New Constructions of MACs from (Tweakable) Block Ciphers

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Summary of the contribution

- we propose four new MAC constructions based on a (tweakable) block cipher:

	stateless and deterministic	nonce-based/randomized
TBC-based	Hash-as-Tweak (HaT)	Nonce-as-Tweak (NaT)
BC-based	Hash-as-Key (HaK)	Nonce-as-Key (NaK)

- all four constructions are secure beyond the birthday bound
- TBC-based constructions are provably secure in the standard model
- BC-based constructions are provably secure in the ideal cipher model
- nonce-based constructions provide graceful security degradation with the maximal number of nonce repetitions

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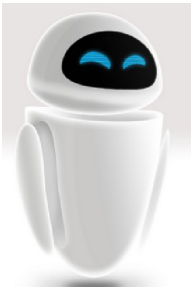
MAC definition

$T = \mathrm{MAC}_K(N, M)$



$\mathrm{MAC}_K(N', M') = T'$?

Security Definition

The adversary is allowed

- q MAC queries $T = \mathrm{MAC}_K(N, M)$
- v verification queries (forgery attempts) (N', M', T')

and is successful if one of the verification queries (N', M', T') passes and no previous MAC query (N', M') returned T'.

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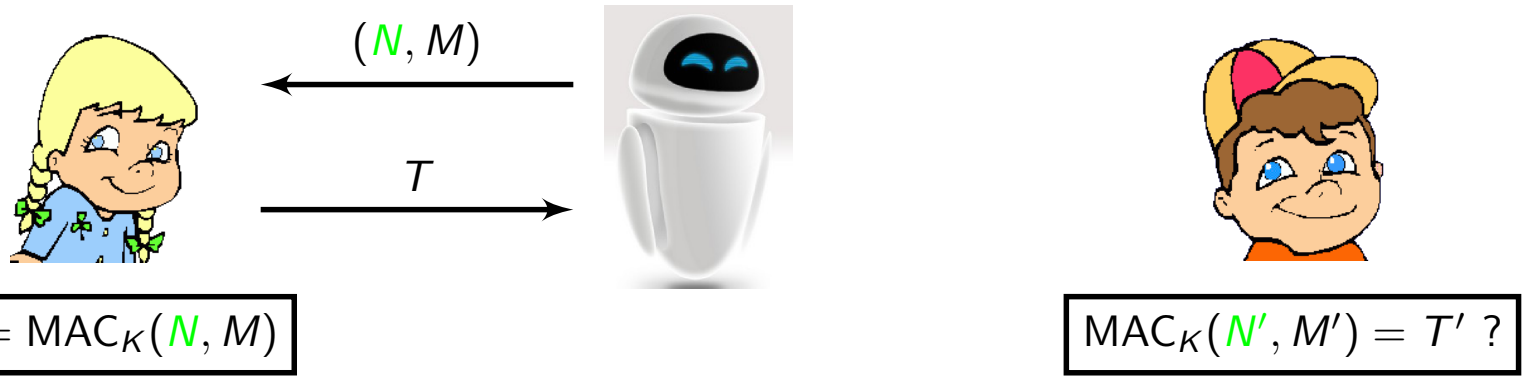

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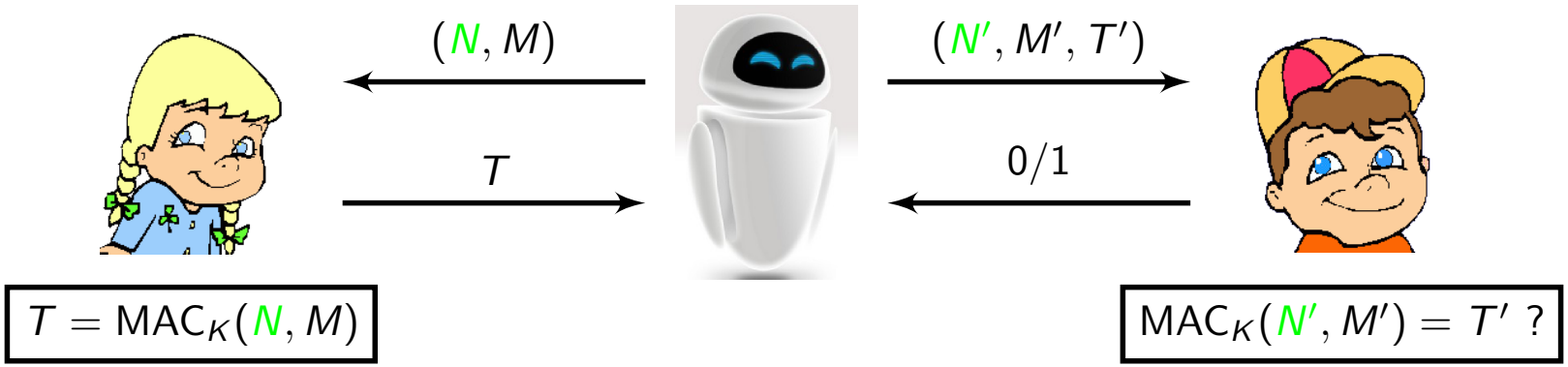

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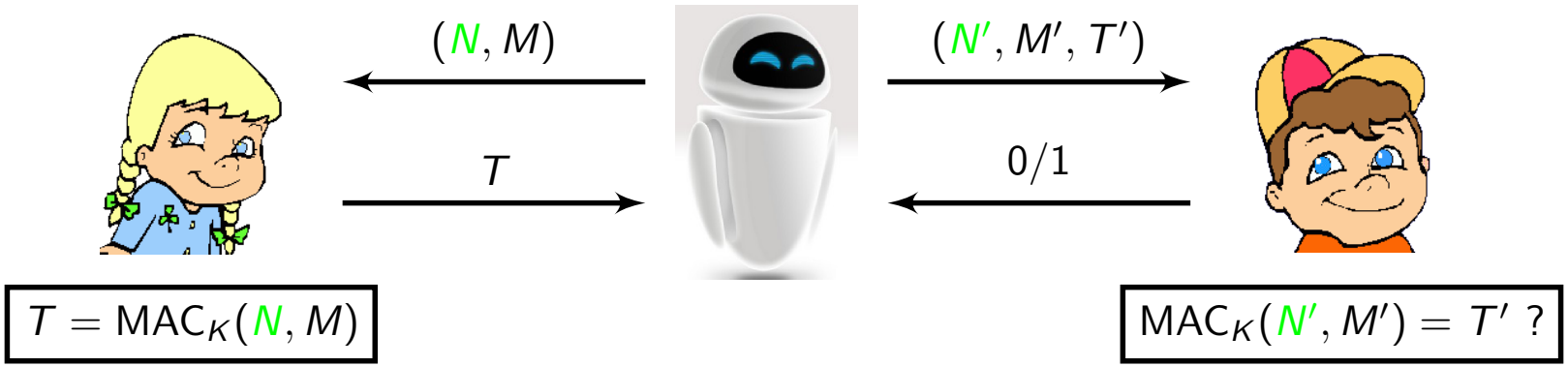

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Three types of MAC

- stateless and deterministic: MAC function only takes the key and the message as input
  (Variable-input-length PRF $\Rightarrow$ stateless deterministic MAC)
- nonce-based:
  - MAC function takes as input a non-repeating nonce N in addition to the key and the message M
  - security model: nonces are chosen by the adversary, any nonce can be used at most μ times in MAC queries
  - $\mu = 1$: nonce-respecting adversary
  - $\mu > 1$: nonce-misusing adversary
- randomized: MAC function takes as input random coins (generated by the sender) in addition to the key and the message

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Graceful nonce-misuse security degradation

- the security of some nonce-based MACs collapses if a single nonce is used twice (e.g. GMAC)
- ideally, security should degrade gracefully in case nonces are repeated
- any BBB-secure nonce-based MAC with graceful security degradation can be turned into a BBB-secure randomized MAC by choosing n-bit nonces uniformly at random:

$$\mathbf{Adv}_F^{\text{rand-MAC}}(q,v) \leq \underbrace{\frac{q^{\mu+1}}{2^{\mu(n+1)}}}_{\substack{\mu\text{-multicoll.}\\ \text{proba.}}} + \underbrace{\mathbf{Adv}_F^{\text{nonce-MAC}}(q,v,\mu)}_{\text{small for } \mu>1}$$

for any value of μ = maximal number of nonce repetitions.

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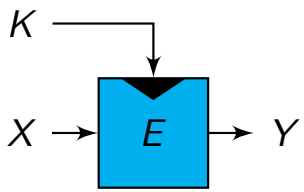
Building blocks: BCs and TBCs



n = block size
t = tweak size

- block cipher E: for each key K, $X \mapsto E(K, X)$ is a permutation
- tweakable block cipher $\widetilde{E}$: for each key K and each tweak W, $X \mapsto \widetilde{E}(K, W, X)$ is a permutation
- one can think of a keyed TBC $\widetilde{E}_K$ as an "imperfect" PRF from $(n + t)$ bits to n bits
- if any tweak W is used at most "a few" times, $\widetilde{E}_K$ is close to a random $(n + t)$-to-n-bit function

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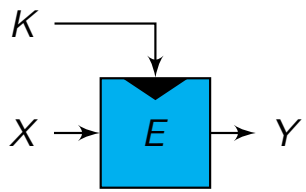

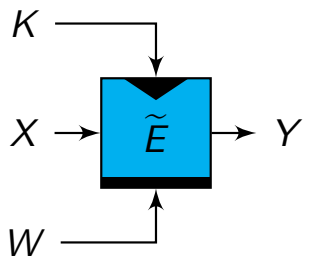

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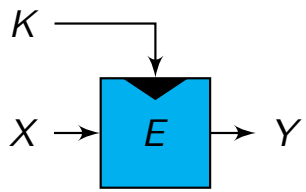

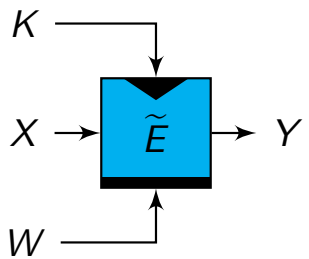

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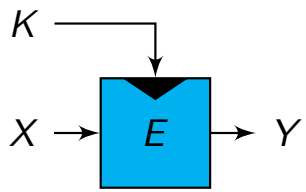

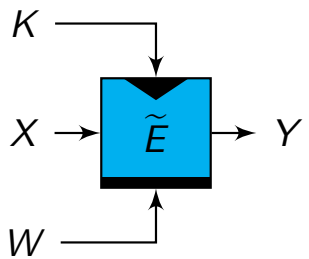

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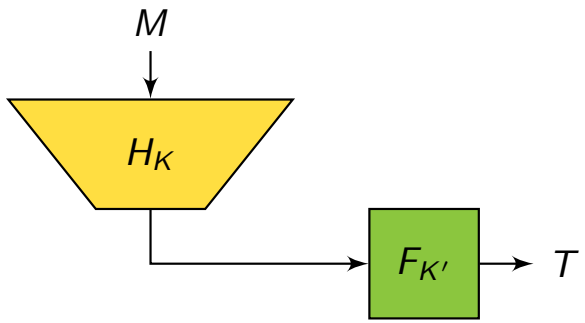
The "standard" UHF-then-PRF Construction



- based on a fixed-input-length PRF F and an ε-almost universal (ε-AU) hash function H:

$$\forall M \neq M', \ \Pr[K \leftarrow_{\$} \mathcal{K} : H_K(M) = H_K(M')] \leq \varepsilon$$

- H can be statistically secure (polynomial evaluation) or computationally secure (BC/TBC-based)
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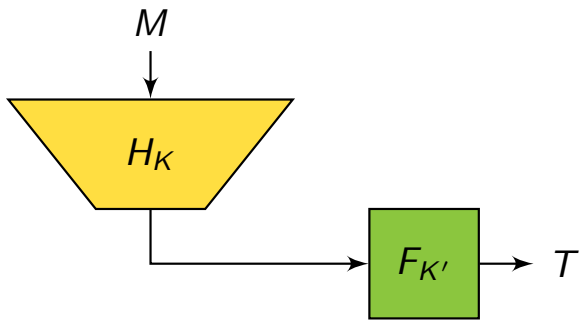

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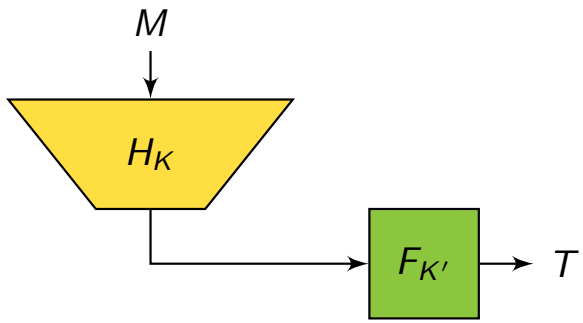

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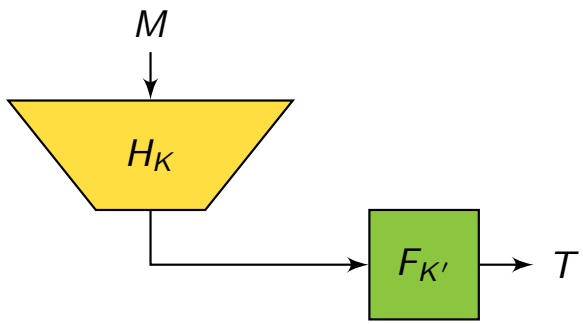

- birthday-bound-secure w.r.t. H collision probability ε

$$\mathbf{Adv}^{\mathrm{PRF}}_{F\circ H}(q) \leq \frac{q^2\varepsilon}{2} + \mathbf{Adv}^{\mathrm{PRF}}_{F}(q)$$

- typical instantiation from a block cipher E:
  - $H \leftarrow$ CBC-MAC[E] or PMAC[E] ($\varepsilon \simeq 2^{-n}$)
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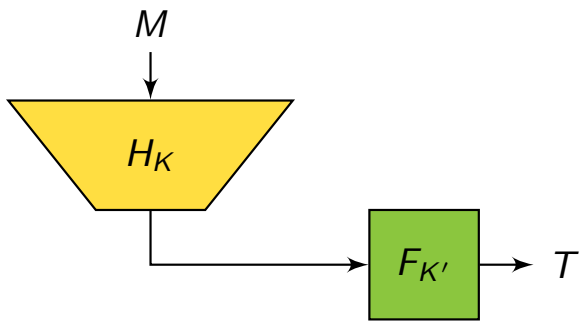

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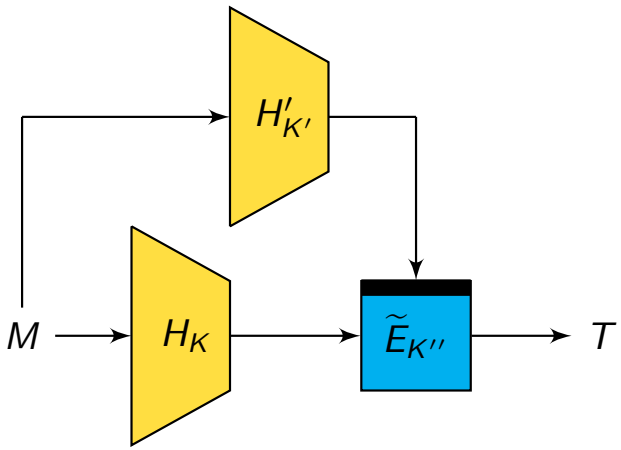

Hash-as-Tweak (HaT)

Hash-then-TBC

- BBB-secure assuming H and H' are ε-AU secure:

$$\mathbf{Adv}^{\mathrm{MAC}}_{\mathrm{HaT}}(q, v) \leq q^2\varepsilon^2 + qv\varepsilon^2 + (\ldots)$$

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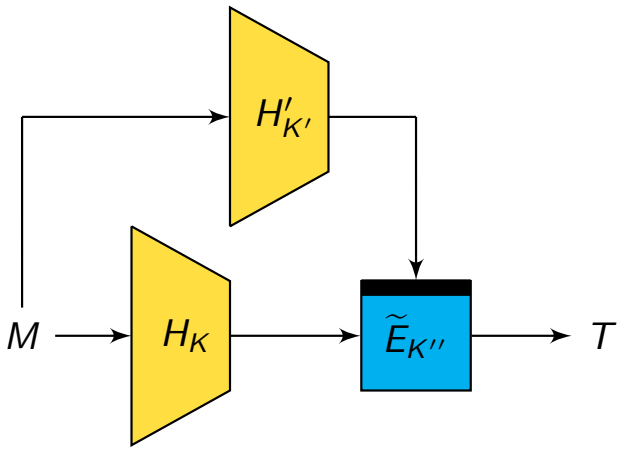

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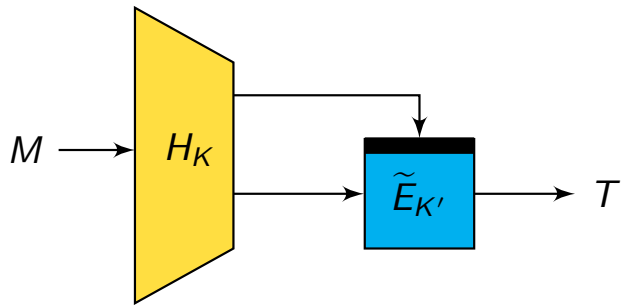

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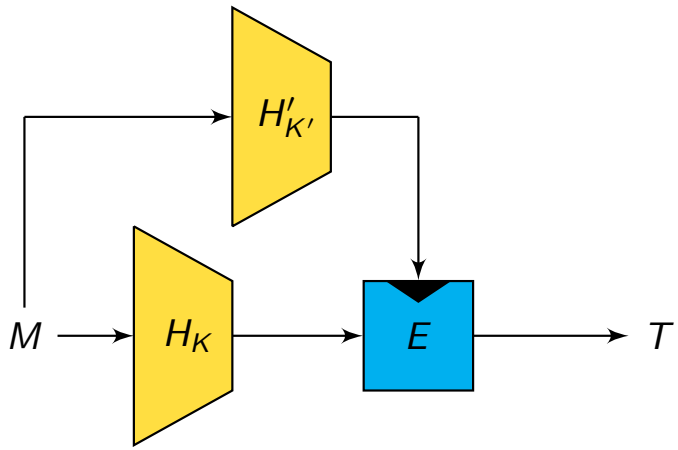


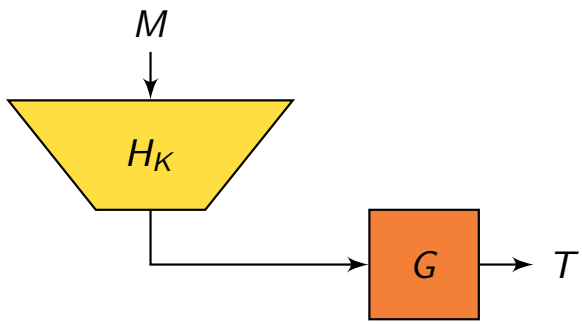
- output transformation unkeyed $\Rightarrow$ H and H' must be ε'-uniform:

$$\forall M,\ \forall Y,\ \Pr[K \leftarrow_{\$} \mathcal{K} : H_K(M) = Y] \leq \varepsilon'$$

- BBB-secure in the ideal cipher model assuming H and H' are ε-AU and ε'-uniform:

$$\mathbf{Adv}^{\mathrm{MAC}}_{\mathrm{HaK}}(q, v) \leq q^2\varepsilon^2 + qv\varepsilon^2 + (\ldots)$$

The UHF-then-RO construction



- Hash-as-Key (HaK) is a special case of the "UHF-then-RO" construction
- modeling G as a random function oracle (q_G queries), the construction is secure if H is ε-AU and ε'-uniform:

$$\mathbf{Adv}^{\mathrm{PRF}}_{G \circ H}(q, q_G) \leq \frac{q^2 \varepsilon}{2} + q q_G \varepsilon'$$

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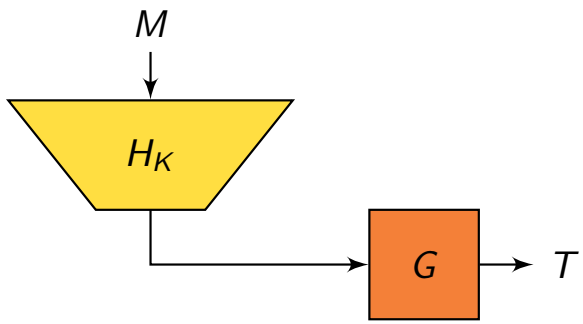

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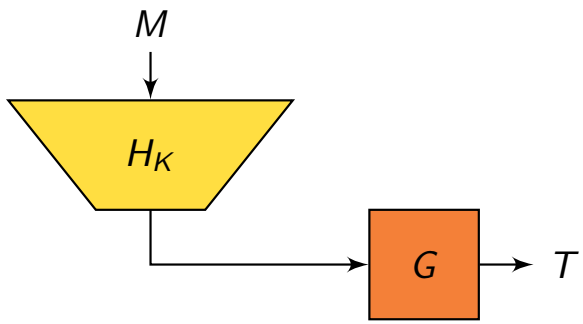

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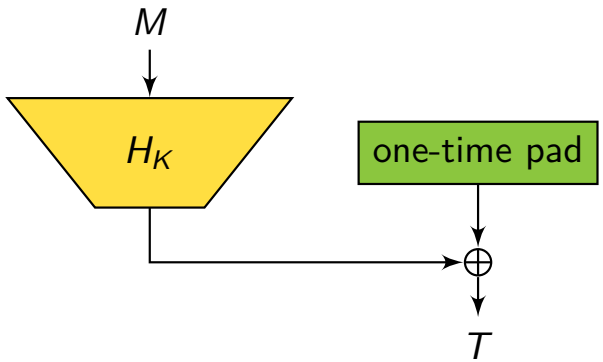

- based on an ε-almost xor-universal (ε-AXU) hash function H:

$$\forall M \neq M',\ \forall Y,\ \Pr[K \leftarrow_{\$} \mathcal{K} : H_K(M) \oplus H_K(M') = Y] \leq \varepsilon$$

- in practice, OTPs are replaced by a PRF applied to a nonce N
- H usually based on polynomial evaluation (GHASH, Poly1305)
- "optimal" security:

$$\mathbf{Adv}^{\text{nonce-MAC}}_{\text{WC}}(q, v) \leq v\varepsilon + \mathbf{Adv}^{\text{PRF}}_{F}(q + v)$$

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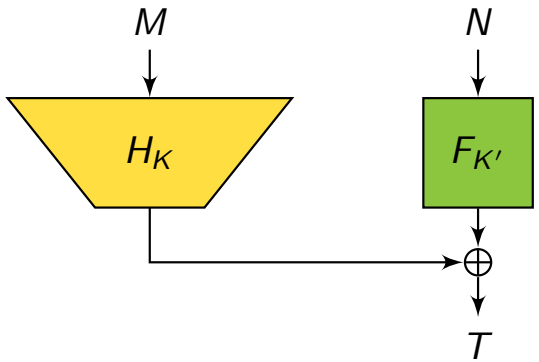

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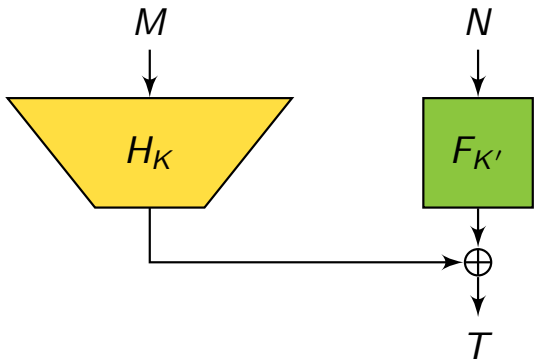

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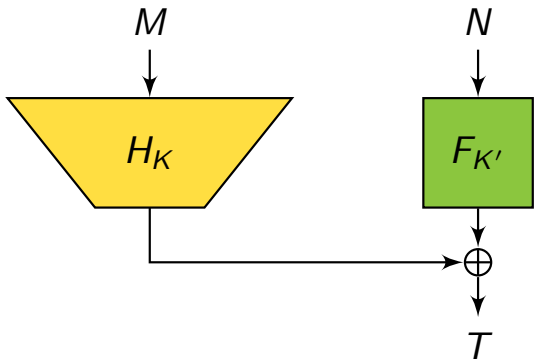
$$\mathbf{Adv}^{\text{nonce-MAC}}_{\text{WC}}(q, v) \leq v\varepsilon + \mathbf{Adv}^{\text{PRF}}_{F}(q + v)$$

The Wegman-Carter construction [GMS74, WC81]



- based on an ε-almost xor-universal (ε-AXU) hash function H:

$$\forall M \neq M',\ \forall Y,\ \Pr[K \leftarrow_{\$} \mathcal{K} : H_K(M) \oplus H_K(M') = Y] \leq \varepsilon$$

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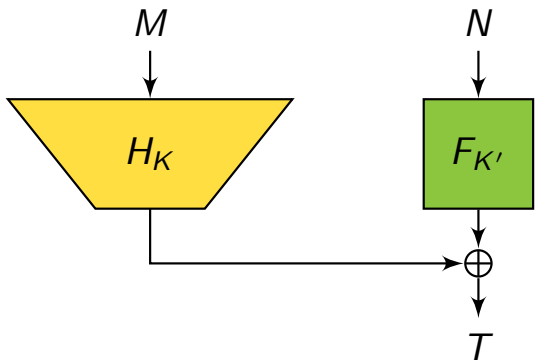

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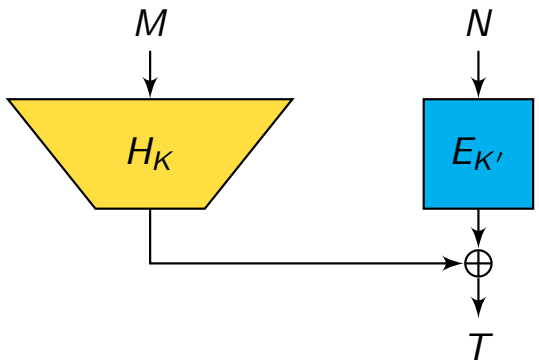

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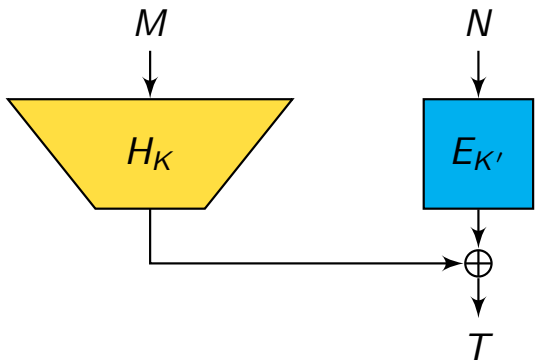

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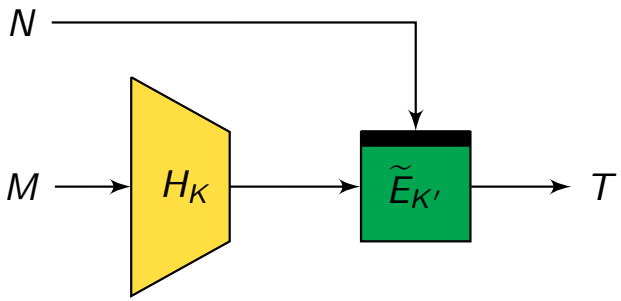

- if nonces don't repeat to often, $\widetilde{E}_{K'}$ is close to a perfect PRF
- graceful security degradation with maximal nonce multiplicity μ

$$\mathbf{Adv}^{\text{nonce-MAC}}_{\text{NaT}}(q, v) \leq 2(\mu - 1)q\varepsilon + \mu v\varepsilon + (\ldots)$$

- can be seen as a special case of the (PRF-based) WMAC construction [BC09]

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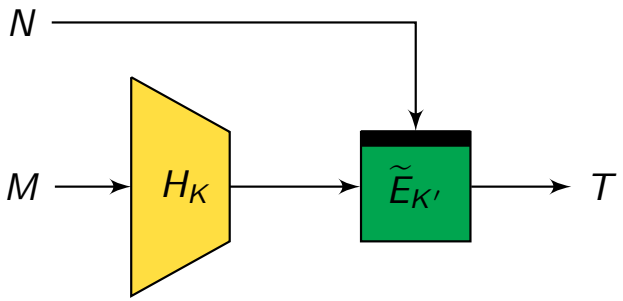

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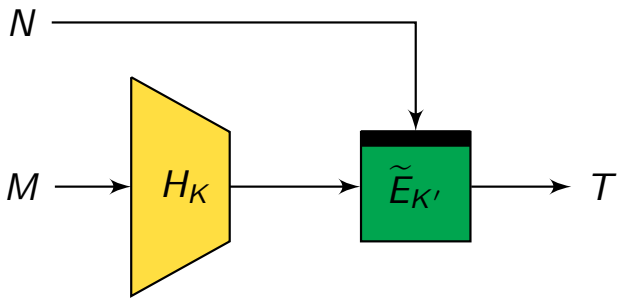

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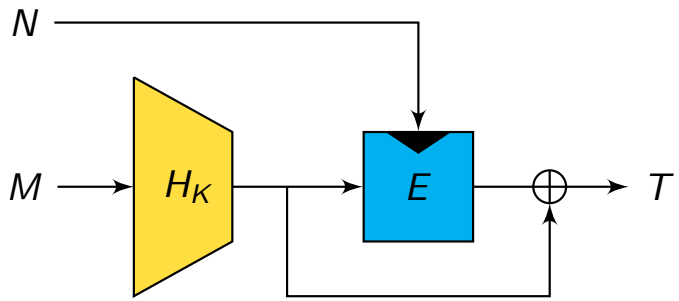

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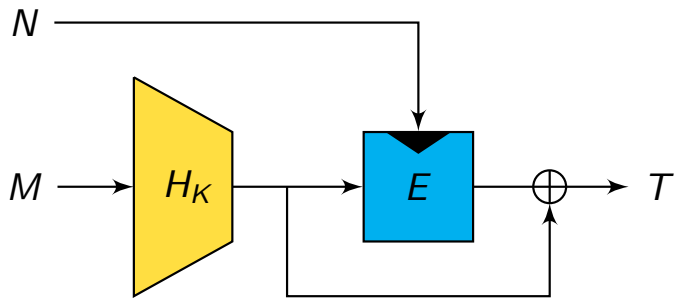

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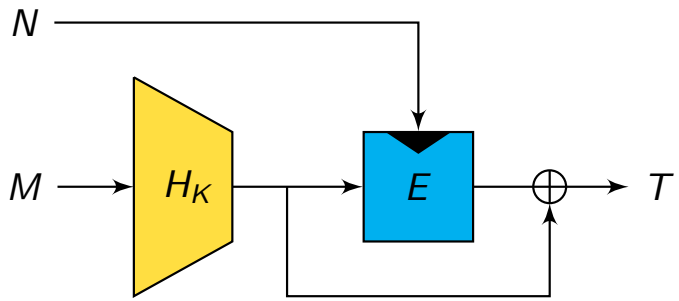

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Conclusion

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	stateless and deterministic	nonce-based/randomized
TBC-based	Hash-as-Tweak (HaT)	Nonce-as-Tweak (NaT)
BC-based	Hash-as-Key (HaK)	Nonce-as-Key (NaK)

- all security proofs rely on the standard H-coefficients technique [Pat08, CS14]
- our work does not address how to construct the UHF from a BC or TBC but many existing constructions can be used (PMAC/PMAC1 [BR02, Rog04], ZHASH [IMPS17], etc.)
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The end...

Thanks for your attention!

Comments or questions?

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