Radbound University

Disk Encryption and Message Authentication

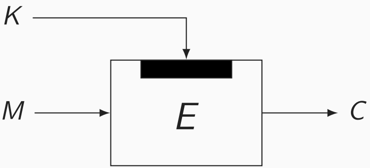
Applied Cryptography – Spring 2024

Bart Mennink

January 31, 2024

Institute for Computing and Information Sciences
Radboud University

Recap: Block Ciphers



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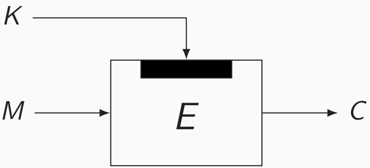

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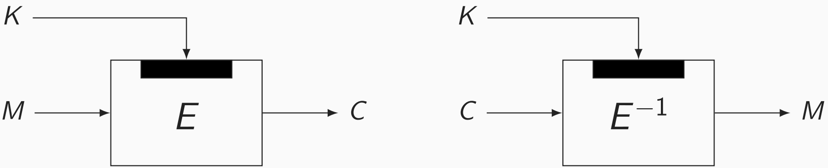

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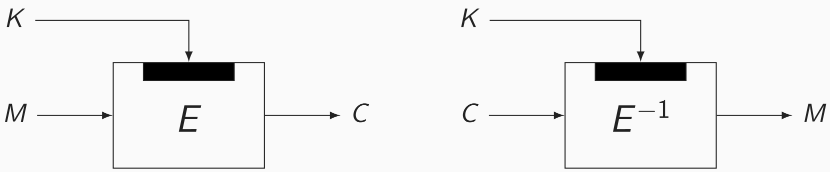

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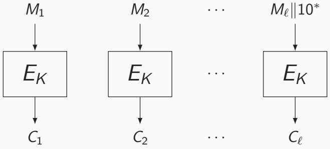
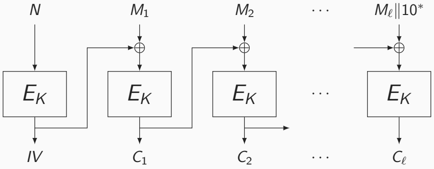
- A good block cipher should behave like a random permutation

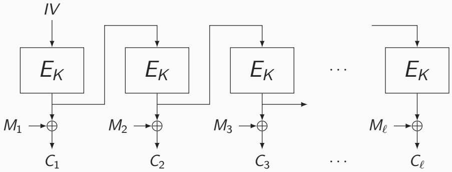
Block Cipher Encryption Modes



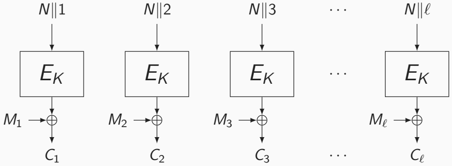
ECB



CBC



OFB



CTR

Last Lecture

- Keyed cryptographic constructions are modular:
  - A small primitive is turned into a larger mode of use
  - Typically, however, we only know how to build primitives that behave like random permutations
  - Most notable, block ciphers like AES
    - Mostly historically, but people still use them a lot!
    - E.g., each website over HTTPS sets up a TLS connection and reportedly over 70% over these connections use AES-GCM
- In this lecture:
  - Disk encryption
  - Message authentication
  - Beginning of authenticated encryption

Outline

Disk Encryption

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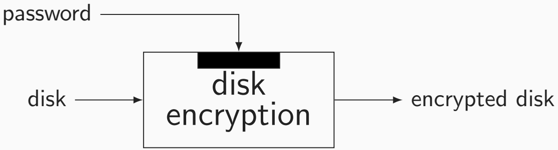

Main Goals

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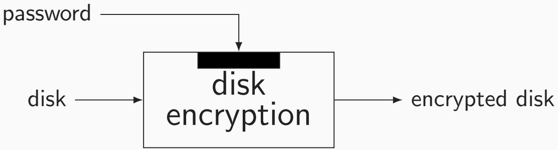

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- Confidentiality
- Efficient in encryption and decryption
- No ciphertext expansion
- User friendly
- Incrementality . . . but not too much

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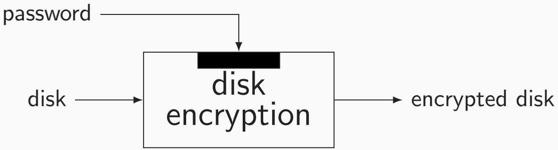

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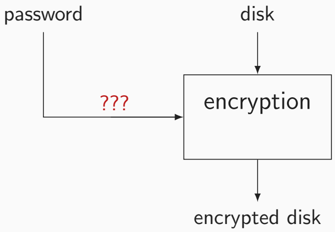
These Slides

- High-level idea
- Core behind VeraCrypt,
  open source disk encryption tool

VeraCrypt Disk Encryption (1/2)



Encryption Scheme

- Actually encrypts all your data
- Requires some symmetric key . . . but we only have our password???

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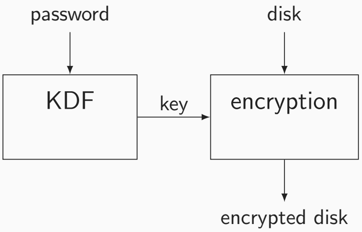

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- Can “generate” a key from “limited information”
- But is this secure?

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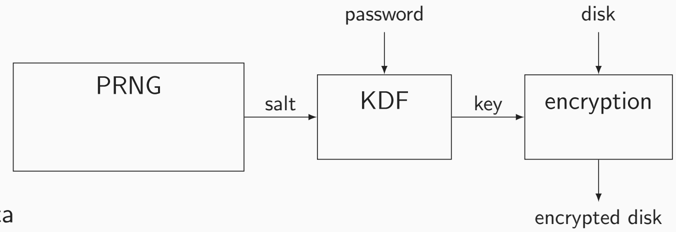

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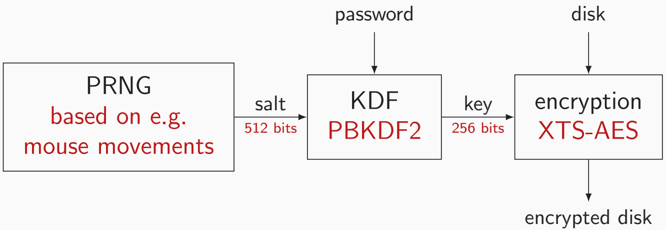
PRNG – Pseudorandom Number Generator

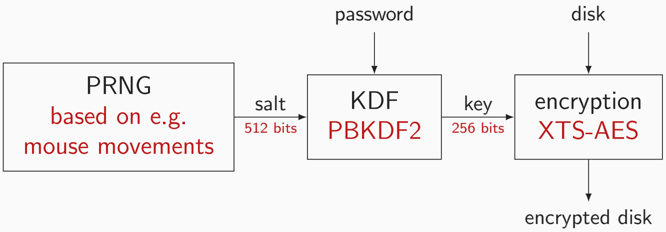
- Accumulates entropy from, e.g., mouse movements
- Turns it into a random looking string, the salt
- Salt fed to KDF to prevent dictionary attacks

VeraCrypt Disk Encryption (2/2)



In VeraCrypt

- Encryption scheme
  - XTS with AES-128 (more in Lecture 3)
  - Widely used standard for data encryption
- KDF
  - PBKDF2, hoped to behave like a pseudorandom function (more in Lecture 4)
  - Salt is 512 bits, so input has quite some “randomness”



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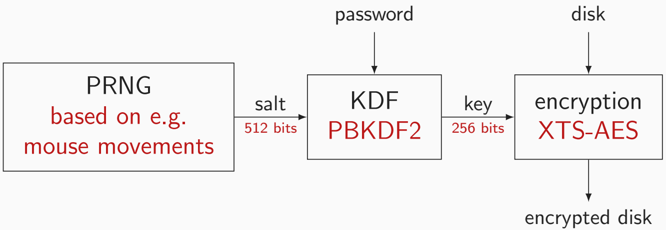

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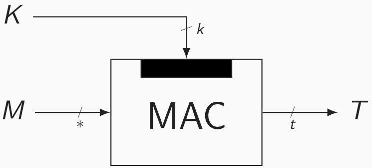
- Weakest spot?
  - The user! Short passwords are easy to guess
  - Salvaged by adjusting the number of rounds in PBKDF2

Message Authentication

Message Authentication (1/2)



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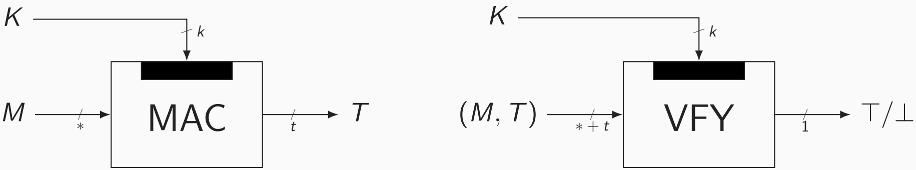

- Using key K, message M is signed with tag T
- Associated verification function takes K and (M, T) and outputs
  - $\top$ if tag is correct
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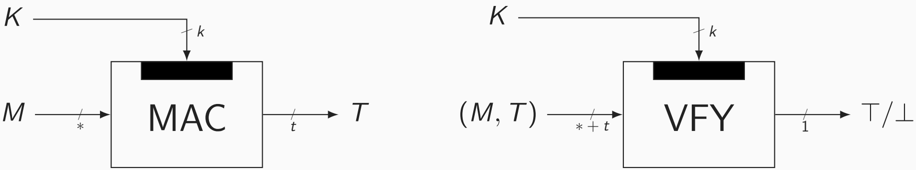

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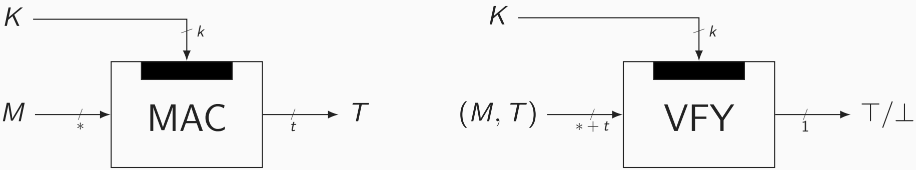

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  - $\top$ if tag is correct
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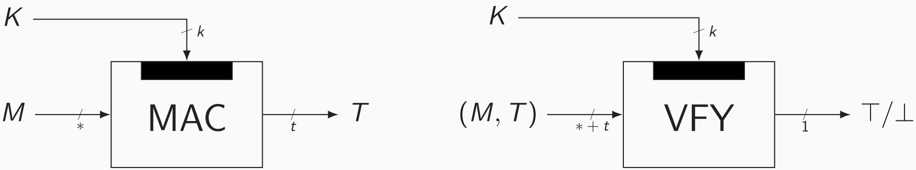
- Sometimes, additional nonce: MAC-evaluations should be for unique nonce

Message Authentication (2/2)



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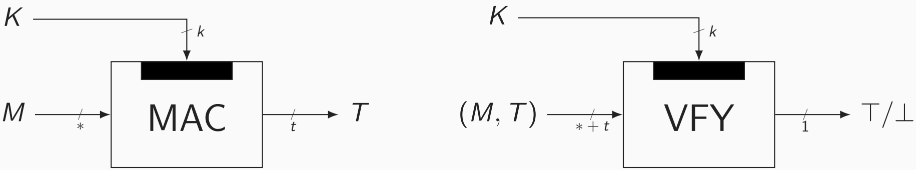

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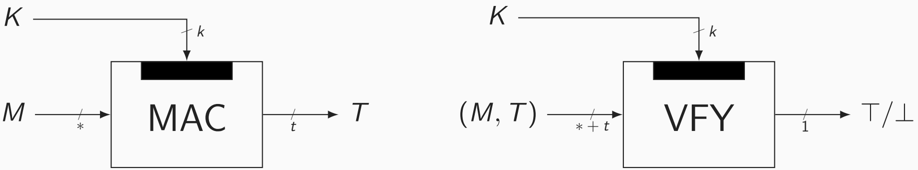

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- Often, one adopts a weaker notion, called unforgeability

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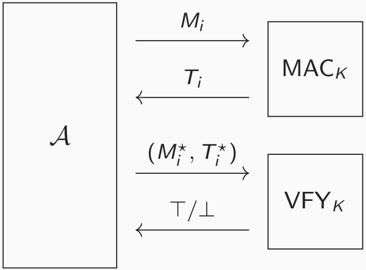

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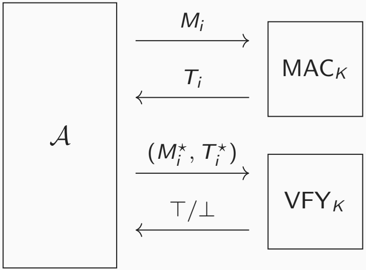

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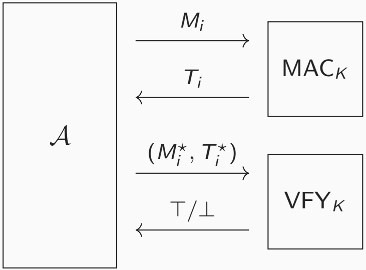

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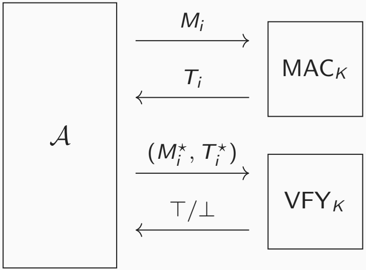

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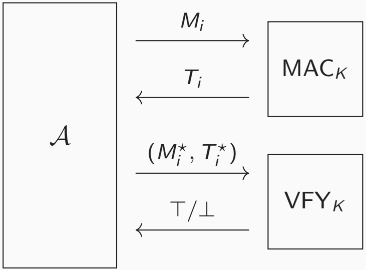
- $\mathbf{Adv}^{\mathrm{unf}}_{\mathsf{MAC}}(q_m, q_v)$: supremal advantage over any $\mathcal{A}$ with:
  - query complexity q_m to MAC_K
  - query complexity q_v to VFY_K



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$$\mathbf{Adv}^{\mathrm{unf}}_{\mathsf{MAC}}(q_m, q_v) \leq \mathbf{Adv}^{\mathrm{prf}}_{\mathsf{MAC}}(q_m + q_v) + \frac{q_v}{2^t}$$

- Proof: see Theorem 6.2.2 of "Intro2Crypto-symmetric.pdf"

Universal Hash Functions

- Same interface as MAC, but weaker security requirements
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  - δ-universal if $\mathbf{Pr}_K\left(H_K(M) = H_K(M')\right) \leq \delta \qquad (\forall\ M \neq M')$
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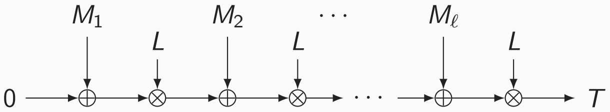
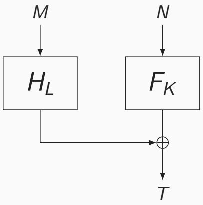
GHASH

- Addition and multiplication over finite field
- $\ell 2^{-t}$-(XOR-)universal [MV04]





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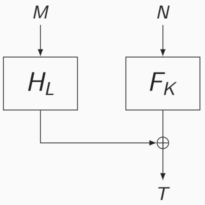

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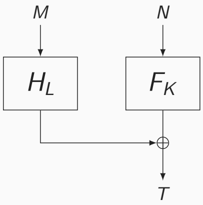

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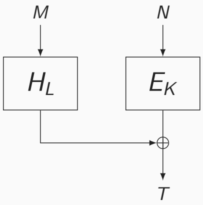

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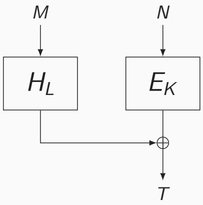

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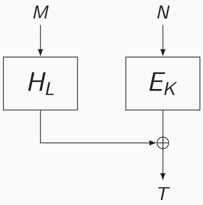

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- Keys $K, R \in \{0,1\}^{128}$ with 22 bits of R fixed
- On input of nonce $N \in \{0,1\}^{128}$ and message $M \in \{0,1\}^*$:
  - M is partitioned into ℓ 128-bit blocks M_i
  - Each block (except last one) is appended with a 1
  - Call the updated blocks $C_1, \ldots, C_\ell$
  - Note, $C_1, \ldots, C_{\ell-1}$ are integers in $[2^{128}, 2^{129} - 1]$

Poly1305 [Ber05]

- Wegman-Carter-Shoup construction with cleverly chosen universal hash
- Originally defined for AES, but commonly used with ChaCha20

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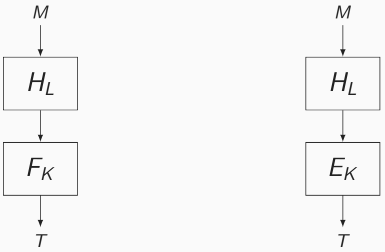
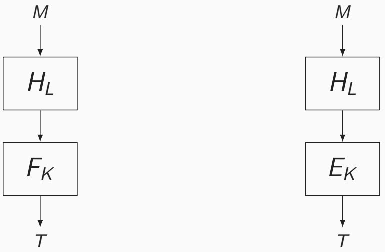
  - $T = \Big(\big((C_1 \cdot R^\ell + C_2 \cdot R^{\ell-1} + \cdots + C_\ell \cdot R) \bmod 2^{130} - 5 \big) + E_K(N) \Big) \bmod 2^{128}$

Protected Hash (1/2)



- Not a dedicated construction "as such", but appears quite frequently in disguise
  - CBC-MAC [BKR94]
  - Protected counter sum [Ber99]
- Process arbitrary length M through universal hash, protect with $F_K(\cdot)$ or $E_K(\cdot)$

Protected Hash (2/2)



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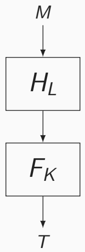

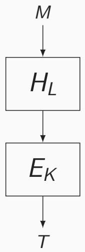

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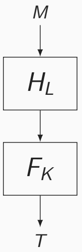

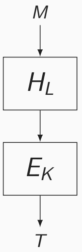

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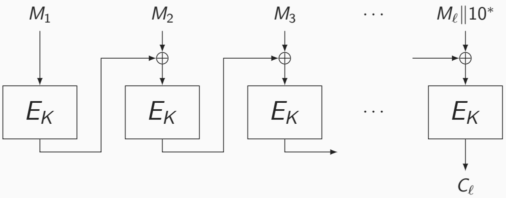
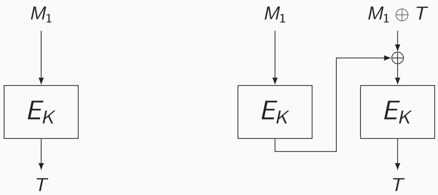
- In case we protect with $E_K(N)$, extra loss of $\binom{q_m+q_v}{2}/2^n$

Cipher Block Chaining MAC (CBC-MAC) Mode



- In CBC encryption: C_i depends on $M_1, \ldots, M_i$
- Idea for message authentication:
  - Apply CBC with $IV = 0$ to padded message M
  - Define tag T to be the last ciphertext block
  - Important: discard all other ciphertext blocks!
- Turns out to be secure if messages are prefix-free

Cipher Block Chaining MAC (CBC-MAC) Mode: Weakness



- In general, CBC-MAC can be distinguished from random in two queries:
  - Query M_1, tag equals $T = E_K(M_1)$
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$$E_K(E_K(M_1) \oplus M_1 \oplus T) = E_K(T \oplus M_1 \oplus T) = E_K(M_1) = T$$

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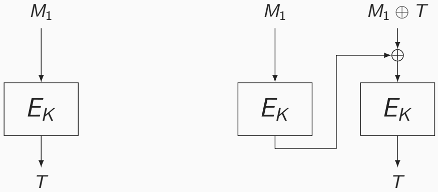

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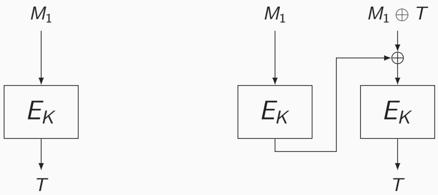

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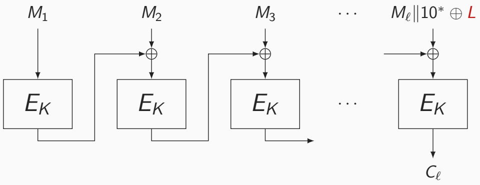
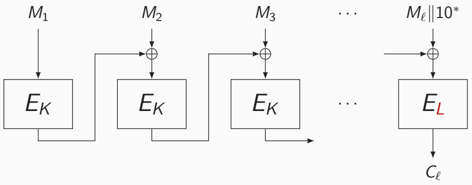
- A random oracle would give independent responses
- CBC-MAC is not unforgeable and definitely not PRF-secure
- Note: attack ignores padding, but this can be dealt with

Cipher Block Chaining MAC (CBC-MAC) Mode: Fix

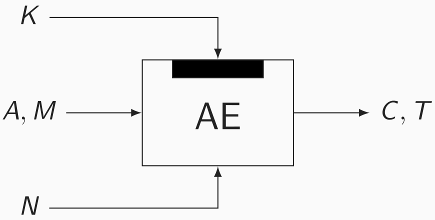




- Length-extension attack can be resolved by "special" finalization
- Solution 1: mask last block with dedicated key L (known as C-MAC)
- Solution 2: apply independent last primitive call
    - Can be seen as protected hash construction
- Both constructions indistinguishable from RO up to around $\binom{q}{2}/2^n$

Authenticated Encryption (Teaser)

Authenticated Encryption



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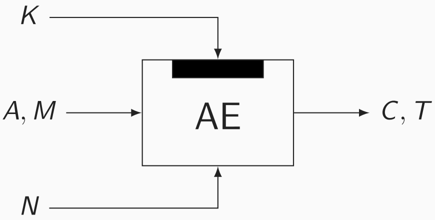

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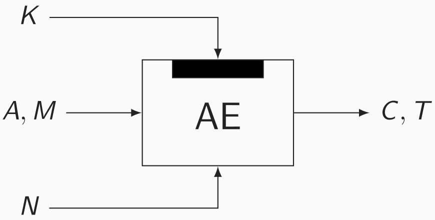
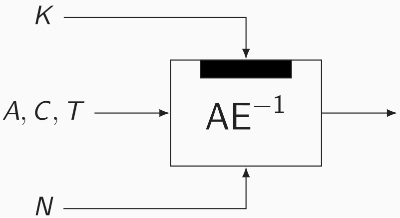


- Using key K:
  - Message M is encrypted in ciphertext C
  - Associated data A and message M are authenticated using T
- Nonce N randomizes the scheme
- Key, nonce, and tag are typically of fixed size
- Associated data, message, and ciphertext could be arbitrary length

Authenticated Decryption



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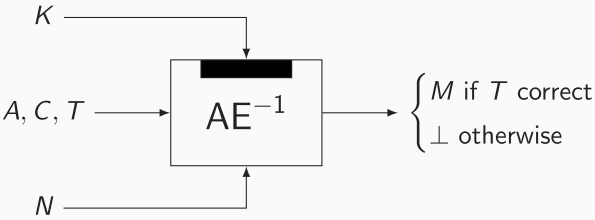

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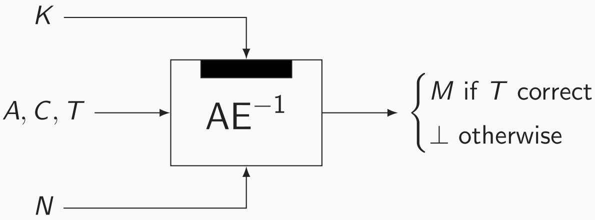

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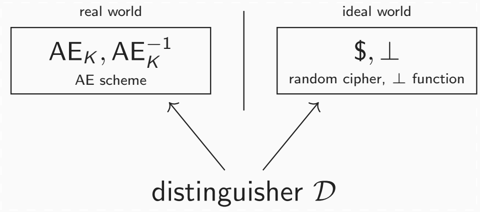
- Correctness: $\mathrm{AE}_K^{-1}(N, A, \mathrm{AE}_K(N, A, M)) = M$

Authenticated Encryption Security



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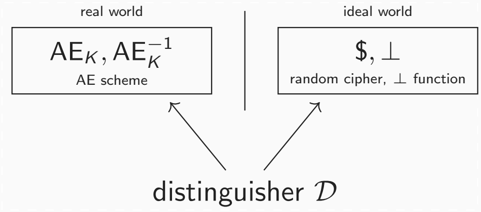

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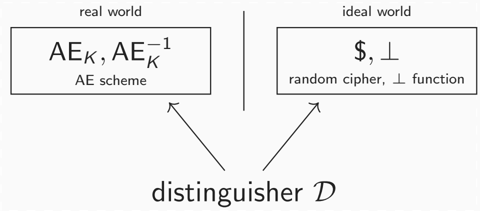

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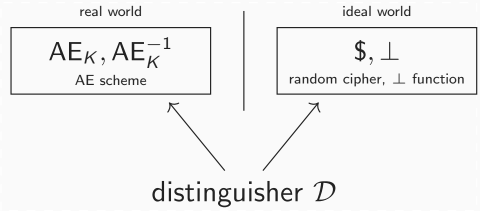

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$$\mathbf{Adv}_{\mathsf{AE}}^{\mathrm{ae}}(\mathcal{D}) = \Delta_{\mathcal{D}}\left(\mathsf{AE}_K, \mathsf{AE}_K^{-1} \; ; \; \$, \perp\right) = \left|\mathbf{Pr}\left(\mathcal{D}^{\mathsf{AE}_K, \mathsf{AE}_K^{-1}} = 1\right) - \mathbf{Pr}\left(\mathcal{D}^{\$,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

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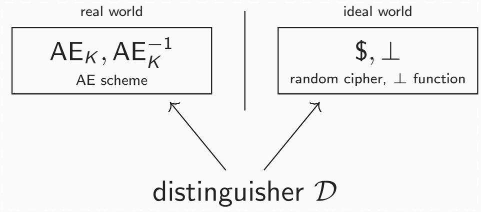

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- $\mathbf{Adv}^{\mathrm{ae}}_{\mathsf{AE}}(q_e, q_v)$: supremal advantage over any $\mathcal{D}$ with query complexity q_e, q_v

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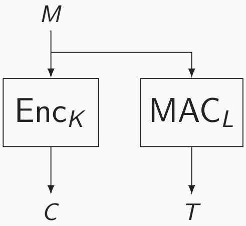
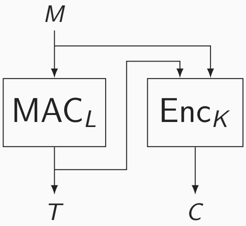
E&M



- Used in SSH

MtE



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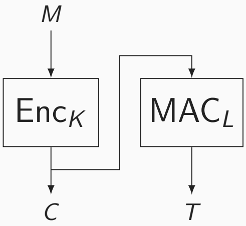

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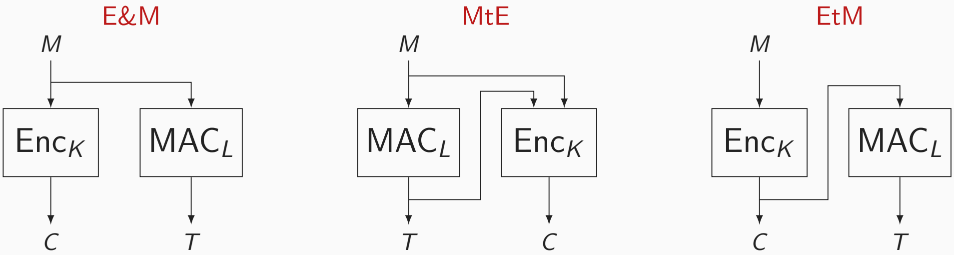

- Used in SSH
- Generically insecure
  - $\mathrm{MAC}_L(M) = M \| T$?

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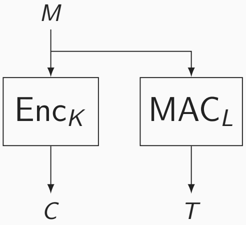

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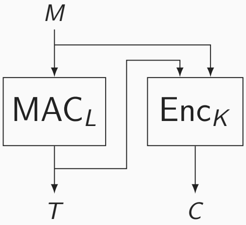

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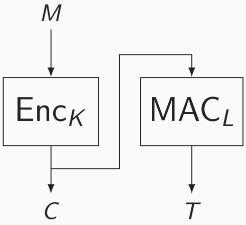

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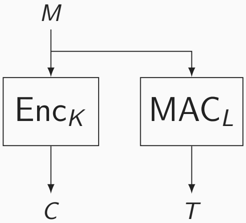

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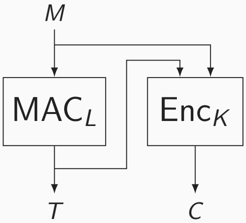

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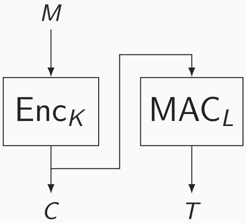

- Used in IPSec
- Most secure variant
- Ciphertext integrity