

# Message Authentication Codes and Collision-Resistant Hash Functions

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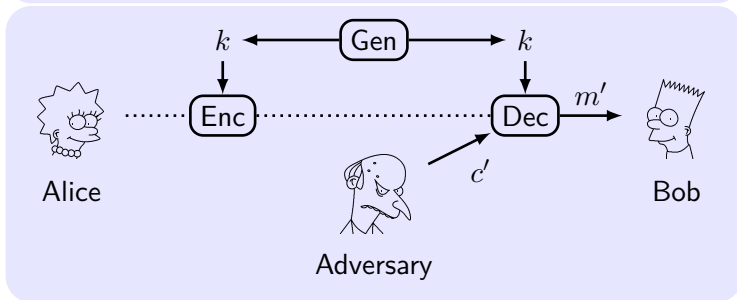
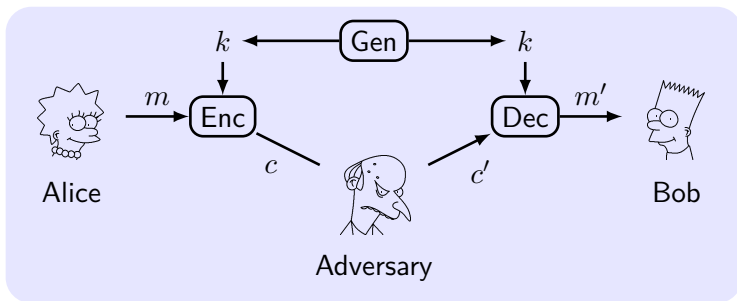
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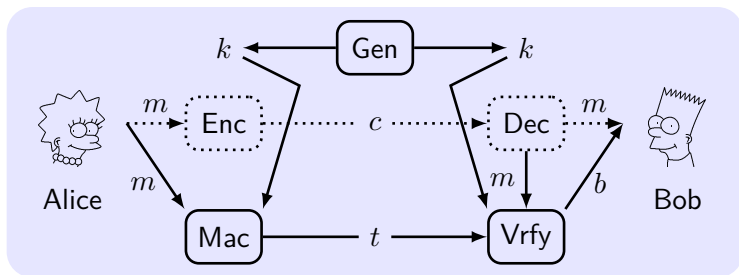
- 1** Message Authentication Codes (MAC) – Definitions
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# Integrity and Authentication



# The Syntax of MAC



- key  $k$ , tag  $t$ , a bit  $b$  means valid if  $b = 1$ ; invalid if  $b = 0$ .
- **Key-generation** algorithm  $k \leftarrow \text{Gen}(1^n)$ ,  $|k| \geq n$ .
- **Tag-generation** algorithm  $t \leftarrow \text{Mac}_k(m)$ .
- **Verification** algorithm  $b := \text{Vrfy}_k(m, t)$ .
- **Message authentication code:**  $\Pi = (\text{Gen}, \text{Mac}, \text{Vrfy})$ .
- **Basic correctness requirement:**  $\text{Vrfy}_k(m, \text{Mac}_k(m)) = 1$ .

- **Intuition:** No adversary should be able to generate a **valid** tag on any “**new**” message<sup>1</sup> that was not previously sent.
- **Replay attack:** Copy a message and tag previously sent. (excluded by only considering “**new**” message)
  - Sequence numbers: receiver must store the previous ones.
  - Time-Stamps: sender/receiver maintain synchronized clocks.
- **Existential unforgeability:** **Not** be able to forge a valid tag on **any** message.
  - **Existential forgery:** *at least one* message.
  - **Selective forgery:** message chosen *prior* to the attack.
  - **Universal forgery:** *any* given message.
- **Adaptive chosen-message attack (CMA):** be able to obtain tags on *any* message chosen adaptively *during* its attack.

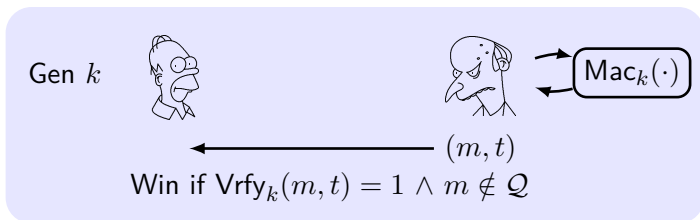
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<sup>1</sup>A stronger requirement is concerning *new message/tag pair*.

# Definition of MAC Security

The message authentication experiment  $\text{Macforge}_{\mathcal{A}, \Pi}(n)$ :

- 1  $k \leftarrow \text{Gen}(1^n)$ .
- 2  $\mathcal{A}$  is given input  $1^n$  and oracle access to  $\text{Mac}_k(\cdot)$ , and outputs  $(m, t)$ .  $\mathcal{Q}$  is the set of queries to its oracle.
- 3  $\text{Macforge}_{\mathcal{A}, \Pi}(n) = 1 \iff \text{Vrfy}_k(m, t) = 1 \wedge m \notin \mathcal{Q}$ .



## Definition 1

A MAC  $\Pi$  is **existentially unforgeable under an adaptive CMA** if  $\forall$  PPT  $\mathcal{A}$ ,  $\exists \text{ negl}$  such that:

$$\Pr[\text{Macforge}_{\mathcal{A}, \Pi}(n) = 1] \leq \text{negl}(n).$$

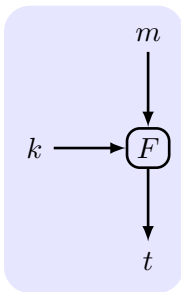
Suppose  $\langle S, V \rangle$  are CMA-secure, are  $\langle S', V' \rangle$  secure?

- $S'_{k_1, k_2}(m) = (S_{k_1}(m), S_{k_2}(m))$   
 $V'_{k_1, k_2}(m, (t_1, t_2)) = V_{k_1}(m, t_1) \wedge V_{k_2}(m, t_2)$
- $S'_k(m) = (S_k(m), S_k(m))$   
 $V'_k(m, (t_1, t_2)) = \begin{cases} V_k(m, t_1) & \text{if } t_1 = t_2 \\ 0 & \text{otherwise} \end{cases}$
- $S'_k(m) = (S_k(m), S_k(0^n))$   
 $V'_k(m, (t_1, t_2)) = V_k(m, t_1) \wedge V_k(0^n, t_2)$
- $S'_k(m) = S_k(m), V'_k(m, t) = \begin{cases} V_k(m, t) & \text{if } m \neq 0^n \\ 1 & \text{otherwise} \end{cases}$
- $S'_k(m) = S_k(m)$  without the LSB  
 $V'_k(m, t) = V_k(m, t \parallel 0) \vee V_k(m, t \parallel 1)$
- $S'_k(m) = (S_k(m), m), V'_k(m, (t_1, t_2)) = V_k(m, t_1) \wedge t_2 = m$



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# Constructing Secure MACs



## Construction 2

- $F$  is PRF.  $|m| = n$ .
- $\text{Gen}(1^n): k \leftarrow \{0, 1\}^n$  u.a.r.
- $\text{Mac}_k(m): t := F_k(m)$ .
- $\text{Vrfy}_k(m, t): 1 \iff t \stackrel{?}{=} F_k(m)$ .

## Theorem 3

*If  $F$  is a PRF, Construction is a secure fixed-length MAC.*

## Lemma 4

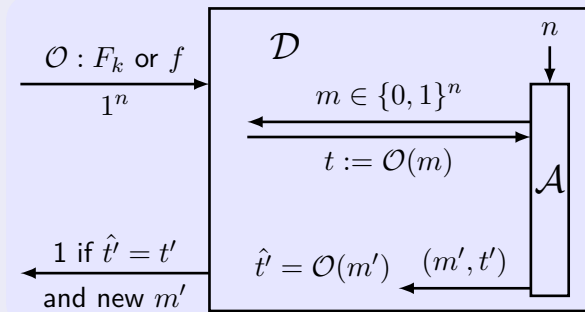
**Truncating MACs based on PRFs:** *If  $F$  is a PRF, so is  $F_k^t(m) = F_k(m)[1, \dots, t]$ .*

# Proof of Secure MAC from PRF

**Idea:** Show  $\Pi$  is secure unless  $F_k$  is not PRF by reduction.

**Proof.**

$D$  distinguishes  $F_k$ ;  $\mathcal{A}$  attacks  $\Pi$ .



# Proof of Secure MAC from PRF (Cont.)

## Proof.

(1) If true random  $f$  is used,  $t = f(m)$  is uniformly distributed.

$$\Pr[D^{f(\cdot)}(1^n) = 1] = \Pr[\text{Macforge}_{\mathcal{A}, \tilde{\Pi}}(n) = 1] \leq 2^{-n}.$$

(2) If  $F_k$  is used, conduct the experiment  $\text{Macforge}_{\mathcal{A}, \Pi}(n)$ .

$$\Pr[D^{F_k(\cdot)}(1^n) = 1] = \Pr[\text{Macforge}_{\mathcal{A}, \Pi}(n) = 1] = \varepsilon(n).$$

According to the definition of PRF,

$$\left| \Pr[D^{F_k(\cdot)}(1^n) = 1] - \Pr[D^{f(\cdot)}(1^n) = 1] \right| \geq \varepsilon(n) - 2^{-n}.$$



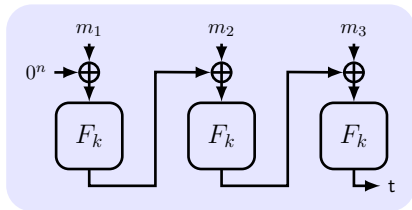
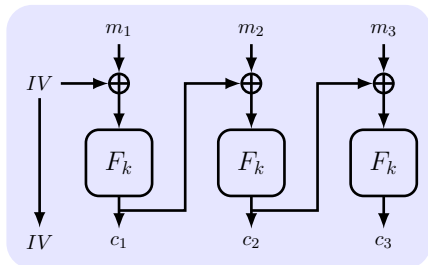
# Extension to Variable-Length Messages

For variable-length messages, would the following suggestions be secure?

- **Suggestion 1:** XOR all the blocks together and authenticate the result.  $t := \text{Mac}'_k(\oplus_i m_i)$ .
- **Suggestion 2:** Authenticate each block separately.  $t_i := \text{Mac}'_k(m_i)$ .
- **Suggestion 3:** Authenticate each block along with a sequence number.  $t_i := \text{Mac}'_k(i \| m_i)$ .

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# Constructing Fixed-Length CBC-MAC



Modify CBC encryption into CBC-MAC:

- Change random  $IV$  to encrypted fixed  $0^n$ , otherwise:  
Q: query  $m_1$  and get  $(IV, t_1)$ ; output  $m'_1 = IV' \oplus IV \oplus m_1$  and  $t' = \underline{\hspace{1cm}}$ .
- Tag only includes the output of the final block, otherwise:  
Q: query  $m_i$  and get  $t_i$ ; output  $m'_i = t'_{i-1} \oplus t_{i-1} \oplus m_i$  and  $t'_i = \underline{\hspace{1cm}}$ .

# Constructing Fixed-Length CBC-MAC (Cont.)

## Construction 5

- a PRF  $F$  and a length function  $\ell$ .  $|m| = \ell(n) \cdot n$ .  $\ell = \ell(n)$ .  
 $m = m_1, \dots, m_\ell$ .
- $\text{Gen}(1^n)$ :  $k \leftarrow \{0, 1\}^n$  u.a.r.
- $\text{Mac}_k(m)$ :  $t_i := F_k(t_{i-1} \oplus m_i)$ ,  $t_0 = 0^n$ . Output  $t = t_\ell$ .
- $\text{Vrfy}_k(m, t)$ :  $1 \iff t \stackrel{?}{=} \text{Mac}_k(m)$ .

## Theorem 6

If  $F$  is a PRF, Construction is a secure **fixed-length** MAC.

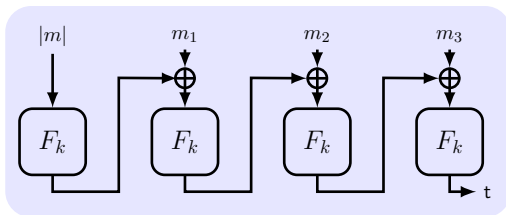
**Not** for **variable-length** message:

Q: For one-block message  $m$  with tag  $t$ , adversary can append a block \_\_\_\_ and output tag  $t$ .



# Secure Variable-Length MAC

- **Input-length key separation:**  $k_\ell := F_k(\ell)$ , use  $k_\ell$  for CBC-MAC.
- **Length-prepend:** Prepend  $m$  with  $|m|$ , then use CBC-MAC.



- **Encrypt last block (ECBC-MAC):** Use two keys  $k_1, k_2$ . Get  $t$  with  $k_1$  by CBC-MAC, then output  $\hat{t} := F_{k_2}(t)$ .

Q: To authenticate a voice stream, which approach do you prefer?

# MAC Padding

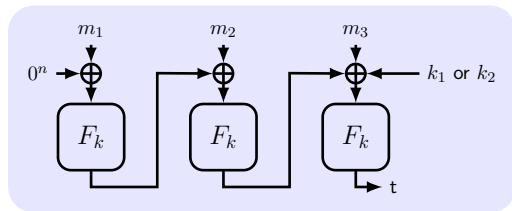
Padding must be invertible!

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

**ISO:** pad with “100...00”. Add dummy block if needed.

**Q:** What if no dummy block?

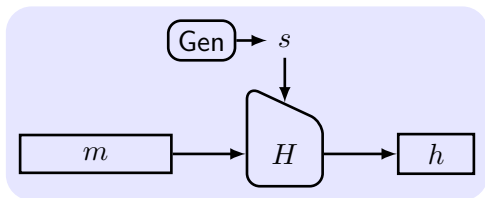
**CMAC (Cipher-based MAC from NIST):** key =  $(k, k_1, k_2)$ .



- No final encryption: extension attack thwarted by keyed XOR.
- No dummy block: ambiguity resolved by use of  $k_1$  or  $k_2$ .

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# Defining Hash Function



## Definition 7

A **hash function (compression function)** is a pair of PPT algorithms  $(\text{Gen}, H)$  satisfying:

- a key  $s \leftarrow \text{Gen}(1^n)$ ,  $s$  is **not kept secret**.
- $H^s(x) \in \{0, 1\}^{\ell(n)}$ , where  $x \in \{0, 1\}^*$  and  $\ell$  is polynomial.

If  $H^s$  is defined only for  $x \in \{0, 1\}^{\ell'(n)}$  and  $\ell'(n) > \ell(n)$ , then  $(\text{Gen}, H)$  is a **fixed-length** hash function.

# Defining Collision Resistance

- **Collision** in  $H$ :  $x \neq x'$  and  $H(x) = H(x')$ .
- **Collision Resistance**: infeasible for any PPT alg. to find.

The collision-finding experiment  $\text{Hashcoll}_{\mathcal{A}, \Pi}(n)$ :

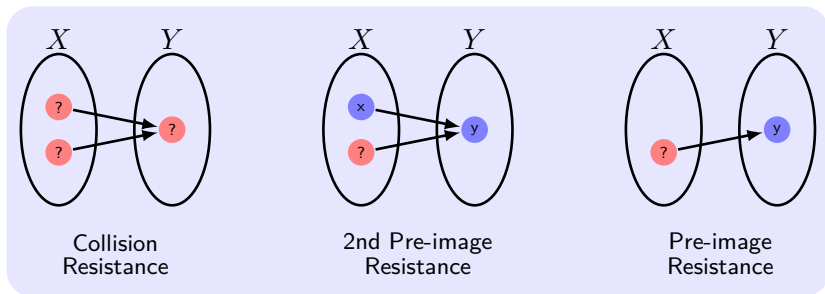
- 1  $s \leftarrow \text{Gen}(1^n)$ .
- 2  $\mathcal{A}$  is given  $s$  and outputs  $x, x'$ .
- 3  $\text{Hashcoll}_{\mathcal{A}, \Pi}(n) = 1 \iff x \neq x' \wedge H^s(x) = H^s(x')$ .

## Definition 8

$\Pi (\text{Gen}, H^s)$  is **collision resistant** if  $\forall$  PPT  $\mathcal{A}$ ,  $\exists \text{negl}$  such that

$$\Pr[\text{Hashcoll}_{\mathcal{A}, \Pi}(n) = 1] \leq \text{negl}(n).$$

# Weaker Notions of Security for Hash Functions



- **Collision resistance:** It is hard to find  $(x, x')$ ,  $x' \neq x$  such that  $H(x) = H(x')$ .
- **Second pre-image resistance:** Given  $s$  and  $x$ , it is hard to find  $x' \neq x$  such that  $H^s(x') = H^s(x)$ .
- **Pre-image resistance:** Given  $s$  and  $y = H^s(x)$ , it is hard to find  $x'$  such that  $H^s(x') = y$ .

## $H$ is CRHF. Is $H'$ CRHF?

- $H'(m) = H(m) \oplus H(m \oplus 1^{|m|})$
- $H'(m) = H(m) \| H(0)$
- $H'(m) = H(m) \| H(m)$
- $H'(m) = H(m) \oplus H(m)$
- $H'(m) = H(m[0, \dots, |m| - 2])$
- $H'(m) = H(m \| 0)$

# Applications of Hash Functions

- **Fingerprinting and Deduplication:**  $H(\text{alargefile})$  for virus fingerprinting, deduplication, P2P file sharing
- **Merkle Trees:**  
 $H(H(H(\text{file1}), H(\text{file2})), H(H(\text{file3}), H(\text{file4})))$   
fingerprinting multiple files / parts of a file
- **Password Hashing:**  $(\text{salt}, H(\text{salt}, \text{pw}))$  mitigating the risk of leaking password stored in the clear
- **Key Derivation:**  $H(\text{secret})$  deriving a key from a high-entropy (but not necessarily uniform) shared secret
- **Commitment Schemes:**  $H(\text{info})$  hiding the committed info; binding the commitment to a info



# The “Birthday” Problem

## The “Birthday” Problem

**Q:** “What size group of people do we need to take such that with probability  $1/2$  some pair of people in the group share a birthday?”

**A:** 23.

## Lemma 9

Choose  $q$  elements  $y_1, \dots, y_q$  u.a.r from a set of size  $N$ , the probability that  $\exists i \neq j$  with  $y_i = y_j$  is  $\text{coll}(q, N)$ , then

$$\text{coll}(q, N) \leq \frac{q^2}{2N}.$$

$$\text{coll}(q, N) \geq \frac{q(q-1)}{4N} \quad \text{if } q \leq \sqrt{2N}.$$

$$\text{coll}(q, N) = \Theta(q^2/N) \quad \text{if } q < \sqrt{N}.$$

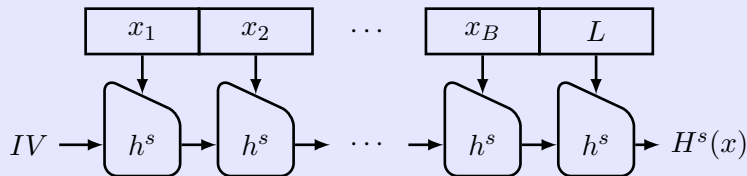
The length of hash value should be long enough.

# Constructing “Meaningful” Collisions

How many different meaningful sentences are in the below paragraph?

It is **hard/difficult/challenging/impossible** to **imagine/believe** that we will **find/locate/hire** another **employee/person** having similar **abilities/skills/character** as Alice. She has done a **great/super** job.

# The Merkle-Damgård Transform



## Construction 10

Construct **variable-length** CRHF  $(\text{Gen}, H)$  from fixed-length  $(\text{Gen}, h)$  ( $2\ell$  bits  $\rightarrow \ell$  bits,  $\ell = \ell(n)$ ):

- $\text{Gen}$ : remains unchanged
- $H$ : key  $s$  and string  $x \in \{0, 1\}^*$ ,  $L = |x| < 2^\ell$ :
  - $B := \lceil \frac{L}{\ell} \rceil$  (# blocks). **Pad  $x$  with 0s.**  $\ell$ -bit blocks  $x_1, \dots, x_B$ .  $x_{B+1} := L$ ,  $L$  is encoded using  $\ell$  bits
  - $z_0 := IV = 0^\ell$ . For  $i = 1, \dots, B + 1$ , compute  $z_i := h^s(z_{i-1} || x_i)$

# Security of the Merkle-Damgård Transform

## Theorem 11

If  $(\text{Gen}, h)$  is a fixed-length CRHF, then  $(\text{Gen}, H)$  is a CRHF.

## Proof.

**Idea:** a collision in  $H^s$  yields a collision in  $h^s$ .

Two messages  $x \neq x'$  of respective lengths  $L$  and  $L'$  such that  $H^s(x) = H^s(x')$ . # blocks are  $B$  and  $B'$ .

$x_{B+1} := L$  is necessary since **Padding with 0s** will lead to the same input with different messages.

1  $L \neq L': z_B \| L \neq z_{B'} \| L'$

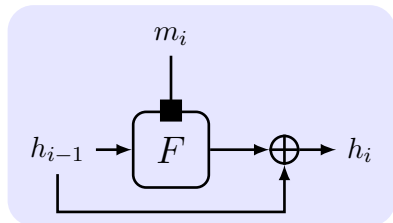
2  $L = L': z_{i^*-1} \| x_{i^*} \neq z'_{i^*-1} \| x'_{i^*}$

So there must be  $x \neq x'$  such that  $h^s(x) = h^s(x')$ . □

Security on MD transform variations in Homework.

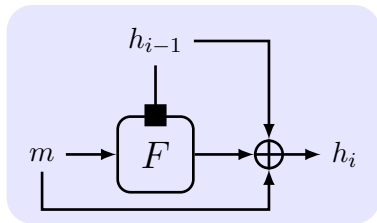
# CRHF from Block Cipher

Davies-Meyer (SHA-1/2, MD5)



$$h_i = F_{m_i}(h_{i-1}) \oplus h_{i-1}$$

Miyaguchi-Preneel (Whirlpool)



$$h_i = F_{h_{i-1}}(m_i) \oplus h_{i-1} \oplus m$$

## Theorem 12

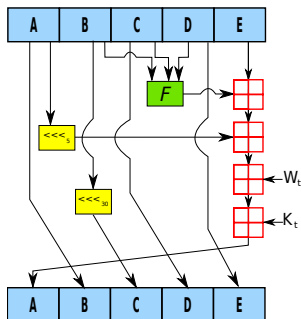
*If  $F$  is modeled as an ideal cipher, then Davies-Meyer construction yields a CRHF.*

Q: what if  $h_i = F_{m_i}(h_{i-1})$  without XOR with  $h_{i-1}$ ?

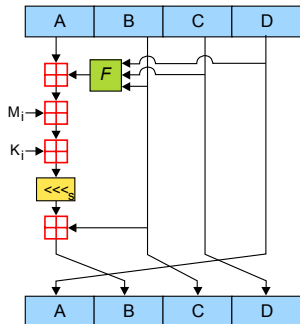
Q: what if  $F$  is not ideal such that  $\exists x, F_k(x) = x$ ?

# Cryptographic Hash Functions: SHA-1 and MD5

SHA-1:



MD5:

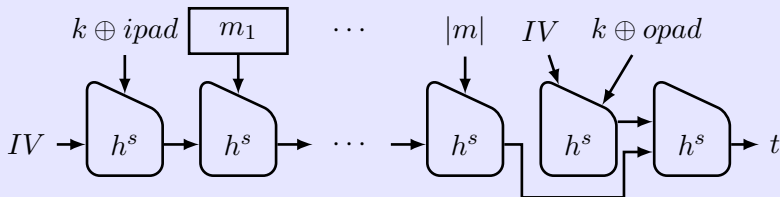


$A, B, C, D$  and  $E$  are 32-bit words of the state;  $F$  is a nonlinear function that varies;  $\lll n$  denotes a left bit rotation by  $n$  places;  $W_t/M_t$  is the expanded message word of round  $t$ ;  $K_t$  is the round constant of round  $t$ ;  $\boxplus$  denotes addition modulo  $2^{32}$ .

- Finding a collision in 128-bit MD5 requires time  $2^{20.96}$
- Finding a collision in 160-bit SHA-1 requires time  $2^{51}$

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# Hash-based MAC (HMAC)



## Construction 13

$(\widetilde{\text{Gen}}, h)$  is a fixed-length CRHF.  $(\widetilde{\text{Gen}}, H)$  is the Merkle-Damgård transform.  $IV$ ,  $opad$  ( $0 \times 36$ ),  $ipad$  ( $0 \times 5C$ ) are fixed constants of length  $n$ . HMAC:

- $\text{Gen}(1^n)$ : Output  $(s, k)$ .  $s \leftarrow \widetilde{\text{Gen}}, k \leftarrow \{0, 1\}^n$  u.a.r
- $\text{Mac}_{s,k}(m)$ :  $t := H_{IV}^s \left( (k \oplus opad) \| H_{IV}^s((k \oplus ipad) \| m) \right)$
- $\text{Vrfy}_{s,k}(m, t)$ :  $1 \iff t \stackrel{?}{=} \text{Mac}_{s,k}(m)$



## Theorem 14

$G(k) \stackrel{\text{def}}{=} h^s(IV \parallel (k \oplus \text{opad})) \parallel h^s(IV \parallel (k \oplus \text{ipad})) = k_1 \parallel k_2$   
 $(\widetilde{\text{Gen}}, h)$  is CRHF. If  $G$  is a PRG, then HMAC is secure.

Before HMAC's  $H^s(k \parallel H^s(k \parallel x))$ , a common mistake was to use:

- $H^s(k \parallel x)$ : Vulnerable to length extension attack. Given  $H^s(k \parallel x)$  and the length of  $x$ , get the valid tag  $H^s(k \parallel x \parallel x')$  for a new message  $x \parallel x'$ .
- $H^s(x \parallel k)$ : A collision in the weak hash function has a collision in the MAC.
- $H^s(k \parallel x \parallel k)$ : Some known vulnerabilities with this approach, even when two different keys are used.

# Security of HMAC (Cont.)

- HMAC is an industry standard (RFC2104)
- HMAC is faster than CBC-MAC
- **Verification timing attacks:**  
Keyczar crypto library (Python):  

```
def Verify(key, msg, sig_bytes):  
    return HMAC(key, msg) == sig_bytes
```

The problem: implemented as a byte-by-byte comparison
- In Xbox 360, a difference of 2.2 milliseconds between rejection times of  $i$  vs.  $i + 1$  bytes.
- *Don't implement it yourself*

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# Definition of Information-Theoretic MAC Security

It is impossible to achieve "perfect" MAC, as the adversary can output a valid tag with probability  $1/2^{|t|}$  at least.

The one-time MAC experiment  $\text{Macforge}_{\mathcal{A}, \Pi}^{1\text{-time}}$ :

- 1  $k \leftarrow \text{Gen}$ .
- 2  $\mathcal{A}$  outputs a message  $m'$ , and is given a tag  $t' \leftarrow \text{Mac}_k(m')$ , and outputs  $(m, t)$ .
- 3  $\text{Macforge}_{\mathcal{A}, \Pi}^{1\text{-time}} = 1 \iff \text{Vrfy}_k(m, t) = 1 \wedge m \neq m'$ .

## Definition 15

A MAC  $\Pi$  is **one-time  $\varepsilon$ -secure** if  $\forall$  PPT  $\mathcal{A}$ :

$$\Pr[\text{Macforge}_{\mathcal{A}, \Pi}^{1\text{-time}} = 1] \leq \varepsilon.$$

## Definition 16

A function  $h: \mathcal{K} \times \mathcal{M} \rightarrow \mathcal{T}$  is a **Strongly Universal Function (SUF)** if for all distinct  $m, m' \in \mathcal{M}$  and all  $t, t' \in \mathcal{T}$ , it holds that:

$$\Pr[h_k(m) = t \wedge h_k(m') = t'] = 1/|\mathcal{T}|^2.$$

where the probability is taken over uniform choice of  $k \in \mathcal{K}$ .

## Construction 17

- Let  $h: \mathcal{K} \times \mathcal{M} \rightarrow \mathcal{T}$  be an SUF.
- Gen:  $k \leftarrow \{0, 1\}^n$  u.a.r.
- Mac $_k(m)$ :  $t := h_k(m)$ .
- Vrfy $_k(m, t)$ :  $1 \iff t \stackrel{?}{=} h_k(m)$ . (If  $m \notin \mathcal{M}$ , then output 0.)

# Construction of An SUF

## Theorem 18

*For any prime  $P$ , the function  $h$  is an SUF:*

$$h_{a,b}(m) \stackrel{\text{def}}{=} [a \cdot m + b \mod p]$$

## Proof.

$h_{a,b}(m) = t$  and  $h_{a,b}(m') = t'$ , only if  $a \cdot m + b = t \mod p$  and  $a \cdot m' + b = t' \mod p$ . We have  $a = [(t - t') \cdot (m - m')^{-1} \mod p]$  and  $b = [t - a \cdot m \mod p]$ , which means there is a unique key  $(a, b)$ . Since there are  $|\mathcal{T}|^2$  keys,

$$\Pr[h_k(m) = t \wedge h_k(m') = t'] = \frac{1}{|\mathcal{T}|^2}.$$



# Security of Construction from An SUF

## Theorem 19

*If  $h$  is an SUF, Construction is a  $1/|\mathcal{T}|$ -secure MAC.*

## Proof.

We assume that  $\mathcal{A}$  is deterministic without loss of generality. The adversary receives tag  $t'$  for the message  $m'$ , where  $m'$  is fixed.

$$\begin{aligned}\Pr[\text{Macforge}_{\mathcal{A}, \Pi}^{1-\text{time}} = 1] &= \sum_{t' \in \mathcal{T}} \Pr[\text{Macforge}_{\mathcal{A}, \Pi}^{1-\text{time}} = 1 \wedge h_k(m') = t'] \\ &= \sum_{t' \in \mathcal{T}} \Pr[h_k(m) = t \wedge h_k(m') = t'] \\ &= \sum_{t' \in \mathcal{T}} \frac{1}{|\mathcal{T}^2|} = \frac{1}{|\mathcal{T}|}\end{aligned}$$



# Limitations on Information-Theoretic MACs

Any  $\ell$ -time  $2^{-n}$ -secure MAC requires keys of length at least  $(\ell + 1) \cdot n$ .

## Theorem 20

*Let  $\Pi$  be a 1-time  $2^{-n}$ -secure MAC where all keys are the same length. Then the keys must have length at least  $2n$ .*

## Proof.

Let  $\mathcal{K}(t) \stackrel{\text{def}}{=} \{k \mid \text{Vrfy}_k(m, t) = 1\}$ . For any  $t$ ,  $|\mathcal{K}(t)| \leq 2^{-n} \cdot |\mathcal{K}|$ . Otherwise,  $(m, t)$  would be a valid forgery with probability at least  $|\mathcal{K}(t)|/|\mathcal{K}| > 2^{-n}$ . The probability that  $\mathcal{A}$  outputs a valid forgery is at least

$$\sum_t \Pr[\text{Mac}_k(m) = t] \cdot \frac{1}{|\mathcal{K}(t)|} \geq \sum_t \Pr[\text{Mac}_k(m) = t] \cdot \frac{2^n}{|\mathcal{K}|} = \frac{2^n}{|\mathcal{K}|}$$

As the probability is at most  $2^{-n}$ ,  $|\mathcal{K}| \geq 2^{2n}$ . Since all keys have the same length, each key must have length at least  $2n$ .  $\square$



- adaptive CMA, replay attack, birthday attack
- existential unforgeability, collision resistance
- CBC-MAC, CRHF, Merkle-Damgård transform, NMAC, HMAC
- information-theoretic MAC