MESSAGE AUTHENTICATION CODES
and
PRF DOMAIN EXTENSION
Integrity and authenticity

The goal is to ensure that

- $M$ really originates with Alice and not someone else
- $M$ has not been modified in transit
Integrity and authenticity example

Adversary Eve might

- Modify “Charlie” to “Eve”
- Modify “$100” to “$1000”

Integrity prevents such attacks.
A message authentication code $\mathcal{T} : \text{Keys} \times D \rightarrow R$ is a family of functions. The envisaged usage is shown below, where $A$ is the adversary:

We refer to $\mathcal{T}$ as the MAC or tag. We have defined

Algorithm $\mathcal{V}_K(M', T')$
If $\mathcal{T}_K(M') = T'$ then return 1 else return 0
MAC usage

Sender and receiver share key $K$.

To authenticate $M$, sender transmits $(M, T)$ where $T = T_K(M)$.

Upon receiving $(M', T')$, the receiver accepts $M'$ as authentic iff $V_K(M', T') = 1$, or, equivalently, iff $T_K(M') = T'$. 
Let $T: \text{Keys} \times D \rightarrow R$ be a message authentication code. Let $A$ be an adversary.

The uf-cma advantage of adversary $A$ is

$$\text{Adv}^{\text{uf-cma}}_{T}(A) = \Pr \left[ \text{UFCMA}_{\tau}^{A} \Rightarrow \text{true} \right]$$
Adversary $A$ does not get the key $K$.

It can call $\text{Tag}$ with any message $M$ of its choice to get back the correct tag $T = T_K(M)$.

To win, the adversary $A$ must output a message $M \in D$ and a tag $T$ that are

- Correct: $T = T_K(M)$
- New: $M \notin S$, meaning $M$ was not a query to $\text{Tag}$

**Interpretation:** $\text{Tag}$ represents the sender and $\text{Finalize}$ represents the receiver. Security means that the adversary can’t get the receiver to accept a message that is not authentic, meaning was not already transmitted by the sender.
Exercise: Tag lengths

Let $T: \text{Keys} \times D \to \{0, 1\}^\ell$ be a message authentication code. Specify in pseudocode an efficient adversary $A$ making zero $\text{Tag}$ queries and achieving $\text{Adv}_{T}^{\text{uf-cma}}(A) = 2^{-\ell}$.

**Conclusion:** Tags have to be long enough.

For 80 bit security, tags have to be at least 80 bits.
Example: Basic CBC MAC

Let $E : \{0, 1\}^k \times B \rightarrow B$ be a blockcipher, where $B = \{0, 1\}^n$. View a message $M \in B^*$ as a sequence of $n$-bit blocks, $M = M[1] \ldots M[m]$.

The basic CBC MAC $T : \{0, 1\}^k \times B^* \rightarrow B$ is defined by

**Alg** $T_K(M)$

\[
\begin{align*}
C[0] & \leftarrow 0^n \\
\text{for } i = 1, \ldots, m \text{ do } C[i] & \leftarrow E_K(C[i - 1] \oplus M[i]) \\
\text{return } C[m]
\end{align*}
\]

$$M[1] \oplus E_K$$

$$M[2] \oplus E_K$$

$$\ldots$$

$$M[m - 1] \oplus E_K$$

$$M[m] \oplus E_K$$

$$C[m] = T_K(M)$$
Splicing attack on basic CBC MAC

**Alg** $T_K(M)$

- $C[0] \leftarrow 0^n$
- for $i = 1, \ldots, m$ do
  - $C[i] \leftarrow E_K(C[i-1] \oplus M[i])$
- return $C[m]$

**adversary** $A$

- Let $x \in \{0, 1\}^n$
- $T_1 \leftarrow \text{Tag}(x)$
- $M \leftarrow x \parallel T_1 \oplus x$
- Return $M, T_1$

Then,

$$T_K(M) = E_K(E_K(x) \oplus T_1 \oplus x)$$

$$= E_K(T_1 \oplus T_1 \oplus x)$$

$$= E_K(x)$$

$$= T_1$$
Insecurity of basic CBC MAC

\textbf{Alg $T_K(M)$}
\begin{align*}
C[0] &\leftarrow 0^n \\
\text{for } i = 1, \ldots, m \text{ do} &\quad C[i] \leftarrow E_K(C[i - 1] \oplus M[i]) \\
\text{return } C[m] &
\end{align*}

\textbf{adversary $A$}
\begin{align*}
\text{Let } x &\in \{0, 1\}^n \\
T_1 &\leftarrow \text{Tag}(x) \\
M &\leftarrow x || T_1 \oplus x \\
\text{Return } M, T_1 &
\end{align*}

Then $\text{Adv}_{T}^{\text{uf-cma}}(A) = 1$ and $A$ is efficient, so the basic CBC MAC is not UF-CMA secure.
Exercise

Let $E: \{0, 1\}^k \times \{0, 1\}^n \rightarrow \{0, 1\}^n$ be a blockcipher. Let

$$D = \{ M \in \{0, 1\}^* : 0 < |M| < n2^n \text{ and } |M| \mod n = 0 \}.$$  

Let $T: \{0, 1\}^k \times D \rightarrow \{0, 1\}^n$ be defined as follows:

**Alg $T_K(M)$**

1. $M[1] \ldots M[m] \leftarrow M$; $M[m + 1] \leftarrow \langle m \rangle$; $C[0] \leftarrow 0^n$
2. For $i = 1, \ldots, m + 1$ do $C[i] \leftarrow E_K(C[i - 1] \oplus M[i])$
3. $T \leftarrow C[m + 1]$; return $T$

Above, $\langle m \rangle$ denotes the $n$-bit binary representation of the integer $m$.

Show that $T$ is not UF-CMA-secure by presenting in pseudocode a practical adversary $A$ making at most 4 $\text{Tag}$ queries and achieving $\text{Adv}^{\text{uf-cma}}_{T}(A) = 1$. 

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Replay

Suppose Alice transmits \((M_1, T_1)\) to Bank where \(M_1 = \text{"Pay $100 to Bob"}\). Adversary

- Captures \((M_1, T_1)\)
- Keeps re-transmitting it to bank

Result: Bob gets $100, $200, $300,...

Our UF-CMA notion of security does not ask for protection against replay, because \(A\) will not win if it outputs \(M, T\) with \(M \in S\), even if \(T = T_K(M)\) is the correct tag.

**Question:** Why not?

**Answer:** Replay is best addressed as an add-on to standard message authentication.
Let $Time_A$ be the time as per Alice’s local clock and $Time_B$ the time as per Bob’s local clock.

- Alice sends $(M, T_K(M), Time_A)$
- Bob receives $(M, T, Time)$ and accepts iff $T = T_K(M)$ and $|Time_B - Time| \leq \Delta$ where $\Delta$ is a small threshold.

Does this work?
Preventing Replay Using Timestamps

Let $Time_A$ be the time as per Alice’s local clock and $Time_B$ the time as per Bob’s local clock.

- Alice sends $(M, T_K(M), Time_A)$
- Bob receives $(M, T, Time)$ and accepts iff $T = T_K(M)$ and $|Time_B - Time| \leq \Delta$ where $\Delta$ is a small threshold.

Does this work?

Obviously forgery is possible within a $\Delta$ interval. But the main problem is that $Time_A$ is not authenticated, so adversary can transmit

$$(M, T_K(M), Time_1), (M, T_K(M), Time_2), \ldots$$

for any times $Time_1, Time_2, \ldots$ of its choice, and Bob will accept.
Let $\text{Time}_A$ be the time as per Alice’s local clock and $\text{Time}_B$ the time as per Bob’s local clock.

- Alice sends $(M, T_K(M||\text{Time}_A), \text{Time}_A)$
- Bob receives $(M, T, \text{Time})$ and accepts iff $T_K(M||\text{Time}) = T$ and $|\text{Time}_B - \text{Time}| \leq \Delta$ where $\Delta$ is a small threshold.
Alice maintains a counter $ctr_A$ and Bob maintains a counter $ctr_B$. Initially both are zero.

- Alice sends $(M, T_K(M || ctr_A))$ and then increments $ctr_A$
- Bob receives $(M, T)$. If $T_K(M || ctr_B) = T$ then Bob accepts and increments $ctr_B$.

Counters need to stay synchronized.
Any PRF is a MAC

If $F$ is PRF-secure then it is also UF-CMA-secure:

**Theorem [GGM86,BKR96]:** Let $F : \{0, 1\}^k \times D \rightarrow \{0, 1\}^n$ be a family of functions. Let $A$ be a uf-cma adversary making $q$ Tag queries and having running time $t$. Then there is a prf-adversary $B$ such that

$$\text{Adv}_{F}^{\text{uf-cma}}(A) \leq \text{Adv}_{F}^{\text{prf}}(B) + \frac{2}{2^n}.$$ 

Adversary $B$ makes $q + 1$ queries to its $F_n$ oracle and has running time $t$ plus some overhead.

We do not prove this here, but we give a little intuition.
Intuition for why PRFs are UF-CMA-secure

1. Random functions make good (UF-CMA) MACs
2. PRFs are pretty much as good as random functions

For (1), suppose $F_n : D \rightarrow \{0, 1\}^n$ is random and consider $A$ who

- Can query $F_n$ at any points $x_1, \ldots, x_q \in D$ it likes
- To win, must output $x, T$ such that $x \notin \{x_1, \ldots, x_q\}$ but $T = F_n(x)$

Then,

$$\Pr[A \text{ wins}] =$$
Intuition for why PRFs are UF-CMA-secure

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For (1), suppose $F_n : D \rightarrow \{0, 1\}^n$ is random and consider $A$ who
   - Can query $F_n$ at any points $x_1, \ldots, x_q \in D$ it likes
   - To win, must output $x, T$ such that $x \not\in \{x_1, \ldots, x_q\}$ but $T = F_n(x)$

Then,

$$\Pr[A \text{ wins}] = \frac{1}{2^n}$$

because $A$ did not query $F_n(x)$. 
1. Random functions make good (UF-CMA) MACs
2. PRFs are pretty much as good as random functions

For (2), consider $A$ who

- Can query $F_K$ at any points $x_1, \ldots, x_q \in D$ it likes
- To win, must output $x, T$ such that $x \notin \{x_1, \ldots, x_q\}$ but $T = F_K(x)$

If $\Pr[A \text{ wins}]$ is significantly more then $2^{-n}$ then we are detecting a difference between $F_K$ and a random function.
A family of functions $F: \text{Keys} \times D \to R$ is

- **FIL (Fixed-input-length)** if $D = \{0, 1\}^\ell$ for some $\ell$
- **VIL (Variable-input-length)** if $D$ is a “large” set like $D = \{0, 1\}^*$ or $D = \{ M \in \{0, 1\}^* : 0 < |M| < n2^n \text{ and } |M| \mod n = 0 \}$ for some $n \geq 1$ or ...

We have families we are willing to assume are PRFs, namely blockciphers and compression functions, but they are FIL.

**PRF Domain Extension Problem:** Given a FIL PRF, construct a VIL PRF.
PRF Domain Extension Problem: Given a FIL PRF, construct a VIL PRF.

The basic CBC MAC is a candidate construction but we saw above that it fails to be UF-CMA and thus also fails to be a PRF. The exercise explored another solution that also failed.

We will see solutions that work including

- ECBC: The encrypted CBC-MAC
- HMAC: A highly standardized and used hash-function based MAC
Let $E : \{0, 1\}^k \times B \to B$ be a block cipher, where $B = \{0, 1\}^n$. The encrypted CBC (ECBC) MAC $T : \{0, 1\}^{2k} \times B^* \to B$ is defined by

**Alg $T_{K_{in}||K_{out}}(M)$**

$C[0] \leftarrow 0^n$

for $i = 1, \ldots, m$ do

$C[i] \leftarrow E_{K_{in}}(C[i - 1] \oplus M[i])$

$T \leftarrow E_{K_{out}}(C[m])$

return $T$
Birthday attacks on MACs

There is a large class of MACs, including ECBC MAC, HMAC, ... which are subject to a birthday attack that violates UF-CMA using about 
\( q \approx 2^{n/2} \) Tag queries, where \( n \) is the tag (output) length of the MAC.

Furthermore, we can typically show this is best possible, so the birthday bound is the “true” indication of security.

The class of MACs in question are called iterated-MACs and work by iterating some lower level primitive such as a blockcipher or compression function.
Exercise

Let $E : \{0, 1\}^k \times \{0, 1\}^n \rightarrow \{0, 1\}^n$ be a blockcipher and $T$ the corresponding ECBC MAC. Let $q \leq 2^{n/2}$.

Give an adversary $A$ that, via a birthday attack, achieves

$$\text{Adv}^{\text{uf-cma}}_T(A) = \Omega \left( \frac{q^2}{2^n} \right)$$

using $q$ Tag queries and running time $O(nq \cdot \log(nq))$. 
Birthday attack is best possible:

**Theorem:** Let $E : \{0, 1\}^k \times B \rightarrow B$ be a family of functions, where $B = \{0, 1\}^n$. Define $F : \{0, 1\}^{2k} \times B^* \rightarrow \{0, 1\}^n$ by

$$
\text{Alg } F_{K_{\text{in}} || K_{\text{out}}} (M) \\
C[0] \leftarrow 0^n \\
\text{for } i = 1, \ldots, m \text{ do } C[i] \leftarrow E_{K_{\text{in}}} (C[i-1] \oplus M[i]) \\
T \leftarrow E_{K_{\text{out}}} (C[m]); \text{ return } T
$$

Let $A$ be a prf-adversary against $F$ that makes at most $q$ oracle queries, these totalling at most $\sigma$ blocks, and has running time $t$. Then there is a prf-adversary $D$ against $E$ such that

$$
\text{Adv}^{\text{prf}}_F (A) \leq \text{Adv}^{\text{prf}}_E (D) + \frac{\sigma^2}{2^n}
$$

and $D$ makes at most $\sigma$ oracle queries and has running time about $t$. 

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The number $q$ of $m$-block messages that can be safely authenticated is about $2^{n/2}/m$, where $n$ is the block-length of the blockcipher, or the length of the chaining input of the compression function.

<table>
<thead>
<tr>
<th>MAC</th>
<th>$n$</th>
<th>$m$</th>
<th>$q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DES-ECBC-MAC</td>
<td>64</td>
<td>1024</td>
<td>$2^{22}$</td>
</tr>
<tr>
<td>AES-ECBC-MAC</td>
<td>128</td>
<td>1024</td>
<td>$2^{54}$</td>
</tr>
<tr>
<td>AES-ECBC-MAC</td>
<td>128</td>
<td>$10^6$</td>
<td>$2^{44}$</td>
</tr>
<tr>
<td>HMAC-SHA1</td>
<td>160</td>
<td>$10^6$</td>
<td>$2^{60}$</td>
</tr>
<tr>
<td>HMAC-SHA256</td>
<td>256</td>
<td>$10^6$</td>
<td>$2^{108}$</td>
</tr>
</tbody>
</table>

$m = 10^6$ means message length 16Mbytes when $n = 128$. 
The software speed of hash functions (MD5, SHA1) lead people in 1990s to ask whether they could be used to MAC.

But such cryptographic hash functions are keyless.

**Question:** How do we key hash functions to get MACs?

**Proposal:** Let $H : D \rightarrow \{0, 1\}^n$ represent the hash function and set

$$T_K(M) = H(K||M)$$

Is this UF-CMA / PRF secure?
Let $M'$ be $M \| \langle m+1 \rangle$. Then $H(K||M') = h(h(h(h(M[m] \langle m + 1 \rangle))))$ so given the MAC $H(K||M)$ of $M$ we can easily forge the MAC of $M'$. 

Exercise: Specify in pseudocode an adversary mounting the above attack to achieve $uf$-cma advantage 1 using 1 Tag query.
Let \( M' = M \| \langle m + 1 \rangle \). Then
\[
H(K \| M') = h(\langle m + 2 \rangle \| H(K \| M))
\]
so given the MAC \( H(K \| M) \) of \( M \) we can easily forge the MAC of \( M' \).

**Exercise:** Specify in pseudocode an adversary mounting the above attack to achieve uf-cma advantage 1 using 1 Tag query.
Suppose $H : D \rightarrow \{0, 1\}^{160}$ is the hash function. HMAC has a 160-bit key $K$. Let

$$K_o = \text{opad} \oplus K \parallel 0^{352} \text{ and } K_i = \text{ipad} \oplus K \parallel 0^{352}$$

where

$$\text{opad} = 5D \text{ and } \text{ipad} = 36$$

in HEX. Then

$$\text{HMAC}_K(M) = H(K_o \parallel H(K_i \parallel M))$$
Features:
- Blackbox use of the hash function, easy to implement
- Fast in software

Usage:
- As a MAC for message authentication
- As a PRF for key derivation

Security:
- Subject to a birthday attack
- Security proof shows there is no better attack [BCK96,Be06]

Adoption and Deployment: HMAC is one of the most widely standardized and used cryptographic constructs: SSL/TLS, SSH, IPSec, FIPS 198, IEEE 802.11, IEEE 802.11b, ...
HMAC Security

**Theorem:** [BCK96] HMAC is a secure PRF assuming

- The compression function is a PRF
- The hash function is collision-resistant (CR)

But attacks show MD5 and SHA1 are **not** CR.

So are HMAC-MD5 and HMAC-SHA1 secure?

- No attacks so far, but
- Proof becomes vacuous!

**Theorem:** [Be06] HMAC is a secure PRF assuming **only**

- The compression function is a PRF

Current attacks do not contradict this assumption. This result may explain why HMAC-MD5 and HMAC-SHA1 are standing even though the hash functions are broken with regard to collision resistance.
HMAC Recommendations

- Don’t use HMAC-MD5
- No immediate need to remove HMAC-SHA1
- Use HMAC-SHA256, HMAC-SHA512 for new applications