MAC.
SKE in Practice.
Lecture 5
Active Adversary
Active Adversary

An active adversary can inject messages into the channel
Active Adversary

- An active adversary can inject messages into the channel.
- Eve can send ciphertexts to Bob and get them decrypted.
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- Chosen Ciphertext Attack (CCA)
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If Bob decrypts all ciphertexts for Eve, no security possible
Active Adversary

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Chosen Ciphertext Attack (CCA)

If Bob decrypts all ciphertexts for Eve, no security possible

What can Bob do?
Symmetric-Key Encryption

SIM-CCA Security

\[ \forall x \exists y \text{ s.t. } \forall z \]
Symmetric-Key Encryption

SIM-CCA Security

**SIM-CCA Security**

∀ s.t.

∀

Key/Enc

Key/Dec

Send

Recv

Env

REAL

IDEAL

REAL ≈ IDEAL

Invalid ciphertexts are silently ignored

RECALL
Symmetric-Key Encryption

SIM-CCA Security

RECALL

SIM-CCA secure if:
∀ ∃ s.t. ∀

REAL ≈ IDEAL
Symmetric-Key Encryption

SIM-CCA Security

Alternately (slightly weaker form): Adv can send its own messages

\[
\text{SIM-CCA secure if: } \forall \exists \text{ s.t. } \forall 
\]

REAL \approx IDEAL
Symmetric-Key Encryption

IND-CCA Security

Experiment picks $b \leftarrow \{0,1\}$ and $K \leftarrow \text{KeyGen}$

Adv gets (guarded) access to $\text{Dec}_K$ oracle

For as long as Adversary wants

- Adv sends two messages $m_0, m_1$ to the experiment
- Expt returns $\text{Enc}(m_b, K)$ to the adversary

Adversary returns a guess $b'$

Experiments outputs 1 iff $b' = b$

IND-CCA secure if for all feasible adversaries $\Pr[b' = b] \approx 1/2$
IND-CCA Security

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Adversary returns a guess $b'$

Experiments outputs 1 iff $b' = b$

IND-CCA secure if for all feasible adversaries $\Pr[b' = b] \approx 1/2$

IND-CCA + \~correctness equivalent to SIM-CCA
CCA Security
CCA Security

How to obtain CCA security?
CCA Security

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Use a CPA-secure encryption scheme, but make sure Bob “accepts” and decrypts only ciphertexts produced by Alice.
CCA Security

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  i.e., Eve can't create new ciphertexts that will be accepted by Bob.
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Achieves the stronger guarantee: in IDEAL, Eve can’t send its own messages to Bob.
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MAC: Message Authentication Code
Message Authentication Codes
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A single short key shared by Alice and Bob
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- Can sign any (polynomial) number of messages
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Message Authentication Codes

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  - Correctness: For all $K$ from KeyGen, and all messages $M$, $\text{Verify}_K(M, \text{MAC}_K(M)) = 1$
Message Authentication Codes

- A single short key shared by Alice and Bob
- Can sign any (polynomial) number of messages
- A triple (KeyGen, MAC, Verify)
- Correctness: For all K from KeyGen, and all messages M, Verify\textsubscript{K}(M,MAC\textsubscript{K}(M))=1
- Security: probability that an adversary can produce (M,s) s.t. Verify\textsubscript{K}(M,s)=1 is negligible unless Alice produced an output s=MAC\textsubscript{K}(M)

\[
\text{Advantage} = \Pr[ \text{Verify}_K(M,s)=1 \text{ and } (M,s) \notin \{(M_i,s_i)\} ]
\]
CCA Secure SKE
CCA Secure SKE

\[ \text{CCA-Enc}_{K_1,K_2}(m) = ( c := \text{CPA-Enc}_{K_1}(m), \ t := \text{MAC}_{K_2}(c) ) \]
CCA Secure SKE

\[ CCA-\text{Enc}_{K_1,K_2}(m) = ( c := CPA-\text{Enc}_{K_1}(m), t := MAC_{K_2}(c) ) \]

CPA secure encryption: Block-cipher/CTR mode construction
CCA Secure SKE

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- CPA secure encryption: Block-cipher/CTR mode construction
- MAC: from a PRF or Block-Cipher (coming up)
CCA Secure SKE

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- SKE in practice can just use Block-Ciphers (coming up)
CCA Secure SKE

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- CPA secure encryption: Block-cipher/CTR mode construction
- MAC: from a PRF or Block-Cipher (coming up)
- SKE in practice can just use Block-Ciphers (coming up)
- In principle, constructions (less efficient) possible based on any One-Way Permutation or even any One-Way Function
Making a MAC
One-time MAC
One-time MAC

To sign a single n bit message
One-time MAC

- To sign a single n bit message
- A simple (but inefficient) scheme
One-time MAC

- To sign a single n bit message
- A simple (but inefficient) scheme
- Shared secret key: \(2n\) random strings (each k-bit long) \((r^i_0, r^i_1)_{i=1..n}\)
One-time MAC

To sign a single n bit message

A simple (but inefficient) scheme

Shared secret key: 2n random strings (each k-bit long) \((r_{i0}, r_{i1})_{i=1..n}\)
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Signature for \(m_1...m_n\) be \((r_{mi})_{i=1..n}\)
To sign a single $n$ bit message

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Negligible probability that Eve can produce a signature on $m' \neq m$
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Doesn't require any computational restrictions on adversary!
One-time MAC

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Signature for \(m_1...m_n\) be \((r_{mi}^i)_{i=1..n}\)

Negligible probability that Eve can produce a signature on \(m'\neq m\)

Doesn’t require any computational restrictions on adversary!

More efficient one-time MACs exist (later)
(Multi-msg) MAC from PRF
When Each Message is a Single Block
(Multi-msg) MAC from PRF
When Each Message is a Single Block

PRF is a MAC!
(Multi-msg) MAC from PRF
When Each Message is a Single Block

PRF is a MAC!

MAC_K(M) := F_K(M) where F is a PRF
(Multi-msg) MAC from PRF

When Each Message is a Single Block

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$\text{MAC}_K(M) := F_K(M)$ where $F$ is a PRF
(Multi-msg) MAC from PRF

When Each Message is a Single Block

PRF is a MAC!

\[ \text{MAC}_K(M) := F_K(M) \] where F is a PRF

\[ \text{Ver}_K(M,S) := 1 \text{ iff } S=F_K(M) \]
(Multi-msg) MAC from PRF

When Each Message is a Single Block

- PRF is a MAC!
- $\text{MAC}_K(M) := F_K(M)$ where $F$ is a PRF
- $\text{Ver}_K(M,S) := 1$ iff $S = F_K(M)$
- Output length of $F_K$ should be big enough
(Multi-msg) MAC from PRF
When Each Message is a Single Block

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\[ \text{MAC}_K(M) := F_K(M) \text{ where } F \text{ is a PRF} \]

\[ \text{Ver}_K(M,S) := 1 \text{ iff } S = F_K(M) \]

Output length of \( F_K \) should be big enough

If an adversary forges MAC with probability \( \epsilon_{MAC} \),
then can break PRF with advantage \( O(\epsilon_{MAC} - 2^{-m(k)}) \)

\( m(k) \) being the output length of the PRF) [How?]
(Multi-msg) MAC from PRF

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$MAC_K(M) := F_K(M)$ where $F$ is a PRF

$Ver_K(M, S) := 1$ iff $S = F_K(M)$

Output length of $F_K$ should be big enough

If an adversary forges MAC with probability $\varepsilon_{MAC}$, then can break PRF with advantage $O(\varepsilon_{MAC} - 2^{-m(k)})$ (m(k) being the output length of the PRF) [How?]
(Multi-msg) MAC from PRF

When Each Message is a Single Block

PRF is a MAC!

- $\text{MAC}_K(M) := F_K(M)$ where $F$ is a PRF
- $\text{Ver}_K(M, S) := 1$ iff $S = F_K(M)$

Output length of $F_K$ should be big enough

If an adversary forges MAC with probability $\varepsilon_{\text{MAC}}$, then can break PRF with advantage $O(\varepsilon_{\text{MAC}} - 2^{-m(k)})$  
($m(k)$ being the output length of the PRF) [How?]

- If random function $R$ used as MAC, then probability of forgery, $\varepsilon_{\text{MAC}}^* = 2^{-m(k)}$

Advantage in breaking a PRF $F$: diff in prob a test has of outputting 1, when given $F$ vs. truly random $R$
MAC for Multiple-Block Messages
MAC for Multiple-Block Messages

What if message is longer than one block?
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MAC’ing each block separately is not secure (unlike in the case of CPA secure encryption)
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Could use a PRF that takes longer inputs
What if message is longer than one block?

MAC’ing each block separately is not secure (unlike in the case of CPA secure encryption)

Eve can rearrange the blocks/drop some blocks

Could use a PRF that takes longer inputs

Can we use a PRF with a fixed block-length (i.e., a block cipher)?
MAC for Multiple-Block Messages
MAC for Multiple-Block Messages

A simple solution: “tie the blocks together”
MAC for Multiple-Block Messages

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Add to each block a random string r (same r for all blocks), total number of blocks, and a sequence number
MAC for Multiple-Block Messages

- A simple solution: “tie the blocks together”

- Add to each block a random string $r$ (same $r$ for all blocks), total number of blocks, and a sequence number

  $B_i = (r, t, i, M_i)$
MAC for Multiple-Block Messages

A simple solution: “tie the blocks together”

- Add to each block a random string \( r \) (same \( r \) for all blocks), total number of blocks, and a sequence number

\[
B_i = (r, t, i, M_i)
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\[
MAC(M) = (r, (MAC(B_i))_{i=1..t})
\]
MAC for Multiple-Block Messages

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$r$ prevents mixing blocks from two messages, $t$ prevents dropping blocks and $i$ prevents rearranging
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Inefficient! Tag length increases with message length
CBC-MAC
CBC-MAC

PRF domain extension: Chaining the blocks
CBC-MAC

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cf. CBC mode for encryption (which is not a MAC!)
**CBC-MAC**

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- t-block messages, a single block tag
CBC-MAC

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Can be shown to be secure
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- If restricted to t-block messages (i.e., same length)
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- cf. CBC mode for encryption (which is not a MAC!)
- t-block messages, a single block tag
- Can be shown to be secure
  - If restricted to t-block messages (i.e., same length)
  - Else attacks possible (by extending a previously signed message)
Patching CBC-MAC
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Patching CBC MAC to handle message of any (polynomial) length but still producing a single block tag (secure if block-cipher is):
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Derive $K$ as $F_{K'}(t)$, where $t$ is the number of blocks
Patching CBC-MAC

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- Derive $K$ as $F_{K'}(t)$, where $t$ is the number of blocks
- Use first block to specify number of blocks
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  - **EMAC**: Output not the last tag $T$, but $F_{K'}(T)$, where $K'$ is an independent key (after padding the message to an integral number of blocks). No need to know message length a priori.
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CMAC: XOR last block with another key (derived from the original key using the block-cipher). Avoids padding when message is integral number of blocks.
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NIST Recommendation. 2005
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Later: Hash-based HMAC used in TLS and IPSec

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NIST Recommendation. 2005

IETF Standard. 1997
SKE in Practice
Stream Ciphers
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- Used for one-time encryption
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- RC4, eSTREAM portfolio, ...
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Also used to denote the random nonce chosen for encryption using a block-cipher
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In practice, stream ciphers take a key and an “IV” (for initialization vector) as inputs

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  - Heuristic goal: behave somewhat like a PRF (instead of a PRG) so that it can be used for multi-message encryption
  - But often breaks if used this way
- NIST Standard: For multi-message encryption, use a block-cipher in CTR mode

Also used to denote the random nonce chosen for encryption using a block-cipher.
Block Ciphers
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- DES, 3DES, Blowfish, AES, ...
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- Heuristic constructions
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Block Ciphers

- DES, 3DES, Blowfish, AES, ...
- Heuristic constructions
- Permutations that can be inverted with the key
- Speed (hardware/software) is of the essence
- But should withstand known attacks
- As a PRP (or at least, against key recovery)
Feistel Network
Feistel Network

Building a permutation from a (block) function
Feistel Network

Building a permutation from a (block) function

Let \( f: \{0,1\}^m \rightarrow \{0,1\}^m \) be an arbitrary function
Feistel Network

Building a permutation from a (block) function

Let $f: \{0,1\}^m \rightarrow \{0,1\}^m$ be an arbitrary function

$F_f: \{0,1\}^{2m} \rightarrow \{0,1\}^{2m}$ defined as $F_f(x,y) = (y, x \oplus f(y))$
Feistel Network

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$F_f$ is a permutation (Why?)
Feistel Network

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\( F_f \) is a permutation (Why?)

Can invert (How?)

Given functions \( f_1, \ldots, f_t \) can build a \( t \)-layer Feistel network \( F_{f_1 \ldots f_t} \)
Building a permutation from a (block) function

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**Feistel Network**

- Building a permutation from a (block) function
- Let \( f: \{0,1\}^m \rightarrow \{0,1\}^m \) be an arbitrary function
- \( F_f: \{0,1\}^{2m} \rightarrow \{0,1\}^{2m} \) defined as \( F_f(x,y) = (y, x \oplus f(y)) \)
- \( F_f \) is a permutation (Why?)
- Can invert (How?)
- Given functions \( f_1, \ldots, f_t \) can build a \( t \)-layer Feistel network \( F_{f_1 \ldots f_t} \)
- Still a permutation from \( \{0,1\}^{2m} \) to \( \{0,1\}^{2m} \)
Feistel Network

Building a permutation from a (block) function

Let \( f: \{0,1\}^m \rightarrow \{0,1\}^m \) be an arbitrary function

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**Luby-Rackoff**: A 3-layer Feistel network, in which 3 PRFs with independent seeds are the 3 round functions, is a PRP. A 4-layer Feistel gives a strong PRP
Feistel Network

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**Luby-Rackoff**: A 3-layer Feistel network, in which 3 PRFs with independent seeds are the 3 round functions, is a PRP. A 4-layer Feistel gives a strong PRP

Fewer layers do not suffice! [Exercise]
DES Block Cipher
DES Block Cipher

NIST Standard. 1976

Data Encryption Standard (DES), Triple-DES, DES-X
DES Block Cipher

- Data Encryption Standard (DES), Triple-DES, DES-X
- DES uses a 16-layer Feistel network (and a few other steps)

NIST Standard. 1976
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  - The round functions are not PRFs, but ad hoc
DES Block Cipher

- Data Encryption Standard (DES), Triple-DES, DES-X
- DES uses a 16-layer Feistel network (and a few other steps)
  - The round functions are not PRFs, but ad hoc
  - "Confuse and diffuse"

NIST Standard. 1976
**DES Block Cipher**

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- Triple DES: 3 successive applications of DES (or DES⁻¹) with 3 keys

NIST Standard. 1976
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NIST Standard. 2001
AES Crib Sheet
(Handy for memorizing)

General Math

Key Expansion: Round Constants

Mix Columns:

Inverse Mix

Ciphertext

S-Box (SRD)

SRD[a] = f(g(a))
g(a) = a^(-1) mod m(x)

Think 53^T + 63^T

5 is and 3 0's [0110 0011]^T

Prev Col + Col from previous round key
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    - Meet-in-the-middle, linear cryptanalysis, differential cryptanalysis, impossible differential cryptanalysis, boomerang attack, integral cryptanalysis, cube attack, ...
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Doing encryption + authentication better
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Generic composition: encrypt, then MAC
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AE with Associated Data: Allows unencrypted (but authenticated) parts of the plaintext, for headers etc.
SKE today
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  - e.g. RC4 in BitTorrent, Skype, PDF