<u>CS255</u>: Winter 2010

PRPs and PRFs

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

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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

- <u>Example PRPs</u>: 3DES, AES, …

  AES: $K \times X \rightarrow X$ 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.

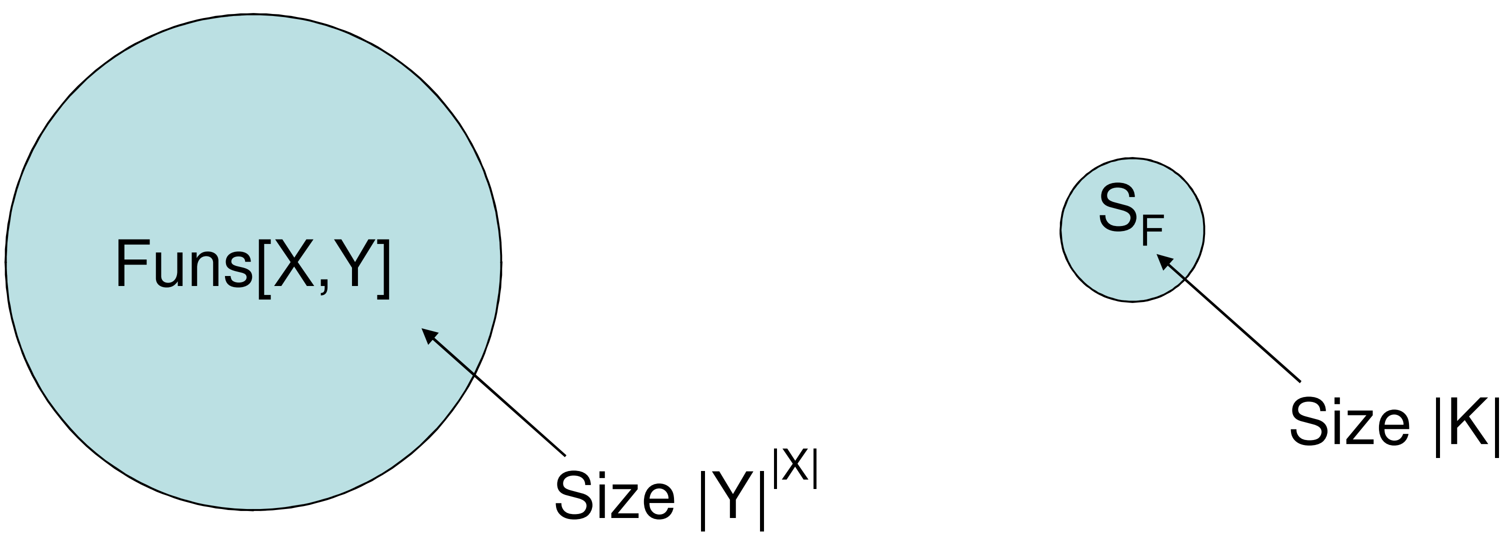
Secure PRFs

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

  Funs[X,Y]: the set of **all** functions from X to Y

  $S_F = \{ \; F(k,\cdot) \;\; \text{s.t.} \;\; k \in K \; \} \subseteq$ Funs[X,Y]

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



Secure PRFs

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

$$\begin{cases} \text{Funs[X,Y]:} & \text{the set of } \textbf{\underline{all}} \text{ functions from X to Y} \\ S_F = \{ F(k,\cdot) \text{ s.t. } k \in K \} & \subseteq \quad \text{Funs[X,Y]} \end{cases}$$

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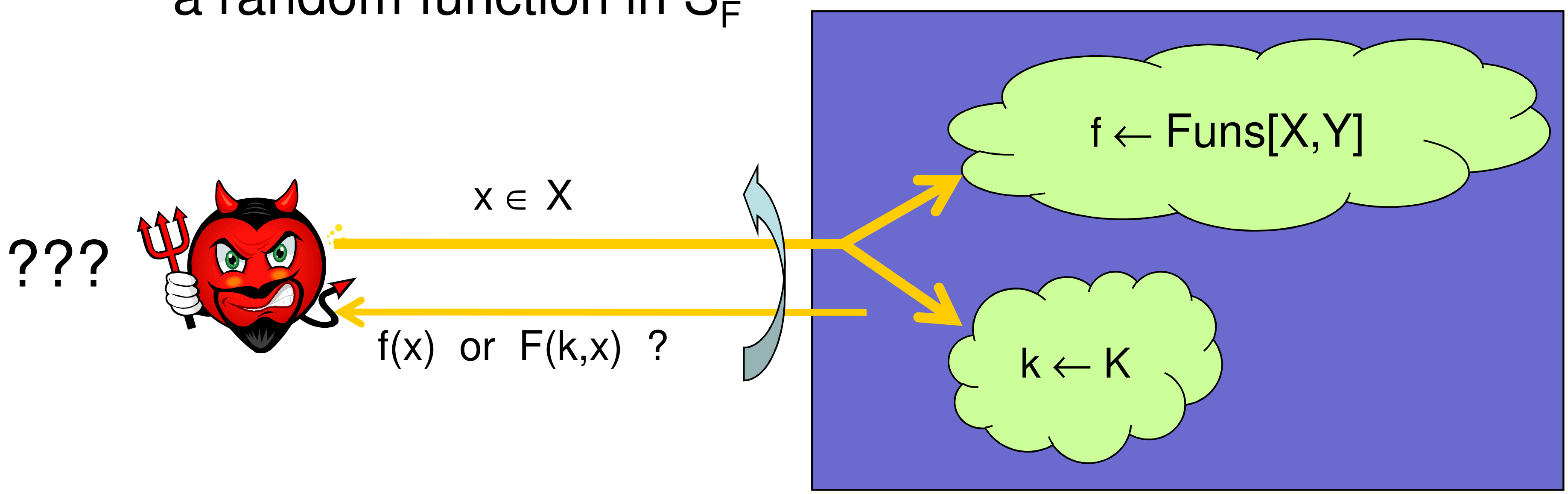
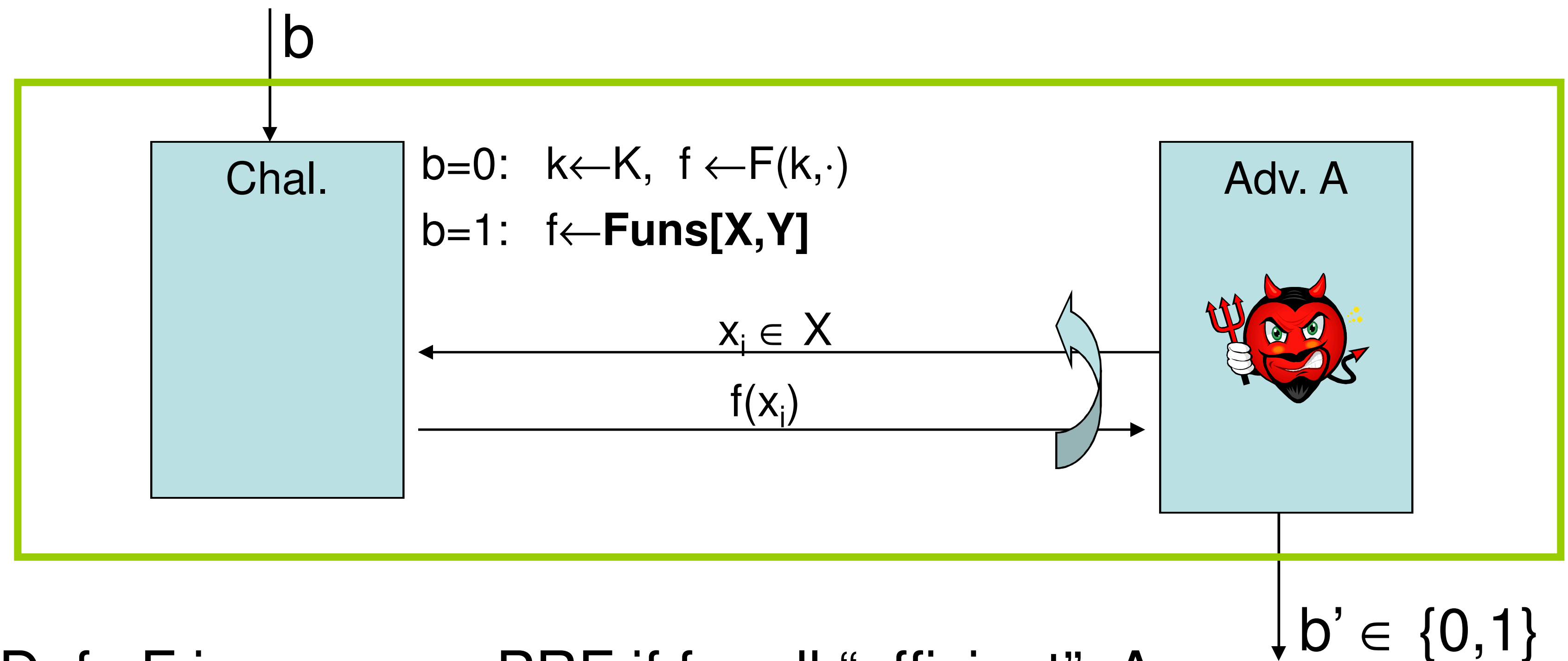


Secure PRF: defintion

- For b=0,1 define experiment EXP(b) as:



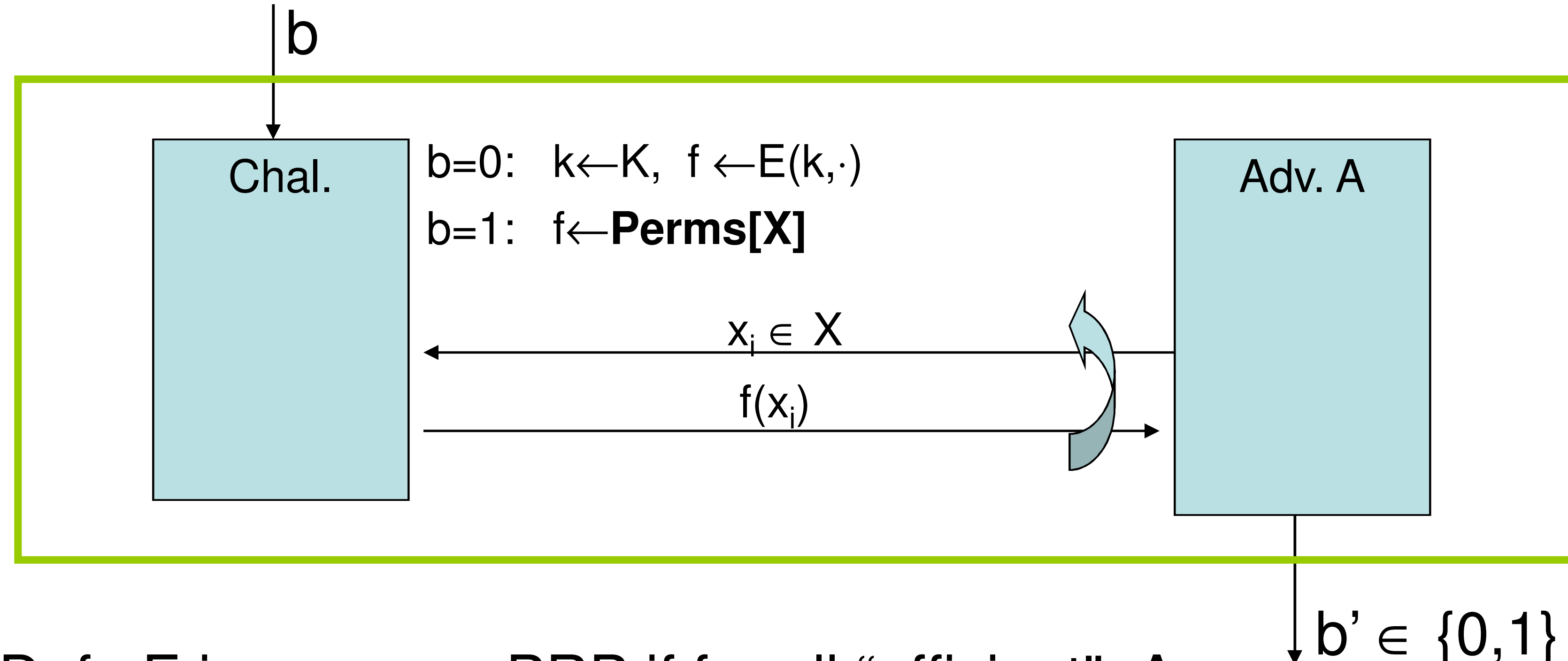
- Def: F is a secure PRF if for all "efficient" A:

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

is "negligible."

Secure PRP

- For b=0,1 define experiment EXP(b) as:



- Def: E is a secure PRP if for all "efficient" A:

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

is "negligible."

Example secure PRPs

- Example secure PRPs: 3DES, AES, …

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

- AES PRP Assumption (example) :

  All 2^{80}–time algs A have PRP Adv[A, **AES**] $< 2^{-40}$

PRF Switching Lemma

- Any secure PRP is also a secure PRF.

- <u>Lemma</u>: Let E be a PRP over (K,X)

  Then for any q-query adversary A:

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

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

Then

PRP Adv[A,E] "negligible" $\Rightarrow$ PRF Adv[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)

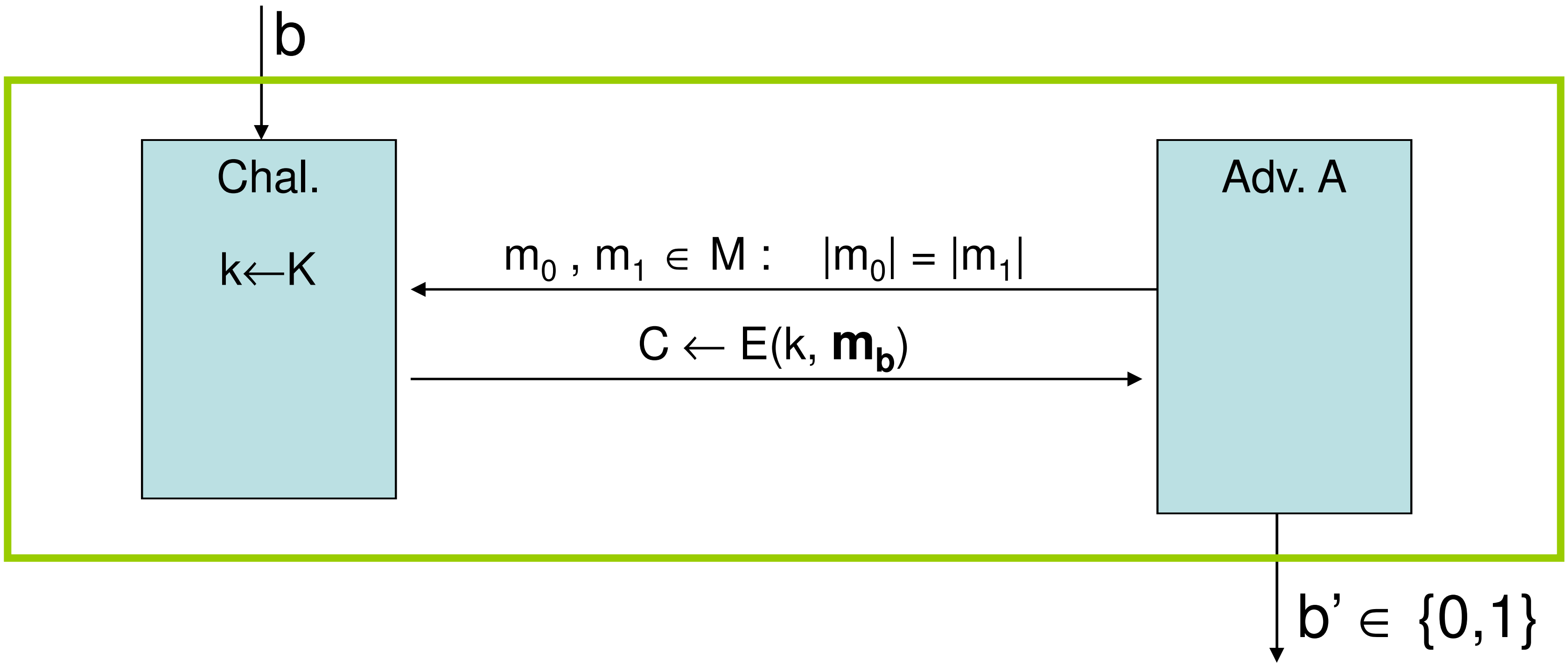
Modes of Operation for One-time Use Key

<u>Example application</u>:

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 EXP(b) as:



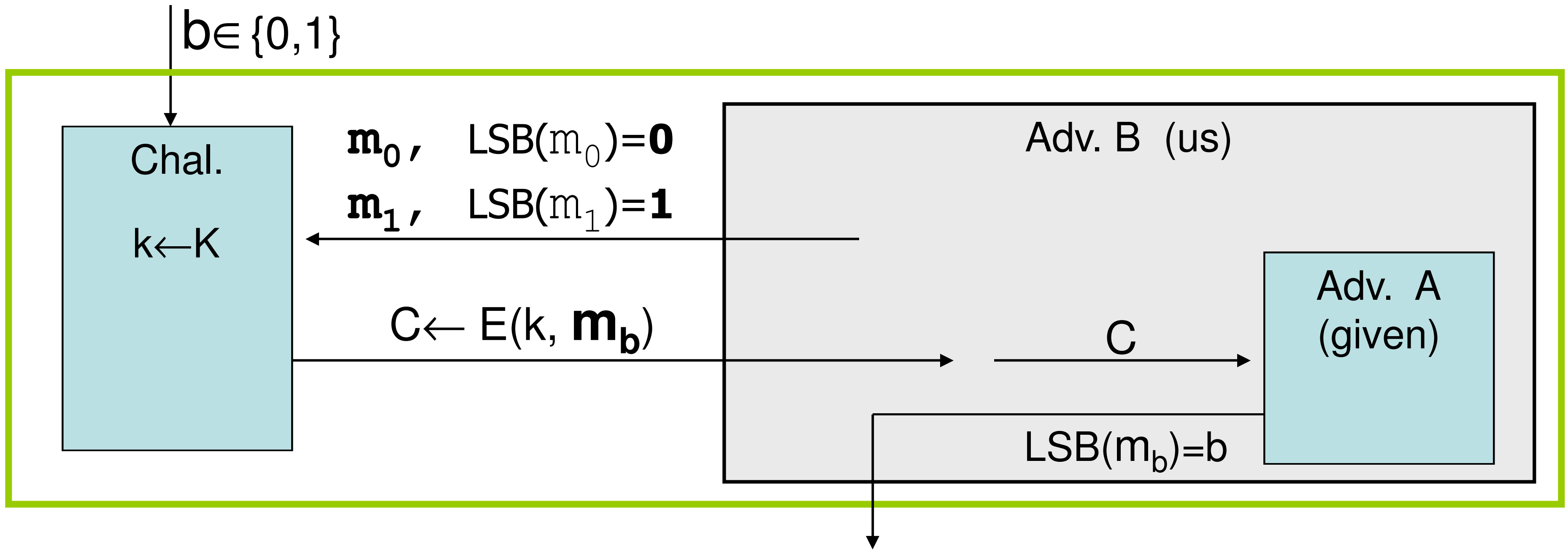
- Def: $\mathbb{E}$ is sem. sec. for one-time key if for all "efficient" A:

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

is "negligible."

Semantic security (cont.)

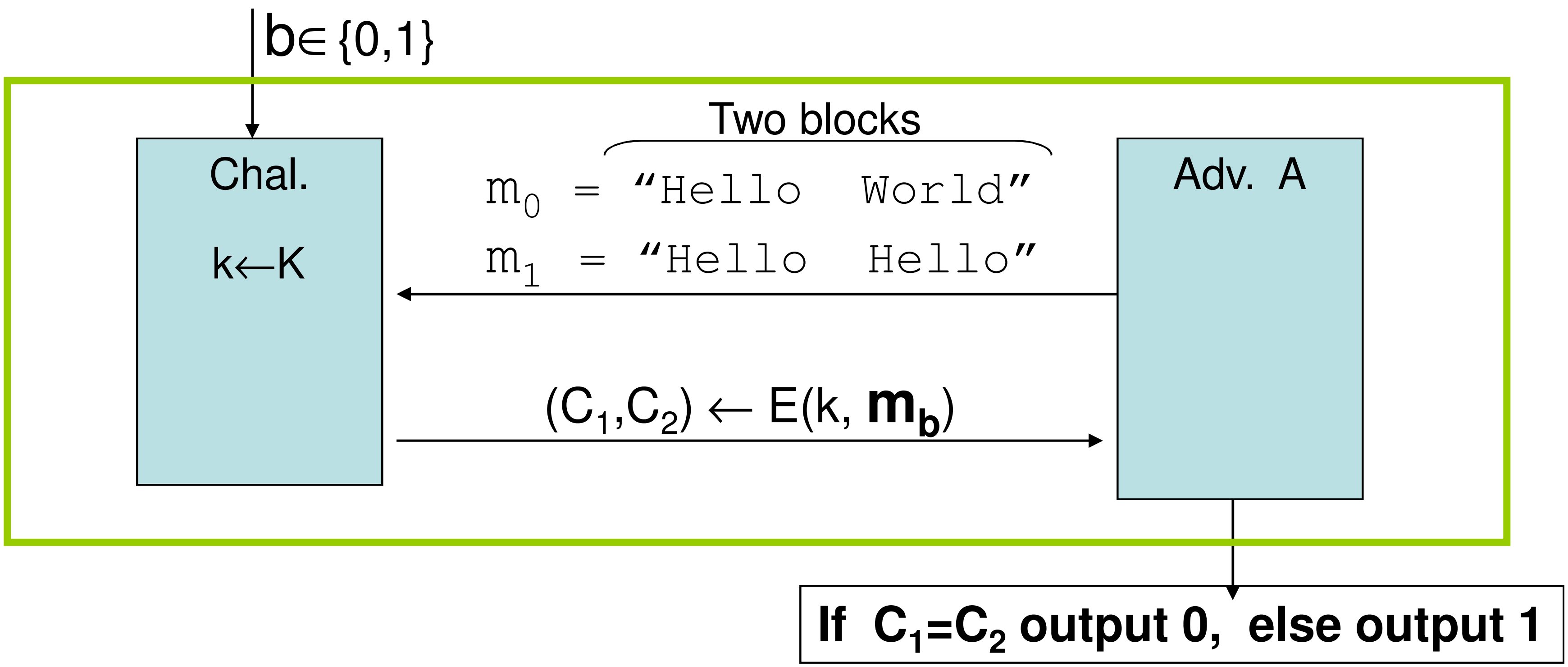
- Sem. Sec. $\Rightarrow$ no "efficient" adversary learns info about PT from a <u>**single**</u> CT.
- Example: suppose efficient A can deduce LSB of PT from CT. Then $\mathbb{E}$ = (E,D) is not semantically secure.



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

Note: ECB is not Sem. Sec.

- Electronic Code Book (ECB):
  – Not semantically secure for messages that contain more than one block.



- Then SS Adv[A, ECB] = 1

Secure Constructions

- Examples of sem. sec. systems:
  1. SS Adv[A, OTP] = 0 for **<u>all</u>** A
  2. Deterministic counter mode from a PRF F :
     - E_{DETCTR} (k,m) =

$$
\begin{array}{r|c|c|c|c|}
\hline
 & m[0] & m[1] & \ldots & m[L] \\
\hline
\oplus & & & & \\
\hline
 & \mathbf{F(k,0)} & \mathbf{F(k,1)} & \ldots & \mathbf{F(k,L)} \\
\hline
\hline
 & c[0] & c[1] & \ldots & c[L] \\
\hline
\end{array}
$$

     - Stream cipher built from PRF (e.g. AES, 3DES)

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).

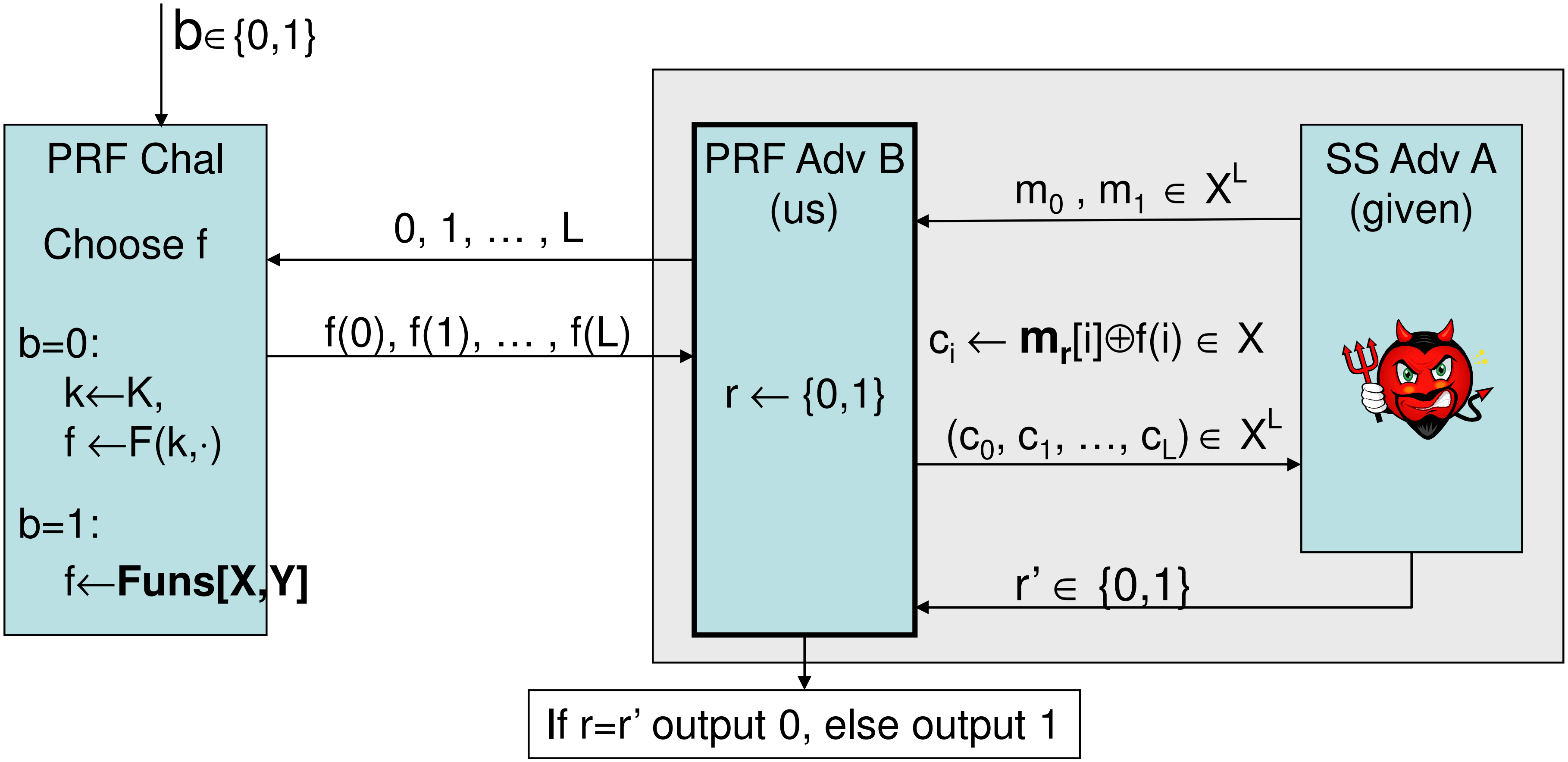
  In particular, for any adversary A attacking E_{DETCTR} there exists a PRF adversary B s.t.:

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

PRF Adv[B, F] is negligible (since F is a secure PRF)

Hence, SS Adv[A, E_{DETCTR}] must be negligible.

Proof (as a reduction)



b=1: f←**Funs[X,X]** $\Rightarrow$ Pr[EXP(1)=0] = Pr[r=r'] = ½

b=0: f←F(k,·) $\Rightarrow$ Pr[EXP(0)=0] = ½ ± ½ ·SS Adv[A, E_{DETCTR}]

Hence, PRF Adv[F, B] = ½ ·SS Adv[A, DETCTR]

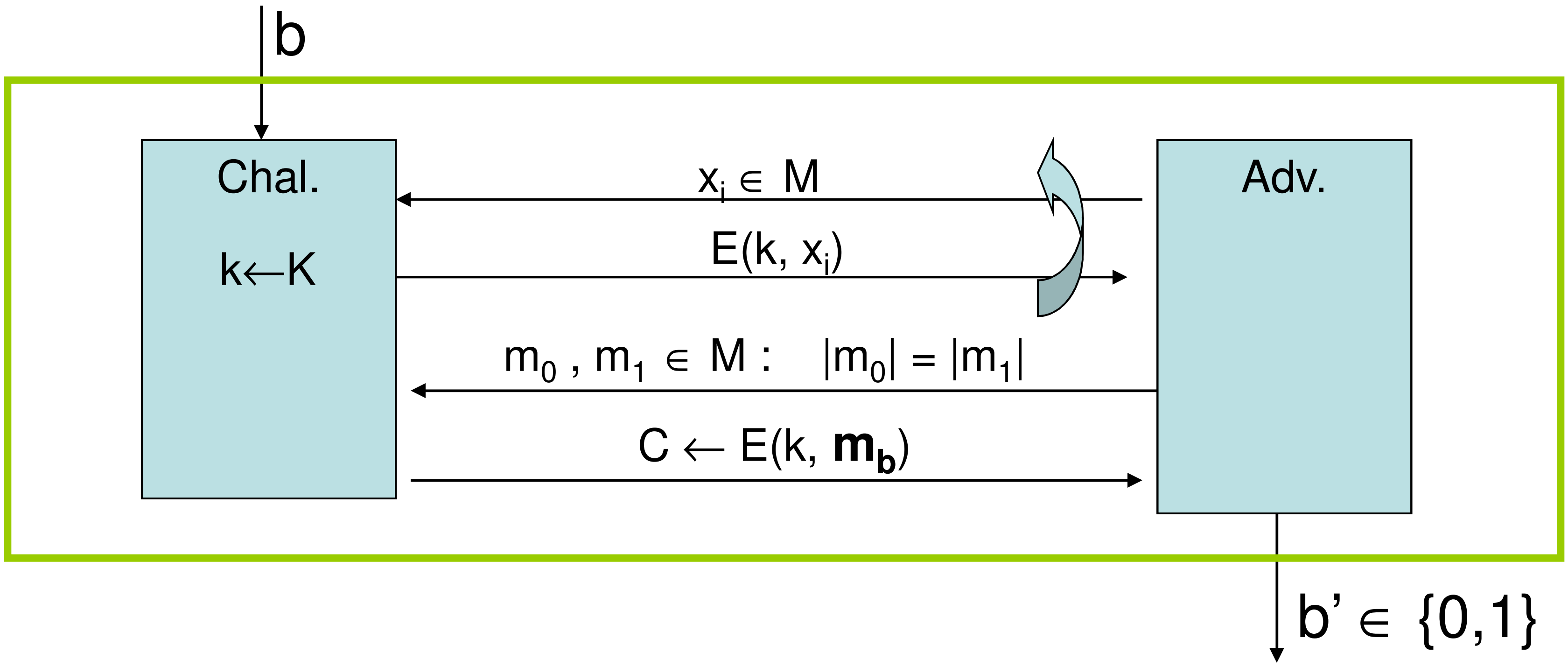
Modes of Operation for Many-time Key

<u>Example applications</u>:

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

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



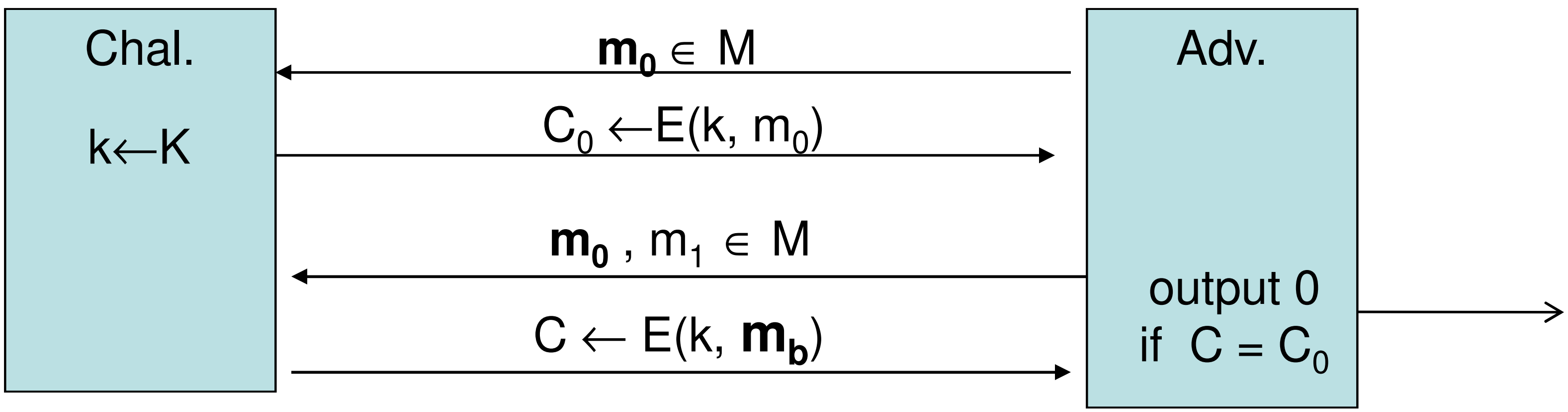
- Def: $\mathbb{E}$ is sem. sec. under CPA if for all “efficient” A:

$$\mathrm{SS}^{\mathrm{CPA}}\,\mathrm{Adv}[A,\mathbb{E}] \;=\; \Big|\Pr[\mathrm{EXP}(0)=1] - \Pr[\mathrm{EXP}(1)=1]\Big|$$

is “negligible.”

Security for many-time key

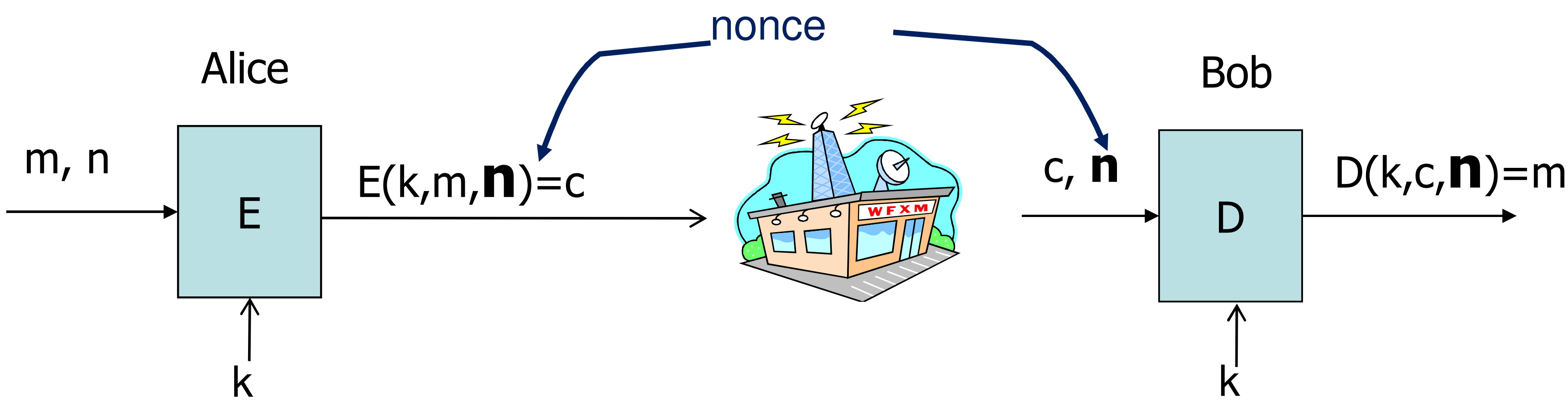
- <u>Fact:</u> stream ciphers are insecure under CPA.
  - More generally: if $E(k,m)$ always produces same ciphertext, then cipher is insecure under CPA.



- 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

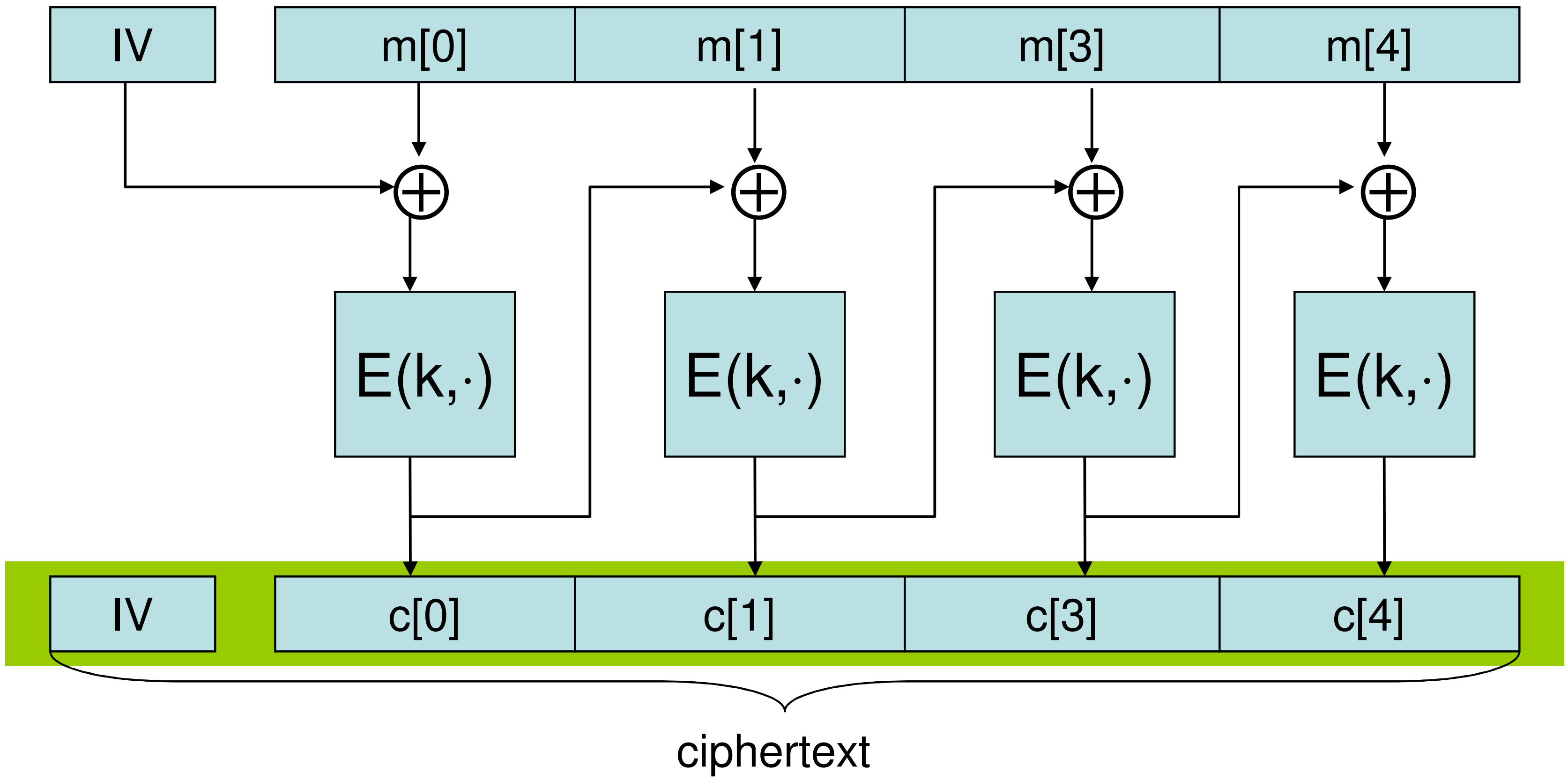
  (k,n) pair never used more than once

- method 1: encryptor picks a random nonce, $n \leftarrow N$

- 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)



note: CBC where attacker can predict the IV is not CPA-secure. HW.

CBC: CPA Analysis

- <u>CBC Theorem</u>: 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.:

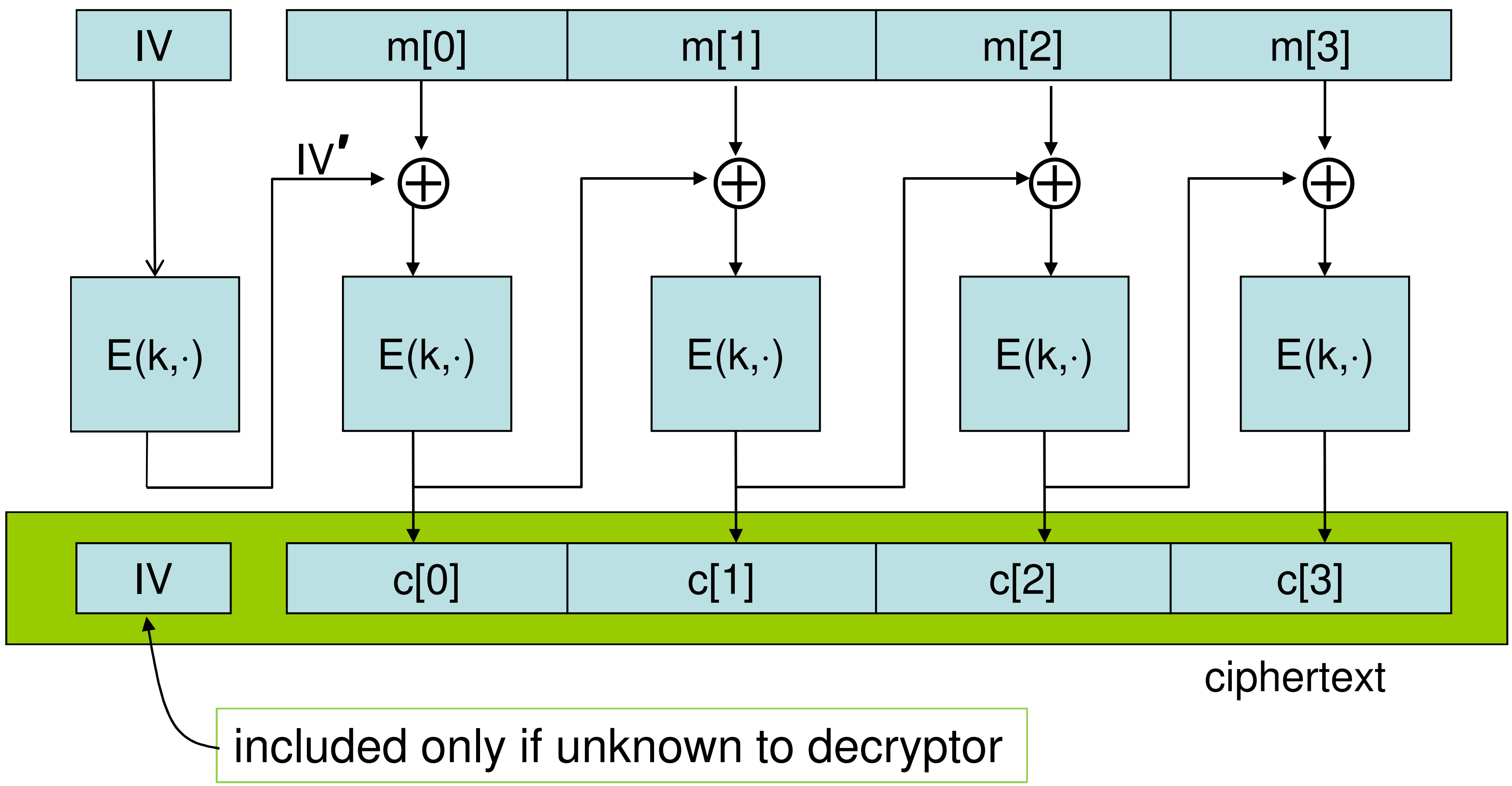
  $$SS_{CPA}\,Adv[A, E_{CBC}] \le 2 \cdot PRP\,Adv[B, E] + 2\,q^2\,L^2 / |X|$$

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

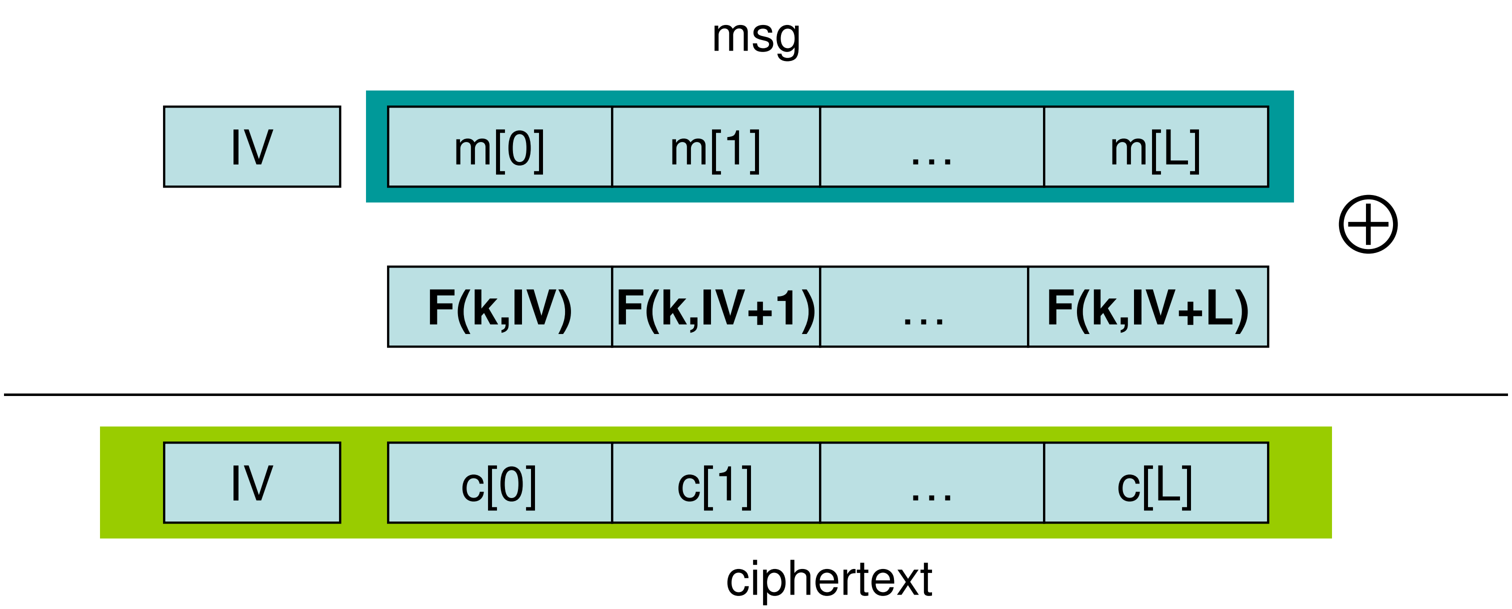
Construction 1': CBC with **unique** nonce

- Cipher block chaining with <u>unique</u> IV (IV = nonce)

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

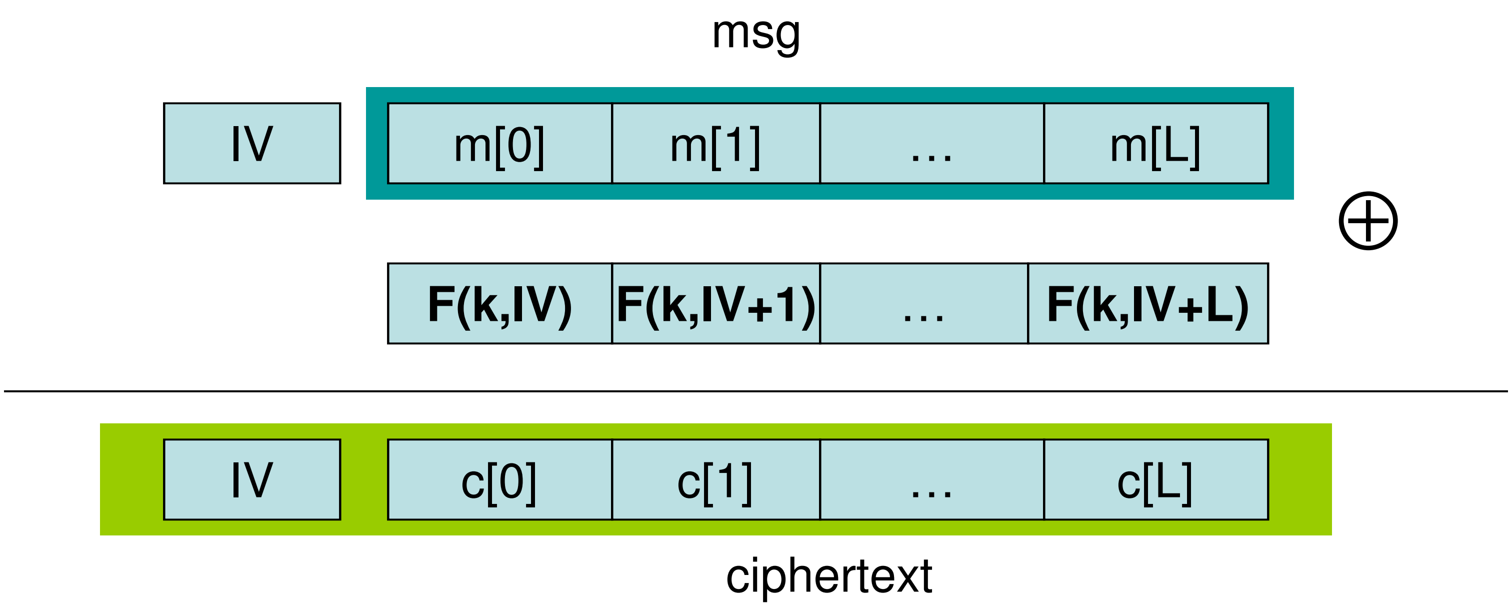


Construction 2: rand ctr-mode

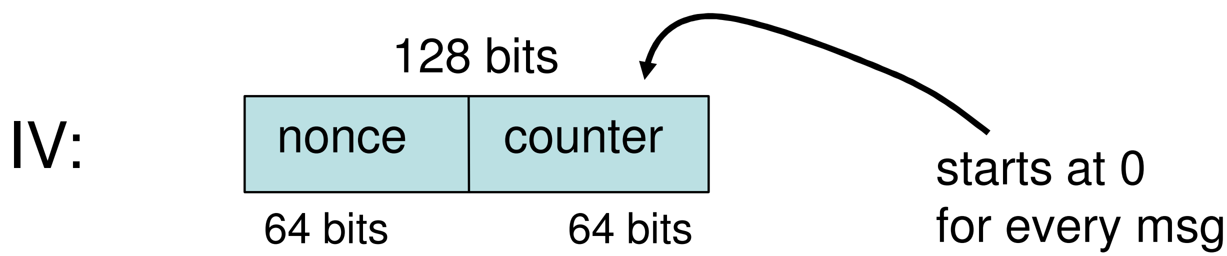


IV - chosen at random for every message

Construction 2': nonce ctr-mode



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



rand ctr-mode: CPA analysis

- Randomized counter mode: random IV.

- <u>Counter-mode Theorem</u>: 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.:

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

- <u>Note</u>: ctr-mode only secure as long as $q^2L \ll |X|$

  Better then CBC !

Summary

- PRPs and PRFs: a useful abstraction of block ciphers.
- We examined two security notions:
  1. Semantic security against one-time CPA.
  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.	steam-ciphers det. ctr-mode	rand CBC rand ctr-mode	later