Why do all these primitives defined over rings/prime fields get broken?

Léo Perrin[1]

[1]Inria, France

SPRING/EC'26/CAHF

Full Round Attacks

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ZK-friendly hash functions

`Jarvis` (2018), `Griffin` (2022), `Anemoi` (2022), `Arion` (2023), and `Skyscrapper v1` (2025)

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What happened?

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What happened? **Should we PANIC?!??**

Outline

1 Full round attacks

2 These primitives are harder to design

3 Causes of death

4 Conclusion

Plan of this Section

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A Question

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Security · Efficiency

Unstable Definitions

What is “efficient” varies

- What are the operations that we **can** use?
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How to get the best security for a given price?

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What are the relevant forms of cryptanalysis?

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What are the relevant forms of cryptanalysis? (We’ll get back to that later)

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Securing Computation

More and more protocols intend to secure computations.

FHE Fully Homomorphic Encryption

MPC Multi Party Computations

ZK-* Zero Knowledge- [proof, argument...]

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One Approach to Rule Them All (?): arithmetization

A Basic Example of Arithmetization

"Arithmetization" depends on the subtleties of the protocol you work with!

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Verifying if $y = c(ax + b)^{10} + x$ in R1CS

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2. $t_1 = t_0 + b$
3. $t_2 = t_1 \times t_1$
4. $t_3 = t_2 \times t_2$
5. $t_4 = t_3 \times t_3$
6. $t_5 = t_2 \times t_4$
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This verification costs R1CS 4 constaints

- How to turn a computation into an arithmetic circuit depends on the operations allowed
- Its cost is also arithmetization-dependent—though low degree is usually welcome!

A not basic at all example of arithmetization

The cost of each operation depends on the arithmetization!

Plonk $\neq$ R1CS

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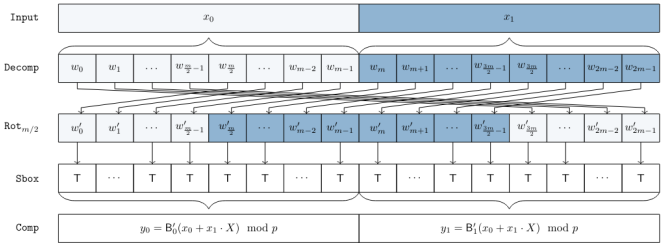


Figure 3: The Bar layer $\mathsf{B}' : \mathbb{F}_{p^n} \to \mathbb{F}_{p^n}$ for $n = 2$ in detail, including the decomposition, the rotation, the S-box, and the composition.

source: *Skyscraper: Fast Hashing on Big Primes*, `https://eprint.iacr.org/2025/058.pdf`

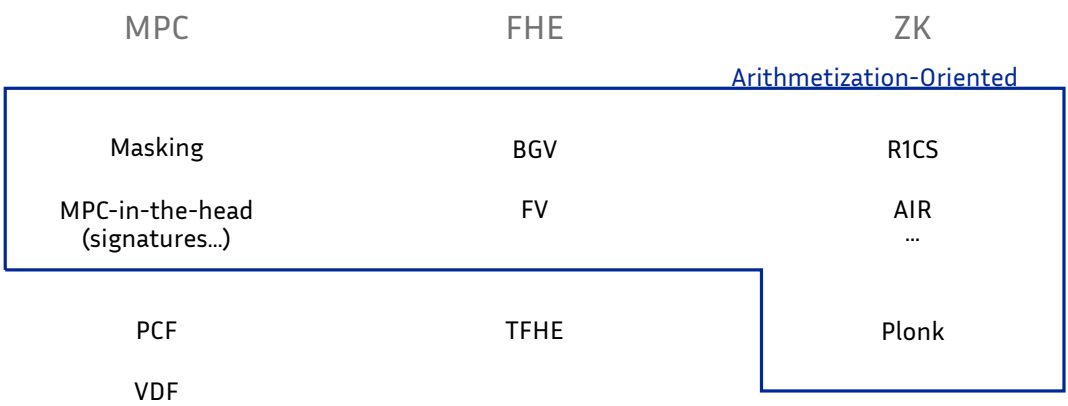
Symmetric Techniques for Advanced Protocols

MPC FHE ZK

Symmetric Techniques for Advanced Protocols

MPC	FHE	ZK
Masking	BGV	R1CS
MPC-in-the-head (signatures...)	FV	AIR ...
PCF	TFHE	Plonk
VDF		

Symmetric Techniques for Advanced Protocols



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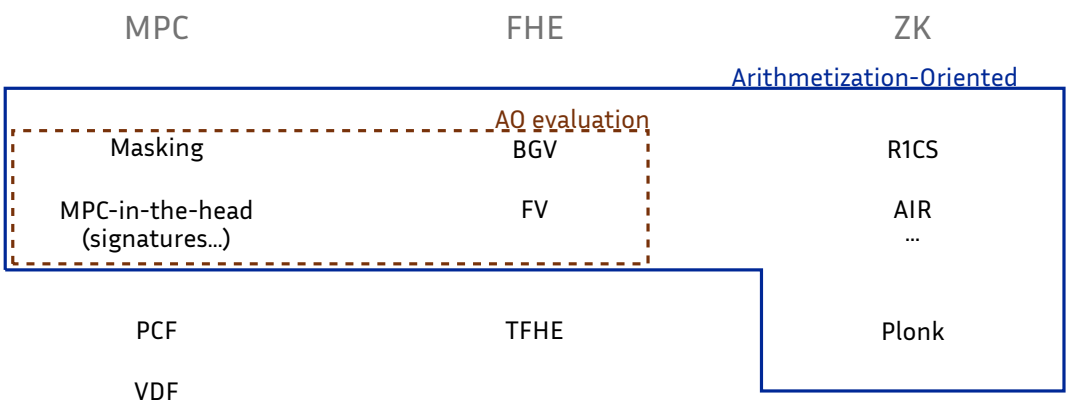

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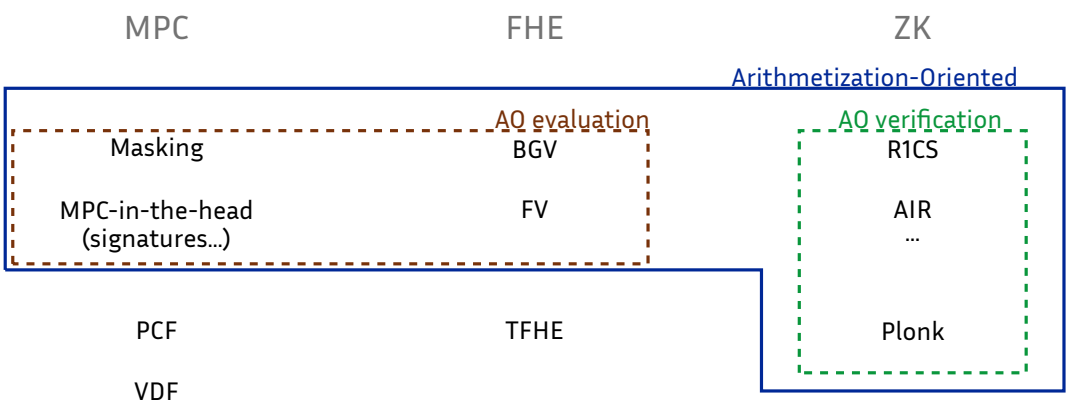

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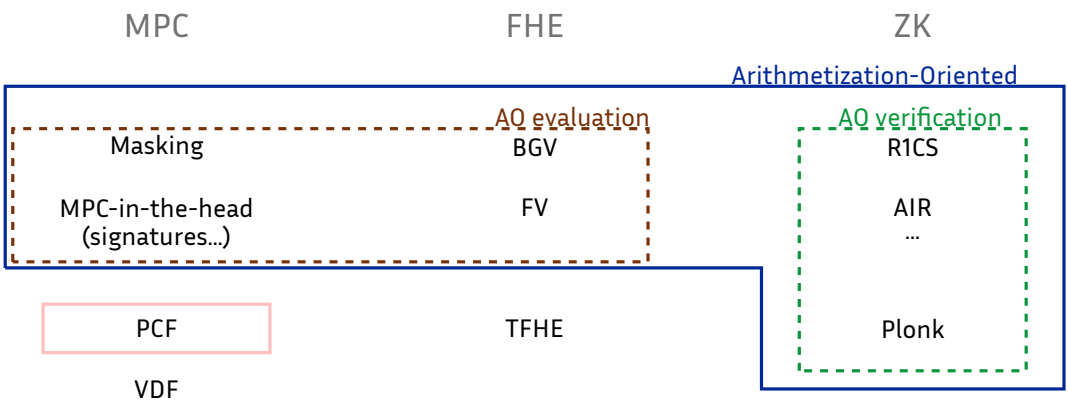

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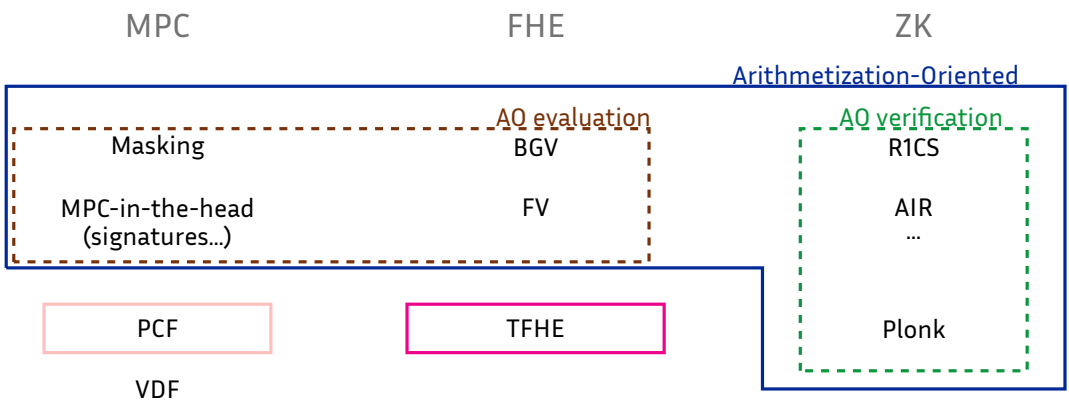

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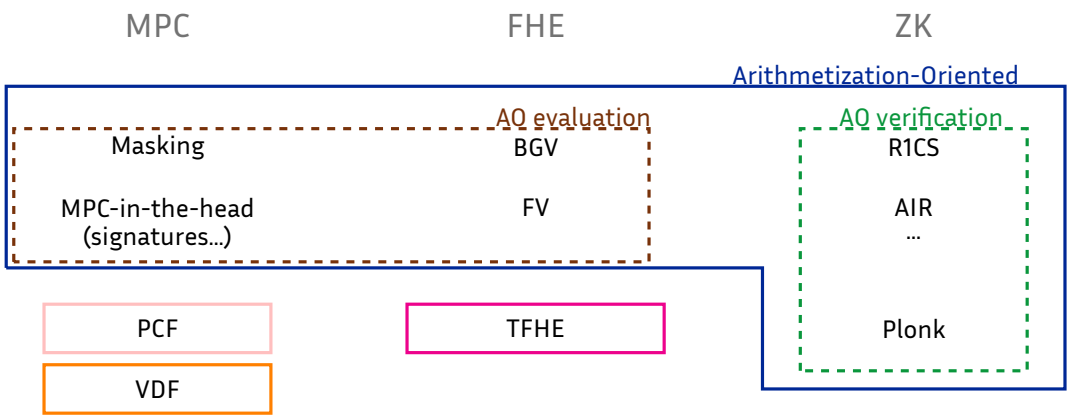

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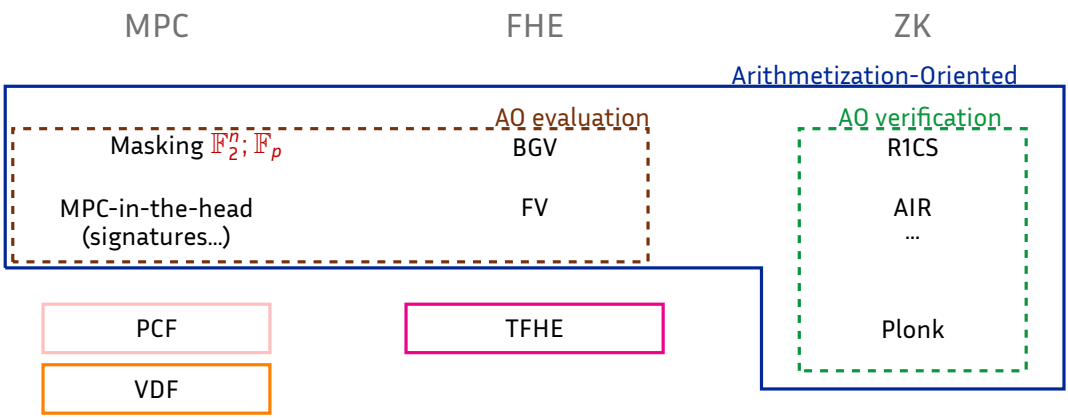

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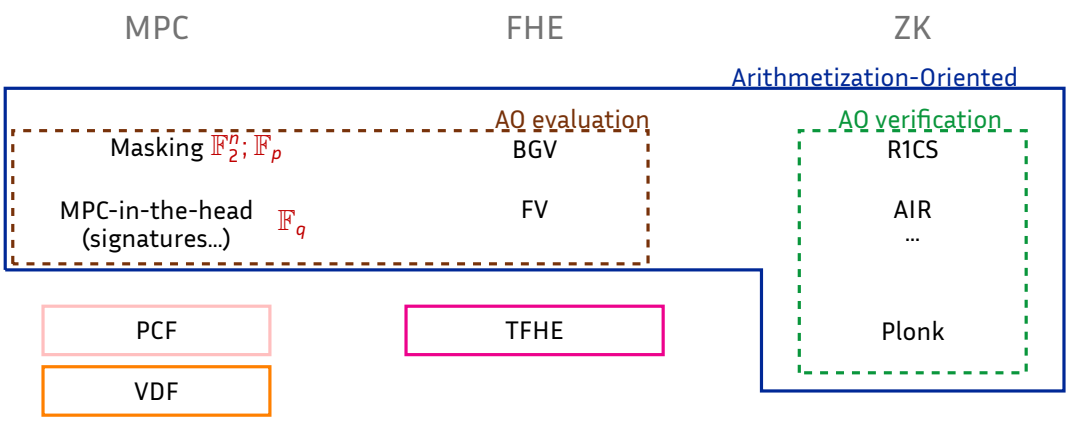

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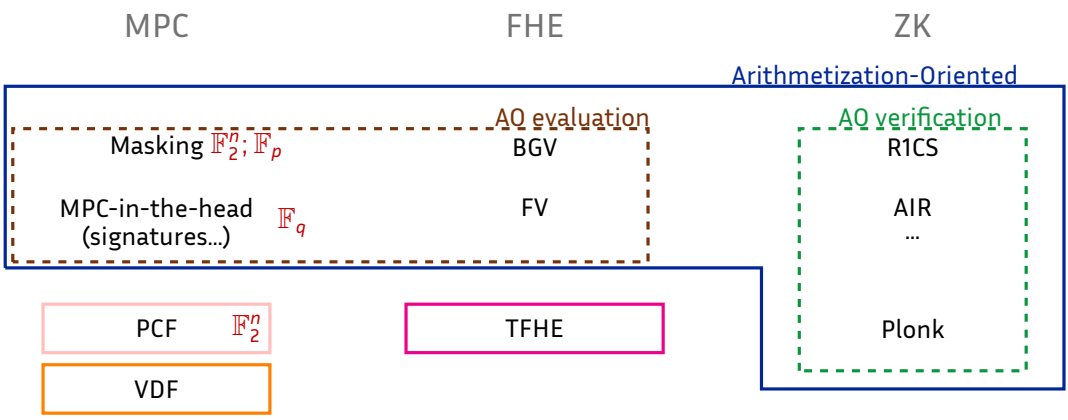

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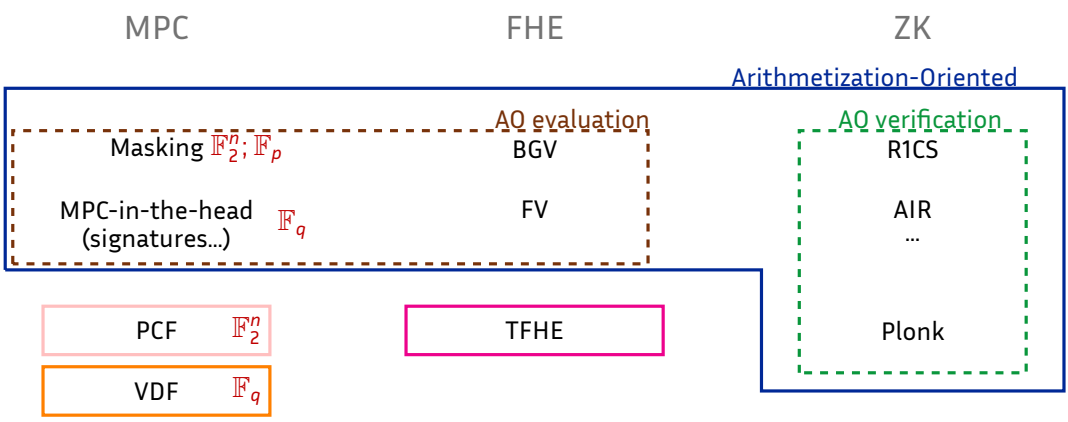

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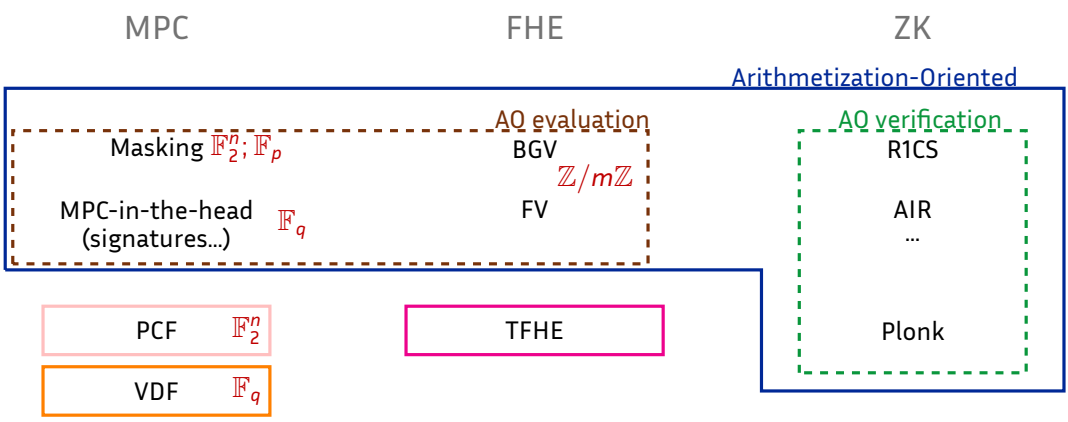

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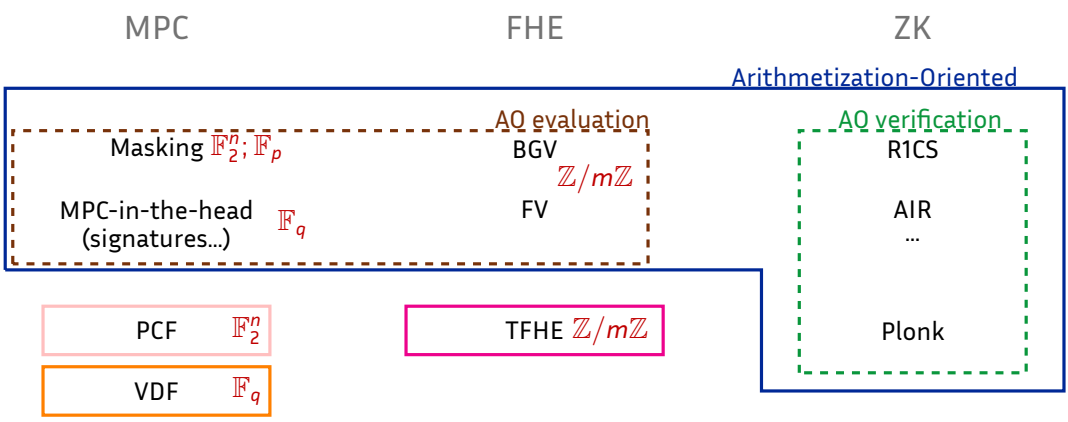

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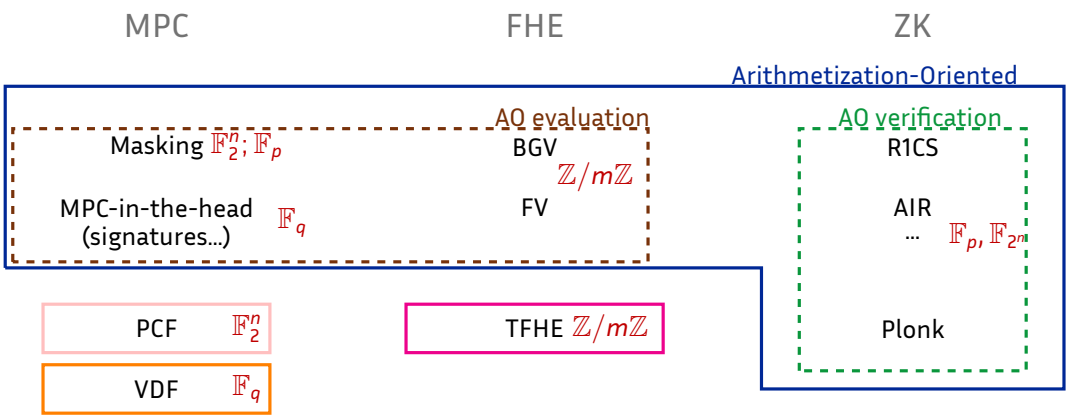

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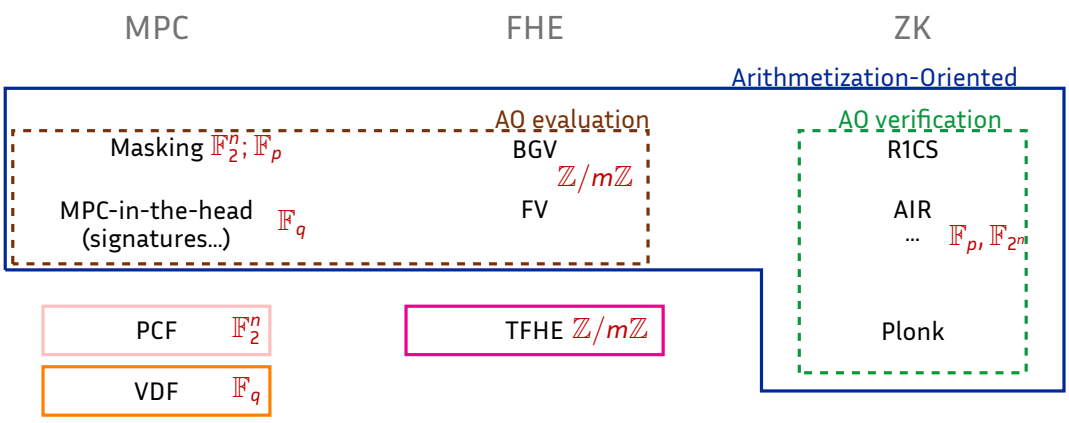

It's kind of a mess!

Du passé, faisons table rase (?)

	Old World	New World

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Design strategy	Prevent diff./integral attacks $\rightarrow$ wide trail strategy	???

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TFHE: corresponding stream ciphers

Elisabeth-4 $q = 2^4$

Uses a constant key register on which index-dependent non-linear functions are applied.

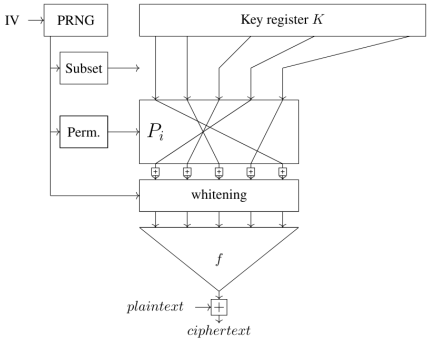

Fig. 1: The group filter permutator design

source: *Towards Case-Optimized Hybrid Homomorphic Encryption Featuring the Elisabeth Stream Cipher*

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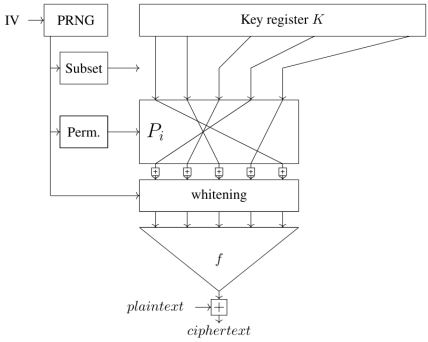

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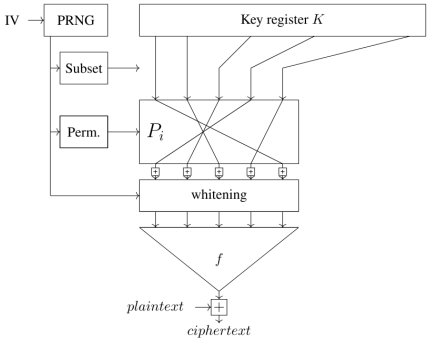

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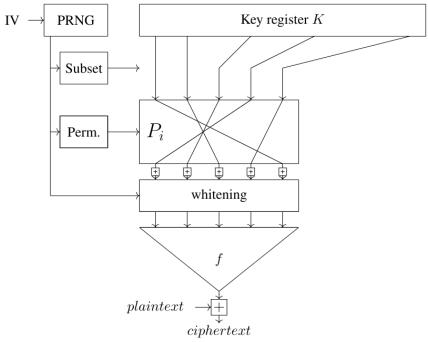
Transistor $q = 2^4 + 1$
SNOW-like round structure



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  Rely on large, randomly generated, nonce-dependent matrices.

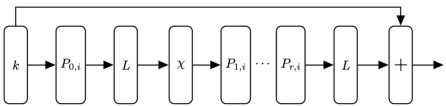

Figure 2: Generation of i-th block of DASTA.

source:
Dasta – Alternative Linear Layer for Rasta

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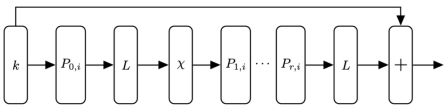

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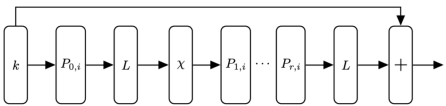
HERA q large prime

A block cipher in a kind of CTR-mode variant.



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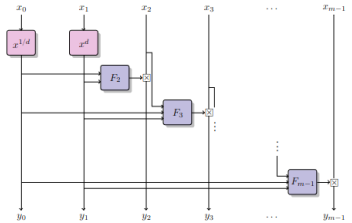

source: *Cryptanalysis and design of symmetric primitives defined over large finite fields*, PhD thesis of C. Bouvier

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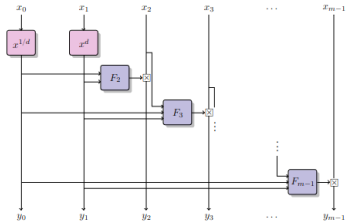
Anemoi $q = 2^n$ or large prime
Uses the "Flystel", a high degree S-box *CCZ-equivalent* to a function of low degree.



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- A graveyard?
- PoSSo-Based Cryptanalysis
- The even-less-simple case

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“Broken” Primitives

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			Complexity	Type
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Plonk	Skysraper v1	128	20	Rebound

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Plonk	Skysraper v1	128	20	Rebound
ZK	Jarvis	128	83	ad hoc PoSSo
	Anemoi	128	80	Resultants
	Arion	128	90	
	Griffin	128	55	
	Rescue	512	475	

“Broken” Primitives

Use		ck Type
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Plonk	S	Rebound
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An appetizer: The case of FRAST

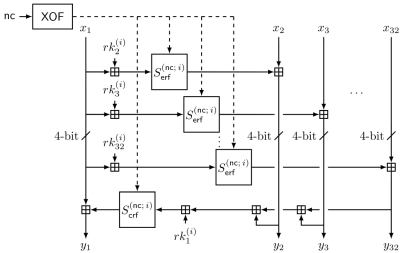
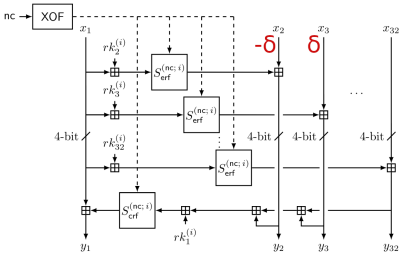


Figure 2: The i-th round function of FRAST. $rk_1^{(i)}, \ldots, rk_{32}^{(i)}$ are the i-th round keys.

An appetizer: The case of FRAST



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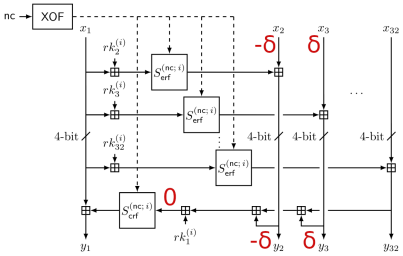

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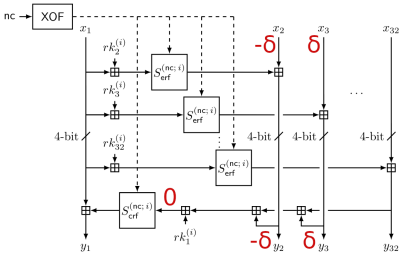

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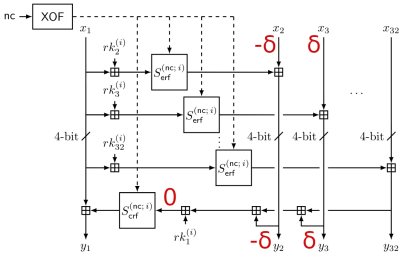

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Almost Affinity

Let E_K be the internal block cipher of FRAST

$$\Pr_{\Delta}\left[\forall x, E_K(x + \Delta) = E_K(x) + \Delta\right] = 2^{-8}$$

Plan of this Section

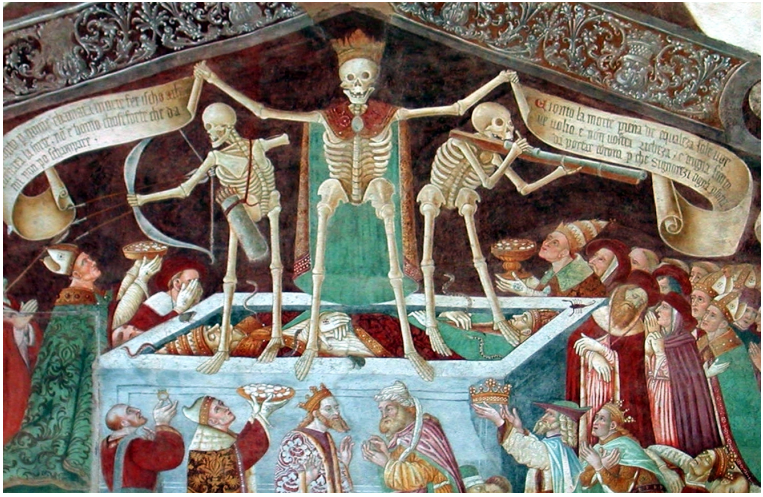
1 Full round attacks

2 These primitives are harder to design

3 Causes of death
- A graveyard?
- PoSSo-Based Cryptanalysis
- The even-less-simple case

4 Conclusion

Allegory



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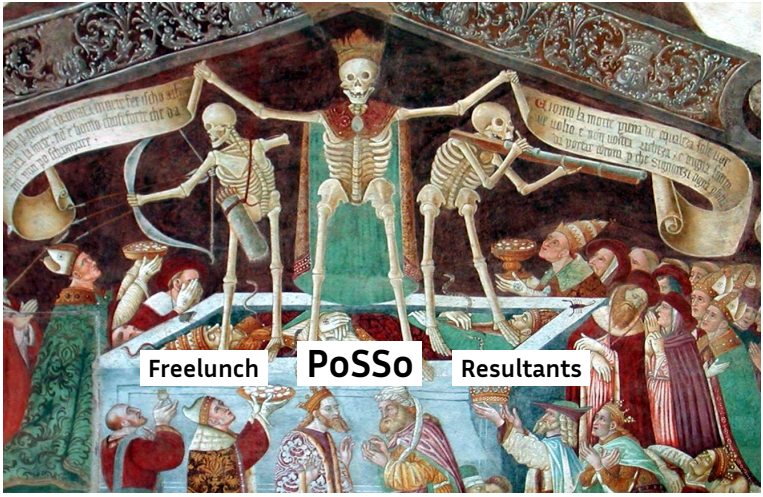

Definition of PoSSo

Polynomial System Solving

$$\begin{cases} p_1(x_1, \ldots, x_N) = 0 \\ \vdots \\ p_{k-1}(x_1, \ldots, x_N) = 0 \\ p_k(x_1, \ldots, x_N) = 0 \end{cases}$$

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PoSSo magic!

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PoSSo magic!

Here, we suppose that there is a finite, small number of solutions (e.g. not a full vector space).

Steps of a PoSSo-Based Attack

Write a system of equations.

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Steps of a PoSSo-Based Attack

Initial Cryptanalysis. Deduce a system of equations as simple as possible from the intended attack.

Write a system of equations.

Solve system. If the system is completely linear, trivial.
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The particular case of Elizabeth (1/2)

Elisabeth
Implements a "filter permutator"

- Key register is never modified
- Optimized for TFHE
- Low multiplicative depth: F is of low degree

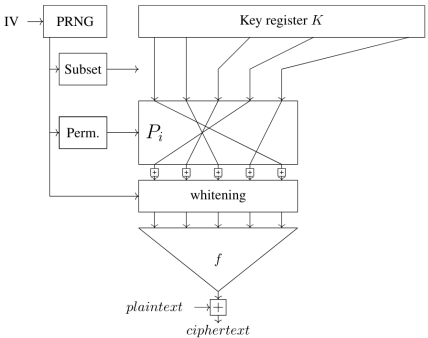

Fig. 1: The group filter permutator design

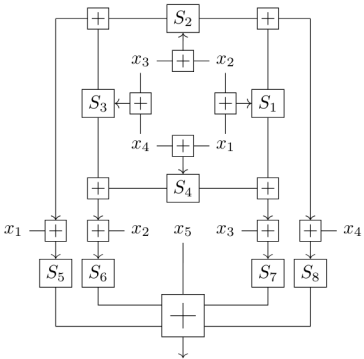

Fig. 2: Elisabeth-4 's 5 to 1 inner function.

The particular case of Elisabeth (2/2)

Basic Linearization

$$s_i = F(x_0, \ldots x_n)$$
$$= \sum_{u \in \mathbb{F}_2^n} \alpha_u \prod_j x_j^{u_j} = \sum_{u \in \mathbb{F}_2^n} \alpha_u P_u$$

α_u is known, both x_j and P_u must be recovered.

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Model	Time (operations)	Data (nibbles)	Memory (bits)
Known IV	2^{124}	2^{43}	2^{87}
Known IV	2^{116}	2^{41}	2^{81}
Known IV	2^{94}	2^{41}	2^{57}
Known IV	2^{88}	2^{87}	2^{54}
Chosen IV	2^{88}	2^{37}	2^{54}

The simplest case: linearization

would be more costly in this context. On a filtered LFSR the security estimation is $\mathcal{O}(D\log^2(D) + ED\log(D) + E^\omega)$ where $D = \sum_{i=1}^{\deg(h)} \binom{N}{i}$ and $E = \sum_{i=1}^{\deg(g)} \binom{N}{i}$. This estimation will be used as an indicator rather than a sharp limit, considering that the complexity of the best attack of the algebraic kind would lie between this (too low) bound and the (too high) one given by the algebraic attack of Courtois-Meier.

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The best algorithm was not the one considered, and its complexity scaled differently.

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Generic System Solving: Steps and Tools

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The Tools Used

SAGE Open source, mostly reliable...

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Berlekamp-Rabin Easy to re-implement

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Usual goal

Ensure that the attack has a time complexity beyond 2^{128}.

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1. Encoding

$$\begin{cases} g_0(x_1, \ldots, x_N) = 0 \\ \ldots \\ g_{N-1}(x_1, \ldots, x_N) = 0 \\ g_N(x_1, \ldots, x_N) = 0 \end{cases}$$

2. Find Gröbner basis

$$\begin{cases} g_1^*(x_1, \ldots, x_N) = 0 \\ \ldots \\ g_{N-1}^*(x_{N-1}, x_N) = 0 \\ g_N^*(x_N) = 0 \end{cases}$$

3. Change order

find x_0

...

deduce all x_i:s

4. Final resolution

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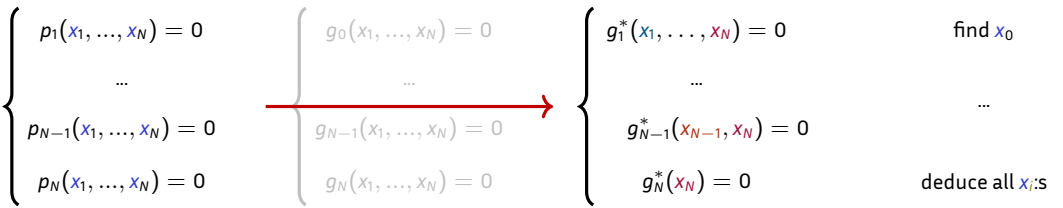

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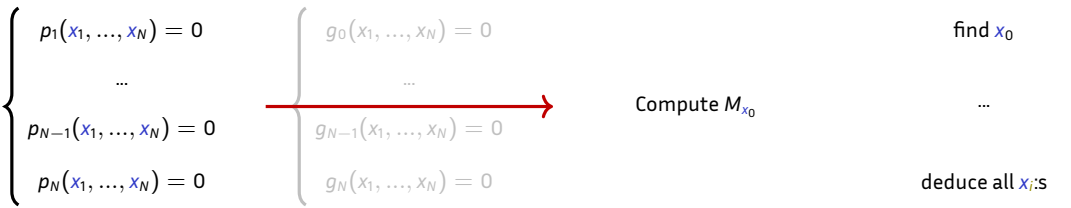

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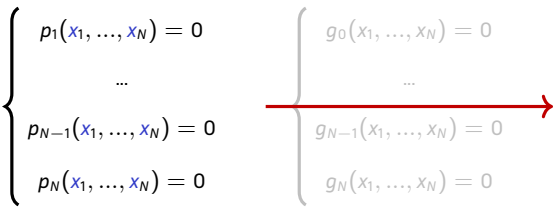

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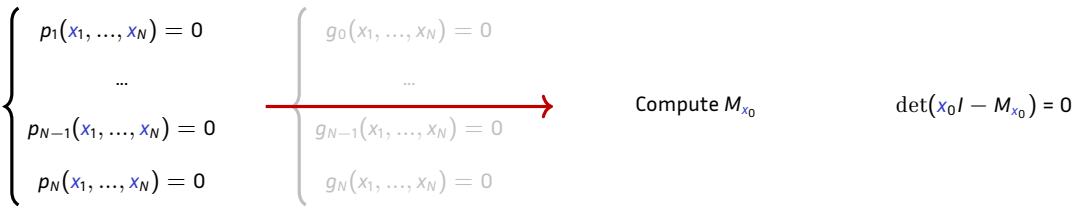

What do we need?

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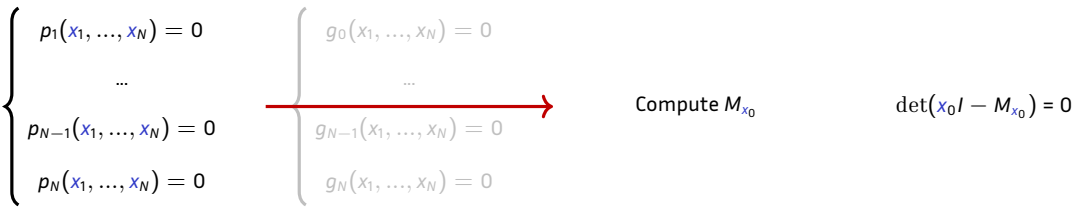

What do we need?

1. Free Gröbner basis: the FreeLunch
2. Compute M_{x_0}: regular Gröbner basis arithmetic
3. Solve $\det(x_0 I - M_{x_0}) = 0$: dedicated algorithm

The Resultant-based Approach

$$\begin{cases} f(x_1, x_2) = 0 \\ g(x_1, x_2) = 0 \end{cases}$$

1. Define system

The Resultant-based Approach

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$$Syl(f,g) = \underbrace{\begin{bmatrix} a_\gamma & \cdots & a_1 & a_0 & & 0 \\ & \ddots & & \ddots & \ddots & \\ 0 & & a_\gamma & \cdots & a_1 & a_0 \\ b_\delta & b_{\delta-1} & \cdots & b_0 & & 0 \\ & \ddots & \ddots & & \ddots & \\ 0 & & b_\delta & b_{\delta-1} & \cdots & b_0 \end{bmatrix}}_{\gamma+\delta} \begin{matrix} \left.\vphantom{\begin{matrix} a \\ a \\ a \end{matrix}}\right\} \delta \\ \left.\vphantom{\begin{matrix} a \\ a \\ a \end{matrix}}\right\} \gamma \end{matrix}$$

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$$r(x_1) = 0 \rightarrow x_1$$

1. Define system
2. Compute resultant
Univariate root

Towards better security arguments

Lessons Learnt

1. The best solving algorithm might not be the one we think of at first

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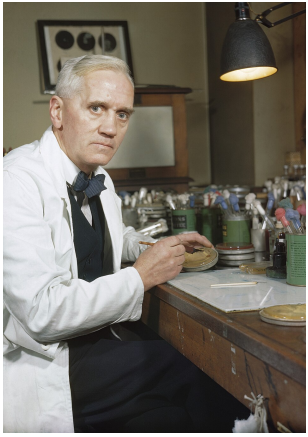
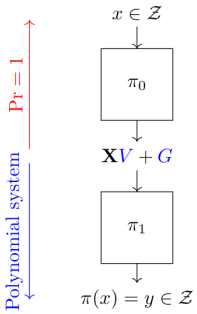


Round Skips: a limit of D_I...



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Use the degrees of freedom to add equations that decrease the ideal degree.

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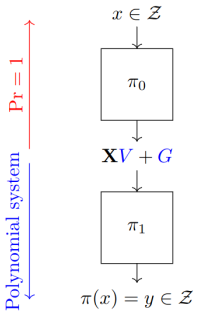

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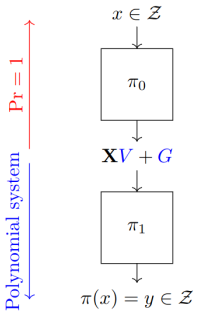

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Bigger blocks $\longrightarrow$ higher D_I, but also more degrees freedom!

Plan of this Section

1 Full round attacks

2 These primitives are harder to design

3 Causes of death

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The particular case of ZK-friendly HF

Uncertainty Different protocols use different primes $\implies$ different possible values for α.

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Table 1: *Number of Rounds of* `Anemoi`.

α	3	5	7	11
$\ell = 1$	21	21	20	19
$\ell = 2$	14	14	13	13
$\ell = 3$	12	12	12	11
$\ell = 4$	12	12	11	11
$\ell = 6$	10	10	10	10
$\ell = 8$	10	10	9	9

(a) *When* $s = 128$.

α	3	5	7	11
$\ell = 1$	37	37	36	35
$\ell = 2$	22	22	21	21
$\ell = 3$	17	17	17	17
$\ell = 4$	16	16	15	15
$\ell = 6$	13	13	13	13
$\ell = 8$	12	12	11	11

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Comparison $\neq$ Security evaluation Cryptanalysts focus on **comparing instances**

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Is there a set of parameters for which my attack works?

$\neq$

What is the security of the variant I care about?

Looking at Rescue

This slide and the following ones are heavily based on

Improved Resultant Attack against Arithmetization-Oriented Primitives, Bariant et al.
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r	`iteRes`	`uniSol`	[26]	Designers' estimation [23]
6	49	40	60	-
7	57	45	69	-
8	64	50	81	-
12	93	70	-	80
18	137	99	-	128
35	257	181	-	256
66	475	330	-	512

Table 3. Theoretical complexities (in $\log_2$ $\mathbb{F}_q$-multiplications) for attacking variants of Rescue with $t = \alpha = 3$ and $\log_2(q) \approx 512$. Our analysis show that the complexity of `sysGen` is negligible compared to the rest of the attack.

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All instance are fine except for a single one (the 512-bit one)

Looking at Anemoi

α	ℓ	r	sysGen	iteRes [3, polyDet] [26]		α	ℓ	r	sysGen	iteRes [3, polyDet] [26]	
3	1	21	78	80	118	110	3	1	37	129	130	203	191
	2	14	89	89	-	-		2	22	133	134	-	-
	3	12	105	104	-	-		3	17	144	144	-	-
	4	12	131	131	-	-		4	16	172	172	-	-
	6	10	154	153	-	-		6	13	199	198	-	-
5	1	21	91	96	156	133	5	1	37	151	157	270	231
	2	14	108	113	-	-		2	22	164	169	-	-
	3	12	131	135	-	-		3	17	182	186	-	-
	4	12	167	171	-	-		4	16	221	224	-	-
	6	10	199	202	-	-		6	13	258	262	-	-
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	2	13	113	119	-	-		2	21	177	183	-	-
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	4	11	174	179	-	-		4	15	236	241	-	-
	6	10	227	232	-	-		6	13	296	300	-	-
11	1	19	102	111	198	158	11	1	35	179	187	358	288
	2	13	129	137	-	-		2	21	203	211	-	-
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Table 4. Theoretical complexities (in $\log_2 \mathbb{F}_q$-multiplications) for attacking full-round variants of Anemoi in odd characteristic proposed for 128-bit security on the left-hand side table, and 256-bit security on the right-hand side table. To stay consistent with the assumptions of previous work, we used $\omega = 2.81$ for the attack of [3] and $\omega = 2.376$ for [26]. Experiments show that the attack on odd-characteristic Anemoi is heavily dominated by `iteRes` in practice.

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- Bigger α $\longrightarrow$ more secure

When these parameters increase, other attacks take over (in the initial security analysis)

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They break because we are still learning

Glaring oversights aside, the main problem was
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We still need to figure out a good way to specify/secure “factories”.

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Primitive factory vs. primitive

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Ideal Degree

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Thank You!

Looking at Arion

e	t	r	sysGen	iteRes	uniSol	[3, polyDet]
3	3	6	75	90	73	128
	4	6	82	96	79	134
	5	5	73	87	71	114
	6	5	78	91	75	119
	8	4	69	82	67	98
5	3	6	79	94	76	132
	4	5	72	86	70	113
	5	5	76	90	74	118
	6	5	81	95	78	122
	8	4	71	85	70	101

e	t	r	sysGen	iteRes	uniSol	[3, polyDet]
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	4	4	57	72	57	87
	5	4	61	75	60	91
	6	4	65	79	64	94
	8	4	71	85	70	101

Table 2. Theoretical complexities (in $\log_2$ $\mathbb{F}_q$-multiplications) of attacks against full-round variants of Arion with 128-bit security using $\alpha = 121$. Normal parameters are in the left table, and the more aggressive α-Arion parameters are in the right table.

Looking at Griffin

α	t	r	`sysGen`	`iteRes`	`uniSol`	[3, `polyDet`]
3	3	16	92	92	83	120
	4	15	87	87	78	112
	8	11	63	61	57	76
	$\geq$12	10	55	53	51	64
5	3	14	102	106	92	141
	4	11	81	85	75	110
	8	9	63	66	58	81
	$\geq$12	9	60	62	56	74

Table 1. Complexity (in $\log_2$ $\mathbb{F}_q$-multiplications) of the steps of our attack on full-round variants of Griffin with 128-bit security claim.