Message Authentication Code

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Outline

1. Message Integrity
2. Message Authentication Code (MAC)

Outline

Message Integrity

- We want parties to *securely* communicate over insecure channels.
- Encrypting messages is only one part of security.
- What if the messages were modified in transit?
- What about authenticity?

Encryption does not guarantee integrity

- Consider the OTP scheme, which is a perfectly secret encryption scheme.
- From a given ciphertext, you can produce a new *valid* ciphertext, by just flipping a single bit!
- Perfect secrecy is not violated here.
- But, perfect secrecy *simply* doesn't imply message integrity.
- Different cryptographic tools should be used to achieve secrecy and integrity.

Outline

1. Message Integrity
2. Message Authentication Code (MAC)

Message Authentication Code (MAC)

- Message authentication code is the cryptographic tool to be used to ensure message integrity.
- Informally speaking, the MAC's goal is to prevent an adversary from tampering with the messages.
- Parties need to share a secret key as in the encryption!

MAC - Formal Definition

Definition

A MAC *consists of the following three probabilistic polynomial-time algorithms* (KeyGen, Mac, Verify)*:*

- KeyGen(1^n)*: takes the security parameter* n *and outputs a key* k *s.t.* $|k| \geq n$
- Mac$_k(m \in \{0,1\}^*)$*: is a tagging algorithm, takes a key* k *and a message* m *and outputs a tag* t*.*
- Verify$_k(m,t)$*: a deterministic algorithm that outputs a bit* b*, 0 for invalid and 1 for valid.*

$Mac_k(\cdot)$ may be randomised or deterministic.

MAC

- **Correctness of MAC:** $\forall n, \forall k \leftarrow \text{KeyGen}(1^n)$ and $\forall m \in \{0,1\}^*$, $\text{Verify}_k(m, \text{Mac}_k(m)) = 1$ holds.
- Fixed-length MAC: if it is just defined for messages $m \in \{0,1\}^{\ell(n)}$, we call the scheme a *fixed-length MAC for messages of length $\ell(n)$.*
- Canonical Verification: when Mac is deterministic, recomputes the tag and checks for equality.

Security of MAC - Intuition

- An adversary should not be able to efficiently produce a valid tag on a new message that was not authenticated before.
- Taking as realistic a scenario where the adversary can see message/tag pairs, in the security definition the adversary is given access to a tagging oracle.

Security of MAC - Formal Definition

Given $S = (\text{KeyGen}, \text{Mac}, \text{Verify})$, an adversary $\mathcal{A}$, and a security parameter n, we define the following experiment:

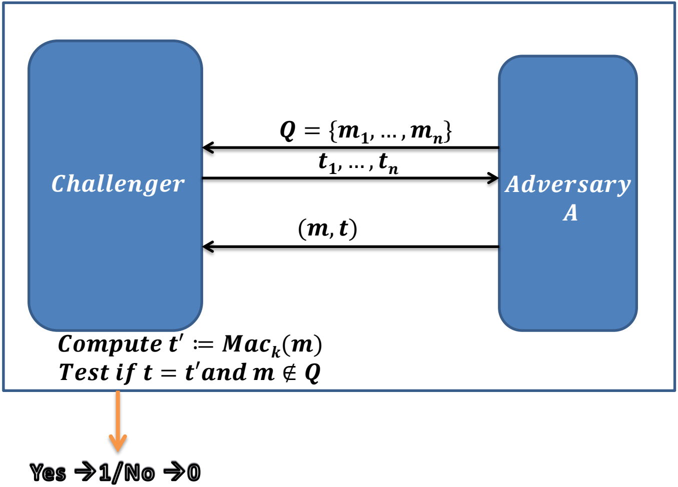
Experiment ($\text{Mac}^{\text{Unforg}}_{\mathcal{A},S}$)

- *Key generation:* $k \leftarrow \text{KeyGen}(1^n)$*.*
- *Tag queries: the adversary $\mathcal{A}$ is given oracle access to* $\text{Mac}_k()$*. The set of all queried messages is Q.*
- *Adversary's output: the adversary $\mathcal{A}$ eventually outputs (m, t)*
- *Experiment's output: if*

$$\text{Verify}_k(m, t) = 1 \wedge m \notin Q$$

outputs 1, otherwise outputs 0.

MAC^{unforg} Game



Security of MAC - Formal Definition

A MAC scheme S is said to be *Existentially unforgeable under an adaptive chosen-message attack* if no PPT adversary $\mathcal{A}$ can win the previous game with non-negligible probability:

Definition

A message authentication code $S = (\mathsf{KeyGen}, \mathsf{Mac}, \mathsf{Verify})$ is secure if for all probabilistic polynomial-time adversary $\mathcal{A}$, the following holds

$$\Pr[\mathsf{Mac}^{\mathsf{Unforg}}_{\mathcal{A},S}(n) = 1] \leq \mathsf{negl}(n)\,.$$

MAC and Replay attacks

- An adversary cannot change the message without being detected by the receiver if it has a valid tag.
- However, the adversary can replay and send the same message again, with the same tag.
- The receiver cannot detect this malicious behaviour.
- Common techniques to prevent replay attacks:
    - Time-stamps: add the current time to the beginning of the message before authenticating it.
    - Counters: users maintain synchronised state.

Security of MAC - Formal Definition (2)

Given $S = (\text{KeyGen}, \text{Mac}, \text{Verify})$, an adversary $\mathcal{A}$, and a security parameter n, we define the following experiment:

Experiment ($\text{Mac}^{\text{s-unforg}}_{\mathcal{A},S}$)

- *Key generation:* $k \leftarrow \text{KeyGen}(1^n)$.
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Strongly Secure MAC

If a MAC scheme is strongly secure, then adversaries win if they produce tags on any messages (including already authenticated ones!).

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$$\Pr[\mathsf{Mac}^{\mathsf{s-unforg}}_{\mathcal{A},S}(n) = 1] \leq \mathsf{negl}(n)\,.$$

If the Mac algorithm in S is deterministic, and the verification is canonical, then secure MACs are strongly secure as well.

MAC - Side Channel Attacks

- When giving the adversary access to a MAC oracle, he just learns the output, not the time taken by the Oracle to perform the task.
- This is not what happens in the real systems!
- An adversary may be able to obtain the time necessary to reject a pair message/tag.
- In the case of deterministic MAC, if the MAC verification does not use time-independent string comparison, then the adversary can exploit the time differences to deduce new bytes of the tag!
- This is a realistic attack. Xbox 360 had a difference of 2.2 milliseconds in comparing j or $j+1$ bytes.
- Attackers managed to exploit this.
- Conclusion: MAC verification should compare all the bytes.

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A fixed-Length MAC from a PRF

Definition

Given a length-preserving pseudorandom function F, a fixed-length MAC S for messages of length n consists of the two following algorithms:

- Mac$(k \in \{0,1\}^n, m \in \{0,1\}^n)$*: it outputs the tag* $t \leftarrow F_k(m)$.
- Verify$(k \in \{0,1\}^n, m \in \{0,1\}^n, t \in \{0,1\}^n)$*: it outputs 1 iff* $F_k(m) = t$

If $|m| \neq |k|$, then Mac outputs $\perp$ and Verify outputs 0.

A fixed-Length MAC from a PRF

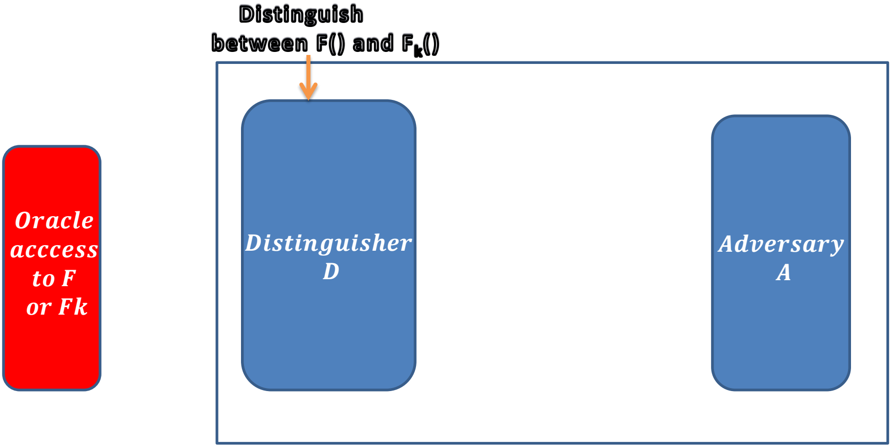
Theorem

If F is a secure pseudorandom function, then the fixed-length MAC for messages of length n is secure.

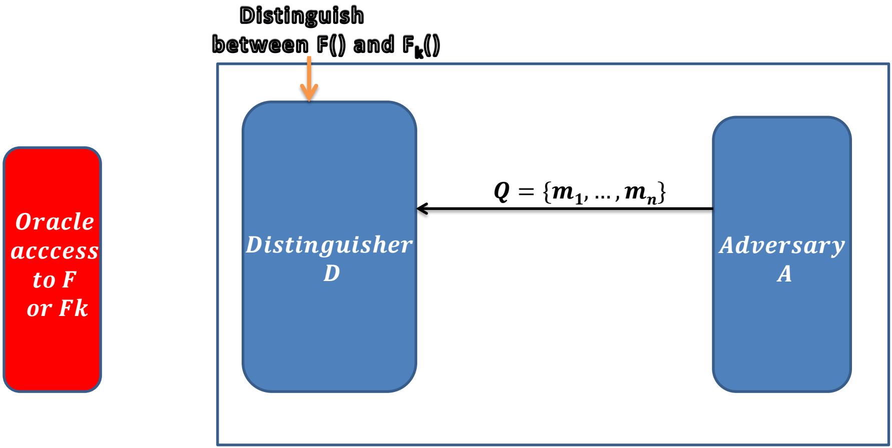
Steps of the proof:

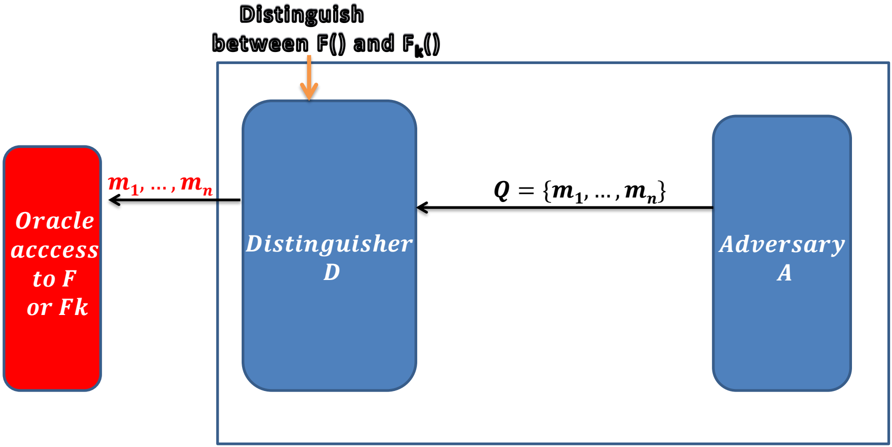
- consider a variation S' of S, where F_k is replaced by a truly random function $f : \{0,1\}^n \to \{0,1\}^n$.
- Let $\mathcal{A}$ be the adversary trying to attack S.
- Define a distinguisher D for F (it is given access to some function and needs to tell whether this function is pseudorandom or truly random).
- D emulates the MAC experiment for $\mathcal{A}$ and check if it succeeds in producing a valid tag on a new message m.
- if $\mathcal{A}$ manages to produce a valid tag, D will guess that its oracle is "pseudo-random" (1), otherwise it outputs "truly random" (0).

F in the left box is the truly random function $f : \{0,1\}^n \rightarrow \{0,1\}^n$.

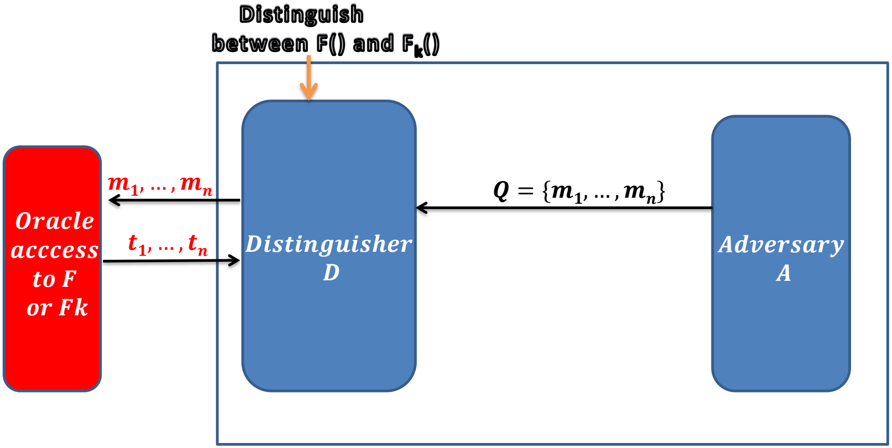


In the “adaptive” setting, the messages $m_1, \ldots, m_n$ will be sent separately.





Distinguish
between F() and $F_k()$
Oracle acccess to F or Fk
$m_1, \ldots, m_n$
Distinguisher D
$Q = \{m_1, \ldots, m_n\}$
Adversary A


Distinguish
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Oracle acccess to F or Fk
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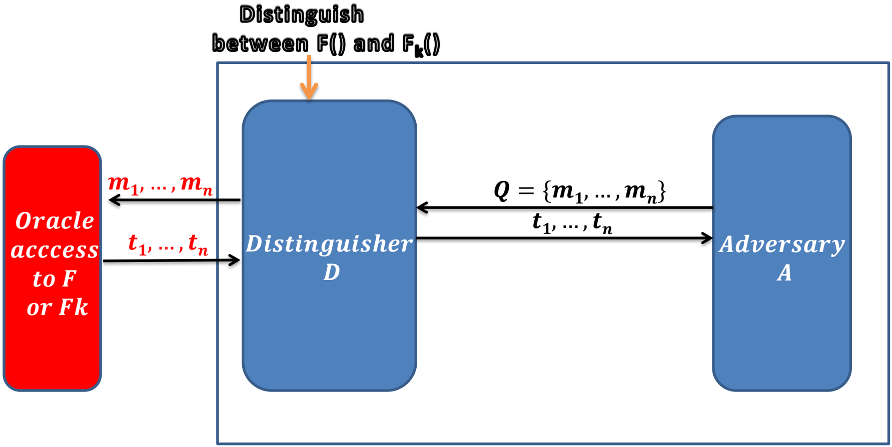
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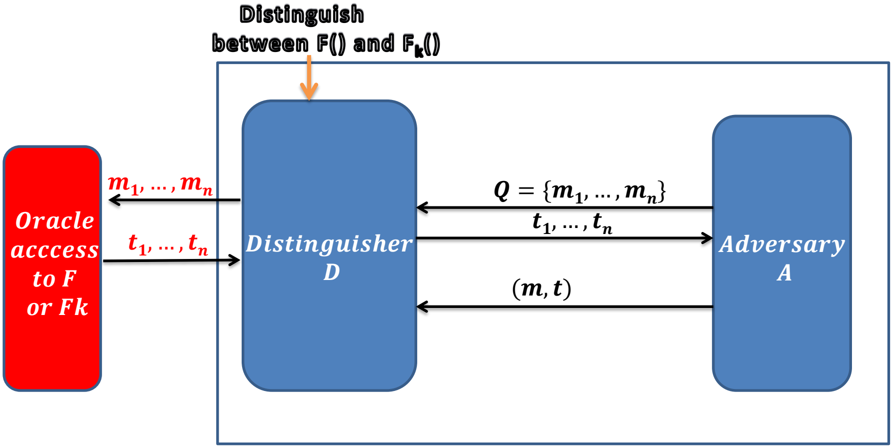
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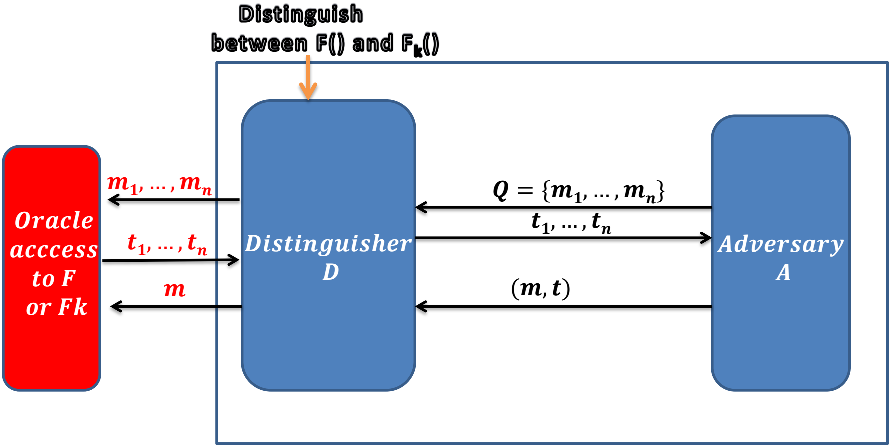
Adversary A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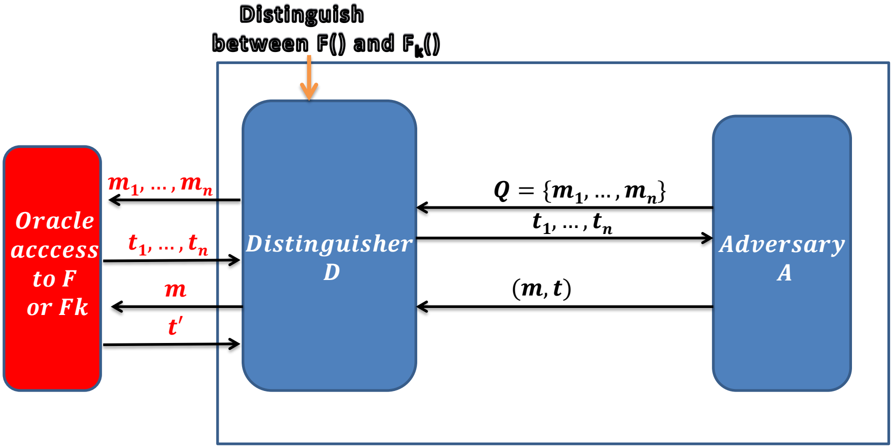
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m_1, ..., m_n
t_1, ..., t_n
m
t'
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t_1, ..., t_n
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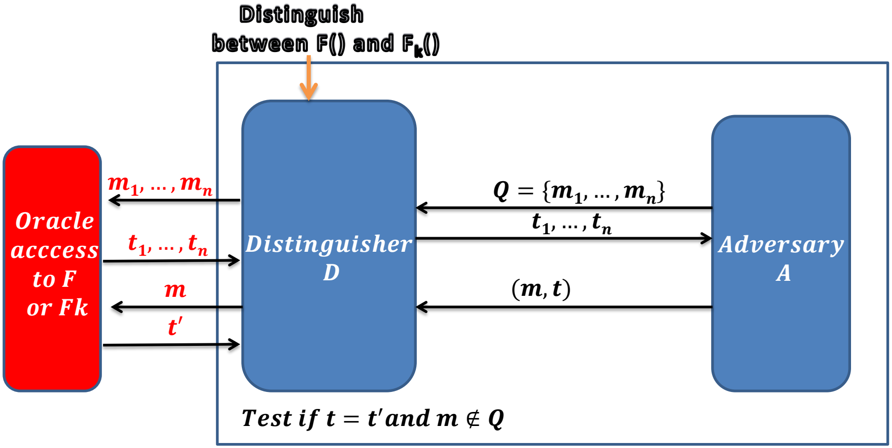
Adversary A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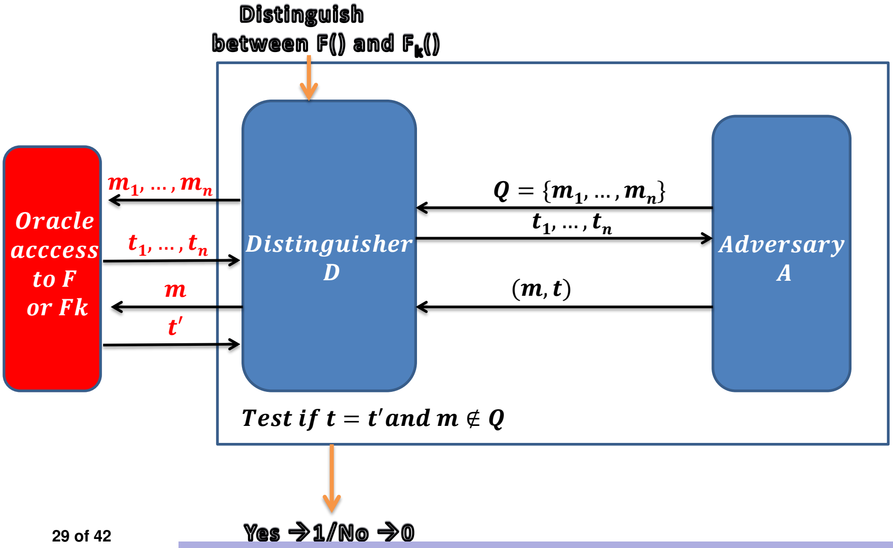
Test if $t = t'$ and $m \notin Q$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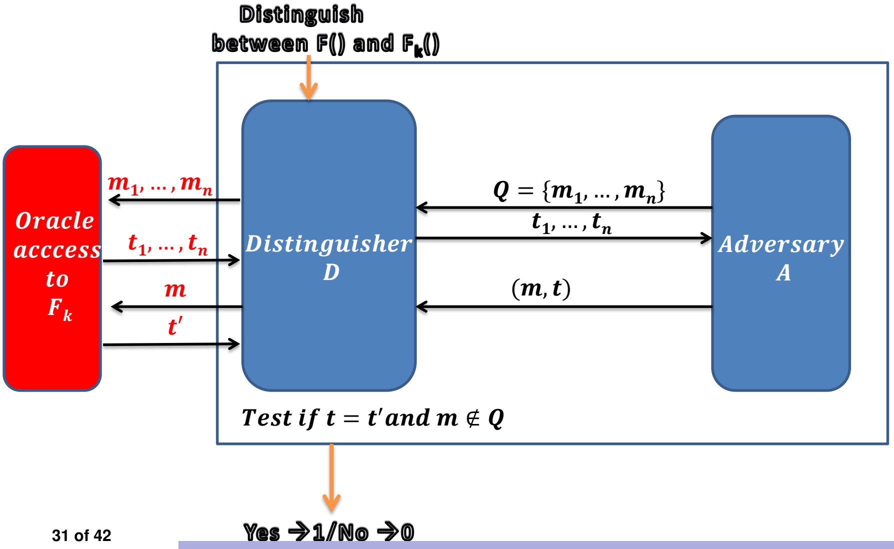
Adversary A
Test if $t = t'$ and $m \notin Q$
Yes → 1/No → 0

A fixed-Length MAC from a PRF

Steps of the Proof

We can distinguish between two cases:

- D*'s oracle is a pseudo-random function: in this case, the view of* $\mathcal{A}$ *that is run as a subroutine by* D *and its view in the experiment* $\mathsf{Mac}^{\mathsf{Unforg}}_{\mathcal{A},S}(n)$ *are distributed identically. Moreover,* D *outputs 1 exactly when* $\mathsf{Mac}^{\mathsf{Unforg}}_{\mathcal{A},S}(n)$ *outputs 1.*
- D*'s oracle is a truly-random function: in this case, the view of* $\mathcal{A}$ *that is run as a subroutine by* D *and its view in the experiment* $\mathsf{Mac}^{\mathsf{Unforg}}_{\mathcal{A},S'}(n)$ *are distributed identically. Moreover,* D *outputs 1 exactly when* $\mathsf{Mac}^{\mathsf{Unforg}}_{\mathcal{A},S'}(n)$ *outputs 1.*



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Test if $t = t'$ and $m \notin Q$
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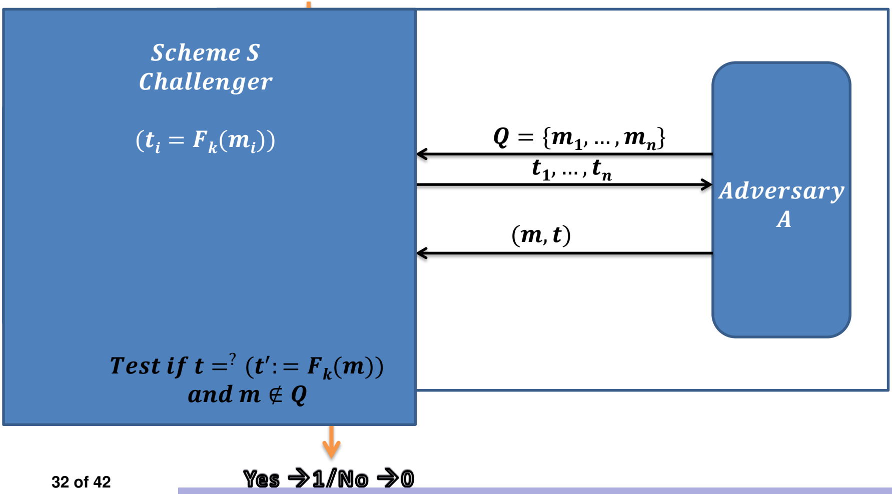
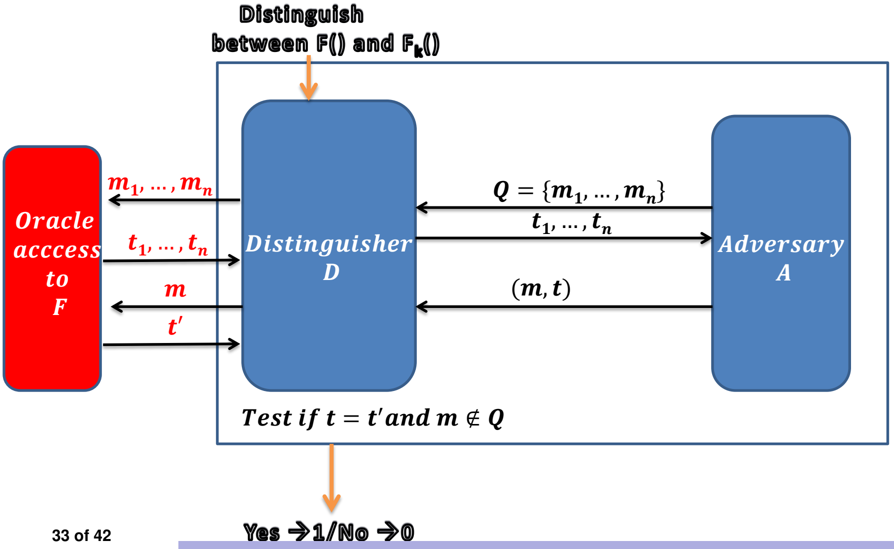
MAC^{unforg}



$Scheme\ S$
$Challenger$
$(t_i = F_k(m_i))$
$Q = \{m_1, \dots, m_n\}$
$t_1, \dots, t_n$
(m, t)
$Adversary$
A
$Test\ if\ t \stackrel{?}{=} (t' := F_k(m))$
$and\ m \notin Q$
Yes →1/No →0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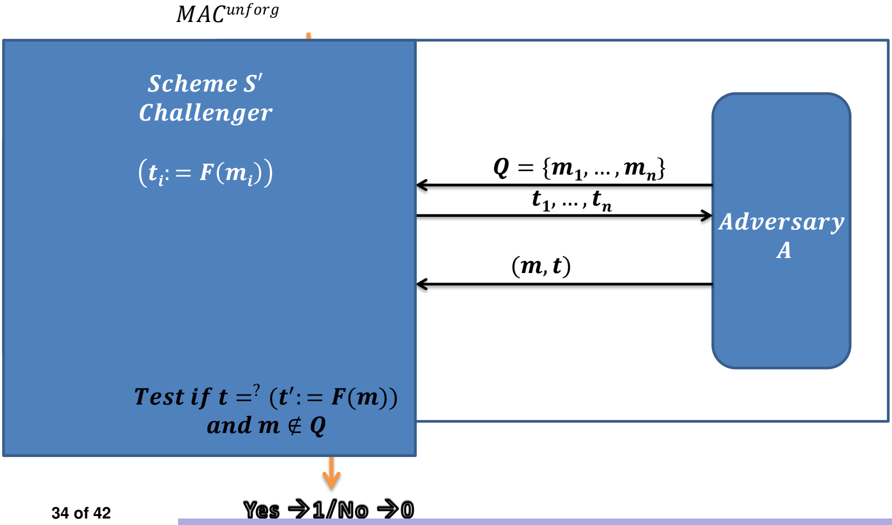

MAC^{unforg}
Scheme S'
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Adversary A
Test if $t \stackrel{?}{=} (t' := F(m))$
and $m \notin Q$
Yes → 1/No → 0

Sketch Proof.

As a result, we have that

$$\Pr[\mathsf{Mac}^{\mathsf{Unforg}}_{\mathcal{A},S'}(n) = 1] = \Pr[D^{f()}(n) = 1] \quad (1)$$

and

$$\Pr[\mathsf{Mac}^{\mathsf{Unforg}}_{\mathcal{A},S}(n) = 1] = \Pr[D^{F_k()}(n) = 1] \quad (2)$$

A fixed-Length MAC from a PRF

Steps of the Proof

Since F is a secure PRF, it holds:

$$|\Pr[D^{f()}(n) = 1] - \Pr[D^{F_k()}(n) = 1]| =$$

$$= |\Pr[\mathsf{Mac}^{\mathsf{Unforg}}_{\mathcal{A},S'}(n) = 1] - \Pr[\mathsf{Mac}^{\mathsf{Unforg}}_{\mathcal{A},S}(n) = 1]| \leq \mathsf{negl}(n).$$

For any message $m \notin Q$, the value $t = f(m)$ is uniformly distributed in $\{0,1\}^n$ from the point of view of the adversary $\mathcal{A}$. So:

$$\Pr[\mathsf{Mac}^{\mathsf{Unforg}}_{\mathcal{A},S'}(n) = 1] \leq 2^{-n}.$$

The relations above then give:

$$\Pr[\mathsf{Mac}^{\mathsf{Unforg}}_{\mathcal{A},S}(n) = 1] \leq 2^{-n} + \mathsf{negl}(n)\,.$$

From fixed length MAC to MAC for arbitrary-length messages.

- If the PRF has a bigger bolck length, the MAC is secure for longer messages.
- Problem: existing pseudo-random functions used in practice (block ciphers) can just take short fixed-length inputs!
- Question: How to build a MAC for arbitrary-length messages?

A general MAC from a fixed-length one

Potential attacks:

- Block re-ordering attack: change the order of blocks. Namely, if (t_1, t_2) is a valid tag on (m_1, m_2) where $m_1 \neq m_2$, then (t_2, t_1) is a valid tag on (m_2, m_1), with $m_1, m_2 \neq m_2, m_1$.
  Solution: authenticate a block index with each block.
- Truncation attack: the attacker removes blocks from the end of the message and their corresponding blocks from the tag.
  Solution: authenticate the message length with each block
- Mix-and-match attack: given the valid tags (t_1, t_2, t_3) and (t'_1, t'_2, t'_3) on the messages (m_1, m_2, m_3) and (m'_1, m'_2, m'_3), output (t_1, t'_2, t_3) on the message (m_1, m'_2, m_3).
  Solution: authenticate a *random message identifier* along with each block.

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A general MAC from a fixed-length one

Potential attacks:

- Block re-ordering attack: change the order of blocks. Namely, if (t_1, t_2) is a valid tag on (m_1, m_2) where $m_1 \neq m_2$, then (t_2, t_1) is a valid tag on (m_2, m_1), with $m_1, m_2 \neq m_2, m_1$.
  Solution: authenticate a block index with each block.
- Truncation attack: the attacker removes blocks from the end of the message and their corresponding blocks from the tag.
  Solution: authenticate the message length with each block
- Mix-and-match attack: given the valid tags (t_1, t_2, t_3) and (t'_1, t'_2, t'_3) on the messages (m_1, m_2, m_3) and (m'_1, m'_2, m'_3), output (t_1, t'_2, t_3) on the message (m_1, m'_2, m_3).
  Solution: authenticate a *random message identifier* along with each block.

A MAC from a fixed-length one

Definition

Let $S_1 = (\text{KeyGen}_1, \text{Mac}_1, \text{Verify}_1)$ *be a fixed-length MAC for messages of length* n*. We define a MAC* S *for arbitrary-length messages as follows:*

- $\text{Mac}(k \in \{0,1\}^n, m \in \{0,1\}^*)$*:*
  - *it takes a key* k *and a messge* m*, where* $|m| = \ell < 2^{n/4}$*.*
  - *it then parses* m *into* d *blocks of length* $n/4$*, i.e.* $m_1, \cdots, m_d$*.*
  - *if the last block is not of size* $n/4$*, we pad it with* $0s$
  - *it uniformly chooses* $r \in \{0,1\}^{n/4}$
  - *For* $i = 1, \cdots, d$*, compute* $t_i \leftarrow \text{Mac}_1(k, r||\ell||i||m_i)$*, where* i, ℓ *are encoded as strings of length* $n/4$*.*
  - *Output* $t = (r, t_1, \cdots, t_d)$*.*
- $\text{Verify}(k, m, (r, t_1, \cdots, t_d))$*: parse* m *into* d' *blocks, then output 1 iff* $d' = d$ *AND* $\text{Verify}_1(k, r||\ell||i||m_i, t_i) = 1$ *for* $1 \leq i \leq d'$*.*

A general MAC from a fixed-length one

Theorem

If S_1 is a secure fixed-length MAC for messages of length n, then S as defined above is a secure MAC for arbitrary-length messages.

Another way to build a secure MAC for arbitrary-length messages is to use hash functions, which will be covered soon!

Further Reading (1)

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Further Reading (2)

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