CS155

# Cryptography Overview

*Acknowledgments: Lecture slides are from the Computer Security course thought by Dan Boneh and John Mitchell at Stanford University. When slides are obtained from other sources, a  a reference will be noted on the bottom of that slide. A full list of references is provided on the last slide.*

# 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

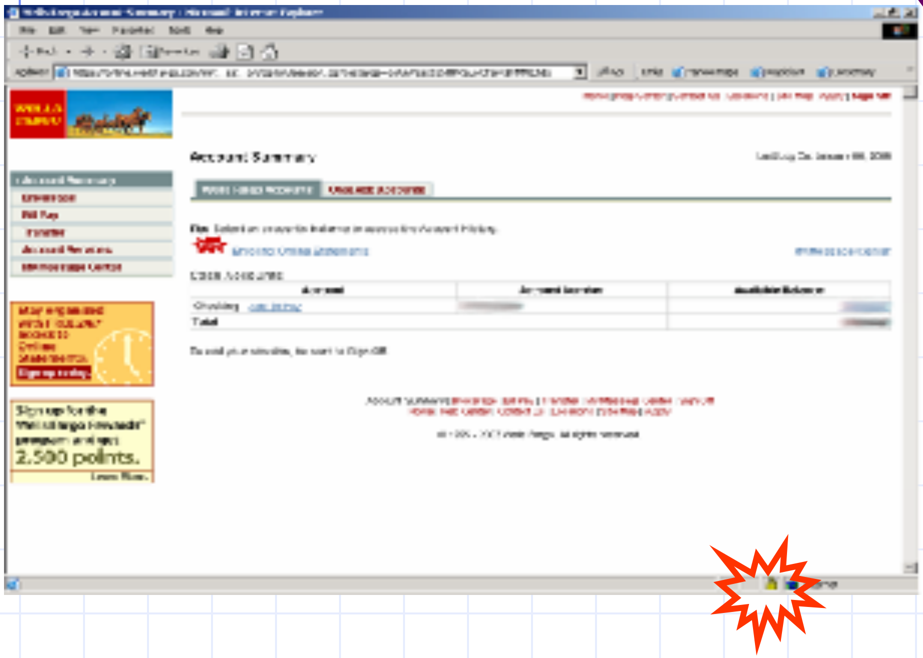
# Kerckhoff's principle

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

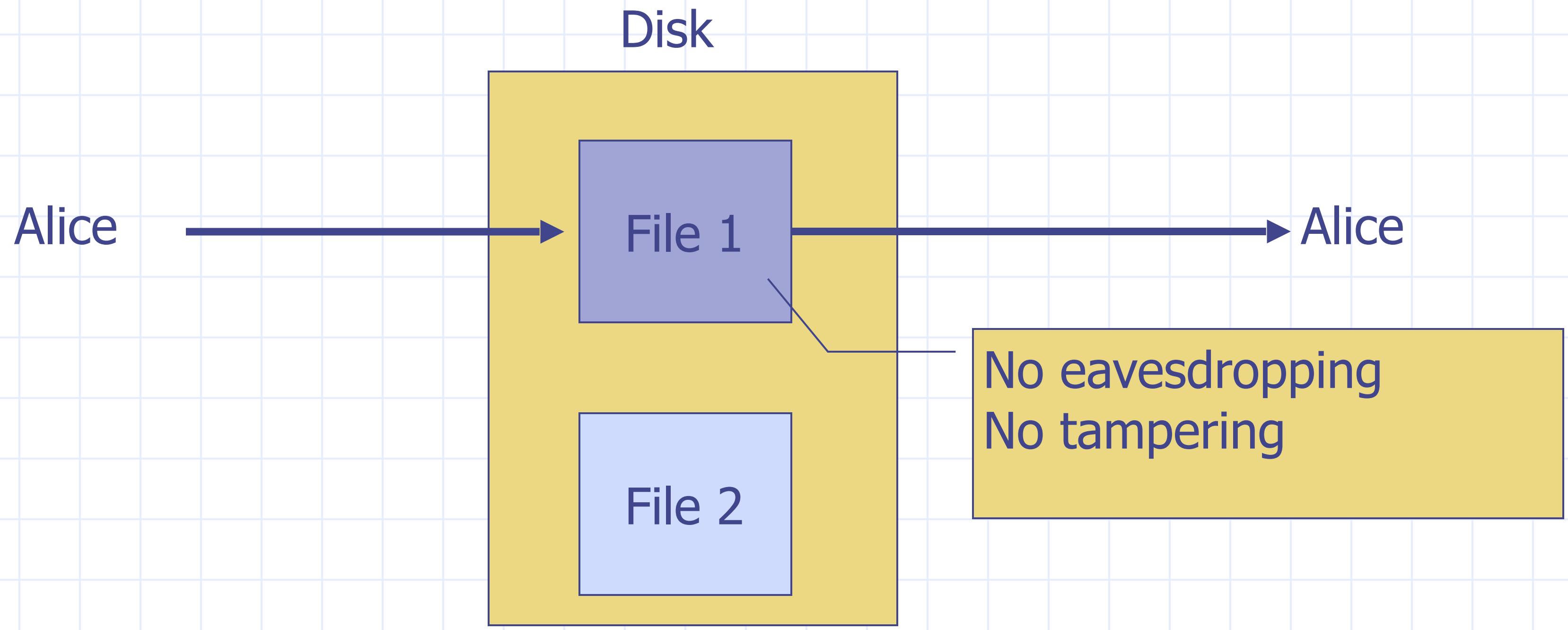
# Goal 1:secure communication

Step 1: Session setup to exchange key

Step 2: encrypt data



# Goal 2: Protected files



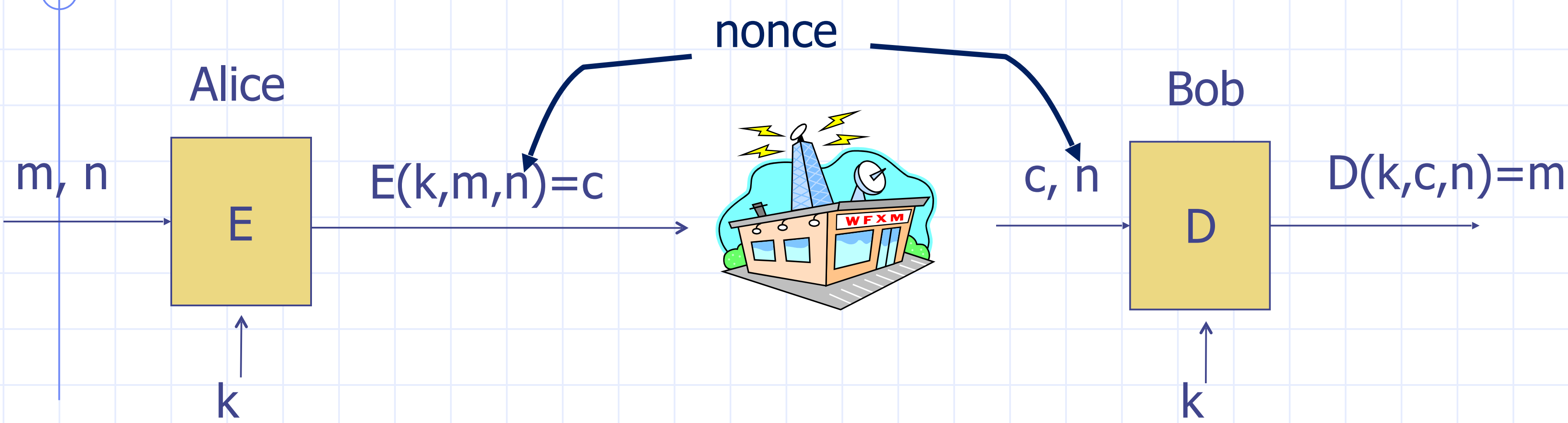

Analogous to secure communication:

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 |

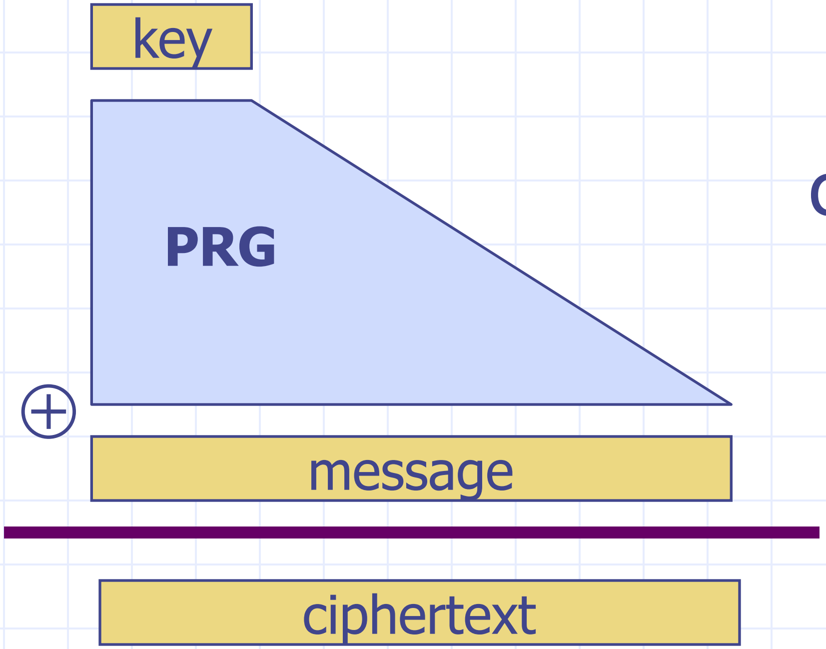
$\oplus$

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

# Stream ciphers (single use key)

Problem: OTP key is not as long as the message

Solution: Pseudo random key -- stream ciphers




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

Stream ciphers: RC4 (126 MB/sec) , Salsa20/12 (643 MB/sec)

# Dangers in using stream ciphers

One time key !!

"Two time pad" is insecure:

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

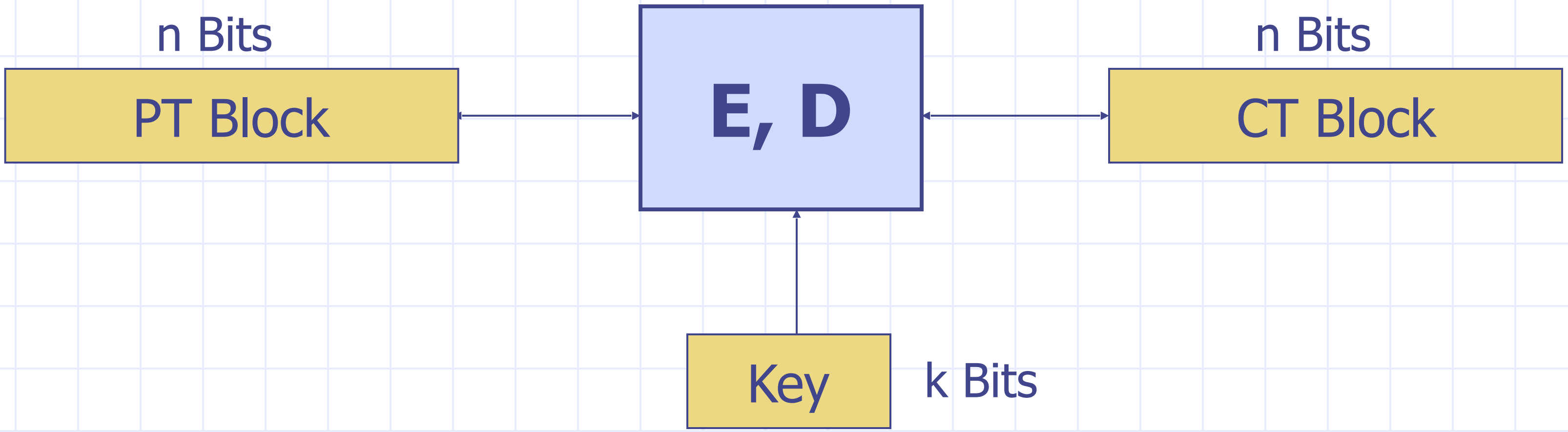
Eavesdropper does:

$$C_1 \oplus C_2 \quad \rightarrow \quad m_1 \oplus m_2$$

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

IV handled as part of PT block

# Building a block cipher

Input: (m, k)

Repeat simple "mixing" operation several times

- DES: Repeat 16 times:

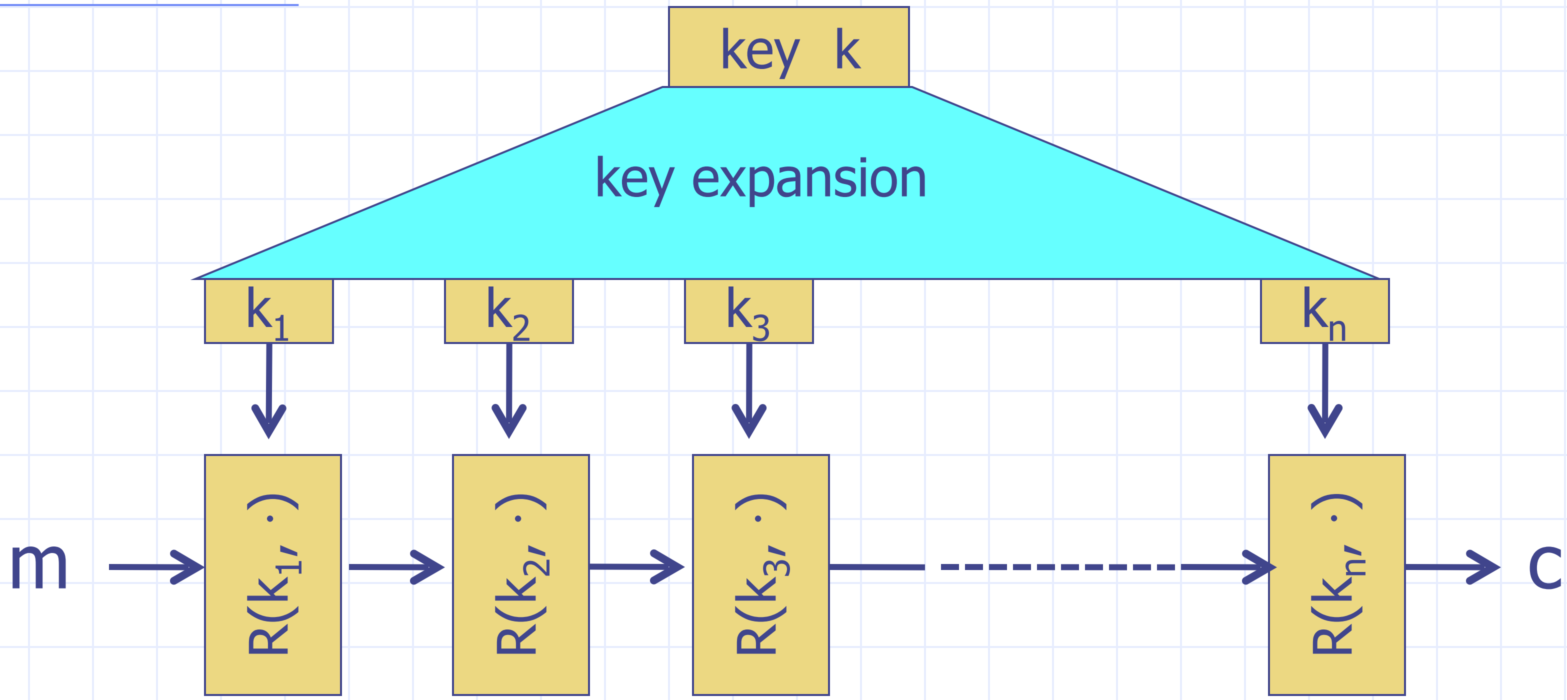
$$\begin{cases} m_L \leftarrow m_R \\ m_R \leftarrow m_L \oplus F(k, m_R) \end{cases}$$

- 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

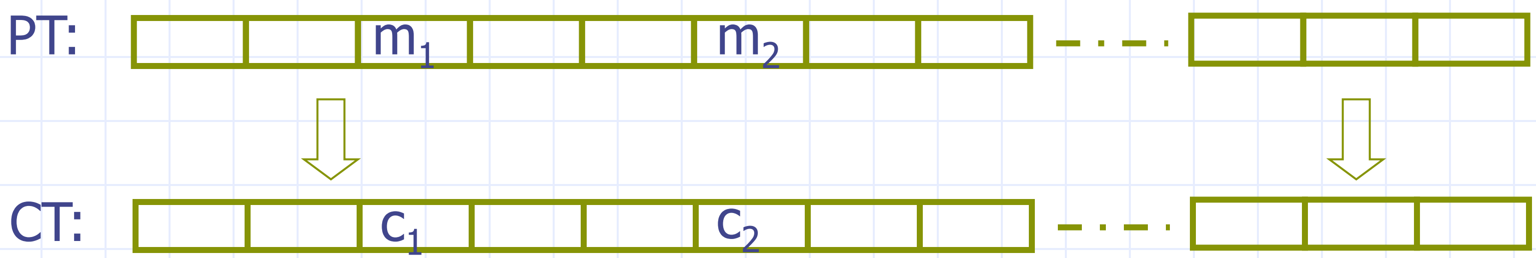



R(k,m): round function

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

# Incorrect use of block ciphers

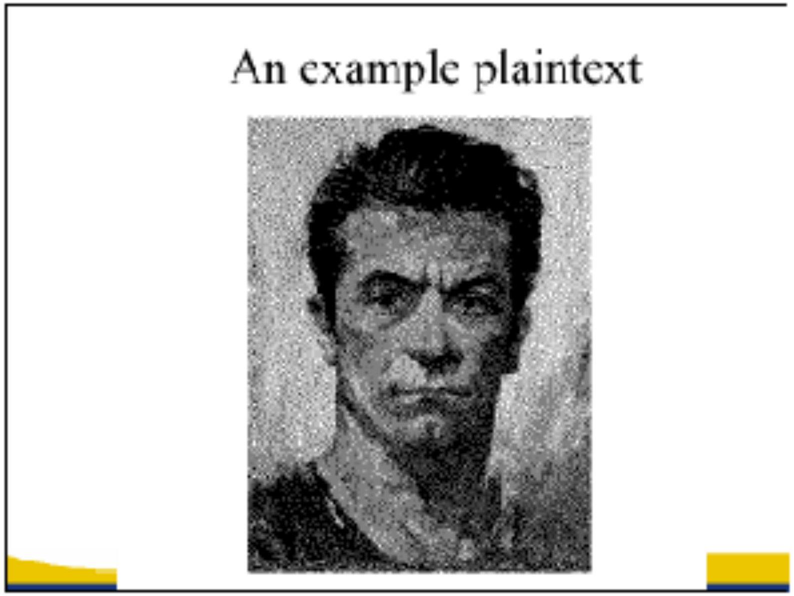
## Electronic Code Book (ECB):

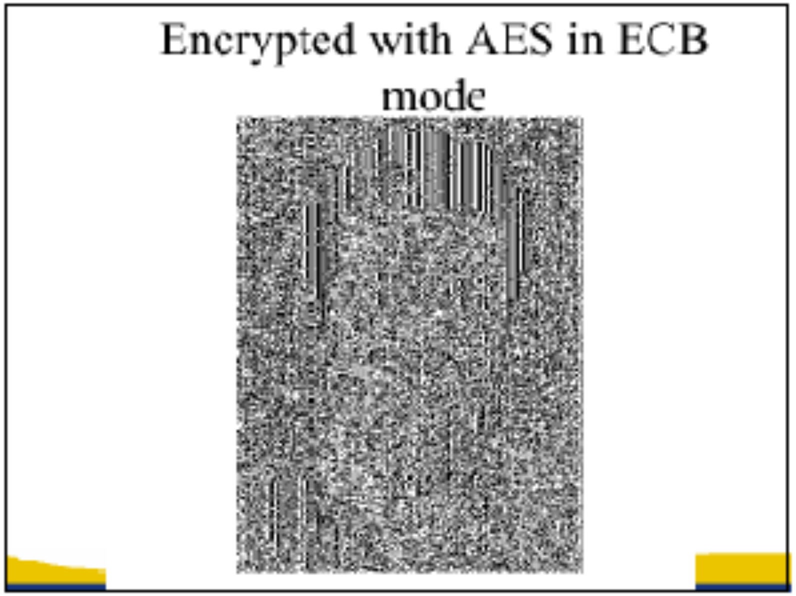



<u>Problem</u>:

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

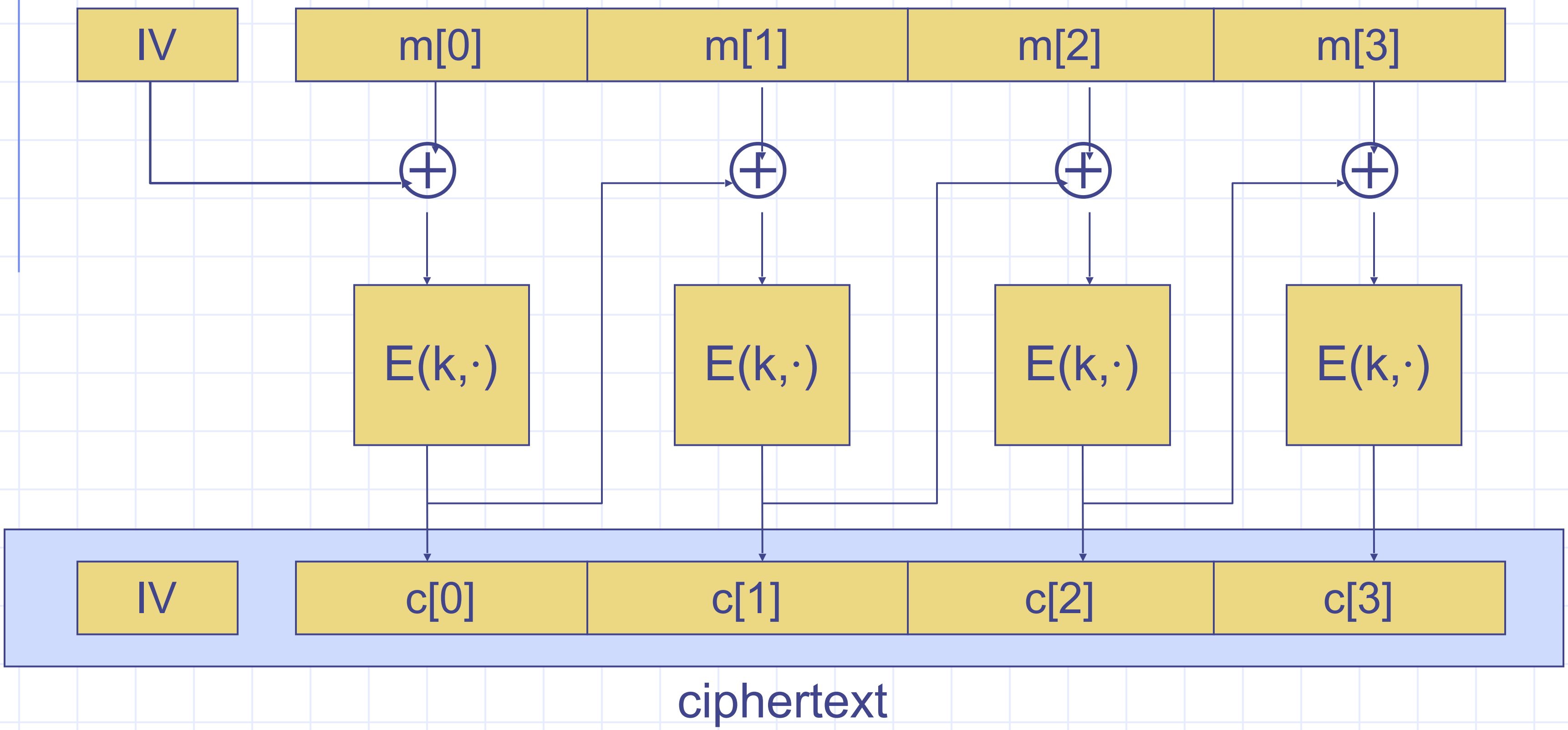
# In pictures



# Correct use of block ciphers I: CBC mode

E a secure PRP. Cipher Block Chaining with random IV:




Q: how to do decryption?

# Use cases: how to choose an IV

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

Multi use key: (CPA Security)

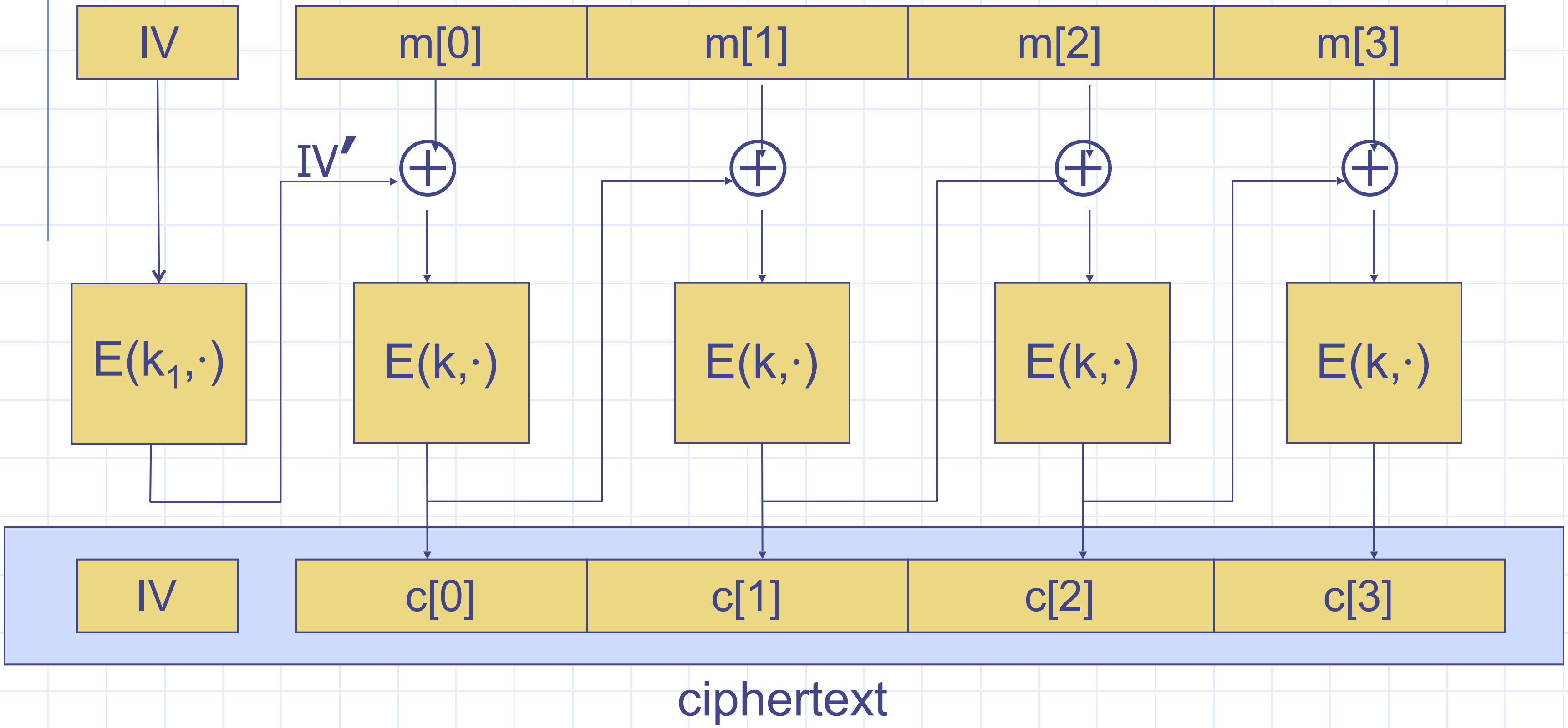
Best: use a fresh <u>random</u> IV for every message

Can use <u>unique</u> IV (e.g counter)

but then first step in CBC <u>must be</u> $IV' \leftarrow E(k_1, IV)$

# CBC with Unique IVs

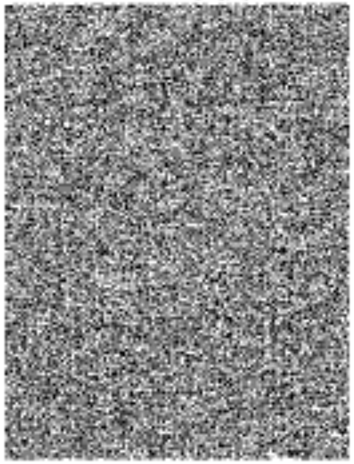
unique IV means: (k,IV) pair is used for only one message.
generate unpredictable IV′ as $E(k_1,IV)$



# In pictures

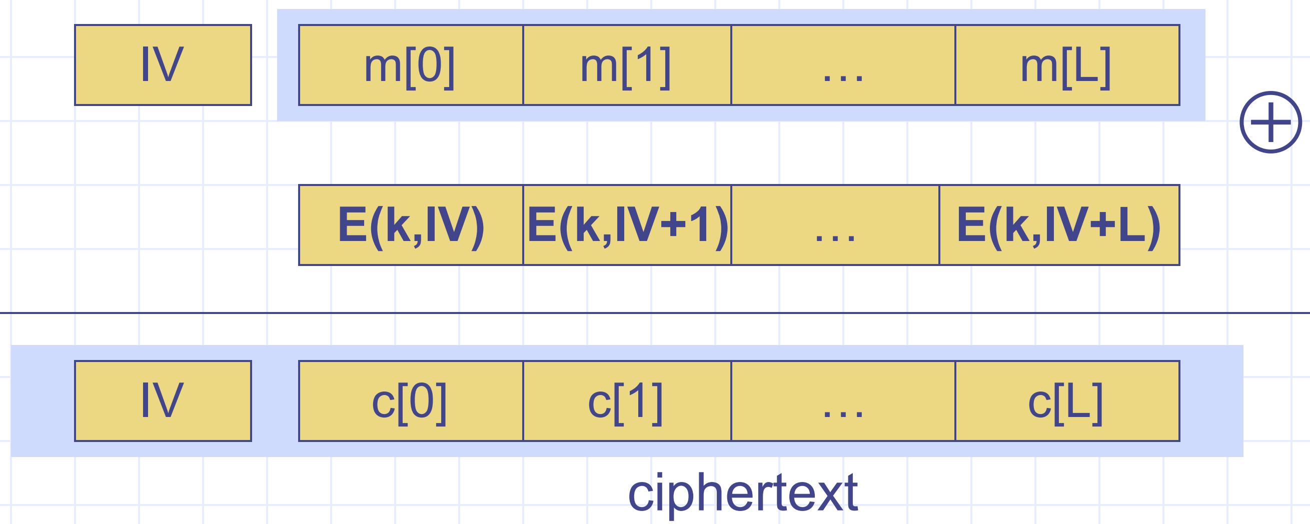
An example plaintext

Encrypted with AES in CBC mode



# Correct use of block ciphers II: CTR mode

Counter mode with a random IV: (parallel encryption)



# Performance: Crypto++ 5.6.0 [ Wei Dai ]

Intel Core 2 (on Windows Vista)

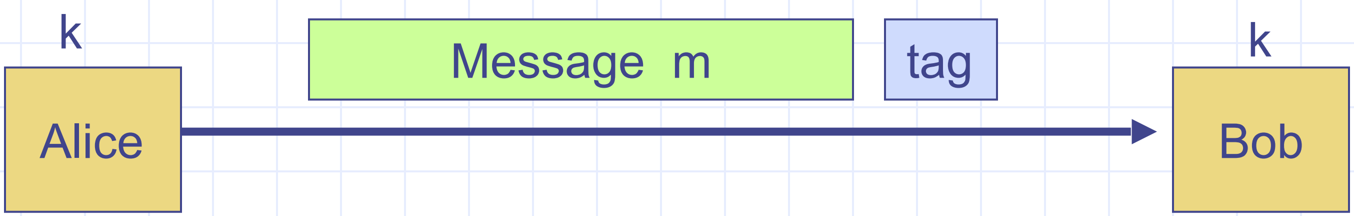
| Cipher | Block/key size | Speed (MB/sec) |
|---|---|---|
| RC4 | | 126 |
| Salsa20/12 | | 643 |
| 3DES | 64/168 | 10 |
| AES/GCM | 128/128 | 102 |

AES is about 8x faster with AES-NI : Intel Westmere and onwards

# Data integrity

# Message Integrity: MACs

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




Generate tag:
$tag \leftarrow S(k, m)$

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 $t_i \leftarrow S(k, m_i)$

- Attacker's goal: existential forgery.
  - produce some **new** valid message/tag pair (m,t).

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

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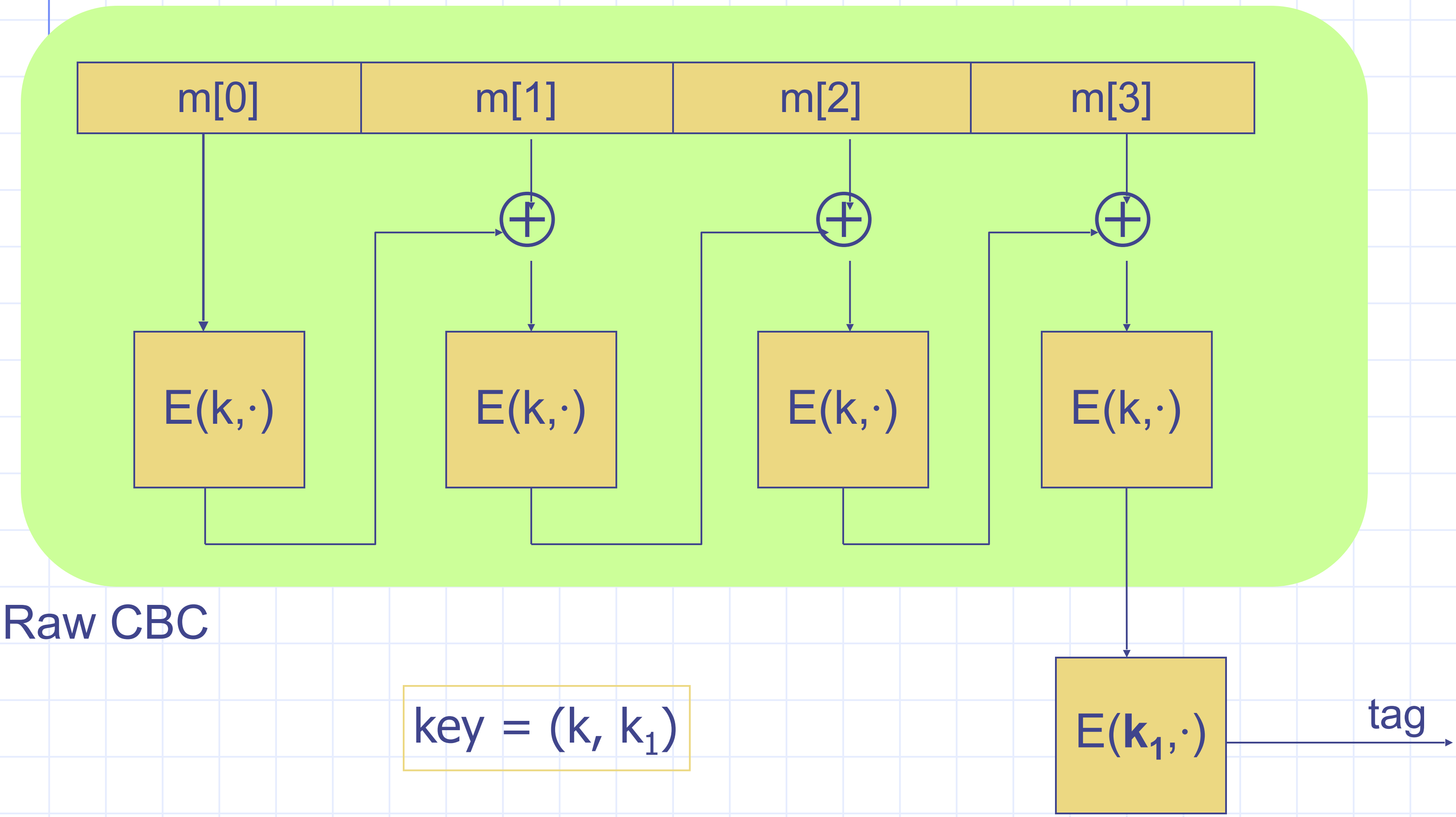
- A secure PRF gives a secure MAC:
  - $S(k,m) = F(k,m)$
  - $V(k,m,t)$: `yes' if $t = F(k,m)$ and `no' otherwise.

# Construction 1: ECBC



# Construction 2: HMAC (Hash-MAC)

Most widely used MAC on the Internet.

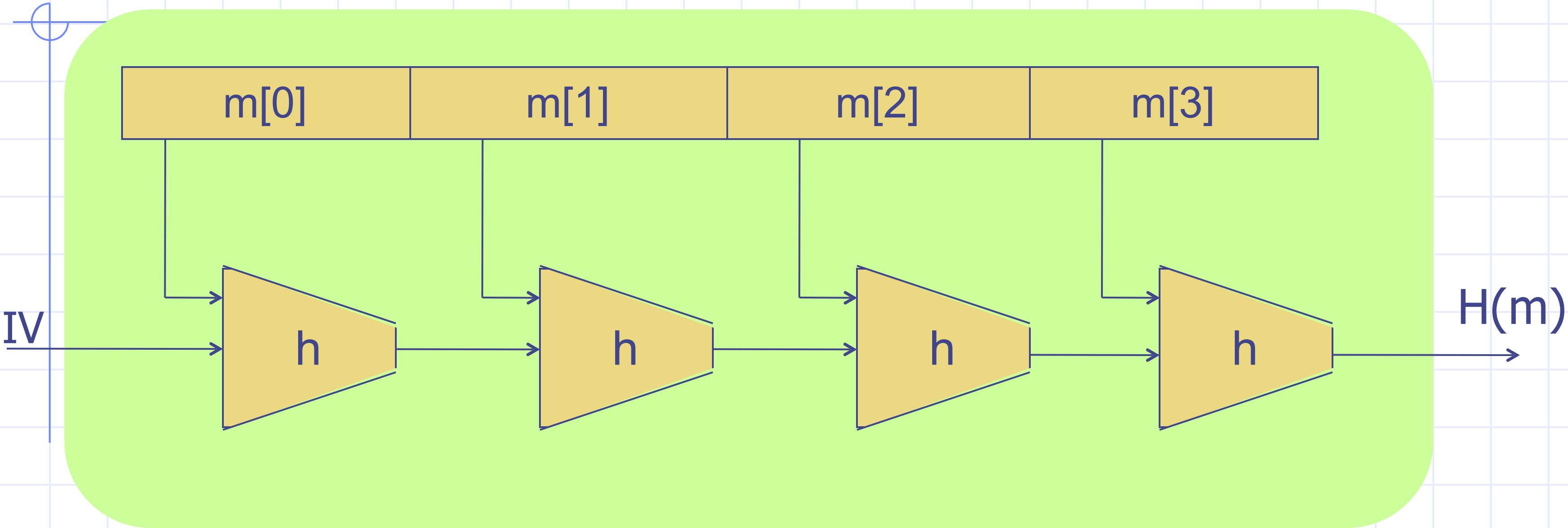
| | |
|---|---|
| H: | hash function. |
| | example: SHA-256 ; output is 256 bits |

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



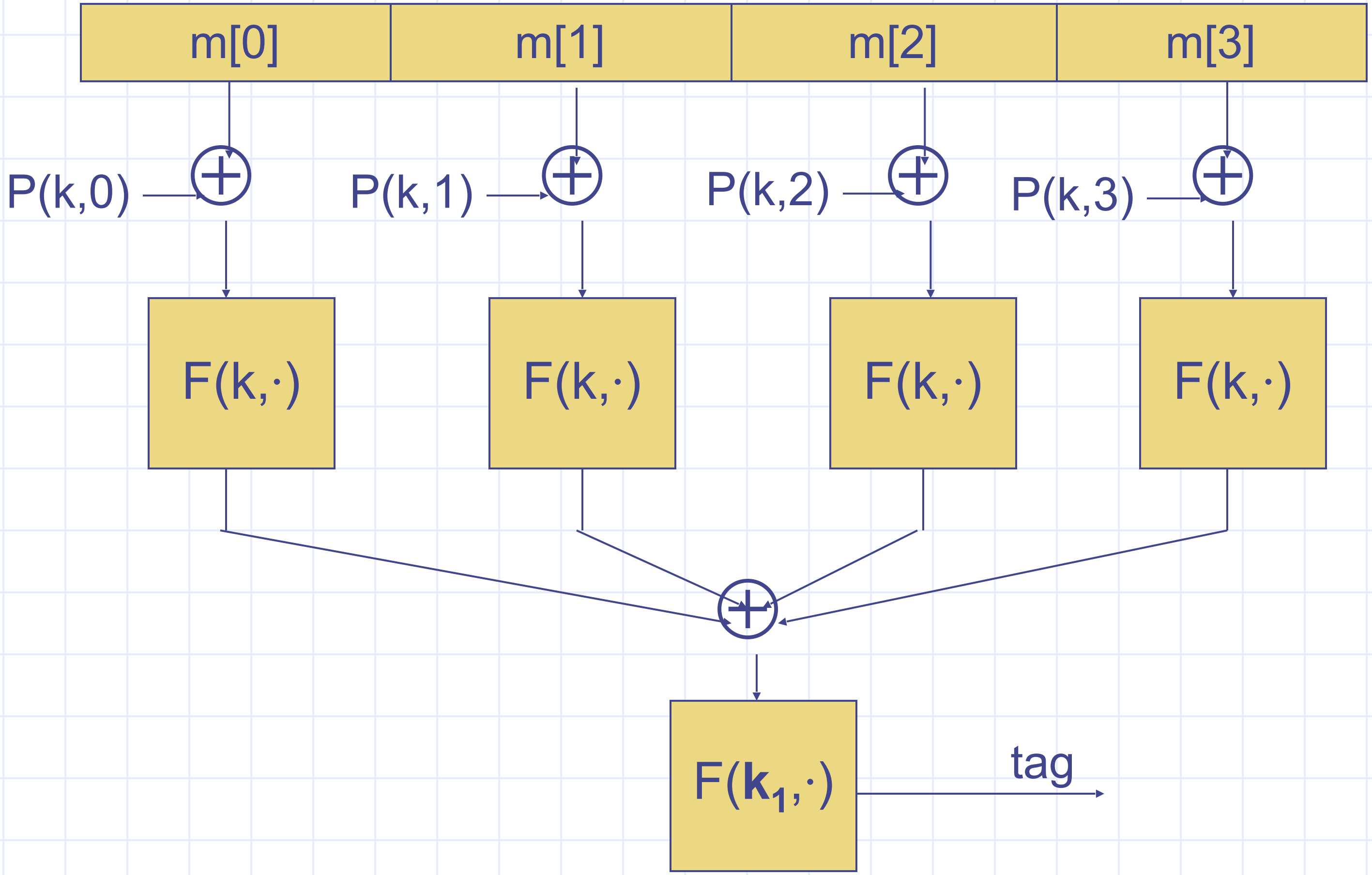

h(t, m[i]): compression function

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

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

# Construction 3: PMAC – parallel MAC

ECBC and HMAC are sequential. PMAC:



## Why are these MAC constructions secure?

… not today – take 40-675

## 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 … take 40-675 ;)

# 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 ⇨ [encrypted]

Option 2: Encrypt-then-MAC (IPsec)

Secure for all secure primitives

Enc $K_E$ MAC(C, $K_I$)

Msg M ⇨ [encrypted] ⇨ [encrypted] | MAC

Option 3: Encrypt-and-MAC (SSH)

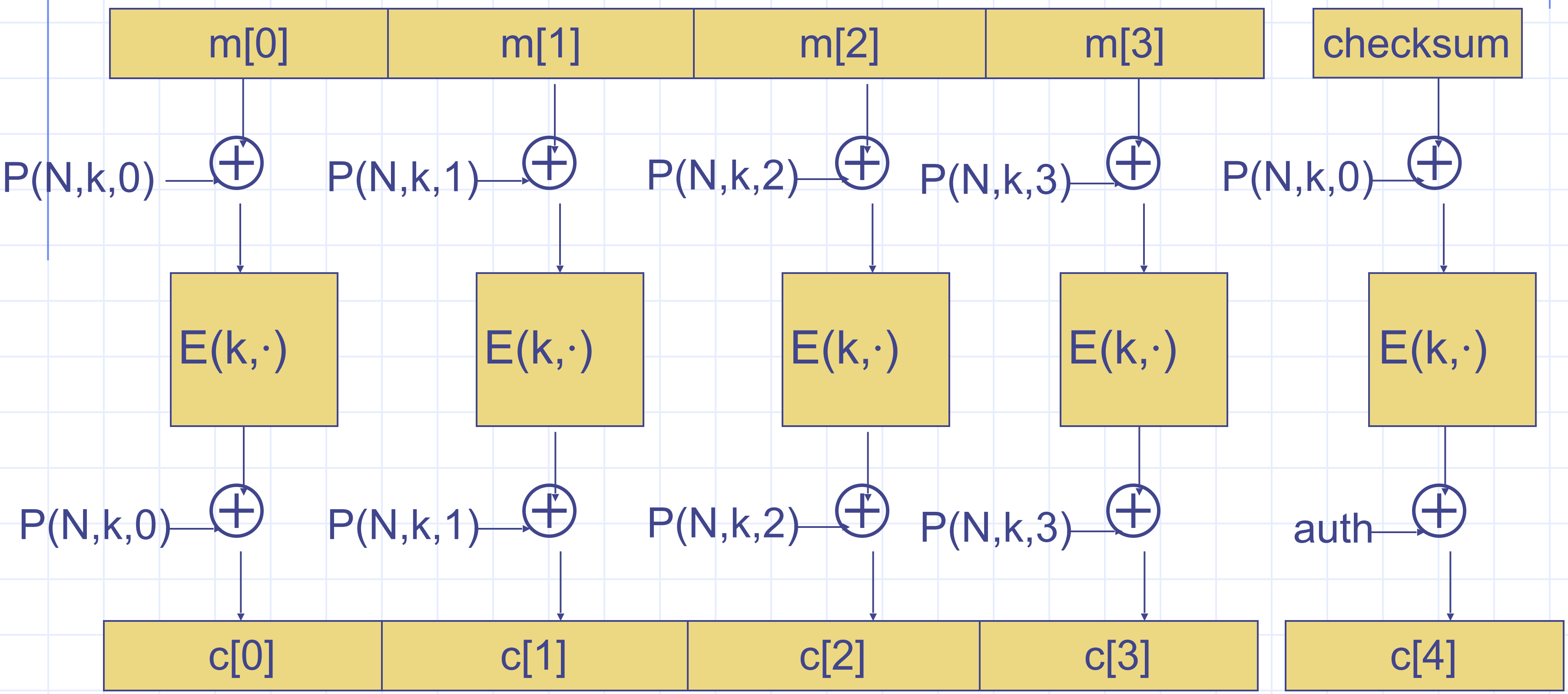
Enc $K_E$ MAC(M, $K_I$)

Msg M ⇨ [encrypted] ⇨ [encrypted] | MAC

# OCB

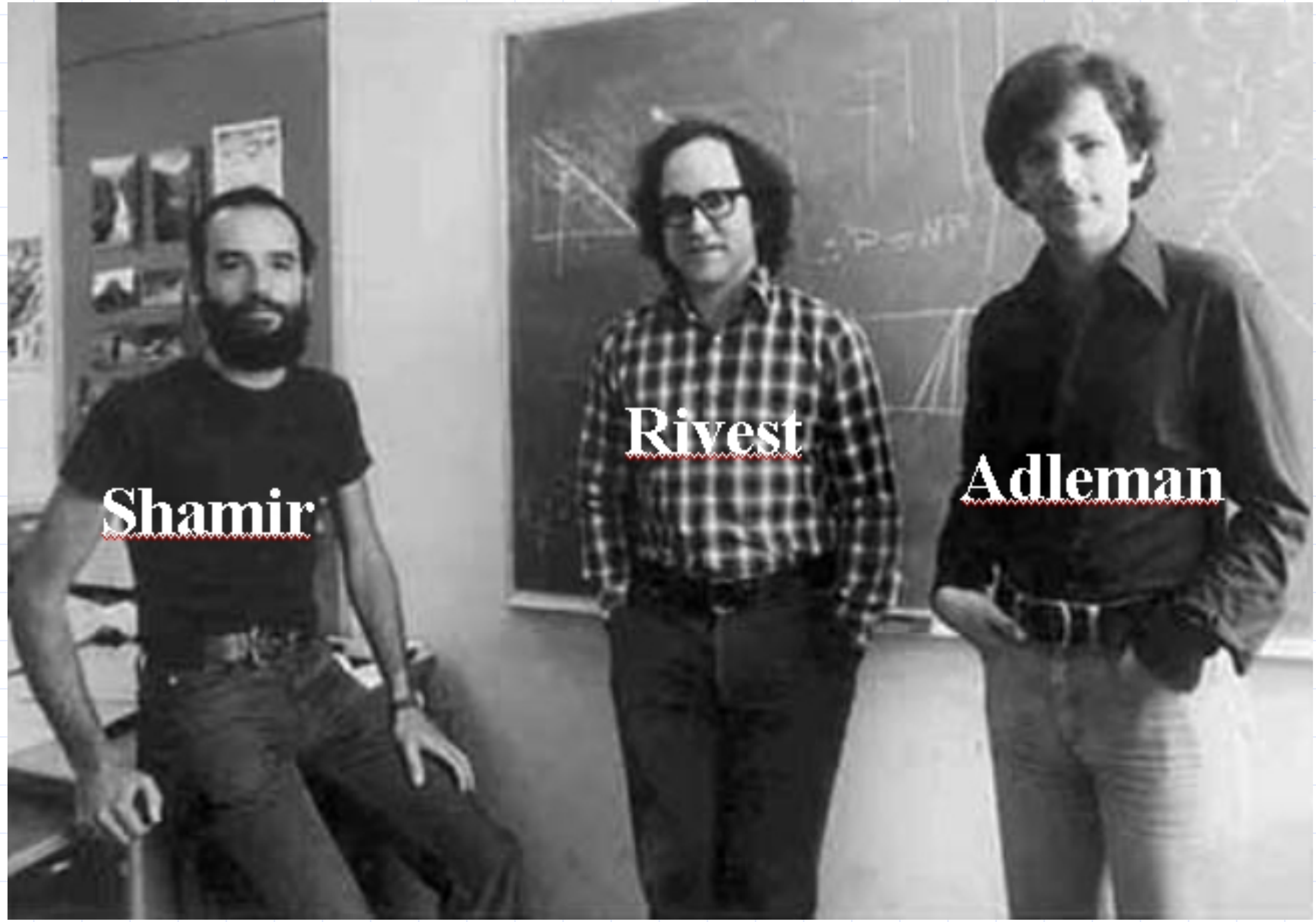
offset codebook mode

**More efficient authenticated encryption**

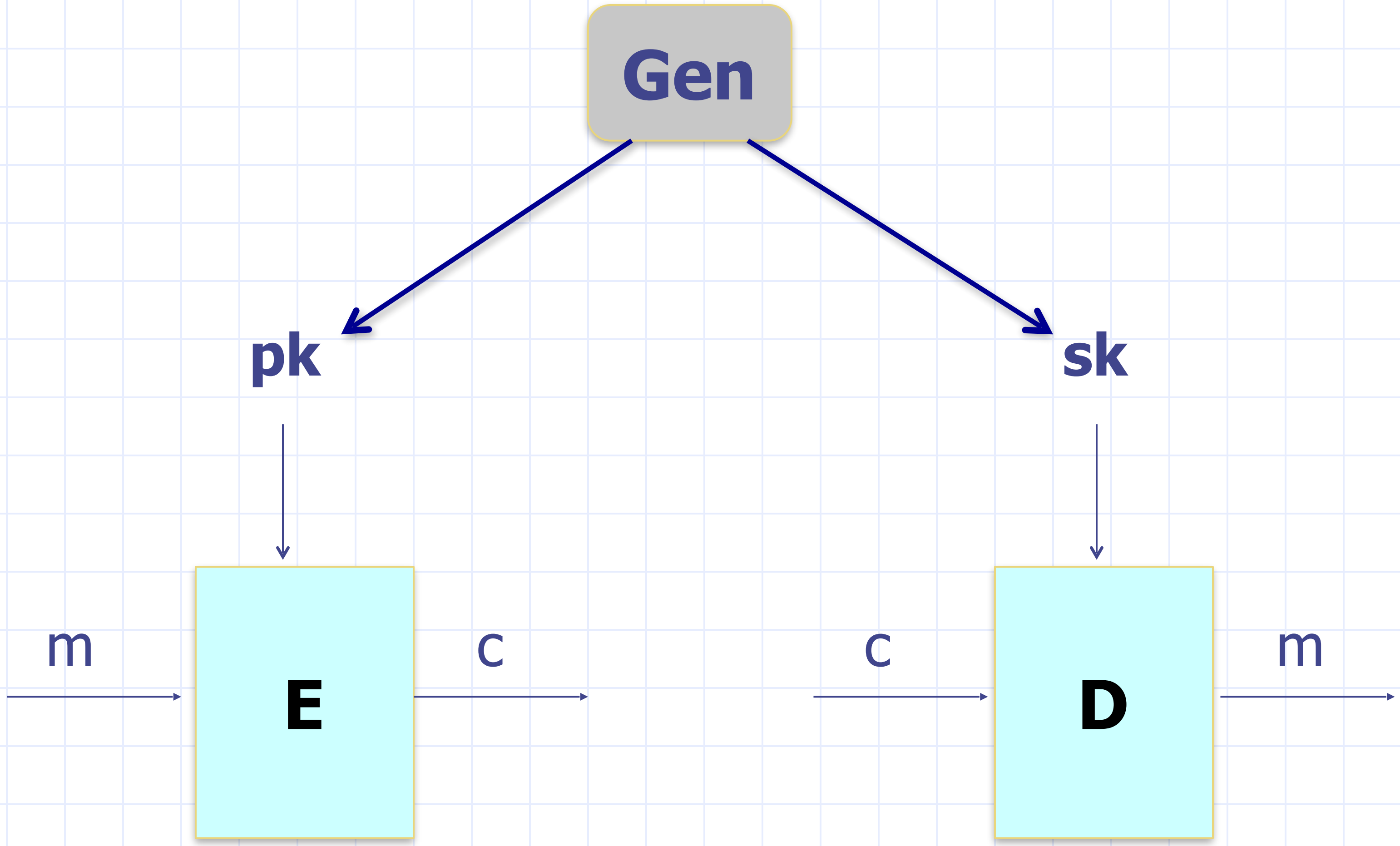



Rogaway, …

# Public-key Cryptography

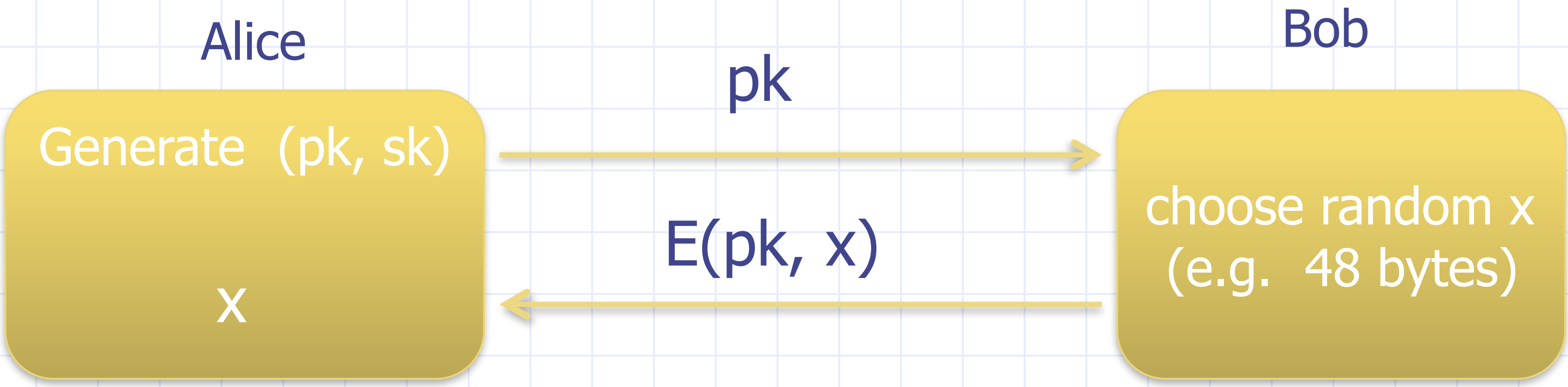

Shamir
Rivest
Adleman

# Public key encryption: (Gen, E, D)



# Applications

## Session setup (for now, only eavesdropping security)

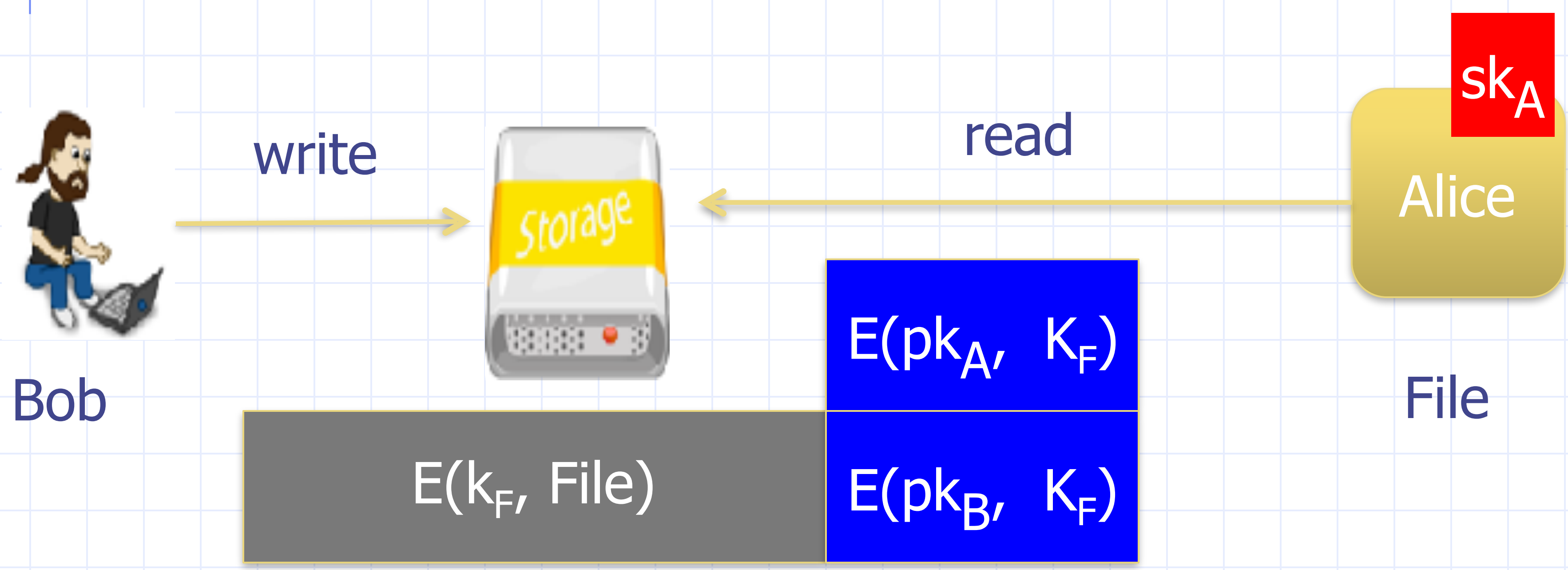



**Non-interactive applications:** (e.g. Email)

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

# Applications

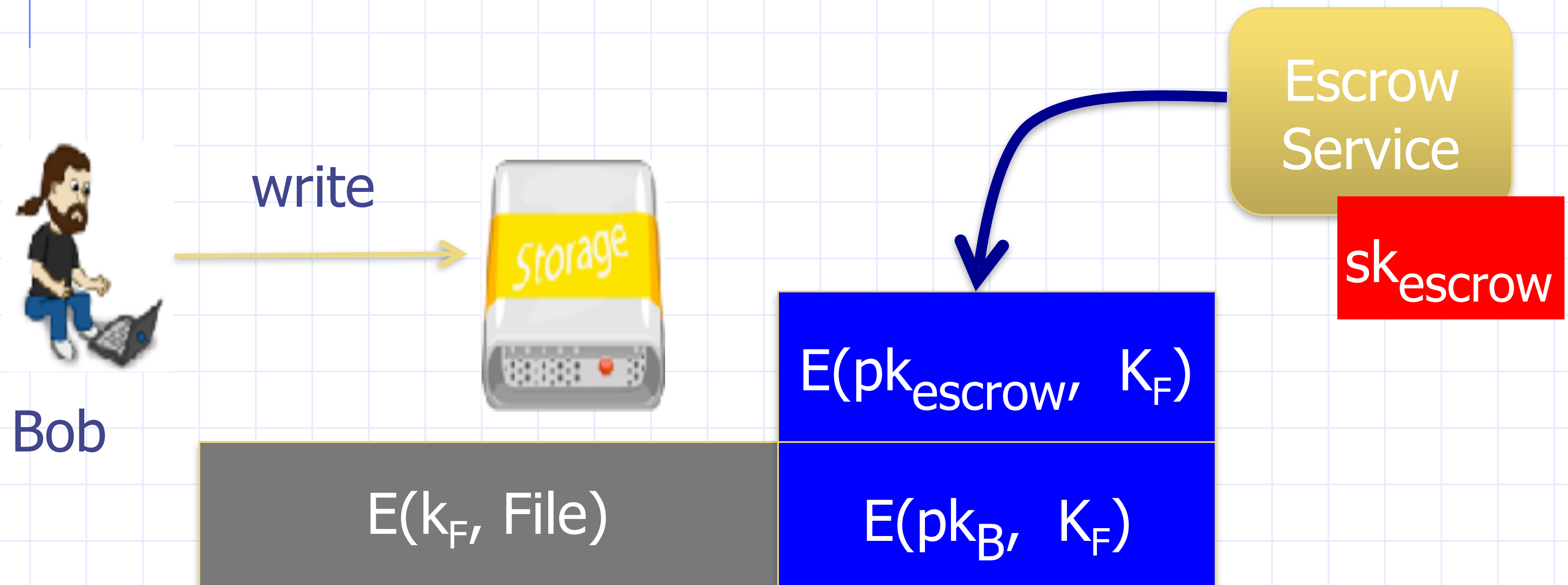
- Encryption in non-interactive settings:
  - Encrypted File Systems



# Applications

Encryption in non-interactive settings:

- Key escrow:  data recovery without Bob's key



# Trapdoor functions (TDF)

**Def**: 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. $X \longrightarrow Y$
- $F^{-1}(sk, \cdot)$: defines a 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) :**

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

$k \longleftarrow H(x),$

$c \longleftarrow E_s(k, m)$

output $(y, c)$

**D( sk, (y,c) ) :**

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

$k \longleftarrow H(x),$

$m \longleftarrow D_s(k, c)$

output $m$

In pictures:

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

**<u>Security Theorem</u>**:

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)

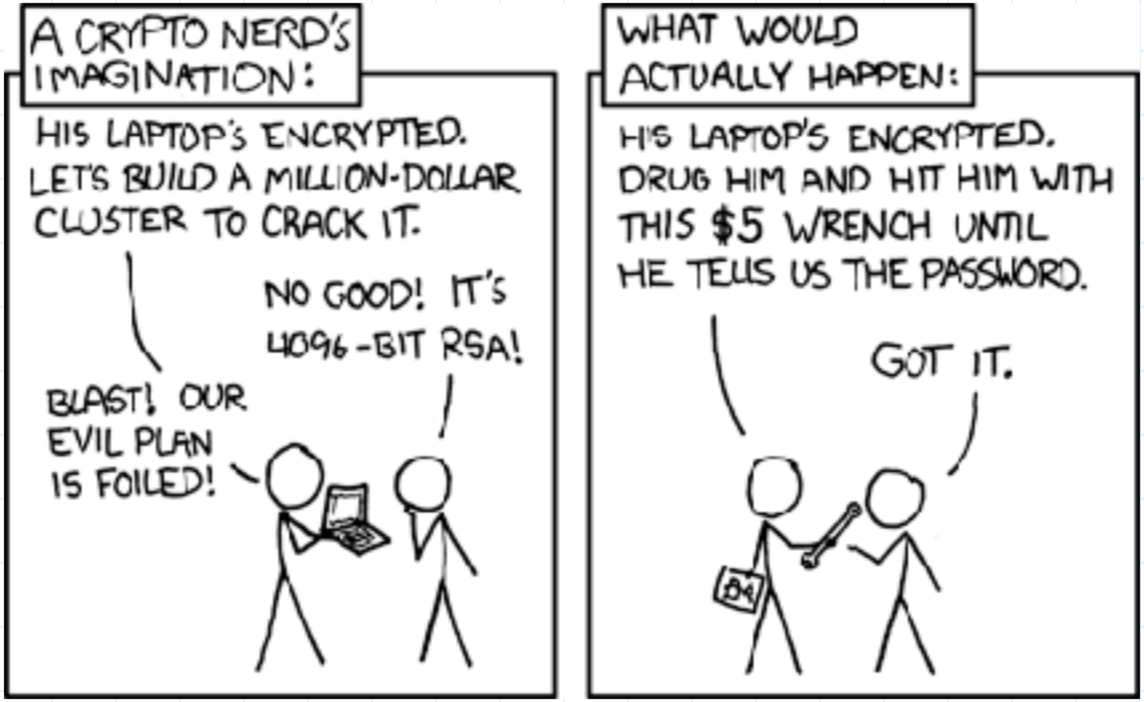
# Public-Key Infrastructure (PKI)

- 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 mail
- One solution: PKI
  - Trusted root Certificate Authority (e.g. Symantec)
    - Everyone must know the verification key of root CA
    - Check your browser; there are hundreds!!
  - Root authority signs intermediate CA
  - Results in a certificate chain

# Limitations of cryptography

Cryptography works when used correctly !!

… but is not the solution to all security problems




XKCD 538