Crypto for Integrity

CS 181S

Spring 2024

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!

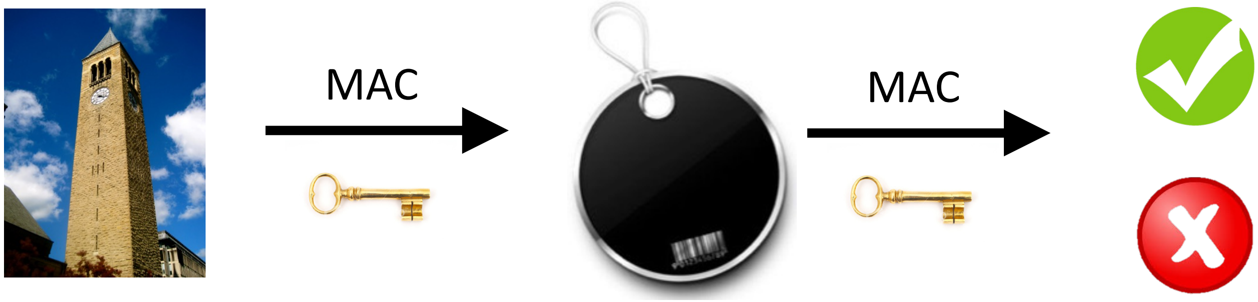
- Plaintext block might be random number, and recipient has no way to detect change in random number
- Attacker might substitute ciphertext from another execution of same protocol (replay)
- Adversary can modify encrypted plaintext in predictable ways (malleability)

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

- $\mathrm{Gen}(1^n)$: generate a **key** k of length n
- $\mathrm{MAC}(m; k)$: produce a **tag** t for message m
- $\mathrm{Verify}(m, t; k)$: 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, $\mathrm{Verify}(m, \mathrm{MAC}(m, t; k))$ evaluates to 1
- A MAC is **secure** if it is hard for a PPT algorithm to forge a valid tag without the key

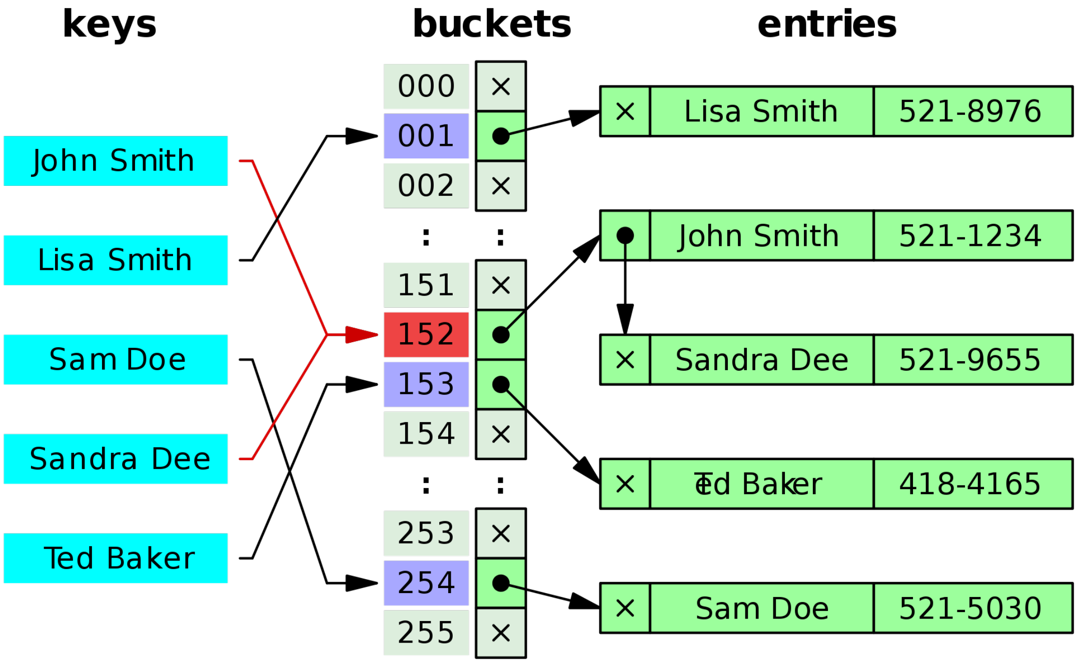
Real-world MACs

- 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**

Exercise: 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**

Historical 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/
  - Don't use it

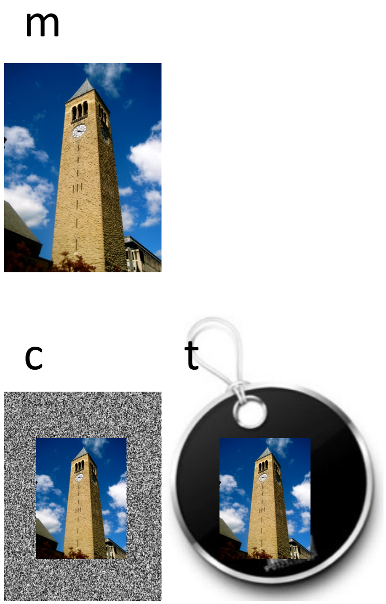
Real world hash functions

- **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 option called SHAKE

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
```



Encrypt and MAC

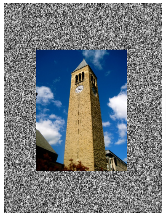
- **Pro:** can compute Enc and MAC in parallel
- **Con:** MAC must protect confidentiality

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, **`ssh`** (Secure Shell) protocol used this
  - default encryption is chacha20
  - default MAC is umac, recommends HMAC-SHA2-512 or 256

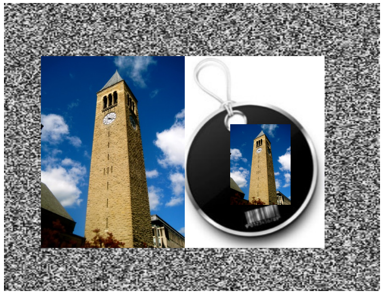
- Example: IPsec (Internet Protocol Security)
  - recommends AES-CBC for encryption and HMAC-SHA2-384 for MAC, among others
  - or AES-GCM

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

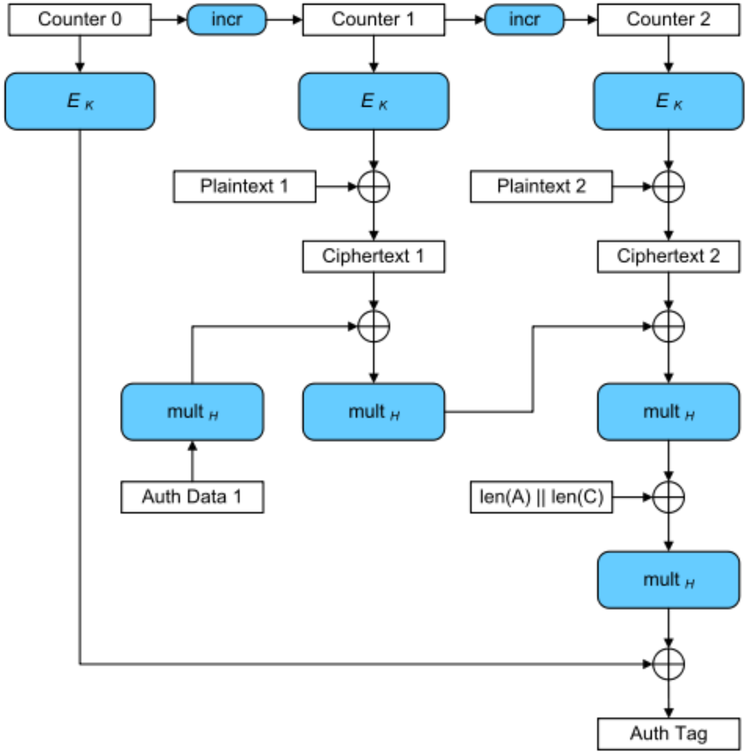
- Example: SSL (Secure Sockets Layer)
  - Many options for encryption, e.g. CHACHA20, AES-256
  - For MAC, standard is HMAC with many options for hash, e.g. SHA-256, SHA-384

Aside: Key reuse

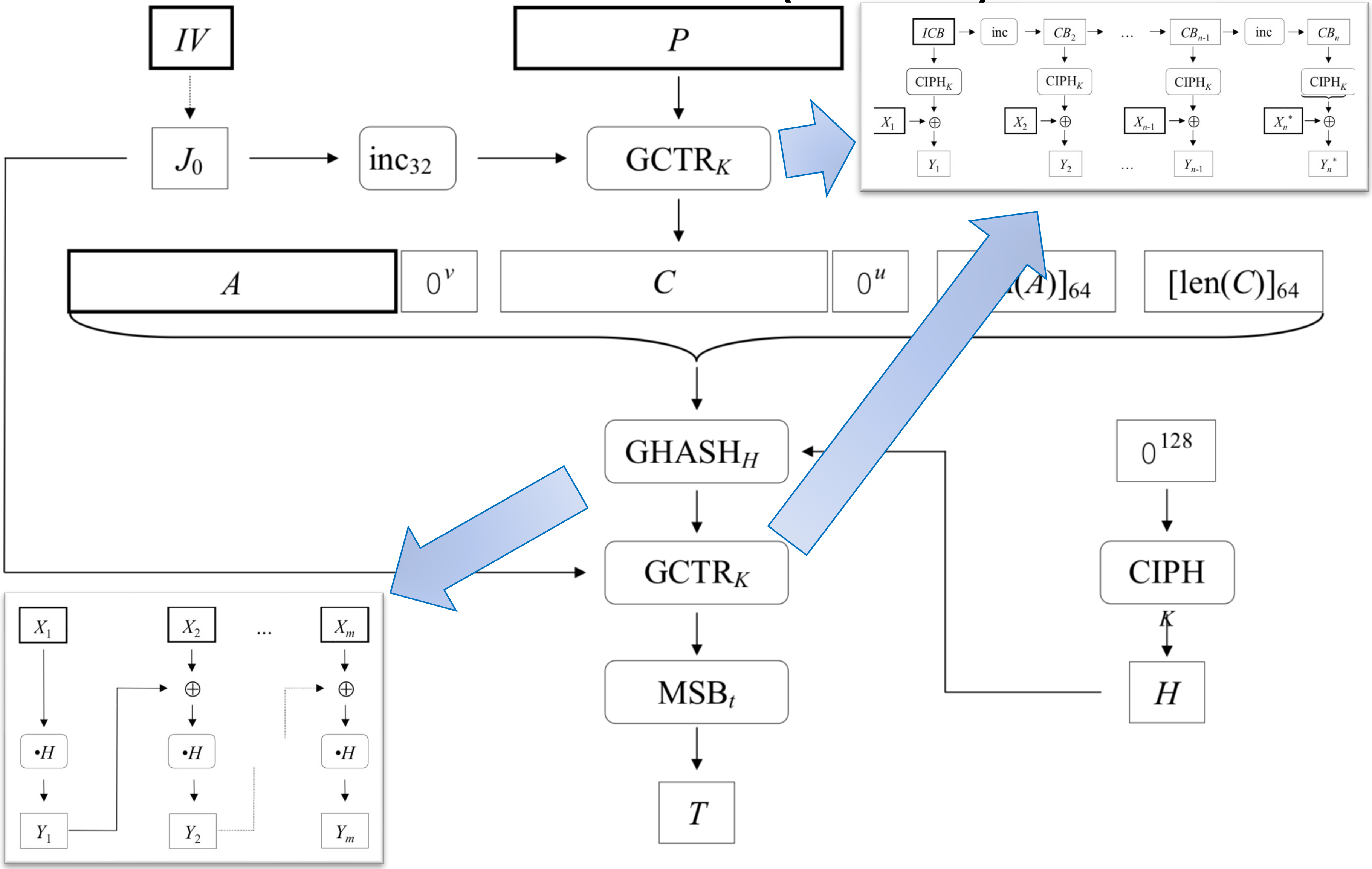
- Never use same key for both encryption and MAC schemes
- **Principle:** every key in system should have unique purpose

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



Galois Counter Mode (GCM)



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):

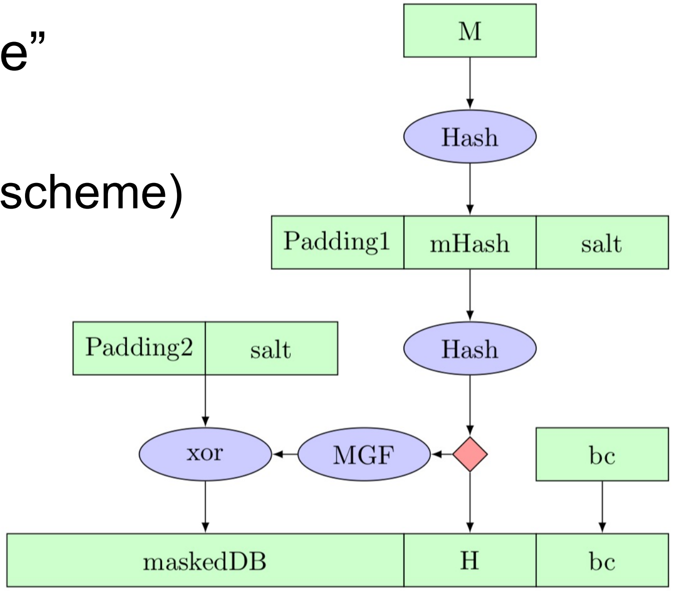
$$m == \sigma^e \bmod n$$

Exercise: 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 $m_1 m_2$?

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, Ed25519)

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