Cryptography Overview

Cryptography

- Is
  - A tremendous tool
  - The basis for many security mechanisms
- Is not
  - The solution to all security problems
  - Reliable unless implemented properly
  - Reliable unless used properly
  - Something you should try to invent or implement yourself

Kerckhoff's principle

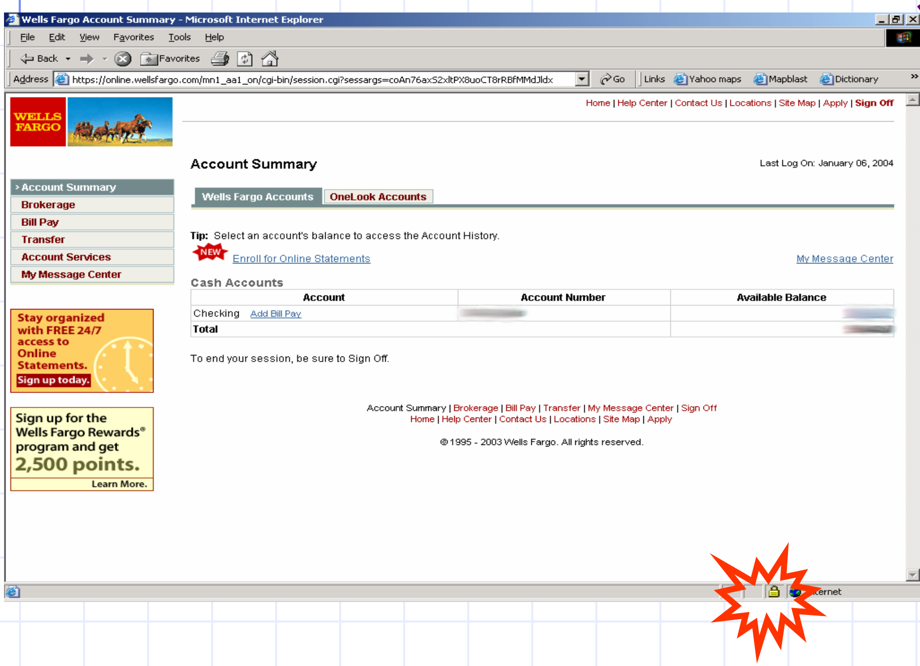
A cryptosystem should be secure even if **everything** about the system, except the secret key, **is public knowledge**.

Goal 1:secure communication

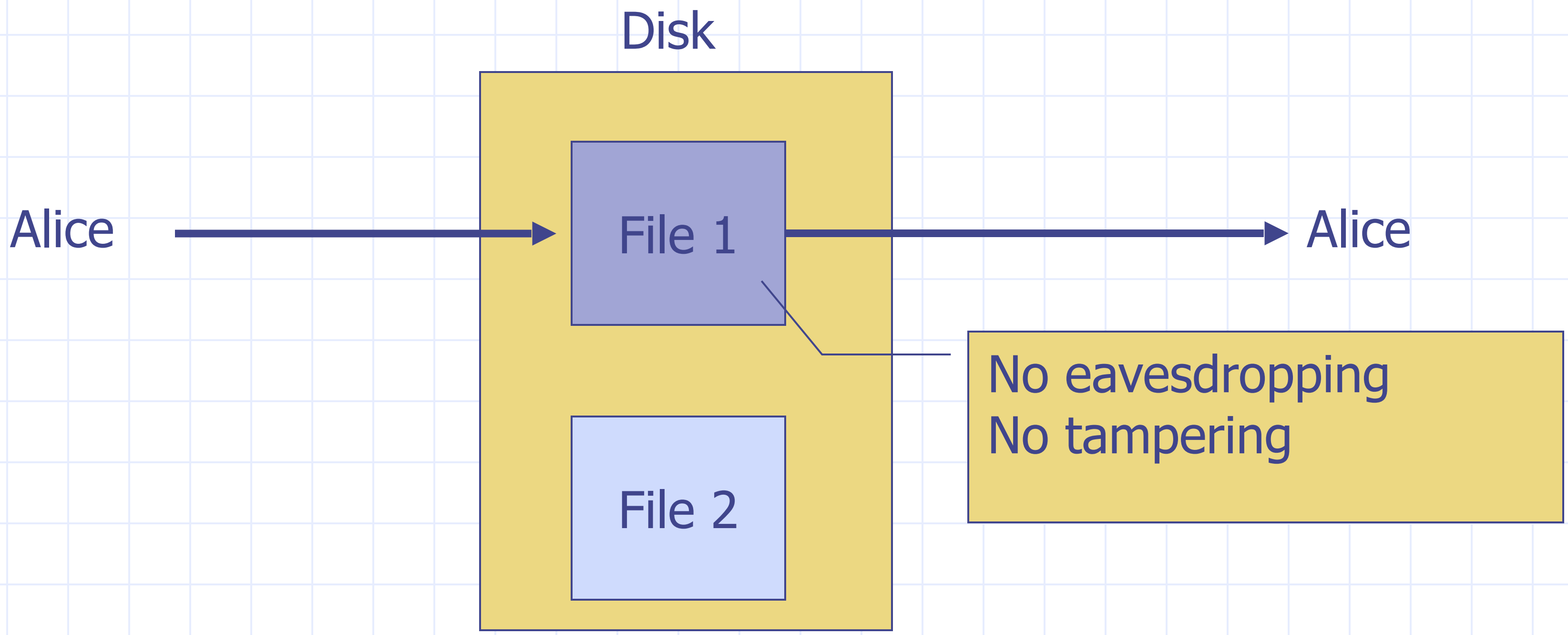
Step 1: Session setup to exchange key

Step 2: encrypt data

HTTPS



Goal 2: Protected files



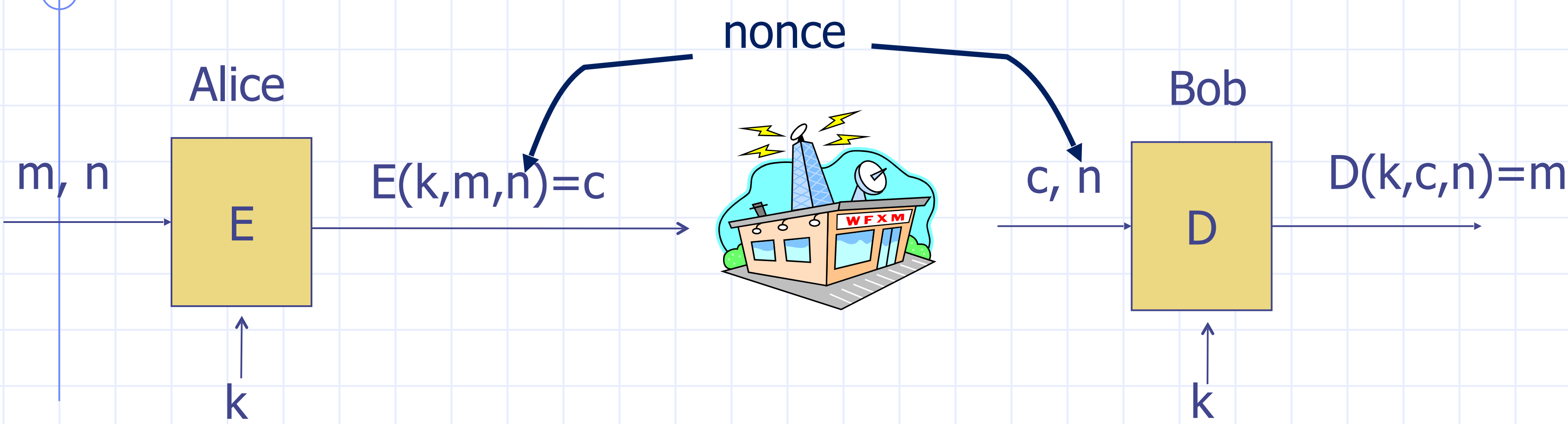
Analogous to secure communication:

Alice today sends a message to Alice tomorrow

Symmetric Cryptography

Assumes parties already share a secret key

Building block: sym. encryption



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

m, c: plaintext, ciphertext n: nonce (aka IV)

Encryption algorithm is **<u>publicly known</u>**

- 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
  - files: same key used to encrypt many files

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

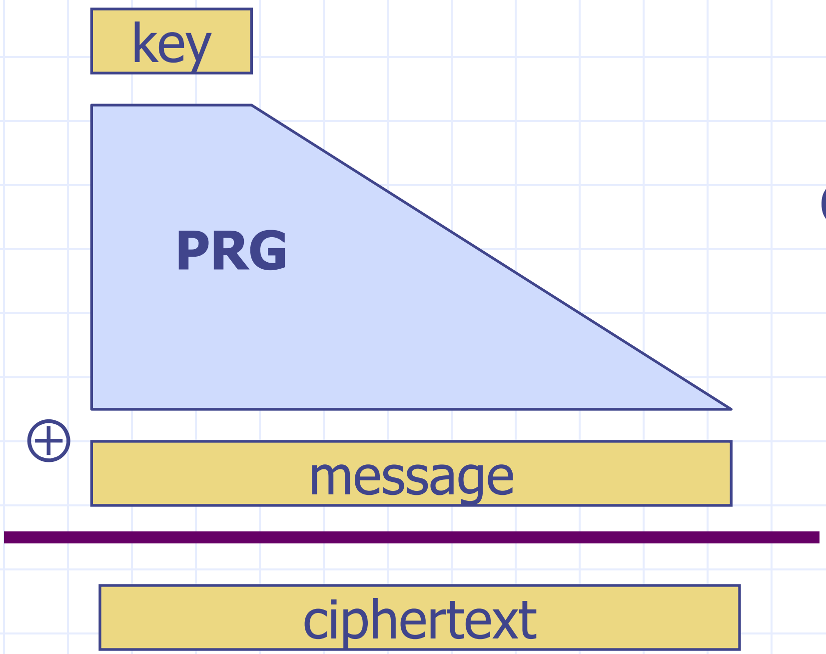
$\oplus$

- Shannon '49:
  - OTP is "secure" against ciphertext-only attacks

Stream ciphers (single use key)

Problem: OTP key is as long the message

Solution: Pseudo random key -- stream ciphers



$$c \longleftarrow \mathrm{PRG}(k) \oplus m$$

Stream ciphers: ChaCha (643 MB/sec)

Dangers in using stream ciphers

One time key !! "Two time pad" is insecure:

$$\begin{cases} C_1 \leftarrow m_1 \oplus PRG(k) \\ C_2 \leftarrow m_2 \oplus PRG(k) \end{cases}$$

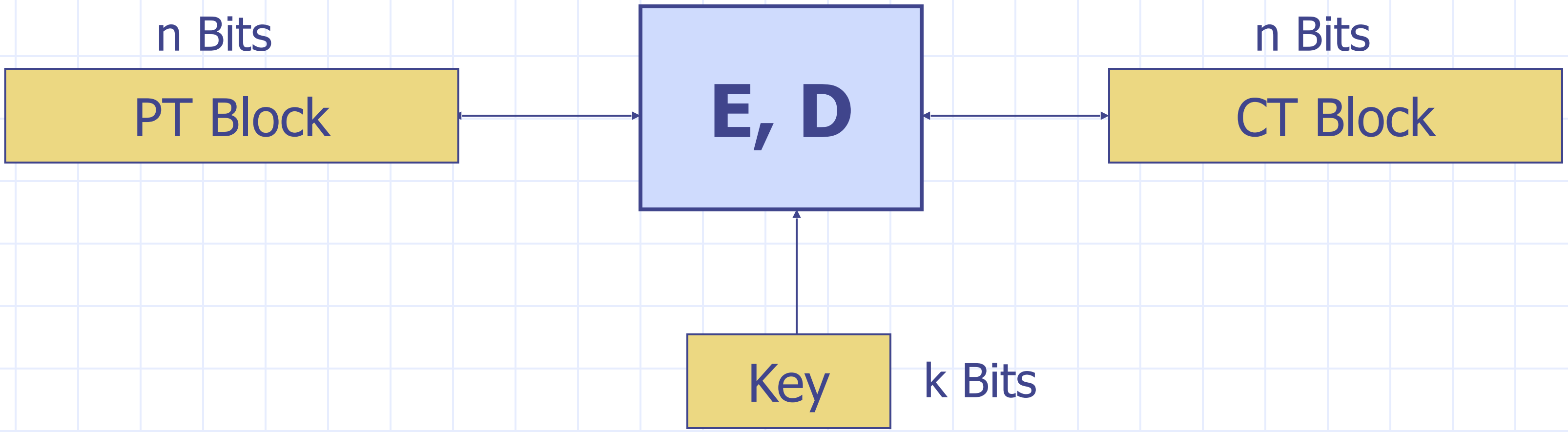
Eavesdropper does:

$$C_1 \oplus C_2 \Rightarrow m_1 \oplus m_2$$

Enough redundant information in English that:

$$m_1 \oplus m_2 \Rightarrow m_1 , m_2$$

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

IV handled as part of PT block

Building a block cipher

Input: (m, k)

Repeat simple "mixing" operation several times

- DES: Repeat 16 times:

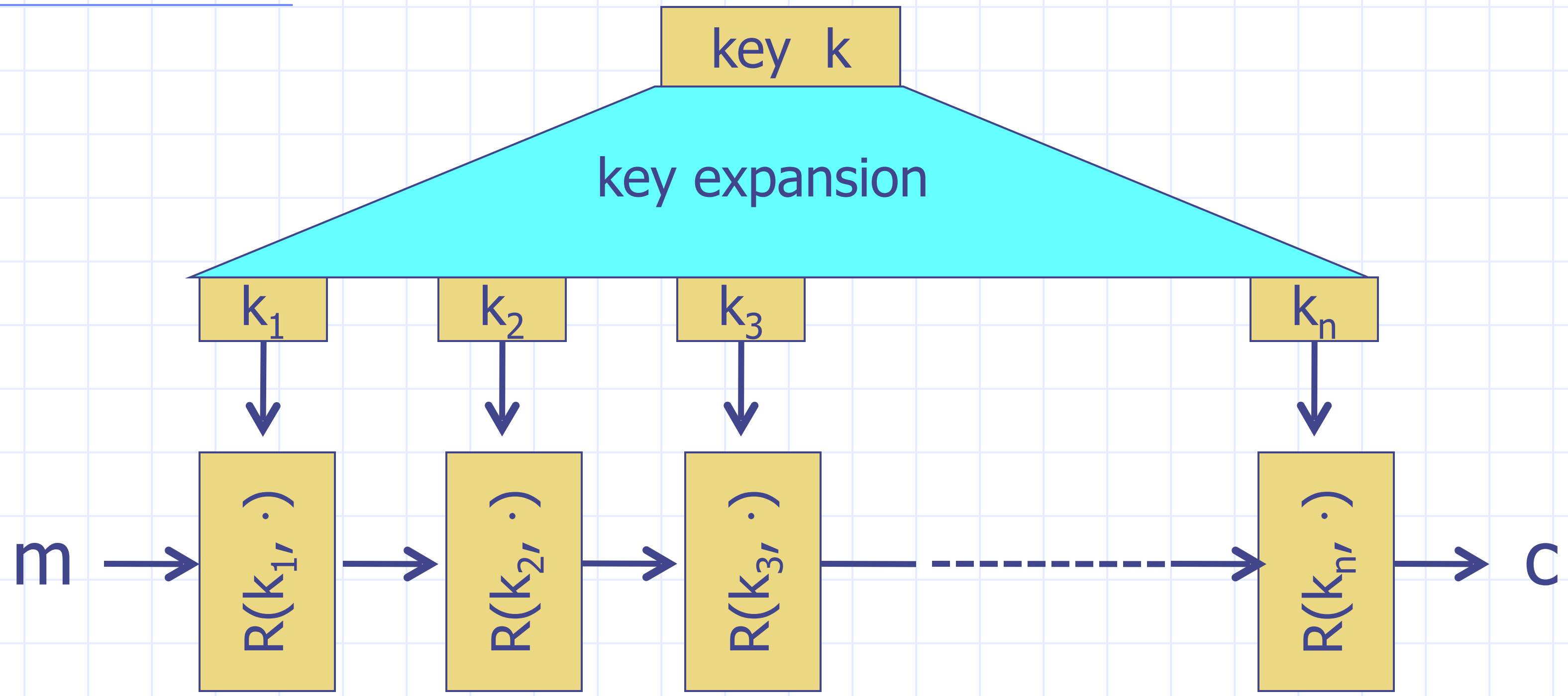
$$\begin{cases} m_L \longleftarrow m_R \\ m_R \longleftarrow m_L \oplus F(k, m_R) \end{cases}$$

- AES-128: Mixing step repeated 10 times

Difficult to design: must resist subtle attacks

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

Block Ciphers Built by Iteration

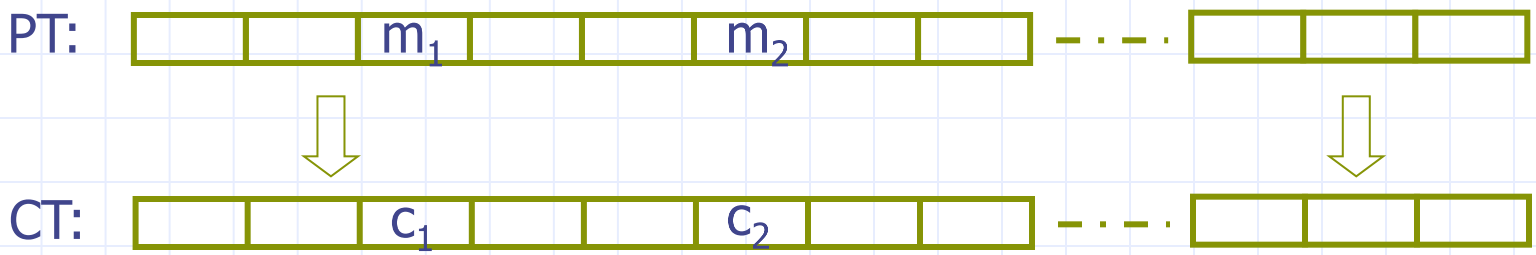


R(k,m): round function

for DES (n=16), for AES-128 (n=10)

Incorrect use of block ciphers

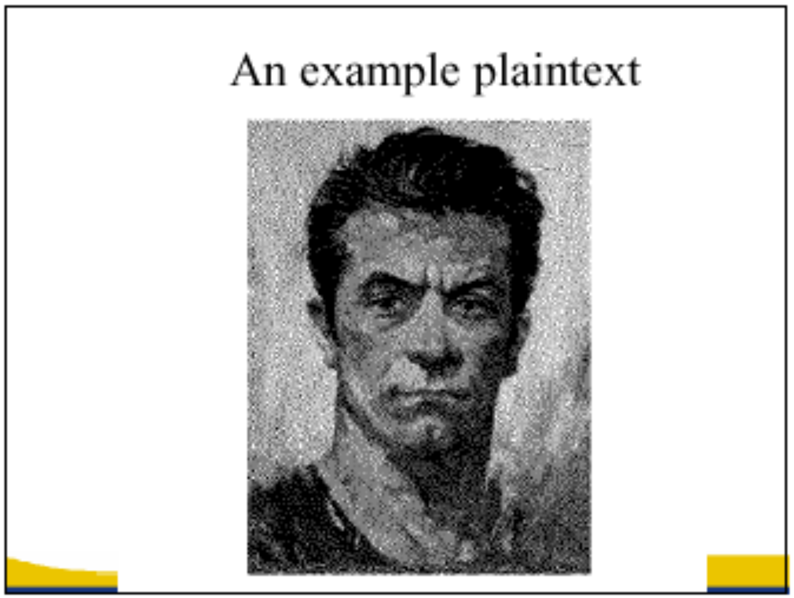
Electronic Code Book (ECB):

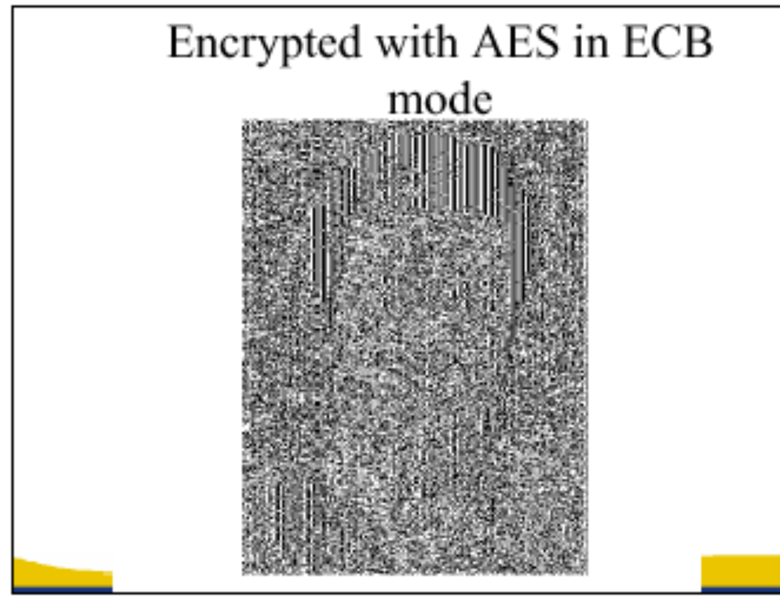


Problem:

- if $m_1=m_2$ then $c_1=c_2$

In pictures

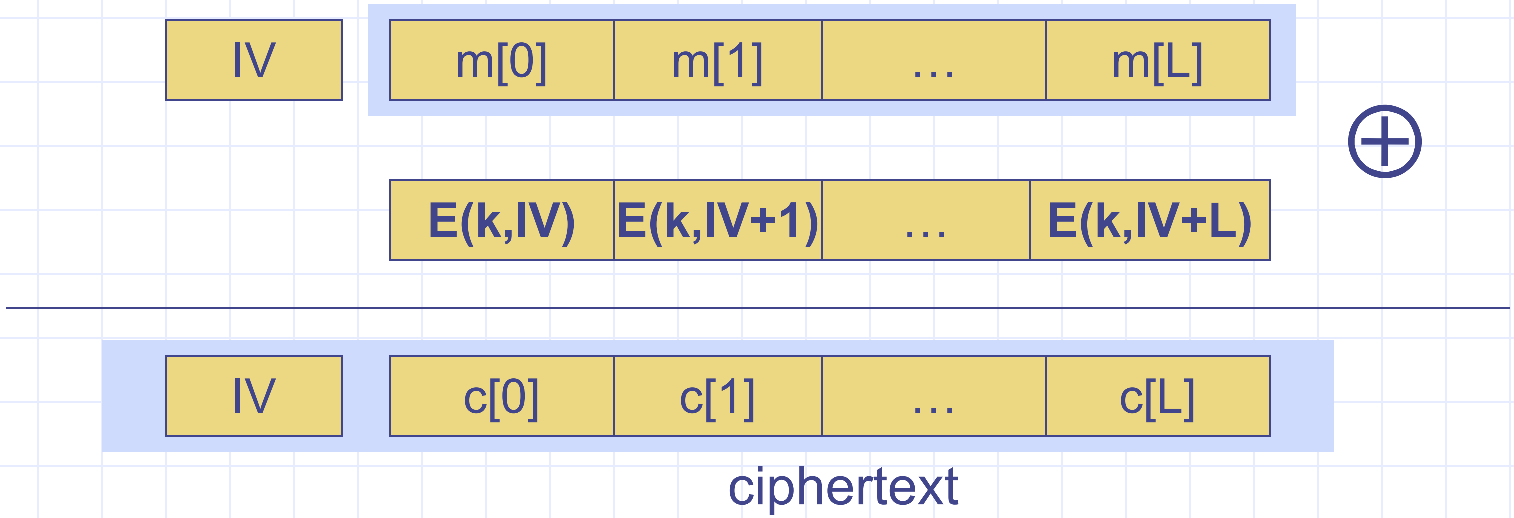




Correct use of block ciphers: CTR mode

E(k,x): maps key k and n-bit block x to a n-bit block y

Counter mode (CTR) with a random IV:



Note: Parallel encryption

Use cases: how to choose an IV

Single use key: no IV needed (IV=0)

Multi use key: (CPA Security)

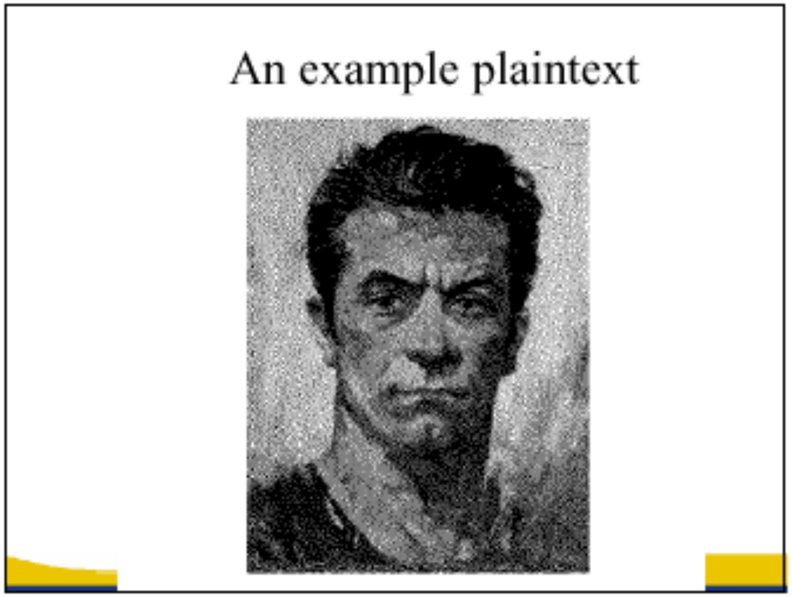
Best: use a fresh <u>random</u> IV for every message

Can use <u>unique</u> IV (e.g 0, 1, 2, 3, …)

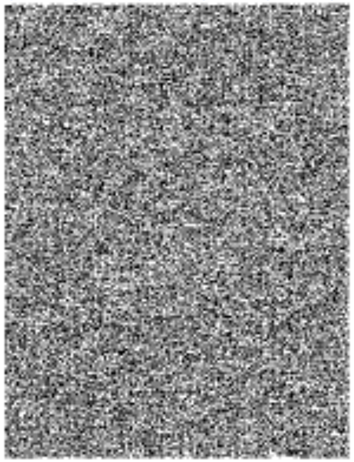
benefit: may save transmitting IV with ciphertext

$$\underbrace{\boxed{\text{uniqueIV}}\boxed{\text{counter}}}_{\text{128 bits}}$$

In pictures



encrypt with CTR



Why is CTR secure?   not today

Performance: [openssl speed]

Intel Core 2 (on Windows Vista)

Cipher	Block/key size	Speed (MB/sec)
ChaCha		643
3DES	64/168	30
AES-128/GCM	128/128	163

AES is dramatically faster with AES-NI instructions:

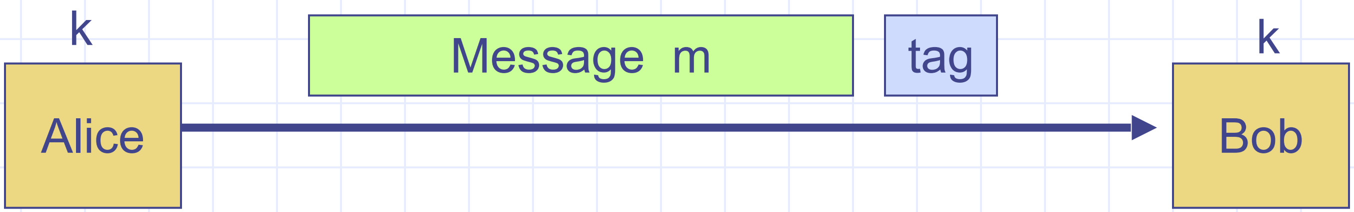
- Intel SkyLake: 4 cycles per round, fully pipelined

AESENC xmm15, xmm1

Data integrity

Message Integrity: MACs

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



Generate tag:

tag $\longleftarrow$ S(k, m)

Verify tag:

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

note: non-keyed checksum (CRC) is an insecure MAC !!

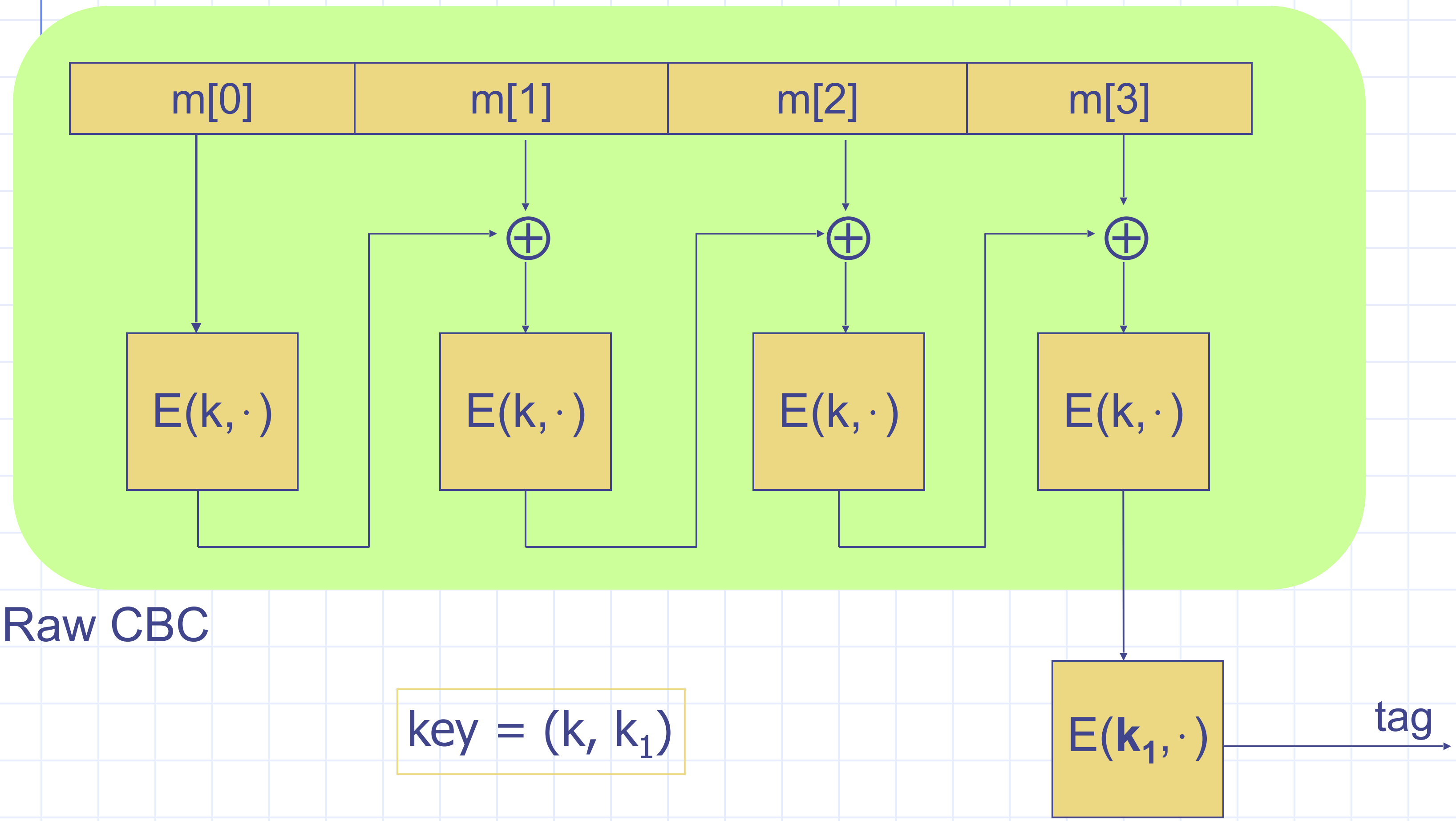
Secure MACs

- Attacker information: chosen message attack
  - for $m_1, m_2, \ldots, m_q$ attacker is given $t_i \longleftarrow S(k, m_i)$
- Attacker's goal: existential forgery.
  - produce some **new** valid message/tag pair (m,t).

$$(m,t) \in \{ (m_1,t_1), \ldots, (m_q,t_q) \}$$

- A secure PRF gives a secure MAC:
  - $S(k,m) = F(k,m)$
  - $V(k,m,t)$: \`yes' if $t = F(k,m)$ and \`no' otherwise.

Construction 1: ECBC



key = (k, k_1)

Construction 2: HMAC (Hash-MAC)

Most widely used MAC on the Internet.

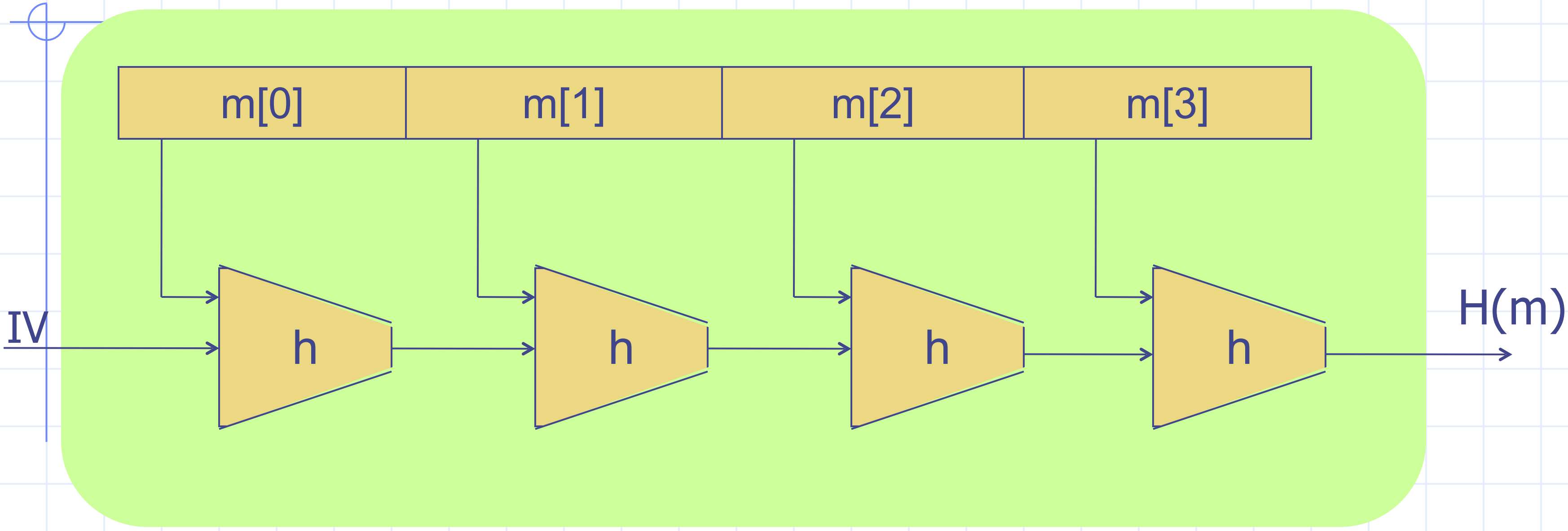
H: hash function.
example: SHA-256 ; output is 256 bits

Building a MAC out of a hash function:

Standardized method: HMAC

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

SHA-256: Merkle-Damgard



h(t, m[i]): compression function

Thm 1: if h is collision resistant then so is H

"Thm 2": if h is a PRF then HMAC is a PRF

Why are these MAC constructions secure?

… not today – take CS255

Why the last encryption step in ECBC?

- CBC (aka Raw-CBC) is not a secure MAC:
  - Given tag on a message m, attacker can deduce tag for some other message m'
  - How: good crypto exercise …

Authenticated Encryption:
Encryption + MAC

Combining MAC and ENC (CCA)

Encryption key K_E MAC key = K_I

Option 1: MAC-then-Encrypt (SSL)

MAC(M,K_I) Enc K_E

Msg M ⇨ Msg M MAC ⇨

Option 2: Encrypt-then-MAC (IPsec)

Enc K_E MAC(C, K_I)

Msg M ⇨ ⇨ MAC

Secure for all secure primitives

Option 3: Encrypt-and-MAC (SSH)

Enc K_E MAC(M, K_I)

Msg M ⇨ ⇨ MAC

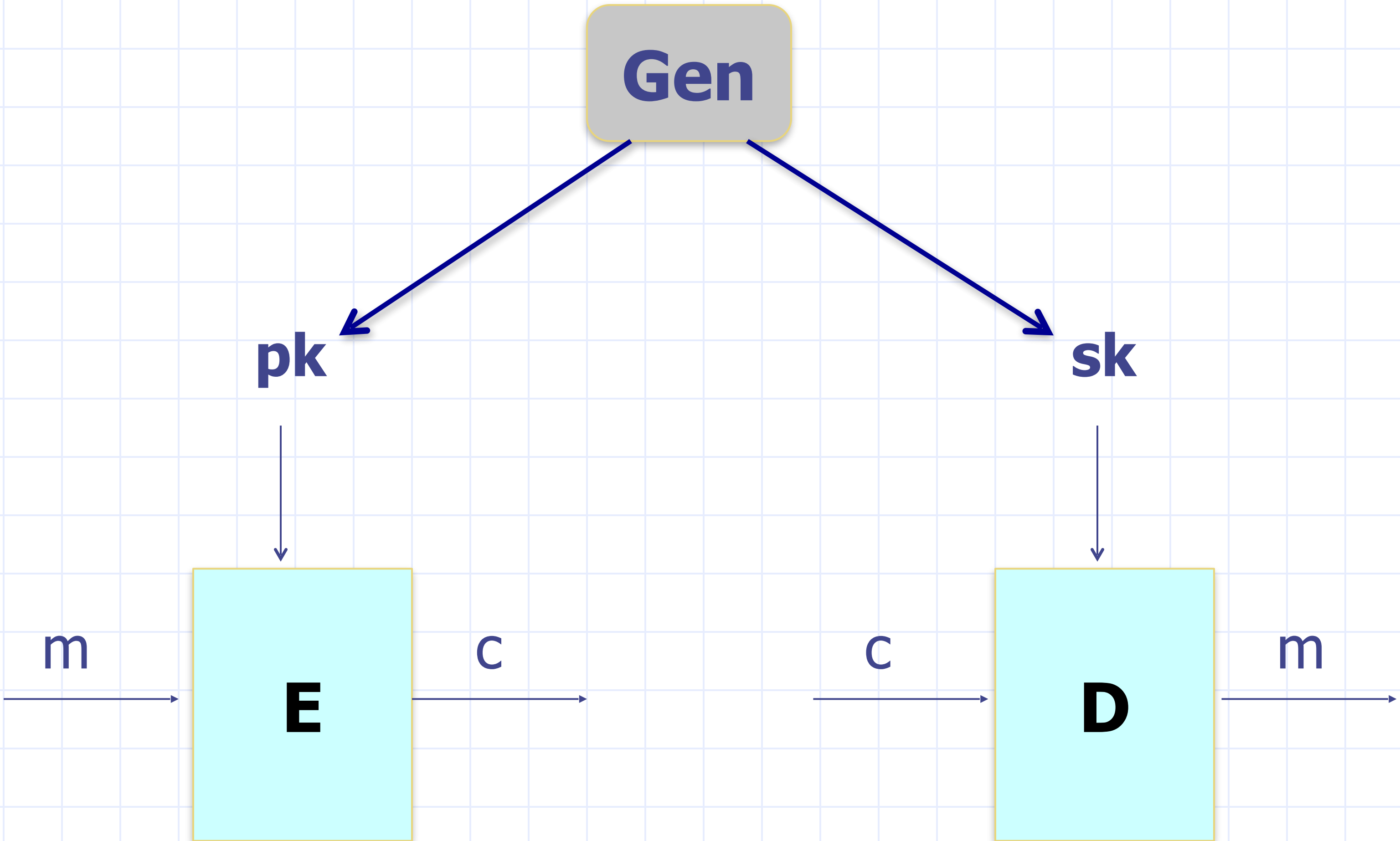
Recommended mode (currently)

AES-GCM:

- encrypt-then-MAC
- Counter mode AES
- Carter-Wagman MAC

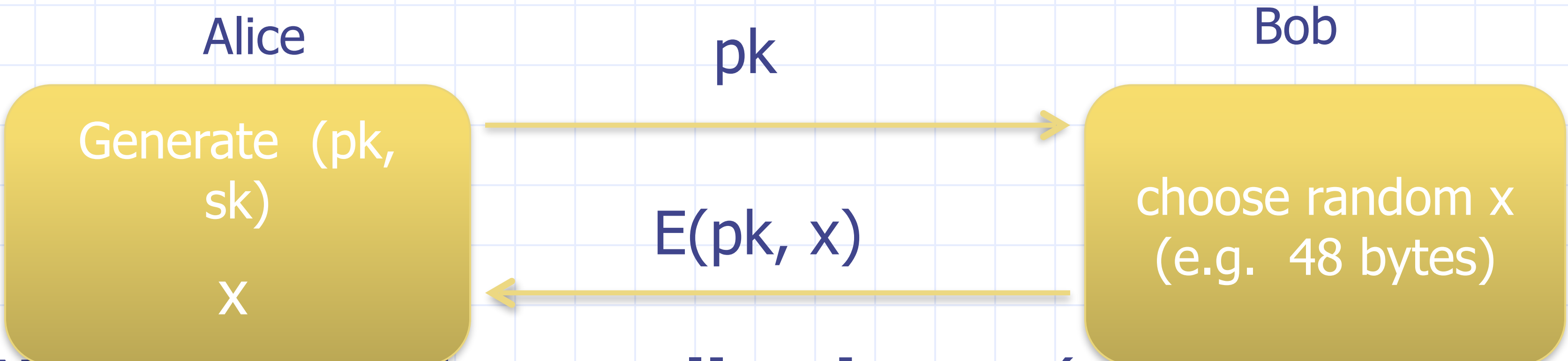
Public-key Cryptography

Public key encryption: (Gen, E, D)



Applications

Session setup (for now, only eavesdropping security)



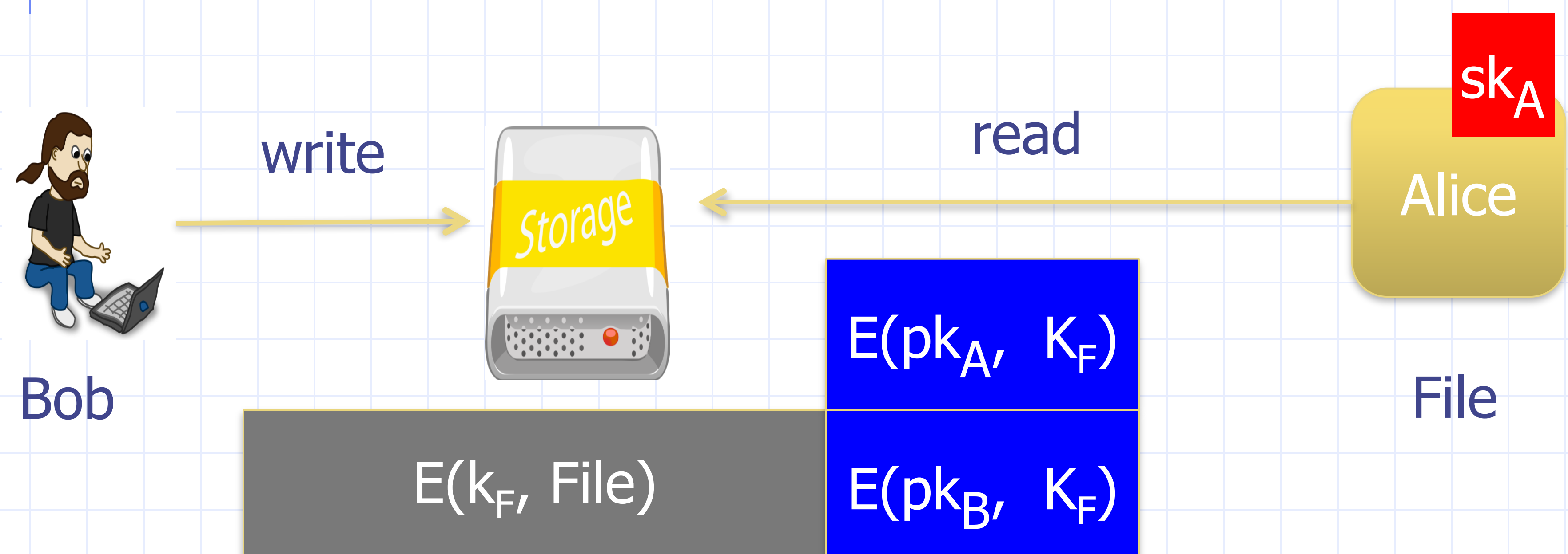
Non-interactive applications: (e.g. Email)

- Bob sends email to Alice encrypted using pk_{alice}
- Note: Bob needs pk_{alice} (public key management)

Applications

Encryption in non-interactive settings:

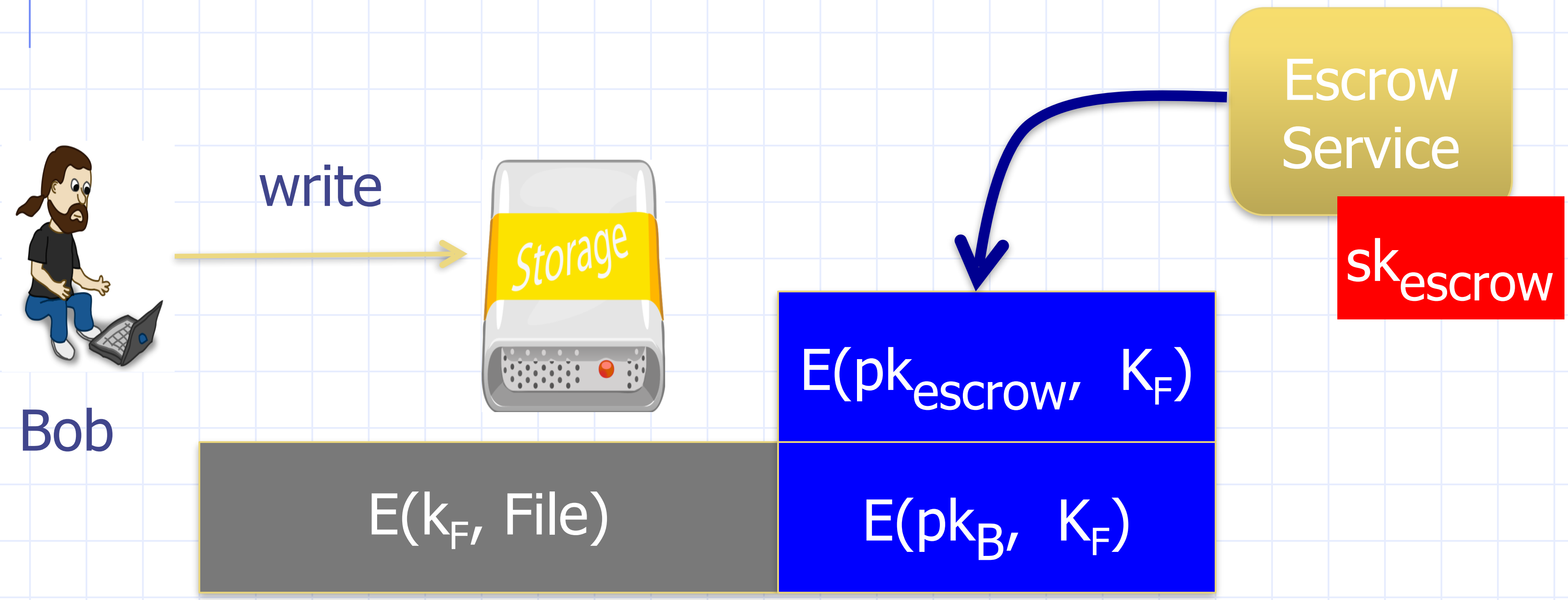
- Encrypted File Systems



Applications

Encryption in non-interactive settings:

- Key escrow: data recovery without Bob's key



Trapdoor functions (TDF)

<u>Def</u>: a trapdoor func. $X \longrightarrow Y$ is a triple of efficient algs. (G, F, F^{-1})

- $G()$: randomized alg. outputs key pair (pk, sk)
- $F(pk, \cdot)$: det. alg. that defines a func. $X \longrightarrow Y$
- $F^{-1}(sk, \cdot)$: func. $Y \longrightarrow X$ that inverts $F(pk, \cdot)$

Security: $F(pk, \cdot)$ is one-way without sk

Public-key encryption from TDFs

- (G, F, F^{-1}): secure TDF $X \longrightarrow Y$
- (E_s, D_s) : symm. auth. encryption with keys in K
- $H: X \longrightarrow K$ a hash function

We construct a pub-key enc. system (G, E, D):

Key generation G: same as G for TDF

Public-key encryption from TDFs

- (G, F, F^{-1}): secure TDF $X \longrightarrow Y$
- (E_s, D_s) : symm. auth. encryption with keys in K
- $H: X \longrightarrow K$ a hash function

E(pk, m) :

$x \xleftarrow{R} X, \quad y \longleftarrow F(pk, x)$

$k \longleftarrow H(x), \quad c \longleftarrow E_s(k, m)$

output (y, c)

D(sk, (y,c)) :

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

$k \longleftarrow H(x), \quad m \longleftarrow D_s(k, c)$

output m

In pictures:

$$\underbrace{\boxed{F(pk, x)}}_{\text{header}}\underbrace{\boxed{E_s(\ H(x),\ \ m\ )}}_{\text{body}}$$

Security Theorem:

If **(G, F, F^{-1})** is a secure TDF,

(E_s, D_s) provides auth. enc.

and **H:** $X \longrightarrow K$ is a "random oracle"

then **(G,E,D)** is CCA^{ro} secure.

Digital Signatures

- Public-key encryption
  - Alice publishes encryption key
  - Anyone can send encrypted message
  - Only Alice can decrypt messages with this key
- Digital signature scheme
  - Alice publishes key for verifying signatures
  - Anyone can check a message signed by Alice
  - Only Alice can send signed messages

Digital Signatures from TDPs

- (G, F, F^{-1}): secure TDP $X \longrightarrow X$
- $H: M \longrightarrow X$ a hash function

Sign(sk, $m \in X$) :

output

$$sig = F^{-1}\big(sk, H(m)\big)$$

Verify(pk, m, sig) :

output

$$\begin{cases} 1 & \text{if} \quad H(m) = F(pk, sig) \\ 0 & \text{otherwise} \end{cases}$$

Security: existential unforgeability under a chosen message attack (in the random oracle model)

Public-Key Infrastructure (PKI)

- Anyone can send Bob a secret message

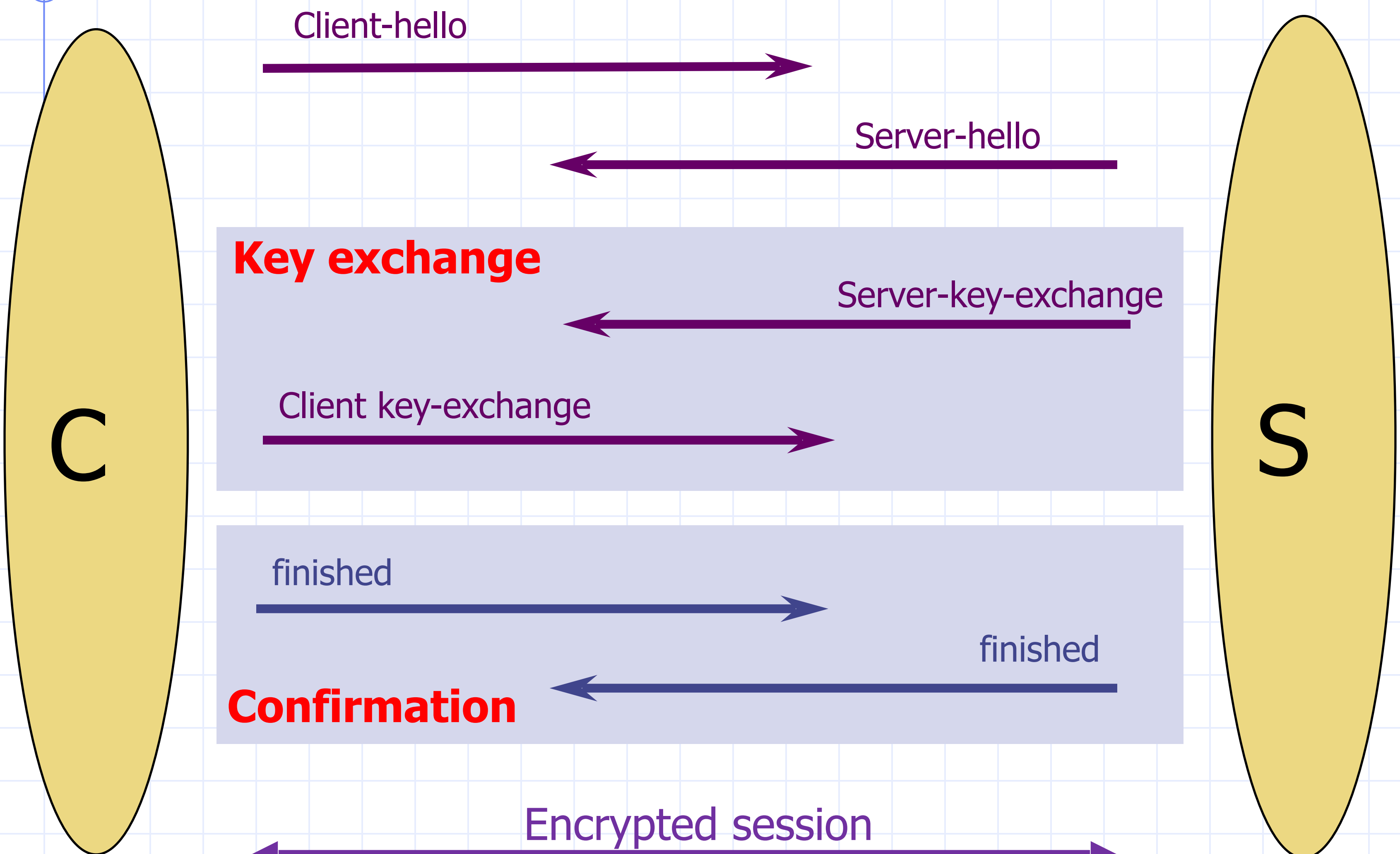
  … provided they know Bob's public key

- How do we know a key belongs to Bob?
  - If imposter substitutes another key, can read Bob's messages

- One solution: **PKI**
  - Trusted root Certificate Authority (CA)
  - CA certifies that a given public-key belongs to Bob

… more on this next time

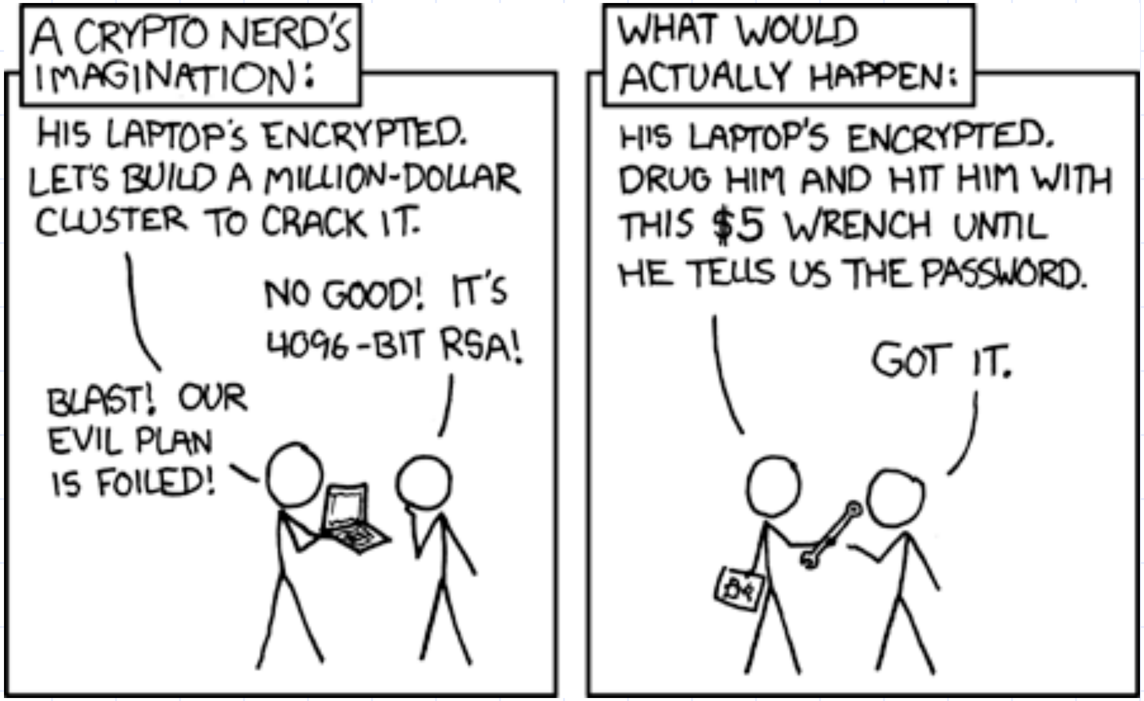
Putting it all together: SSL/TLS (simplified)



Limitations of cryptography

Cryptography works when used correctly !!

… but is not the solution to all security problems



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