ĐẠI HỌC
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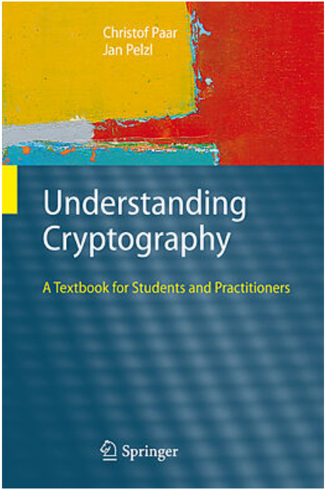
HA NOI UNIVERSITY OF SCIENCE AND TECHNOLOGY
SCHOOL OF INFORMATION AND COMMUNICATION TECHNOLOGY

Introduction to Cryptography and Security

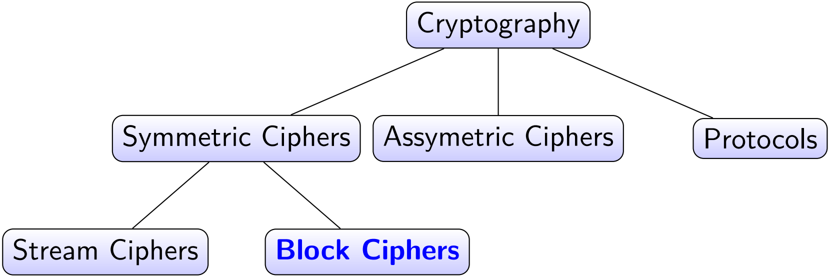
Modes of Operation

Textbook

https://www.crypto-textbook.com


Christof Paar
Jan Pelzl
Understanding Cryptography
A Textbook for Students and Practitioners
Springer

Cryptography



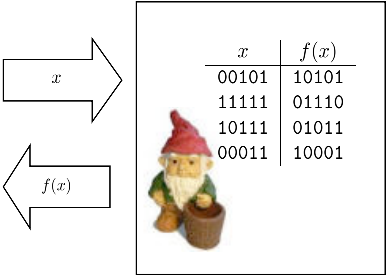
Ideal block cipher

- In fact, we consider AES or 3DES as an **ideal block cipher**
- That is, for each key k, the mapping

$$F_k(x) = \mathrm{Enc}(k, x)$$

is an independent random permutation from X onto itself.

Random Permutation



x	$f(x)$
00101	10101
11111	01110
10111	01011
00011	10001

```
upon receiving the $i$th query $x_i \in \mathcal{X}$ from $\mathcal{A}$ do:
    if $x_i = x_j$ for some $j < i$
        then $y_i \leftarrow y_j$
        else $y_i \overset{R}{\leftarrow} \mathcal{X} \setminus \{y_1, \ldots, y_{i-1}\}$
    send $y_i$ to $\mathcal{A}$
```

Modes of Operations

Question: How to encrypt long messages? (using AES)

Answer: There are several ways of encrypting long messages with a block cipher:

- Electronic Code Book (ECB)
- Cipher Block Chaining (CBC)
- Output Feedback ()
- Output Feedback (OFB)
- Counter Mode (CTR)

Modes of Operation: One-time key and many-time key.

Example applications

Many-time key

File systems

- Same AES key used to encrypt many files.

IPSec

- Same AES key used to encrypt many packets.

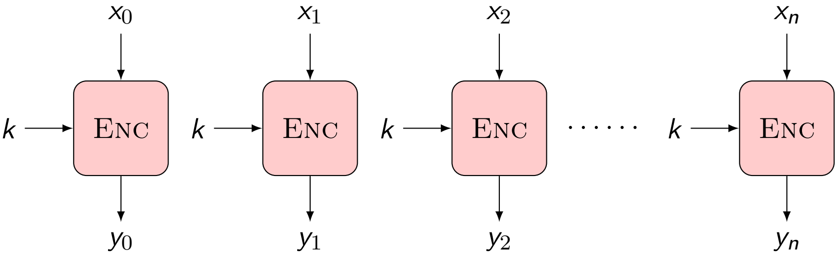
Outline

1. Electronic Codebook Mode (ECB)

2. Cipher Block Chaining Mode (CBC)

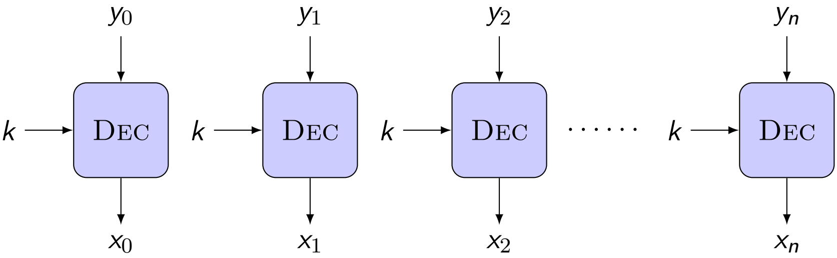
3. Stream cipher

ECB (Electronic code book)



- The messages are partitioned into b-bit blocks, where b is the block size.
- If the length of the message is not a multiple of b bits, it must be padded $10..0$ to a multiple of b bits prior to encryption.
- The padding operation is invertible.

ECB: Decryption



ECB is not secure

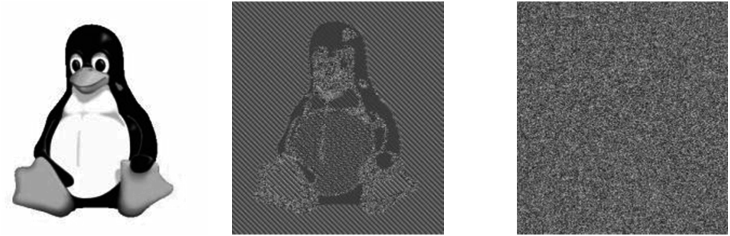


Figure: The middle figure is an encryption using ECB mode; the figure on the right is an encryption using a secure mode.

- Problem: If $x_i = x_j$ then $y_i = y_j$.
- ECB is secure if the message is random (eg., the keys).

Example: Electronic Bank Transfer

Block #	1	2	3	4	5
	Sending Bank A	Sending Account #	Receiving Bank B	Receiving Account #	Amount $

1. Assumption: Each of the fields has exactly the size of the block cipher width (for example 128 bits)
2. Assumption: The encryption key k_{AB} between the two banks A and B does not change too frequently.

Attacker Oscar

Block #	1	2	3	4	5
	Sending Bank A	Sending Account #	Receiving Bank B	Receiving Account #	Amount $

1. He opens one account at bank A and one at bank B.
2. He sends \$1.00 transfers from his account at bank A to his account at bank B repeatedly.
3. He observes the ciphertexts going through the communication network

   $$B_1 \parallel B_2 \parallel B_3 \parallel B_4 \parallel B_5$$

   and he stores blocks $B_1,\ B_3,\ B_4$.
4. For all transfers that are made from B_1 to B_3, he replaces block 4 with B_4.

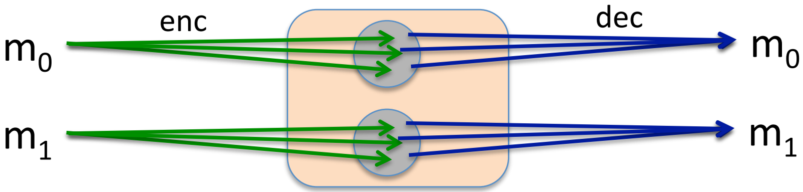
Outline

1. Electronic Codebook Mode (ECB)

2. Cipher Block Chaining Mode (CBC)

3. Stream cipher

Randomized encryption



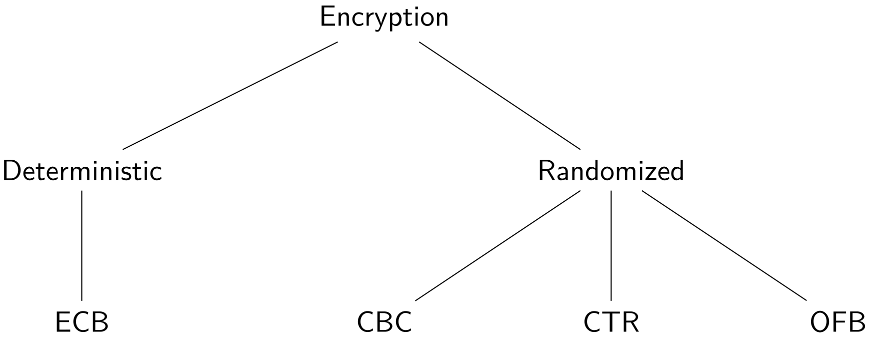
- Enc(k, m) is a randomized algorithm.
- Given the same plaintext message twice, encryption must produce different outputs.
- Ciphertext must be longer than plaintext
- Roughly speaking: CT-size = PT-size + "# random bits"

Exercise

Write the Dec() function for the following Enc().

$$\text{Enc}(k, m) := \begin{cases} r = \texttt{random}() \\ c = \texttt{AES}(k, r) \oplus m \\ \text{output } (r, c) \end{cases}$$

Types of Encryption



Encryption

Deterministic

Randomized

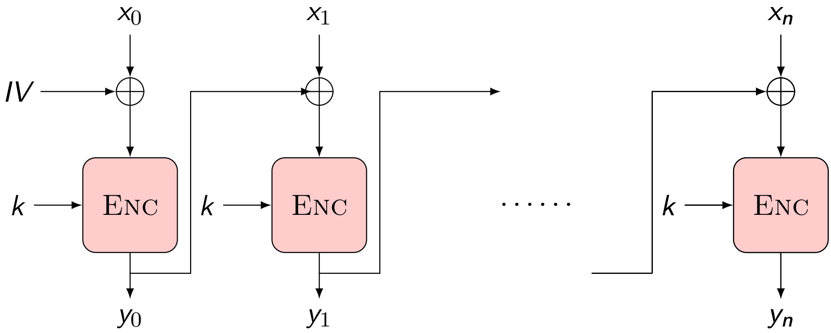
ECB

CBC

CTR

OFB

Cipher Block Chaining mode (CBC)



Algorithm. Choose IV ("initialization value") randomly, use each y_i is "IV" for M_{i+1}. Transmit IV with ciphertext:

$$IV \| y_0 \| y_1 \| \ldots \| y_n$$

How to use the *IV*?

- *IV* does not need to be kept a secret
- But it must be “nonce” = “number used only once”

Example

1. True random number
2. Counter value (must be stored by Alice)
3. $\mathrm{ID}_A \| \mathrm{ID}_B \| \mathrm{time}$

A CBC technicality: PKCS5 padding

- The value is the number of bytes that need to be added.
- Padding n byte, for $n > 0$

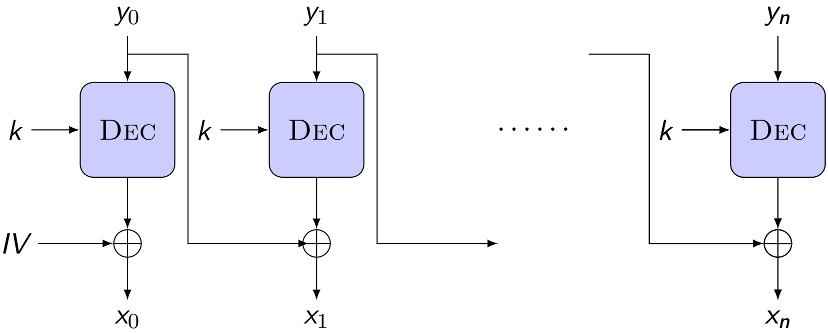
n	n	n	n	$\cdots$	n

- if no padding is needed, we add a dummy block:

b	b	b	b	b	$\cdots$	b

where b is block size (in bytes).

CBC: Decryption



Outline

1. Electronic Codebook Mode (ECB)

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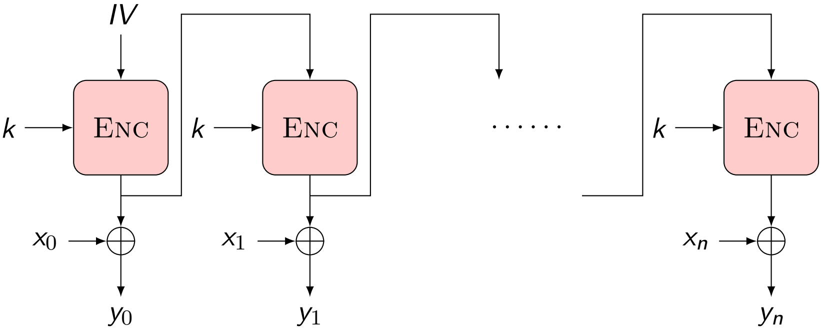
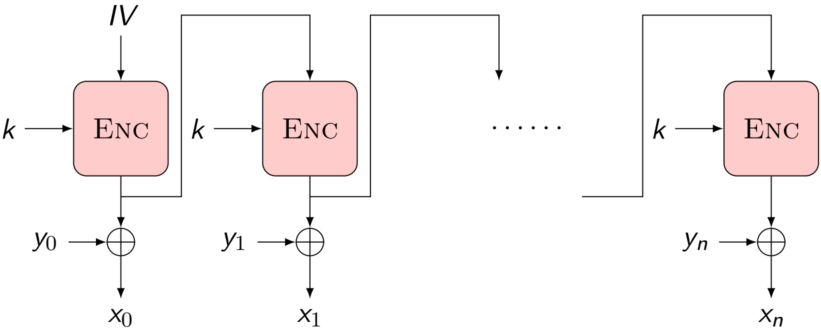
3. Stream cipher

Output Feedback Mode (OFB)

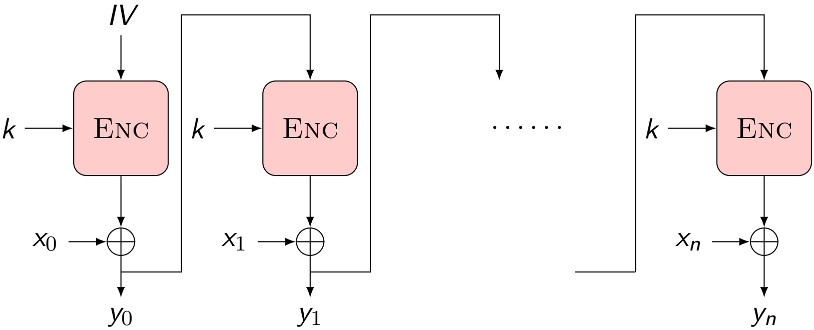


Algorithm. Similar to CBC mode. Use a random IV transmitted with the ciphertext.

OFB: Decryption

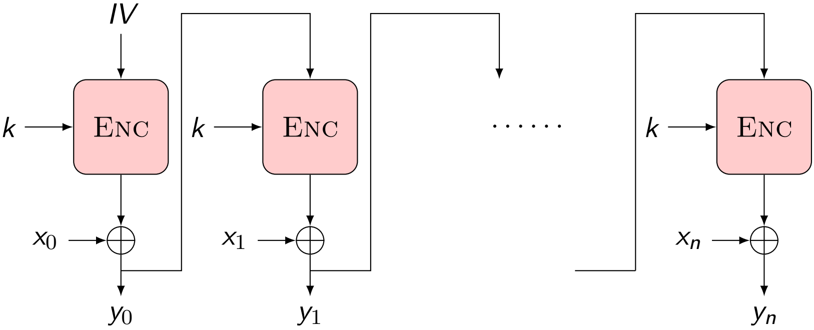


Cipher Feedback Mode (CFB)



Exercise

What is the decryption for CFB mode?



Counter Mode (CTR)

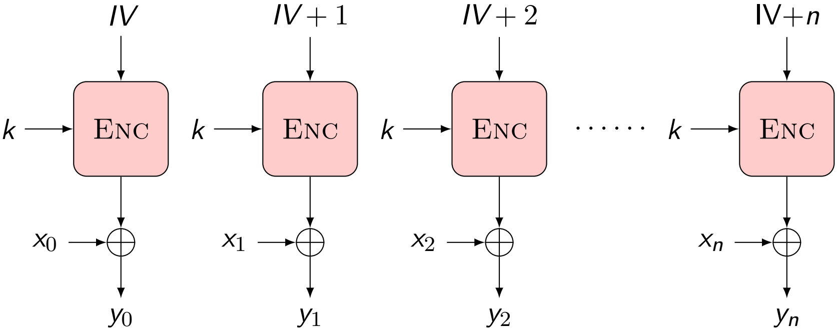
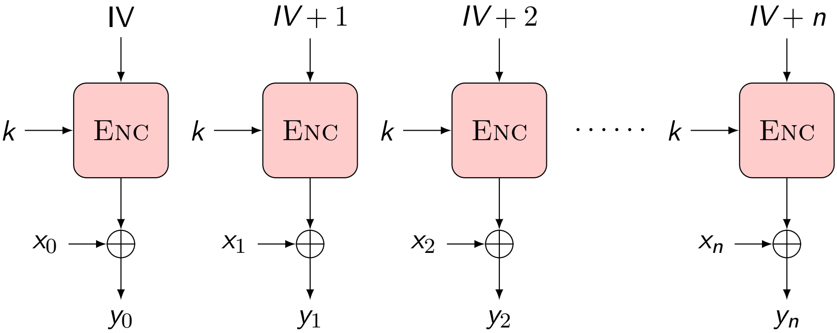


Figure: Use a random IV transmitted with the ciphertext.

Exercise

What is the decryption for CTR mode?



Exercise

- Let m be a message consisting of ℓ AES blocks (say $\ell = 100$).
- Alice encrypts m using CBC mode and transmits the resulting ciphertext to Bob.
- Due to a network error, ciphertext block number $\ell/2$ is corrupted during transmission. All other ciphertext blocks are transmitted and received correctly.
- Once Bob decrypts the received ciphertext, how many plaintext blocks will be corrupted?

Exercise

- Let m be a message consisting of ℓ AES blocks (say $\ell = 100$).
- Alice encrypts m using randomized counter mode and transmits the resulting ciphertext to Bob.
- Due to a network error, ciphertext block number $\ell/2$ is corrupted during transmission. All other ciphertext blocks are transmitted and received correctly.
- Once Bob decrypts the received ciphertext, how many plaintext blocks will be corrupted?

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Thank you!

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