CS 5430

MACs and Digital Signatures

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Review: Encryption

- We can now protect confidentiality of messages against Dolev-Yao attacker
  - efficiently, thanks to hybrid of symmetric and asymmetric encryption
  - assuming existence of phonebook of public keys

- But what about integrity...?

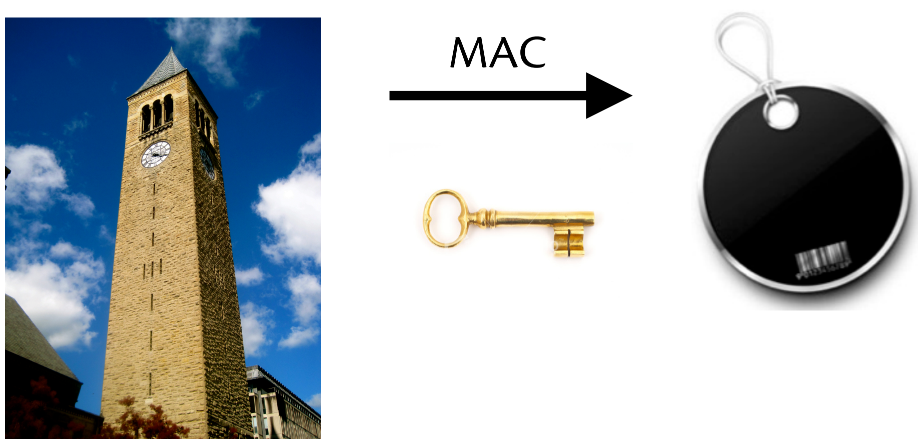
Protection of integrity

- **Threat:** attacker who controls the network
  - Dolev-Yao model: attacker can read, modify, delete messages
- **Harm:** information contained in messages can be changed by attacker (violating integrity)
- **Vulnerability:** communication channel between sender and receiver can be controlled by other principals
- **Countermeasure:** message authentication codes (MACs)
  - beware: not the same "MAC" as *mandatory access control* nor *media access control*

MESSAGE AUTHENTICATION CODES

MAC algorithms

- Gen(len): generate a key of length len
- MAC(m; k): produce a tag for message m with key k
  - message may be arbitrary size
  - tag is typically fixed length



Tag

Security of MAC

- Must be hard to forge tag for a message without knowledge of key
  - message of attackers choice? vs.
  - message that attacker cannot control
- Even if in possession of multiple (message, tag) pairs for that key

Protocol to exchange MAC'd message

```
0.  k = Gen(len)
1.  A: t = MAC(m; k)
2.  A -> B: m, t
3.  B: verify t = MAC(m; k)
```

- Both principals use the same shared key: symmetric key cryptography
- Message is sent in plaintext: no protection of confidentiality
- Goal is to detect modification **not** prevent
- Both principals run same algorithm
  - unlike encryption scheme
  - though for some block ciphers Enc and Dec are effectively the same

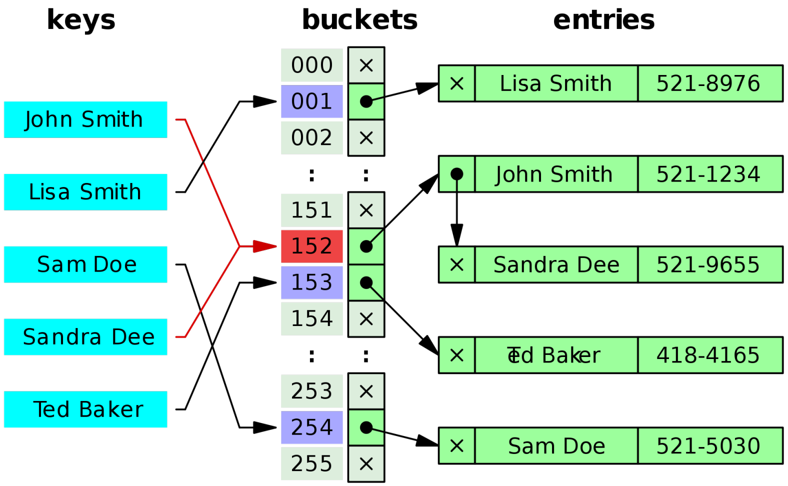
Examples of MACs

- 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

Hash functions

- Input: arbitrary size bit string
- Output: fixed size bit string
  - compression: many inputs map to same output, hence creating collision
  - for use with hash tables, diffusion: minimize collisions (and clustering)



Cryptographic hash functions

- Aka message digest
- Stronger requirements than (plain old) hash functions
- **Goal:** hash is compact representation of original like a fingerprint
  - 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

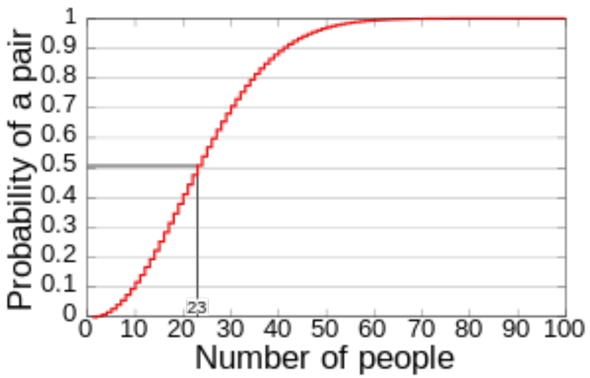
- **MD5:** Ron Rivest (1991)
  - 128 bit output
  - Collision resistance broken 2004-8
  - Can now find collisions in seconds
  - Don't use it
- **SHA-1:** NSA (1995)
  - 160 bit output
  - Theoretical attacks that reduce strength to less than 80 bits
  - On its way out, yet many browsers continue to accept 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 called SHAKE

Strength of hash functions

- Birthday attack: generic attack based on...
  - Birthday paradox: probability of two people in group sharing same birthday (a collision) is much higher than intuition might suggest
  - So collisions are easier to find than you might expect



- Strength of hash function is thus (at most) about half of output length
  - https://www.keylength.com/en/4/

CONFIDENTIALITY & INTEGRITY

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
- In some block modes (e.g., CTR), it's easy to flip individual bits
  - change "admin=0" to "admin=1"
- In some block modes (e.g., CBC), it's easy to truncate blocks from beginning of message
- ...

So you can't get C+I solely from encryption

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
- Or, you could combine encryption schemes with MAC schemes…

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
  (not actually a requirement we ever stipulated)

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

Aside: Key reuse

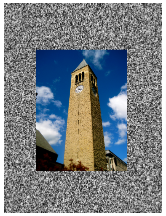
- Never use same key for both encryption and MAC schemes
- **Principle:** every key in system should have unique purpose

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



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Encrypt then MAC

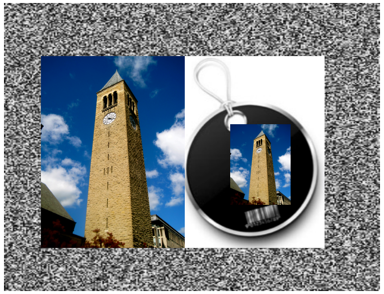
- **Pro:** provably most secure of three options [Bellare & Namprepre 2001]
- **Pro:** don't have to decrypt if MAC fails
  - resist DoS
- Example: IPsec (Internet Protocol Security)
  - recommends AES-CBC for encryption and HMAC-SHA1 for MAC, among others
  - or AES-GCM

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

MACs

- We can now protect integrity of messages against Dolev-Yao attacker
  - MAC algorithms use efficient symmetric-key cryptography
  - but what about quadratic key-sharing problem?

- Asymmetric cryptography for integrity…

DIGITAL SIGNATURES

Recall: Key pairs

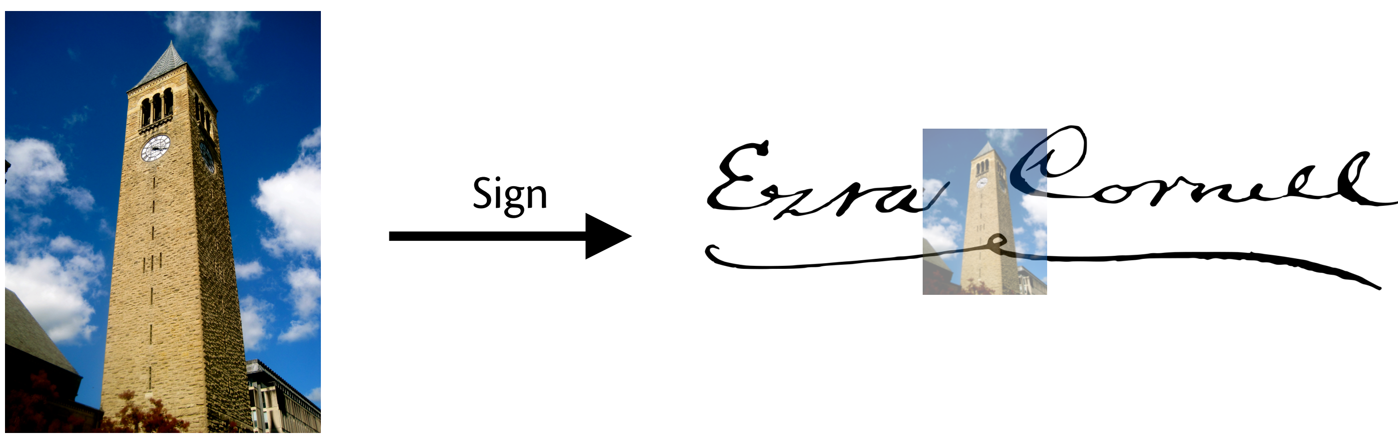
- Instead of sharing a key between pairs of principals...
- ...every principal has a pair of keys
  - **public key:** published for the world to see
  - **private key:** kept secret and never shared

Key pairs

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

Digital signature scheme

- Sign(m; k): sign message m with key k, producing signature s as output
- Ver(m; s; K): verify signature s on message m with key K
- Gen(len): generate a key pair (K,k) of length len



Protocol to exchange signed message

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

- Message is sent in plaintext: no protection of confidentiality
- Goal is to detect modification **not** prevent
- Principals run different algorithms

...what if message is too long for asymmetric algorithms?

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)
```

So common a practice that I won't bother to write the hashing from now on

Security of digital signatures

- Must be hard to forge signature for a message without knowledge of key
  - message of attackers choice? vs.
  - message that attacker cannot control

  ...like handwritten signatures
- Even if in possession of multiple (message, signature) pairs for that key

  ...unlike handwritten signatures

Examples of digital signatures

- **DSA:** Digital Signature Algorithm [NIST 1991]
  - Used for decades without any serious attacks
  - Closely related to Elgamal encryption
- **RSA** [Rivest, Shamir, Adleman 1977]
  - Core ideas are the same as RSA encryption
  - Common mistake: RSA sign = encrypt with your private key
  - Truth (in real world, outside of textbooks):
    - there's a core RSA function R that works with either K or k
    - RSA encrypt = do some prep work on m then call R with K
    - RSA sign = do **different** prep work on m then call R with k

Upcoming events

- [today] A2 due
- [Mon] A3 out

Integrity without knowledge is weak and useless, and knowledge without integrity is dangerous and dreadful. – Samuel Johnson