Éléments de cryptanalyse

Habilitation à Diriger des Recherches

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6 février 2025

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BASICS

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4. We can't prove that a cipher is secure.

We do cryptanalysis

Overview of Contributions

Cryptanalysis of primitives

Pyjamask-96 [ToSC:DRS20]

GEA 1/2 [EC:BDLLRRRS21]

Keccak [ToSC:HNR21]

Panther [AfC:BHR22]

Troïka [SAC:BMR22]

Designs

Subterranean 2.0 [ToSC:DMMR20]

LwPR [C:HMMRSU23]

Transistor [BBBBCLPPRR]

Compression functions [C:FRD23]

Duplex-based modes [EC:GHKR23]

Cryptanalysis of modes

OUTLINE

Cryptanalysis of the GPRS Encryption Algorithms GEA-1 and GEA-2

Beierle, Derbez, Leander, Leurent, Raddum, R,
Rupprecht and Stennes

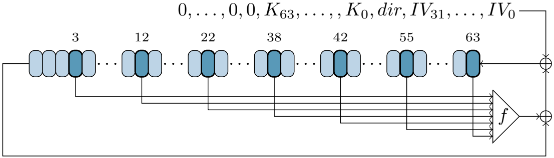
EUROCRYPT 2023

GEA-1 : CONTEXT (BEFORE 2020)

- Proprietary stream cipher, designed by ETSI in 1998
- GPRS (General Packet Radio Service)
- No public specification available
- Reverse engineered (partly) by Nohl and Melette (2011)

GEA-1 : INITIALISATION

S, 225 times :



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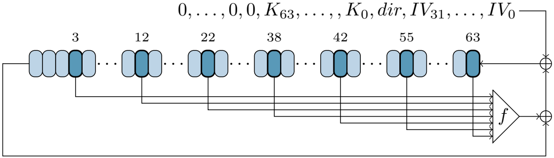
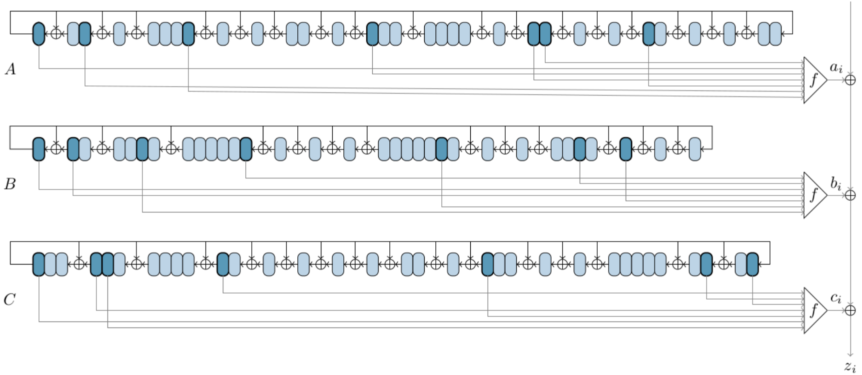
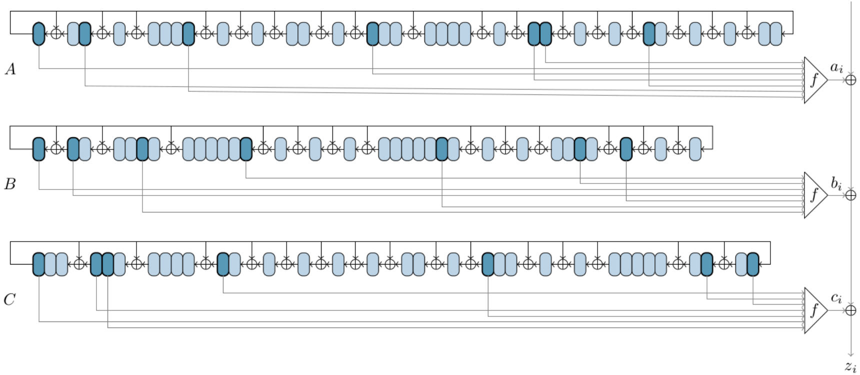


We call s the secret value contained in S.

GEA-1 : STRUCTURE



GEA-1 : Structure



$s \in \mathbb{F}_2^{64}$, 64 initialisation clocks :

$$A \leftarrow s_0 s_1 \cdots s_{63}$$

$$B \leftarrow s_{16} s_{17} \cdots s_{15}$$

$$C \leftarrow s_{32} s_{33} \cdots s_{31}$$

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$\exists\ M_A \in \mathcal{M}(31 \times 64)$, $M_B \in \mathcal{M}(32 \times 64)$, $M_C \in \mathcal{M}(33 \times 64)$ such that

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$$\alpha = M_A s$$
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$$\dim(\ker(M_A) \cap \ker(M_C)) = 24$$

GEA-1 : Attack

$$\mathbb{F}_2^{64} = (\ker(M_A) \cap \ker(M_C)) \oplus \ker(M_B) \oplus V$$

$$\alpha = M_A(t+u+v) = M_A(u+v)$$
$$\beta = M_B(t+u+v) = M_B(t+v)$$
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`for` $v \in V$,

1. `Compute and sort` $\mathcal{L} = (z_i + f(\beta^i(t,v)))_{t,i}$
2. `for` u, `look for` $(f(\alpha^i(u,v)) + f(\gamma^i(u,v)))_{u,i}$ `in` $\mathcal{L}$

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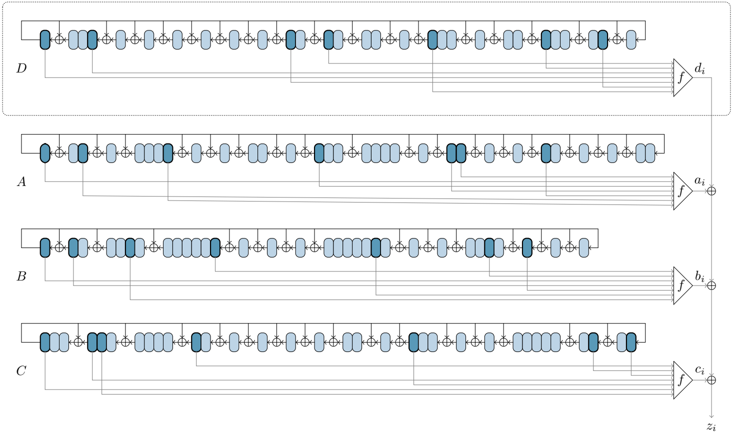
Cost of the attack 2^{40}

GEA-2 : IMPROVEMENTS



GEA-2 : GUESS AND DETERMINE

Number of monomials :

$$1 + \sum_{i=1}^{4} \binom{29}{i} + \binom{31}{i} + \binom{32}{i} + \binom{33}{i} = 152\,682$$

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Guess $n_A + n_B + n_C + n_D$ bits :

$$1 + \sum_{i=1}^{4} \binom{29 - n_D}{i} + \binom{31 - n_A}{i} + \binom{32 - n_B}{i} + \binom{33 - n_C}{i}$$

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2. Derive linear equations $(\langle m_i, s_{A+D}\rangle)_{1\leq i\leq n}$ that do not depend on any bits of A or D (number of monomials < 12800).
3. Apply list-merging to

$$t = \langle m_1, z\rangle \oplus \langle m_1, s_{A+D}\rangle, \langle m_2, z\rangle \oplus \langle m_2, s_{A+D}\rangle, \ldots$$

and

$$f_1 : \beta \mapsto \langle m_1, s_B(\beta)\rangle, \ldots, \langle m_c, s_B(\beta)\rangle$$

and

$$f_2 : \gamma \mapsto \langle m_1, s_C(\gamma)\rangle, \ldots, \langle m_c, s_C(\gamma)\rangle$$

GEA 1/2 : SUMMARY AND FUTURE WORK

Summary :

- `GEA-1` attack in 2^{40}
- `GEA-2` attack in $2^{45.1}$

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Improved by :

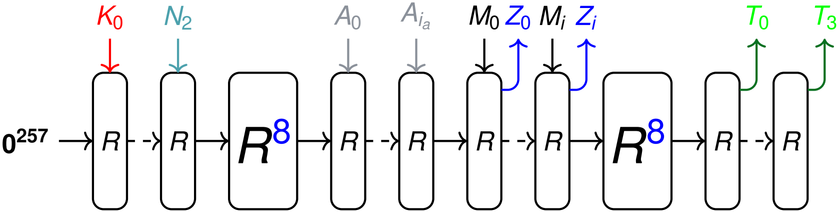
- Amzaleg and Dinur in 2022
- Avoine, Carpent, Claverie, Devine and Leblanc-Albarel in 2024

The Subterranean 2.0 Cipher Suite

Daemen, Maat Costa Massolino, Mehrdad and R.

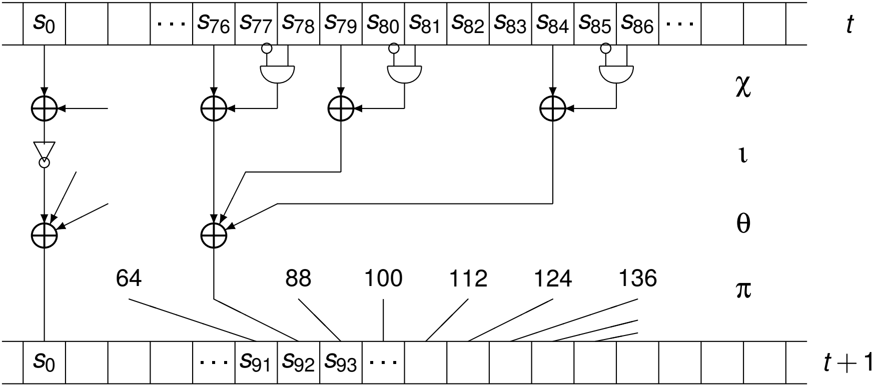
NIST-lwc and ToSC 2020

Subterranean 2.0 : Mode



- $|K_j| = |N_j| = |A_j| = |M_j| = 33 = 32 + 1$: 32 bits of message, 1 bit for padding
- $|Z_j| = |T_j| = 32$
- State size of 257 bits

SUBTERRANEAN 2.0 : ROUND FUNCTION



$\chi : s_i \leftarrow s_i + (s_{i+1} + 1)s_{i+2}$

$\iota : s_i \leftarrow s_i + \delta_i$

$\theta : s_i \leftarrow s_i + s_{i+3} + s_{i+8}$

$\pi : s_i \leftarrow s_{12i}$

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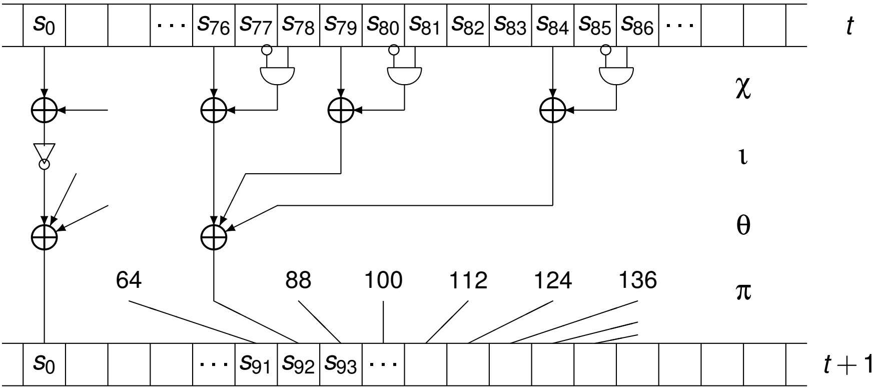

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For j from 0 to 32,

Absorption : $s_{12^{4j}} \leftarrow s_{12^{4j}} + x_j$

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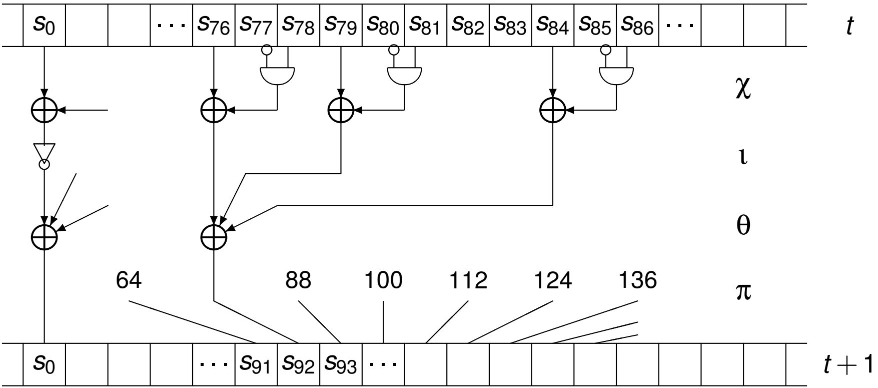

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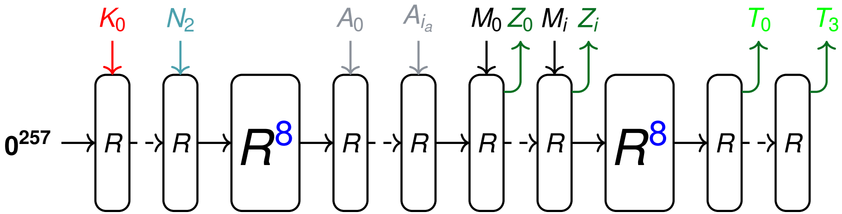
For j from 0 to 31,

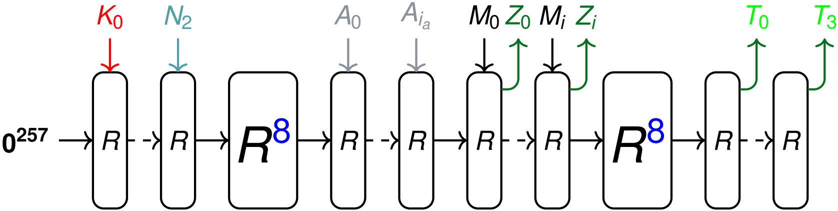
Extraction : $z \leftarrow z || (s_{12^{4j}} + s_{-12^{4j}})$

Subterranean 2.0 : Arguments



”Strong” permutation for initialisation and finalisation

SUBTERRANEAN 2.0 : ARGUMENTS



"Strong" permutation for initialisation and finalisation, corroborated by :

- Liu, Isobe and Meier in 2019 with cubes
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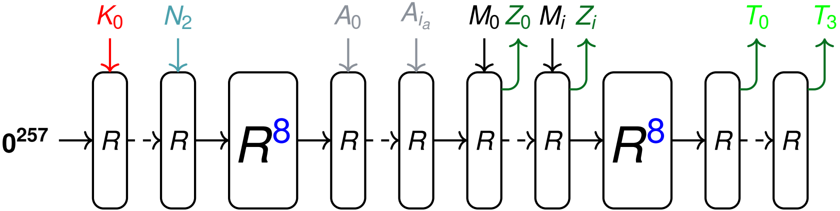

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"Light" permutation in the middle :

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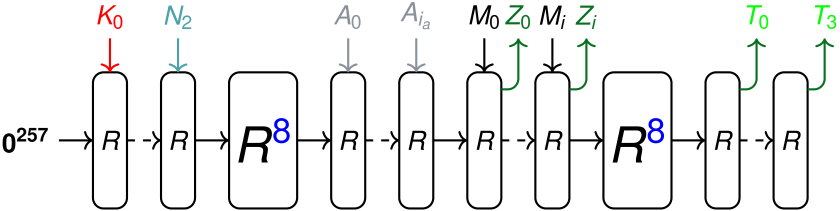

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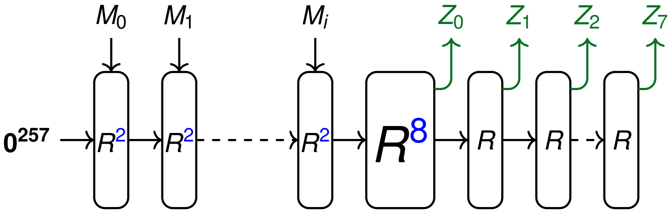
"Light" permutation in the middle :

- Efficiency
- Wise choice of bit positions

SUBTERRANEAN 2.0 : HASHING



- $|M_j| = 9 = 8 + 1$, 8 bits of message, 1 padding
- $|Z_j| = 32$, NIST : 8 output blocks

Subterranean 2.0 : Inner collisions

- Generic attack costs $2^{c/2} = 2^{(257-8)/2} = 2^{124.5}$

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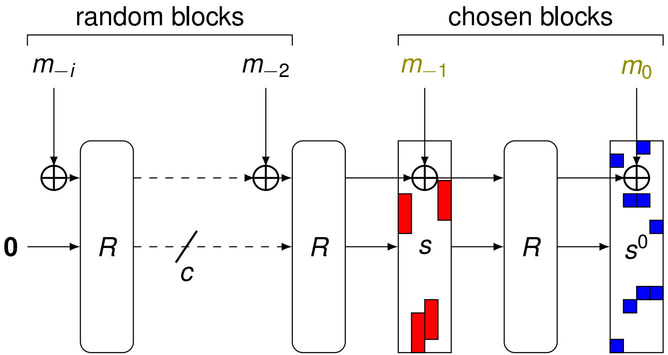

SUBTERRANEAN 2.0 : SYSTEM FOR COLLISIONS

$$
\begin{cases}
q_{124}(s) + q_{124}(s') & = & b_5 s_{133} + b'_5 s'_{133} \\
q_{125}(s) + q_{125}(s') & = & b_5 s_{135} + b'_5 s'_{135} \\
q_{126}(s) + q_{126}(s') & = & b_5 + b'_5 + b_2 s_{135} + b'_2 s'_{135} \\
q_{127}(s) + q_{127}(s') & = & b_2 s_{137} + b'_2 s'_{137} \\
q_{128}(s) + q_{128}(s') & = & b_2 + b'_2 \\
q_{129}(s) + q_{129}(s') & = & b_5 s_{133} + b'_5 s'_{133} \\
q_{130}(s) + q_{130}(s') & = & b_5 s_{135} + b'_5 s'_{135} \\
q_{131}(s) + q_{131}(s') & = & b_5 + b'_5 + b_2 s_{135} + b'_2 s'_{135} \\
q_{132}(s) + q_{132}(s') & = & b_5 s_{133} + b'_5 s'_{133} + b_2 s_{137} + b'_2 s'_{137} \\
q_{133}(s) + q_{133}(s') & = & b_5 s_{135} + b'_5 s'_{135} + b_2 + b'_2 \\
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q_{135}(s) + q_{135}(s') & = & b_2 s_{137} + b'_2 s'_{137} \\
q_{136}(s) + q_{136}(s') & = & b_2 + b'_2
\end{cases}
$$

SUBTERRANEAN 2.0 : SYSTEM FOR COLLISIONS

$$
\left\{
\begin{array}{rcl}
q'_{124}(s) + q'_{124}(s') & = & 0 \\
q'_{125}(s) + q'_{125}(s') & = & 0 \\
q'_{126}(s) + q'_{126}(s') & = & 0 \\
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Attack in 2^{116}

Subterranean 2.0 : Summary and future work

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- Absence proven in `Transistor`, Baudrin, Belaïd, Bon, Boura, Canteaut, Leurent, Paillier, Perrin, Rivain and R.

Algebraic and Higher-Order Differential Cryptanalysis of Pyjamask-96

Dobraunig, R. and Schoone

ToSC 2020

Higher-order derivatives : Principle

- Dates back to 1994 by Lai and Knudsen

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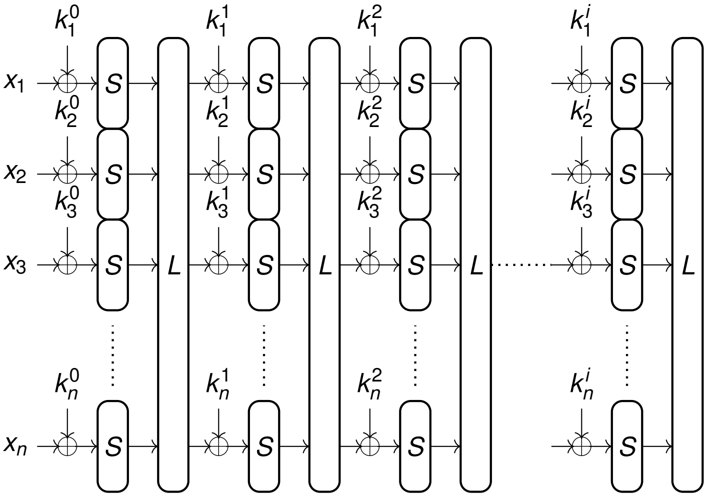
- Division property, many improvements since Todo in 2015

Higher-order differential attacks



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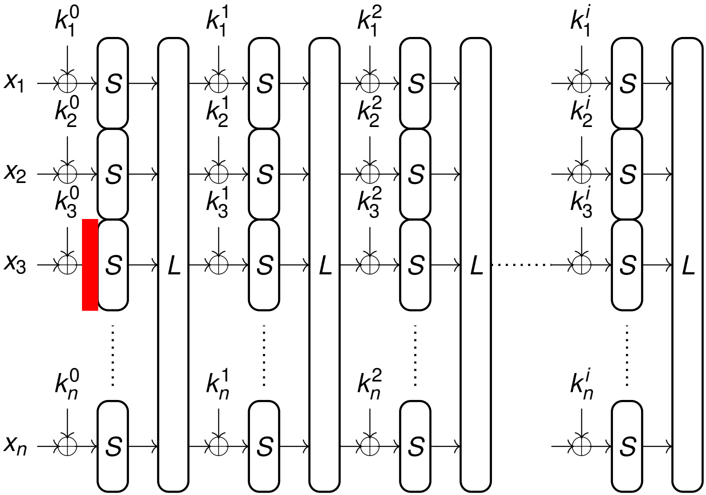

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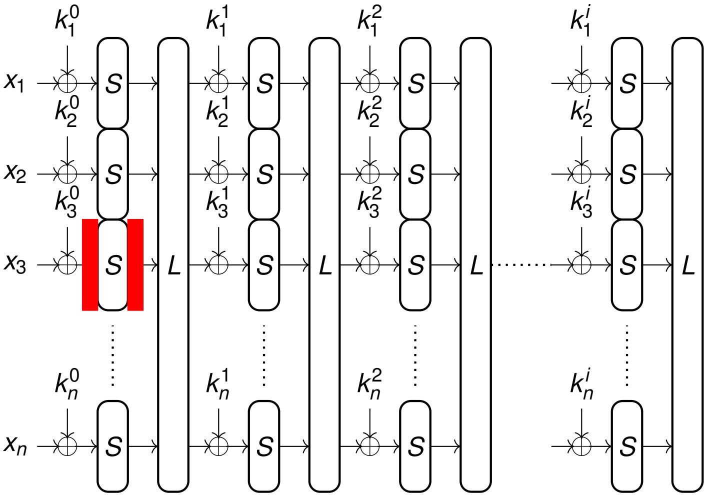

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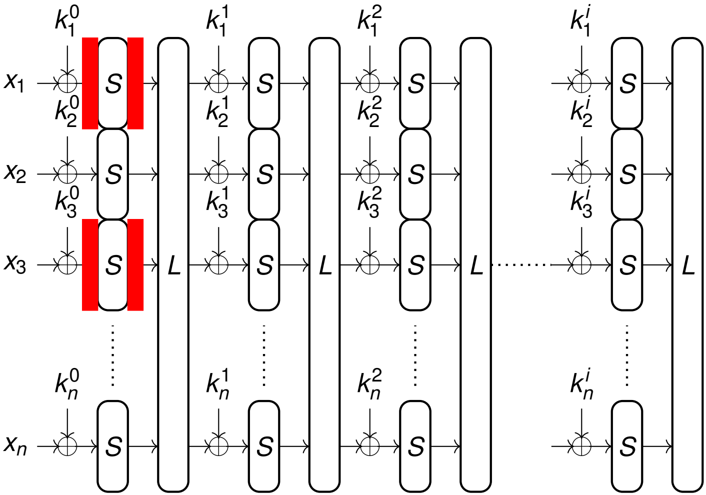

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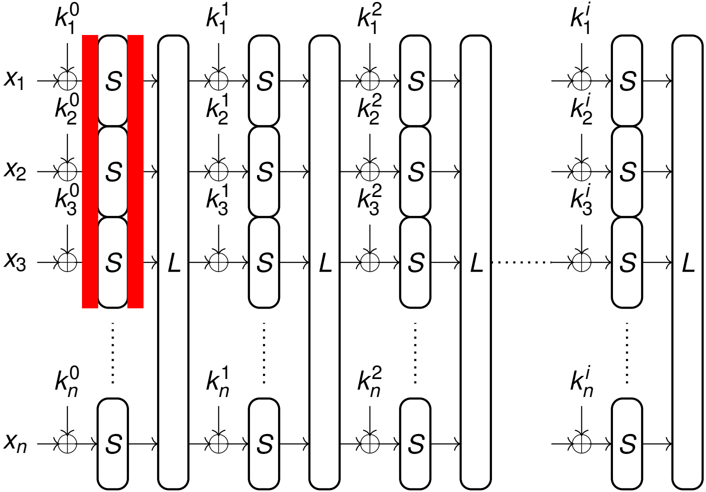

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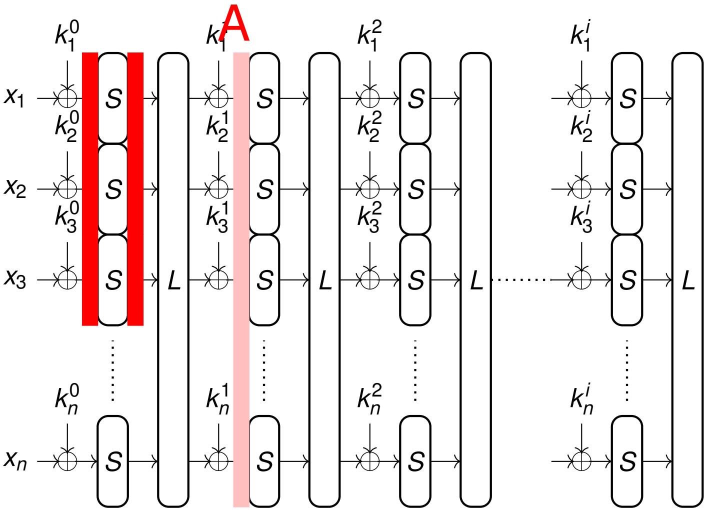
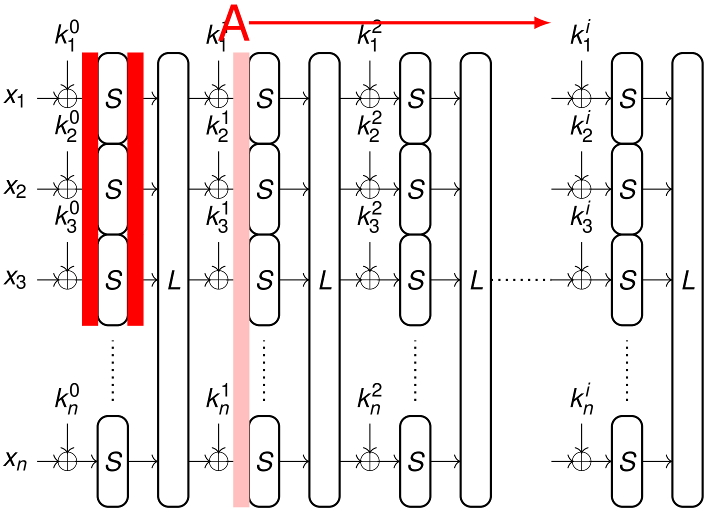


HIGHER-ORDER DIFFERENTIAL ATTACKS



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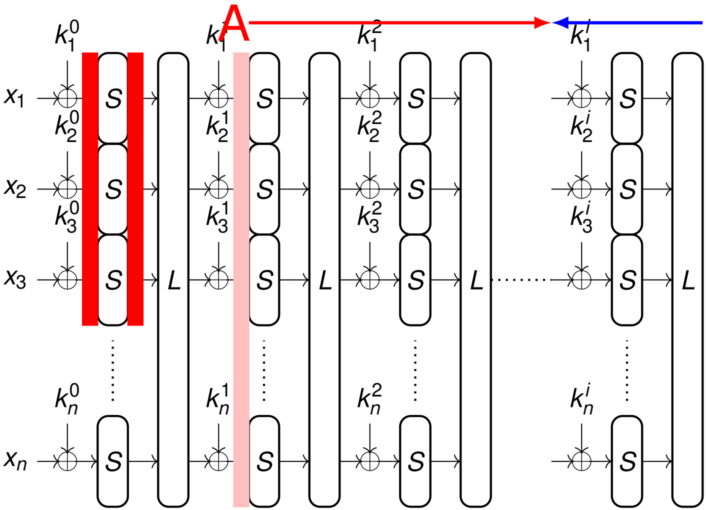
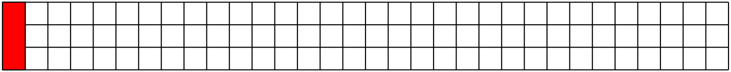


Pyjamask (Goudarzi, Jean, Kölbl, Peyrin, Rivain, Sasaki, Siang Meng Sim, NIST 2019)



The S-box layer :

- 96-bit : quadratic S-box on 3 bits
- 128-bit : S-box of degree 3, on 4 bits

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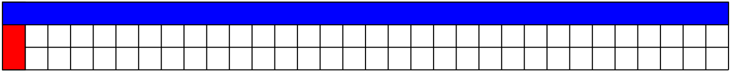

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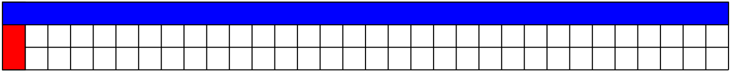

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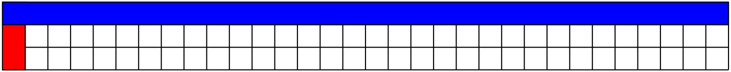

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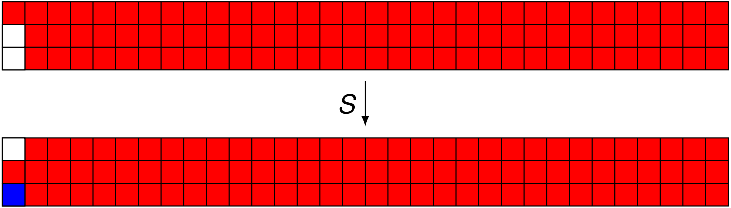
14 rounds

Round	1	2	3	4	5	6	7	8	9	10
96-bit	2	4	8	16	32	64	80	88	92	**94**
128-bit	3	9	27	81	112	122	126	127	127	127

PYJAMASK : 11 ROUNDS DISTINGUISHER



- Value in blue depends on three key bits (7 monomials)

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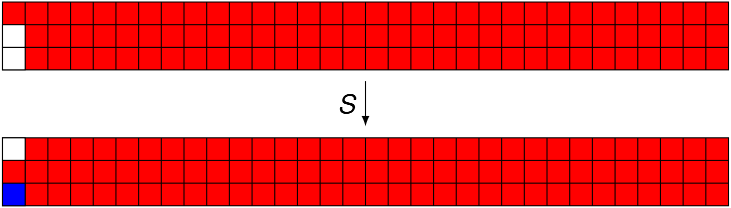

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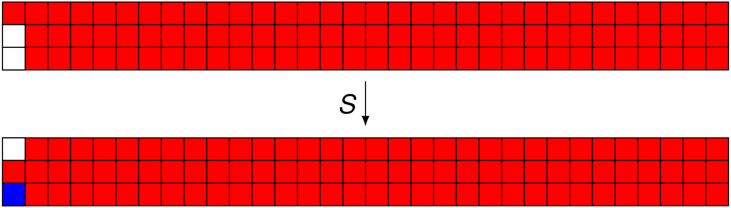

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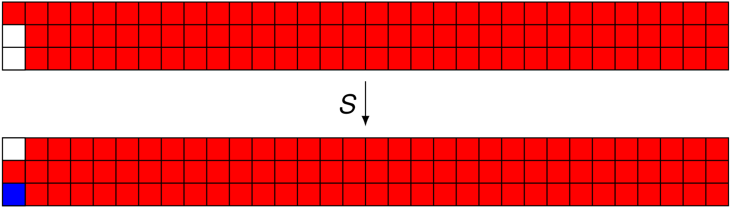

- Value in blue depends on three key bits (7 monomials)
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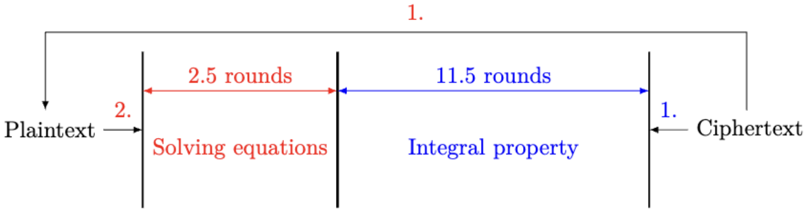
- Gives $(3 \cdot 7 - 7) \cdot 32 = 448$ equations

PYJAMASK : THE DEVIL IS IN THE DETAILS



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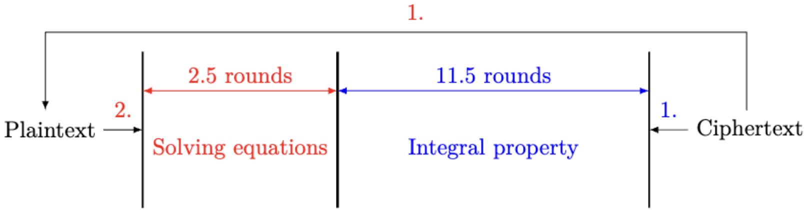

$$\sum_{j=1}^{2^{94}} S \circ A_{k^{(2)}} \circ L \circ \widehat{S} \circ A_{k^{(1)}} \circ L \circ \widehat{S} \circ A_{k^{(0)}} \left(P^{(j)} \right)$$

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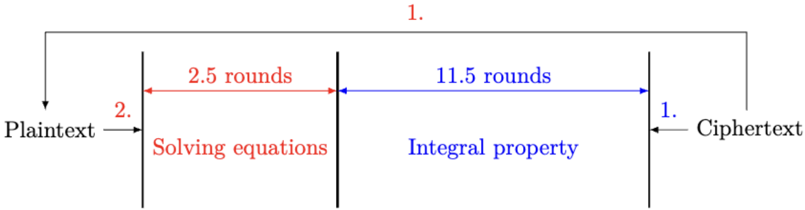

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$$\sum_{i=1}^{8} \binom{96+128}{i} \approx 2^{47}$$

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7642713	3910569	3829480	154

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7 642 713	3 910 569	3 829 480	154

Cost of the attack : 2^{114}

PYJAMASK : SUMMARY AND FUTURE WORK

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Pyjamask : Summary and future work

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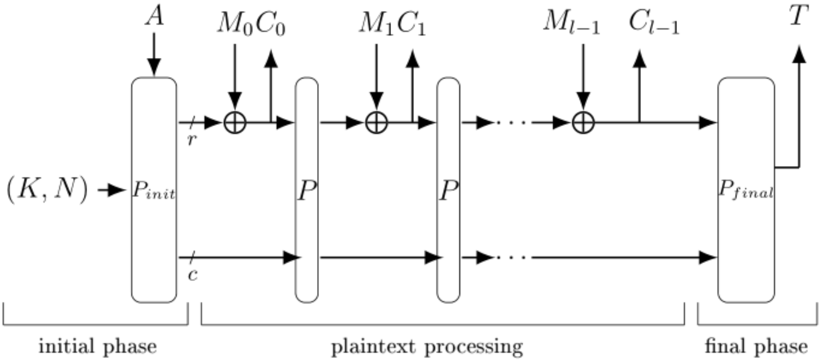
Generic Attack on Duplex-Based AEAD Modes Using Random Function Statistics

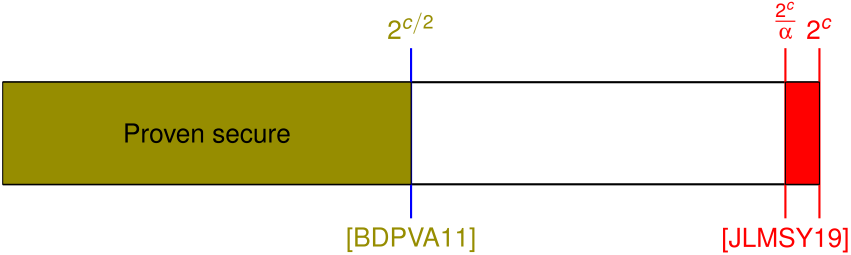
Gilbert, Heim Boissier, Khati, R.

EUROCRYPT 2023

Duplex mode (Bertoni, Daemen, Peeters and Van Assche, 2012)



Duplex mode : Security



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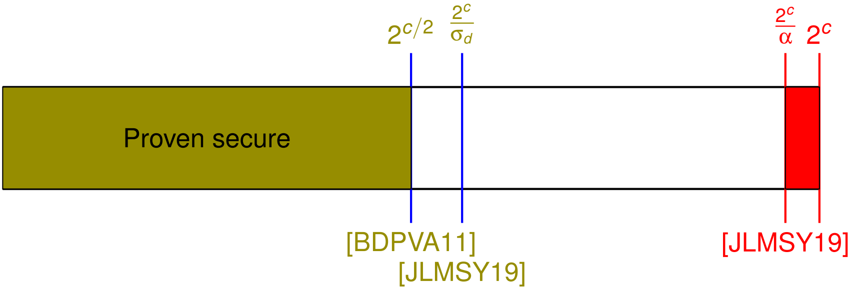
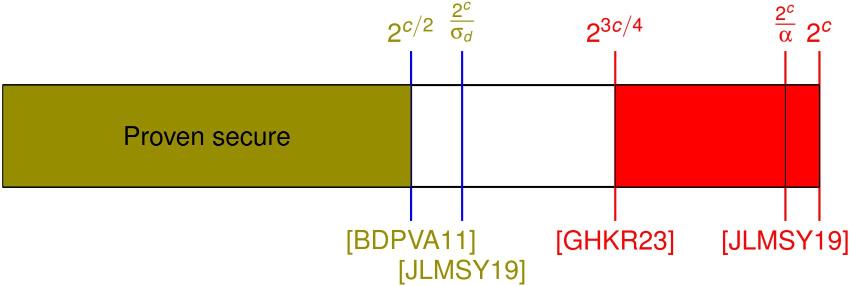


DUPLEX MODE : SECURITY



Duplex mode : Main observation

$C_\beta^\ell = \beta_\ell = \underbrace{\beta||\cdots||\beta}_{\ell}$:

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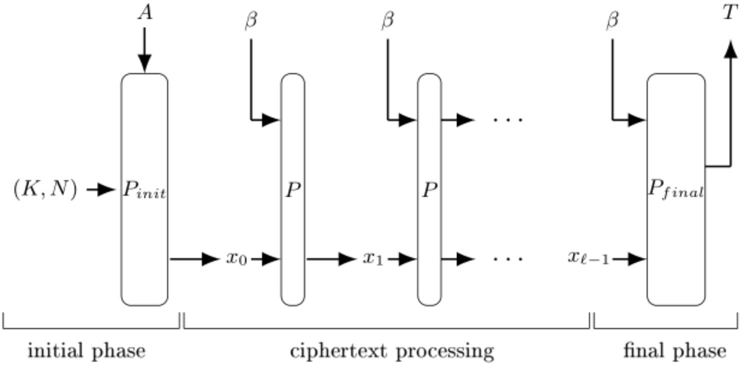
$$C_\beta^\ell = \beta_\ell = \underbrace{\beta || \cdots || \beta}_{\ell} :$$

$$\begin{array}{rcccc} f_\beta & : & \mathbb{F}_2^c & \longrightarrow & \mathbb{F}_2^c \\ & & x & \longmapsto & \lfloor P(\beta || x) \rfloor_c \end{array}$$



Definition : Exceptional function

An exceptional function $f : X \rightarrow X$ is said exceptional if its largest component is big and its cycle is small.

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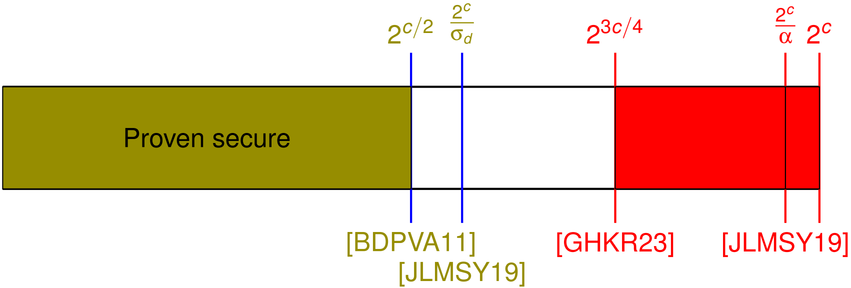
Forgery attack in $O(2^{\frac{3c}{4}})$

DUPLEX MODE : IMPROVEMENTS



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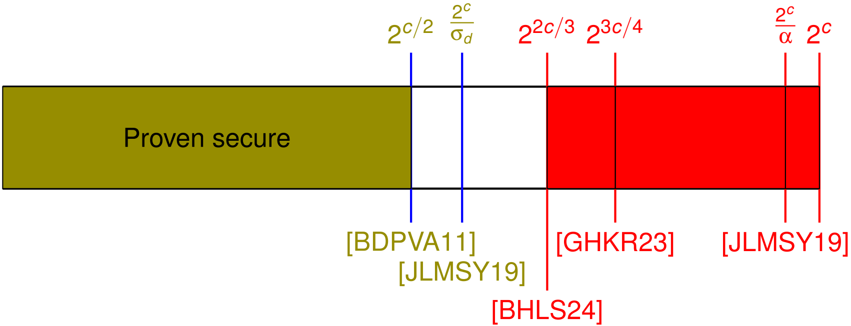


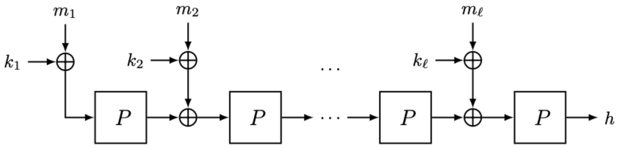
On the Security of Keyed Hashing Based on Public Permutations

Fuchs, R., Daemen

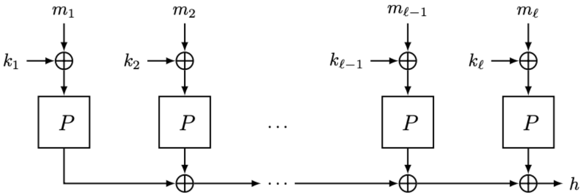
CRYPTO 2023

Comparison of keyed compression functions

The serial construction :



The parallel construction :



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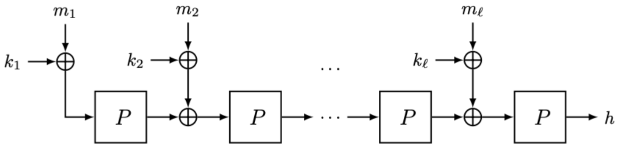

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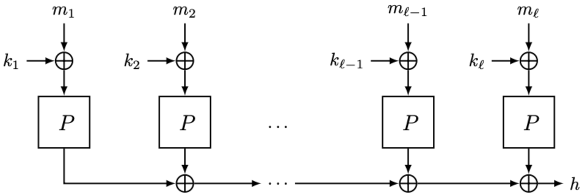

Security model : the attacker only gets $E_{K'}(h)$.

Comparison of keyed compression functions

The relevant security criteria are

- The differential uniformity for the serial case :

$$\mathrm{MDP}_f = \max_{a \neq 0, b} \mathrm{DP}_f(a, b)$$

- The maximum in norm two for the parallel case :

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And

$$\mathrm{MDP}_f \geq \mathrm{MNDP}_f$$

KEYED HASHING : SUMMARY AND FUTURE WORK

Summary :

- The parallel construction provides better security
- Use affine spaces to obtain a quadratic gain

Open question :

- How to estimate accurately the MDP_f and the MNDP_f ?

Conclusion and Perspectives

Conclusion and perspectives

Cryptanalysis with polynomials :

- Collisions, key-recovery and distinguisher

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With a focus on :

- Low-data cryptanalysis
- For reproductibility of cryptanalysis results
- Constrained models such as WPRFs

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I do cryptanalysis