Cryptography Part IV: Encryption Modes

Cryptographic Hardware for Embedded Systems
ECE 3170

Fall 2025

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Reading Assignment

- Please read chapter 9 of the course textbook by Schneier

Introduction

- So far the concept of 64-bit encryption has been introduced
- It turns out that a 64-bit ciphertext per 64-bit plaintext is problematic
- This lecture introduces a variety of encryption modes

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Block Versus Stream Ciphers

- Block ciphers operate on blocks of plaintext or ciphertext, e.g., 64 bits at a time or 128 bits at a time
- Stream ciphers operate on as little as one bit at a time
  - May also consider one byte at a time or one word
- The vast majority of modern cryptography considers block ciphers
- Nevertheless, we will introduce some stream-based attempts later in this course

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Notation

- C_i is ciphertext message i
- P_i is plaintext message i
- E_k is encryption with key k
  - Note that E could be symmetric or asymmetric
  - $E_k(P_i) = C_i$
- D_k is decryption with key k
  - Note that D could be symmetric or asymmetric
  - However, for asymmetric cryptographic, need distinct keys (a “key” may be a set of numbers, e.g., in RSA a “key” is a pair of numbers)
    - E_{k1} and D_{k2} where $k1$ is the public “key” and $k2$ is the private “key”
    - $E_{k1}(P_i) = C_i$
    - $D_{k2}(C_i) = P_i$
- $\{X\}$ is a set of elements of type X
- $|$ is “such that”; e.g., integer $i \mid 3 < i < 5$ implies that $i = 4$

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Electronic Codebook (ECB) Mode

- One to one correspondence between plaintext and ciphertext
  - E.g., consider a message of 1280 bits broken up into 20 “blocks” each of 64 bits of plaintext
  - Each 64-bit P_i is encrypted into a 64-bit $C_i = E_k(P_i)$
- Problem #1: codebook
  - Attacker can compile a codebook of known P_i, C_i pairs *without* knowing the key
  - Over time and especially if the encrypted messages have significant redundancies, an attacker can glean a lot of information
    - Beginnings and endings of messages are particularly vulnerable
- Problem #2: replay attack
  - Classic example: bank transactions

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Classic Bank Example Replay Attack

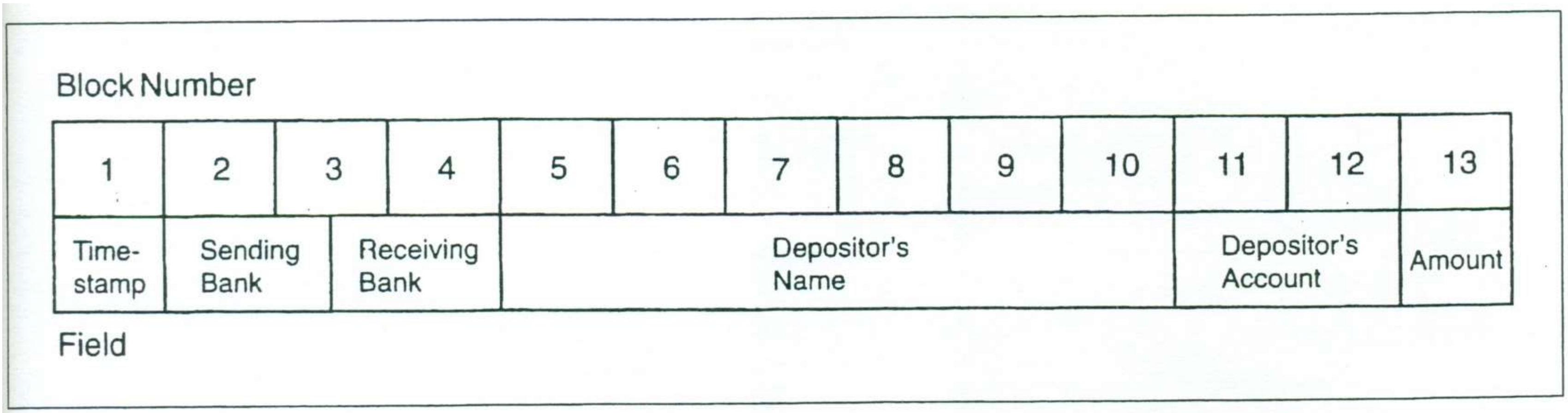

Figure 9.2 Encryption blocks for an example record.

- Attacker deposits $10 and then $100; only blocks 1 and 13 change
- Attacker deposits $10 again later; only block 1 changes; block 13 is $
- Now a variety of attacks on block 13 may commence…

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Ciphertext Stealing Instead of Padding

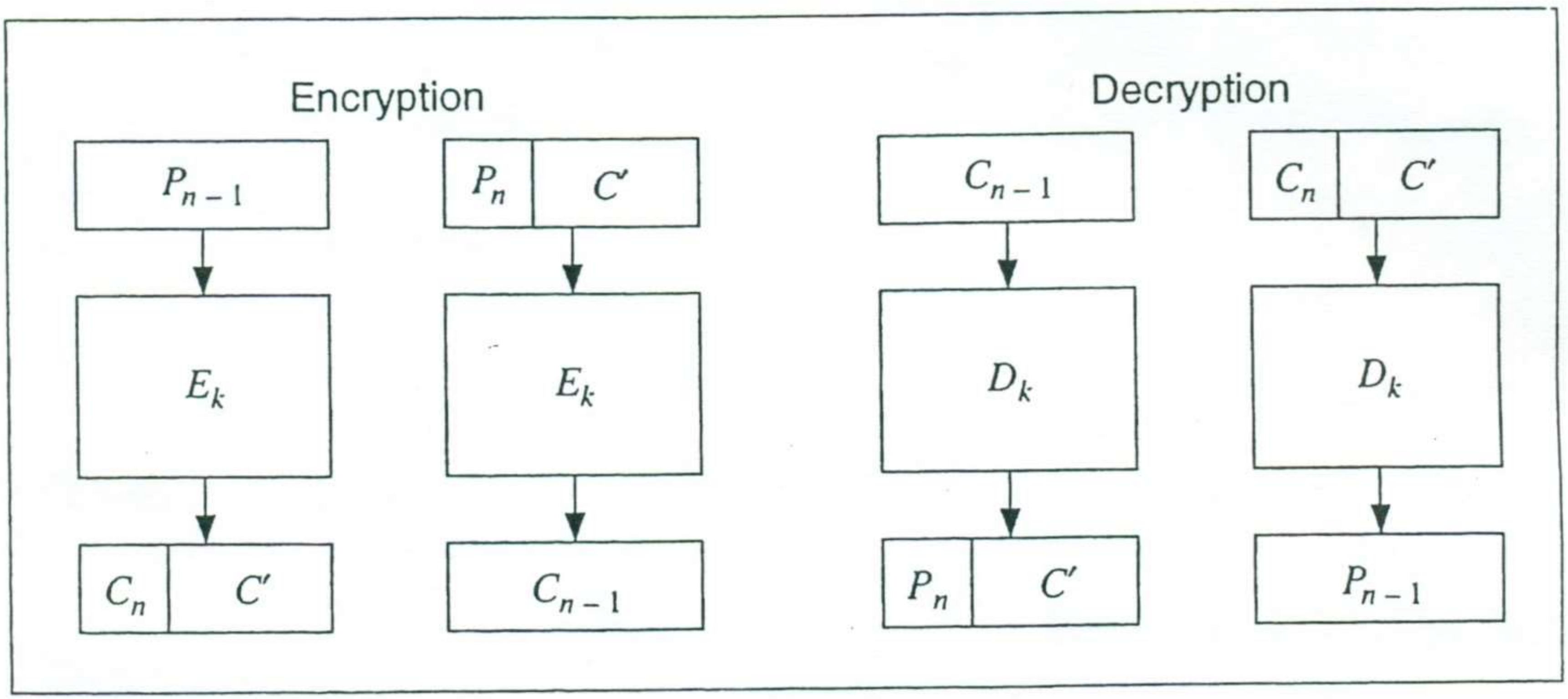

Figure 9.1 Ciphertext stealing in ECB mode.

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Cipher Block Chaining

- Use results of previous block encryption
- Typical use is based on exclusive-or (XOR)
  - For encryption where $i > 1$ (i.e., after the first block), $C_i = E_k(P_i \oplus C_{i-1})$
  - For decryption (except for the first block, i.e., $i \neq 1$), $P_i = C_{i-1} \oplus D_k(C_i)$

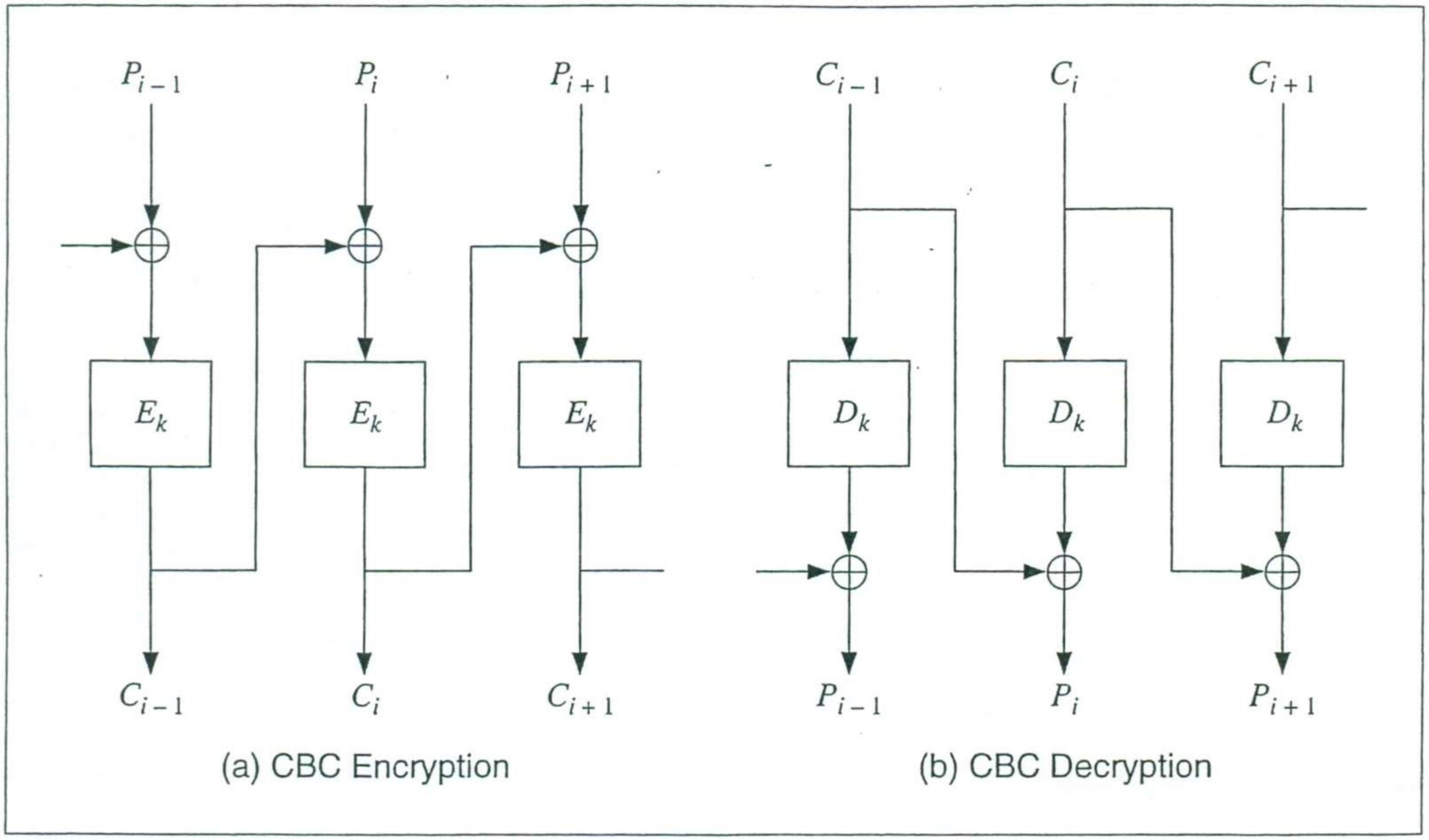

Figure 9.3 Cipher block chaining mode.

Initialization Vector

- Note that so far for the case where the first plaintext block is identical, the block will encrypt to the same ciphertext (assuming the same key)
- In fact, two identical messages will encrypt to the same ciphertext message
- Solution: use an *initialization vector* (**IV**)
  - E.g., timestamp
  - Note that after the first block, the attacker has all of the ciphertext blocks
  - Therefore using a plaintext **IV** does not provide the attacker with significant help

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Cipher Block Chaining with IV

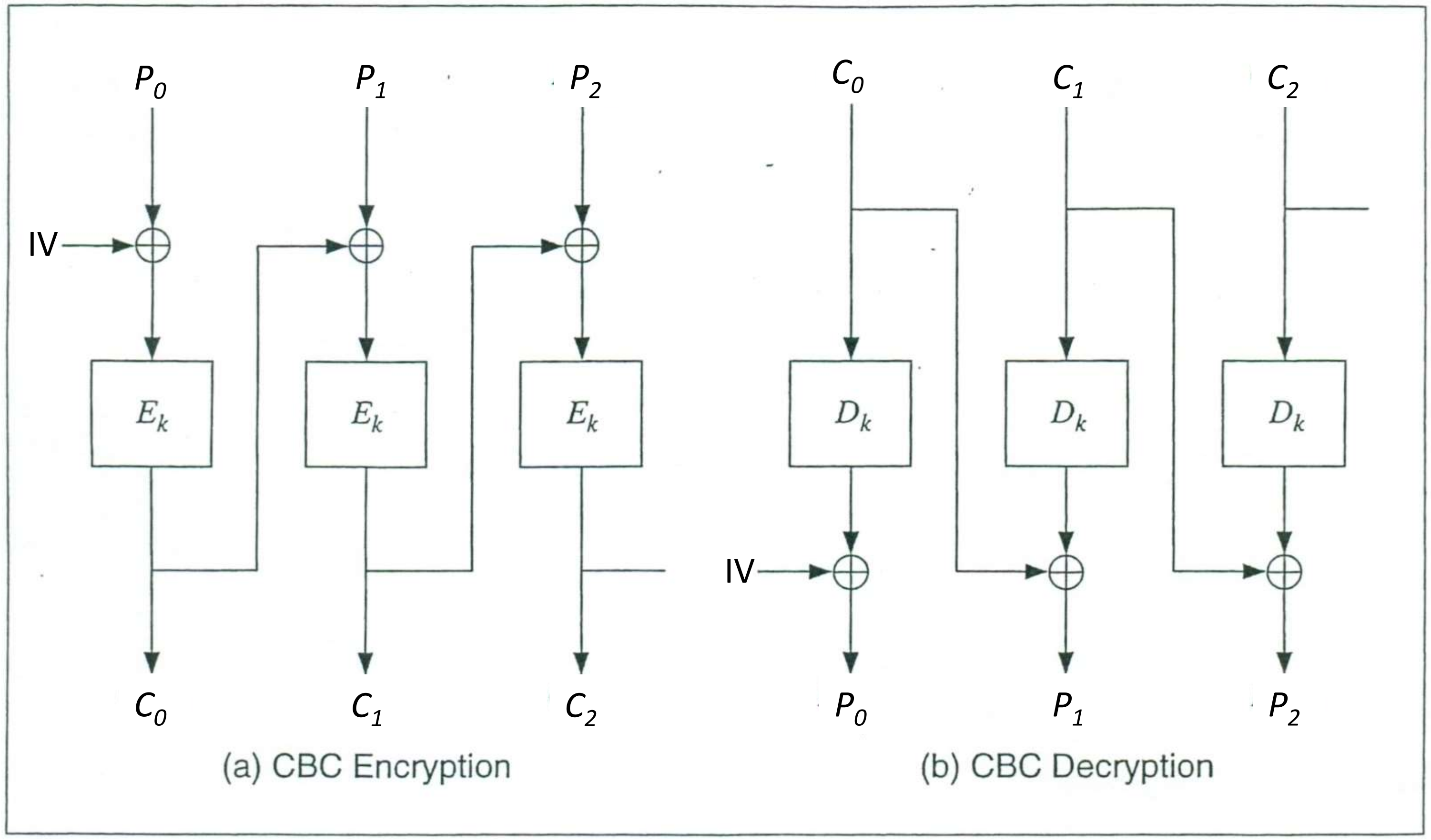

Figure 9.3 Cipher block chaining mode.

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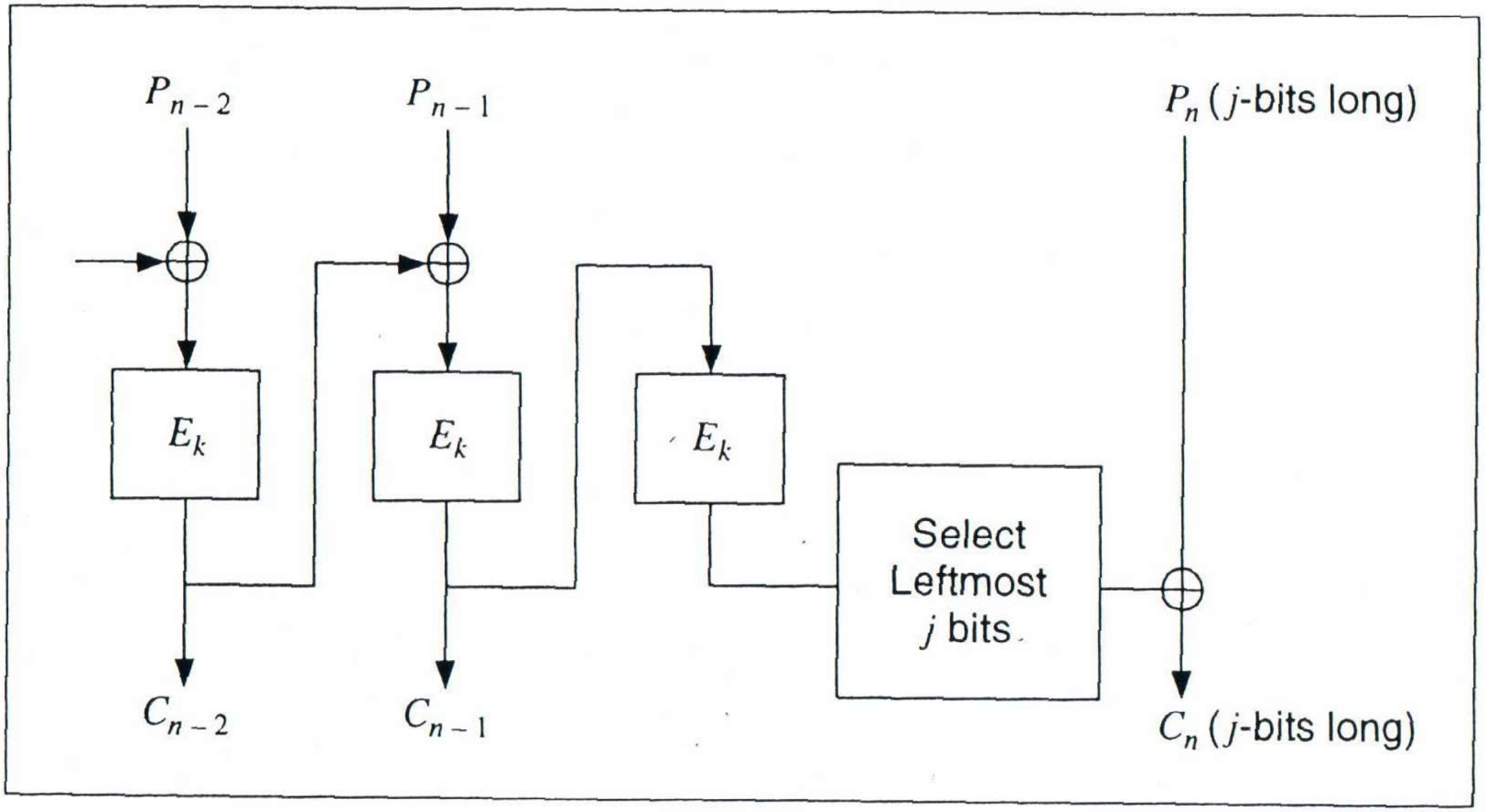

Figure 9.4 Encrypting the last short block in CBC mode.

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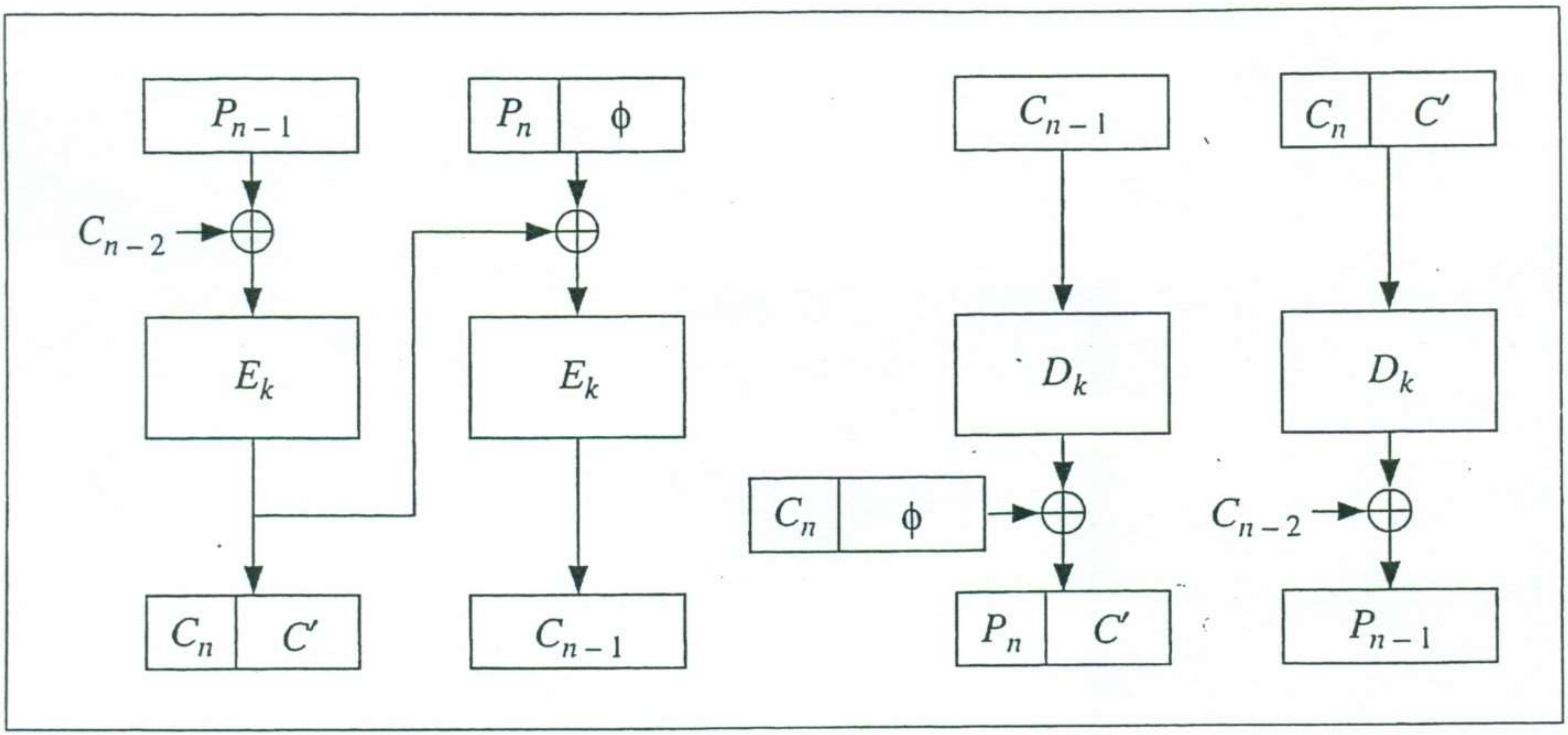

Figure 9.5 Ciphertext stealing in CBC mode.

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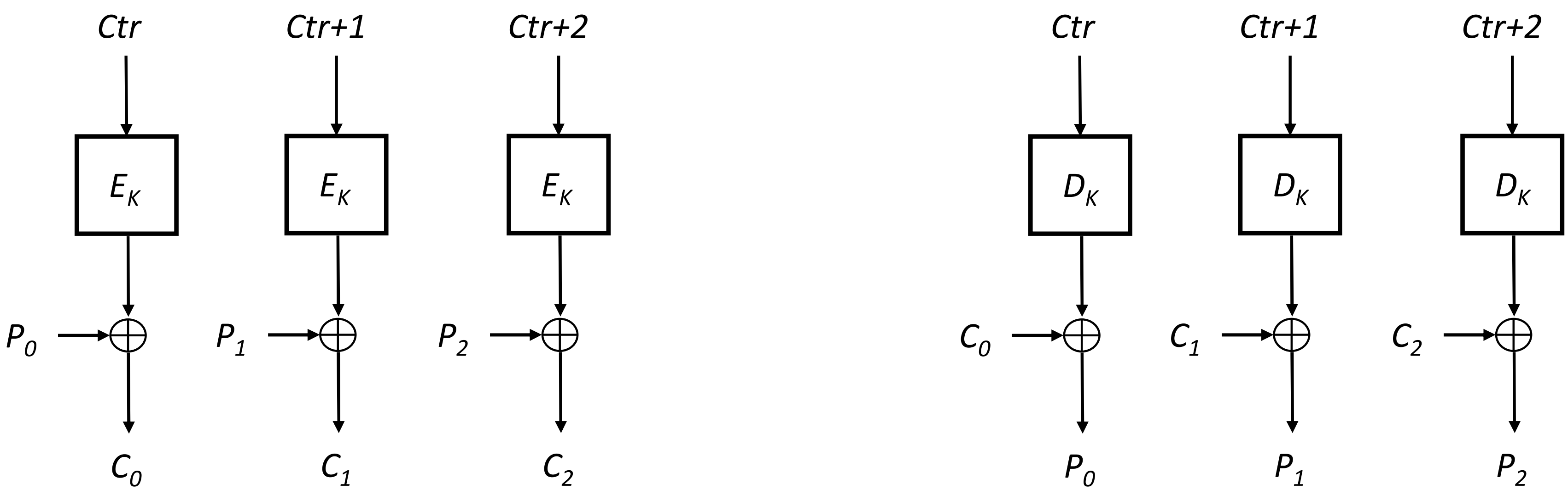
Counter Mode

- Choose a random starting number Ctr



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Stream Ciphers

- We consider the case of converting plaintext to ciphertext one bit at a time
- One simple approach to a keystream generator is a one-time pad

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Stream Ciphers

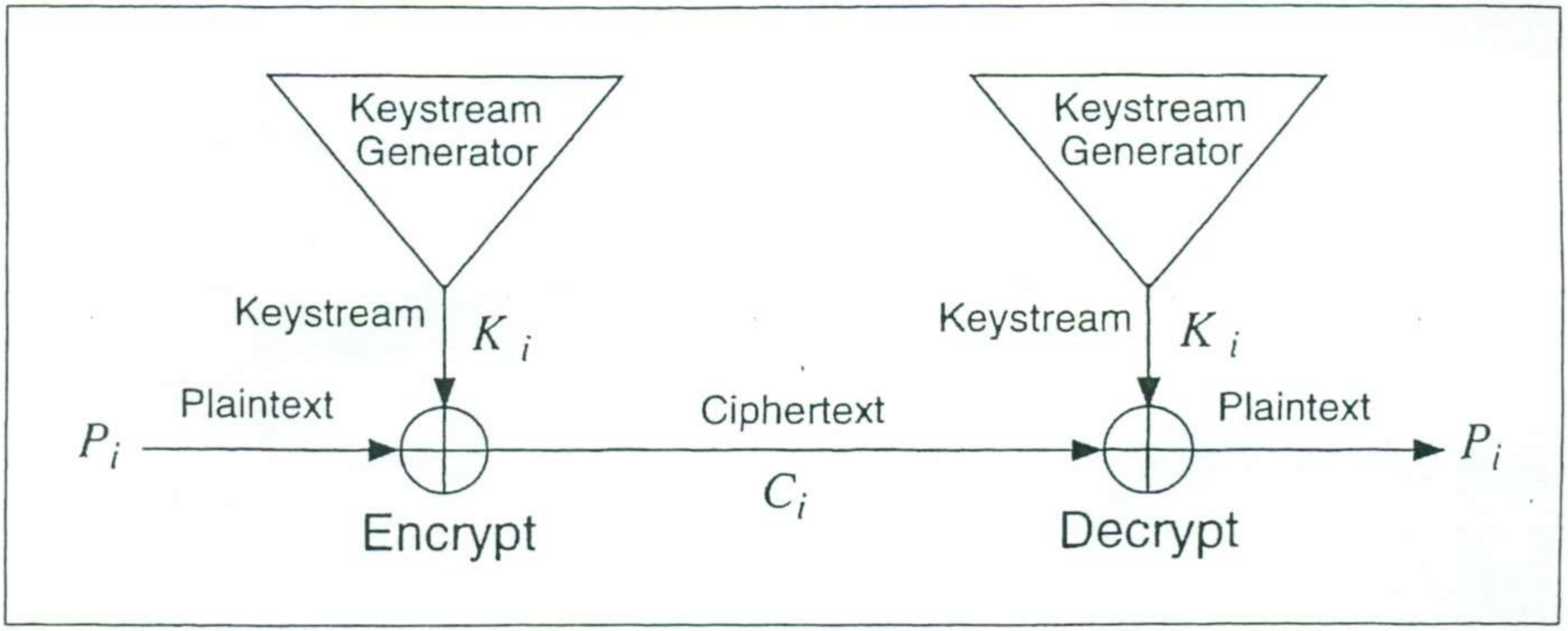

Figure 9.6 Stream cipher.

Weaknesses

- No diffusion or avalanche effect
- If the adversary has any correct (i.e., known) plaintext – ciphertext pairs, that portion of the keystream can be easily calculated

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Keystream Generator Requires a Key

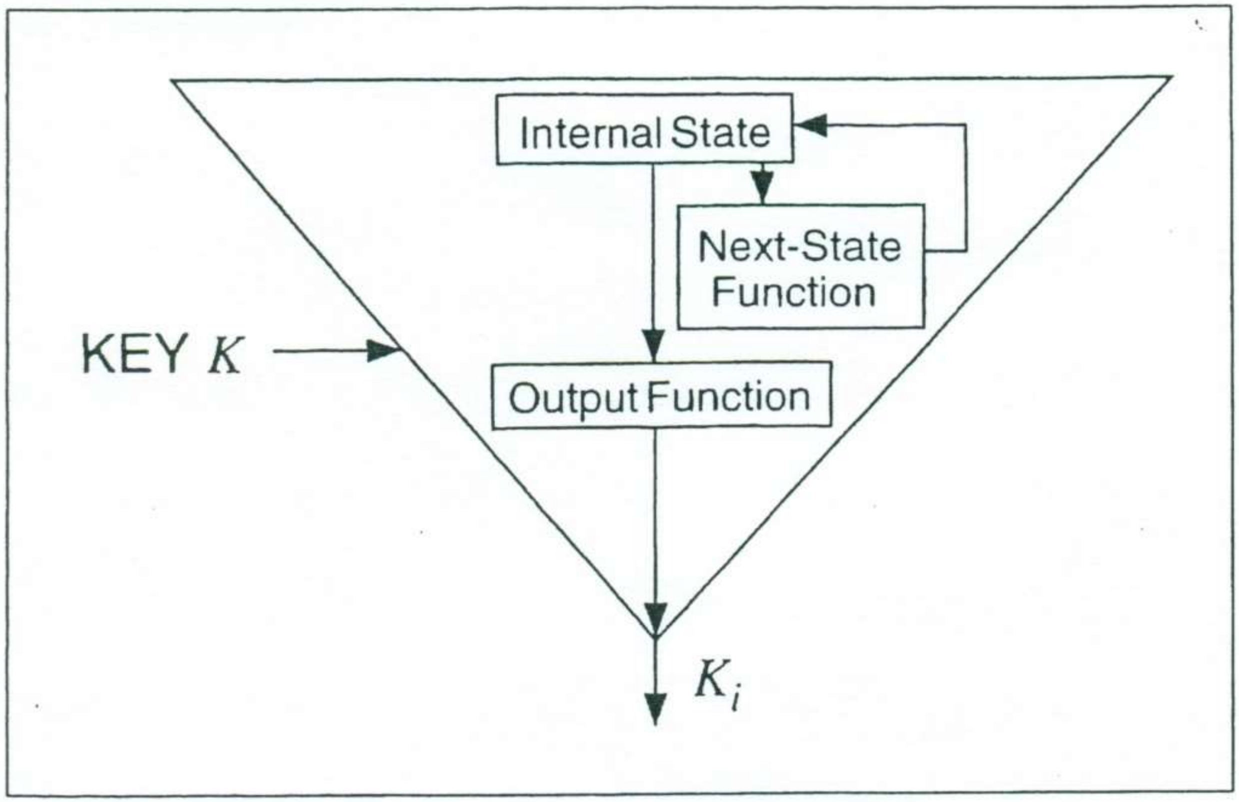

Figure 9.7 Inside a keystream generator.

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Adding a Key

- Keystream generator output is a function of a key as well as prior state
- Now users can update keys regularly
- Attack surface is reduced

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Cipher-feedback (CFB) Mode

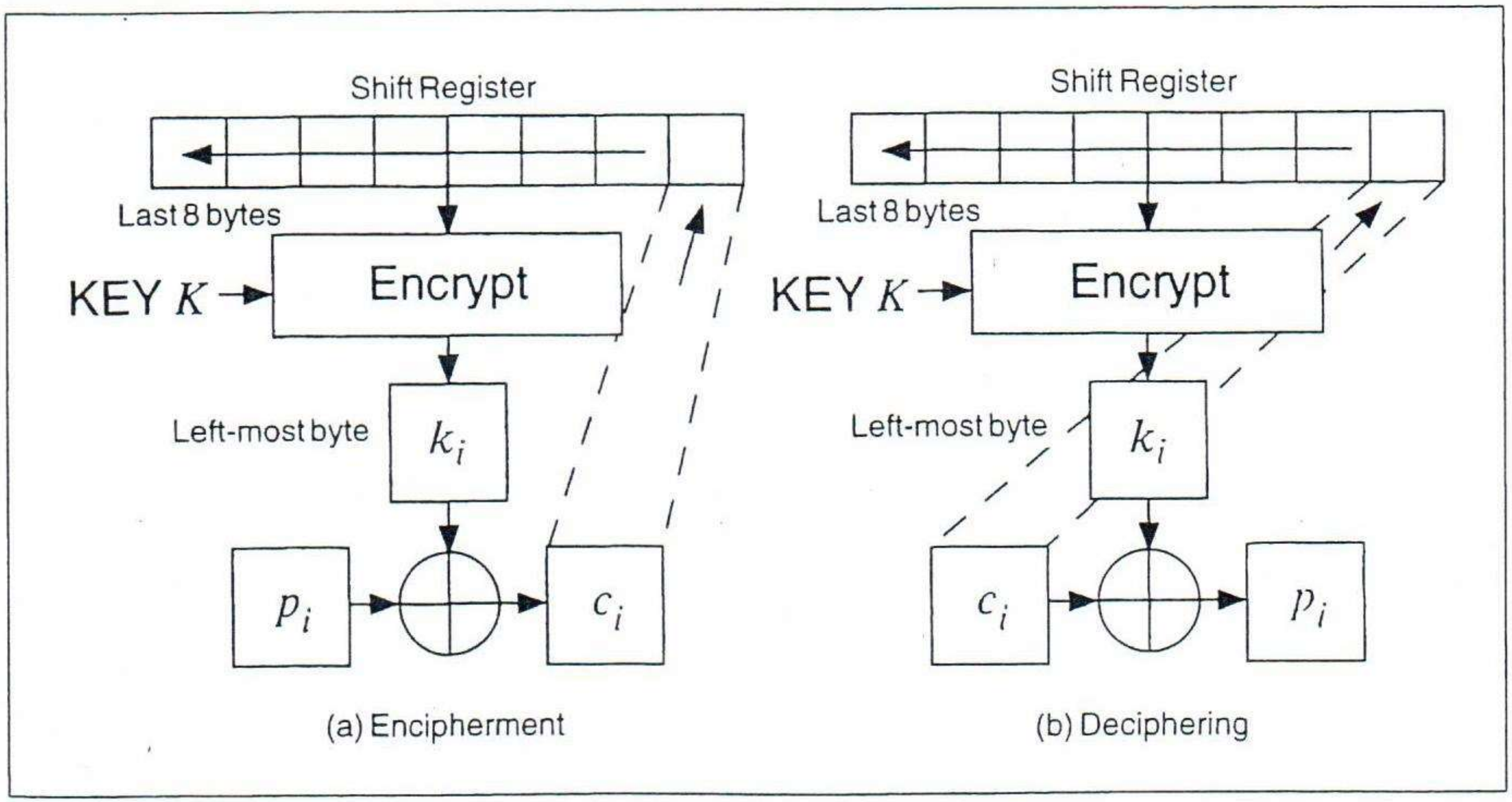

Figure 9.9 8-bit cipher-feedback mode.

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Output-feedback (OFB) Mode

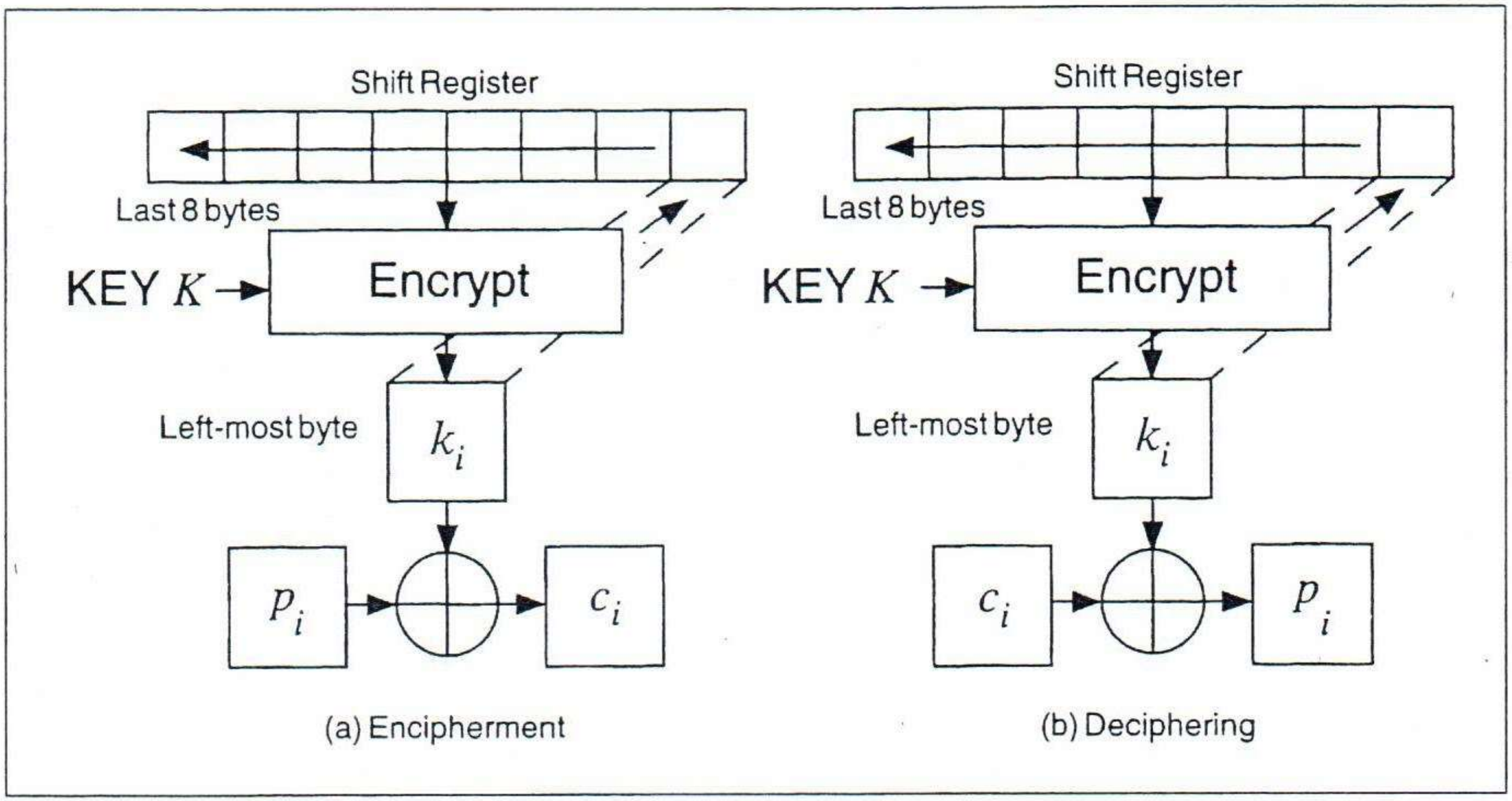

Figure 9.11 8-bit output-feedback mode.