Crypto for Integrity

CS 181S

Fall 2020

Protection of integrity

- **Threat:** attacker who controls the network
  - Dolev-Yao model: attacker can read, modify, delete messages
- **Vulnerability:** communication channel between sender and receiver can be controlled by other principals
- **Harm:** information contained in messages can be changed by attacker (violating integrity)
- **Countermeasure:** more crypto

Encryption and integrity

Encryption and integrity

NO!

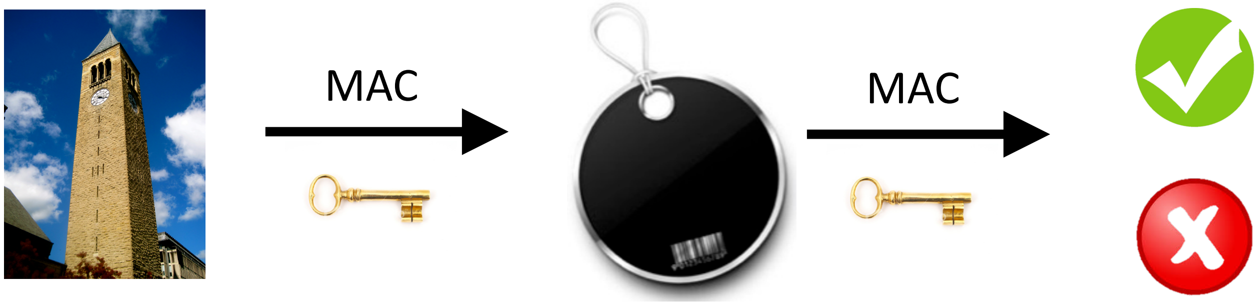
- Plaintext block might be random number, and recipient has no way to detect change in random number
- Attacker might substitute ciphertext from another execution of same protocol (replay)
- Adversary can modify encrypted plaintext in predictable ways (malleability)

Malleable Ciphertexts

- AES-CBC
  - Adversary can truncate blocks from end of message
- AES-CTR
  - Flipping bits of plaintext flips bits of ciphertext
- RSA
  - Adversary can multiply message

MAC algorithms

- $\text{Gen}(1^n)$: generate a **key** k of length n
- $\text{MAC}(m; k)$: produce a **tag** t for message m
- $\text{Verify}(m, t; k)$: returns 1 if m was the message used to generate t and 0 otherwise



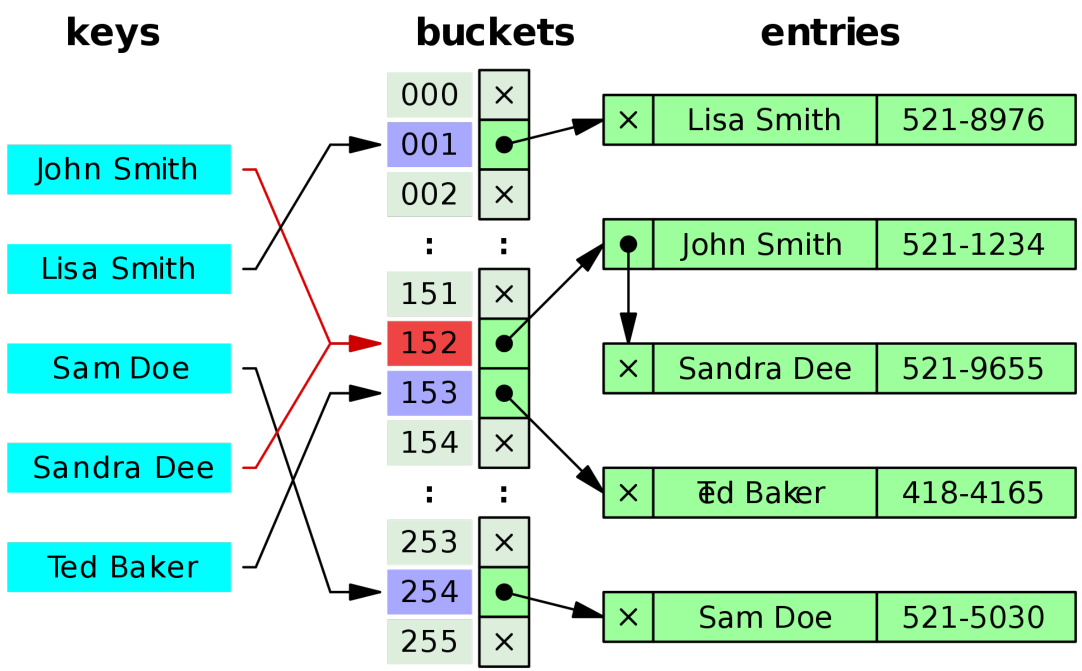
- A MAC is **correct** if the tags produced by MAC are valid, ie, $\text{Verify}(m, \text{MAC}(m, t; k))$ evaluates to 1
- A MAC is **secure** if it is hard for a PPT algorithm to forge a valid tag without the key

Real-world MACs

- CBC-MAC
  - Parameterized on a block cipher
  - Core idea: encrypt message with block cipher in CBC mode, use very last ciphertext block as the tag
- HMAC
  - Parameterized on a hash function
  - Core idea: hash message together with key
  - Your everyday hash function isn't good enough...

Hash functions

- Input: arbitrary size bit string
- Output: fixed size bit string
  - **compression**: size of the output is smaller than the input
  - **diffusion:** minimize collisions (and clustering)



Cryptographic hash functions

- Stronger requirements than (plain old) hash functions
- **Goal:** hash is compact representation of original like a
  - Hard to find 2 people with same fingerprint
  - Whether you get to pick pairs of people, or whether you start with one person and find another

    ...**collision-resistant**
  - Given person easy to get fingerprint
  - Given fingerprint hard to find person

    ...**one-way**

Real-world hash functions

- **MD5:** Ron Rivest (1991)
  - 128 bit output
  - Collision resistance broken 2004-8
  - Can now find collisions in seconds
  - Don't use it

- **SHA-1:** NSA (1995)
  - 160 bit output
  - Theoretical attacks that reduce strength to less than 80 bits
  - As of 2017, “practical attack” on PDFs: https://shattered.io/
  - Industry has been deprecating SHA-1 over the couple years

Real world hash functions

- **SHA-2:** NSA (2001)
  - Family of algorithms with output sizes {224, 256, 385, 512}
  - In principle, could one day be vulnerable to similar attacks as SHA-1

- **SHA-3:** public competition (won in 2012, standardized by NIST in 2015)
  - Same output sizes as SHA-2
  - Plus a variable-length output called SHAKE

Exercise 1: MACs

- Consider a hash function f that breaks a value into 4-byte blocks and returns the xor of these blocks. Would this function make a good HMAC? Why or why not?

1. **compression**
2. **diffusion**
3. **collision-resistant**
4. **one-way**

Exercise 1: MACs

- Consider a hash function f that breaks a value into 4-byte blocks and returns the xor of these blocks. Would this function make a good HMAC? Why or why not?

1. compression 
2. diffusion 
3. collision-resistant 
4. one-way 

Encrypt and MAC

```
0. k_E = Gen_E(len)
   k_M = Gen_M(len)
1. A: c = Enc(m; k_E)
      t = MAC(m; k_M)
2. A -> B: c, t
3. B: m' = Dec(c; k_E)
      t' = MAC(m'; k_M)
      if t = t'
        then output m'
        else abort
```

m

c

t

Encrypt and MAC

- **Pro:** can compute Enc and MAC in parallel
- **Con:** MAC must protect confidentiality

- Example: **`ssh`** (Secure Shell) protocol
  - recommends AES-128-CBC for encryption
  - recommends HMAC with SHA-2 for MAC

Encrypt then MAC

```
1. A: c = Enc(m; k_E)
      t = MAC(c; k_M)
2. A -> B: c, t
3. B: t' = MAC(c; k_M)
      if t = t'
        then output Dec(c; k_E)
        else abort
```

m

c

t

Encrypt then MAC

- **Pro:** provably most secure of three options [Bellare & Namprepre 2001]
- **Pro:** don't have to decrypt if MAC fails
  - resist DoS

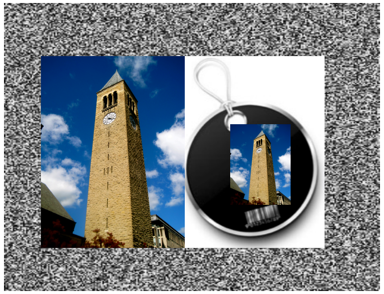
- Example: IPsec (Internet Protocol Security)
  - recommends AES-CBC for encryption and HMAC-SHA1 for MAC, among others
  - or AES-GCM

MAC then encrypt

```
1. A: t = MAC(m; k_M)
      c = Enc(m,t; k_E)
2. A -> B: c
3. B: m',t' = Dec(c; k_E)
      if t' = MAC(m'; k_M)
         then output m'
         else abort
```

m

c



MAC then encrypt

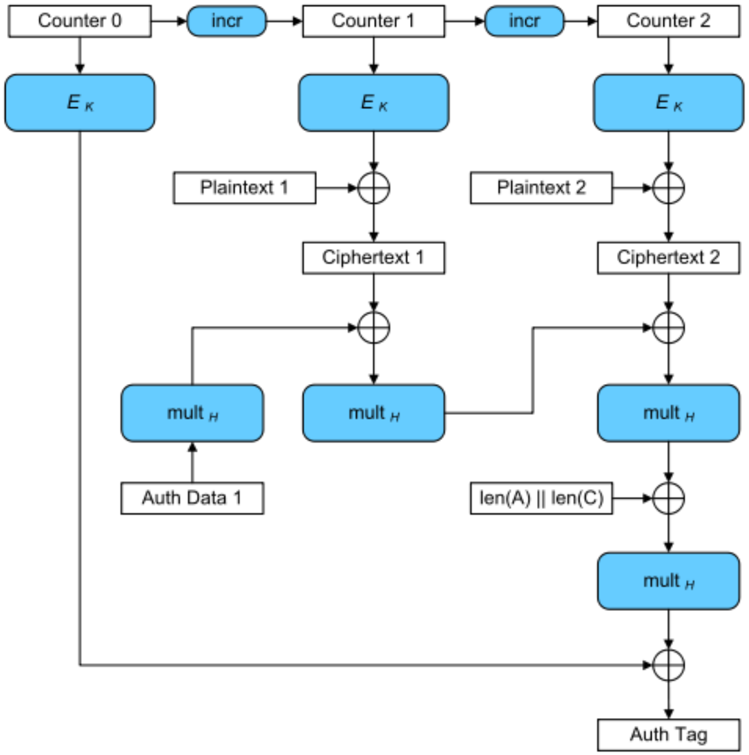
- **Pro:** provably next most secure
  - and just as secure as Encrypt-then-MAC for strong enough MAC schemes
  - HMAC and CBC-MAC are strong enough
- Example: SSL (Secure Sockets Layer)
  - Many options for encryption, e.g. AES-128-CBC
  - For MAC, standard is HMAC with many options for hash, e.g. SHA-256

Aside: Key reuse

- Never use same key for both encryption and MAC schemes
- **Principle:** every key in system should have unique purpose

Authenticated encryption

- Newer block cipher modes designed to provide confidentiality and integrity
  - **OCB:** Offset Codebook Mode
  - **CCM:** Counter with CBC-MAC Mode
  - **GCM:** Galois Counter Mode



DIGITAL SIGNATURES

Recall: Key pairs

- Instead of sharing a key between pairs of principals...
- ...every principal has a pair of keys
  - **public key:** published for the world to see
  - **private key:** kept secret and never shared

Key pair terminology

	Encryption	Digital Signatures
Public key	Encryption key	Verification key
Private key	Decryption key	Signing key

Digital Signatures

- $\mathrm{Gen}(1^n)$: generate a **keypair** (pk, sk) of length n
- $\mathrm{Sign}(m; sk)$: produce a **signature** σ for message m
- $\mathrm{Verify}(m, \sigma; pk)$: returns 1 if m was the message used to generate σ and 0 otherwise

- A digital signature scheme is **correct** if $\mathrm{Verify}(m, \mathrm{Sign}(m, t; sk); \mathrm{pk})$ evaluates to 1
- A digital signature is **secure** if it is hard for a PPT algorithm to forge a valid signature without sk

RSA

- Core ideas are the same as RSA encryption, but backward
- Intuition: "RSA sign = encrypt with private key"
- Gen(len):
  - Pick primes p, q, define $n = p \cdot q$
  - Choose e, d such that $ed = 1 \bmod (p-1)(q-1)$
  - $pk = (n, e), \;\; sk = (p, q, d)$
- Sign(m; sk)

$$\sigma = m^d \bmod n$$

- Verify(m, σ; pk):

$$m == \sigma^e \bmod n$$

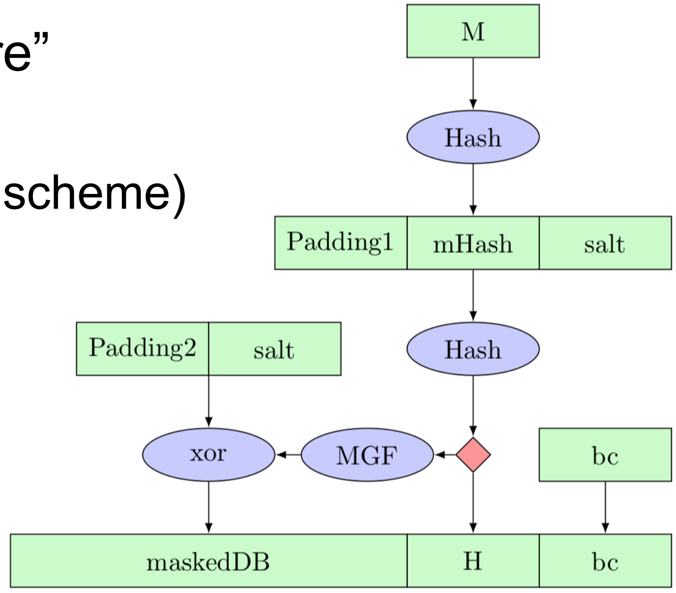
Exercise 2: Forging Signatures

- Assume that an adversary convinces Alice to sign two messages m_1 and m_2 with the same key, producing signatures σ_1 and σ_2. How could this adversary forge a signed message with the value $m_1 m_2$?

$$\begin{aligned}
\mathrm{Sign}(m_1 m_2) &= (m_1 m_2)^d \bmod n \\
&= m_1^d m_2^d \bmod n \\
&= (m_1^d \bmod n)(m_2^d \bmod n) \bmod n \\
&= \sigma_1 \sigma_2 \bmod n
\end{aligned}$$

RSA

- Core ideas are the same as RSA encryption
- Intuition: "RSA sign = encrypt with private key"
- Truth (in real world, outside of textbooks):
  - there's a core RSA function R that works with either pk or sk
  - RSA encrypt = do some prep work on m then call R with pk
  - RSA sign = do **different** prep work on m then call R with sk
  - Prep work: recall "textbook RSA is insecure"
    - (For encryption: OAEP)
    - For signatures: PSS (probabilistic signature scheme)
  - Also need to handle long messages…



Signatures with hashing

```
1. A: s = Sign(H(m); k_A)
2. A -> B: m, s
3. B: accept if Ver(H(m); s; K_A)
```

DSA

DSA: Digital Signature Algorithm [Kravitz 1991]

- Standardized by NIST and made available royalty-free in 1991/1993
- Used for decades without any serious attacks
- Closely related to Elgamal encryption
- Usual implemented with elliptic curve (ECDSA)

Blind signatures

[Chaum 1983]

- Purpose: signer doesn't know what they are signing
- Two additional algorithms: Blind and Unblind
- Unblind(Sign(Blind(m); k)) = Sign(m; k)
- Uses: e-cash, e-voting

Group signatures

[Chaum and van Heyst 1991]

- Purpose: one member of group signs anonymously on behalf of group
- Introduces a *group manager* who controls membership
- Two new protocols: Join and Revoke, to manage membership
- One new algorithm: Open, which manager can run to reveal who signed a message

Exercise 3: Feedback

1. Rate how well you think this recorded lecture worked
    1. Better than an in-person class
    2. About as well as an in-person class
    3. Less well than an in-person class, but you still learned something
    4. Total waste of time, you didn't learn anything

2. How much time did you spend on this video lecture (including time spent on exercises)?

3. Do you have particular questions you would like me to address in this week's problem session?

4. Do you have any other comments or feedback?