Arithmetization-Oriented Primitives

An overview of recent advances

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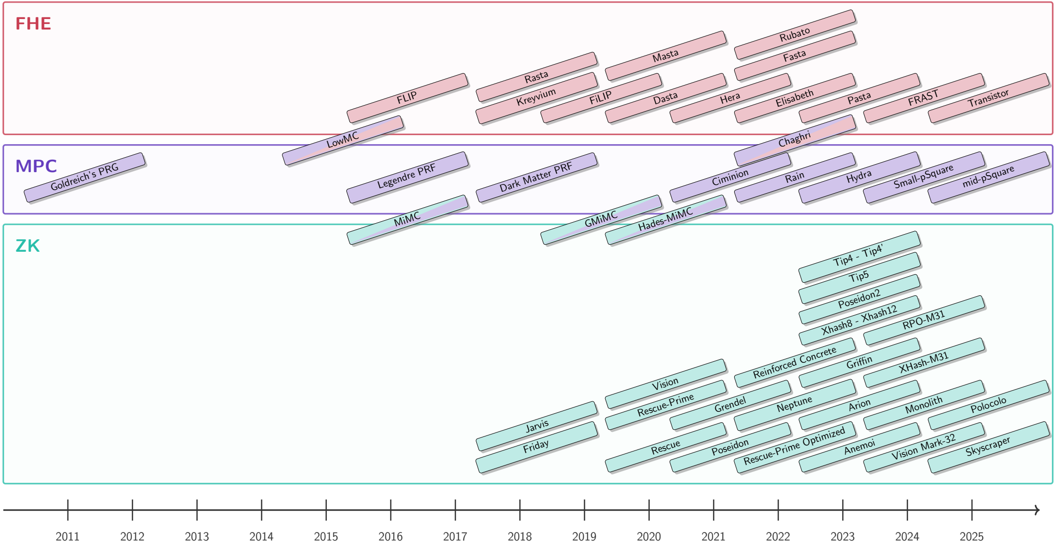
New symmetric primitives



Performance metric

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

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"It depends"

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

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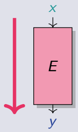
3 constraints

Comparison with the traditional case

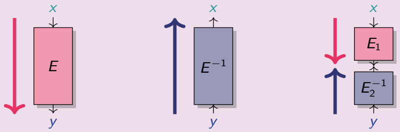
Traditional case

$$y \leftarrow E(x)$$



Arithmetization-oriented

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



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Traditional case

$$y \leftarrow E(x)$$

- ⋆ Optimized for:
  implementation in software/hardware

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

- ⋆ Optimized for:
  integration within advanced protocols

Comparison with the traditional case

Traditional case

$$y \leftarrow E(x)$$

- Optimized for:
  implementation in software/hardware

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

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

Arithmetization-oriented

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

- Optimized for:
  integration within advanced protocols

- 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

$$y \leftarrow E(x)$$

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- Operations:
  logical gates/CPU instructions

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Cryptanalysis

Decades of analysis

Arithmetization-oriented

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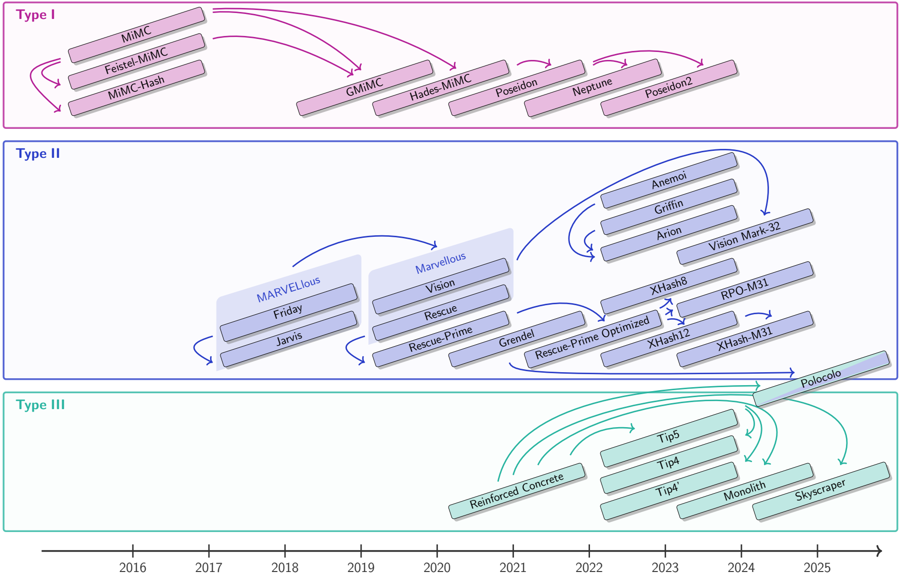
Cryptanalysis

≤ 8 years of analysis

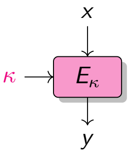
ZKP Primitives overview



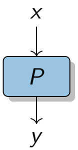
DESIGN

Iterated constructions

Block Ciphers $E_\kappa : \mathbb{F}_q^n \to \mathbb{F}_q^n$ (n fixed)



(a) *Block cipher*



(b) *Random permutation*

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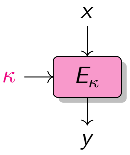

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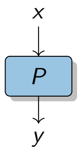

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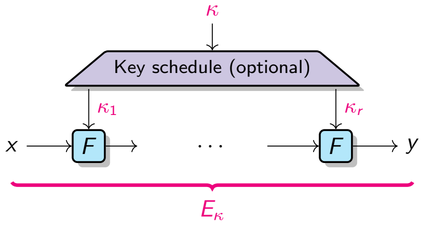

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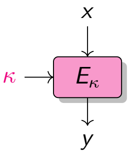

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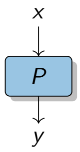

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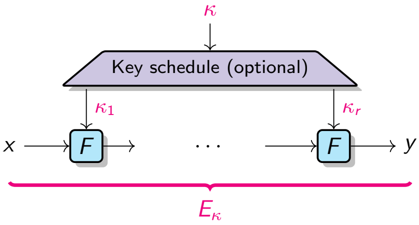
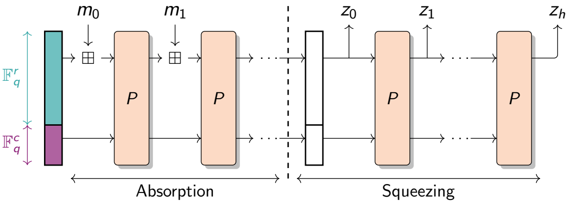


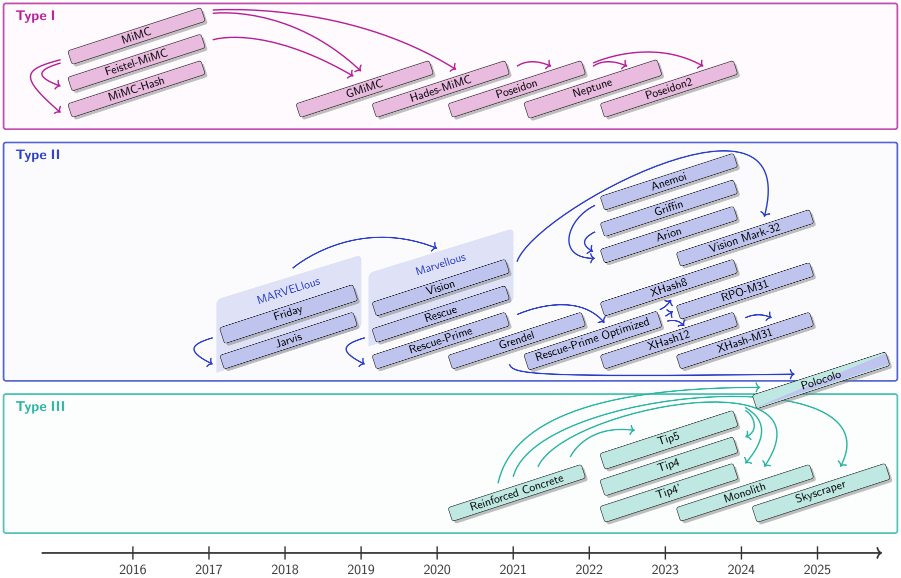
Hash functions $H : \mathbb{F}_q^\ell \to \mathbb{F}_q^h$ (ℓ arbitrary, h fixed)

Sponge construction

- ⋆ rate $r > 0$
- ⋆ capacity $c > 0$
- ⋆ permutation of $\mathbb{F}_q^n$ ($n = r + c$)



ZKP Primitives overview



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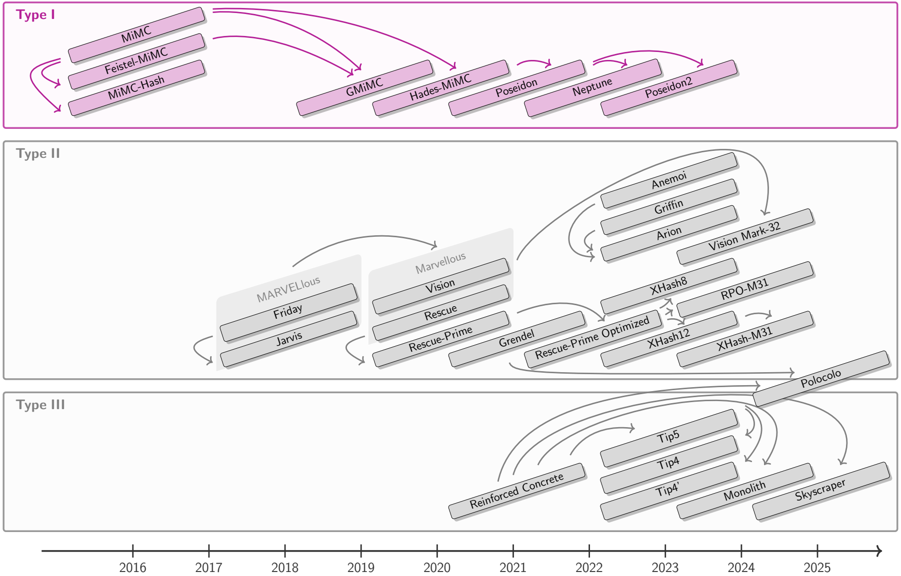
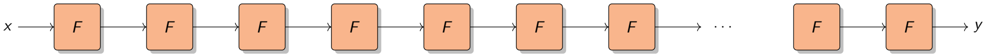


Type I

Low-Degree Primitives



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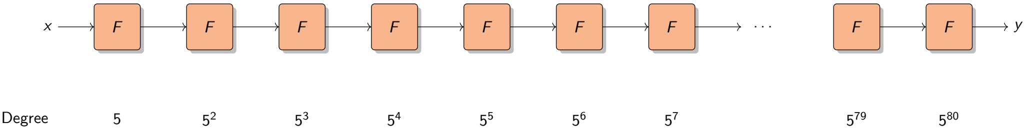

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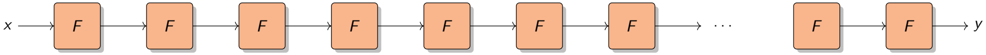
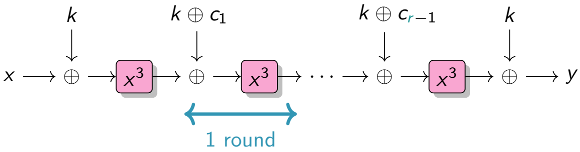


Degree	5	5^2	5^3	5^4	5^5	5^6	5^7	5^{79}	5^{80}
Constraints	3	3×2	3×3	3×4	3×5	3×6	3×7	3×79	3×80

MiMC / Feistel-MiMC

M. Albrecht, L. Grassi, C. Rechberger, A. Roy and T. Tiessen, 2016

- ⋆ n-bit blocks (n odd ≈ 129): $x \in \mathbb{F}_{2^n}$
- ⋆ n-bit key: $k \in \mathbb{F}_{2^n}$
- ⋆ 82 rounds when $n = 129$



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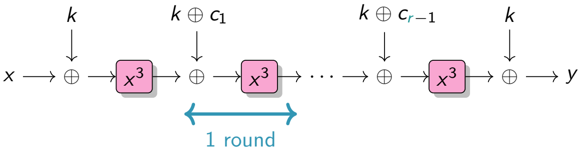
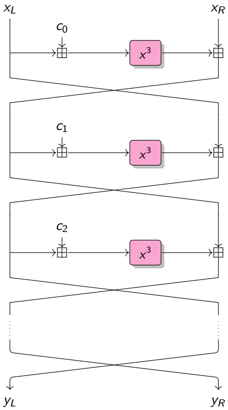
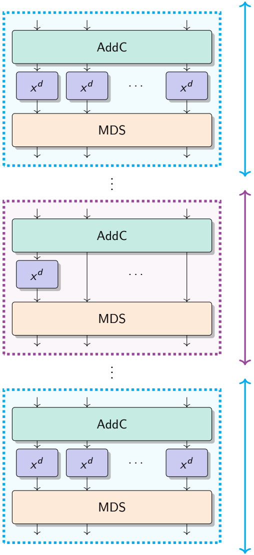




Feistel-MiMC

Poseidon



L. Grassi, D. Khovratovich, C. Rechberger, A. Roy and M. Schofnegger, 2021

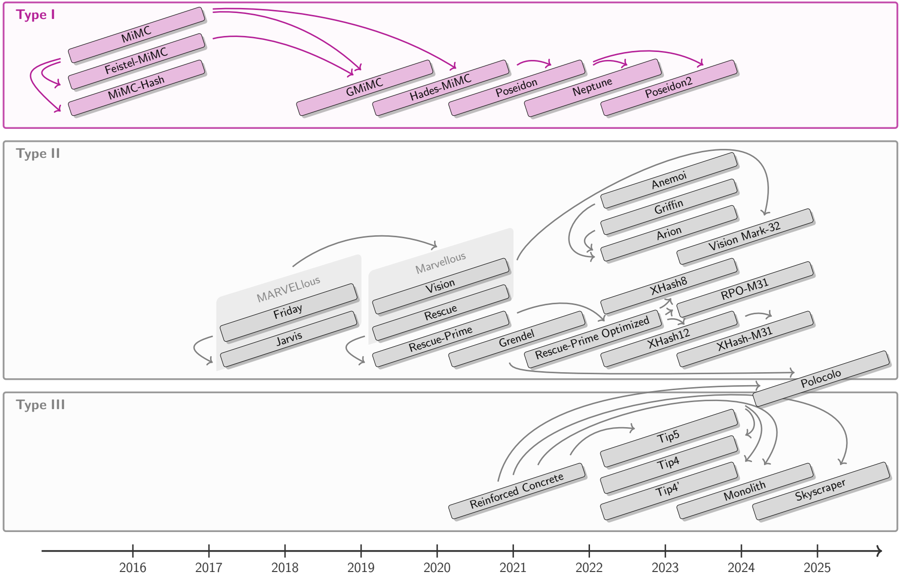
- ⋆ S-box:

$$x \mapsto x^3$$

- ⋆ Nb rounds:

$$\begin{aligned} R &= 2 \times Rf + RP \\ &= 8 + (\text{from } 56 \text{ to } 84) \end{aligned}$$

ZKP Primitives overview



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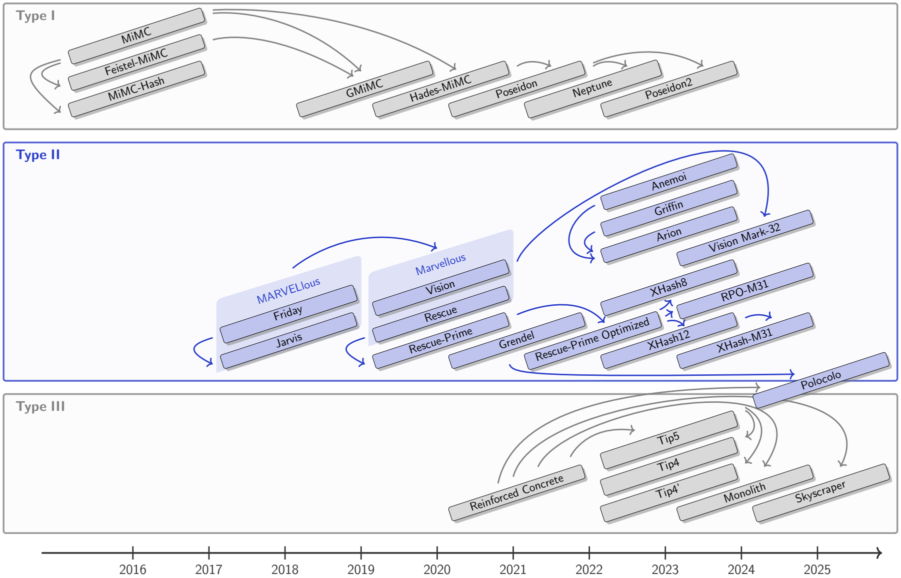
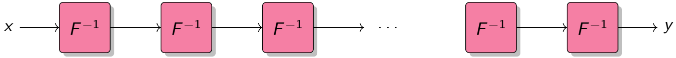


Type II

Primitives based on Equivalence



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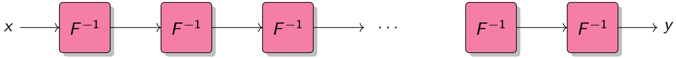

Degree 5^{-1} 5^{-2} 5^{-3} 5^{-19} 5^{-20}

Example

In $\mathbb{F}_p$ with

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

If $F(x) = x^5$ then $F^{-1}(x) = x^{5^{-1}}$ with

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

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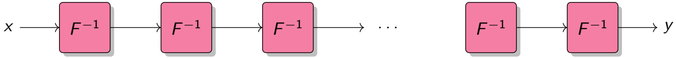

Degree	5^{-1}	5^{-2}	5^{-3}	5^{-19}	5^{-20}
Constraints	3×20	3×19	3×18	3×2	3

Example

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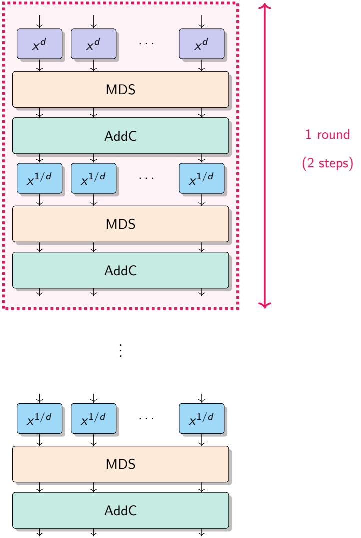
Rescue / Rescue-Prime



A. Aly, T. Ashur, E. Ben-Sasson, S. Dhooghe and A. Szepieniec, 2020

- S-box:

$$x \mapsto x^3 \quad \text{and} \quad x \mapsto x^{1/3}$$

- Nb rounds:

$$R = \text{from 8 to 26}$$

(2 S-boxes per round)

Anemoi

Need: verification using few multiplications.

⋆ **First approach:** evaluation using few multiplications, e.g. Poseidon [GKRRS21]

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

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

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⋆ **First breakthrough:** using inversion, e.g. Rescue [AABDS20]

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

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

$y \leftarrow F(x)$ $\rightsquigarrow$ F: high degree $v == G(u)$ $\rightsquigarrow$ 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:

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

CCZ-equivalence

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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

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

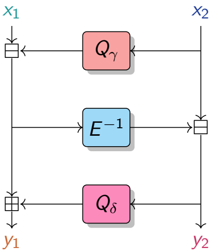
The FLYSTEL

C. Bouvier, P. Briaud, P. Chaidos, L. Perrin, R. Salen, V. Velichkov and D. Willems, 2023

Butterfly + Feistel ⇒ FLYSTEL

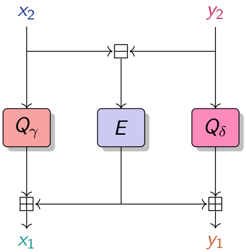
A 3-round Feistel-network with
$Q_\gamma : \mathbb{F}_q \to \mathbb{F}_q$ and $Q_\delta : \mathbb{F}_q \to \mathbb{F}_q$ two quadratic functions, and $E : \mathbb{F}_q \to \mathbb{F}_q$ a permutation

High-Degree permutation



Open FLYSTEL $\mathcal{H}$.

Low-Degree function



Closed FLYSTEL $\mathcal{V}$.

The FLYSTEL

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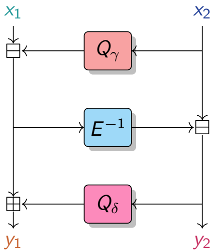

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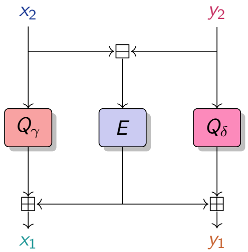


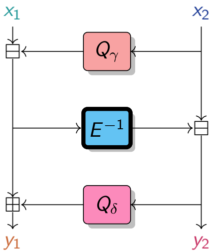
Closed FLYSTEL $\mathcal{V}$.

$$\Gamma_\mathcal{H} = \mathcal{L}(\Gamma_\mathcal{V}) \quad \text{s.t.} \quad ((x_1, x_2), (y_1, y_2)) = \mathcal{L}\left(((y_2, x_2), (x_1, y_1)) \right)$$

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

$$p = \texttt{0x73eda753299d7d483339d80809a1d805}$$
$$\texttt{53bda402fffe5bfeffffffff00000001}$$

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

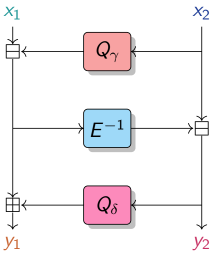
$$5^{-1} = \texttt{0x2e5f0fbadd72321ce14a56699d73f002}$$
$$\texttt{217f0e679998f19933333332cccccccd}$$

Advantage of CCZ-equivalence

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

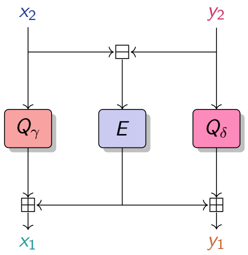
$$(y_1, y_2) == \mathcal{H}(x_1, x_2) \Leftrightarrow (x_1, y_1) == \mathcal{V}(x_2, y_2)$$

High-Degree permutation



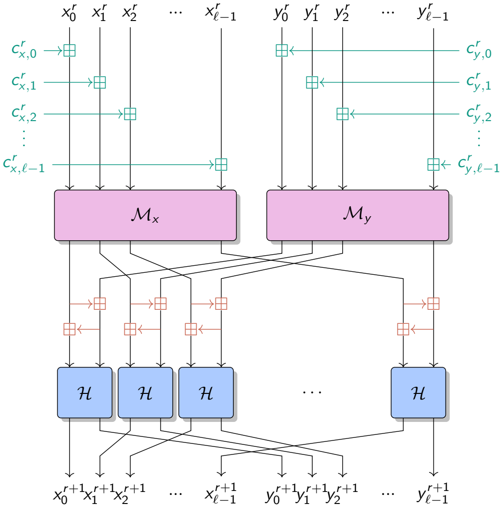
Open FLYSTEL $\mathcal{H}$.

Low-Degree function



Closed FLYSTEL $\mathcal{V}$.

The SPN Structure



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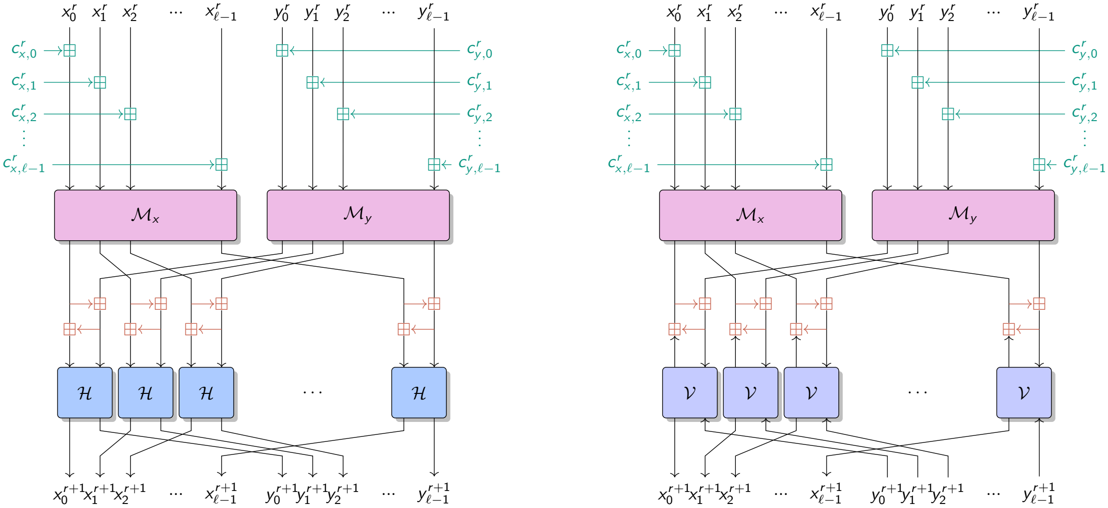

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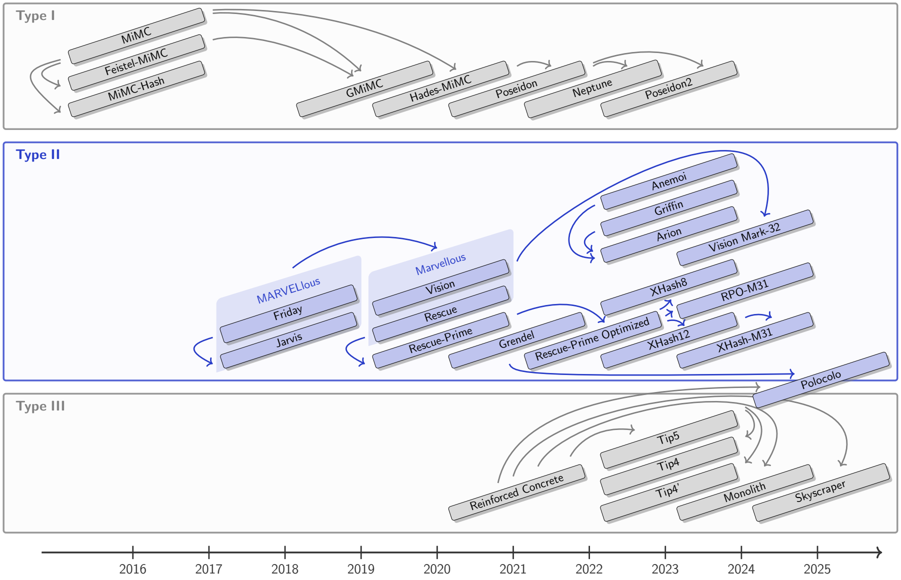
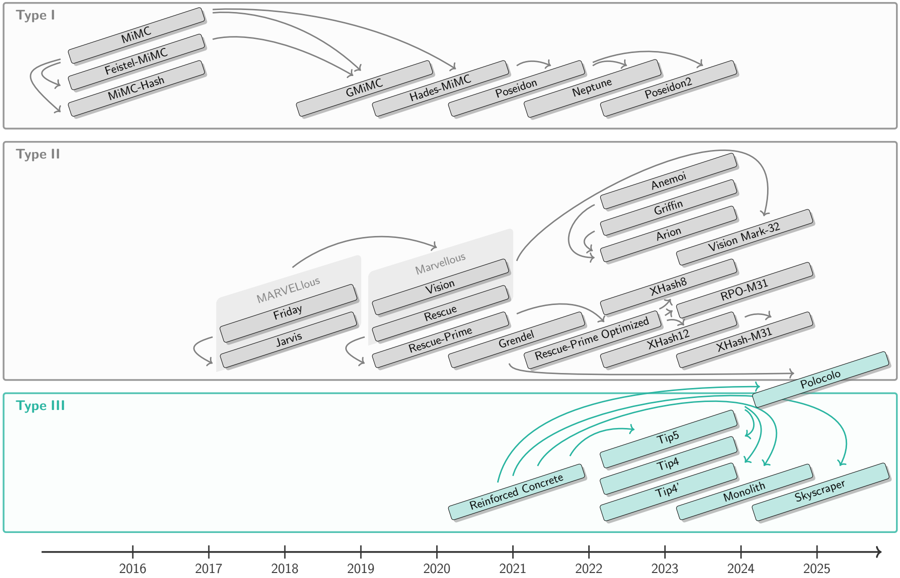
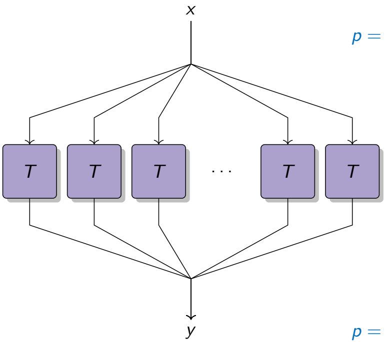


ZKP Primitives overview



Type III

Primitives using Look-up-Tables

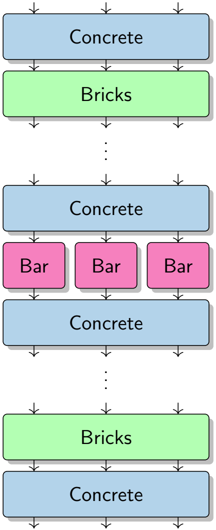


$\mathbb{F}_p$ with
$p =$ 0x73eda753299d7d483339d80809a1d80553bda402fffe5bfeffffffff00000001

$\mathbb{F}_2^8$
$(0,0,0,0,0,0,0,0)\ \ldots\ (1,1,1,1,1,1,1,1)$

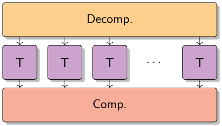
$\mathbb{F}_p$ with
$p =$ 0x73eda753299d7d483339d80809a1d80553bda402fffe5bfeffffffff00000001

Reinforced Concrete



L. Grassi, D. Khovratovich, R. Lüftenegger, C. Rechberger, M. Schofnegger and R. Walch, 2022

- S-box:

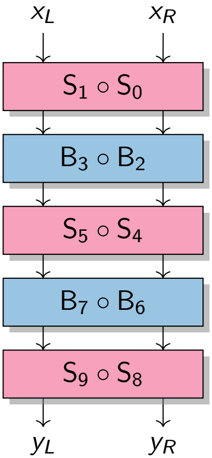


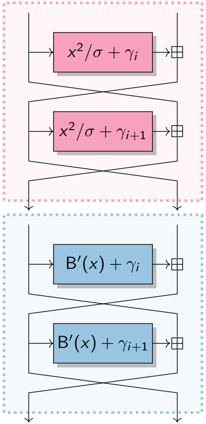
- Nb rounds:

$$R = 7$$

Skyscraper

C. Bouvier, L. Grassi, D. Khovratovich, K. Koschatko, C. Rechberger, F. Schmid and M. Schofnegger, 2025





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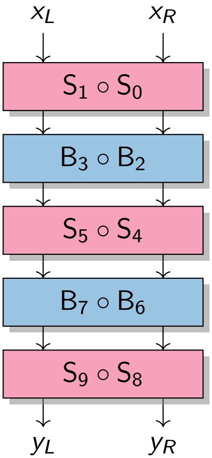

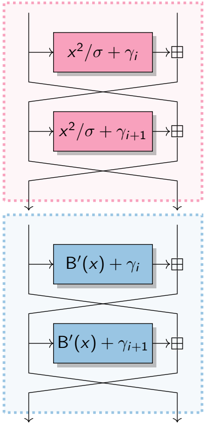

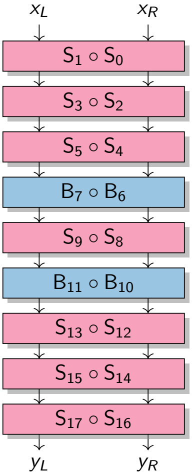

Take-away

	Type I Low-degree primitives	**Type II** Equivalence relation	**Type III** Look-up tables
Alphabet	$\mathbb{F}_q^m$ for various q and m	$\mathbb{F}_q^m$ for various q and m	specific fields
Nb of rounds	many	few	fewer
Plain performance	fast	slow	faster
Nb of constraints	often more	fewer	it depends on the proof system
Examples	Feistel-MiMC Poseidon	Rescue Anemoi	Reinforced Concrete Skyscraper

CRYPTANALYSIS

Cryptanalysis overview

Some cryptanalysis techniques

- ⋆ Statistical attacks (differential and linear)
- ⋆ Algebraic attacks
- ⋆ Higher-Order differential attacks
- ⋆ ...

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Approaches so far:

- ⋆ **Type I**: HO attacks and algebraic attacks
- ⋆ **Type II**: algebraic attacks
- ⋆ **Type III**: combining statistical and algebraic attacks

Algebraic Attack

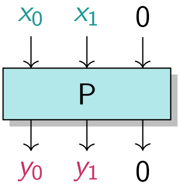
CICO: Constrained Input Constrained Output

Definition

Let $P : \mathbb{F}_q^t \rightarrow \mathbb{F}_q^t$ and $u < t$.

The **CICO** problem is:

$$\text{Finding } X, Y \in \mathbb{F}_q^{t-u} \text{ s.t. } P(X, 0^u) = (Y, 0^u).$$



when $t = 3$, $u = 1$.

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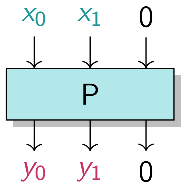

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Need to solve a polynomial system

FreeLunch Attack

A. Bariant, A. Boeuf, A. Lemoine, I. Manterola Ayala, M. Øygarden, L. Perrin, and H. Raddum, 2024

Multivariate solving:

- Define the system
- Compute a grevlex order GB (**F5** algorithm)
- Convert it into lex order GB (**FGLM** algorithm)
- Find the roots in $\mathbb{F}_q^n$ of the GB polynomials using univariate system resolution.

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Impact on the security of:

- ⋆ Griffin (practical attack for 7 out of 10 rounds)
- ⋆ Arion
- ⋆ Anemoi (need some tweak)

Resultant Attack

- **First approach** by HS. Yang, QX. Zheng, J. Yang, QF. Liu, D. Tang, 2024

  Impact on the security of:

  - Anemoi (practical attack for 8 out of 20 rounds)
  - Rescue (practical attack for 5 out of 18 rounds)
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- **Improved** by A. Bariant, A. Boeuf, P. Briaud, M. Hostettler, M. Øygarden, H. Raddum, 2025

  Impact on the security of:

  - Griffin (practical attack for 8 out of 10 rounds)
  - Anemoi (practical attack for 11 out of 20 rounds)
  - Rescue (practical attack for 6 out of 18 rounds)
  - Arion

Linear attacks

Definition

Let $\mathsf{F} : \mathbb{F}_q^n \to \mathbb{F}_q^m$ be a function and ω a primitive element.
The **Linearity** $\mathcal{L}_\mathsf{F}$ of $\mathsf{F} : \mathbb{F}_q^n \to \mathbb{F}_q^m$ is the highest Walsh coefficient.

$$\mathcal{L}_\mathsf{F} = \max_{u,v \neq 0} \left| \sum_{x \in \mathbb{F}_q^n} \omega^{(\langle v, \mathsf{F}(x) \rangle - \langle u, x \rangle)} \right| .$$

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Examples:

- If $\mathrm{F} : \mathbb{F}_2^n \to \mathbb{F}_2^m$, then

$$\mathcal{L}_\mathrm{F} = \max_{u,v\neq 0} \left| \sum_{x\in\mathbb{F}_{2^n}^n} (-1)^{(\langle v,\mathrm{F}(x)\rangle - \langle u,x\rangle)} \right|$$

- If $\mathrm{F} : \mathbb{F}_p^n \to \mathbb{F}_p^m$, then

$$\mathcal{L}_\mathrm{F} = \max_{u,v\neq 0} \left| \sum_{x\in\mathbb{F}_p^n} e^{\left(\frac{2i\pi}{p}\right)(\langle v,\mathrm{F}(x)\rangle - \langle u,x\rangle)} \right|$$

Weil bound

Proposition [Weil, 1948]

Let $f \in \mathbb{F}_p[x]$ be a univariate polynomial with $\deg(f) = d$. Then

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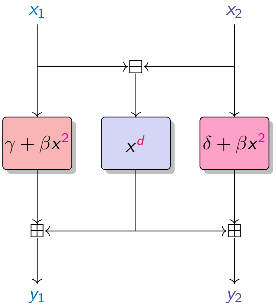


Closed Flystel.

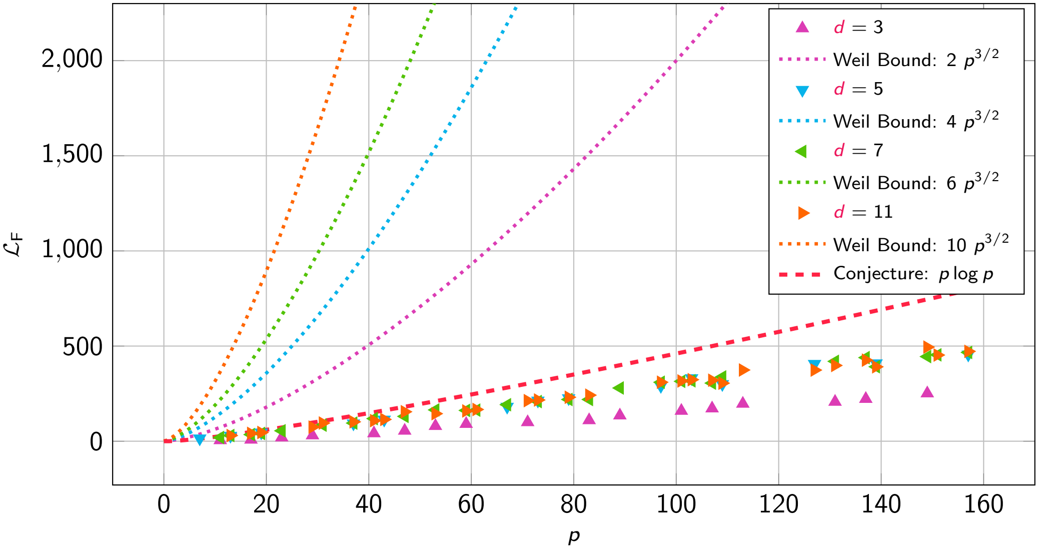
$$\mathcal{L}_F \leq (d-1)p\sqrt{p} \ ?$$

$$\begin{cases} \mathcal{L}_{\gamma+\beta x^2} & \leq \sqrt{p} \ , \\ \mathcal{L}_{x^d} & \leq (d-1)\sqrt{p} \ , \\ \mathcal{L}_{\delta+\beta x^2} & \leq \sqrt{p} \ . \end{cases}$$

Conjecture

$$\mathcal{L}_F = \max_{u,v \neq 0} \left| \sum_{x \in \mathbb{F}_p^2} e^{\left(\frac{2i\pi}{p}\right)(\langle v, F(x)\rangle - \langle u, x\rangle)} \right| \leq p \log p$$

Experimental results



Exponential sums

T. Beyne and C. Bouvier, 2024

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- ⋆ Solving conjecture on the linearity of the Flystel construction (for $d \leq \log p$)

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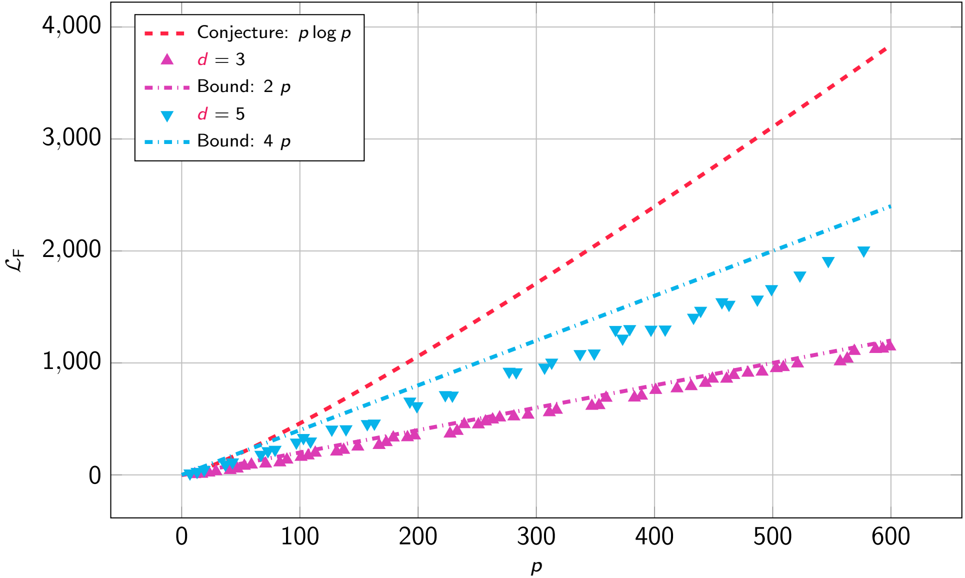
Solving conjecture



Website

`stap-zoo.com`

STAP Zoo   STAP primitive types   STAP use-cases   All STAP primitives

STAP

Symmetric Techniques for Advanced Protocols

The term *STAP* (Symmetric Techniques for Advanced Protocols) was first introduced in STAP'23, an affiliated workshop of **Eurocrypt'23**. It generally refers to algorithms in symmetric cryptography specifically designed to be efficient in new advanced cryptographic protocols. These contexts include zero-knowledge (ZK) proofs, secure multiparty computation (MPC) and (fully) homomorphic encryption (FHE) environments. It encompasses everything from arithmetization-oriented hash functions to homomorphic encryption-friendly stream ciphers.

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Poseidon, Rescue, Anemoi, Skyscraper and many others...

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Thank you