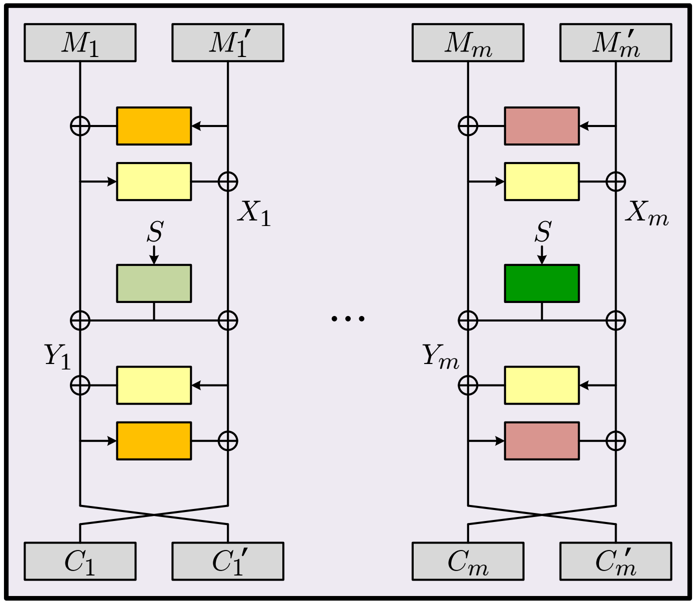

Some thoughts on **AEZ** v. 4

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Reluctant to give a talk

- **No changes** for Round-3
- **Talks** @ DIAC 2014
  EUROCRYPT 2015
  Several AE survey talks

But some reasons to do so

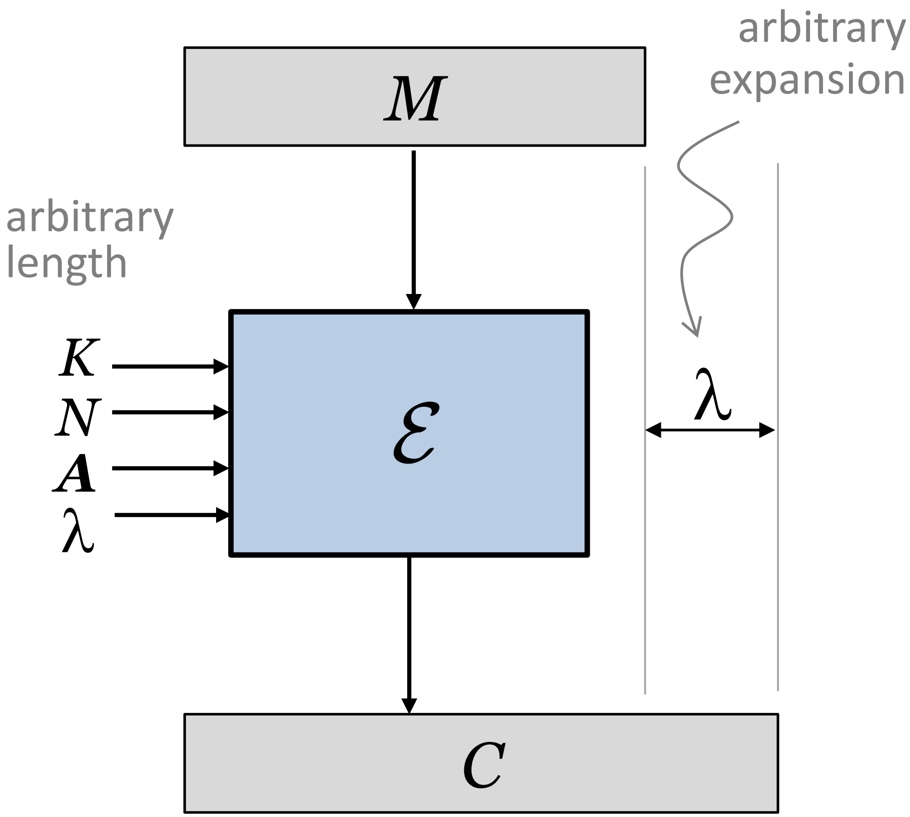
- My view of the mode has evolved
- Attacks @ ASIACRYPT 2015 and at FSE 2017
- AEZ is already in use (should it be?)

What kind of object *is* AEZ ?

- AIL / VIL blockcipher
- Wide-block blockcipher
- An enciphering scheme

An Robust-AE scheme

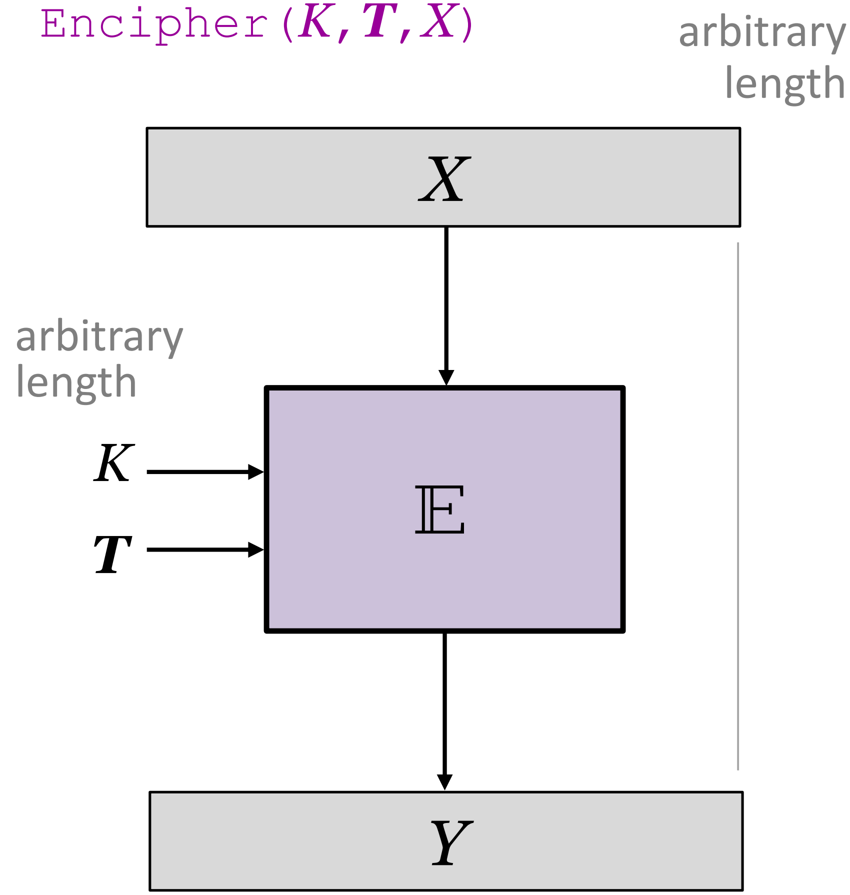
`Encrypt`$(K, N, \boldsymbol{A}, M, \lambda)$



Should look like a uniform λ-**expanding injection** (ind for N, $\boldsymbol{A}$, λ) (forward + backward oracles)

A Generalized Blockcipher

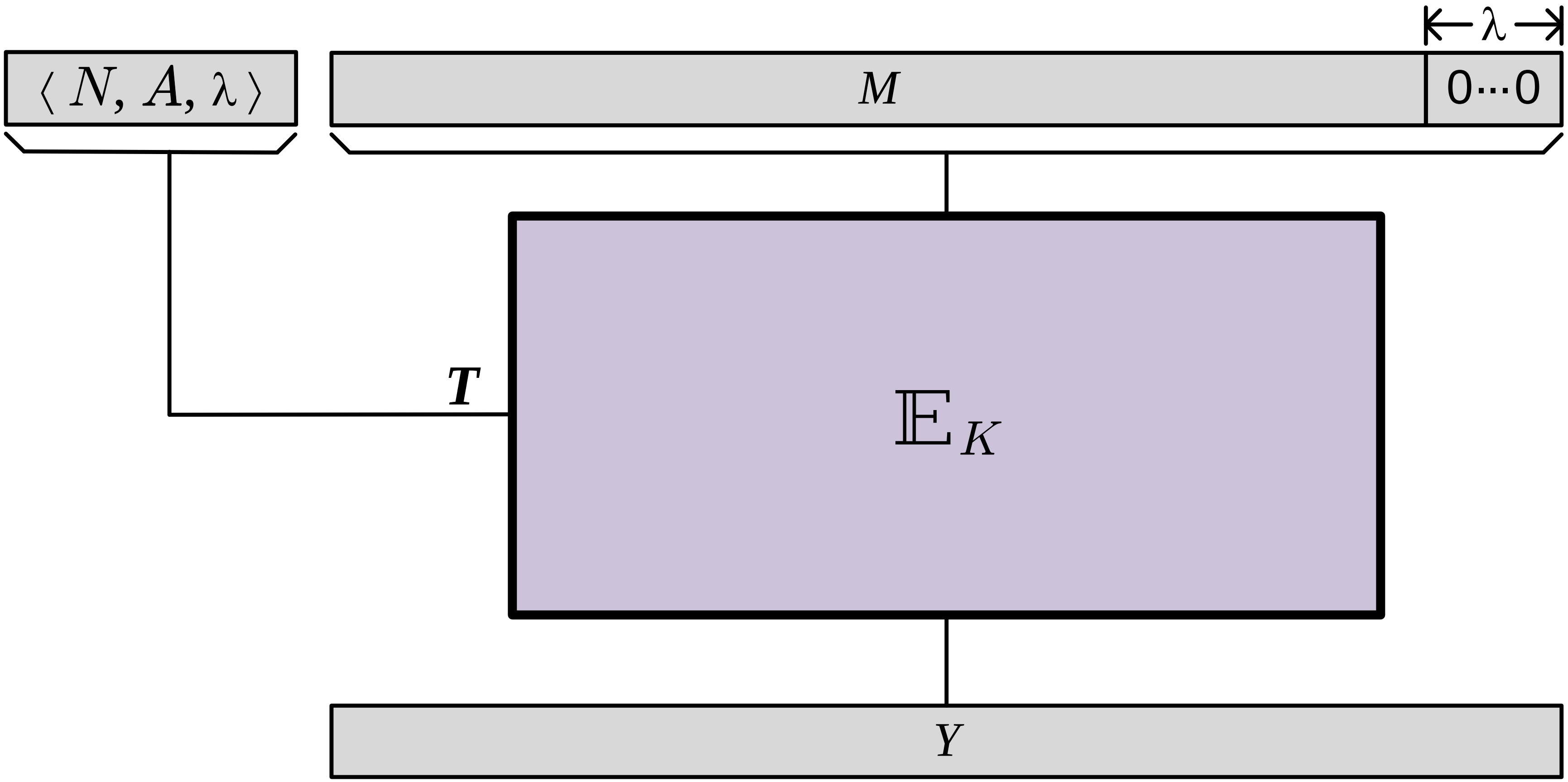
`Encipher`$(K, \boldsymbol{T}, X)$



Should look like a uniform **permutation** (ind for all $\boldsymbol{T}$) (forward and backward oracles)

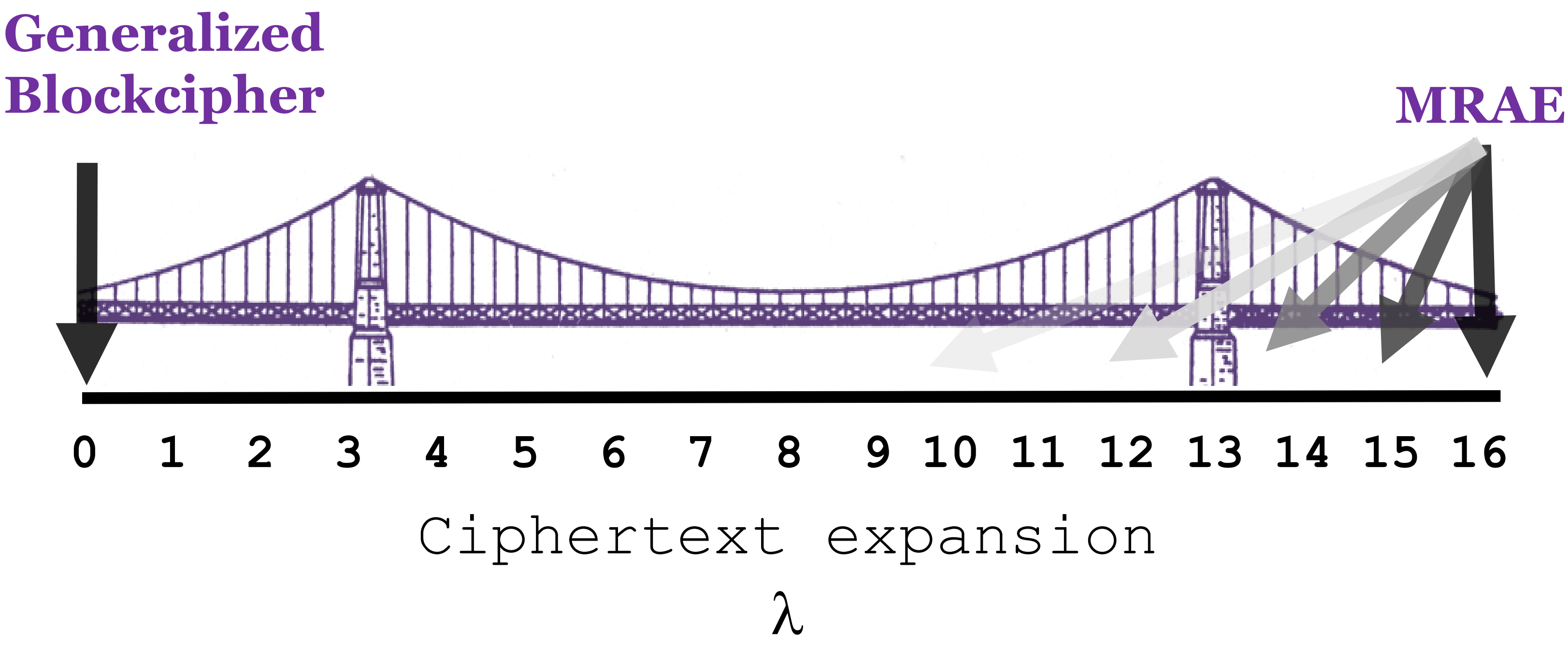
Robust-AE ⇔ Generalized Blockcipher

Following [BR00, ST13]



The natural construction, "enciphering-based AE," to make an RAE scheme from a generalized blockcipher

Unifying MRAE and Blockciphers



Claims lurking behind AEZ

(1) Enciphering-based AE is a great way to achieve AE: very strong properties – not necessarily expensive

a) If (M, $\boldsymbol{A}$) tuples are known not to repeat, no nonce is needed
b) Nonce repetitions: privacy loss is limited to revealing repetitions in (N, $\boldsymbol{A}$, M) tuples, authenticity not damaged at all.
c) Any authenticator-length can be selected, achieving best-possible authenticity for this amount of stretch.
d) If there's redundancy in plaintexts whose presence is verified on decryption, this augments authenticity
e) By last two properties: one can minimize length-expansion for bandwidth-constrained apps
f) If a decrypting party leaks some or all of a putative plaintext that was supposed to be squelched because of an authenticity-check failure, no problem.

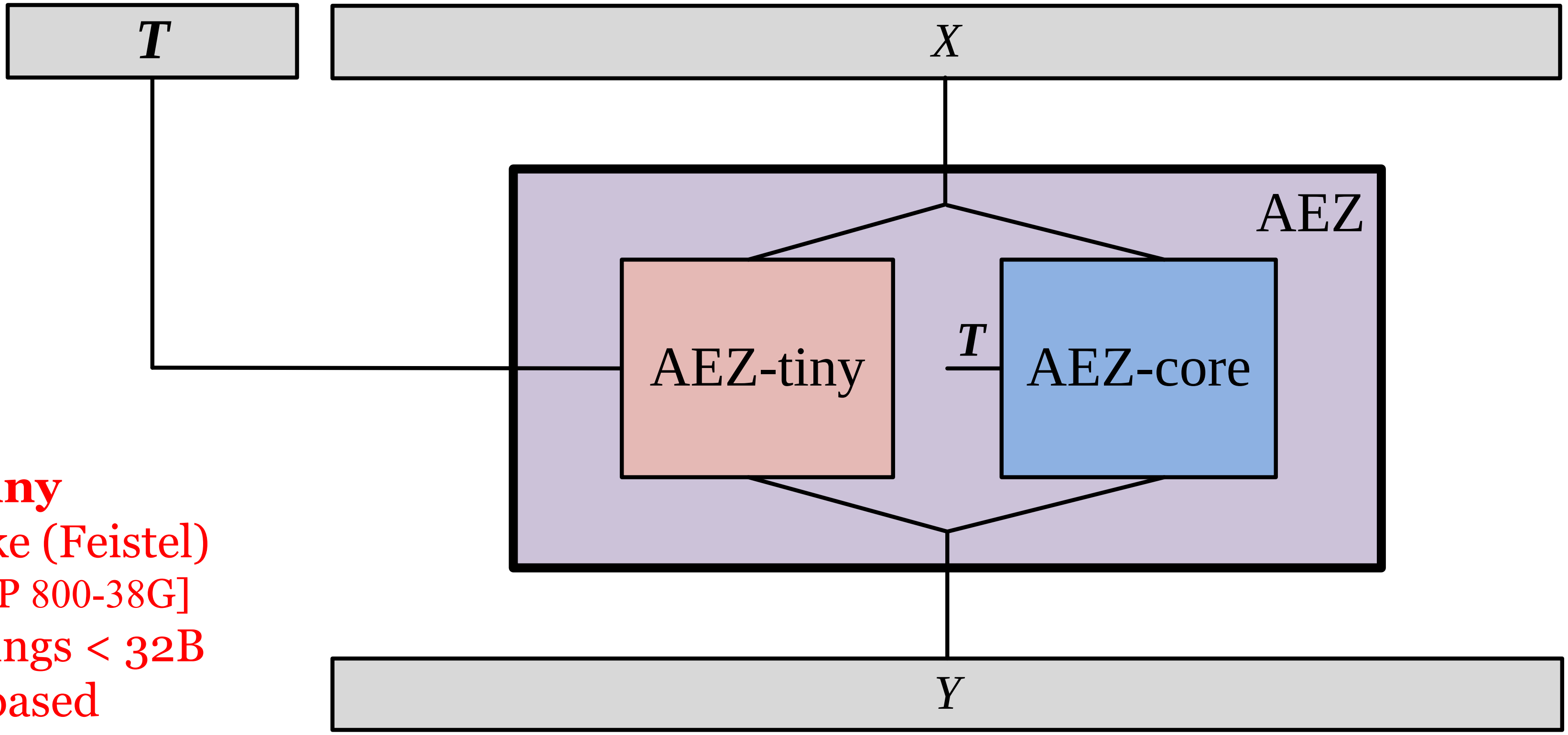
(2) A generalized blockcipher is a great tool to have around

Conceptual simplicity and versatility: it's an AE scheme, a PRG, a MAC, a PRF, a hash function, an entropy extractor, …

AEZ

The first concrete construction of a generalized blockcipher

(although VIL wide-block blockciphers like **EME2** [Halevi; Halevi-Rogaway] come very close)

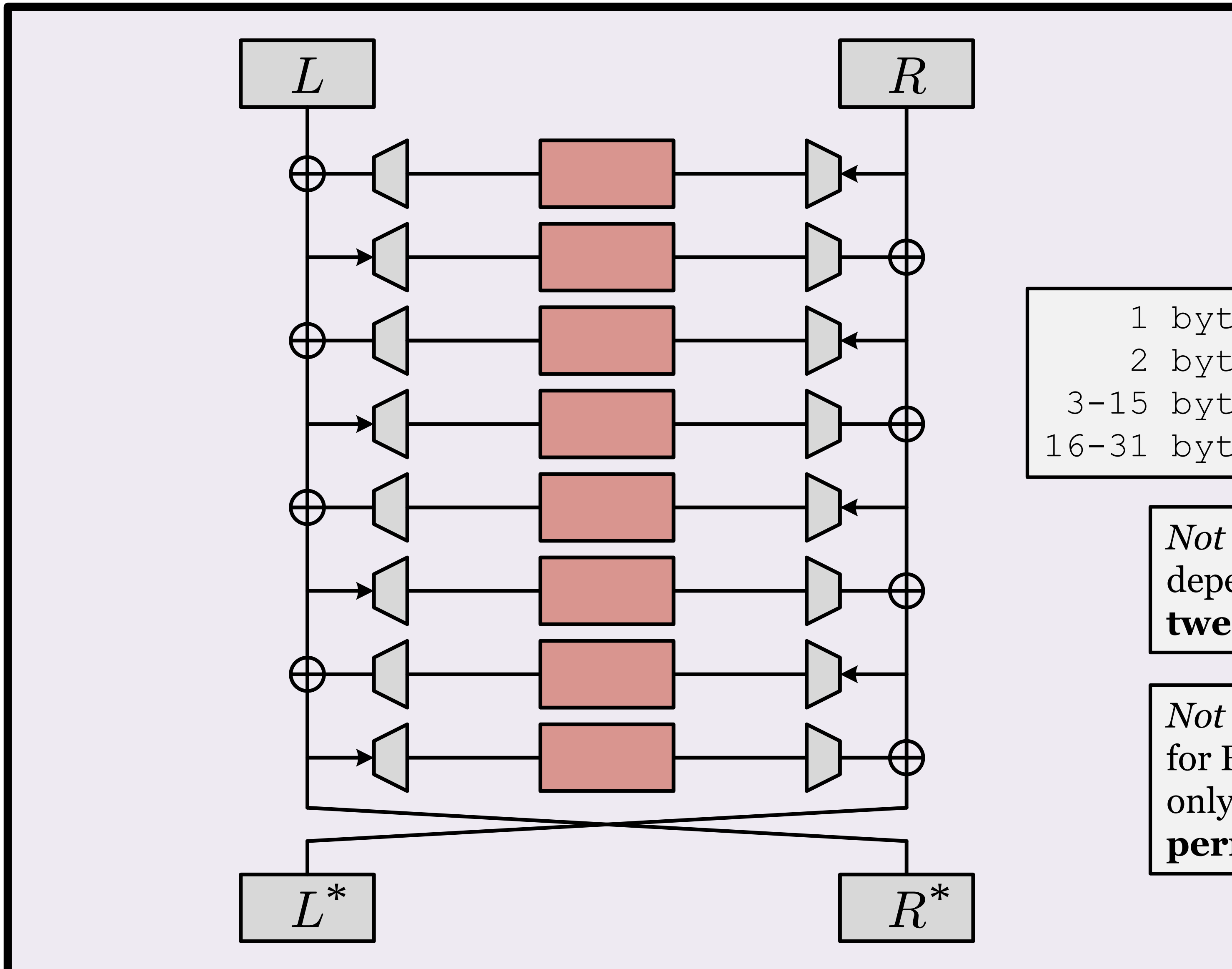


AEZ-tiny
FFX-like (Feistel)
[NIST SP 800-38G]
For strings < 32B
AES4-based

Structure of AEZ

AEZ-core
Builds on EME [HR04]
and OTR [M14]
For strings ≥ 32B
AES4 & AES based.

AEZ-tiny

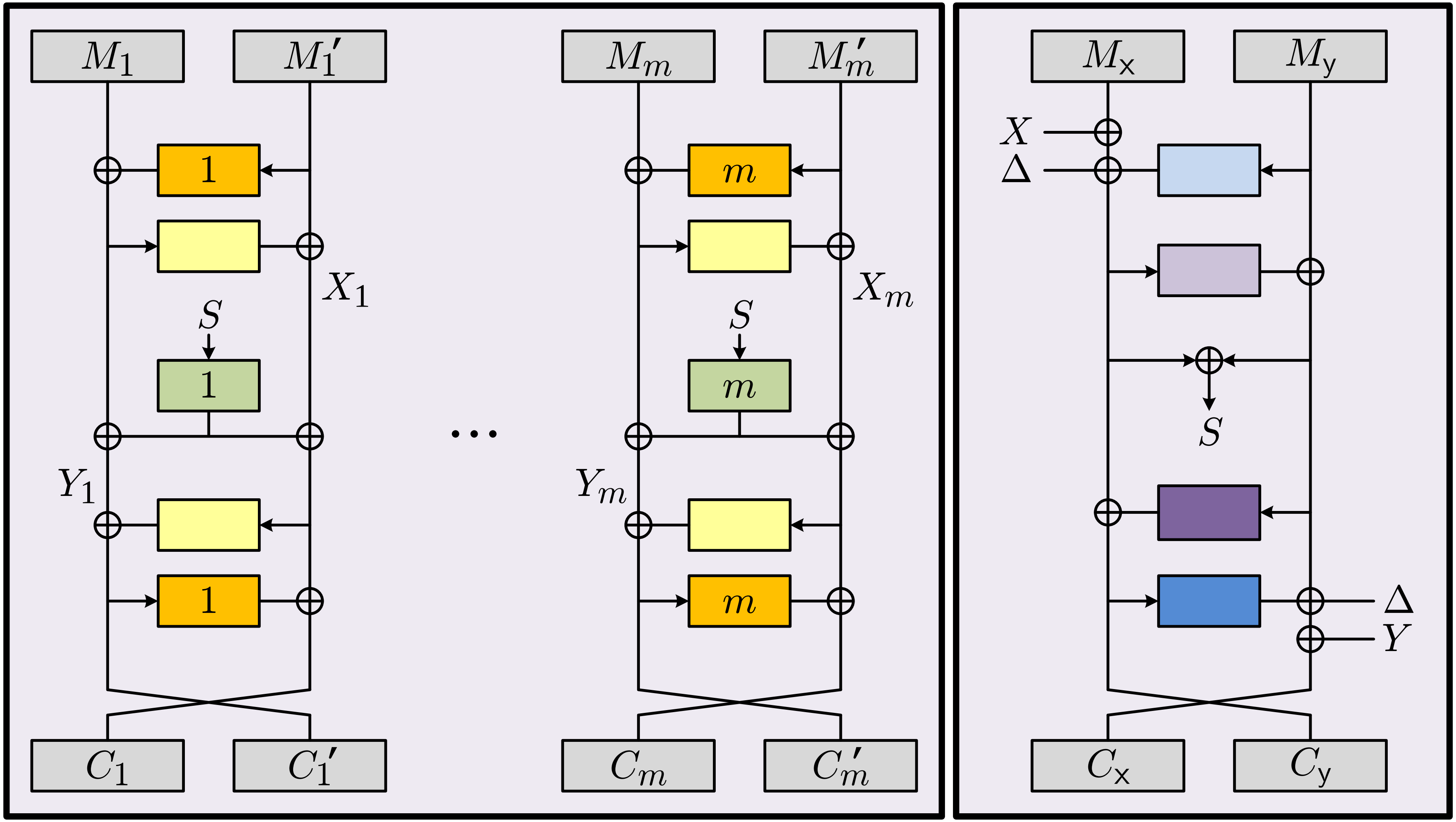


1 byte:	24 rounds
2 bytes:	16 rounds
3-15 bytes:	10 rounds
16-31 bytes:	8 rounds

Not shown: each round depends on the hashed **tweak**

Not shown: we correct for Feistel networks only generating **even permutations**

AEZ-core



M_1
M_1'
M_m
M_m'
M_x
M_y
1
m
X_1
X_m
X
Δ
S
1
m
S
Y_1
Y_m
1
m
Δ
Y
C_1
C_1'
C_m
C_m'
C_x
C_y

What's to Like?

Defense-in-depth *and* good speed

- The **security target**. Robust-AE is a **very strong** notion – implies almost all security properties one might hope for. **Very few** MRAE schemes remain in round-3.

- Wonderful **versatility, ease of use** – arbitrary-length keys, arbitrary ciphertext expansion, single-version scheme

- Amazing **speed** (in SW with AES-NI: peak 0.63 cpb Skylake; 1.0 AES-equivalents/block) considering the goal. Two-pass schemes are *not* inherently slow. HW performance looks respectable. **Quick-rejection** of invalid messages

- A **proof** for AEZ-core, to the birthday bound, in the **prove-then-prune** paradigm

What's <u>not</u> to Like?

- Scheme is **very complex**. *Anything-but-EZ* in HW… and not easy for the SW, either. 58 lines of dense pseudocode.

- Aggressively optimized – **not** a conservative design.

- There are **birthday key-recovery attacks**: [Chaigneau, Gilbert 2017] ($2^{66.5}$ chosen plaintexts) (v.4), following [Fuhr, Leurent, Suder 2015] (v.3). Note: 2^{48} byte usage cap.

- A **prove-then-prune** proof does not, by itself, imply security; **cryptanalysis is still needed**. Should not be treated as a proof in the same sense as assuming some primitive is a PRP.

- Are the RAE \ MRAE properties (particularly the possibility of small ciphertext expansion) **useful**?

Seduced by speed?

"*Don't worry about speed*. An RAE scheme / generalized blockcipher is very strong goal, and a scheme achieving it based on `aesenc` is going to need to be 2× – 3× slower, per block, than AES."

"No! We can **match** AES's speed in an RAE scheme. We can even get features like fast-reject and encipher-direction only processing, at the same time." → **AEZ**

"No!! We should be able to **exceed** AES speed in an aesenc-based MRAE scheme, and even an RAE scheme. What goes for AEGIS/Tioxin can be made to fly here, too."

For in the future, I'd like to see

A generalized blockcipher / RAE scheme

that's **much simpler** than AEZ, yet

Maybe a healthier alternative:

Enjoys (good old-fashioned) provable security

(DJB "boring crypto")

Is just as fast, or faster

Feels more conservative

Apparently has BBB security

Has *at least* an ideal-permutation model proof of security, with good bounds

But, for now: AEZ is the best there is for this degree of versatility and defense in depth.

AEZ (v4)

algorithm Encrypt$(K, N, \boldsymbol{A}, \tau, M)$ // AEZ authenticated encryption
$X \leftarrow M \parallel 0^\tau$; $(A_1, \ldots, A_a) \leftarrow \boldsymbol{A}$
$\boldsymbol{T} \leftarrow ([\tau]_{128}, N, A_1, \ldots, A_a)$
if $M = \varepsilon$ **then return** AEZ-prf$(K, \boldsymbol{T}, \tau)$
return Encipher$(K, \boldsymbol{T}, X)$

algorithm Decrypt$(K, N, \boldsymbol{A}, \tau, C)$ // AEZ authenticated decryption
$(A_1, \ldots, A_a) \leftarrow \boldsymbol{A}$; $\boldsymbol{T} \leftarrow ([\tau]_{128}, N, A_1, \ldots, A_a)$
if $|C| < \tau$ **then return** $\perp$
if $|C| = \tau$ **then if** $C =$ AEZ-prf$(K, \boldsymbol{T}, \tau)$ **then return** ε **else return** $\perp$ **fi fi**
$X \leftarrow$ Decipher$(K, \boldsymbol{T}, C)$
$M \parallel Z \leftarrow X$ where $|Z| = \tau$
if $(Z = 0^\tau)$ **then return** M **else return** $\perp$

algorithm Encipher$(K, \boldsymbol{T}, X)$ // AEZ enciphering
if $|X| < 256$ **then return** Encipher-AEZ-tiny$(K, \boldsymbol{T}, X)$
if $|X| \geq 256$ **then return** Encipher-AEZ-core$(K, \boldsymbol{T}, X)$

algorithm Encipher-AEZ-tiny$(K, \boldsymbol{T}, M)$ // AEZ-tiny enciphering
$\mu \leftarrow |M|$; $n \leftarrow \mu/2$; $\Delta \leftarrow$ AEZ-hash$(K, \boldsymbol{T})$
if $\mu = 8$ **then** $k \leftarrow 24$ **else if** $\mu = 16$ **then** $k \leftarrow 16$ **else if** $\mu < 128$ **then** $k \leftarrow 10$ **else** $k \leftarrow 8$ **fi**
$L \leftarrow M[1..n]$; $R \leftarrow M[n+1..\mu]$; **if** $\mu \geq 128$ **then** $i \leftarrow 6$ **else** $i \leftarrow 7$ **fi**
for $j \leftarrow 0$ **to** $k-1$ **do** $R' \leftarrow L \oplus ((\mathrm{E}_K^{0,i}(\Delta \oplus R10^* \oplus [j]_{128}))[1..n])$; $L \leftarrow R$; $R \leftarrow R'$ **od**
$C \leftarrow R \,\|\, L$; **if** $\mu < 128$ **then** $C \leftarrow C \oplus (\mathrm{E}_K^{0,3}(\Delta \oplus (C0^* \vee 10^*)) \wedge 10^*)$ **fi**
return C

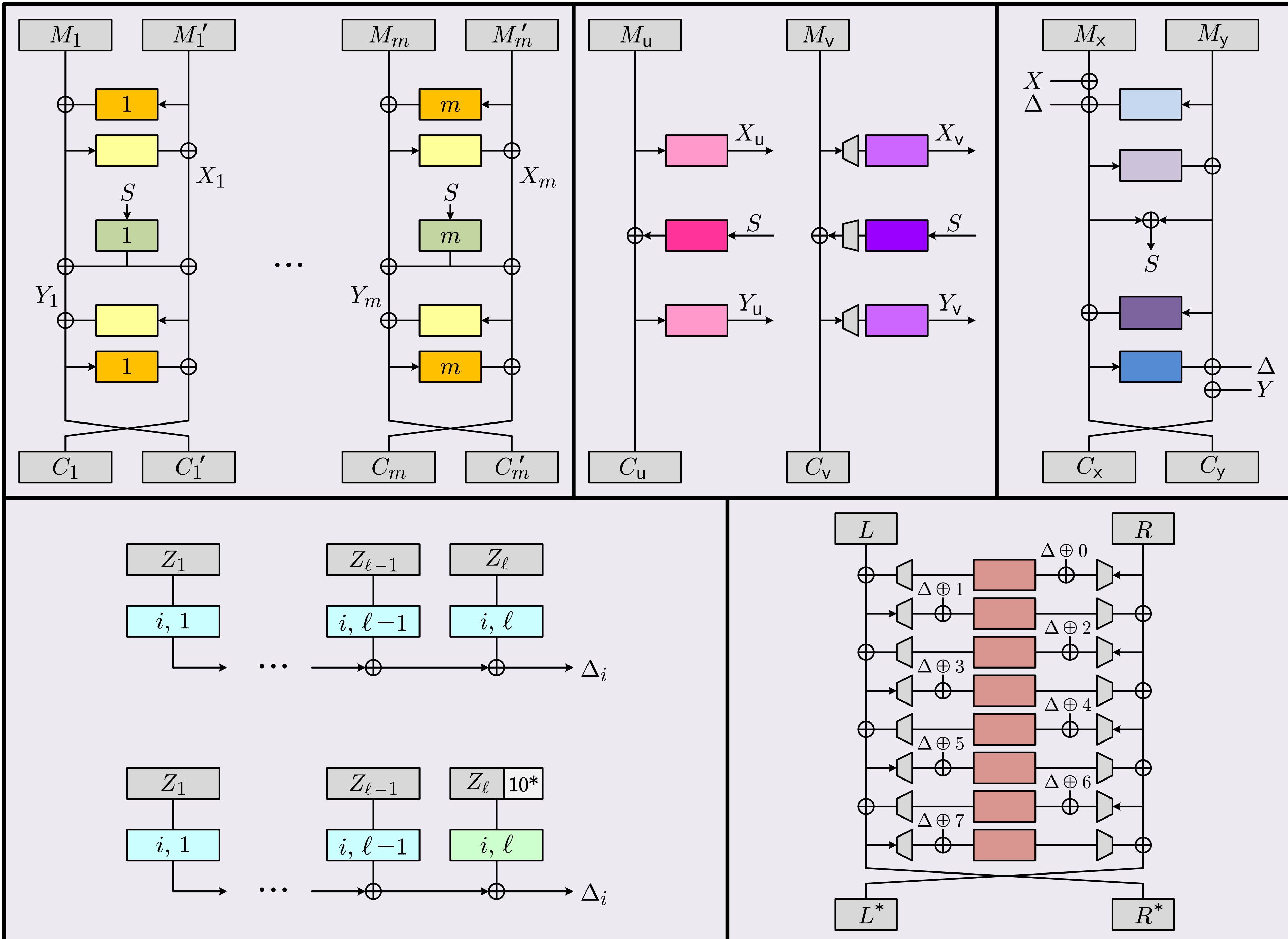
algorithm Encipher-AEZ-core$(K, \boldsymbol{T}, M)$ // AEZ-core enciphering
$\Delta \leftarrow$ AEZ-hash$(K, \boldsymbol{T})$
$M_1 M_1' \cdots M_m M_m'\ M_{\mathsf{uv}}\ M_{\mathsf{x}} M_{\mathsf{y}} \leftarrow M$ where $|M_1| = \cdots = |M_m'| = |M_{\mathsf{x}}| = |M_{\mathsf{y}}| = 128$ and $|M_{\mathsf{uv}}| < 256$
$d \leftarrow |M_{\mathsf{uv}}|$; **if** $d \leq 127$ **then** $M_{\mathsf{u}} \leftarrow M_{\mathsf{uv}}$; $M_{\mathsf{v}} \leftarrow \varepsilon$ **else** $M_{\mathsf{u}} \leftarrow M_{\mathsf{uv}}[1..128]$; $M_{\mathsf{v}} \leftarrow M_{\mathsf{uv}}[129..|M_{\mathsf{uv}}|]$ **fi**
for $i \leftarrow 1$ **to** m **do** $W_i \leftarrow M_i \oplus \mathrm{E}_K^{1,i}(M_i')$; $X_i \leftarrow M_i' \oplus \mathrm{E}_K^{0,0}(W_i)$ **od**
if $d = 0$ **then** $X \leftarrow X_1 \oplus \cdots \oplus X_m \oplus \mathbf{0}$ **else if** $d \leq 127$ **then** $X \leftarrow X_1 \oplus \cdots \oplus X_m \oplus \mathrm{E}_K^{0,4}(M_{\mathsf{u}}10^*)$
else $X \leftarrow X_1 \oplus \cdots \oplus X_m \oplus \mathrm{E}_K^{0,4}(M_{\mathsf{u}}) \oplus \mathrm{E}_K^{0,5}(M_{\mathsf{v}}10^*)$ **fi**
$S_{\mathsf{x}} \leftarrow M_{\mathsf{x}} \oplus \Delta \oplus X \oplus \mathrm{E}_K^{0,1}(M_{\mathsf{y}})$; $S_{\mathsf{y}} \leftarrow M_{\mathsf{y}} \oplus \mathrm{E}_K^{-1,1}(S_{\mathsf{x}})$; $S \leftarrow S_{\mathsf{x}} \oplus S_{\mathsf{y}}$
for $i \leftarrow 1$ **to** m **do** $S' \leftarrow \mathrm{E}_K^{2,i}(S)$; $Y_i \leftarrow W_i \oplus S'$; $Z_i \leftarrow X_i \oplus S'$; $C_i' \leftarrow Y_i \oplus \mathrm{E}_K^{0,0}(Z_i)$; $C_i \leftarrow Z_i \oplus \mathrm{E}_K^{1,i}(C_i')$ **od**
if $d = 0$ **then** $C_{\mathsf{u}} \leftarrow C_{\mathsf{v}} \leftarrow \varepsilon$; $Y \leftarrow Y_1 \oplus \cdots \oplus Y_m \oplus \mathbf{0}$
else if $d \leq 127$ **then** $C_{\mathsf{u}} \leftarrow M_{\mathsf{u}} \oplus \mathrm{E}_K^{-1,4}(S)$; $C_{\mathsf{v}} \leftarrow \varepsilon$; $Y \leftarrow Y_1 \oplus \cdots \oplus Y_m \oplus \mathrm{E}_K^{0,4}(C_{\mathsf{u}}10^*)$
else $C_{\mathsf{u}} \leftarrow M_{\mathsf{u}} \oplus \mathrm{E}_K^{-1,4}(S)$; $C_{\mathsf{v}} \leftarrow M_{\mathsf{v}} \oplus \mathrm{E}_K^{-1,5}(S)$; $Y \leftarrow Y_1 \oplus \cdots \oplus Y_m \oplus \mathrm{E}_K^{0,4}(C_{\mathsf{u}}) \oplus \mathrm{E}_K^{0,5}(C_{\mathsf{v}}10^*)$ **fi**
$C_{\mathsf{y}} \leftarrow S_{\mathsf{x}} \oplus \mathrm{E}_K^{-1,2}(S_{\mathsf{y}})$; $C_{\mathsf{x}} \leftarrow S_{\mathsf{y}} \oplus \Delta \oplus Y \oplus \mathrm{E}_K^{0,2}(C_{\mathsf{y}})$
return $C_1 C_1' \cdots C_m C_m'\ C_{\mathsf{u}} C_{\mathsf{v}}\ C_{\mathsf{x}} C_{\mathsf{y}}$

algorithm AEZ-hash$(K, \boldsymbol{T})$ // AXU hash. T is a vector of strings
$(T_1, \ldots, T_t) \leftarrow \boldsymbol{T}$
for $i \leftarrow 1$ **to** t **do**
  $\ell \leftarrow \max(1, \lceil |T_i|/128 \rceil)$; $j \leftarrow i + 2$; $Z_1 \cdots Z_\ell \leftarrow T_i$ where $|Z_1| = \cdots = |Z_{\ell-1}| = 128$
  if $|Z_\ell| = 128$ **then** $\Delta_i \leftarrow \mathrm{E}_K^{j,1}(Z_1) \oplus \cdots \oplus \mathrm{E}_K^{j,\ell}(Z_\ell)$ **fi**
  if $|Z_\ell| < 128$ **then** $\Delta_i \leftarrow \mathrm{E}_K^{j,1}(Z_1) \oplus \cdots \oplus \mathrm{E}_K^{j,\ell-1}(Z_{\ell-1}) \oplus \mathrm{E}_K^{j,0}(Z_\ell 10^*)$ **fi**
return $\Delta_1 \oplus \cdots \oplus \Delta_t \oplus \mathbf{0}$

algorithm AEZ-prf$(K, \boldsymbol{T}, \tau)$ // PRF used when $M = \varepsilon$
$\Delta \leftarrow$ AEZ-hash$(K, \boldsymbol{T})$
return $(\mathrm{E}_K^{-1,3}(\Delta) \,\|\, \mathrm{E}_K^{-1,3}(\Delta \oplus [1]_{128}) \,\|\, \mathrm{E}_K^{-1,3}(\Delta \oplus [2]_{128}) \,\|\, \cdots)[1..\tau]$

algorithm $\mathrm{E}_K^{j,i}(X)$ // Scaled-down TBC
$I \,\|\, J \,\|\, L \leftarrow \mathrm{Extract}(K)$ where $|I| = |J| = |L| = 128$
$\boldsymbol{K} \leftarrow (\mathbf{0}, I, J, L, I, J, L, I, J, L, I)$
if $j = -1$ **then** $\Delta \leftarrow iJ$; **return** $\mathrm{AES10}_{\boldsymbol{K}}(X \oplus \Delta)$ **fi**
$\boldsymbol{k} \leftarrow \boldsymbol{k}_1 \leftarrow (\mathbf{0}, J, I, L, \mathbf{0})$; $\boldsymbol{k}_2 \leftarrow (\mathbf{0}, L, I, J, L)$
if $j = 0$ **then** $\Delta \leftarrow iI$; **return** $\mathrm{AES4}_{\boldsymbol{k}}(X \oplus \Delta)$ **fi**
if $1 \le j \le 2$ **then** $\Delta \leftarrow (2^{3+\lfloor (i-1)/8 \rfloor} + ((i-1) \bmod 8))I$; **return** $\mathrm{AES4}_{\boldsymbol{k}_j}(X \oplus \Delta)$ **fi**
if $j \ge 3$ **and** $i = 0$ **then** $\Delta \leftarrow 2^{j-3} \cdot L$; **return** $\mathrm{AES4}_{\boldsymbol{k}}(X \oplus \Delta) \oplus \Delta$ **fi**
if $j \ge 3$ **and** $i \ge 1$ **then** $\Delta \leftarrow 2^{j-3} \cdot L \oplus (2^{3+\lfloor (i-1)/8 \rfloor} + (i - 1 \bmod 8))J$; **return** $\mathrm{AES4}_{\boldsymbol{k}}(X \oplus \Delta) \oplus \Delta$ **fi**

algorithm Extract(K) // Map key to subkeys
if $|K| = 384$ **then return** K
else return BLAKE2b(K)



M1
M1′
Mm
Mm′
1
m
X1
Xm
S
Y1
Ym
C1
C1′
Cm
Cm′
···
Mu
Mv
Xu
Xv
S
Yu
Yv
Cu
Cv
Mx
My
X
Δ
S
Δ
Y
Cx
Cy
Z1
Zℓ−1
Zℓ
i, 1
i, ℓ−1
i, ℓ
···
Δi
10*
L
R
Δ ⊕ 0
Δ ⊕ 1
Δ ⊕ 2
Δ ⊕ 3
Δ ⊕ 4
Δ ⊕ 5
Δ ⊕ 6
Δ ⊕ 7
L*
R*