

CS255: Winter 2024

PRPs and PRFs

Recap

Simple stream ciphers:

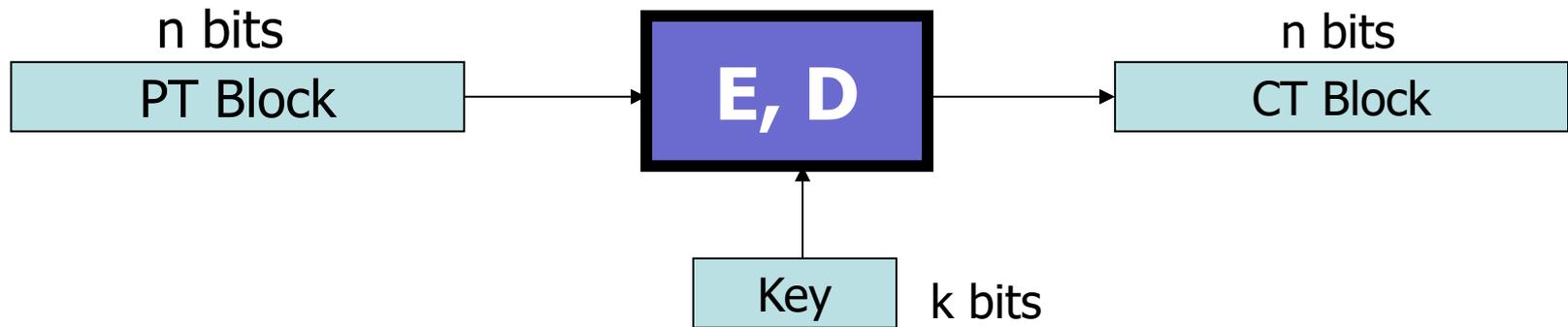
can only use key to encrypt one message

Next goal: ciphers where a single key can be used to encrypt many messages

First, let's introduce block ciphers.

Quick Recap

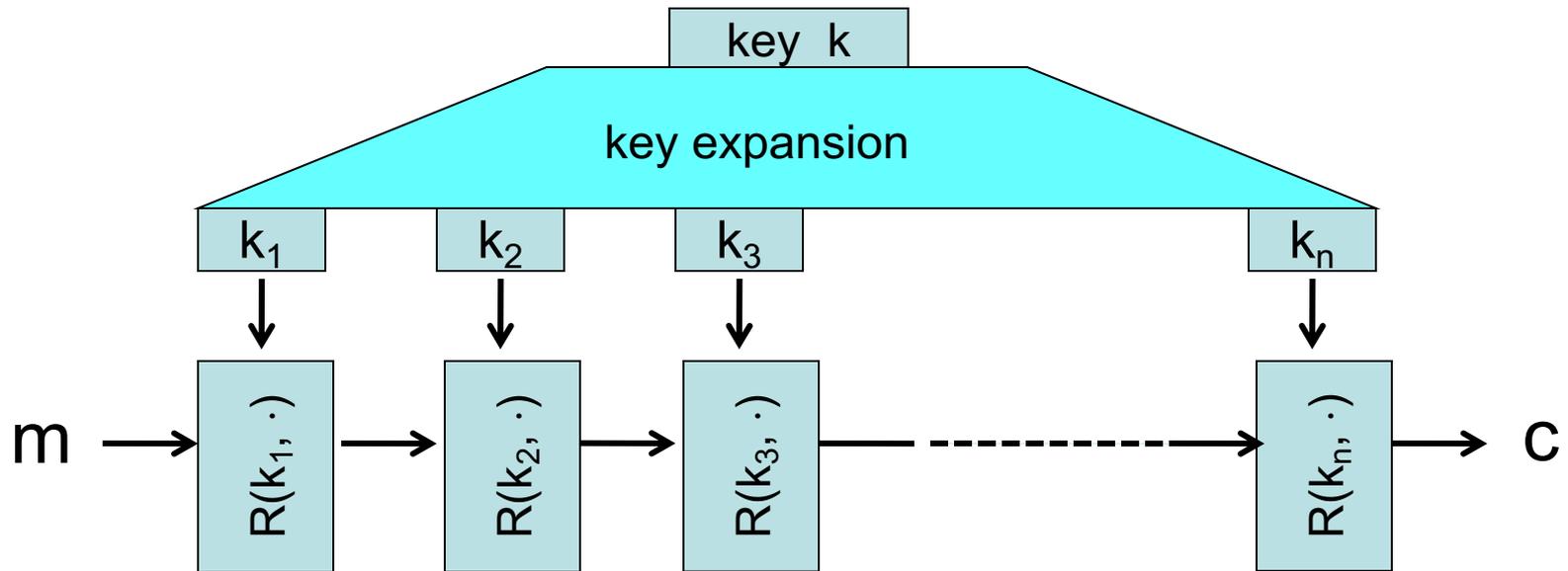
A **block cipher** is a pair of efficient algs. (E, D):



Canonical examples:

- 1. AES:** $n=128$ bits, $k = 128, 192, 256$ bits
- 2. 3DES:** $n= 64$ bits, $k = 168$ bits (historical)

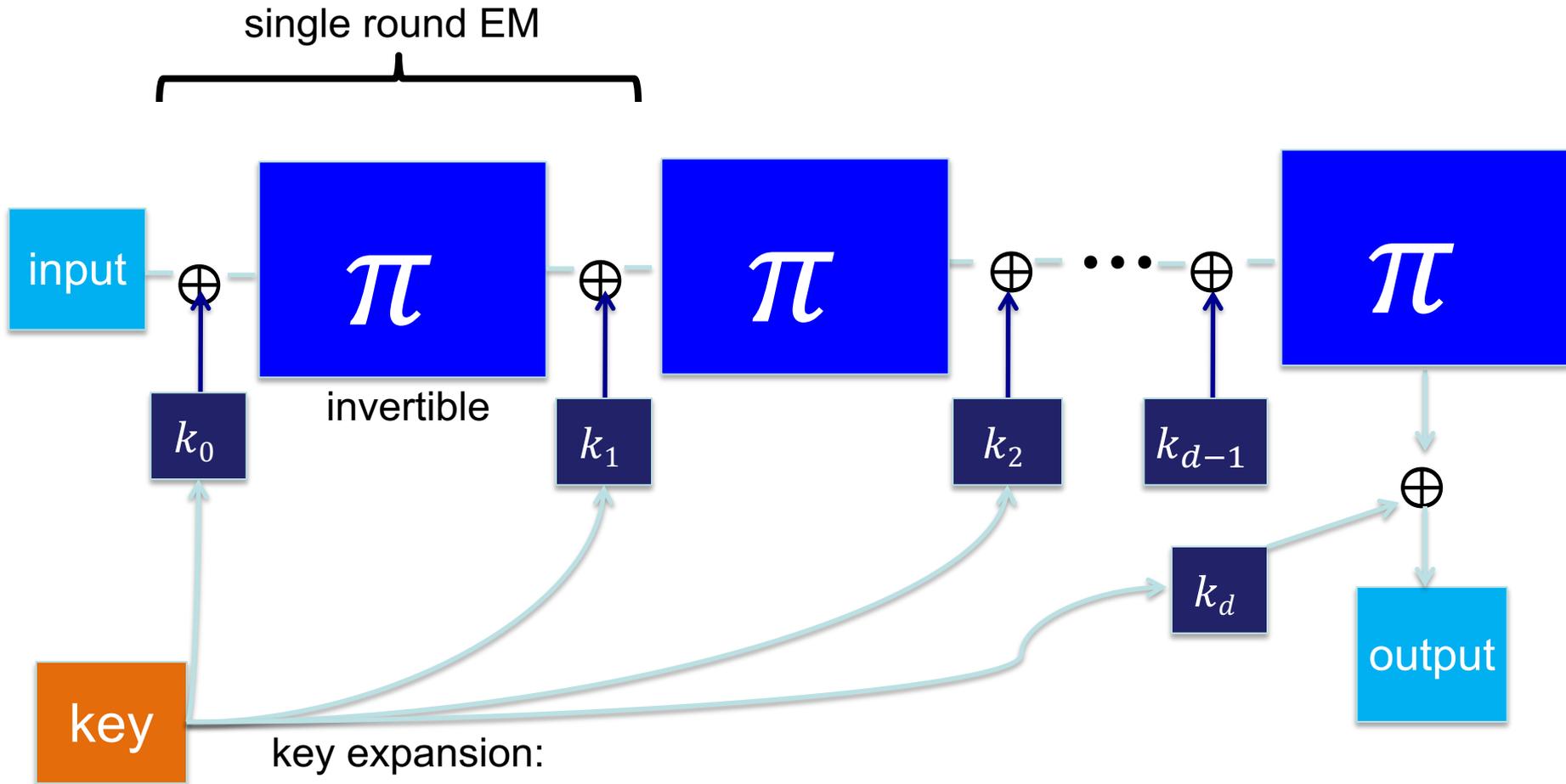
Block Ciphers Built by Iteration



$R(k, m)$ is called a round function

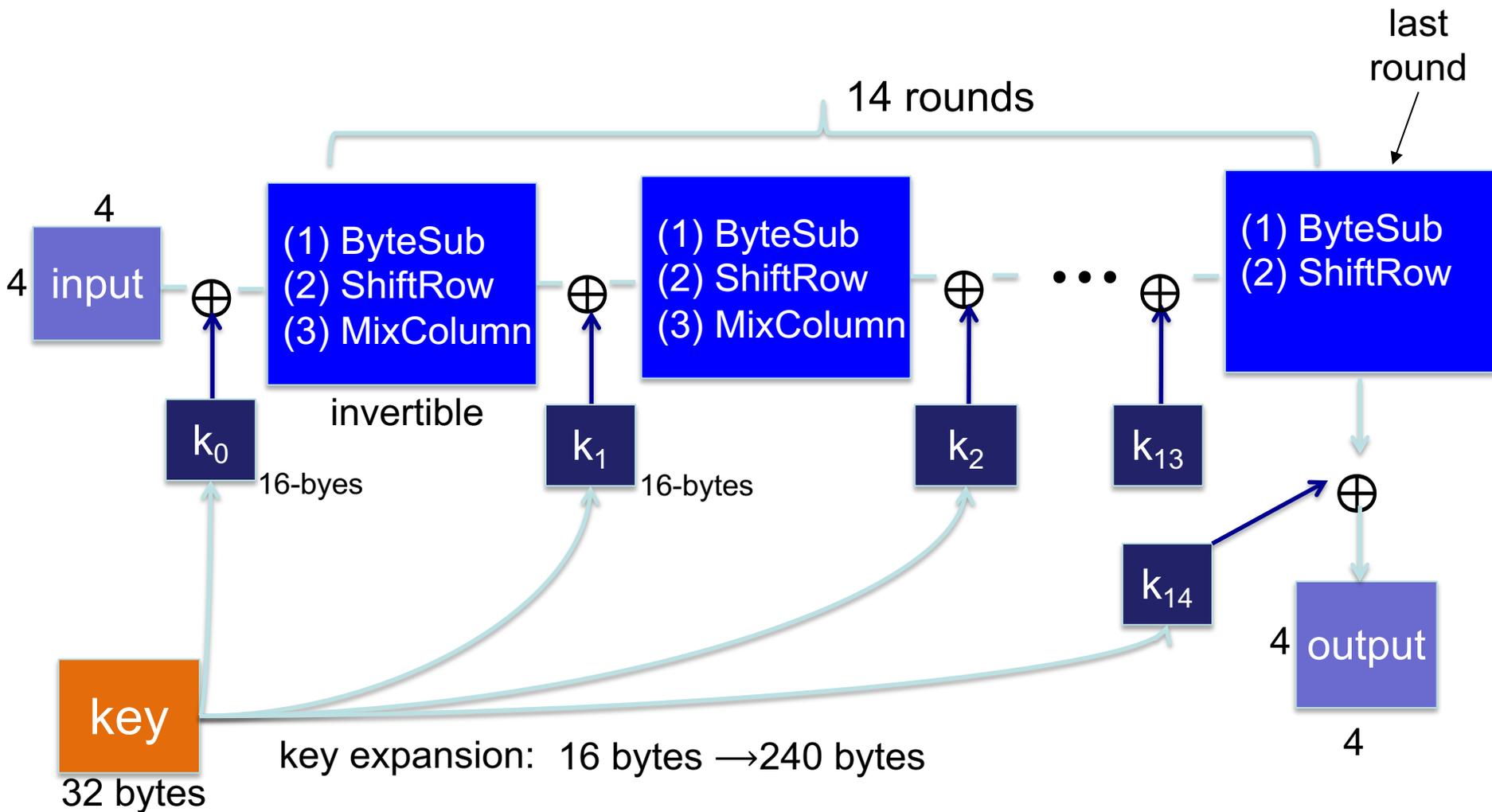
3DES: $n=48$, **AES128:** $n=10$, **AES256:** $n=14$

AES: an iterated Even-Mansour cipher



$$\pi: \{0,1\}^n \rightarrow \{0,1\}^n \quad \text{invertible function}$$

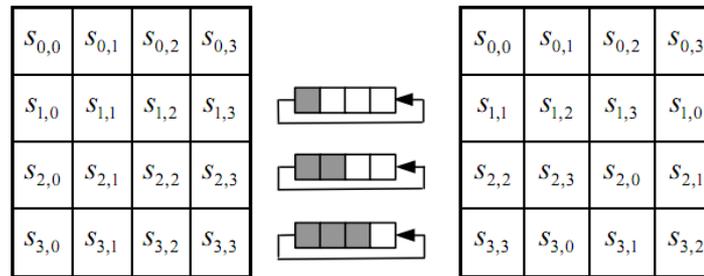
AES256: 14 rounds of EM



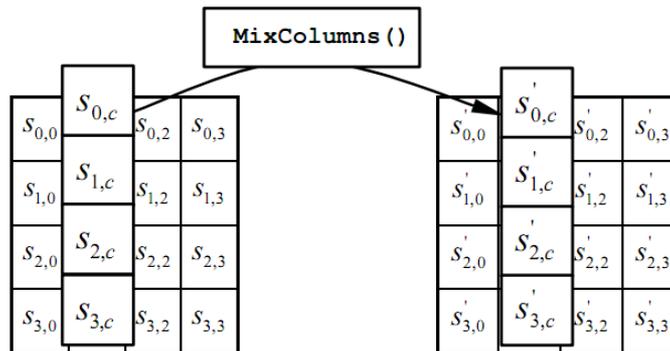
The permutation π

(1) **ByteSub:** a 1 byte S-box. 256 byte table. (invertible)

(2) **ShiftRows:**



(3) **MixColumns:**



Recall the AES pledge

I promise that I will not implement AES myself in production code, even though it might be fun. This agreement will remain in effect until I learn all about side-channel attacks and countermeasures to the point where I lose all interest in implementing AES myself.

Performance (no HW acceleration)

<u>Cipher</u>	<u>Block/key size</u>	<u>Speed (MB/sec)</u>
ChaCha20	- / 256	643
3DES	64 / 168	30
AES128	128 / 128	163
AES256	128 / 256	115

block



AES-NI: AES hardware instructions

AES instructions (Intel, AMD, ARM, ...)

- **aesenc, aesenclast:** do one round of AES

128-bit registers: xmm1=state, xmm2=round key

aesenc xmm1, xmm2 ; puts result in xmm1

- **aesdec, aesdeclast:** one round of AES⁻¹
- **aeskeygenassist:** performs AES key expansion

Claim 1: 20 x speed-up over OpenSSL on same hardware

Claim 2: constant time execution

AES-NI: Encrypting one block (AES256)

step 0: `aeskeygenassist`(256-bit key) →
round keys in `xmm2, xmm3, ..., xmm16`

step 1: load plaintext block into **`xmm1`** (128-bit block)

step 2:

- `xor xmm1, xmm2`
- `aesenc xmm1, xmm3`
- `aesenc xmm1, xmm4`
- `aesenc xmm1, xmm5`
- ...
- `aesenclast xmm1, xmm16`

} 15 instructions

AES-NI: parallelism and pipelining

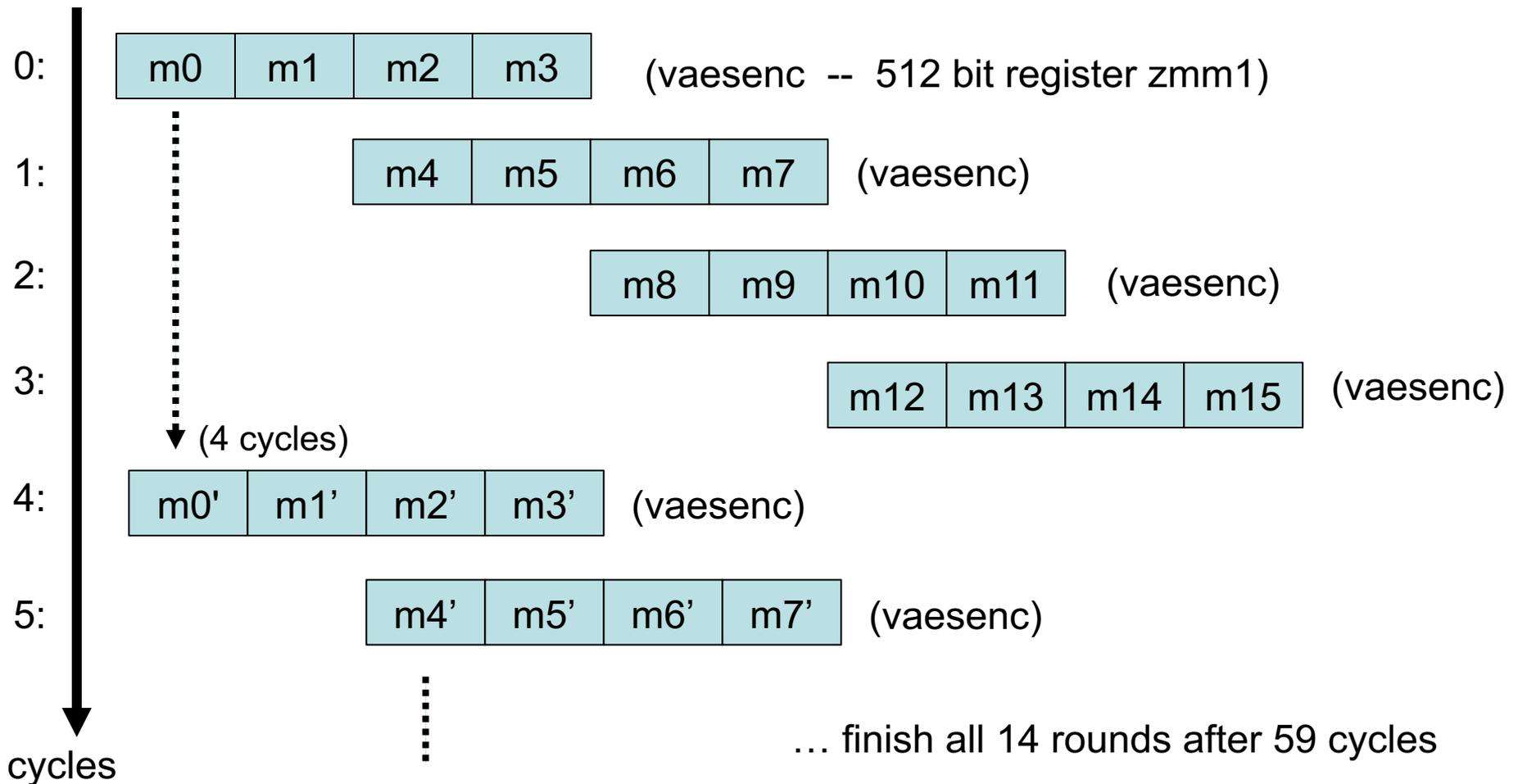
- Intel Skylake (old): 4 cycles for one aesenc
 - **fully pipelined**: can issue one instruction every cycle
- Intel Icelake (2019): **vectorized aesenc** (vaesenc)
 - **vaesenc**: compute aesenc on four blocks in parallel
 - fully pipelined

Implications:

- AES256 encrypt a single block takes **56 cycles** (14 rounds)
- AES256 encrypt **16 blocks** on Icelake takes **59 cycles**

AES256 encrypt on Icelake

To encrypt 16 blocks do: $m_0, \dots, m_{15} \in \{0,1\}^{128}$



Abstract view of a block cipher:

PRPs and PRFs

Topics:

1. Abstract block ciphers: PRPs and PRFs
2. Security models for encryption
3. Analysis of CBC and counter mode

PRPs and PRFs

- Pseudo Random Function (**PRF**) defined over (K, X, Y) :

$$F: K \times X \rightarrow Y$$

such that exists “efficient” algorithm to evaluate $F(k, x)$

- Pseudo Random Permutation (**PRP**) defined over (K, X) :

$$E: K \times X \rightarrow X$$

such that:

1. Exists “efficient” algorithm to evaluate $E(k, x)$
2. The function $E(k, \cdot)$ is one-to-one
3. Exists “efficient” inversion algorithm $D(k, x)$

Running example

- Example PRPs: 3DES, AES, ...

AES128: $K \times X \rightarrow X$ where $K = X = \{0,1\}^{128}$

DES: $K \times X \rightarrow X$ where $X = \{0,1\}^{64}$, $K = \{0,1\}^{56}$

3DES: $K \times X \rightarrow X$ where $X = \{0,1\}^{64}$, $K = \{0,1\}^{168}$

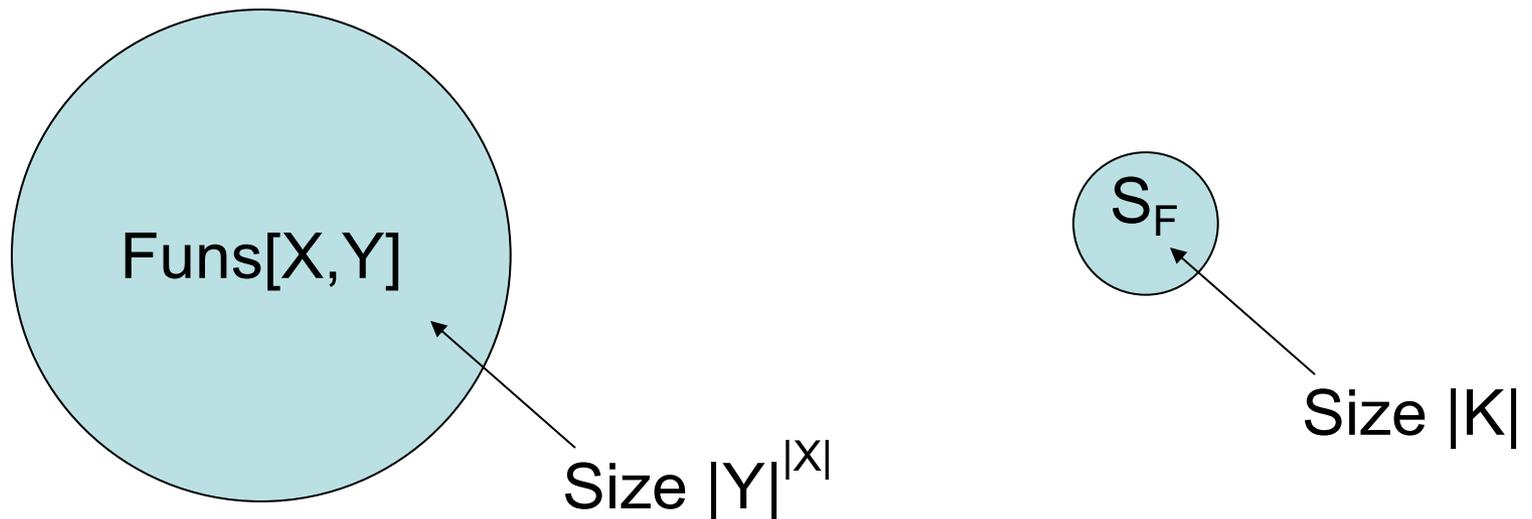
- Functionally, any PRP is also a PRF.
 - A PRP is a PRF where $X=Y$ and is efficiently invertible
 - A PRP is sometimes called a ***block cipher***

Secure PRFs

- Let $F: K \times X \rightarrow Y$ be a PRF

$$\left\{ \begin{array}{l} \text{Funs}[X,Y]: \text{ the set of all functions from } X \text{ to } Y \\ S_F = \{ F(k, \cdot) \text{ s.t. } k \in K \} \subseteq \text{Funs}[X,Y] \end{array} \right.$$

- Intuition: a PRF is **secure** if
a random function in $\text{Funs}[X,Y]$ is indistinguishable from
a random function in S_F

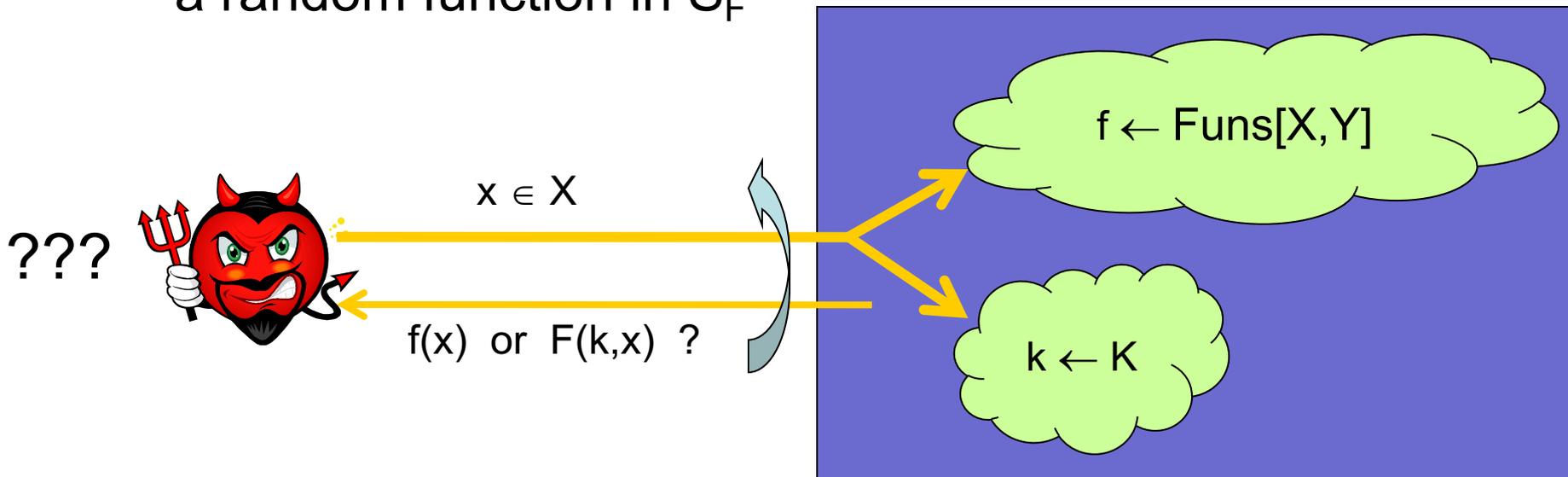


Secure PRFs

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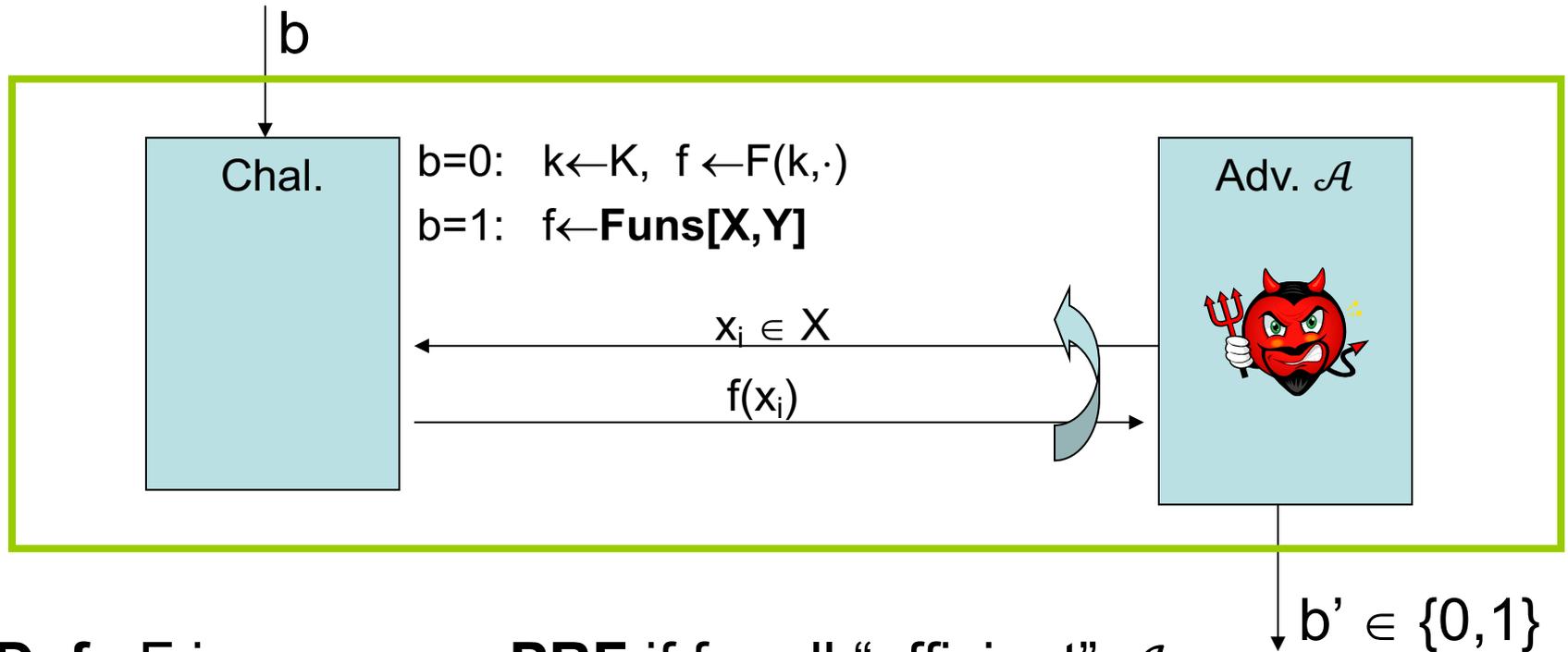
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- Intuition: a PRF is **secure** if a random function in $\text{Funs}[X,Y]$ is indistinguishable from a random function in S_F



Secure PRF: definition

- For $b=0,1$ define experiment $\text{EXP}(b)$ as:



- Def:** F is a **secure PRF** if for all “efficient” \mathcal{A} :

$$\text{Adv}_{\text{PRF}}[\mathcal{A}, F] = \left| \Pr[\text{EXP}(0) = 1] - \Pr[\text{EXP}(1) = 1] \right|$$

is “negligible.”

An example

Let $K = X = \{0,1\}^n$.

Consider the PRF: $F(k, x) = k \oplus x$ defined over (K, X, X)

Let's show that F is insecure:

- Adversary \mathcal{A} :
- (1) choose arbitrary $x_0 \neq x_1 \in X$
 - (2) query for $y_0 = f(x_0)$ and $y_1 = f(x_1)$
 - (3) output '0' if $y_0 \oplus y_1 = x_0 \oplus x_1$, else '1'

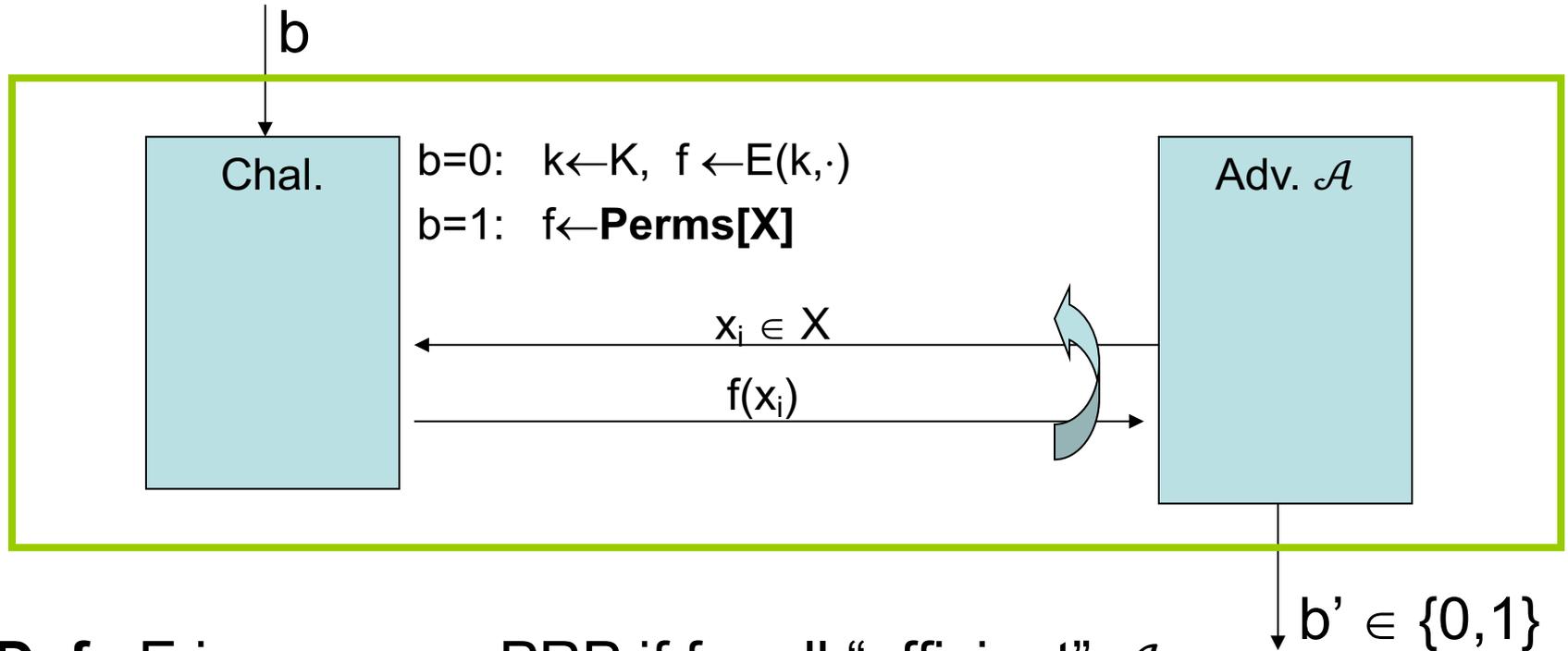
$$\Pr[\text{EXP}(0) = 0] = 1$$

$$\Pr[\text{EXP}(1) = 0] = 1/2^n$$

$$\Rightarrow \text{Adv}_{\text{PRF}}[\mathcal{A}, F] = 1 - (1/2^n) \quad (\text{not negligible})$$

Secure PRP

- For $b=0,1$ define experiment $\text{EXP}(b)$ as:



- Def:** E is a secure PRP if for all “efficient” \mathcal{A} :

$$\text{Adv}_{\text{PRP}}[\mathcal{A}, E] = \left| \Pr[\text{EXP}(0) = 1] - \Pr[\text{EXP}(1) = 1] \right|$$

is “negligible.”

Example secure PRPs

- Example secure PRPs: 3DES, AES, ...

$$\text{AES256: } K \times X \rightarrow X \quad \text{where } X = \{0,1\}^{128}$$
$$K = \{0,1\}^{256}$$

- AES256 PRP Assumption (example) :

$$\text{For all } \mathcal{A} \text{ s.t. } \text{time}(\mathcal{A}) < 2^{80} : \quad \text{Adv}_{\text{PRP}}[\mathcal{A}, \text{AES256}] < 2^{-40}$$

The PRP-PRF Switching Lemma

Any secure PRP is also a secure PRF.

Lemma: Let E be a PRP over (K, X) .

Then for any q -query adversary \mathcal{A} :

$$\left| \text{Adv}_{\text{PRF}}[\mathcal{A}, E] - \text{Adv}_{\text{PRP}}[\mathcal{A}, E] \right| < q^2 / 2|X|$$

\Rightarrow Suppose $|X|$ is large so that $q^2 / 2|X|$ is “negligible”

Then $\text{Adv}_{\text{PRP}}[\mathcal{A}, E]$ “negligible” \Rightarrow $\text{Adv}_{\text{PRF}}[\mathcal{A}, E]$ “negligible”

Using PRPs and PRFs

- Goal: build “secure” encryption from a PRP.
- Security is always defined using two parameters:

1. What “**power**” does adversary have?

examples:

- Adv sees only one ciphertext (one-time key)
- Adv sees many PT/CT pairs (many-time key, CPA)

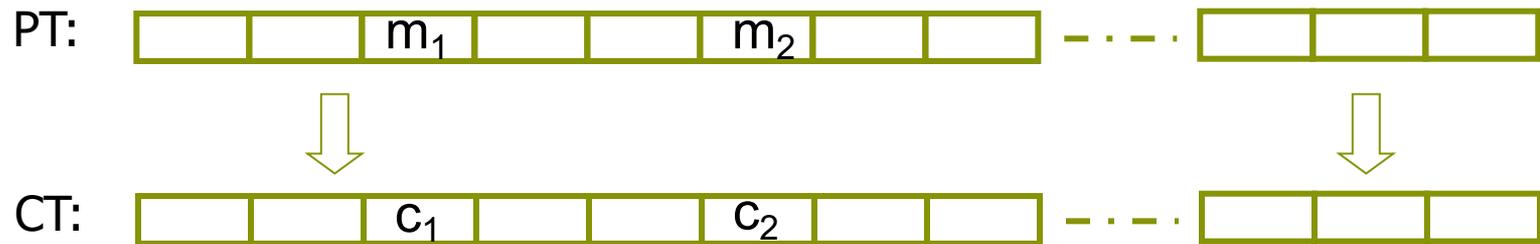
2. What “**goal**” is adversary trying to achieve?

examples:

- Fully decrypt a challenge ciphertext.
- Learn info about PT from CT (semantic security)

Incorrect use of a PRP

Electronic Code Book (ECB):



Problem:

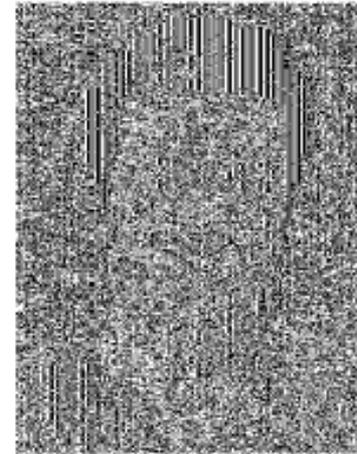
– if $m_1 = m_2$ then $c_1 = c_2$

In pictures

An example plaintext



Encrypted with AES in ECB mode



(courtesy B. Preneel)

How to use a block cipher?

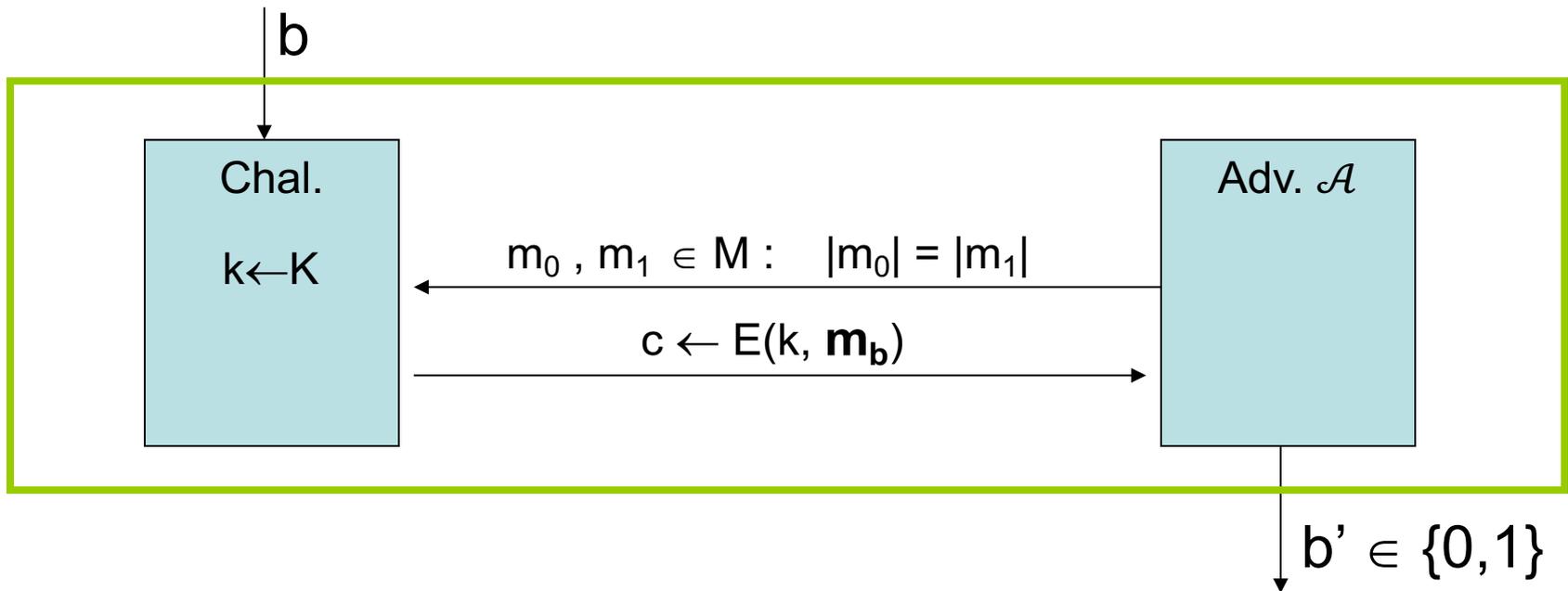
Modes of Operation for One-time Use Key

Example application:

Encrypted email. New key for every message.

Semantic Security for one-time key

- $\mathbb{E} = (E, D)$ a cipher defined over (K, M, C)
- For $b=0,1$ define $\text{EXP}(b)$ as:



- Def: \mathbb{E} is sem. sec. for one-time key if for all “efficient” \mathcal{A} :

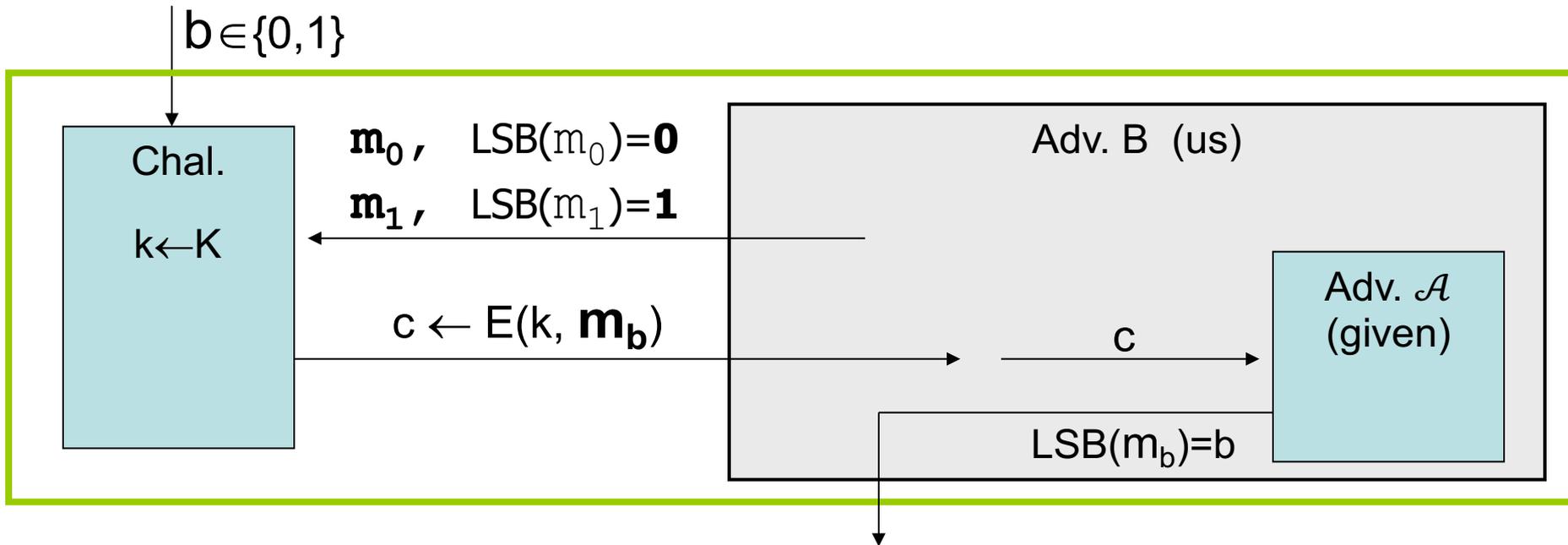
$$\text{Adv}_{\text{SS}}[\mathcal{A}, \mathbb{E}] = \left| \Pr[\text{EXP}(0)=1] - \Pr[\text{EXP}(1)=1] \right|$$

is “negligible.”

Semantic security (cont.)

Sem. Sec. \Rightarrow no “efficient” adversary learns “info” about PT from a **single** CT.

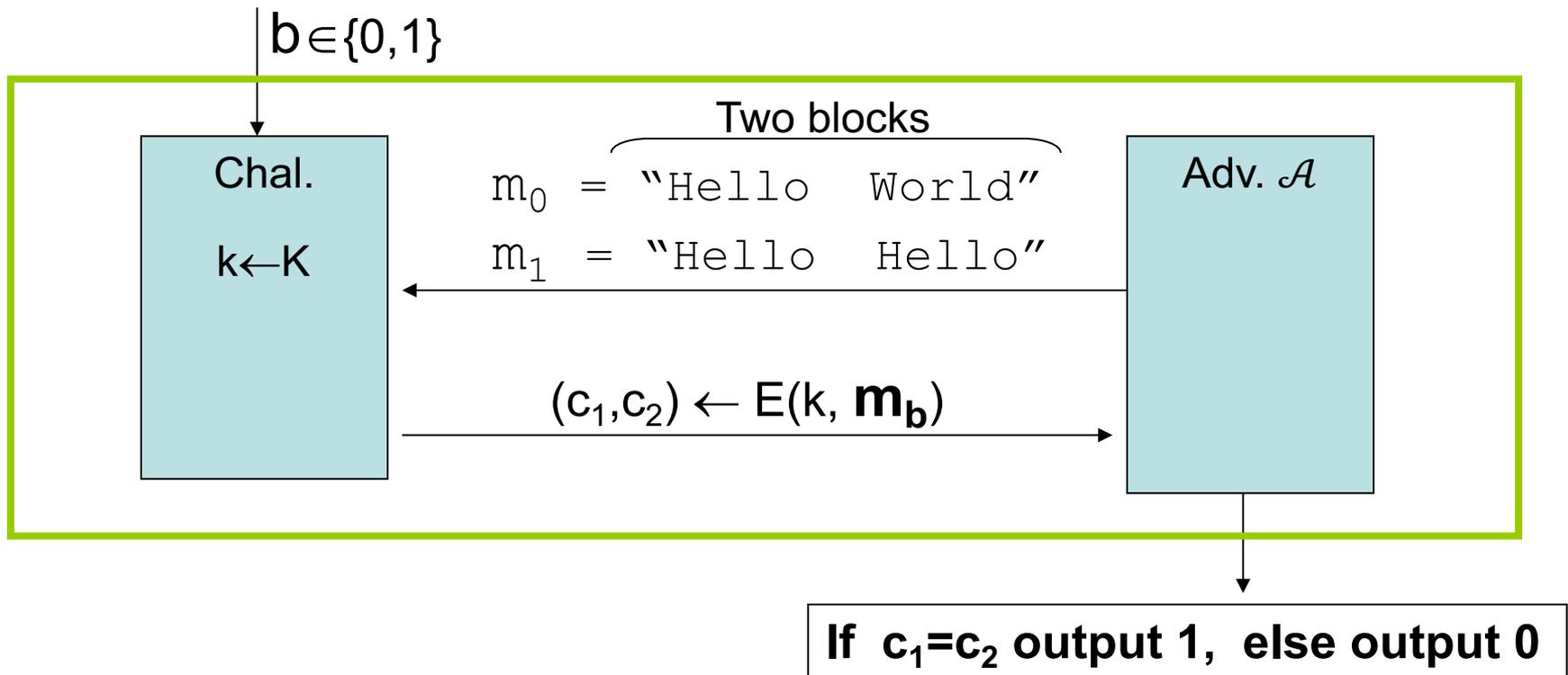
Example: suppose efficient \mathcal{A} can deduce LSB of PT from CT. Then $\mathbb{E} = (E, D)$ is not semantically secure.



Then $\text{Adv}_{\text{SS}}[\mathcal{B}, \mathbb{E}] = 1 \Rightarrow \mathbb{E}$ is not sem. sec.

Note: ECB is not Sem. Sec.

ECB is not semantically secure for messages that contain two or more blocks.



Then $\text{Adv}_{\text{SS}}[\mathcal{A}, \text{ECB}] = 1$

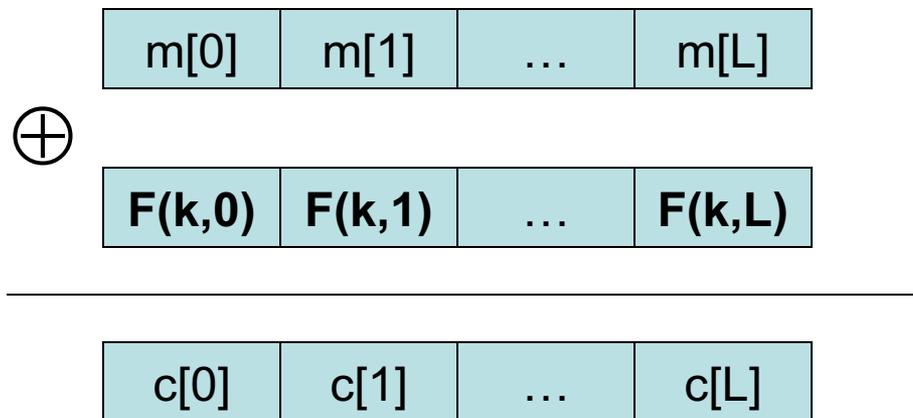
Secure Constructions

Examples of sem. sec. systems:

1. $\text{Adv}_{\text{SS}}[\mathcal{A}, \text{OTP}] = 0$ for all \mathcal{A}

2. Deterministic counter mode from a PRF F :

• $E_{\text{DETCTR}}(k,m) =$



- Stream cipher built from PRF (e.g. AES)

Det. counter-mode security

Theorem: For any $L > 0$.

If F is a secure PRF over (K, X, X) then

E_{DETCTR} is sem. sec. cipher over (K, X^L, X^L) .

In particular, for any adversary \mathcal{A} attacking E_{DETCTR} there exists a PRF adversary B s.t.:

$$\text{Adv}_{\text{SS}}[\mathcal{A}, E_{\text{DETCTR}}] = 2 \cdot \text{Adv}_{\text{PRF}}[B, F]$$

$\text{Adv}_{\text{PRF}}[B, F]$ is negligible (since F is a secure PRF)

$\Rightarrow \text{Adv}_{\text{SS}}[\mathcal{A}, E_{\text{DETCTR}}]$ must be negligible.

Modes of Operation for Many-time Key

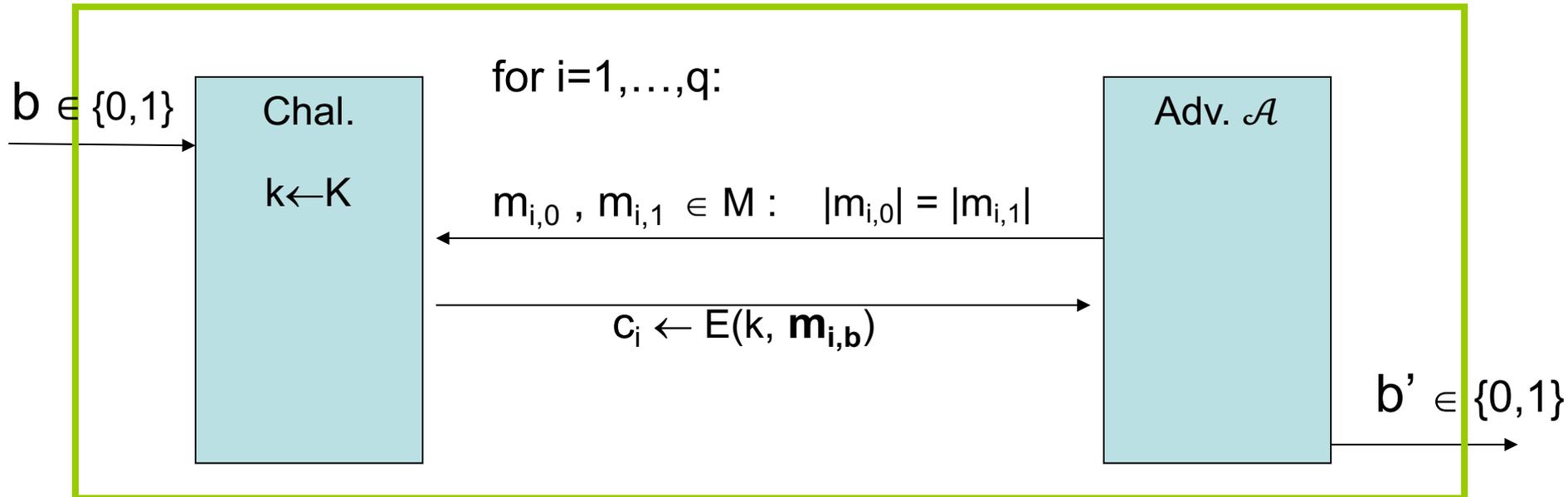
Example applications:

1. File systems: Same AES key used to encrypt many files.
2. IPsec: Same AES key used to encrypt many packets.

Semantic Security for many-time key (CPA security)

Cipher $\mathbb{E} = (E, D)$ defined over (K, M, C) .

For $b=0,1$ define $\text{EXP}(b)$ as:



if adv. wants $c = E(k, m)$ it queries with $m_{j,0} = m_{j,1} = m$

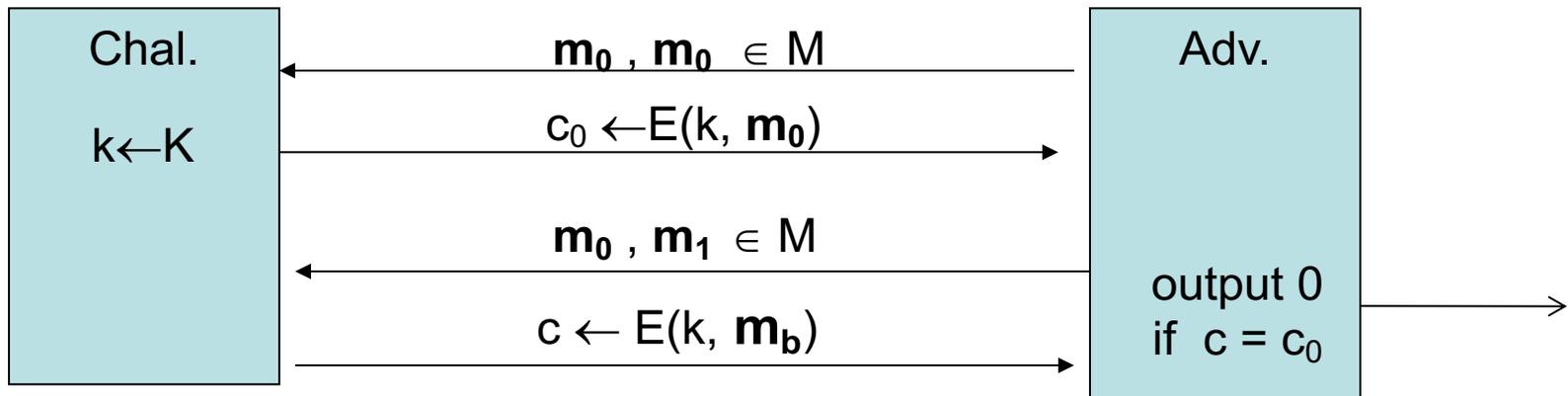
Def: \mathbb{E} is sem. sec. under CPA if for all "efficient" \mathcal{A} :

$\text{Adv}_{\text{CPA}}[\mathcal{A}, \mathbb{E}] = \left| \Pr[\text{EXP}(0)=1] - \Pr[\text{EXP}(1)=1] \right|$
is "negligible."

Security for many-time key

Fact: stream ciphers are insecure under CPA.

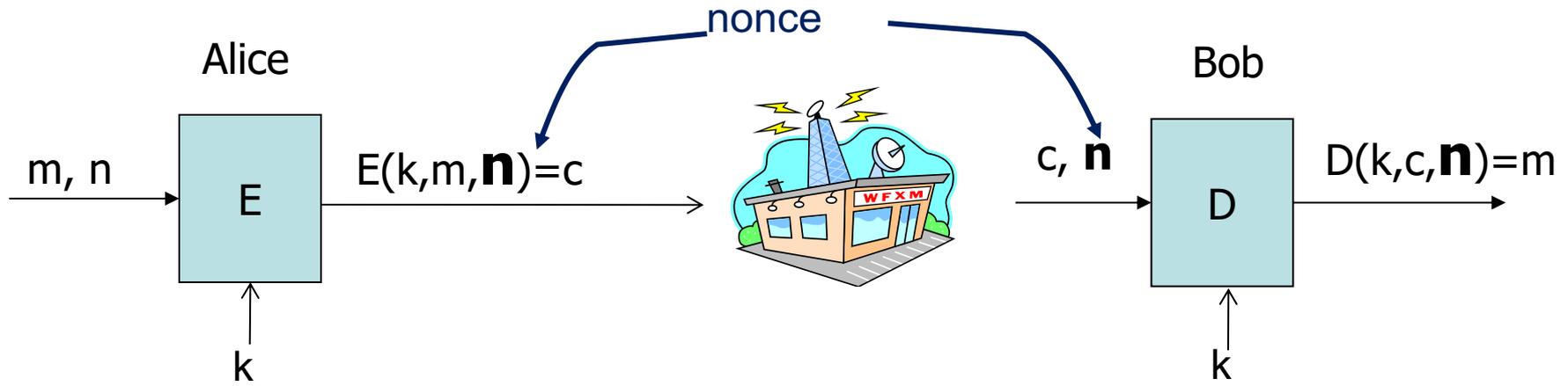
- More generally: if $E(k,m)$ always produces same ciphertext, then cipher is insecure under CPA.



If secret key is to be used multiple times \Rightarrow

given the same plaintext message twice,
the encryption alg. must produce different outputs.

Nonce-based Encryption

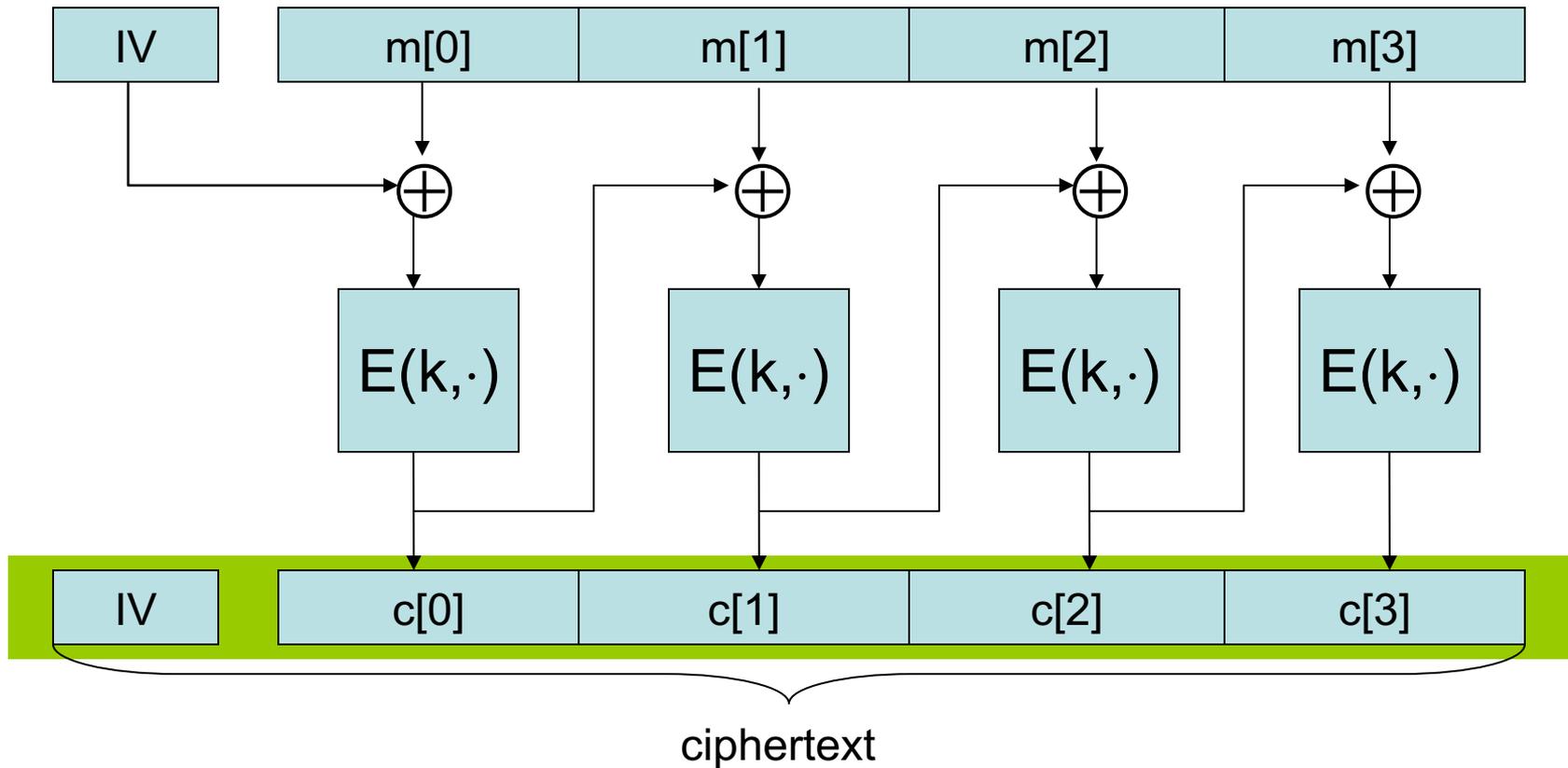


nonce n : a value that changes from msg to msg
(k, n) pair never used more than once

- method 1: encryptor chooses a random nonce, $n \leftarrow \mathcal{N}$
- method 2: nonce is a counter (e.g. packet counter)
 - used when encryptor keeps state from msg to msg
 - if decryptor has same state, need not send nonce with CT

Construction 1: CBC with random nonce

Cipher block chaining with a random IV (IV = nonce)



CBC: CPA Analysis

CBC Theorem: For any $L > 0$,

If E is a secure PRP over (K, X) then

E_{CBC} is a sem. sec. under CPA over (K, X^L, X^{L+1}) .

In particular, for a q -query adversary A attacking E_{CBC} there exists a PRP adversary B s.t.:

$$\text{Adv}_{\text{CPA}}[A, E_{\text{CBC}}] \leq 2 \cdot \text{Adv}_{\text{PRP}}[B, E] + 2q^2 L^2 / |X|$$

Note: CBC is only secure as long as $q^2 \cdot L^2 \ll |X|$

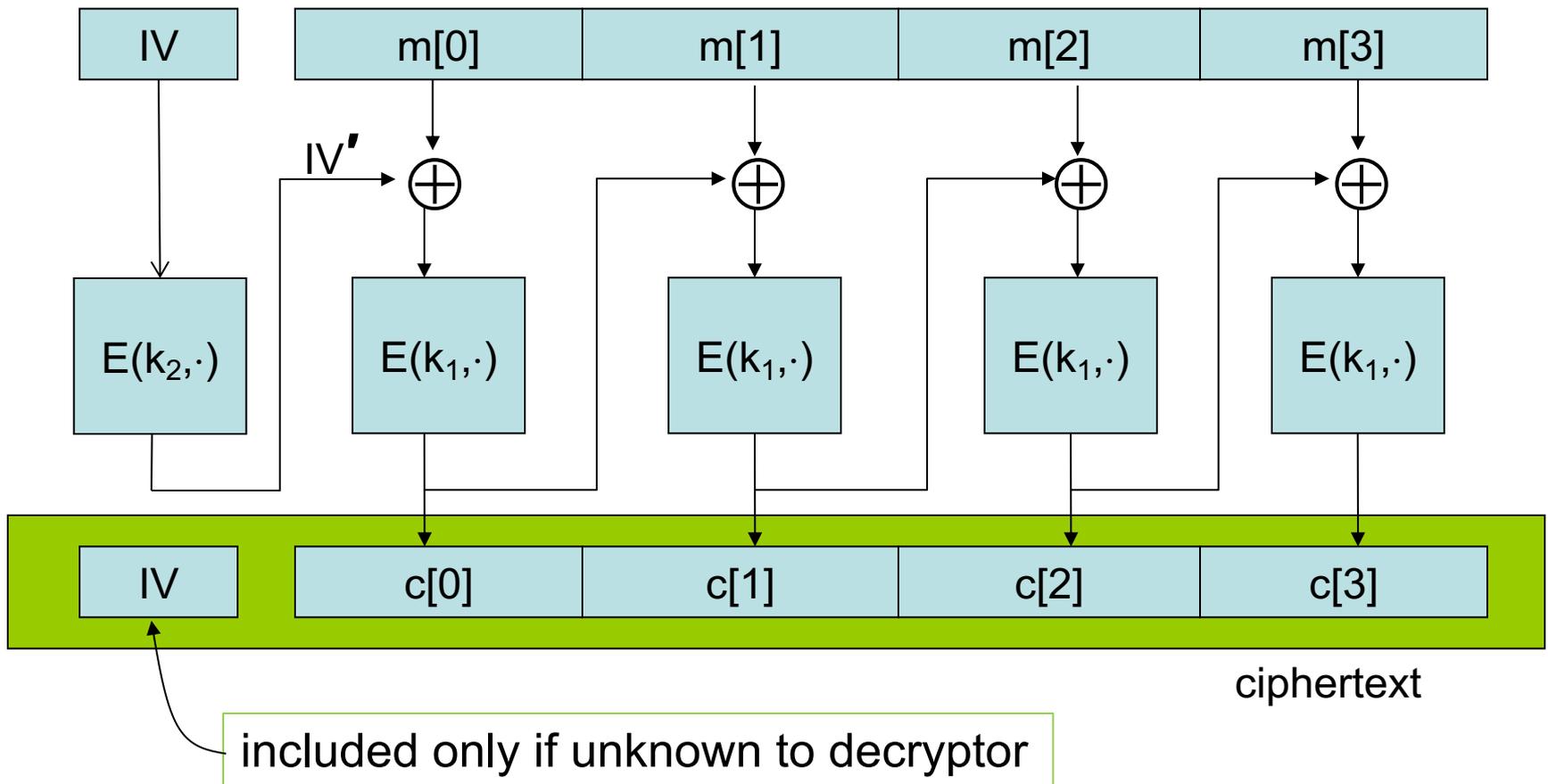
messages enc. with key

max msg length

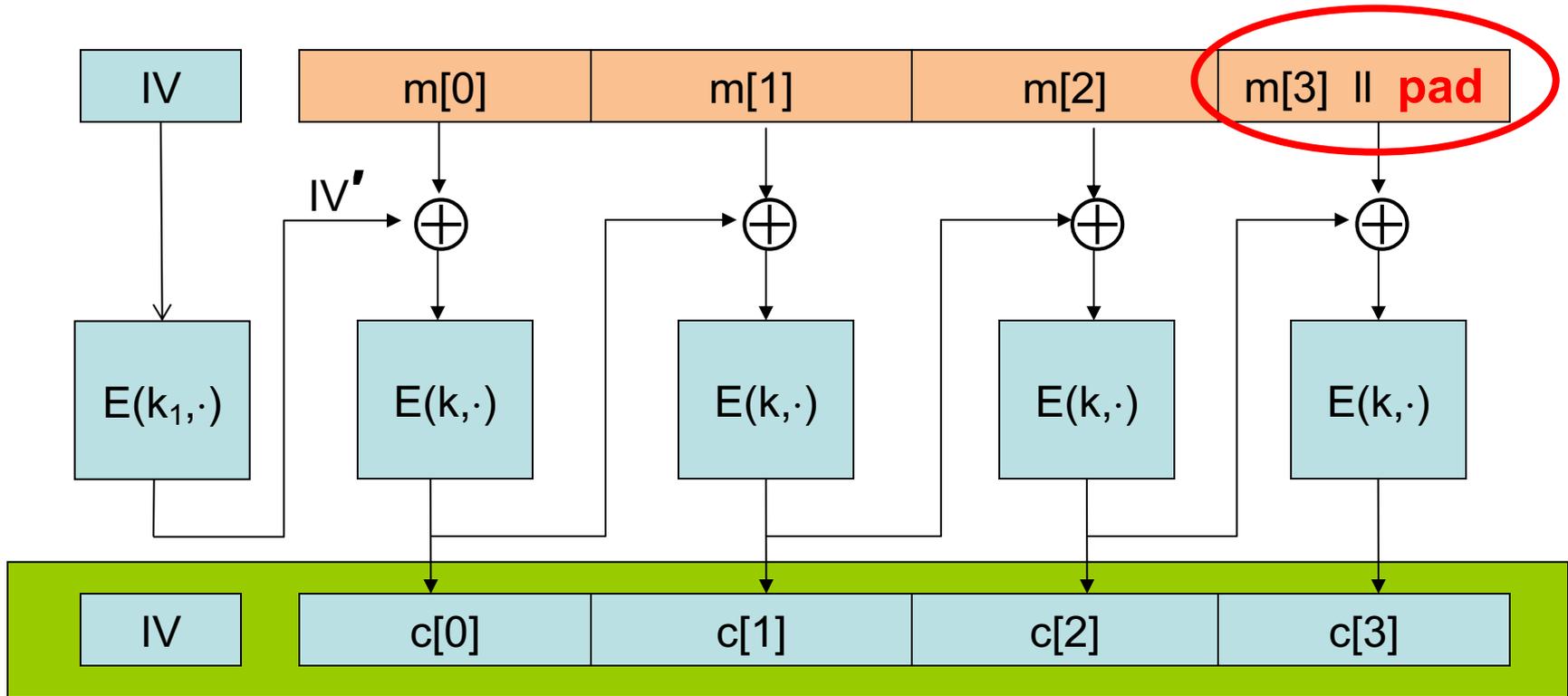
Construction 1': CBC with **unique** nonce

Cipher block chaining with unique IV (IV = nonce)

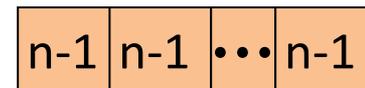
unique IV means: (key,IV) pair is used for only one message



A CBC technicality: padding



TLS 1.0: if need n -byte pad, $n > 0$, use:



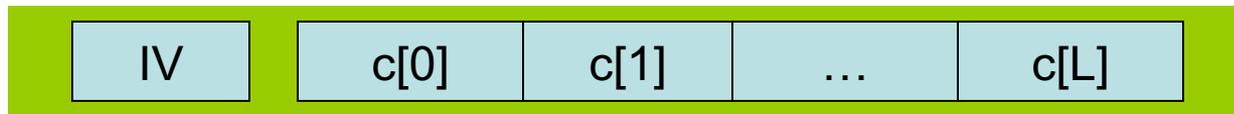
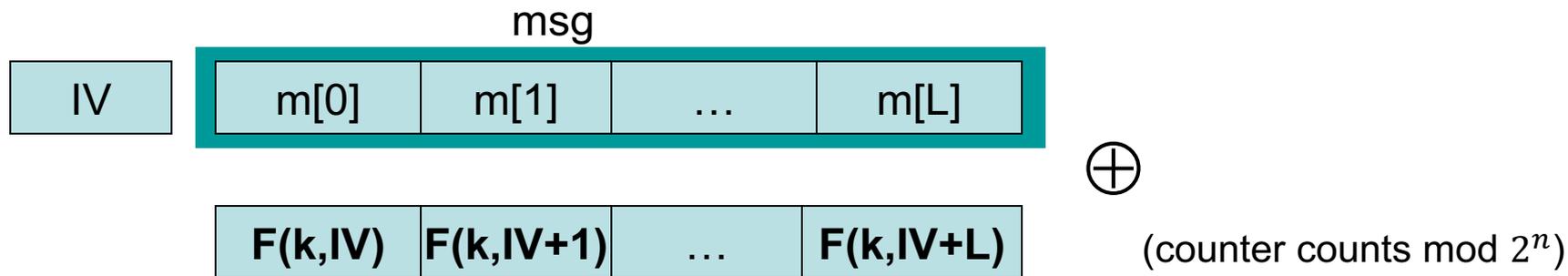
if no pad needed, add a dummy block

pad is removed during decryption

Construction 2: rand ctr-mode

F: PRF defined over (K, X, Y) where $X = \{0, 1, \dots, 2^n - 1\}$ and $Y = \{0, 1\}^n$

(e.g., $n=128$)



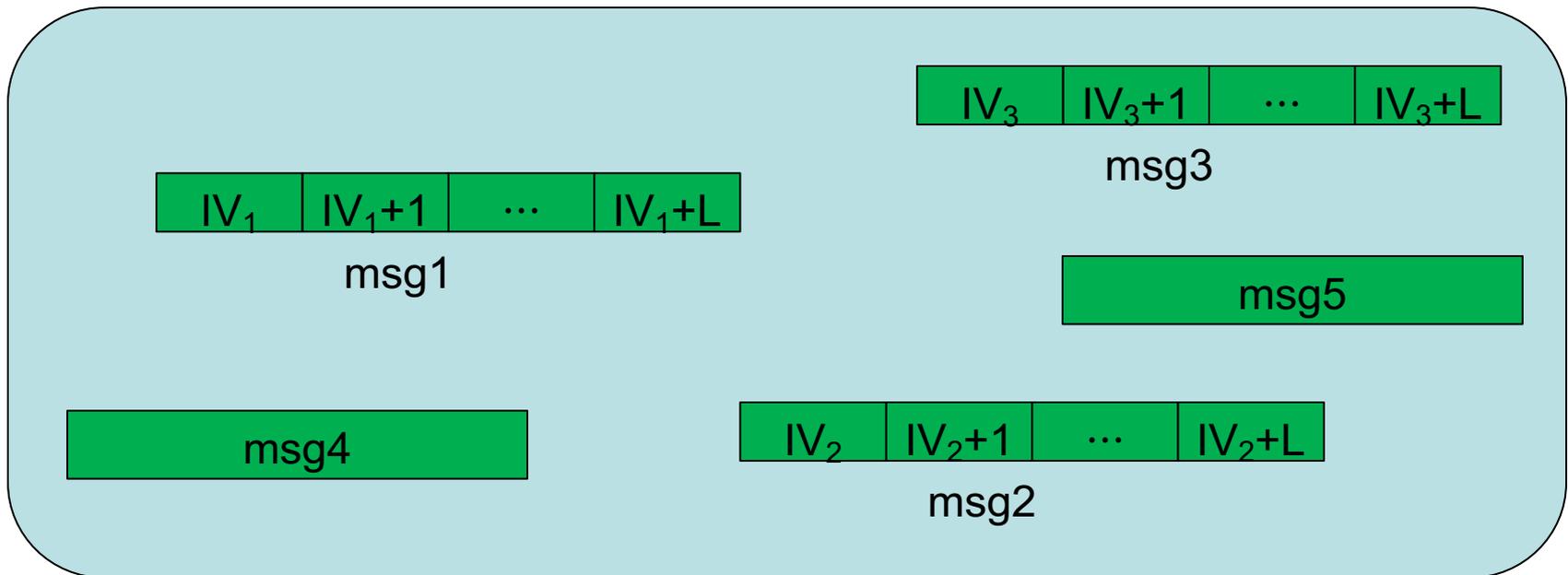
ciphertext

IV - chosen at random for every message

note: parallelizable (unlike CBC)

Why is this CPA secure?

the set X: domain of PRF



CPA security holds as long as intervals do not intersect

- q msgs, L blocks each $\Rightarrow \Pr[\text{intersection}] \leq \underbrace{2 q^2 L / |X|}_{\text{needs to be negligible}}$

rand ctr-mode: CPA analysis

Randomized counter mode: random IV.

Counter-mode Theorem: For any $L > 0$,

If F is a secure PRF over (K, X, X) then

E_{CTR} is a sem. sec. under CPA over (K, X^L, X^{L+1}) .

In particular, for a q -query adversary A attacking E_{CTR} there exists a PRF adversary B s.t.:

$$\text{Adv}_{CPA}[A, E_{CTR}] \leq 2 \cdot \text{Adv}_{PRF}[B, F] + 2q^2 L / |X|$$

Note: ctr-mode only secure as long as $q^2 \cdot L \ll |X|$

Better than CBC !

An example

$$\text{Adv}_{\text{CPA}}[A, E_{\text{CTR}}] \leq 2 \cdot \text{Adv}_{\text{PRF}}[B, E] + 2 q^2 L / |X|$$

$q = \#$ messages encrypted with k , $L =$ length of max msg

Suppose we want $\text{Adv}_{\text{CPA}}[A, E_{\text{CTR}}] \leq 1 / 2^{31}$

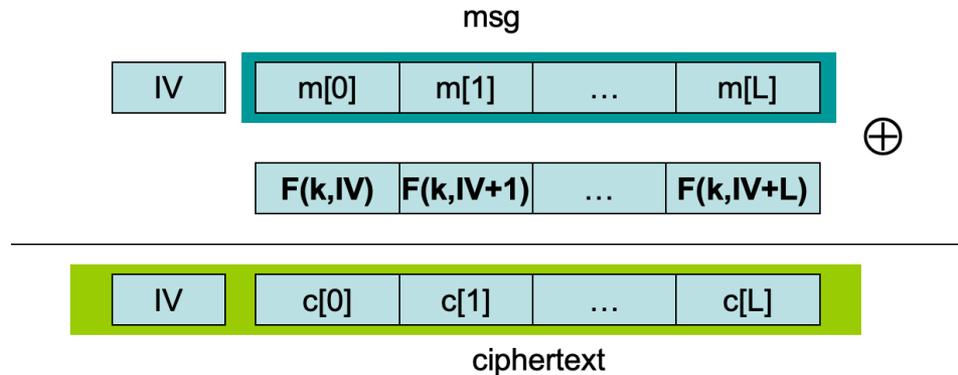
- Then need: $q^2 L / |X| \leq 1 / 2^{32}$

- AES: $|X| = 2^{128} \Rightarrow q L^{1/2} < 2^{48}$

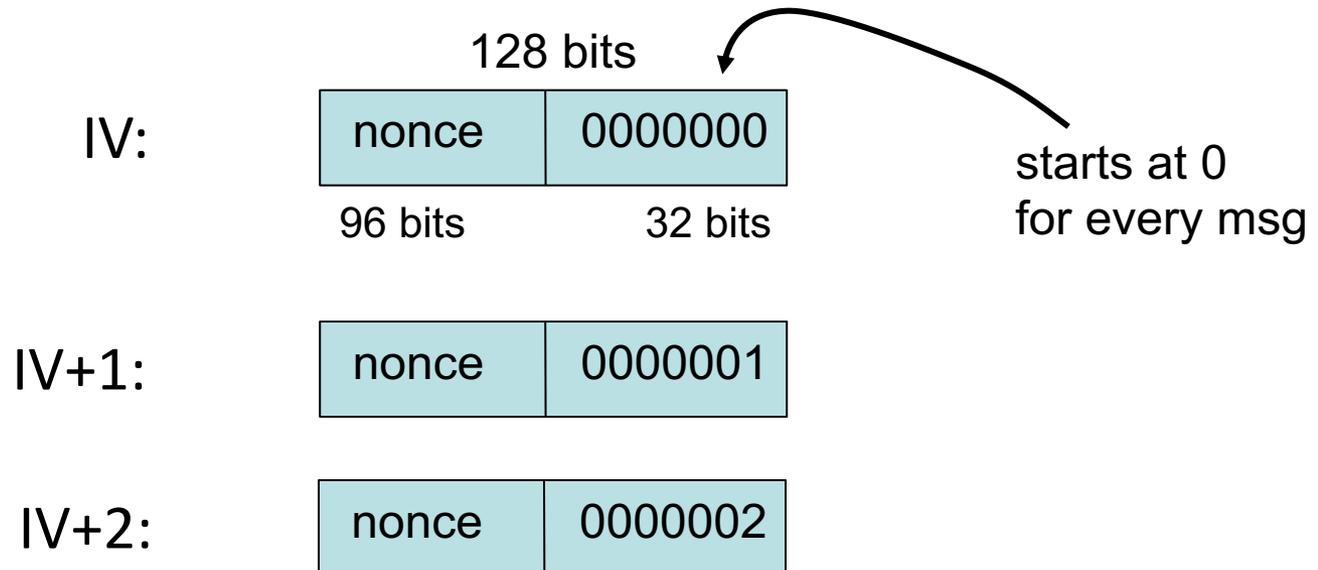
So, after 2^{32} CTs each of len 2^{32} , must change key

(total of 2^{64} AES blocks)

Construction 2': nonce ctr-mode



To ensure $F(k,x)$ is never used more than once, choose IV as:



Comparison: ctr vs. CBC

	CBC	ctr mode
required primitive	PRP	PRF
parallel processing	No	Yes
security	$q^2 L^2 \ll X $	$q^2 L \ll X $
dummy padding block	Yes*	No
1 byte msgs (nonce-based)	16x expansion	no expansion

* for CBC, dummy padding block can be avoided using *ciphertext stealing*

Summary

PRPs and PRFs: a useful abstraction of block ciphers.

We examined two security notions:

1. Semantic security against one-time.
2. Semantic security against many-time CPA.

Note: neither mode ensures data integrity.

Stated security results summarized in the following table:

Goal \ Power	one-time key	Many-time key (CPA)	CPA and CT integrity
Sem. Sec.	stream-ciphers det. ctr-mode	rand CBC rand ctr-mode	later

Attacks on block ciphers

Goal: distinguish block cipher from a random permutation

- if this can be done efficiently then block cipher is broken

Harder goal:

find key k given many $c_i = E(k, m_i)$ for random m_i

(1) Linear and differential attacks

[BS'89,M'93]

Given *many* (m_i, c_i) pairs, can recover key much faster than exhaustive search

Linear cryptanalysis (overview): let $c = \text{DES}(k, m)$

Suppose for random k, m :

$$\Pr \left[m[i_1] \oplus \cdots \oplus m[i_r] \oplus c[j_1] \oplus \cdots \oplus c[j_v] = k[l_1] \oplus \cdots \oplus k[l_u] \right] = \frac{1}{2} + \varepsilon$$

For some ε .

For DES, this exists with $\varepsilon = 1/2^{21} \approx 0.0000000477$!!

Linear attacks

$$\Pr \left[m[i_1] \oplus \dots \oplus m[i_r] \oplus c[j_1] \oplus \dots \oplus c[j_v] = k[l_1] \oplus \dots \oplus k[l_u] \right] = \frac{1}{2} + \varepsilon$$

Thm: given $1/\varepsilon^2$ random pairs $(m, c = \text{DES}(k, m))$ then

$$k[l_1] \oplus \dots \oplus k[l_u] = \text{MAJ} \left[m[i_1] \oplus \dots \oplus m[i_r] \oplus c[j_1] \oplus \dots \oplus c[j_v] \right]$$

with prob. $\geq 97.7\%$

\Rightarrow with $1/\varepsilon^2$ inp/out pairs can find $k[l_1] \oplus \dots \oplus k[l_u]$ in time $\approx 1/\varepsilon^2$

Linear attacks

For DES, $\varepsilon = 1/2^{21} \Rightarrow$

with 2^{42} inp/out pairs can find $k[l_1] \oplus \dots \oplus k[l_u]$ in time 2^{42}

Roughly speaking: can find 14 key “bits” this way in time 2^{42}

Brute force remaining $56-14=42$ bits in time 2^{42}

Attack time: $\approx 2^{43}$ ($\ll 2^{56}$) with 2^{42} random inp/out pairs

Lesson

A tiny bit of linearity leads to a 2^{42} time attack.

⇒ don't design ciphers yourself !!

(2) Side channel attacks on software AES

Attacker measures the **time** to compute AES128(k,m) for many random blocks m.

- Suppose that the 256-byte S table is not in L1 cache at the start of each invocation
 - ⇒ time to encrypt reveals the order in which S entries are accessed
 - ⇒ leaks info. that can compromise entire key

Lesson: don't implement AES yourself !

Mitigation: AES-NI or use vetted software (e.g., BoringSSL)

(3) Quantum attacks

Generic search problem:

Let $f: X \rightarrow \{0,1\}$ be a function.

Goal: find $x \in X$ s.t. $f(x)=1$.

Classical computer: best generic algorithm time = $O(|X|)$

Quantum computer [Grover '96]: time = $O(|X|^{1/2})$

(requires a long running quantum computation)

Quantum exhaustive search

Given m , $c=E(k,m)$ define

$$f(k) = \begin{cases} 1 & \text{if } E(k,m) = c \\ 0 & \text{otherwise} \end{cases}$$

Grover \Rightarrow quantum computer can find k in time $O(|K|^{1/2})$

AES128: quantum key recovery time $\approx 2^{64}$

Adversary has access to a quantum computer \Rightarrow

encrypt data using a cipher with 256-bit keys (AES256)

THE END

Recap

Secure PRF: $F: K \times X \rightarrow Y$ and

$\{f(x) = F(k,x) \text{ for } k \leftarrow K\}$ is indist. from random f in $\text{Funs}[X,Y]$

Secure PRP: $E: K \times X \rightarrow X$, efficiently invertible, and

$\{\pi(x) = E(k,x) \text{ for } k \leftarrow K\}$ is indist. from random π in $\text{Perms}[X]$

How to use a secure PRF and a secure PRP for encryption?

- One-time key (semantic security): det. CTR-mode
- Many-time key (CPA security):
 nonce-based CBC, nonce-based CTR mode