Towards Fresh Re-Keying with Leakage-Resilient PRFs: Cipher Design Principles and Analysis

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PROOFS Workshop

Outline

Intro

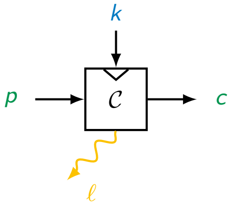
Efficient Leakage-Resilient PRFs

Fresh Re-Keying with Efficient Leakage-Resilient PRFs

Conclusion

Side-Channel Information Leakage

- Cryptographic implementations leak information over side-channels

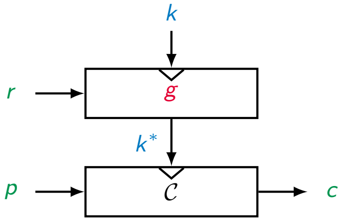


- Implementation countermeasures:
  - ➥ Protected logic styles, masking schemes, re-keying schemes, ...

- Focus on: re-keying schemes for symmetric cryptography

Re-Keying Schemes [AB00, MSGR10]

- The success probability of many (physical) attacks depends on the amount of cryptographic operations which are observable under the same key
- Idea: generate fresh keys from a master key using a re-keying function g



- Requirements:
  - ➥ g is DPA/SPA secure
  - ➥ $\mathcal{C}$ is SPA secure
  - ➥ r is a public *random* nonce

Re-keying Functions

Re-keying functions in the literature:

- Modular multiplication [MSGR10]

$$g\colon (\mathrm{GF}(2^8)[x]/(x^d+1))^2 \to \mathrm{GF}(2^8)[x]/(x^d+1)\colon (k,r) \to k\cdot r$$

Our proposal:

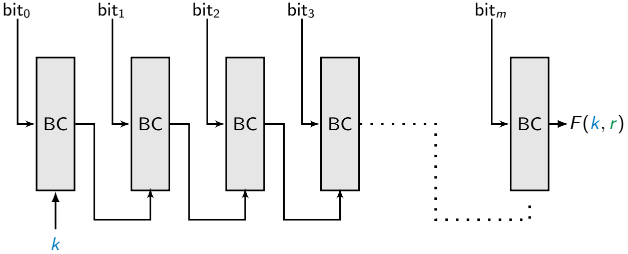
- Leakage resilient pseudo-random function [SPY$^+$09]

Informally:

- A pseudo-random function (PRF) is a function which is computationally indistinguishable from a *truly* random function
- A leakage resilient pseudo-random function (LRPRF) is a PRF which preserves "some" security, even in presence of leakages

Instantiating Block Cipher based PRFs

From *classical* construction [GGM86], $r = \text{bit}_0 \| \text{bit}_1 \| \text{bit}_2 \|, \text{bit}_3 \| \ldots \| \text{bit}_m$



Instantiating Block Cipher based PRFs

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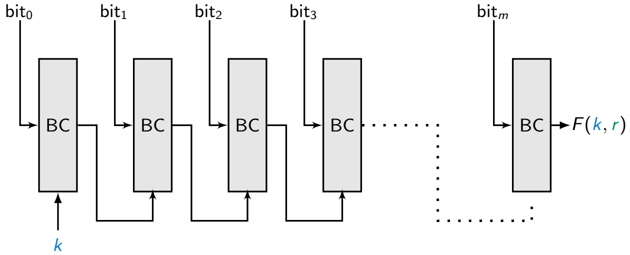
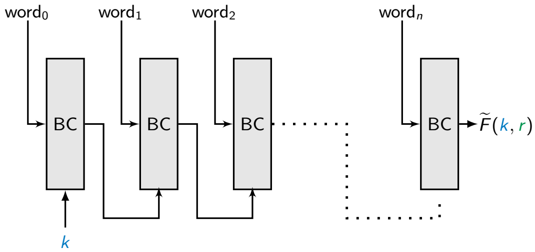
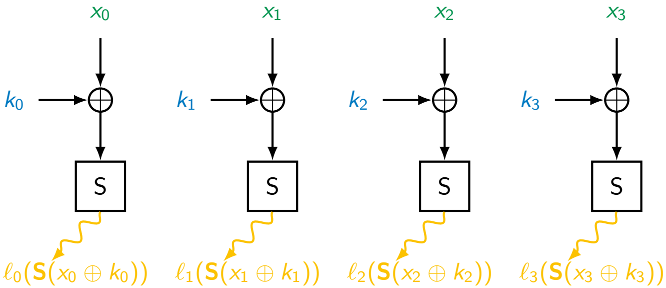


From *efficient* construction [SPY⁺09], r=$\text{word}_0\|\text{word}_1\|\text{word}_2\|\ldots\|\text{word}_n$

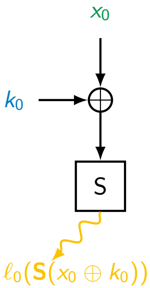


Classical DPA Attack Scenario



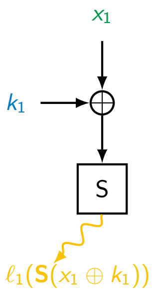
Divide et Impera: attack each S-box output independently

Classical DPA Attack Scenario



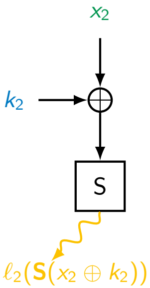
Divide et Impera: attack first S-box output

Classical DPA Attack Scenario



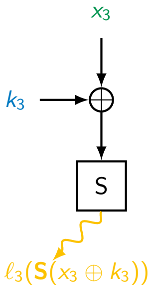
Divide et Impera: attack second S-box output

Classical DPA Attack Scenario



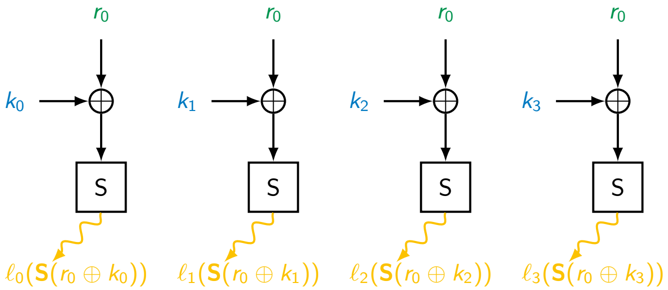
Divide et Impera: attack third S-box output

Classical DPA Attack Scenario



Divide et Impera: attack fourth S-box output ...

BC-based PRF DPA Attack Scenario [MSJ12]



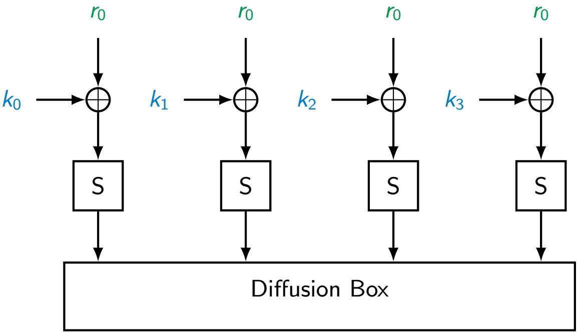
- The implementation is parallel
- The leakage functions ℓ_i are all equal
- The subkey words k_i are successfully recovered

$\Rightarrow$ Still there is a super-exponential time complexity of an enumeration over N_s to recover the full key, in case of AES: $16! = 2^{44}$ time complexity

Contributions

1. Which block cipher best suits a leakage resilient PRF in hardware?
2. Which performance can be achieved for re-keying applications?
3. Is it possible to mount classical DPA attacks in a localized EM setting?

Efficient Leakage-Resilient PRFs: Block Cipher Design Principles



SP-networks:

1. Define the round structure
2. Define the key schedule

Efficient Leakage-Resilient PRFs: Block Cipher Design Principles

- Design Parameter: number of S-boxes N_s and S-box size b
- Design Criteria: best security vs performance trade-off

N_s	16	32
$b = 4$	2^{39}	2^{95}
$b = 8$	2^{44}	2^{116}

Table: Time complexity in the 1^{st} round

N_s	16	32
$b = 4$	$2^{13.4}$	$2^{15.5}$
$b = 8$	$2^{28.8}$	$2^{38.1}$

Table: Time complexity in the 2^{nd} round

N_s	16	32
$b = 4$	432	1051
$b = 8$	1060	2954

Table: # Tr. CPA VS data complexity

N_s	16	32
$b = 4$	64	128
$b = 8$	128	256

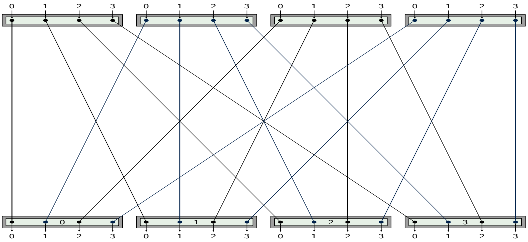
Table: Datapath size $N_s b$

$\Rightarrow$ Our Choice: 4-bit PRESENT S-box with $N_s = 32$

Efficient Leakage-Resilient PRFs: Block Cipher Design Principles

- Design Parameter: Diffusion layer
- Design Criteria: Efficient in hardware and not leaking intermediate values

First option: SMALL-PRESENT pLayer

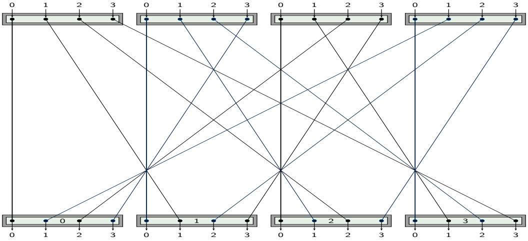


Issue: HD leaks the relative position of nibbles ...

Efficient Leakage-Resilient PRFs: Block Cipher Design Principles

- Design Parameter: Diffusion layer
- Design Criteria: Efficient in hardware and not leaking intermediate values

Our proposal: SINGLE-PATTERN



The relative offset of inputs bits must be preserved after the permutation

⇒ Our Choice: SINGLE-PATTERN

Efficient Leakage-Resilient PRFs: Block Cipher Design Principles

- Design Parameter: Number of rounds
- Design Criteria: Full diffusion (minimum property for re-keying)

- ≥ 3 rounds for $N_s = 32, b = 4$

⇒ Our Choice: 5 rounds

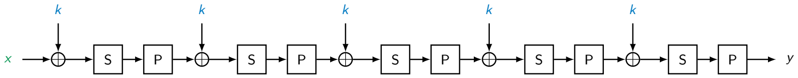
- Design Parameter: Key schedule
- Design Criteria: Efficient and not leaking intermediate values

⇒ Our Choice: No key schedule, simple key addition

Efficient Leakage-Resilient PRFs: Block Cipher Design Principles

To sum up:

- S-box layer: 32 × 4-bit PRESENT S-boxes
- Diffusion layer: SINGLE-PATTERN wire crossing with improved "regularity"
- Key schedule: Simple key addition as for the LED block cipher
- Number of rounds: 5
- Iterations: 32 for 128-bit nonces



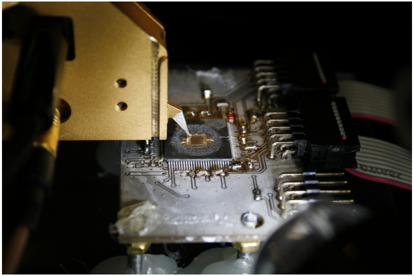
Note: intended for re-keying application only !

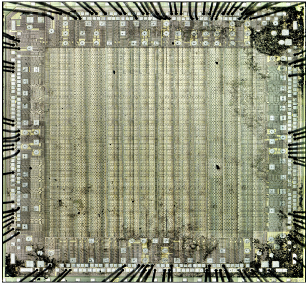
Fresh Re-Keying with Efficient Leakage-Resilient PRFs: Implementation Results

g	BC	Area [kGE]	Latency [Clock Cycles]
[MSGR10]	8-bit AES [FWR05]	10.7	562
Our PRF	8-bit AES [HAHH06]	7.19	324
	Threshold AES [MPL+11]	10.8	266
Our PRF	PRESENT(ser) [RPLP08]	4.09	643
Our PRF	PRESENT(par) [RPLP08]	4.47	131
	Threshold PRESENT [PMK+11]	3.59	578

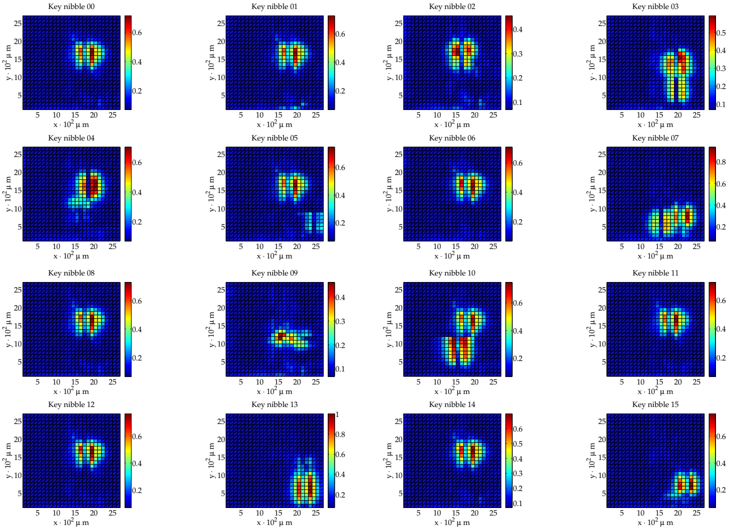
Fresh Re-Keying with Efficient Leakage-Resilient PRFs: Localized EM Attacks

- Analysis conducted on a depackaged (VQ100) Xilinx Spartan FPGA 3
- EM activity measured on the frontside
- Univariate profiled CPA attacks

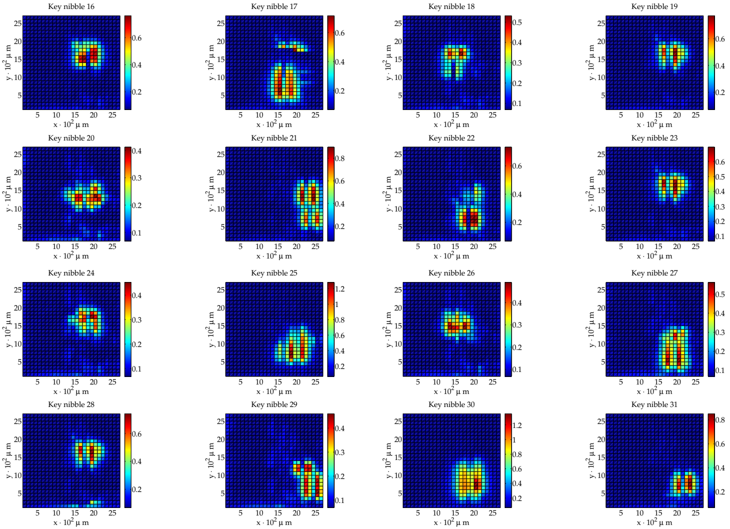




Fresh Re-Keying with Efficient Leakage-Resilient PRFs: Localized EM Attacks

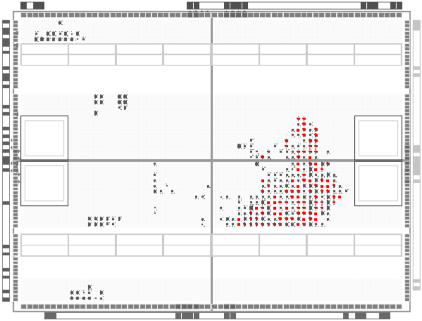


Fresh Re-Keying with Efficient Leakage-Resilient PRFs: Localized EM Attacks



Fresh Re-Keying with Efficient Leakage-Resilient PRFs: Localized EM Attacks

- An optimal key enumeration algorithm [VCGRS13] was used to evaluate the remaining time complexity after localized EM attacks
- Yet experimental results suggest security bounds $> 2^{80}$ time complexity



Fresh Re-Keying with Efficient Leakage-Resilient PRFs:
Localized EM Attacks

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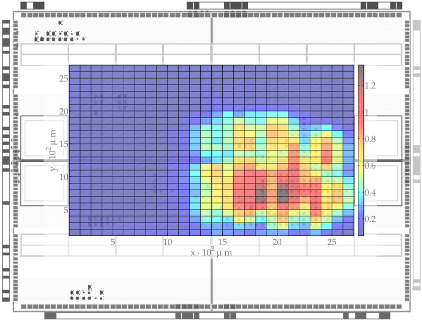

Conclusion

1. We provided block cipher design principles to best suit an efficient leakage-resilient PRF in hardware
   - ➥ Security should be considered at **all** abstraction levels

2. We showed that efficient leakage resilient PRFs are valid alternatives for fresh re-keying in hardware

3. We showed that the key-dependent algorithmic noise is still hard to exploit, even in a localized EM setting (univariate)

Future work:

- Full specification of our BC-like proposal
- Multivariate attacks
- Randomization countermeasure to thwart localized EM attacks

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