Applied Cryptography and Computer Security
CSE 664 Spring 2017

Lecture 8: Data Integrity

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Overview

- **Going back to the security objectives cryptography helps to achieve:**
  - **confidentiality**
  - **integrity**
  - **authentication**
    - **entity authentication**
    - **data authentication**
  - **access control**
  - **non-repudiability**
- **We'll discuss the integrity objective next (in the symmetric key setting)**

Data Integrity

- **Encryption does not protect data from modification by another party**
  - **recall the modes of encryption we talked about**
- **We normally want to ensure that the data arrives in its original form**
  - **i.e., we want data integrity**
- **How can we do that?**
  - **attach a verification tag?**
  - **how can we make sure that an adversary cannot compute the tag for messages of its choice?**

Data Integrity

- **This means that we also want to ensure that data comes from an authenticated source**
  - **i.e., we want data origin authentication**
- **We'll use message authentication codes (MAC)**
  - **a secret key is shared by two communicating parties**
  - **a MAC cannot be computed (or verified) without the key**
- **To achieve source authentication and message integrity:**
  - **the sender computes** $t = \mathsf{MAC}_k(m)$ **and sends** (m, t)
  - **the receiver recomputes** $t' = \mathsf{MAC}_k(m)$ **for received** m **and compares it to** t

Message Authentication Codes

- **Formally, a message authentication code is composed of PPT algorithms** (Gen, Mac, Vrfy) **s.t.:**

  1. **key generation algorithm** Gen**, on input a security parameter 1^n, outputs a key k, where $|k| \geq n$.**
  2. **tag generation algorithm** Mac**, on input a key k and message $m \in \{0, 1\}^*$, outputs a tag t, i.e., $t \leftarrow \mathsf{Mac}_k(m)$**
  3. **verification algorithm** Vrfy**, on input a key k, a message m, and a tag t, outputs a bit b, where $b = 1$ means the tag is valid and $b = 0$ means it is invalid, i.e., $b := \mathsf{Vrfy}_k(m, t)$**

MAC

- **What properties do we want?**
  - **correctness**
    - **?**
  - **security**
    - **someone without the key shouldn't be able to forge a MAC on a message**
    - **given pairs $(m_i, \mathsf{Mac}_k(m_i))$, computing a new pair $(m, \mathsf{Mac}_k(m))$ such that $m \neq m_i$ should be hard**

MAC

- **Classification of attacks on MACs:**
  - **known-text attack: one or more pairs $(m_i, \mathsf{Mac}_k(m_i))$ are available**
  - **chosen-text attack: one of more pairs $(m_i, \mathsf{Mac}_k(m_i))$ are available for m_i's chosen by the adversary**
  - **adaptive chosen-text attack: the m_i's are chosen by the adversary, where successive choices can be based on the results of prior queries**
- **Which one do we want?**

MAC

- **Classification of forgeries:**
  - **selective forgery: an adversary is able to produce a new MAC pair for a message under her control**
  - **existential forgery: an adversary is able to produce a new MAC pair but with no control of the value of the message**
- **Which would we prefer??**
- **And, as usual, key recovery is the most damaging attack on MAC**

MAC Security

- We construct an experiment for MACs **existentially unforgeable under an adaptive chosen-message attack**
- Let $\Pi = (\mathsf{Gen}, \mathsf{Mac}, \mathsf{Vrfy})$ be a message authentication code
- **Message authentication experiment** $\mathsf{Mac\text{-}forge}_{\mathcal{A},\Pi}(n)$:
  1. generate $k \leftarrow \mathsf{Gen}(1^n)$
  2. adversary $\mathcal{A}$ is given 1^n and oracle access to $\mathsf{Mac}_k(\cdot)$; let Q denote the set of queries $\mathcal{A}$ makes to the oracle
  3. $\mathcal{A}$ eventually outputs a pair (m, t)
  4. output 1 ($\mathcal{A}$ wins) iff (a) $\mathsf{Vrfy}_k(m, t) = 1$ and (b) $m \notin Q$

MAC Security

- **Definition: A message authentication code $\Pi = (\mathsf{Gen}, \mathsf{Mac}, \mathsf{Vrfy})$ is secure if any PPT adversary $\mathcal{A}$ has at most negligible probability of suceeding in the above experiment, i.e.,**

$$\Pr[\mathsf{Mac\text{-}forge}_{\Pi,\mathcal{A}}(n) = 1] \leq \mathsf{negl}(n)$$

- **Important: MACs do not prevent all traffic injections (e.g., replay attacks)**
  - **a replayed message will pass verification process**
  - **addressing this problem by MACs only cannot be done and is left to the application**
    - **use sequence numbers or time-stamps to make each message unique**

Constructing Message Authentication Codes

- **We can use pseudo-random functions for constructing fixed-length MACs**
  - **let** $F : \{0,1\}^n \times \{0,1\}^n \to \{0,1\}^n$ **be a pseudo-random function**
- **MAC construction (for security parameter** n**):**
  - Gen**: on input** 1^n**, choose** $k \stackrel{R}{\leftarrow} \{0,1\}^n$
  - Mac**: on input key** $k \in \{0,1\}^n$ **and message** $m \in \{0,1\}^n$**, output tag** $t := F_k(m)$
  - Vrfy**: on input key** $k \in \{0,1\}^n$**, message** $m \in \{0,1\}^n$**, and tag** $t \in \{0,1\}^n$**, output 1 if and only if** $t = F_k(m)$**; and output 0 otherwise**

Constructing Message Authentication Codes

- **Security of our MAC construction:**
  - **Theorem:** **assuming that F is a pseudo-random function, the above fixed-length MAC construction is secure (existentially unforgeable under an adaptive chosen-message attack)**
  - **Proof intuition**
    - **as before, first substitute the pseudo-random object with a truly random**
    - **what is the probability that the output of random function can be predicted on a "new point"?**
    - **what is the "difference" between pseudo-random and random functions?**

Variable-Length MACs

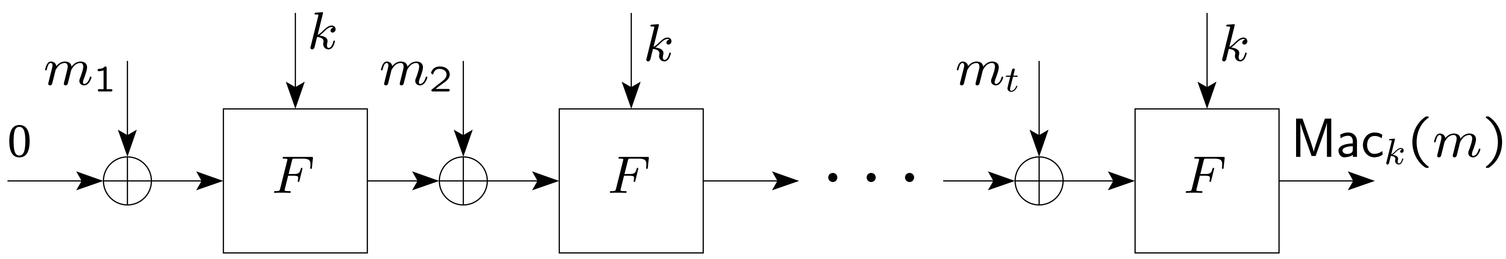
- Now how do we authenticate messages longer than n bits?
  - can partition a message into n-bit blocks
  - authenticate each block separately?
  - combine all messages into a single block?
- It is possible to construct secure MACs using only pseudo-random functions
  - must sequentially tie all blocks together
  - must ensure that tag forging based on message length is not possible

Variable-Length MACs

- MAC algorithms widely used in practice use chaining:
  - CBC-MAC (based on a block cipher)
  - HMAC (based on a hash function)
- They produce only one n-bit tag for messages of any length
  - specifically were designed to be efficient

MAC Algorithms

- **CBC-MAC**
  - **DES in the cipher block chaining (CBC) mode has been a widely used MAC algorithm (FIPS 113 and ANSI standard X9.17)**
  - **uses the initialization vector 0**
  - **last block is used as the MAC**



CBC-MAC

- **Security of CBC-MAC**
  - **random IV is not used, it is set to constant 0^n**
  - **CBC-MAC is secure for messages of a fixed number of t blocks**
- **Compare this with CBC mode of encryption**
  - **random IV was necessary in encryption to prevent a codebook attack**
  - **random IV in a MAC construction gives room to tampering**
  - **all ciphertext blocks are necessary for decryption**
  - **using all ciphertext blocks as a MAC tag results in an insecure construction**

CBC-MAC

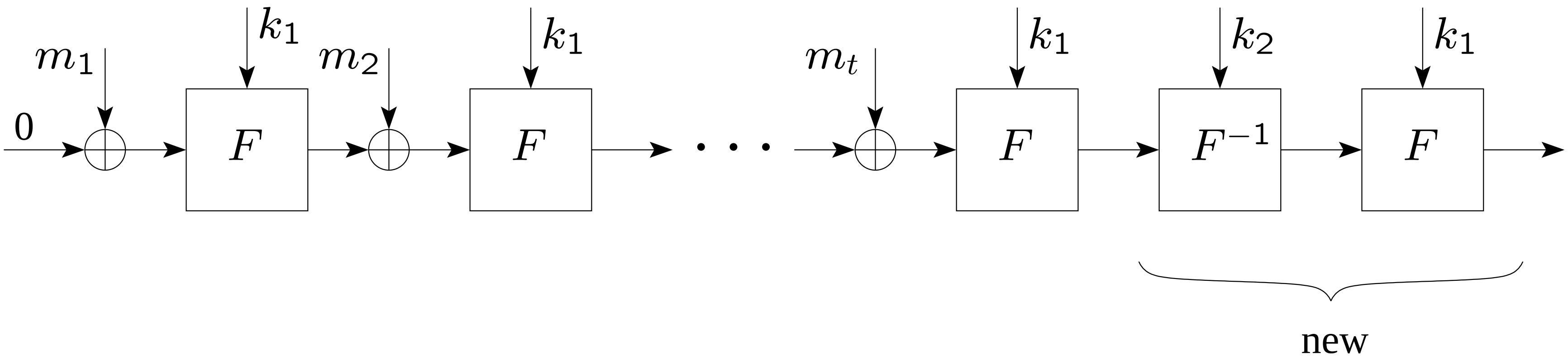
- **If the number of blocks can vary, (adaptive chosen-text) existential forgery is possible**
  - **assume the adversary obtains a message-MAC pair** (m_1, t_1)
  - **the adversary queries a MAC for** $m_2 = t_1$ **and obtains** (m_2, t_2)
  - **then** $t_2 = F_k(F_k(m_1))$ **and is the MAC for the 2-block message** $(m_1||0)$

CBC-MAC

- **Another example of forgery in CBC-MAC**
  - assume we have two pairs (m_1, t_1) and (m_2, t_2) for one-block messages m_1 and m_2
  - we request the MAC on a 2-block third message $m_3 = (m_1||z)$ and obtain $((m_1||z), t_3)$
  - then $t_1 = F_k(x_1)$, $t_2 = F_k(x_2)$, and $t_3 = F_k(t_1 \oplus z)$
  - we are able to construct the MAC for the new 2-block message $m_4 = m_2||(t_1 \oplus z \oplus t_2)$; it is also t_3
- **The fix: do MAC strengthening**

CBC-MAC

- **One possibility of CBC-MAC strengthening:**



  - **this prevents the forgery without impacting the intermediate stages**
  - **(it also reduces the threat of exhaustive key search)**
  - **we can derive k_1 and k_2 from k as $k_1 = F_k(1)$ and $k_2 = F_k(2)$**

CBC-MAC

- Other solutions are possible as well:
  1. prepend the input with a length block before the MAC computation
     - it is important that this block is not at the end
  2. create a length-dependent key from k
     - if ℓ is the number of blocks, first compute a new key as $k_\ell = F_k(\ell)$
     - use k_ℓ to produce the authentication tag
  3. …

MAC Algorithms

- The next construction is HMAC
  - requires knowledge of hash functions
  - we'll look at cryptographic hash functions next
- To summarize what we've learned so far:
  - integrity is a separate security goal that requires tools designed for it
  - integrity or message authentication can be achieved using pseudo-random functions
  - CBC-MAC and HMAC are used in practice
- The key used for integrity protection must differ from the key used for confidentiality protection