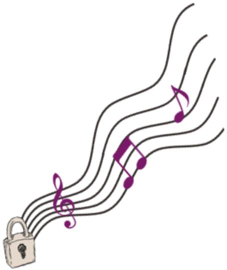
Arithmetization-Oriented Primitives (AOP): A need for new design and cryptanalysis tools



Clémence Bouvier

Seminar CAS^{3}C^3, Grenoble
January 19th, 2024

RUHR UNIVERSITÄT BOCHUM RUB

Toy example of Zero-Knowledge Proof

	2		5		1		9	
8			2		3			6
	3			6			7	
		1				6		
5	4						1	9
		2				7		
	9			3			8	
2			8		4			7
	1		9		7		6	

Unsolved Sudoku

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	9			3			8	
2			8		4			7
	1		9		7		6	

Unsolved Sudoku

4	2	*6*	5	*7*	1	*3*	9	*8*
8	*5*	*7*	2	*9*	3	*1*	*4*	6
1	3	*9*	*4*	6	*8*	*2*	7	*5*
9	*7*	1	*3*	*8*	*5*	6	*2*	*4*
5	4	*3*	*7*	*2*	*6*	*8*	1	9
6	*8*	2	*1*	*4*	*9*	7	*5*	*3*
7	9	*4*	*6*	3	*2*	*5*	8	*1*
2	*6*	*5*	8	*1*	4	*9*	*3*	7
3	1	*8*	9	*5*	7	*4*	6	*2*

Solved Sudoku

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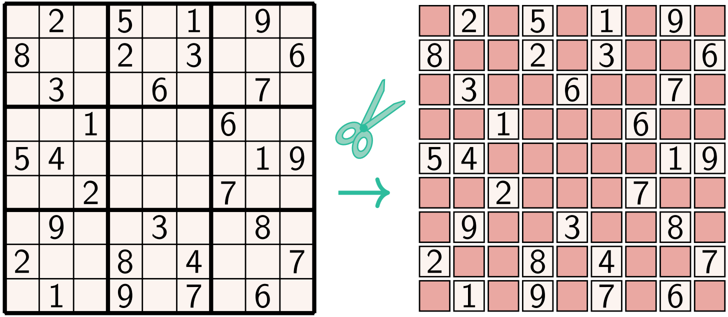

Unsolved Sudoku

Grid cutting

Toy example of Zero-Knowledge Proof

	2		5		1		9	
8			2		3			6
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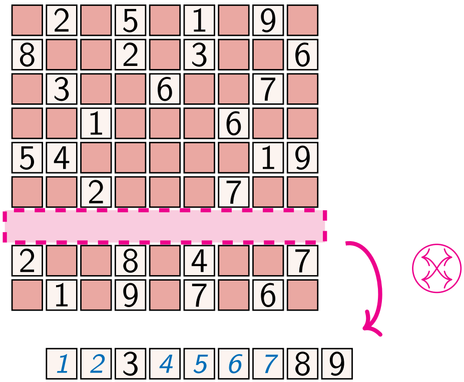

Rows checking

Toy example of Zero-Knowledge Proof

	2		5		1		9	
8			2		3			6
	3			6			7	
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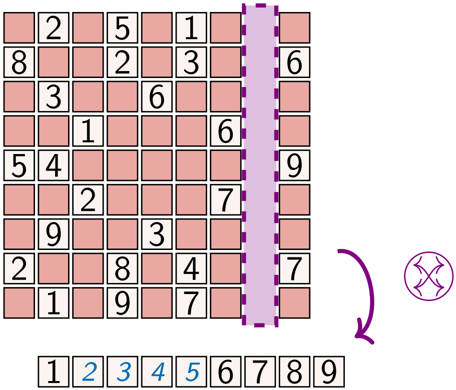
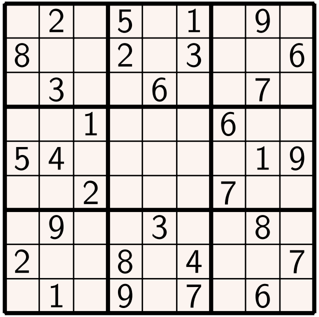
Unsolved Sudoku

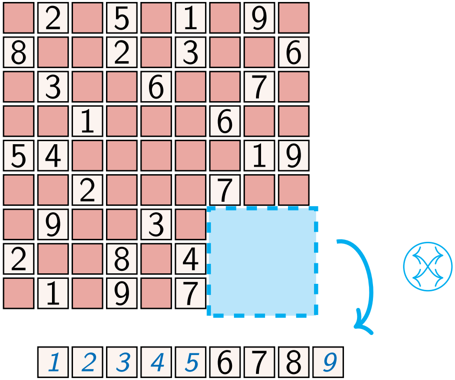


Columns checking

Toy example of Zero-Knowledge Proof



Unsolved Sudoku

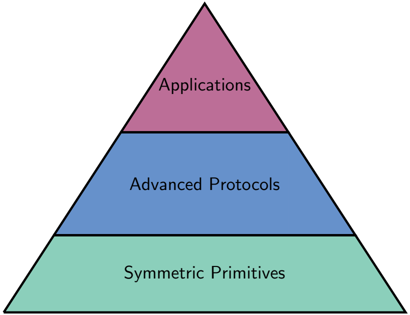


Squares checking

A need for new primitives

Protocols requiring new primitives:

- ⋆ **MPC**: Multiparty Computation
- ⋆ **FHE**: Fully Homomorphic Encryption
- ⋆ **ZK**: Systems of Zero-Knowledge proofs
  Example: SNARKs, STARKs, Bulletproofs



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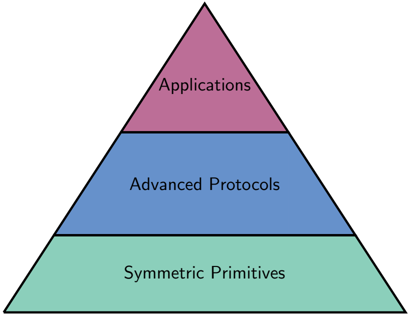


Problem: Designing new symmetric primitives

And analyse their security!

Block ciphers

- input: n-bit block

$$x \in \mathbb{F}_2^n$$

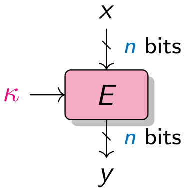
- parameter: k-bit key

$$\kappa \in \mathbb{F}_2^k$$

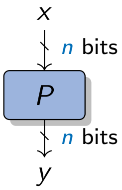
- output: n-bit block

$$y = E_\kappa(x) \in \mathbb{F}_2^n$$

- symmetry: E and E^{-1} use the same κ



(a) *Block cipher*



(b) *Random permutation*

Block ciphers

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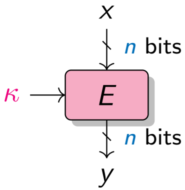
A block cipher is a family of 2^k permutations of $\mathbb{F}_2^n$.



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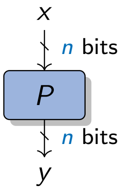

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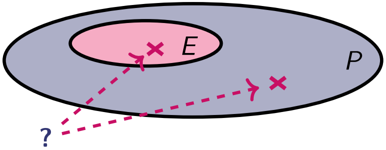
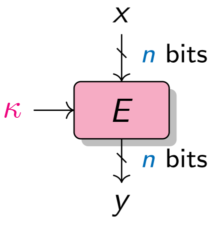


Iterated constructions

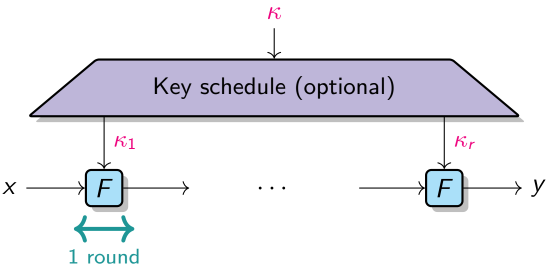
How to build an efficient block cipher?

By iterating a round function.



Block cipher

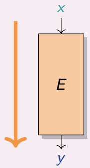
$\Rightarrow$



Comparison with the traditional case

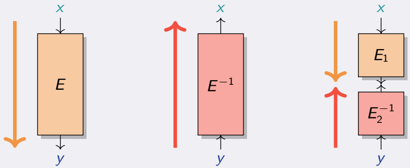
Traditional case

$$y \leftarrow E(x)$$



Arithmetization-oriented

$$y \leftarrow E(x) \quad \text{and} \quad y == E(x)$$



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- ⋆ Optimized for:
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- ⋆ Alphabet size:
  $\mathbb{F}_2^n$, with $n \simeq 4, 8$

  Ex: Field of AES: $\mathbb{F}_{2^n}$ where $n = 8$

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$$y \leftarrow E(x) \quad \text{and} \quad y == E(x)$$

- ⋆ Optimized for:
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- ⋆ Alphabet size:
  $\mathbb{F}_q$, with $q \in \{2^n, p\}, p \simeq 2^n,\ n \geq 64$

  Ex: Scalar Field of Curve BLS12-381: $\mathbb{F}_p$ where

  $p =$ 0x73eda753299d7d483339d80809a1d805 53bda402fffe5bfeffffffff00000001

Comparison with the traditional case

Traditional case

$$y \leftarrow E(x)$$

- Optimized for:
  implementation in software/hardware
- Alphabet size:
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- Operations:
  logical gates/CPU instructions

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- Operations:
  large finite-field arithmetic

Comparison with the traditional case

Traditional case

$$y \leftarrow E(x)$$

⋆ Optimized for:
impleme… …/hardware

…size:
…2, with $n \simeq 4, 8$

⋆ Operations:
logical gates/CPU instructions

Decades of Cryptanalysis

Arithmetization-oriented

$$y \leftarrow E(x) \quad \text{and} \quad y == E(x)$$

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integration… …rotocols

…e:
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⋆ Operations:
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$\leq$ 5 years of Cryptanalysis

Overview of the contributions

Design of a new AO primitive

- *New Design Techniques for Efficient Arithmetization-Oriented Hash Functions: Anemoi Permutations and Jive Compression Mode.*
  Bouvier, Briaud, Chaidos, Perrin, Salen, Velichkov, Willems. **CRYPTO 2023**.

Practical cryptanalysis

- *Algebraic Attacks Against some Arithmetization-Oriented Primitives.*
  Bariant, Bouvier, Leurent, Perrin. **ToSC, 2022**.

Theoretical cryptanalysis

- *On the Algebraic Degree of Iterated Power Functions.*
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- *Coefficient Grouping for Complex Affine Layers.*
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Design of Anemoi

- ⋆ Link between CCZ-equivalence and Arithmetization-Orientation
- ⋆ A new S-Box: the Flystel
- ⋆ A new family of ZK-friendly hash functions: Anemoi

Performance metric

What does "efficient" mean for Zero-Knowledge Proofs?

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"It depends"

Performance metric

What does "efficient" mean for Zero-Knowledge Proofs?

"It depends"

Example

R1CS (Rank-1 Constraint System): minimizing the number of multiplications

$$y = (ax + b)^3(cx + d) + ex$$

$t_0 = a \cdot x$ | $t_3 = t_2 \times t_1$ | $t_6 = t_3 \times t_5$

$t_1 = t_0 + b$ | $t_4 = c \cdot x$ | $t_7 = e \cdot x$

$t_2 = t_1 \times t_1$ | $t_5 = t_4 + d$ | $t_8 = t_6 + t_7$

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3 constraints

Our approach

Need: verification using few multiplications.

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⋆ **First approach:** evaluation using few multiplications, e.g. Poseidon [Grassi et al., USENIX21]

$\boxed{y \leftarrow E(x)}$ $\rightsquigarrow$ E: low degree

$\boxed{y == E(x)}$ $\rightsquigarrow$ E: low degree

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⋆ **First breakthrough:** using inversion, e.g. *Rescue* [Aly et al., ToSC20]

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- ⋆ **Our approach:** using $(u, v) = \mathcal{L}(x, y)$, where $\mathcal{L}$ is linear

$\boxed{y \leftarrow F(x)}$ $\rightsquigarrow$ F: high degree

$\boxed{v == G(u)}$ $\rightsquigarrow$ G: low degree

CCZ-equivalence

Inversion

$$\Gamma_F = \{(x, F(x)), x \in \mathbb{F}_q\} \quad \text{and} \quad \Gamma_{F^{-1}} = \left\{\left(y, F^{-1}(y)\right), y \in \mathbb{F}_q\right\}$$

Noting that

$$\Gamma_F = \left\{\left(F^{-1}(y), y\right), y \in \mathbb{F}_q\right\} \ ,$$

then, we have:

$$\Gamma_F = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \Gamma_{F^{-1}} \ .$$

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Definition [Carlet, Charpin and Zinoviev, DCC98]

$F : \mathbb{F}_q \rightarrow \mathbb{F}_q$ and $G : \mathbb{F}_q \rightarrow \mathbb{F}_q$ are **CCZ-equivalent** if

$$\Gamma_F \ = \ \mathcal{L}(\Gamma_G) + c \ , \quad \text{where } \mathcal{L} \text{ is linear.}$$

Advantages of CCZ-equivalence

If $F : \mathbb{F}_q \to \mathbb{F}_q$ and $G : \mathbb{F}_q \to \mathbb{F}_q$ are **CCZ-equivalent**. Then

- ⋆ Differential properties are the same: $\delta_F = \delta_G$.

Differential uniformity

Maximum value of the DDT

$$\delta_F = \max_{a \neq 0, b} |\{x \in \mathbb{F}_q^m, F(x+a) - F(x) = b\}|$$

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$$\delta_F = \max_{a \neq 0, b} |\{x \in \mathbb{F}_q^m, F(x+a) - F(x) = b\}|$$

⋆ Linear properties are the same: $\mathcal{W}_F = \mathcal{W}_G$.

Linearity

Maximum value of the LAT

$$\mathcal{W}_F = \max_{a, b \neq 0} \left| \sum_{x \in \mathbb{F}_{2^n}^m} (-1)^{a \cdot x + b \cdot F(x)} \right|$$

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- ⋆ Verification is the same: if $y \leftarrow F(x)$, $v \leftarrow G(u)$ and $(u, v) = \mathcal{L}(x, y)$

$$y == F(x)? \quad \Longleftrightarrow \quad v == G(u)?$$

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$$y == F(x)? \quad \Longleftrightarrow \quad v == G(u)?$$

- ⋆ The degree is **not preserved**.

Example

in $\mathbb{F}_p$ where

$$p = \texttt{0x73eda753299d7d483339d80809a1d80553bda402fffe5bfeffffffff00000001}$$

if $F(x) = x^5$ then $F^{-1}(x) = x^{5^{-1}}$ where

$$5^{-1} = \texttt{0x2e5f0fbadd72321ce14a56699d73f002217f0e679998f19933333332cccccccd}$$

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$$\boxed{y == F(x)? \quad \iff \quad v == G(u)?}$$

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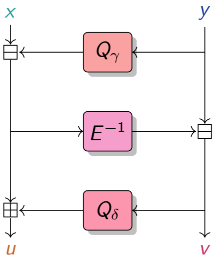
The Flystel

Butterfly + Feistel ⇒ Flystel

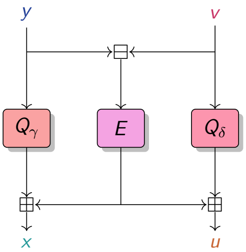
A 3-round Feistel-network with
$Q_\gamma : \mathbb{F}_q \rightarrow \mathbb{F}_q$ and $Q_\delta : \mathbb{F}_q \rightarrow \mathbb{F}_q$ two quadratic functions, and $E : \mathbb{F}_q \rightarrow \mathbb{F}_q$ a permutation

High-Degree
permutation



Open Flystel $\mathcal{H}$.

Low-Degree
function



Closed Flystel $\mathcal{V}$.

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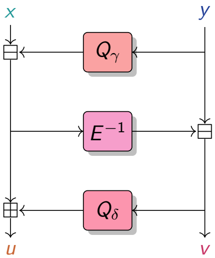
High-Degree permutation



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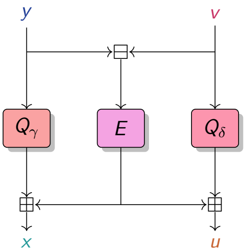
Low-Degree function



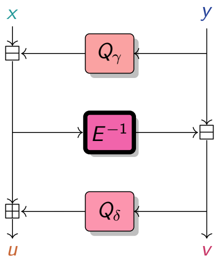
Closed Flystel $\mathcal{V}$.

$$\Gamma_{\mathcal{H}} = \mathcal{L}(\Gamma_{\mathcal{V}}) \quad \text{s.t.} \quad ((x,y),(u,v)) = \mathcal{L}\left(\ ((v,y),(x,u))\ \right)$$

Advantage of CCZ-equivalence

⋆ High-Degree Evaluation.

High-Degree permutation



Open `Flystel` $\mathcal{H}$.

Example

if $E : x \mapsto x^5$ in $\mathbb{F}_p$ where

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`53bda402fffe5bfeffffffff00000001`

then $E^{-1} : x \mapsto x^{5^{-1}}$ where

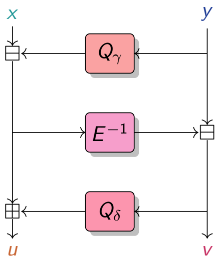
$5^{-1} =$ `0x2e5f0fbadd72321ce14a56699d73f002`
`217f0e679998f19933333332cccccccd`

Advantage of CCZ-equivalence

- ⋆ High-Degree Evaluation.
- ⋆ Low-Degree Verification.

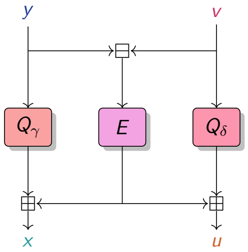
$$\boxed{(u, v) == \mathcal{H}(x, y) \Leftrightarrow (x, u) == \mathcal{V}(y, v)}$$

High-Degree permutation



Open `Flystel` $\mathcal{H}$.

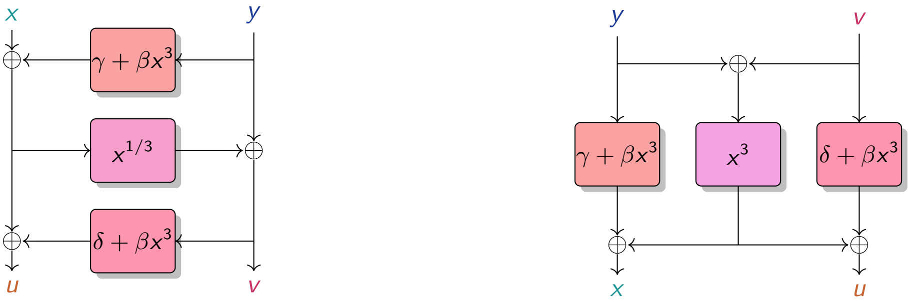
Low-Degree function



Closed `Flystel` $\mathcal{V}$.

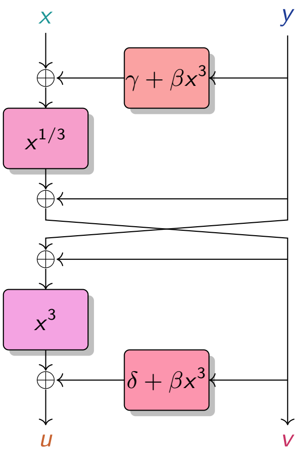
Flystel in $\mathbb{F}_{2^n}$, n odd

$$Q_\gamma(x) = \gamma + \beta x^3 \,, \quad Q_\delta(x) = \delta + \beta x^3 \,, \quad \text{and} \quad E(x) = x^3$$



Open `Flystel`$_2$. *Closed* `Flystel`$_2$.

Properties of Flystel in $\mathbb{F}_{2^n}$, n odd



Degenerated Butterfly.

Introduced by [Perrin et al. 2016].

Theorems in [Li et al. 2018] state that if $\beta \neq 0$:

- Differential properties

$$\delta_{\mathcal{H}} = \delta_{\mathcal{V}} = 4$$

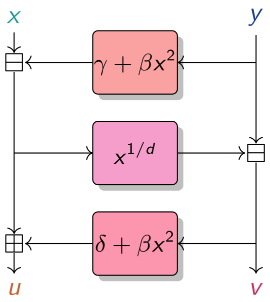
- Linear properties

$$\mathcal{W}_{\mathcal{H}} = \mathcal{W}_{\mathcal{V}} = 2^{n+1}$$

- Algebraic degree
  - Open $\texttt{Flystel}_2$: $\deg_{\mathcal{H}} = n$
  - Closed $\texttt{Flystel}_2$: $\deg_{\mathcal{V}} = 2$

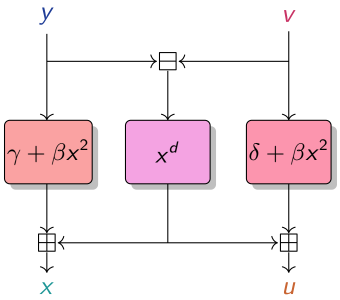
Flystel in $\mathbb{F}_p$

$$Q_\gamma(x) = \gamma + \beta x^2 \,, \quad Q_\delta(x) = \delta + \beta x^2 \,, \quad \text{and} \quad E(x) = x^d$$



Open $\texttt{Flystel}_p$.

usually
$d = 3$ or 5.



Closed $\texttt{Flystel}_p$.

Properties of Flystel in $\mathbb{F}_p$

⋆ Differential properties

$\texttt{Flystel}_\texttt{p}$ has a differential uniformity:

$$\delta_{\mathcal{H}} = \max_{a \neq 0, b} |\{x \in \mathbb{F}_p^2, \mathcal{H}(x + a) - \mathcal{H}(x) = b\}| \leq d - 1$$

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Solving the open problem of finding an APN (Almost-Perfect Non-linear) permutation over $\mathbb{F}_p^2$

⋆ Linear properties

Conjecture:

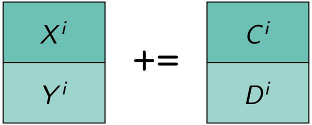
$$\mathcal{W}_{\mathcal{H}} = \max_{a, b \neq 0} \left| \sum_{x \in \mathbb{F}_p^2} exp\left(\frac{2\pi i(\langle a, x\rangle - \langle b, \mathcal{H}(x)\rangle)}{p}\right) \right| \leq p \log p \ ?$$

The SPN Structure

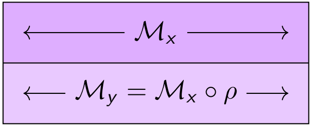
The internal state of `Anemoi` and its basic operations.

A Substitution-Permutation Network with:

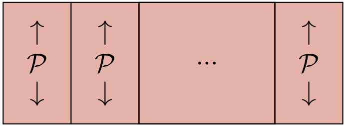
(a) *Internal state.*



(b) *The constant addition.*

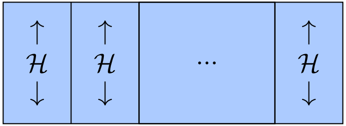


(c) *The diffusion layer.*



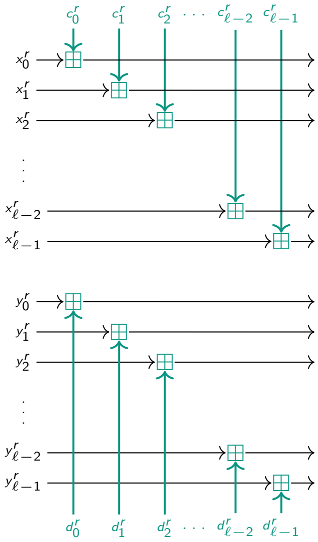
with $\mathcal{P} = \begin{bmatrix} 2 & 1 \\ 1 & 1 \end{bmatrix}$

(d) *The Pseudo-Hadamard Transform.*



(e) *The S-box layer.*

The SPN Structure



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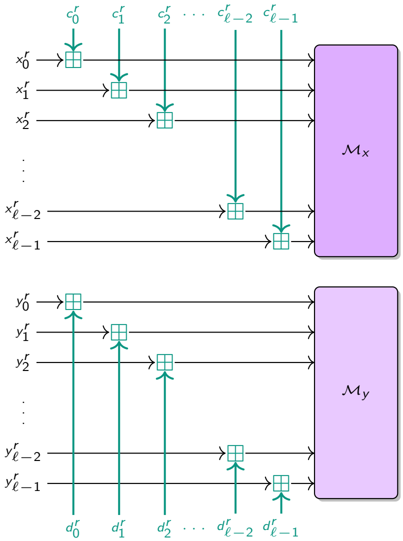

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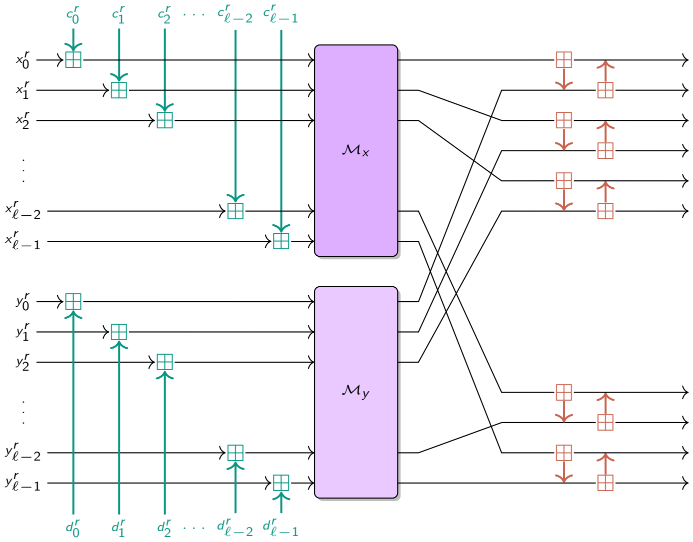

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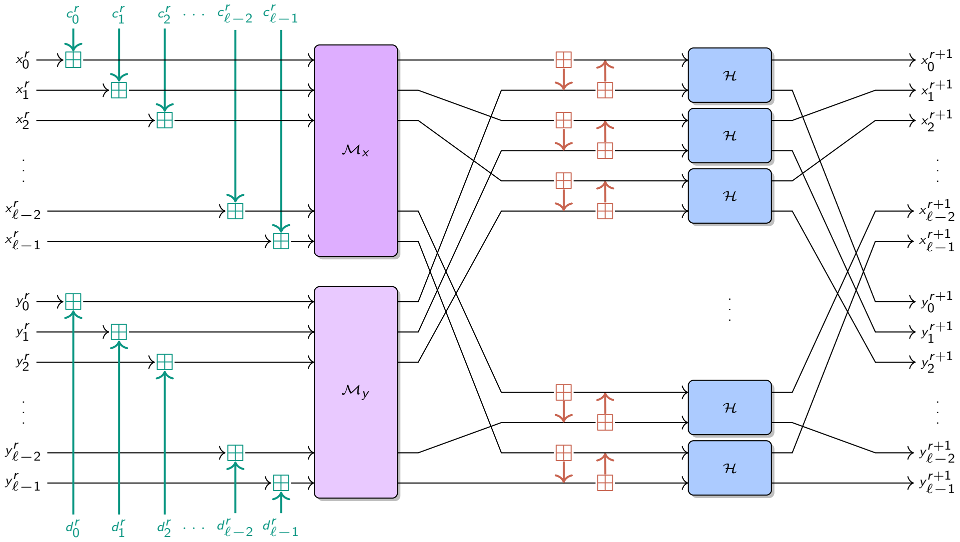

Number of rounds

$$\boxed{\texttt{Anemoi}_{q,d,\ell} = \mathcal{M} \circ \mathrm{R}_{n_r-1} \circ \ldots \circ \mathrm{R}_0}$$

⋆ Choosing the number of rounds

$$n_r \geq \max\left\{ 8\ ,\ \underbrace{\min(5, 1+\ell)}_{\text{security margin}} + \underbrace{2 + \min\left\{ r \in \mathbb{N} \;\middle|\; \binom{4\ell r + \kappa_d}{2\ell r}^2 \geq 2^s \right\}}_{\text{to prevent algebraic attacks}} \right\} .$$

d (κ_d)	3 (1)	5 (2)	7 (4)	11 (9)
$\ell = 1$	21	21	20	19
$\ell = 2$	14	14	13	13
$\ell = 3$	12	12	12	11
$\ell = 4$	12	12	11	11

Number of rounds of `Anemoi` *($s = 128$).*

Performance metric

What does "efficient" mean for Zero-Knowledge Proofs?

"It depends"

Example

R1CS (Rank-1 Constraint System): minimizing the number of multiplications

$$y = (ax + b)^3(cx + d) + ex$$

$t_0 = a \cdot x$	$t_3 = t_2 \times t_1$	$t_6 = t_3 \times t_5$
$t_1 = t_0 + b$	$t_4 = c \cdot x$	$t_7 = e \cdot x$
$t_2 = t_1 \times t_1$	$t_5 = t_4 + d$	$t_8 = t_6 + t_7$

3 constraints

Some Benchmarks

	m $(= 2\ell)$	RP[1]	Poseidon[2]	Griffin[3]	Anemoi
R1CS	2	208	198	-	**76**
	4	224	232	112	**96**
	6	216	264	-	**120**
	8	256	296	176	**160**
Plonk	2	312	380	-	**191**
	4	560	832	**260**	316
	6	756	1344	-	**460**
	8	1152	1920	**574**	648
AIR	2	156	300	-	**126**
	4	**168**	348	**168**	**168**
	6	**162**	396	-	216
	8	**192**	456	264	288

(a) *when* $d = 3$.

	m $(= 2\ell)$	RP	Poseidon	Griffin	Anemoi
R1CS	2	240	216	-	**95**
	4	264	264	**110**	120
	6	288	315	-	**150**
	8	384	363	**162**	200
Plonk	2	320	344	-	**212**
	4	528	696	**222**	344
	6	768	1125	-	**496**
	8	1280	1609	**492**	696
AIR	2	**200**	360	-	210
	4	**220**	440	**220**	280
	6	**240**	540	-	360
	8	**320**	640	360	480

(b) *when* $d = 5$.

Constraint comparison for standard arithmetization, without optimization ($s = 128$).

[1] *Rescue* [Aly et al., ToSC20]

[2] Poseidon [Grassi et al., USENIX21]

[3] Griffin [Grassi et al., CRYPTO23]

Take-Away

Anemoi: A new family of ZK-friendly hash functions

- ⋆ Identify a link between AO and CCZ-equivalence
- ⋆ Contributions of fundamental interest:
  - ⋆ New S-box: Flystel
  - ⋆ New mode: Jive

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Related works

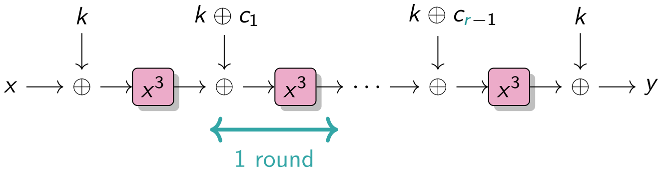
- ⋆ $\texttt{AnemoiJive}_3$ with TurboPlonK [Liu et al., 2022]
- ⋆ Arion [Roy, Steiner and Trevisani, 2023]
- ⋆ APN permutations over prime fields [Budaghyan and Pal, 2023]

Cryptanalysis of MIMC

- ⋆ Study of the corresponding sparse univariate polynomials
- ⋆ Bounding the algebraic degree
- ⋆ Tracing maximum-weight exponents reaching the upper bound
- ⋆ Study of higher-order differential attacks

The block cipher MiMC

- ⋆ Minimize the number of multiplications in $\mathbb{F}_{2^n}$.
- ⋆ Construction of MiMC_3 [Albrecht et al., AC16]:
  - ⋆ n-bit blocks (n odd ≈ 129): $x \in \mathbb{F}_{2^n}$
  - ⋆ n-bit key: $k \in \mathbb{F}_{2^n}$
  - ⋆ decryption : replacing x^3 by x^s where $s = (2^{n+1} - 1)/3$



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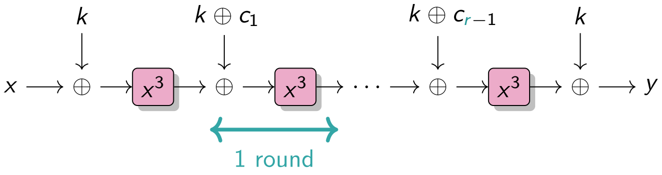
$$r := \lceil n \log_3 2 \rceil \ .$$

n	129	255	769	1025
r	82	161	486	647

Number of rounds for MiMC.



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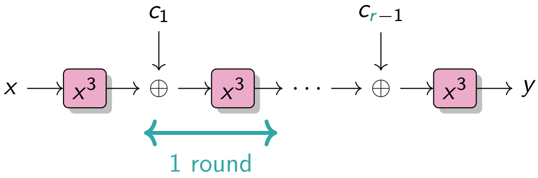

Algebraic degree - 1st definition

Let $f : \mathbb{F}_2^n \to \mathbb{F}_2$, there is **a unique multivariate polynomial** in $\mathbb{F}_2[x_1, \dots x_n] / \left((x_i^2 + x_i)_{1 \le i \le n}\right)$:

$$f(x_1, ..., x_n) = \sum_{u \in \mathbb{F}_2^n} a_u x^u, \text{ where } a_u \in \mathbb{F}_2,\ x^u = \prod_{i=1}^{n} x_i^{u_i} \ .$$

This is the **Algebraic Normal Form (ANF)** of f.

Definition

Algebraic degree of $f : \mathbb{F}_2^n \to \mathbb{F}_2$:

$$\deg^a(f) = \max\left\{\mathrm{wt}(u) : u \in \mathbb{F}_2^n, a_u \neq 0\right\} \ .$$

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If $F : \mathbb{F}_2^n \to \mathbb{F}_2^m$, with $F(x) = (f_1(x), \dots f_m(x))$, then

$$\deg^a(F) = \max\{\deg^a(f_i), \; 1 \le i \le m\} \; .$$

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This is the **Algebraic Normal Form (ANF)** of f.

Example: ANF of $x \mapsto x^3$ in $\mathbb{F}_{2^{11}}$

$$\begin{aligned}
(&x_0x_{10} + x_0 + x_1x_5 + x_1x_9 + x_2x_7 + x_2x_9 + x_2x_{10} + x_3x_4 + x_3x_5 + x_4x_8 + x_4x_9 + x_5x_{10} + x_6x_7 + x_6x_{10} + x_7x_8 + x_9x_{10},\\
&x_0x_1 + x_0x_6 + x_2x_5 + x_2x_8 + x_3x_6 + x_3x_9 + x_3x_{10} + x_4 + x_5x_8 + x_5x_9 + x_6x_9 + x_7x_8 + x_7x_9 + x_7 + x_{10},\\
&x_0x_1 + x_0x_2 + x_0x_{10} + x_1x_5 + x_1x_6 + x_1x_9 + x_2x_7 + x_3x_4 + x_3x_7 + x_4x_5 + x_4x_8 + x_4x_{10} + x_5x_{10} + x_6x_7 + x_6x_8 + x_6x_9 + x_7x_{10} + x_8 + x_9x_{10},\\
&x_0x_3 + x_0x_6 + x_0x_7 + x_1 + x_2x_5 + x_2x_6 + x_2x_8 + x_2x_{10} + x_3x_6 + x_3x_8 + x_3x_9 + x_4x_5 + x_4x_6 + x_4 + x_5x_8 + x_5x_{10} + x_6x_9 + x_7x_9 + x_7 + x_8x_9 + x_{10},\\
&x_0x_2 + x_0x_4 + x_1x_2 + x_1x_6 + x_1x_7 + x_2x_9 + x_2x_{10} + x_3x_5 + x_3x_6 + x_3x_7 + x_3x_9 + x_4x_5 + x_4x_7 + x_4x_9 + x_5 + x_6x_8 + x_7x_8 + x_8x_9 + x_8x_{10},\\
&x_0x_5 + x_0x_7 + x_0x_8 + x_1x_2 + x_1x_3 + x_2x_6 + x_2x_7 + x_2x_{10} + x_3x_8 + x_4x_5 + x_4x_8 + x_5x_6 + x_5x_9 + x_7x_8 + x_7x_9 + x_7x_{10} + x_9,\\
&x_0x_3 + x_0x_6 + x_1x_4 + x_1x_7 + x_1x_8 + x_2 + x_3x_6 + x_3x_7 + x_3x_9 + x_4x_7 + x_4x_9 + x_4x_{10} + x_5x_6 + x_5x_7 + x_5 + x_6x_9 + x_7x_{10} + x_8x_{10} + x_8 + x_9x_{10},\\
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&x_0x_5 + x_0x_{10} + x_1x_8 + x_1x_9 + x_1x_{10} + x_2x_4 + x_2x_6 + x_3x_4 + x_3x_8 + x_3x_9 + x_5x_7 + x_5x_8 + x_5x_9 + x_6x_7 + x_6x_9 + x_7 + x_8x_{10} + x_9x_{10}) .
\end{aligned}$$

Algebraic degree - 2nd definition

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there is **a unique univariate polynomial representation** on $\mathbb{F}_{2^n}$ of degree at most $2^n - 1$:

$$F(x) = \sum_{i=0}^{2^n-1} b_i x^i;\ b_i \in \mathbb{F}_{2^n}$$

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If $F : \mathbb{F}_2^n \to \mathbb{F}_2^n$ is a permutation, then

$$\boxed{\deg^a(F) \leq n - 1}$$

Higher-Order differential attacks

Exploiting a low algebraic degree

For any affine subspace $\mathcal{V} \subset \mathbb{F}_2^n$ with $\dim \mathcal{V} \geq \deg^a(F) + 1$, we have a 0-sum distinguisher:

$$\bigoplus_{x \in \mathcal{V}} F(x) = 0.$$

Random permutation: degree $= n - 1$

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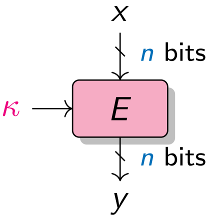
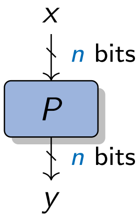
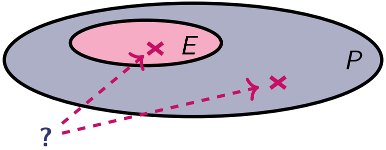


(a) *Block cipher*



(b) *Random permutation*



First Plateau

Polynomial representing r rounds of MIMC$_3$:

$$\mathcal{P}_{3,r}(x) = F_r \circ \ldots F_1(x) \ , \ \text{where } F_i = (x + c_{i-1})^3 \ .$$

Upper bound [Eichlseder et al., AC20]:

$$\lceil r \log_2 3 \rceil \ .$$

Aim: determine

$$B_3^r := \max_c \deg^a(\mathcal{P}_{3,r}) \ .$$

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Example

- ⋆ Round 1: $B_3^1 = 2$

$$\mathcal{P}_{3,1}(x) = x^3$$

$$3 = [11]_2$$

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- Round 1: $B_3^1 = 2$

$$\mathcal{P}_{3,1}(x) = x^3$$

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- Round 2: $B_3^2 = 2$

$$\mathcal{P}_{3,2}(x) = x^9 + c_1 x^6 + c_1^2 x^3 + c_1^3$$

$$9 = [1001]_2\ 6 = [110]_2\ 3 = [11]_2$$

Observed degree

Definition

There is a **plateau** between rounds r and $r+1$ whenever:

$$B_3^{r+1} = B_3^{r} \ .$$

Proposition

If $d = 2^j - 1$, there is always a **plateau** between rounds 1 and 2:

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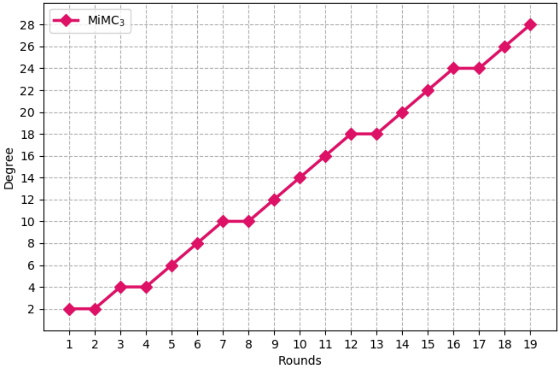

Algebraic degree observed for $n = 31$.

Missing exponents

Proposition

Set of exponents that might appear in the polynomial:

$$\mathcal{E}_{3,r} = \{3 \times j \bmod (2^n - 1) \text{ where } j \text{ is covered by } i,\ i \in \mathcal{E}_{3,r-1}\}$$

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Example

$$\mathcal{P}_{3,1}(x) = x^3 \quad \text{so} \quad \mathcal{E}_{3,1} = \{3\} \ .$$

$$3 = [11]_2 \quad \xrightarrow{\text{cover}} \quad \begin{cases} [00]_2 = 0 & \xrightarrow{\times 3} \quad 0 \\ [01]_2 = 1 & \xrightarrow{\times 3} \quad 3 \\ [10]_2 = 2 & \xrightarrow{\times 3} \quad 6 \\ [11]_2 = 3 & \xrightarrow{\times 3} \quad 9 \end{cases}$$

$$\mathcal{E}_{3,2} = \{0, 3, 6, 9\} \ , \quad \text{indeed} \quad \mathcal{P}_{3,2}(x) = x^9 + c_1 x^6 + c_1^2 x^3 + c_1^3 \ .$$

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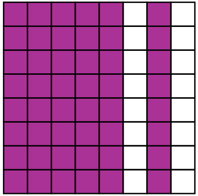
Missing exponents: no exponent $2^{2k} - 1$

Proposition

$$\forall i \in \mathcal{E}_{3,r}, i \not\equiv 5, 7 \bmod 8$$

0	1	2	3	4	5	6	7
8	9	10	11	12	13	14	15
16	17	18	19	20	21	22	23
24	25	26	27	28	29	30	31
32	33	34	35	36	37	38	39
40	41	42	43	44	45	46	47
48	49	50	51	52	53	54	55
56	57	58	59	60	61	62	63

Representation exponents.



Missing exponents $\bmod 8$.

Bounding the degree

Theorem

After r rounds of MIMC_3, the algebraic degree is

$$B_3^r \leq 2 \times \lceil \lfloor r \log_2 3 \rfloor / 2 - 1 \rceil$$

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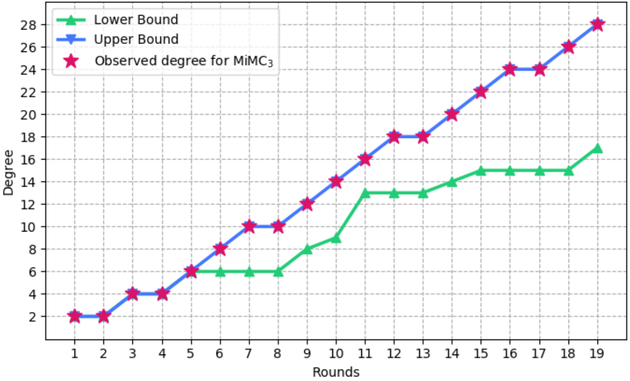
If $3^r < 2^n - 1$:

- A lower bound

$$B_3^r \geq \max\{\text{wt}(3^i), i \leq r\}$$

- **Upper bound reached for almost 16265 rounds**

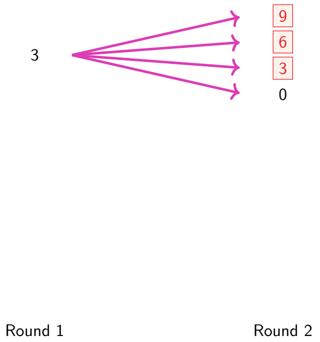


Tracing exponents

3

Round 1

Tracing exponents



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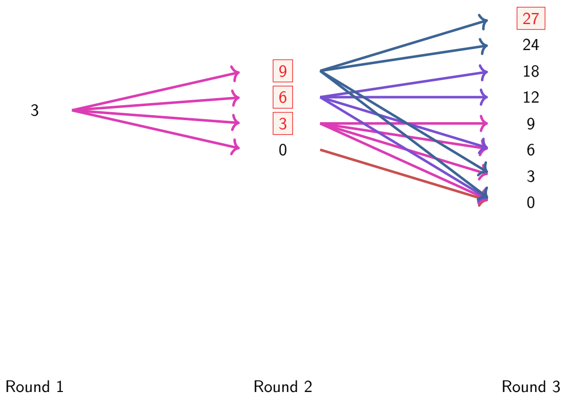
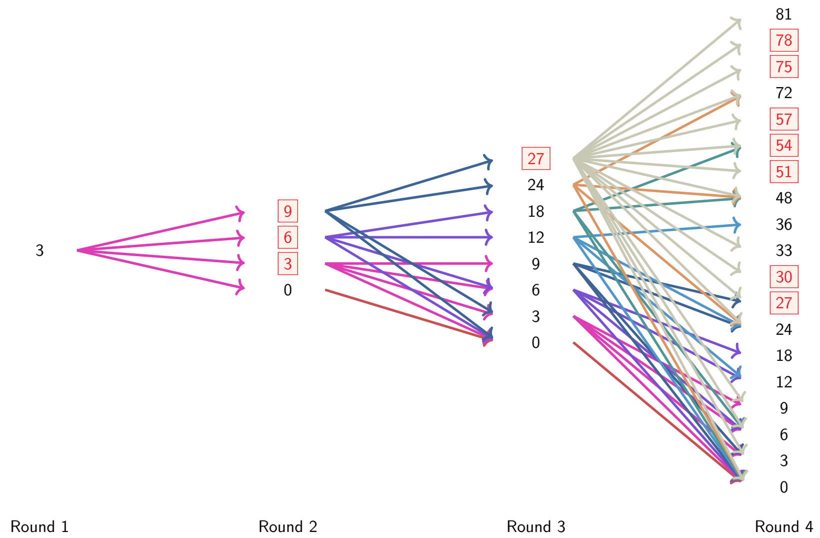


Tracing exponents



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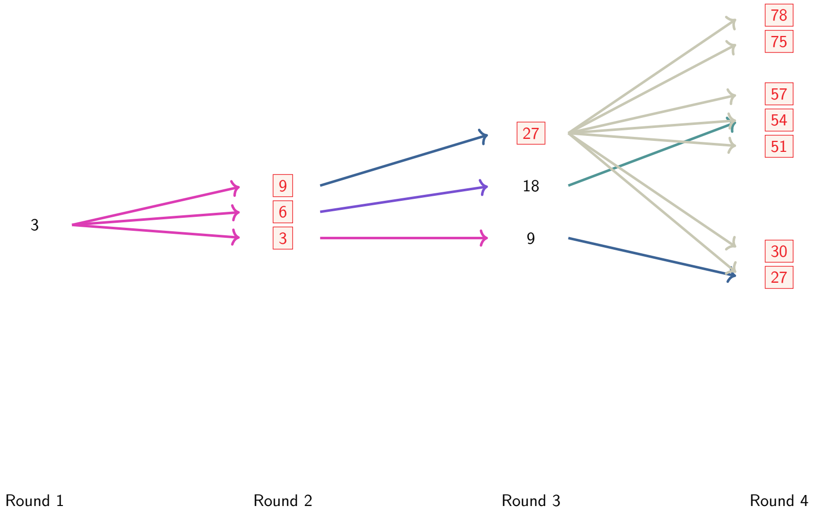

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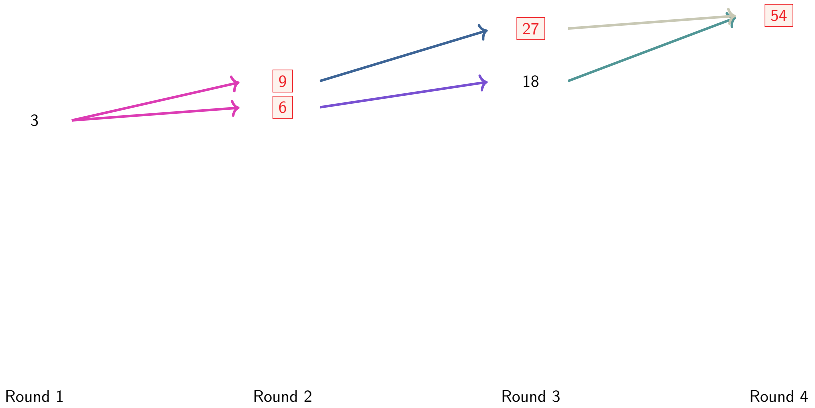

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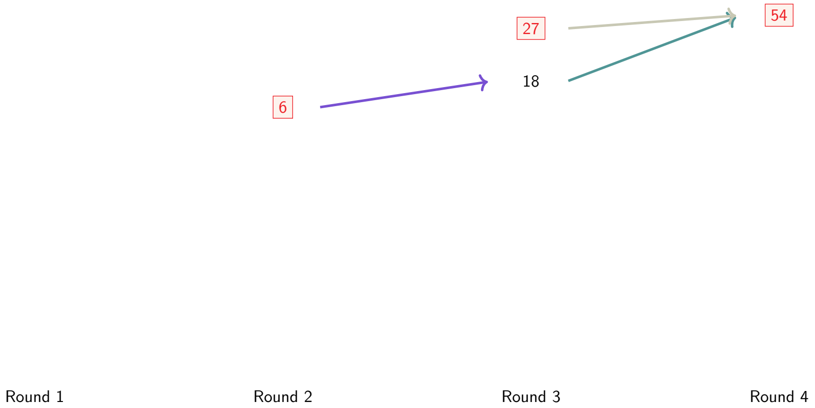

Exact degree

Maximum-weight exponents:

Let $k_r = \lfloor \log_2 3^r \rfloor$.

$\forall r \in \{4, \ldots, 16265\} \backslash \mathcal{F}$ with $\mathcal{F} = \{465, 571, \ldots\}$:

- if $k_r = 1 \bmod 2$,

$$\omega_r = 2^{k_r} - 5 \in \mathcal{E}_{3,r},$$

- if $k_r = 0 \bmod 2$,

$$\omega_r = 2^{k_r} - 7 \in \mathcal{E}_{3,r}.$$

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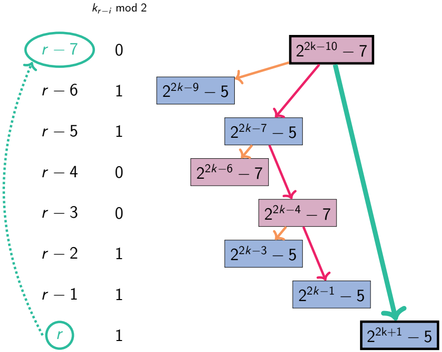

Constructing exponents.

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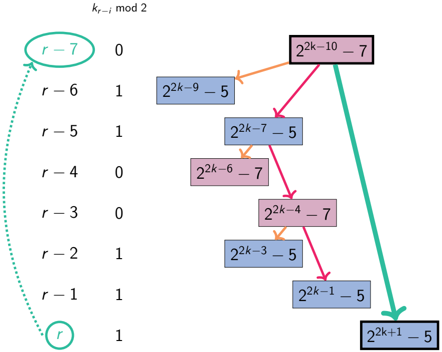


Constructing exponents.

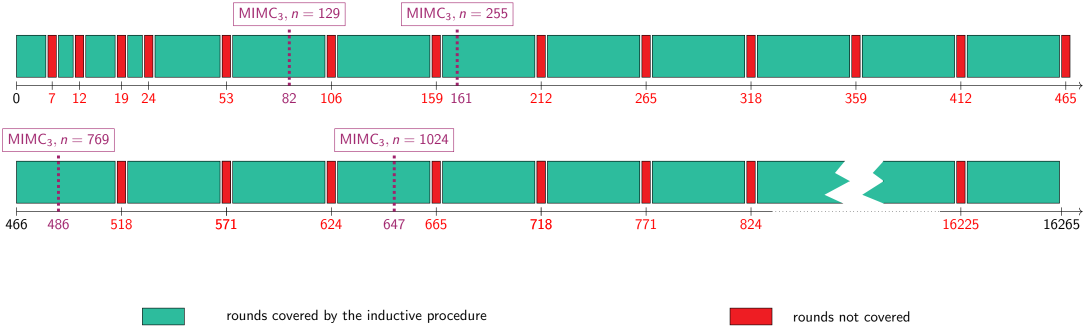
$$\boxed{\text{In most cases,} \quad \exists\, \ell \text{ s.t.} \quad \omega_{r-\ell} \in \mathcal{E}_{3,r-\ell} \Rightarrow \omega_r \in \mathcal{E}_{3,r}}$$

Covered rounds

Idea of the proof:

- ⋆ inductive proof: existence of "good" ℓ

Rounds for which we are able to exhibit a maximum-weight exponent.



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Idea of the proof:

- ⋆ inductive proof: existence of "good" ℓ
- ⋆ MILP solver (`PySCIPOpt`)

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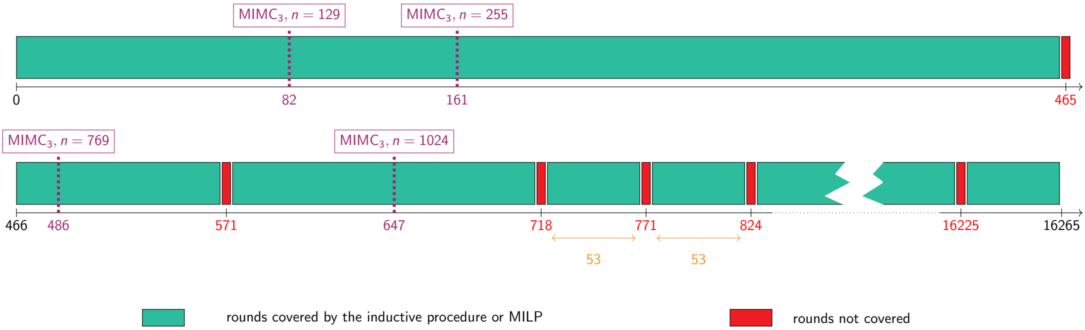
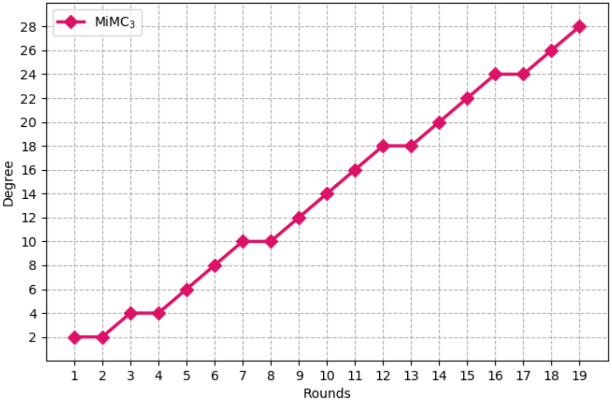


Plateau

Proposition

There is a plateau when $k_r = \lfloor r \log_2 3 \rfloor = 1 \bmod 2$ and $k_{r+1} = \lfloor (r+1) \log_2 3 \rfloor = 0 \bmod 2$



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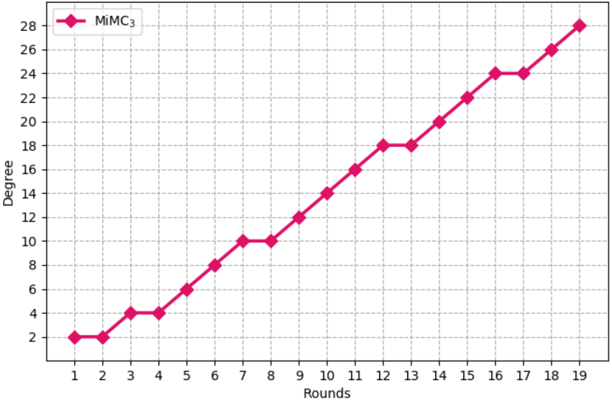


If we have a plateau

$$B_3^r = B_3^{r+1} ,$$

Then the next one is

$$B_3^{r+4} = B_3^{r+5}$$

or

$$B_3^{r+5} = B_3^{r+6} .$$

Music in MIMC_3

- Patterns in sequence $(\lfloor r \log_2 3 \rfloor)_{r>0}$: denominators of semiconvergents of

$$\log_2(3) \simeq 1.5849625$$

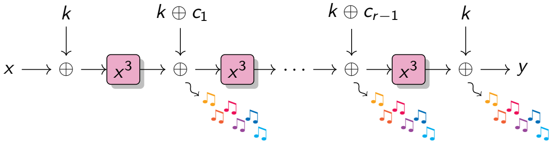
$$\mathfrak{D} = \{\boxed{1}, \boxed{2}, 3, 5, \boxed{7}, \boxed{12}, 17, 29, 41, \boxed{53}, 94, 147, 200, 253, 306, \boxed{359}, \dots\},$$

$$\log_2(3) \simeq \frac{a}{b} \quad \Leftrightarrow \quad 2^a \simeq 3^b$$

- **Music theory:**
  - perfect octave 2:1
  - perfect fifth 3:2

$$2^{19} \simeq 3^{12} \quad \Leftrightarrow \quad 2^7 \simeq \left(\frac{3}{2}\right)^{12}$$

$$\Leftrightarrow \quad \text{7 octaves} \sim \text{12 fifths}$$



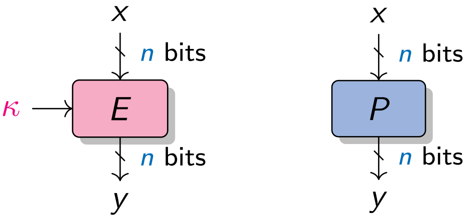
Higher-Order differential attacks

Exploiting a low algebraic degree

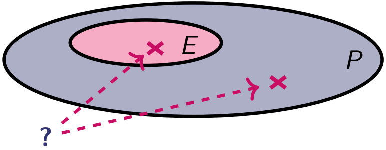
For any affine subspace $\mathcal{V} \subset \mathbb{F}_2^n$ with $\dim \mathcal{V} \geq \deg^a(F) + 1$, we have a 0-sum distinguisher:

$$\bigoplus_{x \in \mathcal{V}} F(x) = 0.$$

Random permutation: degree $= n - 1$

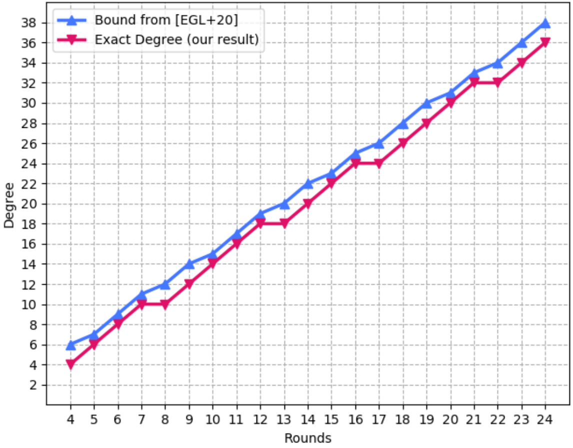


(a) *Block cipher* **(b)** *Random permutation*



Comparison to previous work

First Bound: $\lceil r \log_2 3 \rceil$ Exact degree: $2 \times \lceil \lfloor r \log_2 3 \rfloor / 2 - 1 \rceil$.



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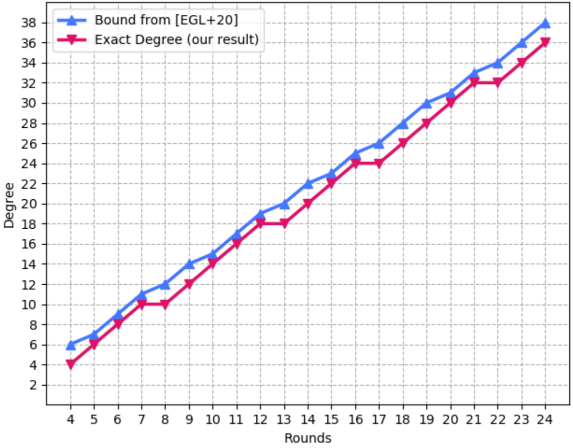

For $n = 129$, $\mathrm{MIMC}_3 = 82$ rounds

Rounds	Time	Data	Source
80/82	2^{128}XOR	2^{128}	[EGL+20]
81/82	2^{128}XOR	2^{128}	**New**
80/82	2^{125}XOR	2^{125}	**New**

Secret-key distinguishers ($n = 129$)

Take-Away

A better understanding of the algebraic degree of MiMC

- guarantee on the degree of MIMC_3
  - upper bound on the algebraic degree
$$2 \times \lceil \lfloor r \log_2 3 \rfloor / 2 - 1 \rceil \ .$$
  - bound tight, up to 16265 rounds
- minimal complexity for higher-order differential attack

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Missing exponents in the univariate representation

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Bounds on the algebraic degree → Higher-Order differential attacks

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↓

Bounds on the algebraic degree → Higher-Order differential attacks

Conclusions

- New tools for designing primitives:
  - `Anemoi`: a new family of ZK-friendly hash functions
  - a link between CCZ-equivalence and AO
  - more general contributions: `Jive`, `Flystel`

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- New tools for designing primitives:
  - Anemoi: a new family of ZK-friendly hash functions
  - a link between CCZ-equivalence and AO
  - more general contributions: Jive, Flystel
- Practical and theoretical cryptanalysis
  - a better insight into the behaviour of algebraic systems
  - a comprehensive understanding of the univariate representation of MiMC
  - guarantees on the algebraic degree of MiMC

Perspectives

- On the design
  - a Flystel with more branches
  - solve the conjecture for the linearity

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  - a `Flystel` with more branches
  - solve the conjecture for the linearity
- On the cryptanalysis
  - solve conjectures to trace maximum-weight exponents
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Cryptanalysis and designing of arithmetization-oriented primitives remain to be explored!

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Cryptanalysis and designing of arithmetization-oriented primitives remain to be explored!

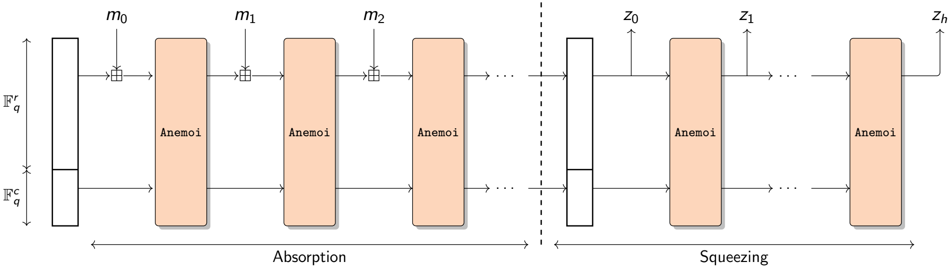
Thank you

Anemoi

More benchmarks and Cryptanalysis

Sponge construction

- Hash function (random oracle):
  - input: arbitrary length
  - ouput: fixed length

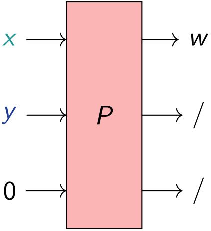


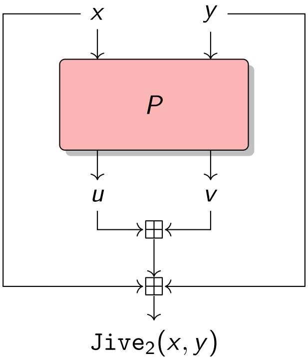
New Mode: Jive

- Compression function (Merkle-tree):
  - input: fixed length
  - output: (input length) /2

Dedicated mode: 2 words in 1

$$(x, y) \mapsto x + y + u + v\ .$$



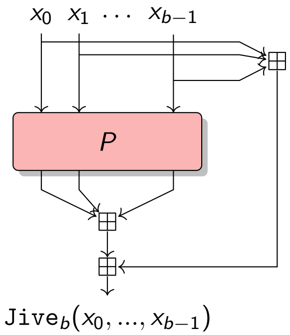


New Mode: Jive

- Compression function (Merkle-tree):
  - input: fixed length
  - output: (input length) /b

Dedicated mode: b words in 1

$$\texttt{Jive}_b(P) : \begin{cases} (\mathbb{F}_q^m)^b & \to \mathbb{F}_q^m \\ (x_0, \ldots, x_{b-1}) & \mapsto \sum_{i=0}^{b-1} (x_i + P_i(x_0, \ldots, x_{b-1})) \end{cases} .$$



Comparison for Plonk (with optimizations)

	m	Constraints
Poseidon	3	110
	2	88
Reinforced Concrete	3	378
	2	236
Rescue–Prime	3	252
Griffin	3	125
AnemoiJive	2	~~86~~ 56

(a) *With 3 wires.*

	m	Constraints
Poseidon	3	98
	2	82
Reinforced Concrete	3	267
	2	174
Rescue–Prime	3	168
Griffin	3	111
AnemoiJive	2	**64**

(b) *With 4 wires.*

Constraints comparison with an additional custom gate for x^α. ($s = 128$).

with an additional quadratic custom gate: 56 constraints

Native performance

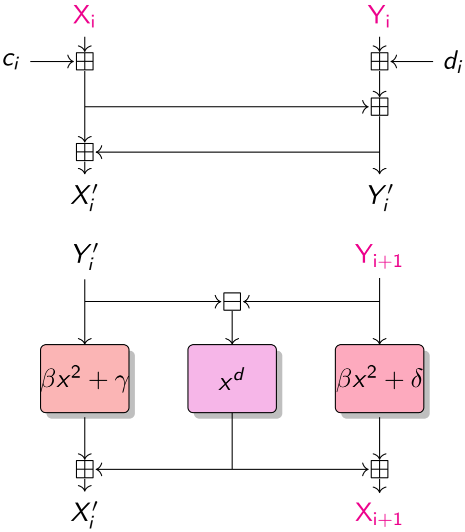
Rescue-12	*Rescue*-8	Poseidon-12	Poseidon-8	Griffin-12	Griffin-8	Anemoi-8
15.67 μs	9.13 μs	5.87 μs	2.69 μs	2.87 μs	**2.59 μs**	4.21 μs

2-to-1 compression functions for $\mathbb{F}_p$ *with* $p = 2^{64} - 2^{32} + 1$ *(*$s = 128$*).*

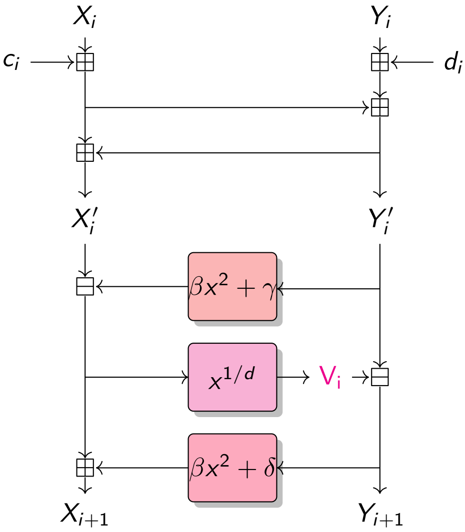
Rescue	Poseidon	Griffin	Anemoi
206 μs	**9.2 μs**	74.18 μs	128.29 μs

For $BLS12 - 381$, *Rescue*, Poseidon, *Anemoi with state size of* 2, Griffin *of* 3 *(*$s = 128$*).*

Algebraic attacks: 2 modelings



(a) *Model 1.*

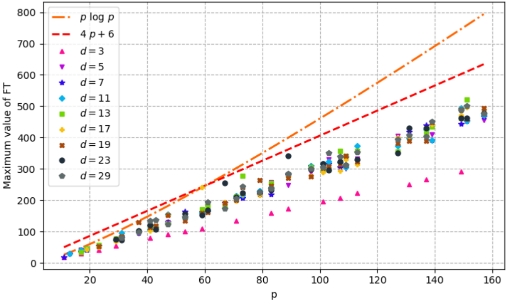


(b) *Model 2.*

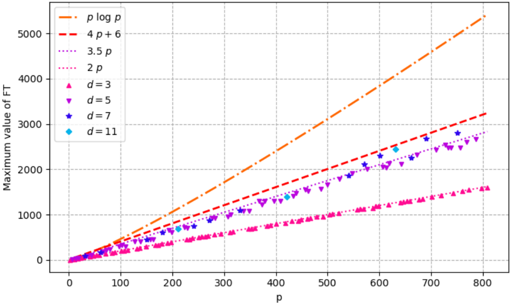
Properties of `Flystel` in $\mathbb{F}_p$

⋆ Linear properties

$$\mathcal{W}_{\mathcal{H}} = \max_{a,b\neq 0}\left|\sum_{x\in\mathbb{F}_p^2} exp\left(\frac{2\pi i(\langle a,x\rangle - \langle b,\mathcal{H}(x)\rangle)}{p}\right)\right| \leq p\log p\ ?$$



(a) *For different d.*



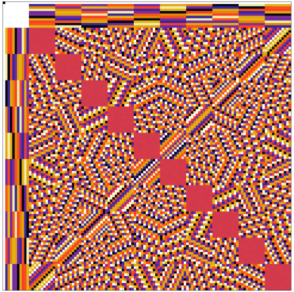
(b) *For the smallest d.*

Conjecture for the linearity.

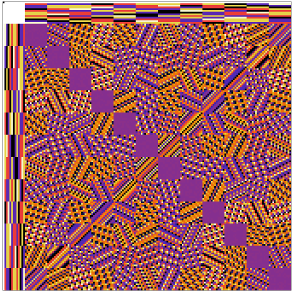
Properties of `Flystel` in $\mathbb{F}_p$

⋆ Linear properties

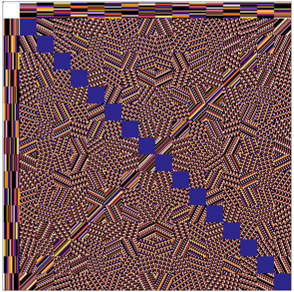
$$\mathcal{W}_{\mathcal{H}} = \max_{a,b \neq 0} \left| \sum_{x \in \mathbb{F}_p^2} exp\left(\frac{2\pi i(\langle a, x \rangle - \langle b, \mathcal{H}(x) \rangle)}{p} \right) \right| \leq p \log p \ ?$$



(a) *when* $p = 11$ *and* $d = 3$.



(b) *when* $p = 13$ *and* $d = 5$.

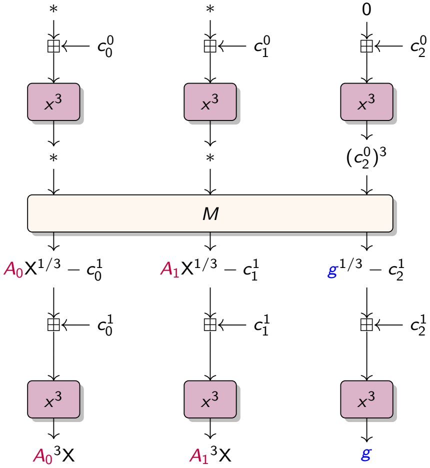


(c) *when* $p = 17$ *and* $d = 3$.

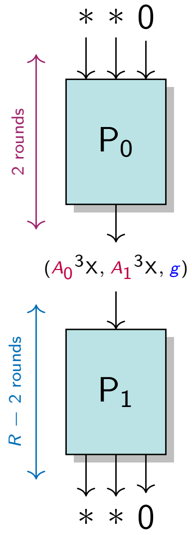
LAT of $\texttt{Flystel}_p$.

Algebraic attacks

Trick for POSEIDON

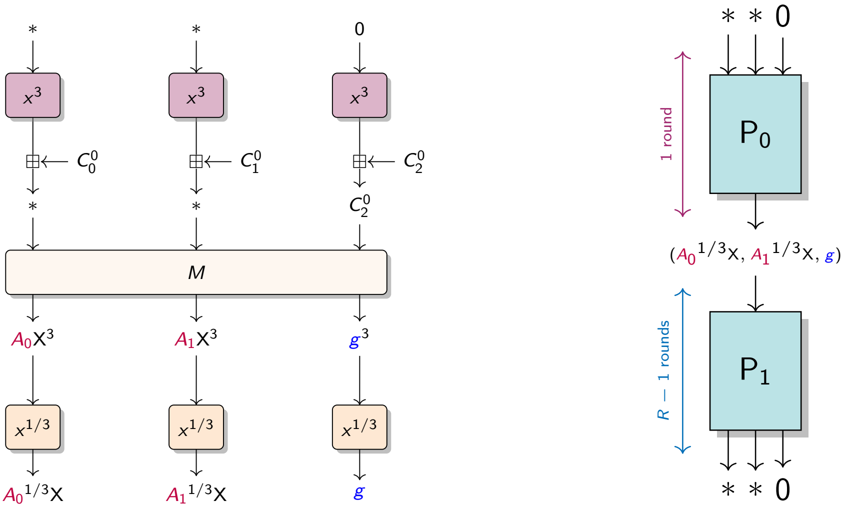


(a) *First two rounds.*



(b) *Overview.*

Trick for Rescue–Prime



(a) *First round.*

(b) *Overview.*

Attack complexity

RP	Authors claims	Ethereum claims	$\deg^u$	Our complexity
3	2^{17}	2^{45}	$3^9 \approx 2^{14.3}$	2^{26}
8	2^{25}	2^{53}	$3^{14} \approx 2^{22.2}$	2^{35}
13	2^{33}	2^{61}	$3^{19} \approx 2^{30.1}$	2^{44}
19	2^{42}	2^{69}	$3^{25} \approx 2^{39.6}$	2^{54}
24	2^{50}	2^{77}	$3^{30} \approx 2^{47.5}$	2^{62}

(a) *For* POSEIDON.

R	m	Authors claims	Ethereum claims	$\deg^u$	Our complexity
4	3	2^{36}	$2^{37.5}$	$3^9 \approx 2^{14.3}$	2^{43}
6	2	2^{40}	$2^{37.5}$	$3^{11} \approx 2^{17.4}$	2^{53}
7	2	2^{48}	$2^{43.5}$	$3^{13} \approx 2^{20.6}$	2^{62}
5	3	2^{48}	2^{45}	$3^{12} \approx 2^{19.0}$	2^{57}
8	2	2^{56}	$2^{49.5}$	$3^{15} \approx 2^{23.8}$	2^{72}

(b) *For Rescue–Prime.*

Cryptanalysis Challenge

Category	Parameters	Security level	Bounty
~~Easy~~	$\cancel{N = 4, m = 3}$	~~25~~	~~$2,000~~
Easy	$N = 6, m = 2$	25	$4,000
Medium	$N = 7, m = 2$	29	$6,000
Hard	$N = 5, m = 3$	30	$12,000
Hard	$N = 8, m = 2$	33	$26,000

(a) *Rescue–Prime*

Category	Parameters	Security level	Bounty
~~Easy~~	$\cancel{r = 6}$	~~9~~	~~$2,000~~
~~Easy~~	$\cancel{r = 10}$	~~15~~	~~$4,000~~
~~Medium~~	$\cancel{r = 14}$	~~22~~	~~$6,000~~
~~Hard~~	$\cancel{r = 18}$	~~28~~	$12,000
~~Hard~~	$\cancel{r = 22}$	~~34~~	$26,000

(b) *Feistel–MiMC*

Category	Parameters	Security level	Bounty
~~Easy~~	~~RP = 3~~	~~8~~	~~$2,000~~
~~Easy~~	~~RP = 8~~	~~16~~	~~$4,000~~
~~Medium~~	~~RP = 13~~	~~24~~	~~$6,000~~
Hard	RP = 19	32	$12,000
Hard	RP = 24	40	$26,000

(c) Poseidon

Category	Parameters	Security level	Bounty
Easy	$p = 281474976710597$	24	$4,000
Medium	$p = 72057594037926839$	28	$6,000
Hard	$p = 18446744073709551557$	32	$12,000

(d) `Reinforced Concrete`

Open problems

on the Algebraic Degree

Missing exponents when $d = 2^j - 1$

- For MIMC_3

$$i \bmod 8 \notin \{5, 7\} \ .$$

- For MIMC_7

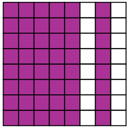
$$i \bmod 16 \notin \{9, 11, 13, 15\} \ .$$

- For MIMC_{15}

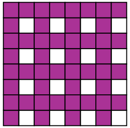
$$i \bmod 32 \notin \{17, 19, 21, 23, 25, 27, 29, 31\} \ .$$

- For MIMC_{31}

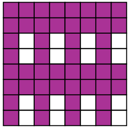
$$i \bmod 64 \notin \{33, 35, 37, 39, 41, 43, 45, 47, 49, 51, 53, 55, 57, 59, 61, 63\} \ .$$



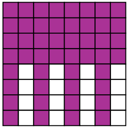
(a) *For* MIMC_3.



(b) *For* MIMC_7.



(c) *For* MIMC_{15}.



(d) *For* MIMC_{31}.

Proposition

Let $i \in \mathcal{E}_{d,r}$, where $d = 2^j - 1$. Then:

$$\forall\, i \in \mathcal{E}_{d,r}, \ i \bmod 2^{j+1} \in \{0, 1, \dots 2^j\} \ \cup \ \{2^j + 2\gamma, \gamma = 1, 2, \dots 2^{j-1} - 1\} \ .$$

Missing exponents when $d = 2^j + 1$

⋆ For MIMC_5

$$i \bmod 4 \in \{0, 1\} \ .$$

⋆ For MIMC_9

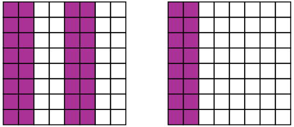
$$i \bmod 8 \in \{0, 1\} \ .$$

⋆ For MIMC_{17}

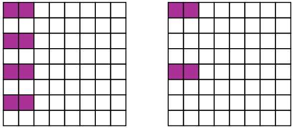
$$i \bmod 16 \in \{0, 1\} \ .$$

⋆ For MIMC_{33}

$$i \bmod 32 \in \{0, 1\} \ .$$



(a) *For* MIMC_5. **(b)** *For* MIMC_9.



(c) *For* MIMC_{17}. **(d)** *For* MIMC_{33}.

Proposition

Let $i \in \mathcal{E}_{d,r}$ where $d = 2^j + 1$ and $j > 1$. Then:

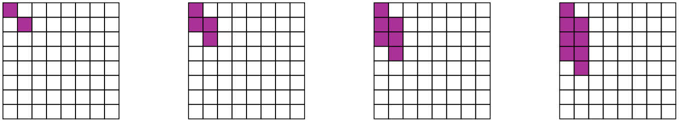
$$\forall\, i \in \mathcal{E}_{d,r}, \ i \bmod 2^j \in \{0, 1\} \ .$$

Missing exponents when $d = 2^j + 1$ (first rounds)

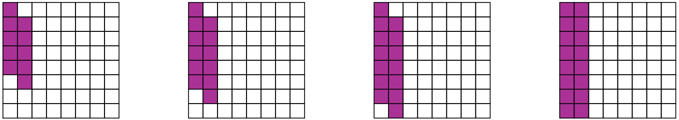
Corollary

Let $i \in \mathcal{E}_{d,r}$ where $d = 2^j + 1$ and $j > 1$. Then:

$$\begin{cases} i \bmod 2^{2j} \in \{\{\gamma 2^j, (\gamma+1)2^j + 1\},\ \gamma = 0, \ldots r-1\} & \text{if } r \le 2^j \ , \\ i \bmod 2^j \in \{0, 1\} & \text{if } r \ge 2^j \ . \end{cases}$$



(a) *Round 1* **(b)** *Round 2* **(c)** *Round 3* **(d)** *Round 4*



(a) *Round 5* **(b)** *Round 6* **(c)** *Round 7* **(d)** *Round* $r \ge 8$

Bounding the degree when $d = 2^j - 1$

Note that if $d = 2^j - 1$, then

$$2^i \bmod d \equiv 2^{i \bmod j} \ .$$

Proposition

Let $d = 2^j - 1$, such that $j \geq 2$. Then,

$$B_d^r \leq \lfloor r \log_2 d \rfloor - (\lfloor r \log_2 d \rfloor \bmod j) \ .$$

Note that if $2 \leq j \leq 7$, then

$$2^{\lfloor r \log_2 d \rfloor + 1} - 2^j - 1 > d^r \ .$$

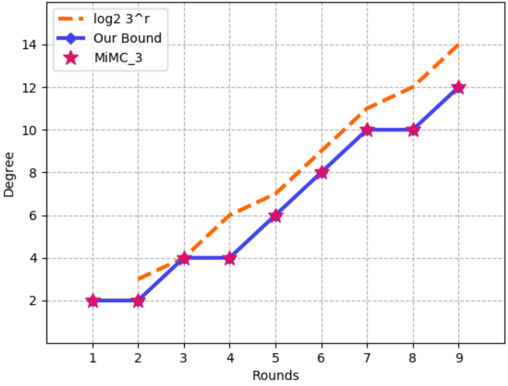
Corollary

Let $d \in \{3, 7, 15, 31, 63, 127\}$. Then,

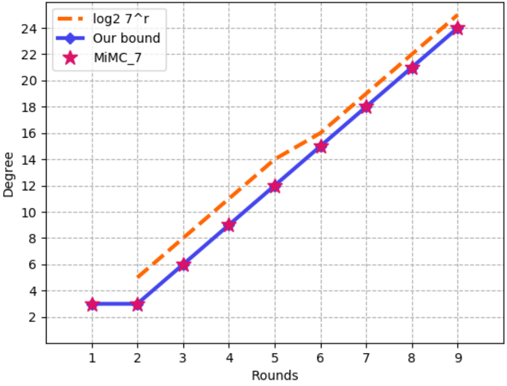
$$B_d^r \leq \begin{cases} \lfloor r \log_2 d \rfloor - j & \text{if } \lfloor r \log_2 d \rfloor \bmod j = 0 \ , \\ \lfloor r \log_2 d \rfloor - (\lfloor r \log_2 d \rfloor \bmod j) & \text{else} \ . \end{cases}$$

Bounding the degree when $d = 2^j - 1$

Particularity: Plateau when $\lfloor r \log_2 d \rfloor \bmod j = j - 1$ and $\lfloor (r+1) \log_2 d \rfloor \bmod j = 0$.



Bound for MIMC_3



Bound for MIMC_7

Bounding the degree when $d = 2^j + 1$

Note that if $d = 2^j + 1$, then

$$2^i \bmod d \equiv \begin{cases} 2^{i \bmod 2j} & \text{if } i \equiv 0, \ldots, j \bmod 2j \ , \\ d - 2^{(i \bmod 2j) - j} & \text{if } i \equiv 0, \ldots, j \bmod 2j \ . \end{cases}$$

Proposition

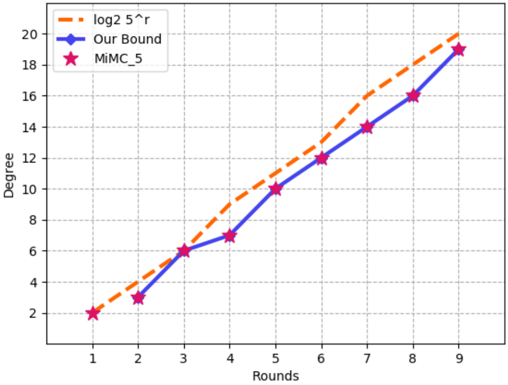
Let $d = 2^j + 1$ s.t. $j > 1$. Then if $r > 1$:

$$B_d^r \leq \begin{cases} \lfloor r \log_2 d \rfloor - j + 1 & \text{if } \lfloor r \log_2 d \rfloor \bmod 2j \in \{0, j-1, j+1\} \ , \\ \lfloor r \log_2 d \rfloor - j & \text{else} \ . \end{cases}$$

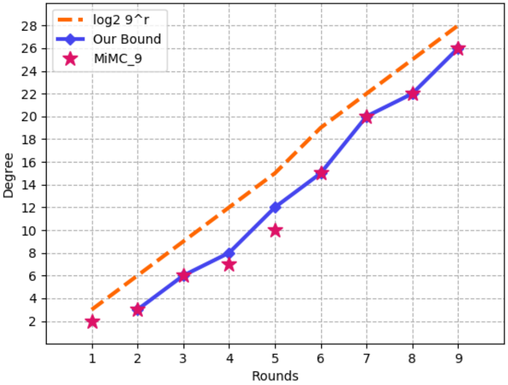
The bound can be refined on the first rounds!

Bounding the degree when $d = 2^j + 1$

Particularity: There is a gap in the first rounds.



Bound for MIMC_5



Bound for MIMC_9

Sporadic Cases

Observation

Let $k_{3,r} = \lfloor r \log_2 3 \rfloor$. If $4 \leq r \leq 16265$, then

$$3^r > 2^{k_{3,r}} + 2^r \,.$$

Observation

Let t be an integer s.t. $1 \leq t \leq 21$. Then

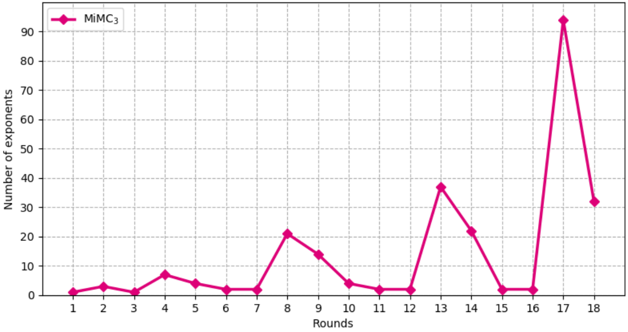
$$\forall x \in \mathbb{Z}/3^t\mathbb{Z},\ \exists \varepsilon_2, \ldots, \varepsilon_{2t+2} \in \{0,1\},\ \text{s.t. } x = \sum_{j=2}^{2t+2} \varepsilon_j 4^j \bmod 3^t \,.$$

Is it true for any t?

Should we consider more ε_j for larger t?

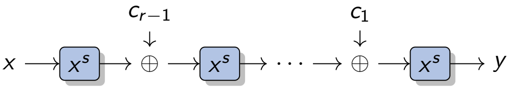
More maximum-weight exponents

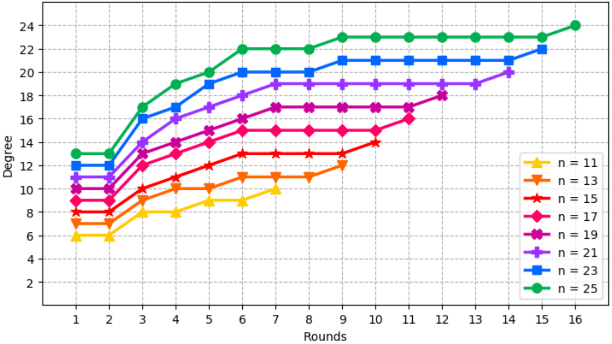
r	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
$k_{3,r}$	1	3	4	6	7	9	11	12	14	15	17	19	20	22	23	25	26	28
$b_{3,r}$	1	1	0	0	1	1	1	0	0	1	1	1	0	0	1	1	0	0



Study of MiMC_3^{-1}

Inverse: $F : x \mapsto x^s,\ s = (2^{n+1} - 1)/3 = [101..01]_2$





First plateau

Plateau between rounds 1 and 2, for $s = (2^{n+1} - 1)/3 = [101..01]_2$

- Round 1:

$$B_s^1 = \mathrm{wt}(s) = (n+1)/2$$

- Round 2:

$$B_s^2 = \max\{\mathrm{wt}(is),\ \text{for } i \preceq s\} = (n+1)/2$$

Proposition

For $i \preceq s$ such that $\mathrm{wt}(i) \geq 2$:

$$\mathrm{wt}(is) \in \begin{cases} [\mathrm{wt}(i) - 1, (n-1)/2] & \text{if } \ wt(i) \equiv 2 \bmod 3 \\ [\mathrm{wt}(i), (n+1)/2] & \text{if } \ wt(i) \equiv 0, 1 \bmod 3 \end{cases}$$

Next Rounds

Proposition [Boura and Canteaut, IEEE13]

$\forall i \in [1, n-1]$, if the algebraic degree of encryption is $\deg^a(F) < (n-1)/i$, then the algebraic degree of decryption is $\deg^a(F^{-1}) < n - i$

$$r_{n-i} \geq \left\lceil \frac{1}{\log_2 3} \left(2 \left\lceil \frac{1}{2} \left\lceil \frac{n-1}{i} \right\rceil \right\rceil + 1 \right) \right\rceil$$

In particular:

$$\boxed{r_{n-2} \geq \left\lceil \frac{1}{\log_2 3} \left(2 \left\lceil \frac{n-1}{4} \right\rceil + 1 \right) \right\rceil}$$