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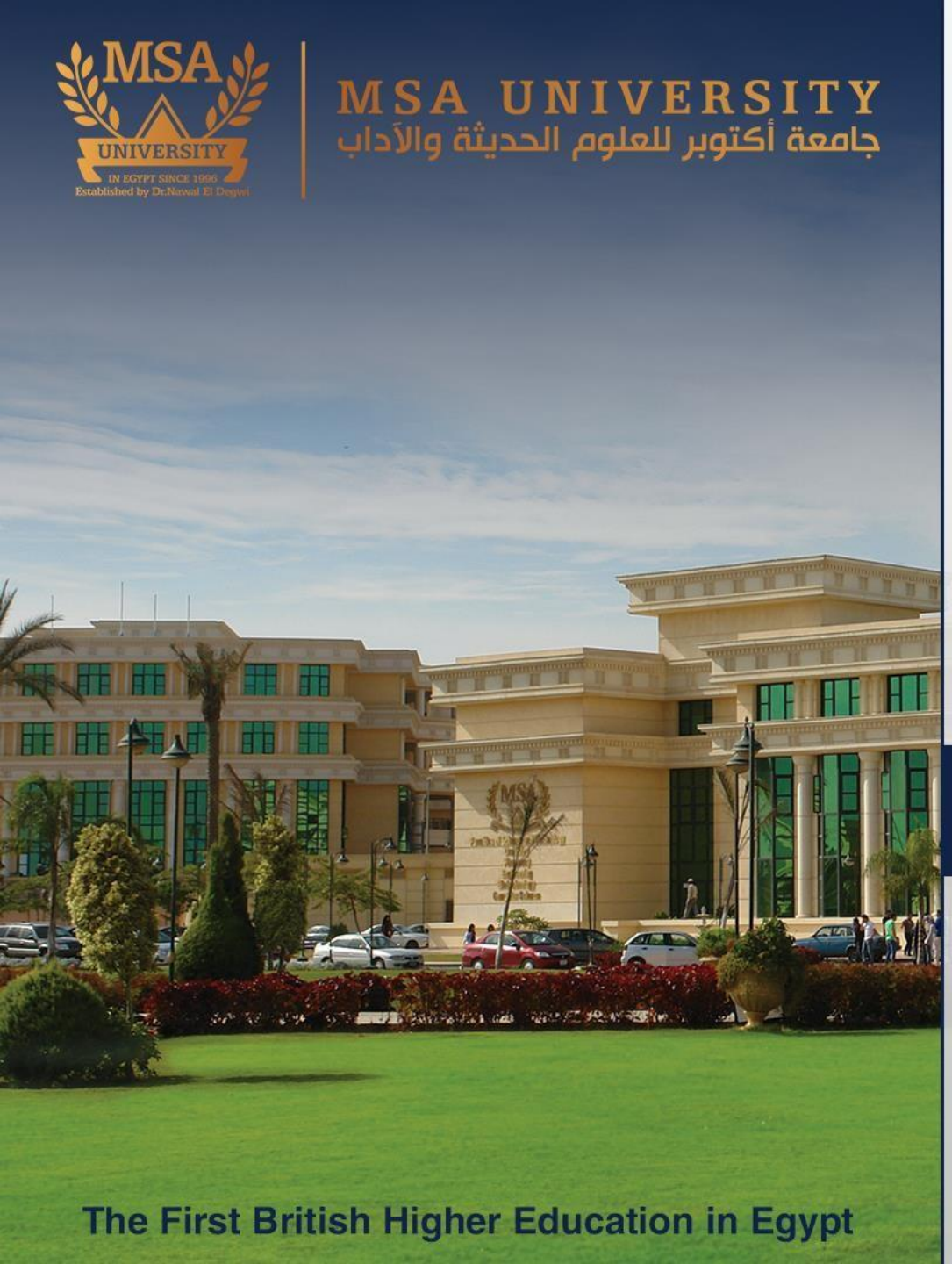


Cryptography
ECE5632 - Spring 2025

Lecture 4B

Dr. Farah Raad

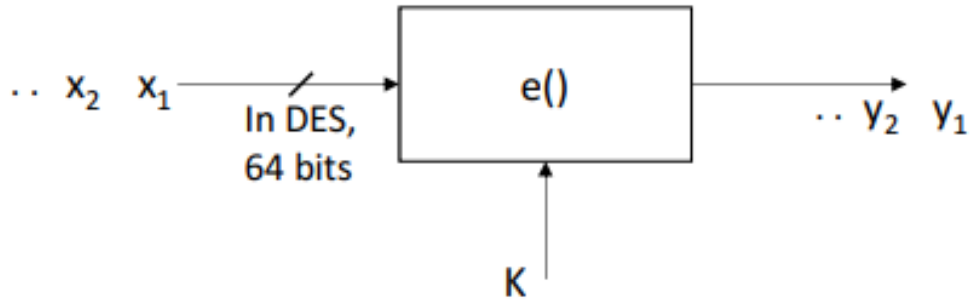
Lecture Topic

Modes of Operation for Block Ciphers

Block Ciphers

Block cipher is an encryption algorithm that takes a fixed size of input say b bits and produces a ciphertext of b bits again.
If the input is larger than b bits it can be divided further.

- **A block cipher is much more than just an encryption algorithm, it can be used:-**
  - ✓ to build different types of block-based encryption schemes
  - ✓ to realize stream ciphers
  - ✓ to construct hash functions
  - ✓ to make message authentication codes
  - ✓ to build key establishment protocols
  - ✓ to make a pseudo-random number generator



- **The security of block ciphers also can be increased by**
  - key whitening
  - multiple encryption

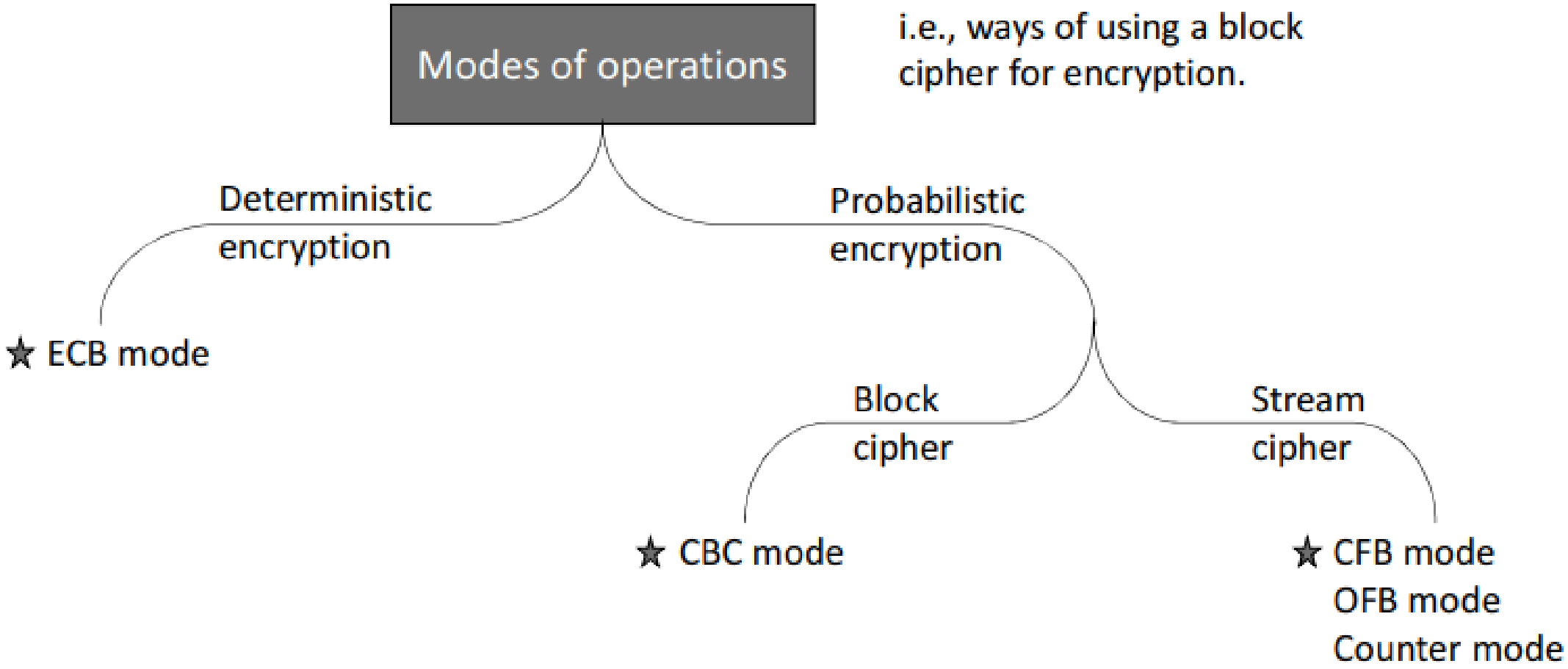
Encryption with Block Ciphers

- There are several ways of encrypting long plaintexts, e.g., an e-mail or a computer file, with a block cipher ("modes of operation")
  - Electronic Code Book mode (ECB)
  - Cipher Block Chaining mode (CBC)
  - Output Feedback mode (OFB)
  - Cipher Feedback mode (CFB)
  - Counter mode (CTR)
  - Galois Counter Mode (GCM)
- All of the 6 modes have one goal:
  - In addition to confidentiality, they provide authenticity and integrity:
  - Is the message really coming from the original sender? (authenticity)
  - Was the ciphertext altered during transmission? (integrity)

Deterministic vs Probabilistic Encryption

- In a deterministic encryption scheme, a particular plaintext is mapped to a fixed ciphertext, if the key is unchanged.

- In a probabilistic encryption scheme is non-deterministic.
  i.e., if the same plaintext is encrypted twice, different ciphertexts are obtained.


Modes of operations
i.e., ways of using a block cipher for encryption.
Deterministic encryption
Probabilistic encryption
★ ECB mode
Block cipher
Stream cipher
★ CBC mode
★ CFB mode
OFB mode
Counter mode

★ i.e., today.

Modes of Operation for Block Ciphers

- Encryption with Block Ciphers: Modes of Operation
  - ✓ **Electronic Codebook Mode (ECB).**
  - ✓ Cipher Block Chaining Mode (CBC).
  - ✓ Cipher Feedback mode (CFB)
  - ✓ Output Feedback mode (OFB)
  - ✓ Counter mode (CTR)
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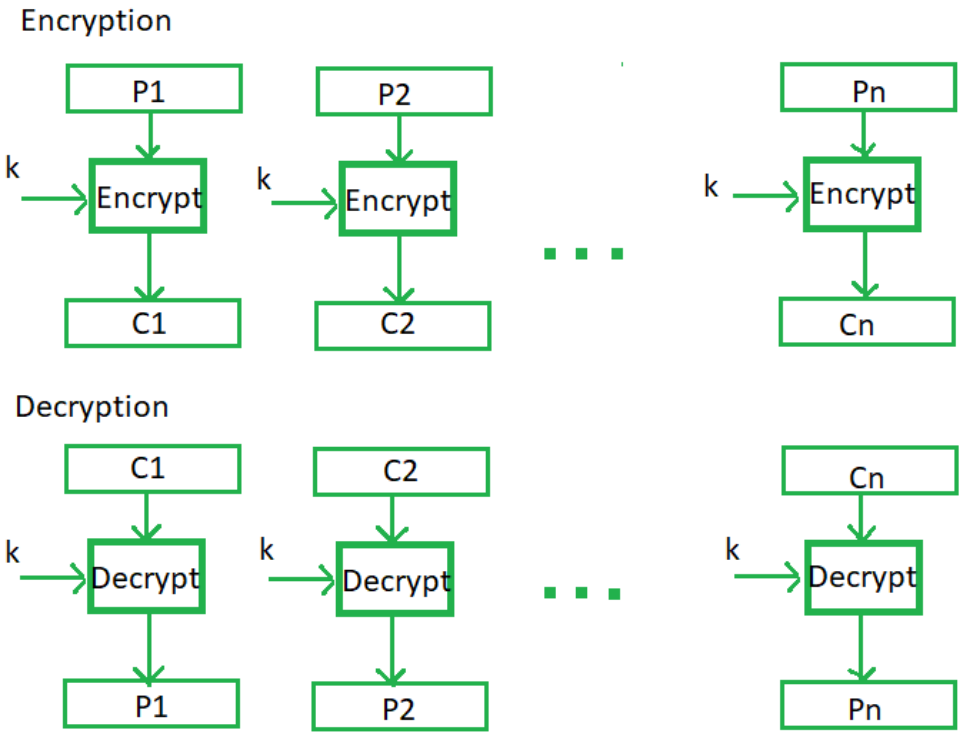
Electronic Code Book mode (ECB)

- It is the easiest block cipher mode of functioning.
- It is easier because of direct encryption of each block of input plaintext and output is in form of blocks of encrypted ciphertext.
- Generally, if a message is large bits in size, it can be broken down into a bunch of blocks and the procedure is repeated
- Each block encrypted independently.
- Identical plaintexts encrypted similarly.
- No chaining, no error propagation
- No need for preprocessing

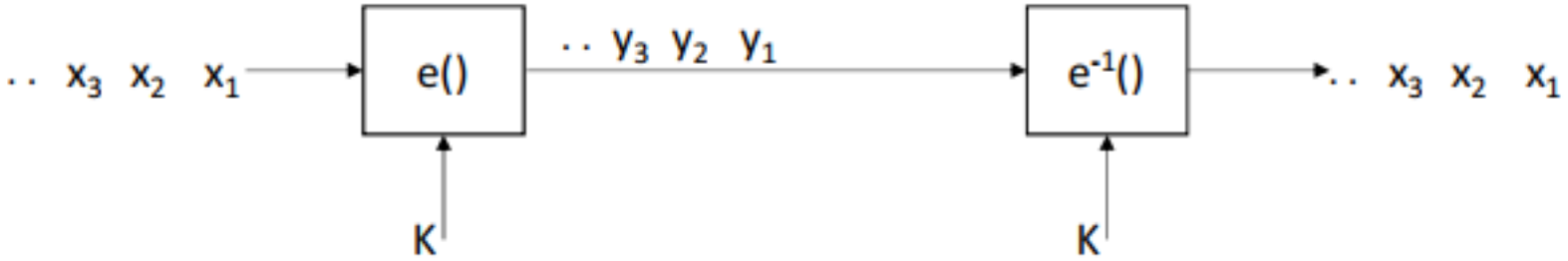
during encryption / decryption

- Allows random access to ciphertext



Electronic Code Book mode (ECB)

- $e_k(x_i)$ denote the encryption of a b-bit plaintext block x_i with key k
- $e_k^{-1}(y_i)$ denote the decryption of b-bit ciphertext block y_i with key k
- Messages which exceed b bits are partitioned into b-bit blocks
  - **Each Block is encrypted separately**



$y_i = e(x_i)$ $x_i = e^{-1}(y_i)$

Encryption: $y_i = e_k(x_i),\ i \geq 1$
Decryption: $x_i = e_k^{-1}(y_i) = e_k^{-1}(e_k(x_i)),\ i \geq 1$

Seems like the natural way of doings encryption..
But . . . Not a very good way, as we're going to see!

Electronic Code Book mode (ECB)

- **Advantages**
  - no block synchronization between sender and receiver is required
  - bit errors caused by noisy channels only affect the corresponding block but not succeeding blocks
  - Block cipher operating can be parallelized
  - Parallel encryption of blocks of bits is possible, thus it is a faster way of encryption.
  - Simple way of the block cipher.

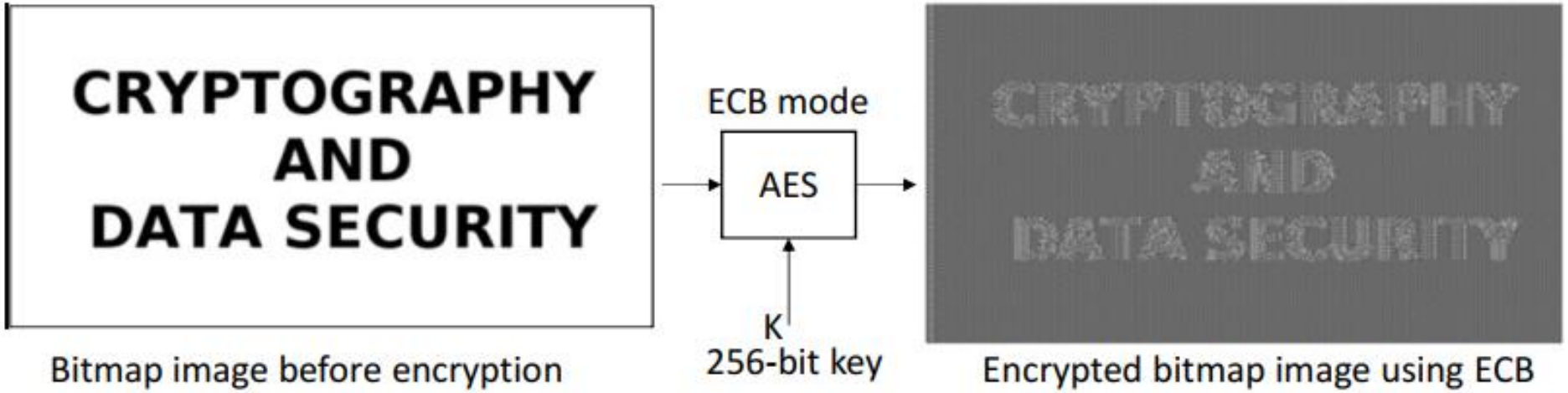
➢ **Disadvantages**

- ECB encrypts highly deterministically (Prone to cryptanalysis since there is a direct relationship between plaintext and ciphertext).
- identical plaintexts result in identical ciphertexts
- an attacker recognizes if the same message has been sent twice
- plaintext blocks are encrypted independently of previous blocks
- an attacker may reorder ciphertext blocks which results in valid plaintext

➢ **ECB mode is secure only in case the message is one block.**

ECB

- **Another weakness, Encryption of bitmaps in ECB mode**



Simply because ECB is deterministic.

Identical plaintext blocks are mapped into identical cyphertext blocks.

Statistical properties in the plaintext are preserved in the ciphertext

Modes of Operation for Block Ciphers

- Encryption with Block Ciphers: Modes of Operation
  - ✓ Electronic Codebook Mode (ECB)
  - ✓ **Cipher Block Chaining Mode (CBC)**
  - ✓ Cipher Feedback mode (CFB)
  - ✓ Output Feedback mode (OFB)
  - ✓ Counter mode (CTR)
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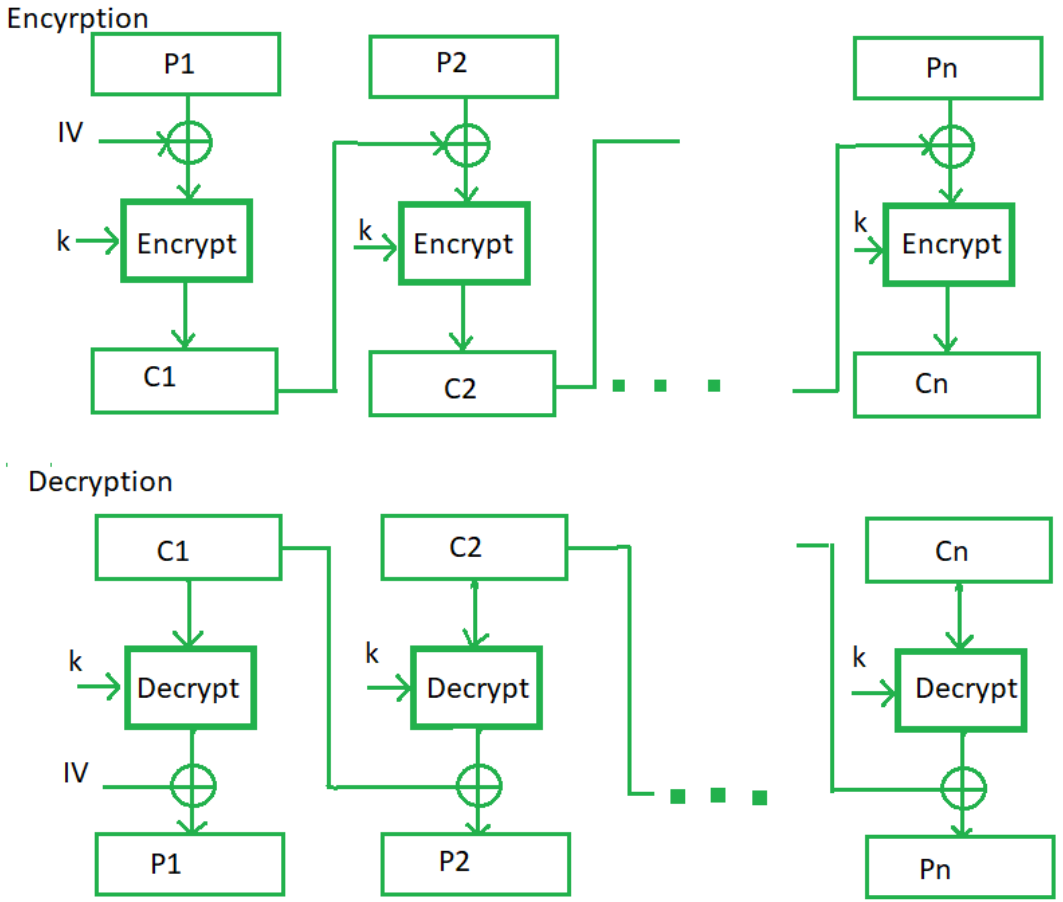
Cipher Block Chaining Mode (CBC)

- It is an advancement made on ECB since ECB compromises some security requirements.
- In CBC, the previous cipher block is given as input to the next encryption algorithm after XOR with the original plaintext block.

- In a nutshell here, a cipher block is produced by encrypting an XOR output of the previous cipher block and present plaintext block.
- **Main goal:** Make the encryption probabilistic
- **Idea:** Use the ciphertext from the previous block, to impact the current block.
- No need for preprocessing during encryption / decryption
- Aallows random access to ciphertext
- Decryption is parallelizable: Plaintext block xj requires ciphertext blocks cj and cj-1



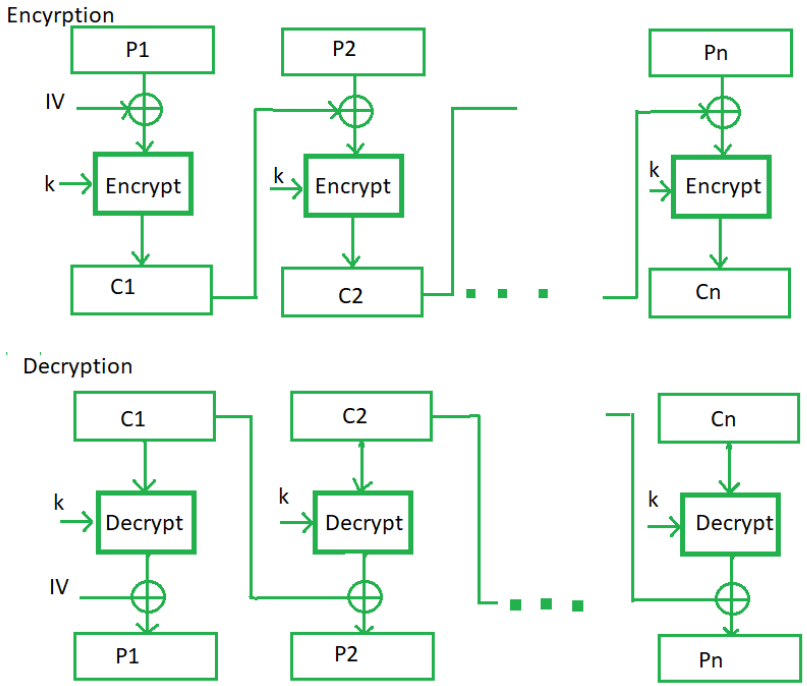
Cipher Block Chaining Mode (CBC)

- Identical messages: changing IV or the first plaintext block results in different ciphertext
- Chaining: Ciphertext block cj depends on xj and all preceding plaintext blocks (dependency contained in cj-1)
- Error propagation: Single bit error on cj may flip the corresponding bit on xj+1, but changes xj significantly.
- IV need not be secret, but its integrity should be protected

There are two main ideas behind the CBC mode:

1. The encryption of all blocks are “chained together”
2. ciphertext y_i depends not only on block x_i but on all previous plaintext blocks as well

- The encryption is randomized by using an initialization vector (IV)



Encryption (first block): $y_1 = e_k(x_1 \oplus \text{IV})$

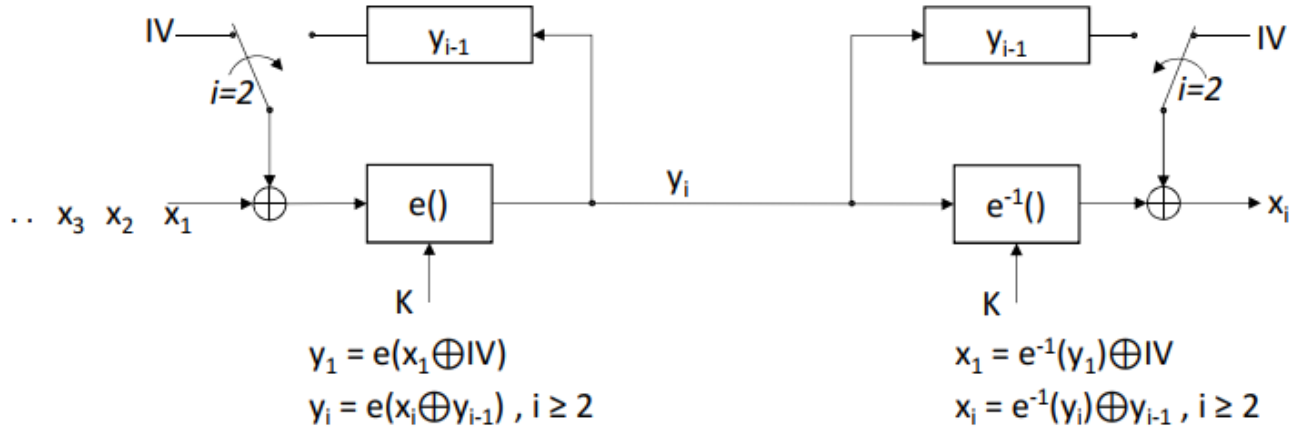
Encryption (general block): $y_i = e_k(x_i \oplus y_{i-1}),\ i \geq 2$

Decryption (first block): $x_1 = e_k^{-1}(y_1) \oplus \text{IV}$

Decryption (general block) : $x_i = e_k^{-1}(y_i) \oplus y_{i-1},\ i \geq 2$

Cipher Block Chaining Mode (CBC)

- For the first plaintext block x_1 there is no previous ciphertext
  - an IV is added to the first plaintext to make each CBC encryption nondeterministic
  - the first ciphertext y_1 depends on plaintext x_1 and the IV
- The second ciphertext y_2 depends on the IV, x_1 *and* x_2
- The third ciphertext y_3 depends on the IV and x_1, x_2 *and* x_3, and so on



IV: Initialization Vector.

Cipher Block Chaining Mode (CBC)

➢ Advantages of CBC

- CBC works well for input with large bits.
- CBC is a good authentication mechanism.
- Better resistive nature towards cryptanalysis than ECB.

➢ Disadvantages of CBC

- Parallel encryption is not possible since every encryption requires a previous cipher.
- Doesn’t have to be a secret.
- Error transfer to the end

Modes of Operation for Block Ciphers

- Encryption with Block Ciphers: Modes of Operation
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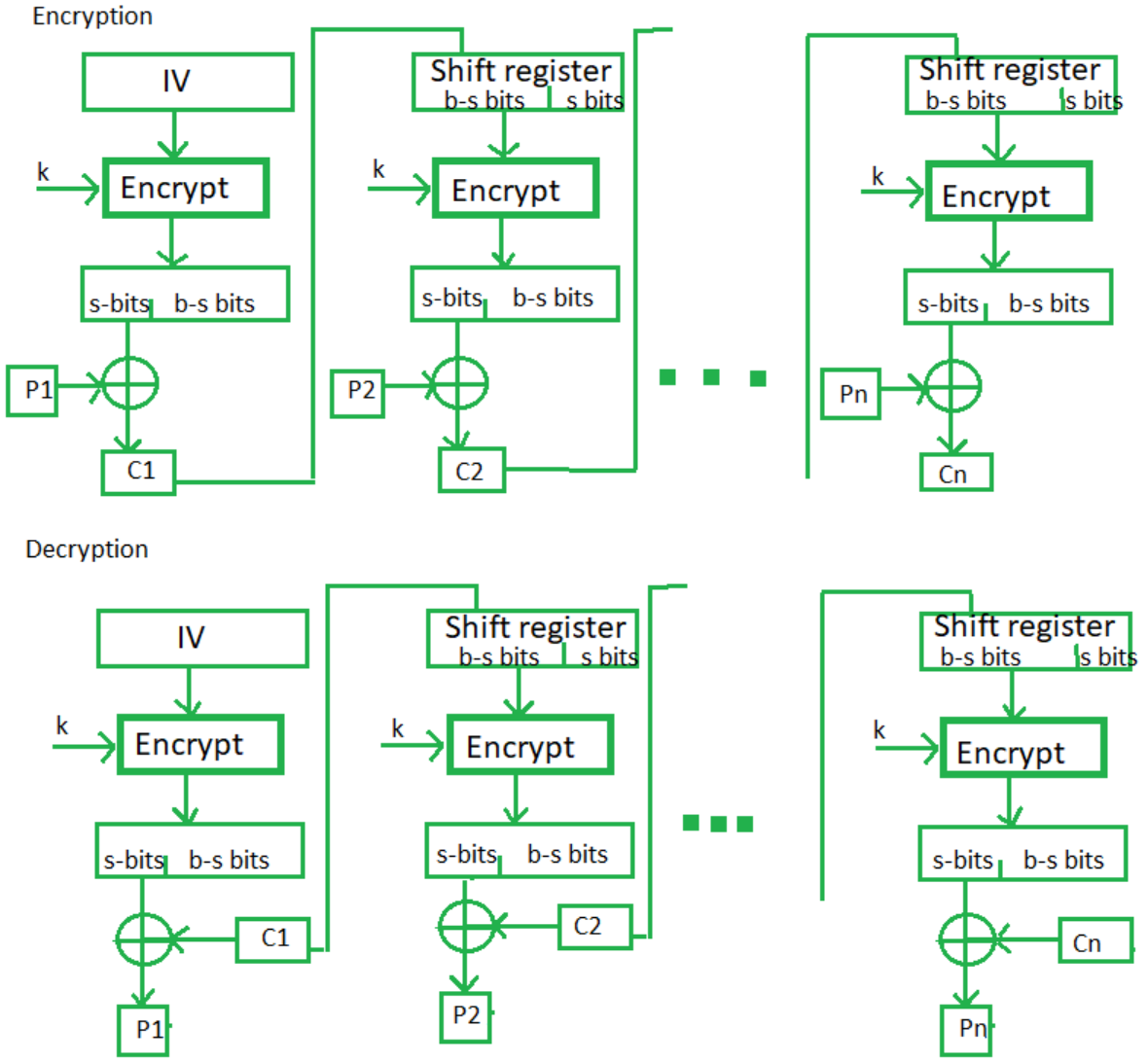
Cipher Feedback Mode (CFB)

- It uses a block cipher as a building block for an asynchronous **stream cipher**
- In this mode the cipher is given as feedback to the next block of encryption with some new specifications:
  - first, an initial vector IV is used for first encryption
  - output bits are divided as a set of *s* and *b-s* bits.
  - The left-hand side *s* bits are selected along with plaintext bits to which an XOR operation is applied.
  - The result is given as input to a shift register having b-s bits to LHS, and s bits to RHS and the process continues.

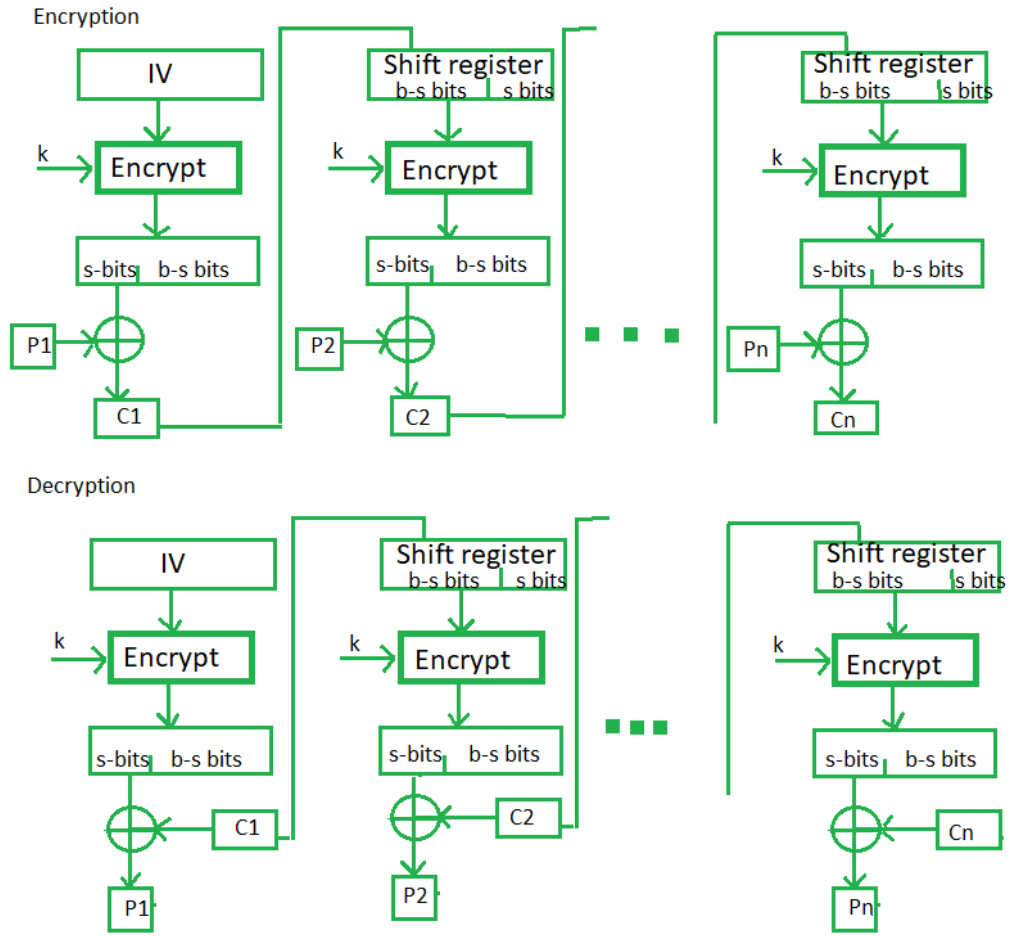


Cipher Feedback Mode (CFB)

Goal: Generate an unpredictable key stream for stream cipher

Idea: Construct the key stream generator using a block cipher

- Allows random access to ciphertext
- Decryption is parallelizable : Plaintext block xj requires ciphertext blocks cj and cj-1
- Identical messages: as in CBC
- Chaining: Similar to CBC
- Error propagation: Single bit error on cj may flip the corresponding bit on xj , but changes xj+1 significantly.
- IV need to be secret (XORed with x1)



Encryption (first block): $y_1 = e_k(\mathrm{IV}) \oplus x_1$

Encryption (general block): $y_i = e_k(y_{i-1}) \oplus x_i, \quad i \geq 2$

Decryption (first block): $x_1 = e_k(\mathrm{IV}) \oplus y_1$

Decryption (general block) : $x_i = e_k(y_{i-1}) \oplus y_i, \quad i \geq 2$

Cipher Feedback Mode (CFB)

➢ Advantages of CFB

•Since, there is some data loss due to the use of shift register, thus it is difficult for applying cryptanalysis.

➢ Disadvantages of using CFB

• The drawbacks of CFB are the same as those of CBC mode.
• Both block losses and concurrent encryption of several blocks are not supported by the encryption.
• Decryption, however, is parallelizable and loss-tolerant.

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Thank You!

See You next Lectures!!
Any Question?

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