Forking a Blockcipher for Authenticated Encryption of Very Short Messages

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ASK 2018, Kolkata

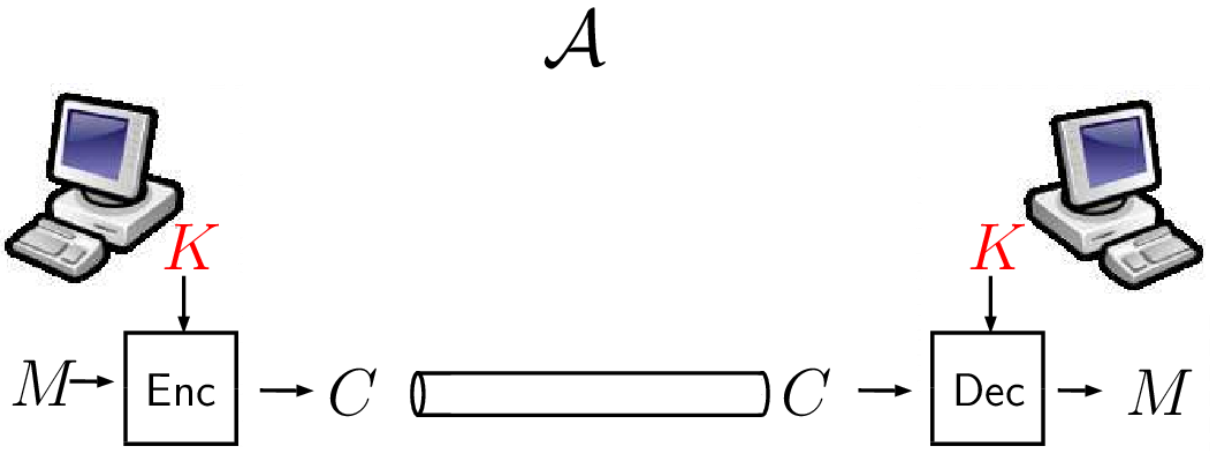
Joint work with:

Elena Andreeva (KU Leuven, Belgium)

Reza Reyhanitabar (Elektrobit, Germany)

Kerem Varici (KU Leuven, Belgium)

Authenticated Encryption



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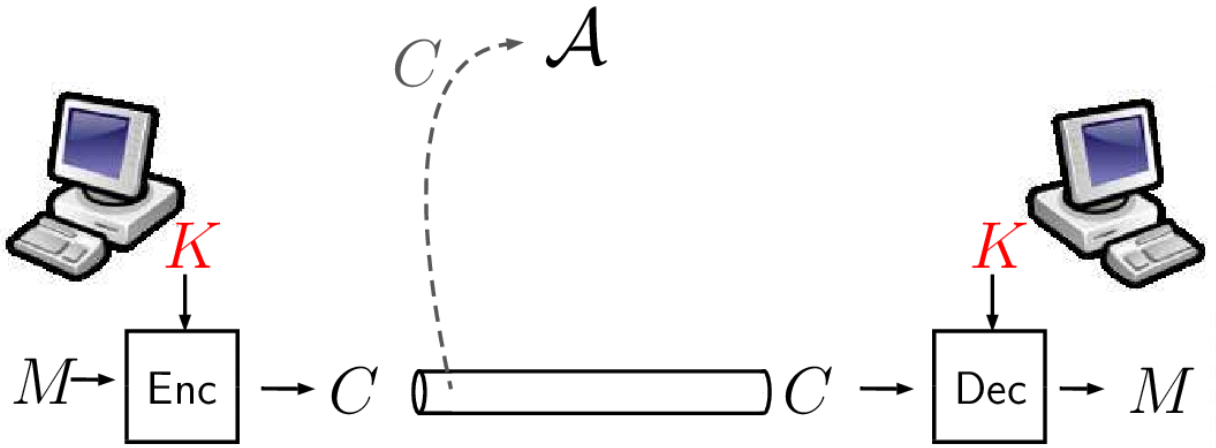

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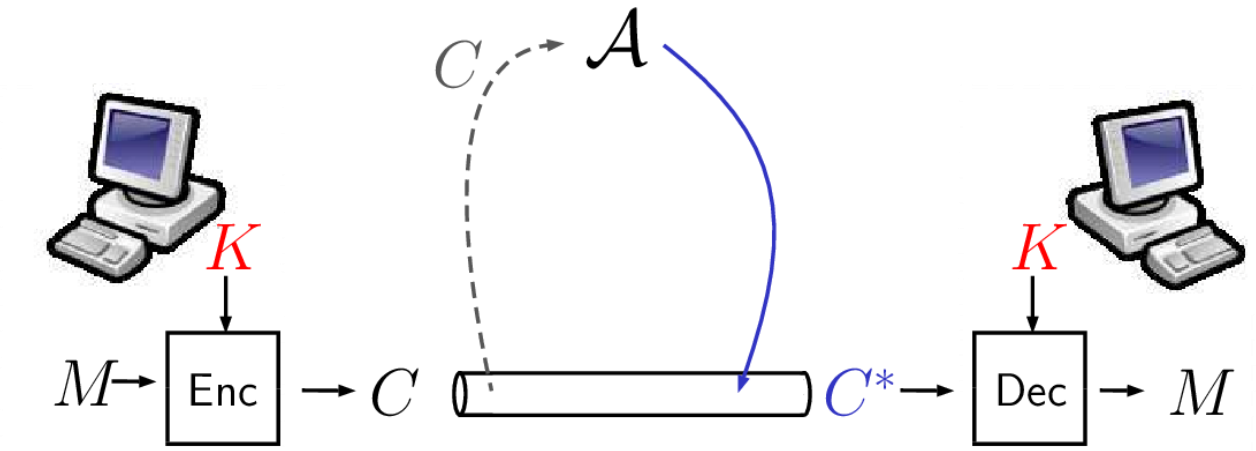

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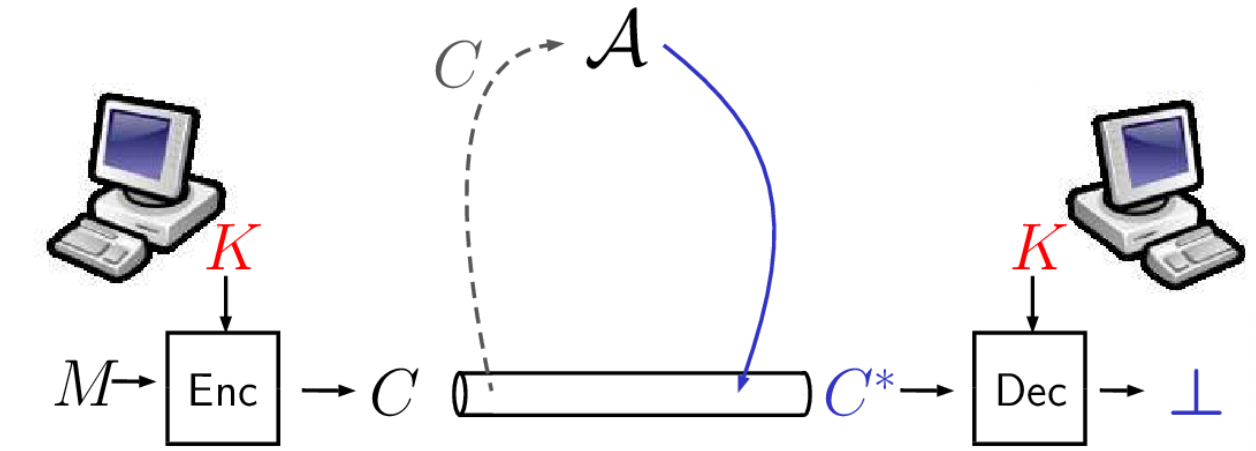

- Confidentiality and Integrity

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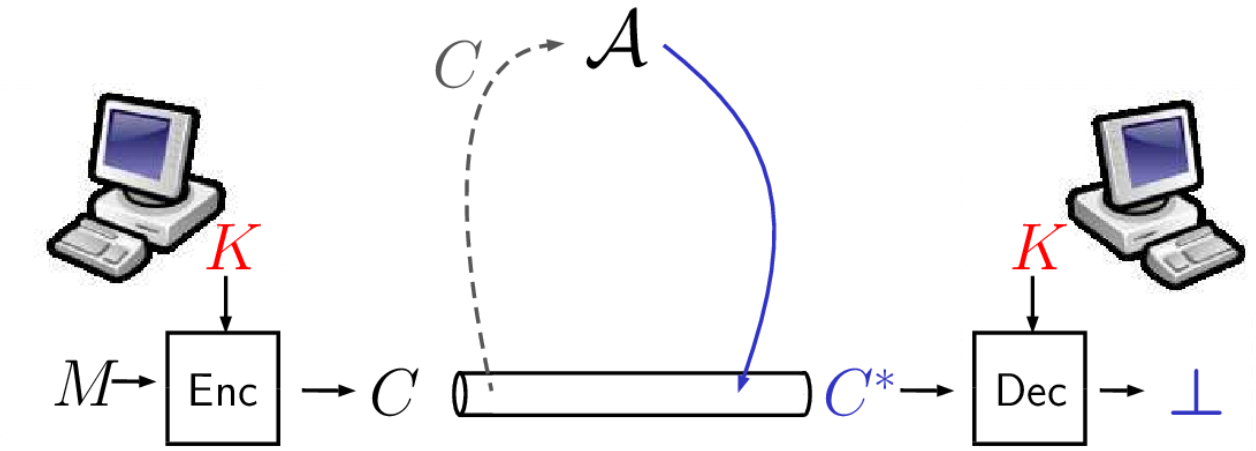

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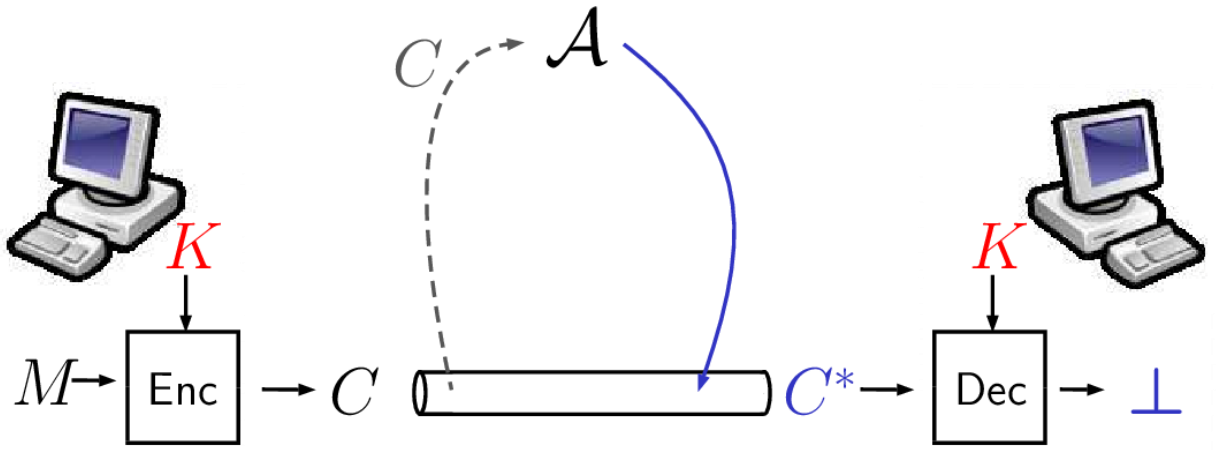

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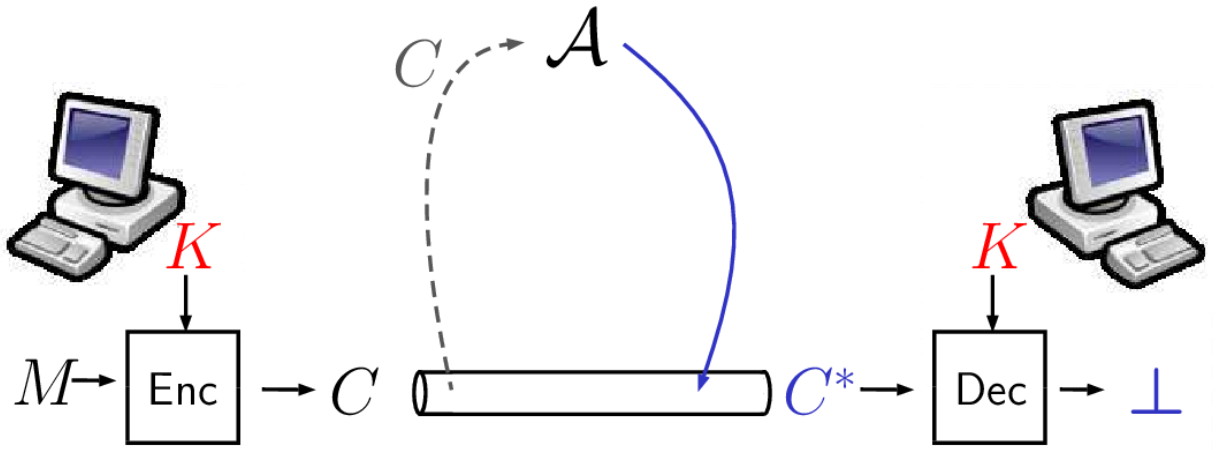

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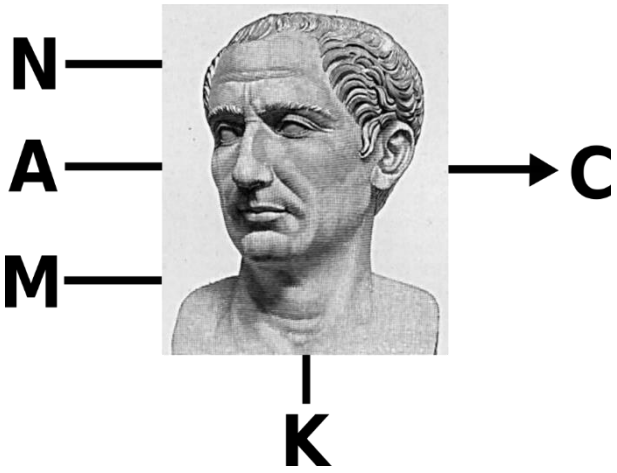
- Useful and widely used
- BUT issues with performance, robustness, patent burden …

Authenticated Encryption

CAESAR competition:

- Boost research, find new AEAD schemes
  - 57 submissions
  - ~~3~~ 5 years of activity



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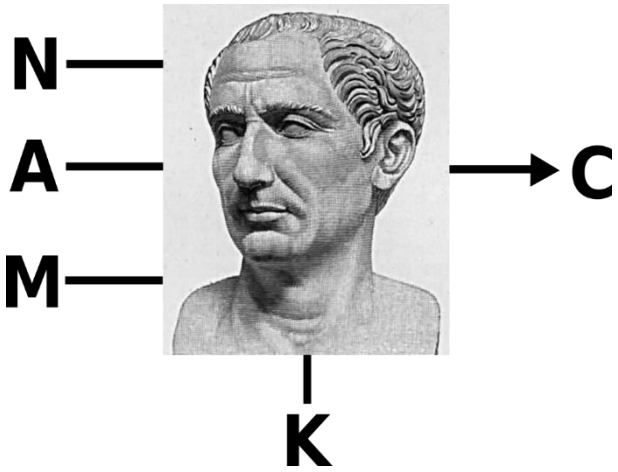

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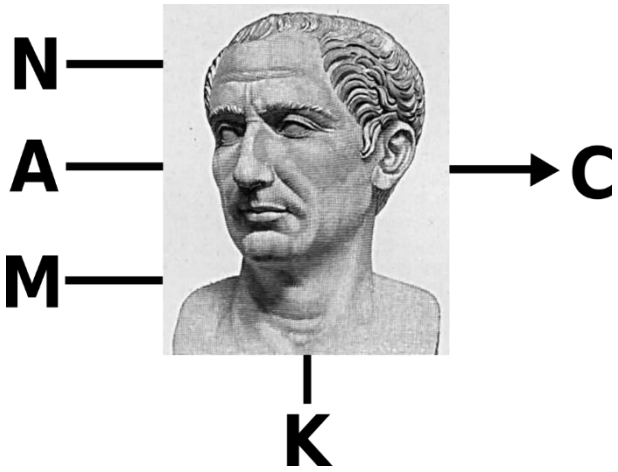

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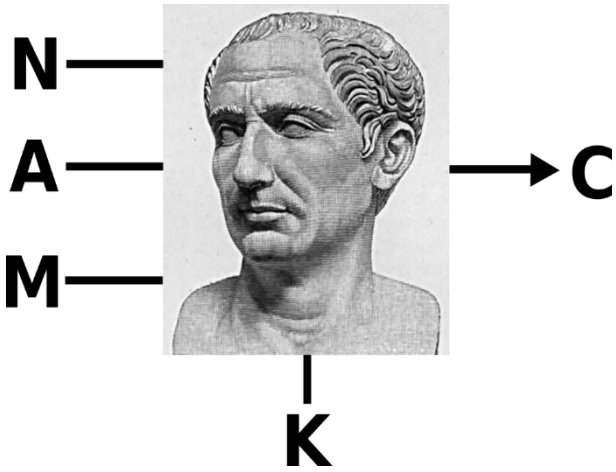

Authenticated Encryption: is it solved?

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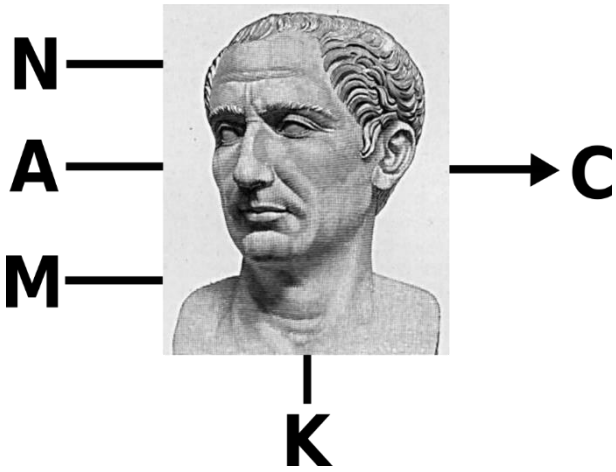
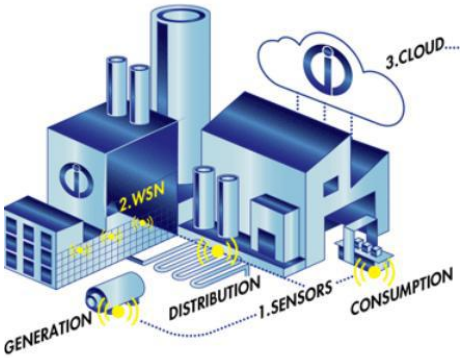


New Challenges



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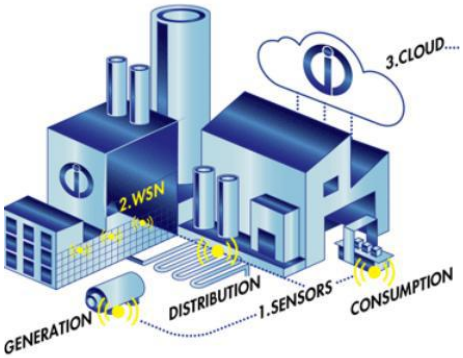

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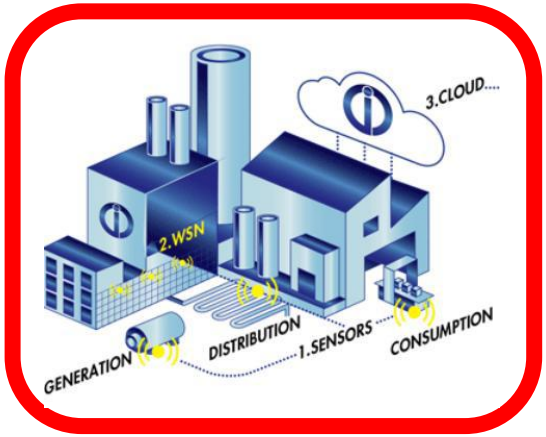

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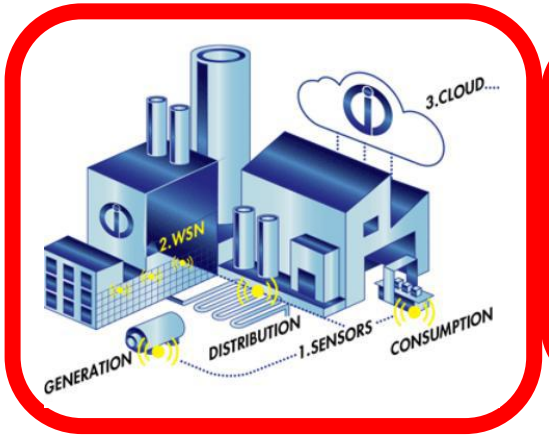

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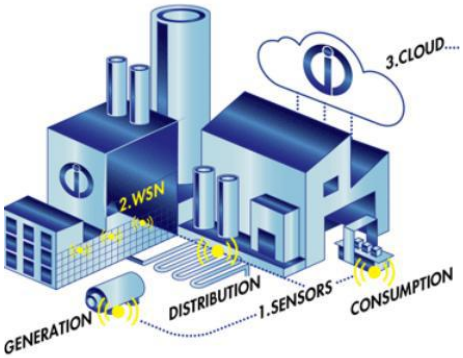

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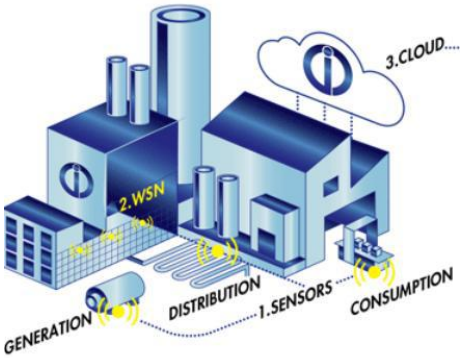

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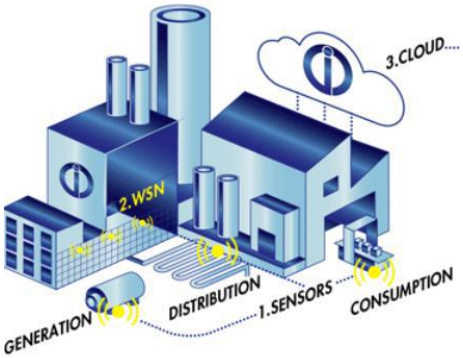

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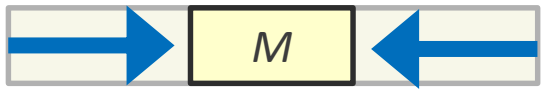
- New communication patterns
  - Dominated by (very) short messages



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(Very) Short Messages: Possibly <= 1 AES Block

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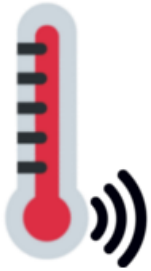

Existing AES-based AE vs Very Short Messages

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scheme	Cost of encryption in (# of AES rounds)/10 + GF(2^{128})mul									
	$a=0$				$a=1$				$a=2$	
	m=1	m=2	m=3	m=4	m=0	m=1	m=2	m=3	m=1	m=2
GCM	2+2	3+3	4+4	5+5	1+2	2+3	3+4	4+5	2+4	3+5
CCM	4	6	8	10	3	5	7	9	6	8
OCB3	3	4	5	6	3	4	5	6	5	6
CLOC	3	5	7	9	2	4	6	8	5	7
Deoxys-I	2.8	4.2	5.6	7	2.8	4.2	5.6	7	5.6	7
KIASU$^{\neq}$	2	3	4	5	2	3	4	5	4	5

a,m: length of A and M in 128-bit blocks; per-session key derivation excluded

Existing AES-based AE vs Very Short Messages

scheme	Cost of encryption in (# of AES rounds)/10 + GF(2^{128})mul
	$m=1$
GCM	
CCM	4
OCB3	3
CLOC	3
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KIASU$^{\neq}$	2

GHASH: $a + m + 1$ GF(2^{128}) mul.

&

CTR mode: $m + 1$ AES calls

extra AES and $m+1$ mul. for tag

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CBC MAC: *a + m +1* AES calls

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CTR: *m + 1* AES calls

extra AES for tag, ***m+1* extra calls for MAC**

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AD-HASH: *a* AES calls

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OCB core: *m + 2* AES calls

2x extra AES for tag and for derived key

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IV + CFB: *a + m* AES calls

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Tag: *m + 1* AES calls

***m+1* extra AES** calls for tag

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AD-HASH: *a* Deoxys calls (1.4 AES)

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OCB core: *m + 1* Deoxys calls (1.4 AES)

1.4 extra AES for tag

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AD-HASH: *a* KIASU calls (~ AES)

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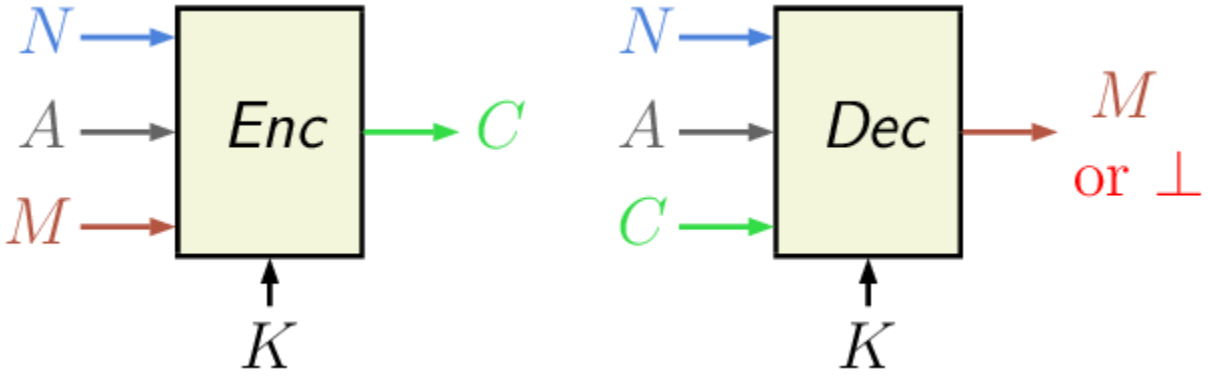
"The performance target is wrong · · · an authenticated cipher is applied to many small messages · · · The challenge here is to minimize overhead." [ECRYPT-CSA 2017]

Nonce-based Authenticated Encryption with Associated Data



- **Enc,Dec:** deterministic algorithms
- **N: Nonce,** must not repeat
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- **M: Plaintext,** encrypted and authenticated
- **K: Secret key**

Also **|C| = |M| + τ** and Dec(K,N,A,Enc(K,N,A,M)) = M

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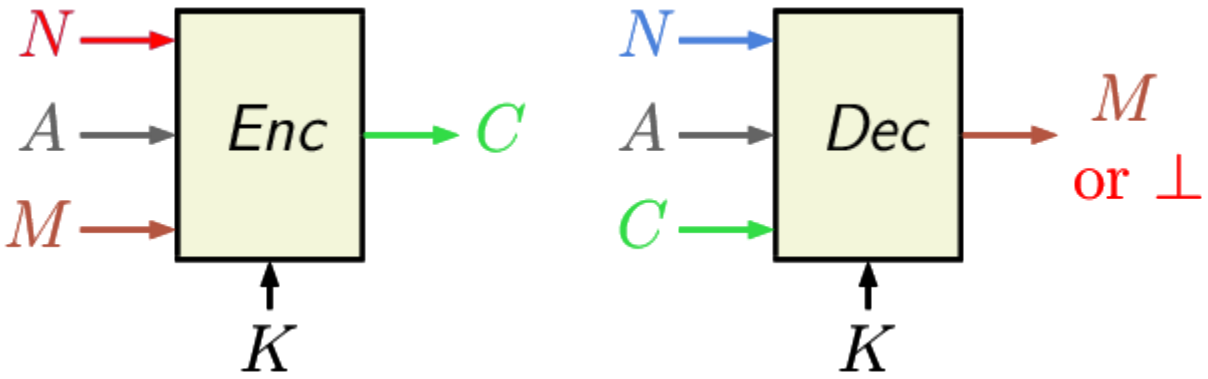

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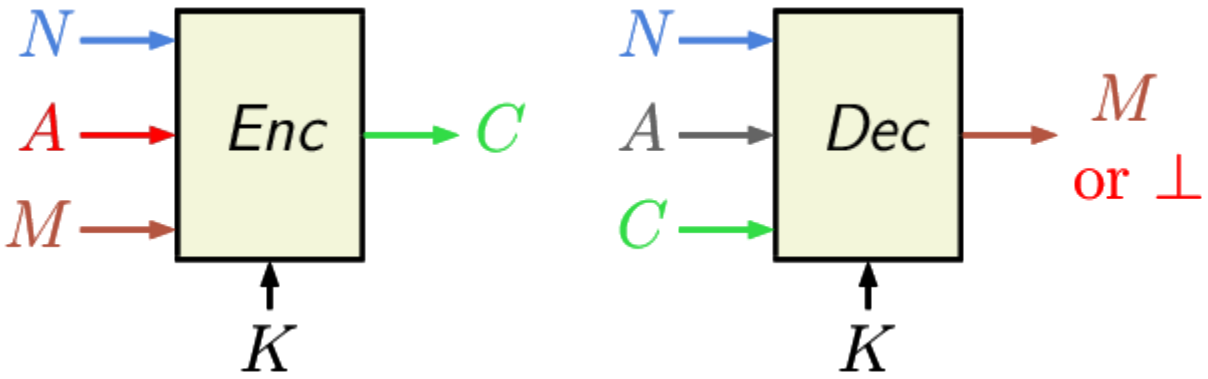

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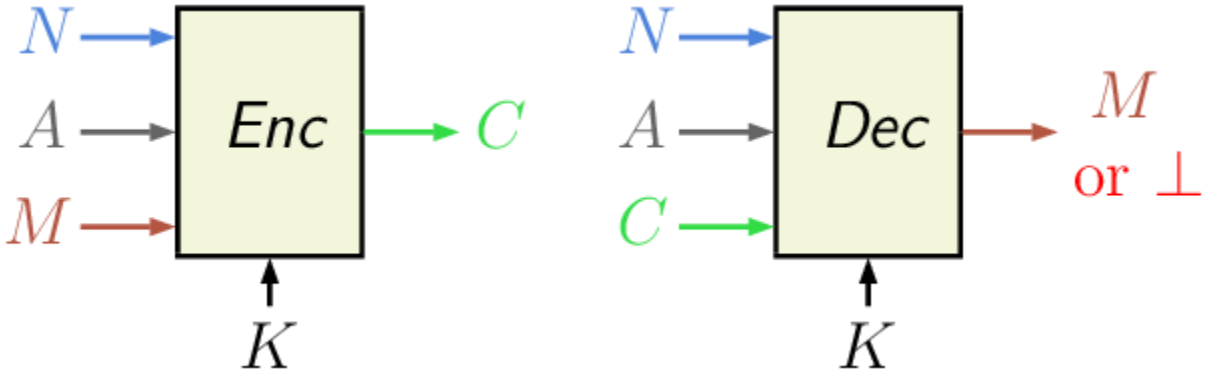

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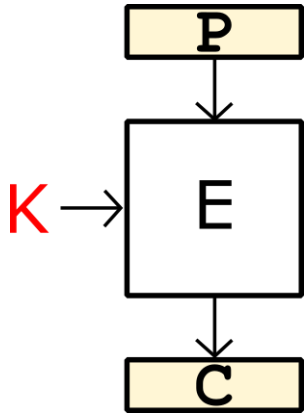

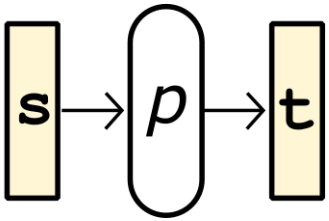

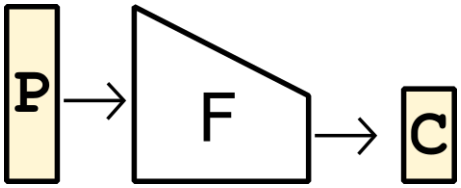

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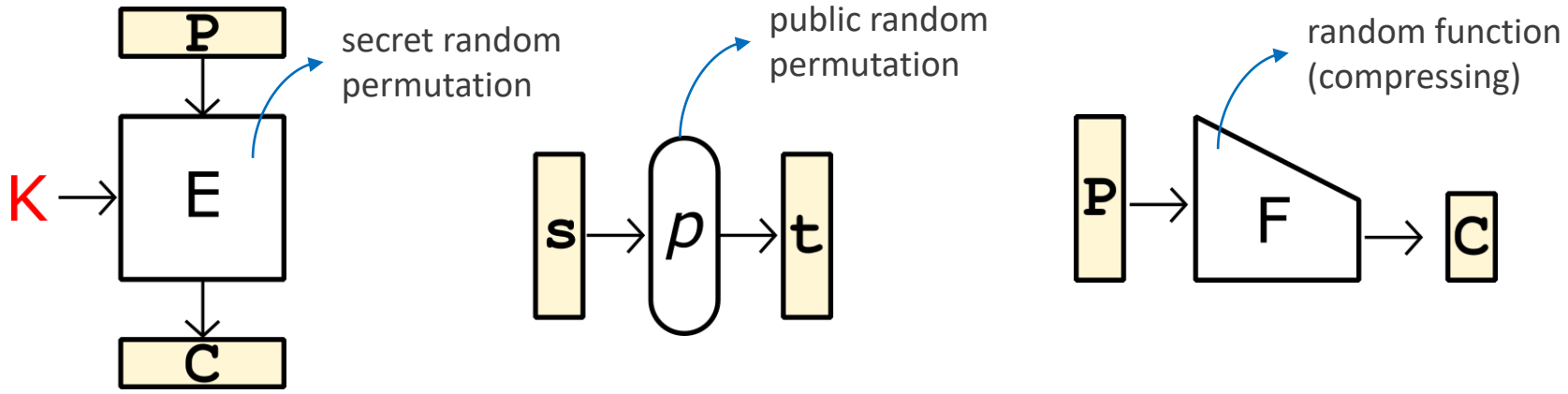

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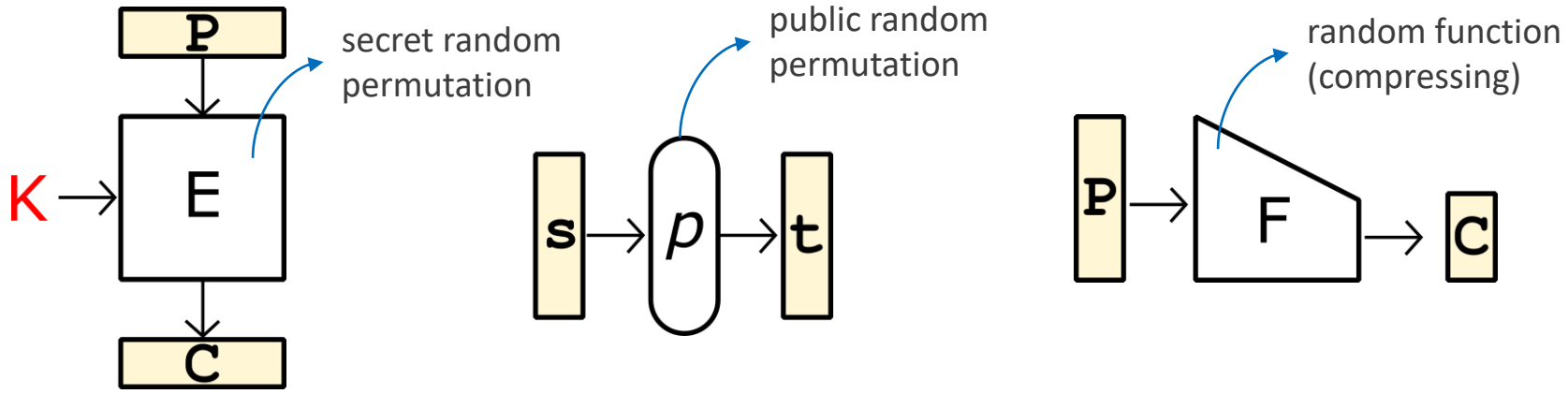

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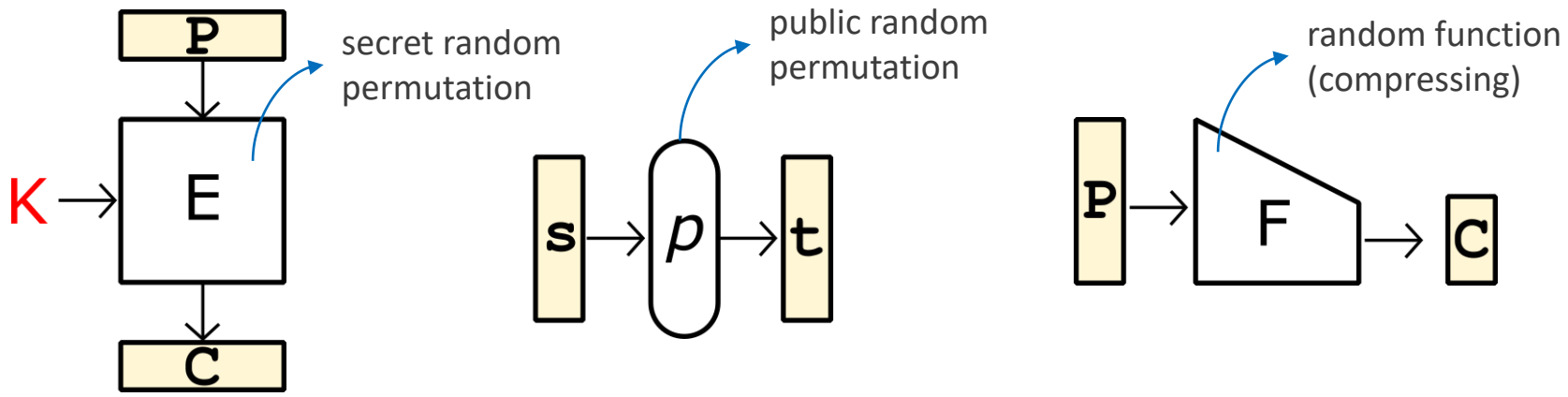

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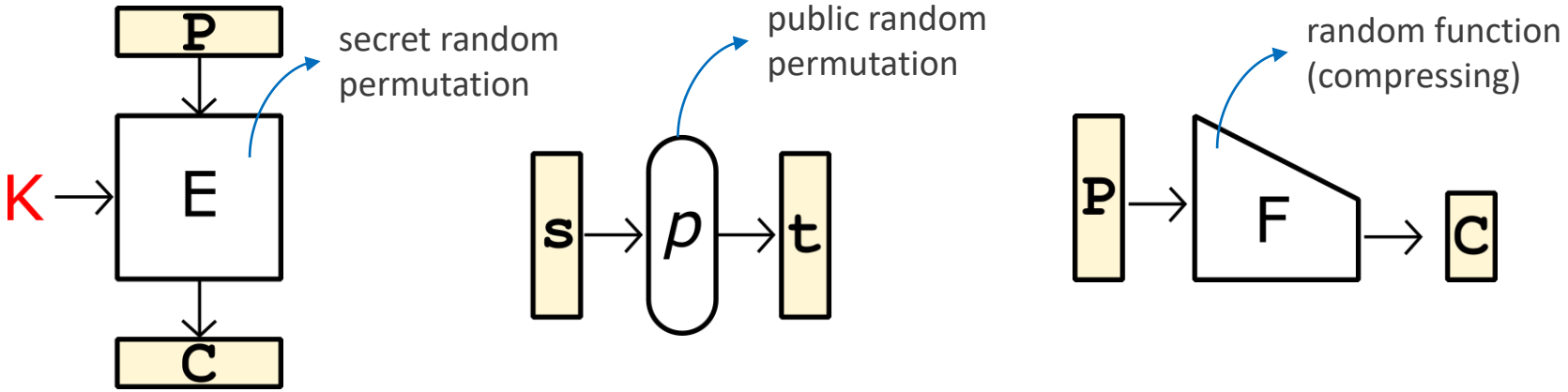

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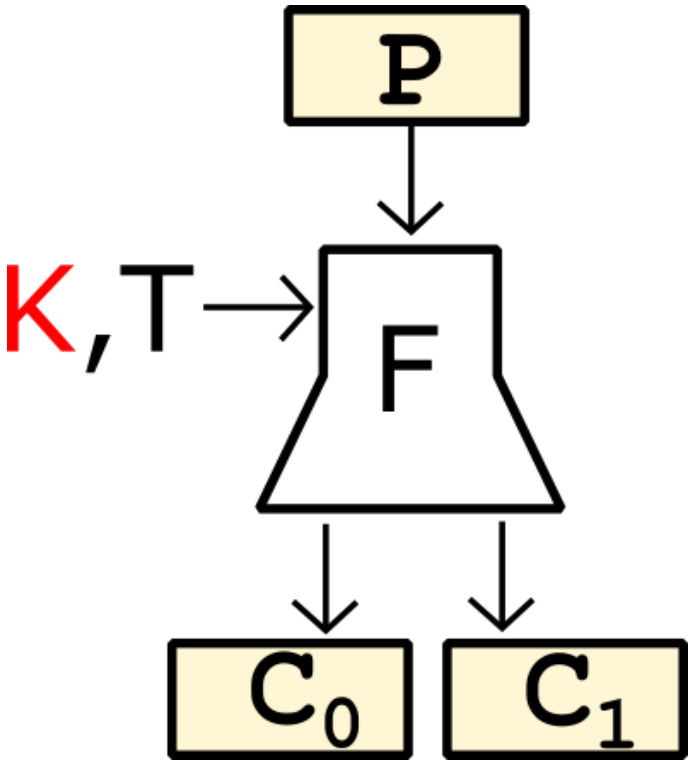
Solution:

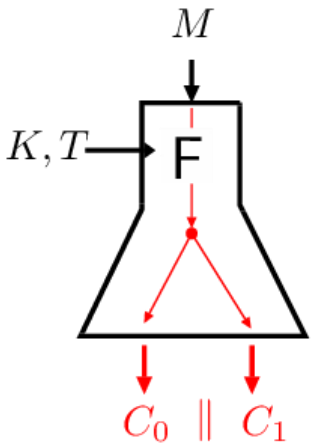
Invent a new primitive

Forkcipher



- Keyed
- Expanding
- Tweakable
- Invertible
  - Parallel permutations

Forkcipher: Syntax



- Forward: *n*-bit block → **2 *n*-bit blocks**

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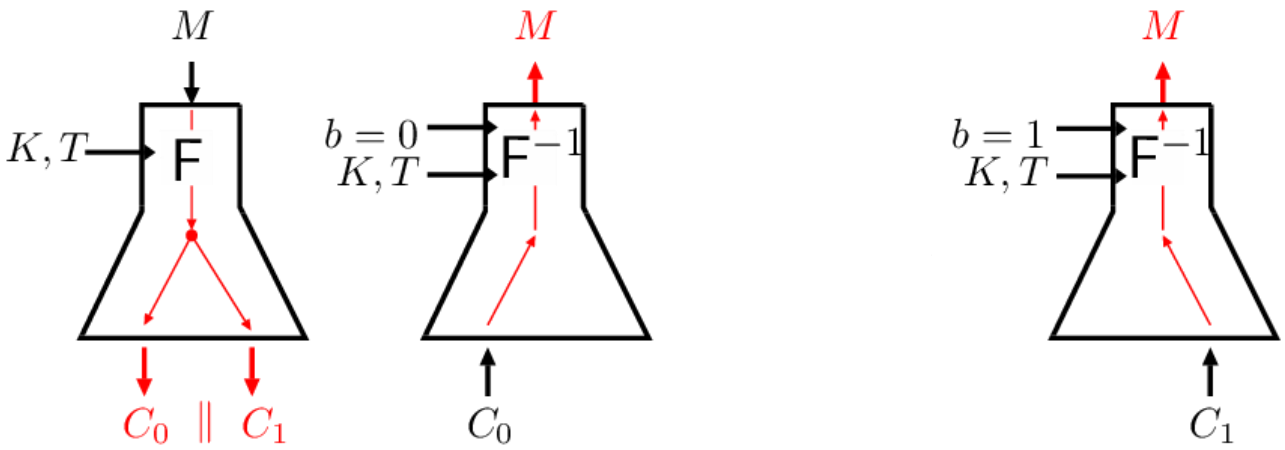

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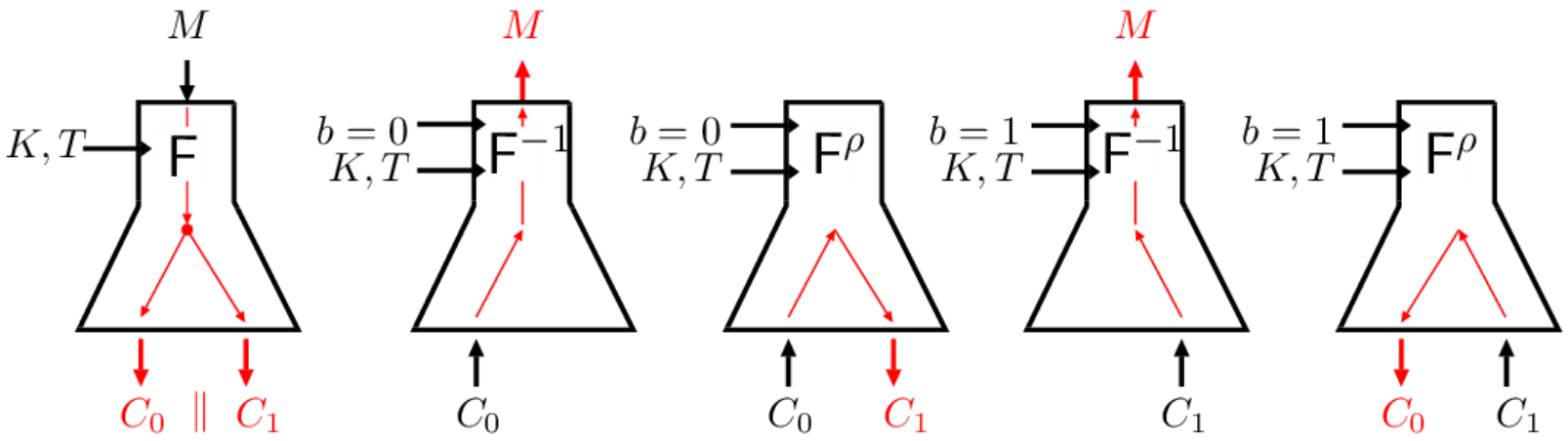

- Forward: *n*-bit block → **2 *n*-bit blocks**
- Inverse: ***n*-bit block, binary flag** → *n*-bit block
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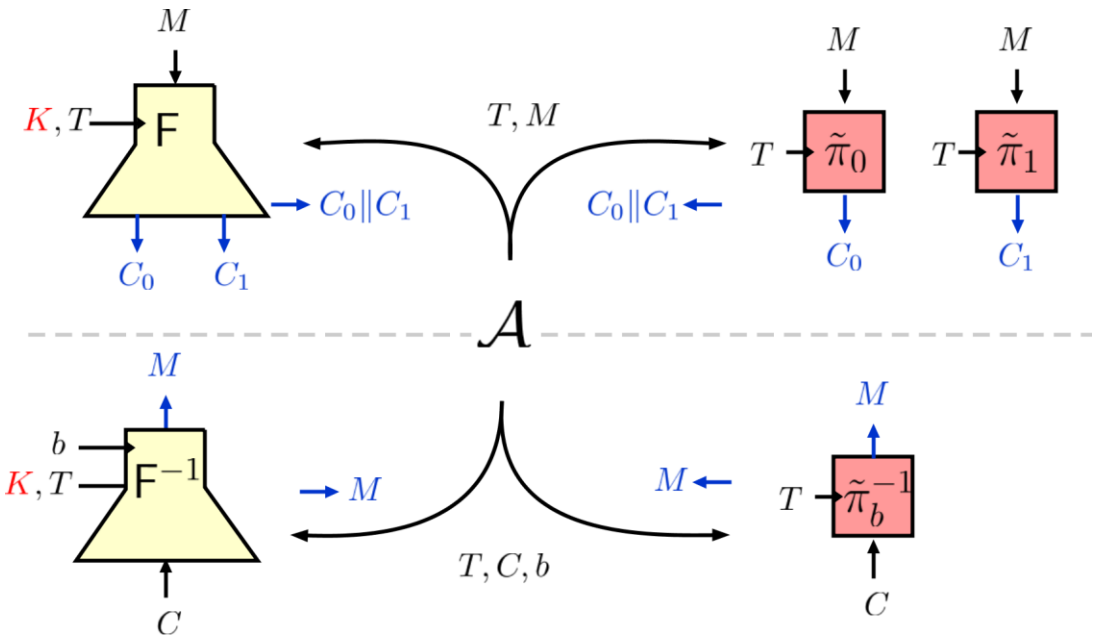
- **Reconstruction:** *n*-bit block, binary flag → *n*-bit block
  - Can reconstruct **either** ouput block **from the other output block**

Forkcipher: Security



$$\mathbf{Adv}_{\mathsf{F}}^{\mathrm{prtfp}}(\mathcal{A}) = \Pr\left[\mathcal{A}^{\mathrm{real}} \Rightarrow 1\right] - \Pr\left[\mathcal{A}^{\mathrm{ideal}} \Rightarrow 1\right]$$

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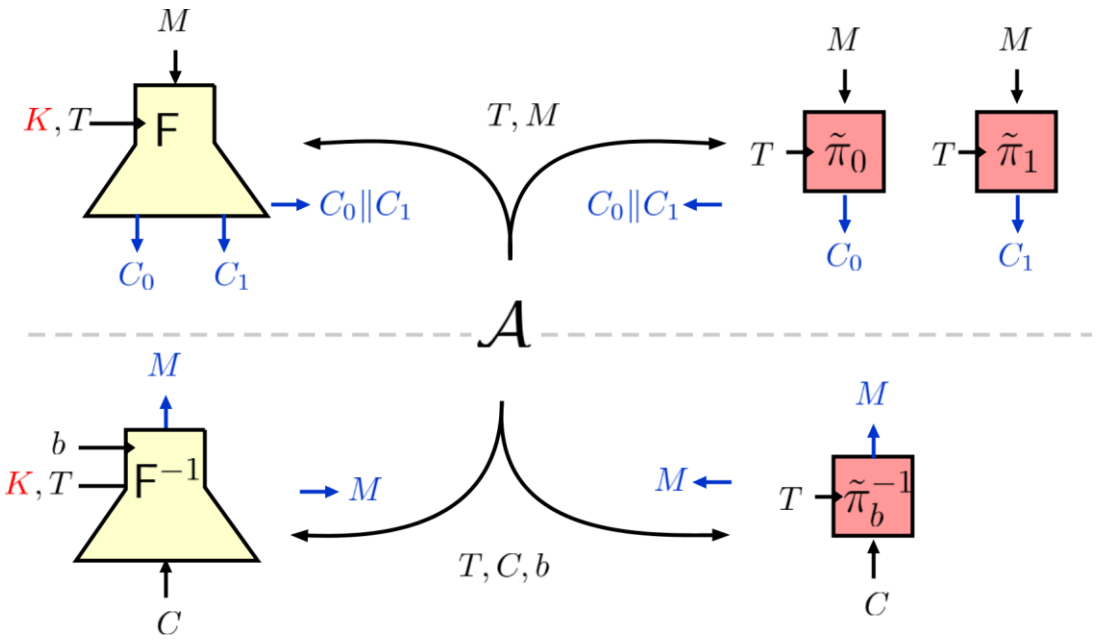

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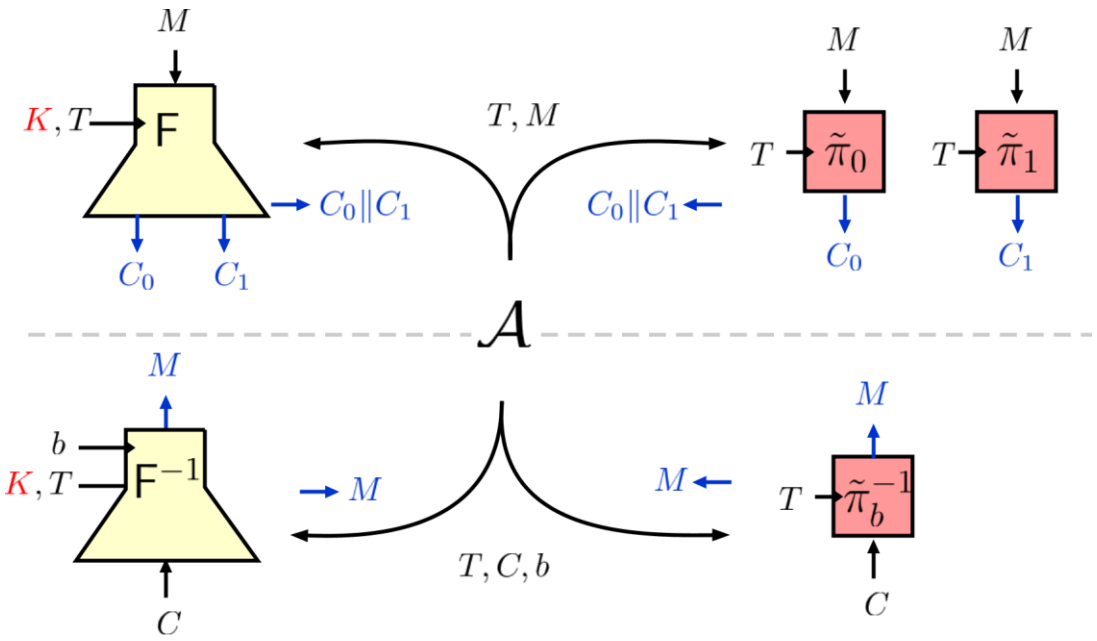

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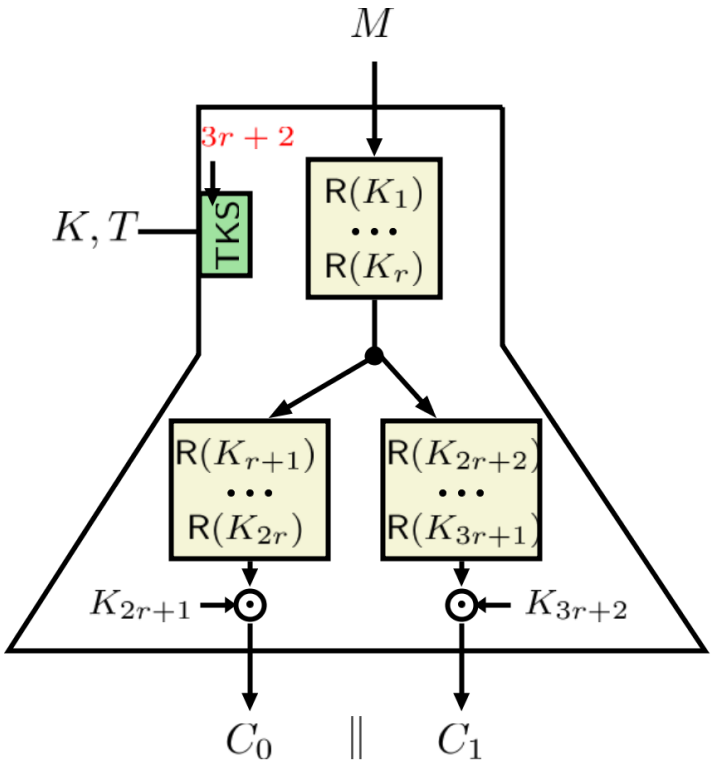
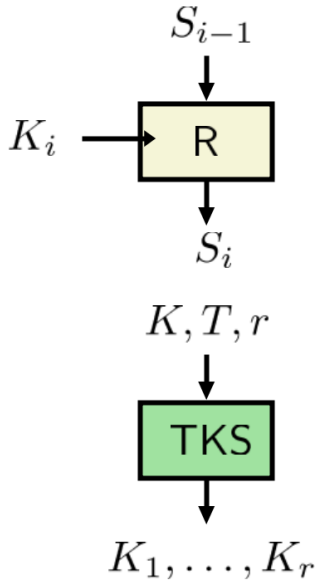
- **Almost AE security** (natural PRI construction)
- **“Two TBCs? What’s so novel about that?”**

Forkcipher Instantiation: Iterate-Fork-Iterate





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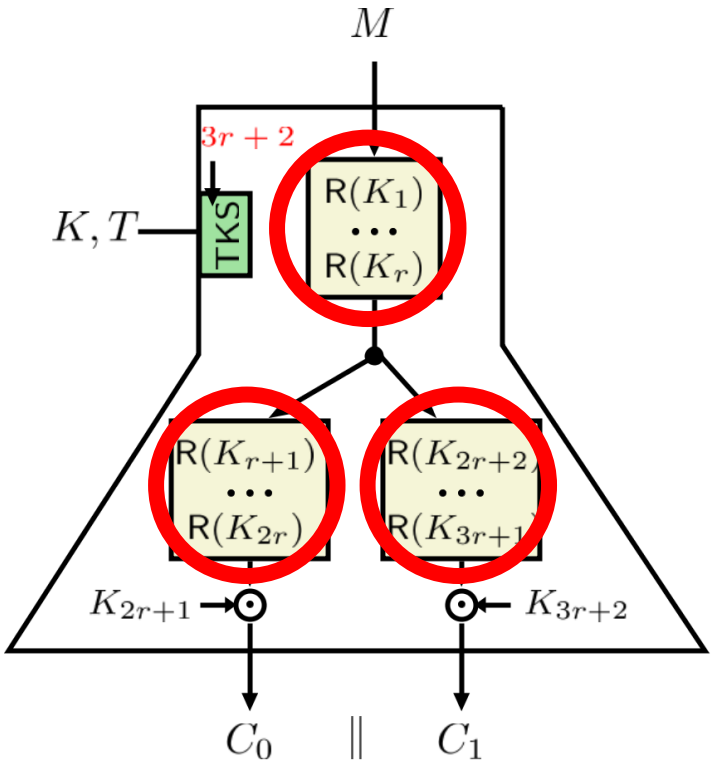
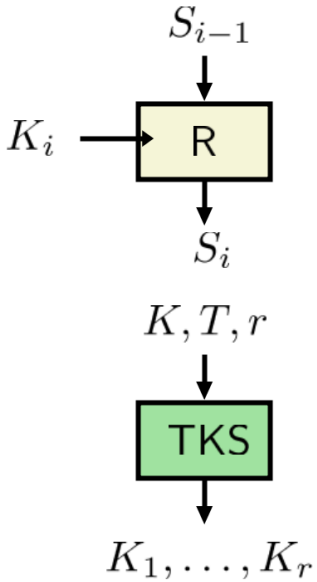
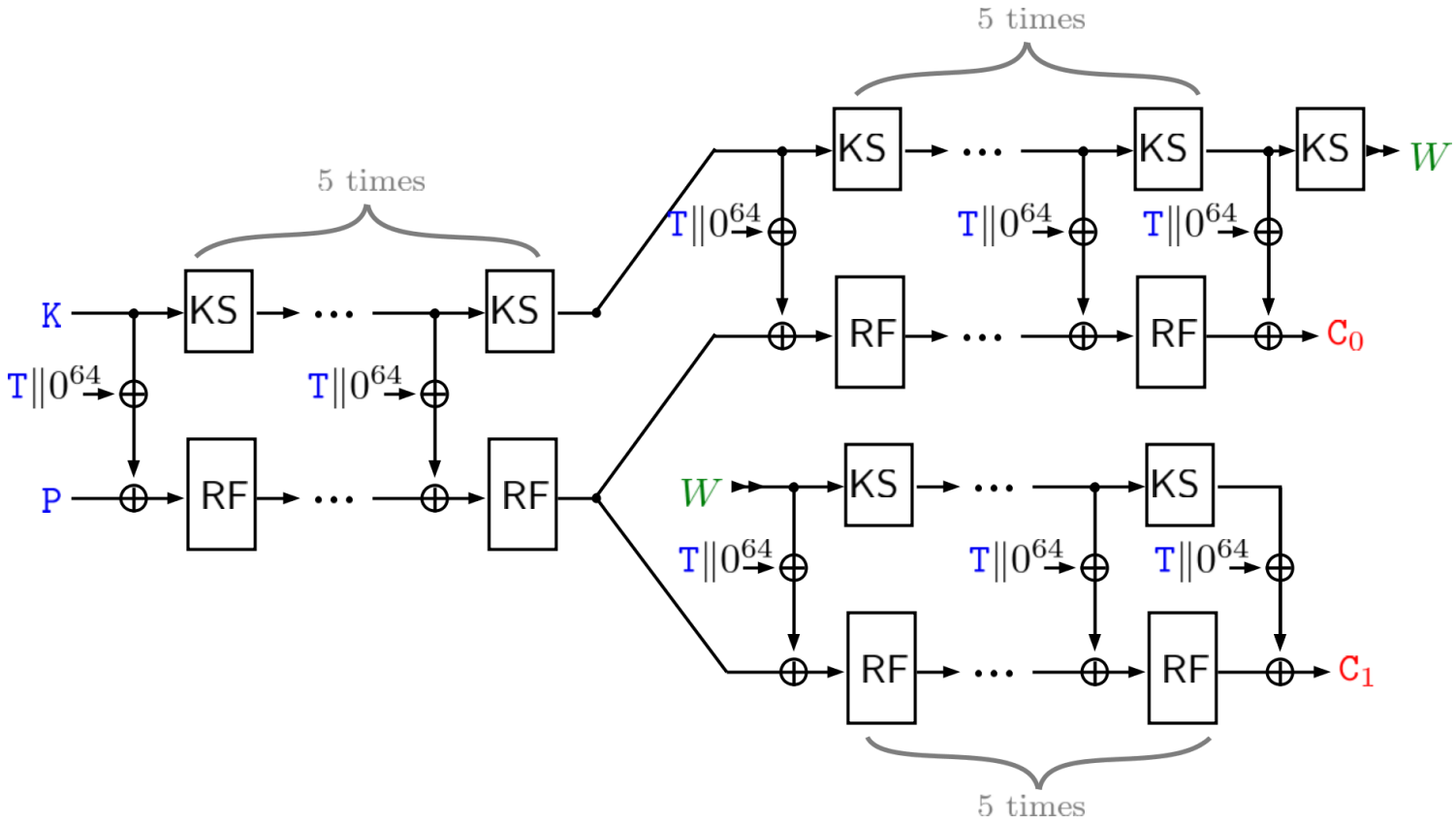




- IFI: **Round Function + Tweakey Schedule + #rounds/3**
- **No pathological structural weakness** (3 tweakable rand. perm. => perfectly secure)

ForkAES = IFI[KIASU,r=5]



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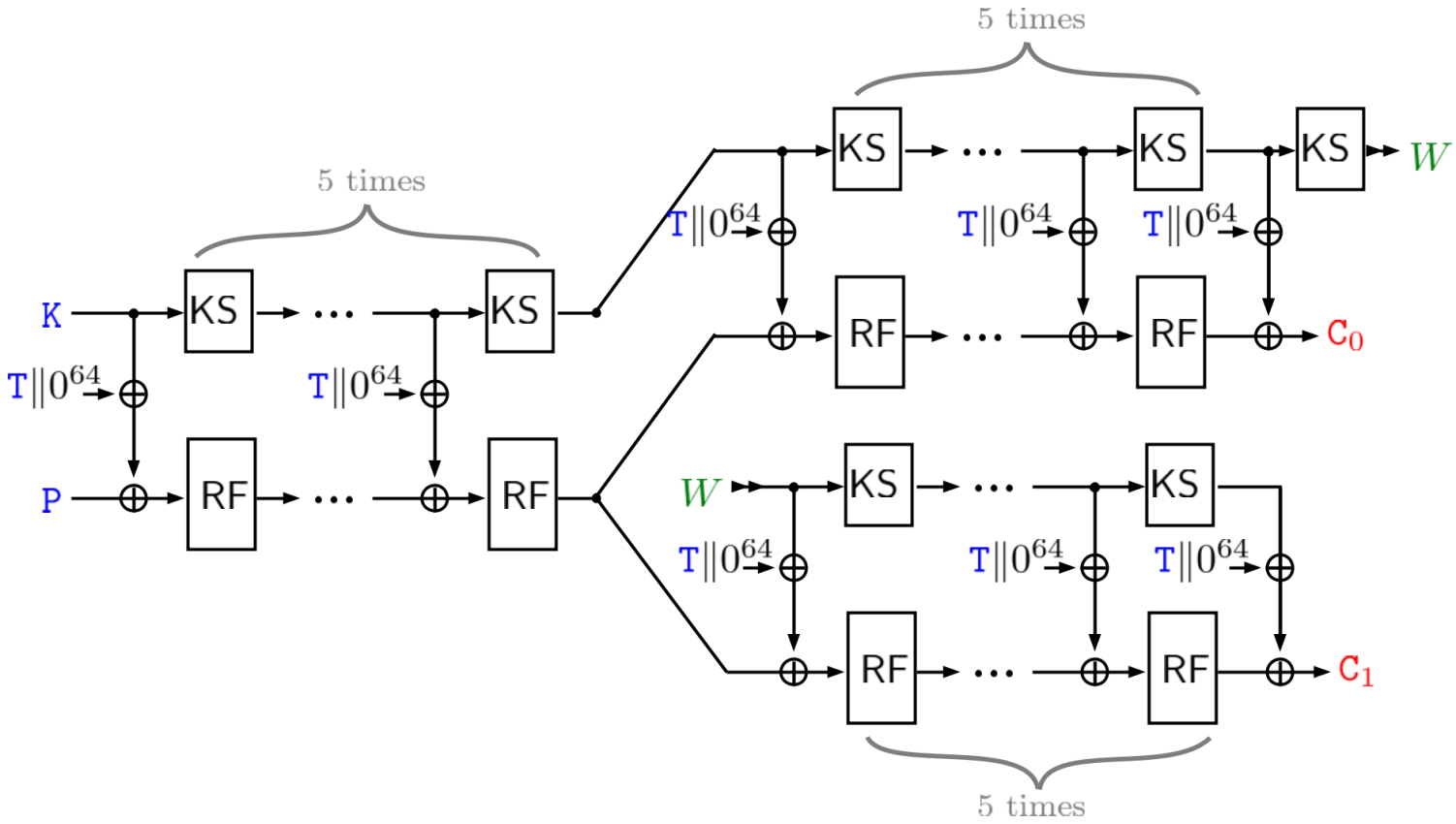

- RF and KS from AES, 64 bit tweak
- Provocative prototype: **Aggressively optimized for efficiency**

ForkAES: Security

- Mostly inherited from AES/KIASU
  - Differential/Linear propagation as in AES
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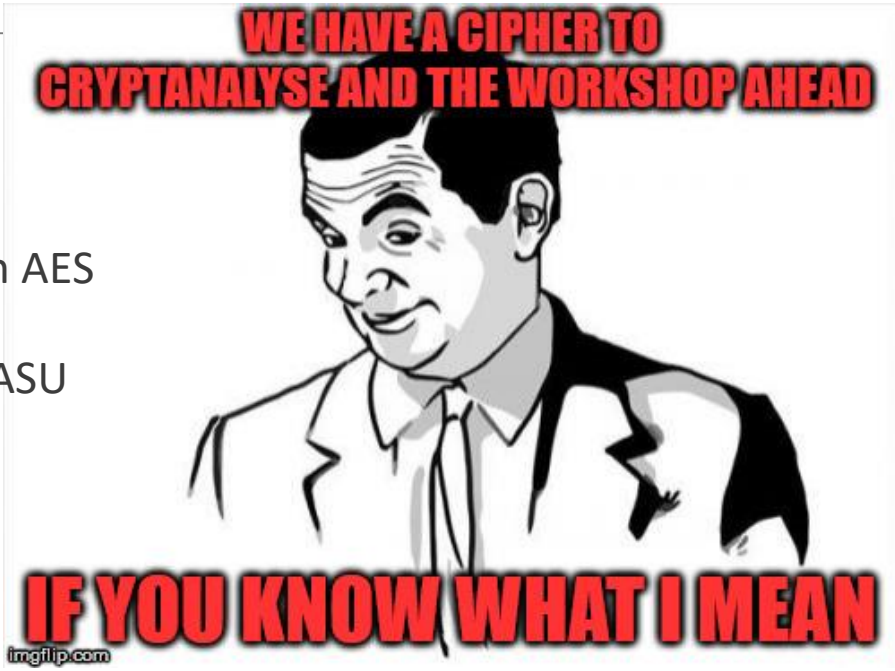

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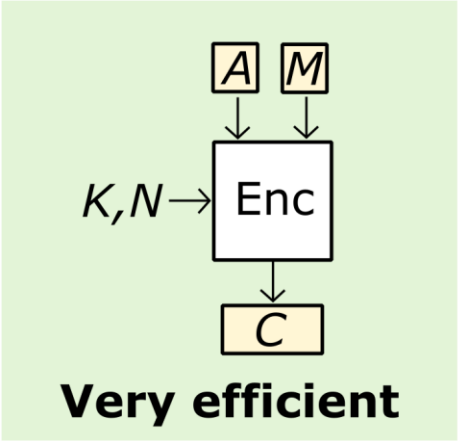
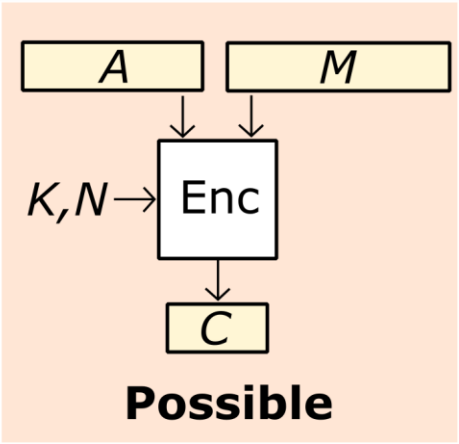
- **Need more cryptanalysis and constructive results**

Forkcipher Modes for Short-Input AE

- Design target: Nonce-based AEAD
- Goal:





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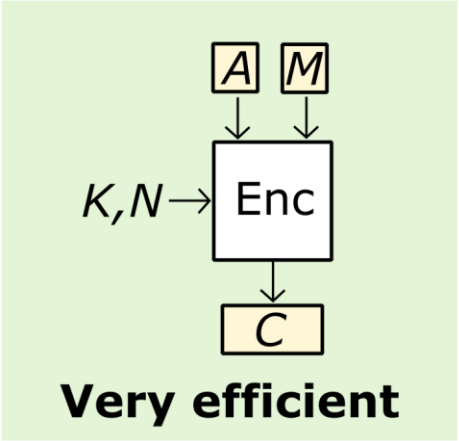

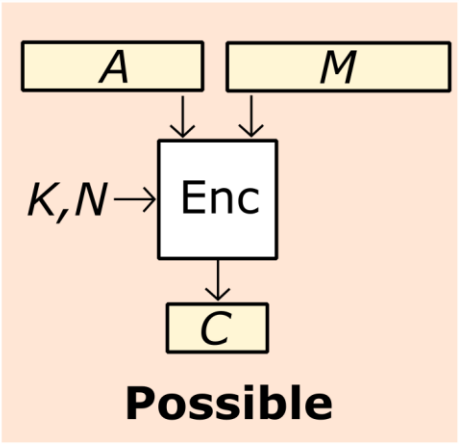

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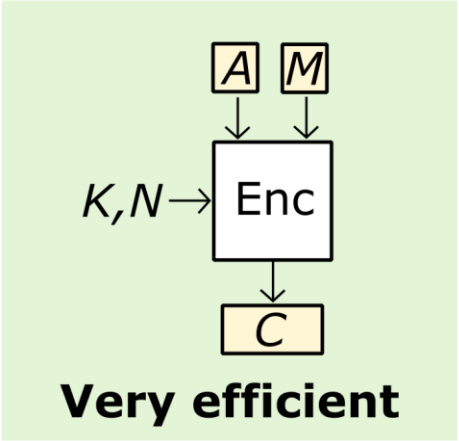
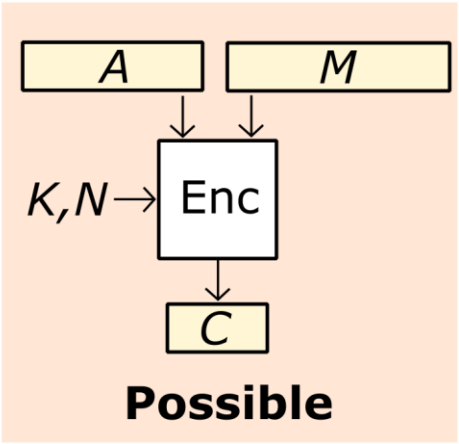
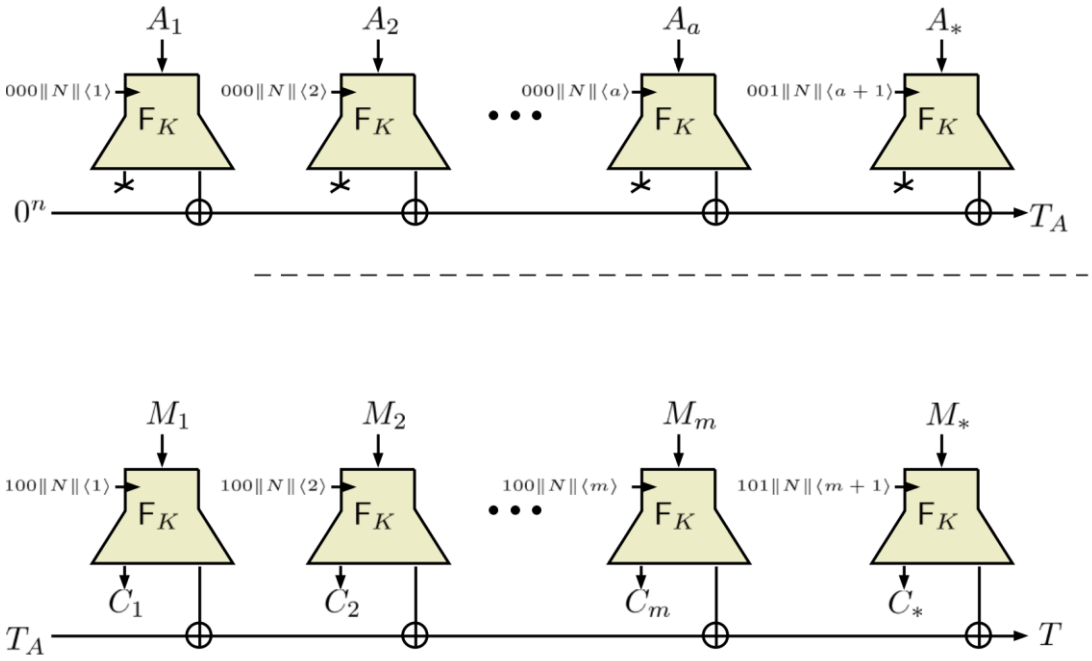




- **A single F-call for shortest messages**
- Parallelizable AE, Serial AE, a GCM variant

PAEF



- Single F-call per block of data => **single F call for short queries**
- Ciphertext expansion: *n* bits
- Fully parallelizable

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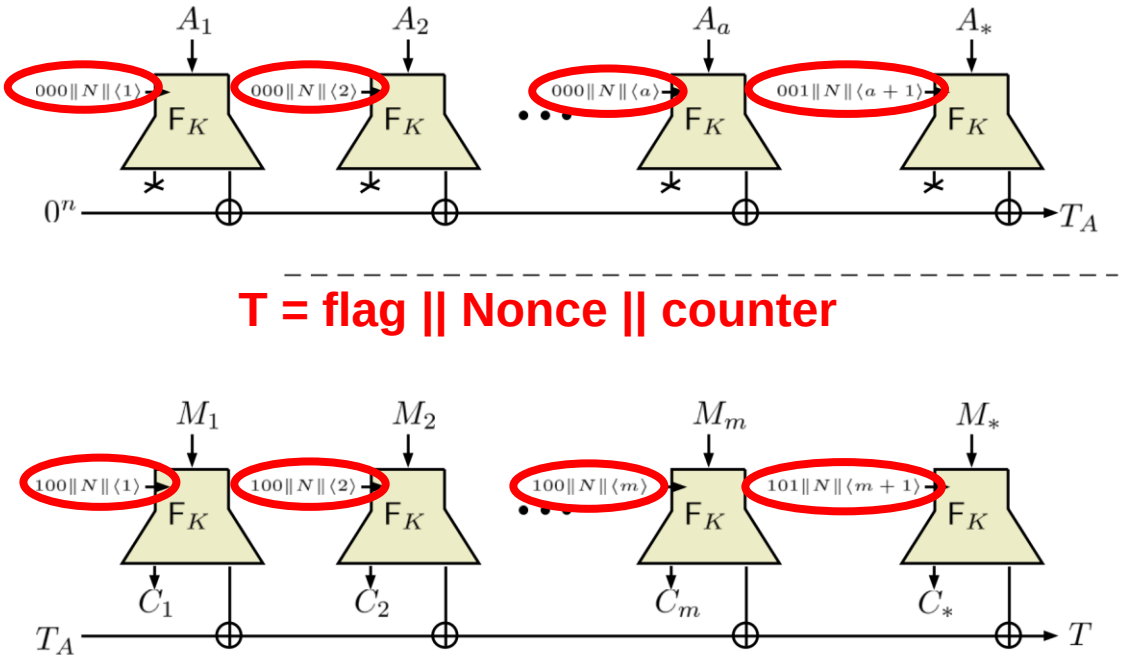

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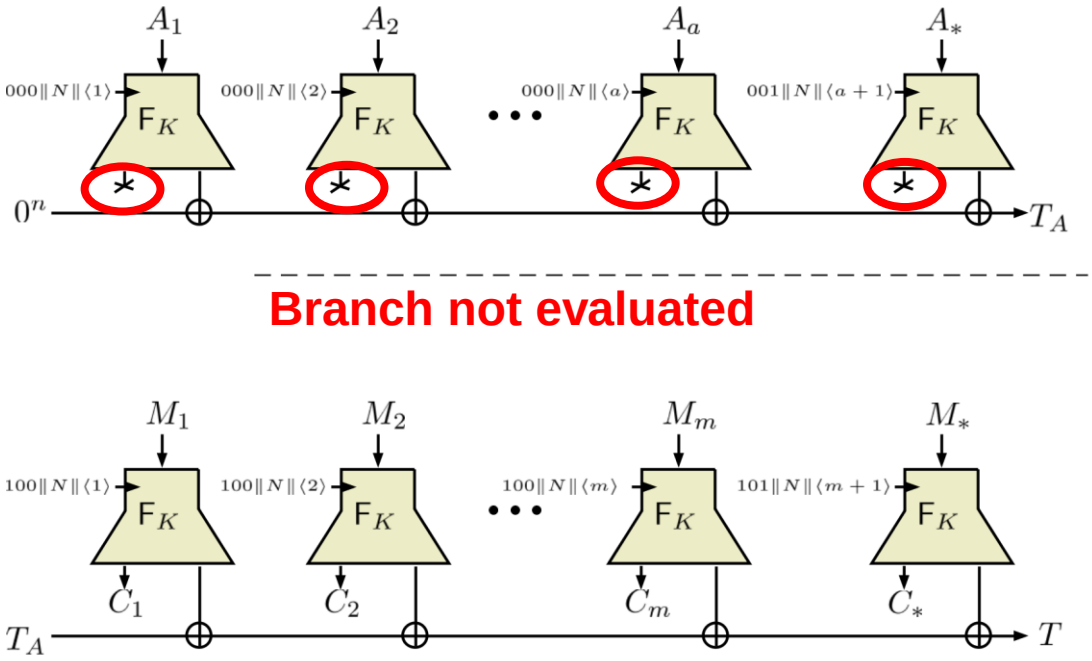

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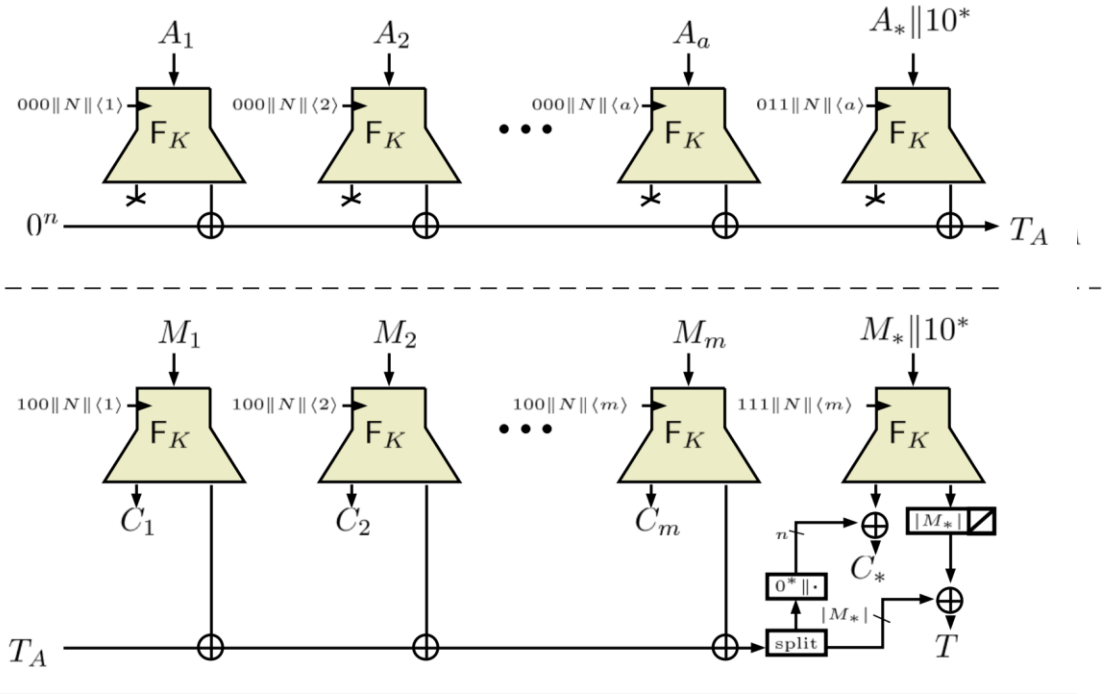

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PAEF

q_v # of verification queries

n block size

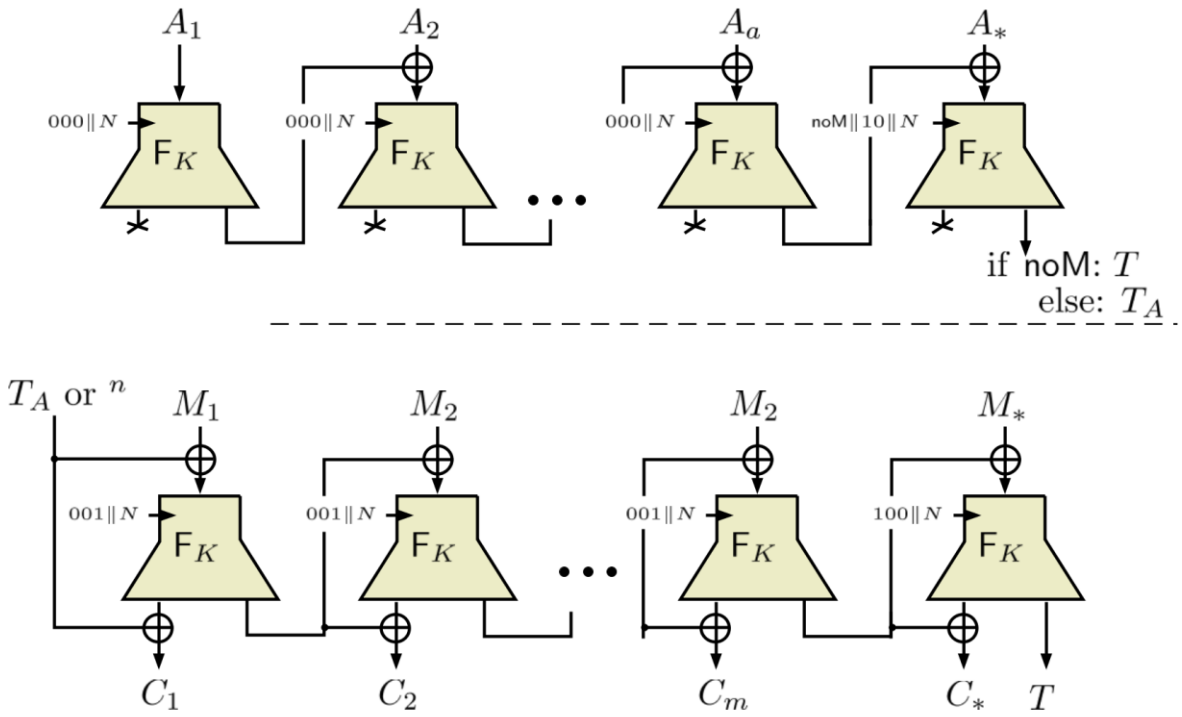
ν nonce size

Tradeoff: max # of enc: 2^{ν}; max len: $2^{|T|-(\nu+3)}$ blocks

$$\mathbf{Adv}^{\mathrm{priv}}_{\mathsf{PAEF}[\mathsf{F},\nu]}(\mathcal{A}) \leq \mathbf{Adv}^{\mathrm{prtfp}}_{\mathsf{F}}(\mathcal{B})$$

$$\mathbf{Adv}^{\mathrm{auth}}_{\mathsf{PAEF}[\mathsf{F},\nu]}(\mathcal{A}) \leq \mathbf{Adv}^{\mathrm{prtfp}}_{\mathsf{F}}(\mathcal{C}) + \frac{q_v \cdot 2^n}{(2^n-1)^2}$$

SAEF



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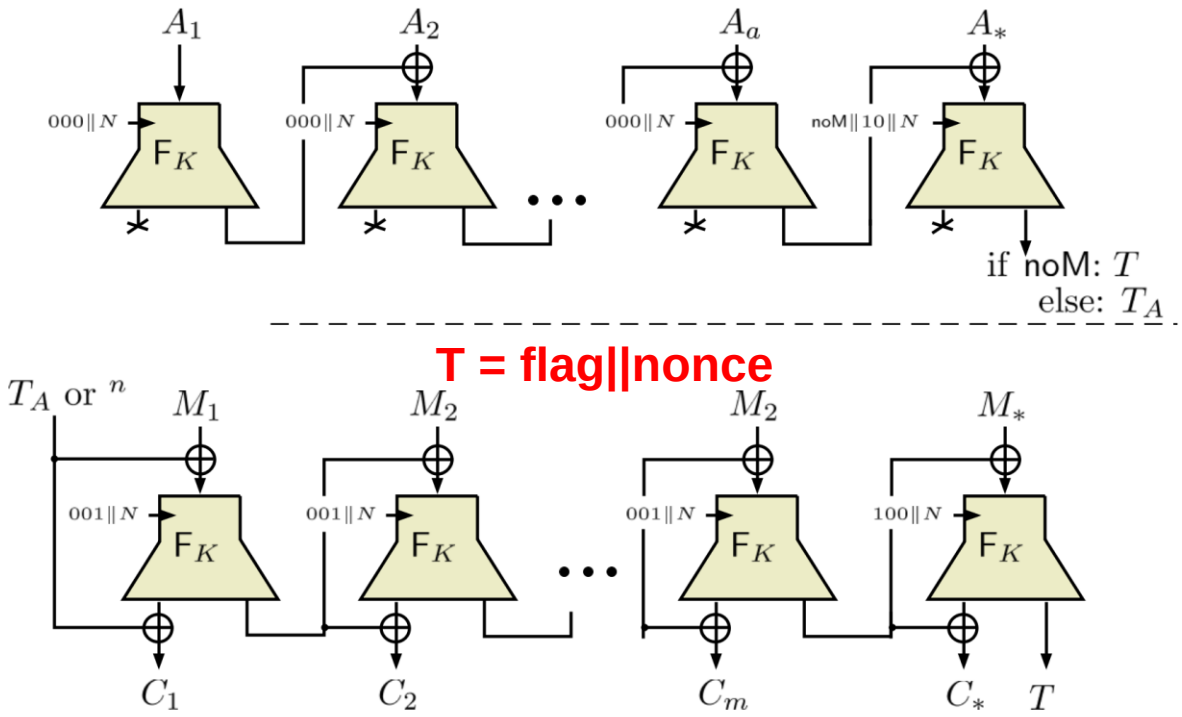

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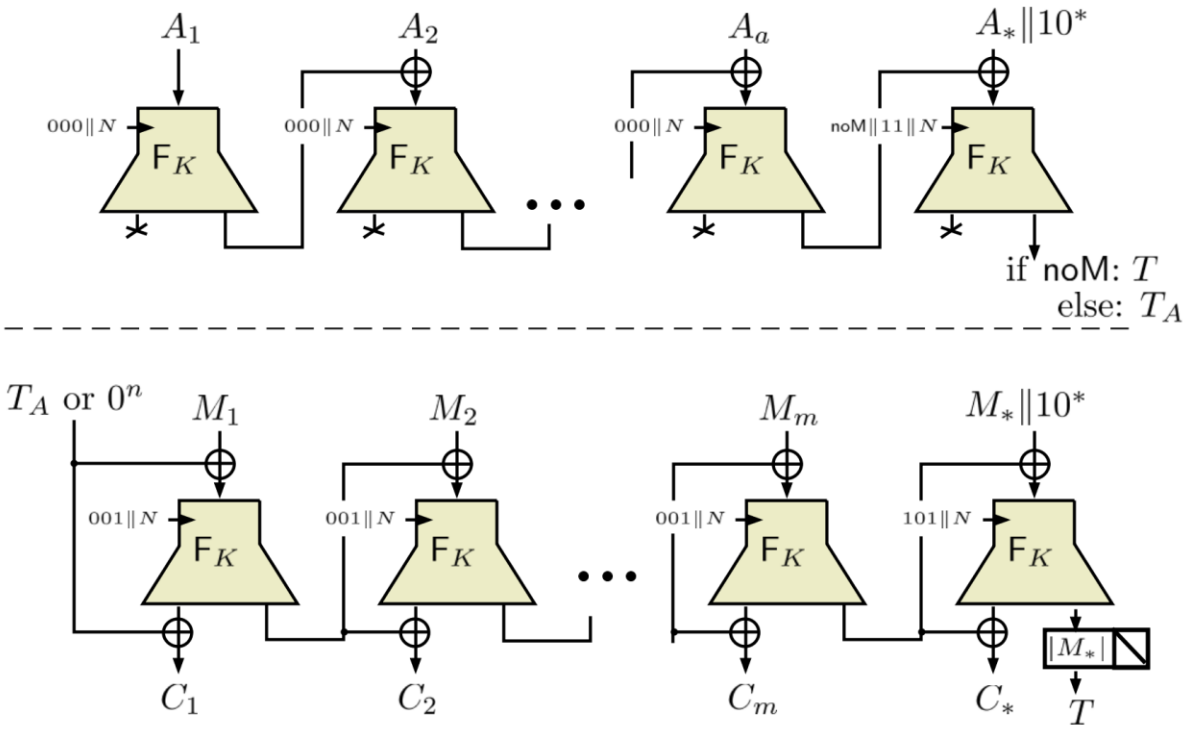

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SAEF

$\boldsymbol{L}$ set of possible block lengths

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$\boldsymbol{q_\ell}$ # of Enc queries w/ ℓ blocks $= \max|A|, |M|$

$\boldsymbol{q_v}$ # of verification queries

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$$\mathbf{Adv}^{\text{priv}}_{\text{SAEF[F]}}(\mathcal{A}) \leq \mathbf{Adv}^{\text{prtfp}}_{\text{F}}(\mathcal{B}) + \sum_{\ell \in L} 3 \cdot \frac{\mathbf{q}_\ell \cdot \ell \cdot (\ell - 1)}{2^n}$$

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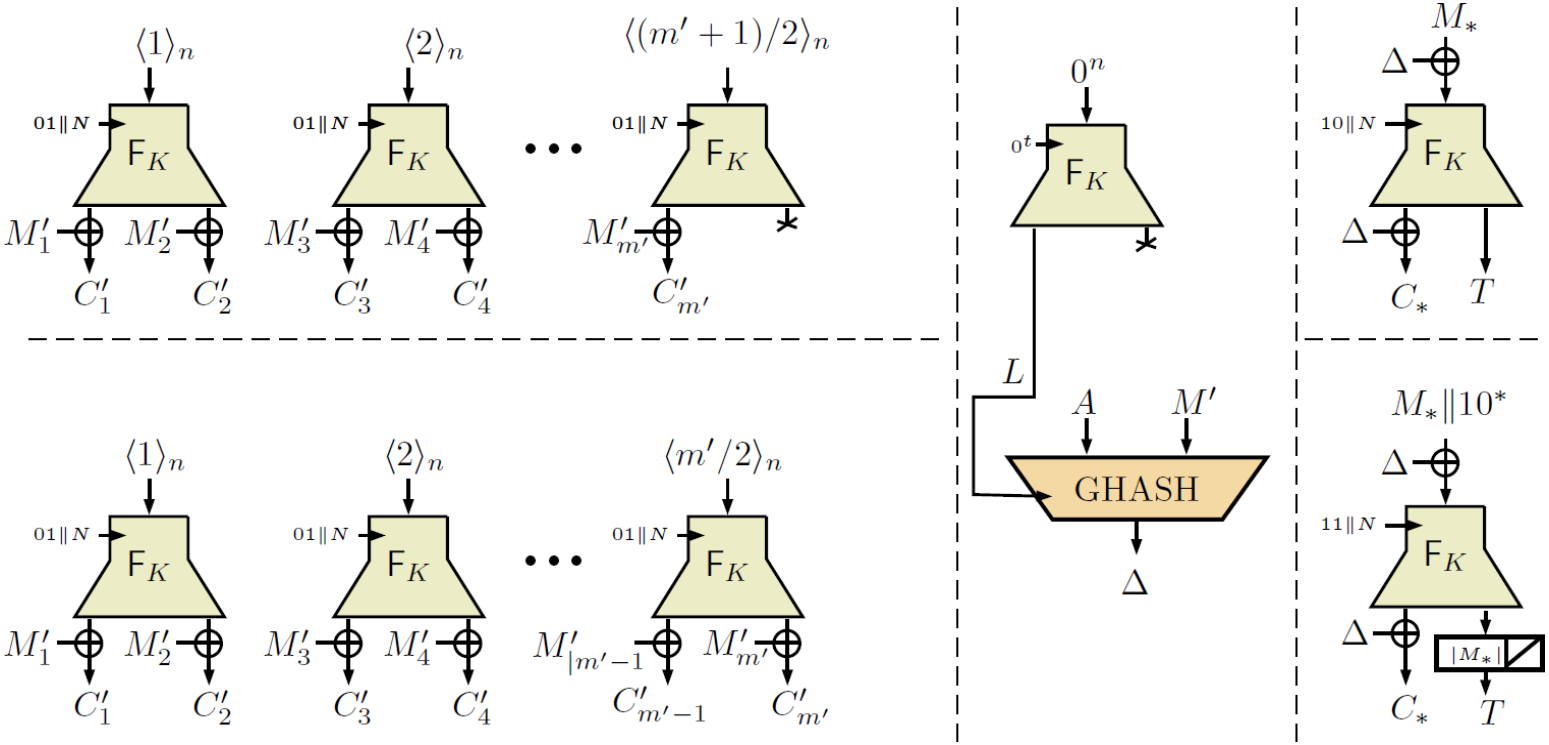
fGCM



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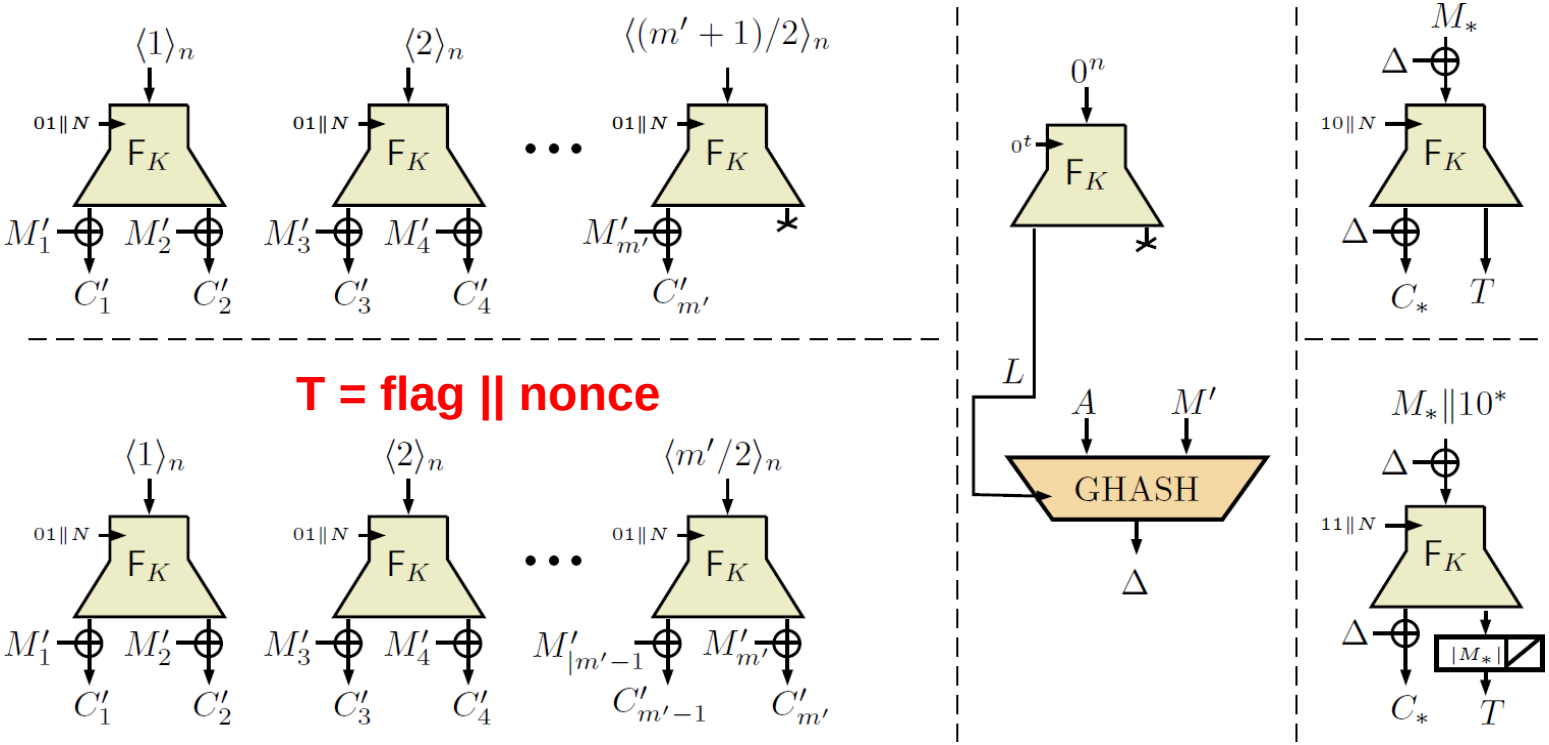

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Forkcipher Modes vs Very Short Messages

scheme	Cost of encryption in (# of AES rounds)/10 + GF(2^{128})mul									
	$a=0$				$a=1$				$a=2$	
	m=1	m=2	m=3	m=4	m=0	m=1	m=2	m=3	m=1	m=2
GCM	2+2	3+3	4+4	5+5	1+2	2+3	3+4	4+5	2+4	3+5
CCM	4	6	8	10	3	5	7	9	6	8
OCB3	3	4	5	6	3	4	5	6	5	6
CLOC	3	5	7	9	2	4	6	8	5	7
Deoxys-I	2.8	4.2	5.6	7	2.8	4.2	5.6	7	5.6	7
KIASU$^{\neq}$	2	3	4	5	2	3	4	5	4	5
PAEF	1.5	3	4.5	6	1.5	2.5	4	5.5	3.5	5
SAEF	1.5	3	4.5	6	1.5	2.5	4	5.5	3.5	5
fGCM	1.5+1	2.5+2	3+3	5+4	1.5+2	1.5+2	2.5+3	3+4	1.5+3	2.5+4

a,m: length of A and M in 128-bit blocks; per-session key derivation excluded

Conclusion

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- **Open problems:**
  - Cryptanalysis of IFI, new instances
  - Modes: same efficiency, tunable expansion
  - Other applications of forkcipher (e.g., stream in fGCM)
  - Forkcipher ≠ PRI (Bday gap); a tweakable FIL PRI primitive?

Thank you for your attention!

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