CS396: Security, Privacy & Society

Fall 2022

Lecture 10: MACs & Hashing

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Outline

- Message authentication
  - Message Integrity
  - Message Authentication Codes (MACs)
  - MAC constructions

Message authentication

Recall: Integrity

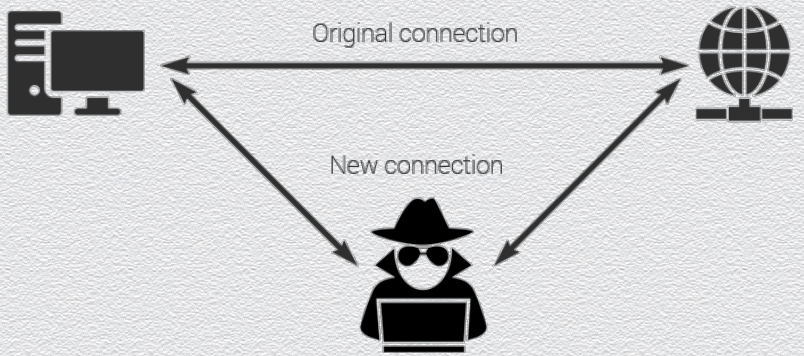
Fundamental security property

- **an asset is modified only by authorized parties**
- "I" in the CIA triad

> *"computer security seeks to prevent **unauthorized** viewing (confidentiality) or **modification (integrity)** of **data** while preserving access (availability)"*

Alteration

- main threat against integrity of **in-transit** data
- e.g., MITM attack



Man in the middle, Phisher, or annonymous proxy

Security problems studied by modern cryptography

- Classical cryptography: **message encryption**
  - early crypto schemes tried to provide **secrecy / confidentiality**
- Modern cryptography: **wide variety** of security problems
  - today we need to study a large set of **security properties** beyond secrecy
- The sibling of message encryption: **message authentication**
  - **another cornerstone** of any secure system aiming to provide **authenticity & integrity**

Message authentication: Motivation

Information has **value**, but only when it is **correct**

- random, incorrect, inaccurate or maliciously altered data is **useless** or **harmful**
  - **message authentication = message integrity + authenticity**
    - while in transit (or at rest), no message should be **modified** by an outsider
    - no outsider can **impersonate** the stated message sender (or owner)

- it is often necessary / worth to protect critical / valuable data
  - **message encryption**
    - while in transit (or at rest), no message should be **leaked** to an outsider

Example 1

Secure electronic banking

- a bank receives an electronic request to transfer $1,000 from Alice to Bob

Concerns

- who ordered the transfer, Alice or an attacker (e.g., Bob)?
- is the amount the intended one or was maliciously modified while in transit?
  - adversarial Vs. random message-transmission errors
    - standard error-correction is **<u>not sufficient</u>** to address this concern

Example 2

Web browser cookies

- a user is performing an online purchase at Amazon
- a “cookie” contains session-related info, as client-server HTTP traffic is stateless
  - stored at the client, included in messages sent to server
  - contains client-specific info that affects the transaction
    - e.g., the user’s shopping cart along with a discount due to a coupon

Concern

- was such state maliciously altered by the client (possibly harming the server)?

Integrity of communications / computations

Highly important

- any unprotected system cannot be assumed to be trustworthy w.r.t.
  - origin/source of information (due to impersonation attacks, phishing, etc.)
  - contents of information (due to man-in-the-middle attacks, email spam, etc.)
  - overall system functionality

Prevention Vs. detection

- unless system is “closed,” adversarial tampering with its integrity **cannot be avoided**!
- goal: identify system components that are not trustworthy
  - **detect tampering** or **prevent undetected tampering**
    - e.g., avoid “consuming” falsified information

Encryption does not imply authentication

A common misconception

> "since ciphertext c hides message m, Mallory cannot meaningfully modify m via c"

Why is this incorrect?

- all encryption schemes (seen so far) are based on one-time pad, i.e., masking via XOR
- consider flipping a single bit of ciphertext c; what happens to plaintext m?
  - such property of one-time pad does not contradict the secrecy definitions

Generally, secrecy and integrity are distinct properties

- encrypted traffic generally provides **no integrity** guarantees

Message authentication codes (MACs)

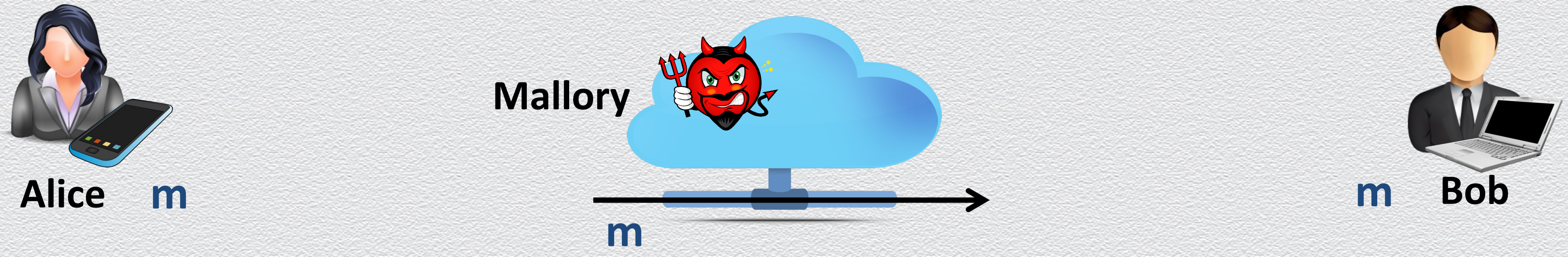
Problem setting: Reliable communication

Two parties wish to communicate over a channel

- Alice (sender/source) wants to send a message m to Bob (recipient/destination)

Underlying channel is unprotected

- attacker (mallory / adversary) can manipulate any sent messages
- e.g., message transmission via a compromised router



Solution concept: Symmetric-key message authentication

Main idea

- secretly annotate or "sign" message so that it is **unforgeable** while in transit
  - Alice **tags** her message m with **tag t**, which is sent **along** with **plaintext m**
  - Bob **verifies** authenticity of received message using tag t
  - Mallory can manipulate m, t but "**cannot forge**" a fake verifiable pair m', t'
  - Alice and Bob share a **secret key k** that is used for both operations

Security tool: Symmetric Message Authentication Code

- The tag is computed using a **tag-generation algorithm** (**Mac**)

$$t \leftarrow \mathrm{Mac}_k(m)$$

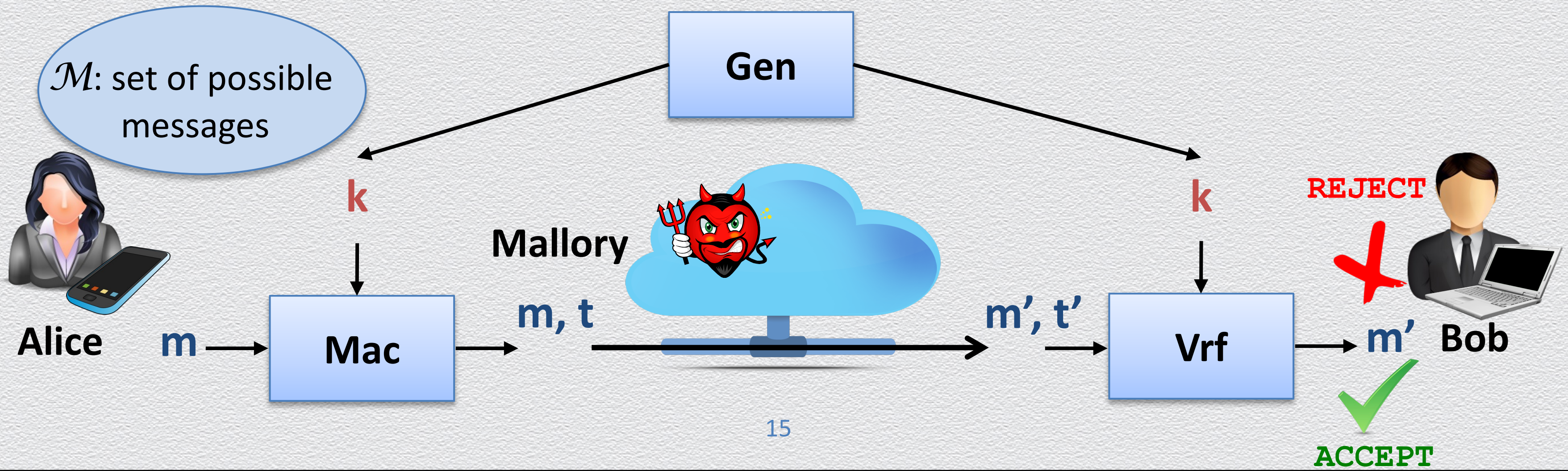
- **verification algorithm** (**Vrfy**)

$$b := \mathrm{Vrf}_k\,(m, t)$$

Security tool: Symmetric Message Authentication Code

Abstract cryptographic primitive, **a.k.a. MAC**, defined by

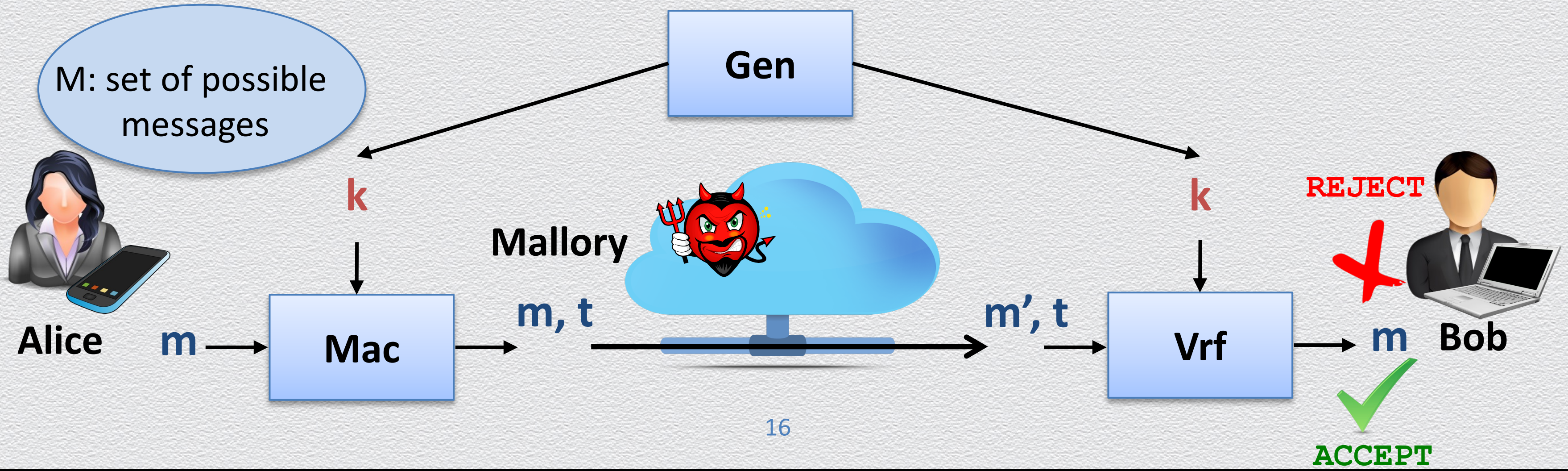
- a **message space** $\mathcal{M}$; and
- a triplet of algorithms **(Gen, Mac, Vrf)**
  - Gen, Mac are probabilistic algorithms, whereas Vrf is deterministic



Desired properties for MACs

By design, any MAC should satisfy the following

- **efficiency**: key generation & message transformations "are fast"
- **correctness**: for all m and k, it holds that $\mathrm{Vrf}_k(m, \mathrm{Mac}_k(m))$ = ACCEPT
- **security**: one "cannot forge" a fake verifiable pair m', t'



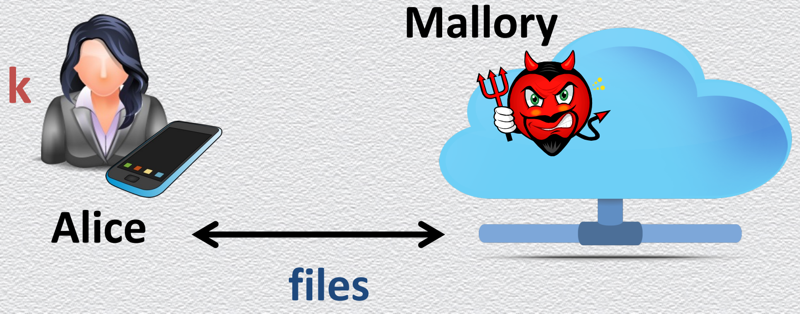
Main application areas

Secure communication

- **verify authenticity of messages** sent among parties
- assumption
  - Alice and Bob **securely generate, distribute and store shared key k**
  - attacker does not learn key k

Secure storage

- **verify authenticity of files** outsourced to the cloud
- assumption
  - Alice **securely generates and stores key k**
  - attacker does not learn key k



Conventions

Random key selection

- typically, Gen selects key k **uniformly at random** from the key space $\mathcal{K}$

Canonical verification

- when Mac is deterministic, Vrf typically amounts to re-computing the tag t
  - $\mathrm{Vrf}_k(m, t)$: 1. $t' := \mathrm{Mac}_k(m)$ 2. if $t = t'$, output `ACCEPT` else output `REJECT`
- but conceptually the following operations are distinct
  - authenticating m (i.e., running Mac) Vs. verifying authenticity of m (i.e., running Vrf)

MAC security

MAC scheme
(Gen, Mac, Vrf)

$\mathcal{T}$

Gen $\rightarrow$ k

$\text{Mac}_k(m_i) \rightarrow t_i$

Attacker **wins** the game if

1. $\text{Vrf}_k(m^*, t^*)$ = ACCEPT &
2. m^* not in $\mathcal{Q}$

m_1

t_1

m_2

t_2

…

m^*, t^*

$\mathcal{A}^{\text{Mac}(k,\ )}$

$\mathcal{Q} = m_1, m_2, \ldots$

The MAC scheme is **secure** if any PPT $\mathcal{A}$ wins the game only negligibly often.

Replay attacks

Recall: MAC

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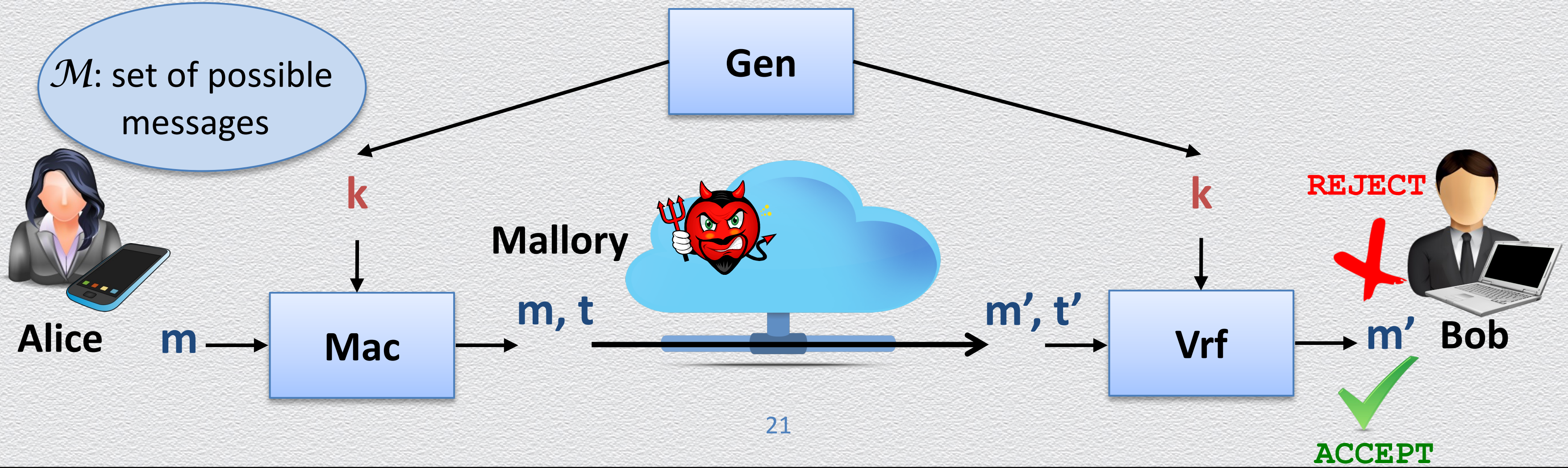

Recall: MAC security

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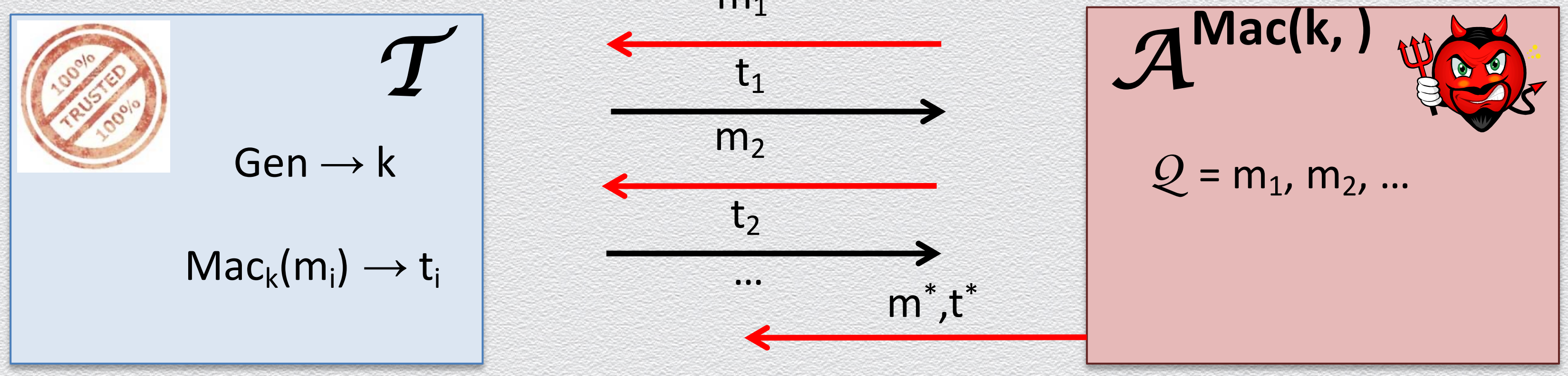
MAC scheme
(Gen, Mac, Vrf)



The MAC scheme is **secure** if any PPT $\mathcal{A}$ wins the game only negligibly often.

Real-life attacker

In practice, an attacker may

- observe a traffic of authenticated (and successfully verified) messages
- manipulate (or often also partially influences) traffic
  - aims at inserting an invalid but verifiable message m^*, t^* into the traffic
    - interesting case: forged message is a <u>new</u> (unseen) one
    - trivial case: forged message is a <u>previously observed</u> one, a.k.a. a **replay attack**
- launch a **brute-force attack** (given that $Mac_k(m) \rightarrow t$ is publicly known)
  - given any observed pair m, t, exhaustively search key space to find the used key k

Threat model

In the security game, Mallory is an adversary $\mathcal{A}$ who is

- “active” (on the wire)
  - we allow $\mathcal{A}$ to **observe** and **manipulate** sent messages
- “well-informed”
  - we allow $\mathcal{A}$ to **request MAC tags** of messages of **its choice**
- “replay-attack safe”
  - we restrict $\mathcal{A}$ to **forge only new** messages
- “PPT”
  - we restrict $\mathcal{A}$ to be **computationally bounded**
  - new messages may be forged undetectably only **negligibly** often

Notes on security definition

Is it a rather strong security definition?

- we allow $\mathcal{A}$ to **query MAC tags for any message**
  - but real-world senders will authenticate only “meaningful” messages
- we allow $\mathcal{A}$ to break the scheme by **forging any new message**
  - but real-world attackers will forge only “meaningful” messages

Yes, it is the right approach…

- message “**meaningfulness” depends on higher-level application**
  - text messaging apps require authentication of English-text messages
  - other apps may require authentication of binary files
  - security definition should better be **agnostic** of the specific higher application

Notes on security definition (II)

Are replay attacks important in practice?

- absolutely yes: a **very realistic & serious threat!**
  - e.g., what if a money transfer order is "replayed"?

Yet, a "replay-attack safe" security definition is preferable

- again, whether replayed messages are valid depends on higher-lever app
- better to delegate to this app the specification of such details
  - e.g., semantics on traffic or validity checks on messages before they're "consumed"

Eliminating replay attacks

- use of counters (i.e., common shared state) between sender & receiver
- use of timestamps along with a (relaxed) authentication window for validation

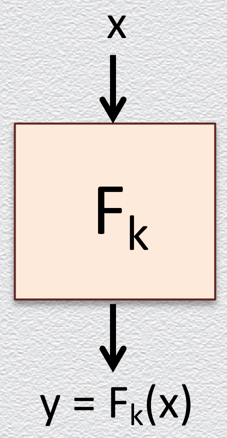
MAC constructions

Three generic MAC constructions

- fixed-length MAC
  - direct application of a PRF for tagging
  - limited applicability
- domain extension for MACs
  - straightforward secure extension of fix-length MAC
  - inefficient
- CBC-MAC
  - resembles CBC-mode encryption
  - efficient

1. Fixed-length MAC

- based on use of a PRF
  - employ a PRF F_k in the obvious way to compute and canonically verify tags
  - set tag t to be the pseudorandom string derived by evaluating F_k on message m
- secure, provided that F_k is a secure PRF



<u>MAC scheme Π</u>

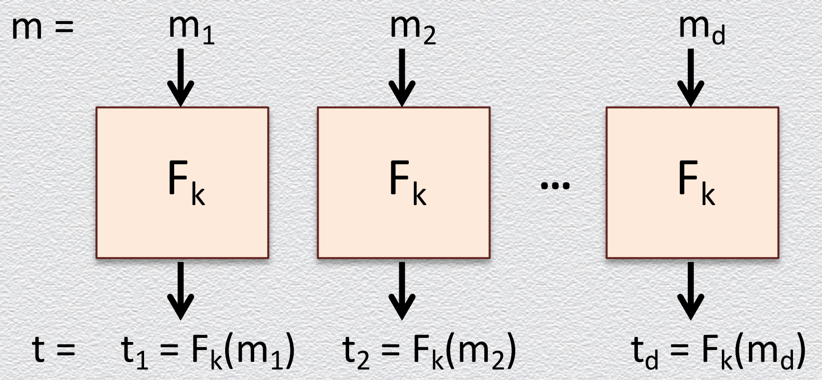
$Gen(1^n)$: $\{0,1\}^n \longrightarrow k$

$Mac_k(m)$: set $t = F_k(m)$

$Vrfy_k(m,t)$: return 1 iff $t = F_k(m)$

2. Domain extension for MACs (I)

- suppose we have the previous fix-length MAC scheme
- how can we authenticate a message m of arbitrary length?
- naïve approach
  - pad m and view it as d blocks $m_1, m_2, \ldots, m_d$
  - separately apply MAC to block m_i



- security issues
  - reordering attack; verify block index, $t = F_k(m_i||i)$
  - truncation attack; verify message length $\delta = |m|$, $t = F_k(m_i||i||\delta)$
  - mix-and-match attack; randomize tags (using message-specific fresh nonce)

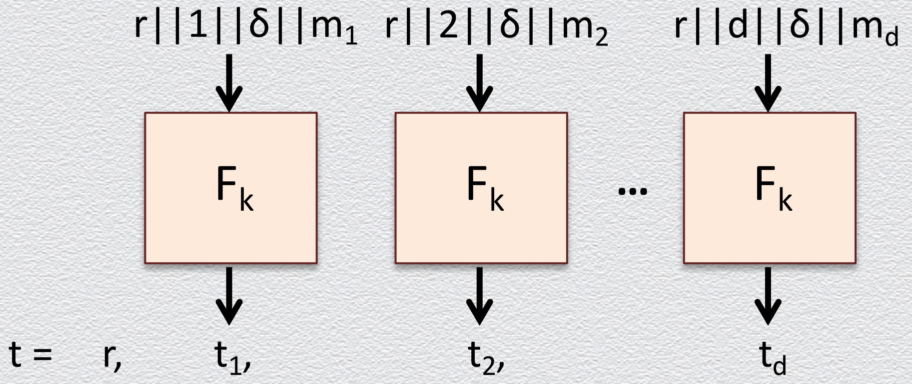
2. Domain extension for MACs (II)

Final scheme

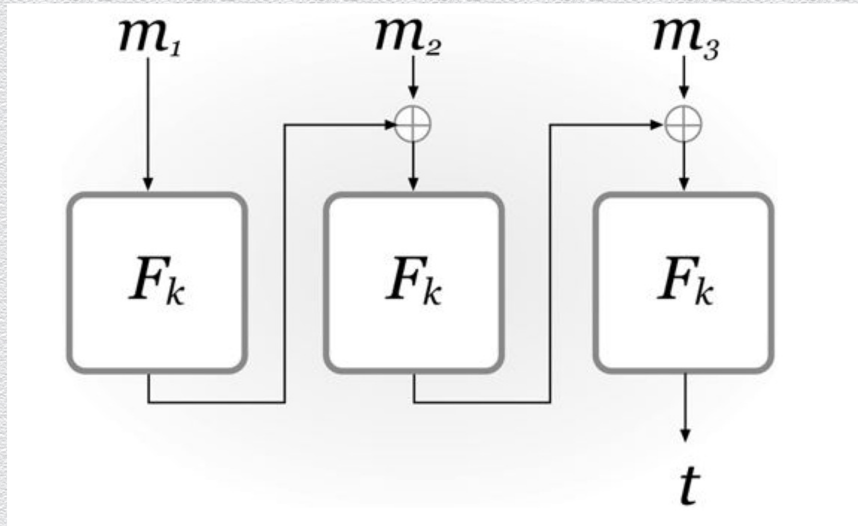
- assumes a secure MAC scheme for messages of size n
- set tag of message m of size δ at most $2^{n/4}$ as follows
  - choose fresh random nonce r of size n/4; view m as d blocks of size n/4 each
  - separately apply MAC on each block, authenticating also its index, δ and nonce r

Security

- extension is secure, if F_k is a secure PRF



3. CBC-MAC



Idea

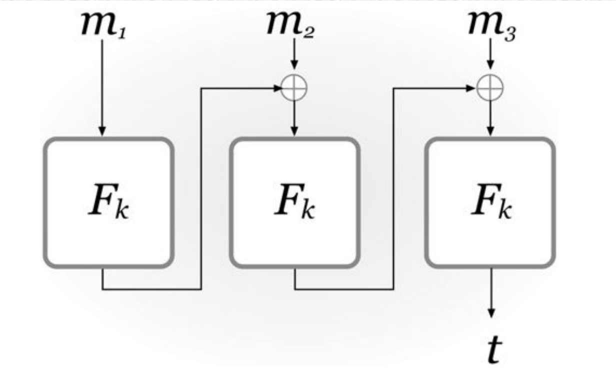
- employ a PRF in a manner similar to CBC-mode encryption

Security

- extension is secure, if
  - F_k is a secure PRF; and
  - only **fixed-length** messages are authenticated
- messages of length equal to any multiple of n can be authenticated
  - but this length need be fixed in advance
  - insecure, otherwise

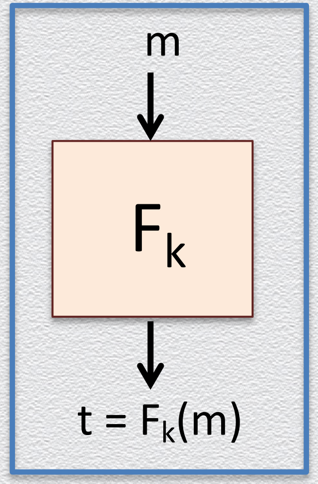
3. CBC-MAC Vs. previous schemes

- can authenticate longer messages than basic PRF-based scheme (1)

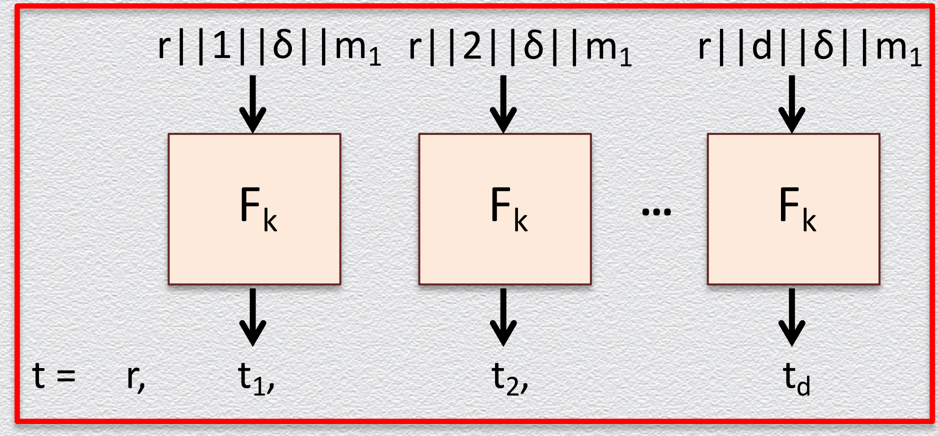


- more efficient than domain-extension MAC scheme (2)

Scheme (1)



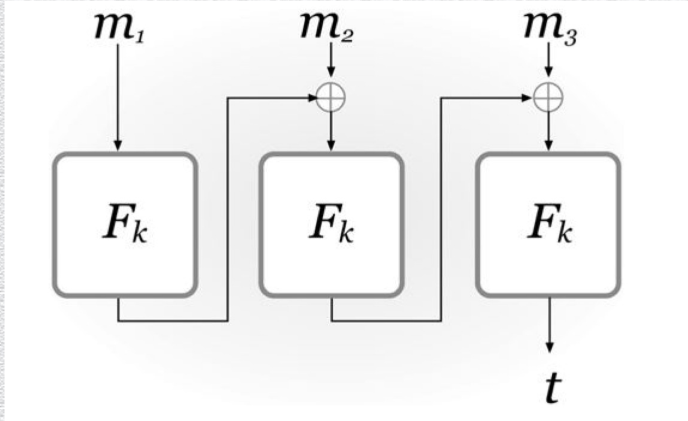
Scheme (2)



3. CBC-MAC Vs. CBC-mode encryption

- crucially for their security
  - CBC-MAC uses **no IV** (or uses an IV set to 0) and only the **last PRF output**
  - CBC-mode encryption uses a **random IV** and **all PRF outputs**
  - “simple”, innocent modification can be catastrophic…

CBC-MAC



CBC-mode encryption