

# Private-Key Encryption and Pseudorandomness (Part II)

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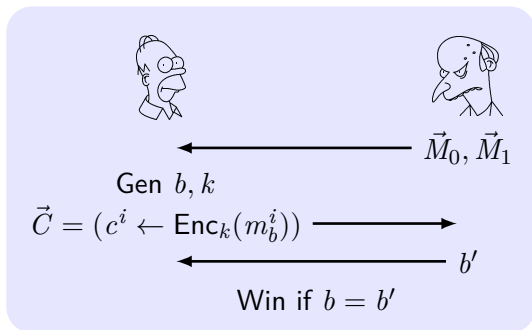
- 1 Stream Ciphers and Multiple Encryption**
- 2 Security Against Chosen-Plaintext Attacks (CPA)**
- 3 Constructing CPA-Secure Encryption Schemes**
- 4 Modes of Operation**
- 5 Security Against Chosen-Ciphertext Attacks (CCA)**

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# Security for Multiple Encryptions

The multiple-message eavesdropping experiment  $\text{PrivK}_{\mathcal{A},\Pi}^{\text{mult}}(n)$ :

- 1  $\mathcal{A}$  is given input  $1^n$ , outputs  $\vec{M}_0 = (m_0^1, \dots, m_0^t)$ ,  $\vec{M}_1 = (m_1^1, \dots, m_1^t)$  with  $\forall i, |m_0^i| = |m_1^i|$ .
- 2  $k \leftarrow \text{Gen}(1^n)$ , a random bit  $b \leftarrow \{0, 1\}$  is chosen. Then  $c^i \leftarrow \text{Enc}_k(m_b^i)$  and  $\vec{C} = (c^1, \dots, c^t)$  is given to  $\mathcal{A}$ .
- 3  $\mathcal{A}$  outputs  $b'$ . If  $b' = b$ ,  $\text{PrivK}_{\mathcal{A},\Pi}^{\text{mult}} = 1$ , otherwise 0.



# Definition of Multi-Encryption Security

## Definition 1

$\Pi$  has **indistinguishable multiple encryptions in the presence of an eavesdropper** if  $\forall$  PPT  $\mathcal{A}$ ,  $\exists$   $\text{negl}$  such that

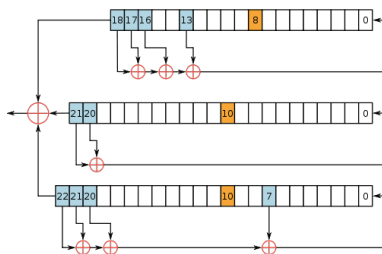
$$\Pr \left[ \text{PrivK}_{\mathcal{A}, \Pi}^{\text{mult}}(n) = 1 \right] \leq \frac{1}{2} + \text{negl}(n).$$

## Question:

- Does any cipher we have learned so far have indistinguishable multiple encryptions in the presence of an eavesdropper?
- Generally, if  $\Pi$ 's encryption function is **deterministic**, is  $\Pi$  multiple-encryption-secure?

# Stream Ciphers

- **Stream cipher:** Encrypting by XORing with pseudorandom stream
- **State of the art:** No standardized and popular one<sup>1</sup>  
Security is questionable, e.g., RC4 in WEP protocol in 802.11,  
Linear Feedback Shift Registers (LFSRs)

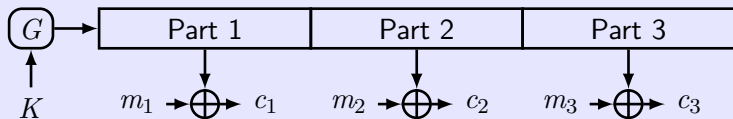


## WARNING

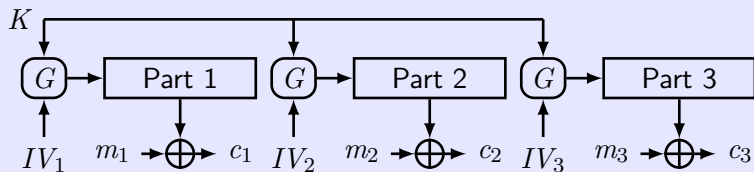
Don't use any stream cipher. If necessary, construct one from a block cipher.

<sup>1</sup>eStream project worked on it. Salsa20/12 is a promising candidate.

# Secure Multiple Encryptions Using a Stream Cipher



*Synchronized Mode*



*Unsynchronized Mode*

Initial vector  $IV$  is chosen *u.a.r* and public

Q: which mode is better in your opinion?

Keys (the  $IV$ -key pair) for multiple enc. must be independent

### Attacks on 802.11b WEP

Unsynchronized mode:  $\text{Enc}(m_i) := \langle IV_i, G(IV_i || k) \oplus m_i \rangle$

- Length of  $IV$  is 24 bits, repeat  $IV$  after  $2^{24} \approx 16\text{M}$  frames
- On some WiFi cards,  $IV$  resets to 0 after power cycle
- $IV_i = IV_{i-1} + 1$ . For RC4, recover  $k$  after 40,000 frames



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# Chosen-Plaintext Attacks (CPA)

**CPA:** the adversary has the ability to obtain the encryption of plaintexts of its choice

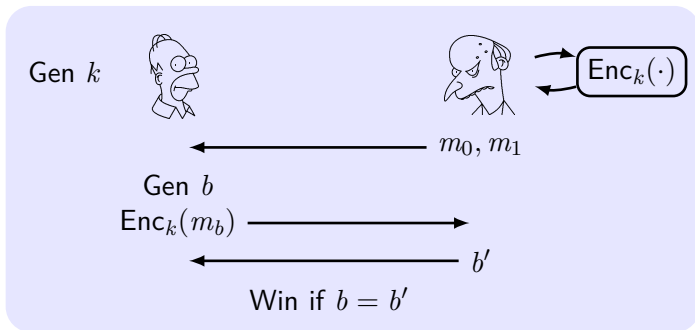
## A story in WWII

- Navy cryptanalysts believe the ciphertext “AF” means “Midway island” in Japanese messages
- But the general did not believe that Midway island would be attacked
- Navy cryptanalysts sent a plaintext that the freshwater supplies at Midway island were low
- Japanese intercepted the plaintext and sent a ciphertext that “AF” was low in water
- The US forces dispatched three aircraft carriers and won

# Security Against CPA

The CPA indistinguishability experiment  $\text{PrivK}_{\mathcal{A}, \Pi}^{\text{cpa}}(n)$ :

- 1  $k \leftarrow \text{Gen}(1^n)$
- 2  $\mathcal{A}$  is given input  $1^n$  and **oracle access**  $\mathcal{A}^{\text{Enc}_k(\cdot)}$  to  $\text{Enc}_k(\cdot)$ , outputs  $m_0, m_1$  of the same length
- 3  $b \leftarrow \{0, 1\}$ . Then  $c \leftarrow \text{Enc}_k(m_b)$  is given to  $\mathcal{A}$
- 4  $\mathcal{A}$  **continues to have oracle access** to  $\text{Enc}_k(\cdot)$ , outputs  $b'$
- 5 If  $b' = b$ ,  $\mathcal{A}$  succeeded  $\text{PrivK}_{\mathcal{A}, \Pi}^{\text{cpa}} = 1$ , otherwise 0



## Definition 2

$\Pi$  has **indistinguishable encryptions under a CPA (CPA-secure)** if  $\forall$  PPT  $\mathcal{A}$ ,  $\exists$   $\text{negl}$  such that

$$\Pr \left[ \text{PrivK}_{\mathcal{A}, \Pi}^{\text{cpa}}(n) = 1 \right] \leq \frac{1}{2} + \text{negl}(n).$$

- Q: Is any cipher we have learned so far CPA-secure? Why?

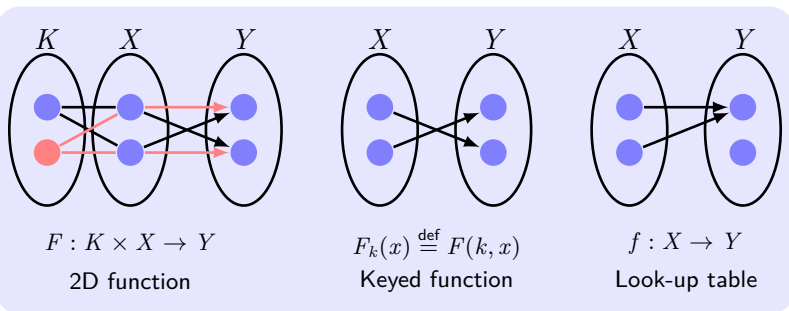
## Proposition 3

*Any private-key encryption scheme that is CPA-secure also is **multiple-encryption** CPA-secure.*

- Q: Does **multiple-encryption-security** mean CPA-security? (homework)

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# Concepts on Pseudorandom Functions



- **Keyed function**  $F : \{0, 1\}^* \times \{0, 1\}^* \rightarrow \{0, 1\}^*$   
 $F_k : \{0, 1\}^* \rightarrow \{0, 1\}^*, F_k(x) \stackrel{\text{def}}{=} F(k, x)$
- **Look-up table**  $f : \{0, 1\}^n \rightarrow \{0, 1\}^n$  with size = ? bits
- **Function family**  $\text{Func}_n$ : all functions  $\{0, 1\}^n \rightarrow \{0, 1\}^n$ .  
 $|\text{Func}_n| = 2^{n \cdot 2^n}$
- **Length Preserving:**  $\ell_{key}(n) = \ell_{in}(n) = \ell_{out}(n)$

# Definition of Pseudorandom Function

**Intuition:** A PRF  $F$  generates a function  $F_k$  that is indistinguishable from truly random selected function  $f$  (look-up table) in  $\text{Func}_n$ .

However, the function has **exponential length**. Give  $D$  the deterministic **oracle access**  $D^{\mathcal{O}}$  to the functions  $\mathcal{O}$ .

## Definition 4

An efficient length-preserving, keyed function  $F$  is a **pseudorandom function (PRF)** if  $\forall$  PPT distinguishers  $D$ ,

$$\left| \Pr[D^{F_k(\cdot)}(1^n) = 1] - \Pr[D^{f(\cdot)}(1^n) = 1] \right| \leq \text{negl}(n),$$

where  $f$  is chosen *u.a.r* from  $\text{Func}_n$ .

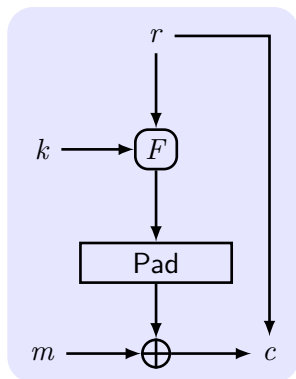
**Q: Is the fixed-length OTP a PRF?**

**Let  $F : \{0, 1\}^n \times \{0, 1\}^n \rightarrow \{0, 1\}^n$  be a secure PRF. Is  $G$  a secure PRF?**

- $G((k_1, k_2), x) = F(k_1, x) \| F(k_2, x)$
- $G(k, x) = F(k, x \oplus 1^n)$
- $G(k, x) = \text{reverse}(F(k, x))$
- $G(k, x) = \begin{cases} F(k, x) & \text{when } x \neq 0^n \\ 0^n & \text{otherwise} \end{cases}$
- $G(k, x) = \begin{cases} F(k, x) & \text{when } x \neq 0^n \\ k & \text{otherwise} \end{cases}$
- $G(k, x) = F(k, x) \oplus F(k, x \oplus 1^n)$



# CPA-Security from Pseudorandom Function



## Construction 5

- Fresh random string  $r$ .
- $F_k(r)$ :  $|k| = |m| = |r| = n$ .
- Gen:  $k \in \{0, 1\}^n$ .
- Enc:  $s := F_k(r) \oplus m$ ,  
 $c := \langle r, s \rangle$ .
- Dec:  $m := F_k(r) \oplus s$ .

## Theorem 6

*If  $F$  is a PRF, this fixed-length encryption scheme  $\Pi$  is CPA-secure.*

# Proof of CPA-Security from PRF

**Idea:** First, analyze the security in an idealized world where  $f$  is used in  $\tilde{\Pi}$ ; next, claim that if  $\Pi$  is insecure when  $F_k$  was used then this would imply  $F_k$  is not PRF by reduction.

## Proof.

(1) Analyze  $\Pr[\text{Break}]$ , Break means  $\text{PrivK}_{\mathcal{A}, \tilde{\Pi}}^{\text{cpa}}(n) = 1$ :  
 $\mathcal{A}$  collects  $\{\langle r_i, f(r_i) \rangle\}$ ,  $i = 1, \dots, q(n)$  with  $q(n)$  queries;  
The challenge  $c = \langle r_c, f(r_c) \oplus m_b \rangle$ .

- Repeat:  $r_c \in \{r_i\}$  with probability  $\frac{q(n)}{2^n}$ .  $\mathcal{A}$  can know  $m_b$ .
- $\overline{\text{Repeat}}$ : As OTP,  $\Pr[\text{Break}] = \frac{1}{2}$

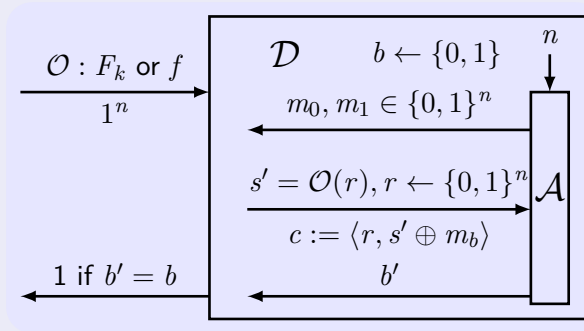
$$\begin{aligned}\Pr[\text{Break}] &= \Pr[\text{Break} \wedge \text{Repeat}] + \Pr[\text{Break} \wedge \overline{\text{Repeat}}] \\ &\leq \Pr[\text{Repeat}] + \Pr[\text{Break} | \overline{\text{Repeat}}] \\ &\leq \frac{q(n)}{2^n} + \frac{1}{2}.\end{aligned}$$



# Proof of CPA-Security from PRF (Cont.)

## Proof.

(2) Reduce  $D$  to  $\mathcal{A}$ :



$$\Pr[D^{F_k(\cdot)}(1^n) = 1] = \Pr[\text{PrivK}_{\mathcal{A}, \Pi}^{\text{cpa}}(n) = 1] = \frac{1}{2} + \varepsilon(n).$$

$$\Pr[D^{f(\cdot)}(1^n) = 1] = \Pr[\text{PrivK}_{\mathcal{A}, \Pi}^{\text{cpa}}(n) = 1] = \Pr[\text{Break}] \leq \frac{1}{2} + \frac{q(n)}{2^n}.$$

$$\Pr[D^{F_k(\cdot)}(1^n) = 1] - \Pr[D^{f(\cdot)}(1^n) = 1] \geq \varepsilon(n) - \frac{q(n)}{2^n}. \quad \varepsilon(n) \text{ is negligible.} \quad \square$$

- For arbitrary-length messages,  $m = m_1, \dots, m_\ell$

$$c := \langle r_1, F_k(r_1) \oplus m_1, r_2, F_k(r_2) \oplus m_2, \dots, r_\ell, F_k(r_\ell) \oplus m_\ell \rangle$$

## Corollary 7

*If  $F$  is a PRF, then  $\Pi$  is CPA-secure for arbitrary-length messages.*

- **Efficiency:**  $|c| = 2|m|$ .

# Pseudorandom Permutations

- **Bijection:**  $F$  is one-to-one and onto
- **Permutation:** A bijective function from a set to itself
- **Keyed permutation:**  $\forall k, F_k(\cdot)$  is permutation
- $F$  is a bijection  $\iff F^{-1}$  is a bijection

## Definition 8

An efficient, keyed permutation  $F$  is a **strong pseudorandom permutation (PRP)** if  $\forall$  PPT distinguishers  $D$ ,

$$\left| \Pr[D^{F_k(\cdot), F_k^{-1}(\cdot)}(1^n) = 1] - \Pr[D^{f(\cdot), f^{-1}(\cdot)}(1^n) = 1] \right| \leq \text{negl}(n),$$

where  $f$  is chosen *u.a.r* from the set of permutations on  $n$ -bit strings.

**If  $F$  is a pseudorandom permutation then is it a PRF?**

Let  $X = \{0, 1\}$  (1 bit), answer the following questions.

- 1 What are the functions in the permutation over  $X$ ?
- 2  $K = \{0, 1\}$ , what is the simplest permutation  $F(k, x)$  over  $X$ ?
- 3 Is your  $F$  a secure PRP?
- 4 Is your  $F$  a secure PRF?
- 5 What if  $X = \{0, 1\}^{128}$  and  $K = \{0, 1\}^{128}$ ?
- 6 Could you give a (or another) PRP over  $X = \{0, 1\}^{128}$ ?

## Proposition 9

*IF  $F$  is a PRP and additionally  $\ell_{in}(n) \geq n$ , then  $F$  is also a PRF.*

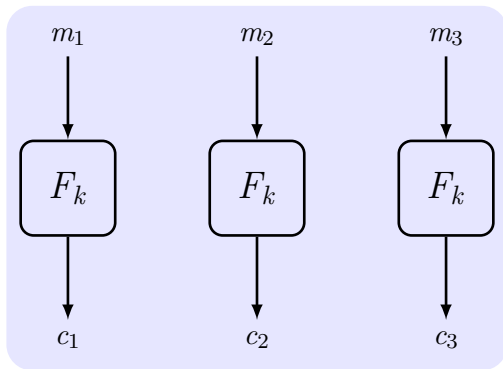
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## Modes of Operation:

- A way of encrypting arbitrary-length messages using a PRP or PRF
- A way of constructing a PRG from a PRP or PRF



# Electronic Code Book (ECB) Mode

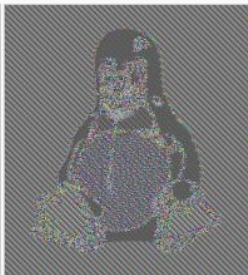


- Q: is it indistinguishable in the presence of an eavesdropper?
- Q: can  $F$  be any PRF?

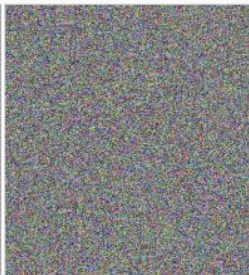
# Attack on ECB mode



Original image

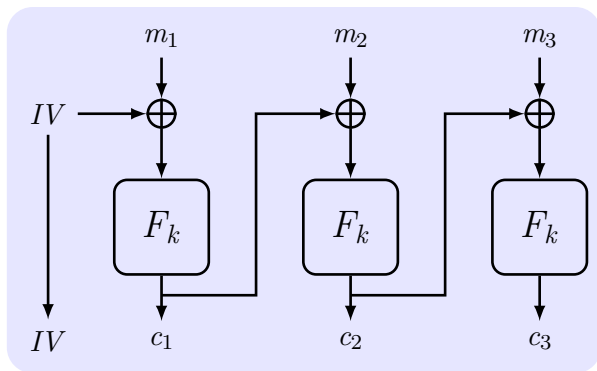


Encrypted using ECB mode



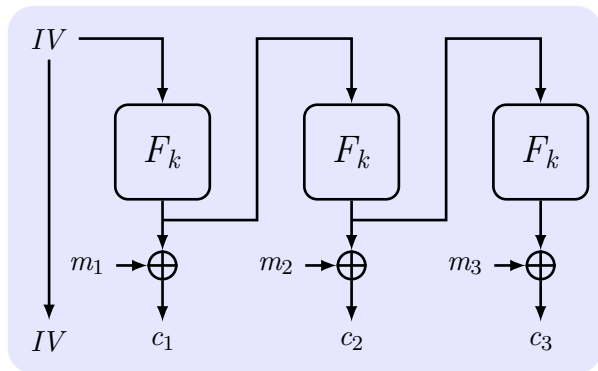
Modes other than ECB result in pseudo-randomness

# Cipher Block Chaining (CBC) Mode



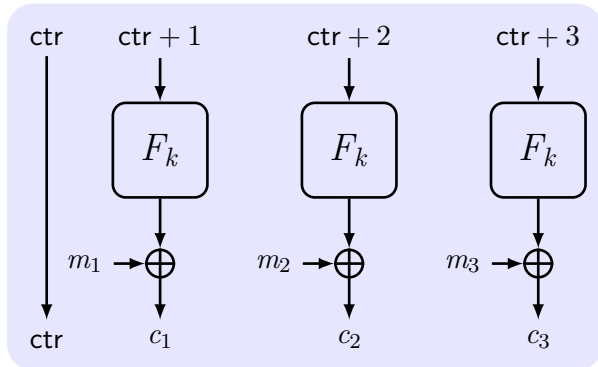
- $IV$ : initial vector, a fresh random string.
- Q: is it CPA-secure? what if  $IV$  is always 0?
- Q: is the encryption parallelizable, i.e., outputting  $c_2$  before getting  $c_1$ ?
- Q: can  $F$  be any PRF?

# Output Feedback (OFB) Mode



- Q: is it CPA-secure?
- Q: is the encryption parallelizable?
- Q: can  $F$  be any PRF?

# Counter (CTR) Mode



- $ctr$  is an  $IV$
- Q: is it CPA-secure?
- Q: is the encryption parallelizable?
- Q: can  $F$  be any PRF?

## Theorem 10

*If  $F$  is a PRF, then randomized CTR mode is CPA-secure.*

## Proof.

The message length and the number of query are  $q(n)$ .

**Overlap:** the sequence for the challenge overlaps the sequences for the queries from the adversary.

$\text{ctr}^*$ : ctr in the challenge.  $\text{ctr}_i$ : ctr in the queries,  $i = 1, \dots, q(n)$ .

Overlap:  $\text{ctr}_i - q(n) < \text{ctr}^* < \text{ctr}_i + q(n)$ .

$$\Pr[\text{Overlap}] \leq \frac{2q(n) - 1}{2^n} \cdot q(n)$$



# Proof of CPA-secure CTR Mode (Cont.)

## Proof.

See proof of theorem 6. (1) Analyze Break :  $\text{PrivK}_{\mathcal{A}, \tilde{\Pi}}^{\text{cpa}}(n) = 1$ .

$$\begin{aligned}\Pr[\text{Break}] &= \Pr[\text{Break} \wedge \text{Overlap}] + \Pr[\text{Break} \wedge \overline{\text{Overlap}}] \\ &\leq \Pr[\text{Overlap}] + \Pr[\text{Break} | \overline{\text{Overlap}}] \\ &\leq \frac{2q(n)^2}{2^n} + \frac{1}{2}.\end{aligned}$$

(2) Reduce  $D$  to  $\mathcal{A}$

$$\Pr[D^{f(\cdot)}(1^n) = 1] = \Pr[\text{PrivK}_{\mathcal{A}, \tilde{\Pi}}^{\text{cpa}}(n) = 1] \leq \frac{2q(n)^2}{2^n} + \frac{1}{2}$$

$$\Pr[D^{F_k(\cdot)}(1^n) = 1] = \Pr[\text{PrivK}_{\mathcal{A}, \Pi}^{\text{cpa}}(n) = 1] \leq \frac{1}{2} + \varepsilon(n)$$

If  $F$  is PRP,  $\varepsilon(n)$  is negligible.



# IV Should Not Be Predictable

If *IV* is predictable, then CBC/OFB/CTR mode is not CPA-secure.

Q: Why? (homework)

## Bug in SSL/TLS 1.0

*IV* for record  $\#i$  is last CT block of record  $\#(i - 1)$ .

## API in OpenSSL

```
void AES_cbc_encrypt (  
    const unsigned char *in,  
    unsigned char      *out,  
    size_t              length,  
    const AES_KEY       *key,  
    unsigned char      *ivec,      User supplies IV  
    AES_ENCRYPT or AES_DECRYPT);
```



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# Security Against CCA

The CCA indistinguishability experiment  $\text{PrivK}_{\mathcal{A}, \Pi}^{\text{cca}}(n)$ :

- 1  $k \leftarrow \text{Gen}(1^n)$ .
- 2  $\mathcal{A}$  is given input  $1^n$  and oracle access  $\mathcal{A}^{\text{Enc}_k(\cdot)}$  and  $\mathcal{A}^{\text{Dec}_k(\cdot)}$ , outputs  $m_0, m_1$  of the same length.
- 3  $b \leftarrow \{0, 1\}$ .  $c \leftarrow \text{Enc}_k(m_b)$  is given to  $\mathcal{A}$ .
- 4  $\mathcal{A}$  continues to have oracle access **except for**  $c$ , outputs  $b'$ .
- 5 If  $b' = b$ ,  $\mathcal{A}$  succeeded  $\text{PrivK}_{\mathcal{A}, \Pi}^{\text{cca}} = 1$ , otherwise 0.

## Definition 11

$\Pi$  has **indistinguishable encryptions under a CCA (CCA-secure)** if  $\forall$  PPT  $\mathcal{A}$ ,  $\exists$   $\text{negl}$  such that

$$\Pr \left[ \text{PrivK}_{\mathcal{A}, \Pi}^{\text{cca}}(n) = 1 \right] \leq \frac{1}{2} + \text{negl}(n).$$

# Understanding CCA-security

- In real world, the adversary might conduct CCA by influencing what gets decrypted
  - If the communication is not authenticated, then an adversary may send certain ciphertexts on behalf of the honest party
- CCA-security implies “**non-malleability**”
- None of the above scheme is CCA-secure

## CCA against Construction 5

$\mathcal{A}$  gives  $m_0, m_1$  and gets  $c = \langle r, F_k(r) \oplus m_b \rangle$ , and then queries  $c'$  which is the same with  $c$  except that a single bit is flipped. The  $m' = c' \oplus F_k(r)$  should be the same with  $m_b$  **except \_\_\_\_?**

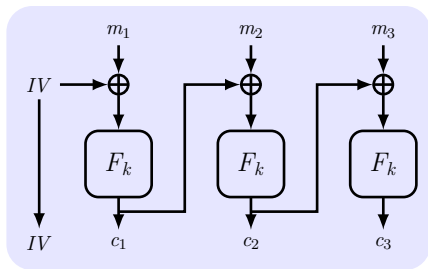
Q: Show that the above modes (CBC, OFB and CTR) are also not CCA-secure. (homework)

# Padding-Oracle Attacks

**PKCK #5 Padding:** append  $b$  bytes of  $b$  to the message in order to make the total length a multiple of the block length (append a dummy block if needed). The decryption server will return a **Bad Padding Error** for incorrect padding.

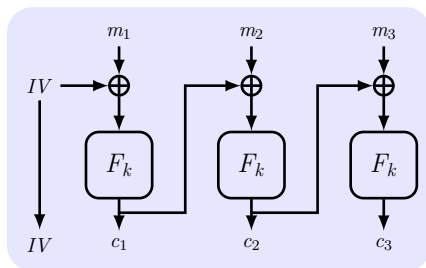
## Padding-Oracle Attacks:

- In a one-block CBC, by modifying the 1st byte of  $IV$ , attacker can learn whether  $m$  is NULL. If yes, error will occur.



- append  $\{b\}^b$  as a dummy block if  $m$  is NULL
- change the 1st byte of  $IV$  from  $x$  to  $y$ , get decrypted block  $(x \oplus y \oplus b) || \{b\}^{b-1}$ , and trigger an error

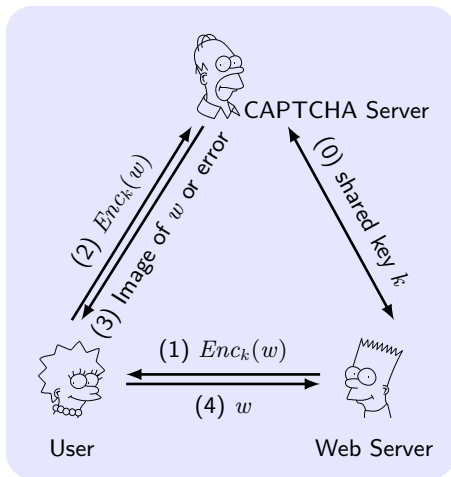
# Padding-Oracle Attacks (Cont.)



- If no error, then learn whether  $m$  is 1 byte by modifying the 2nd byte of  $IV$  and so on (changing the ciphertext)
- Once learn the length of  $m$ , learn the last byte of  $m$  ( $s$ ) by modifying the one before the last block in the ciphertext
- $m_{last} = \dots s \parallel \{b\}^b$ ,  $c_{last-1} = \dots t \parallel \{\cdot\}^b$
- modify  $c_{last-1}$  to  $c'_{last-1} = \dots u \parallel (\{\cdot\}^b \oplus \{b\}^b \oplus \{b+1\}^b)$
- Q: If no padding error, then  $s = ?$

# Padding-Oracle Attacks: Real-world Case

CAPTCHA server will return an error when deciphering the CT of a CAPTCHA text received from a user.



- Asymptotic approach, proof of reduction, indistinguishable
- PRG, PRF, PRP, stream cipher, block cipher
- Security/construction against eavesdropping/CPA
- EBC, CBC, OFB, CTR
- CCA, padding-oracle attack