CSE 484/M584: Computer Security (and Privacy)

Spring 2025

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Admin

- Lab 2 (Cryptolab) next Wednesday
- Lab 1a/b Exploits
  - Again, check partner status. Please.
  - Partner status is *per-submission*. You have to do it each time.
  - Grades out.

Person-in-the-Middle Attacks

- Diffie-Hellman protocol (by itself) does not provide integrity (against <u>active</u> attackers)

$sk_A \leftarrow x$
$pk_A \leftarrow g^x$

$sk_B \leftarrow y$
$pk_B \leftarrow g^y$

Public Key Encryption

Alice

pk_B

Bob

pk_B, sk_B

Public Key Encryption

Alice

pk_B

ct

Bob

pk_B, sk_B

$\text{Encrypt}(pk_B , m) \rightarrow ct$

Public Key Encryption

Alice

pk_B

$\xrightarrow{\text{ct}}$

Bob

pk_B, sk_B

$\text{Encrypt}(\text{pk}_B, m) \rightarrow \text{ct}$

$\text{Decrypt}(\text{sk}_B, \text{ct}) \rightarrow m$

Public Key Encryption from Diffie-Hellman

pk_B

Alice

pk_B, sk_B

$sk_B \leftarrow y$
$pk_B \leftarrow g^y$

Bob

Public Key Encryption from Diffie-Hellman

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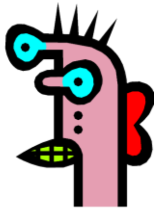

Bob

$sk_B \leftarrow y$
$pk_B \leftarrow g^y$

<u>Sample one-time key:</u>

$sk_A \leftarrow r$
$pk_A \leftarrow g^r$

<u>Compute DH shared secret:</u>

$K = H(g^{ry})$

<u>Encrypt with authenticated symmetric encryption:</u>

$ct_{SE} = SE.Enc(K, m)$

Public Key Encryption from Diffie-Hellman

pk_B

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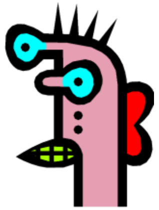

Bob

$sk_B \leftarrow y$
$pk_B \leftarrow g^y$

<u>Sample one-time key:</u>
$sk_A \leftarrow r$
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$ct = (g^r, ct_{SE})$ $\longrightarrow$

<u>Compute DH shared secret:</u>
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Public Key Encryption from Diffie-Hellman

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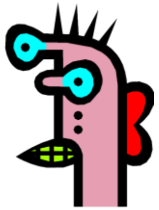

Bob

$sk_B \leftarrow y$
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<u>Sample one-time key:</u>

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$pk_A \leftarrow g^r$

$$ct = (g^r, ct_{SE})$$

<u>Compute DH shared secret:</u>

$K = H(g^{ry})$

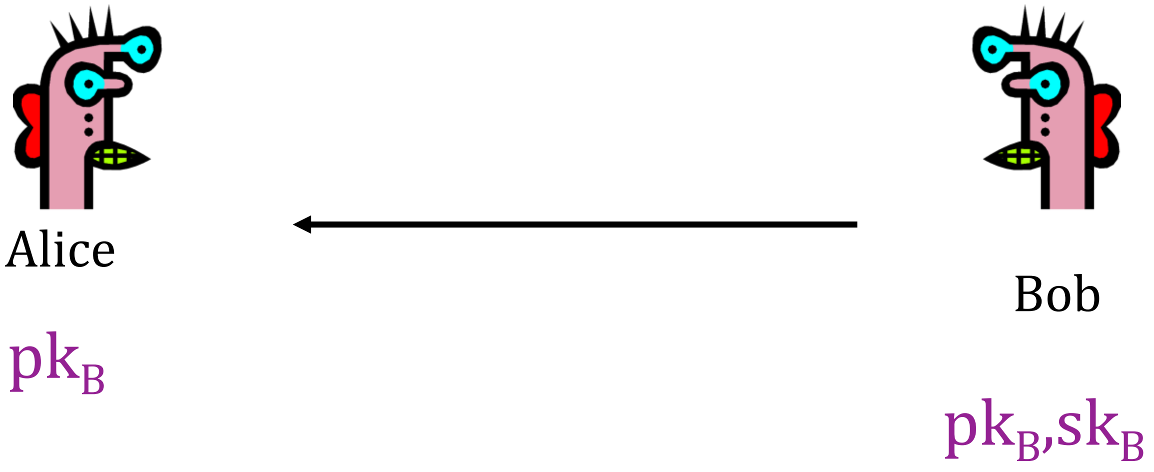
<u>Encrypt with authenticated symmetric encryption:</u>

$ct_{SE} = SE.Enc(K, m)$

$K = H(g^{ry})$
$m = SE.Dec(K, ct_{SE})$

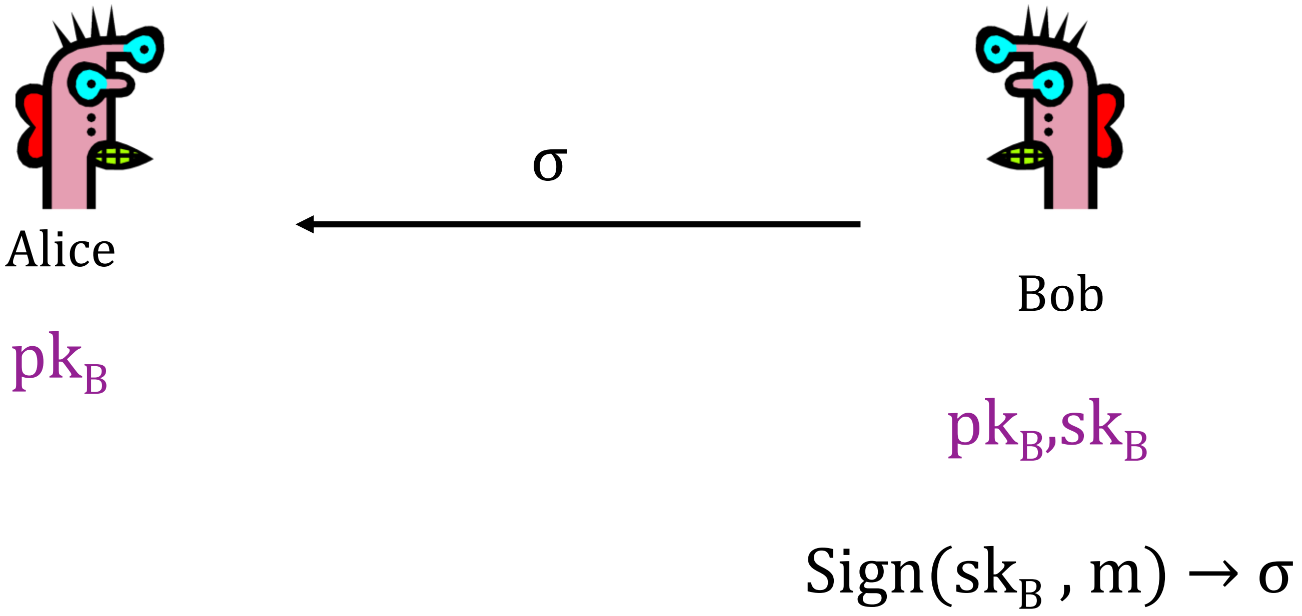
Digital Signatures

- No one should be able to forge signatures from Bob's public key without Bob's secret key



Digital Signatures

- No one should be able to forge signatures from Bob's public key without Bob's secret key



Digital Signatures

- No one should be able to forge signatures from Bob's public key without Bob's secret key

Alice

pk_B

σ

$\longleftarrow$

Bob

pk_B, sk_B

$\mathrm{Verify}(pk_B, m, \sigma) \to 0/1$

$\mathrm{Sign}(sk_B, m) \to \sigma$

Digital Signatures

- No one should be able to forge signatures from Bob’s public key without Bob’s secret key

Alice

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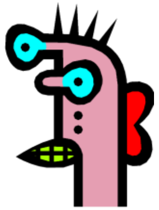
$\longleftarrow$



Bob

pk_B

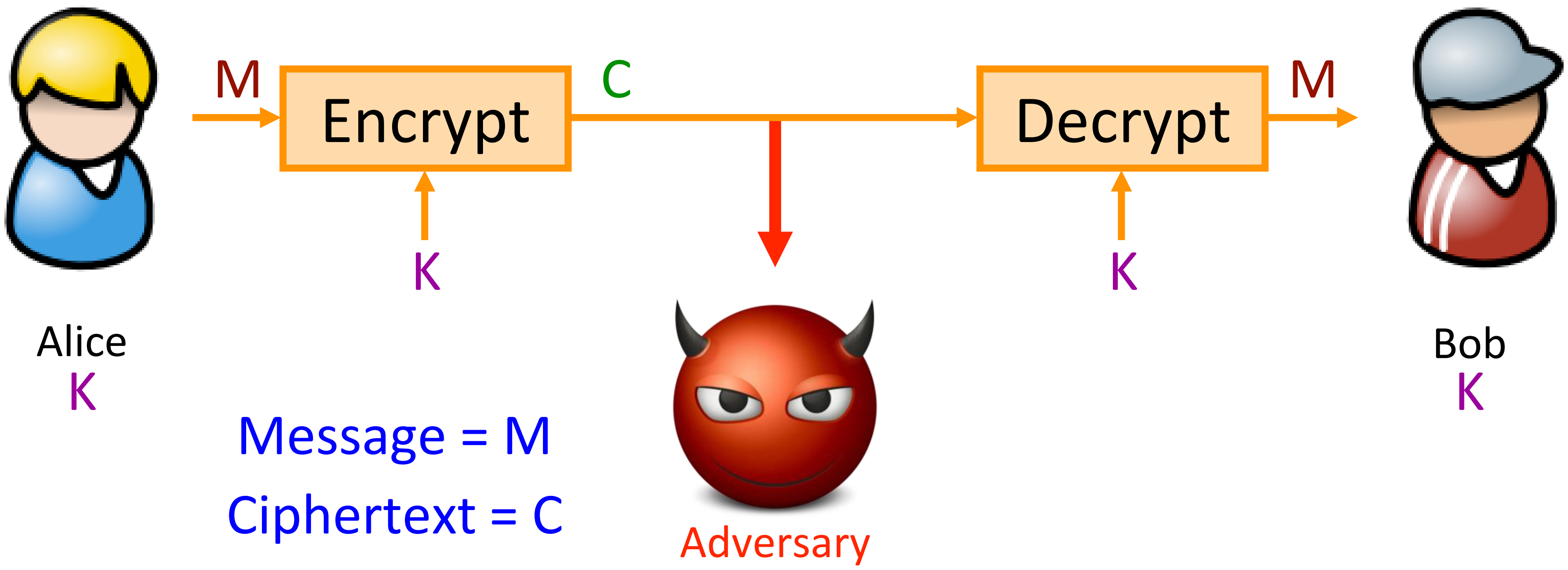
pk_B, sk_B

$\mathrm{Verify}(pk_B, m, \sigma) \rightarrow 0/1$

$\mathrm{Sign}(sk_B, m) \rightarrow \sigma$

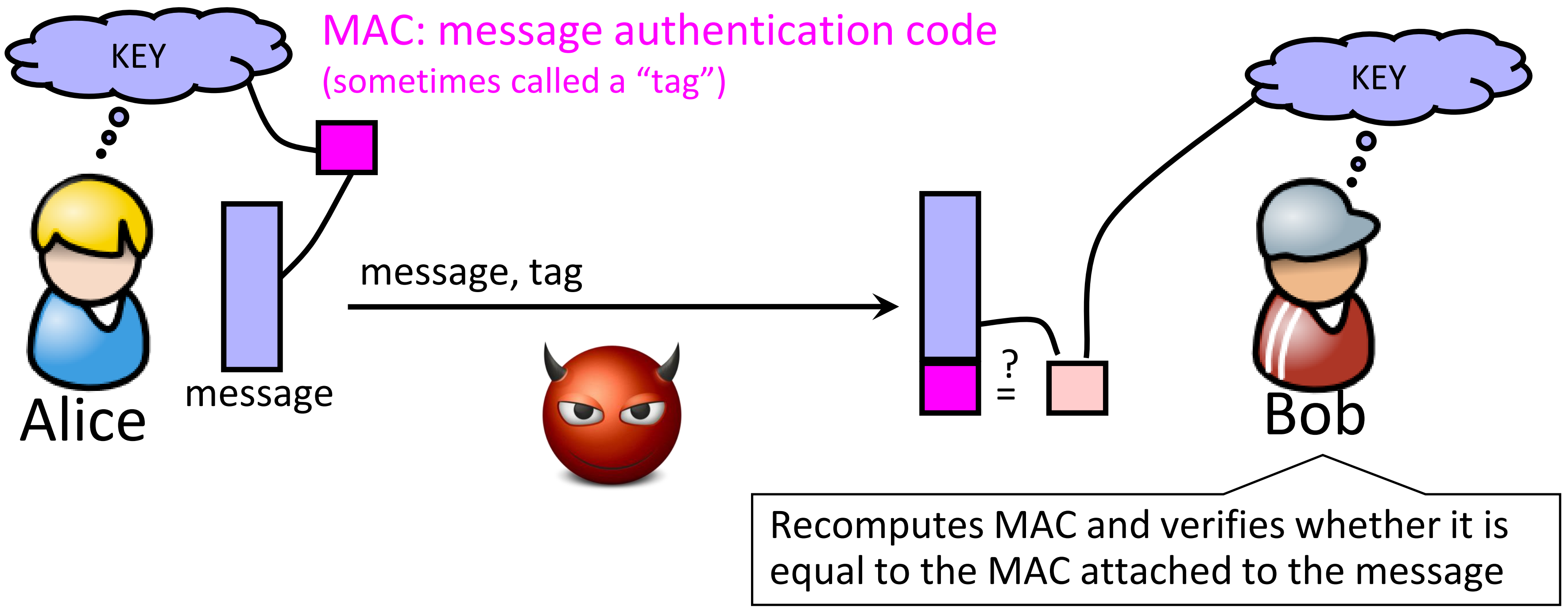
So Far: Achieving Confidentiality/Authenticity

Encryption schemes: A tool for protecting confidentiality.



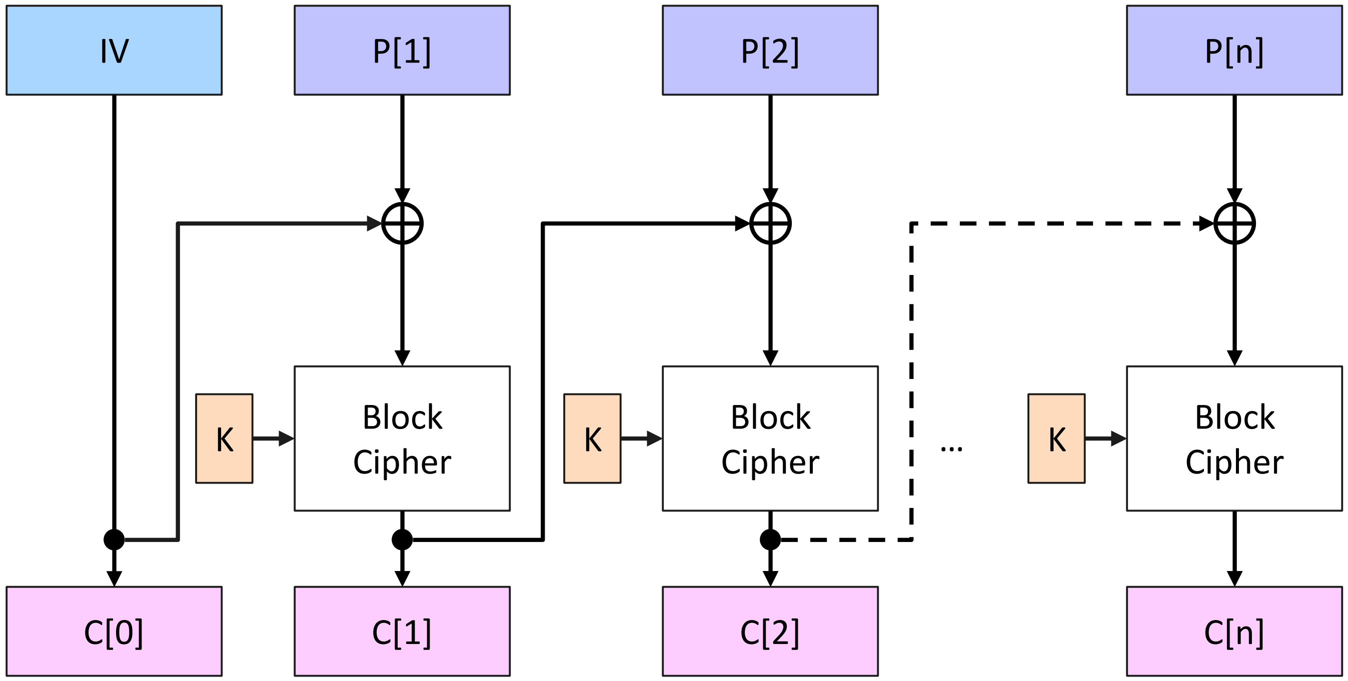
Now: Achieving Integrity

Message authentication schemes: A tool for protecting integrity.

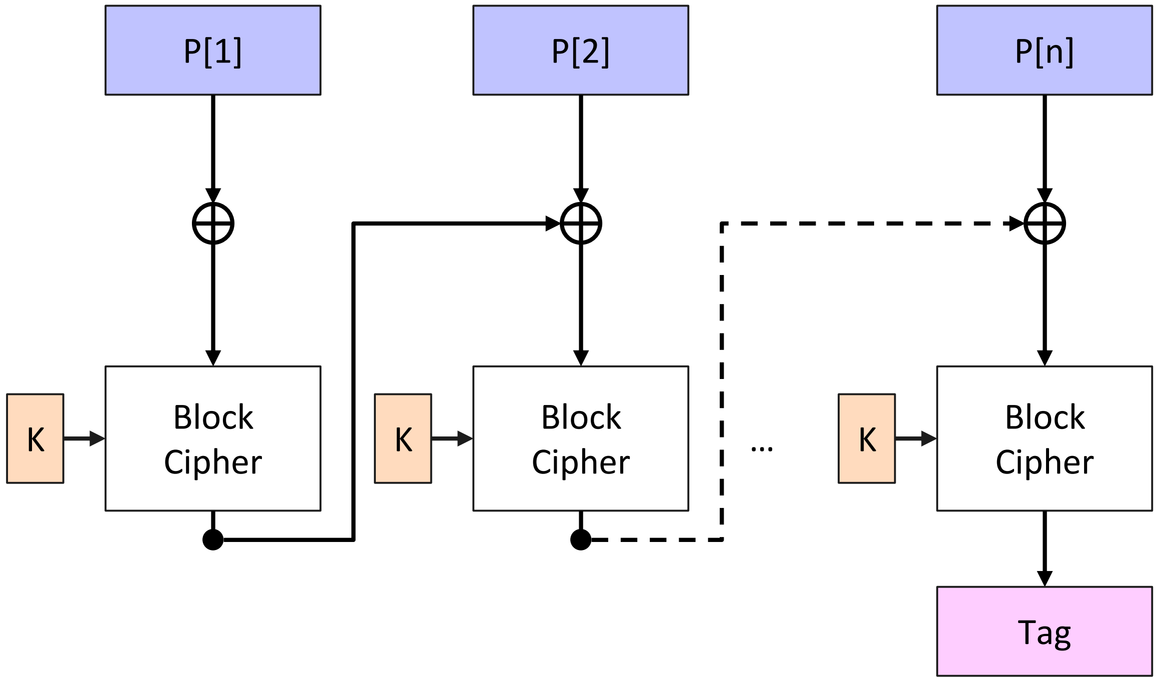


Integrity and authentication: only someone who knows KEY can compute correct MAC for a given message.

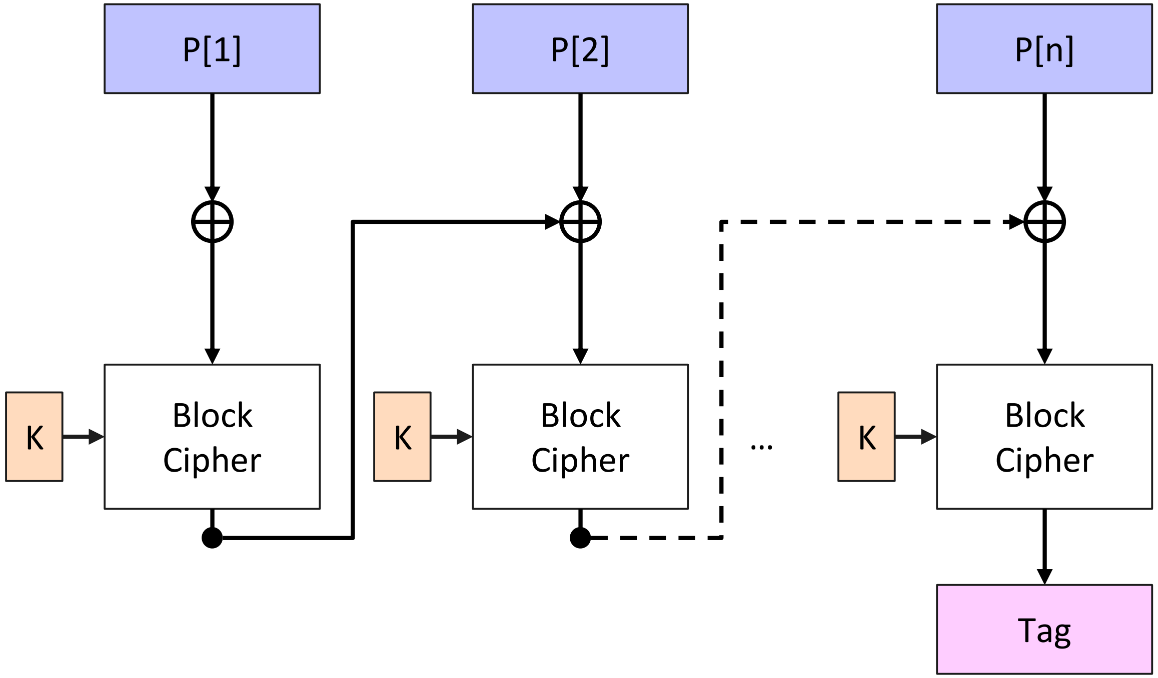
MAC from CBC Mode (CBC-MAC)



MAC from CBC Mode (CBC-MAC)

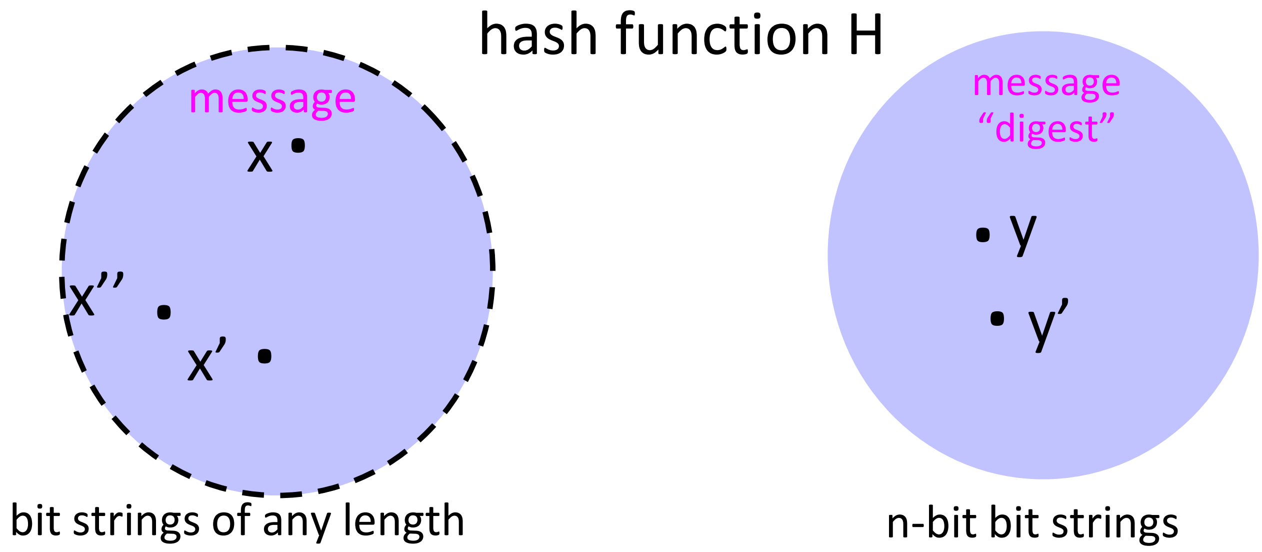


MAC from CBC Mode (CBC-MAC)



- Not secure when system may MAC messages of different lengths
- Adapt by concatenating message length to front of plaintext

Hash Functions: Main Idea



- Hash function H is a lossy compression function
  - Collision: h(x)=h(x') for distinct inputs x, x'
- Cryptographic hash function needs a few properties…

Hash Functions: Useful!

- Distributing software
- Checking integrity of files
- Hashtables
- Commitments
- Etc.

Property 1: One-Way

- Intuition: hash should be hard to invert
  - "Preimage resistance"
  - Let $h(x') = y \in \{0,1\}^n$ for a random x'
  - Given y, it should be hard to find any x such that h(x)=y
- How hard?
  - Brute-force: try every possible x, see if h(x)=y
  - SHA-2 (common hash function) has 256-bit output
    - Expect to try 2^{255} inputs before finding one that hashes to y.

Property 2: Collision Resistance

- Should be hard to find $x \neq x'$ such that $h(x)=h(x')$

Birthday Paradox

In a class with q students, what is the probability that two of them have the same birthday? [Assuming birthdays are uniform!]

- $\mathcal{S} = \{\text{Jan } 1, \dots, \text{Dec } 31\}$, $|\mathcal{S}| = 365$ [ignore leap year]

Birthday Paradox

In a class with q students, what is the probability that two of them have the same birthday? [Assuming birthdays are uniform!]

- $\mathcal{S} = \{\text{Jan } 1, \dots, \text{Dec } 31\}$, $|\mathcal{S}| = 365$ [ignore leap year]
- For $q = 23$: $0.500001 \ldots \leq p \leq 0.69315 \ldots$

Theorem. We have

$$1 - e^{-\frac{q(q-1)}{2|\mathcal{S}|}} \leq \mathrm{p}_{coll}(q, \mathcal{S}) \leq \frac{q(q-1)}{2|\mathcal{S}|}$$

Note: For $q = \sqrt{|\mathcal{S}|}$ we have $0.39 \leq \mathrm{p}_{coll}(q, \mathcal{S}) \leq 0.5$

Birthday Paradox

- Why is the birthday paradox important for collision resistance?
  - 2^{128} different 128-bit values
    - Pick one value at random. To exhaustively search for this value requires trying on average 2^{127} values.
    - **Expect "collision" after selecting approximately 2^{64} random values.**
    - **64 bits** of security against collision attacks, not 128 bits.

- Should be hard to find $x \neq x'$ such that $h(x)=h(x')$
- Birthday paradox means that brute-force collision search is only $O(2^{n/2})$, *not* $O(2^n)$
  - For SHA-2 with 256-bit output, this means $O(2^{128})$ vs. $O(2^{256})$

Property 3: Indifferentiability

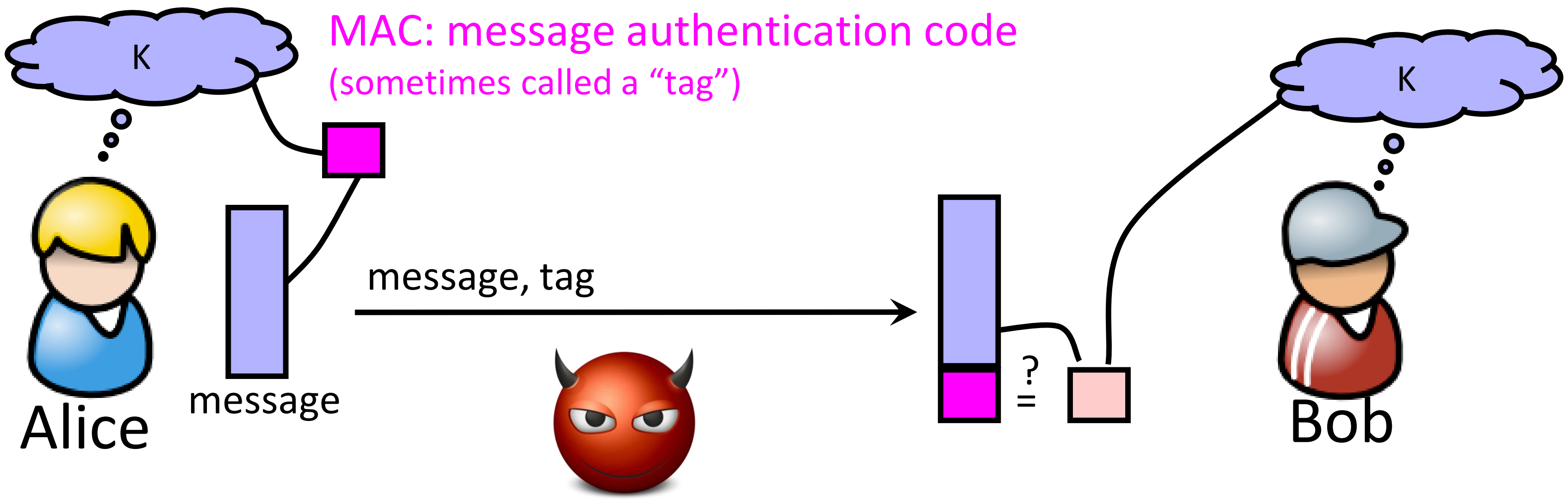
- Informal: Outputs of the hash function look “random” (in a certain ideal model)

Hashing vs. Encryption

- Hashing is one-way. There is no “un-hashing” (one-way)
  - A ciphertext can be decrypted with a decryption key
- Hashing is deterministic
  - Hash the same input twice => same hash value
  - Encrypt the same input twice => different ciphertexts

MAC via Hashing

Message authentication schemes: A tool for protecting integrity.



Tag = Hash(K || message)

Common Hash Functions

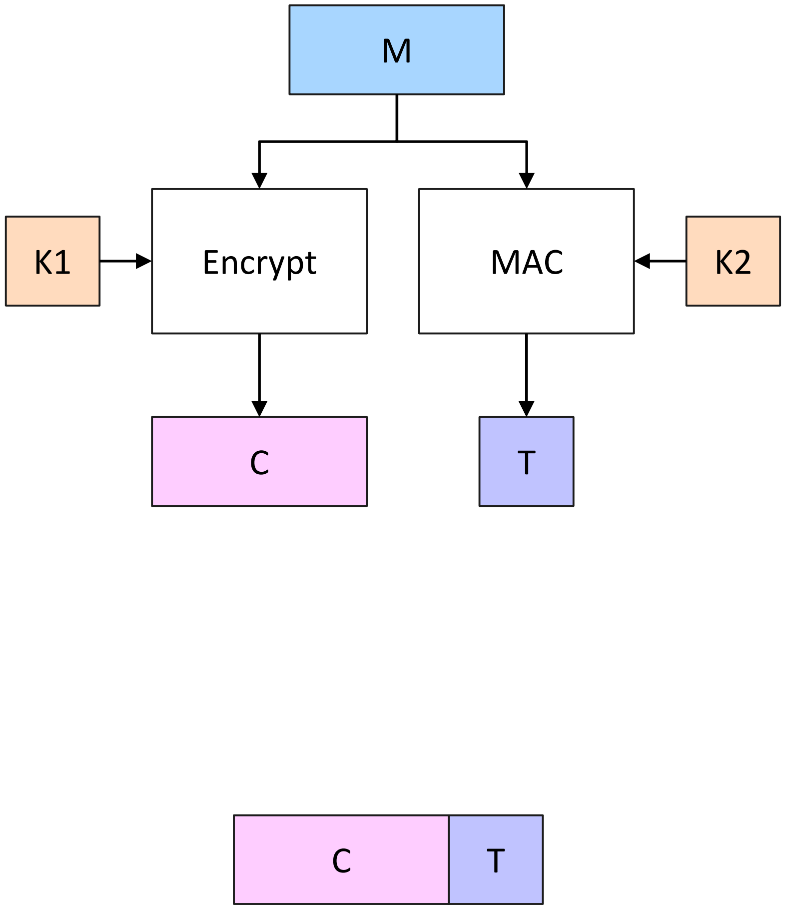
- **SHA-2: SHA-256, SHA-512, SHA-224, SHA-384**
- **SHA-3: standard released by NIST in August 2015**
- MD5 – Don’t use for security!
  - 128-bit output
  - Collision-resistance broken (summer of 2004)
- SHA-1 (Secure Hash Algorithm) – Don’t use for security!
  - 160-bit output
  - US government (NIST) standard as of 1993-95
  - Theoretically broken 2005; practical attack 2017!

Authenticated Encryption

- What if we want both confidentiality and integrity?
- Natural approach: combine encryption scheme and a MAC.

How to combine Encryption and MACs?

Encrypt-and-MAC



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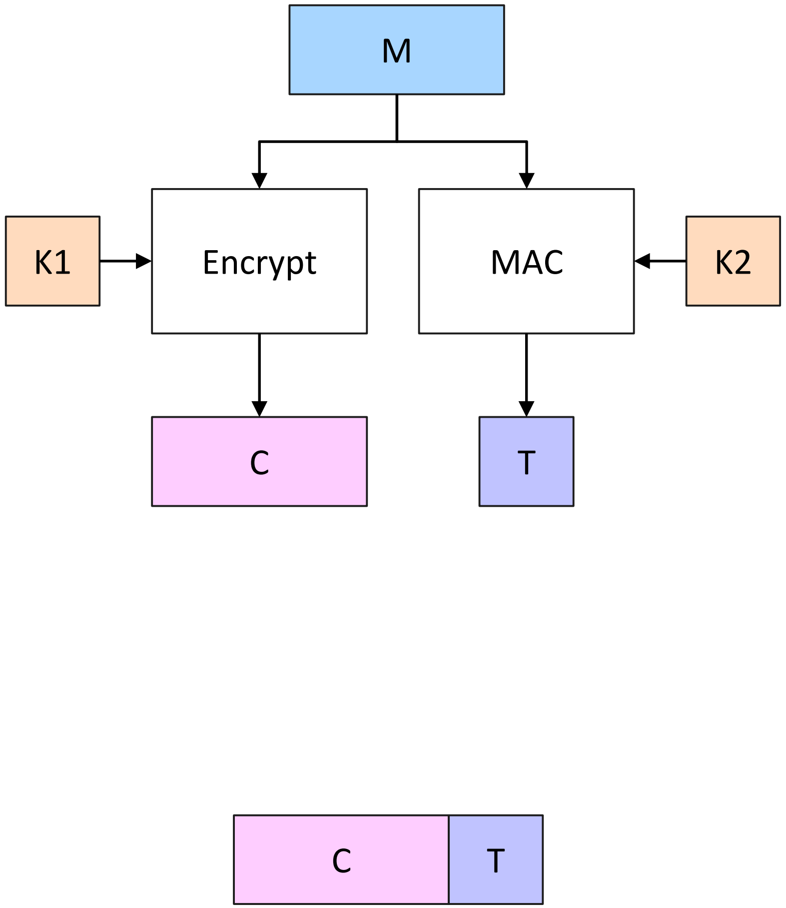
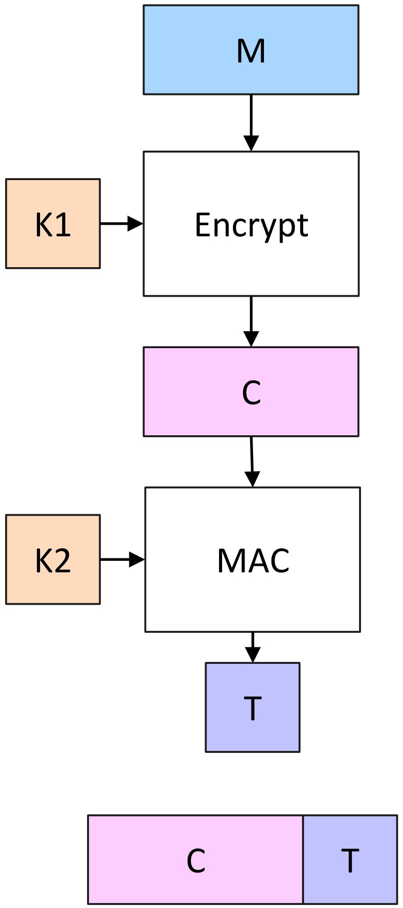


Encrypt-then-MAC



Gradescope!

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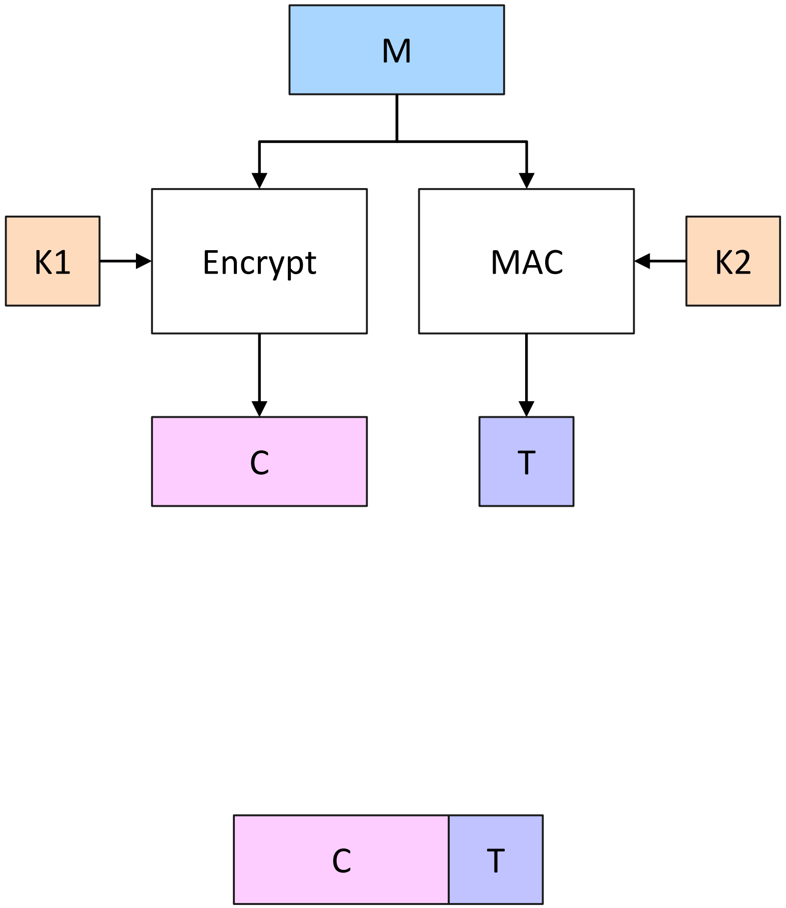

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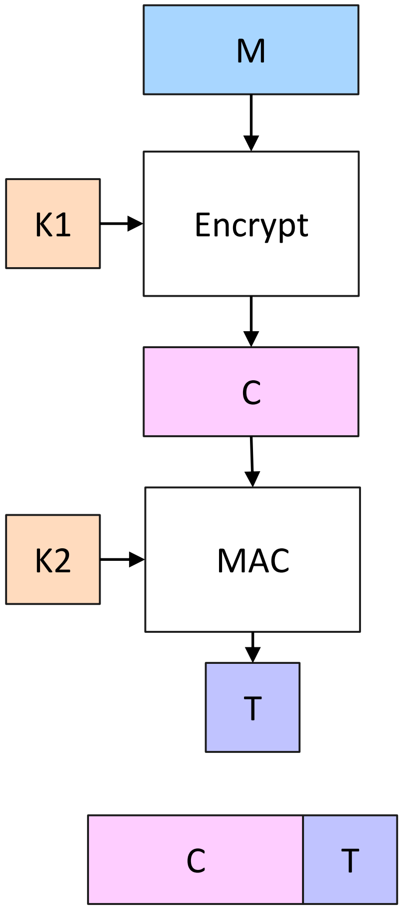
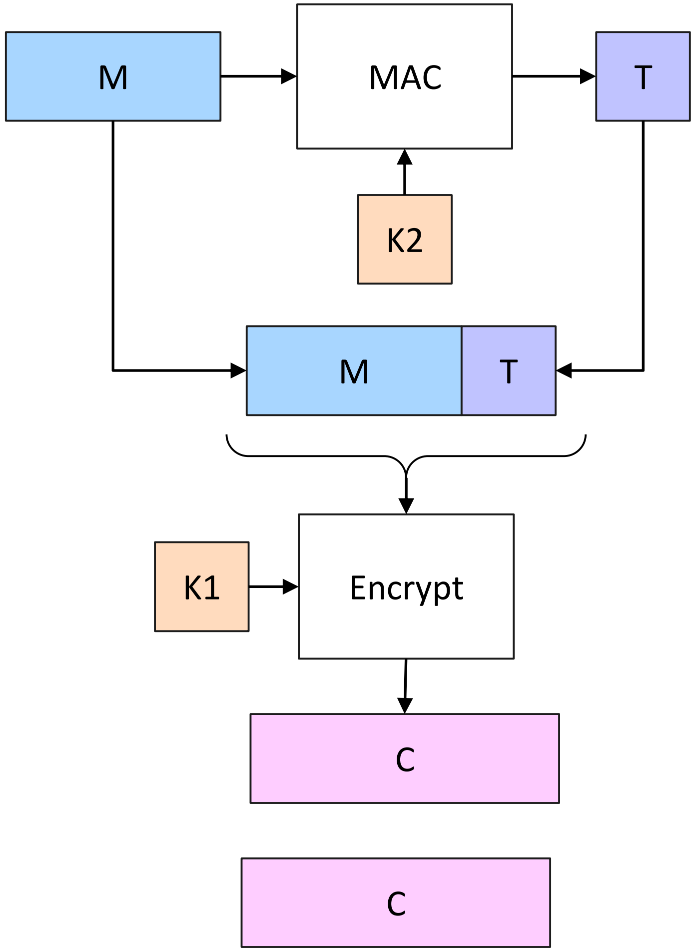
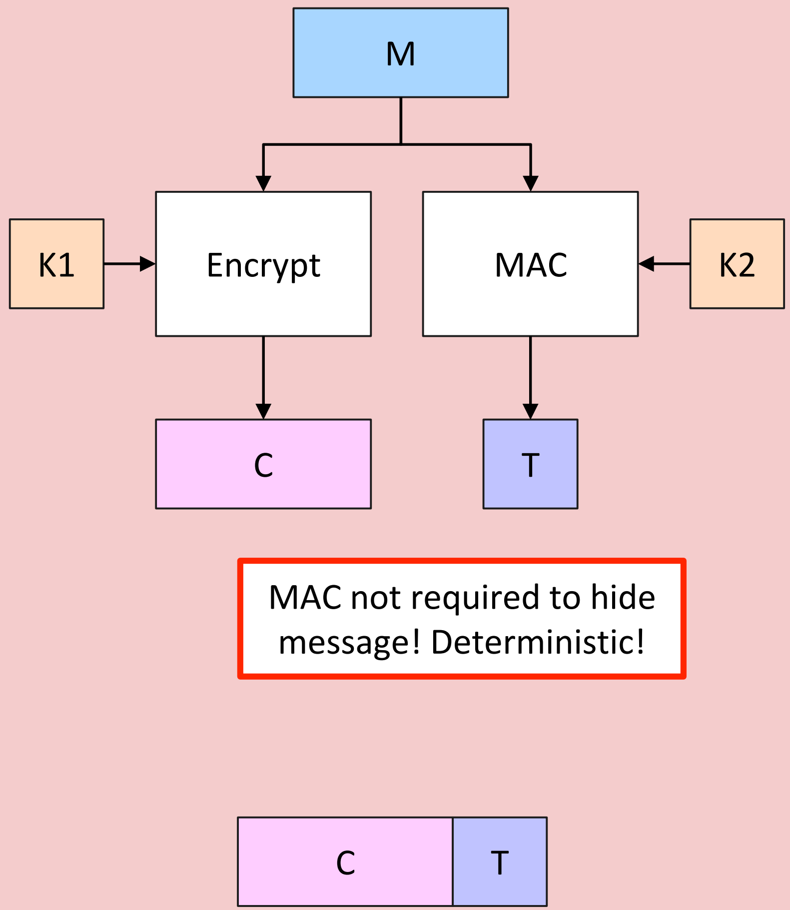


MAC-then-Encrypt

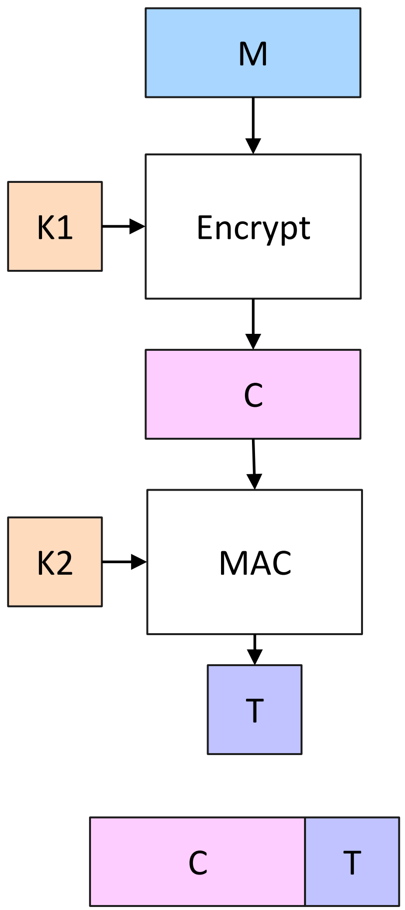


How to combine Encryption and MACs?

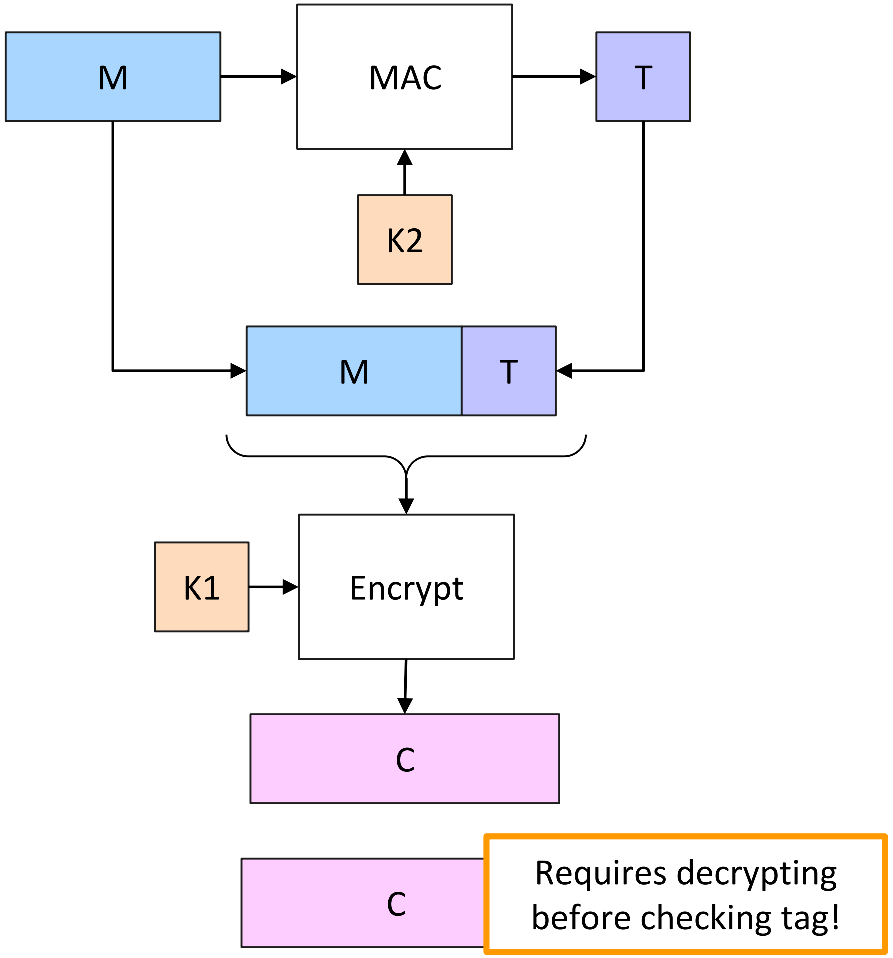
Encrypt-and-MAC



Encrypt-then-MAC



MAC-then-Encrypt



What do Quantum Computers mean for Cryptography?

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1. Implications for existing cryptography
    - Quantum algorithms exist to solve “hard” assumptions quickly
        - Shor’s algorithm can solve factoring and discrete logarithm
    - “Post-quantum” cryptography
        - Build asymmetric cryptography for classical computers based on assumptions that we think are “hard” even for quantum computers
        - “Lattice-based” cryptography

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1. Implications for existing cryptography
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     - Build asymmetric cryptography for classical computers based on assumptions that we think are “hard” even for quantum computers
     - “Lattice-based” cryptography
2. Implications for future cryptography
   - Quantum computing offers new hardness assumptions and new functionality from which to build cryptography