CRAFT: Lightweight Tweakable Block Cipher with Efficient Protection Against DFA Attacks

Christof Beierle Gregor Leander Amir Moradi
Shahram Rasoolzadeh

SnT, University of Luxembourg

Horst Görtz Institute for IT Security, Ruhr University Bochum

FSE 2019
March 25, 2019

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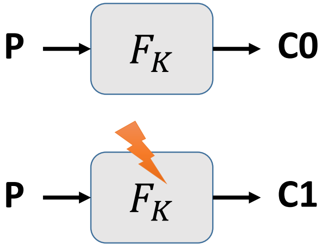

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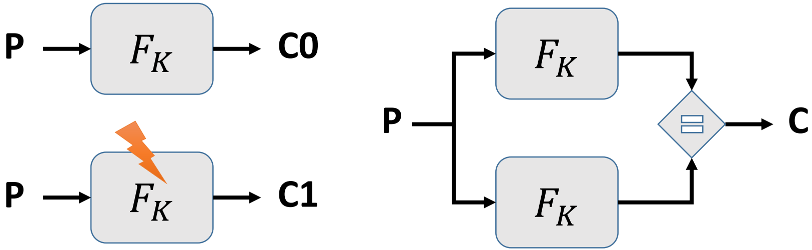

Impeccable Circuits [1]

Two general construction for Concurrent Error Detection

Adversary Model

Univariate(/Multivariate) Model, $\mathcal{M}_t$:
The adversary is able to make at most t cells of the entire circuit faulty at only one (/every) clock cycle.

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Independence Property

To prevent fault propagation, the coordinate functions of each operation have to be implemented independently.

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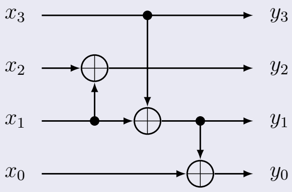

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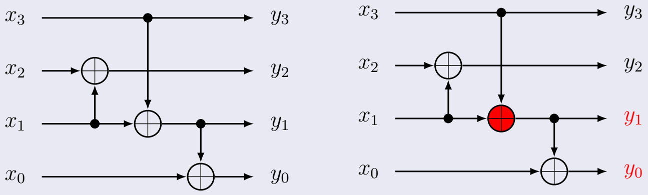

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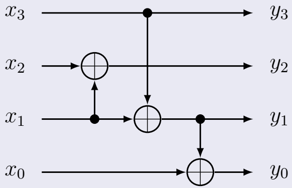

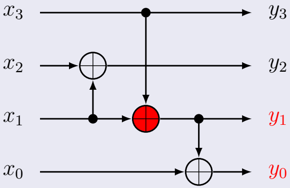

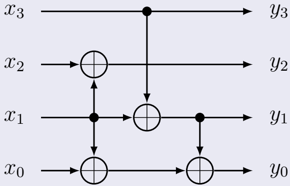

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- Protection against DFA Attacks with efficient hardware implementation
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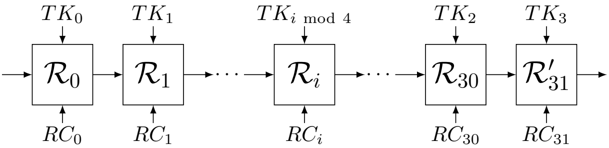
- Skinny-like structure with 128-bit key, 64-bit block & tweak

Structure



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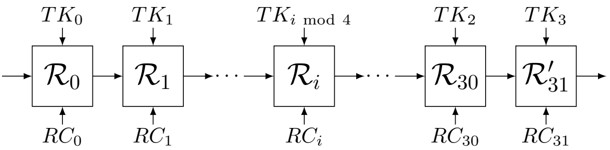

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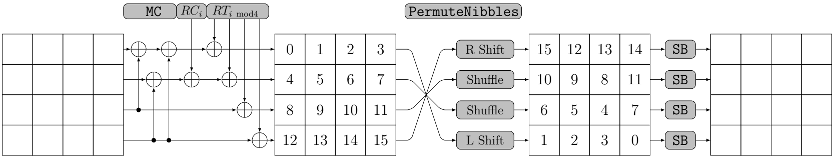

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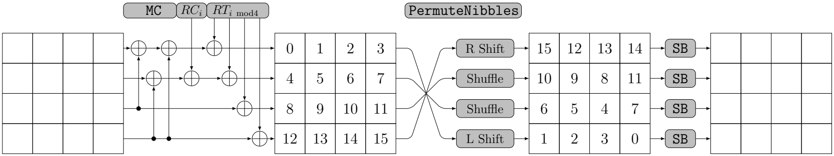

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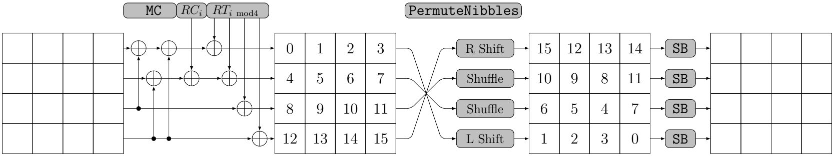

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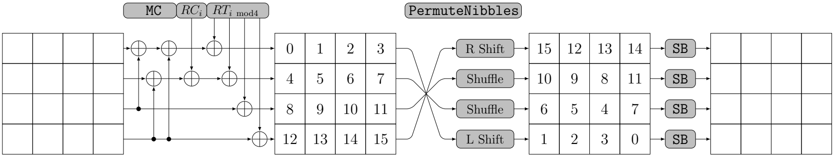

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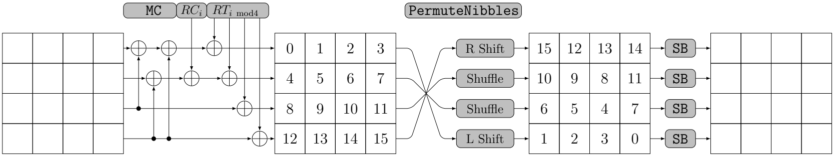

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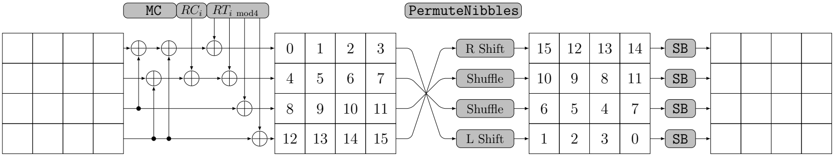

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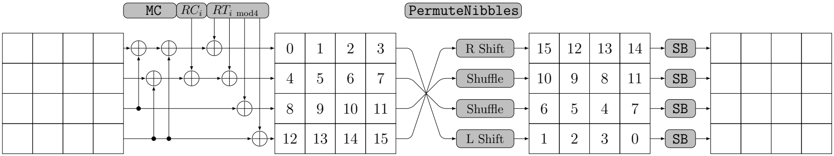

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- `SubBox(SB)`:
  4-bit involutory Sbox S is applied to each nibble.

Tweakey Schedule

If (K_0, K_1) are two 64-bit halves of the key and T is the tweak, then

$$\begin{aligned} TK_0 &= K_0 \oplus T \\ TK_1 &= K_1 \oplus T \end{aligned}$$

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where Q is a circular permutation on the position of tweak nibbles:

$$[12, 10, 15, 5,\ 14, 8, 9, 2,\ 11, 3, 7, 4,\ 6, 0, 1, 13]$$

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$$\mathrm{MC} \circ \mathrm{ARC} \circ \mathrm{ATK} = \mathrm{ATK}' \circ \mathrm{ARC} \circ \mathrm{MC}$$

$$\mathrm{TK}' = \mathrm{MC}(\mathrm{TK})$$

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Problem

There are 46 206 736 involutory 4-bit Sboxes which implementing and synthesizing all of them is impossible.

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Results for Sbox

Among all the smallest found Soxes, we use the Midori's one.

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- Solution: using 64 multiplexers to choose T or a nibble-wise permutation of it, $Q(T)$.
- To provide maximum possible security against TDM-TO attack, Q must be circular (there are $15! \approx 2^{40}$).
- Trying 1000 of them, Q is the one with most active Sboxes in related-tweak differential attack.

Security

Security Analysis

- Time-Data-Memory Trade-off
- (Truncated / Impossible) (ST/RT) Differential
- (Linear Hulls / Zero-Correlation) Linear
- Integral
- Meet in the Middle
- (Linear Subspace/Nonlinear) Invariant Attacks

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Security Claim

- 124 bit security in the related-tweak model
- No claim in chosen-key, known-key or related-key models

Accelerated Exhaustive Search

Related-key Property:

If $\Delta = (x, x, \ldots, x)$, since $Q(\Delta) = \Delta$, both (K_0, K_1, T) and $(K_0 + \Delta, K_1 + \Delta, T + \Delta)$ cause the same tweakeys:

$$TK_i = TK'_i \quad (0 \leq i \leq 3)$$

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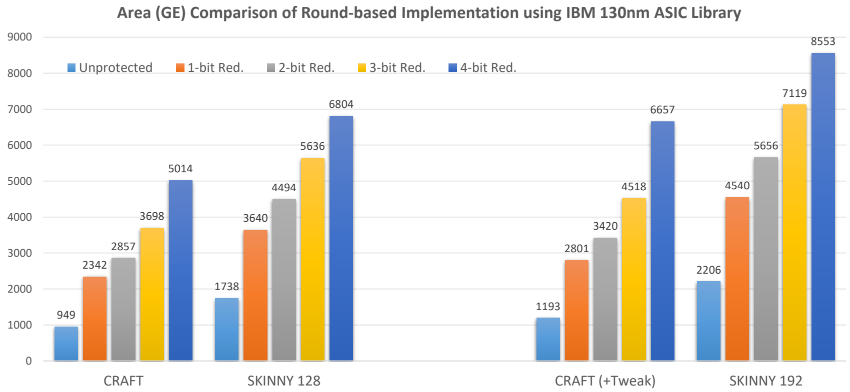
Attack Procedure:

- Attacker asks for encryption of the same plaintext P under 16 different tweaks of $T, T + \Delta_1, \ldots, T + \Delta_{15}$: $C_0, C_1, \ldots, C_{15}$.
- By setting one of the key nibbles to zero, for each of 2^{124} possible key candidate (K_0^*, K_1^*), he computes C^*, the encryption of P using K_0^*, K_1^* and T.
- If C^* is equal to C_x, then $(K_0^* + \Delta_x,\ K_1^* + \Delta_x)$ is a candidate for the master key.

Hardware Implementations



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Providing 124-bit security in the related-tweak model

The End

Thank you for your attention.

Looking forward for further analysis by you

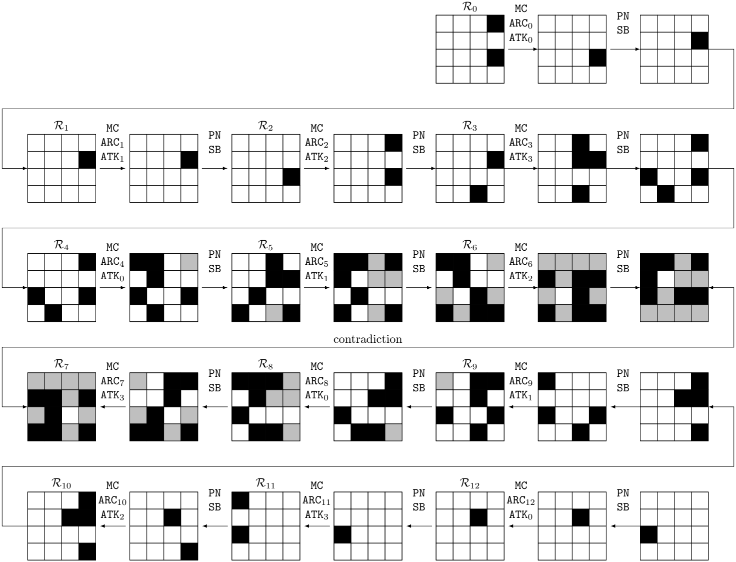
Time-Data-Memory Trade-off Attack

- Attacker fixes the tweakeys to $TK_0 = 0$, $TK_1 = X$, $TK_2 = T'$ and $TK_3 = X + T'$.
- For plaintext P and all possible X and T', he computes the ciphertext $C_{T',X}$ and saves X in the index (T', C) of table $\mathcal{T}$.

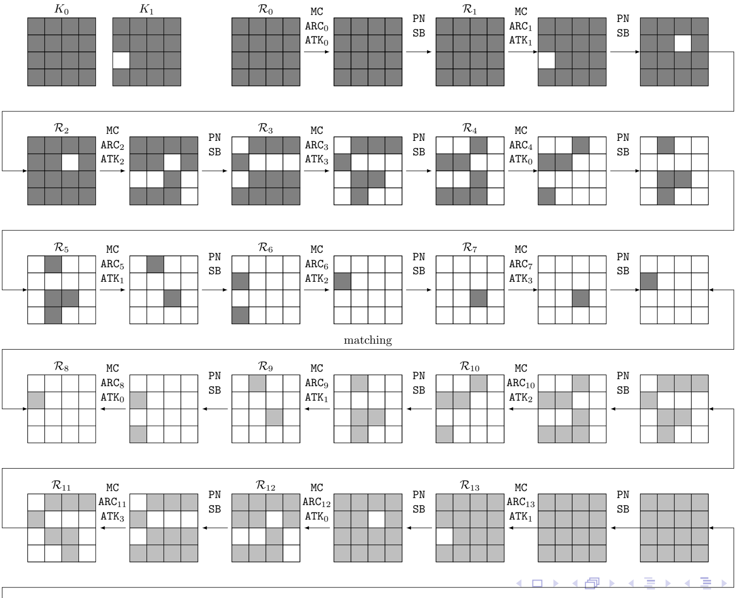
- For all possible tweaks T, attacker requests for encryption of P; C_T.
- For each of T, he gets a candidate for $K_0 + K_1$ by looking up to the index $(T + Q(T), C_T)$ of $\mathcal{T}$.

- $2^{64+\dim\{T+Q(T)\}}$ pre-computations, $2^{64+\dim\{T+Q(T)\}}$ memory, 2^{65} online computions and 2^{64} data.
- All online attack: $2^{64+\dim\{T+Q(T)\}}$ computations, 2^{64} data and memory.

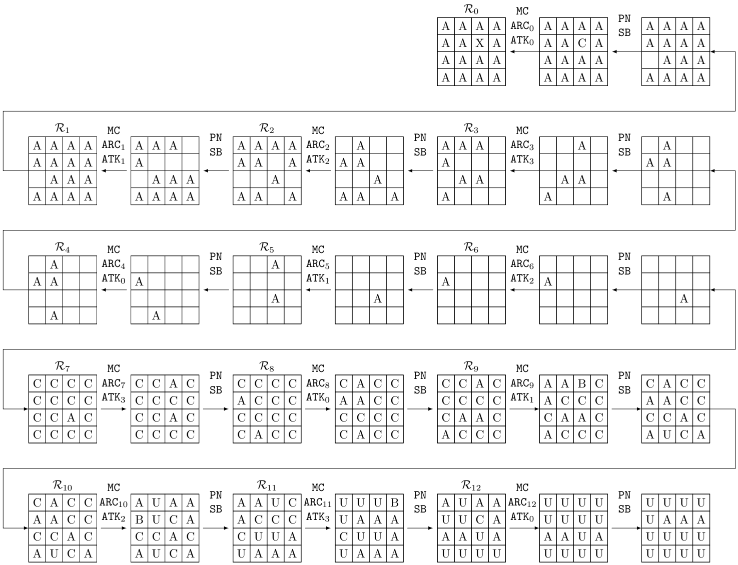
13-Round Impossible Truncated Differentials



15-Round Meet-in-the-Middle Attacks



13-Round Integral Distinguisher



Enc. & Dec. Algorithms

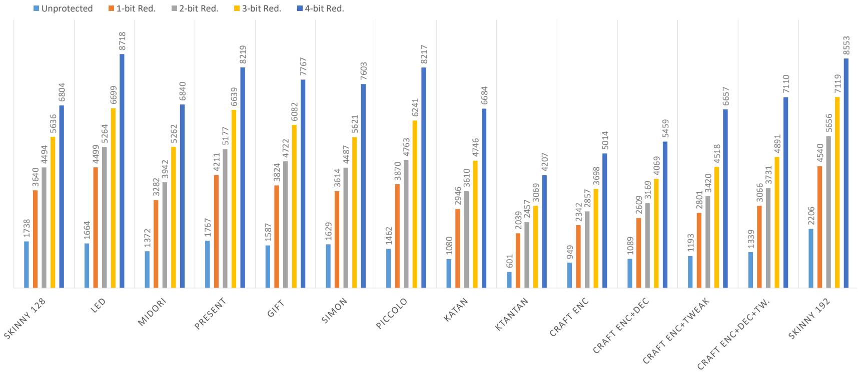
Input : X: *plaintext*
$K_0||K_1$: *cipher key*
T: *tweak*
Output : Y: *ciphertext*

$TK_0 \leftarrow K_0 \oplus T$
$TK_1 \leftarrow K_1 \oplus T$
$TK_2 \leftarrow K_0 \oplus Q(T)$
$TK_3 \leftarrow K_1 \oplus Q(T)$
$Y \leftarrow X$
for $i \leftarrow 0$ **to** 31 **do**
  $Y \leftarrow \texttt{MC}(Y)$
  $Y_{4,5} \leftarrow Y_{4,5} \oplus RC_i$
  $Y \leftarrow Y \oplus TK_{i \bmod 4}$
  if $i \neq 31$ **then**
    $Y \leftarrow \texttt{PN}(Y)$
    $Y \leftarrow \texttt{SB}(Y)$
  end
end

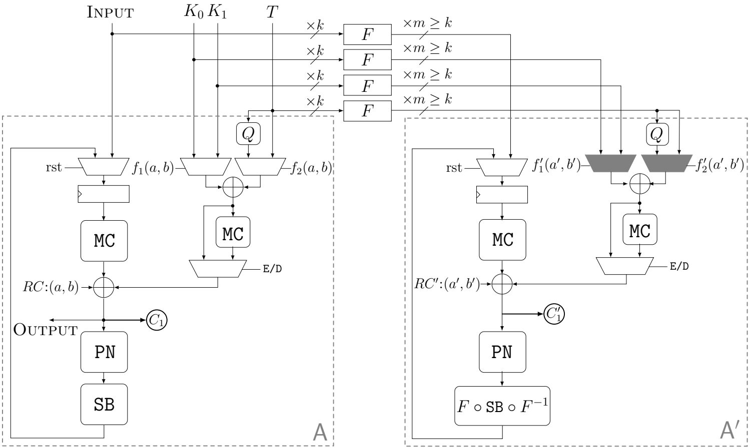
Input : X: *ciphertext*
$K_0||K_1$: *cipher key*
T: *tweak*
Output : Y: *plaintext*

$TK_0 \leftarrow \texttt{MC}(K_0 \oplus T)$
$TK_1 \leftarrow \texttt{MC}(K_1 \oplus T)$
$TK_2 \leftarrow \texttt{MC}(K_0 \oplus Q(T))$
$TK_3 \leftarrow \texttt{MC}(K_1 \oplus Q(T))$
$Y \leftarrow X$
for $i \leftarrow 31$ **to** 0 **do**
  $Y \leftarrow \texttt{MC}(Y)$
  $Y_{4,5} \leftarrow Y_{4,5} \oplus RC_i$
  $Y \leftarrow Y \oplus TK_{i \bmod 4}$
  if $i \neq 0$ **then**
    $Y \leftarrow \texttt{PN}(Y)$
    $Y \leftarrow \texttt{SB}(Y)$
  end
end

Implementation Results



Round-based Implementation with Fault Detection



Round-based Implementation with Fault Detection