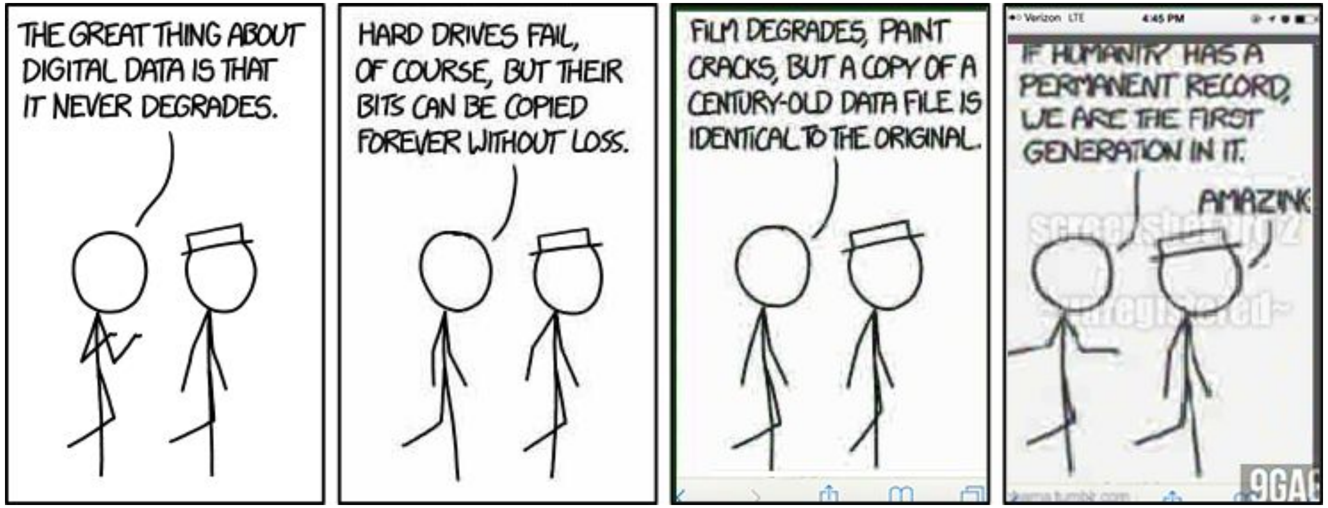
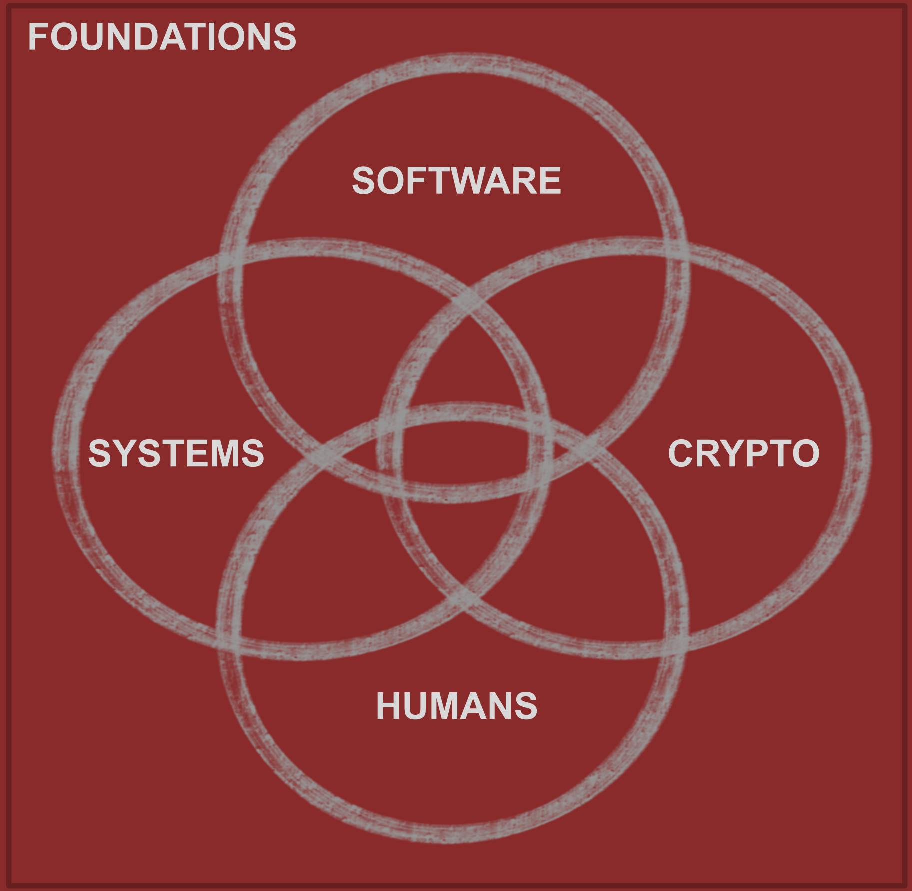
Διάλεξη #16 - Integrity

Εθνικό και Καποδιστριακό Πανεπιστήμιο Αθηνών

Εισαγωγή στην Ασφάλεια

Θανάσης Αυγερινός





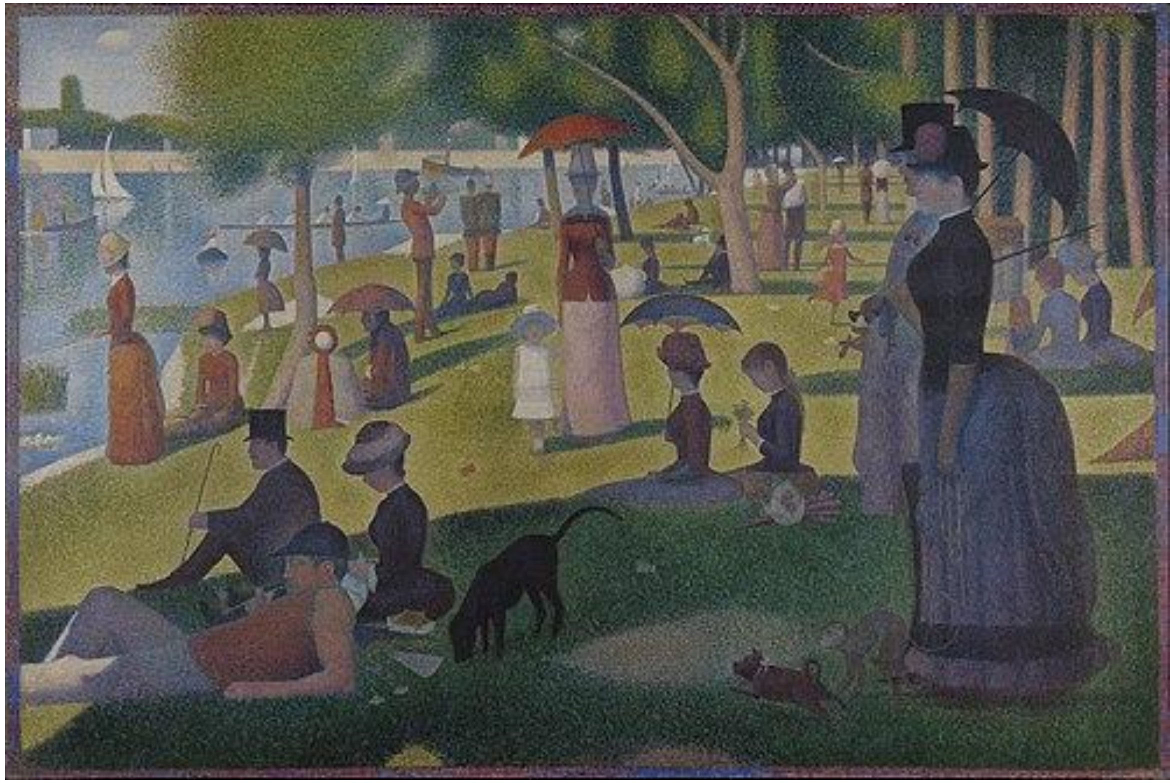
Huge thank you to David Brumley from Carnegie Mellon University for the guidance and content input while developing this class (lots of slides from Dan Boneh @ Stanford!)

Ανακοινώσεις / Διευκρινίσεις

- Η εργασία #2 μόλις βγήκε - προθεσμία: 4 Ιουνίου, 23:59
- Γιατί είναι το όριο ασφαλείας του CTR mode $qL^2 \ll |X|$;
- Αναπλήρωση την Δευτέρα, 12/5, 11πμ-1μμ στην Α2

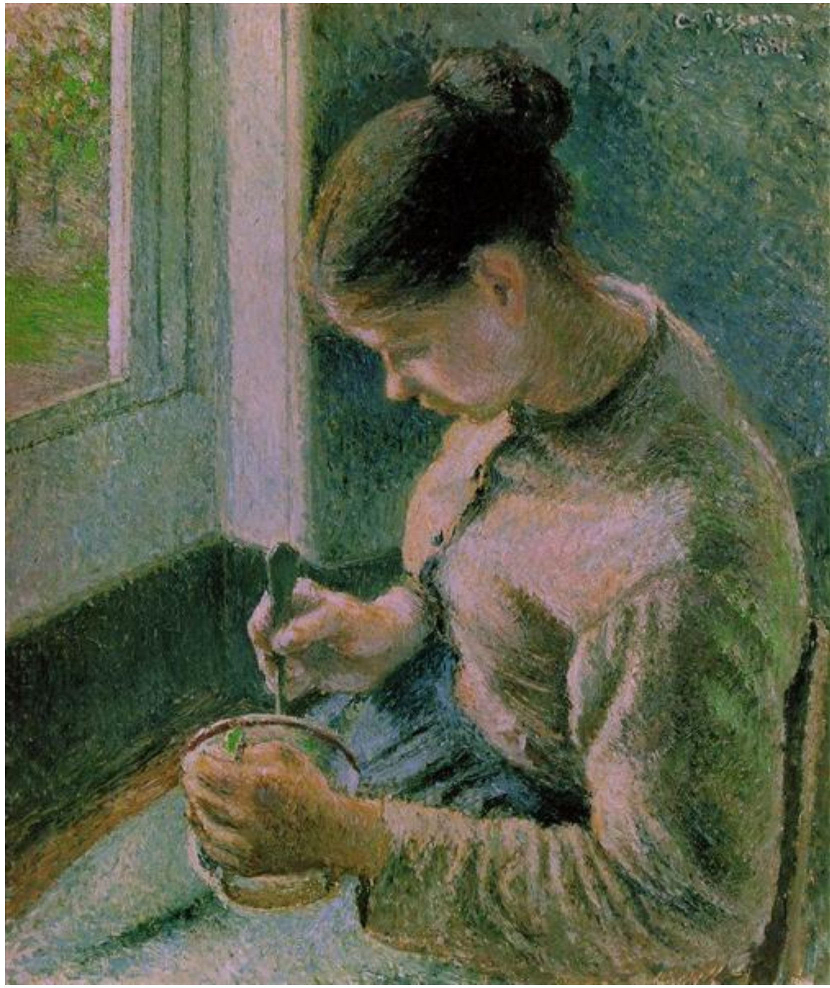
Την προηγούμενη φορά

- Encryption Modes
  - Electronic Code Book (ECB)
  - Cipher Block Chaining (CBC)
  - Counter Mode (CTR)
- Mistakes and Attacks



Σήμερα

- Message Integrity
  - Message Authentication Codes (MACs)
  - CBC-MAC, NMAC, CMAC
- Introduction to Hashing



Security in the News

Cisco Patches CVE-2025-20188 (10.0 CVSS) in IOS XE That Enables Root Exploits via JWT

May 08, 2025 Ravie Lakshmanan Vulnerability / Network Security

Cisco has released software fixes to address a maximum-severity security flaw in its IOS XE Wireless Controller that could enable an unauthenticated, remote attacker to upload arbitrary files to a susceptible system.

The vulnerability, tracked as **CVE-2025-20188**, has been rated 10.0 on the CVSS scoring system.

"This vulnerability is due to the presence of a hard-coded JSON Web Token (JWT) on an affected system," the company said in a Wednesday advisory.

"An attacker could exploit this vulnerability by sending crafted HTTPS requests to the AP image download interface. A successful exploit could allow the attacker to upload files, perform path traversal, and execute arbitrary commands with root privileges."

Block Cipher Attacks

Exhaustive Search for block cipher key

Goal: given a few input output pairs $\big(m_i, c_i = E(k, m_i)\big)$ i=1,..,3
find key k.

Lemma: Suppose DES is an ***ideal cipher***
(2^{56} random invertible functions)
Then ∀ m, c there is at most **<u>one</u>** key k s.t. c = DES(k, m)

Proof: $P[\exists k' \neq k : c = DES(k,m) = DES(k',m)] \leq$

$$\sum_{k' \in \{0,1\}^{56}} P[DES(k,m) = DES(k',m)] \leq 2^{56} \cdot \frac{1}{2^{64}} = \frac{1}{2^8}$$

with prob. ≥ 1 – 1/256 ≈ 99.5%

Exhaustive Search for block cipher key

For two DES pairs $(m_1, c_1=DES(k, m_1)), \ (m_2, c_2=DES(k, m_2))$

unicity prob. $\approx 1 - 1/2^{71}$

For AES-128: given two inp/out pairs, unicity prob. $\approx 1 - 1/2^{128}$

$\Rightarrow$ two input/output pairs are enough for exhaustive key search.

Strengthening DES against ex. search

Method 1: **Triple-DES**

- Let $E : K \times M \longrightarrow M$ be a block cipher
- Define **3E**: $K^3 \times M \longrightarrow M$ as

$$\mathbf{3E}\Big((k_1,k_2,k_3), m\Big) = E(k_1, D(k_2, E(k_3, m)))$$

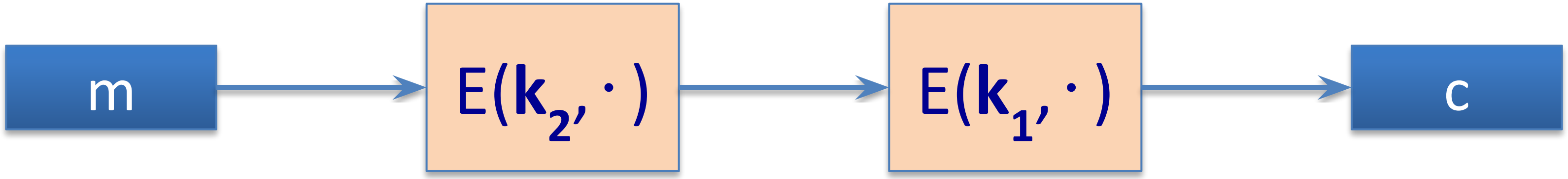
For 3DES: key-size = 3×56 = 168 bits. 3×slower than DES.

(simple attack in time $\approx 2^{118}$)

Why not double DES?

- Define $2E\big((k_1,k_2), m\big) = E\big(k_1 , E(k_2 , m) \big)$

key-len = 112 bits for DES



Attack: $M = (m_1,\ldots, m_{10})$, $C = (c_1,\ldots,c_{10})$.

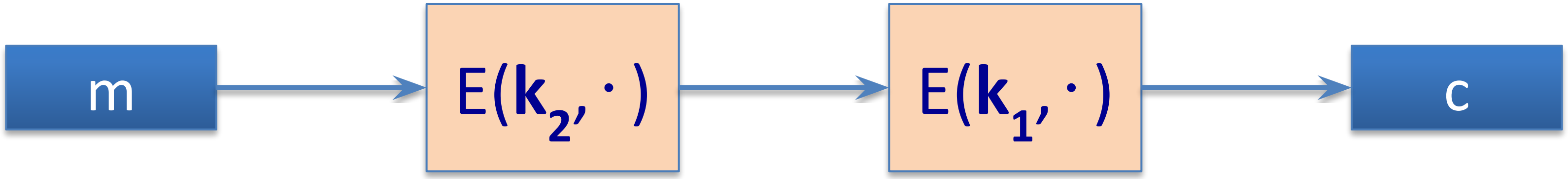
- step 1: build table.

  sort on 2nd column

k^0 = 00…00	$E(k^0, M)$
k^1 = 00…01	$E(k^1, M)$
k^2 = 00…10	$E(k^2, M)$
⋮	⋮
k^N = 11…11	$E(k^N, M)$

2^{56} entries

Meet in the middle attack



$k^0 = 00\ldots00$	$E(k^0, M)$
$k^1 = 00\ldots01$	$E(k^1, M)$
$k^2 = 00\ldots10$	$E(k^2, M)$
⋮	⋮
$k^N = 11\ldots11$	$E(k^N, M)$

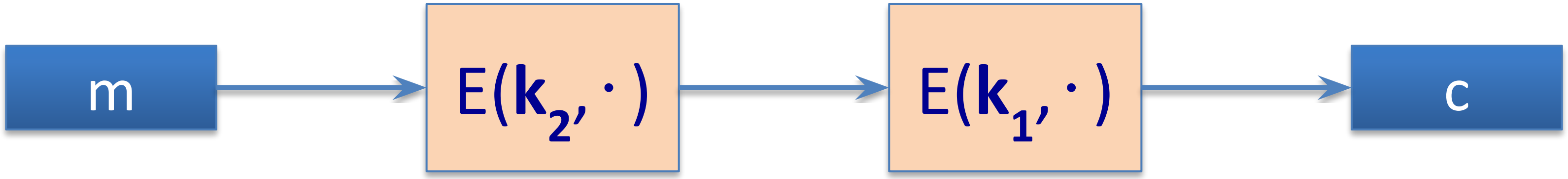
Attack: $M = (m_1, \ldots, m_{10})$, $C = (c_1, \ldots, c_{10})$

- step 1: build table.
- Step 2: for all $k \in \{0,1\}^{56}$ do:

  test if $D(k, C)$ is in 2^{nd} column.

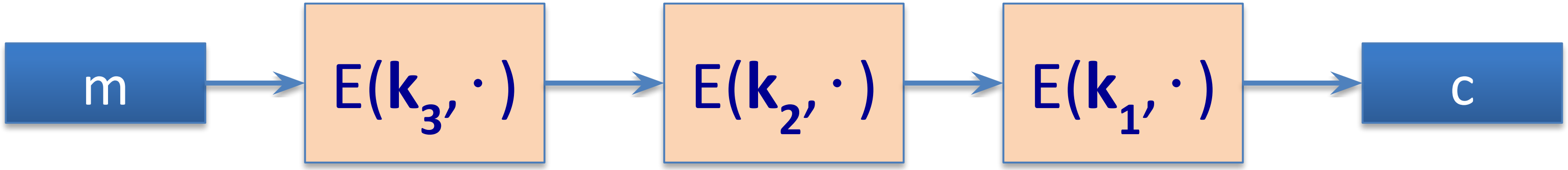
if so then $E(k^i, M) = D(k, C) \Rightarrow (k^i, k) = (k_2, k_1)$

Meet in the middle attack



Time = $2^{56}\log(2^{56})$ + $2^{56}\log(2^{56}) < 2^{63}$ << 2^{112} , space ≈ 2^{56}

Same attack on 3DES: Time = 2^{118} , space ≈ 2^{56}



Method 2: DESX

$E : K \times \{0,1\}^n \longrightarrow \{0,1\}^n$ a block cipher

Define EX as $EX\big((k_1,k_2,k_3), m\big) = k_1 \oplus E(k_2, m \oplus k_3)$

For DESX: key-len = 64+56+64 = 184 bits

… but easy attack in time $2^{64+56} = 2^{120}$

Note: $k_1 \oplus E(k_2, m)$ and $E(k_2, m \oplus k_1)$ does nothing !!

Quantum attacks

Generic search problem:

Let $f: X \longrightarrow \{0,1\}$ be a function.

Goal: find $x \in X$ s.t. $f(x)=1$.

Classical computer: best generic algorithm time = $O(\ |X|\ )$

Quantum computer [Grover '96] : time = $O(\ |X|^{1/2}\ )$

Can quantum computers be built: unknown

Quantum exhaustive search

Given m, c=E(k,m) define

$$f(k) = \begin{cases} 1 & \text{if } E(k,m) = c \\ 0 & \text{otherwise} \end{cases}$$

Grover ⇒ quantum computer can find k in time $O(|K|^{1/2})$

DES: time $\approx 2^{28}$, AES-128: time $\approx 2^{64}$

quantum computer ⇒ 256-bits key ciphers (e.g. AES-256)

PRF Switching Lemma

Any secure PRP is also a secure PRF, if |X| is sufficiently large.

<u>Lemma</u>: Let E be a PRP over (K,X)

Then for any q-query adversary A:

$$\left| \text{Adv}_{\text{PRF}}[A,E] - \text{Adv}_{\text{PRP}}[A,E] \right| < q^2 / 2|X|$$

⇒ Suppose |X| is large so that $q^2 / 2|X|$ is "negligible"

Then $\text{Adv}_{\text{PRP}}[A,E]$ "negligible" ⇒ $\text{Adv}_{\text{PRF}}[A,E]$ "negligible"

Message Integrity

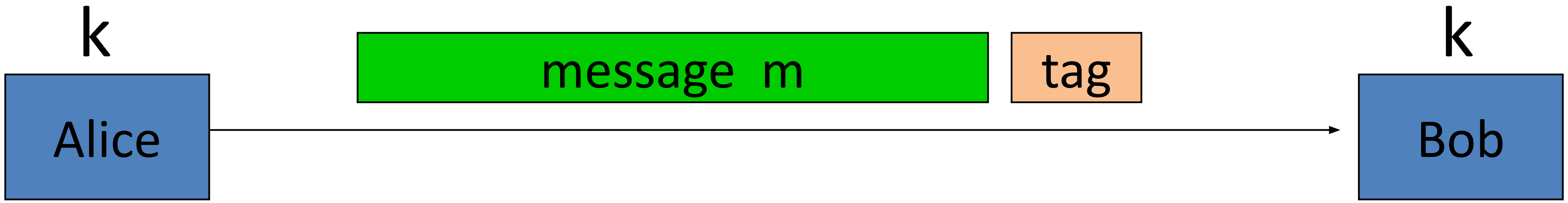
Message Integrity

Goal: **integrity**, no confidentiality.

Examples:

- Transaction data / ledger.
- Communications.
- Public binaries on disk.
- Banner ads on web pages.

Message integrity: MACs



Generate tag (Sign):

tag $\leftarrow$ S(k, m)

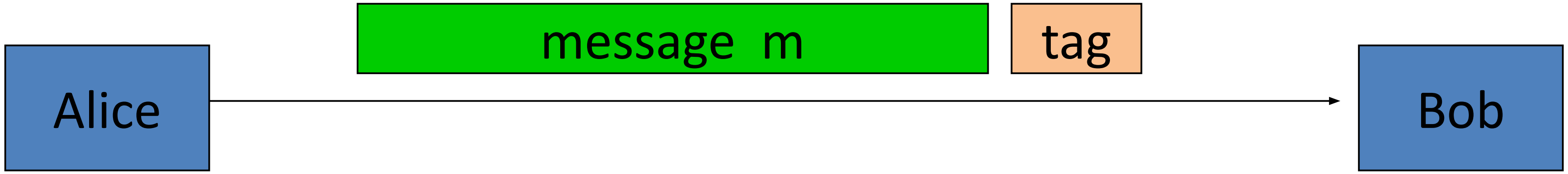
Verify tag:

V(k, m, tag) $\stackrel{?}{=}$ \`yes'

Def: **MAC** I = (S,V) defined over (K,M,T) is a pair of algs:

- S(k,m) outputs t in T
- V(k,m,t) outputs \`yes' or \`no'

Integrity requires a secret key



Generate tag:

tag ← CRC(m)

Verify tag:

V(m, tag) $\stackrel{?}{=}$ \`yes'

- Attacker can easily modify message m and re-compute CRC.
- CRC designed to detect **random**, not malicious errors.

Secure MACs

Attacker's power: **chosen message attack**

- for $m_1,m_2,\ldots,m_q$ attacker is given $t_i \leftarrow S(k,m_i)$

Attacker's goal: **existential forgery**

- produce some **<u>new</u>** valid message/tag pair (m,t).

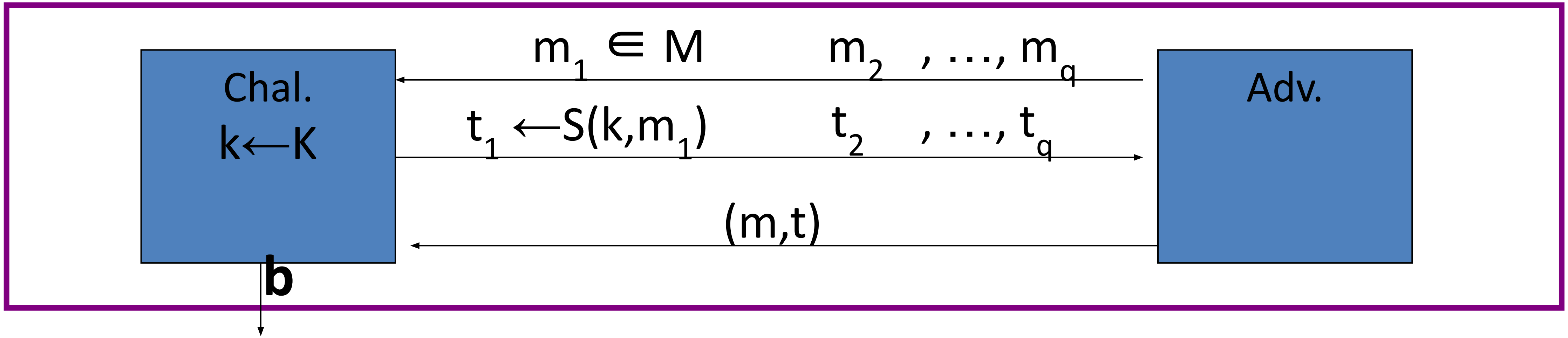
$$(m,t) \notin \{ (m_1,t_1), \ldots, (m_q,t_q) \}$$

⇒ attacker cannot produce a valid tag for a new message

⇒ given (m,t) attacker cannot even produce (m,t') for $t' \neq t$

Secure MACs

- For a MAC I=(S,V) and adv. A define a MAC game as:



b=1 if V(k,m,t) = `yes' and $(m,t) \notin \{ (m_1,t_1), \ldots, (m_q,t_q) \}$

b=0 otherwise

Def: I=(S,V) is a **secure MAC** if for all "efficient" A:

$Adv_{MAC}[A,I]$ = Pr[Chal. outputs 1] is "negligible."

Let I = (S,V) be a MAC.

Suppose an attacker is able to find $m_0 \neq m_1$ such that

$S(k, m_0) = S(k, m_1)$ for ½ of the keys k in K

Can this MAC be secure?

- ◯ Yes, the attacker cannot generate a valid tag for m_0 or m_1
- ◯ No, this MAC can be broken using a chosen msg attack
- ◯ It depends on the details of the MAC
- ◯

Let I = (S,V) be a MAC.

Suppose S(k,m) is 5 bits long

Can this MAC be secure?

- ◯ No, an attacker can simply guess the tag for messages
- ◯ It depends on the details of the MAC
- ◯ Yes, the attacker cannot generate a valid tag for any message
- ◯

Example: protecting system files

Suppose at install time the system computes:

filename F_1	filename F_2	…	filename F_n
$t_1 = S(k,F_1)$	$t_2 = S(k,F_2)$		$t_n = S(k,F_n)$

k derived from user's password

Later a virus infects system and modifies system files

User reboots into clean OS and supplies his password

– Then: secure MAC $\Rightarrow$ all modified files will be detected

Using PRFs to build MACs

Review: Secure MACs

MAC: signing alg. **$S(k,m) \longrightarrow t$** and verification alg. **$V(k,m,t) \longrightarrow 0,1$**

Attacker's power: **chosen message attack**

- for $m_1,m_2,\ldots,m_q$ attacker is given $t_i \leftarrow S(k,m_i)$

Attacker's goal: **existential forgery**

- produce some **new** valid message/tag pair (m,t).

$$(m,t) \notin \{ (m_1,t_1), \ldots, (m_q,t_q) \}$$

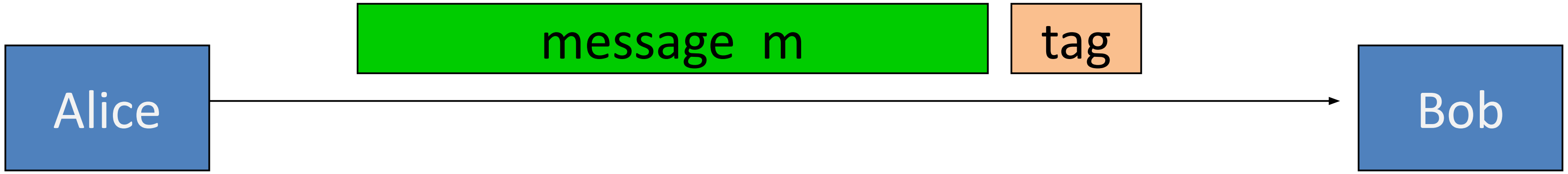
⇒ attacker cannot produce a valid tag for a new message

Secure PRF ⇒ Secure MAC

For a PRF $F: K \times X \longrightarrow Y$ define a MAC $I_F = (S,V)$ as:

– $S(k,m) := F(k,m)$

– $V(k,m,t)$: output `yes' if $t = F(k,m)$ and `no' otherwise.



tag ← F(k,m)

accept msg if

tag = F(k,m)

A bad example

Suppose **$F: K \times X \longrightarrow Y$** is a secure PRF with **$Y = \{0,1\}^{10}$**

Is the derived MAC I_F a secure MAC system?

- ○ Yes, the MAC is secure because the PRF is secure
- ○ No tags are too short: anyone can guess the tag for any msg
- ○ It depends on the function F
- ○

Security

Thm: If **$F: K \times X \longrightarrow Y$** is a secure PRF and $1/|Y|$ is negligible

(i.e. $|Y|$ is large) then I_F is a secure MAC.

In particular, for every eff. MAC adversary A attacking I_F

there exists an eff. PRF adversary B attacking F s.t.:

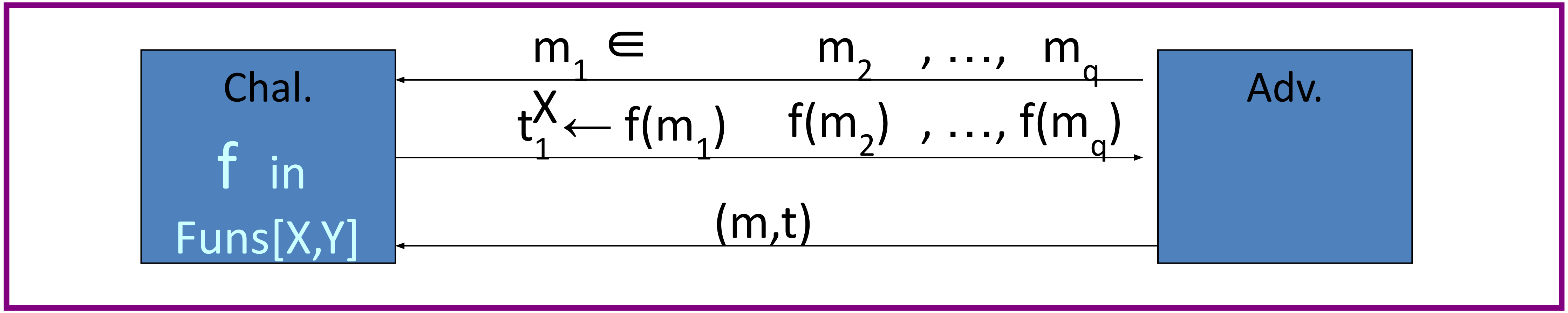
$$Adv_{MAC}[A, I_F] \leq Adv_{PRF}[B, F] + 1/|Y|$$

$\Rightarrow$ I_F is secure as long as $|Y|$ is large, say $|Y| = 2^{128}$.

Proof Sketch

Suppose $f: X \longrightarrow Y$ is a truly random function

Then MAC adversary A must win the following game:



A wins if $t = f(m)$ and $m \notin \{ m_1 , \ldots , m_q \}$

$\Rightarrow$ $\Pr[\text{A wins}] = 1/|Y|$

same must hold for F(k,x)

Examples

- AES: a MAC for 16-byte messages.

- Main question: how to convert Small-MAC into a Big-MAC ?

- Two main constructions used in practice:
  - **CBC-MAC** (banking – ANSI X9.9, X9.19, FIPS 186-3)
  - **HMAC** (Internet protocols: SSL, IPsec, SSH, …)

- Both convert a small-PRF into a big-PRF.

Truncating MACs based on PRFs

Easy lemma: suppose $F: K \times X \longrightarrow \{0,1\}^n$ is a secure PRF.

Then so is $F_t(k,m) = F(k,m)[1\ldots t]$ for all $1 \leq t \leq n$

$\Rightarrow$ if (S,V) is a MAC is based on a secure PRF outputting n-bit tags

the truncated MAC outputting w bits is secure

… as long as $1/2^w$ is still negligible (say $w \geq 64$)

CBC-MAC and NMAC

MACs and PRFs

Recall: secure PRF **F** ⇒ secure MAC, as long as |Y| is large

$S(k, m) = F(k, m)$

Our goal:

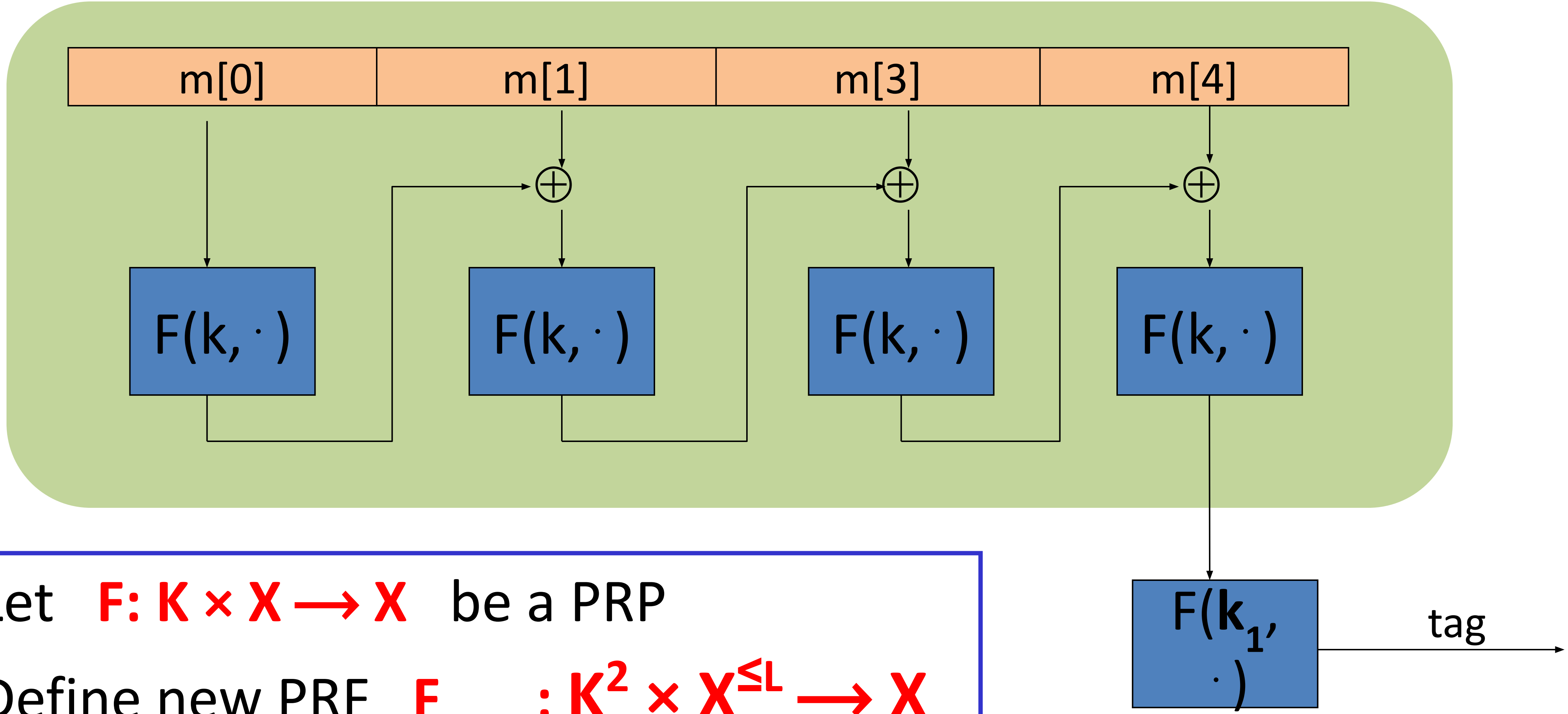
given a PRF for short messages (AES)

construct a PRF for long messages

From here on let $X = \{0,1\}^n$ (e.g. n=128)

Construction 1: encrypted CBC-MAC

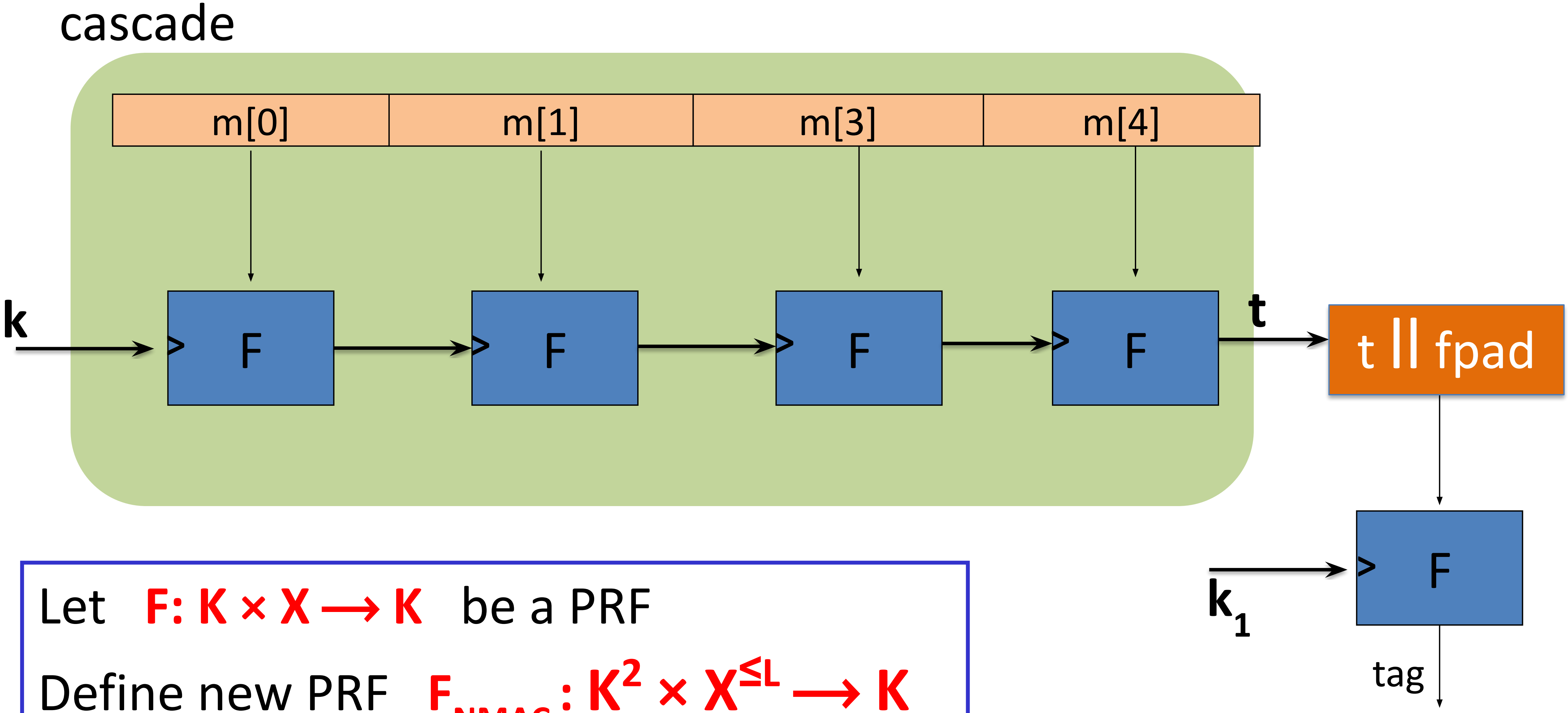
raw CBC



Let $F: K \times X \longrightarrow X$ be a PRP

Define new PRF $F_{ECBC} : K^2 \times X^{\leq L} \longrightarrow X$

Construction 2: NMAC (nested MAC)



Let $F: K \times X \longrightarrow K$ be a PRF

Define new PRF $F_{NMAC} : K^2 \times X^{\leq L} \longrightarrow K$

Why the last encryption step in ECBC-MAC and NMAC?

NMAC: suppose we define a MAC I = (S,V) where

S(k,m) = cascade(k, m)

- This MAC is secure
- This MAC can be forged without any chosen msg queries
- This MAC can be forged with one chosen msg query
- This MAC can be forged, but only with two msg queries

Why the last encryption step in ECBC-MAC?

Suppose we define a MAC $I_{RAW} = (S,V)$ where

$$S(k,m) = rawCBC(k,m)$$

Then I_{RAW} is easily broken using a 1-chosen msg attack.

Adversary works as follows:

- Choose an arbitrary one-block message $m \in X$
- Request tag for m. Get $t = F(k,m)$
- Output t as MAC forgery for the 2-block message $(m,\ t \oplus m)$

Indeed: $rawCBC\big(k, (m,\ t \oplus m)\big) = F\big(k, F(k,m) \oplus (t \oplus m)\big) = F\big(k, t \oplus (t \oplus m)\big) = t$

ECBC-MAC and NMAC analysis

Theorem: For any L>0,

For every eff. q-query PRF adv. A attacking F_{ECBC} or F_{NMAC}

there exists an eff. adversary B s.t.:

$$\mathrm{Adv_{PRF}}[A, F_{ECBC}] \le \mathrm{Adv_{PRP}}[B, F] + 2\, q^2 / |X|$$

$$\mathrm{Adv_{PRF}}[A, F_{NMAC}] \le q \cdot L \cdot \mathrm{Adv_{PRF}}[B, F] + q^2 / 2|K|$$

CBC-MAC is secure as long as $q \ll |X|^{1/2}$

NMAC is secure as long as $q \ll |K|^{1/2}$ (2^{64} for AES-128)

An example

$$\text{Adv}_{\text{PRF}}[A, F_{\text{ECBC}}] \le \text{Adv}_{\text{PRP}}[B, F] + \mathbf{2\,q^2 / |X|}$$

q = # messages MAC-ed with k

Suppose we want $\text{Adv}_{\text{PRF}}[A, F_{\text{ECBC}}] \le 1/2^{32}$ $\Leftarrow$ $q^2 / |X| < 1/2^{32}$

- AES: $|X| = 2^{128}$ $\Rightarrow$ $q < 2^{48}$

  So, after 2^{48} messages must, must change key

- 3DES: $|X| = 2^{64}$ $\Rightarrow$ $q < 2^{16}$

The security bounds are tight: an attack

After signing $|X|^{1/2}$ messages with ECBC-MAC or
$|K|^{1/2}$ messages with NMAC
the MACs become insecure

Suppose the underlying PRF F is a PRP (e.g. AES)

- Then both PRFs (ECBC and NMAC) have the following extension property:

$$\forall x,y,w: \quad F_{BIG}(k, x) = F_{BIG}(k, y) \quad \Rightarrow \quad F_{BIG}(k, \mathbf{x \| w}) = F_{BIG}(k, \mathbf{y \| w})$$

The security bounds are tight: an attack

Let $F_{BIG}: K \times X \longrightarrow Y$ be a PRF that has the extension property

$$F_{BIG}(k, x) = F_{BIG}(k, y) \quad \Rightarrow \quad F_{BIG}(k, \mathbf{x \| w}) = F_{BIG}(k, \mathbf{y \| w})$$

Generic attack on the derived MAC:

step 1: issue $|Y|^{1/2}$ message queries for rand. messages in X.

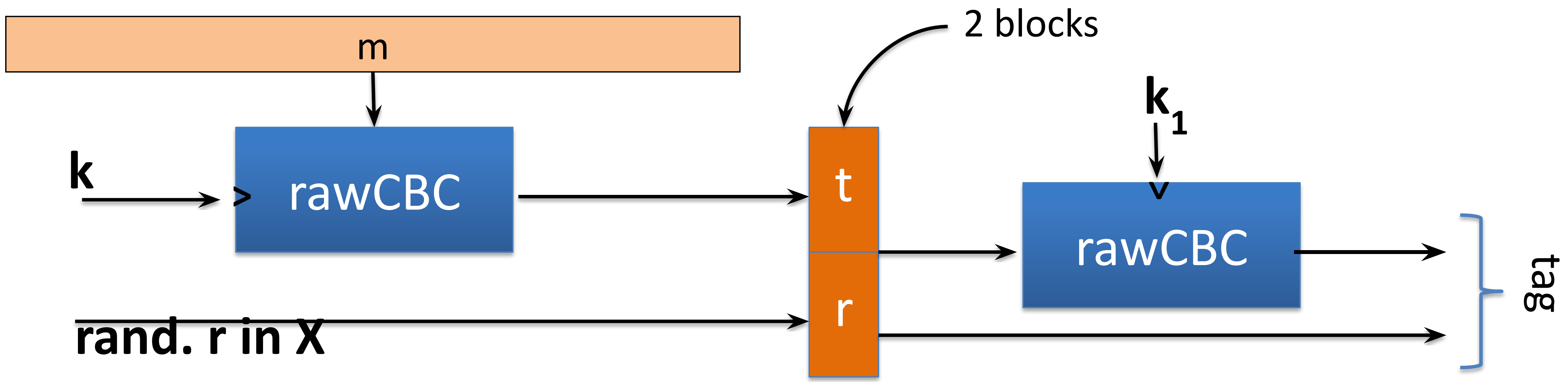
obtain (m_i, t_i) for $i = 1 ,\ldots, |Y|^{1/2}$

step 2: find a collision $t_u = t_v$ for $u \neq v$ (one exists w.h.p by b-day paradox)

step 3: choose some w and query for $t := F_{BIG}(k, \mathbf{m_u \| w})$

step 4: output forgery $(\mathbf{m_v \| w, t})$. Indeed $t := F_{BIG}(k, \mathbf{m_v \| w})$

Better security: a rand. construction



Let **F: K × X ⟶ X** be a PRF. Result: MAC with tags in X^2.

Security: $\text{Adv}_{\text{MAC}}[A, I_{\text{RCBC}}] \leq \text{Adv}_{\text{PRP}}[B, F] \cdot (1 + 2\, q^2 / |X|)$

⇒ For 3DES: can sign $q = 2^{32}$ msgs with one key

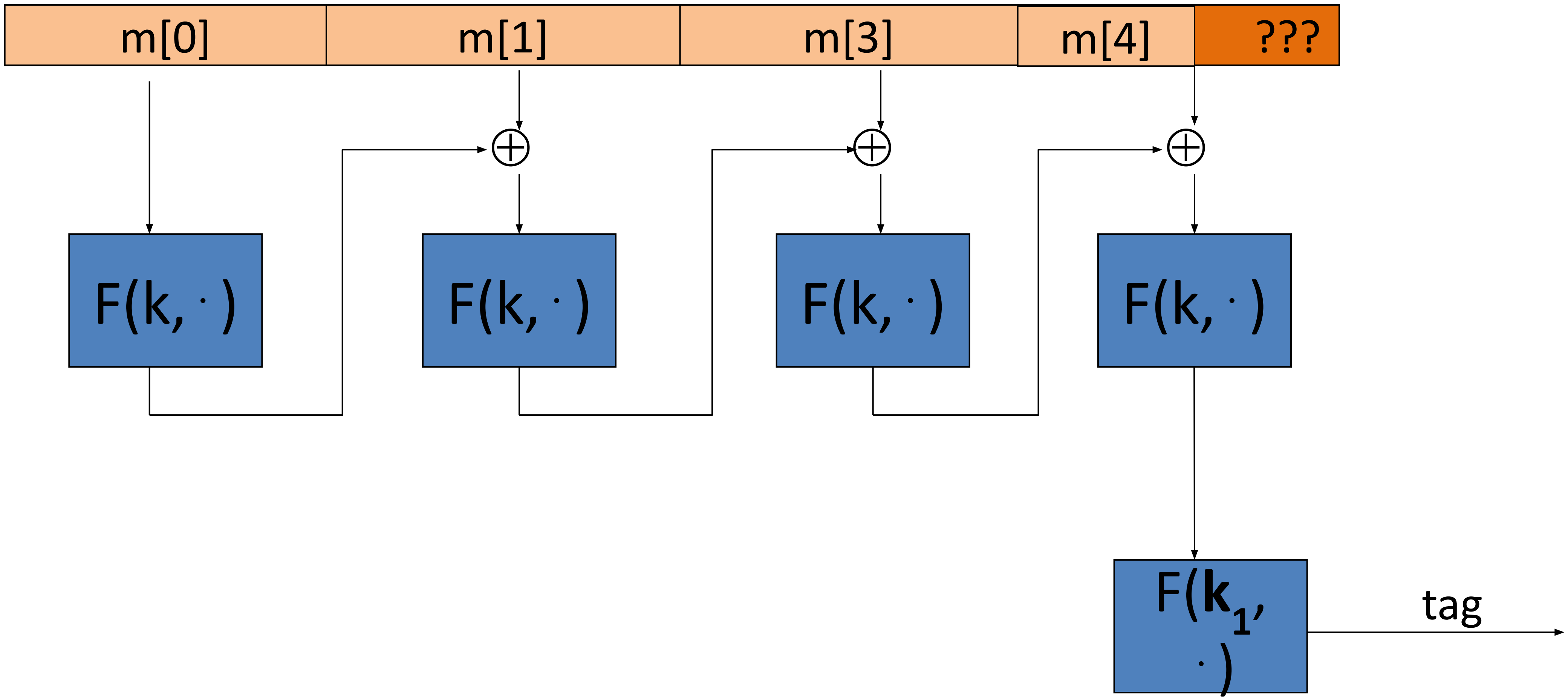
Comparison

ECBC-MAC is commonly used as an AES-based MAC
- CCM encryption mode (used in 802.11i)
- NIST standard called CMAC

NMAC not usually used with AES or 3DES
- Main reason: need to change AES key on every block
  requires re-computing AES key expansion
- But NMAC is the basis for a popular MAC called HMAC (next)

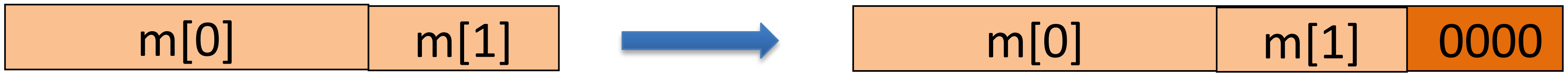
What about padding?

What if msg. len. is not multiple of block-size?



CBC MAC padding

Bad idea: pad m with 0's



Is the resulting MAC secure?

- ◯ Yes, the MAC is secure
- ◯ It depends on the underlying MAC
- ◯ No, given tag on msg **m** attacker obtains tag on **m||0**
- ◯

Problem: pad(m) = pad(m||0)

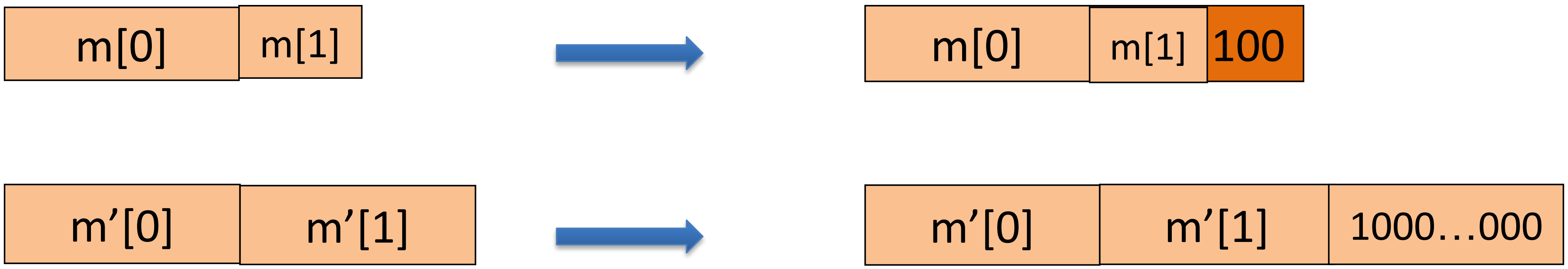
CBC MAC padding

For security, padding must be invertible !

$$\text{len}(m_0) \neq \text{len}(m_1) \quad \Rightarrow \quad \text{pad}(m_0) \neq \text{pad}(m_1)$$

<u>ISO</u>: pad with "1000…00". Add new dummy block if needed.

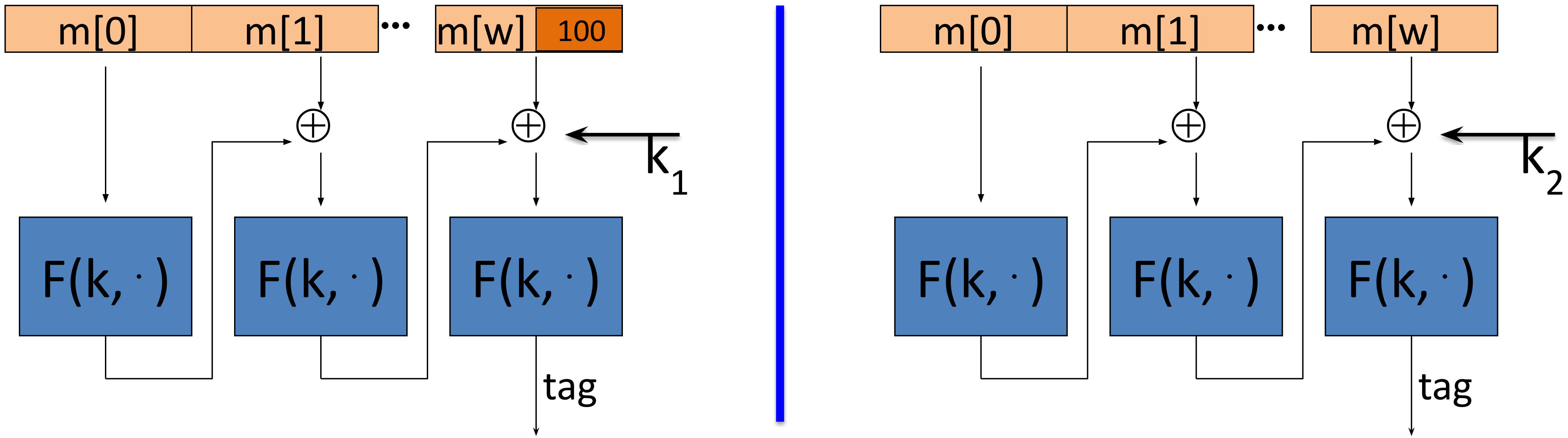
– The "1" indicates beginning of pad.



CMAC (NIST standard)

Variant of CBC-MAC where key = (k, k_1, k_2)

- No final encryption step (extension attack thwarted by last keyed xor)
- No dummy block (ambiguity resolved by use of k_1 or k_2)



More MACs - More Fun!

- PMAC - parallel MAC computation!
- One-time MAC / Many-time MAC
- Carter-Wegman MAC
- … and many more

but we still didn't talk about the extremely common <u>HMAC (Hash MAC)</u>

Hashes and Resistance

Cryptographic Hash Functions

A Cryptographic Hash Function (CHF) is an algorithm that maps an arbitrary binary string to a string of n bits. $H : \{0, 1\}^* \rightarrow \{0,1\}^n$

- Message space much larger than output space

$$H: M \rightarrow T, |M| >> |T|$$

- Given the output, we want the input to remain secret and also make it hard for other inputs to get the same output (collision).
- Applications: everywhere (from storing passwords to commitment protocols)

Hash Function Properties

Let H: M -> T, |M| >> |T|

- Pre-image resistance. H is pre-image resistant if given a hash value h, it should be difficult to find any message m such that H(m) = h. In other words, P[H(random m) = h] = 1/|T|.
- Second pre-image resistance (weak collision resistance). H is second-preimage resistant if given a message m_1, it should be difficult to find a different m_2 such that $H(m_1) = H(m_2)$.
- (Strong) Collision resistance. H is collision resistant if it is difficult to find any two different messages m_1 and m_2 such that $H(m_1) = H(m_2)$.

Collision Resistance =>
Second-preimage Resistance

Second-preimage Resistance =>
Preimage Resistance?

*only true under certain conditions (|M| >> |T|)

Collision Resistance Definition

Let H: M ⟶T be a hash function (|M| >> |T|)

A **<u>collision</u>** for H is a pair m_0 , m_1 ∈ M such that:

$$H(m_0) = H(m_1) \quad \text{and} \quad m_0 \neq m_1$$

A function H is **<u>collision resistant</u>** if for all (explicit) "eff" algs. A:

$Adv_{CR}[A,H]$ = Pr[A outputs collision for H]

is "neg".

Example: SHA-256 (outputs 256 bits)

Ευχαριστώ και καλή μέρα εύχομαι!

Keep hacking!