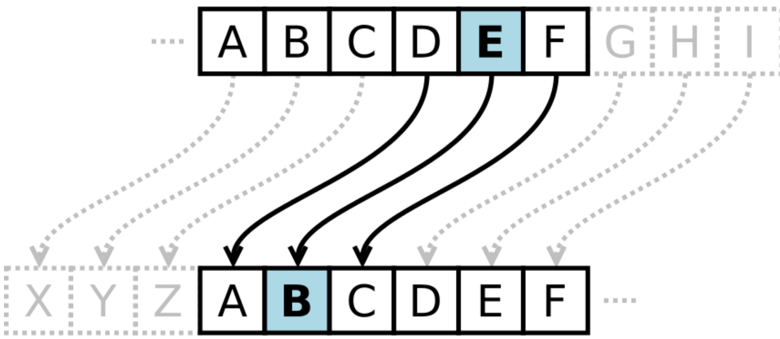
Lecture 6: Symmetric Cryptography

CS 5430 February 21, 2018

The Big Picture Thus Far…

Attacks
are perpetrated by
threats
that inflict
harm
by exploiting
vulnerabilities
which are controlled by
countermeasures.

Classical Cryptography



Kerckhoffs' Principle

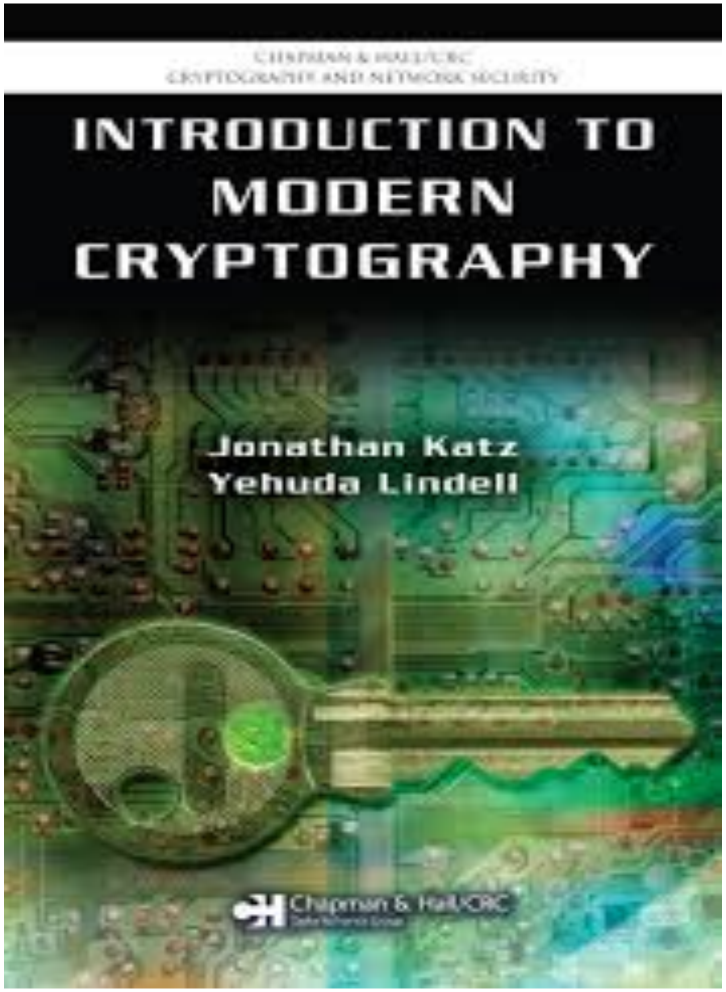
- Secrecy should depend upon the key remaining secret
- Secrecy should **not** depend upon the algorithm remaining secret
- Instance of Open Design
- Proprietary encryption schemes are to be avoided
  - Just google "proprietary encryption broken"

Tenants of modern cryptography

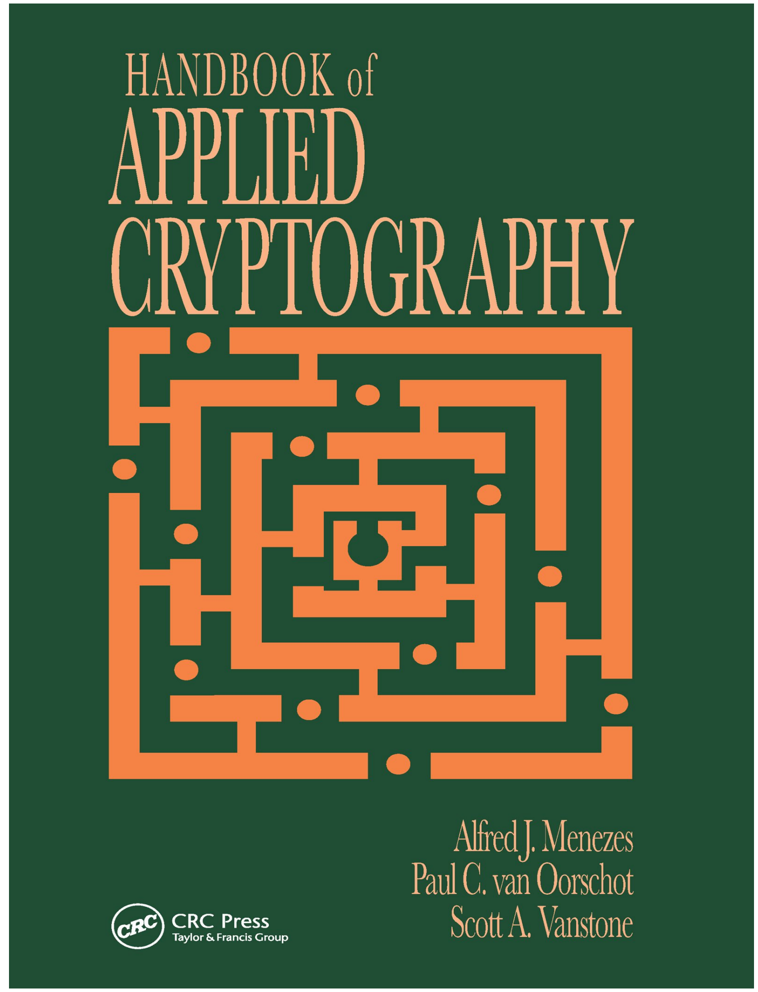
When inventing a cryptographic algorithm/protocol:

- Formulate a precise definition of security
- Provide a rigorous mathematical proof that the cryptographic algorithm/protocol satisfies the definition of security
- State any required assumptions in the proof, keeping them as minimal as possible

Cryptography



cf. CS 4830/6830



cf. CS 6832

Purpose of Encryption

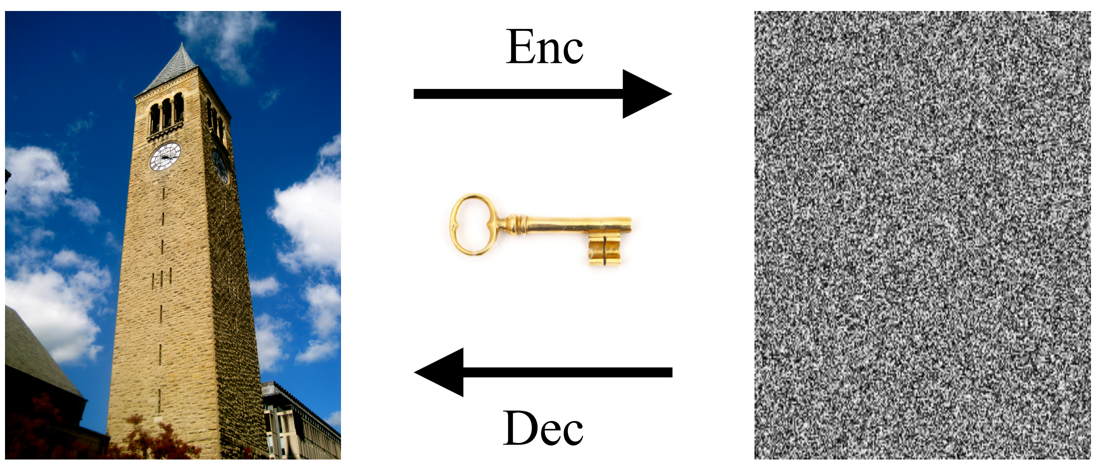
- **Threat:** attacker who controls the network
  - can read, modify, delete messages
  - in essence, the attacker *is* the network
  - *Dolev-Yao model* [1983]

Purpose of encryption

- **Threat:** attacker who controls the network
  - can read, modify, delete messages
  - in essence, the attacker *is* the network
  - *Dolev-Yao model* [1983]
- **Harm:** messages containing secret information disclosed to attacker (violating confidentiality)
- **Vulnerability:** communication channel between sender and receiver can be read by other principals
- **Countermeasure:** encryption

(Symmetric) Encryption algorithms

- Gen(len): generate a key of length len
- Enc(m; k): encrypt message (aka plaintext or cleartext) m under key k
- Dec(c; k): decrypt ciphertext c with key k
  - note the semicolon



(Gen, Enc, Dec) is a symmetric-key encryption scheme aka cryptosystem

Shared key

- How did Alice and Bob come to share key k?
  - maybe they met way in advance
  - maybe a trusted third party distributed the same key to both of them
  - better answers to come...
- But at some point, it was generated and shared
- Generation: **`k = Gen(len)`**
  - len is the length of the key

"Secure" encryption scheme?

Given ciphertext, cannot...

- **Determine key?**
  - Misses the point: we want to protect message secrecy
- **Determine plaintext?**
  - What if you could get 90% of plaintext?
- **Determine any character of plaintext?**
  - What if you could determine it's greater than 1000?
- **Determine any function of the plaintext!**
  - "Right" definition, but must be formulated carefully, and is stronger than some (many) real-world practical encryption schemes

Breaking encryption schemes

- Assume that attack of concern is determining the key, given many ciphertext/plaintext pairs
- Brute-force attack: recover key by trying every possible key
  - e.g., AES-128, try all 2^128 keys
- Break is an attack that recovers key in less work than brute-force
- Suppose best-known attack requires 2^X operations....then X is the strength aka security level of the encryption scheme
  - Best case is that strength = key length
  - As attacks are discovered, strength degrades
    - e.g., 3DES-168 has known attack that requires 2^112 operations, reducing strength from 168 to 112

Perfect encryption

One-time pad:

- Gen(len) = uniformly random sequence of bits of length len
- Enc(m; k) = Dec(m; k) = m XOR k
  - length(m) = length(k)

Security:

- Does reveal length of plaintext
- But nothing else!

Practicality:

- Keys must be long (as long as messages)
- Keys can never be reused, would reveal relationships
  - e.g., (m1 XOR k) XOR (m2 XOR k) = m1 XOR m2
- Distributing one-time use long keys is hard

Stream Ciphers

Block Ciphers

- Encryption schemes that operate on fixed-size messages
- The fixed-size is a *block*
- Well-known examples:
  - DES
  - 3DES
  - AES

DES

- **DES (Data Encryption Standard)**
  - Block size: 64 bits
  - Key size: 56 bits
  - Designed by IBM in 1973-4, tweaked by the NSA, then became the US standard for encryption. International adoption followed.
- **3DES (Triple DES)**
  - Block size: 64 bits
  - Key size: 112 or 168 bits
  - Introduced in 1998, because 56 bit keys had become feasible to brute force.
  - 3DES is simply three DES encryptions with two different keys, for an effective 112 bit key; or with three different keys, for an effective 168 bit key.

AES

AES (Advanced Encryption Standard)

- Block size: 128 bits
- Key size: 128, 192, or 256 bits
- Public competition held by NIST, ending in 2001
- Now the US standard, approved by the NSA for Top Secret information
- Currently no practical attacks known

Key lengths

- Various recommendations for strength summarized at https://www.keylength.com/en/
- Based on:
  - known attacks
  - hardware capabilities
  - predicted advances
- Why not use highest strength possible? Performance.

Key lengths

Security	Symmetric	NIST Rec.
≤ 80	2TDEA	No
112	3TDEA	until 2030
128	AES-128	Yes
≥ 256	AES-256	Yes

The obvious idea...

- Divide long message into short chunks, each the size of a block
- Encrypt each block with the block cipher

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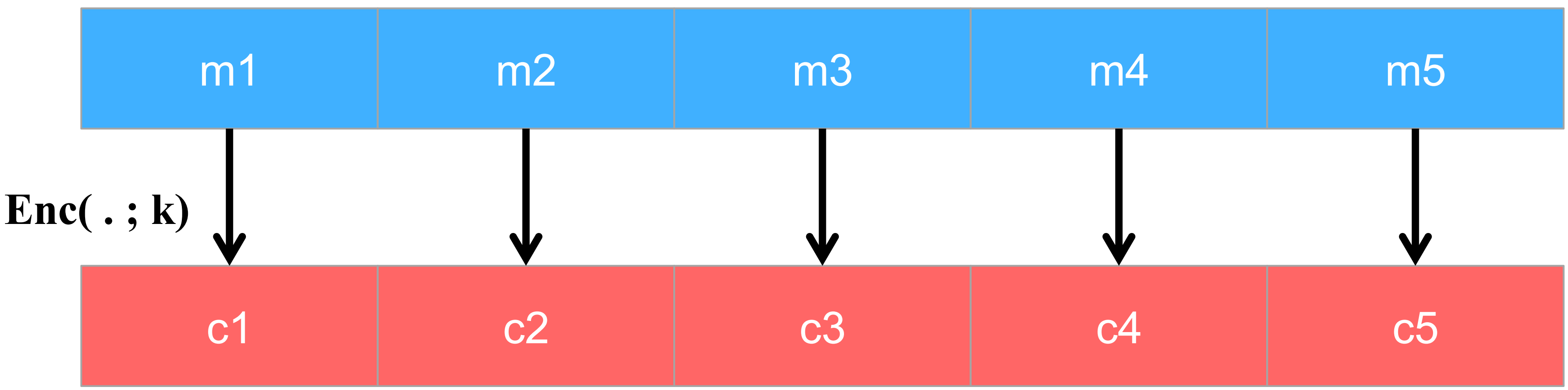
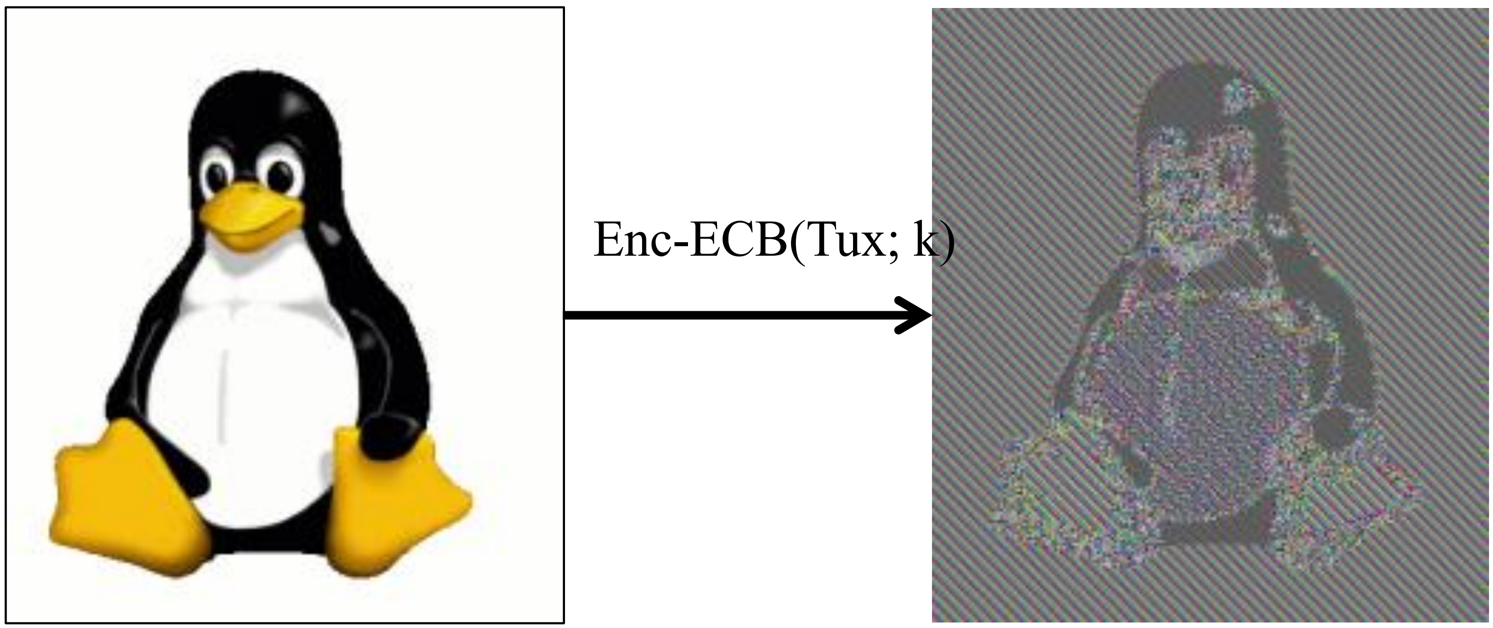


...is a bad idea

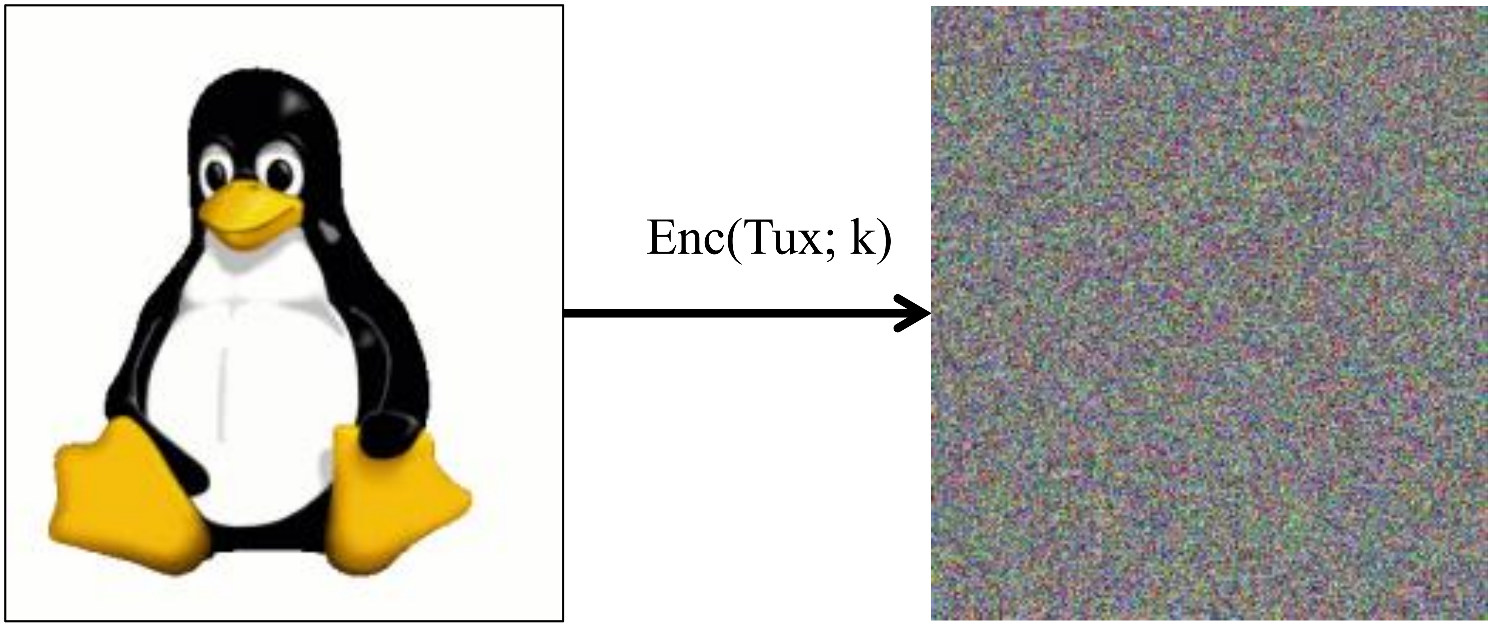


Called *electronic code book* (ECB) mode

Good modes

- Cipher Block Chaining (CBC) mode
  - idea: XOR previous ciphertext block into current plaintext block
- Counter (CTR) mode
  - idea: derive one-time pad from increasing counter
- (and others)
- With both:
  - every ciphertext block depends in some way upon previous plaintext or ciphertext blocks
  - so even if plaintext blocks repeat, ciphertext blocks don't
  - so *intra-message* repetition doesn't disclose information

Good modes

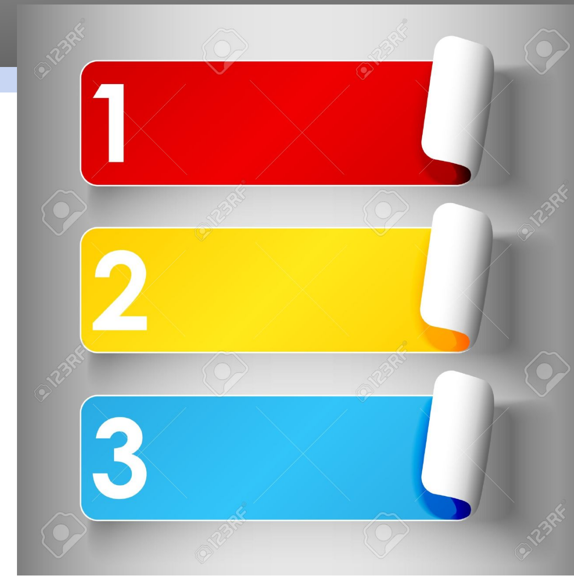


but what if you encrypt Tux twice under the same key?

Good modes

- Problem: block ciphers are *deterministic*: inter-message repetition is visible to attacker
- Both CBC and CTR modes require an additional parameter: a *nonce*
  - Enc(m; nonce; k)
  - Dec(c; nonce; k)
  - CBC calls the nonce an *initialization vector* (IV)
- Different nonces make each encryption different than others
  - Hence inter-message repetition doesn't disclose information

Nonces



A nonce is a number used once

Must be

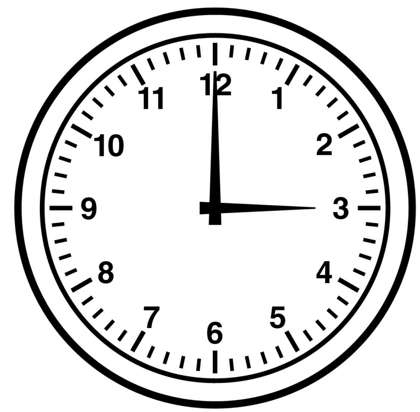
- **unique:** never used before in lifetime of system

and/or (depending on intended usage)

- **unpredictable:** attacker can't guess next nonce given all previous nonces in lifetime of system

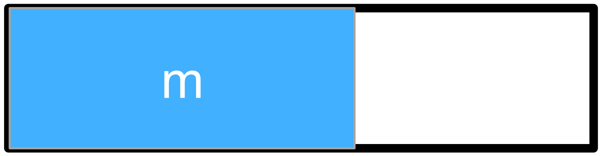
Nonce sources

- **counter**
  - requires state
  - easy to implement
  - can overflow
  - highly predictable
- **clock:** just a counter
- **random number generator**
  - might not be unique, unless drawn from large space
  - might or might not be unpredictable
  - generating randomness:
    - standard library generators often are not cryptographically strong, i.e., unpredictable by attackers
    - cryptographically strong randomness is a black art



Padding

What if the message length isn't *exactly* a multiple of block length? End up with final block that isn't full:



Non-solution: pad out final block with 0's (not reversible)

Solution: Let B be the number of bytes that need to be added to final plaintext block to reach block length. Pad with B copies of the byte representing B. Called *PKCS #5 or #7 padding.*

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*

Encryption and integrity

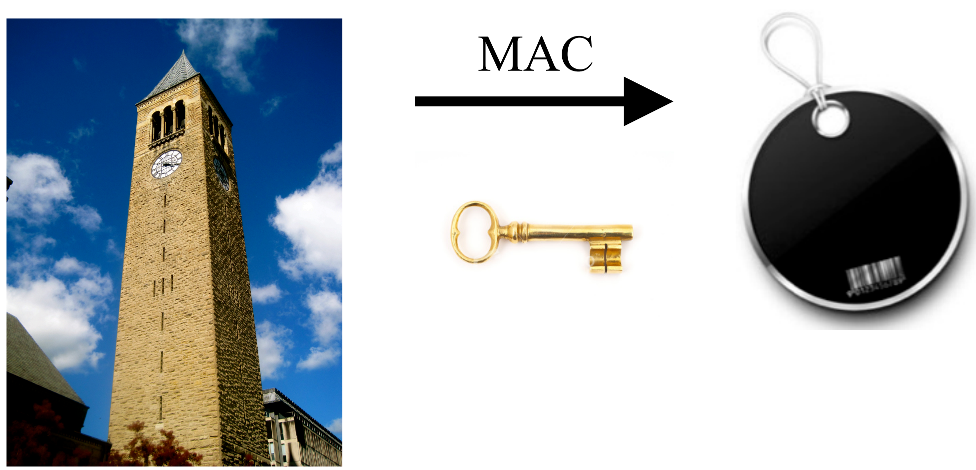
Encryption and integrity

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
- ...

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

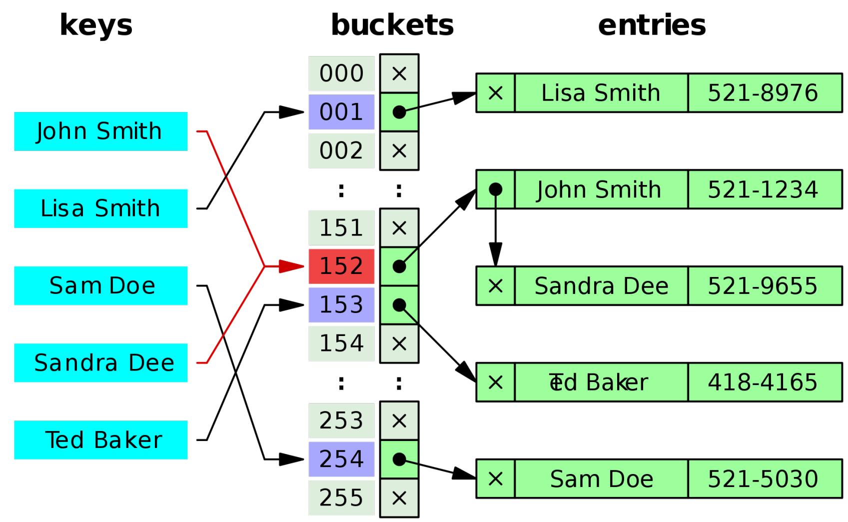


Real-world MACs

- 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: 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
  - 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

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

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

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

Authenticated encryption

- Three combinations:
  - Enc and MAC
  - Enc then MAC
  - MAC then Enc
- Let's unify all with a pair of algorithms:
  - AuthEnc(m; ke; km): produce an authenticated ciphertext x of message m under encryption key ke and MAC key km
  - AuthDec(x; ke; km): recover the plaintext message m from authenticated ciphertext x, and verify that the MAC is valid, using ke and km
    - Abort if MAC is invalid

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