Symmetric Techniques for Advanced Protocols: What *are* They?

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Inria, Paris

14th of March 2025

Trendy topics

MPC-friendly?

Arithmetization-Oriented?

Verification efficiency?

Algebraic attacks?

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MPC-friendly?

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Symmetric crypto **for the blockchain...**

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MPC-friendly?

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Symmetric crypto **for the blockchain...**

... for neural networks???

The conclusion of today: **symmetric cryptography** has always had to deal with specific **implementation criteria**, but the new ones are indeed a bit **stranger than before**.

Outline

1. What is the Purpose of a Symmetric Primitive
2. “Advanced” Protocols
3. Symmetric Primitives for Advanced Protocols
4. Conclusion

Plan of this Section

1 What is the Purpose of a Symmetric Primitive

2 "Advanced" Protocols

3 Symmetric Primitives for Advanced Protocols

4 Conclusion

Plan of this Section

1. What is the Purpose of a Symmetric Primitive
   - Let’s look at primitives we all know
   - A Small Cog in a Big Machine
2. “Advanced” Protocols
3. Symmetric Primitives for Advanced Protocols
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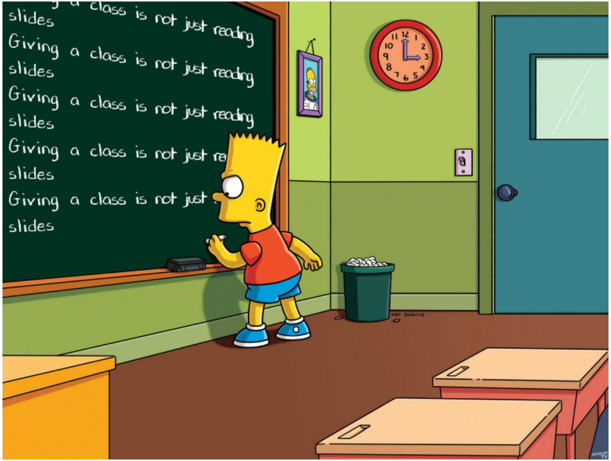
Why do we need symmetric primitives?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Unstable Definitions

What is "efficient" varies

- What are the operations that we **can** use?
- What are the associated **costs**?

How to get the best security for a given price?

What is "secure" varies

- Should the primitive work in many context?
- Do we care about nonce-misuse?

How do we define the **security** that the primitive must provide?

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What is "secure" varies

- Should the primitive work in many context? Modularity vs. Single use
- Do we care about nonce-misuse? Robustness vs. "not our problem"

How do we define the **security** that the primitive must provide?

What are the relevant forms of cryptanalysis?

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Web Encryption

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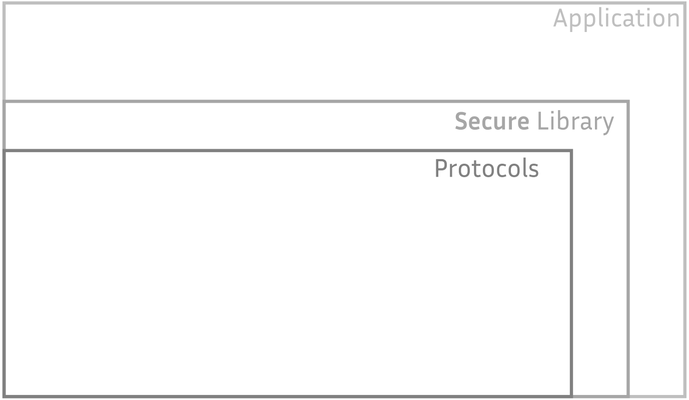
Application
Secure Library

Web Encryption



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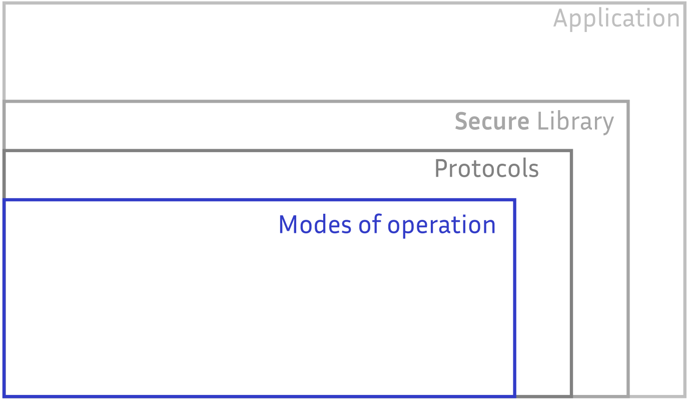

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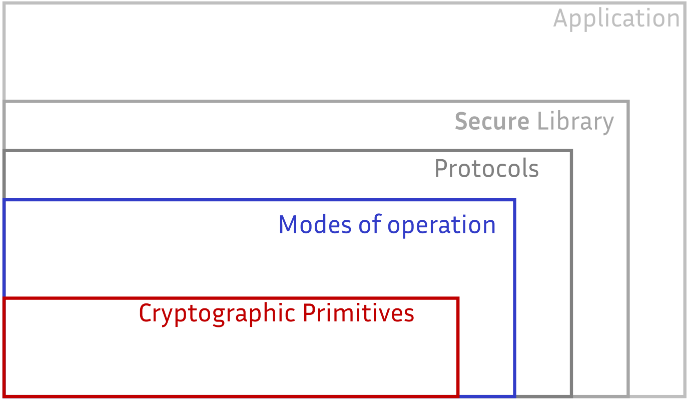

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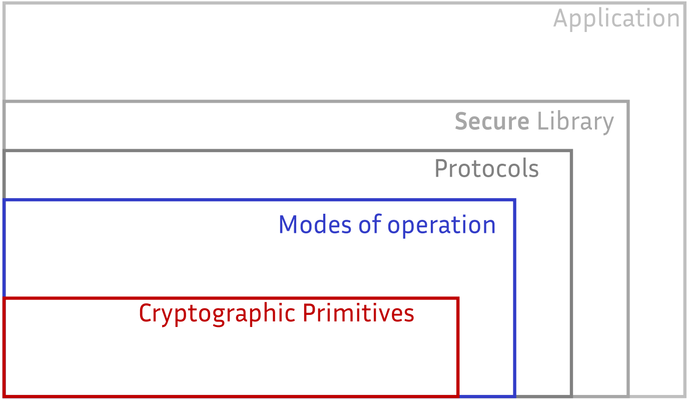

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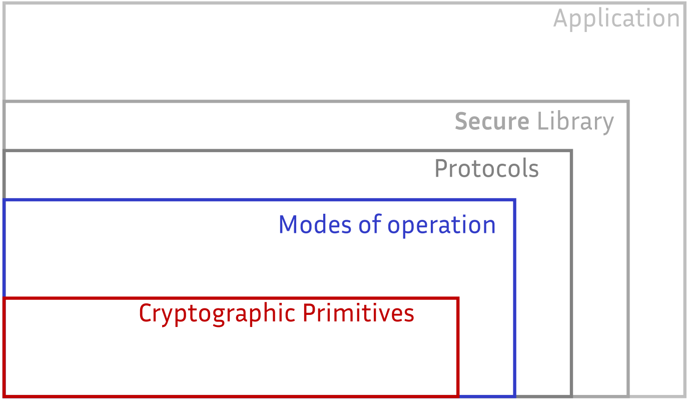

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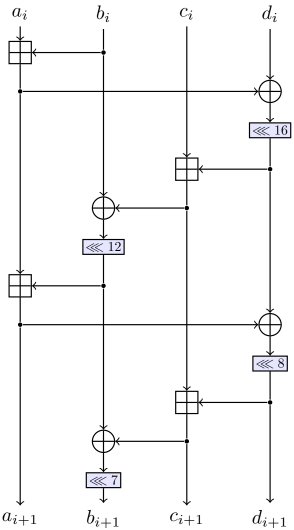
- AES-GCM; Chacha-poly1305.

What Chacha looks like



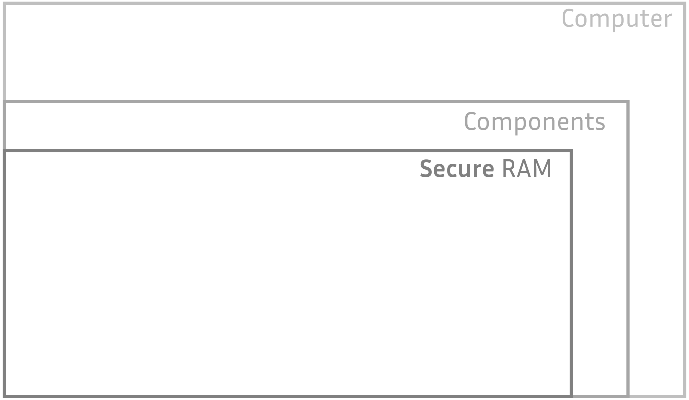
- Addition / Rotation / XOR
- 256-bit key
- 512-bit state
- Defined over 32-bit words

RAM Encryption

Computer

RAM Encryption

RAM Encryption



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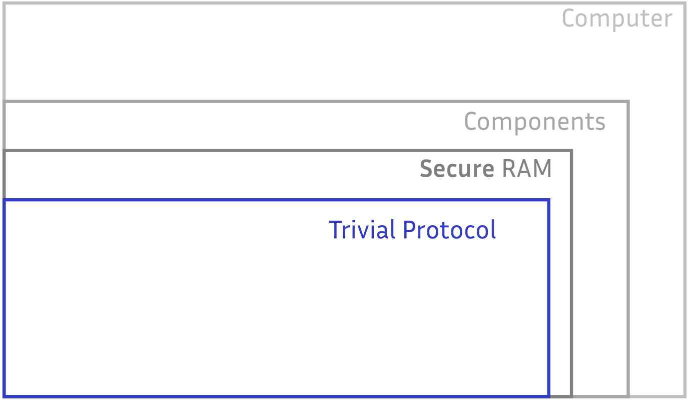

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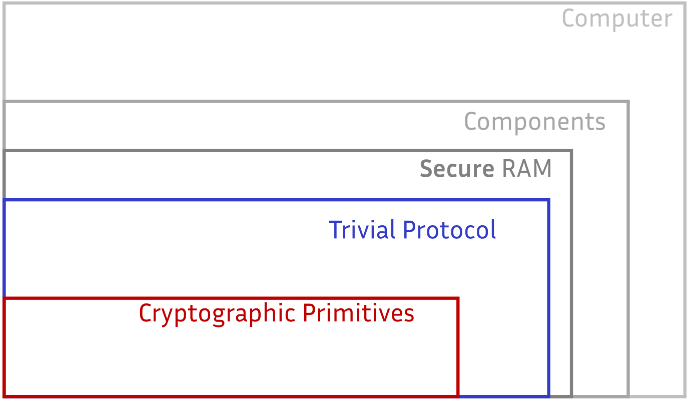

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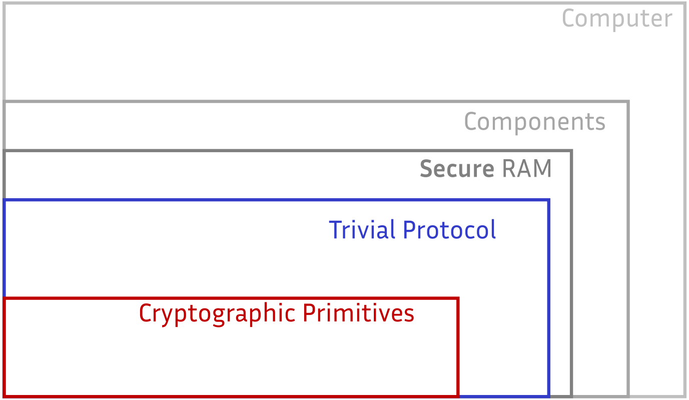

- We want very low latency block encryption for specific (and small) block sizes.

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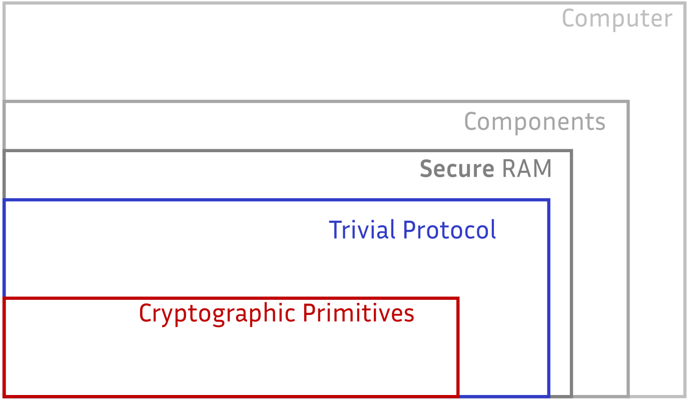
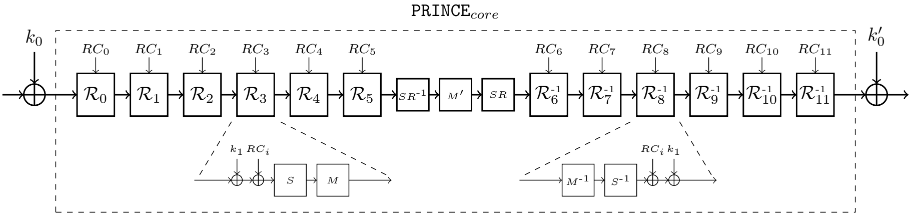


- We want very low latency block encryption for specific (and small) block sizes.
- PRINCE? QARMA? not so clear at this stage.

What PRINCE looks like



- 4-bit S-box optimized for hardware
- 2 different matrices
- FX construction
- “α-reflexion”
- inverse rounds used in the second half

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- A symmetric primitive is a very small (but crucial) cog in a very big machine,
- there are many different "big machines", and
- this has a huge influence on what the primitive looks like.

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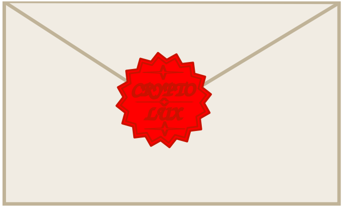
Securing Data

Usually, we secure data (at rest or in transit).



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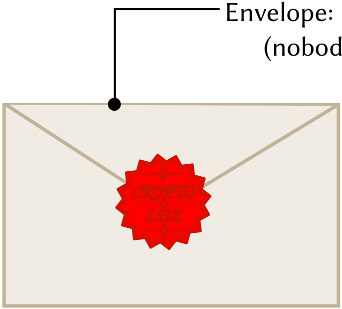

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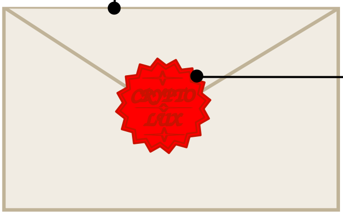

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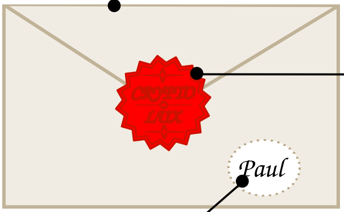

Seal: Integrity
(nobody can modify it)

Signature: Authentication
(it was written by the right person)

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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Allow a third party to perform some operations on encrypted ciphertext that correspond to meaningful operations on the corresponding plaintext.

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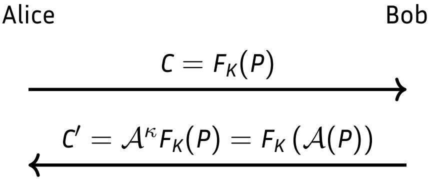

Alice

Bob

$C = F_K(P)$

$C' = \mathcal{A}^{\kappa} F_K(P) = F_K\left(\mathcal{A}(P)\right)$

F_K is a homomorphic cipher,
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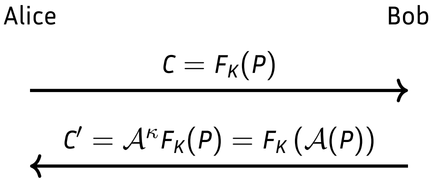

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An example of (not F)HE

XOR-ing a constant to a ciphertext obtained using a stream cipher XORs the same constant in the plaintext:

$$C \oplus t = (P \oplus K) \oplus t = (P \oplus t) \oplus K$$

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Allow multiple parties to evaluate a function together even if some parties are not trustworthy.

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Example

Shamir’s secret sharing

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Applications

- Masking (the side-channel attack counter-measure)
- MPC-in-the-head paradigm (e.g. for Picnic signatures)
- ...

Zero-Knowledge

Principle

I want to convince you I know a secret without revealing it

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- BLOCKCHAIN!!1!

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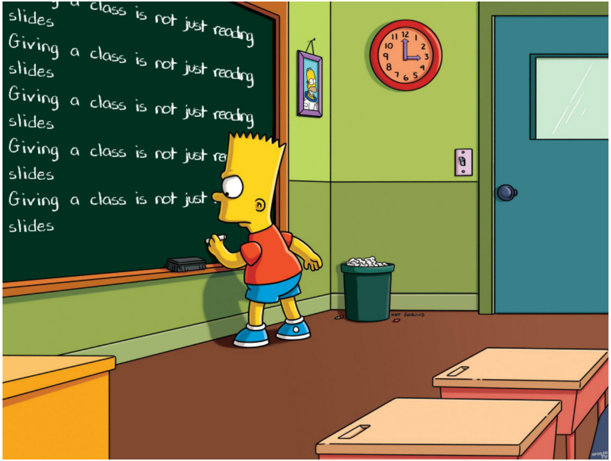
Arithmetization: General Principle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Verifying if $y = c(ax + b)^{10} + x$ in R1CS

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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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- 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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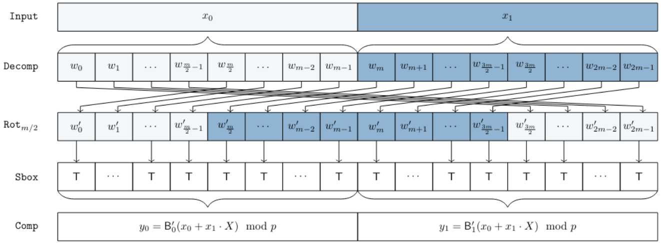
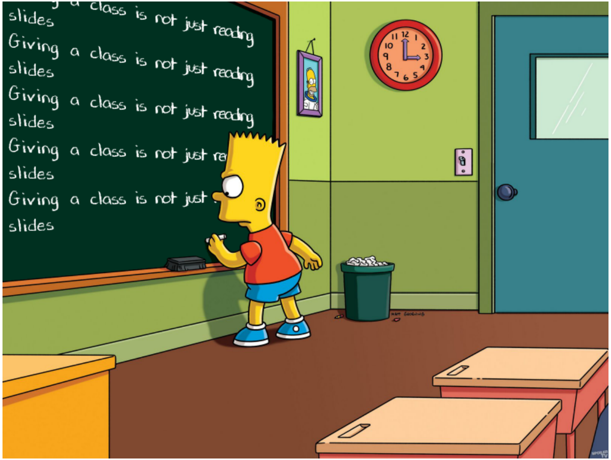


Figure 3: The Bar layer $\mathsf{B}' : \mathbb{F}_{p^n} \to \mathbb{F}_{p^n}$ for $n = 2$ in detail, including the decomposition, the rotation, the S-box, and the composition.

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

"Arithmetization-Oriented"? Evaluation vs. Verification

(the term was coined in [AAB$^+$20])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Symmetric Techniques for Advanced Protocols

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Masking	BGV	R1CS
MPC-in-the-head (signatures...)	FV	AIR ...
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VDF		

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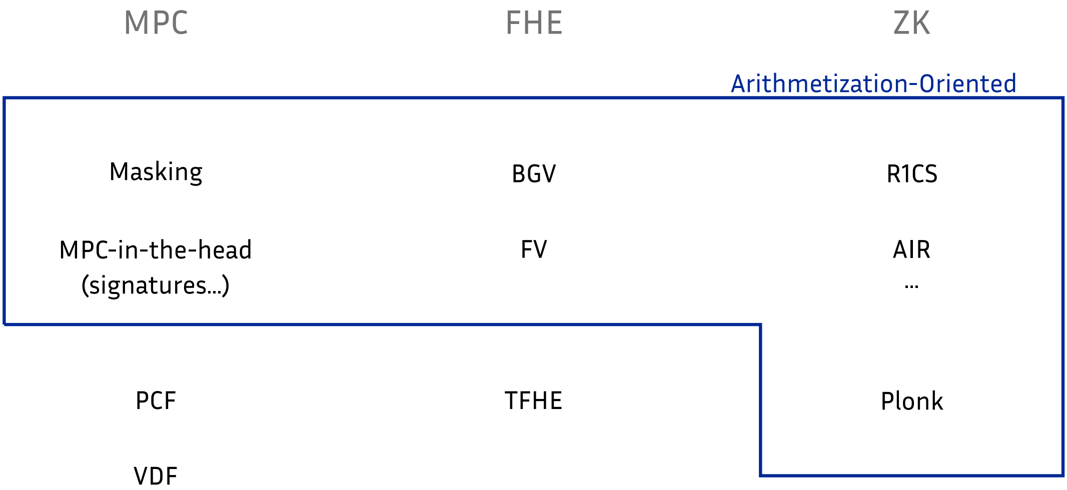

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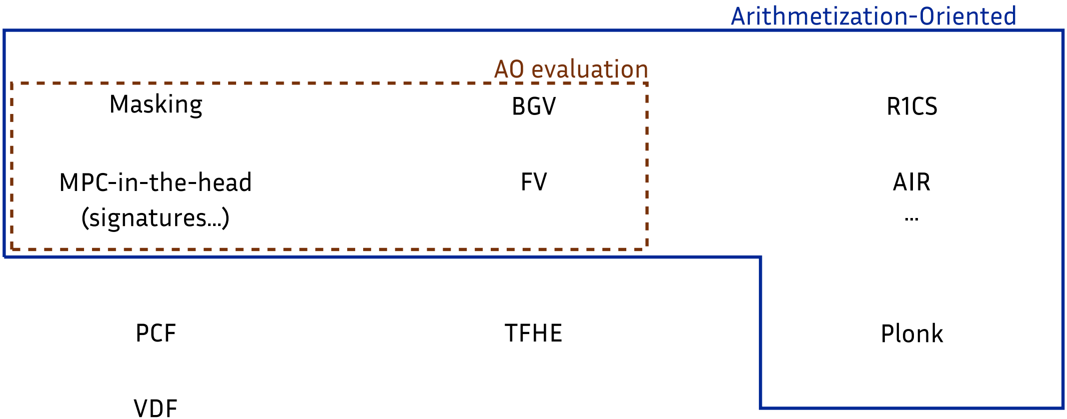

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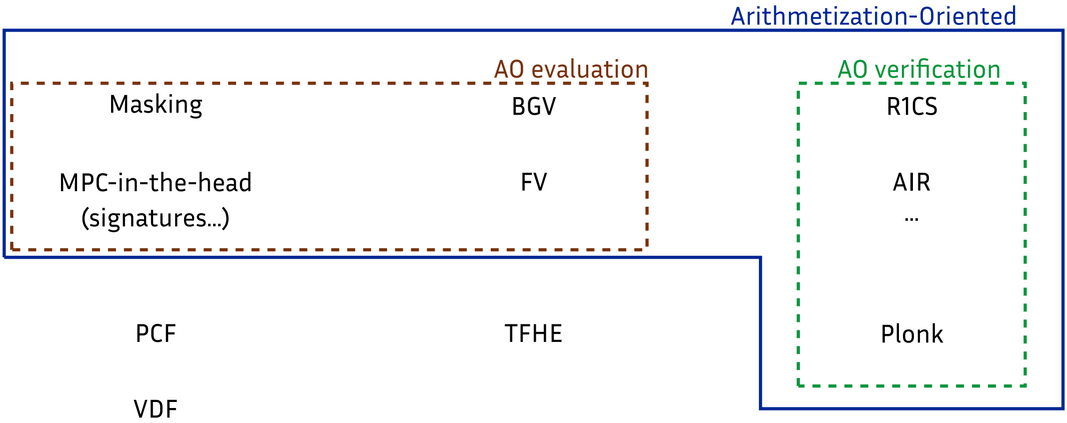

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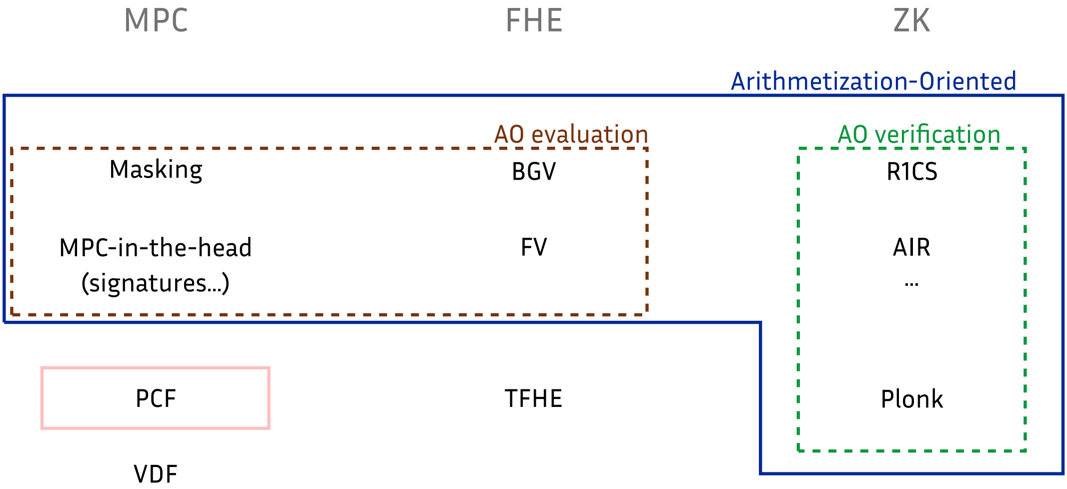

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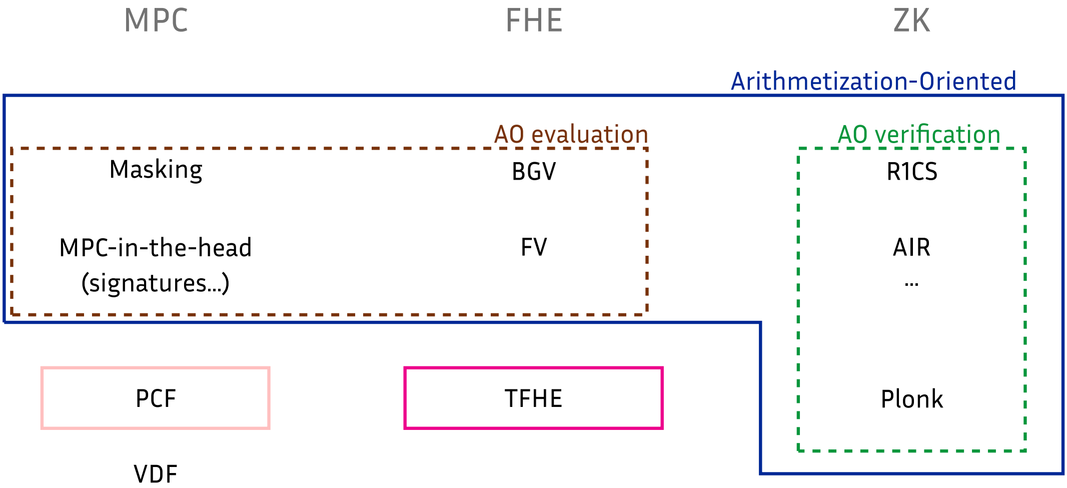

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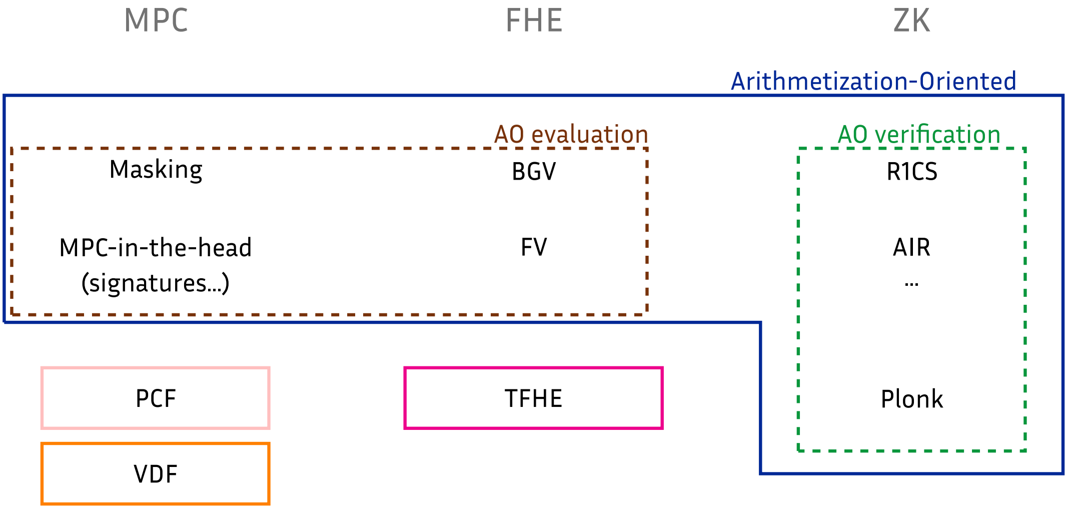

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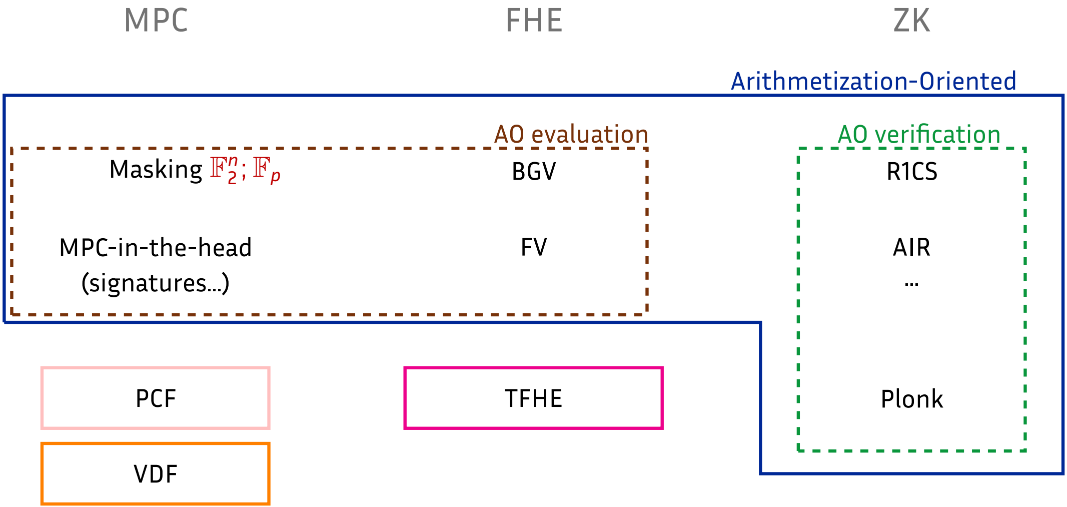

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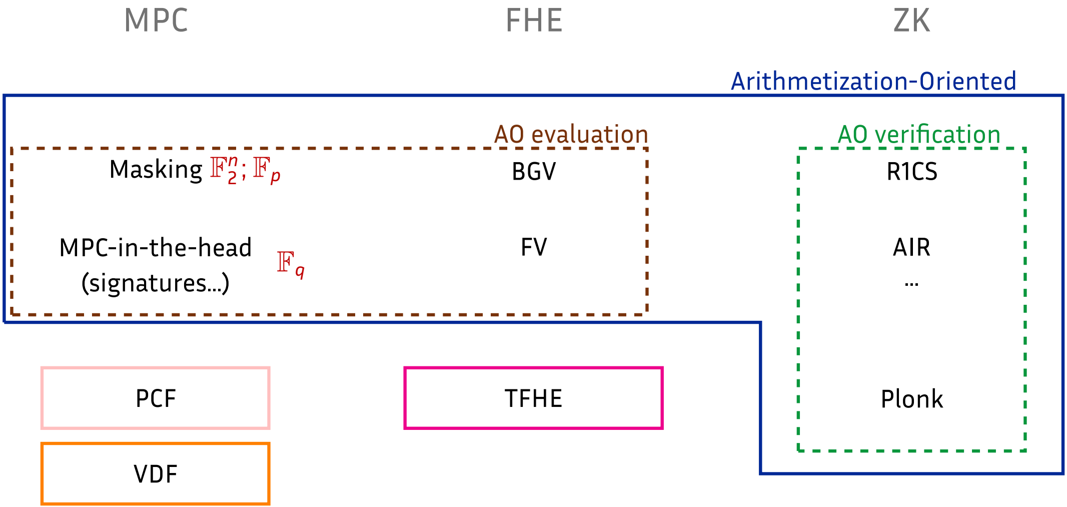

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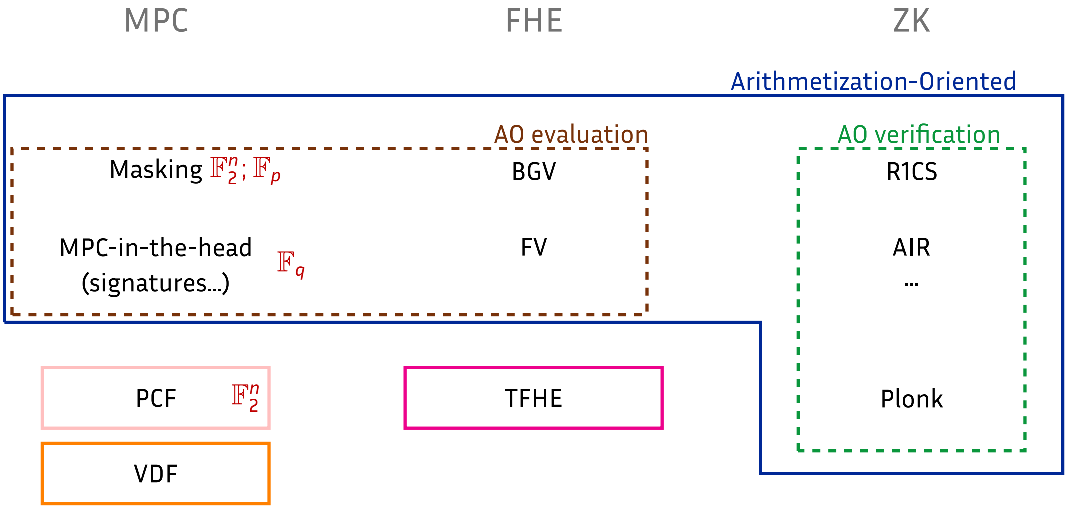

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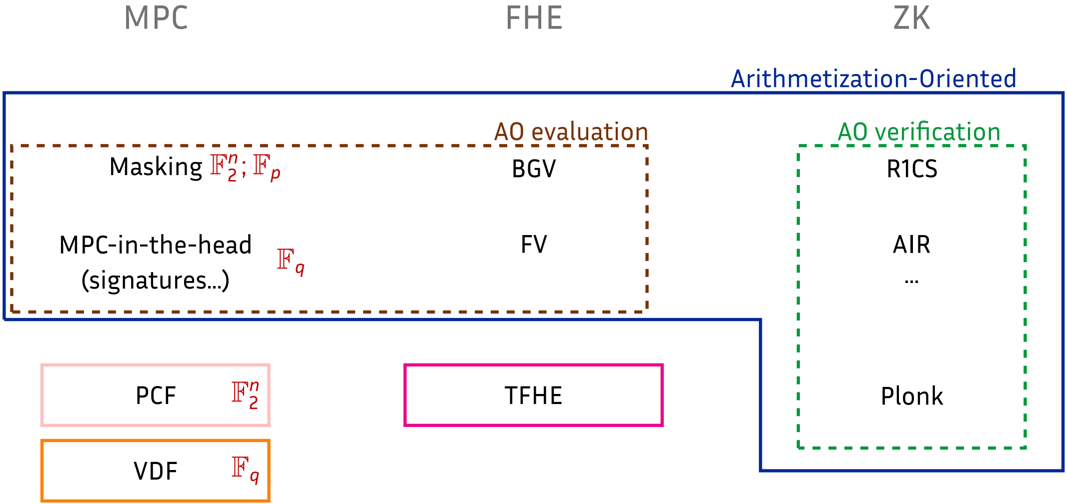

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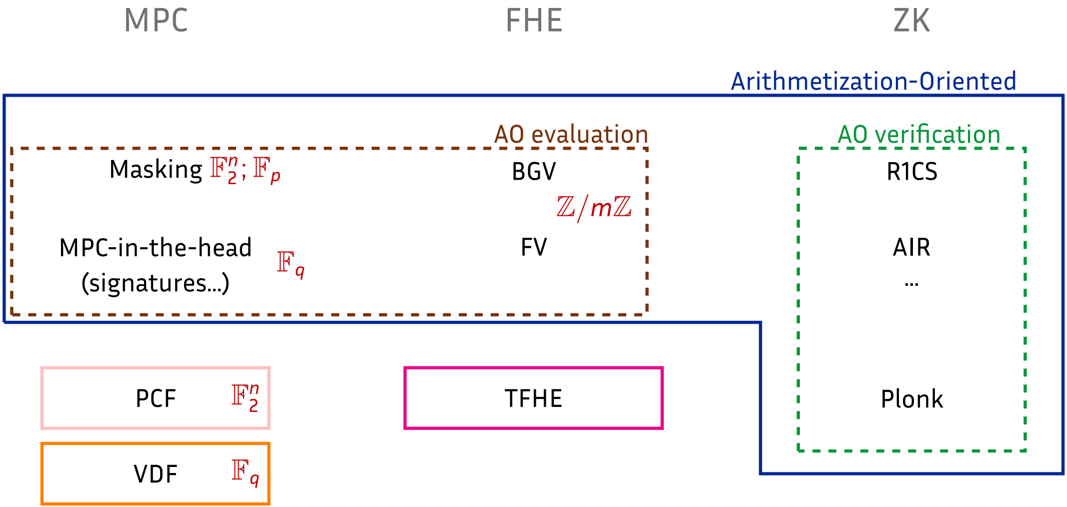

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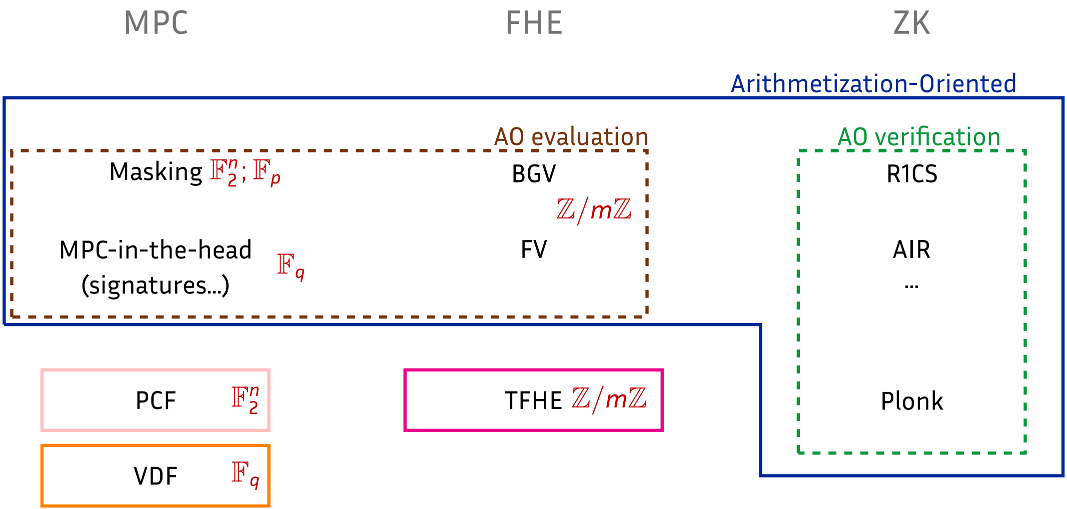

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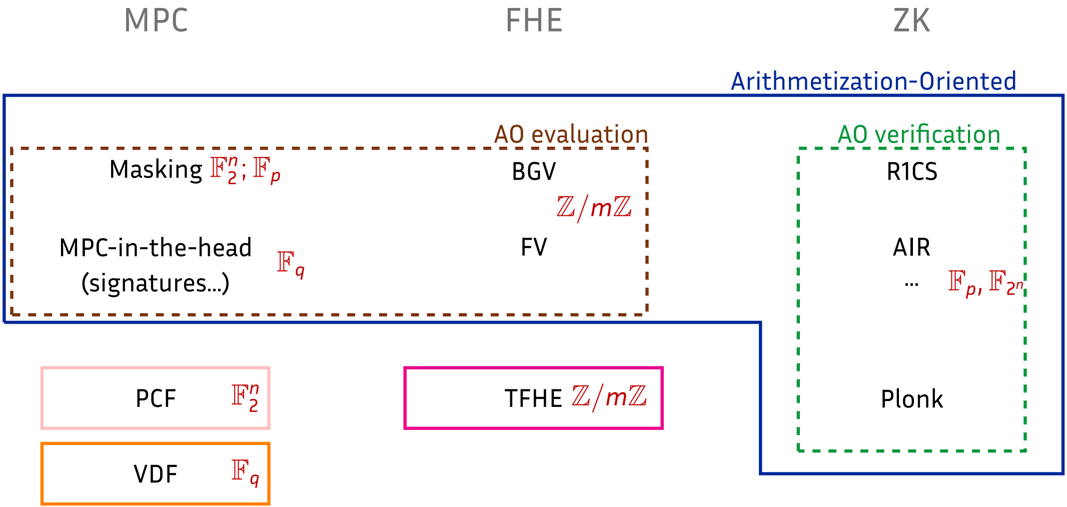

MPC

FHE

ZK

Arithmetization-Oriented

AO evaluation

Masking $\mathbb{F}_2^n; \mathbb{F}_p$

MPC-in-the-head (signatures...) $\mathbb{F}_q$

BGV

$\mathbb{Z}/m\mathbb{Z}$

FV

AO verification

R1CS

AIR

... $\mathbb{F}_p, \mathbb{F}_{2^n}$

Plonk

PCF $\mathbb{F}_2^n$

VDF $\mathbb{F}_q$

TFHE $\mathbb{Z}/m\mathbb{Z}$

A Crucial Change?

$\mathbb{F}_q$ and $\mathbb{F}_2^n$ are not the same!

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My Personal Opinion

- Indeed.

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Working over $\mathbb{F}_q$ (especially if low degree arithmetizations are needed) introduces new challenges, but solutions will rely on tried and true methods.

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Transciphering

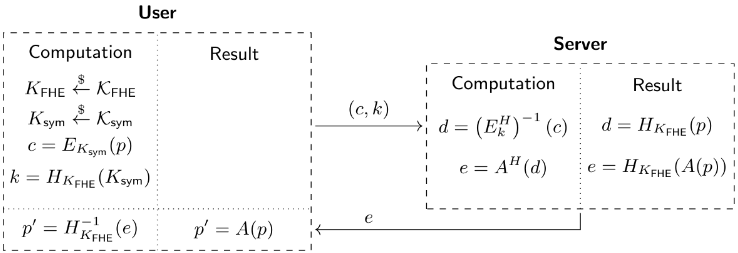
User
Computation
Result
$K_{\mathsf{FHE}} \xleftarrow{\$} \mathcal{K}_{\mathsf{FHE}}$
$K_{\mathsf{sym}} \xleftarrow{\$} \mathcal{K}_{\mathsf{sym}}$
$c = E_{K_{\mathsf{sym}}}(p)$
$k = H_{K_{\mathsf{FHE}}}(K_{\mathsf{sym}})$
$p' = H^{-1}_{K_{\mathsf{FHE}}}(e)$
$p' = A(p)$
(c, k)
e
Server
Computation
Result
$d = \left(E^H_k\right)^{-1}(c)$
$e = A^H(d)$
$d = H_{K_{\mathsf{FHE}}}(p)$
$e = H_{K_{\mathsf{FHE}}}(A(p))$

Fig. 1: The principle of transciphering, where E is a symmetric cipher (with secret key K_{sym} sampled from the space $\mathcal{K}_{\mathsf{sym}}$), H is a fully homomorphic cipher (with private key K_{FHE} sampled from the space $\mathcal{K}_{\mathsf{FHE}}$), E^H is a homomorphic evaluation of E, A corresponds to some arbitrary operations, and A^H to their homomorphic evaluation.

source: *Transistor: a TFHE-friendly Stream Cipher*

`https://eprint.iacr.org/2025/282`

The case of TFHE

Operates on $\mathbb{Z}/m\mathbb{Z}$, where m can be anything, though: more efficient if m is smaller.

Operations allowed

Linear Combinations $\sum_i \alpha_i x_i$, where the α_i are constant while x_i is input/key dependent.

- Costs almost nothing in terms of time/communication complexity...
- But noise increases

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- Very time consuming...
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- Can be composed with arbitrary table lookups! $*$ *S-box sounds* $*$
- If the ring size is even, it is better if it is nega-cyclic ($S(x + 2^{n-1}) = -S(x)$)

TFHE: corresponding stream ciphers

Elisabeth-4 [CHMS22] ; $q = 2^4$

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

Can be linearized [GBJR23]

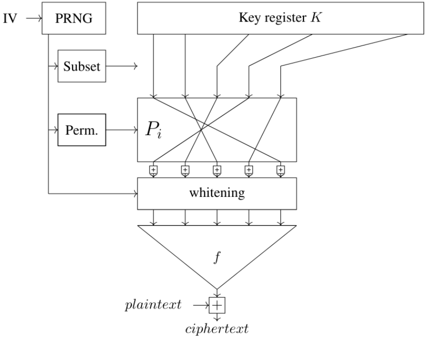

Fig. 1: The group filter permutator design

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

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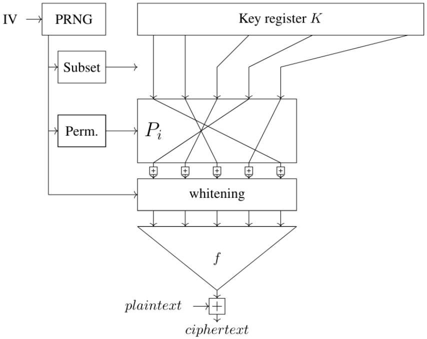

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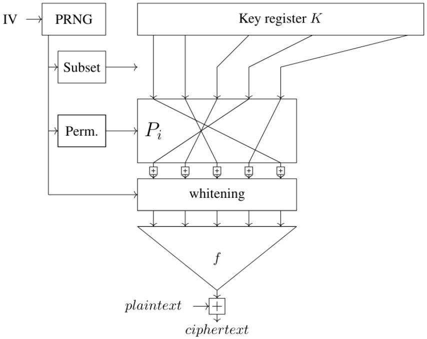

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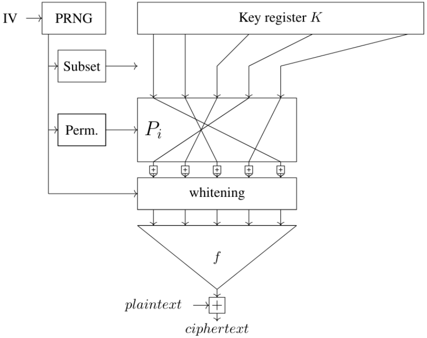
Transistor [BBB$^+$25] ; $q = 2^4 + 1$
SNOW-like round structure
See you at Anne’s invited talk :D



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  Use very few rounds with a low degree.

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

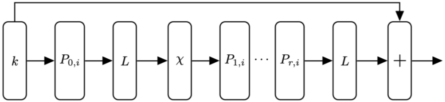

Figure 2: Generation of i-th block of DASTA.

source:

Dasta – Alternative Linear Layer for Rasta

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Binary state updated with NLFSRs.

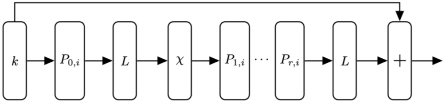

Figure 2: Generation of i-th block of Dasta.

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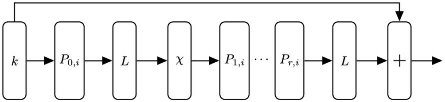
HERA [CHK+21] q large prime
A block cipher in a kind of CTR-mode variant.



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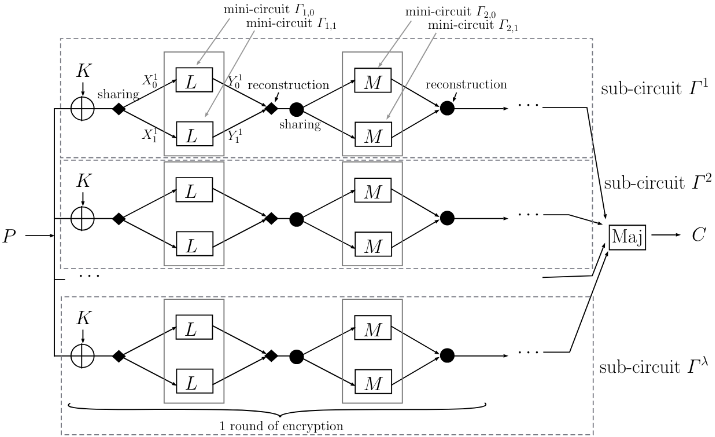
Trojan Resilience



source: *MOE: Multiplication Operated Encryption with Trojan Resilience*

`https://tosc.iacr.org/index.php/ToSC/article/view/8834`

MPC-Friendly Encryption

LowMC [ARS^{+}15] $q = 2$

SPN with partial layer of quadratic S-boxes.

Rely on large, randomly generated matrices.

Only one encryption/key; broken anyway

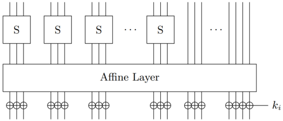


Fig. 1. Depiction of one round of encryption with LowMC.

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Ciphers for MPC and FHE

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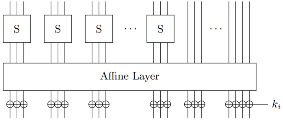

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small-pSquare [GMM+24] $p = q = 127$

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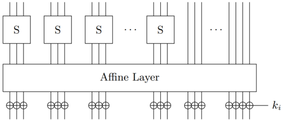

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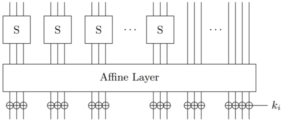
MOE [BFL$^+$21] $q = 2^{128}$, $m = 2^{128}$

Dedicated structure with linear operations in $\mathbb{F}_q$ and $\mathbb{Z}/q\mathbb{Z}$. Intended for hardware trojan resilience.



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Pseudo-Correlated Functions

A new challenger!

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$$F_k(x) := \left(\sum_{i=0}^{n-1} k_i x_i \mod 2 + \sum_{i=0}^{n-1} k_i x_i \mod 3 \right) \mod 2, \quad \text{for } x \in \{0,1\}^n.$$

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VDLPN [BCG+20]

$$f_k(x) = \bigoplus_{i=1}^{D} \bigoplus_{j=1}^{w} \bigwedge_{\ell=1}^{i} (x_{i,j,\ell} \oplus k_{i,j,\ell}),$$

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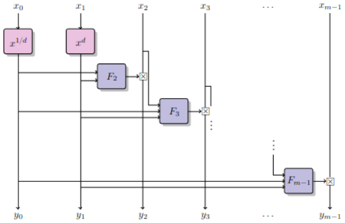

source: *Cryptanalysis and design of symmetric primitives defined over large finite fields*, PhD thesis of C. Bouvier

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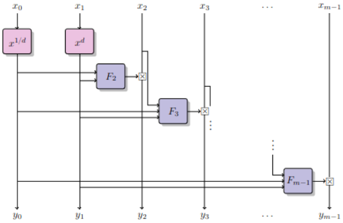
CCZ-equivalent to a function of low degree.



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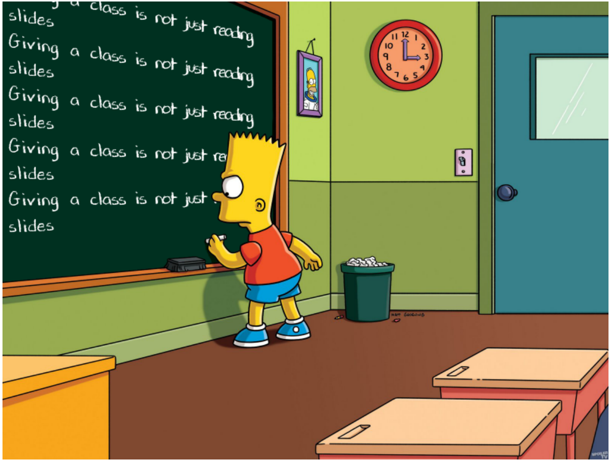
Arithmetization-Oriented Verification: CCZ-equivalence?


a class is not just reading
slides
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Coffee Break!

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