CS 5430

MACs and Digital Signatures

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Review

- 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

- Today: 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*

Encryption and integrity

Encryption and integrity

NO!

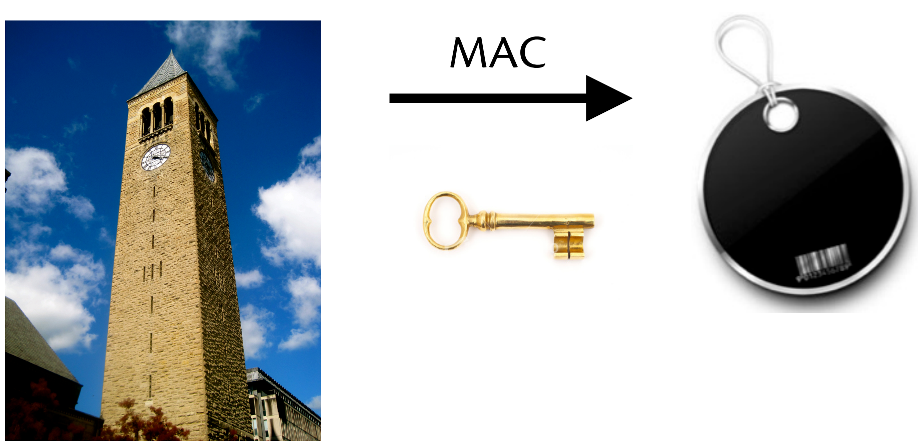
- Plaintext block might be random number, and recipient has no way to detect change in random number
- Attacker might substitute ciphertext from another execution of same protocol
- In some block modes (e.g., CTR), it's easy to flip individual bits
  - change "admin=0" to "admin=1"
- In some block modes (e.g., CBC), it's easy to truncate blocks from beginning of message
- ...

So you can't get integrity solely from encryption

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
- "Secure MAC"? Must be hard to forge tag for a message without knowledge of 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

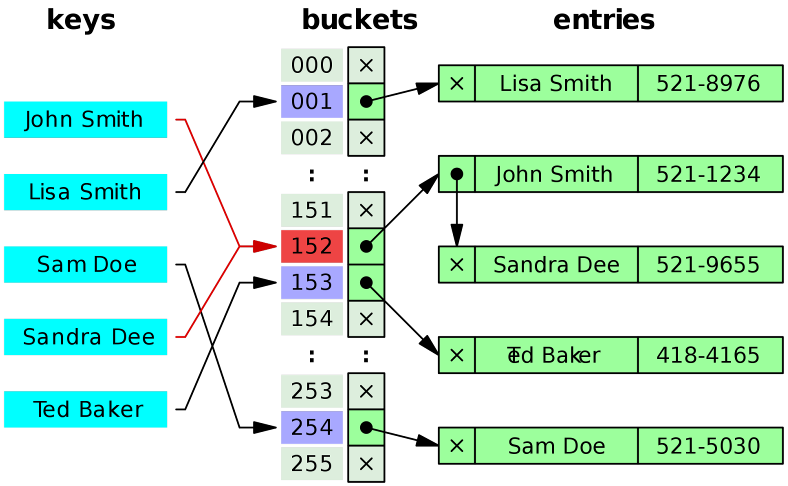
Real-world MACs

- 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

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

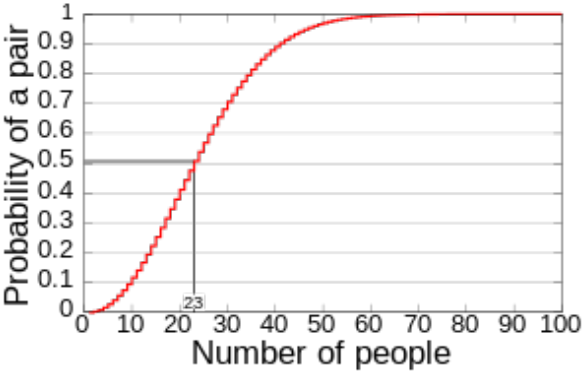
- **MD5:** Ron Rivest (1991)
  - 128 bit output
  - Collision resistance broken 2004-8
  - Can now find collisions in seconds
  - Don't use it
- **SHA-1:** NSA (1995)
  - 160 bit output
  - Theoretical attacks that reduce strength to less than 80 bits
  - As of 2/23/17, "practical attack" on PDFs: https://shattered.io/
  - Industry has been deprecating SHA-1 over the couple years
    - E.g. MS IE 11 supposed to start rejecting SHA-1 last week

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/

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

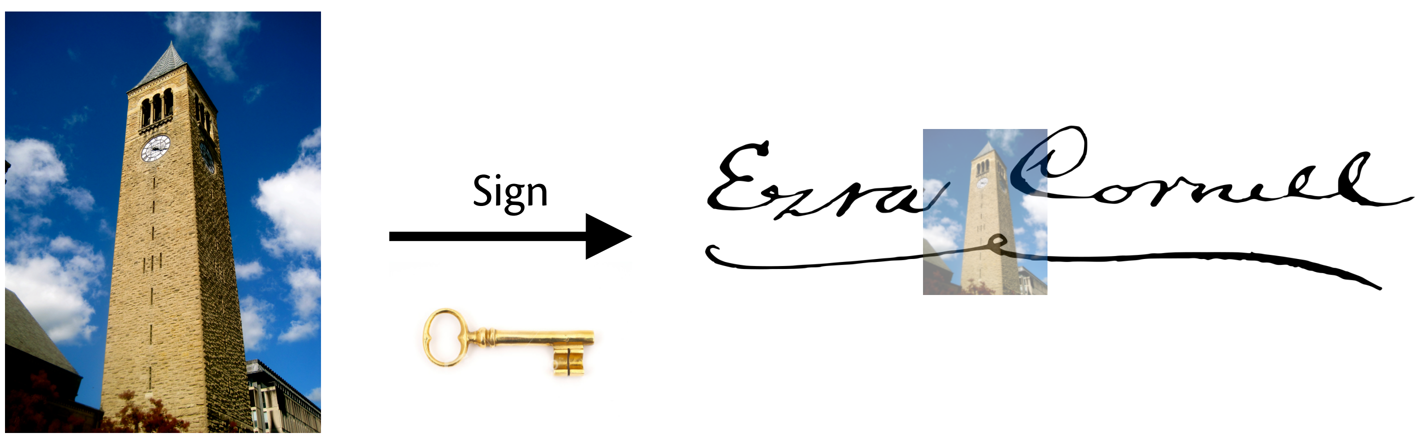
- Instead of sharing a key between pairs of principals...
- ...every principal has a pair of keys
  - **public key:** published for the world to see
  - **private key:** kept secret and never shared


Key pair terminology

	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

```
0. A:  (K_A,k_A) = Gen(len)
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

  ...like handwritten signatures

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

  ...unlike handwritten signatures

REAL-WORLD DIGITAL SIGNATURES

RSA

- Core ideas are the same as RSA encryption
- Common mistake: "RSA sign = encrypt with 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
  - Prep work: recall "textbook RSA is insecure"
    - (For encryption: OAEP)
    - For signatures: PSS (probabilistic signature scheme)

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

EXTENSIONS

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

Undeniable signatures

[Chaum and van Antwerpen 1989]

- Purpose: signer doesn't want the whole world to be able to verify
- Eliminate Ver algorithm; require signer to be available to verify signatures
- Two additional **protocols** between verifier and purported signer:
  - Confirm: convinces verifier that signature is valid
  - Disavow: convinces verifier that signature is invalid (i.e. signer did not sign that message)
- Either way, verifier can't convince anyone else of that fact

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

David Chaum

b. 1955

- Invented e-cash
- Invented anonymous communication
- Many inventions in e-voting
- Founded IACR (1982)

Upcoming events

- [next Wed] A2 due

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