Sept. 12-19

Cryptography Part IV: Encryption Modes

Cryptographic Hardware for Embedded Systems
ECE 3170

Fall 2025

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No
Gt file
hr 3
Sept. 14 & 16

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

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

Notation

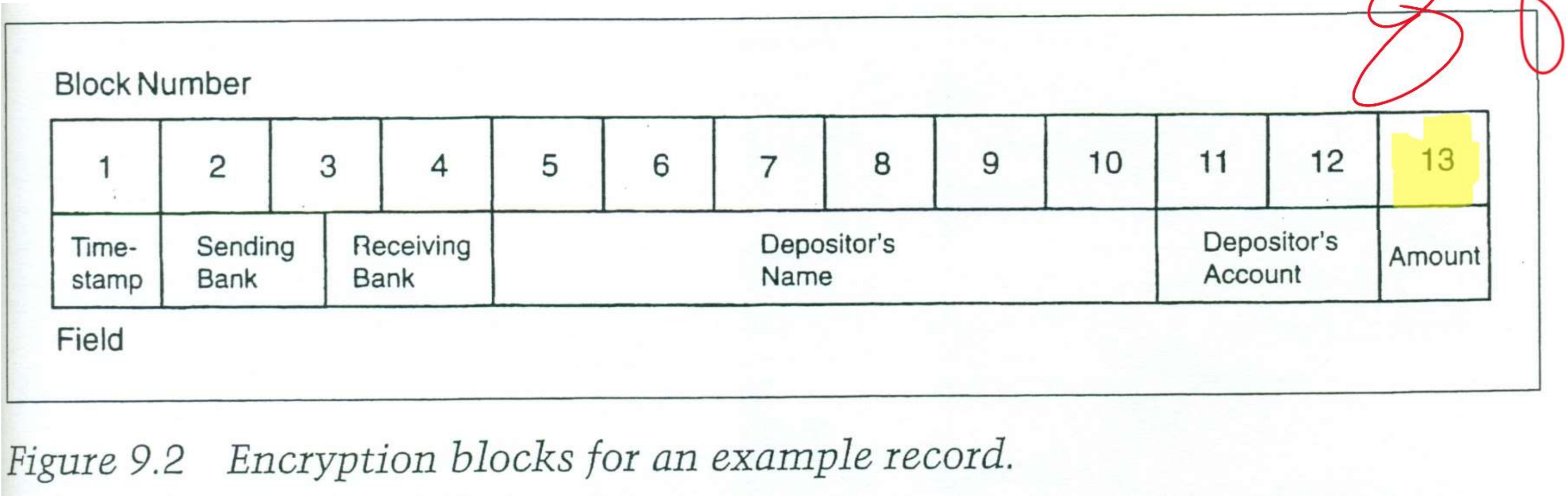
- C_i is ciphertext message i
- P_i is plaintext message i
- E_k is encryption with key k
  - Note that E could be symmetric or asymmetric
  - $E_k(P_i) = C_i$
- D_k is decryption with key k
  - Note that D could be symmetric or asymmetric
  - However, for asymmetric cryptographic, need distinct keys (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 $i = 4$

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

Classic Bank Example Replay Attack

8 bits



Block Number

1	2	3	4	5	6	7	8	9	10	11	12	13
Time-stamp	Sending Bank	Receiving Bank		Depositor's Name						Depositor's Account		Amount

Field

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…

Ciphertext Stealing Instead of Padding

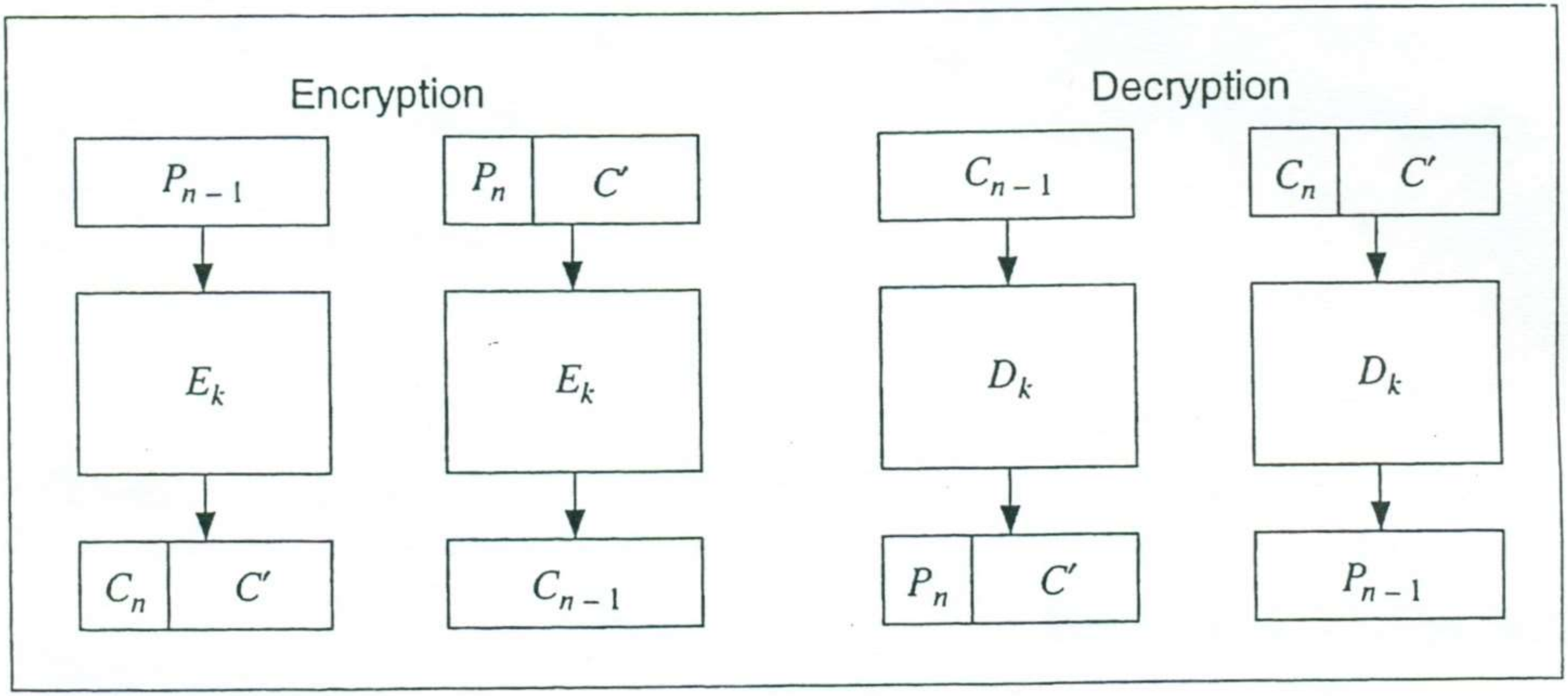


Figure 9.1 Ciphertext stealing in ECB mode.

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* ≠ 1), $P_i = C_{i-1} \oplus D_k(C_i)$

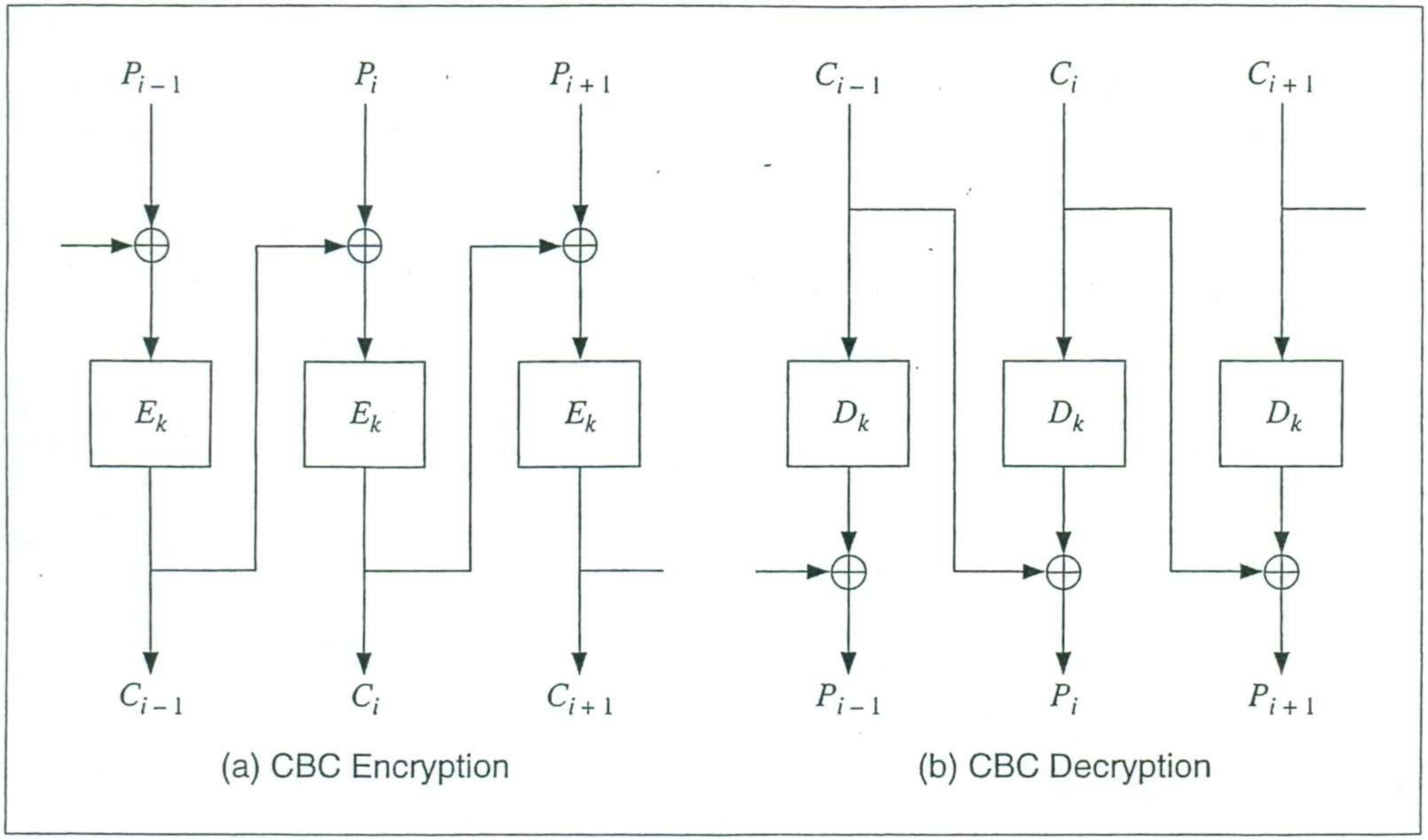


Figure 9.3 Cipher block chaining mode.

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

Cipher Block Chaining with IV

IV from uniform distr

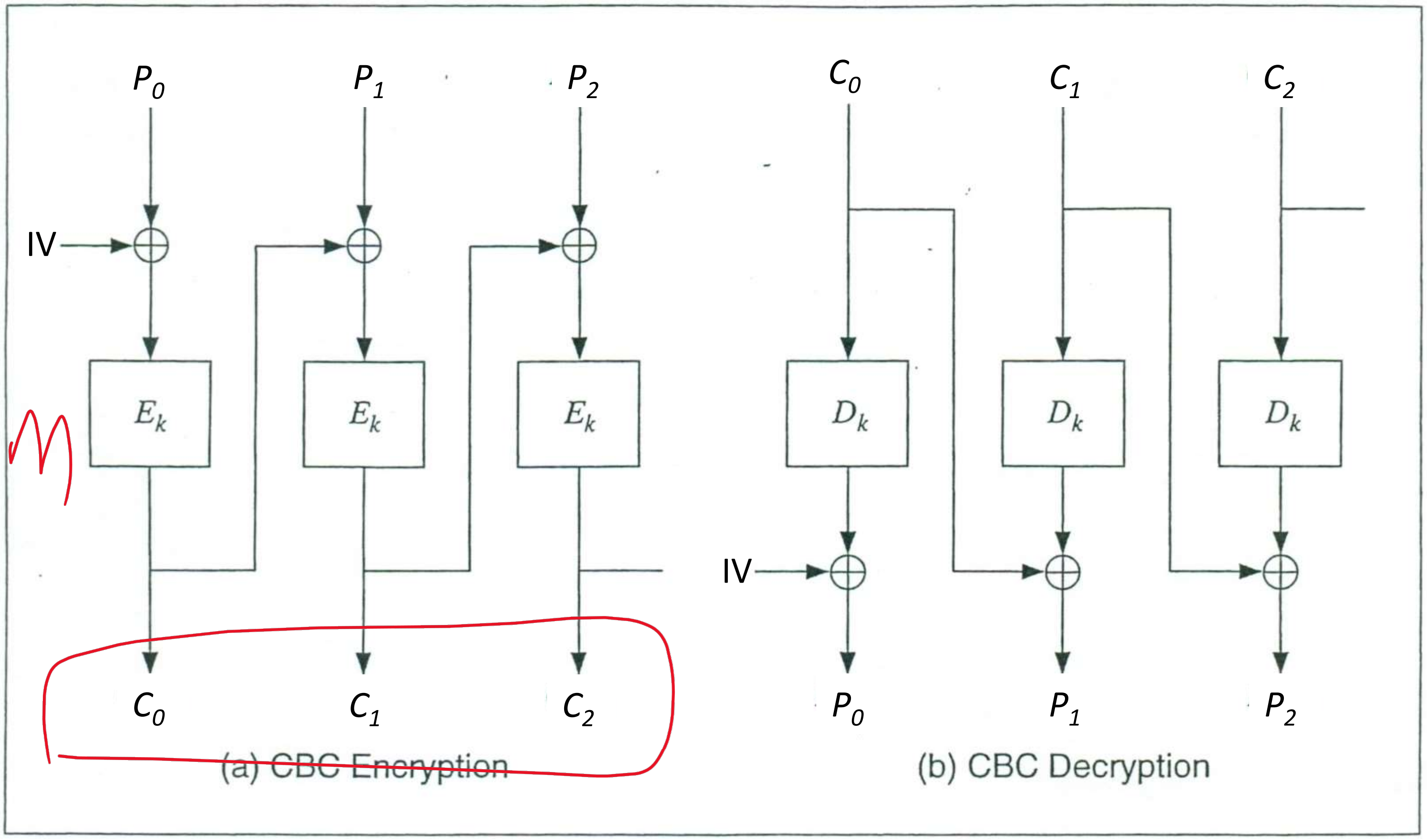
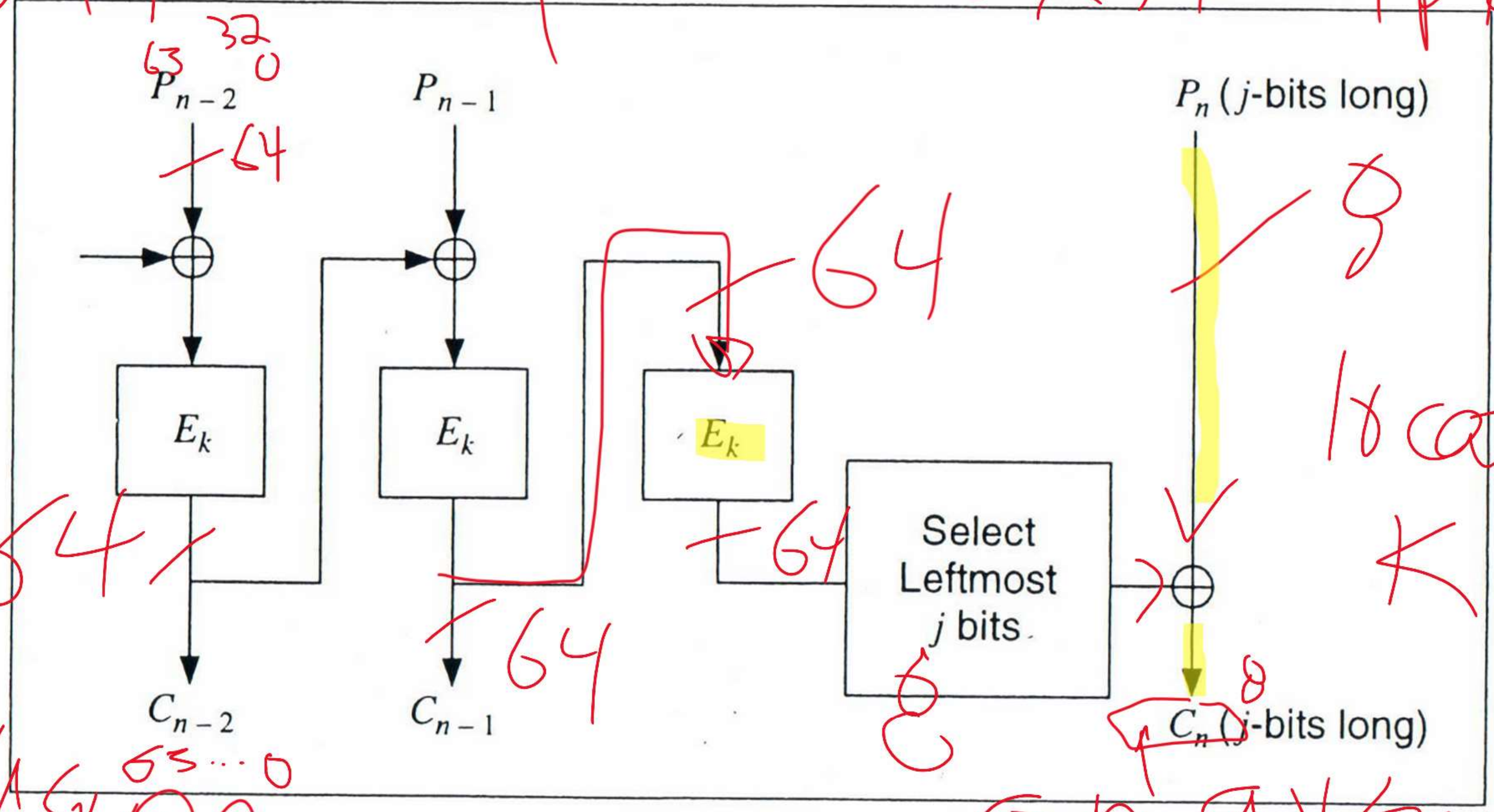


Figure 9.3 Cipher block chaining mode.

Motive: |enc.text| = |plaintext|



location known

diffusion

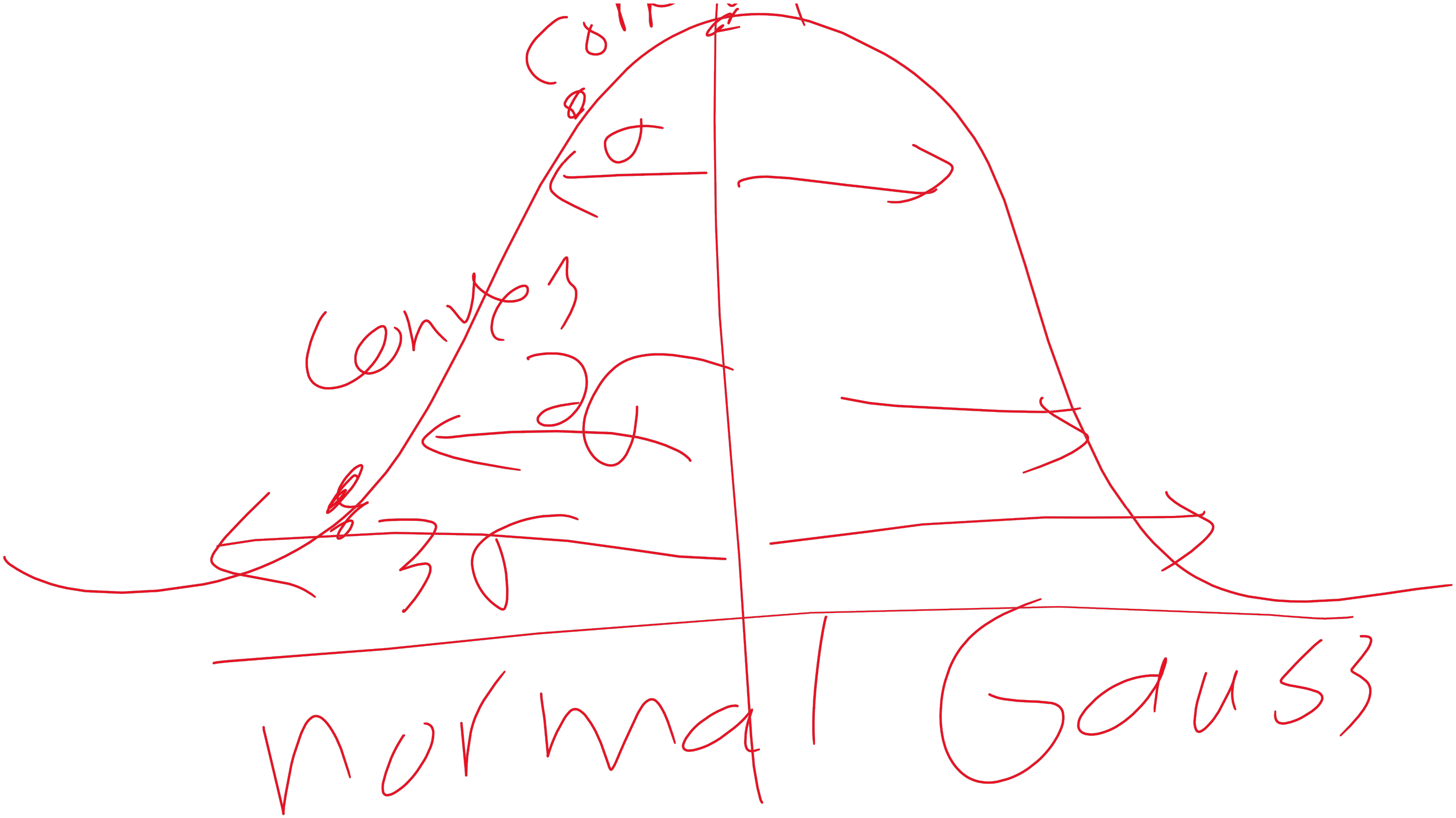
Figure 9.4 Encrypting the last short block in CBC mode

63→32 of P_{n-2} changes => on avg, C_n 50% bits

$P_1 \rightarrow DES_{K_1} \rightarrow E_1$

$P_2 \rightarrow DES_{K_1} \rightarrow E_2$

16


Conca
σ
convex
2σ
3σ
normal Gauss

Better approach

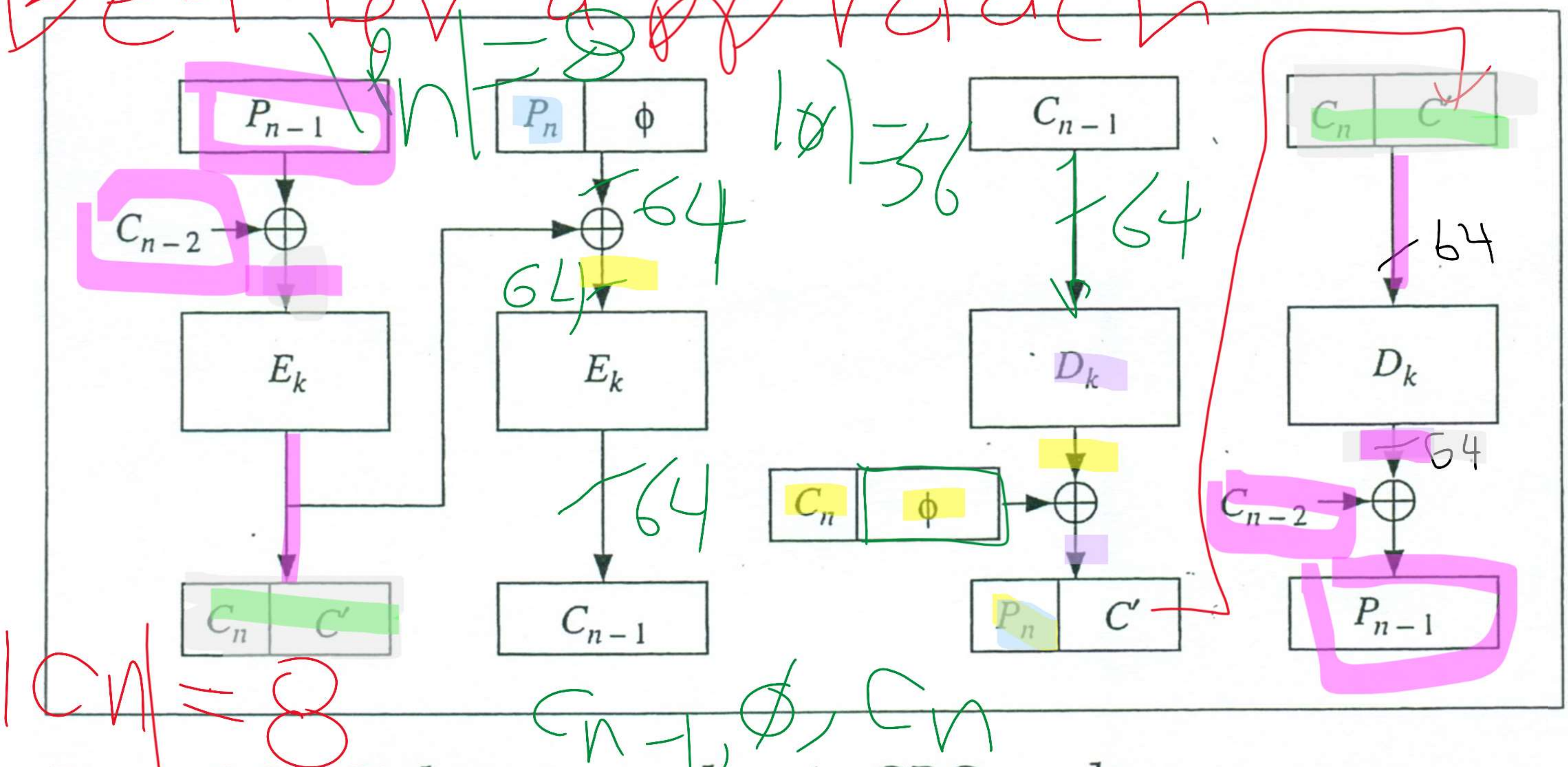


Figure 9.5 Ciphertext stealing in CBC mode.

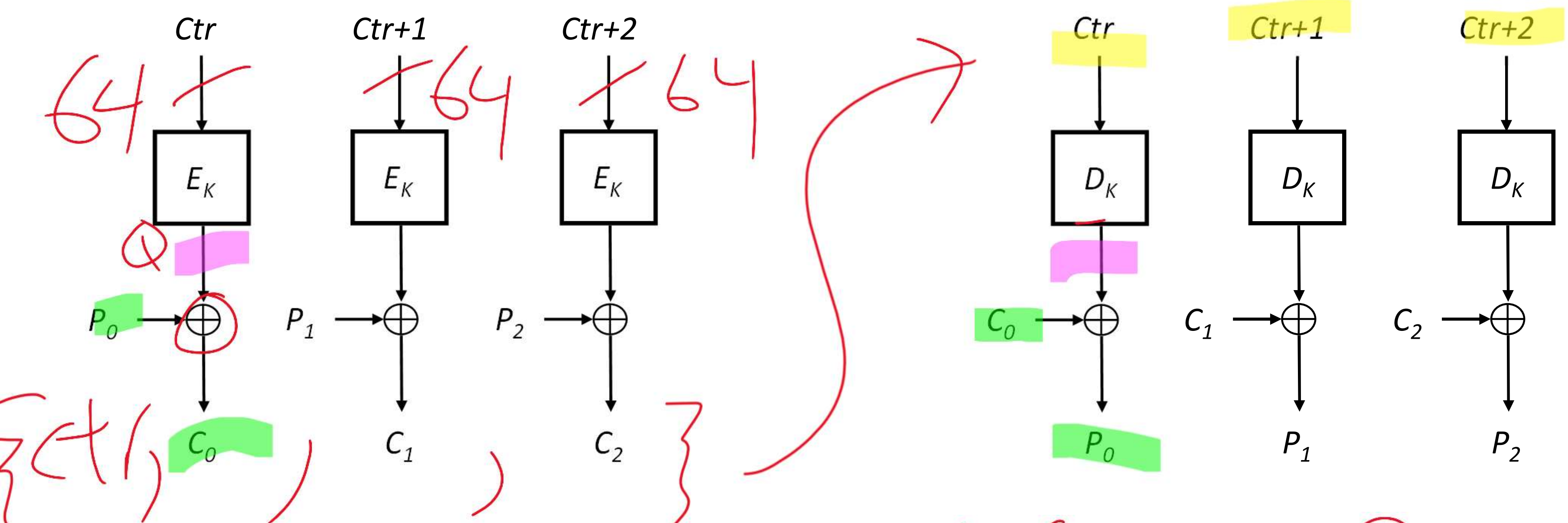
Ctr

Counter Mode

Bob K

Alice K

- Choose a random starting number Ctr



$Q \oplus P_0 = C_0 \rightarrow Q \oplus C_0 = P_0$

ctr_1 from 64 last

Ctr needs to ctr_2 be random (from uniform distr.)

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what if Ctr $ctr_2 = ctr_1$

$1/2^{64}$

3DES

$P_0 = \text{Midway}$

$C + r = 0$

C_0

$P_1 = \text{Midway}$

$C + r = 0$

C_1

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

problem:

Key size = message size

Stream Ciphers

$P_3 \oplus K_3 = C_3$ $K_5 \oplus P_5 = C_5$

Alice Bob

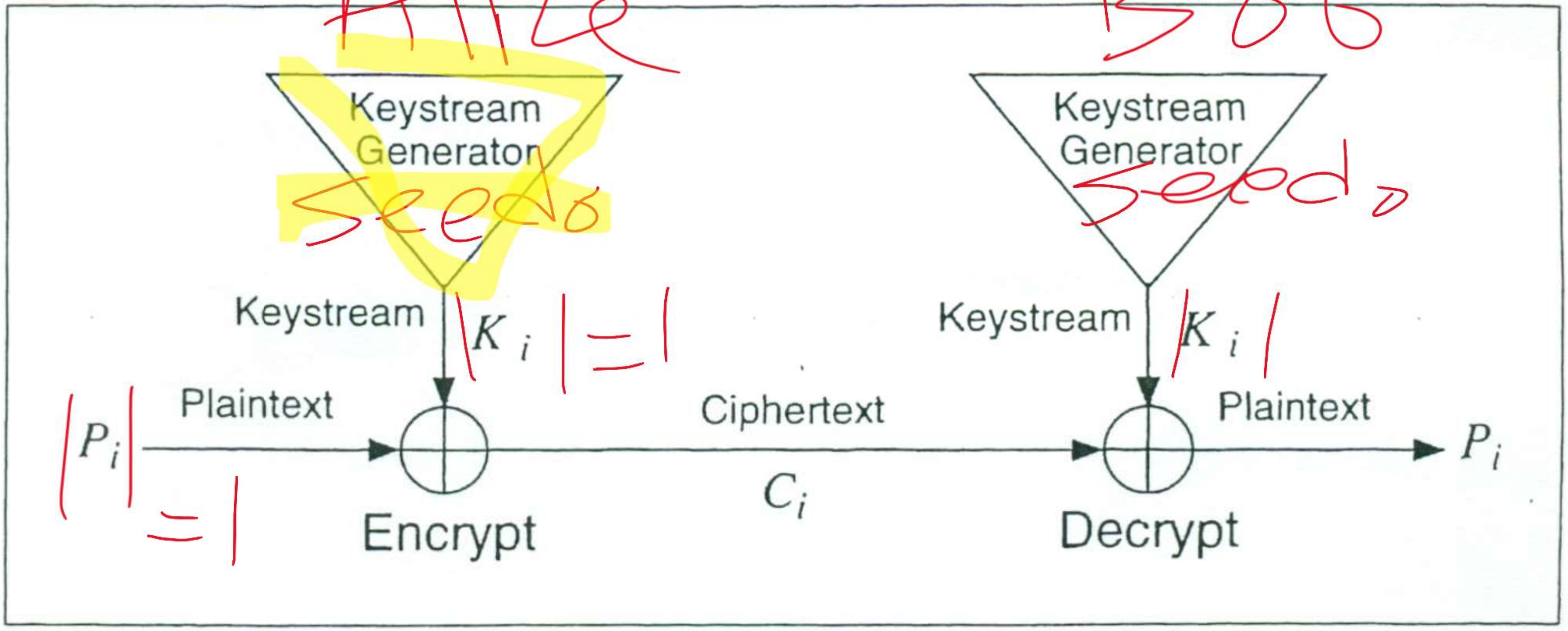

Figure 9.6 Stream cipher.

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

1KB = 1024 Bytes

= 8196 bits

Keystream Generator Requires a Key

$I_{127} \cdots I_0$

$I_7 \oplus I_3 \oplus I_0 = K_i$

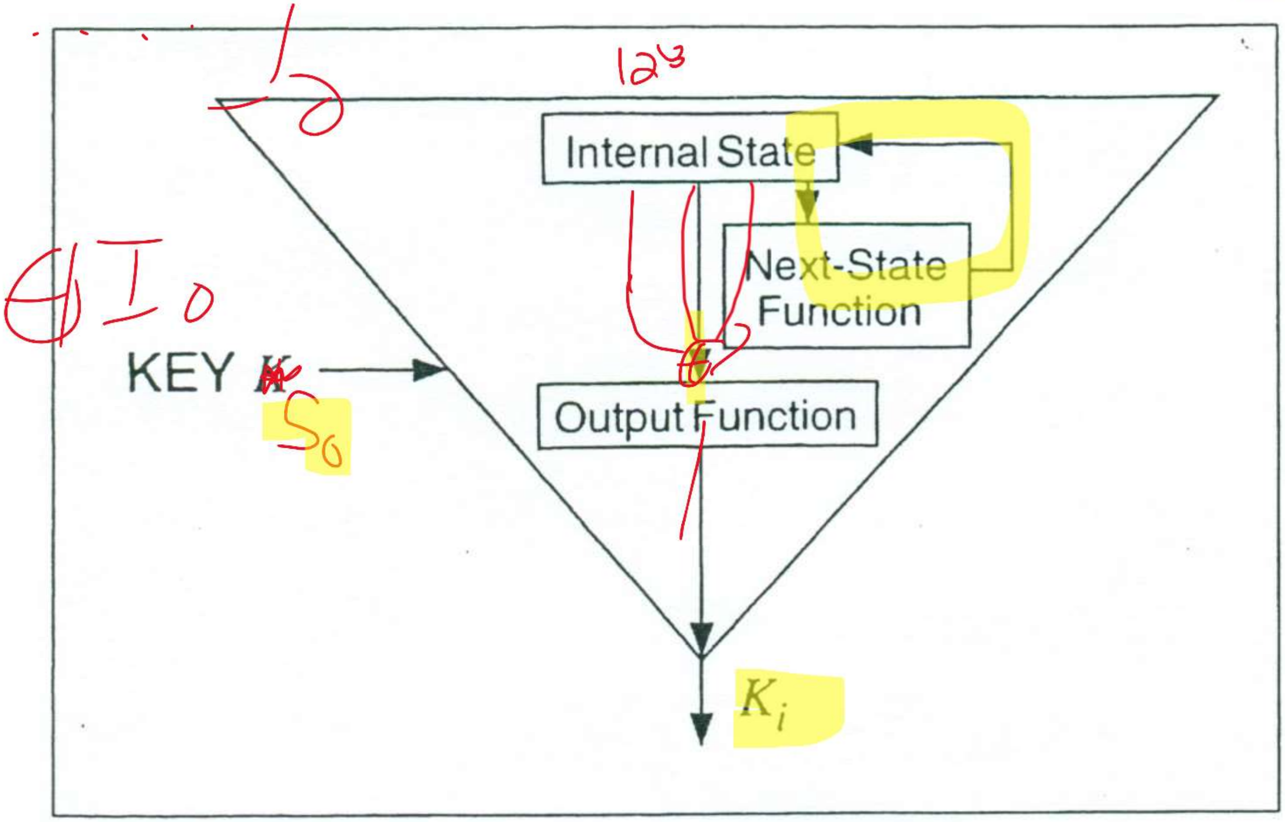

Figure 9.7 Inside a keystream generator.

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

S_1

S_2

Cipher-feedback (CFB) Mode

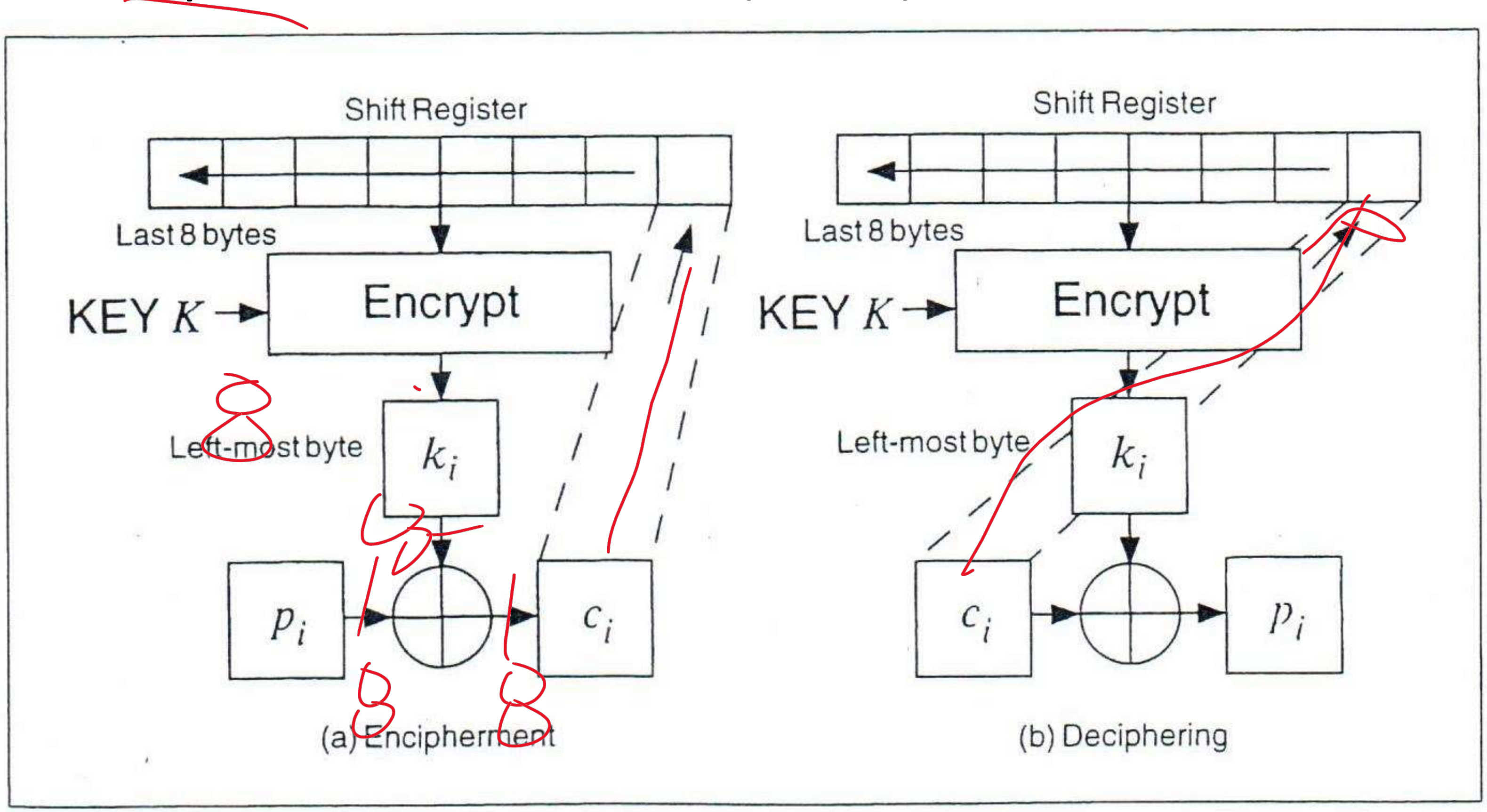

Figure 9.9 8-bit cipher-feedback mode.

Output-feedback (OFB) Mode

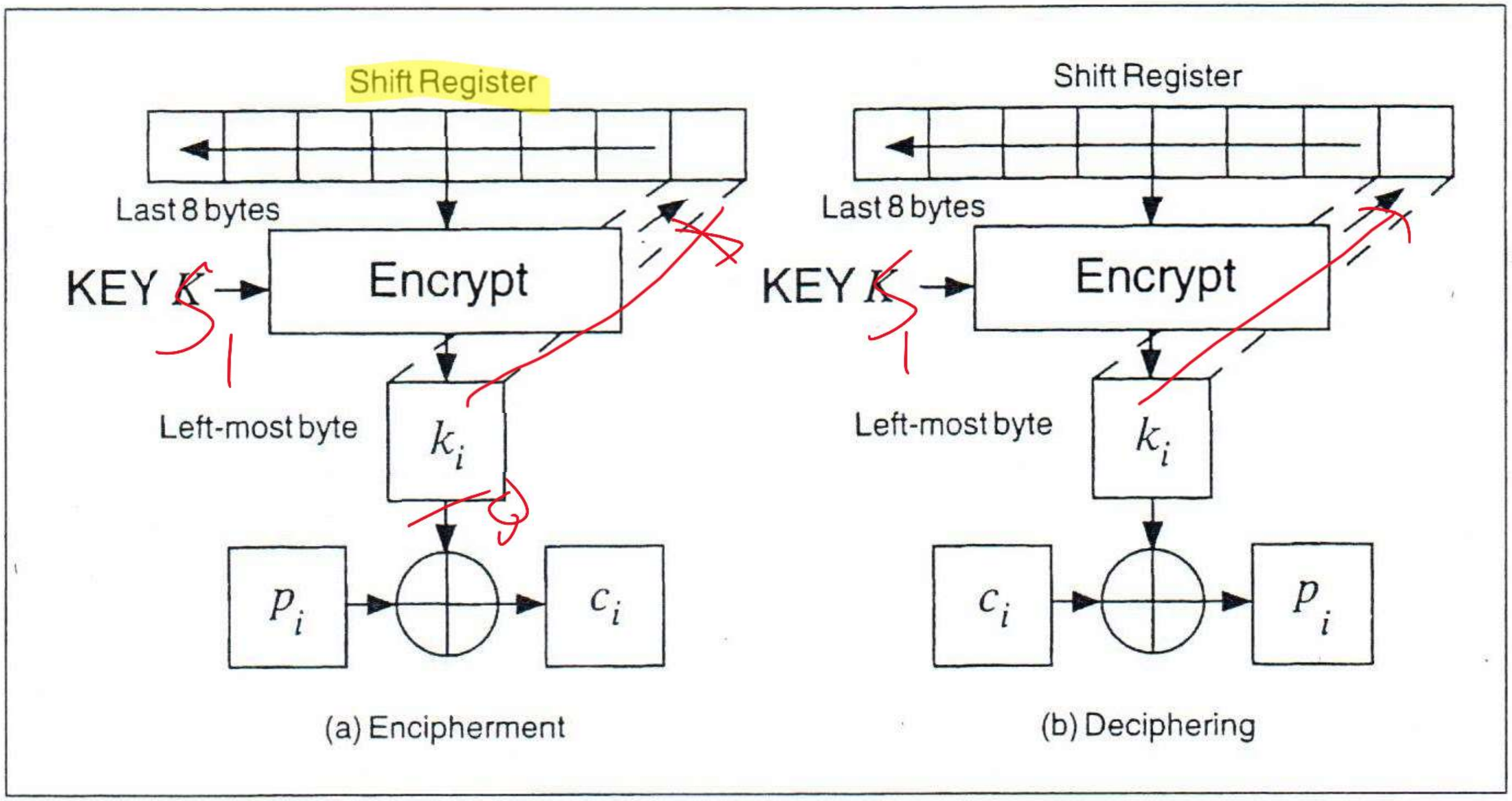

Figure 9.11 8-bit output-feedback mode.