# Counter-in-Tweak: Authenticated Encryption Modes for Tweakable Block Ciphers

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# Context

- starting point: CAESAR competition for Authenticated Encryption (AE)
- more precisely, candidates Deoxys, Joltik and KIASU (Jean, Nikolic, Peyrin)
- each is based on a tweakable block cipher (Deoxys-BC, Joltik-BC, or KIASU-BC) and two modes of operation:
  - ΘCB for the nonce-respecting setting
  - COPA for the nonce-misuse setting
- problems with COPA:
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  - for fractional messages, relied on XLS which has been broken [Nan14]

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# Our Goal

- in replacement of COPA, design an AE mode of operation for tweakable block ciphers which provides:
  1. (full, not online) nonce-misuse resistance up to the birthday bound
  2. beyond-birthday-bound (BBB) security in the nonce-respecting setting
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  - ΘCB [KR11] is perfectly secure in the nonce-respecting scenario, but not secure at all in the nonce-misuse scenario
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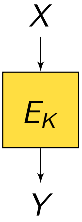


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- $T$ assumed public or even adversarially controlled
- each tweak should give an "independent" permutation
- few "natively tweakable" BCs:
  - Hasty Pudding Cipher [Sch98]
  - Mercy [Cro00]
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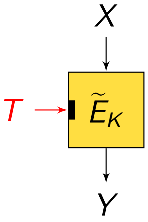


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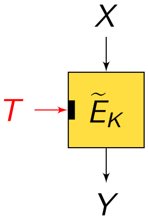


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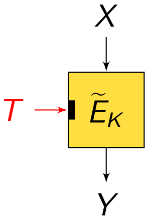


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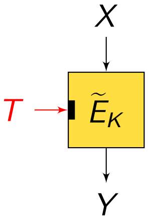


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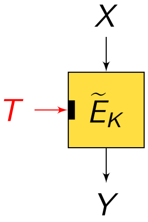


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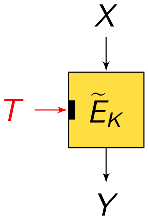


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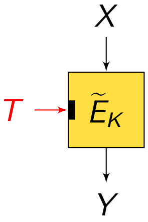


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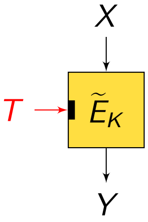


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# Goal: Nonce-Based Authenticated Encryption (nAE)

## Syntax

A nAE scheme $\Pi$ is a pair of algorithms $(\Pi.\mathrm{Enc}, \Pi.\mathrm{Dec})$ where

- algorithm $\Pi.\mathrm{Enc}$ takes
  - (a key $K$)
  - a nonce $N$
  - associated data $A$
  - a message $M$

  and returns a ciphertext $C$.
- algorithm $\Pi.\mathrm{Dec}$ takes $K$ and $(N, A, C)$ and returns $M$ or $\perp$.

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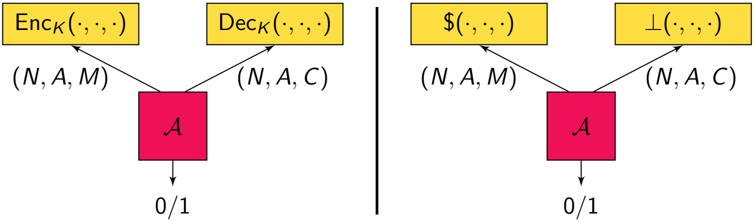


## Security (all-in-one definition)

- The scheme $\Pi$ is secure if adversary $\mathcal{A}$ cannot distinguish $(\mathrm{Enc}_K, \mathrm{Dec}_K)$ and $(\$, \bot)$.
- $\mathcal{A}$ cannot ask a decryption query $(N, A, C)$ if it received $C$ from an encryption query $(N, A, M)$
- $\mathcal{A}$ is said nonce-respecting if it never repeats a nonce in encryption queries.

# Misuse-Resistant AE (MRAE)

## Nonce-misuse resistance (informal) [RS06]

A nAE scheme is said nonce-misuse resistant if repeating a nonce in encryption queries:

- does not harm authenticity
- hurts confidentiality only insofar as repetitions of triplets $(N, A, M)$ are detectable

- $\simeq$ deterministic authenticated encryption
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# Outline

# Generic Composition

Starting from two building blocks:

- a MAC (or a PRF) $F_{K_1}(\cdot, \cdot, \cdot)$
- an encryption scheme $\text{Enc}_{K_2}(\cdot, \cdot)$

combine them to obtain a nAE scheme [BN00, NRS14].

Two types of encryption schemes:

- (random) IV-based encryption (ivE): $C = \text{Enc}_{K_2}(IV, M)$, $IV$ randomly chosen by the encryption oracle (ex: CBC)
- nonce-based encryption (nE): $C = \text{Enc}_{K_2}(N, M)$, $N$ chosen by the adversary but non-repeating (ex: nonce-based CTR mode, GCM)

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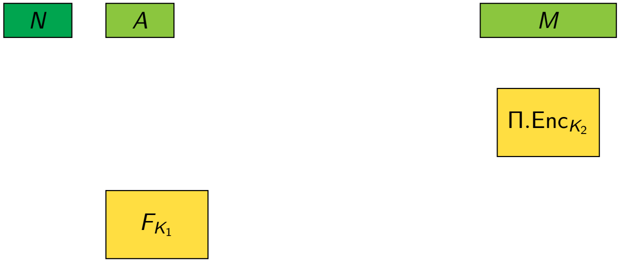


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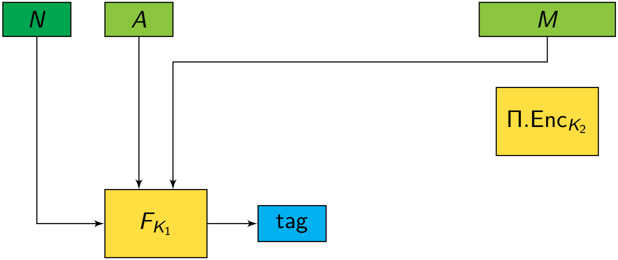


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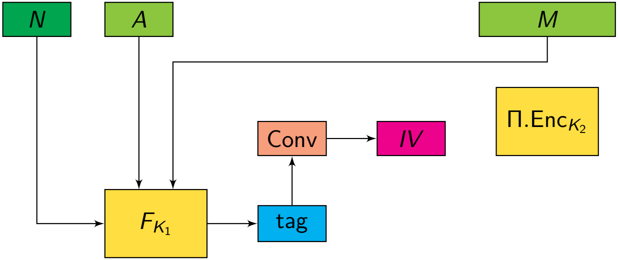


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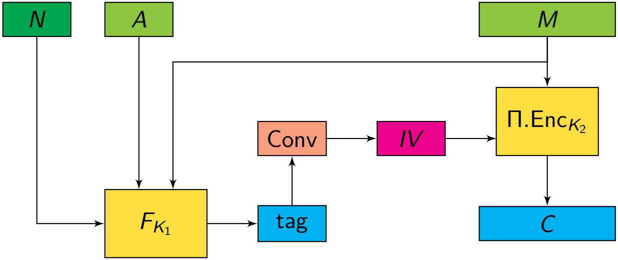


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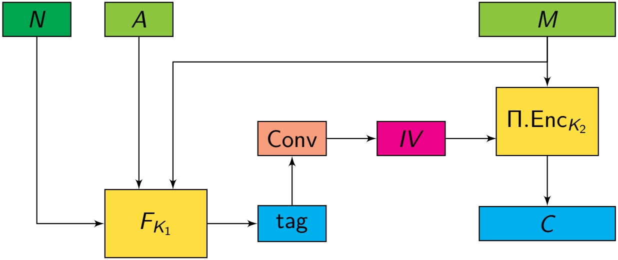


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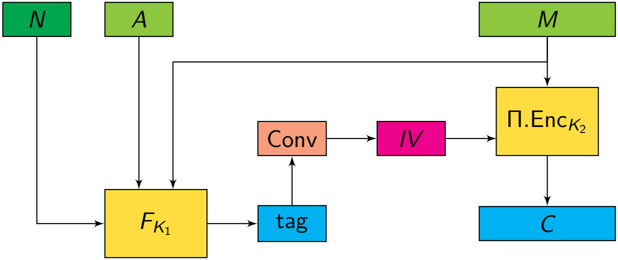


- SIV (*Synthetic IV*) [RS06] combines a PRF $F_{K_1}(N, A, M)$ and an IV-based encryption scheme $\Pi.\mathrm{Enc}_{K_2}(IV, M)$
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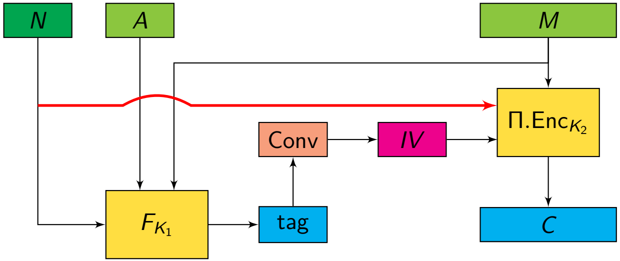


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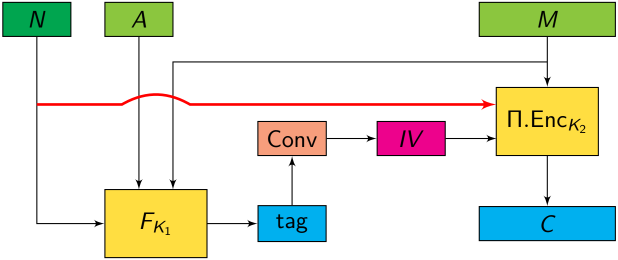
  $\Rightarrow$ Re-use the nonce $N$ in the encryption scheme!

# Combined Nonce and IV-based (nivE) Encryption




- the encryption algorithm Π.Enc takes a nonce and a random IV!
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- NB: when nonces can be repeated, ≃ (family of) standard IV-based encryption scheme

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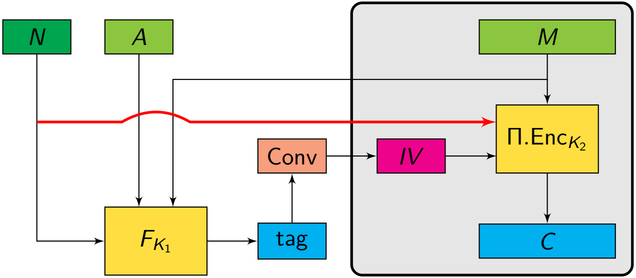


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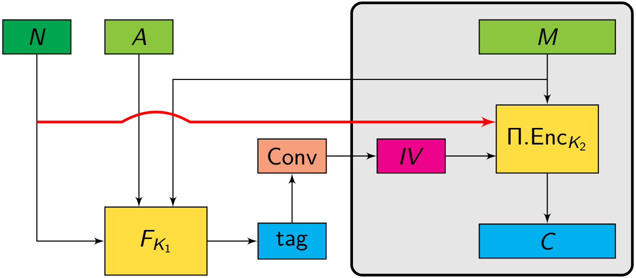


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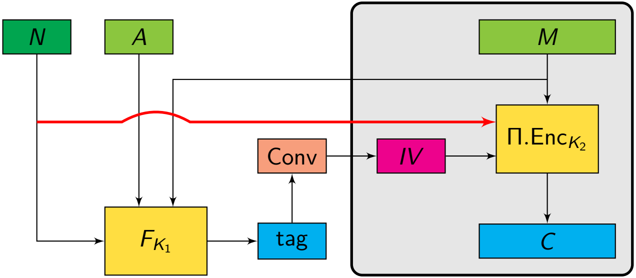


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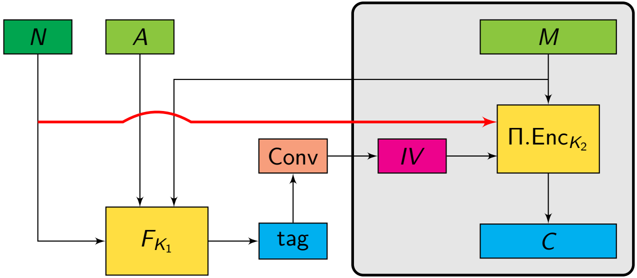


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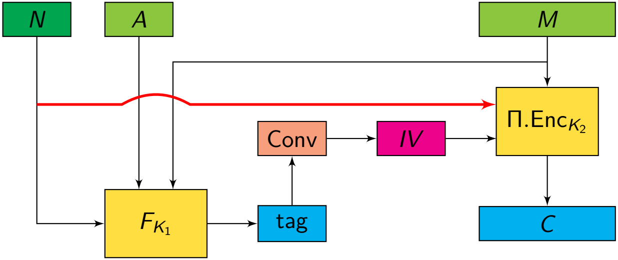
# Security Result for NSIV



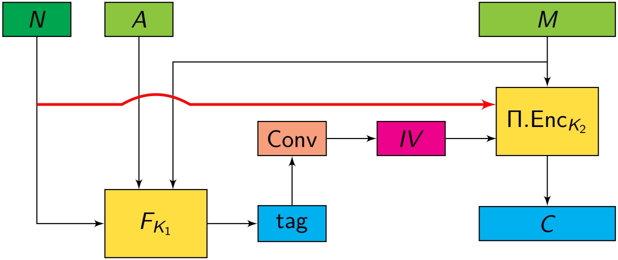

## Theorem

*For any adversary* $\mathcal{A}$ *against* NSIV$[F, \Pi]$,

$$\mathbf{Adv}^{\mathrm{nAE}}_{\mathsf{NSIV}}(\mathcal{A}) \leq \mathbf{Adv}^{\mathrm{nivE}}_{\Pi}(\mathcal{A}') + \mathbf{Adv}^{\mathrm{nPRF}}_{F}(\mathcal{A}'') + \mathbf{Adv}^{\mathrm{nMAC}}_{F}(\mathcal{A}''').$$

*Moreover, if* $\mathcal{A}$ *repeats any nonce at most m times, then* $\mathcal{A}'$, $\mathcal{A}''$, *and* $\mathcal{A}'''$ *also repeat any nonce at most m times.*

# Instantiating $F$ and $\Pi$




## Remaining of the talk:

How to instantiate the PRF $F$ and the nivE encryption scheme $\Pi$ from a TBC $\widetilde{E}$ so that

- we get BBB-security in the nonce-respecting setting
- we retain birthday-bound security in the nonce-misuse setting

# Outline

TBCs and AE

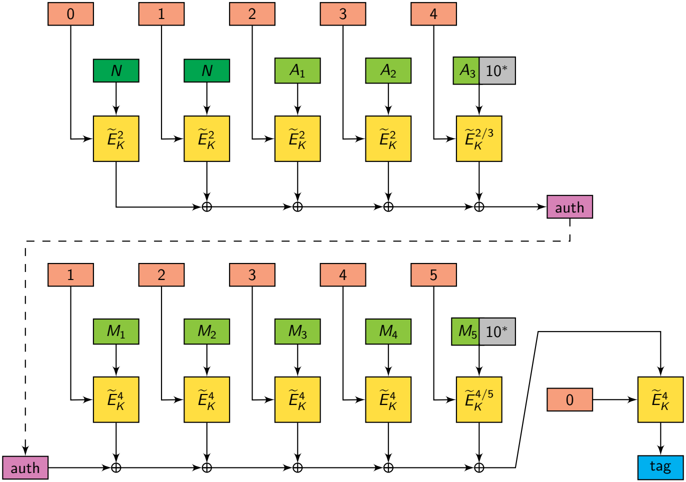
Generic Composition: the NSIV Method

Authentication: the EPWC Mode

Encryption: the CTRT Mode

Conclusion

# The EPWC (*Encrypted Parallel Wegman-Carter*) Mode



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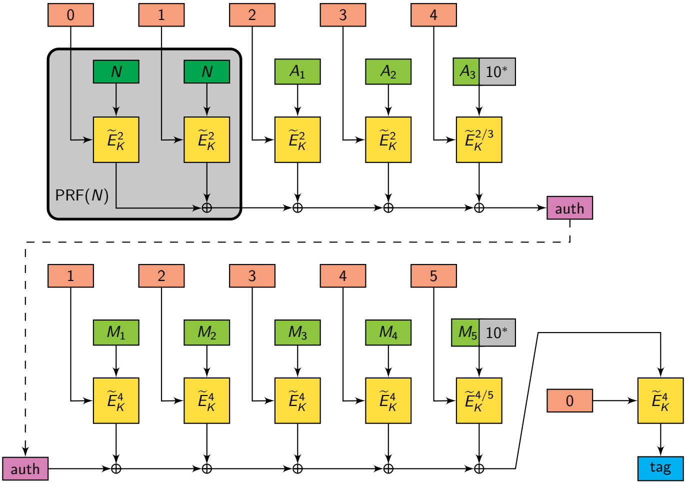

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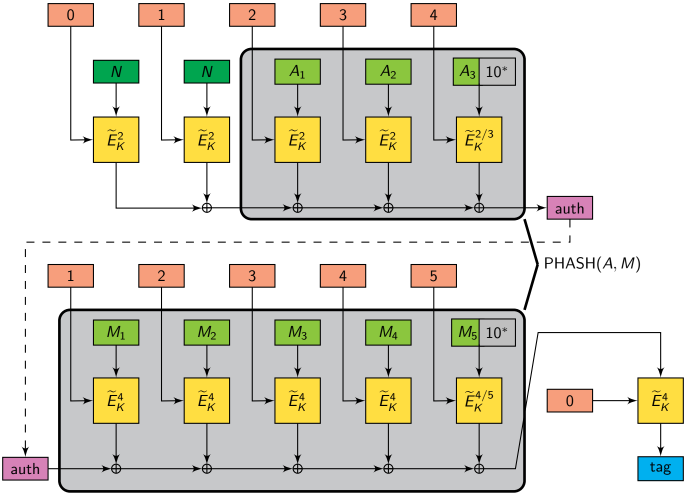

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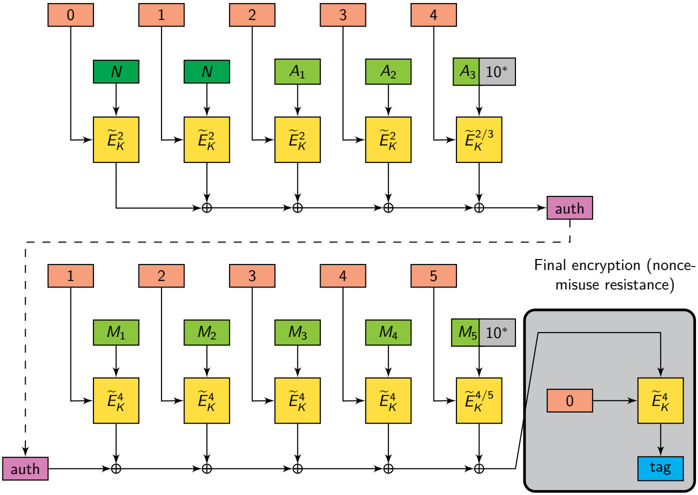

# Security of EPWC

**Theorem**

*Let $\mathcal{A}$ be an adversary against* EPWC *with an ideal TBC with block-length $n$ making at most $q$ queries. Then*

(a) *If $\mathcal{A}$ is nonce-respecting,*

$$\mathbf{Adv}^{\mathrm{nPRF}}_{\mathsf{EPWC}}(\mathcal{A}) \leq \mathcal{O}\left(\frac{q}{2^n}\right), \qquad \mathbf{Adv}^{\mathrm{nMAC}}_{\mathsf{EPWC}}(\mathcal{A}) \leq \mathcal{O}\left(\frac{q}{2^n}\right).$$

(b) *If $\mathcal{A}$ is allowed to repeat nonces, then*

$$\mathbf{Adv}^{\mathrm{PRF}}_{\mathsf{EPWC}}(\mathcal{A}) \leq \frac{q^2}{2^n}, \qquad \mathbf{Adv}^{\mathrm{MAC}}_{\mathsf{EPWC}}(\mathcal{A}) \leq \frac{q^2+q}{2^n}.$$

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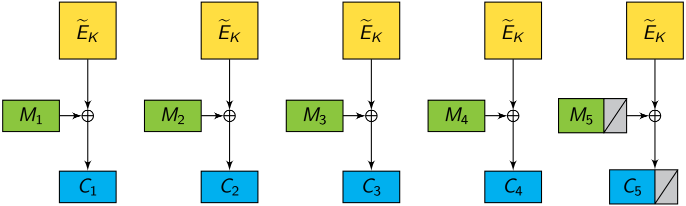


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- nonce in the tweak ⇒ birthday attack!
- switch inputs: nonce in "message input" and counter in tweak
- key observation: $T \mapsto \widetilde{E}_K(T, N)$ is a pseudorandom *function*

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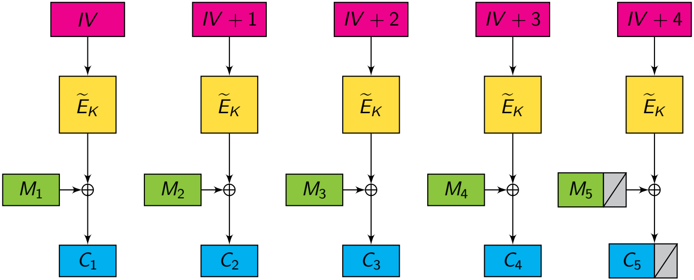


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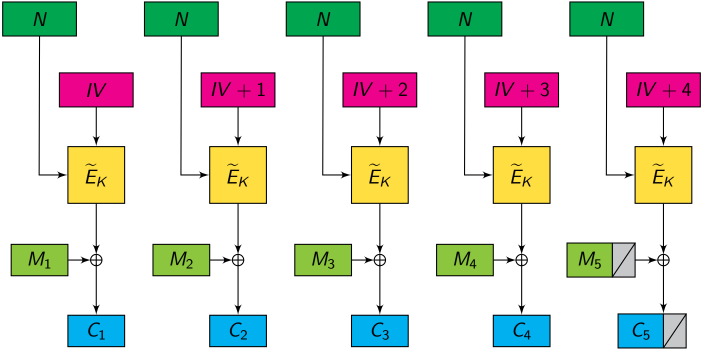


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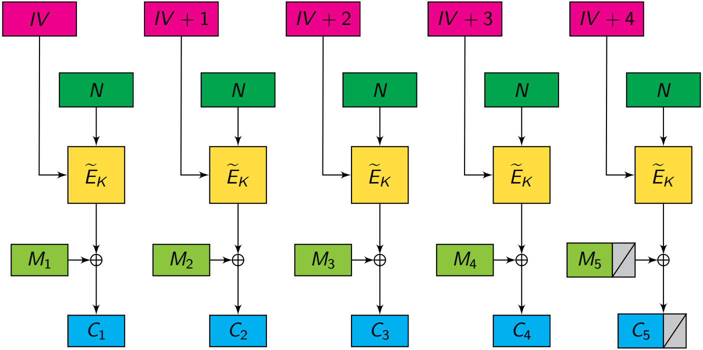


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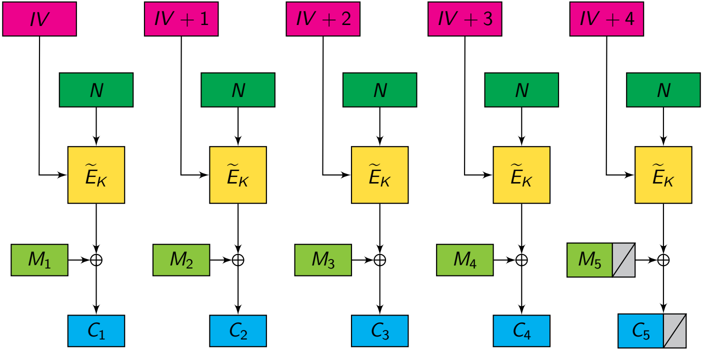


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# Security of CTRT

## Theorem

- *$n$ = block-length*
- *$t$ = tweak-length*
- *$\sigma$ = total length of queries (in n-bit blocks)*
- *$m$ = maximal number of repetitions of any nonce*

$$\mathbf{Adv}^{\mathrm{nivE}}_{\mathsf{CTRT}}(\mathcal{A}) \leq \frac{2(m-1)\sigma}{2^t} + \frac{1}{2^t} + \begin{cases} \dfrac{2\sigma\log^2\sigma}{2^n} & \text{when } \sigma \leq 2^t, \\ \dfrac{2t^2\sigma^2}{2^{n+t}} & \text{when } \sigma \geq 2^t. \end{cases}$$

- nonce-respecting ($m = 1$): security up to $\sigma \simeq \min\{2^n, 2^{(n+t)/2}\}$
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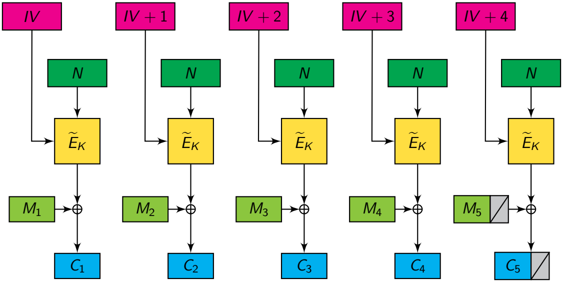


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- we want to show that ciphertexts are indist. from random
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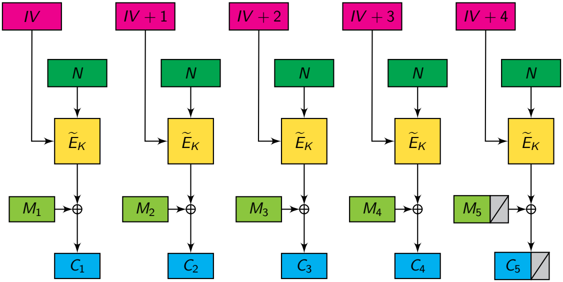


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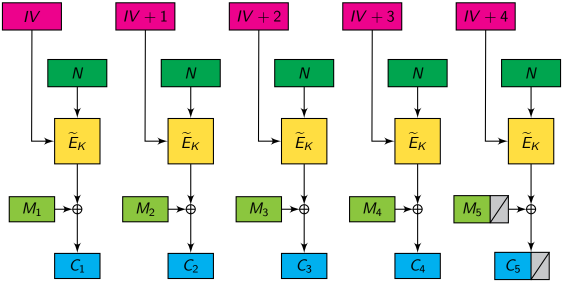


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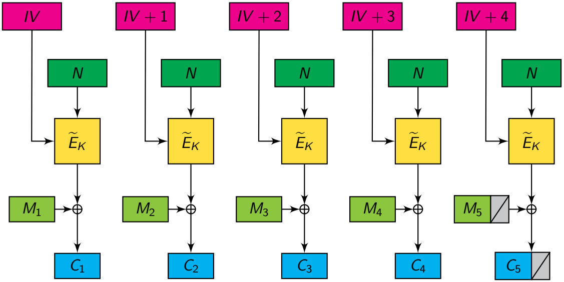


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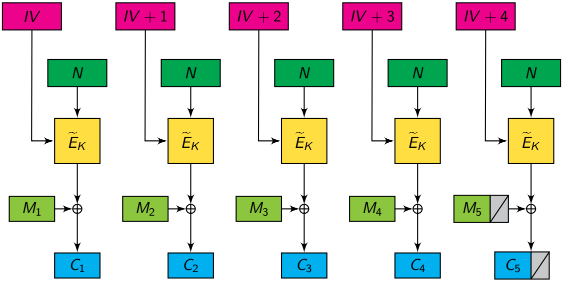


- for each tweak, we have an independent PRF/PRP distinguishing problem with $L(T)$ "queries" (nonces):

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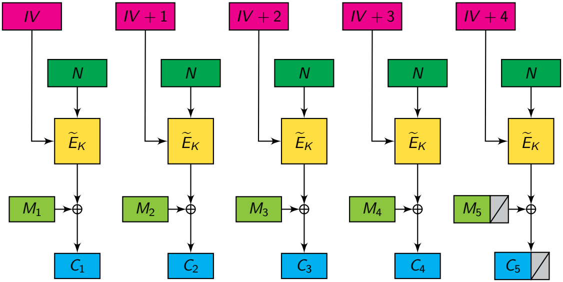


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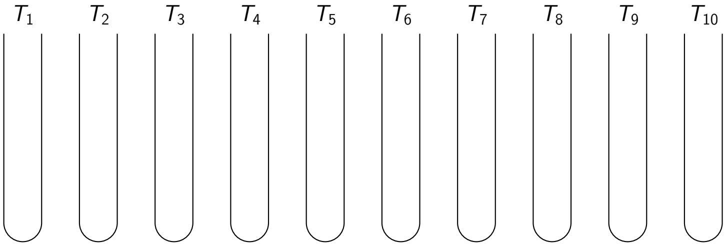


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- $\sigma$ balls = nonces
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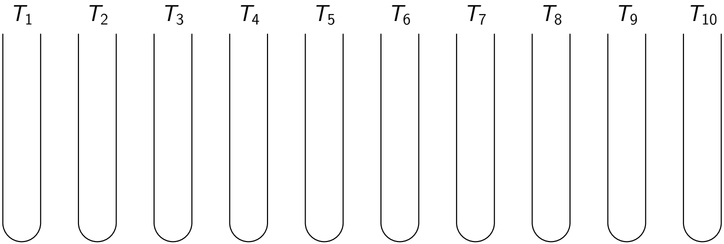


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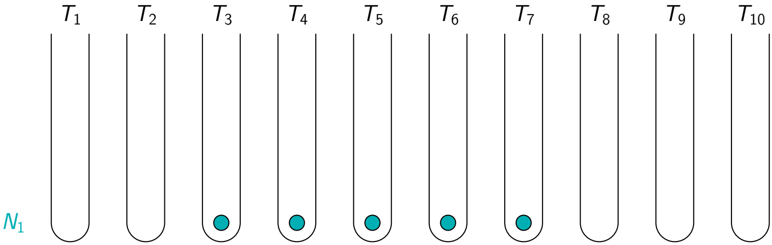


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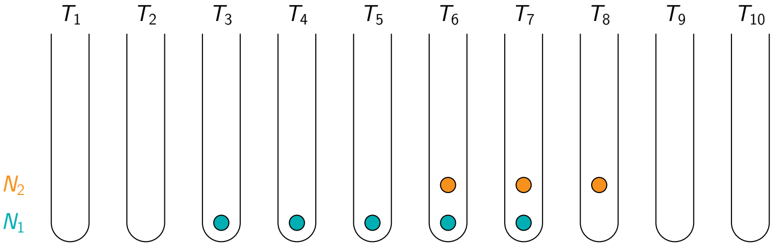


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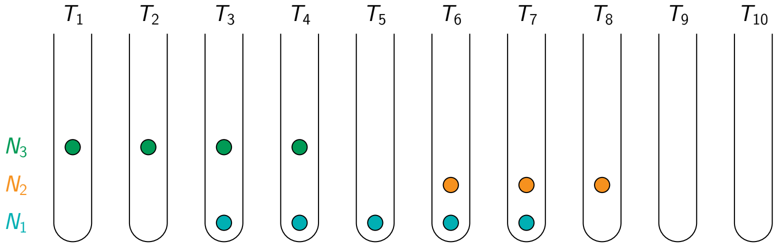


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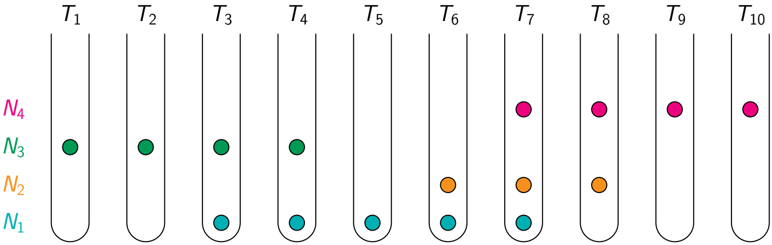


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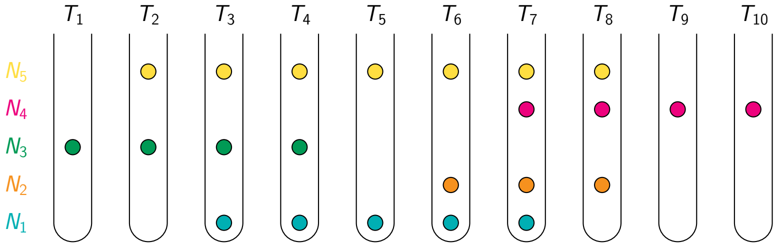


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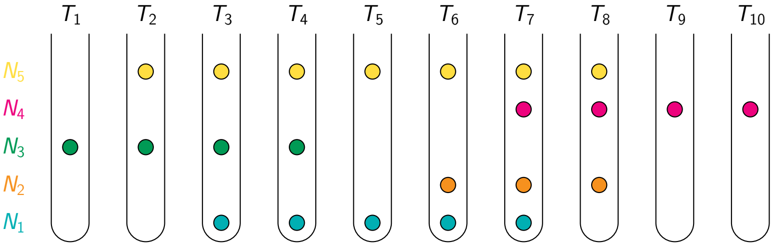


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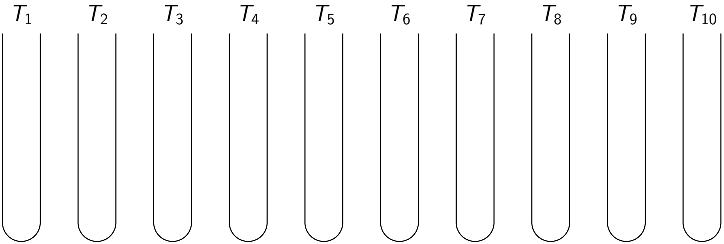
  - (a) if $\sigma \leq 2^t$, then $\max L(T) \leq 2 \log \sigma$;
  - (b) if $\sigma \geq 2^t$, then $\max L(T) \leq \frac{2t\sigma}{2^t}$.

# Proof of Security of CTRT (nonce-misuse)




- bad event that allows to distinguish outputs from random: $\exists$ two encryption queries with the same nonce and a common tweak (counter)
- for two messages of length $\ell$ and $\ell'$, happens with proba. $(\ell + \ell' - 1)/2^t$
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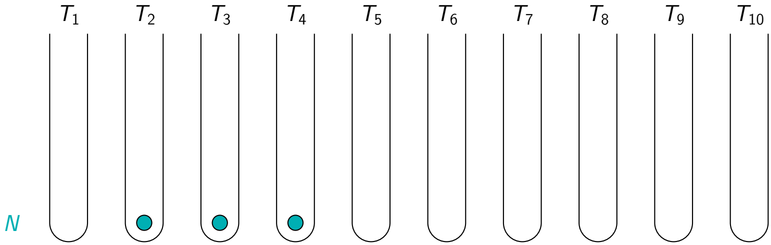


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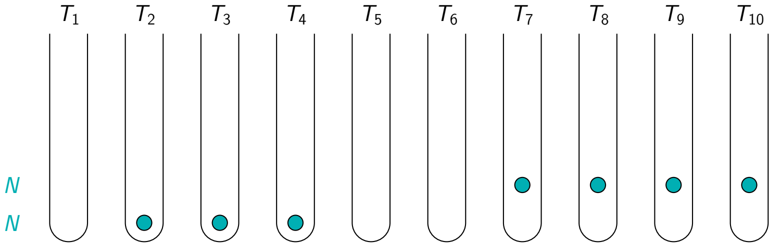


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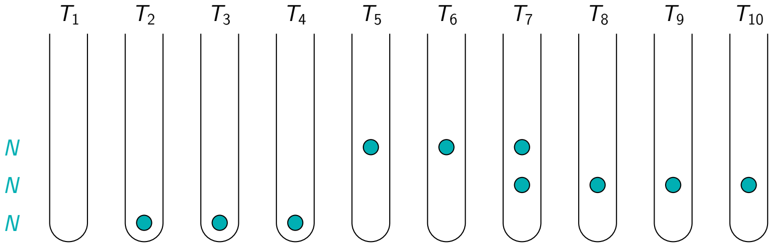


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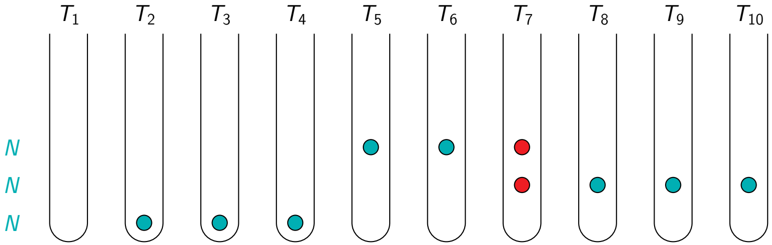


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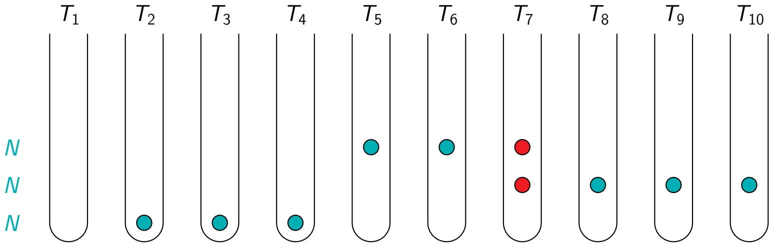


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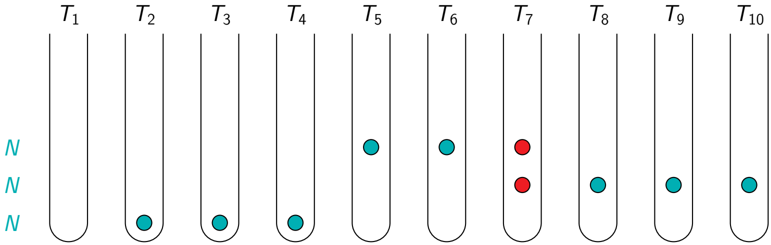


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# Outline

# Wrap-up and Final Remarks

- EPWC + CTRT combined using the NSIV composition method
  = SCT (*Synthetic Counter in Tweak*) mode
- BBB-secure in the nonce-respecting setting
- retains birthday-bound security in the nonce-misuse setting
- parallel, quite efficient, does not need the decryption direction
- instantiation of the TBC: needs to be BBB-secure!
  ⇒ XEX does not work
  ⇒ use ad-hoc TBCs such as Deoxys-BC and Joltik-BC

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# The end...

Thanks for your attention!

Comments or questions?

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