Authenticated Encryption with Variable Stretch

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ASIACRYPT 2016, Hanoi

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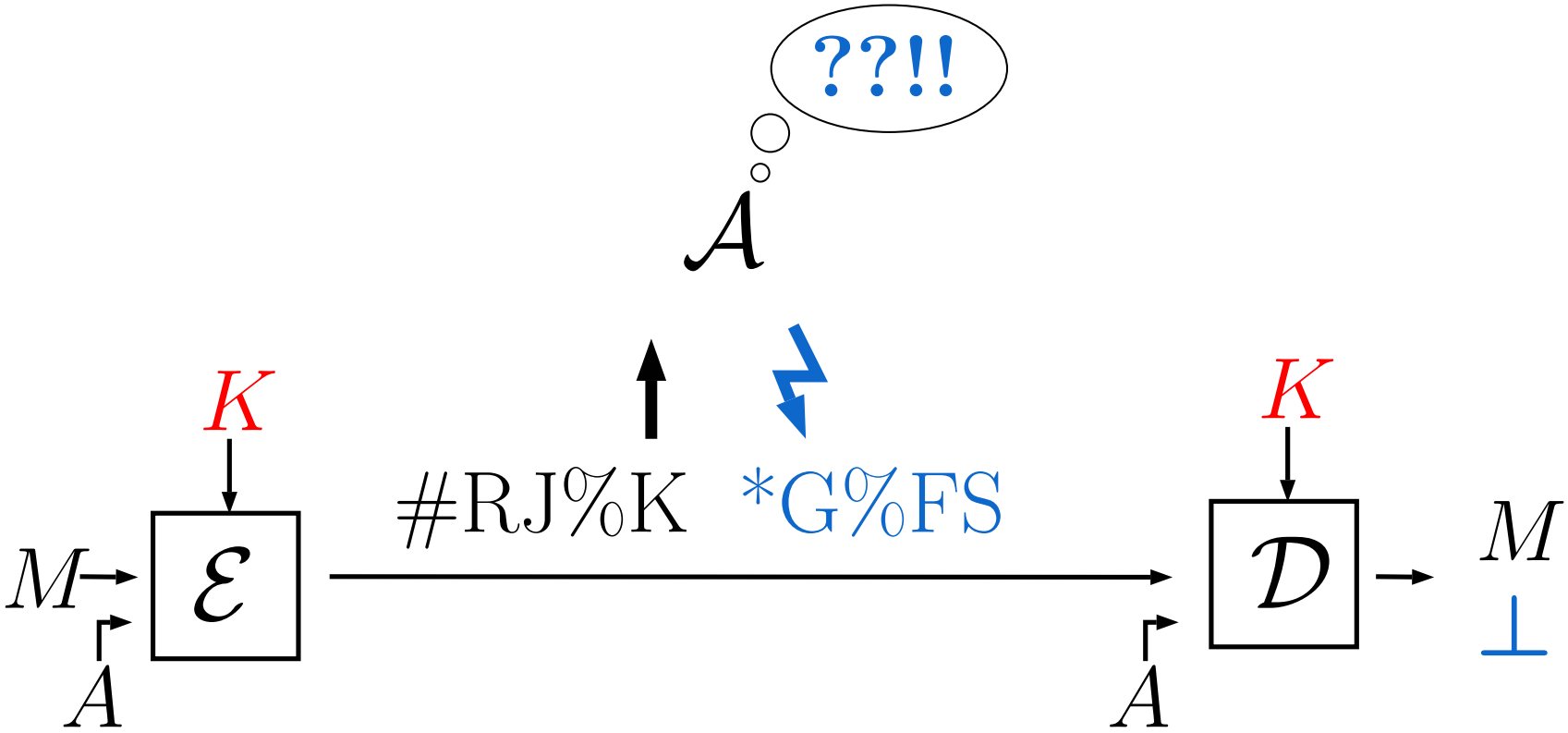
Authenticated Encryption



- **Confidentiality+Authenticity/Integrity for M**

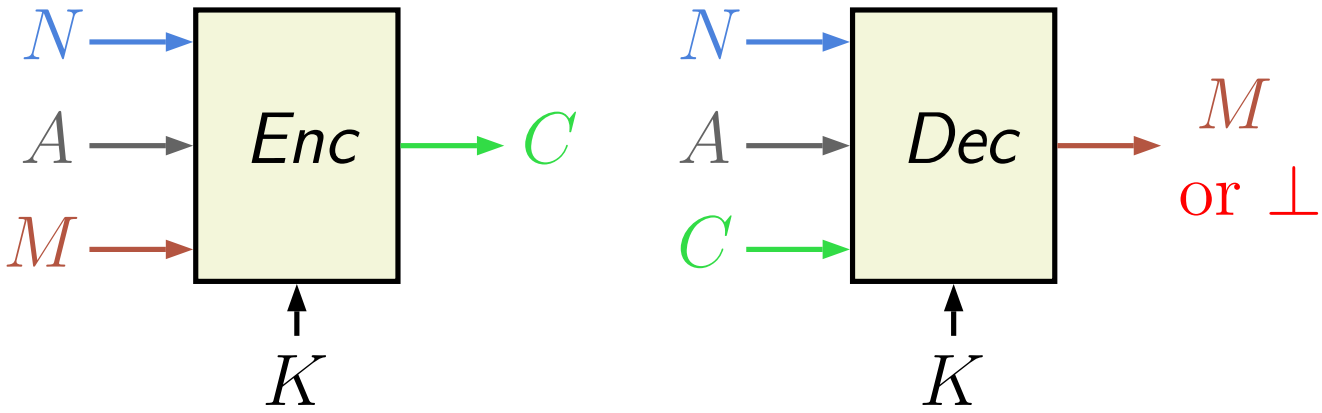
  [Bellare,Namprempre 00],[Katz,Yung 00]

- **Authenticity for A**

  [Rogaway 02]

Nonce-based AE with Associated Data (AEAD)

[Rogaway 02]



- *Enc*, *Dec*: deterministic algorithms
- *N*: Nonce, must not repeat
- *A*: Associated Data, must be authenticated, but not encrypted
- *M*: Plaintext, must be encrypted and authenticated
- *C*: Ciphertext
- *K*: Secret key

- for all K, N, A, M: $Dec(K, N, A, Enc(K, N, A, M)) = M$

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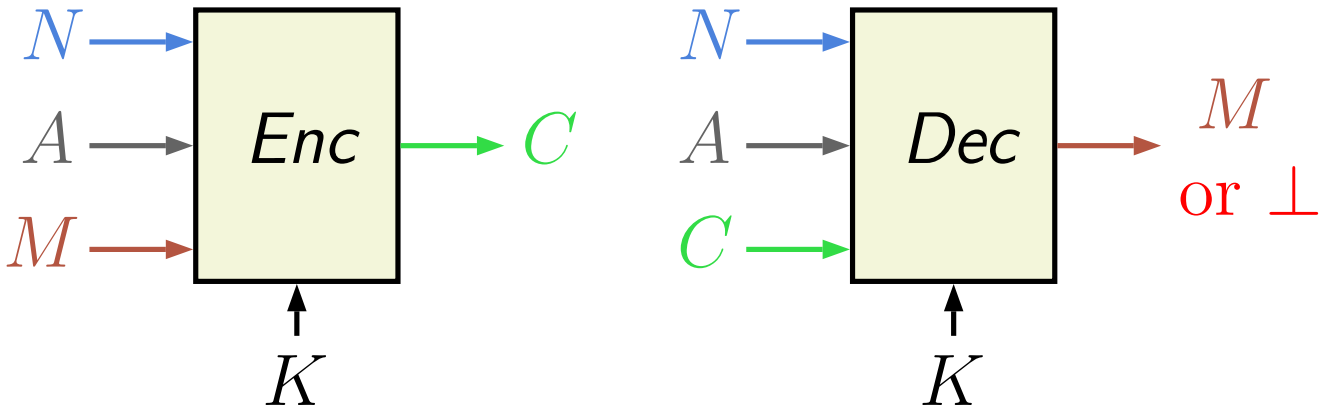

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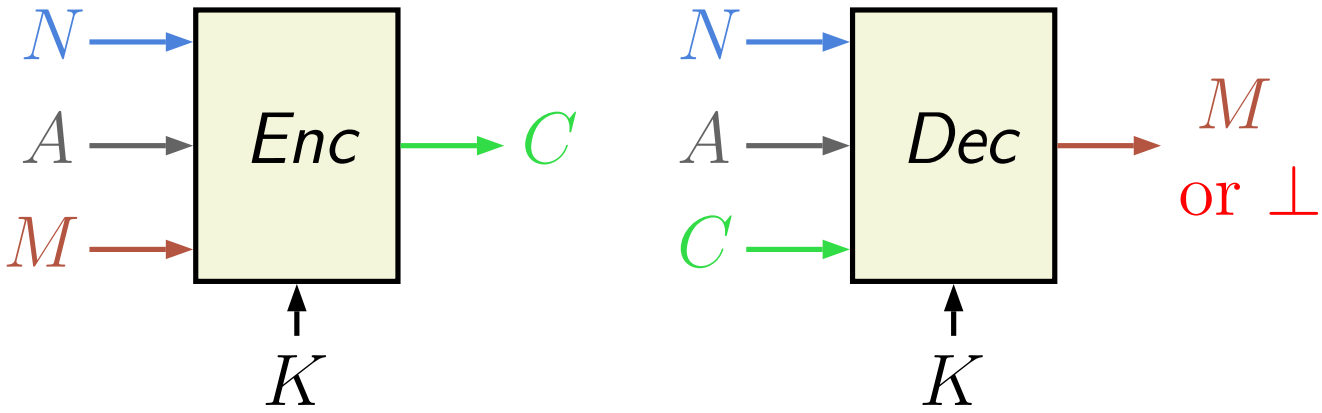

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  - Problems, possibly complete failure
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  - **OAE** [Fleischmann, Forler, Lucks 12]
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- **Stretch misuse:** Varying "tag-length"

Stretch-Misuse

- Ciphertext expansion (a.k.a. stretch)
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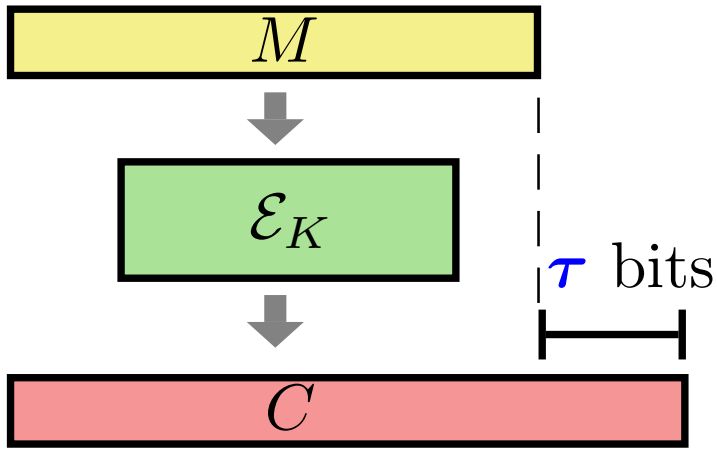
- A constant parameter
- Expected cost of forgery: $\approx \mathbf{2}^{\tau}$ decryption queries



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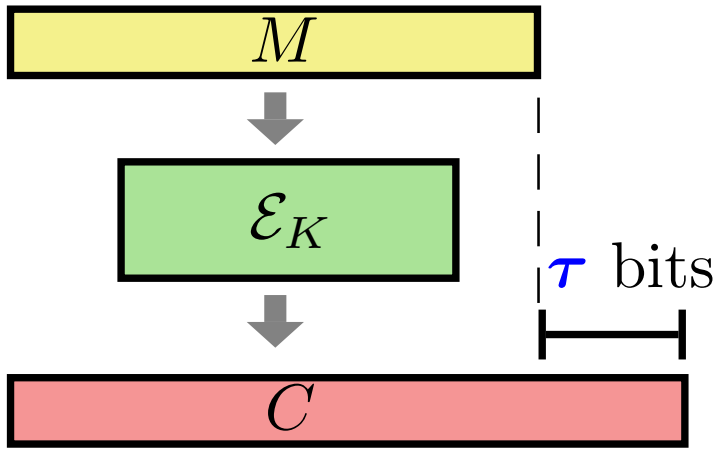

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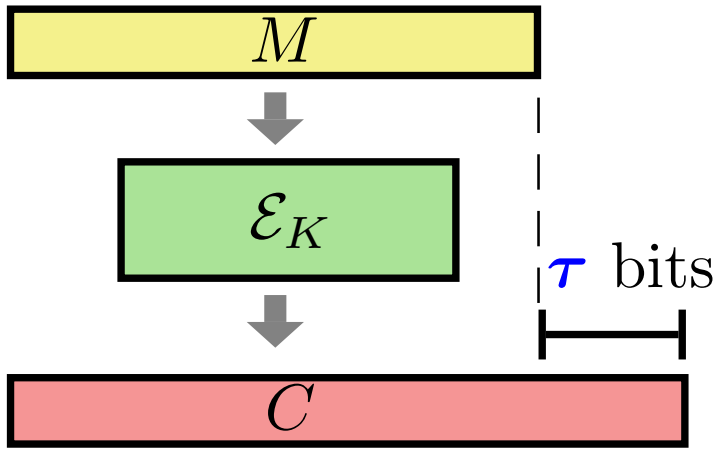

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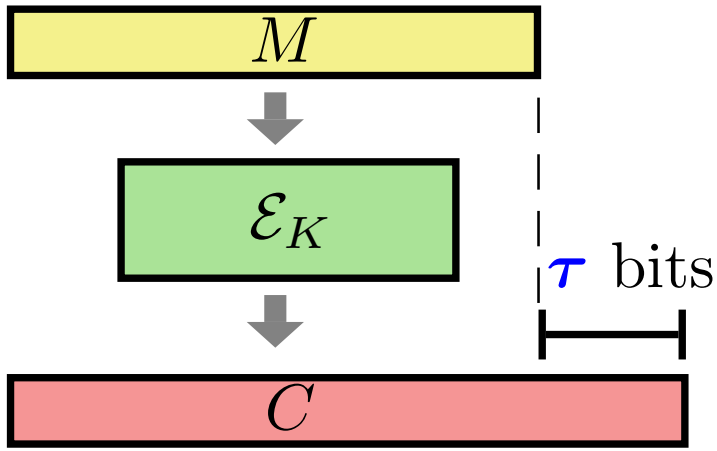

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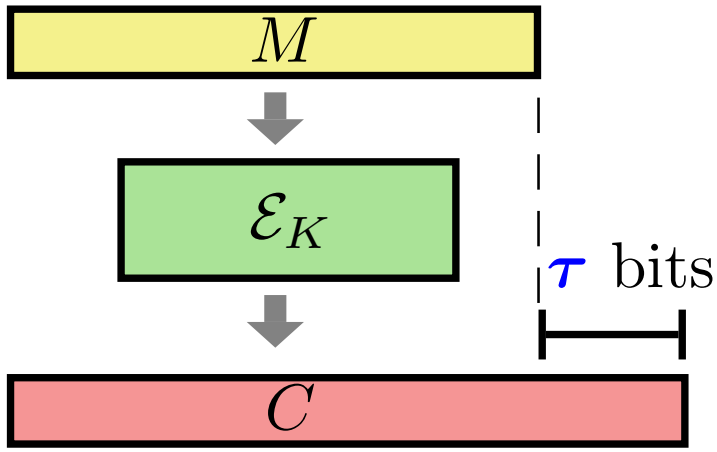


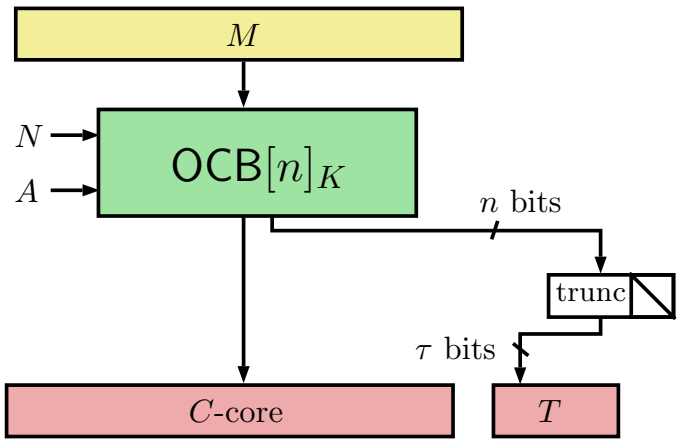
Stretch misuse: varying stretch with the same key

- **It can be attractive:** "sliding scale authenticity" for same K
- **It is easy to implement:** truncated tags
- **It impacts security**
  - "Attacks" that violate the intuitive security

Trivial Tag Length-Variation Attack on AEAD

[Manger 13, CFRG discussion]

Tag computation in OCB (and others): compute tag of n bits, then truncate



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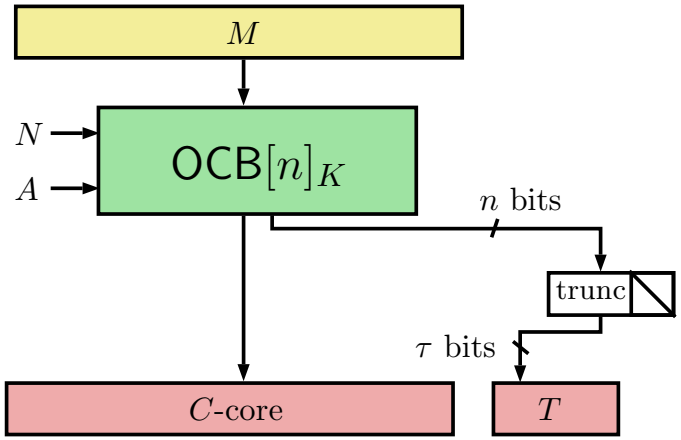

1. Query $C \| T \leftarrow \mathrm{OCB}[128]_K(N, A, M)$ for target (N, A, M)
2. Compute $T' \leftarrow \mathrm{trunc}_{64}(T)$
3. "Forge" $C \| T' \leftarrow \mathrm{OCB}[64]_K^{-1}(N, A, C \| T')$

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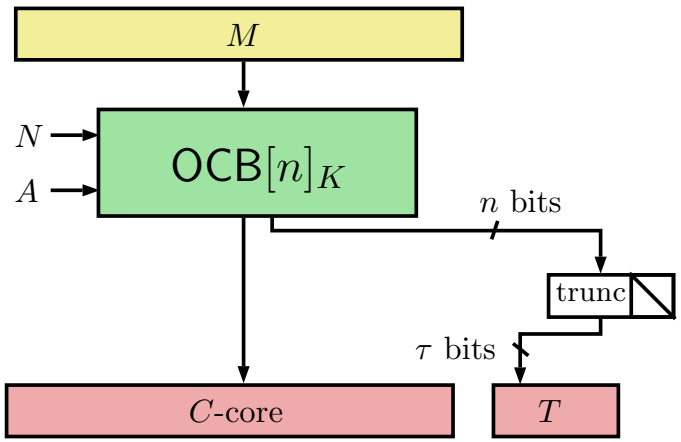

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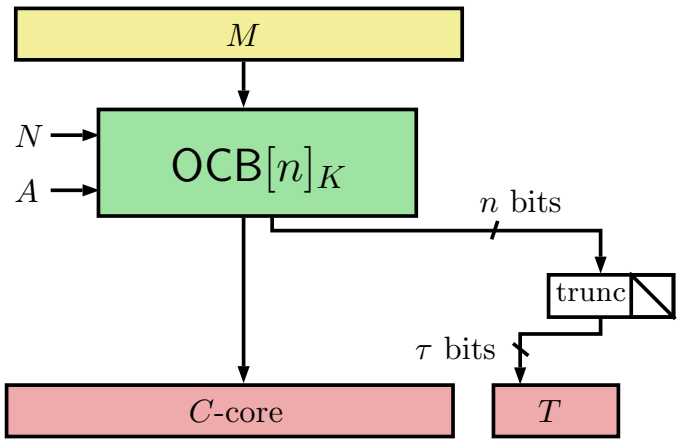

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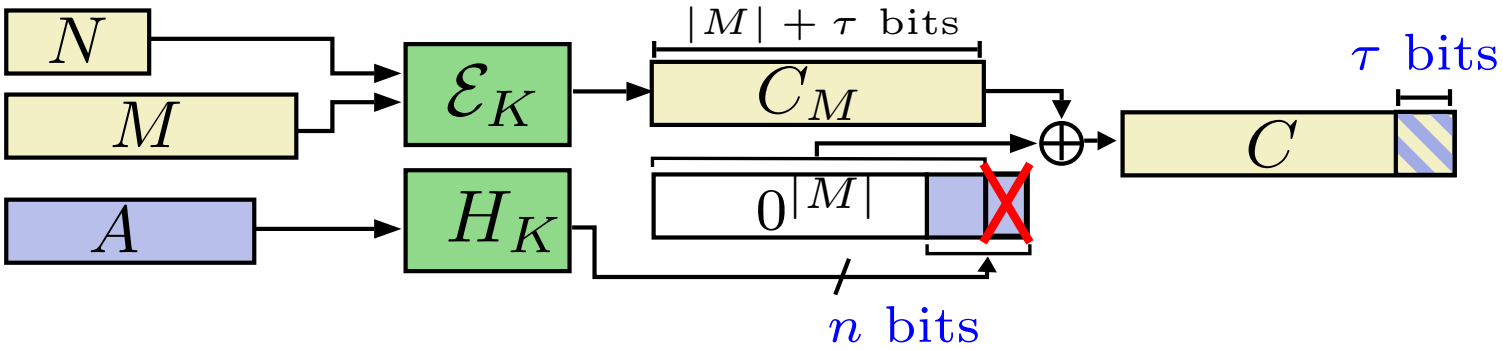
Heuristic countermeasures proposed
(OCB, OMD, OTR, CLOC&SILC)

Gradual Forgery for Ciphertext Translation

Original attack on OMD [Dobraunig, Eichlseder, Mendel, Schläffer 14]

Message-only core + AD-"hash" (H_K can be AXU)



Key property: $Enc(K, N, A, M) \oplus Enc(K, N, A^*, M) = \mathrm{trunc}_\tau(H_K(A) \oplus H_K(A^*))$

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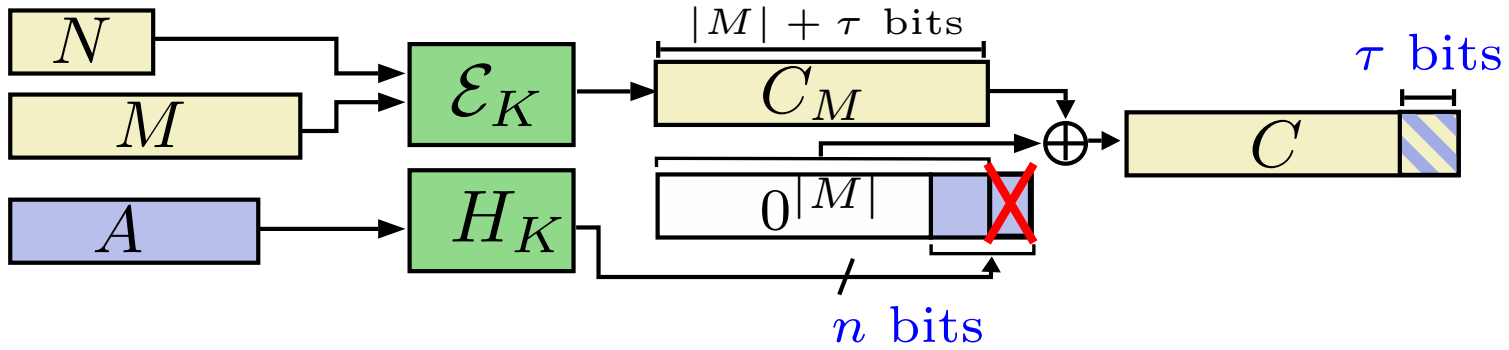

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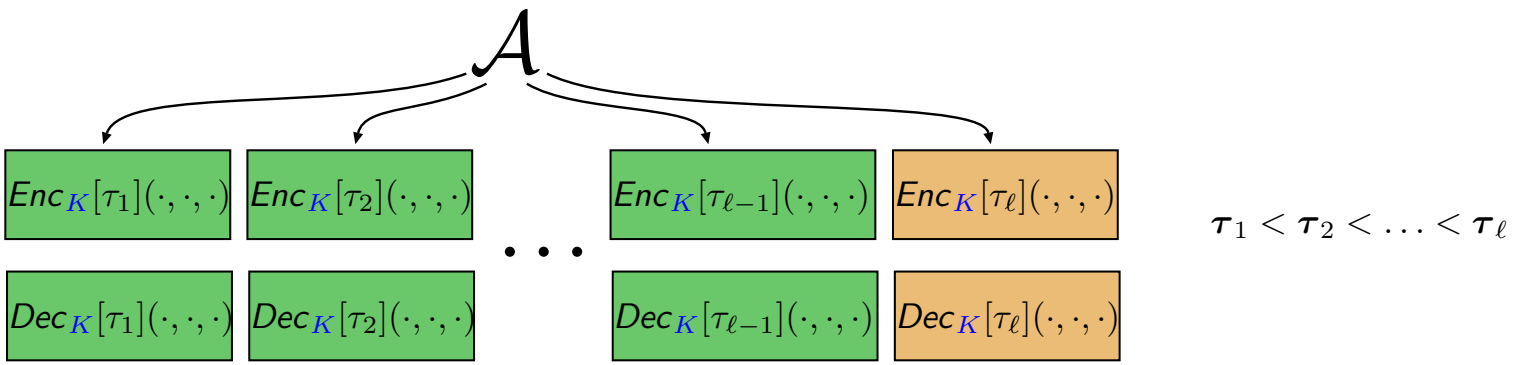
Attack: forge $Enc(N, A^*, M)$ with τ_ℓ bits of stretch



Gradual Forgery for Ciphertext Translation

Forgery for N, A^*, M with τ_g bits of stretch

1. Pick some $\mathbf{A} \neq \mathbf{A}^*$
2. Get $\mathbf{C}\|\mathbf{T} \leftarrow \mathbf{Enc}[\tau_1](\mathbf{N}, \mathbf{A}, \mathbf{M})$
3. Find $\delta \in \{\mathbf{0},\mathbf{1}\}^{\tau_1}$ s.t. $\mathbf{Dec}[\tau_1](\mathbf{N}, \mathbf{A}^*, \mathbf{C}\|(\mathbf{T} \oplus \delta))$ **succeeds**
4. Set $\mathbf{\Delta_A} \leftarrow \delta$
5. Get $\mathbf{C}\|\mathbf{T} \leftarrow \mathbf{Enc}[\tau_2](\mathbf{N}, \mathbf{A}, \mathbf{M})$
6. Find $\delta \in \{\mathbf{0},\mathbf{1}\}^{\tau_2 - \tau_1}$ s.t. $\mathbf{Dec}[\tau_2](\mathbf{N}, \mathbf{A}^*, \mathbf{C}\|(\mathbf{T} \oplus \mathbf{\Delta_A}\|\delta))$ **succeeds**
7. Set $\mathbf{\Delta_A} \leftarrow \mathbf{\Delta_A}\|\delta$
8. **...**
9. Get $\mathbf{C}\|\mathbf{T} \leftarrow \mathbf{Enc}[\tau_\ell](\mathbf{N}, \mathbf{A}, \mathbf{M})$
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Find first τ_1 bits of $H_K(A) \oplus H_K(A^*)$ | Find next $\tau_2 - \tau_1$ bits of $H_K(A) \oplus H_K(A^*)$ | • • • | Find last $\tau_\ell - \tau_{\ell-1}$ bits of $H_K(A) \oplus H_K(A^*)$

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Applicability

- If **no countermeasures** OR τ **in nonce** $\Rightarrow$ works for **arbitrary** $\mathbf{H_K}$
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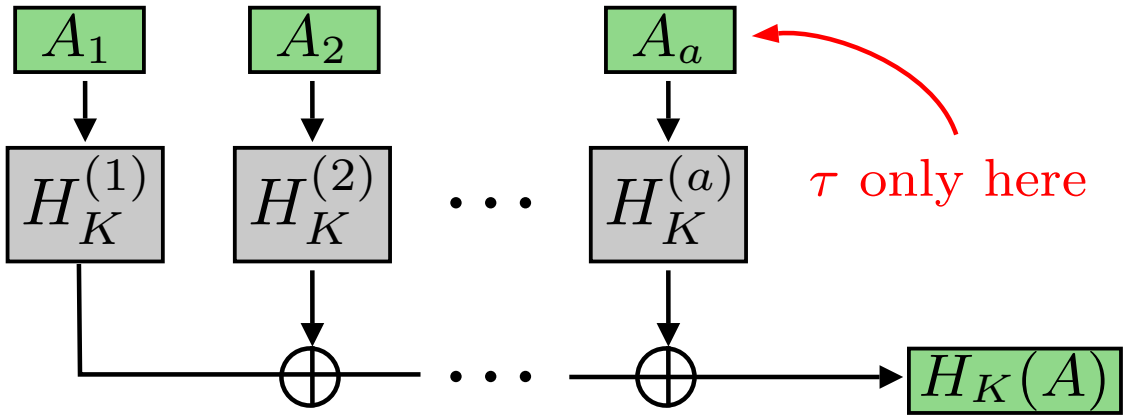

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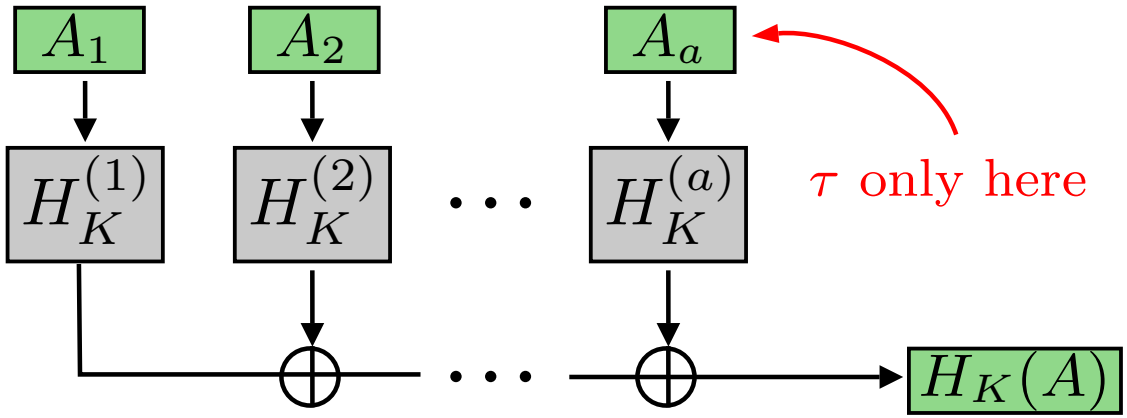
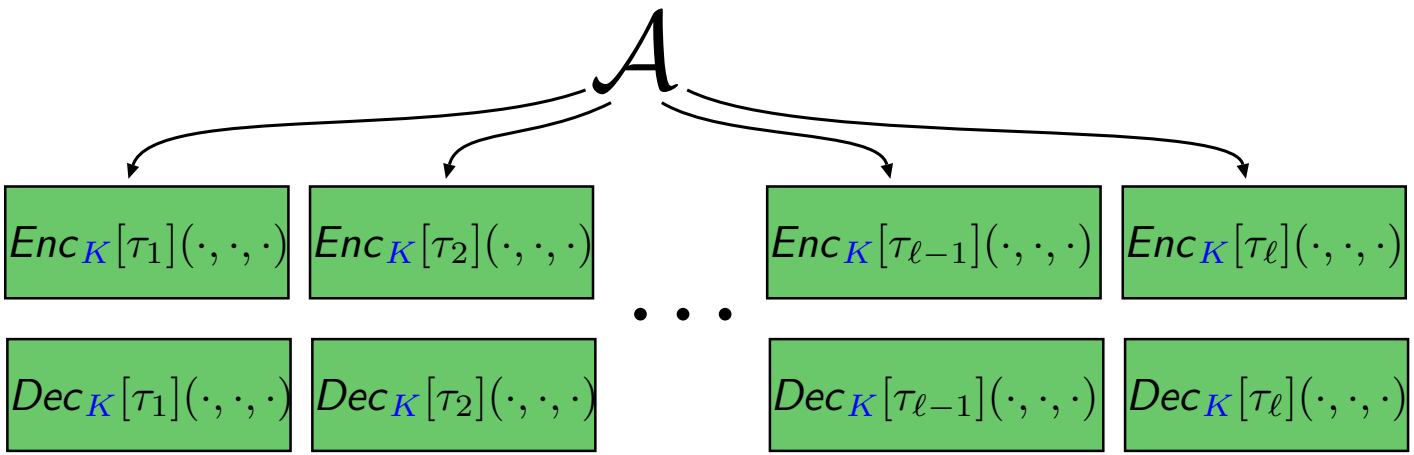


$\Rightarrow$ **Need systematic treatment!**

Capturing AEAD Security with Variable Stretch

- ✓ Define *stretch space* $\mathcal{I}_T = \{\tau_1, \tau_2, \ldots, \tau_\ell\}$
- ✓ Capture the attacks
- ✓ Show interactions between different amounts of stretch
- ✓ Security achievable by efficient, nonce-based schemes



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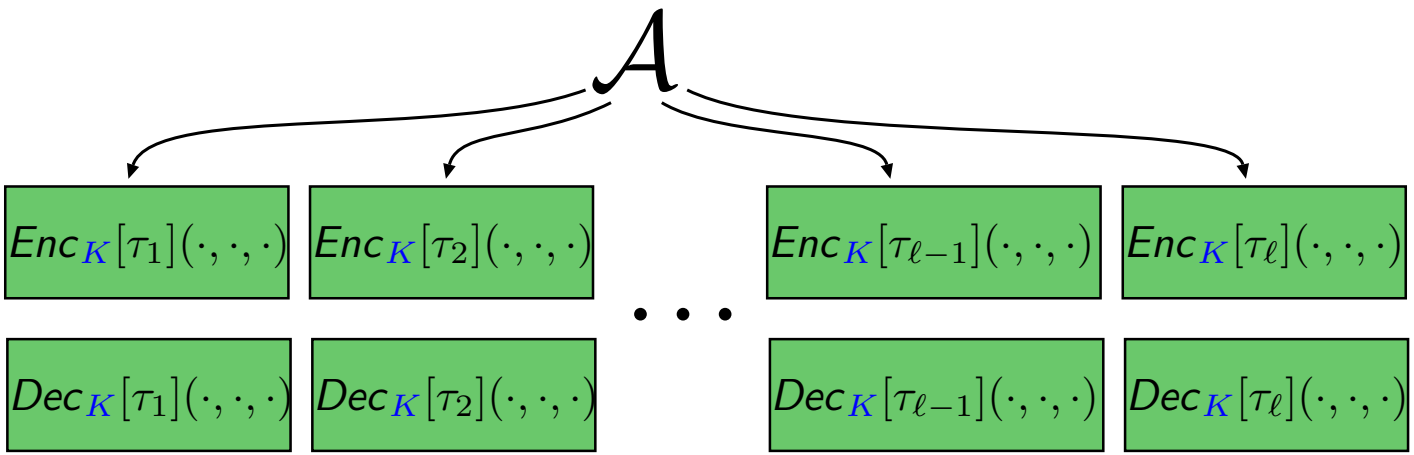
- ? What is the ideal system
- ? How to define advantage function



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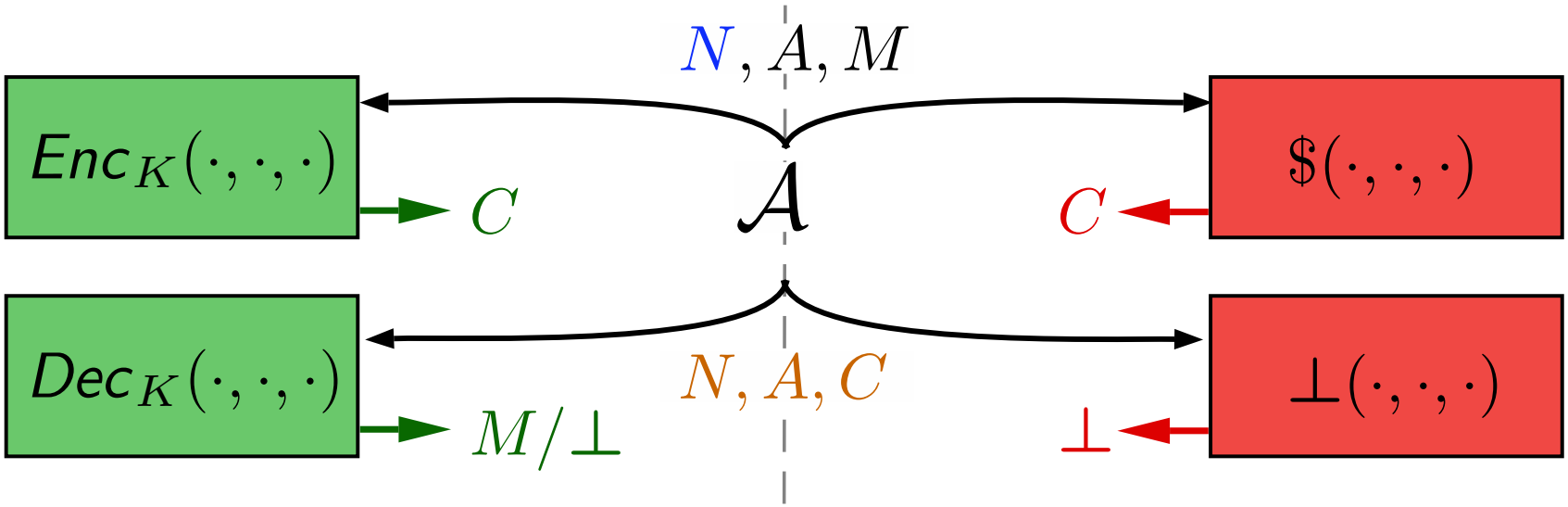

$$\mathbf{Adv}^{aead}_{\Pi}(\mathcal{A}) = \Pr\left[\mathcal{A}^{Enc_K(\cdot,\cdot,\cdot),Dec_K(\cdot,\cdot,\cdot)} \Rightarrow 1\right] - \Pr\left[\mathcal{A}^{\$(\cdot,\cdot,\cdot),\perp(\cdot,\cdot,\cdot)} \Rightarrow 1\right]$$

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[Rogaway 02], [Rogaway, Shrimpton 06]

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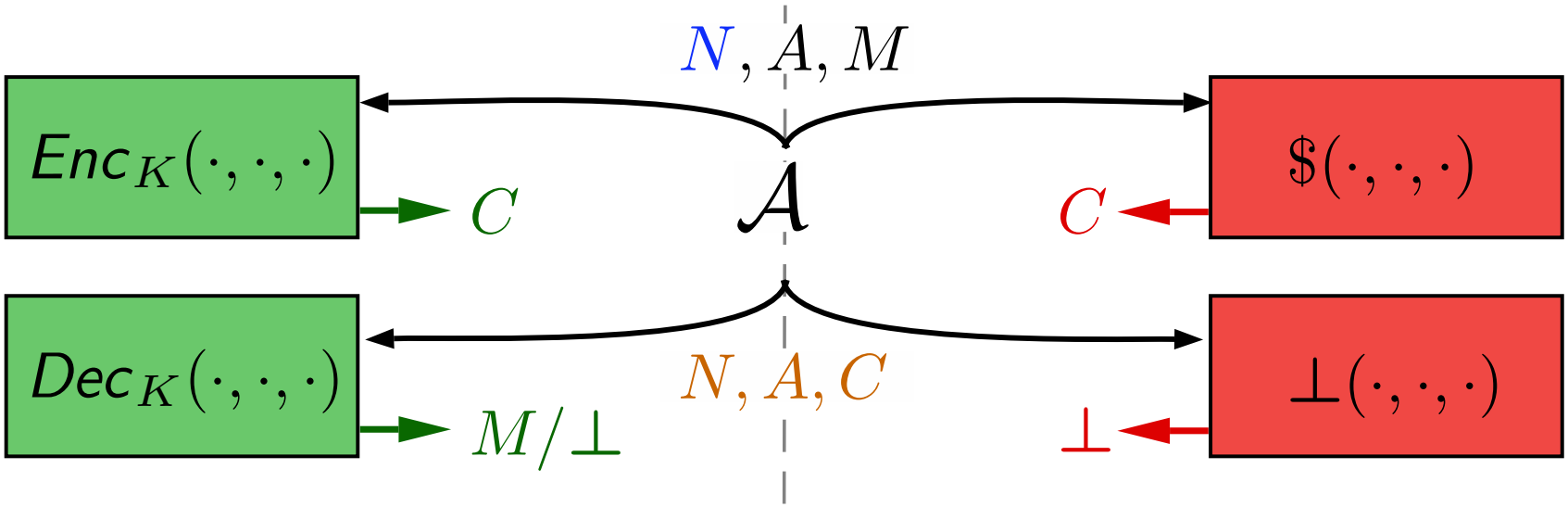
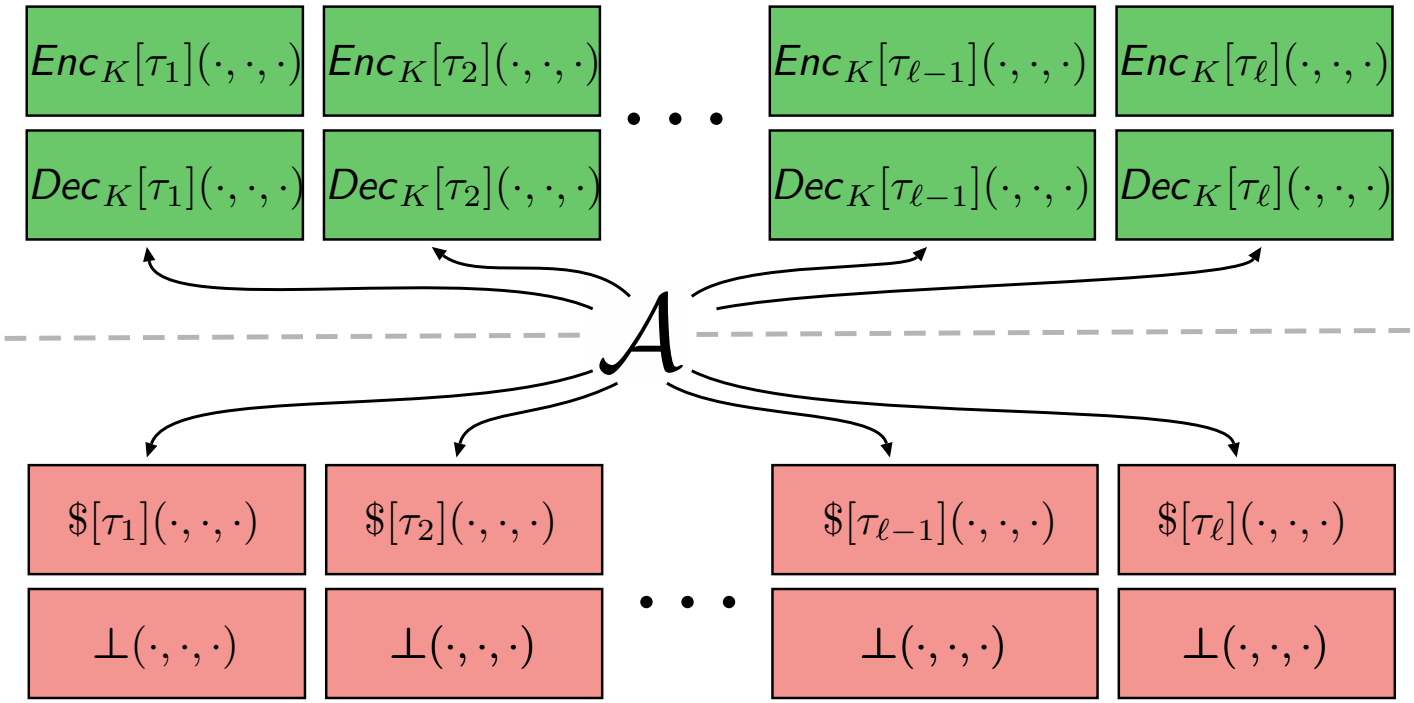


. . . and the ciphertext expansion is assumed to be constant

$$\mathbf{Adv}^{aead}_{\Pi}(\mathcal{A}) = \Pr\left[\mathcal{A}^{Enc_K(\cdot,\cdot,\cdot),Dec_K(\cdot,\cdot,\cdot)} \Rightarrow 1\right] - \Pr\left[\mathcal{A}^{\$(\cdot,\cdot,\cdot),\perp(\cdot,\cdot,\cdot)} \Rightarrow 1\right]$$

(Not) Capturing AEAD Security with Variable Stretch

- $\Pi = (\mathsf{Enc}, \mathsf{Dec}, \mathcal{K})$ defined with $\tau \in \mathcal{I}_T = \{\tau_1, \tau_2, \ldots, \tau_\ell\}$
- Distinguishing **all** instances: not capturing intuition

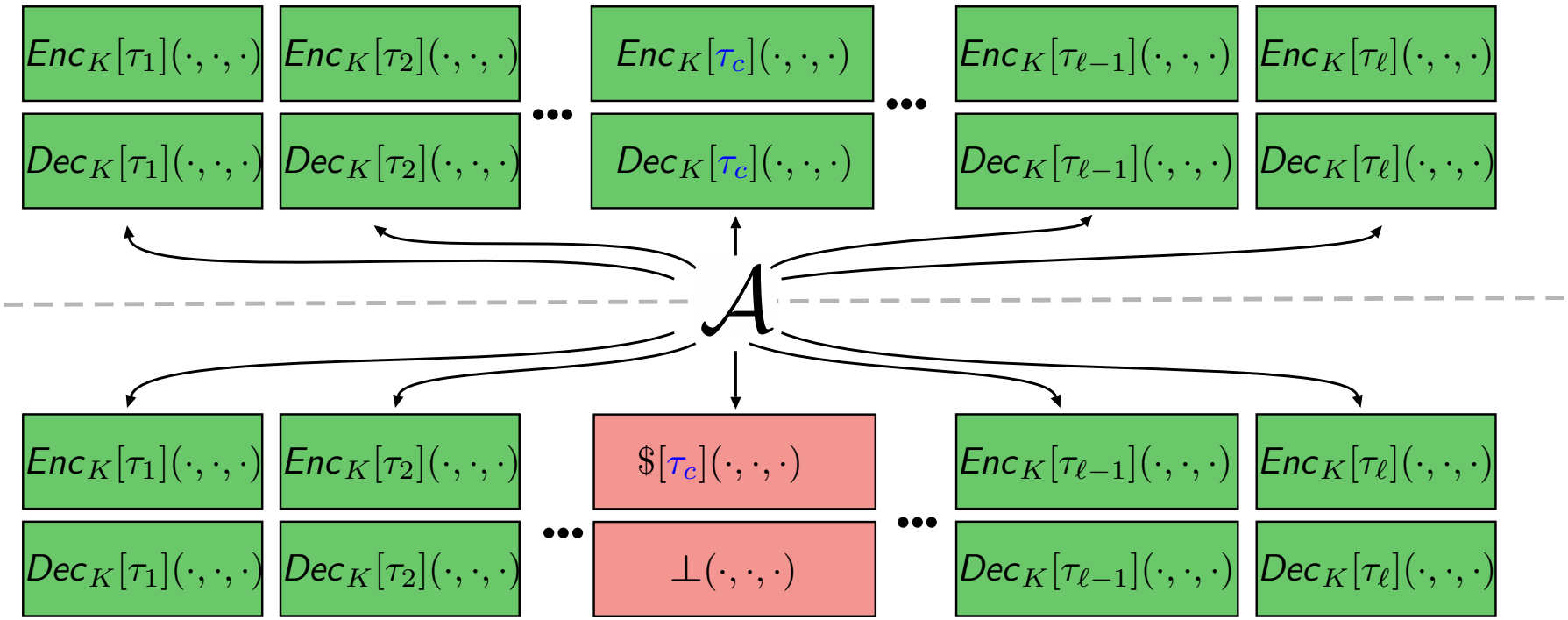


- **$\mathcal{A}$ can trivially win with $2^{\min \mathcal{I}_T}$ queries**
- **Other problems (All-in-one $\not\Leftrightarrow$ priv+auth)**

AEAD Security with Variable Stretch: $nvae(\tau_c)$

fixed but arbitrary "challenge" stretch $\tau_c \in \mathcal{I}_T = \{\tau_1, \tau_2, \ldots, \tau_\ell\}$:

- Unique (nonce,stretch) pairs
- Only non-trivial forgeries stretched by τ_c bits



$$\mathbf{Adv}_{\Pi}^{nvae(\tau_c)}(\mathcal{A}) = \Pr\left[\mathcal{A}^{\text{top system}} \Rightarrow 1\right] - \Pr\left[\mathcal{A}^{\text{lower system}} \Rightarrow 1\right]$$

Interpreting $nvae(\tau_c)$

Exact security level for queries stretched by τ_c

- Captures interactions with queries stretched by $\tau \neq \tau_c$ thanks to focusing on τ_c
- A proven bound applies to *every* $\tau_c \in \mathcal{I}_T$

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Expected advantage

$$\mathbf{Adv}_{\Pi}^{nvae(\tau_c)} \leq \text{“small”} + c \cdot (q_{d(\tau_c)}/2^{\tau_c})^{\alpha}$$

- $c \cdot (q_{d(\tau_c)}/2^{\tau_c})^{\alpha}$ related to forging with τ_c bits of stretch
- “small” due to construction, should only depend on on total resources

E.g. “small”$= \mathbf{Adv}_{\mathsf{B}}^{prp}(t, \sigma) + \sigma^2/2^n$ with B an n-bit blockcipher and $c = \alpha = 1$.

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Does not say small stretch is secure!

- Advantage always big for small τ_c

Capturing the attacks

Resources and advantage for stretch-variation forgery attacks

	Truncation	Gradual*
q_e	1	$\ell - 1$
q_d	0	$2^{\tau_2} + \sum_{i=1}^{\ell-1} 2^{\tau_i - \tau_{i-1}}$
$q_{e(\tau_c)}$	0	1
$q_{d(\tau_c)}$	1	$2^{\tau_c - \tau_{\ell-1}}$
Adv	1	1
Expected Adv	$1/2^{\tau_c}$	$2^{\tau_\ell - \tau_{\ell-1}}/2^{\tau_c}$

*where $\tau_1 < \tau_2 < \ldots < \tau_{\ell-1} < \tau_c$

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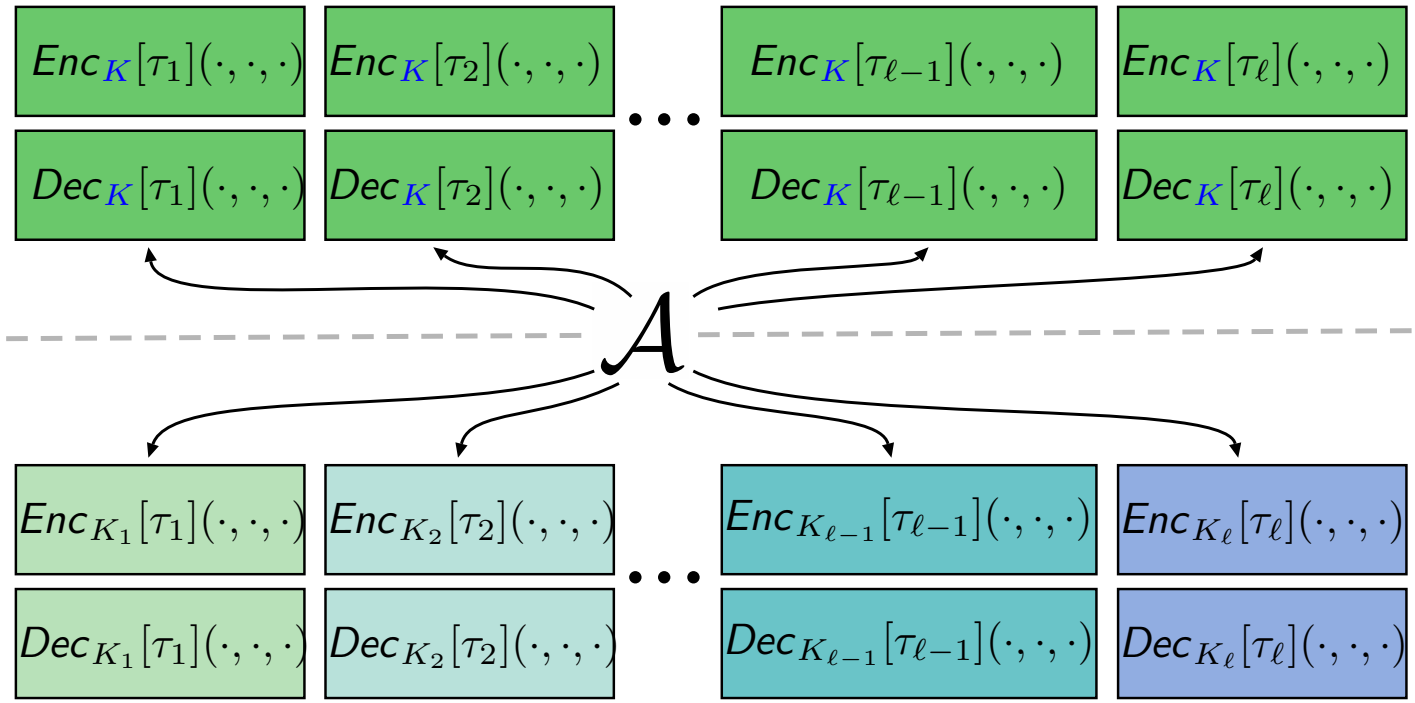
Example: $\{\tau_1, \tau_2, \tau_3, \tau_c\} = \{32, 64, 96, 128\}$

- 2^{32} decryption queries stretched by 2^{128}
- advantage 1 (compared to expected adv. $2^{32-128} = 2^{-96}$)

Achieving nvAE Modularly

Key-Equivalent Separation by Stretch

- Working with stretch space $\mathcal{I}_T = \{\tau_1, \tau_2, \ldots, \tau_\ell\}$
- Encryptions with fresh nonces per stretch



$$\mathbf{Adv}^{\mathit{kess}}_{\Pi}(\mathcal{A}) = \Pr\left[\mathcal{A}^{\text{top system}} \Rightarrow 1\right] - \Pr\left[\mathcal{A}^{\text{lower system}} \Rightarrow 1\right]$$

Achieving nvAE Modularly

Key-Equivalent Separation by Stretch

Low kess advantage $\neq$ AE security, but for any AEAD scheme Π with stretch space $\mathcal{I}_T = \{\tau_1, \tau_2, \ldots, \tau_\ell\}$:

$$\mathbf{Adv}_{\Pi}^{nvae(\tau_c)}(t, \mathbf{q_e}, \mathbf{q_d}, \sigma) \leq \mathbf{Adv}_{\Pi}^{kess}(t', \mathbf{q_e}, \mathbf{q_d}, \sigma) + \mathbf{Adv}_{\Pi[\tau_c]}^{aead}(t'', q_e^{\tau_c}, q_d^{\tau_c}, \sigma^{\tau_c})$$

where $\Pi[\tau_c]$ is Π used with τ_c-bit stretch, and

- $\mathbf{q_e}$ the encryption query complexities $(q_e^\tau | \tau \in \mathcal{I}_T)$
- $\mathbf{q_d}$ the decryption query complexities $(q_d^\tau | \tau \in \mathcal{I}_T)$
- σ the data complexities $(\sigma^\tau | \tau \in \mathcal{I}_T)$

- **Easier analysis if AEAD security already established!**

Achieving nvAE Security

Proof of concept: vOCB

OCB modified to be nvAE secure

- Add τ as tweak component **in all tweaks**
- Modified XEX construction
- Should not harm efficiency
- Analysis: only kess security (easy with TBC!)

$$\mathbf{Adv}^{nvae(\tau_c)}_{\mathrm{vOCB}[E]}(t, \mathbf{q_e}, \mathbf{q_d}, \sigma) \leq (|\mathcal{I}_T| + 2) \cdot \mathbf{Adv}^{\pm prp}_{E}(t', 2q) + \frac{28.5q^2}{2^n} + q_d^{\tau_c} \cdot \frac{2^{n-\tau_c}}{2^n - 1}$$

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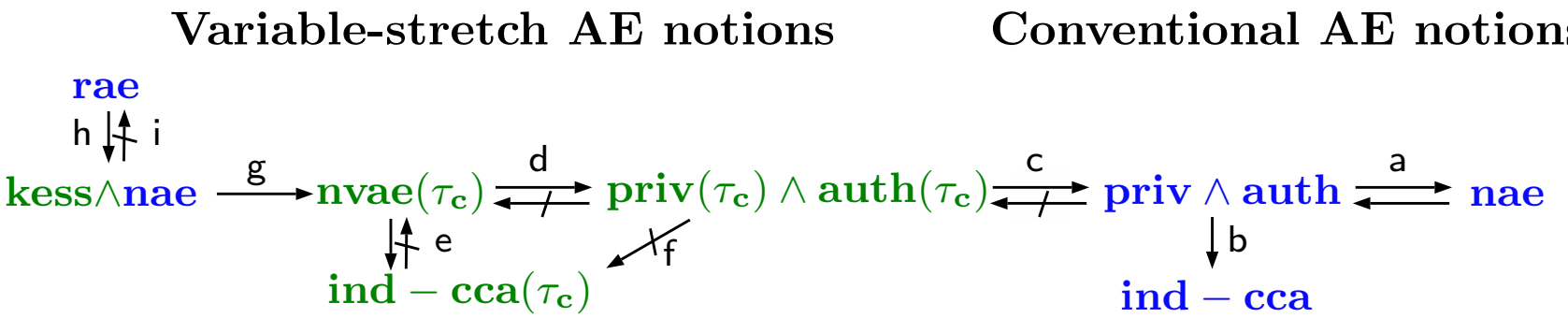
Beyond proof of concept:

- Applicable to all AE schemes based on tweakable primitives
- Can treat OTR, Deoxys etc.

Conclusions

- We define security of nonce-based AEAD with variable stretch ☺
- We determine relations with existing notions ☺



- We show that nvAE security can be achieved and that schemes based on tweakable primitives are easily patched ☺
- Other schemes? ☹ **Generic transformation: open problem**

Thank you!

Postdocs-to-be mailto:**job_lasec@epfl.ch**

$nvae(\tau_c)$: Adversarial Resources

Default resources:

- Time t
- For **every** value of stretch $\tau \in \mathcal{I}_T$ watch:
  - Number of encryption queries q_e^τ
  - Number of decryption queries q_d^τ
  - Amount of data σ^τ

Fine granularity, generality

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Fine granularity, generality

Coarser granularity best in most cases:

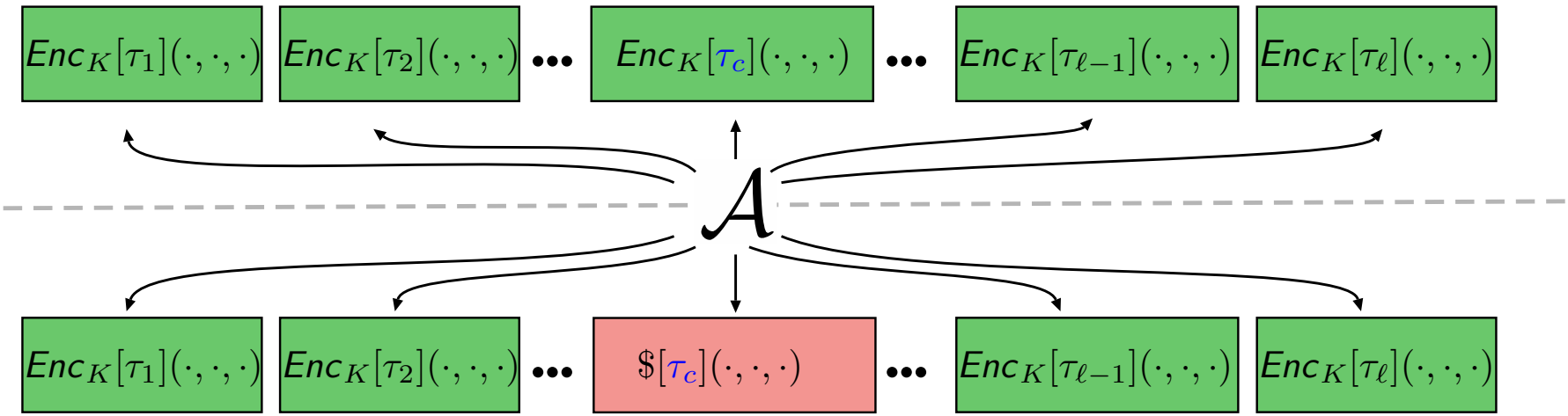
- Total number of encryptions $q_e = \sum_{\tau \in \mathcal{I}_T} q_e^\tau$
- Total number of decryptions $q_d = \sum_{\tau \in \mathcal{I}_T} q_d \tau$
- Total amount of data $\sigma = \sum_{\tau \in \mathcal{I}_T} \sigma_d \tau$
- Keep $q_e^{\tau_c}, q_d^{\tau_c}, \sigma^{\tau_c}$ apart

AEAD Security with Variable Stretch

Priv + Auth $\not\Leftrightarrow$ All-in-One

fixed but arbitrary "challenge" stretch $\tau_c \in \mathcal{I}_T = \{\tau_1, \tau_2, \ldots, \tau_\ell\}$:

- Unique nonces for (nonce,stretch) pairs



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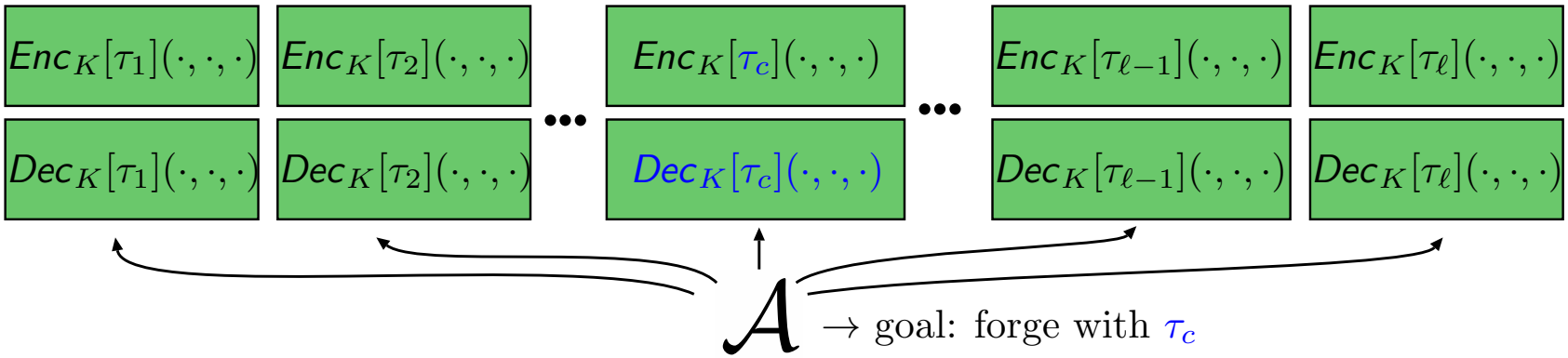

$$\mathbf{Adv}_{\Pi}^{auth(\tau_c)}(\mathcal{A}) = \Pr\left[\mathcal{A}^{\text{the system}} \text{ forges }\right]$$

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We have

$$nvae(\tau_c) \Rightarrow priv(\tau_c) \quad \text{and} \quad nvae(\tau_c) \Rightarrow auth(\tau_c)$$
$$nvae(\tau_c) \Rightarrow ind-cca(\tau_c)$$

but

$$priv(\tau_c) \wedge auth(\tau_c) \not\Rightarrow nvae(\tau_c)$$
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Decryption queries expanded by $\tau \neq \tau_c$ may leak information about queries expanded by τ_c

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All-in-one AE security $\Leftrightarrow$ privacy+confidentiality [Rogaway, Shrimpton 06]

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Define *ind-cca*(τ_c)**,** *priv*(τ_c) **and** *auth*(τ_c)**:** ▷ similarly as *nvae*(τ_c)

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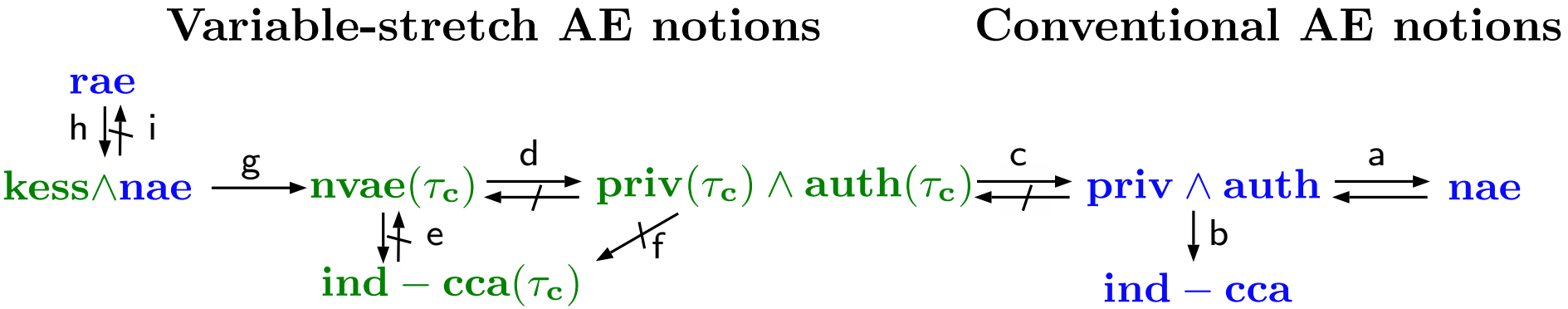
Relations among Notions



Previous works: a [Rogaway, Shrimpton 06] b [Bellare, Namprempre 00]
This work: c, d, e, f, g, h, i

Extending XEX

- Label every $\tau \in \mathcal{I}_T$ bijectively with $\lambda : \mathcal{I}_T \to \{0, 1, \ldots, |\mathcal{I}_T| - 1\}$.
- Compute $m = \lceil \log_2 |\mathcal{I}_T| \rceil$ and
  - $L_* = E_K(0^n)$
  - $L_\tau = \lambda(\tau) \cdot 2^2 \cdot L_*$ for $\tau \in \mathcal{I}_T$
  - $L(0) = 2^{2+m} \cdot L_*$
  - $L(\ell) = 2 \cdot L(\ell - 1)$ for $\ell > 0$.
- Compute Δ-values:

$$
\begin{aligned}
&\Delta_{N,0,0,0} = H(K, N),\\
&\Delta_{N,\tau,0,0} = \Delta_{N,0,0,0} \oplus L_\tau,\\
&\Delta_{N,\tau,i+1,0} = \Delta_{N,\tau,i,0} \oplus L(\mathrm{ntz}(i+1)) \text{ for } i \geq 0,\\
&\Delta_{N,\tau,i,j} = \Delta_{N,\tau,i,0} \oplus j \cdot L_* \text{ for } j \in \{0, 1, 2, 3\},\\
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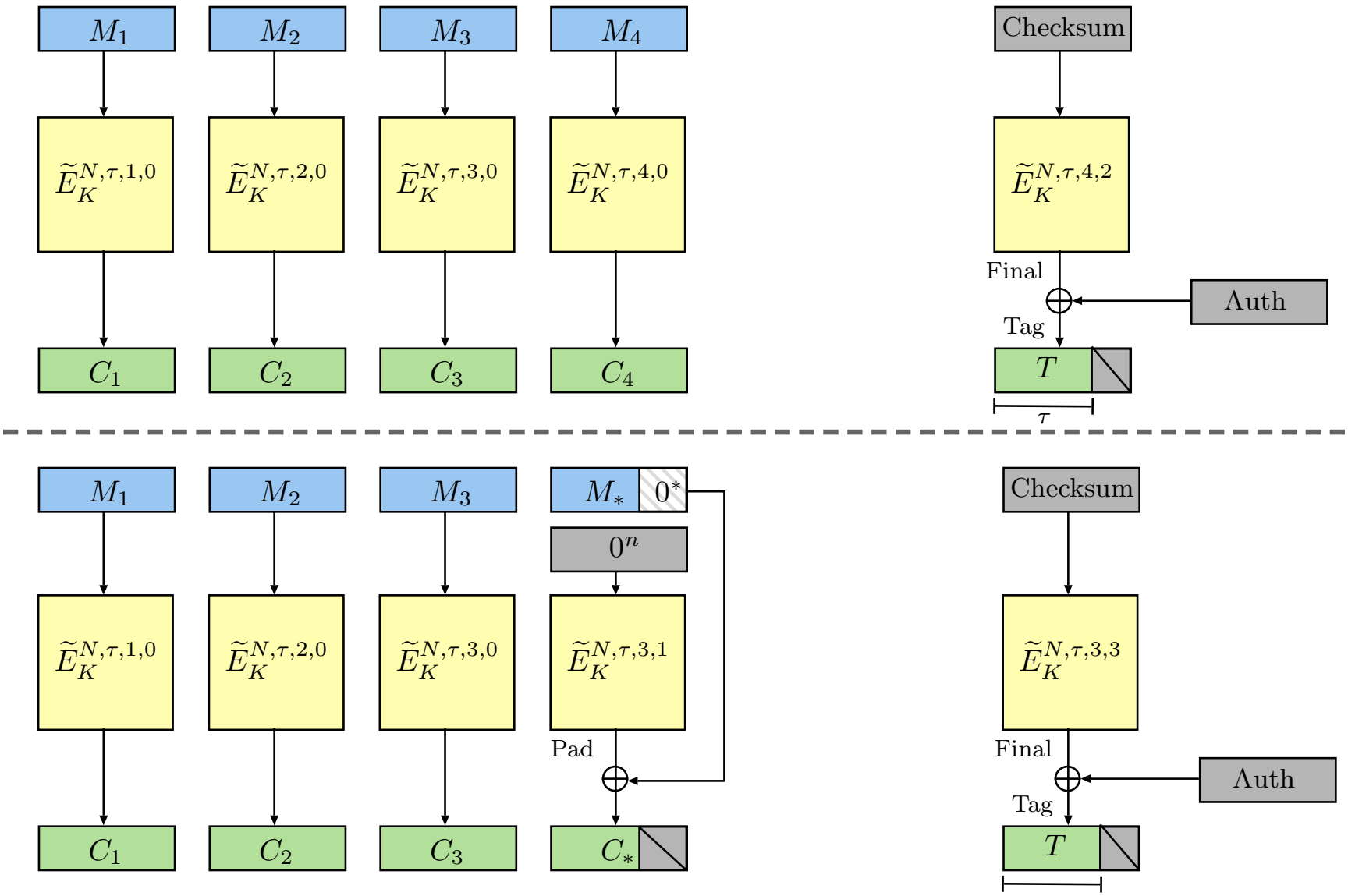
\end{aligned}
$$

A call to $\widetilde{E}$ is evaluated as follows:

$$\widetilde{E}_K^{N,\tau,i,j}(X) = E_K(X \oplus \Delta_{N,\tau,i,j}) \oplus \Delta_{N,\tau,i,j}, \quad \text{or} \quad \widetilde{E}_K^{\tau,i,j}(X) = E_K(X \oplus \Delta_{\tau,i,j}).$$

Achieving nvAE security

vΘCB



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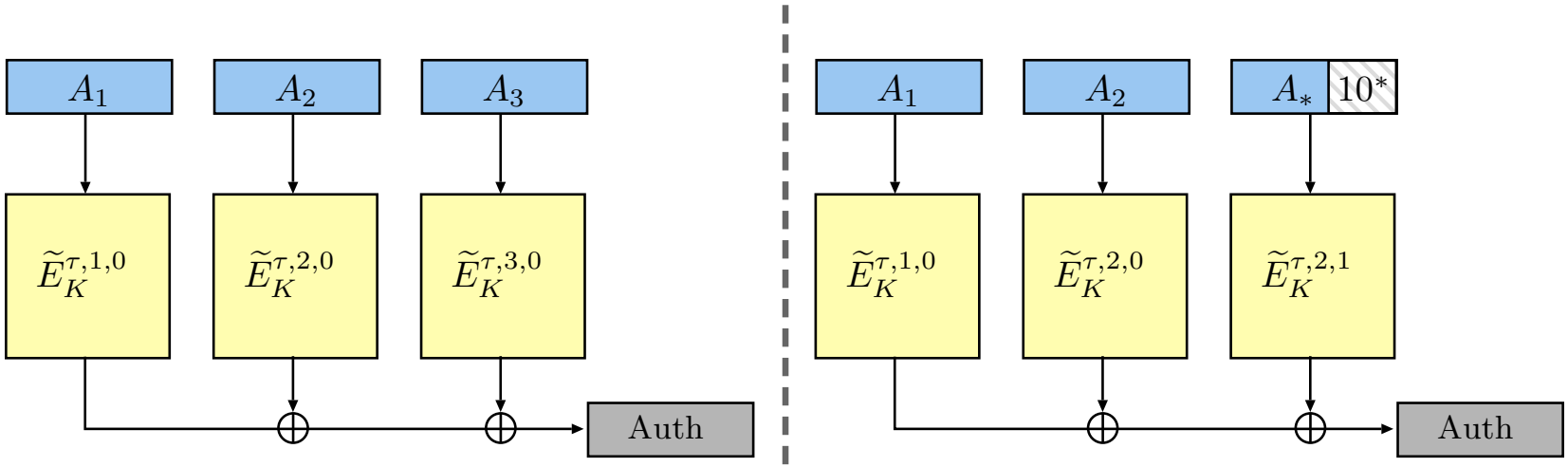

With a suitable tweakable blockcipher $\widetilde{E}$

- With modified XEX (small impact on performance):

$$\mathbf{Adv}^{nvae(\tau_c)}_{\mathrm{vOCB}[E]}(t, \mathbf{q_e}, \mathbf{q_d}, \sigma) \leq (|\mathcal{I}_T| + 2) \cdot \mathbf{Adv}^{\pm prp}_{E}(t', 2q) + \frac{28.5q^2}{2^n} + q_d^{\tau_c} \cdot \frac{2^{n-\tau_c}}{2^n - 1}$$

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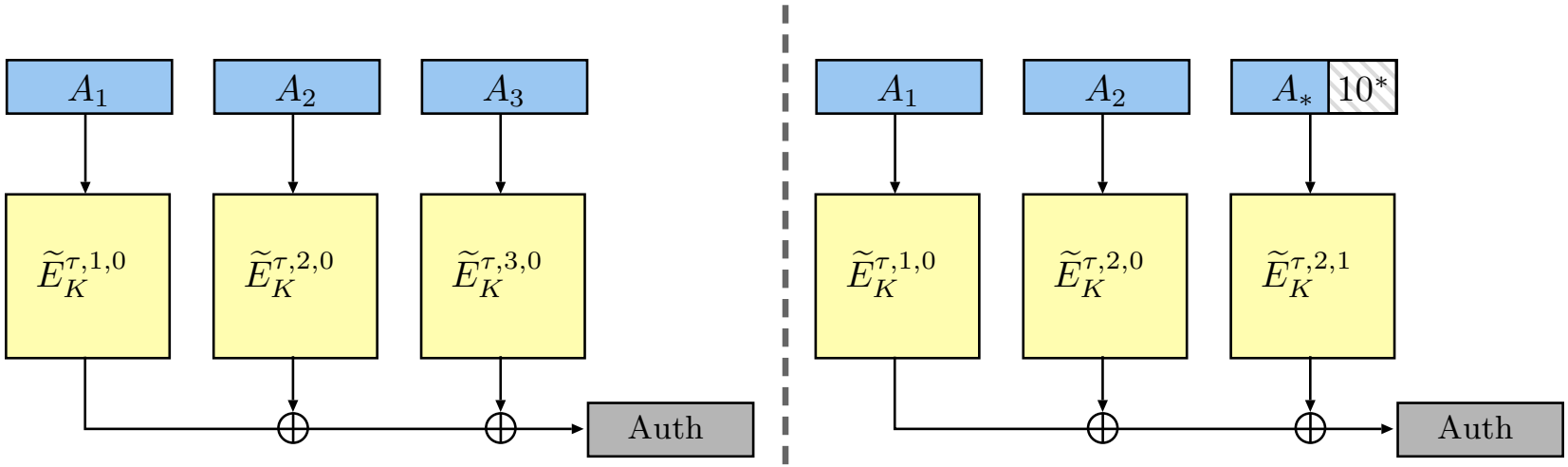

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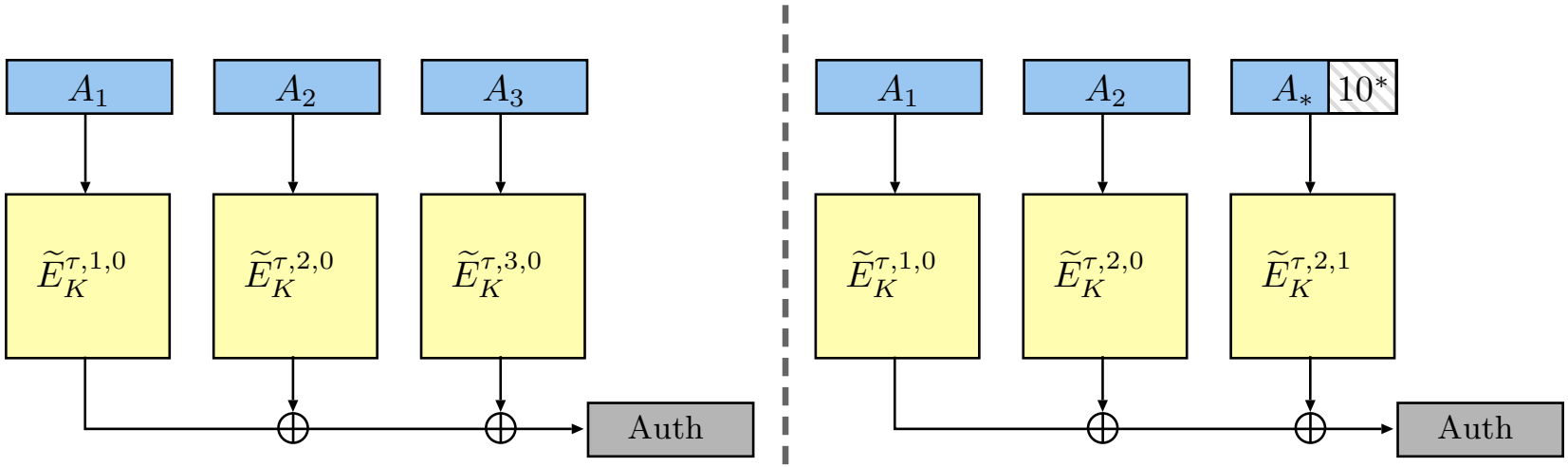

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