Authenticated Encryption

Applied Cryptography – Spring 2024

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Encryption

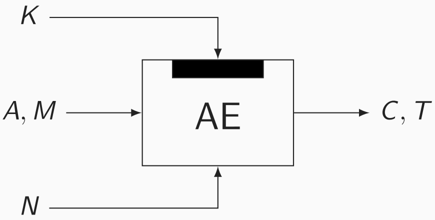
- Security goal: confidentiality
- Examples: ECB, counter mode

Authentication

- Security goal: data integrity
- Examples: CBC-MAC, Poly1305

Authenticated encryption combines both

Authenticated Encryption



- Using key K:
  - Message M is encrypted in ciphertext C
  - Associated data A and message M are authenticated using T
- Nonce N randomizes the scheme

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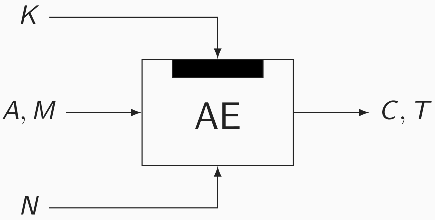

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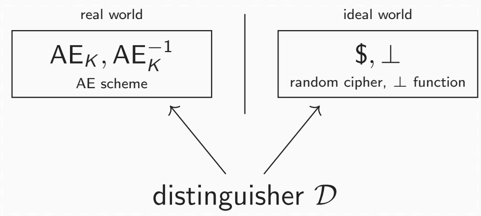
- Authenticated decryption discloses M if and only if T is correct

Authenticated Encryption Security



- Two oracles: $(\mathrm{AE}_K, \mathrm{AE}_K^{-1})$ (for secret key K) and $(\$, \perp)$ (secret)
- Distinguisher $\mathcal{D}$ has query access to one of these
  $\rightarrow$ unique nonce for each encryption query, and no trivial queries
- $\mathcal{D}$ tries to determine which oracle it communicates with

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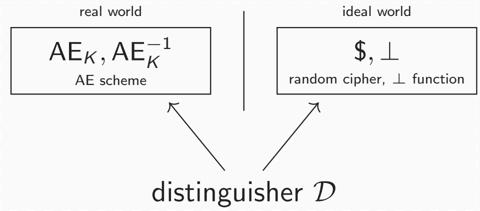

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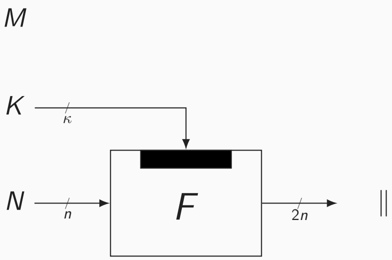
- $\mathcal{D}$ tries to determine which oracle it communicates with
- Its advantage is defined as:

$$\mathbf{Adv}_{\mathsf{AE}}^{\mathrm{ae}}(\mathcal{D}) = \Delta_{\mathcal{D}}\left(\mathsf{AE}_K, \mathsf{AE}_K^{-1} \,;\, \$, \perp\right) = \left|\mathbf{Pr}\left(\mathcal{D}^{\mathsf{AE}_K, \mathsf{AE}_K^{-1}} = 1\right) - \mathbf{Pr}\left(\mathcal{D}^{\$, \perp} = 1\right)\right|$$

- $\mathbf{Adv}_{\mathsf{AE}}^{\mathrm{ae}}(q_e, q_v)$: supremal advantage over any $\mathcal{D}$ with query complexity q_e, q_v

Outline

Authenticated Encryption Design



Encryption

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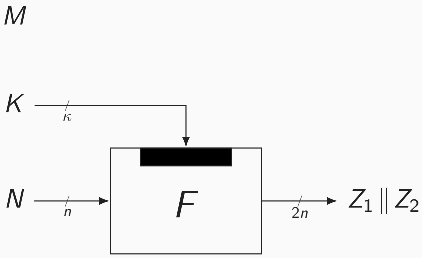

Encryption

- Input: (N, M)
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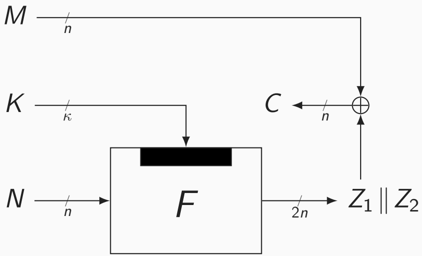

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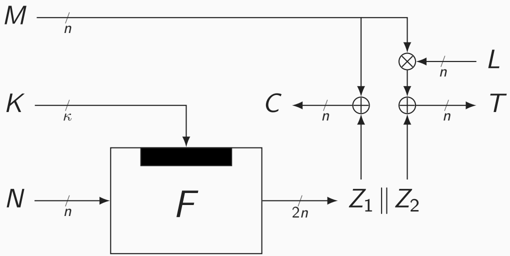

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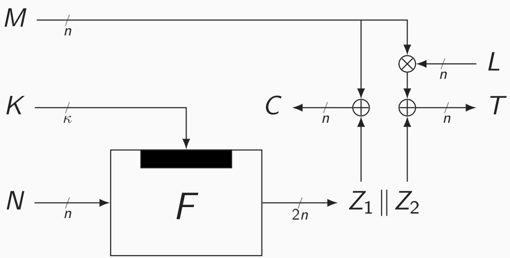

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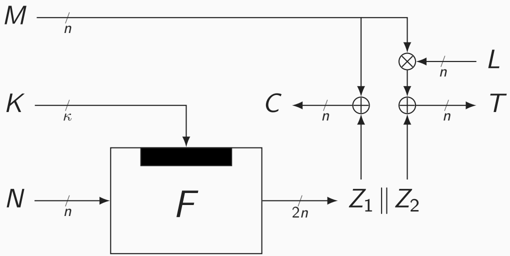

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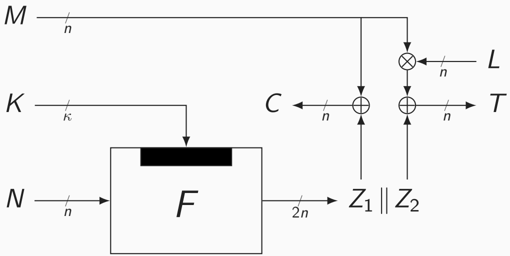

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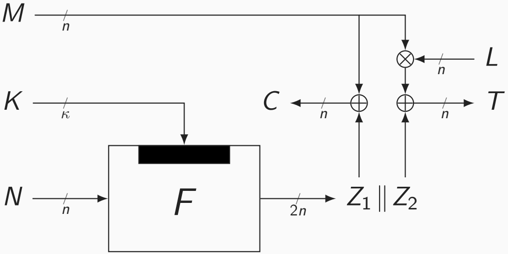

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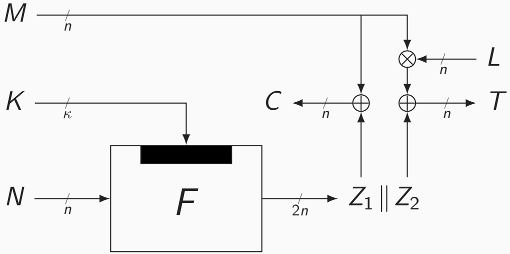
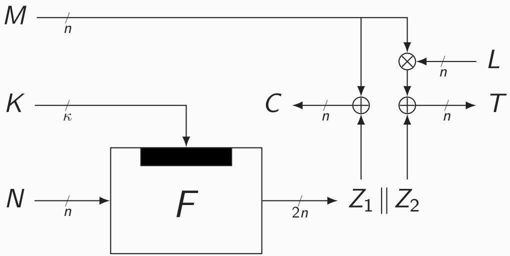
- Output: $\begin{cases} M \text{ if } T = T^\star \\ \perp \text{ otherwise} \end{cases}$

Simple Example: Confidentiality



Confidentiality

- Consider new query (N, M)
- N should be fresh



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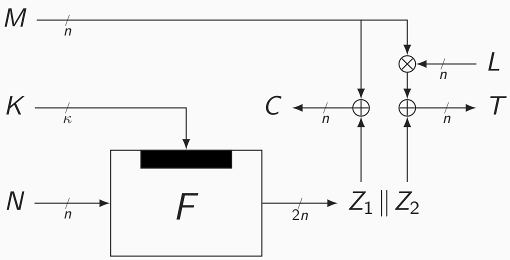

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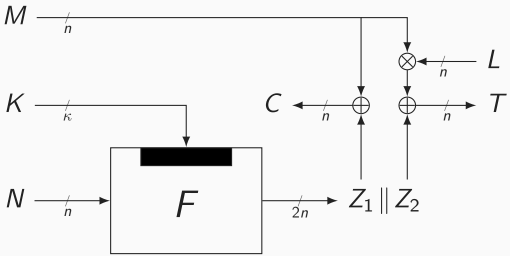
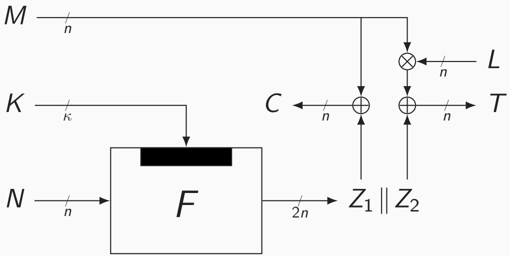


Authenticity

- Consider forgery attempt (N, C, T)



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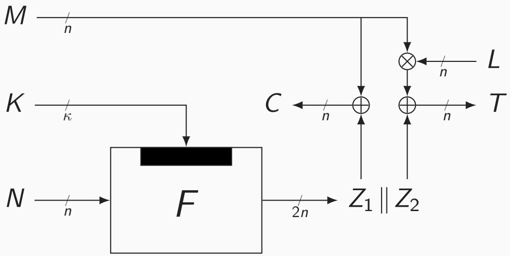

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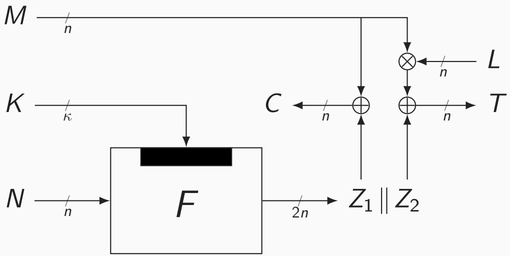

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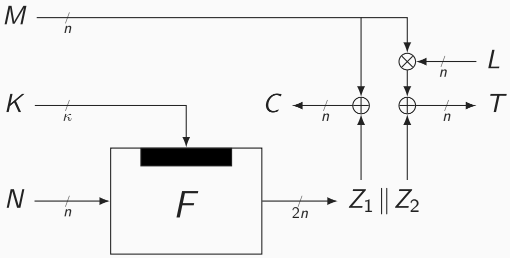

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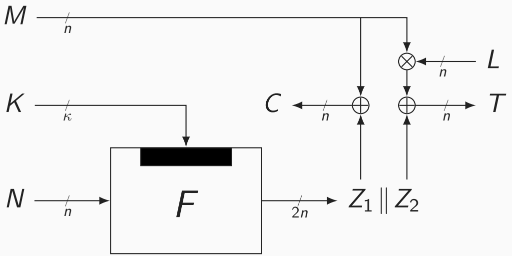

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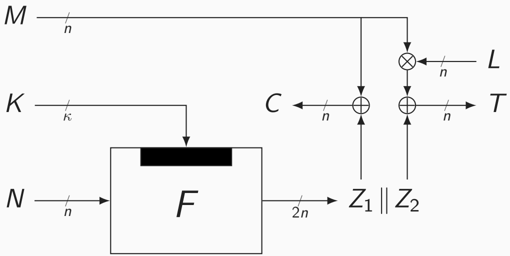

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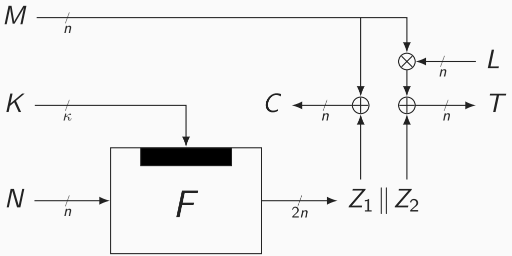

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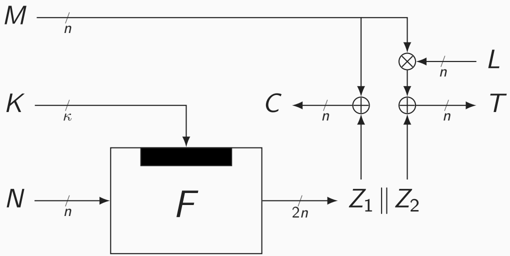
  - Requires guessing L

Simple Example: How to Support Variable Length?



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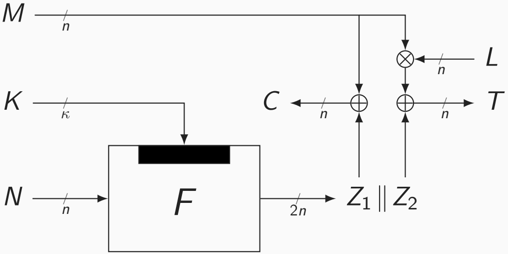

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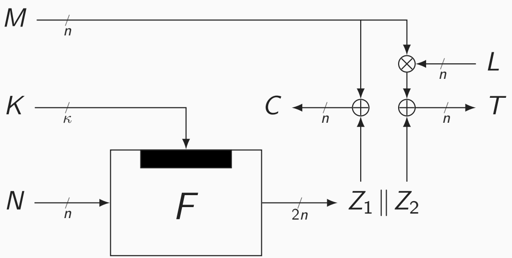

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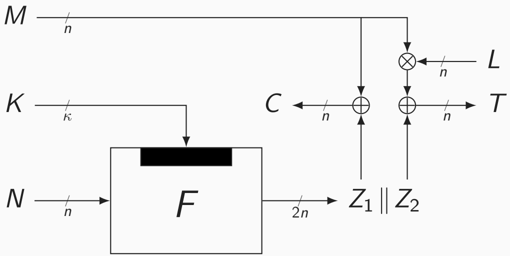

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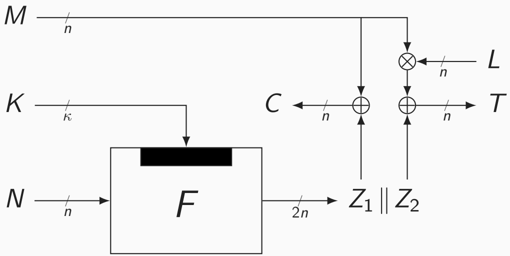

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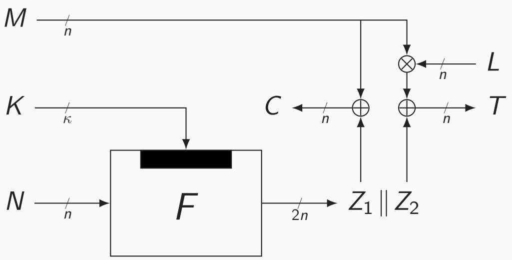

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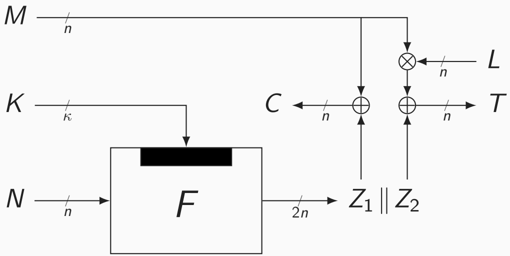

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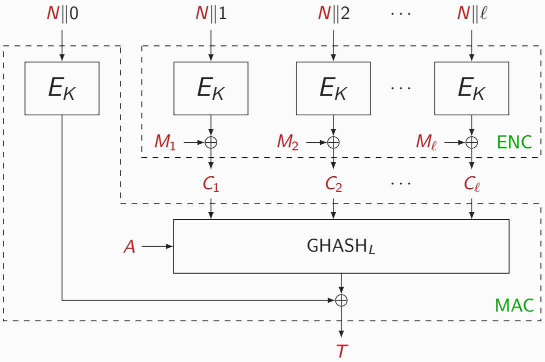
- Encrypt-*then*-MAC: $H_L(A, C)$
- Take CTR mode for F

GCM for 96-bit Nonce N



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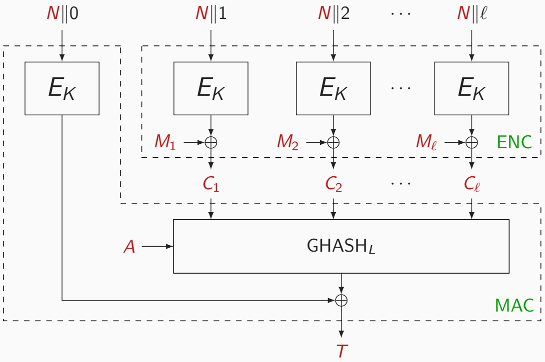

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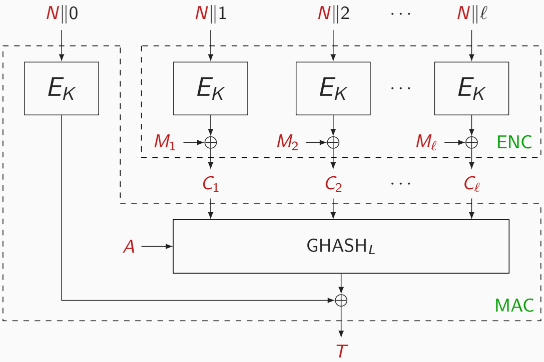

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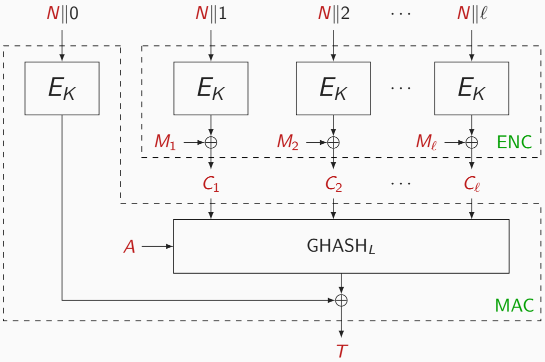

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What happens if nonce is re-used?

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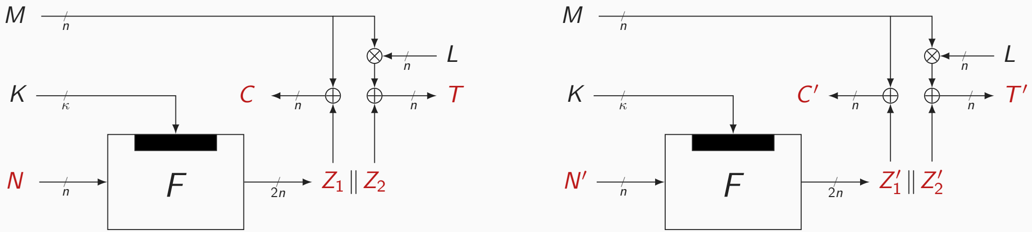

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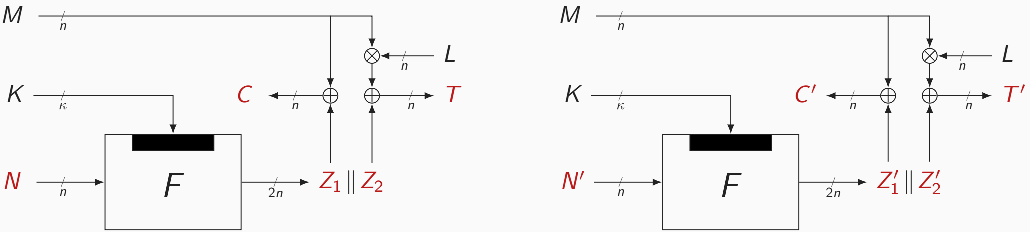

- Nonces N and N' should be distinct for two different evaluations
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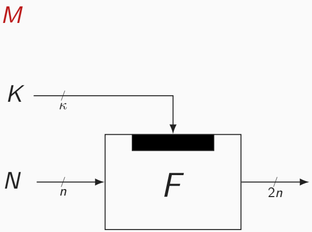

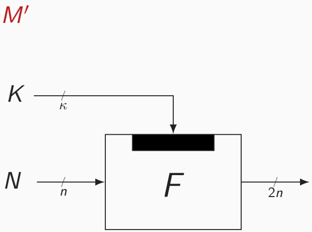

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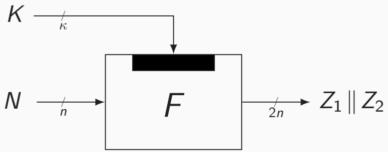
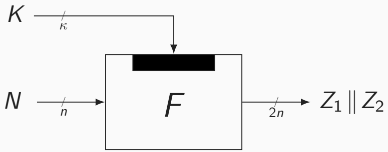
What if a Nonce is Repeated?

M



M'



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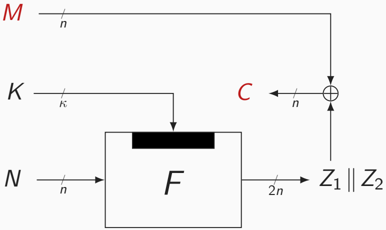

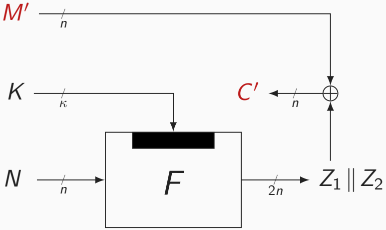

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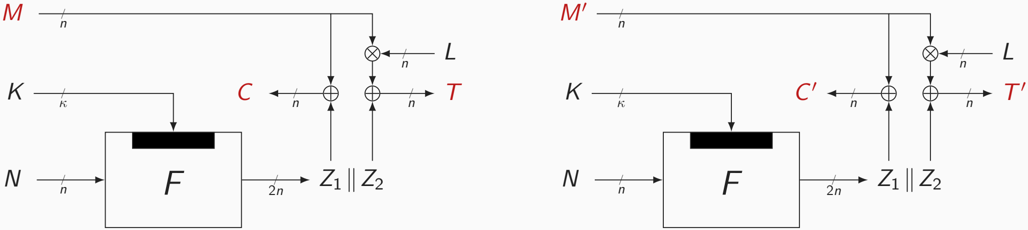

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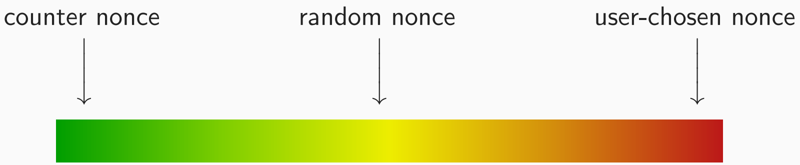
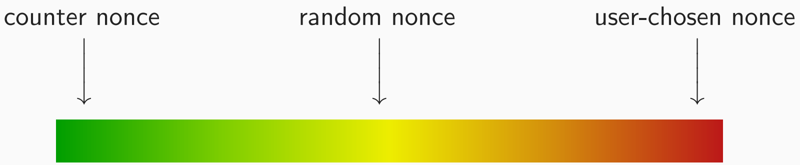
- Tags satisfy $T \oplus T' = M \otimes L \oplus M' \otimes L = (M \oplus M') \otimes L$ $\longrightarrow$ key recovery

Guaranteeing Uniqueness of Nonce



Guaranteeing Uniqueness of Nonce



- Issues with nonce generation:
  - Counter needs storage
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  - Laziness or mistake of implementor
  - ...

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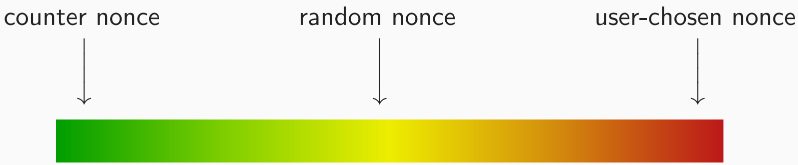

- Issues with nonce generation:
  - Counter needs storage
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  - Laziness or mistake of implementor
  - ...
- Sometimes, attacker can use same nonce multiple times

Nonce-Reuse in Practice

Nonce-Disrespecting Adversaries: Practical Forgery Attacks on GCM in TLS

Böck et al., USENIX WOOT 2016

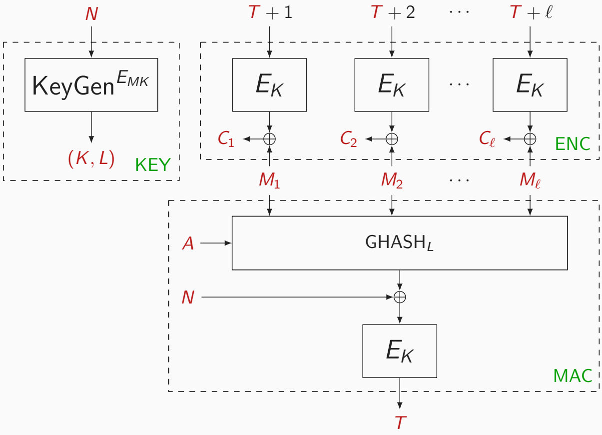
- GCM is widely used authenticated encryption scheme
- Used in TLS ("https")

- Internet-wide scan for GCM implementations
- 184 devices with duplicated nonces
    - VISA, Polish bank, German stock exchange, ...
- $\approx$ 70.000 devices with random nonce

Intuition

- All input should be cryptographically transformed
- Any change in $(N, A, M) \longrightarrow$ unpredictable (C, T)
- Often comes at a price:
  - Efficiency
  - Security
  - Parallelizability
  - ...

GCM-SIV



- Gueron and Lindell (2015)
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- Ongoing standardization (IETF RFC)
- Patent-free

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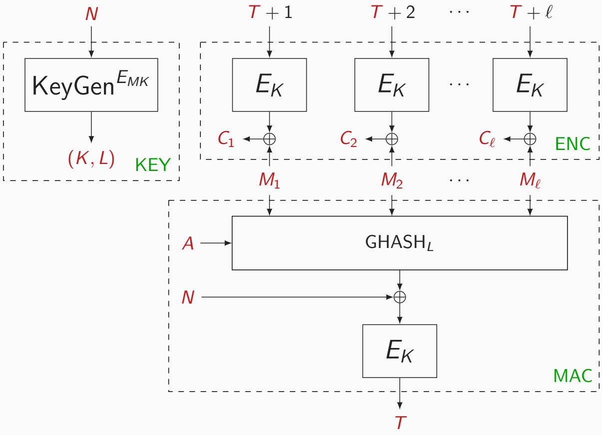
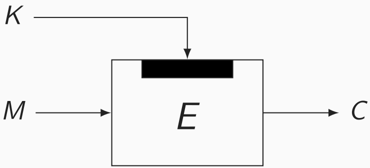


- Gueron and Lindell (2015)
- MtE design
- Ongoing standardization (IETF RFC)
- Patent-free
- Inherits GCM features
- Secure against nonce-reuse
- Proof: Iwata and Seurin (2017)

Tweakable Block Ciphers



- Using key K, message M is bijectively transformed to ciphertext C

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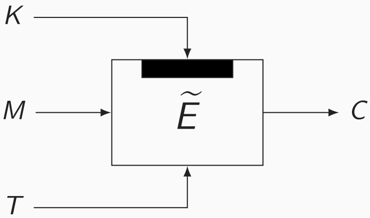

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- Each tweak gives different permutation

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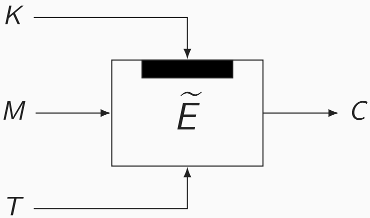
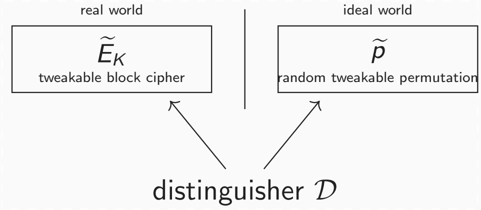


- Using key K, message M is bijectively transformed to ciphertext C
- Tweak T: flexibility to the cipher
- Each tweak gives different permutation
- A good tweakable block cipher should behave like a random tweakable permutation

Tweakable Block Cipher Security



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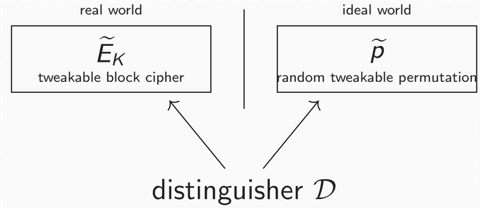

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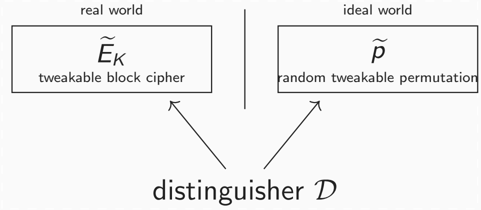

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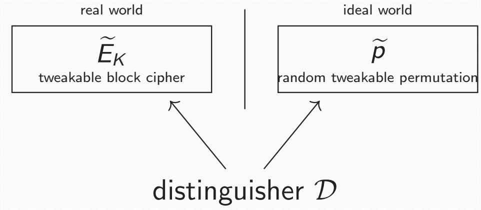

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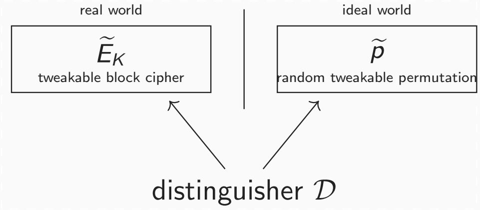

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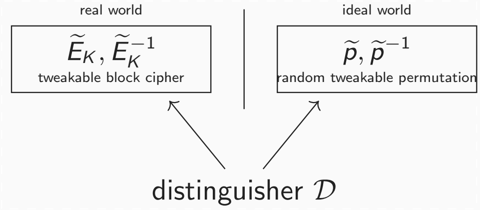

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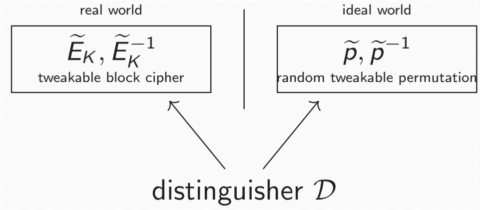

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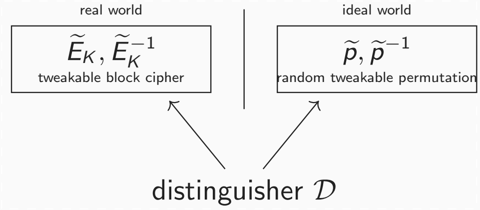

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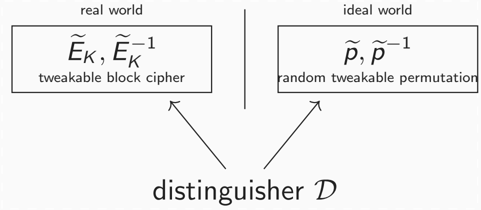

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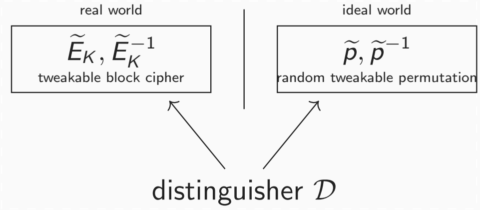

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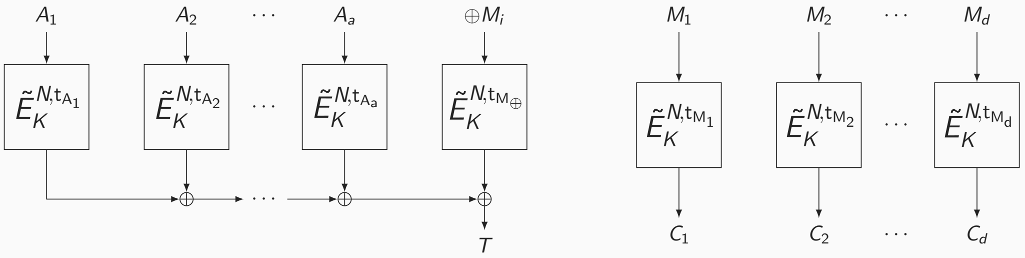

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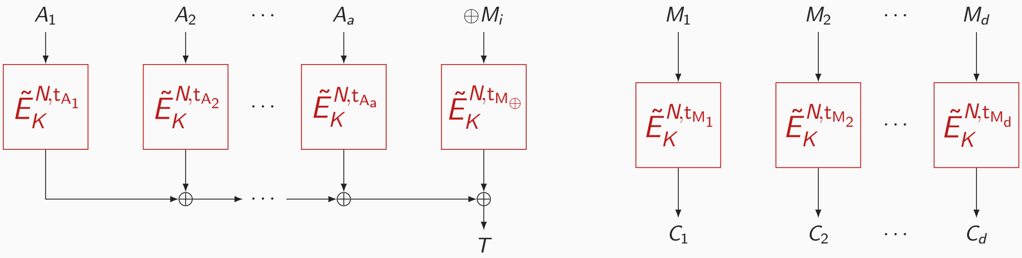

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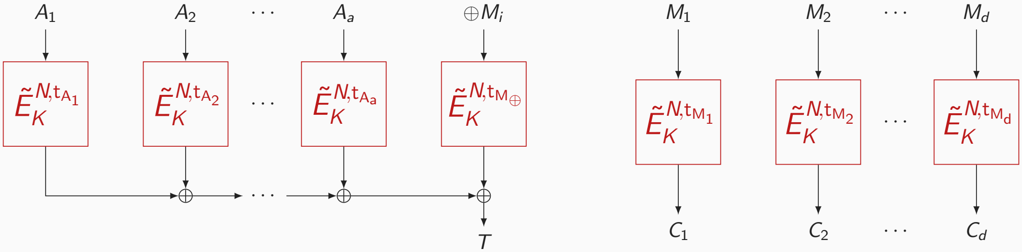
  - Different blocks always transformed under different tweak



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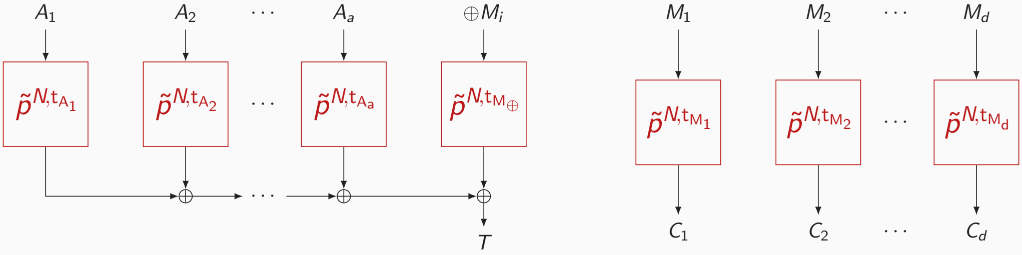

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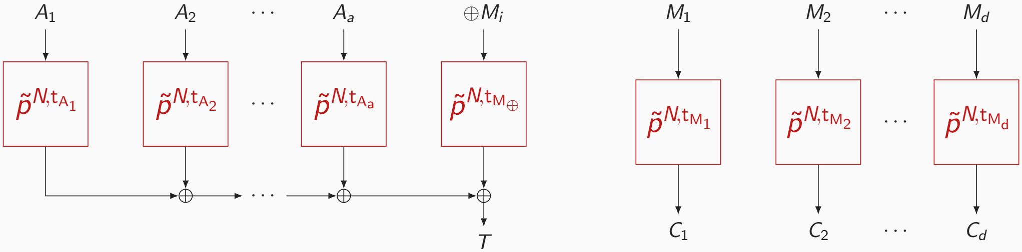
A_1
A_2
A_a
$\oplus M_i$
$\tilde{p}^{N,t_{A_1}}$
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T
M_1
M_2
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C_2
C_d

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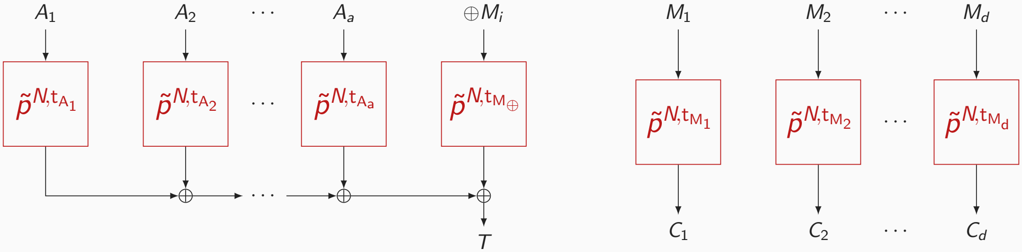
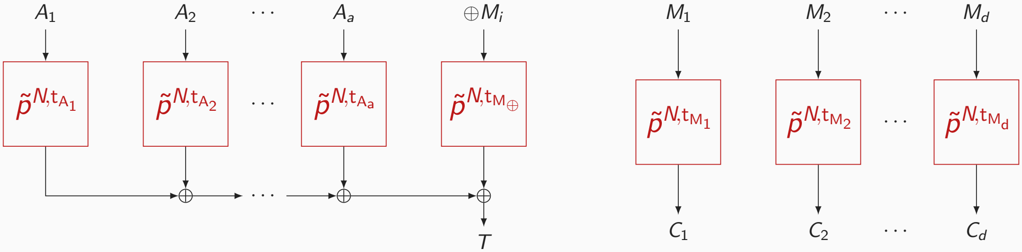


- Nonce uniqueness $\Rightarrow$ tweak uniqueness



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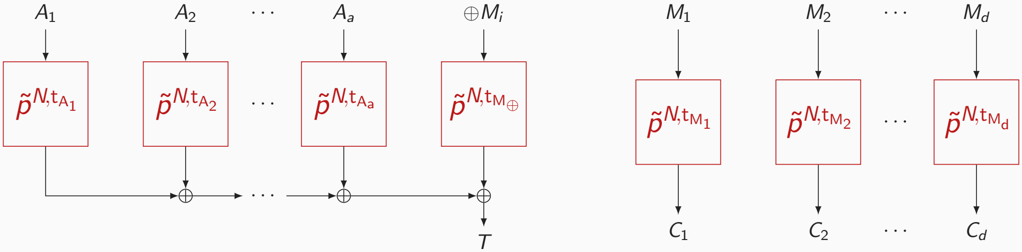

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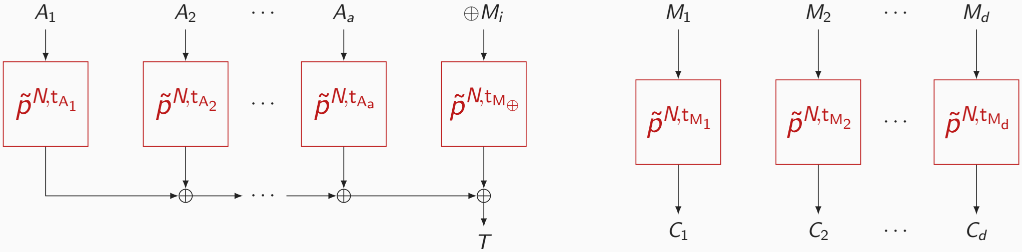

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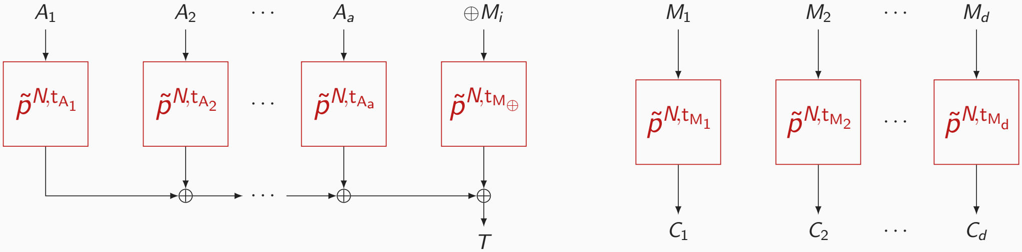

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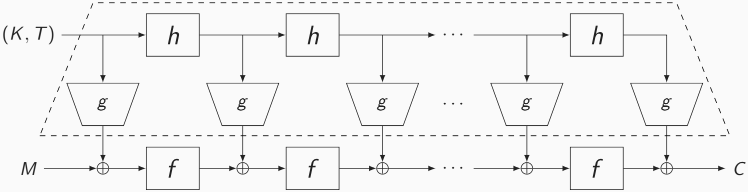
$$\mathbf{Adv}^{\mathrm{ae}}_{\mathrm{AE}[\tilde{p}]}(q) \leq 1/(2^n - 1)$$

Building Tweakable Block Ciphers

- TWEAKEY by Jean et al. [JNP14]:



- f: round function
- g: subkey computation
- h: transformation of (K, T)

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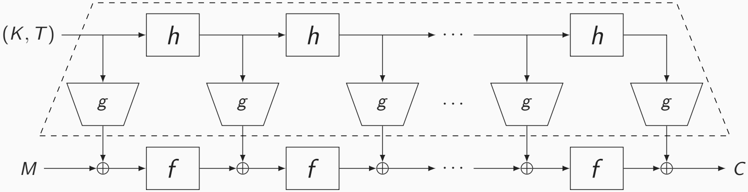

- f: round function
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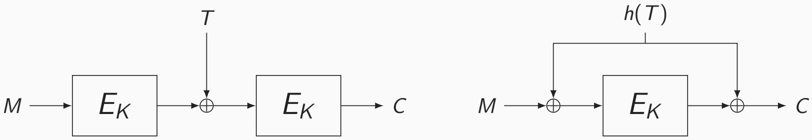
- Security measured through cryptanalysis
- Our focus: modular design

Original Constructions

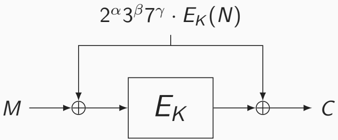
- LRW_1 and LRW_2 by Liskov et al. [LRW02]:



- h is XOR-universal hash
  - E.g., $h(T) = h \otimes T$ for n-bit "key" h

Powering-Up Masking (XEX)

- XEX by Rogaway [Rog04]:



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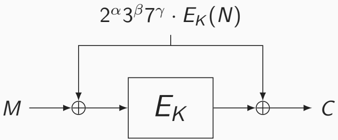

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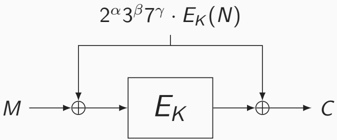

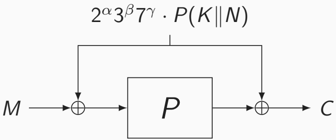

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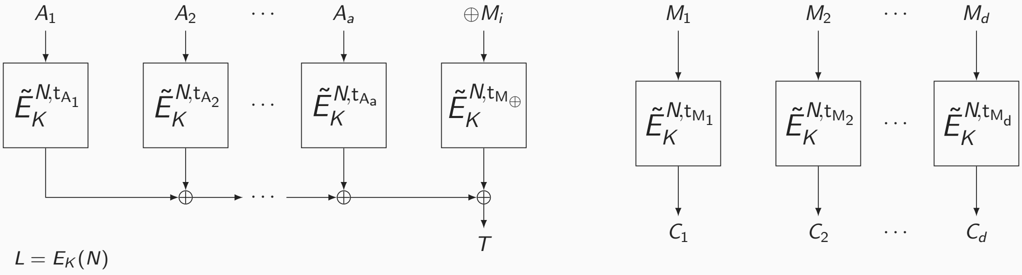
- STPRP up to $2^{n/2}$ queries provided masks are all distinct

Powering-Up Masking in OCB2-Like Construction



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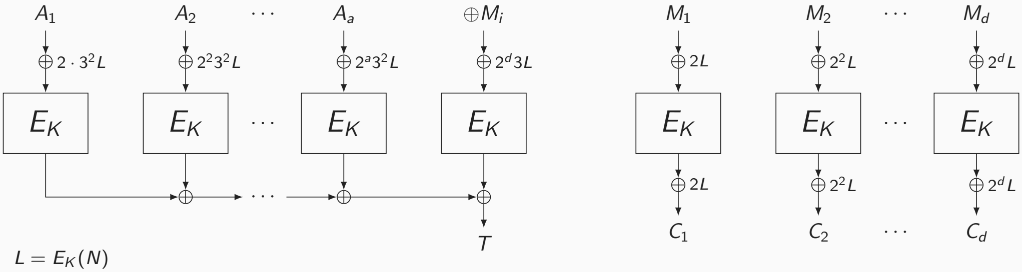

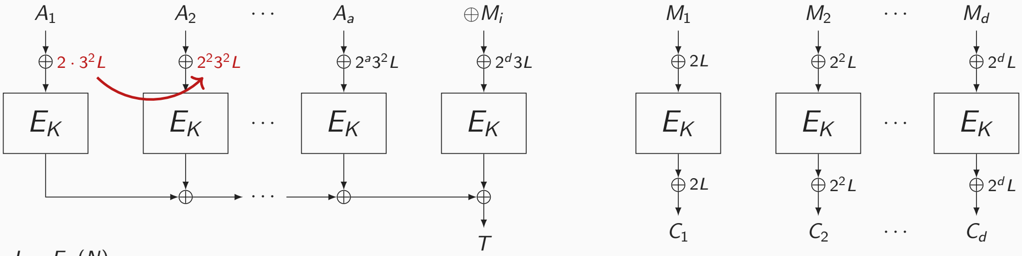
A_1
A_2
A_a
$\oplus M_i$
M_1
M_2
M_d
$2 \cdot 3^2 L$
$2^2 3^2 L$
$2^a 3^2 L$
$2^d 3L$
$2L$
$2^2 L$
$2^d L$
E_K
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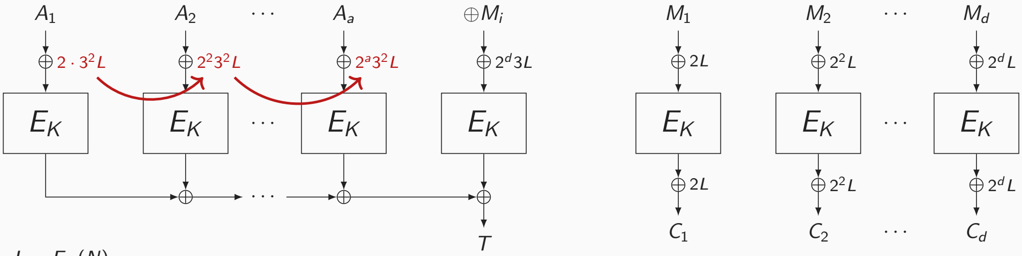
$L = E_K(N)$

Powering-Up Masking in OCB2-Like Construction



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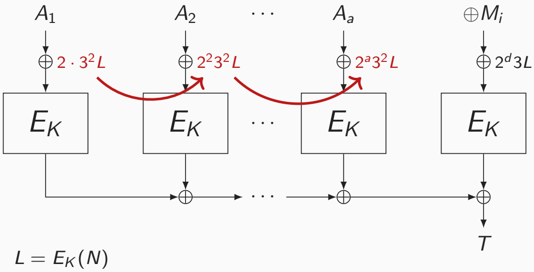

A_1
A_2
$\cdots$
A_a
$\oplus M_i$
$2 \cdot 3^2 L$
$2^2 3^2 L$
$2^a 3^2 L$
$2^d 3L$
E_K
E_K
$\cdots$
E_K
E_K
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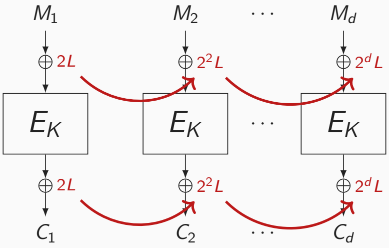
T
$L = E_K(N)$



M_1
M_2
$\cdots$
M_d
$2L$
$2^2 L$
$2^d L$
E_K
E_K
$\cdots$
E_K
$2L$
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$2^d L$
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C_2
$\cdots$
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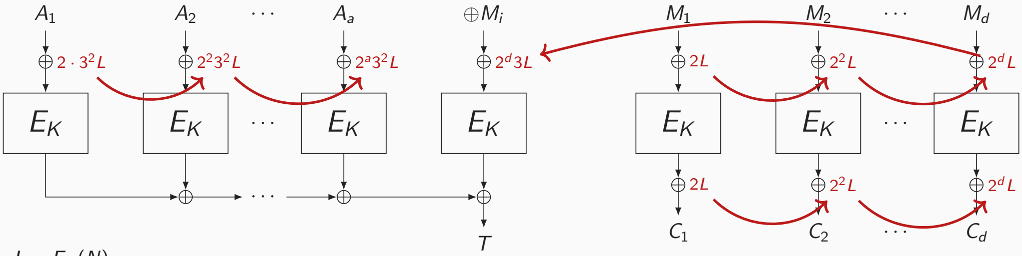

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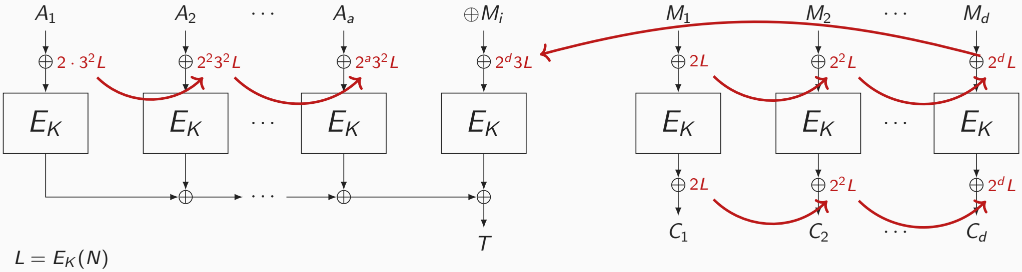
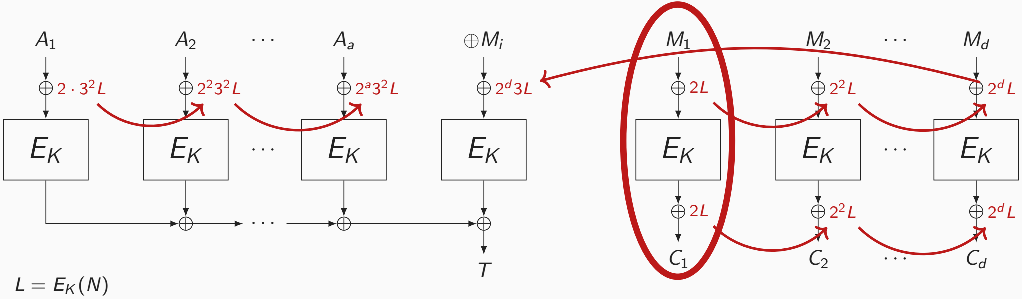


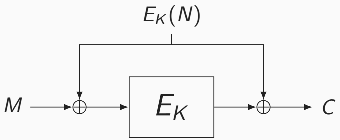
- Update of mask:
  - Shift and conditional XOR
- Variable time computation
- Expensive on certain platforms

Intermezzo: Why Start at $2 \cdot E_K(N)$? (1/2)



- Update of mask:
    - Shift and conditional XOR
- Variable time computation
- Expensive on certain platforms

- Suppose we would mask with $E_K(N)$:



Intermezzo: Why Start at $2 \cdot E_K(N)$? (2/2)

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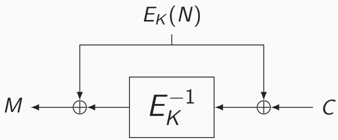

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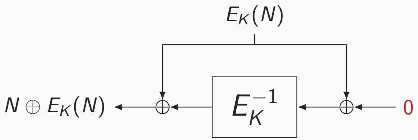

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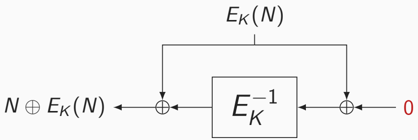
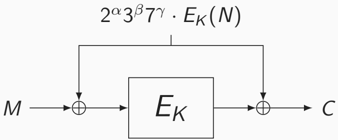


- Distinguisher can make inverse queries
- Putting $C = 0$ gives $M = N \oplus E_K(N)$
- Distinguisher knows N so learns "subkey" $E_K(N)$

Powering-Up Masking (XEX): Setting Admissible Domain

- XEX by Rogaway [Rog04]:



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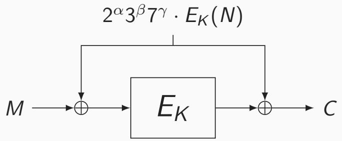

- $(\alpha, \beta, \gamma, N)$ is tweak (simplified)
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- We need that $2^\alpha 3^\beta 7^\gamma \neq 2^{\alpha'} 3^{\beta'} 7^{\gamma'}$ for any $(\alpha, \beta, \gamma) \neq (\alpha', \beta', \gamma')$
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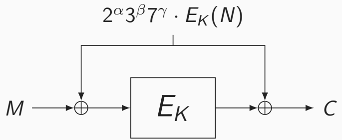

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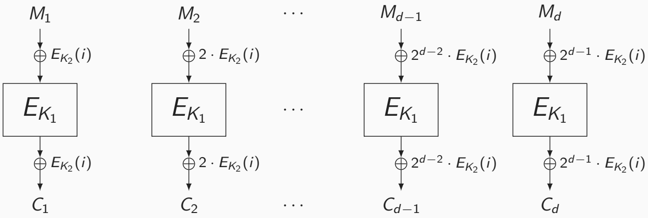
  - Otherwise, attacker can obviously break the scheme
- Typical: $\alpha \in \{1, \ldots, \text{large}\}$, and $\beta, \gamma \in \{0, 1, 2\}$

Intermezzo: XTS Disk Encryption Mode (1/2)



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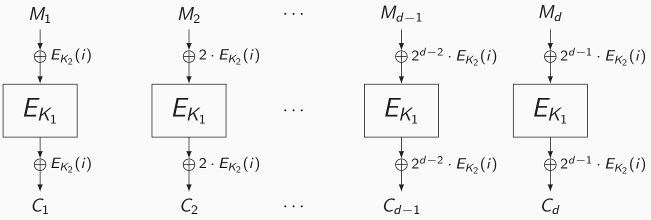

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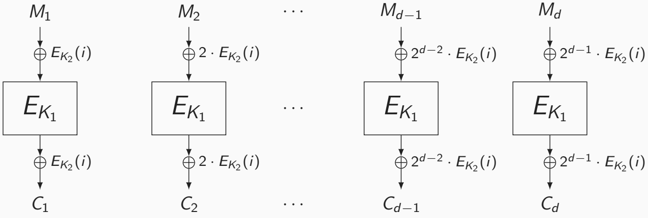

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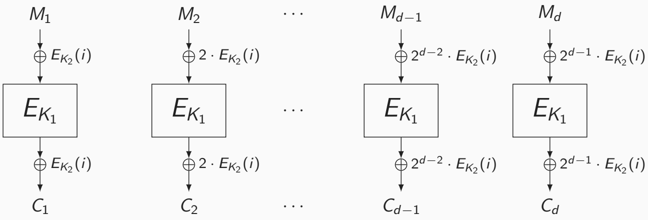

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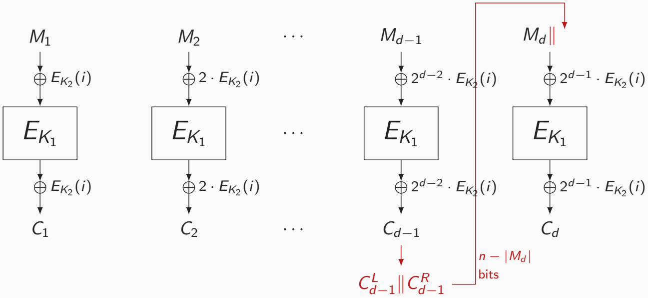

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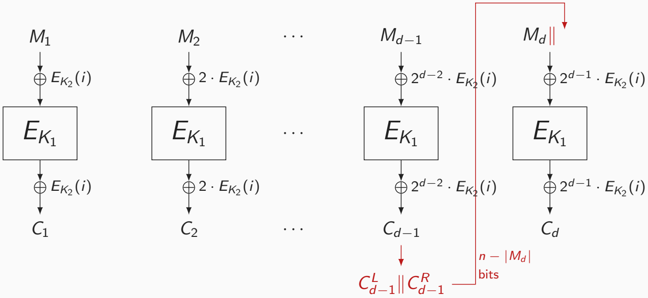

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  - Electronic CodeBook (ECB) ...
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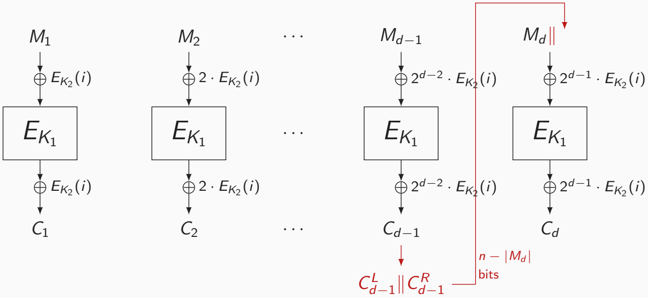
- One sector consists of 512 bytes, or 32 blocks

Intermezzo: XTS Disk Encryption Mode (2/2)



- Features:
  - Tweak unique for every block, changing tweak is efficient
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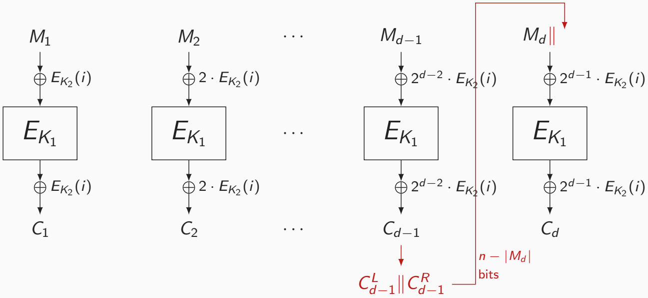
Intermezzo: XTS Disk Encryption Mode (2/2)



- Features:
  - Tweak unique for every block, changing tweak is efficient
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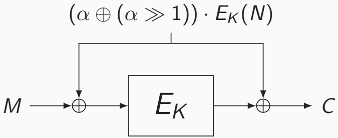
- XTS-AES is standardized as IEEE P1619
- Supported by myriad disk encryption tools: BestCrypt, dm-crypt, TrueCrypt, VeraCrypt, DiskCryptor, FileVault 2 (MacOS), BitLocker (Windows 10)

Gray Code Masking

- OCB1 and OCB3 use Gray Codes:



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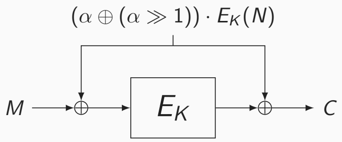
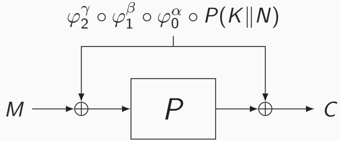


- (α, N) is tweak
- Updating: $G(\alpha) = G(\alpha - 1) \oplus 2^{\mathrm{ntz}(\alpha)}$
    - Single XOR
    - Logarithmic amount of field doublings (precomputed)
- More efficient than powering-up [KR11]

Masked Even-Mansour (MEM)

- MEM by Granger et al. [GJMN16]:



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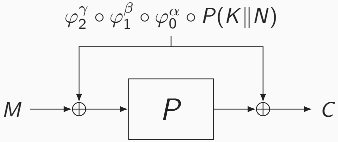

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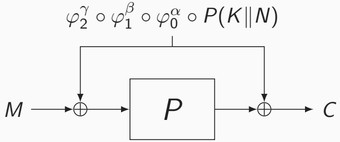
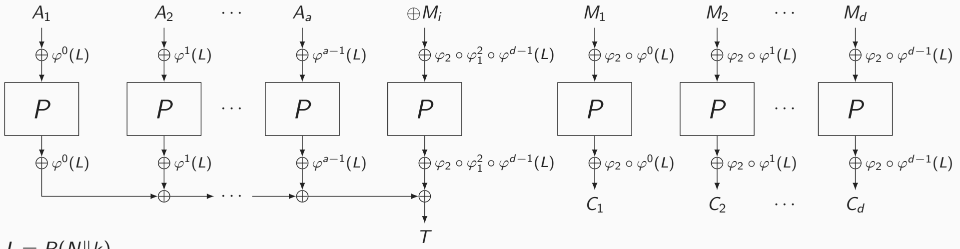


- φ_i are fixed LFSRs, $(\alpha, \beta, \gamma, N)$ is tweak (simplified)
- Combines advantages of:
  - Powering-up masking
  - Word-based LFSRs
- Simpler, constant-time (by default), more efficient

Application to AE: OPP



$L = P(N \| k)$

$\varphi_1 = \varphi \oplus id$, $\varphi_2 = \varphi^2 \oplus \varphi \oplus id$

- Offset Public Permutation (OPP)
- Generalization of OCB3:
  - Permutation-based
  - More efficient MEM masking
- Security against nonce-respecting adversaries

NIST Competition

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- Some submissions were sponge-based (like Ascon)
- Some submissions used techniques from this lecture