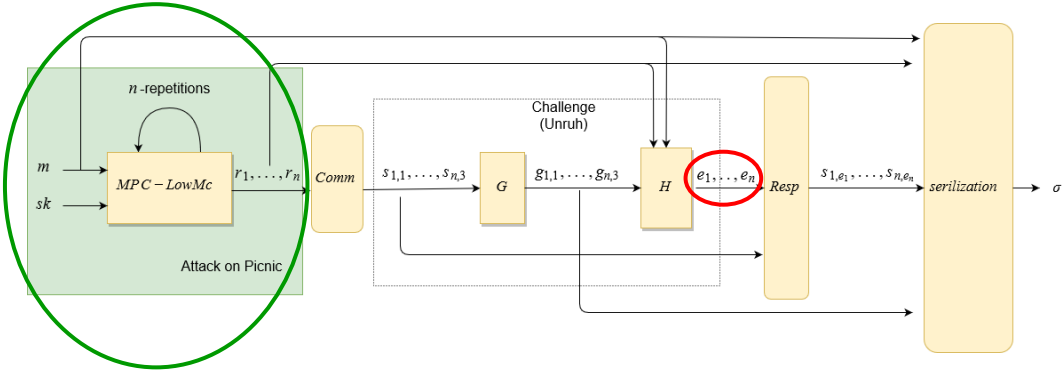
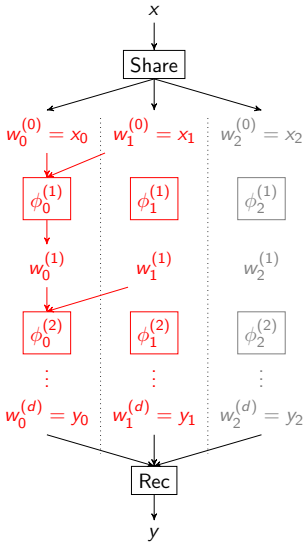


Probing MPC-in-the-head Protocol



Eve can access opened branches.

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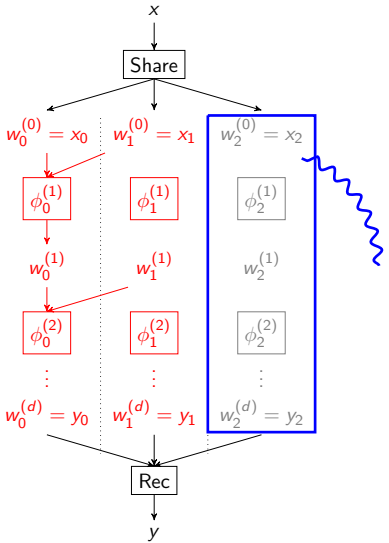

Eve can access opened branches.

A single probe on unopened branch will leak information!

Attack on the Secret Sharing Process

- Two n bit keys (or key shares) for two players k_0 and k_1 are generated randomly.
- The key share for the last player k_2 is calculated as:

$$k_2 = k_s \oplus k_0 \oplus k_1.$$

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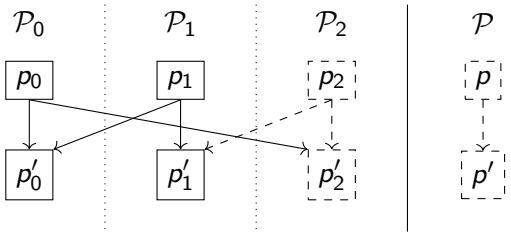
For the challenge C_0:

k_2 is the result of two chained xor-operations:

1. $R \leftarrow k_s \oplus k_0$ stored in a register R,
2. $k_2 \leftarrow R \oplus k_1$.

Attack on the Substitution Layer



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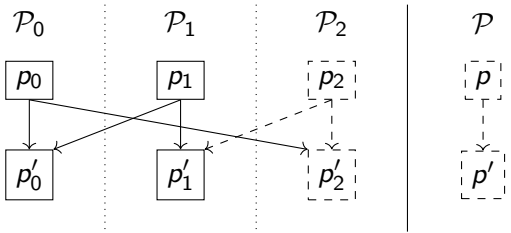

`SboxLayer` calculation for MPC-LowMC

Dashed boxes and arrows represent the values that are *not* opened during C_0

$$p = p_0 \oplus p_1 \oplus p_2 \text{ and } p' = p'_0 \oplus p'_1 \oplus p'_2$$

A Practical Measurement Setup

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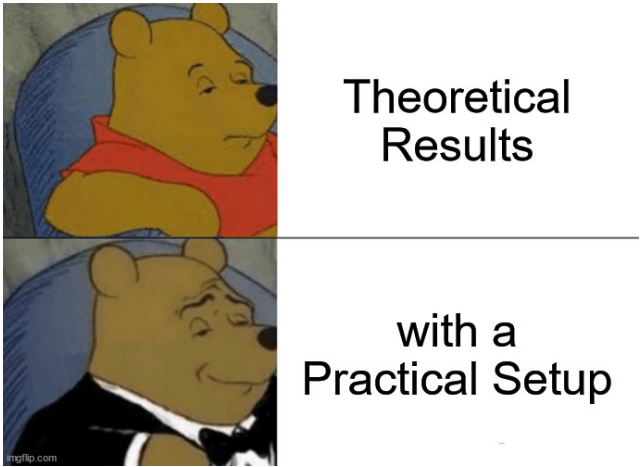

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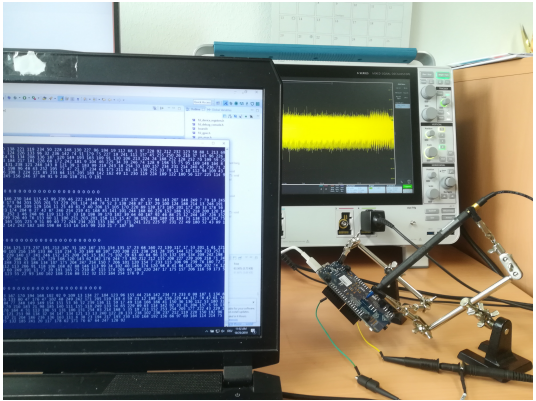
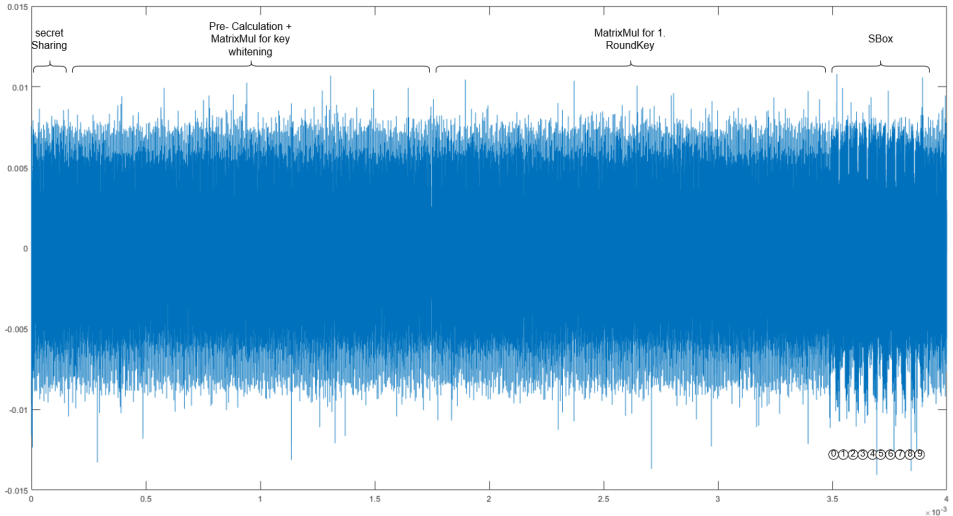


- Capture: Tektronix MSO 6 with 312.5 MHz sampling rate

A Practical Measurement Setup

- Capture: Tektronix MSO 6 with 312.5 MHz sampling rate
- Target device: SNXP Cortex-M4F MCU, operated at 120 MHz
- Source: EM emanations on a blocking cap (C37)

An Example Trace



First Step: Verifying the leakage

Test Vector Leakage Assessment (TVLA)

A pass-fail test to decide if an implementation has exploitable leakage

- fixed-vs-random (FvR): to detect all possible first-order leakage
- random-vs-random (RvR): to identify a specific exploitable leakage

```
---------------- Encryption -----------------------------
00000 00000000000000000000000000000000 -> 7DF76B0C1AB899B33E42F047B91B546F
00001 00000000000000000000000000000000 -> 7DF76B0C1AB899B33E42F047B91B546F
00002 94C3076F0433989CF3651E1C323E3F58 -> 6C76202524A3A9BD14524BC8A7749F5D
00003 00000000000000000000000000000000 -> 7DF76B0C1AB899B33E42F047B91B546F
00004 00000000000000000000000000000000 -> 7DF76B0C1AB899B33E42F047B91B546F
00005 3A3A3757CC71598FC3D6F38BCB16766A -> FB01C070BA4957A56A2DF6A0BFBBFD06
00006 65DDC4DB94B991A249EB219CC5946891 -> CF837BE15C720FEBFDA1754D0A9C9D2F
00007 94DC1372D1BC5DFBA43D08FF65863DFF -> 8E93841327CA4DF8045248E11DC71919
00008 D5286B83BACFFC763B1C0863564A9827 -> C26C0EA9C3576FEE2168CCD344CA3FFC
00009 00000000000000000000000000000000 -> 7DF76B0C1AB899B33E42F047B91B546F
00010 00000000000000000000000000000000 -> 7DF76B0C1AB899B33E42F047B91B546F
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Probing the opened share

$$a_2 = a \oplus a_0 \oplus a_1$$

- Measurements from 10th Sbox calculation with 6000 traces.

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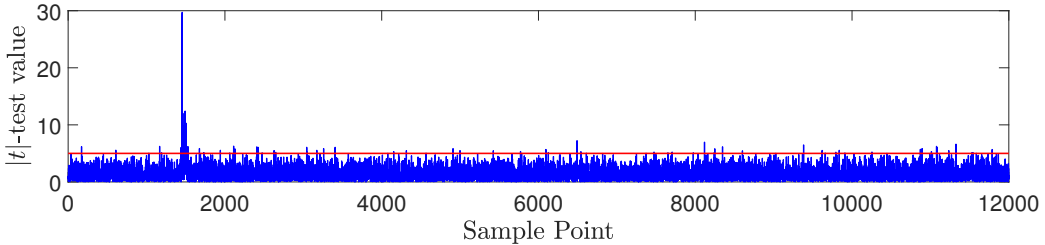
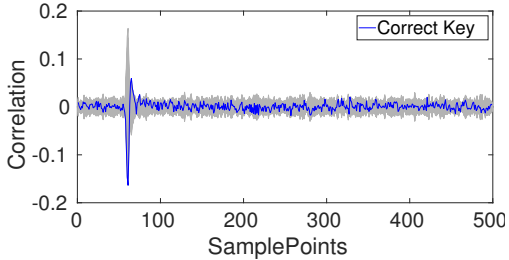
- Measurements from 10th Sbox calculation with 6000 traces.
- the $|t|$-value clearly exceeds 4.5.



Attack on the Secret Sharing Process

- DPA results shows a peak with 20,000 traces.

$$H_{k^*} = \mathrm{HW}(k_1 \oplus (k^* \oplus k_0)) \; \forall k^* \in \mathbb{F}_2^8$$



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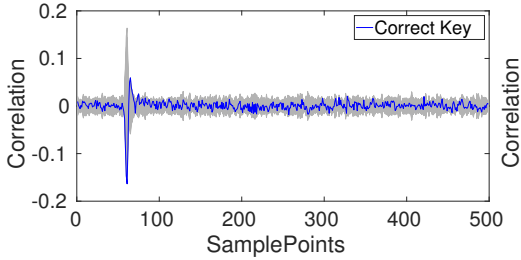
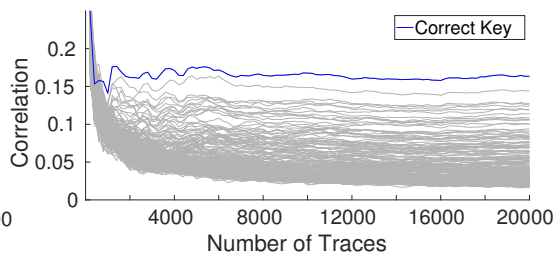
$$H_{k^*} = \mathrm{HW}(k_1 \oplus (k^* \oplus k_0)) \; \forall k^* \in \mathbb{F}_2^8$$

- The second figure shows that the correct key is distinguishable with 2000 traces.
- Every signature contains 219 repetitions $\rightarrow$ 30 signature





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- DPA results shows a peak with 20,000 traces.
- The correct key (which has the highest-negative value) is distinguishable with 2,000 traces
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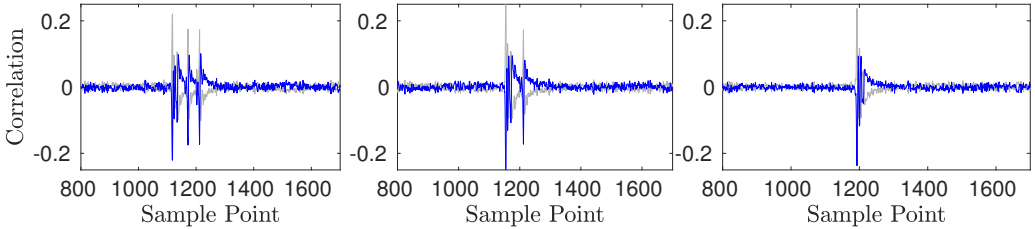

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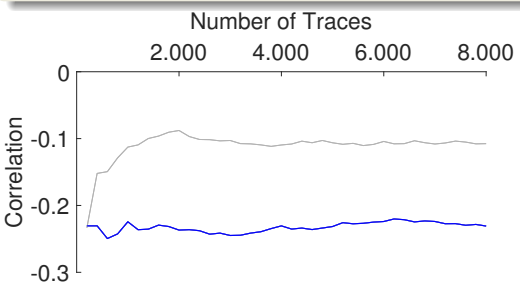

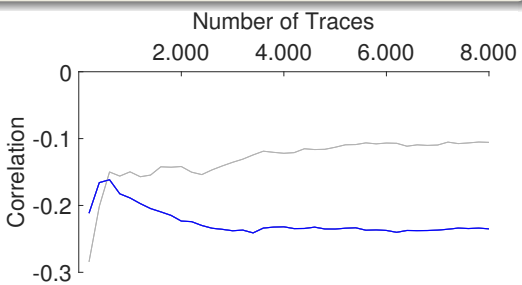

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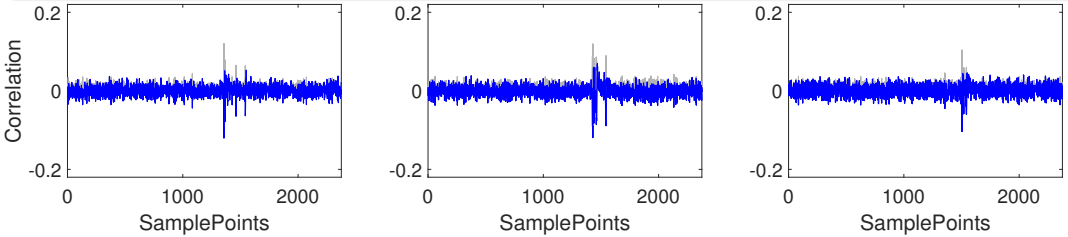

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- Due to the MPC-in-the-Head structure the values are opened for each round.
- This lead us to attacks on deeper rounds.
- Combine the key related information to solve the following system:

$$\mathcal{U}k_s = \mathcal{V}$$

  - $\mathcal{U}$ is the coefficient deduced from LowMC structure: $30r \times 128$ matrix
  - k_s is the secret key: 128×1 bit vector
  - $\mathcal{V}$ bits derived from DPA: $30r \times 1$ bit vector

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Thank you! & Questions?
More details at `https://ia.cr/2020/267`