The Committing Security of MACs with Applications to Generic Composition

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Committing Security

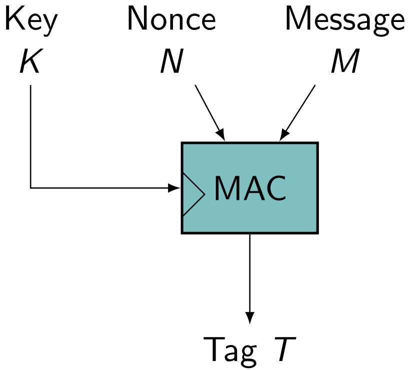
Committing Security

- Notion originating from the public-key encryption literature [ABN10]
- Adapted to symmetric primitives by Farshim et al. [FOR17]
- Latest research focuses on authenticated encryption with associated data (AEAD)
  - **Vulnerable settings:** moderation in encrypted messaging apps, key rotation mechanisms, password-based encryption, etc. [GLR17, DGRW18, LGR21, ADG+22]
  - **Vulnerable schemes:** AES-GCM, AES-GCM-SIV, ChaCha20-Poly1305, OCB3, CCM, EAX, SIV [LGR21, ADG+22, MLGR23]

→ Almost all standardized AEAD are vulnerable to committing attacks

What about MACs (Message Authentication Codes)?

- Provide only authentication
- Many MAC standards based on:
  - Universal hash functions
  - Block ciphers
  - Hash functions
  - Permutations
- Used in a wide variety of scenarios:
  - Message authentication and integrity checks
  - Authentication protocols and authenticated encryption schemes
  - Pseudorandom functions
  - Key derivation functions



→ Committing security scarcely studied for MACs!

Settings Requiring Committing MACs

Practical Applications of Committing MACs

- We found four practical settings needing committing security:
  - The OPAQUE Augmented PAKE Protocol
  - Authentication without key identification
  - Collision Resistant KDF
  - Timed Efficient Stream Loss-Tolerant Authentication (TESLA)

- Three of them implicitly assumed it to be guaranteed by their underlying MAC

The OPAQUE Augmented PAKE Protocol

- Password-authenticated key exchanges (PAKE) recommended by the CFRG
- Explicitly requires *random-key robustness*

$$\Pr_{K_1,K_2 \leftarrow\$}[M \leftarrow \mathcal{A}(K_1, K_2)\,;\, \mathsf{MAC}(K_1, M) = \mathsf{MAC}(K_2, M)] \leq \epsilon$$

$\rightarrow$ we capture this property in the MAC key-committing notion CMT_k

- Proposed instantiation by HMAC

Key Derivation Function (KDF)

- HMAC, CMAC, and KMAC are recommended in NIST SP800-108r1 for sub-keys derivation
- Used to derive a sub-key $K_{\mathsf{OUT}} = \mathsf{MAC}(K_{\mathsf{IN}}, \mathsf{Ctx})$ from a key K_{IN} and a context Ctx

NIST SP800-108r1

> *If those parties have different understandings, then they will derive different keying material.*

$\rightarrow$ not guaranteed by standard MAC security
$\rightarrow$ we capture this property in the MAC context-committing notion CMT

- CMAC is not context-committing

Timed Efficient Stream Loss-Tolerant Authentication (TESLA)

- Provide sender authentication for broadcast streams and defined in RFC 4082
- Uses a one-way chain:

Generate (←)

$$K_0 \xleftarrow{F(K_1)} K_1 \xleftarrow{F(K_2)} \cdots \quad \cdots \xleftarrow{F(K_\ell)} K_\ell \xleftarrow{F(K_{\ell+1})} K_{\ell+1}$$

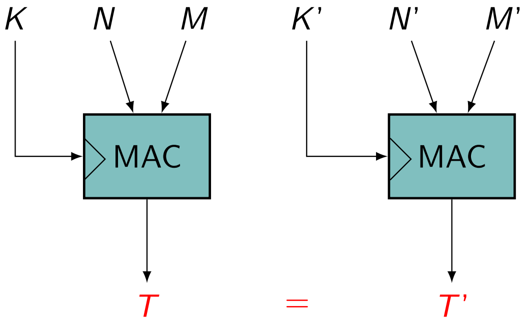
Reveal (→)

- F is defined as $F(K) = \mathrm{MAC}(K, 0)$
- Given K_i, it should be hard to find x such that $F(x) = K_i$

$\rightarrow$ not guaranteed by standard MAC security
$\rightarrow$ we capture this property in the MAC context-discovery notion CDY

Committing and CDY Security Notions for MACs

MACs Committing Security (CMT)



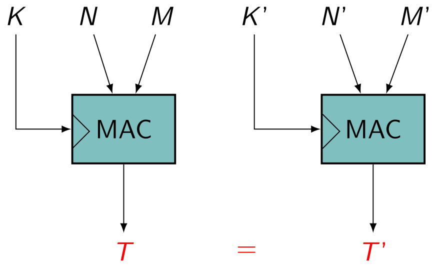
Notion	Requirement
CMT_k	$K \neq K'$
CMT	$(K, N, M) \neq (K', N', M')$

← Key Commitment

← Context Commitment

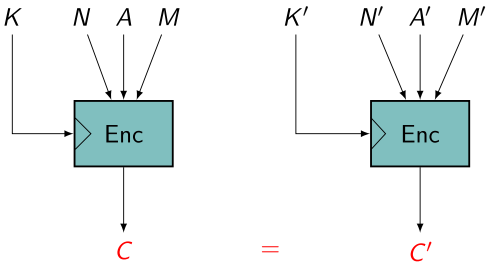
MACs Committing Security (CMT)

MAC



Notion	Requirement
CMT_k	$K \neq K'$
CMT	$(K, N, M) \neq (K', N', M')$

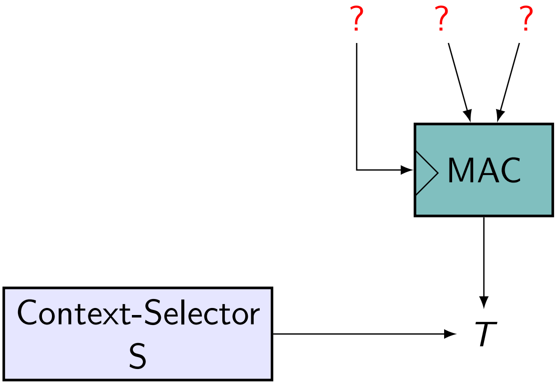
AEAD



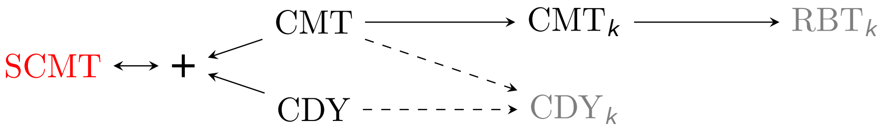
Notion	Requirement	[BH22]
CMT_k	$K \neq K'$	← CMT-1
CMT	$(K, N, A) \neq (K', N', A')$	← CMT-3

MACs Context-Discovery Security (CDY)

→ Adaptation of the context-discovery notion for AEAD from Menda et al. [MLGR23]



Relations between Commitment and Context-Discovery Notions



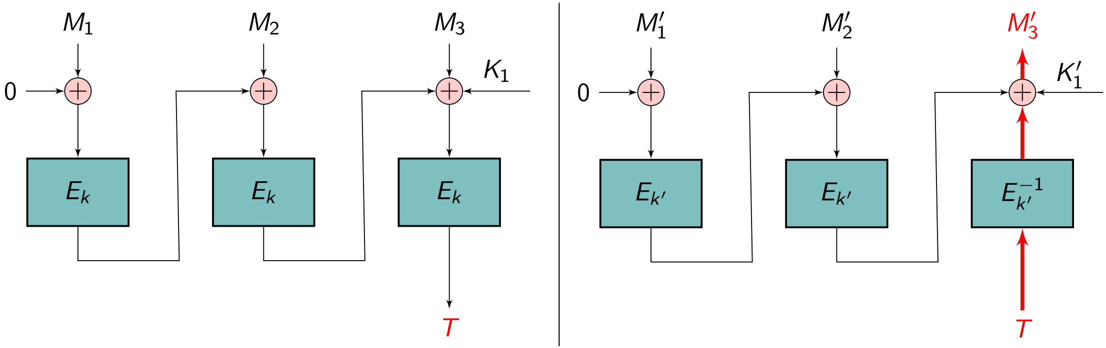
Security Analysis of Standardized MACs

Summary Table

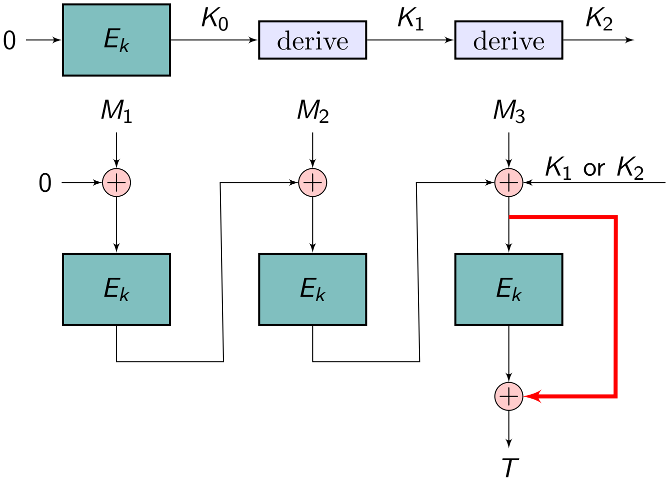
Scheme	CMT_k	CMT	CDY
CBC-type MACs	no	no	no
HMAC with variable-length keys	no	no	?
Badger	no	no	no
Poly1305-AES	no	no	no
GMAC	no	no	no
LightMAC	no	no	no
Chaskey	no	no	no
CBC-MAC-C1 [this work]	yes	no	yes
CMAC-C1 [this work]	yes	no	yes
HMAC with fixed-length keys	yes	yes	yes

Key-Committing Attack on CMAC

$\rightarrow$ Choose the values k, k' such that $k \neq k'$



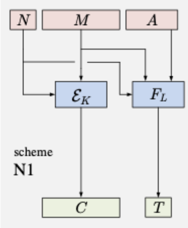
CMAC-C1: a Key-Committing Secure Variant of CMAC



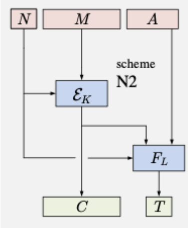
Applications to Generic Composition

Generic Composition Paradigms [NRS14]

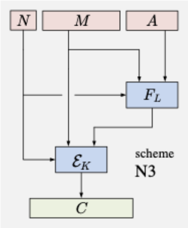
Encrypt-and-MAC (EaM)



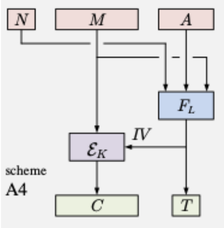
Encrypt-then-MAC (EtM)



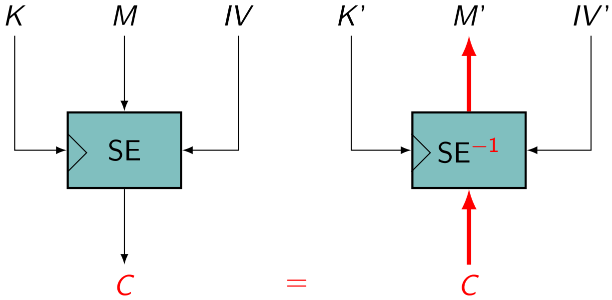
MAC-then-Encrypt (MtE)



SIV



Key-Committing Insecurity of IV-Based Symmetric Encryption



Generic Composition without Assumptions on IV-Based Encryption

If the MAC is CDY

$\rightarrow$

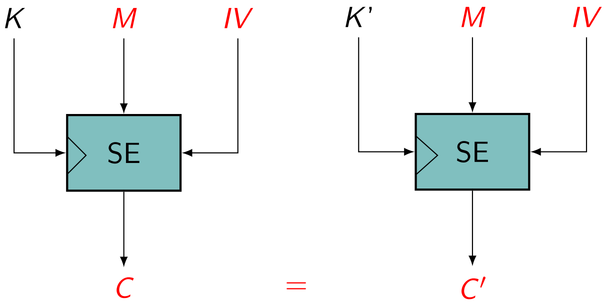
Encrypt-then-MAC, Encrypt-and-MAC and SIV are CDY

If the MAC is CMT_k or CMT

$\rightarrow$

Encrypt-then-MAC and Mac-then-Encrypt are not necessarily

Key-Robustness Security (RBT_k) of IV-Based Encryption



- CTR and CBC encryption mode are RBT_k
- If SE is RBT_k and the MAC is CMT $\rightarrow$ Encrypt-and-MAC and SIV are CMT
  $\rightarrow$ Encrypt-then-MAC and MAC-then-Encrypt are not

Generic Composition with a Key Schedule

- Keys for MAC and SE are derived from a single key with a Key Schedule function:

$$\mathsf{KS}(K) = (K_m, K_e)$$

If Key Schedule is COLL and the MAC is CMT_k, CMT or CDY

$\rightarrow$

Encrypt-then-MAC, Encrypt-and-MAC and SIV are CMT_k, CMT or CDY

Summary of Analyses

	MAC Assumption	SCMT	CDY	CDY_k	CMT	CMT_k
Scheme	SE/KS Assumption					
MtE	none	?	?	?	no	no
MtE	RBT_k	?	?	?	no	no
EtM	none	no	yes	yes	no	no
EtM	RBT_k	no	yes	yes	no	no
KEtM	COLL	yes	yes	yes	yes	yes
EaM	none	?	yes	yes	?	?
EaM	RBT_k	yes	yes	yes	yes	?
KEaM	COLL	yes	yes	yes	yes	yes
SIV	none	?	yes	yes	?	?
SIV	RBT_k	yes	yes	yes	yes	?
KSIV	COLL	yes	yes	yes	yes	yes

Future Work

- Analyze the remaining generic composition combinations
- Identify further settings requiring MAC commitment and CDY security
- Design efficient key/context-committing MACs
- Design MAC schemes with BBB committing security

Full version available on IACR ePrint:

https://ia.cr/2024/928

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