# Crypto Concepts

## Symmetric encryption, Public key encryption, and TLS

# Cryptography

Is:

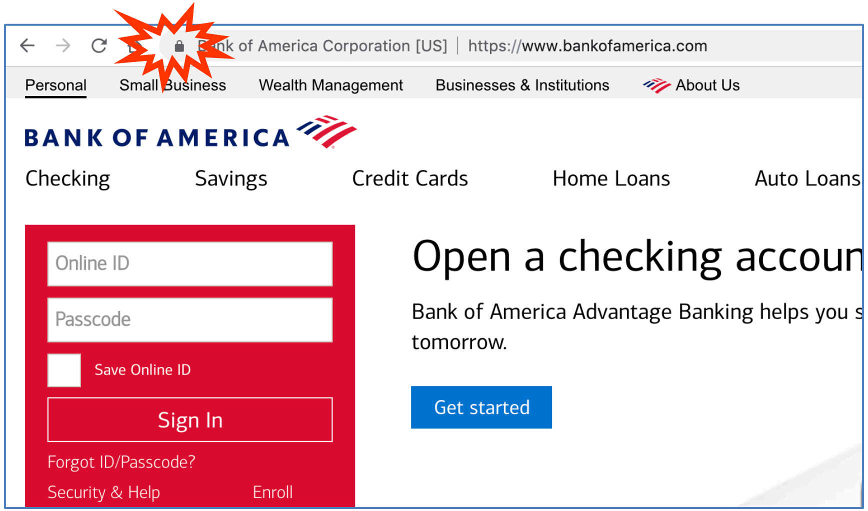
- A tremendous tool
- The basis for many security mechanisms

Is not:

- The solution to all security problems
- Reliable unless implemented and used properly
- Something you should try to invent yourself

# Goal 1: Secure communication

(protecting data in motion)




no eavesdropping
no tampering

# Secure Sockets Layer / TLS

Standard for Internet security

- Goal: "... provide privacy and reliability between two communicating applications"

Two main parts

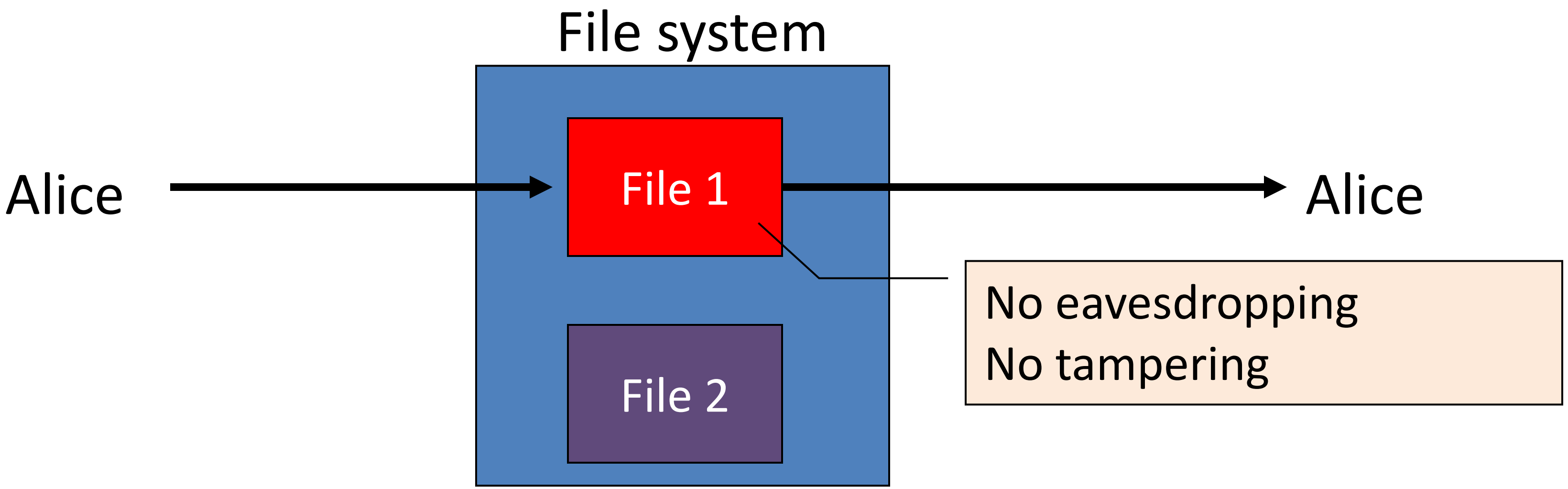
1. Handshake Protocol: **Establish shared secret key using public-key cryptography**

2. Record Layer: **Transmit data using negotiated key**

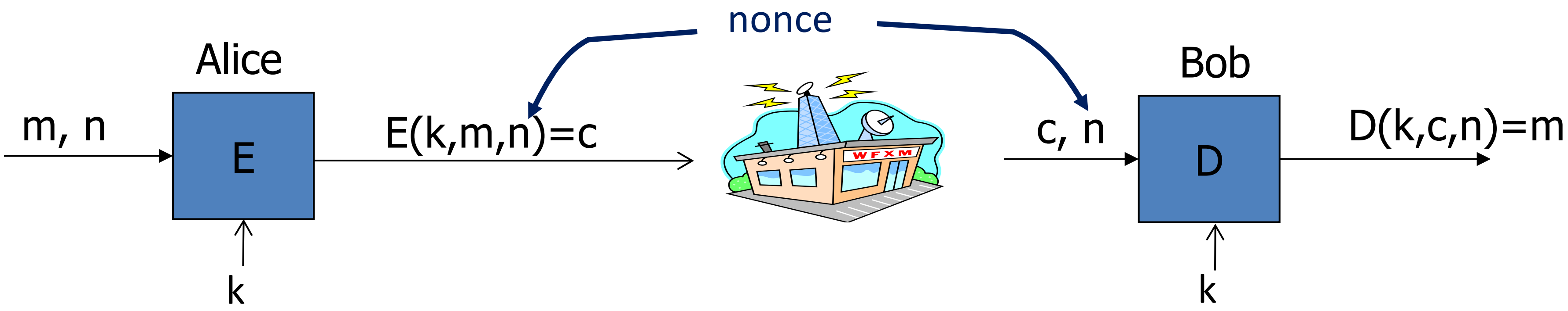
   Our starting point: Using a key for encryption and integrity

# Goal 2:   protected files

(protecting data at rest)



# Building block: symmetric cipher




E, D: cipher  k: secret key (e.g. 128 bits)

m, c: plaintext, ciphertext  n: nonce (non-repeating)

Encryption algorithm is publicly known

⇒ never use a proprietary cipher

# Use Cases

**Single use key**: (one time key)

- Key is only used to encrypt one message
  - encrypted email: new key generated for every email
- No need for nonce (set to 0)

**Multi use key**: (many time key)

- Key used to encrypt multiple messages
  - TLS: same key used to encrypt many packets
- Use either a *unique* nonce or a *random* nonce

# First example: One Time Pad (single use key)

Vernam (1917)

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Key: | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 |
| Plaintext: | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| Ciphertext: | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 0 |

$\oplus$

Encryption: $c = E(k, m) = m \oplus k$

Decryption: $D(k, c) = c \oplus k \quad = (m \oplus k) \oplus k = m$

# One Time Pad (OTP) Security

Shannon (1949):

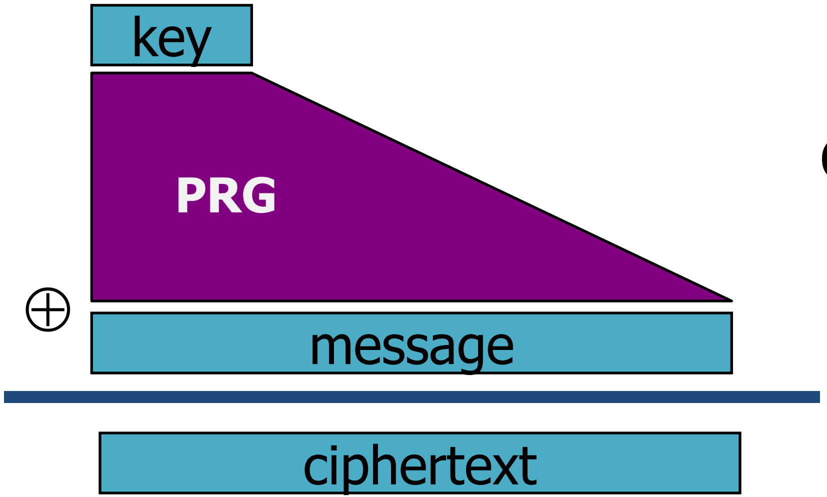
- OTP is “secure” against one-time eavesdropping
- without key, ciphertext reveals no “information” about plaintext

**Problem**: OTP key is as long as the message

# Stream ciphers (single use key)

Problem: OTP key is as long as the message

<u>Solution</u>: Pseudo random key -- stream ciphers




$c \leftarrow \textbf{PRG}(k) \oplus m$

Example: **ChaCha20** (one-time if no nonce) key: 128 or 256 bits.

# Dangers in using stream ciphers

One time key !!

"Two time pad" is insecure:

$$c_1 \leftarrow m_1 \oplus PRG(k)$$
$$c_2 \leftarrow m_2 \oplus PRG(k)$$

What if want to use same key to encrypt two files?

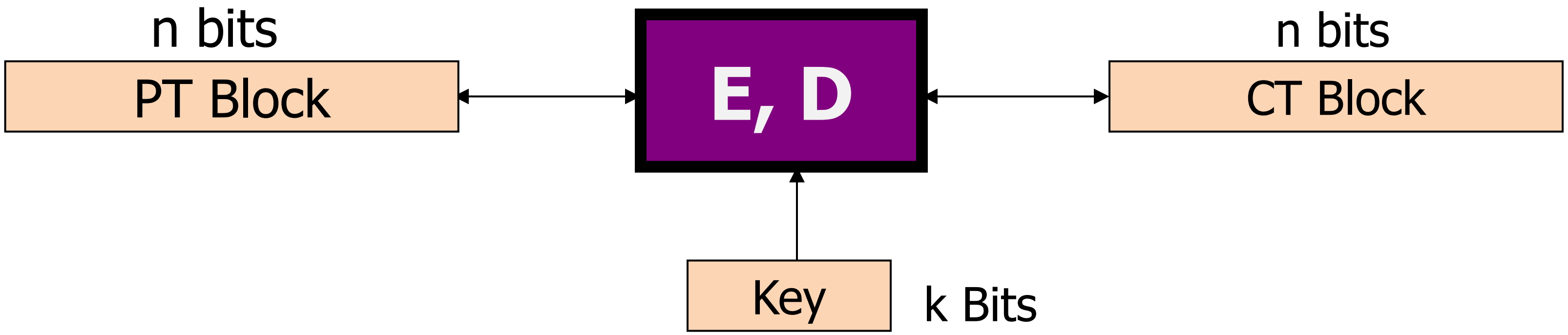
Eavesdropper does:

$$c_1 \oplus c_2 \quad \rightarrow \quad m_1 \oplus m_2$$

Enough redundant information in English that:

$$m_1 \oplus m_2 \rightarrow \quad m_1 , m_2$$

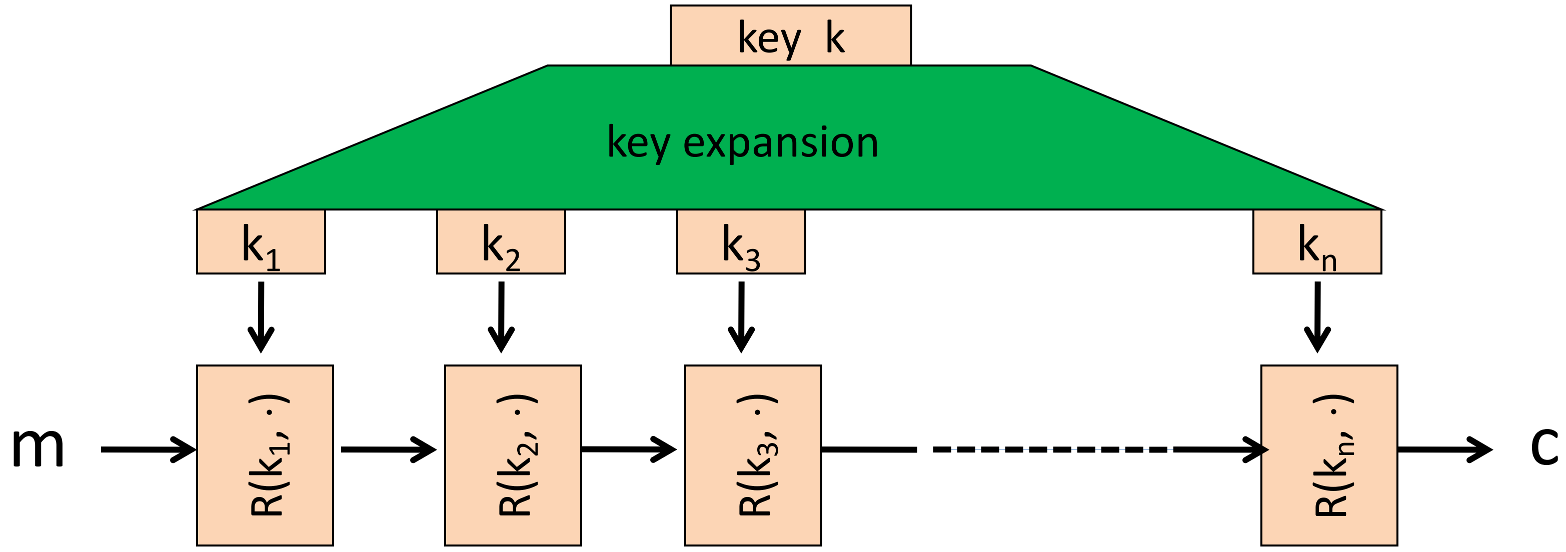
# Block ciphers: crypto work horse




Canonical examples:

1. 3DES: n= 64 bits, k = 168 bits
2. AES: n=128 bits, k = 128, 192, 256 bits

# Block Ciphers Built by Iteration

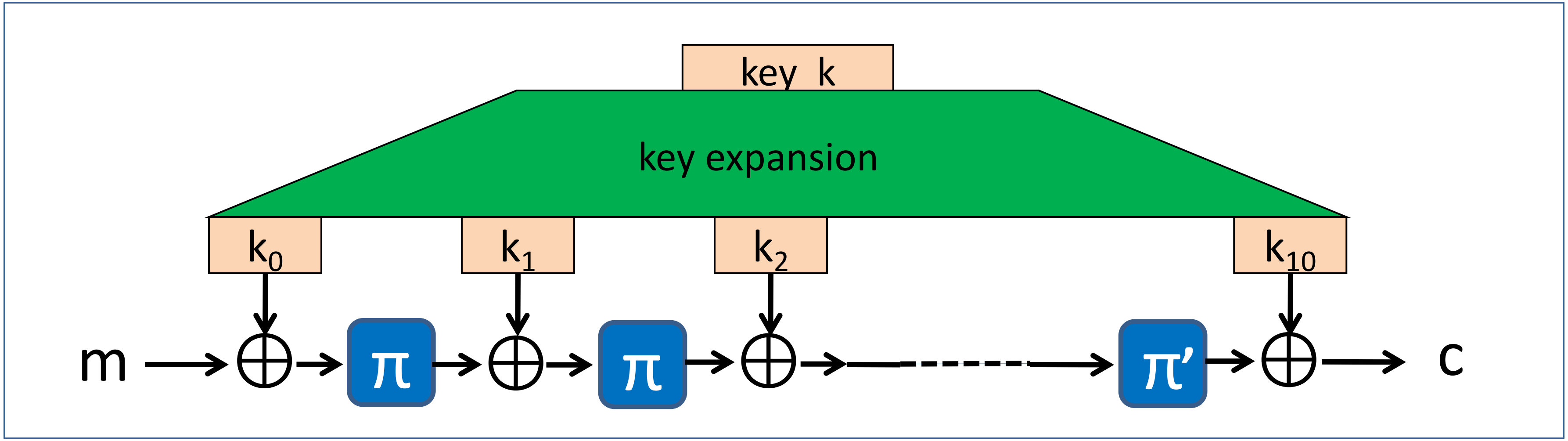



R(k,m): round function

for 3DES (n=48), for AES-128 (n=10)

# Example: AES128

**input**: 128-bit block m, 128-bit key k. **output**: 128-bit block c.

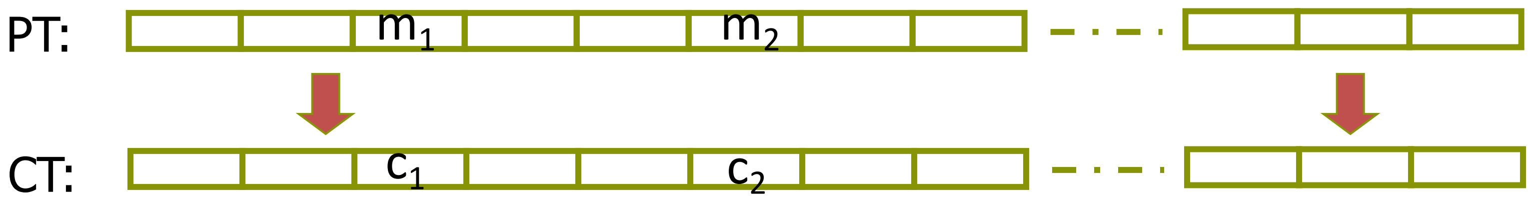



Difficult to design: must resist subtle attacks

- differential attacks, linear attacks, brute-force, …

# Incorrect use of block ciphers

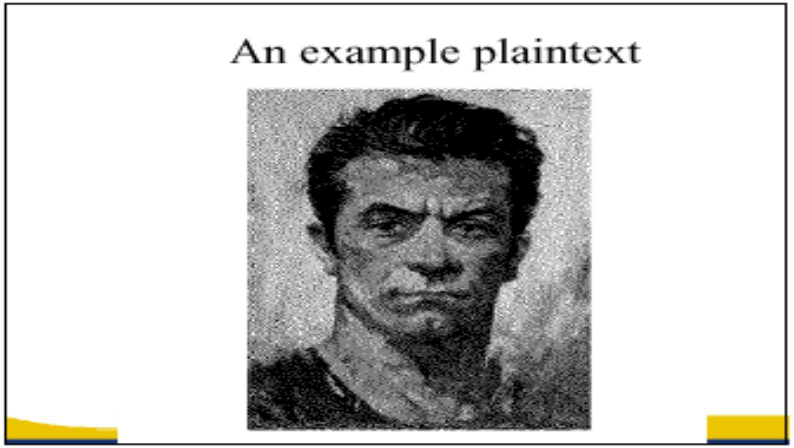
Electronic Code Book (ECB):

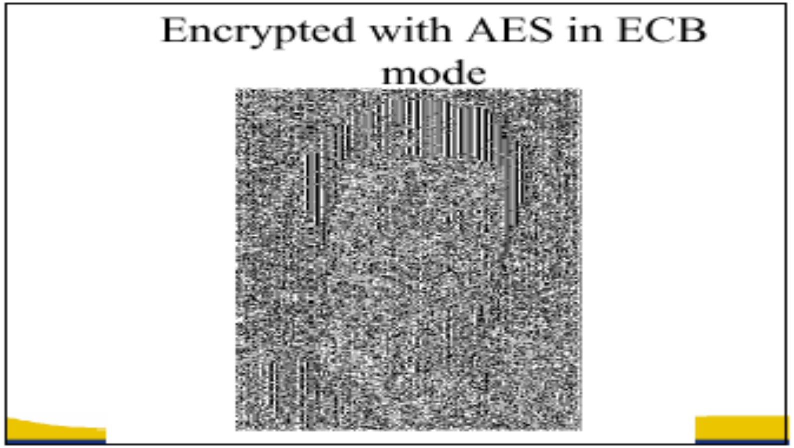



Problem:

– if $m_1 = m_2$ then $c_1 = c_2$

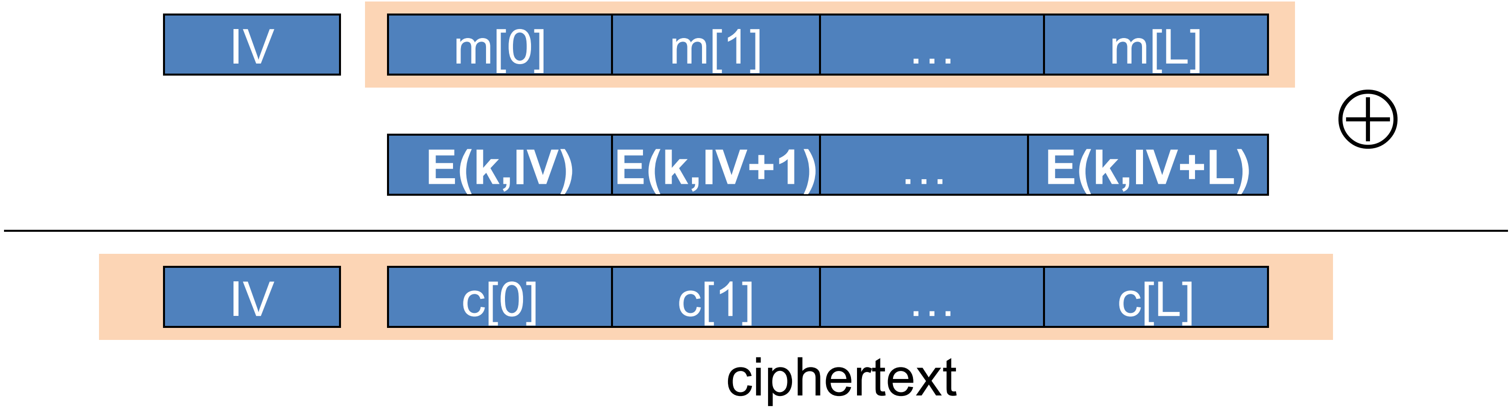
# In pictures



# CTR mode encryption (eavesdropping security)

Counter mode with a random IV: (parallel encryption)




Why is this secure for multiple messages? See the crypto course (cs255)

# Performance

OpenSSL on Intel Haswell, 2.3 GHz ( Linux)

| | Cipher | Block/key size | Speed (MB/sec) |
|---|---|---|---|
| stream | ChaCha | | 408 |
| block | 3DES | 64/168 | 30 |
| block | AES128 | 128/128 | 176 |
| block | AES256 | 128/256 | 135 |

(w/o AES-NI)

# A Warning

**eavesdropping security is insufficient for most applications**

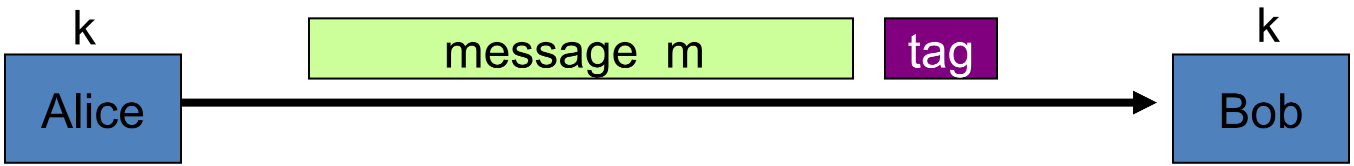
Need also to defend against active (tampering) attacks.

CTR mode is insecure against active attacks!

Next: methods to ensure message integrity

# Message Integrity: MACs

- Goal: provide message integrity. No confidentiality.
  - ex: Protecting public binaries on disk.




**Generate tag:**
**tag ← S(k, m)**

**Verify tag:**
**V(k, m, tag) $\stackrel{?}{=}$ `yes'**

# Construction: HMAC (Hash-MAC)

Most widely used MAC on the Internet.

H: hash function.
example: SHA-256 ; output is 256 bits

Building a MAC out of a hash function:

– Standardized method: HMAC

$$S(k, msg) = H\big( k \oplus opad \,\|\, \mathbf{H( k \oplus ipad \,\|\, msg )} \big)$$

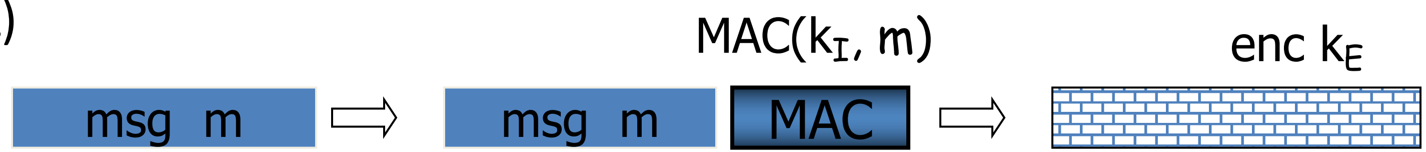
Why is this MAC construction secure?

… see the crypto course (cs255)

# Combining MAC and ENC (Auth. Enc.)

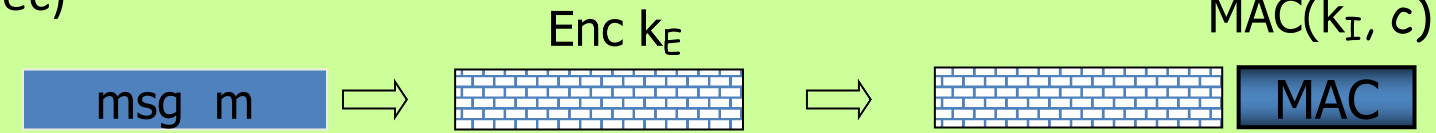
Encryption key $k_E$. MAC key = $k_I$

Option 1: (SSL)

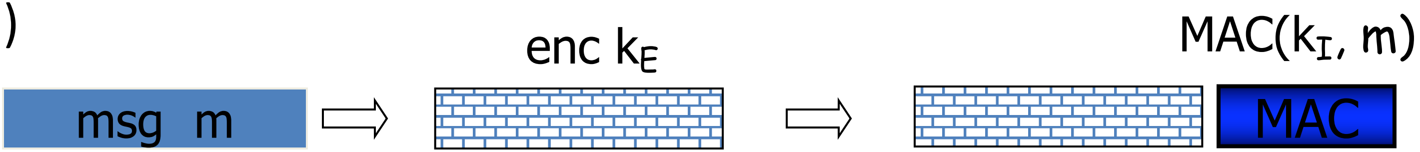



Option 2: (IPsec)

**always correct**

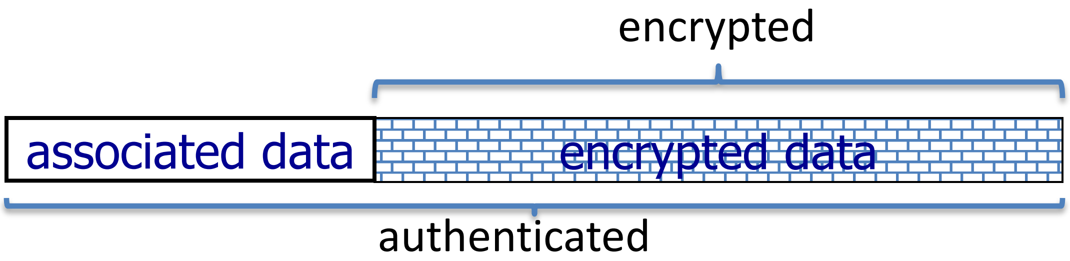



Option 3: (SSH)



# **AEAD**: Auth. Enc. with Assoc. Data

AEAD:




**AES-GCM**: CTR mode encryption then MAC

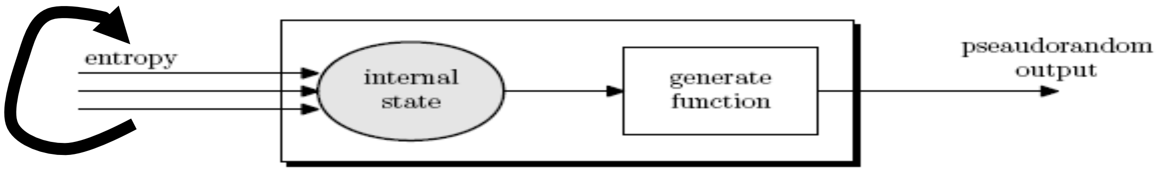
(MAC accelerated via Intel's PCLMULQDQ instruction)

# Example AES-GCM encryption function

```
int encrypt(
    unsigned char *key,                                   // key
    unsigned char *iv,   int iv_len,                      // nonce
    unsigned char *plaintext,    int plaintext_len,       // plaintext
    unsigned char *aad,   int aad_len,                    // assoc. data

    unsigned char *ciphertext                             // output ct
)
```

# Generating Randomness (e.g. keys, nonces)




Pseudo random generators in practice: (e.g. /dev/random)

- Continuously add entropy to internal state
- Entropy sources:
  - Hardware RNG: Intel **RdRand** inst. (Ivy Bridge). 3Gb/sec.
  - Timing: hardware interrupts (keyboard, mouse)

# Summary

Shared secret key:

- Used for secure communication and document encryption

**Encryption**: (eavesdropping security) **[should not be used standalone]**

- One-time key: stream ciphers, CTR with fixed IV
- Many-time key: CTR with random IV

**Integrity**: HMAC or CW-MAC

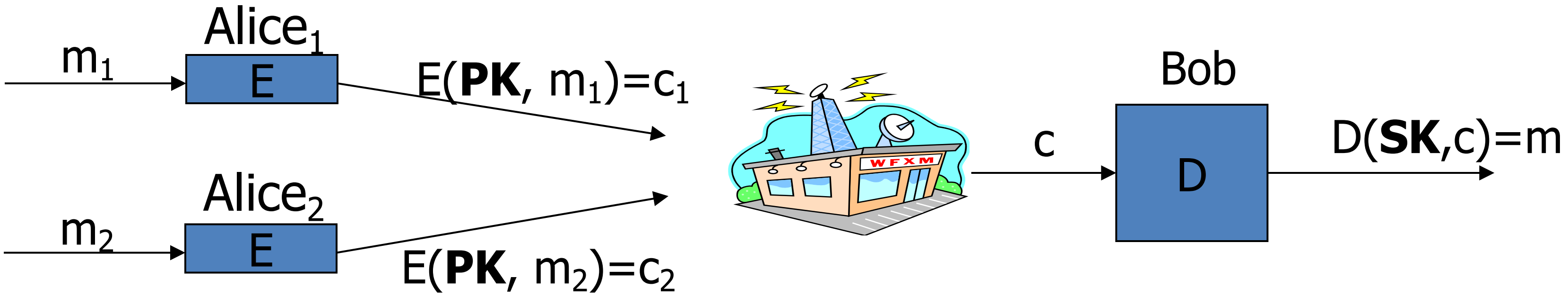
**Authenticated encryption**: encrypt-then-MAC using GCM

# Crypto Concepts

## Public key cryptography

# Public-key encryption

Tool for managing or generating symmetric keys




- E – Encryption alg. PK – Public encryption key
- D – Decryption alg. SK – Private decryption key

Algorithms E, D are publicly known.

# Building block: trapdoor permutations

1. Algorithm KeyGen: outputs pk and sk

2. Algorithm $F(pk, \cdot)$ : a one-way function
   - Computing $y = F(pk, x)$ is easy
   - One-way: given random y finding x s.t. $y = F(pk,x)$ is difficult

3. Algorithm $F^{-1}(sk, \cdot)$ : Invert $F(pk, \cdot)$ using trapdoor SK

$$F^{-1}(sk, y) = x$$

# Example: RSA

1. KeyGen: generate two equal length primes $p, q$

   set $N \leftarrow p \cdot q$ (3072 bits $\approx$ 925 digits)

   set $e \leftarrow 2^{16}+1 = 65537$ ; $d \leftarrow e^{-1} \pmod{\varphi(N)}$

   $pk = (N, e)$ ; $sk = (N, d)$

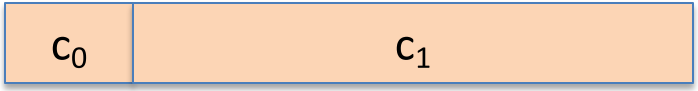
2. RSA(pk, x) : $x \rightarrow (x^e \bmod N)$

   Inverting this function is believed to be as hard as factoring N

3. $RSA^{-1}(pk, y)$ : $y \rightarrow (y^d \bmod N)$

# Public Key Encryption with a TDF

KeyGen: generate pk and sk




Encrypt(pk, m):

- choose random $x \in$ domain(F) and set $k \leftarrow H(x)$
- $c_0 \leftarrow F(pk, x)$ , $c_1 \leftarrow E(k, m)$ (E: symmetric cipher)
- send $c = (c_0, c_1)$

Decrypt$\big($sk, $c=(c_0,c_1)$ $\big)$: $x \leftarrow F^{-1}(sk, c_0)$ , $k \leftarrow H(x)$ , $m \leftarrow D(k, c_1)$

security analysis in crypto course

# Digital signatures

Goal: bind document to author

- Problem: attacker can copy Alice's sig from one doc to another

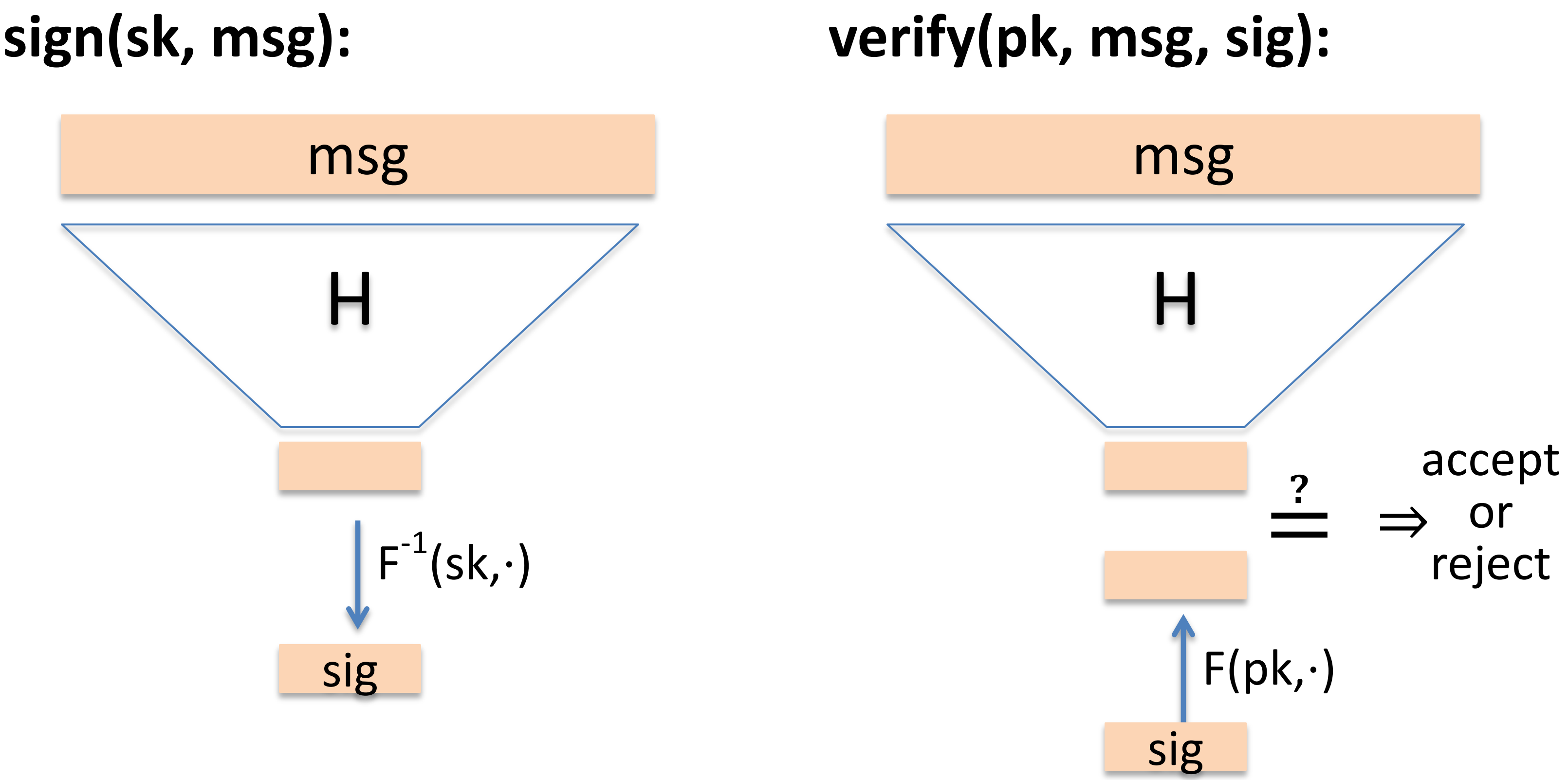
Main idea: make signature depend on document

**Example**: signatures from trapdoor functions (e.g. RSA)

$$\text{sign}(sk, m) \quad := \quad F^{-1}(sk, H(m))$$

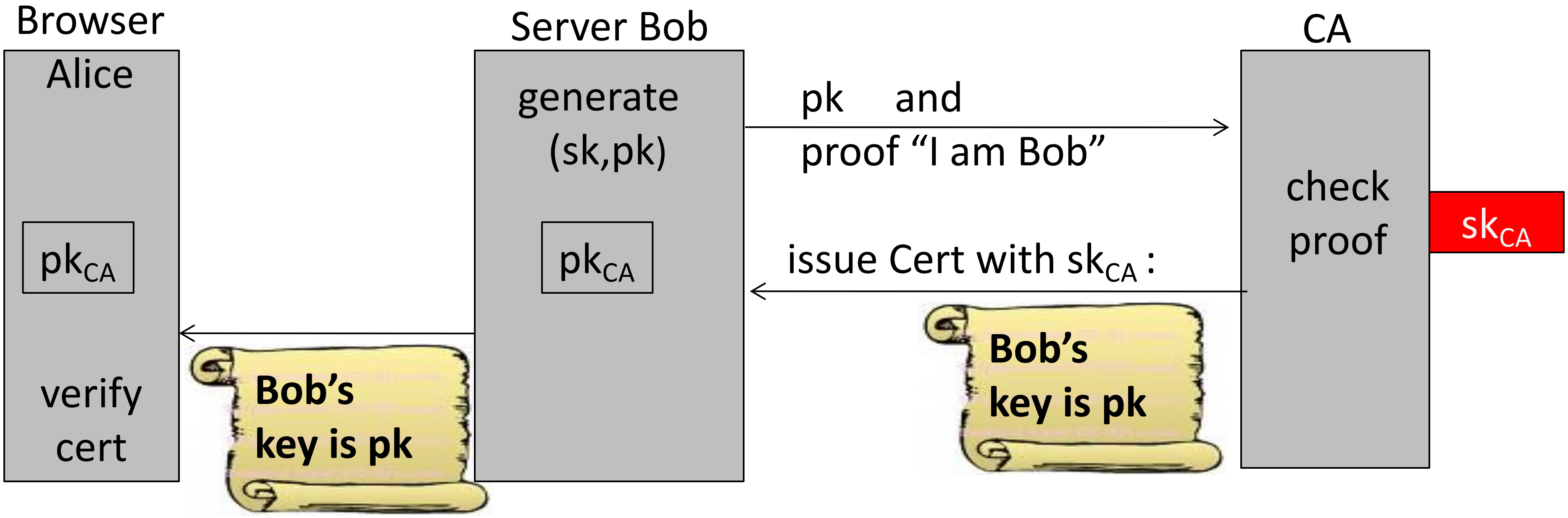
$$\text{verify}(pk, m, sig) \quad := \quad \text{accept if} \quad F(pk, sig) = H(m)$$

# Digital Sigs. from Trapdoor Functions



# Certificates: bind Bob's ID to his PK

How does Alice (browser) obtain Bob's public key $pk_{Bob}$ ?




**Bob uses Cert for an extended period** (e.g. one year)

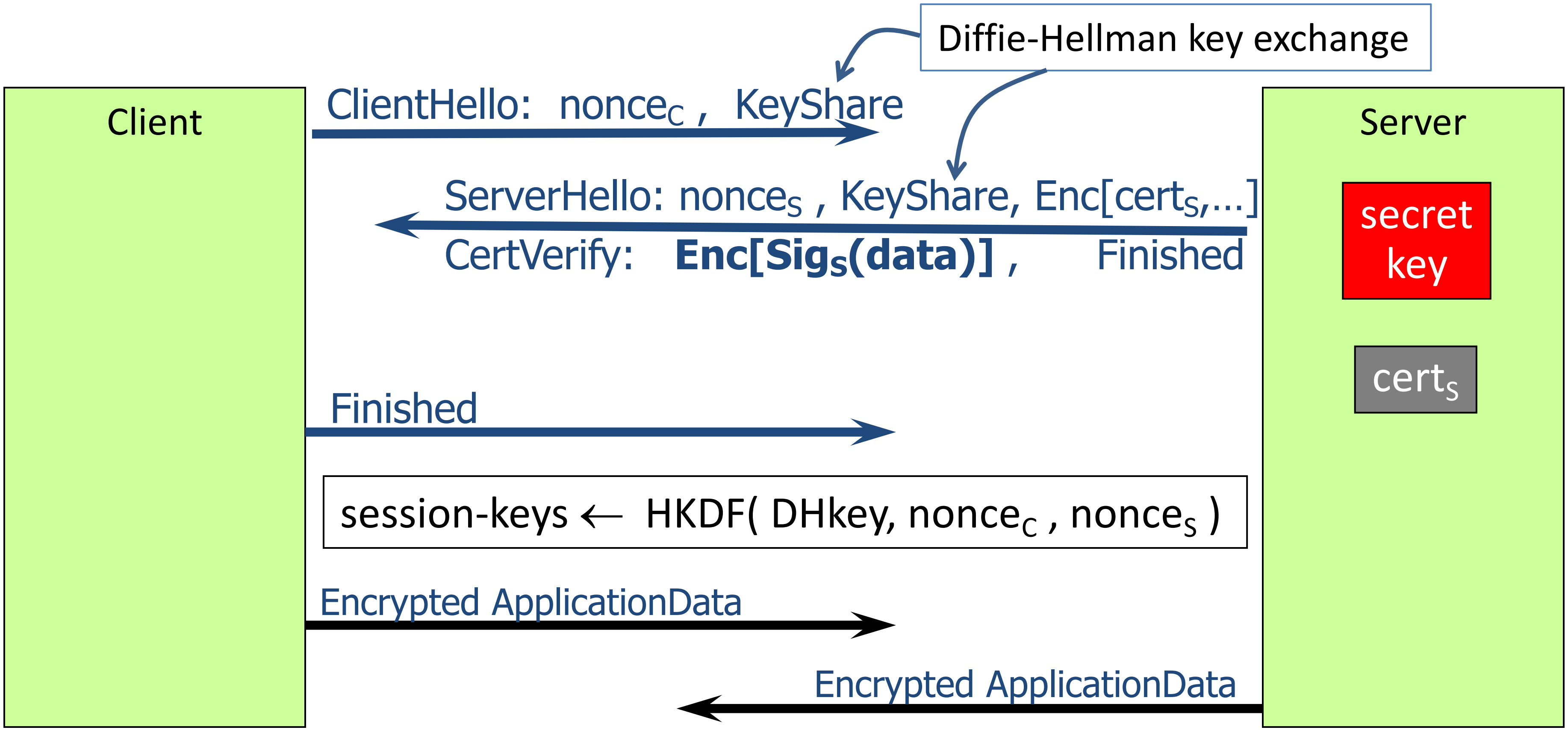
# Sample certificate:

**mail.google.com**
Issued by: Google Internet Authority G3
Expires: Wednesday, June 20, 2018 at 6:25:00 AM Pacific Daylight Time
This certificate is valid

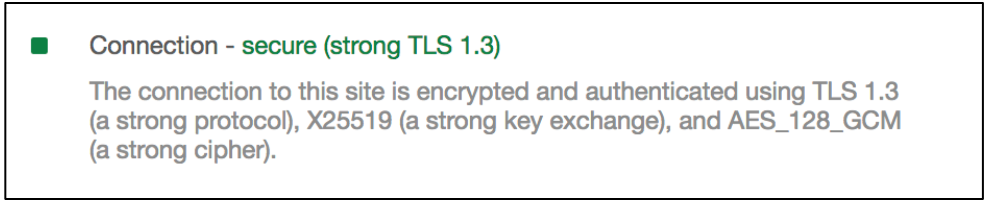
**Details**

| | |
|---|---|
| **Subject Name** | |
| Country | US |
| State/Province | California |
| Locality | Mountain View |
| Organization | Google Inc |
| Common Name | mail.google.com |
| **Issuer Name** | |
| Country | US |
| Organization | Google Trust Services |
| Common Name | Google Internet Authority G3 |
| Serial Number | 3495829599616174946 |
| Version | 3 |
| Signature Algorithm | SHA-256 with RSA Encryption |
| **Public Key Info** | |
| Algorithm | Elliptic Curve Public Key ( 1.2.840.10045.2.1 ) |
| Parameters | Elliptic Curve secp256r1 ( 1.2.840.10045.3.1.7 ) |
| Public Key | 65 bytes : 04 D5 63 FC 4D F9 4E 91 ... |
| Key Size | 256 bits |
| Key Usage | Encrypt, Verify, Derive |
| Signature | 256 bytes : 3F FE 04 7B BE B0 32 1D ... |

# TLS 1.3 session setup (simplified)



# Properties




Gmail

**Nonces**: prevent replay of an old session

**Forward secrecy**: server compromise does not expose old sessions

**Some identity protection**: certificates are sent encrypted

**One sided authentication**:

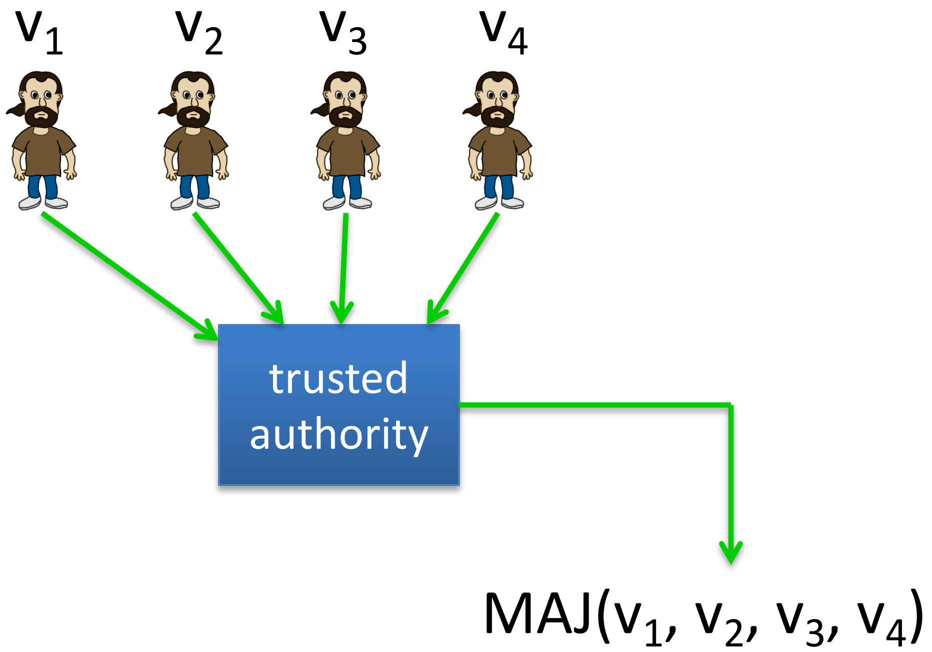
- Browser identifies server using server-cert
- TLS has support for mutual authentication
  - Rarely used: requires a client pk/sk and client-cert

# Crypto Concepts

## A brief sample of advanced crypto

# Protocols

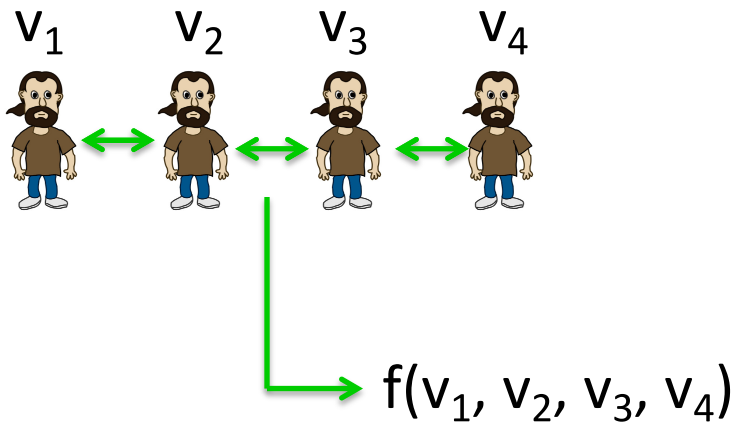
- Elections




Can we do the same without a trusted party?

# Protocols

- Elections
- Private auctions



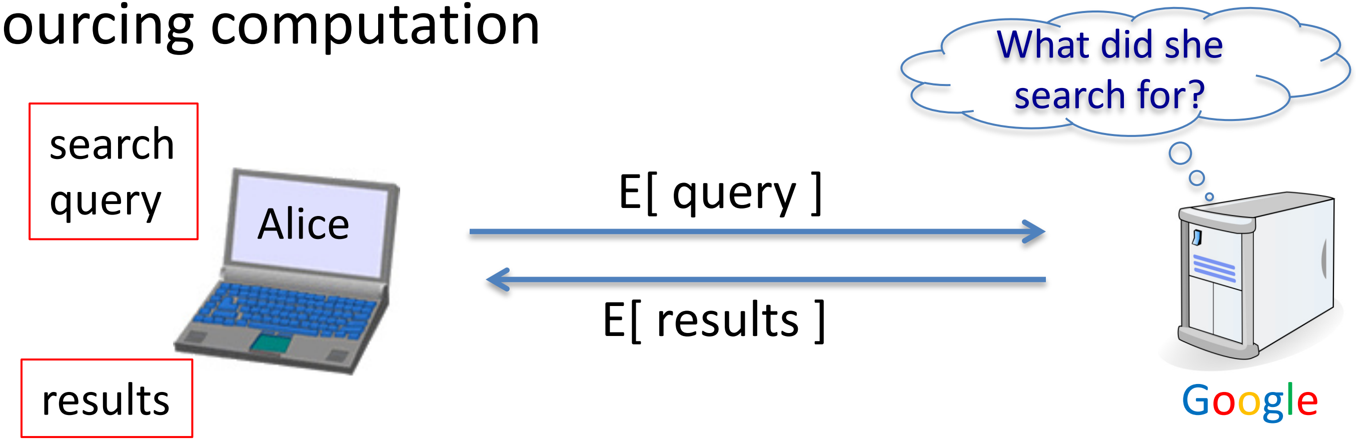

Goal: compute $f(v_1, v_2, v_3, v_4)$

"Thm:" anything that can be done with a trusted authority
can also be done without

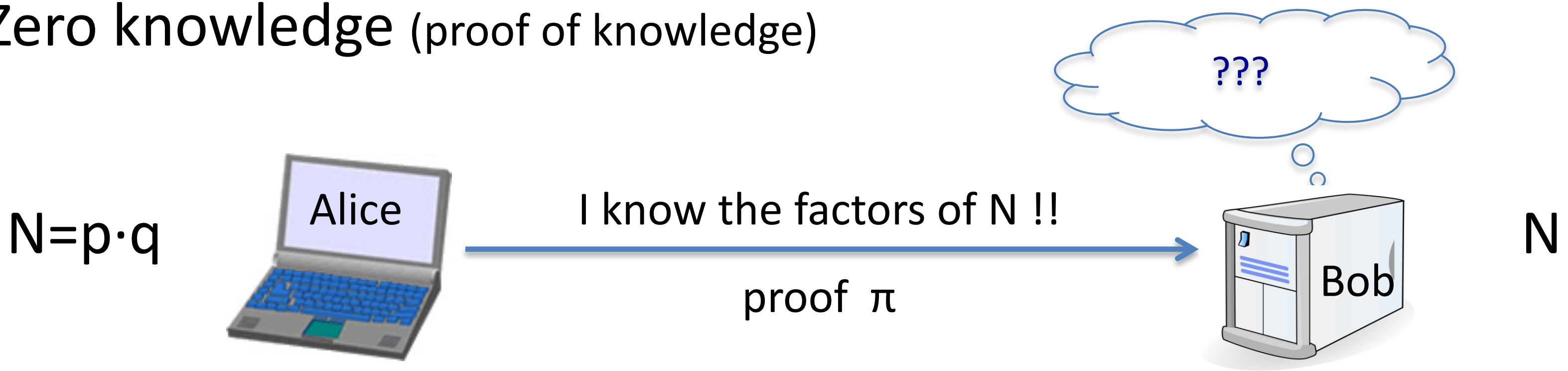
- Secure multi-party computation

# Magical applications

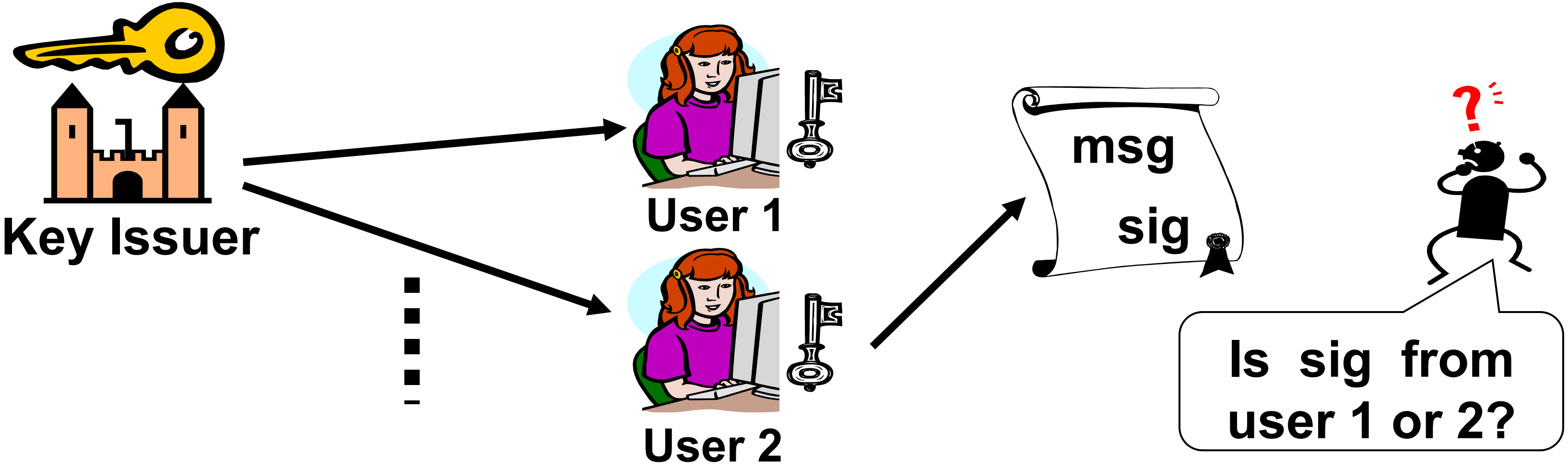
- Privately outsourcing computation




- Zero knowledge (proof of knowledge)



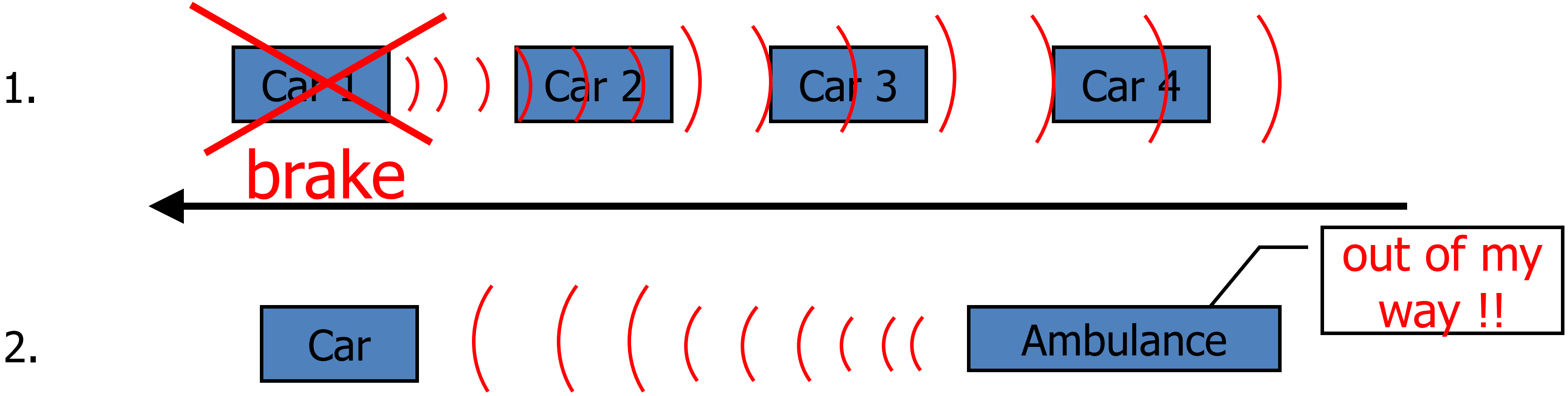
# Privacy: Group Signatures




Simple solution: give all users same private key

… but also need to revoke signers when they misbehave

# Example: Vehicle Safety Comm. (VSC)




Require authenticated (signed) messages from cars.

- Prevent impersonation and DoS on traffic system.

<u>Privacy problem</u>: cars broadcasting <u>signed</u> (x,y, **V**).

Clean solution: group sigs. Group = set of all cars.

# Summary: crypto concepts

Symmetric cryptography:

Authenticated Encryption (AE) and message integrity

Public-key cryptography:

Public-key encryption, digital signatures, key exchange

Certificates: bind a public key to an identity using a CA

- Used in TLS to identify server (and possibly client)

Modern crypto: goes far beyond basic encryption and signatures