Breaking the IEEE Encryption Standard XCB-AES in Two Queries

CRYPTO 2025

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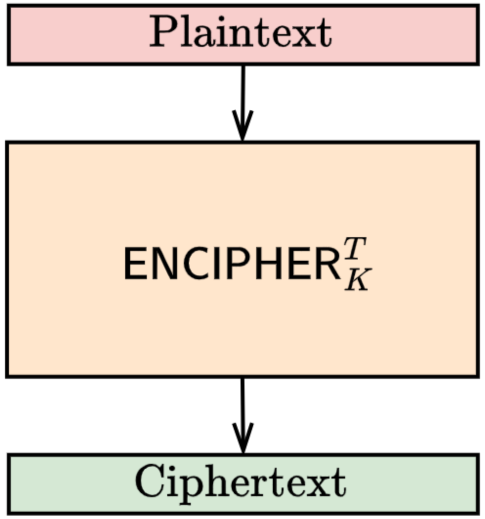
Tweakable Enciphering Modes (TEMs)

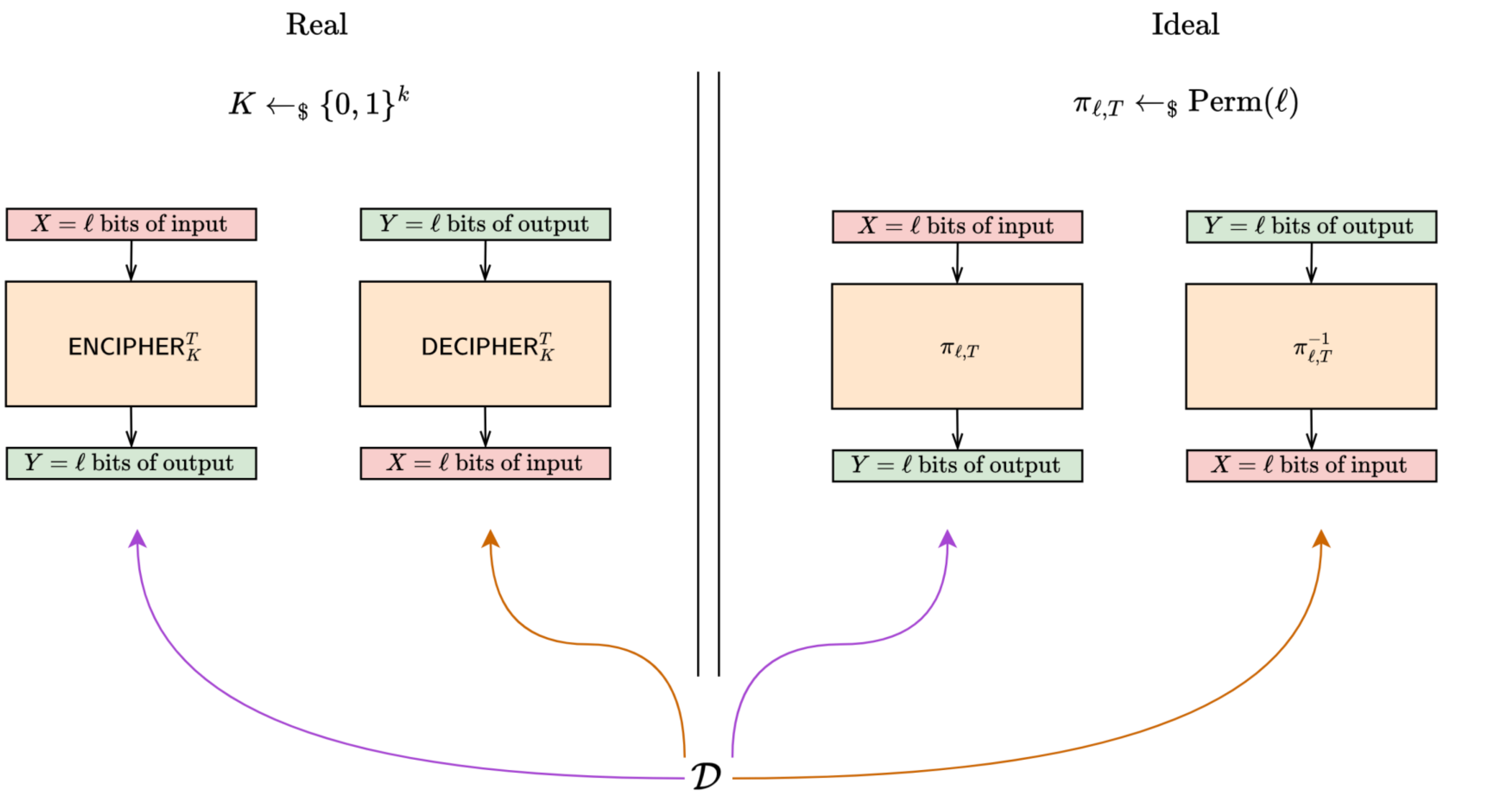
Tweakable Enciphering Mode (TEM) [HR03]



1. Length Preserving Encryption (LPE)
2. Generalization of (tweakable) block ciphers
   - Variable tweak and input size
3. NIST reintroduced it as accordion mode [CD+24]
4. Uses: disk-sector and full-disk encryption, key-wrapping, robust AEAD [HKR17]

What is a Secure TEM?

TEM Security [HR03]



- Variable-Input-Length Strong Tweakable Pseudo-Random Permutation (VIL-STPRP)
- Analogous to IND-CCA encryption notion

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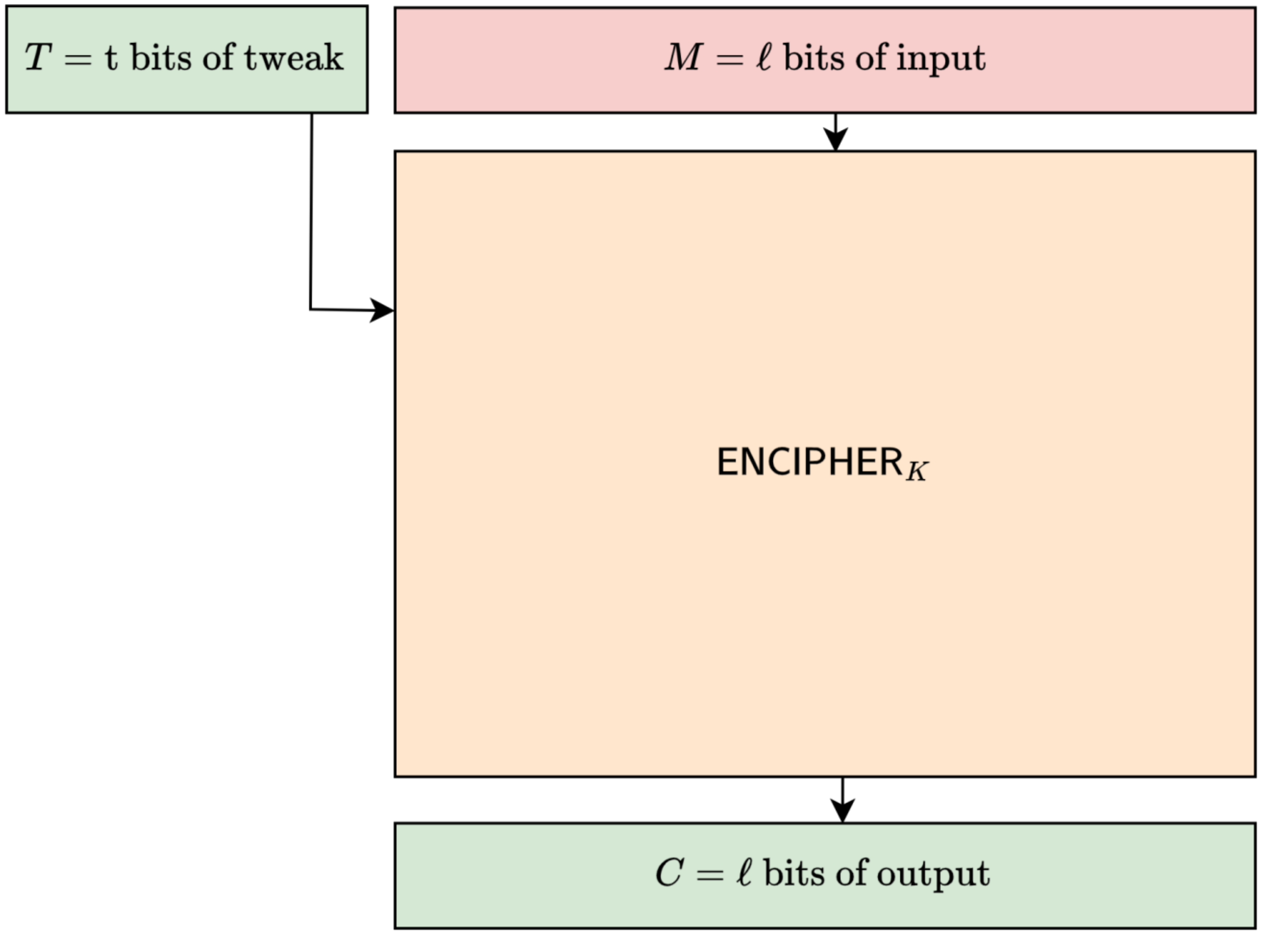
XCB-AES: IEEE 1619.2 TEM Standard

XCB-AES: IEEE 1619.2 TEM Standard [MF07]

- A TEM standardized for storage media encryption (2010, 2021)
- An efficient Hash-CTR-Hash design
- Built on AES and polynomial hashing
- Alias XCBv2fb

XCB-AES: IEEE 1619.2 TEM Standard [MF07]



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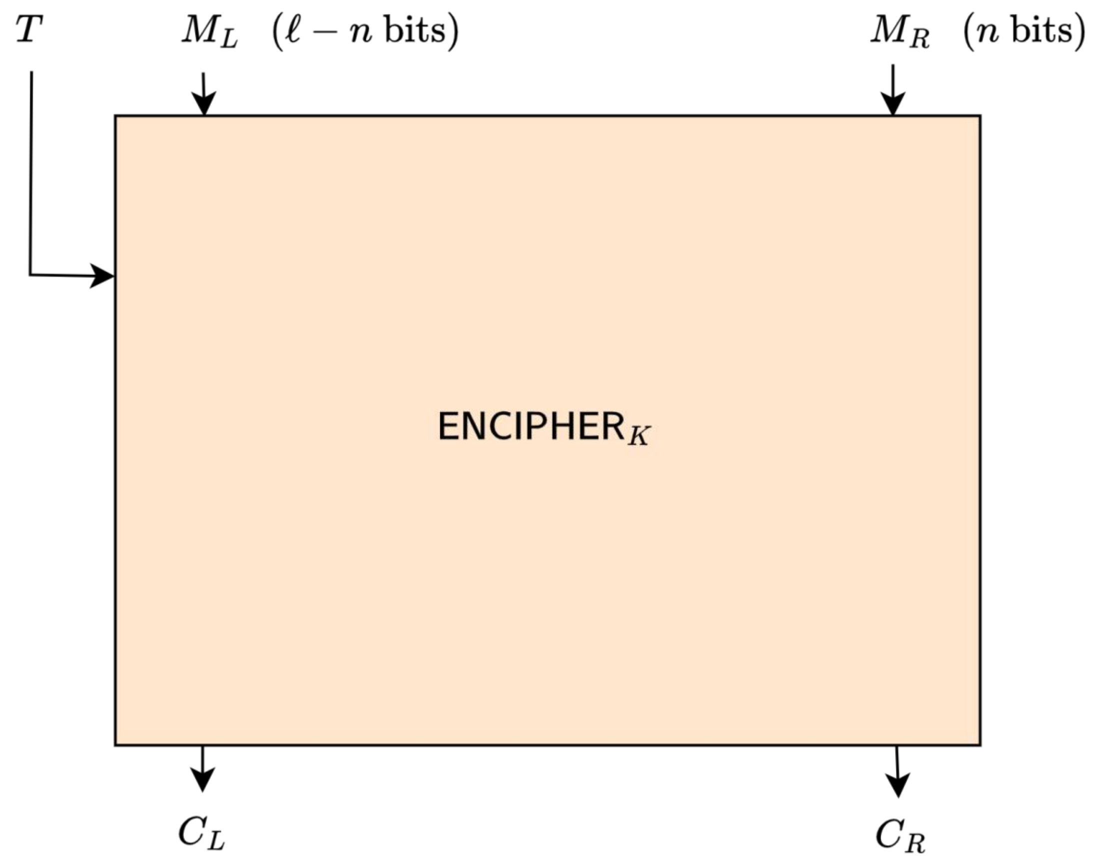

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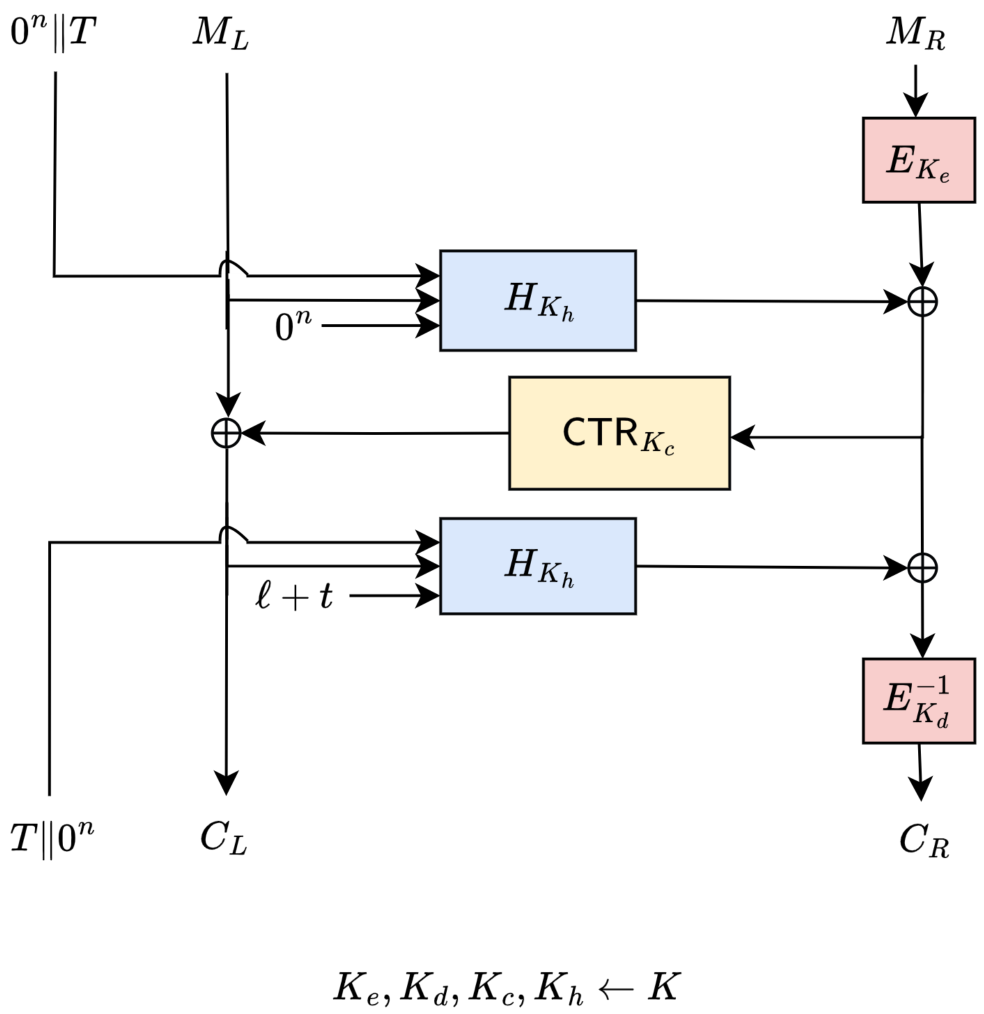

- Internal components
  1. CTR = Counter mode
  2. E = AES blockcipher
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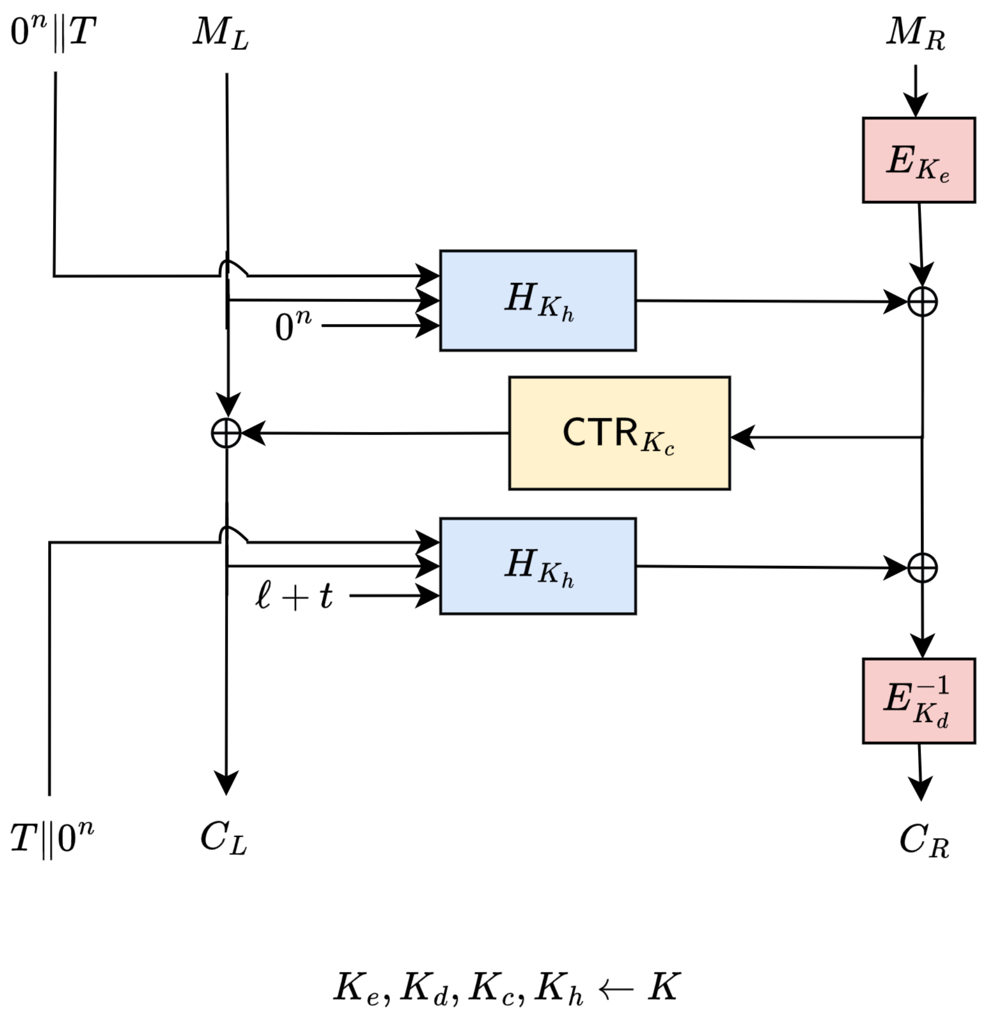

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$$\text{Poly}_K(A_1 \| A_2 \| \ldots) = A_1 K \oplus A_2 K^2 \oplus \ldots$$

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- **2010** IEEE standardized XCB-AES for storage media encryption
- **2013** Padding attack found on XCB-AES [CHS13]
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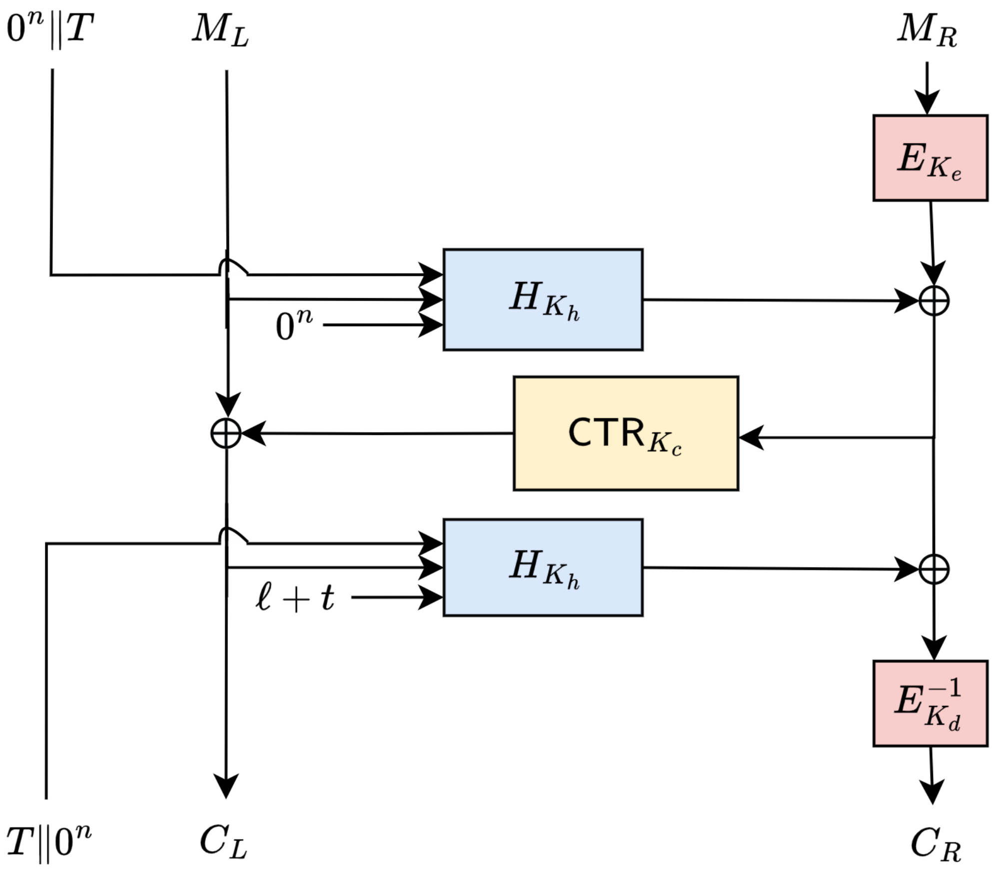
2024 We break XCB-AES's VIL-STPRP, STPRP and SPRP security in 2 queries

Our attack applies to all other XCB-style modes as well

Our Result 1:
A 2-Query Plaintext Recovery Attack

Our Shared Difference Attack



$K_e, K_d, K_c, K_h \leftarrow K$

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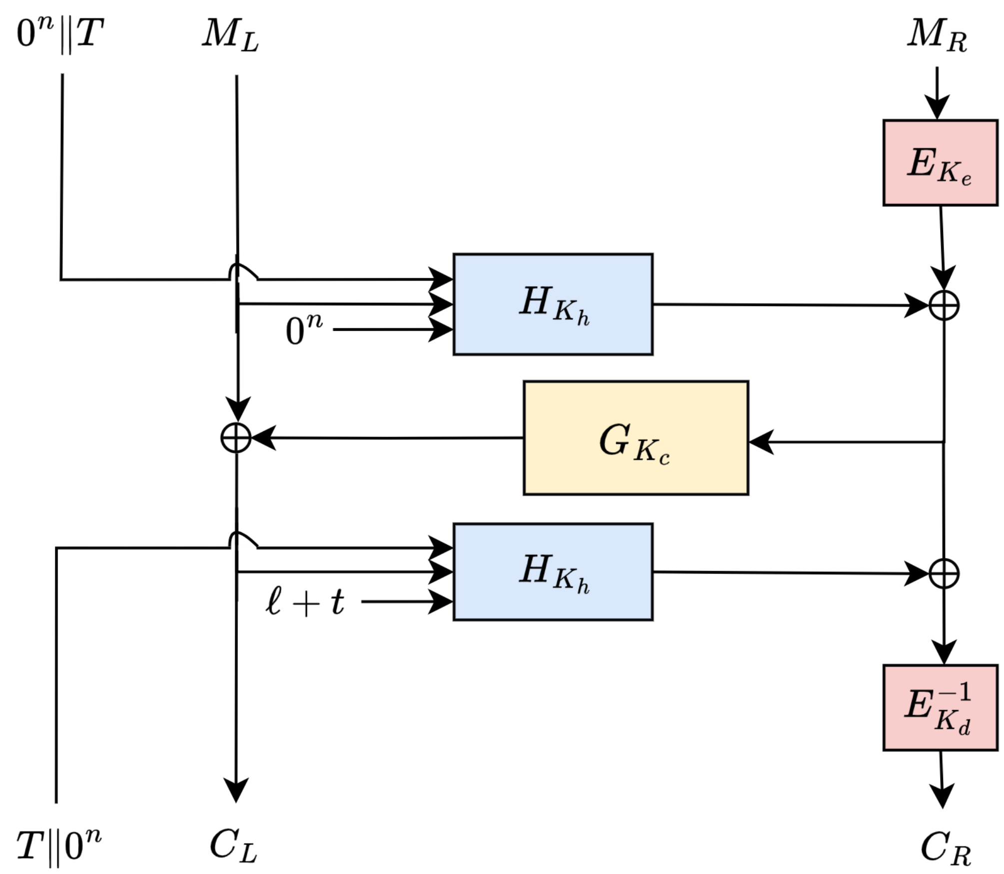

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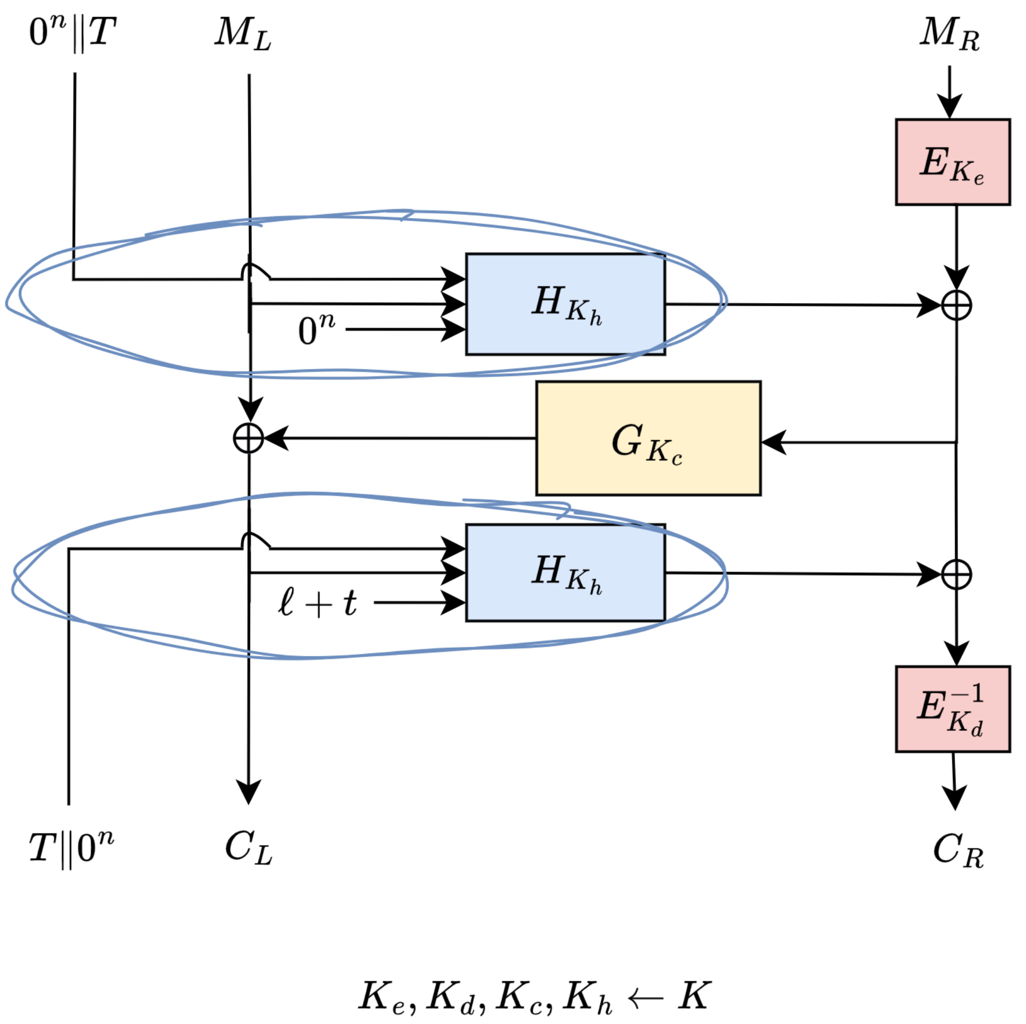

- $H_{K_h}(0^n\|T, M_L, 0^n)$

$$= \mathsf{Poly}_{K_h}(0^n\|\mathsf{pad}_n(T)\|\mathsf{pad}_n(M_L)\|0^n)$$

- $H_{K_h}(T\|0^n, C_L, \ell + t)$

$$= \mathsf{Poly}_{K_h}(\mathsf{pad}_n(T)\|0^n\|\mathsf{pad}_n(C_L)\|\mathsf{bin}_n(\ell + t))$$

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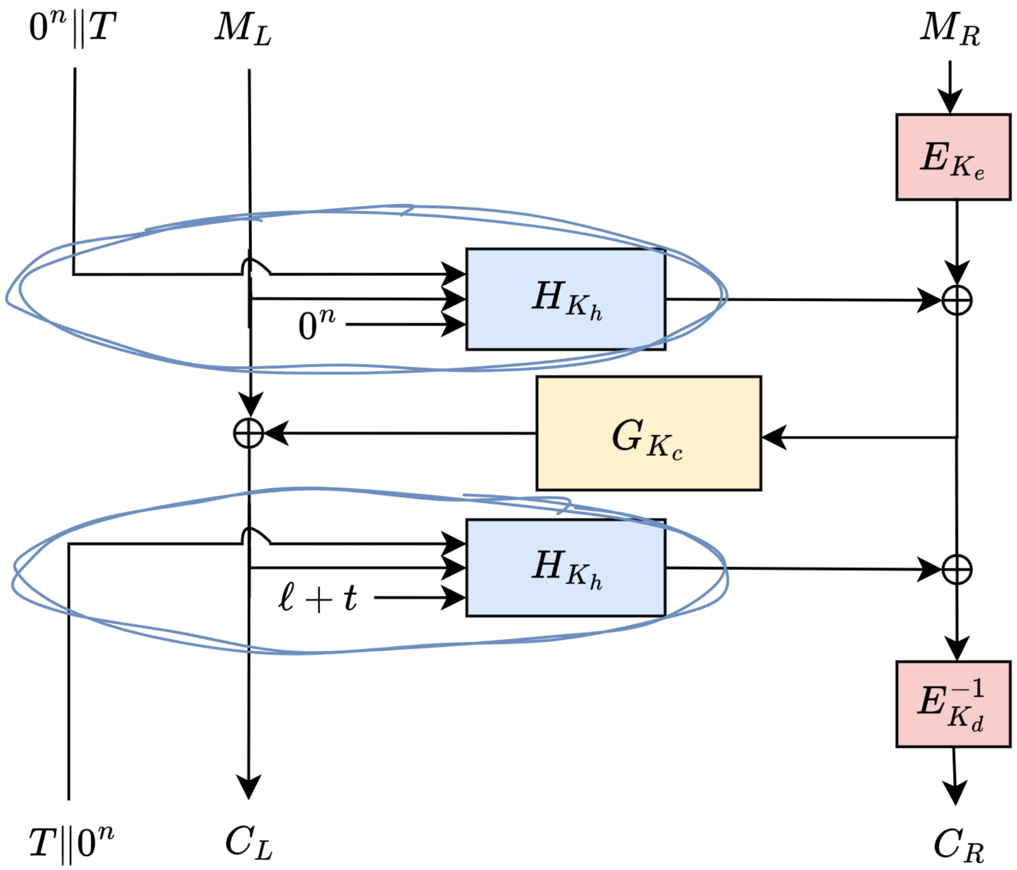

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$$= H_1(K_h, T, M_L)$$

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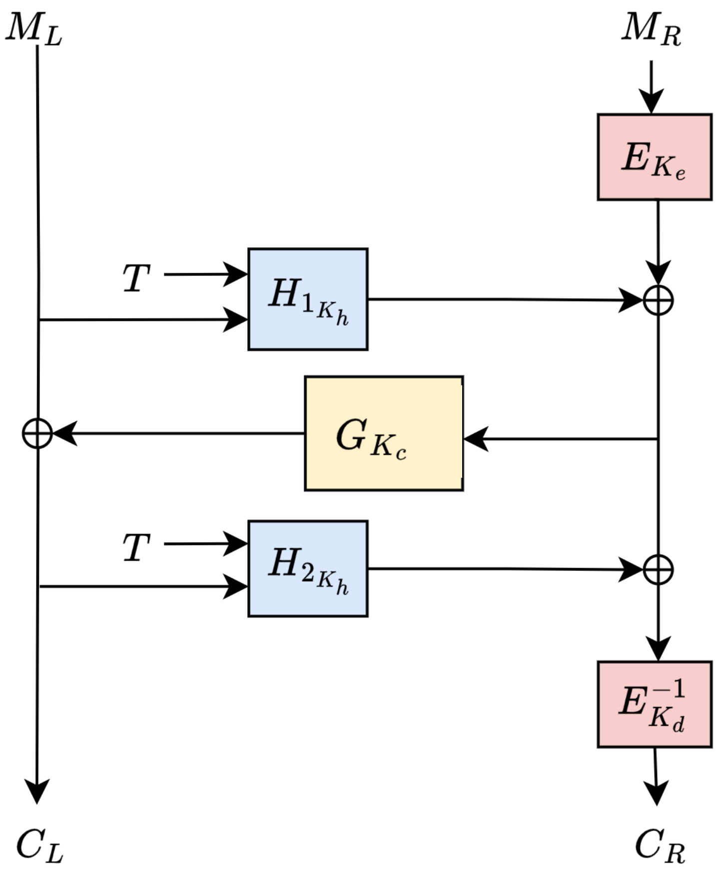

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Polynomial Hash Separability

$$\mathsf{Poly}_K(A_1 \| A_2 \| (A_3 \oplus \Delta) \| A_4) = A_1 K \oplus A_2 K^2 \oplus (A_3 \oplus \Delta) K^3 \oplus A_4 K^4$$

$$= A_1 K \oplus A_2 K^2 \oplus A_3 K^3 \oplus A_4 K^4 \oplus \Delta K^3$$

$$= \mathsf{Poly}_K(A_1 \| A_2 \| A_3 \| A_4) \oplus \mathsf{Poly}_K(0^n \| 0^n \| \Delta \| 0^n)$$

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$$H_1(K_h, T, M_L \oplus \Delta) = \mathsf{Poly}_{K_h}(0^n \| \mathsf{pad}_n(T) \| \mathsf{pad}_n(M_L \oplus \Delta) \| 0^n)$$

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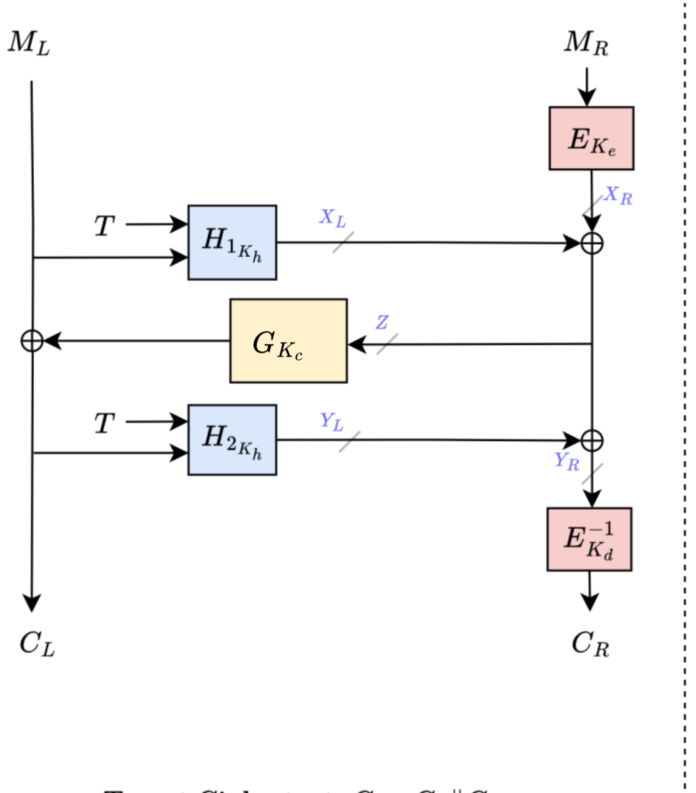

Target Ciphertext: $C = C_L \| C_R$

$\mathcal{A}$

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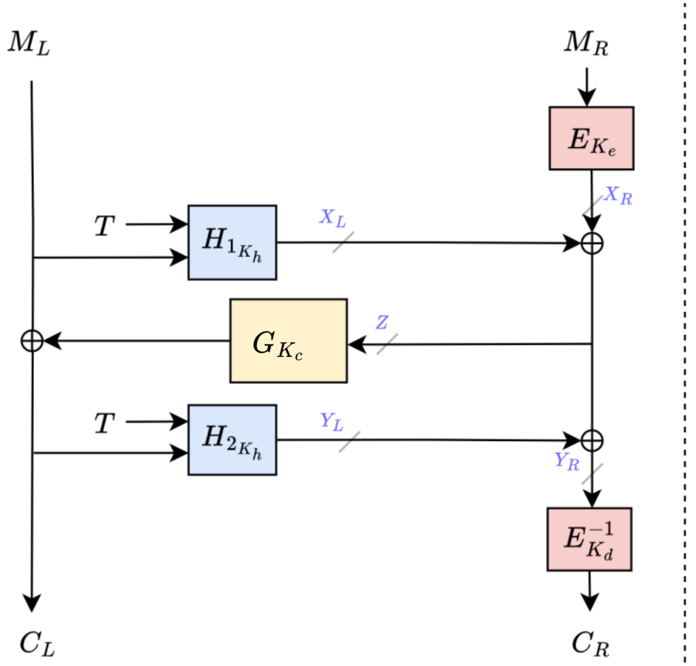

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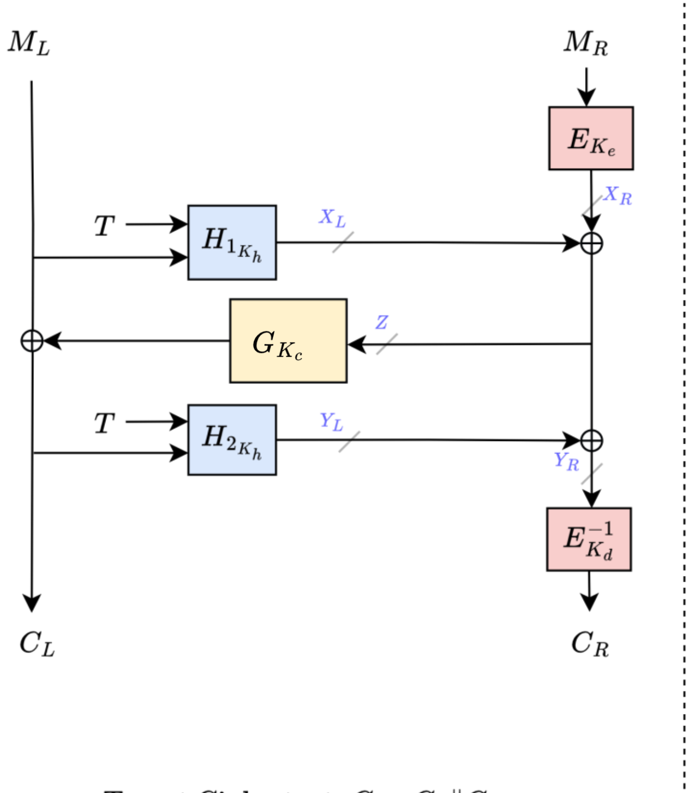

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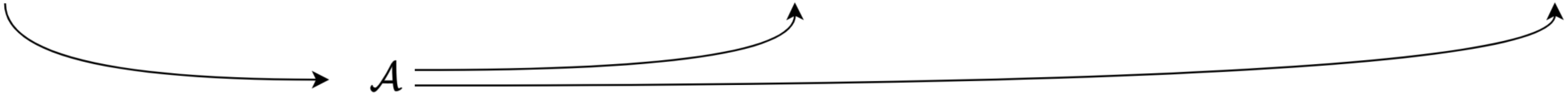

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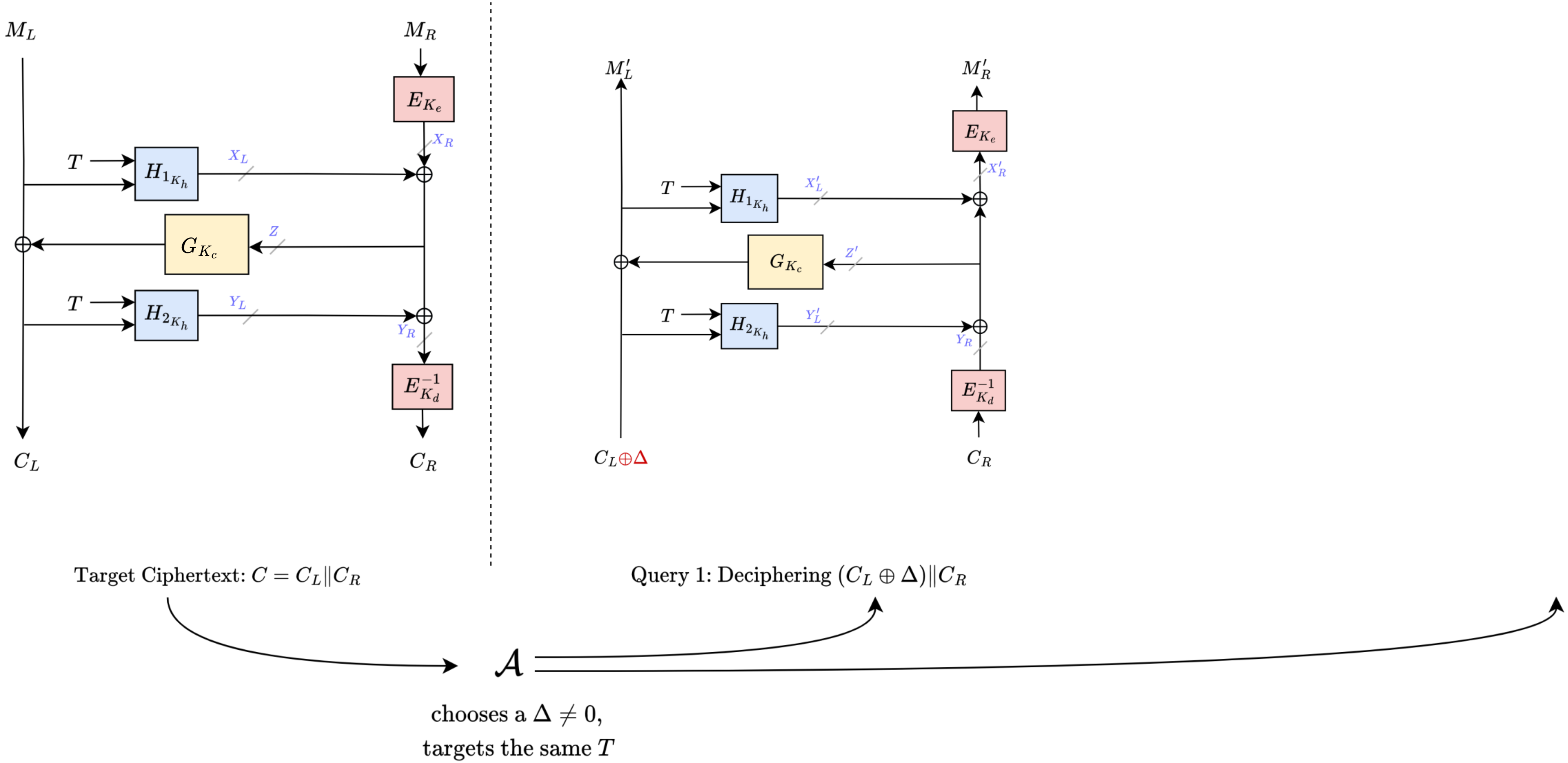

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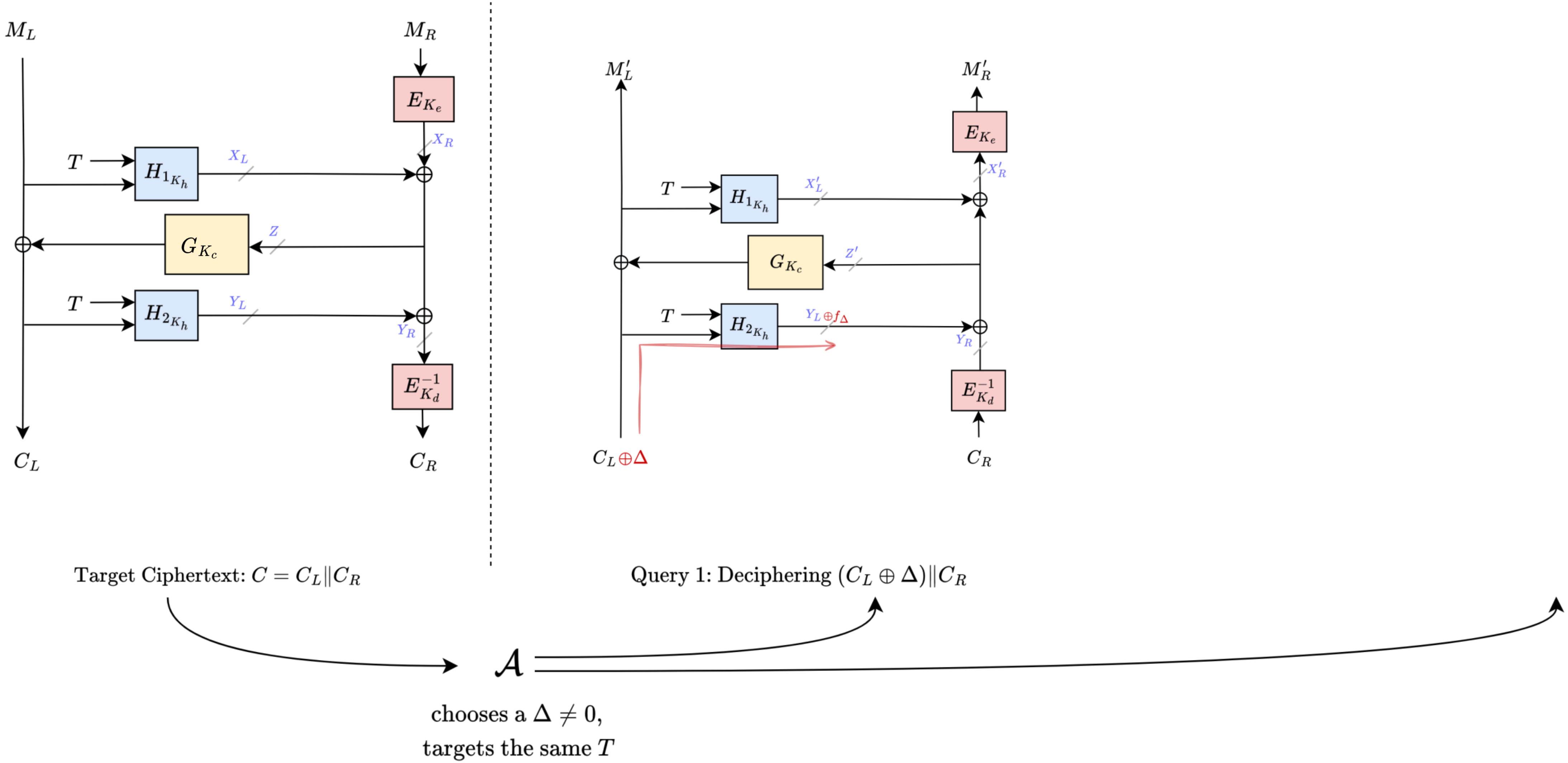

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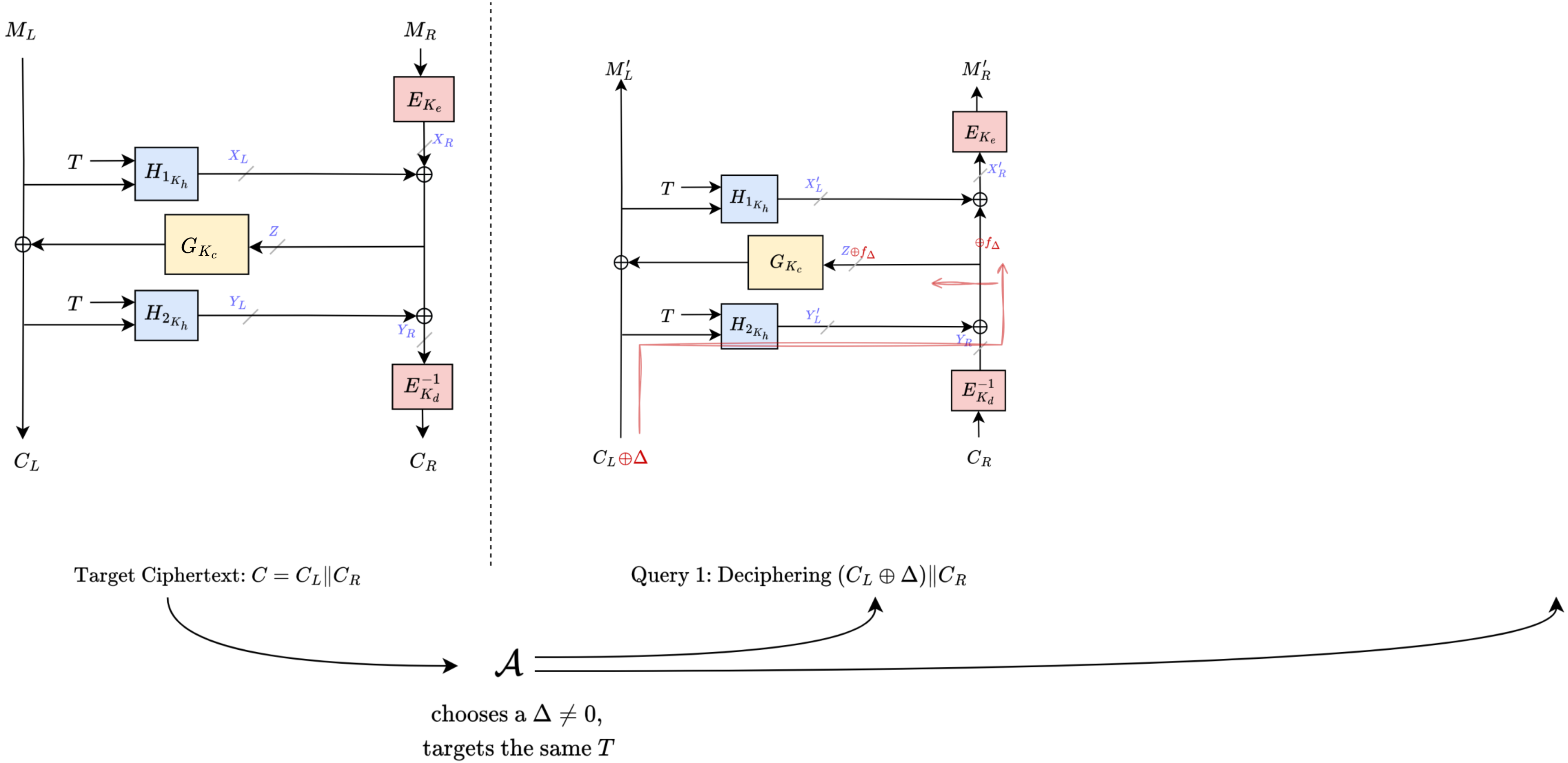

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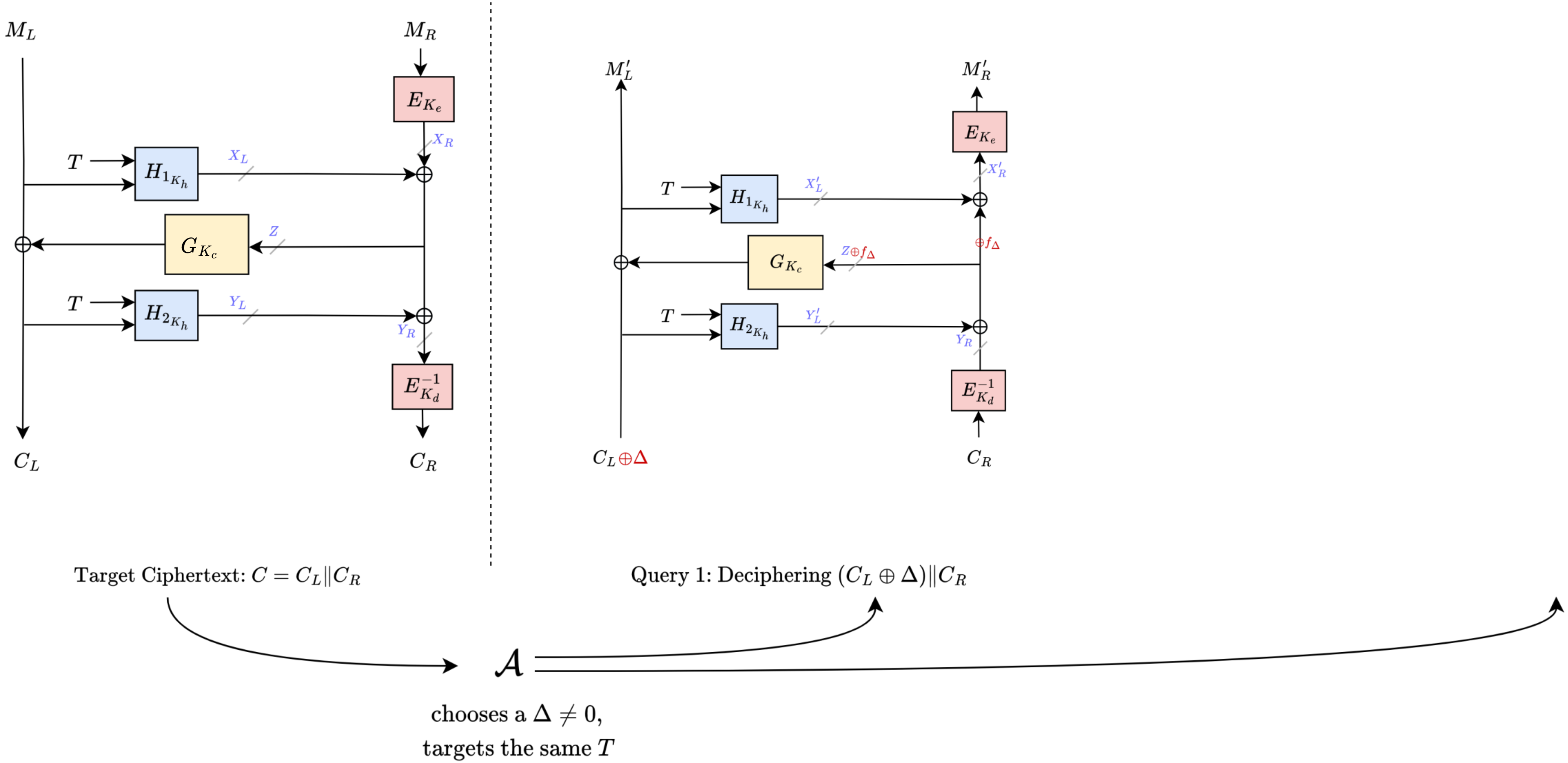

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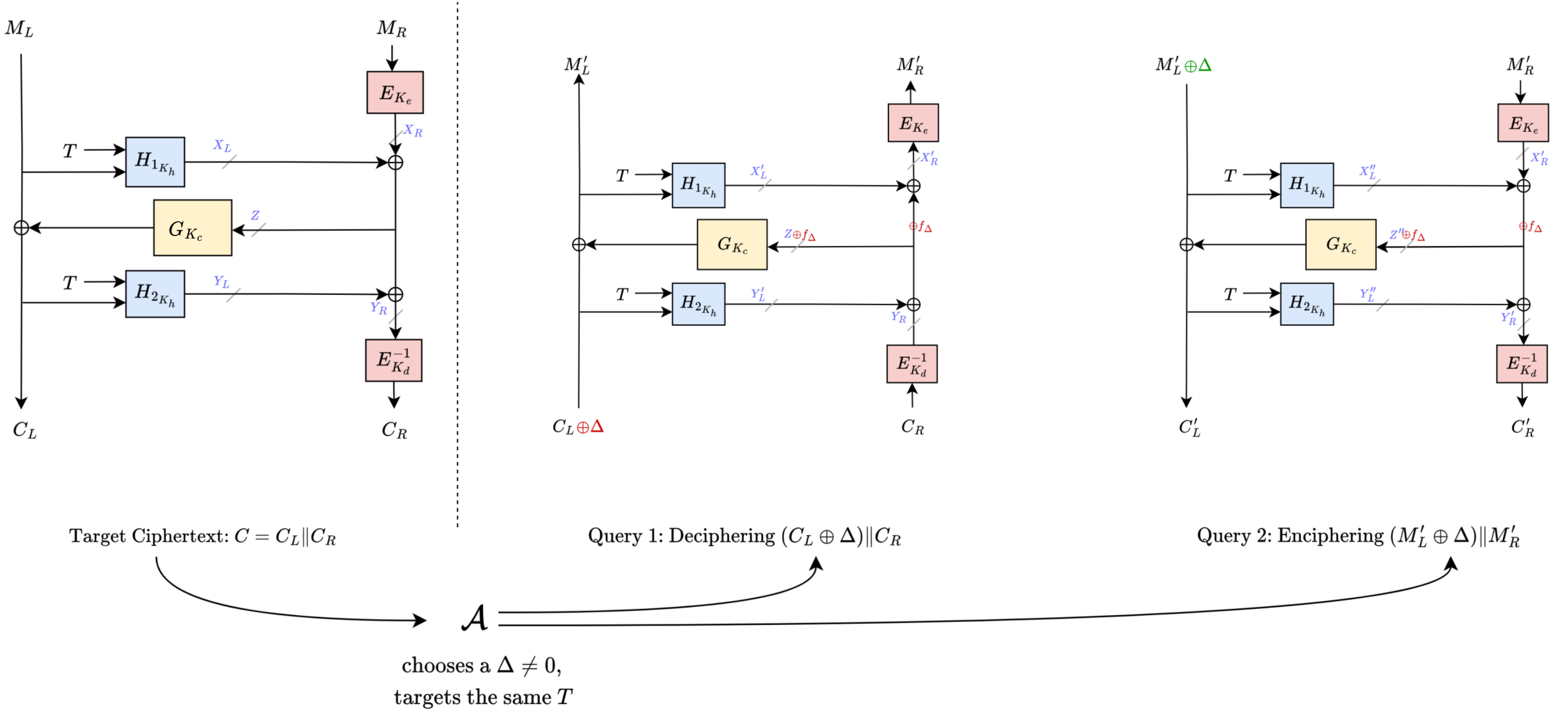

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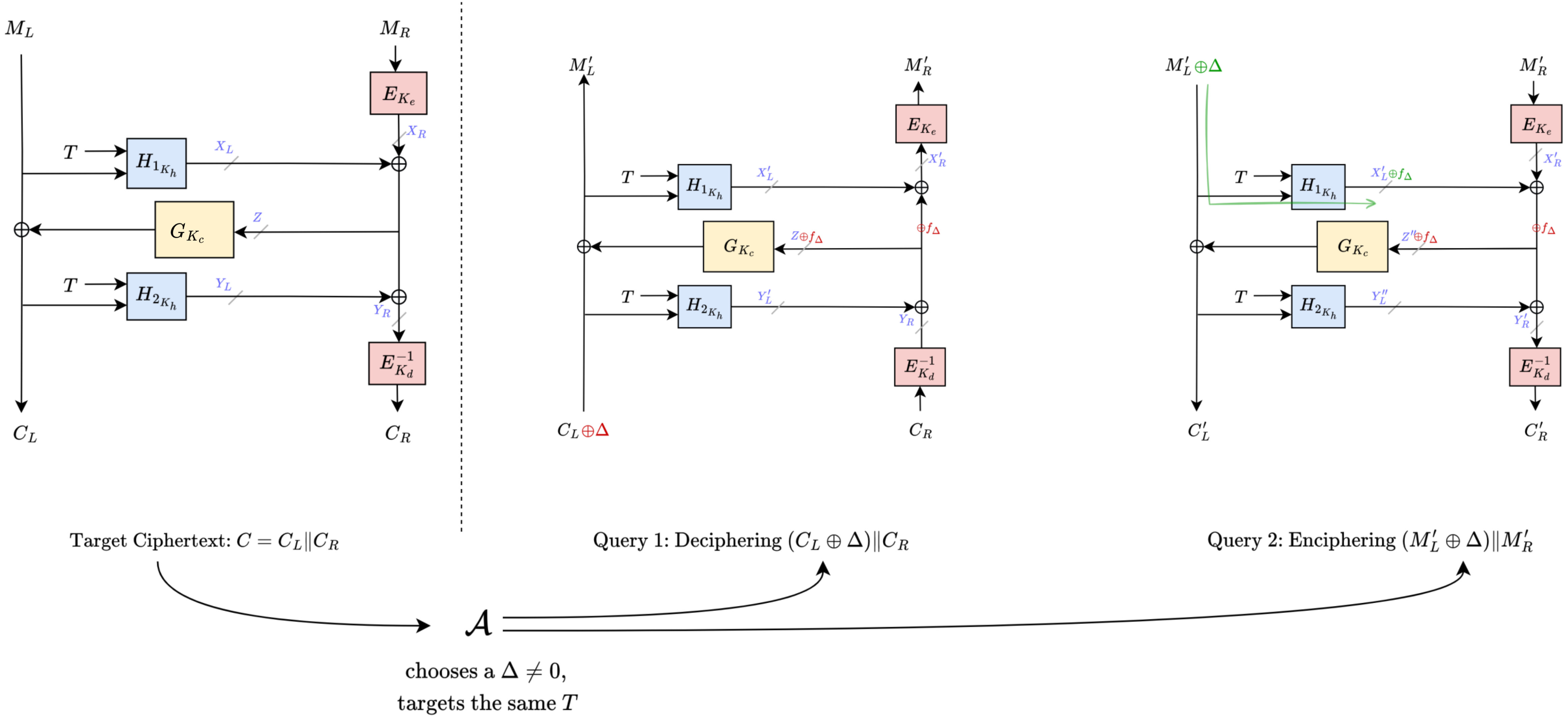

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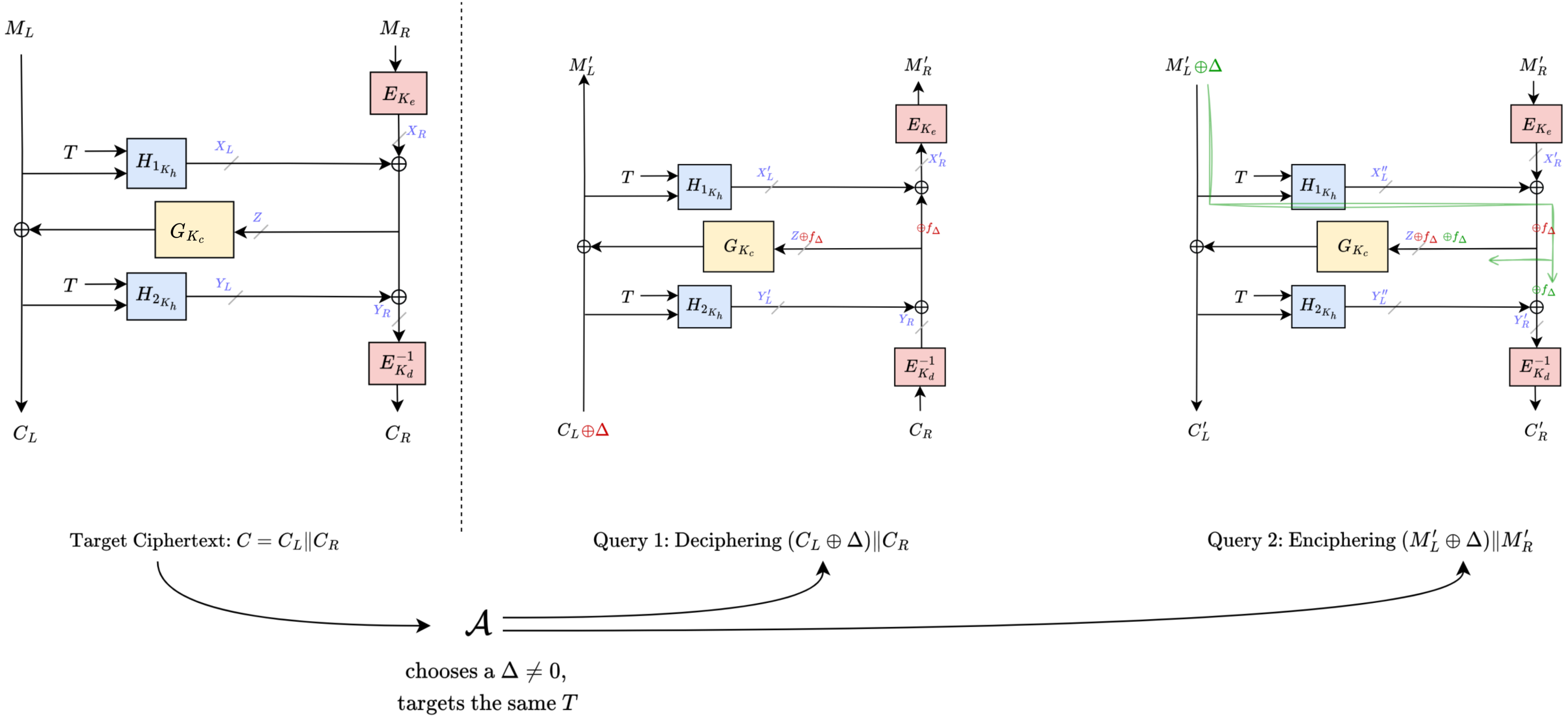

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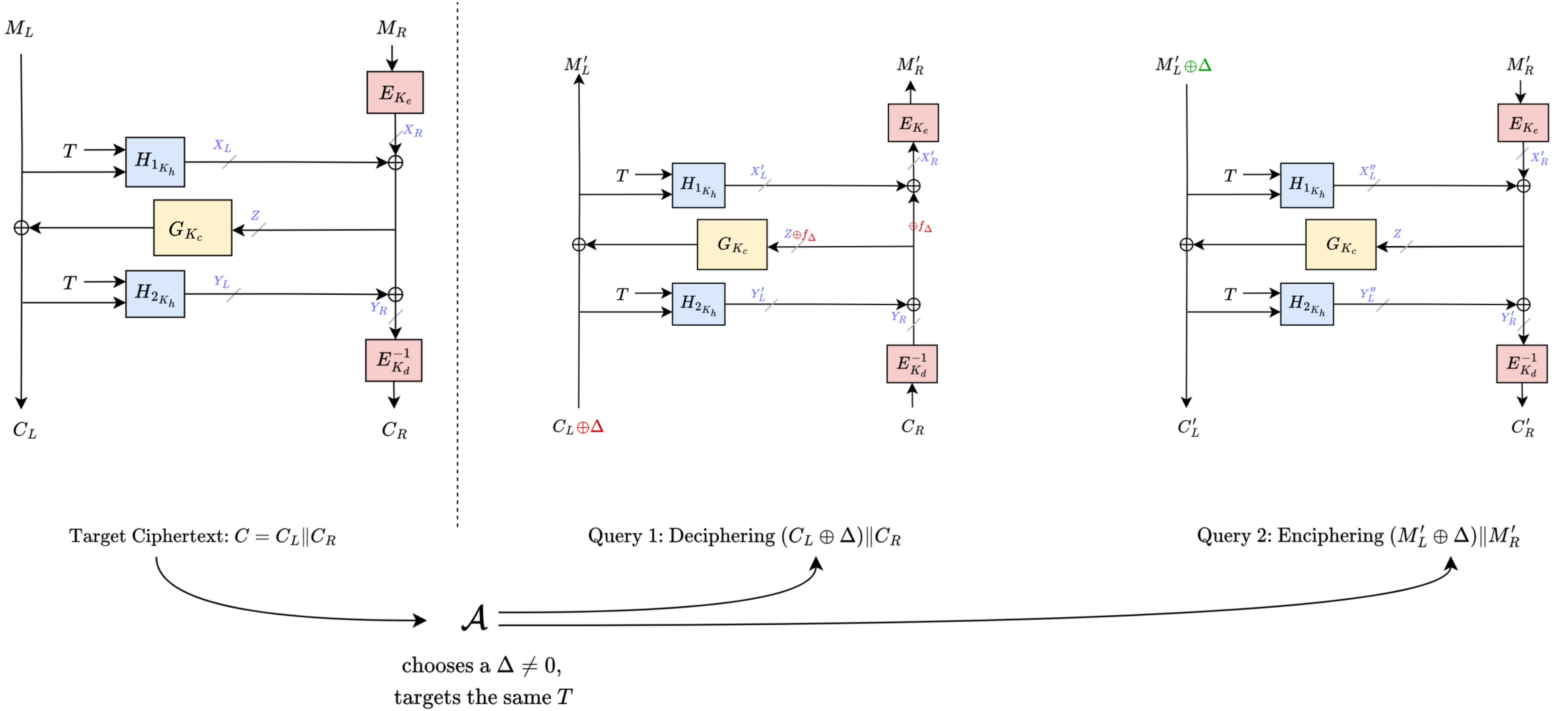

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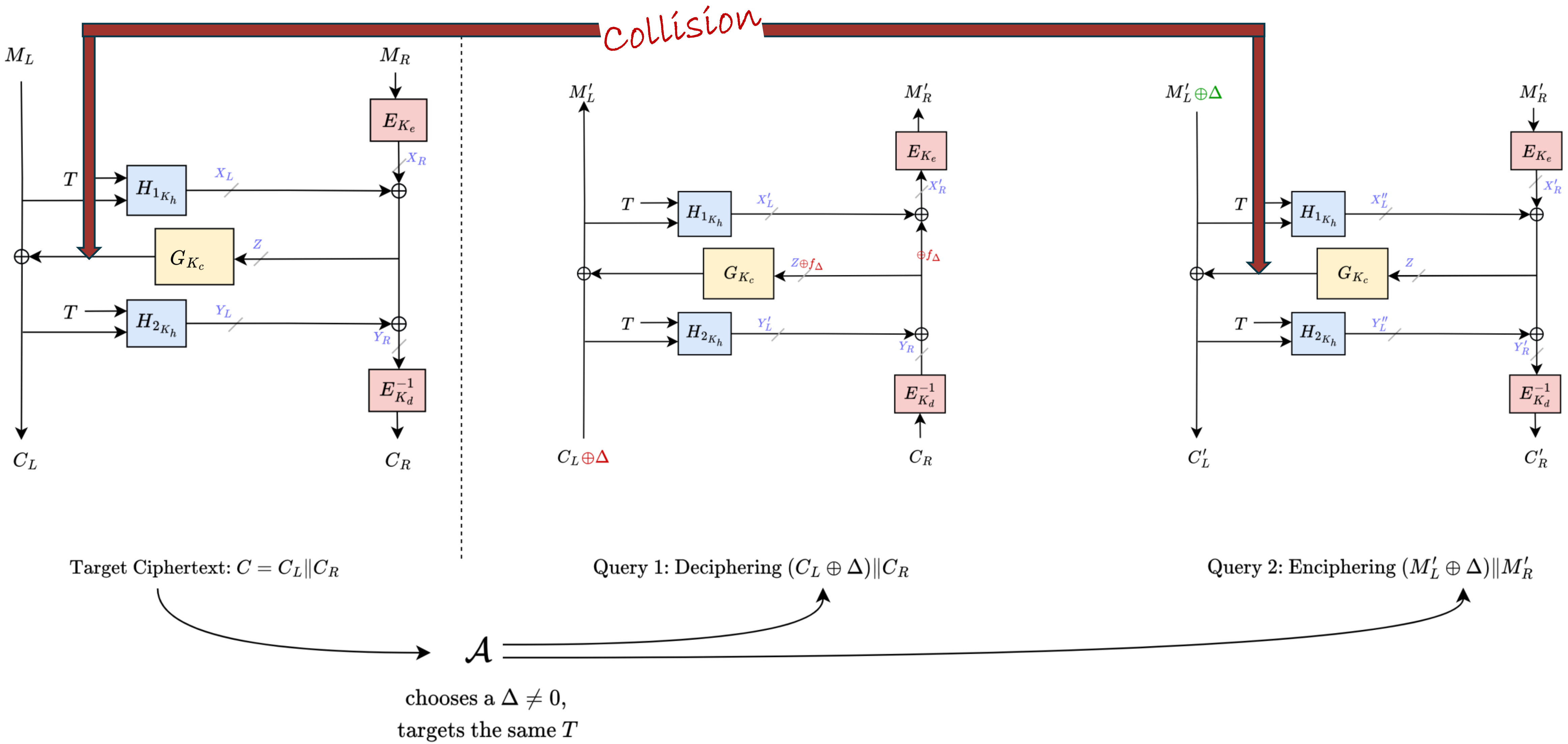

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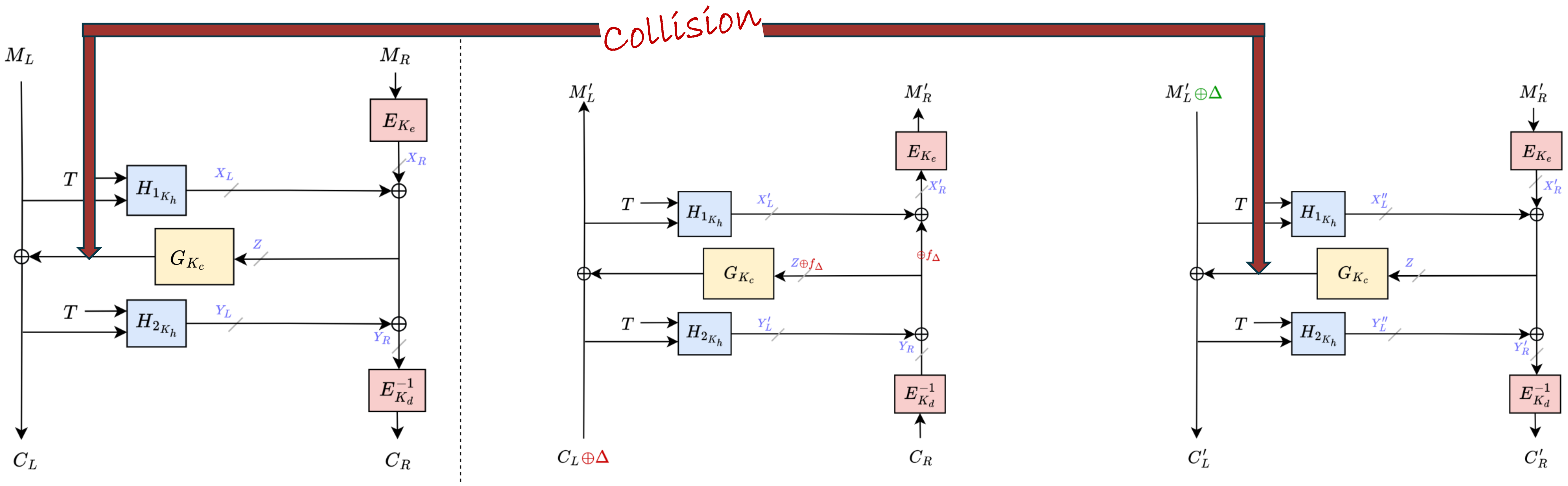

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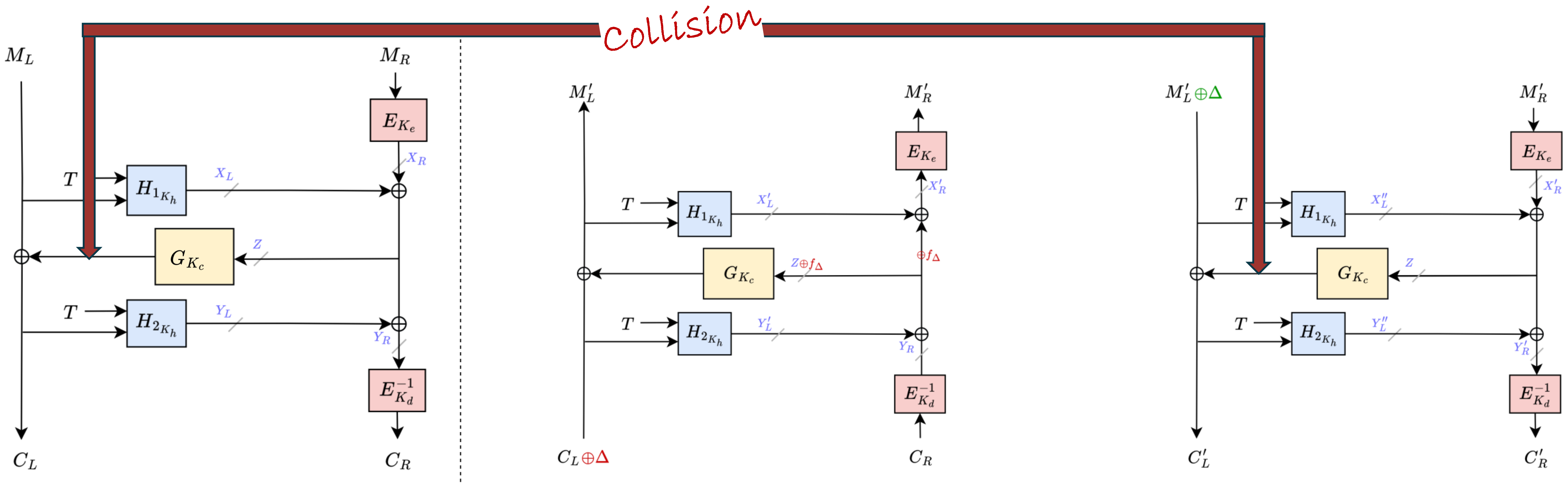

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Message Recovered

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Why Does This Work?

Root Cause: A Shared Difference Property

Shared Difference Property of Polynomial Sum

- $H_{\text{sum}}(K, T, M, C) = H_1(K, T, M) \oplus H_2(K, T, C)$

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$$H_{\text{sum}}(K, T, M \oplus \Delta, C \oplus \Delta) = H_{\text{sum}}(K, T, M, C)$$

due to separability of polynomial hash

Our attack was first disclosed on 13th Feb 2024 in our CRYPTO'24 submission. Had quite a rollercoaster with a case of established reviewer misconduct during submissions, before making it to CRYPTO'25.

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- Existing proofs based on XOR-universal hash functions

Assumes H_1, H_2 are XOR-universal

↓

Implies H_{sum} is universal

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CTR IV unpredictable and hard to collide

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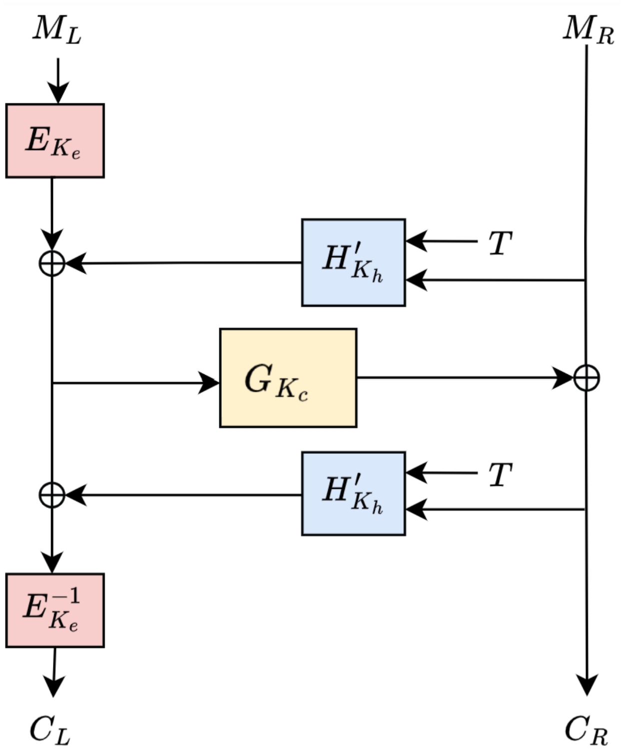
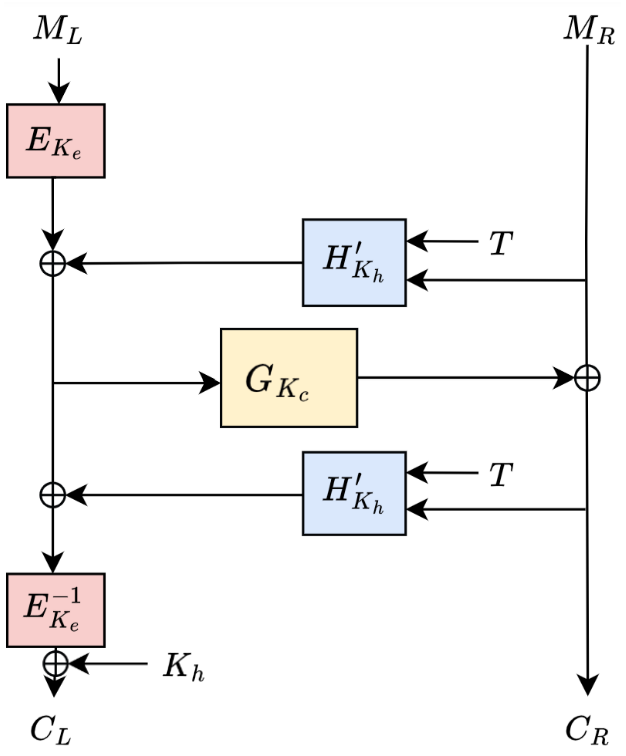
Our Result 2:
Applications of Shared Difference Attack to Other XCB-style TEMs

Shared Difference Attack on Other XCB-style TEMs

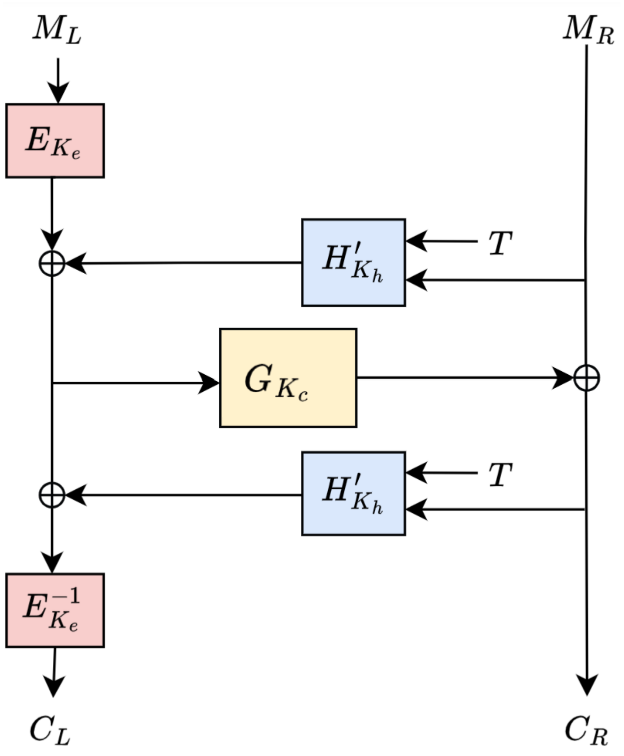


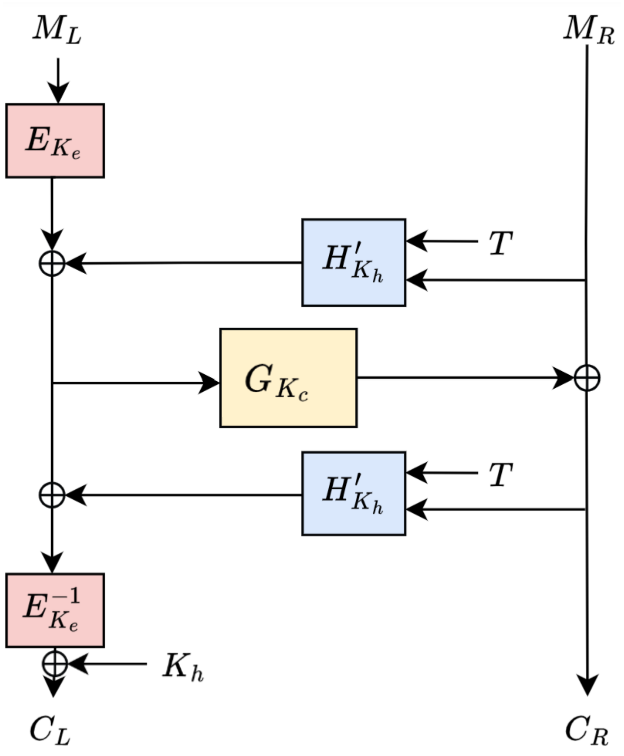
HCI [Nan08]



MXCB [Nan08]

Shared Difference Attack on Other XCB-style TEMs





HCI [Nan08]

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Mirrored XCB-AES,
Direct application of our attack

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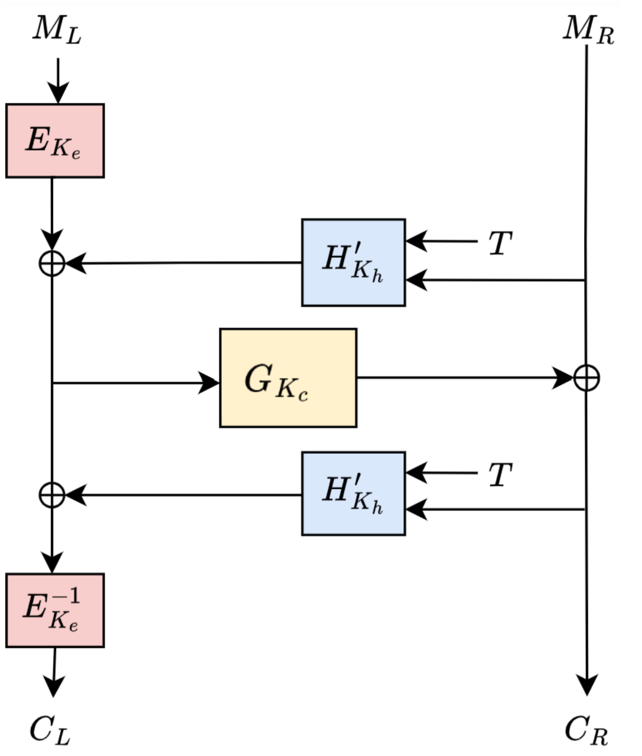

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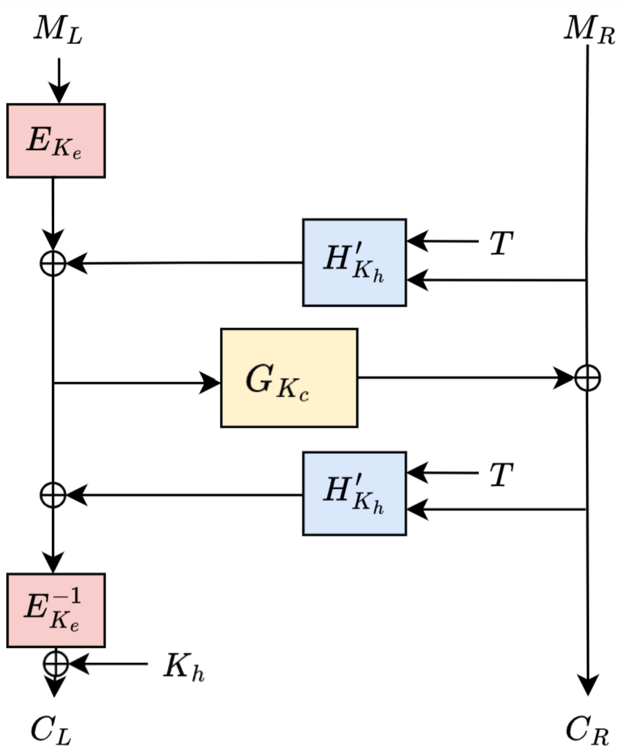

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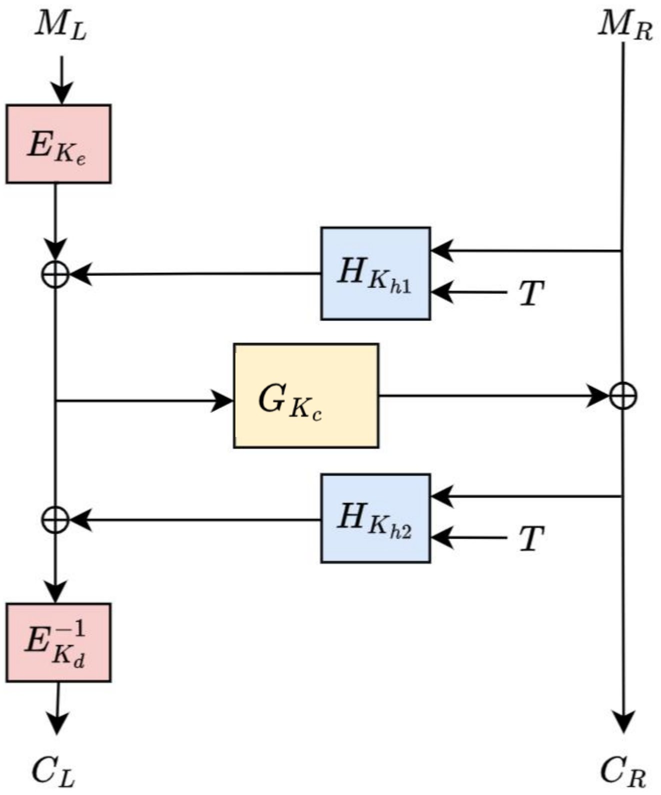

XCBv1 [MF07]

Two-hash-key XCB-AES,
Attack by contradiction

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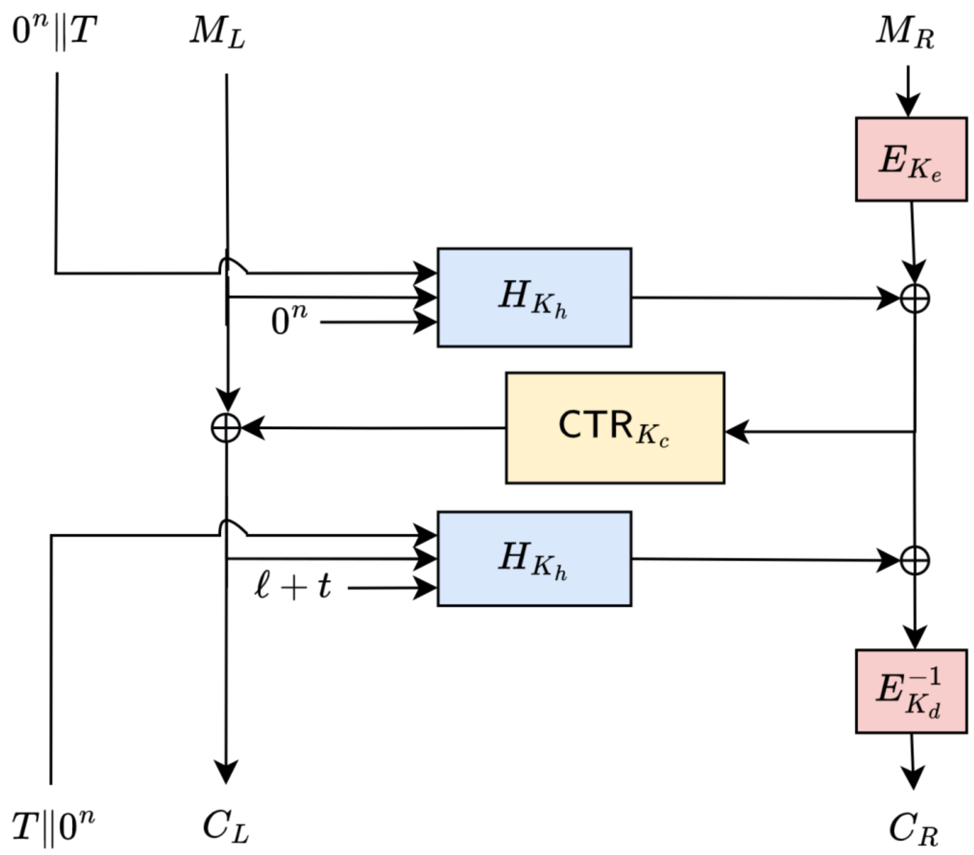
Summary of Results

Attack	Schemes	Message length	Attack type	# queries
LRW1 CCA attack by Khairallah [Kha23]	XCBv1, XCBv2, XCBv2fb	n bits	recovery of n bits	3
Shared difference attack [This work]	XCBv1	all $m > n$ bits	recovery of $m - n$ bits	4
	XCBv2, XCBv2fb, HCI, MXCB	all $m > n$ bits	recovery of $m - n$ bits	2
Flipped parts attack [This work]	HCI	all $m > n$ bits	distinguishing attack	3

m can be arbitrarily large

Countermeasures for XCB

Repairing and Enhancing XCB



- XCB style

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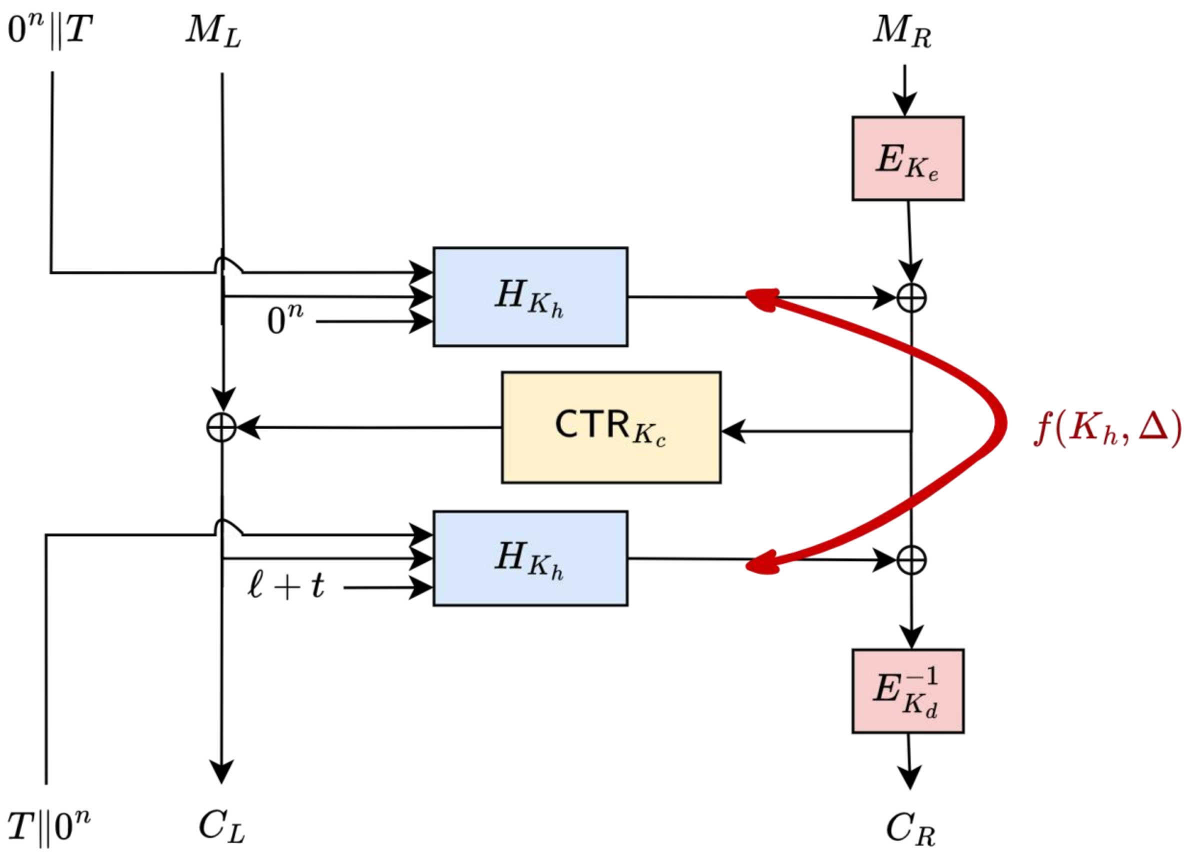
Repairing and Enhancing XCB



- XCB style
  - Insecure in current form

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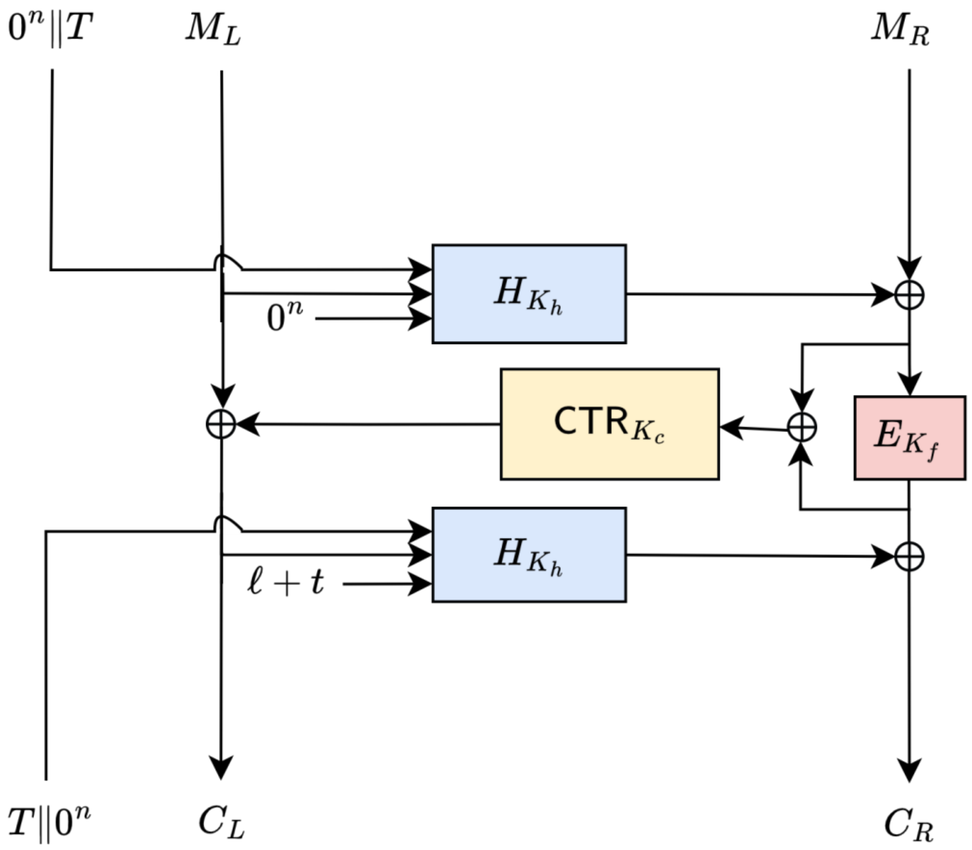
Repairing and Enhancing XCB



Avoid the Sum

- XCB style
  - Insecure in current form

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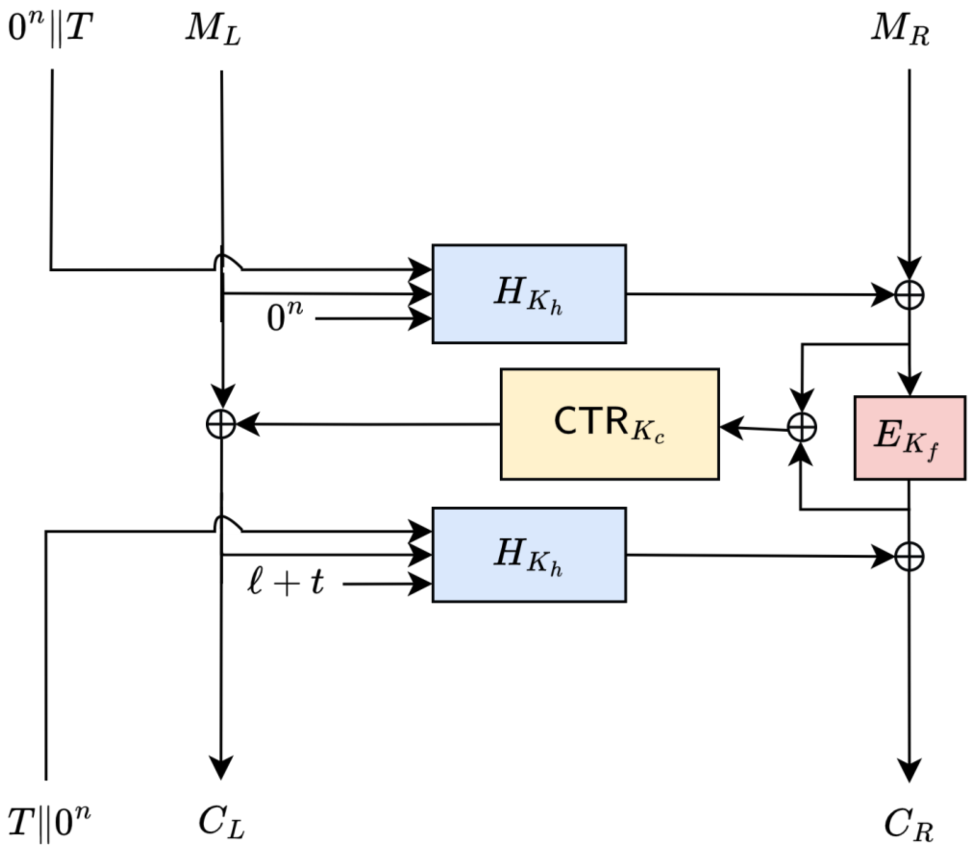

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- XCB style
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- HCTR2 style [CHB23]
  - AES-128, PolyVal
  - 64-bit STPRP security
  - 1.1 cpb on Gracemont

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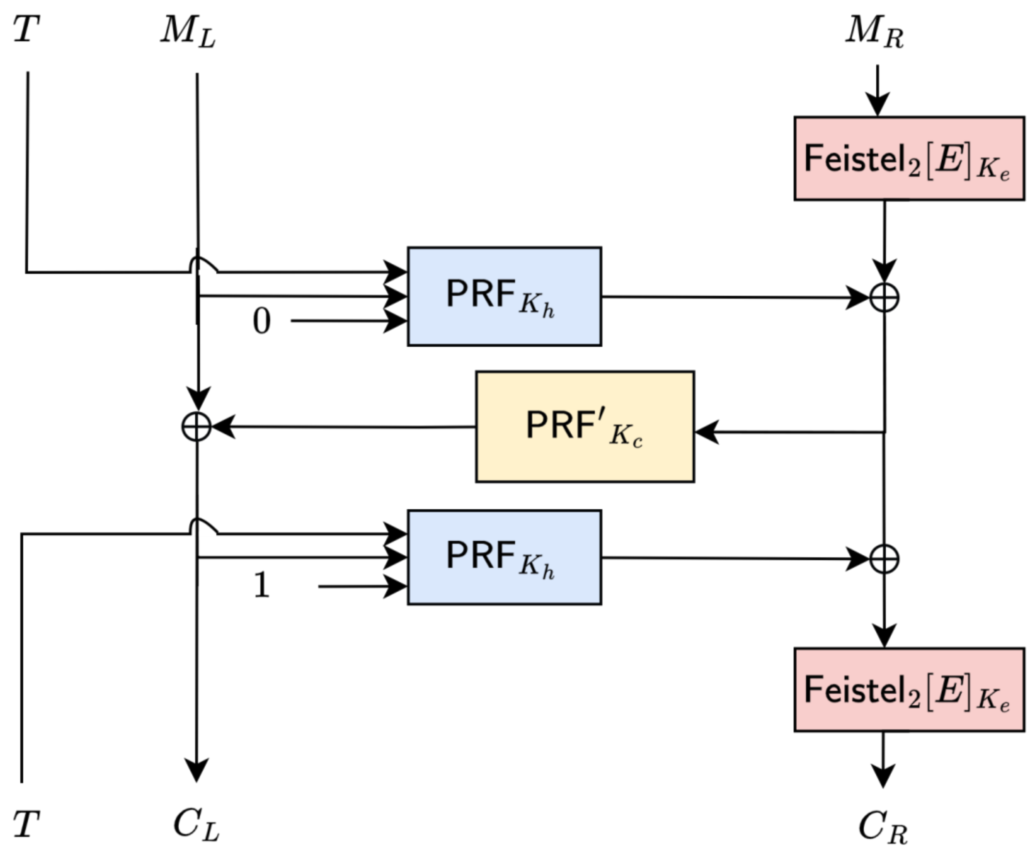

Use Inseparable Hashes

- XCB style
  - Insecure in current form
- HCTR2 style [CHB23]
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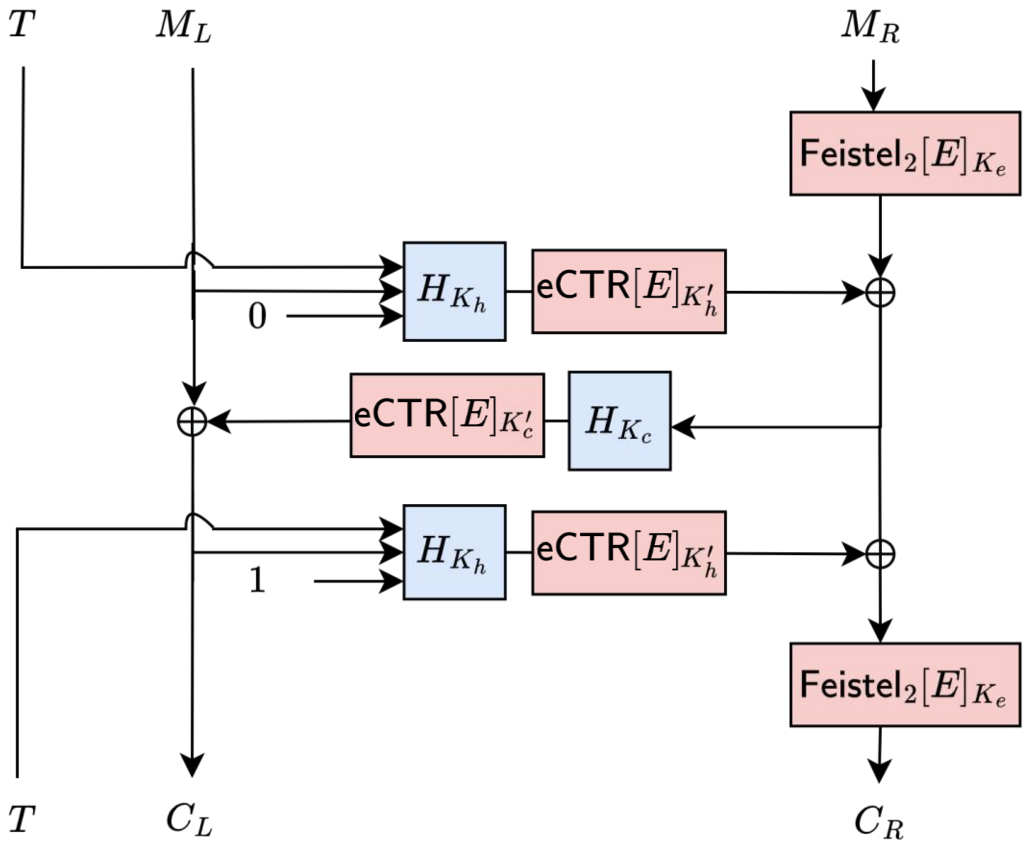

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- GEM style [BVA24]
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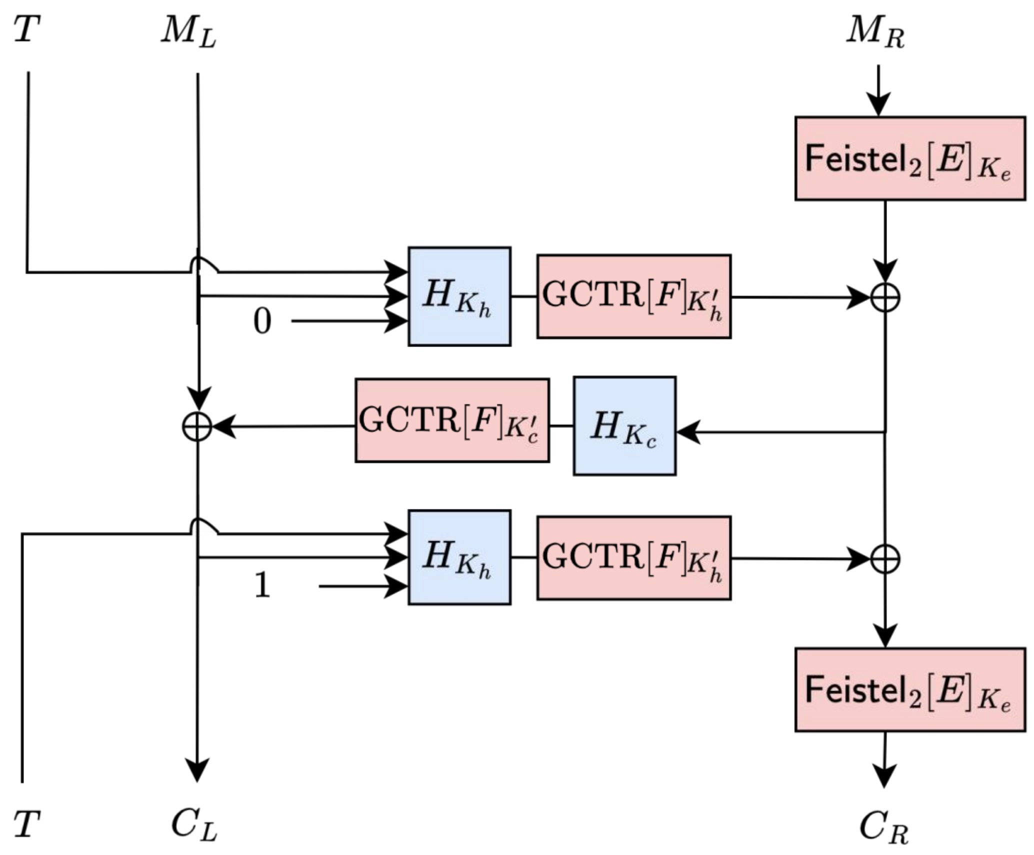
  - 1.4 cpb on Gracemont

Repairing and Enhancing XCB



Use Inseparable Hashes

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- HCTR2 style [CHB23]
  - AES-128, PolyVal
  - 64-bit STPRP security
  - 1.1 cpb on Gracemont
- GEM style [BVA24]
  - Butterknife [ACL+22], PolyVal
  - 128-bit STPRP security
  - 1.1 cpb on Gracemont

Conclusion

Conclusion

1. Introduced shared difference attack against XCB
    - Breaking SPRP, STPRP, VIL-STPRP security of all XCB variants
    - Including XCB-AES; a 15 year old IEEE standard
2. Pinpointed exact flaw in existing analyses
3. Presented some countermeasures – HCTR2 and GEM

Impact: IEEE has officially removed XCB-AES from 1619.2 standard

Takeaway: 1. Efforts toward TEM design and analysis through NIST's accordion initiative are essential

2. To protect innovation, we must enforce clear professional consequences for reviewer misconduct

Thank You!

(ia.cr/2024/1554)

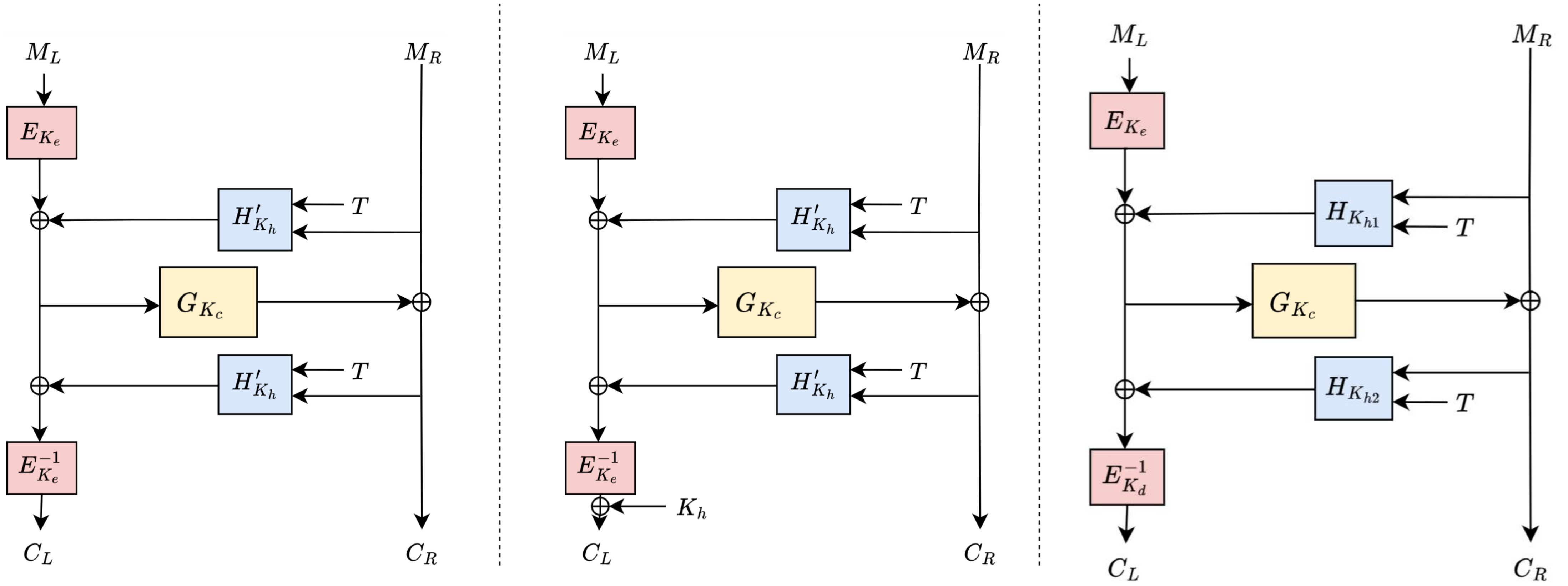
Contact:
Amitsingh.bhati@esat.kuleuven.be

“Knowledge gained without ethics is a loss, not a gain”

- Aristotle (attributed)

Backup Slides

Shared Difference Attack on Other XCB-style TEMs



HCI [Nan08]

MXCB [Nan08]

XCBv1 [MF07]

Mirrored XCB-AES,
Direct adaptation of our attack

Two-hash-key XCB-AES,
Attack applied by contradiction

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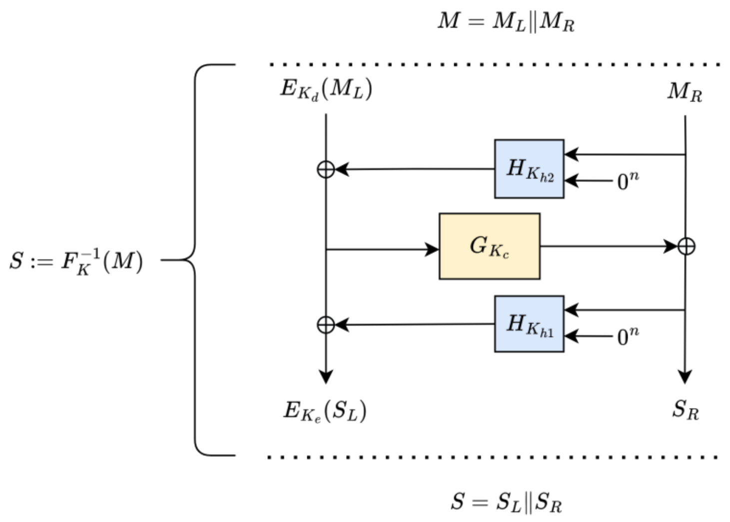
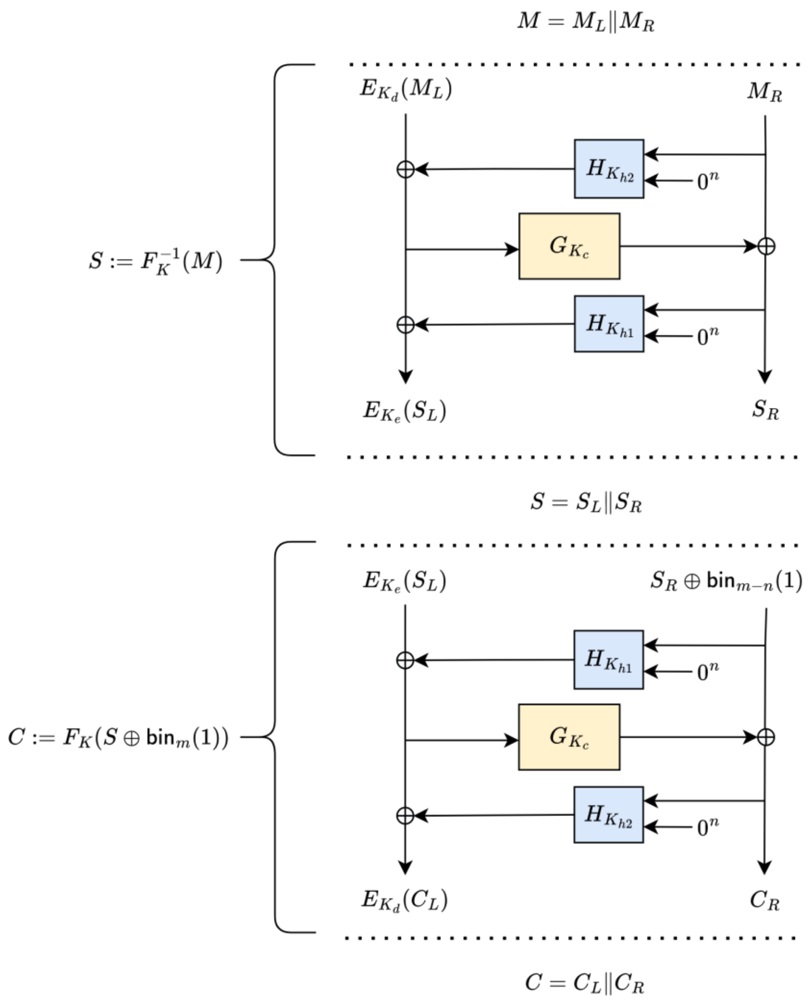
Shared Difference Attack by Contradiction on XCBv1

Attack by Contradiction on XCBv1



Attack by Contradiction on XCBv1



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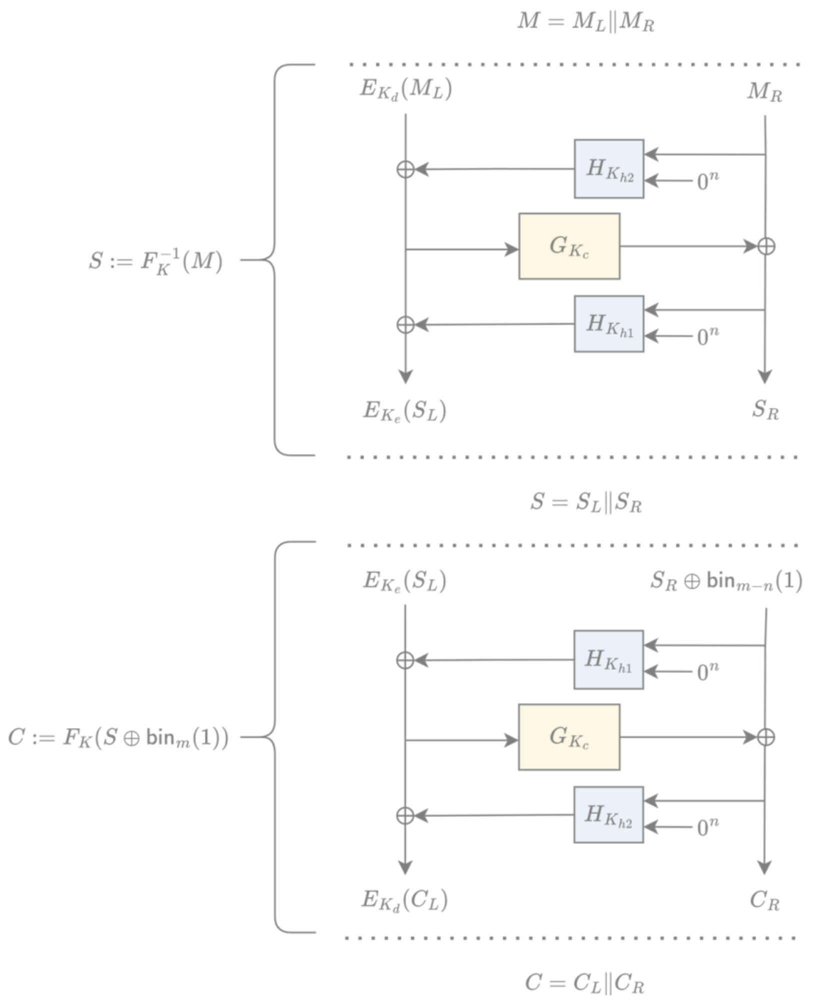

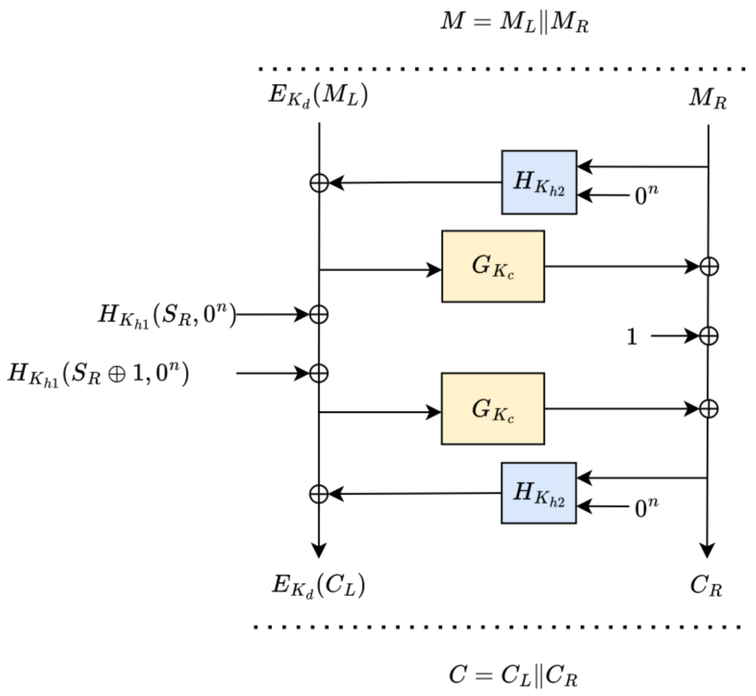

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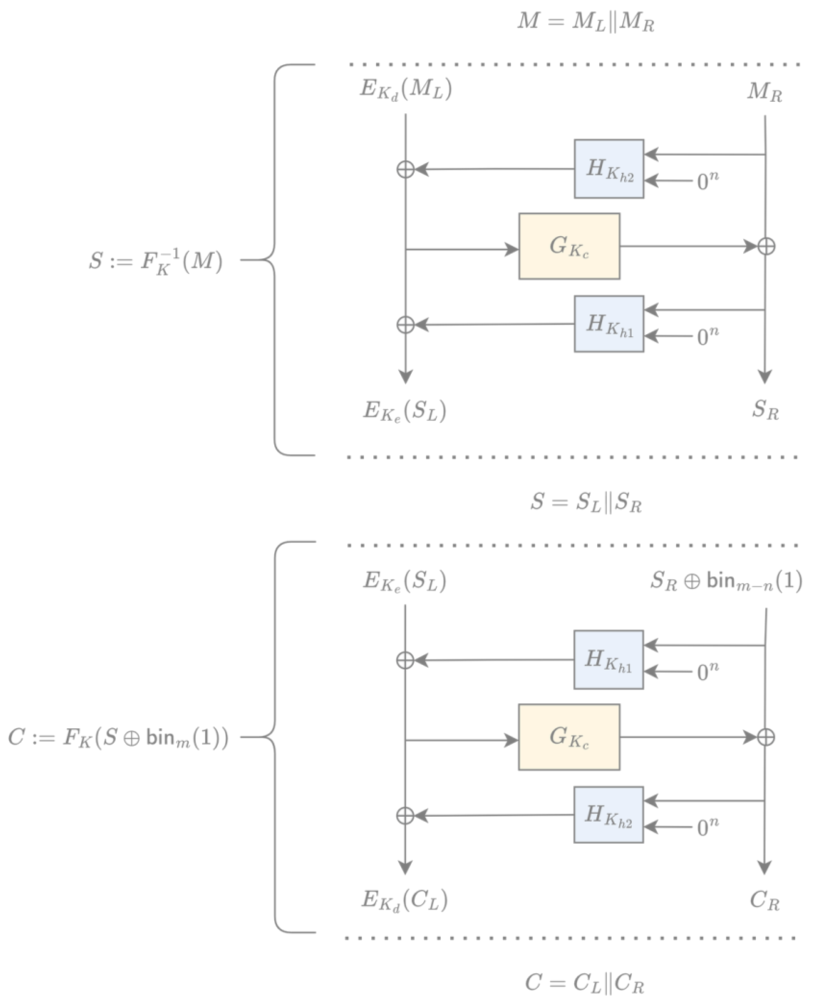

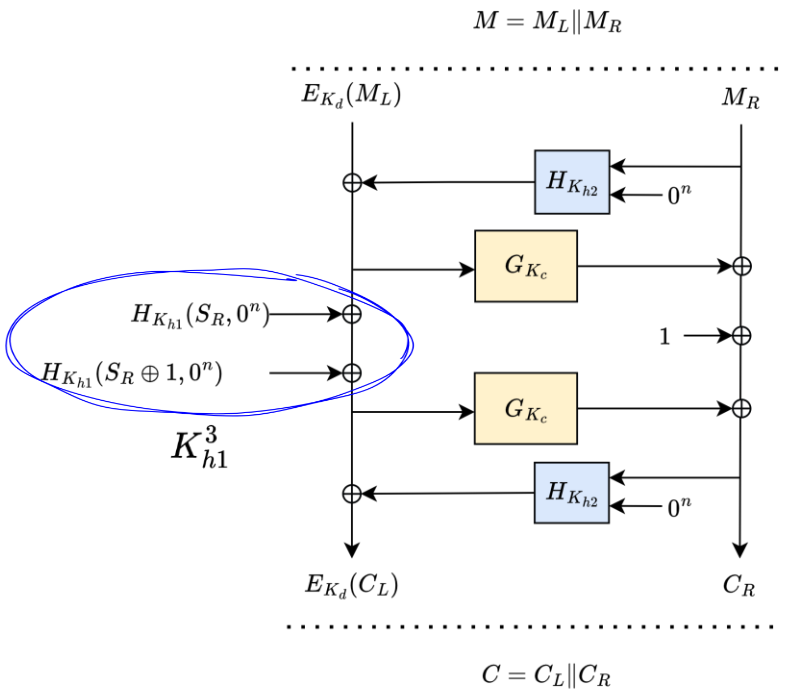

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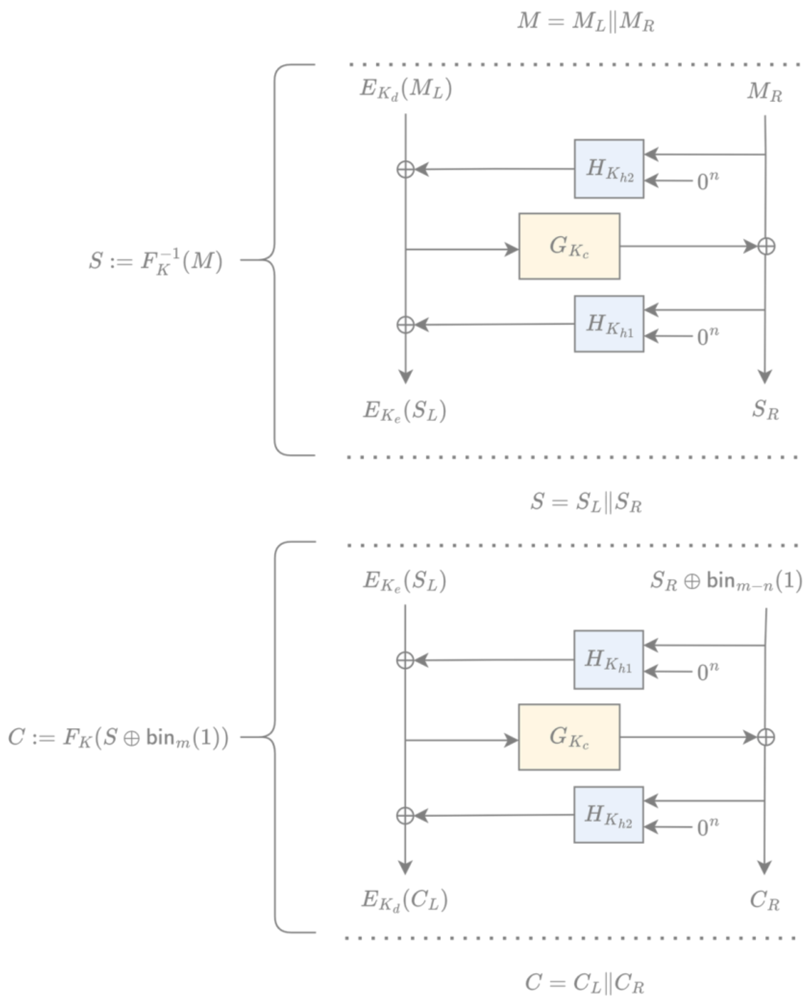

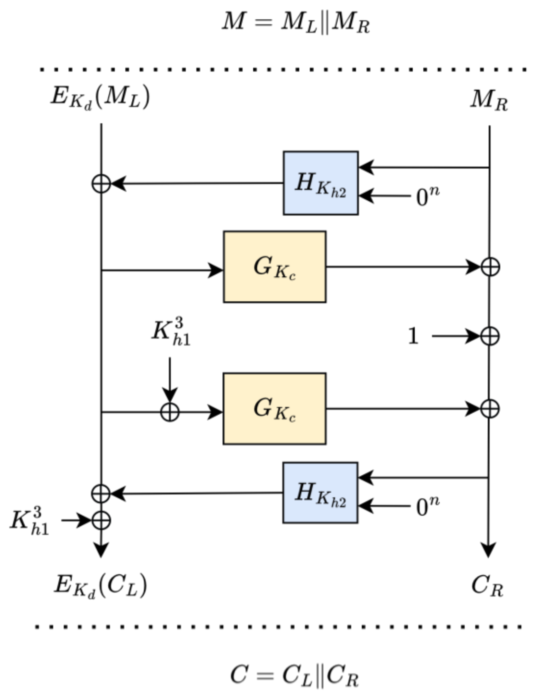

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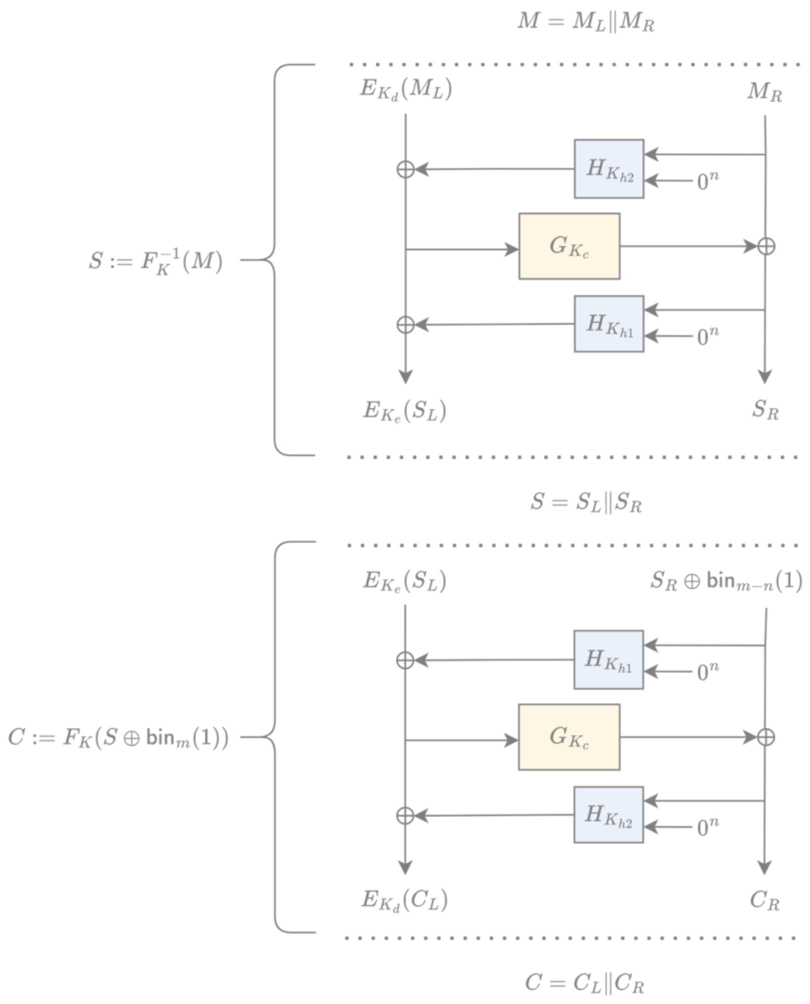

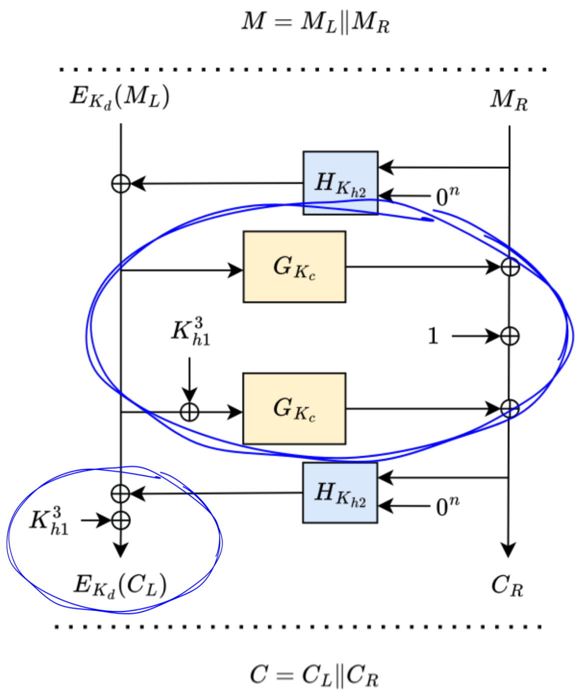

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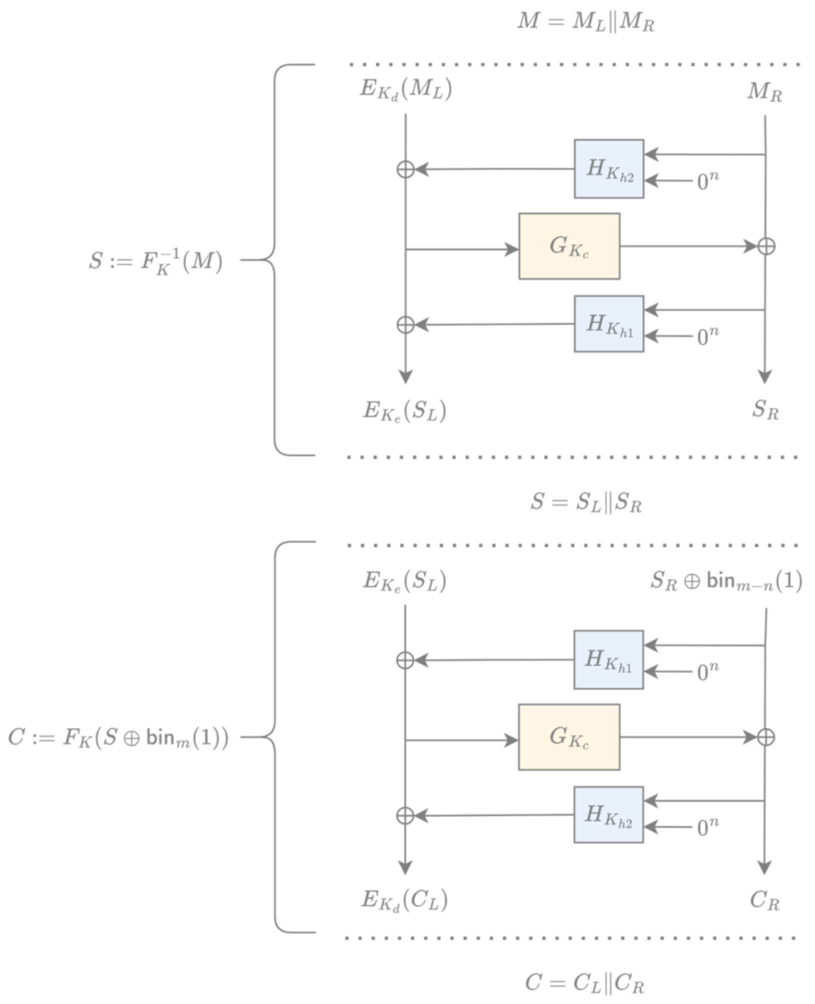

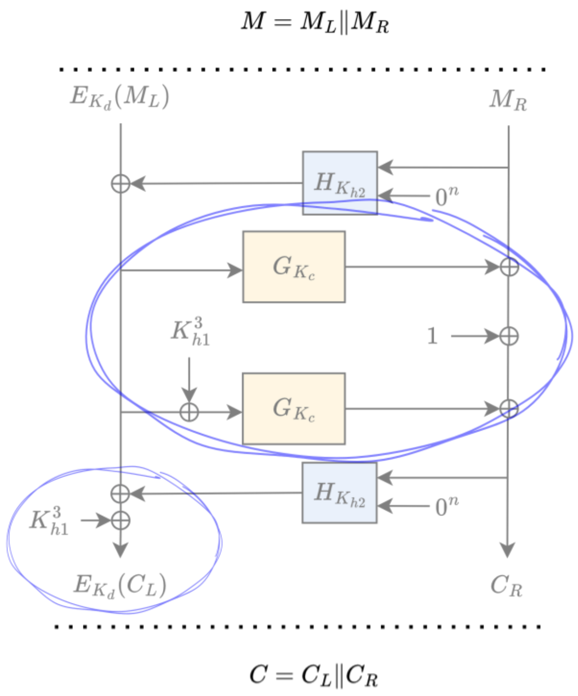

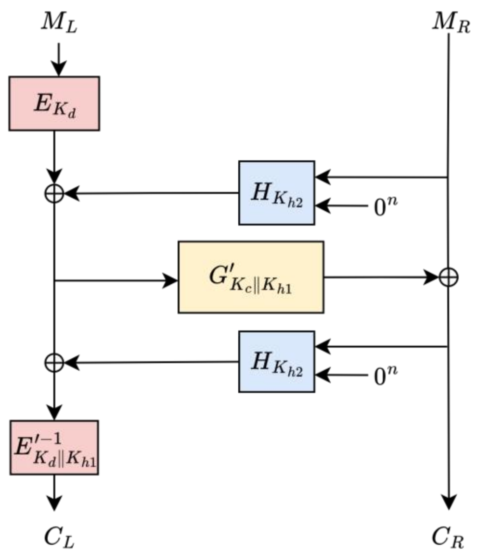

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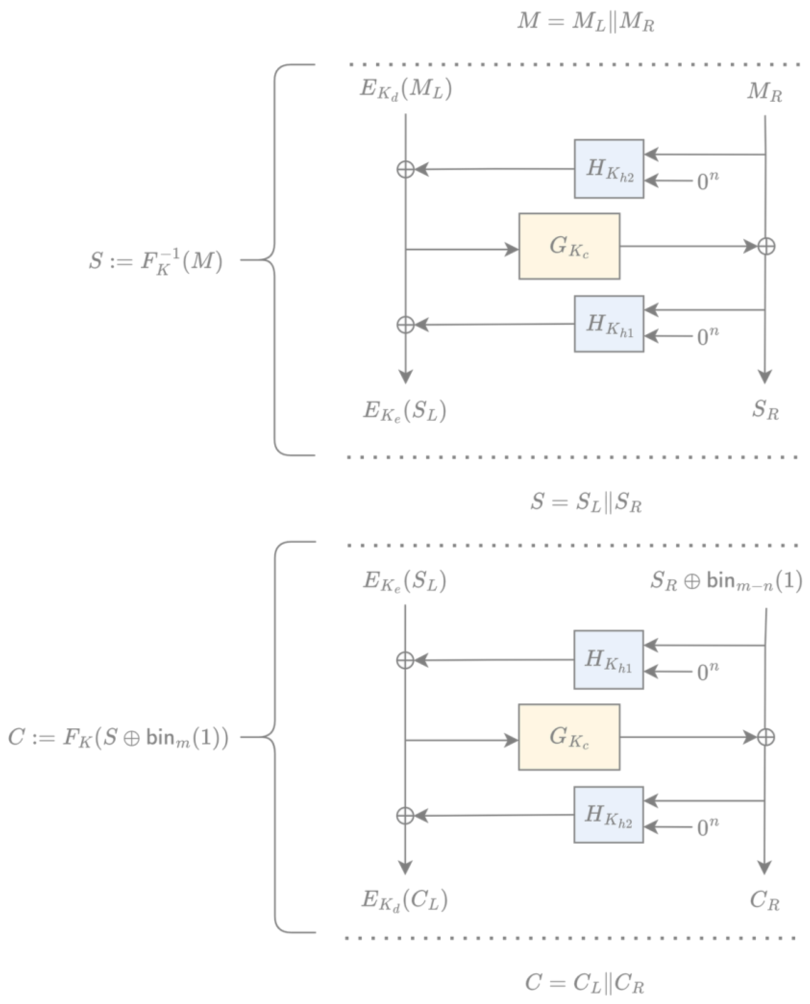

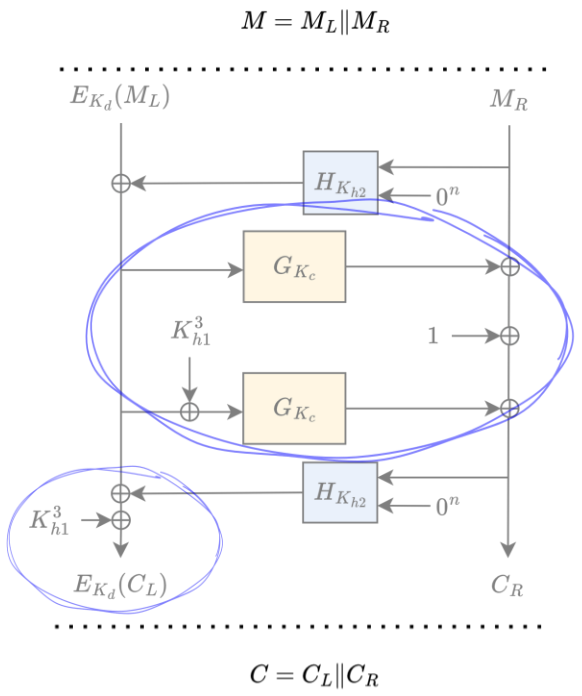

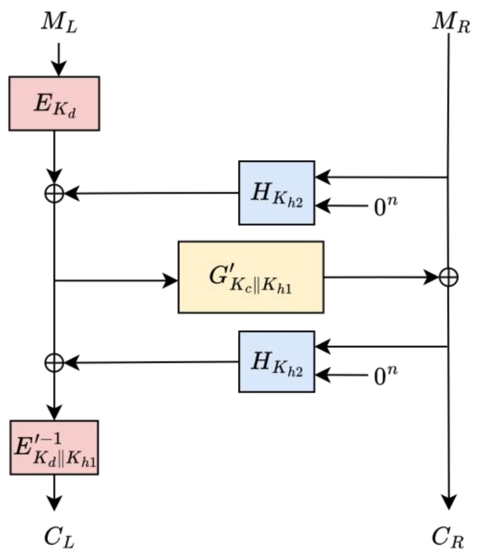

SPRP(SPRP^{-1}(M) $\oplus\gamma$) ⟶ Naor-Reingold, 2002 ⟶ PRI(M)

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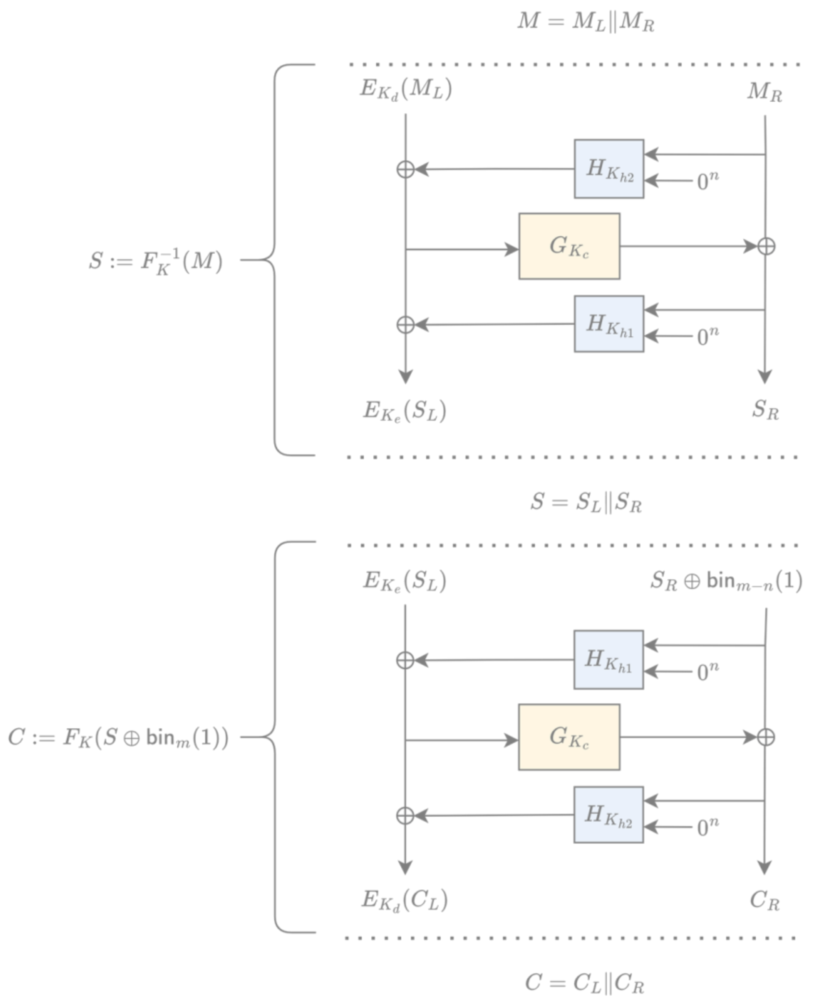
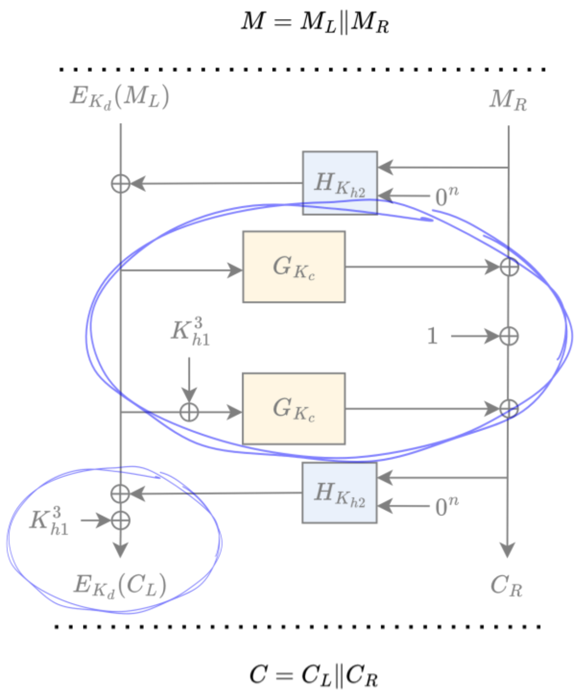
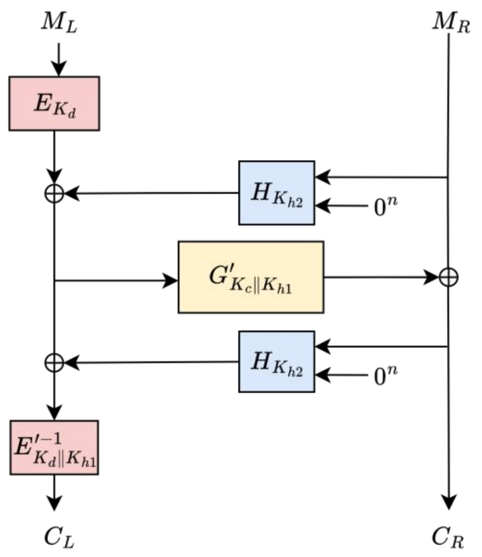
Attack by Contradiction on XCBv1







SPRP(SPRP$^{-1}(M) \oplus \gamma$) → Naor-Reingold, 2002 → ~~PRI~~(M)

Shared Difference Attack

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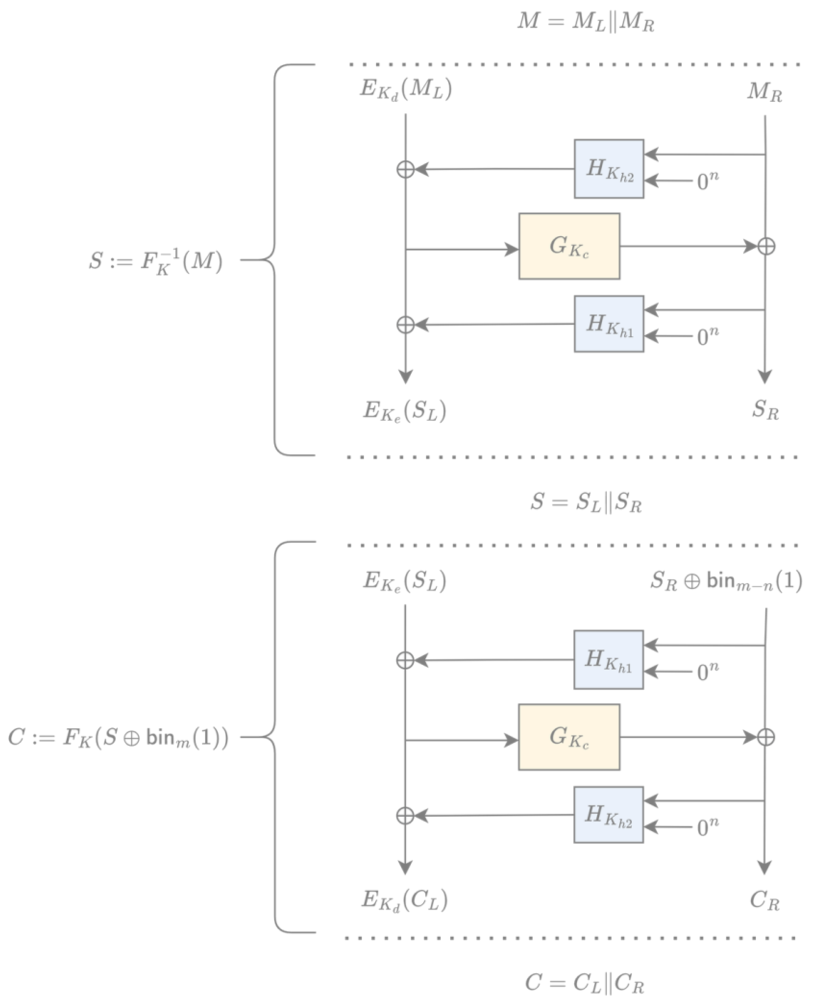

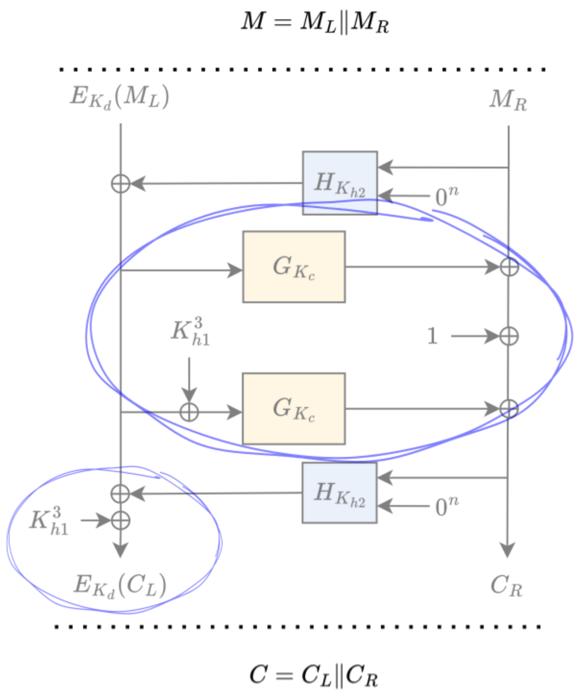

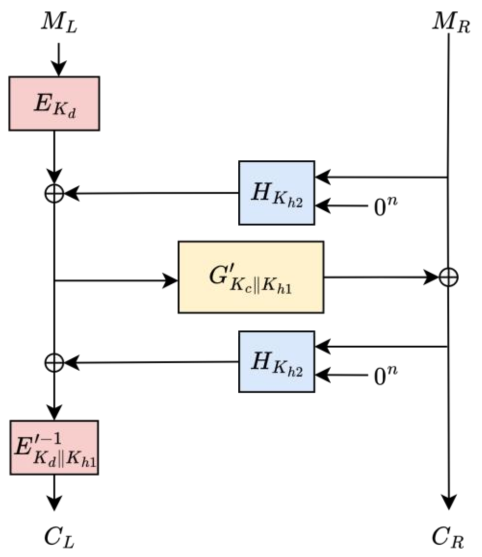

~~SPRP~~(~~SPRP^{-1}~~$(M) \oplus \gamma$) —— Naor-Reingold, 2002 ——→ ~~PRI~~(M)

Shared Difference Attack

Separability contradicts XOR-Universality of Sum

Flaw in Existing Analysis

- For any two inputs $(T,M) \neq (T',M')$, output Y, and random secret key K,

$$\Pr(H_1(K,T,M) \oplus H_1(K,T',M') = Y) \leq \epsilon_1$$

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- For any two inputs $(T,M) \neq (T',M')$, output Y, and random secret key K,

$$\Pr(H_1(K,T,M) \oplus H_1(K,T',M') = Y) \leq \ell/2^n$$

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H_1 is XOR-universal

- For any two inputs $(T,C) \neq (T',C')$, output Y, and random secret key K,

$$\Pr(H_2(K,T,C) \oplus H_2(K,T',C') = Y) \leq \ell/2^n$$

H_2 is XOR-universal

Flaw in Existing Analysis

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- For any two inputs $(T,M,C) \neq (T',M',C')$, output Y, and random secret key K,

$$\Pr(H_{\text{sum}}(K,T,M,C) \oplus H_{\text{sum}}(K,T',M',C') = 0) \leq \epsilon_{\text{sum}}$$

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$M \oplus \Delta, C \oplus \Delta$

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$$\Pr(H_{\text{sum}}(K,T,M,C) \oplus H_{\text{sum}}(K,T',M',C') = 0) = 1$$

H_{sum} is not XOR-universal

$$M \oplus \Delta, C \oplus \Delta$$

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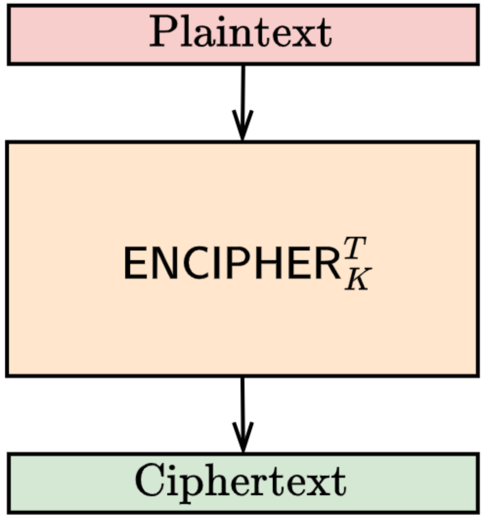
Where are TEMs Used in Real-World?

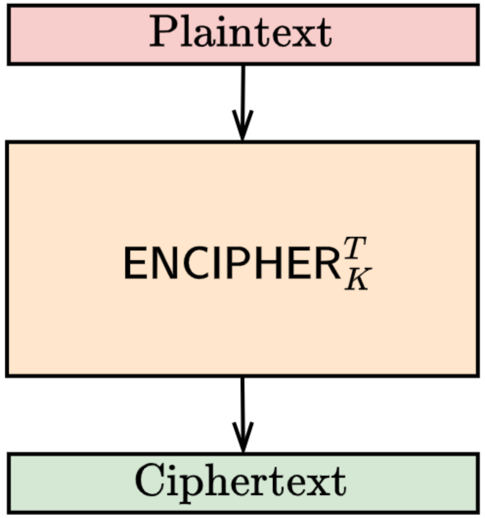
Primary Applications



1. Key-wrapping and swap-file encryption

2. Disk-sector and full-disk encryption

Primary Applications



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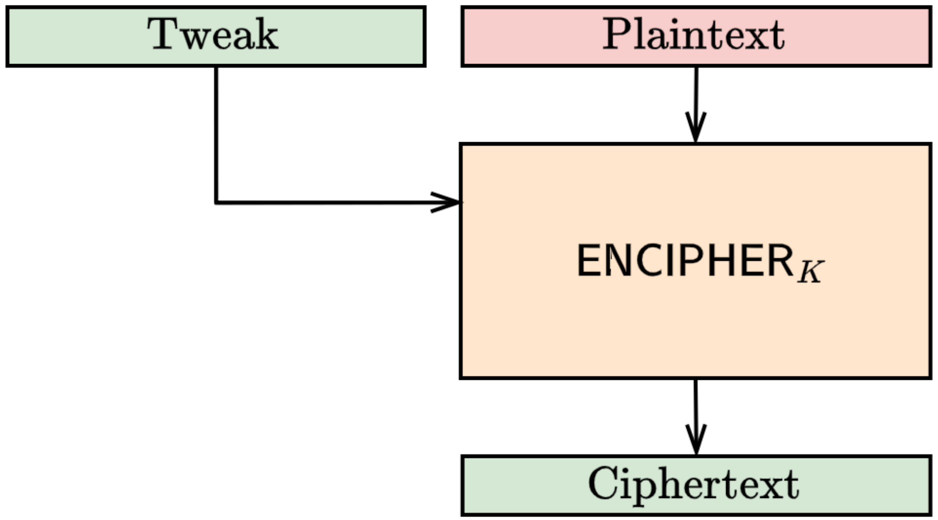
VeraCrypt
Windows BitLocker
vmware vSphere
AWS KMS
Microsoft Azure Key Vault
OpenSSL Cryptography and SSL/TLS Toolkit
LUKS Linux Unified Key Setup
Encrypting Drives in Linux

Primary Applications



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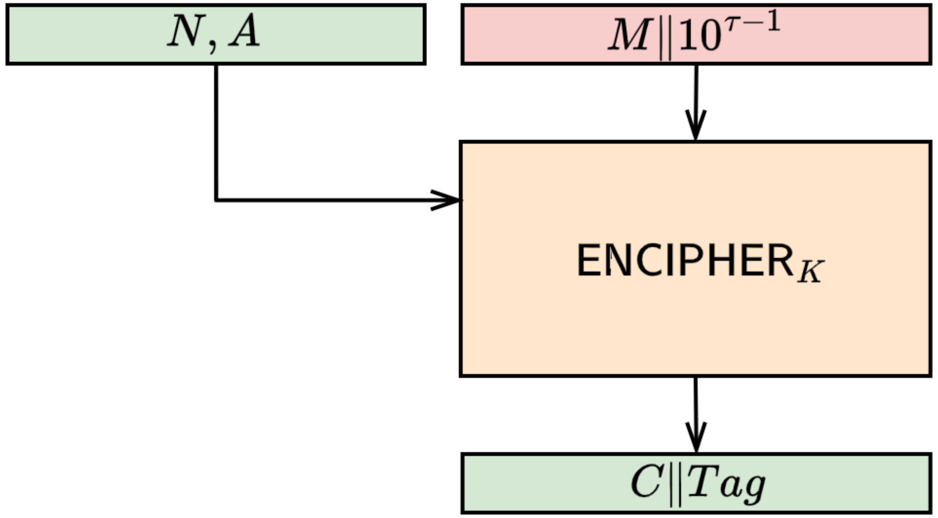

Encode-then-Encipher (EtE) [BR00]

1. Key-wrapping and swap-file encryption
2. Disk-sector and full-disk encryption
3. Robust authenticated encryption [HKR17]
    1. Resisting nonce-misuse and
    2. Decryptional leakage (RUP) [AB+14]

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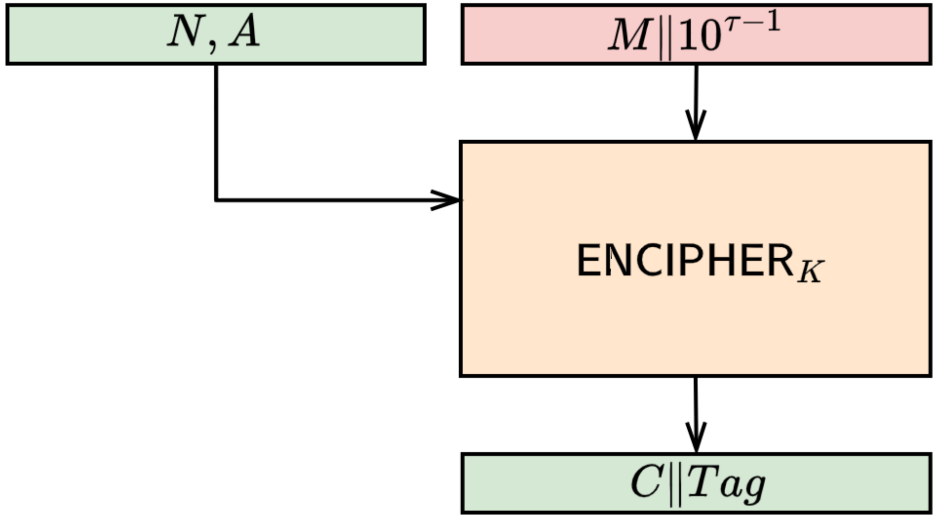

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Goals also covered under NIST's accordion call

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