AEZ v2

Authenticated Encryption by Enciphering

1. Why we created AEZ
2. Enciphering-based AE
3. Robust-AE
4. Accelerated provable-security
5. Components FF0 and EME4
6. AEZ Extensions

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AE Thesis

Giving **definitions** that guarantee more.
Giving **schemes** that achieve them.

By **strengthening** symmetric encryption, we can provide a **simpler-to-use** primitive for users, and thereby **minimize misuse**.

(Also: by focusing on the new target, we can **maximize efficiency**.)

Symmetric Encryption

Robust AE

Misuse-Resistant AE (MRAE)

Online AE

Nonce-based AEAD

Nonce-based AE

Probabilistic AE

IND-CCA2 prob encryption

IND-CPA prob encryption

Strength

Isn't MRAE already very strong?

Robust AE
MRAE
Online AE (OAE)
Nonce-based AEAD

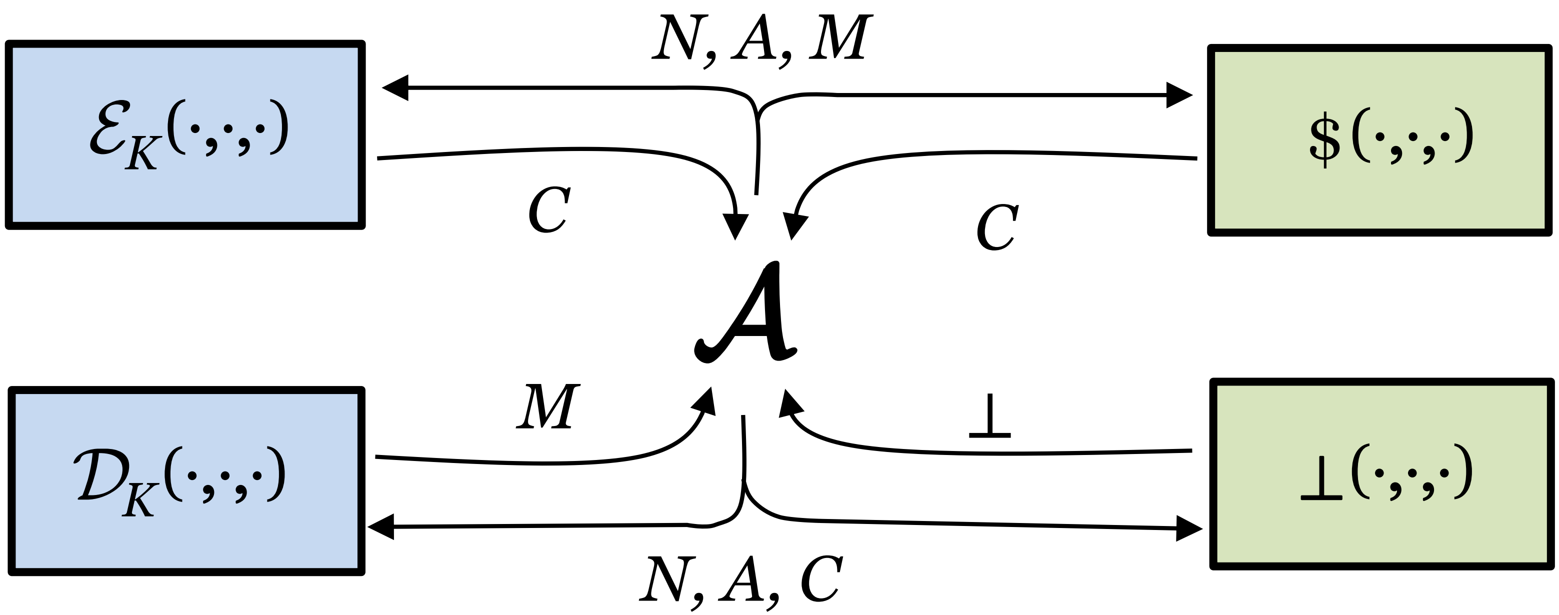
Yes.

Still, there are **important ways** in which MRAE **falls short** of maximizing strength/ease of correct use, in both

- the service it provides (**syntax**)
- what it guarantees (**security**)

MRAE

[Rogaway, Shrimpton 2006]

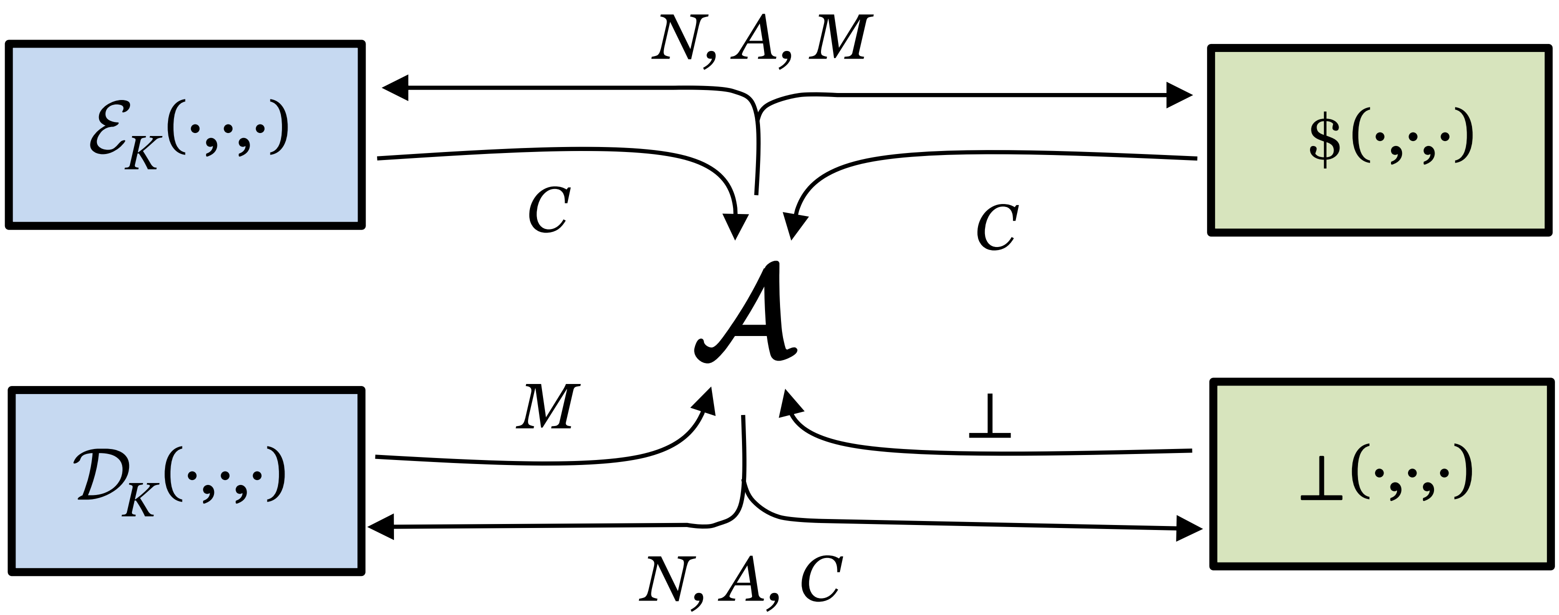


$\mathcal{A}$ may not ask queries that would trivially result in a win

- Repeat an (N, A, M) enc query
- Ask a dec query (N, A, C) after C is returned by an $(N, A, \cdot)$ enc query

MRAE

[Rogaway, Shrimpton 2006]



Effectively **assumes**

$|C| = |M| + 128$

Some *reasonably large* constant τ .
Big enough that, with the "real" scheme, forgeries almost *never* occur.

There <u>are</u> settings where we don’t want to grow plaintexts ~16 bytes

> August 13, 2013 DIAC 2013
>
> **AEAD Ciphers**
> **for**
> **Highly Constrained Networks**
>
> —
>
> René Struik
>
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Constrained devices: sensor networks, ad hoc networks, “internet of things”:
short tags save energy.

Shaving off 8 octets may justify making symmetric-key crypto 10× more expensive [sl.12]

Crypto cost should *not* ignore cost of data expansion. Authentication tags may be “evil” (authenticity is *not*) [sl.29]

Struik also speaks of the importance of supporting **very short plaintexts** and enabling exploitation of **already-present redundancy**.

At some level, we know how to fix this: *Encrypt by Enciphering*

Encode-Then-Encipher Encryption: How to Exploit Nonces or Redundancy in Plaintexts for Efficient Cryptography

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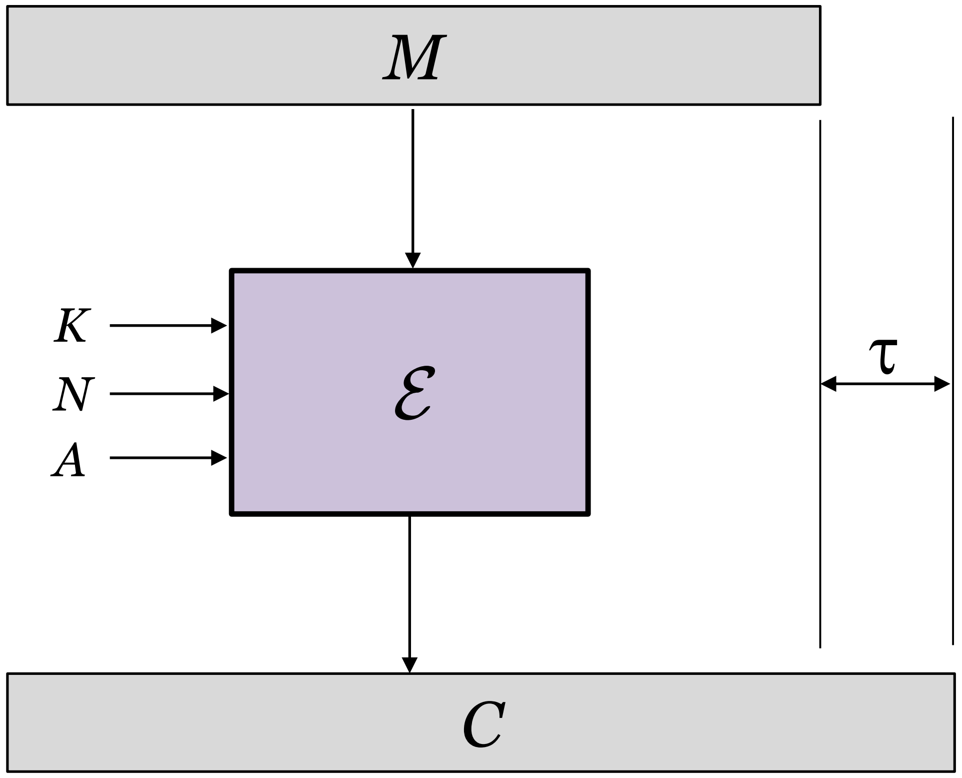
Abstract. We investigate the following approach to symmetric encryption: first *encode* the message via some keyless transform, and then *encipher* the encoded message, meaning apply a permutation F_K based on a shared key K. We provide conditions on the encoding functions and the cipher which ensure that the resulting encryption scheme meets strong privacy (eg. semantic security) and/or authenticity goals. The encoding can either be implemented in a simple way (eg. prepend a counter and append a checksum) or viewed as modeling existing redundancy or entropy already present in the messages, whereby encode-then-encipher encryption provides a way to exploit structured message spaces to achieve compact ciphertexts.

Enciphering-Based AE

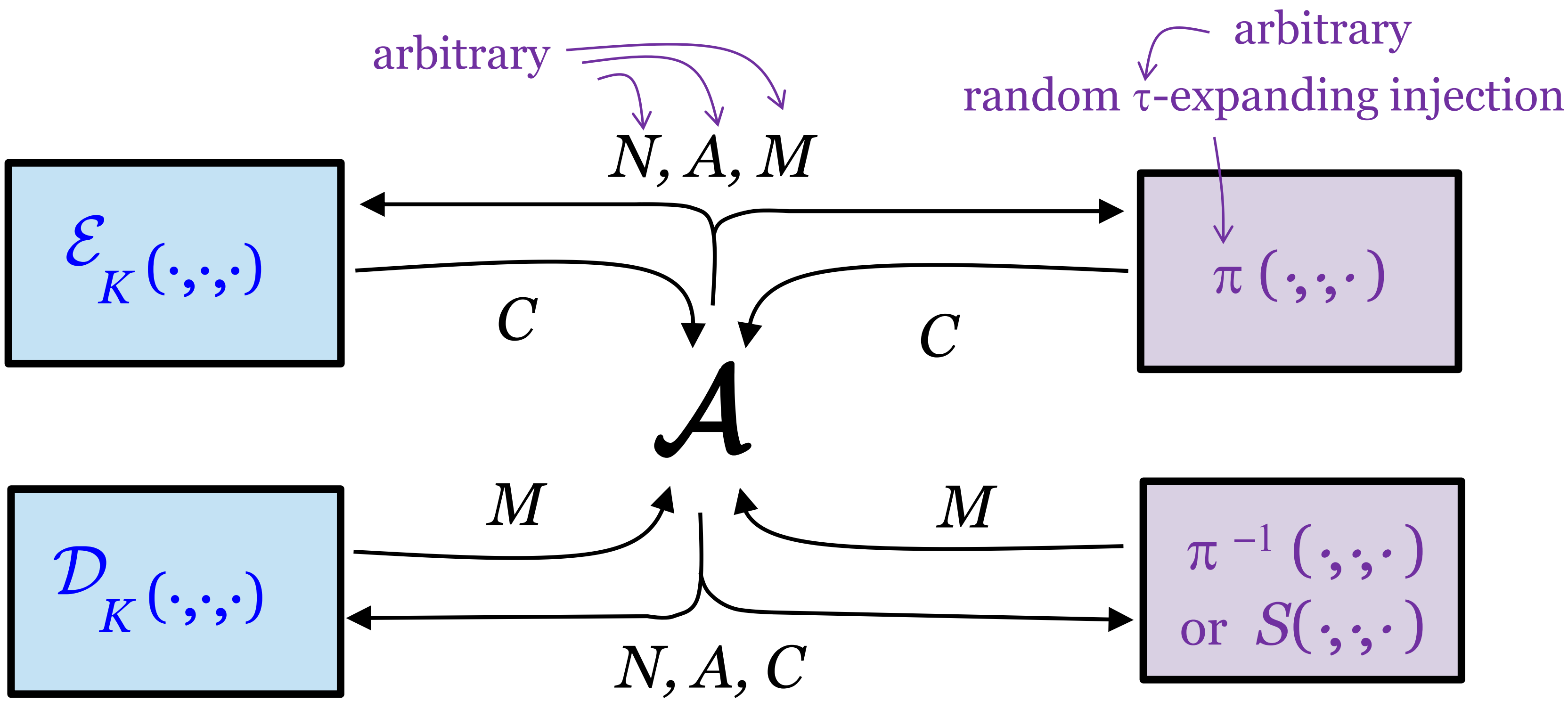
[Bellare, Rogaway 2000]
[Shrimpton, Terashima 2013]



$|K|$, $|N|$, $|A|$, $|M|$, τ
arbitrary

Robust AE: User chooses K, N, A, M, and $\tau \geq 0$.

Scheme is expected to deliver **best-security-possible** for τ.



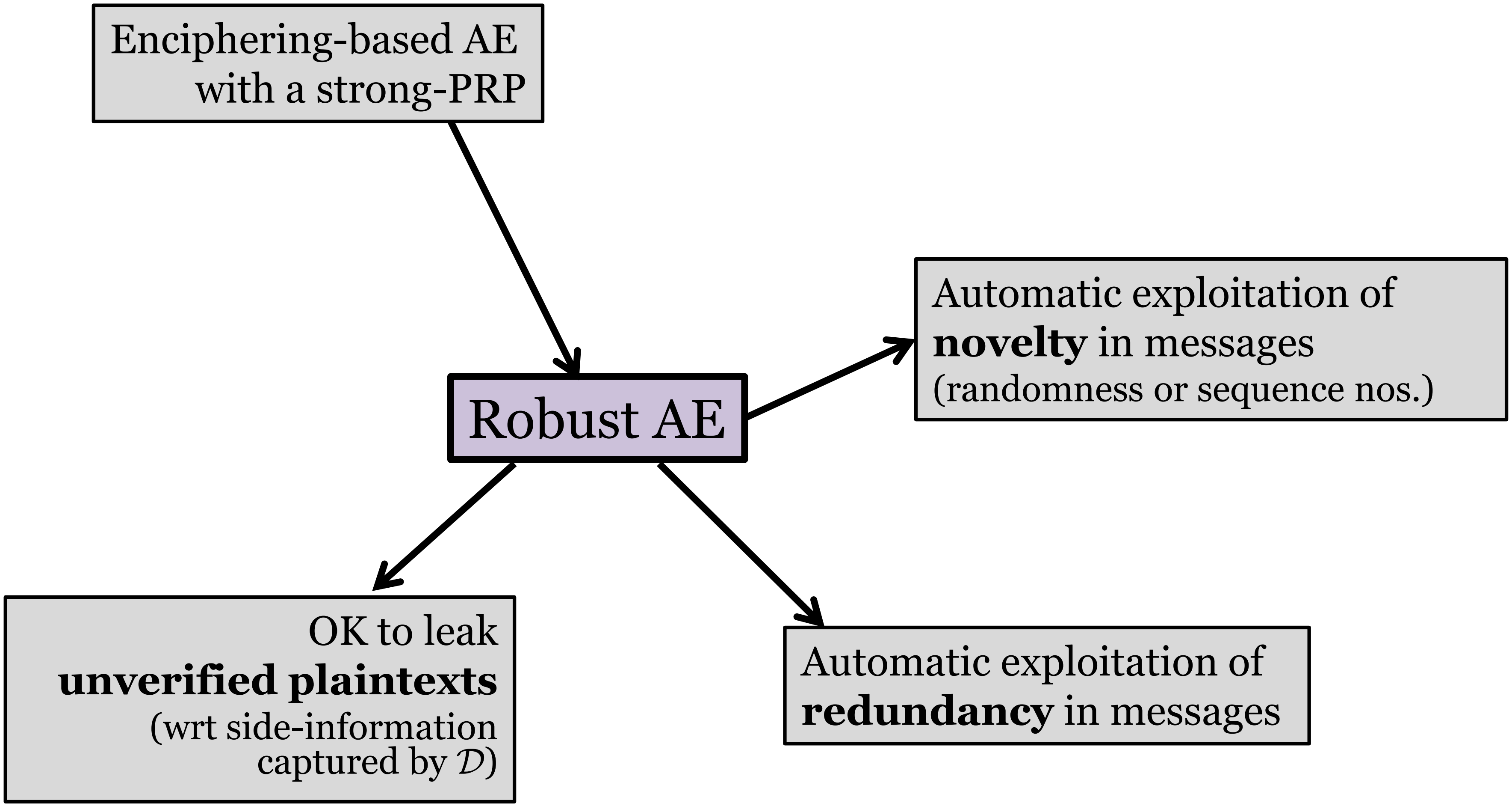
Pseudorandom injection

[R, Shrimpton 2006]

but now understood **prescriptively**, for all τ — not just an alternative characterization of an MRAE scheme

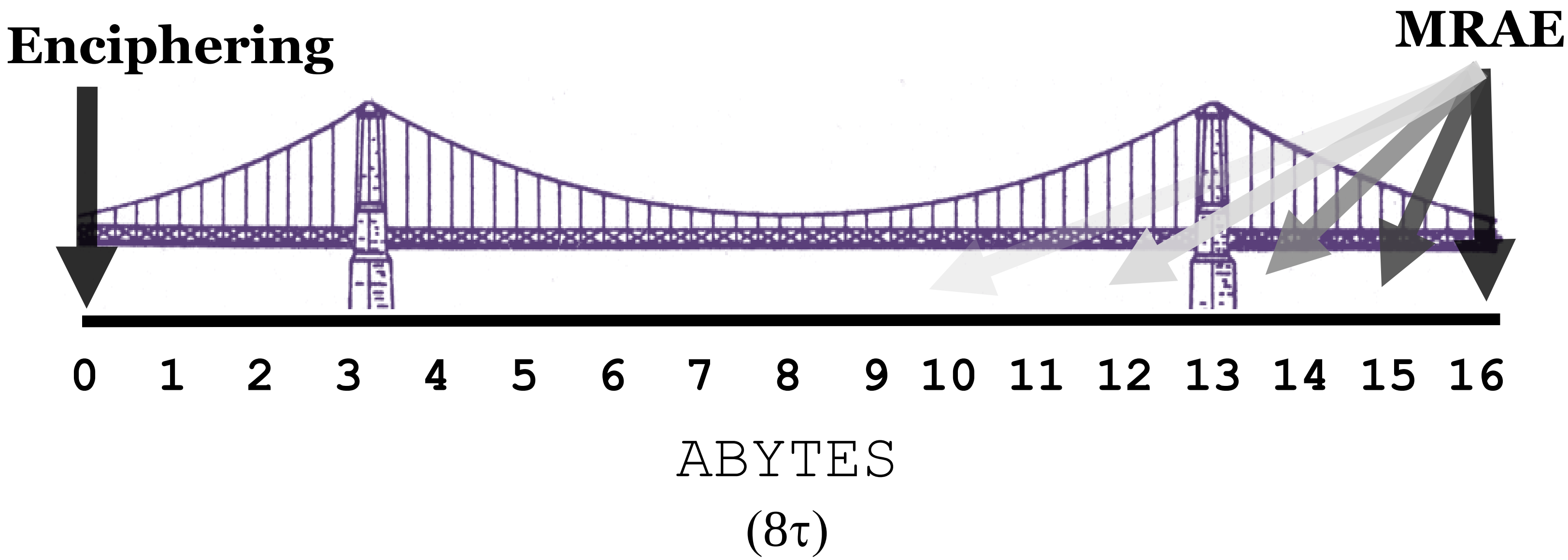
Inclusion of the simulator lets one formalize that release of **unverified plaintext** is not damaging

(cf: [ABLMMY14])

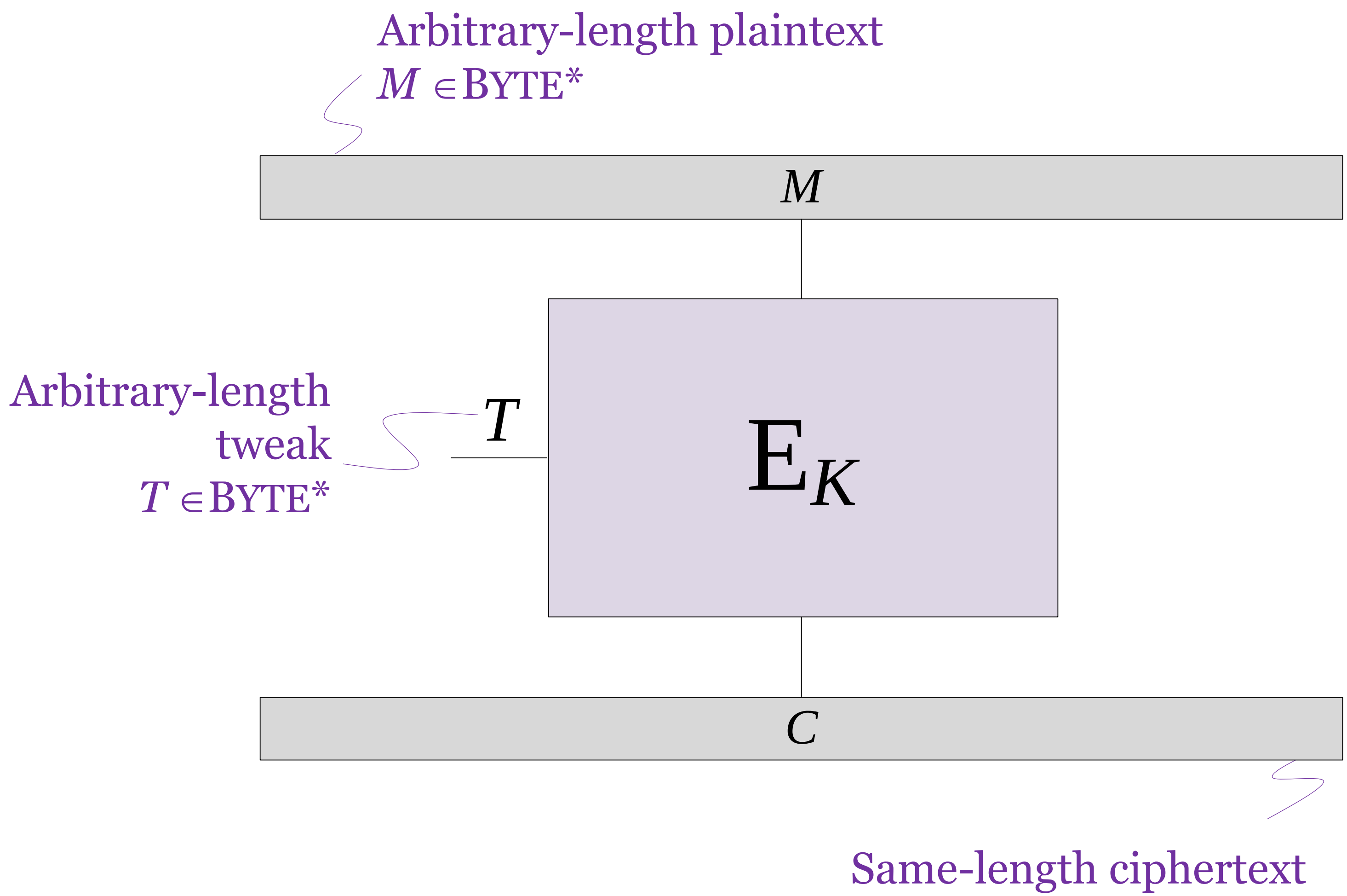

Enciphering-based AE with a strong-PRP
Robust AE
Automatic exploitation of **novelty** in messages (randomness or sequence nos.)
OK to leak **unverified plaintexts** (wrt side-information captured by $\mathcal{D}$)
Automatic exploitation of **redundancy** in messages

Robust AE

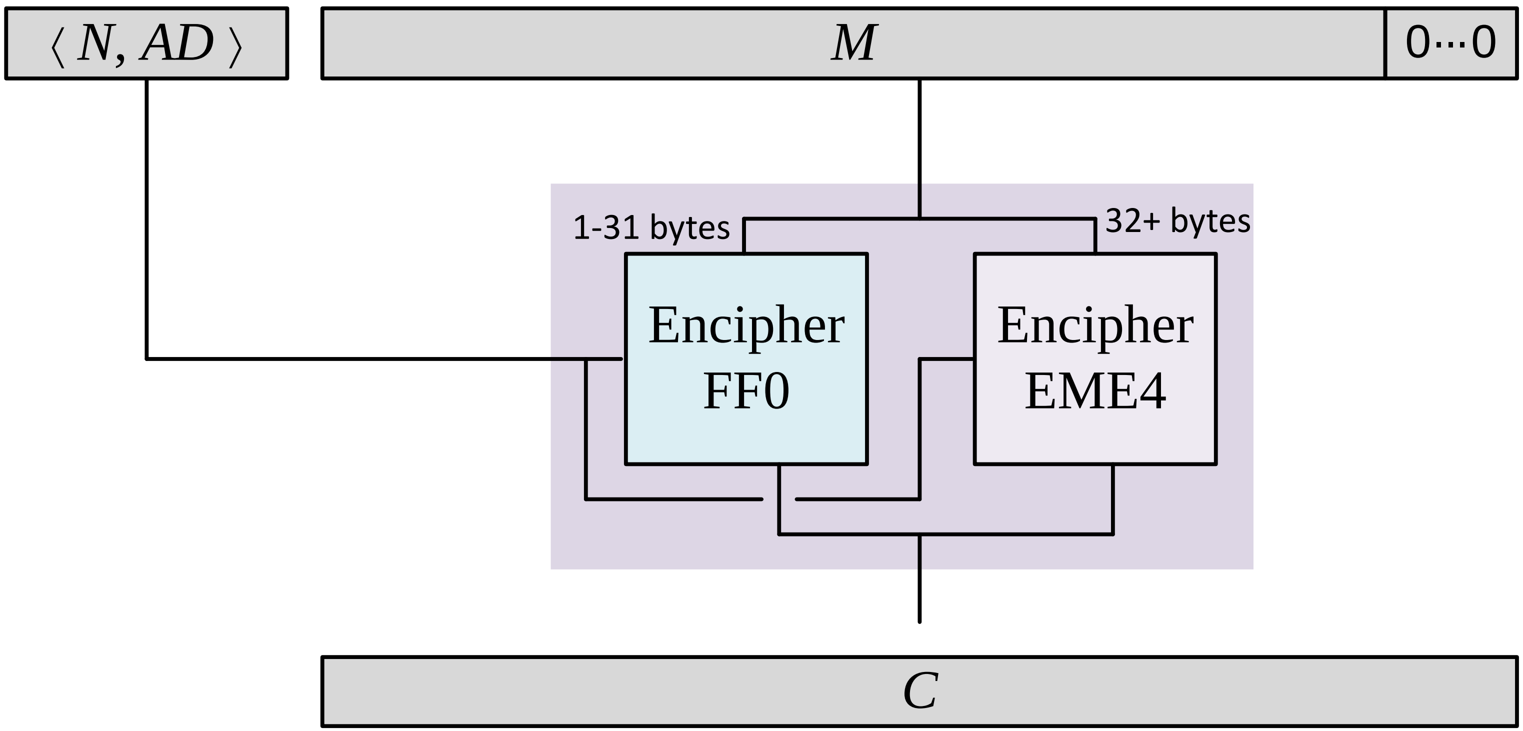
Generalizes strong-PRP and MRAE definitions



What to use for the enciphering scheme?



Length-Dependent Dispatch



FF0
FFX-like (Feistel)
[NIST SP 800-38G]
AES4-Based

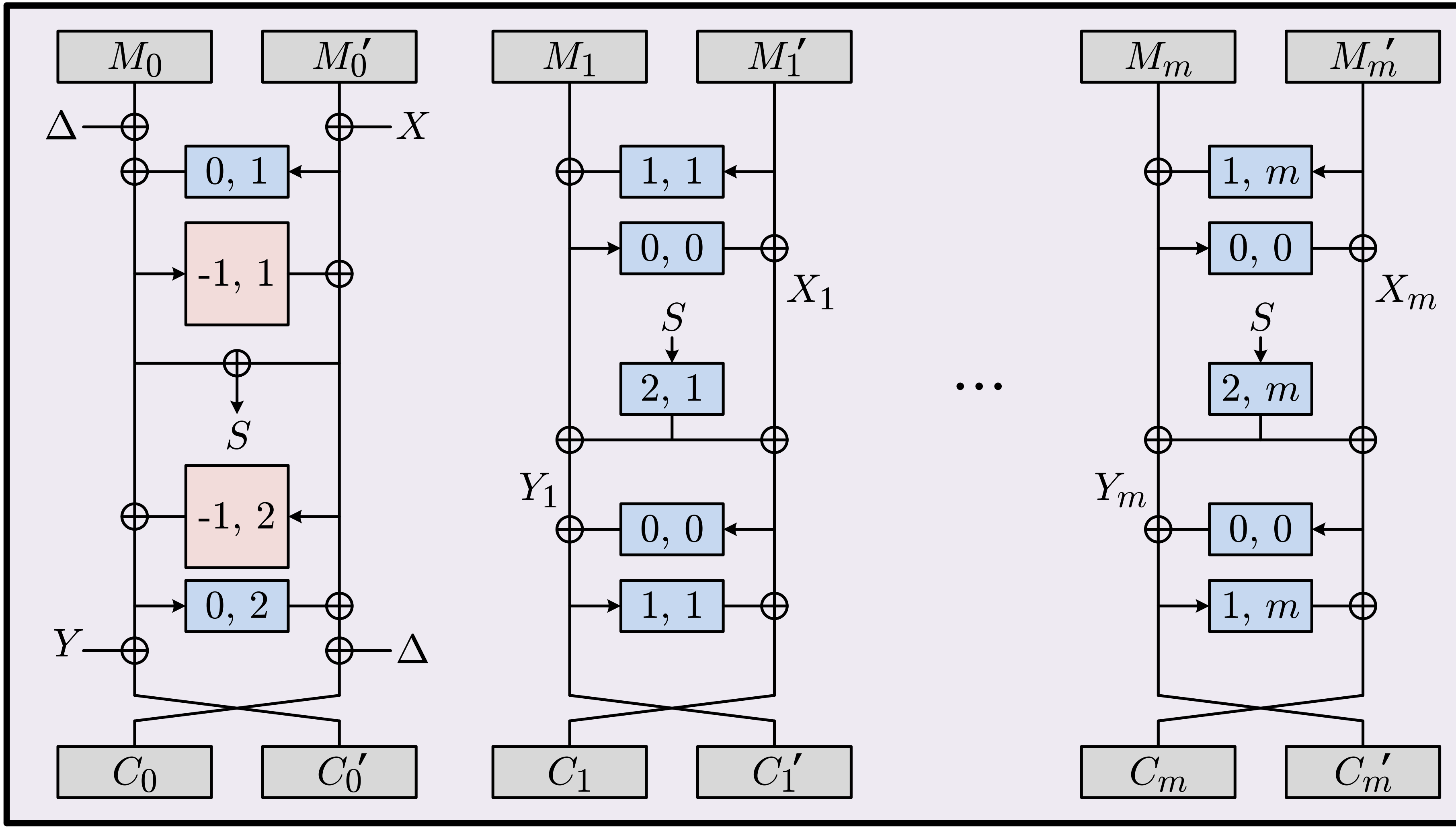
EME4
Builds on EME [Halevi, Rogaway]
and OTR [Minematsu 2014]
AES4 & AES based.

Designing FF0 and EME4

Accelerated Provable-Security Paradigm

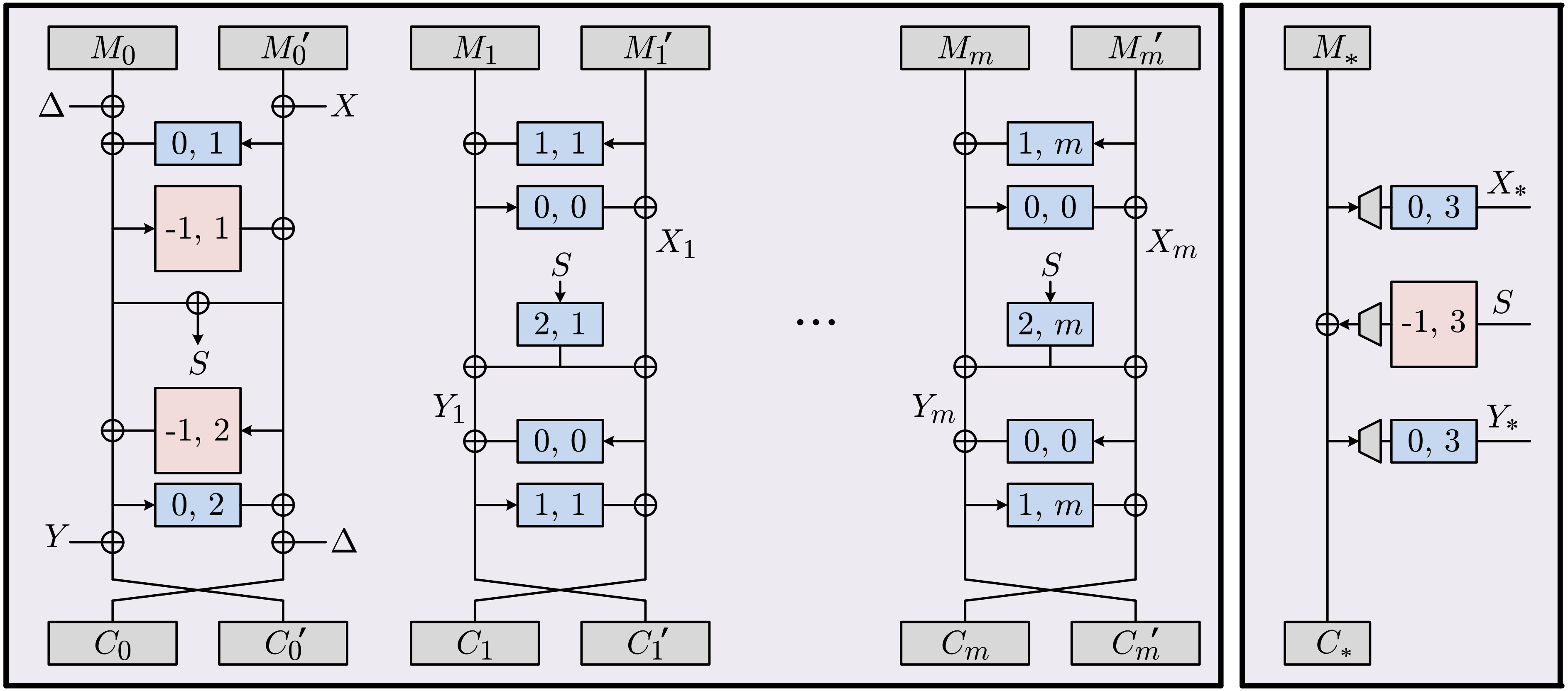
In general	**In our case**
Assume some primitive	[Liskov, Rivest, Wagner 2002] A tweakable blockcipher (TBC) (tweak space $\{0,1,2,3\} \times \mathbb{N}$)
Design assuming the primitive meets some standard assumption	The TBC is good as a tweakable PRP
Instantiate with "standard" primitive: the **scaled-up** design	Realize the TBC with AES / XE. **Not** what we submitted
Selectively instantiate with a mix of standard and reduced-round primitives: the **scaled-down** design	Use AES + AES4

EME4



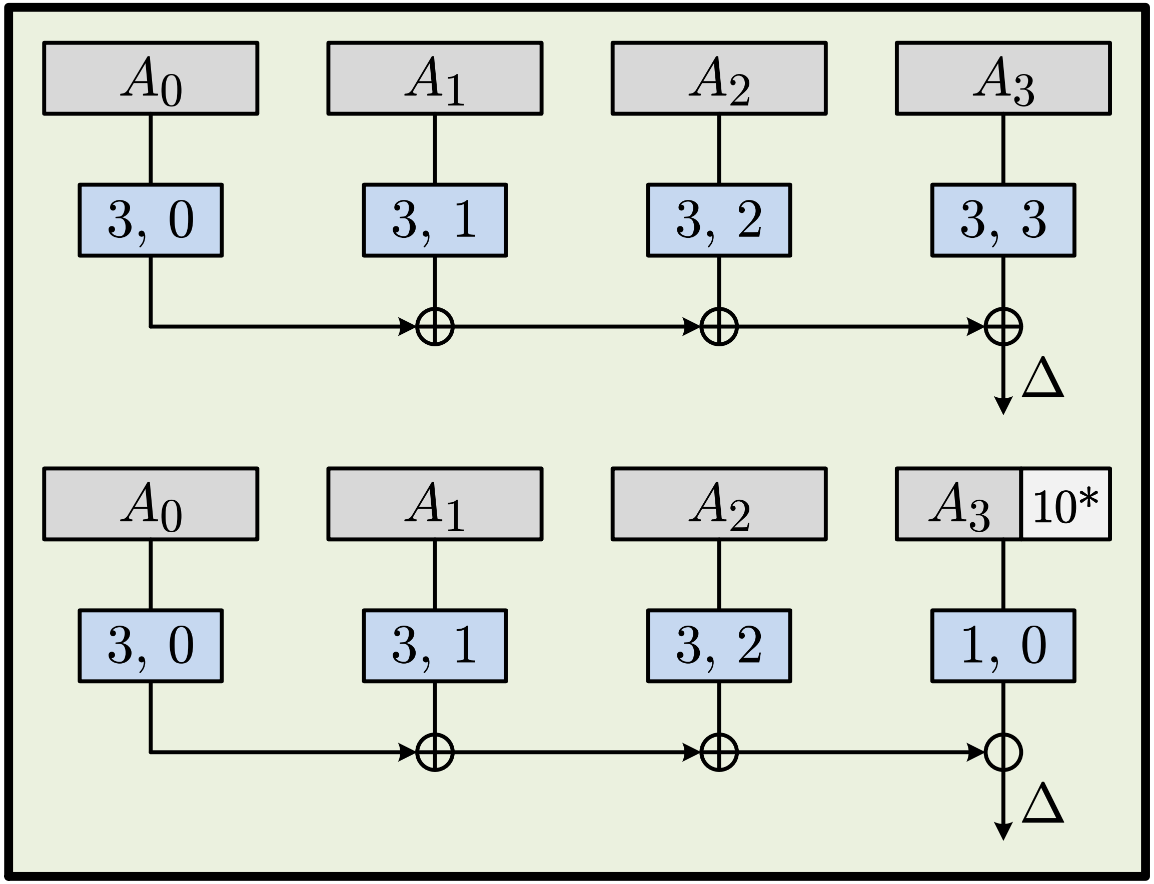
Message with an even number of blocks, no fragment at the end

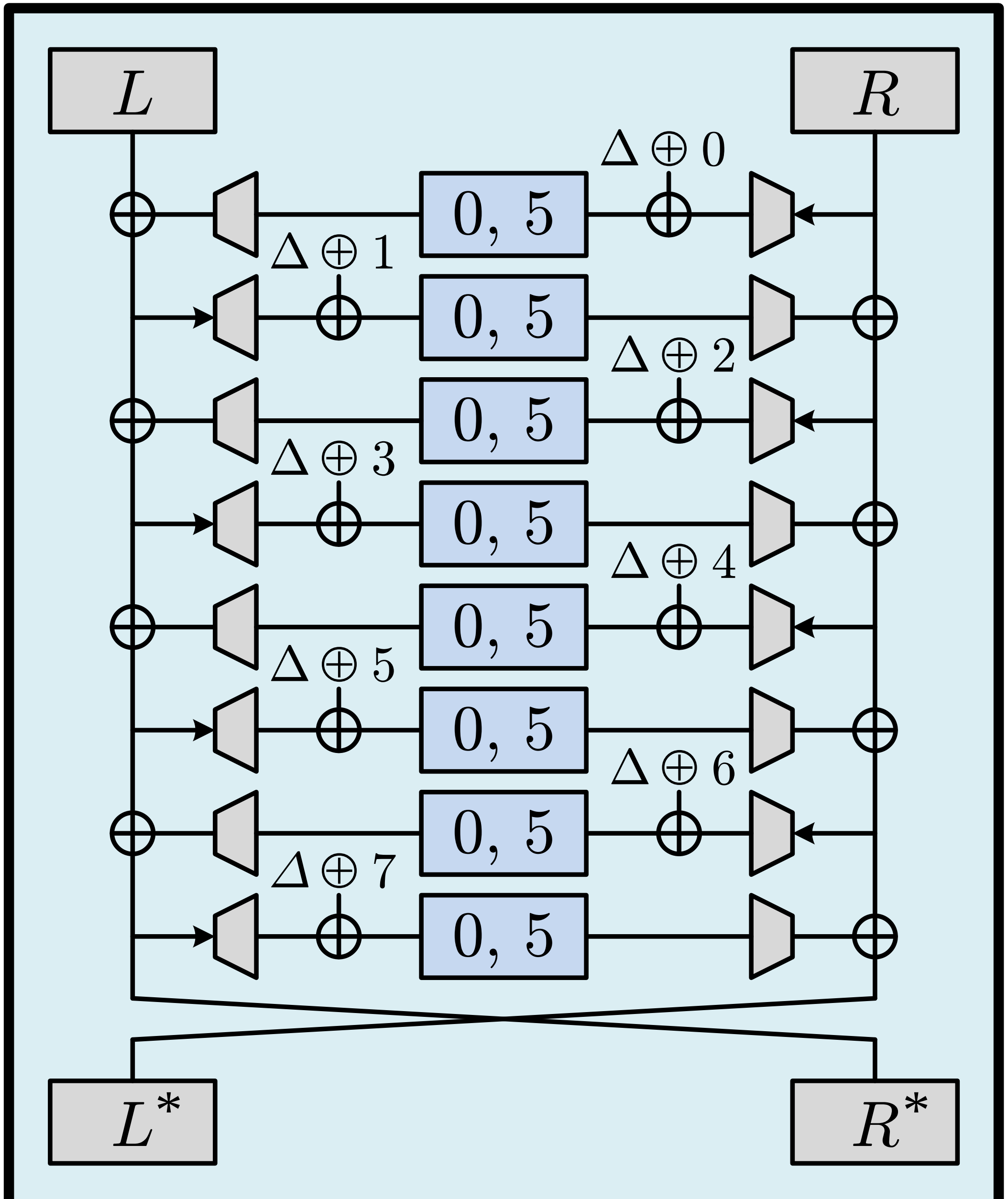
EME4



Message with an odd number of blocks, the last possibly a fragment

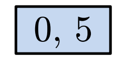
AHash



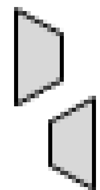


FF0

Δ is a universal-hash of A

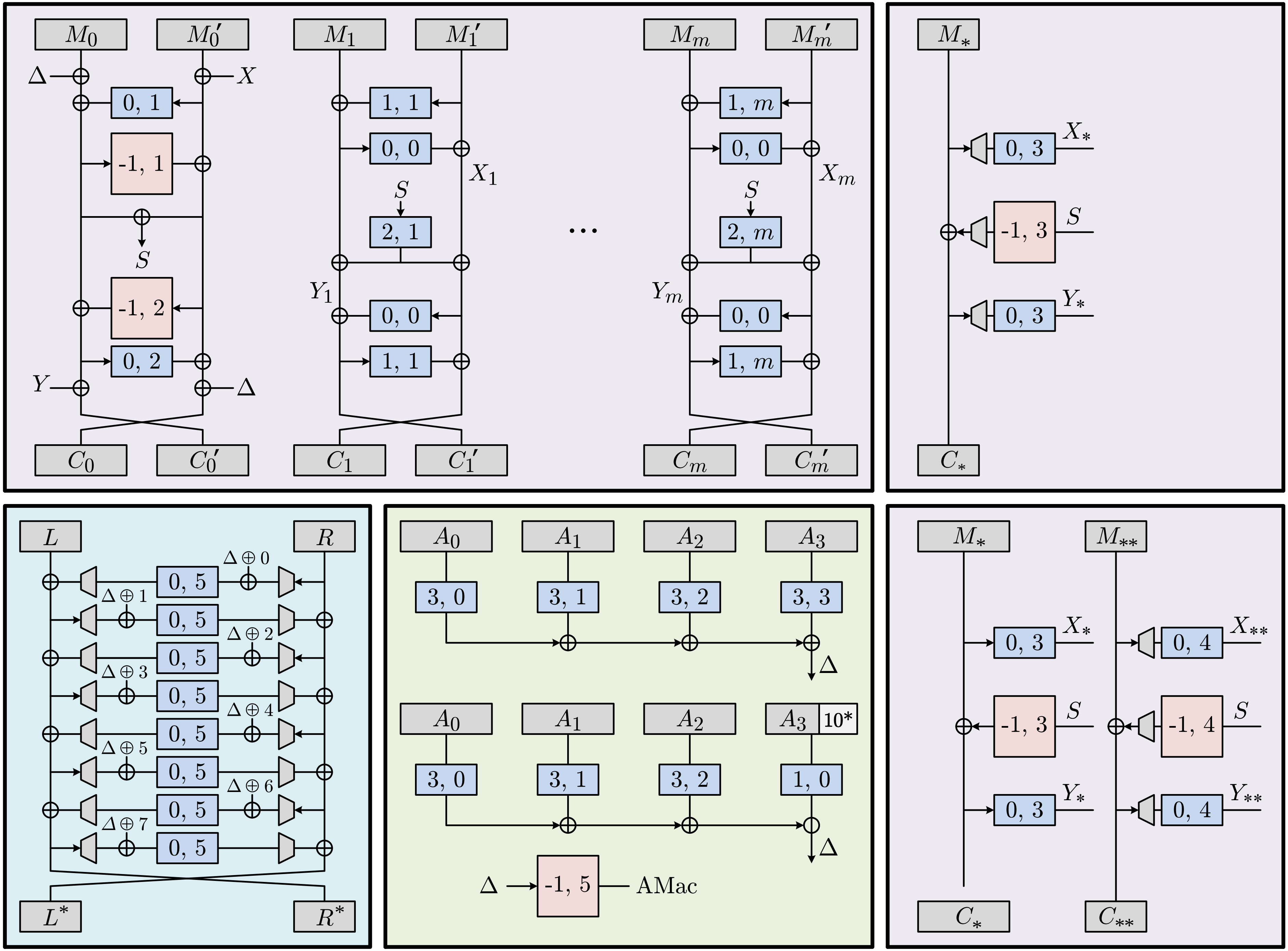


is our TBC


is truncation or $X\,0^*$ padding
(depending on orientation)

← 16-31 bytes

1-15 bytes: more rounds
(up to 24) and correct the
“even permutation” issue



M0
M0′
M1
M1′
Mm
Mm′
Δ
X
0, 1
-1, 1
S
-1, 2
0, 2
Y
Δ
1, 1
0, 0
X1
S
2, 1
Y1
0, 0
1, 1
1, m
0, 0
Xm
S
2, m
Ym
0, 0
1, m
…
C0
C0′
C1
C1′
Cm
Cm′
M*
X*
0, 3
S
-1, 3
Y*
0, 3
C*
L
R
Δ ⊕ 0
Δ ⊕ 1
Δ ⊕ 2
Δ ⊕ 3
Δ ⊕ 4
Δ ⊕ 5
Δ ⊕ 6
Δ ⊕ 7
0, 5
L*
R*
A0
A1
A2
A3
3, 0
3, 1
3, 2
3, 3
Δ
A0
A1
A2
A3
10*
3, 0
3, 1
3, 2
1, 0
Δ
Δ
-1, 5
AMac
M*
M**
X*
0, 3
X**
0, 4
S
-1, 3
S
-1, 4
Y*
0, 3
Y**
0, 4
C*
C**

Security property

The user chooses the ciphertext-expansion $\tau \geq 0$ and the scheme delivers *best-possible-security* for τ.

- Robust AE (Robust AE > MRAE $\gg$ Online-AE)
- Automatic novelty & redundancy exploitation
- Unverified-plaintext-release OK

Basic approach

- Enciphering-based AE
- FF0 and EME4
- Accelerated provable security (AES+AES4; ~~AES key schedule)~~

Additional features

- Blockcipher calls: 1× AES enc; **0.4**× AES for AD and fast-reject
- Inverse-free
- Parameter-free (well, ABYTES)
- Highly symmetric: encipher ≈ decipher
- Good key-agility
- Arbitrary-length keys (extract 256 bits; then expand) & nonces
- Small context size (≈ 144 bytes for speed-optimized)
- AEZ Extensions (coming soon)

AEZ Efficiency

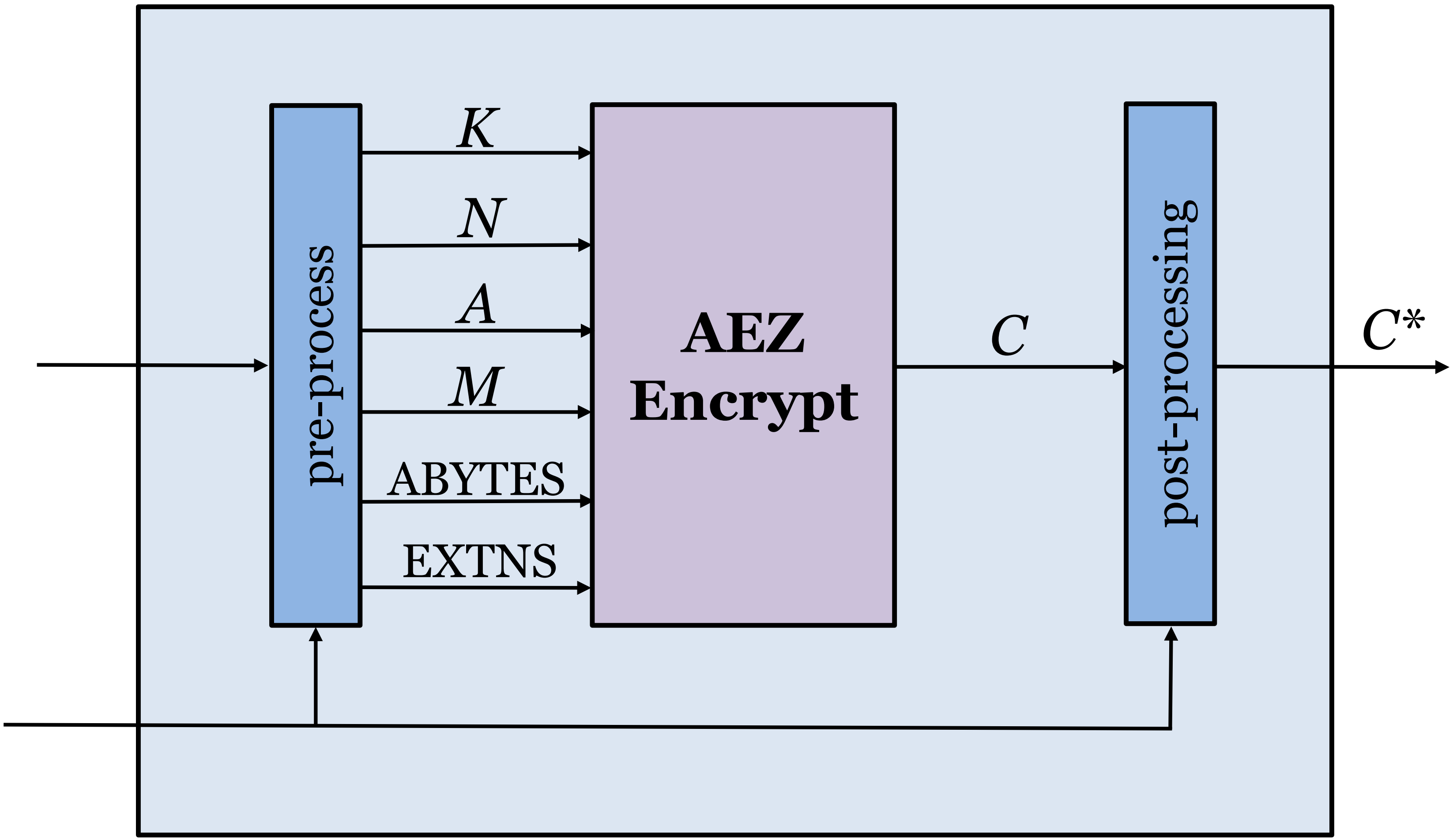
Message of $m \geq 2$ blocks	in "AES equivalents" (10 AES rounds) computation $\leq$	latency $\leq$
Encipher/Decipher	$m + 2.4$	**3.6**
Encrypt/Decrypt	$m + 3.8$	**3.6**
Reject invalid ciphertext	$0.4\,m + 3$	**3.2**
Process AD	$0.4\,m$	**0.4**
Setup 128-bit key	**2.4**	**0.8**

Experimental implementation:

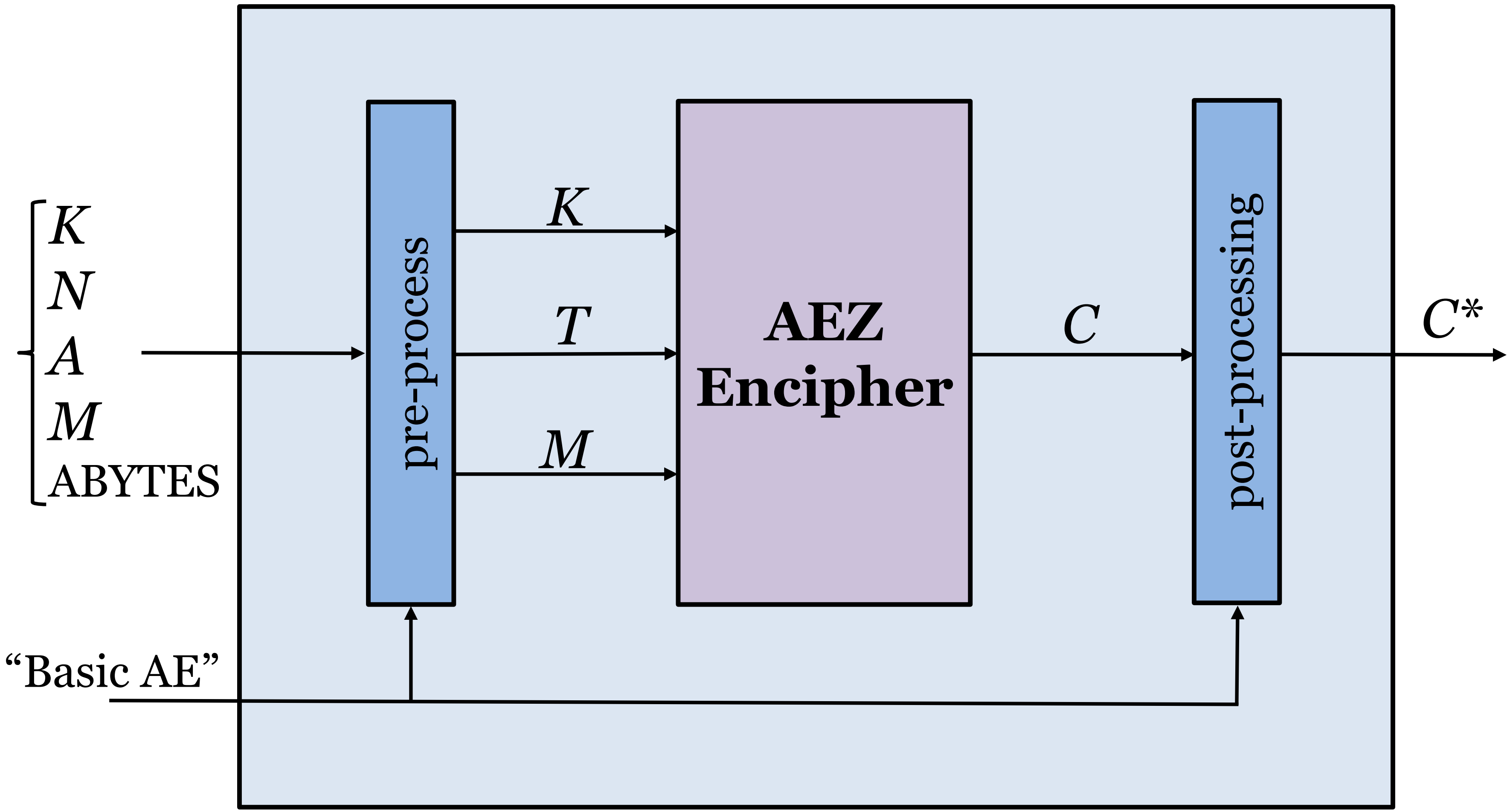
0.75 cpb (4Kb, Haswell)
0.69 cpb (marginal cost, Haswell)
(cf. the CTR, OCB: **0.64 cpb**)

AEZ Extensions

A wrapper to realize additional functionality



AEZ-Encrypt is Already an Extension
of its underlying enciphering scheme



Functionality Deliverable via AEZ Extensions

1. Secret Message Numbers — By encoding the SMN into the plaintext
2. Plaintext length-obfuscation — By padding (eg, to 2^n blocks)
3. Salting passwords — By encoding the salt in with the key
4. Slow PW-processing — By iterating a permutation
5. Convenient ciphertext alphabet — By, eg, base64url [RFC 4648] encoding
6. Vector-valued plaintexts and AD — By argument-encoding

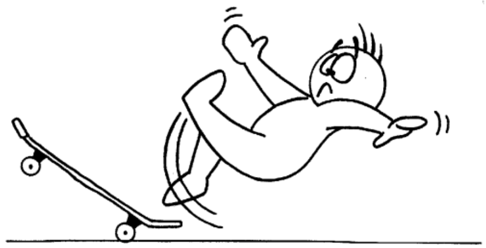
Arbitrary-length keys could have been delivered by an AEZ Extension, but were put into AEZ itself.

AEZ Conclusions

- Getting the **strongest** security & versatility guarantee is **not** expensive
  - **Cost**(Robust AE) ≈ **Cost** (AES-CTR)

- Properly done, deterministic encryption can be **good**:
  - Eliminates need for coins and state
  - Shortens ciphertexts
  - Main security concern – equality leakage – is often irrelevant
  - Frustrates one line of mass-surveillance [Bellare, Paterson, Rogaway 14]

[Bellare, Boldyreva, Knudsen, Namprempre 2001]
[Boldyreva, Taesombut 2004], [Rogaway, Zhang 2011]
[Fleischmann, Forler, Lucks, Wenzel 2012]



Online AE

- Requires a parameter — OAE[n] — to be meaningful.
- With fixed n: makes an implementation characteristic a security goal.
- Does not approximate best-possible security for an online scheme.
- Far weaker than MRAE — no exploitation of novelty or redundancy
- Notion will not be understandable by users. Attacks likely.
- Name: ~~*Online-MR*~~ ~~*max-online MR*~~

Paper on this in the coming months.

```
algorithm Encrypt(K, N, A, M)                                  // AEZ authenticated encryption
X ← M ∥ [0]^ABYTES
T ← Format(N, A)
if M = ε then return AMac(K, T)[1..ABYTES]
C ← Encipher(K, T, X)
return C
```

```
algorithm Decrypt(K, N, A, C)                                  // AEZ authenticated decryption
T ← Format(N, A)
if ∥C∥ ≤ ABYTES then if (C = AMac(K, T)[1..ABYTES]) then return ε else return ⊥
X ← Decipher(K, T, C)
M ∥ Z ← X where ∥Z∥ = ABYTES
if (Z = [0]^ABYTES) then return M else return ⊥
```

```
algorithm Format(N, A)                                         // Encode inputs and parameters
if ∥N∥ ≤ 11 then return 00 ∥ (ABYTES)_6 ∥ EXTNS ∥ N ∥ 10* ∥ A
if ∥N∥ = 12 then return 01 ∥ (ABYTES)_6 ∥ EXTNS ∥ N ∥ A
if ∥N∥ ≥ 13 then return 10 ∥ (ABYTES)_6 ∥ EXTNS ∥ N[1..12] ∥ A ∥ 10* ∥ N[13..∥N∥] ∥ [∥N∥]_8
```

```
algorithm Encipher(K, T, X)                                    // AEZ enciphering
if ∥X∥ < 32 then return EncipherFF0(K, T, X)
if ∥X∥ ≥ 32 then return EncipherEME4(K, T, X)
```

algorithm EncipherFF0(K, T, M) // FF0 enciphering
$m \leftarrow |M|$; $n \leftarrow m/2$; $\Delta \leftarrow \mathrm{AHash}(K,T)$
if $m = 8$ **then** $k \leftarrow 24$ **else if** $m = 16$ **then** $k \leftarrow 16$ **else if** $m < 128$ **then** $k \leftarrow 10$ **else** $k \leftarrow 8$
$L \leftarrow M(1\,..\,n)$; $R \leftarrow M(n+1\,..\,m)$; **if** $m \geq 128$ **then** $j \leftarrow 5$ **else** $j \leftarrow 6$
for $i \leftarrow 0$ **to** $k-1$ **do** $R' \leftarrow L \oplus ((\mathrm{E}_K^{0,j}(\Delta \oplus R10^* \oplus [i]_{16}))(1..n))$; $L \leftarrow R$; $R \leftarrow R'$ **od**; $C \leftarrow R \parallel L$
if $m < 128$ **then** $C \leftarrow C \oplus (\mathrm{E}_K^{0,7}(\Delta \oplus (C \vee 10^*)) \wedge 10^*)$
return C

algorithm EncipherEME4(K, T, M) // EME4 enciphering
$\Delta \leftarrow \mathrm{AHash}(K,T)$; $(M_0, M_0', \ldots, M_m, M_m', M_*, M_{**}) \leftarrow M$; $d \leftarrow |M| \bmod 256$
for $i \leftarrow 1$ **to** m **do** $X_i' \leftarrow M_i \oplus \mathrm{E}_K^{1,i}(M_i')$; $X_i \leftarrow M_i' \oplus \mathrm{E}_K^{0,0}(X_i')$ **od**
if $d = 0$ **then** $X \leftarrow X_1 \oplus \cdots \oplus X_m \oplus \mathbf{0}$ **else if** $d \leq 127$ **then** $X \leftarrow X_1 \oplus \cdots \oplus X_m \oplus \mathrm{E}_K^{0,3}(M_*10^*)$
else $X \leftarrow X_1 \oplus \cdots \oplus X_m \oplus \mathrm{E}_K^{0,3}(M_*) \oplus \mathrm{E}_K^{0,4}(M_{**}10^*)$ **fi**
$R \leftarrow M_0 \oplus \mathrm{E}_K^{0,1}(M_0' \oplus X) \oplus \Delta$; $R' \leftarrow M_0' \oplus \mathrm{E}_K^{-1,1}(R) \oplus X$; $S \leftarrow R \oplus R'$
for $i \leftarrow 1$ **to** m **do** $Z \leftarrow \mathrm{E}_K^{2,i}(S)$; $Y_i \leftarrow X_i' \oplus Z$; $Y_i' \leftarrow X_i \oplus Z$; $C_i' \leftarrow Y_i \oplus \mathrm{E}_K^{0,0}(Y_i')$; $C_i \leftarrow Y_i' \oplus \mathrm{E}_K^{1,i}(C_i')$ **od**
if $d = 0$ **then** $C_* \leftarrow C_{**} \leftarrow \varepsilon$; $Y \leftarrow Y_1 \oplus \cdots \oplus Y_m \oplus \mathbf{0}$
else if $d \leq 127$ **then** $C_* \leftarrow M_* \oplus \mathrm{E}_K^{-1,3}(S)$; $C_{**} \leftarrow \varepsilon$; $Y \leftarrow Y_1 \oplus \cdots \oplus Y_m \oplus \mathrm{E}_K^{0,3}(C_*10^*)$
else $C_* \leftarrow M_* \oplus \mathrm{E}_K^{-1,3}(S)$; $C_{**} \leftarrow M_{**} \oplus \mathrm{E}_K^{-1,4}(S)$; $Y \leftarrow Y_1 \oplus \cdots \oplus Y_m \oplus \mathrm{E}_K^{0,3}(C_*) \oplus \mathrm{E}_K^{0,4}(C_{**}10^*)$ **fi**
$C_0'' \leftarrow R \oplus \mathrm{E}_K^{-1,2}(R')$; $C_0 \leftarrow R' \oplus \mathrm{E}_K^{0,2}(C_0'') \oplus \Delta$; $C_0' \leftarrow C_0'' \oplus Y$
return $C_0 C_0' \cdots C_m C_m'\, C_* C_{**}$

algorithm AHash(K, A) // AXU hash
$(A_0, \ldots, A_m) \leftarrow A$
if $|A_m| \bmod 128 = 0$ **then return** $\mathrm{E}_K^{3,0}(A_0) \oplus \mathrm{E}_K^{3,1}(A_1) \oplus \cdots \oplus \mathrm{E}_K^{3,m}(A_m)$
if $|A_m| \bmod 128 \neq 0$ **then return** $\mathrm{E}_K^{3,0}(A_0) \oplus \mathrm{E}_K^{3,1}(A_1) \oplus \cdots \oplus \mathrm{E}_K^{3,m-1}(A_{m-1}) \oplus \mathrm{E}_K^{1,0}(A_m 10^*)$

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algorithm AMac(K, A) // PRF
return $\mathrm{E}_K^{-1,5}(\mathrm{AHash}_K(A))$

---

algorithm $\mathrm{E}_K^{i,j}(X)$ // TBC on $\mathcal{T} = \{0\} \times [0..7] \cup \{1,2,3\} \times \mathbb{N}$
$(J, L, K_0, K_1, K_2, K_3) \leftarrow \mathrm{Expand}(\mathrm{Extract}(K))$
$\boldsymbol{k}_0 \leftarrow (K_0, K_1, K_2, K_3, \mathbf{0})$; $\boldsymbol{k}_2 \leftarrow (K_2, K_3, K_0, K_1, \mathbf{0})$
$\boldsymbol{k}_1 \leftarrow (K_1, K_2, K_3, K_0, \mathbf{0})$; $\boldsymbol{k}_3 \leftarrow (K_3, K_0, K_1, K_2, \mathbf{0})$
$\boldsymbol{K} \leftarrow (L, J, 2J, 4J, K_0, K_1, K_2, K_3, K_0, K_1, K_2)$
if $i = -1$ **then return** $\mathrm{AES}_{\boldsymbol{K}}(X \oplus jJ)$
if $i = 0$ **or** $j = 0$ **then return** $\mathrm{AES4}_{\boldsymbol{k}_i}(X \oplus jJ)$
return $\mathrm{AES4}_{\boldsymbol{k}_i}(X \oplus (j \bmod 8)J \oplus 2^{\lfloor (j-1)/8 \rfloor} L)$

---

algorithm Extract(K) // Convert key to 256 bits
$\boldsymbol{z} \leftarrow [0][1][2]\cdots[15]$; **for** $i \leftarrow 1$ **to** 7 **do** $C_i \leftarrow \mathrm{AES4}_{(\boldsymbol{z},\boldsymbol{z},\boldsymbol{z},\boldsymbol{z},\boldsymbol{z})}([i]^{16})$
$\boldsymbol{a} \leftarrow (\mathbf{0}, C_1, C_2, C_3, \mathbf{0})$; $\boldsymbol{b} \leftarrow (\mathbf{0}, C_4, C_5, C_6, \mathbf{0})$; $C \leftarrow C_7$
$(I_0, \ldots, I_m) \leftarrow K$; **if** $\|I_m\| = 16$
then $J \leftarrow \mathrm{AES4}_{\boldsymbol{a}}(I_0 \oplus C) \oplus \mathrm{AES4}_{\boldsymbol{a}}(I_1 \oplus 2C) \oplus \mathrm{AES4}_{\boldsymbol{a}}(I_2 \oplus 2^2\,C) \oplus \cdots \oplus \mathrm{AES4}_{\boldsymbol{a}}(I_m \oplus 2^m\,C)$
$\quad L \leftarrow \mathrm{AES4}_{\boldsymbol{b}}(I_0 \oplus C) \oplus \mathrm{AES4}_{\boldsymbol{b}}(I_1 \oplus 2C) \oplus \mathrm{AES4}_{\boldsymbol{b}}(I_2 \oplus 2^2\,C) \oplus \cdots \oplus \mathrm{AES4}_{\boldsymbol{b}}(I_m \oplus 2^m\,C)$
else $J \leftarrow \mathrm{AES4}_{\boldsymbol{a}}(I_0 \oplus C) \oplus \mathrm{AES4}_{\boldsymbol{a}}(I_1 \oplus 2C) \oplus \mathrm{AES4}_{\boldsymbol{a}}(I_2 \oplus 2^2\,C) \oplus \cdots \oplus \mathrm{AES4}_{\boldsymbol{a}}(I_m 10^* \oplus 3C)$
$\quad L \leftarrow \mathrm{AES4}_{\boldsymbol{b}}(I_0 \oplus C) \oplus \mathrm{AES4}_{\boldsymbol{b}}(I_1 \oplus 2C) \oplus \mathrm{AES4}_{\boldsymbol{b}}(I_2 \oplus 2^2\,C) \oplus \cdots \oplus \mathrm{AES4}_{\boldsymbol{b}}(I_m 10^* \oplus 3C)$
return $J \,\|\, L$

---

algorithm Expand(K) // Map 256-bit string to vector of 128-bit subkeys
$(J, L) \leftarrow K$; $\boldsymbol{k} \leftarrow (J, L, 2J, L, 4J)$
for $i \leftarrow 0$ **to** 3 **do** $K_i \leftarrow \mathrm{AES4}_{\boldsymbol{k}}([i]^{16})$
return $(J, L, K_0, K_1, K_2, K_3)$