

CRYE 6127 Introduction to Cryptology

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UBa Cyber Crypto Center, Fall 2025

Symmetric Key Encryption

Outline

- 1 Stream Ciphers
- 2 Block Ciphers
- 3 Block Chaining Modes
- 4 Key Management

Construction Strategies

- **Stream ciphers:** For arbitrarily long messages (e.g., data streams).
A key $k \in \mathcal{K}$ and a nonce r are expanded to a **pseudorandom** stream, $g(r, k)$, used as a one-time pad.

$$\text{Enc}(k, m) = (r, m \oplus g(r, k))$$

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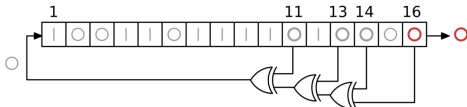
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with a **chaining mode** can encrypt arbitrarily long messages

Examples of stream ciphers

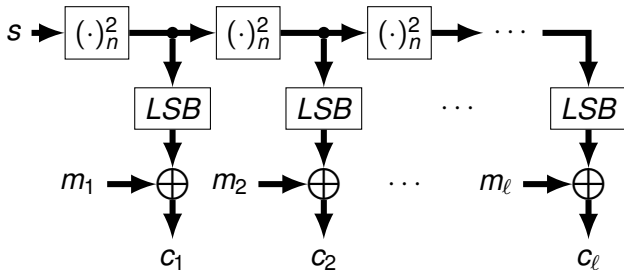
- **Linear Feedback Shift Registers.** Ultra fast but insecure.



(image based on <https://commons.wikimedia.org/w/index.php?curid=60225898>)

- **Blum-Blum-Shub generator.** Very slow. Provably secure.
- **Non-Linear Feedback Shift Registers.** Very fast. Widely used (GSM, Bluetooth, ...). In general, they lead to weak symmetric encryption schemes.
- **Other designs:** RC4 (obsolete), chacha, ...

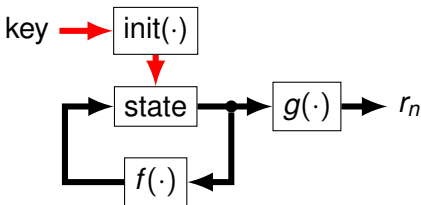
Stream Cipher from Blum-Blum-Shub Generator



$n = pq, p = 2p' + 1, q = 2q' + 1$
 p, q, p', q' primes (512 to 1024 bits).

RC4 Stream Cipher

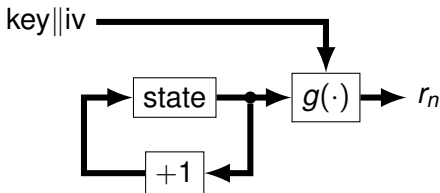
- Internal state: a permutation s of $\{0, \dots, 255\}$ and two counters i, j .



- initial state: computed from the key.
 - Every message byte m_n is XORed with the output byte r_n .
- The key is too short (from 40 bits to 128 bits).
 - No specified way to use an initialization value (iv).
 - Some real systems using RC4 have been attacked.

Chacha Stream Cipher

- Internal state: just a counter i .
- It works with 512 bit words.



- initial state: $i = 0$.
- Every message word m_n is XORed with the output word r_n .

- key has 256 bits and the iv has 64 bits.
- fully parallelizable (random access to words)
- No successful attack is currently known.

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Practical Construction of Block Ciphers

Heuristic constructions based on:

- **Confusion:** every bit in the ciphertext must depend on several bits of the key.
- **Diffusion:** flipping a single plaintext bit must change half of the ciphertext bits.
- **Iteration:** the encryption procedure consists of a given number of rounds.

Structure:

- **Key expansion:** a set of round keys is generated from the original key
- **Mixing** of permutation (**shuffling, shifting...**), substitution (**S-boxes**) and XORing the subkeys in each round.

Example: DES

Key size: 56 bits

Message and ciphertext block size: 64 bits

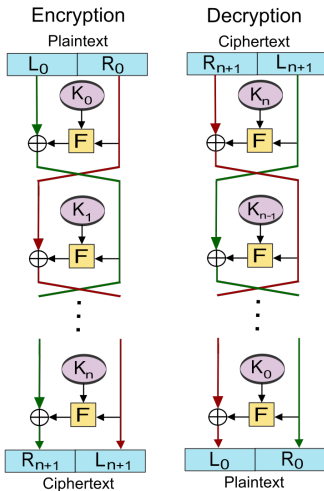
Number of encryption rounds: 16

Key expansion: from 56 bits to 768 bits (16 subkeys, each one of 48 bits)

Encryption rounds: Feistel Network

- Start with the 64 bit message block
- In each iteration, divide the intermediate block into two halves (L_i, R_i)
- Apply a transformation to compute next block
 $(L_{i+1}, R_{i+1}) = (R_i, L_i \oplus F(k_i, R_i))$
- The resulting ciphertext block is (R_{16}, L_{16}) .

Feistel Network



Example: DES (II)

The function F combines:

- Expands the 32 bit half-block into 48 bits, and XORs the round subkey.
- Divides the 48 bits into 8 6-bit words.
- Transforms each word into a 4 bit word with a table (S-box).
- Glues the 4 bit words to obtain a 32 bit half-block.
- Applies a fixed permutation to the 32 bits.

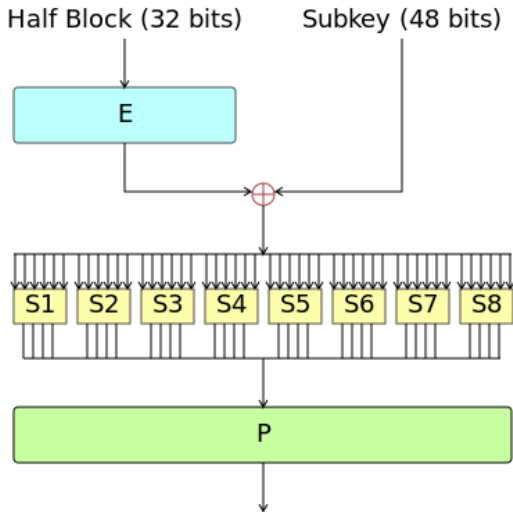
3DES combines three independent keys (168 bits in total) and it is still considered secure.

$$3DES_{k_1, k_2, k_3}(m) = DES_{k_3} \circ DES_{k_2}^{-1} \circ DES_{k_1}(m)$$

More details in

http://en.wikipedia.org/wiki/Data_Encryption_Standard

Example: DES Round Function



Example: AES256

Key size: 256 bits

Message and ciphertext block size: 128 bits (4×4 byte matrix)

Number of encryption rounds: 14

Key expansion: from 256 bits to 1920 bits (15 subkeys, each one a 4×4 matrix of bytes) in an iterative procedure (it adds 4 new bytes in each iteration)

Encryption round:

- Apply a substitution box to each byte
- Perform rotation operations to rows
- Perform linear transformation to columns
- XOR with the round key

More details in

http://en.wikipedia.org/wiki/Advanced_Encryption_Standard

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ECB (Electronic Codebook):

$$c_i = \text{Enc}(k, m_i)$$



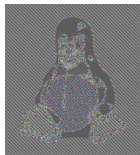
(from Wikipedia)

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Equal message blocks result in equal ciphertext blocks!

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CBC (Cipher Block Chaining):

$$c_0 = iv$$

$$c_i = \text{Enc}(k, m_i \oplus c_{i-1})$$



(from Wikipedia)

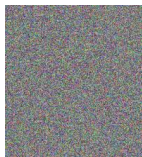
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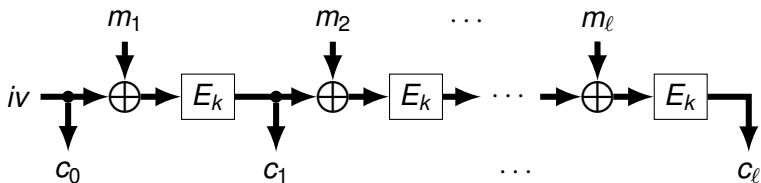
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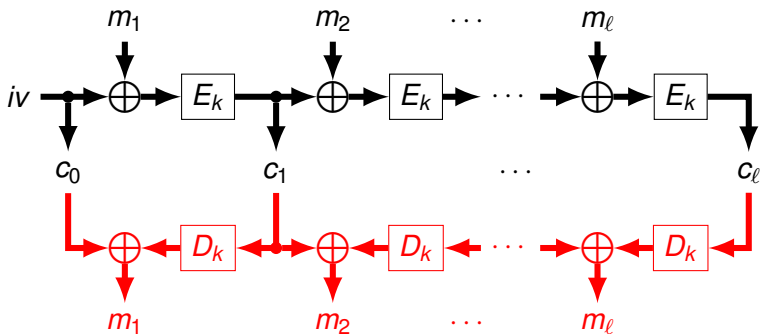
(from Wikipedia)

The ciphertext has an extra random block c_0 , the “initialization vector”

CBC Mode

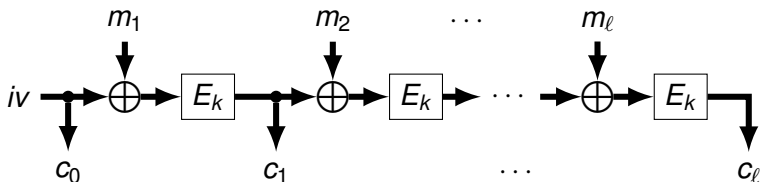
[▶ Comp. ...](#)

CBC Mode

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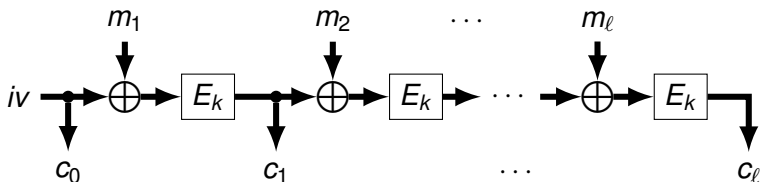
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Collision probability must be small

Other Block Chaining Modes

- CFB (Cipher Feedback) operation mode:

$$c_0 = iv$$

$$c_i = \text{Enc}(k, c_{i-1}) \oplus m_i$$

- OFB (Output Feedback) operation mode:

$$r_0 = iv$$

$$r_i = \text{Enc}(k, r_{i-1})$$

$$c_i = m_i \oplus r_i$$

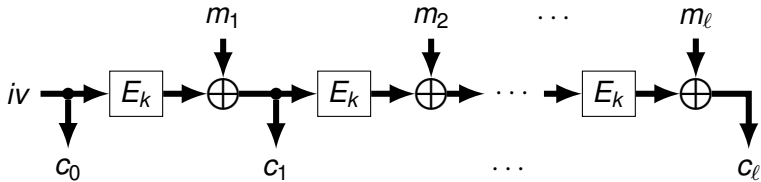
- CTR (Counter) operation mode:

$$r_i = \text{Enc}(k, iv + i)$$

$$c_i = m_i \oplus r_i$$

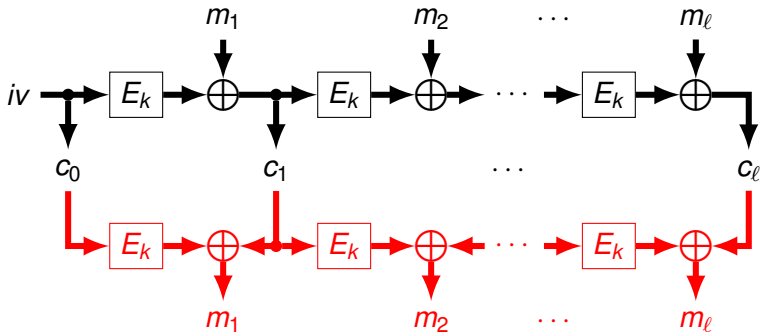
CFB Mode

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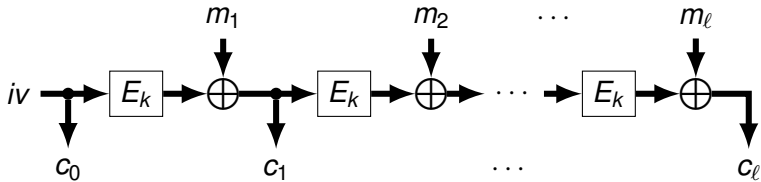
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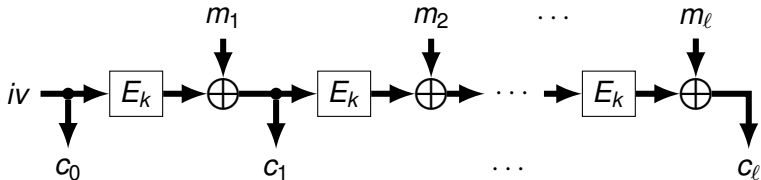
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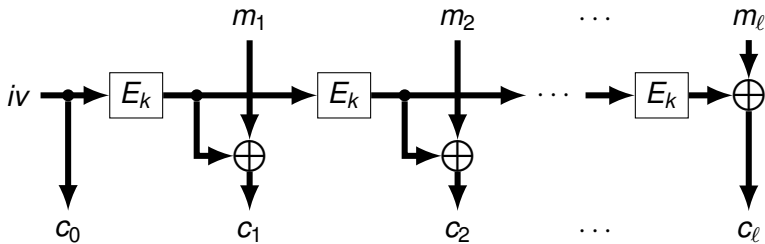
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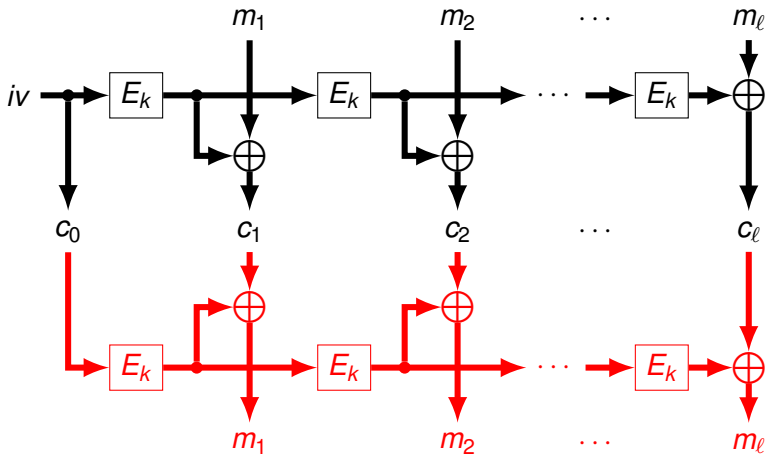
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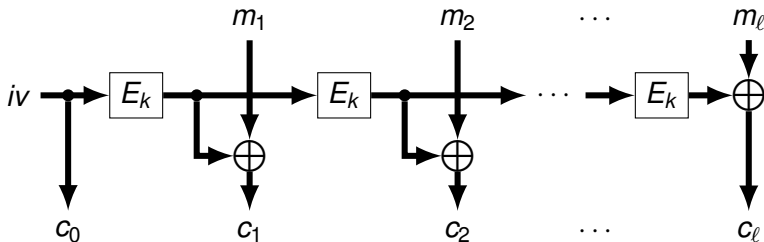
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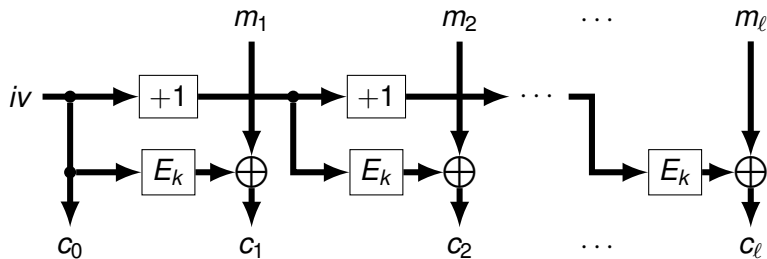
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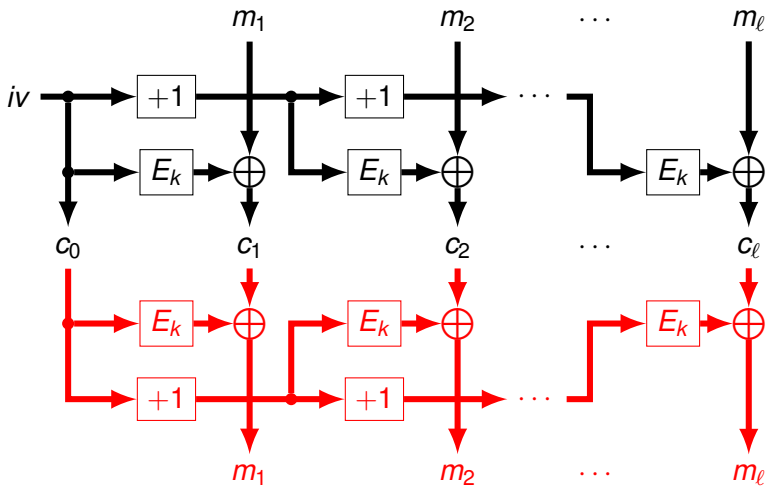
A short cycle of E_k of length r reveals $m_i \oplus m_{i+r}$ for all i

CTR Mode

[▶ Comp...](#)

CTR Mode

▶ Comp. ...



Comparison of Block Chaining Modes

- CFB, OFB and CTR require only the encryption box (even for decryption)
- CBC and CFB are “self-synchronizable”
- CTR can use random access for encryption and decryption (i.e., it is parallelizable)
- CBC and CFB decryption are also parallelizable (random access)
- A corrupted *iv* in OFB and CTR makes all blocks undecryptable
- Only ECB and CBC require padding of the last incomplete message block

▶ CBC...

▶ CFB...

▶ OFB...

▶ CTR...

Plaintext Padding

If the last message block is not complete, a bit string is appended such that:

- It has the minimum possible length.
- It has to not introduce any ambiguity in decryption.

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Example:

- Append a string: “1” followed by zero or more “0”.
- The empty string is not a valid padding. **A last complete block also needs to be padded!**
- In decryption, the last “1” and all trailing zeros (if any) are discarded.

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- Use hierarchical encryption: encrypt some keys under a common dedicated key.
- Can incur in **circularity**: plaintext depending on the key!
- Use a **Key Derivation Function** applied to a passphrase and a (public) nonce.

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Symmetric Key Encryption

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