# Block Ciphers

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# Outline



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## Definition

*A mapping $f_{\{0,1\}^k} : \{0,1\}^n \rightarrow \{0,1\}^n$ is called a **block cipher** with block size $n$ bits and key size $k$ bits, if the mapping $f_K(\cdot)$ is a bijection for each $K \in \{0,1\}^k$, i.e., if $f_K^{-1}(\cdot)$ exists with $f_K^{-1}(f_K(x)) = x$ for each $K \in \{0,1\}^k$ & $x \in \{0,1\}^n$.*

# Simple Substitution

## Example

| A | B | C | D | E | F | G | H | ... | Z |
|---|---|---|---|---|---|---|---|---|---|
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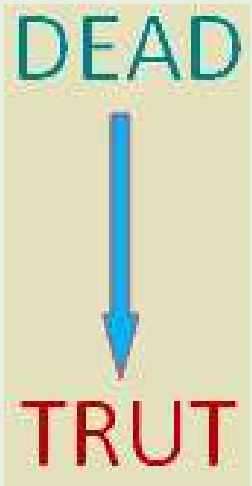

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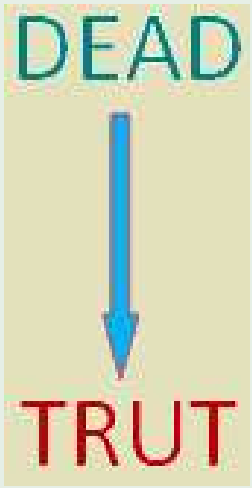


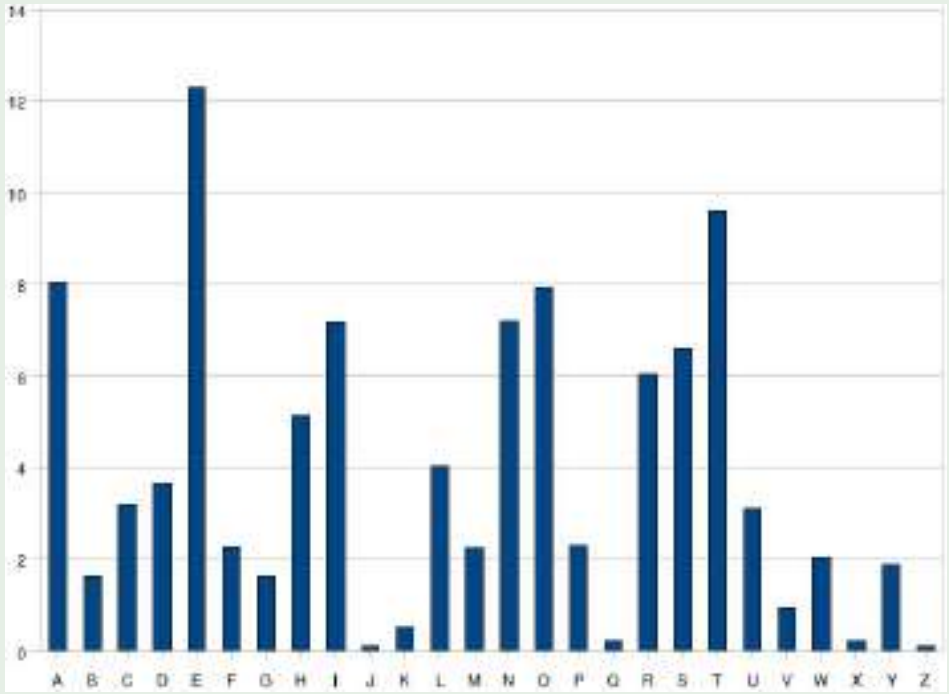

# Permutation on Block of Characters

## Example

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- '*code book*'
- If blocks are large enough, then frequency analysis becomes impossible (infeasible).

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- Introduce computation rule to compute table elements:

$$T[X] = f_{key}(X)$$

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  - Secure
  - Efficient

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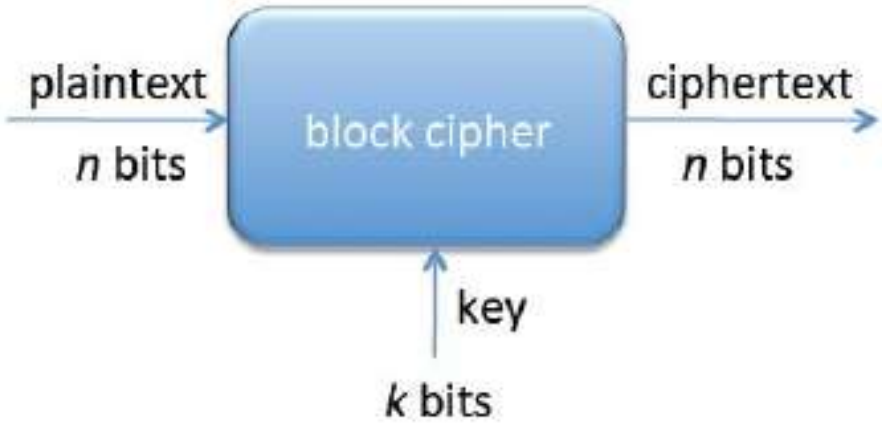

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All models are wrong; the practical question is how wrong do they have to be to not be useful – George E. P. Box

# Attack Models

## Black-Box Model:

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- **Ciphertext-only Attack (COA):** the adversary knows nothing but a number of ciphertexts polynomial in the input size.
- **Known Plaintext Attack (KPA):** the adversary has access to a polynomial number of plaintext ciphertext pairs.
- **Chosen Ciphertext Attack (CCA/CCA1 :** the adversary may select a polynomial number of ciphertexts for which to see the plaintext.
- **Chosen Plaintext Attack (CPA/CPA1):** Some attacks only succeed when the plaintexts have a specific form. In order to mount such attacks, Eve must find a way to influence the encrypted plaintexts.
- **Adaptive Chosen Plaintext Attack (ACPA/CPA2):** the adversary submits plaintexts based on previously obtained ciphertexts.
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- In this model, the attacker has access to a cipher's implementation.
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- Side-channel attacks are a family of attacks within gray-box model.

# Attack Models

## White-Box Model:

- In this model, cryptography is deployed in applications that are executed on open devices.
- Attacker has full access to the execution platform.
- Internal details of implementations are completely and alterable at will.
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- Software implementations that resist such white-box attacks are denoted **white-box implementations.**

# Computational vs Information-Theoretic Security

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**Definition**

*A scheme is $(t, \epsilon)$-secure if any adversary running for time at most $t$, succeeds in breaking the scheme with probability at most $\epsilon$.*

# Security Goals

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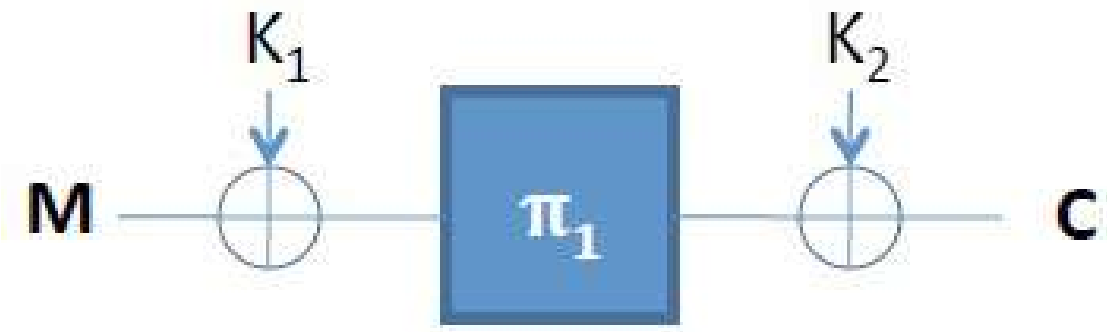
- **Indistinguishability (IND)** Ciphertexts should be indistinguishable from random strings.

- **Nonmalleability (NM)** Given a ciphertext $C_1 = \mathbb{E}_K(P_1)$, it should be impossible to create another ciphertext, $C_2$, whose corresponding plaintext, $P_2$, is related to $P_1$ in a meaningful way.

# Even-Mansour



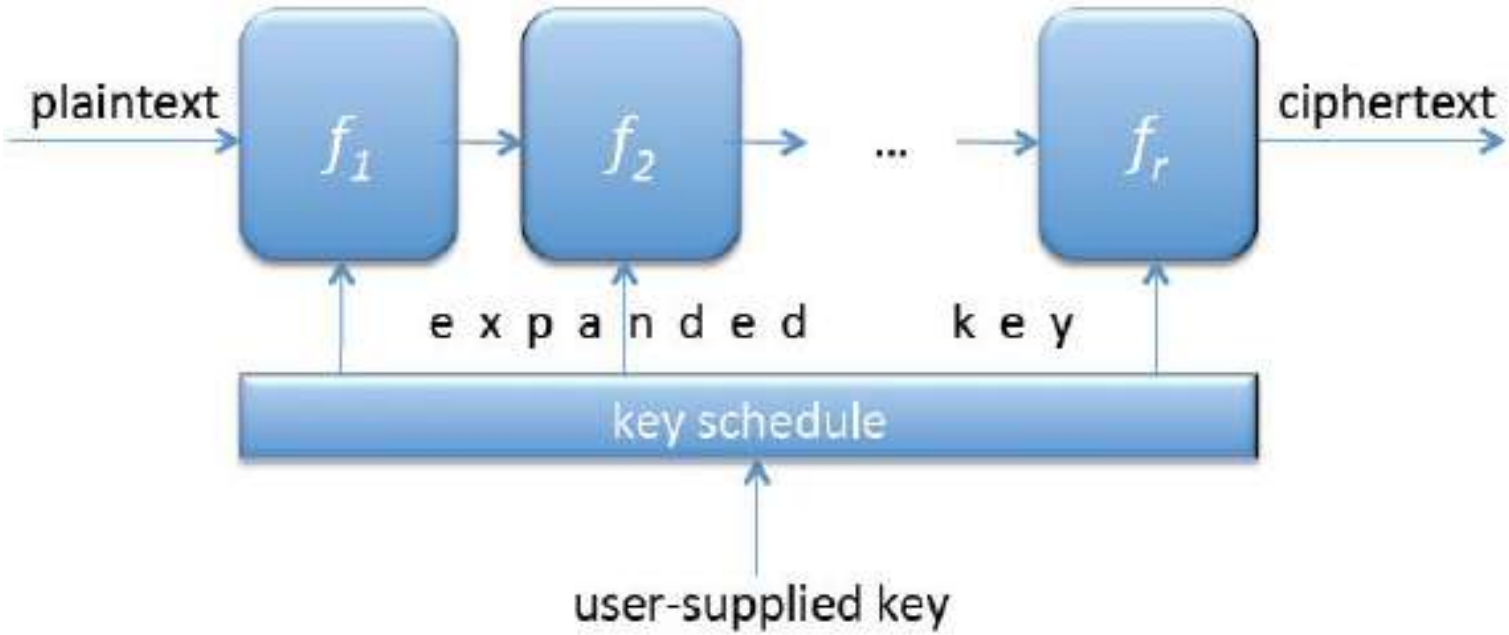

- The Even-Mansour[1] construction is a block cipher.
- Let $n$ be the block-length.
- Fixed public known permutation $\pi_1$, where it is easy to compute $\pi(M)$ and $\pi^{-1}(M)$ for any given input $M \in \{0,1\}^n$
- Indistinguishable for $\leq 2^{n/2}$ queries when $\mathbf{A}$ accesses to $\pi_1$
- Key recovery attack in $2^{n/2}$ by Daemen Asiacrypt'91

[1] S. Even, Y. Mansour, A Construction of a Cipher From a Single Pseudo-random Permutation, Asiacrypt '91, Springer-Verlag 1992.

# Iterative Block Ciphers

- An iterative block cipher consists of $r$ consecutive applications of simpler key-dependent transforms

$$f = f_r \circ f_{r-1} \circ \cdots \circ f_2 \circ f_1$$



# Block Cipher Primitives

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**Claude Elwood Shannon**

C. E. SHANNON,
*Communication Theory of Secrecy Systems*, 1949.

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Both operations by themselves cannot provide security. The idea is to concatenate confusion and diffusion elements to build so called product ciphers.

# Confusion

## Example

Let $\mathbf{x}, \mathbf{y}$ & $\mathbf{k} \in \{0,1\}^8$ and $\mathbf{y} = conf(\mathbf{x}, \mathbf{k})$, where

$$
\begin{aligned}
y_1 &= x_1 \oplus x_2 \oplus x_3 \oplus x_4 \oplus k_1 \oplus k_2 \oplus k_3 \oplus k_4 \\
y_2 &= x_2 \oplus x_3 \oplus x_4 \oplus x_5 \oplus k_2 \oplus k_3 \oplus k_4 \oplus k_5 \\
y_3 &= x_3 \oplus x_4 \oplus x_5 \oplus x_6 \oplus k_3 \oplus k_4 \oplus k_5 \oplus k_6 \\
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y_5 &= x_5 \oplus x_6 \oplus x_7 \oplus x_8 \oplus k_5 \oplus k_6 \oplus k_7 \oplus k_8 \\
y_6 &= x_6 \oplus x_7 \oplus x_8 \oplus x_1 \oplus k_6 \oplus k_7 \oplus k_8 \oplus k_1 \\
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It has bad confusion, as they are linear relations.

# Diffusion

## Example

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It has good diffusion.

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  i. S-box + Permutation
  ii. S-box + MDS matrix
  iii. ARX (Mod Addition + Rotation & Xoring)

# Comparison Among Feistel Networks, SPN and ARX

| | Confusion | Diffusion |
|---|---|---|
| **Feistel** | Nonlinear function $F$ | Branch swapping |
| **SPN** | S-box | Linear transformation |
| **ARX** | Modular addition | XOR, Bit rotation |

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  - If it is a multiple of 16 bytes, add 16 bytes 10.

# Padding

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | 01 |
| | | | | | | | | | | | | | | 02 | 02 |
| | | | | | | | | | | | | | 03 | 03 | 03 |
| | | | | | | | | | | | | 04 | 04 | 04 | 04 |
| | | | | | | | | | | | 05 | 05 | 05 | 05 | 05 |
| | | | | | | | | | | 06 | 06 | 06 | 06 | 06 | 06 |
| | | | | | | | | | 07 | 07 | 07 | 07 | 07 | 07 | 07 |
| | | | | | | | | 08 | 08 | 08 | 08 | 08 | 08 | 08 | 08 |
| | | | | | | | 09 | 09 | 09 | 09 | 09 | 09 | 09 | 09 | 09 |
| | | | | | | 0A | 0A | 0A | 0A | 0A | 0A | 0A | 0A | 0A | 0A |
| | | | | | 0B | 0B | 0B | 0B | 0B | 0B | 0B | 0B | 0B | 0B | 0B |
| | | | | 0C | 0C | 0C | 0C | 0C | 0C | 0C | 0C | 0C | 0C | 0C | 0C |
| | | | 0D | 0D | 0D | 0D | 0D | 0D | 0D | 0D | 0D | 0D | 0D | 0D | 0D |
| | | 0E | 0E | 0E | 0E | 0E | 0E | 0E | 0E | 0E | 0E | 0E | 0E | 0E | 0E |
| | 0F | 0F | 0F | 0F | 0F | 0F | 0F | 0F | 0F | 0F | 0F | 0F | 0F | 0F | 0F |
| 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |

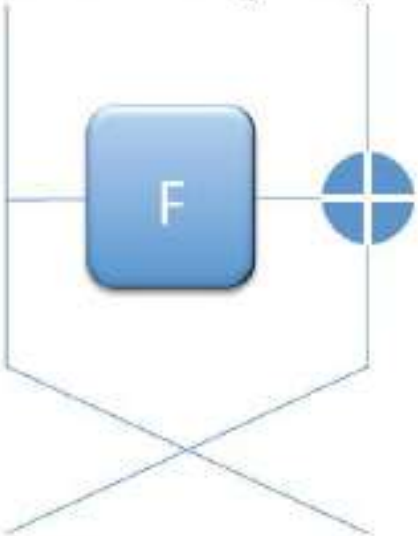
**Horst Feistel**

# Outline



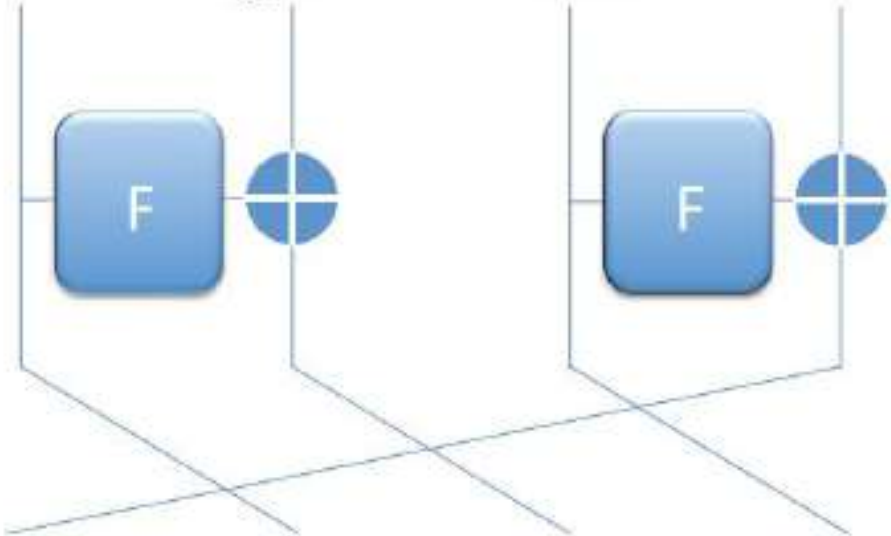
# Balanced and Generalized Feistels

Balanced Feistel Network (BFN)



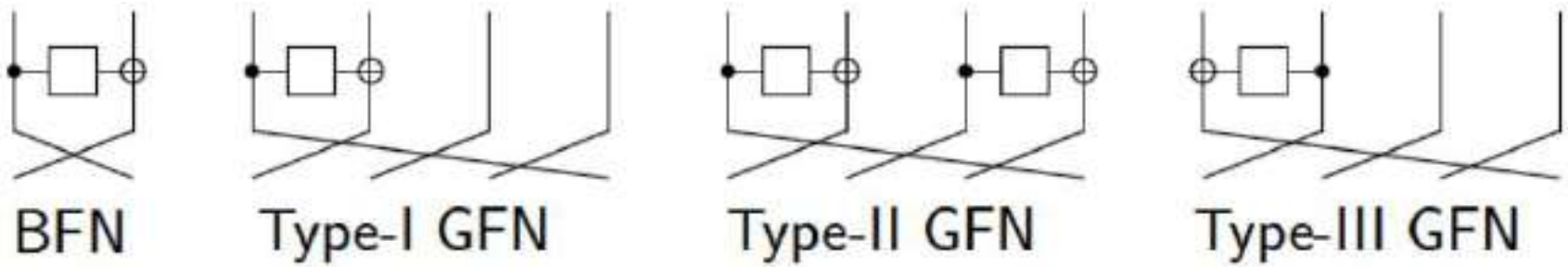

Used in DES, Camellia, E2, Blowfish, Twofish, CAST128, KASUMI, MISTY, ...

Generalized Feistel Network (GFN) – type-II 4-line GFN

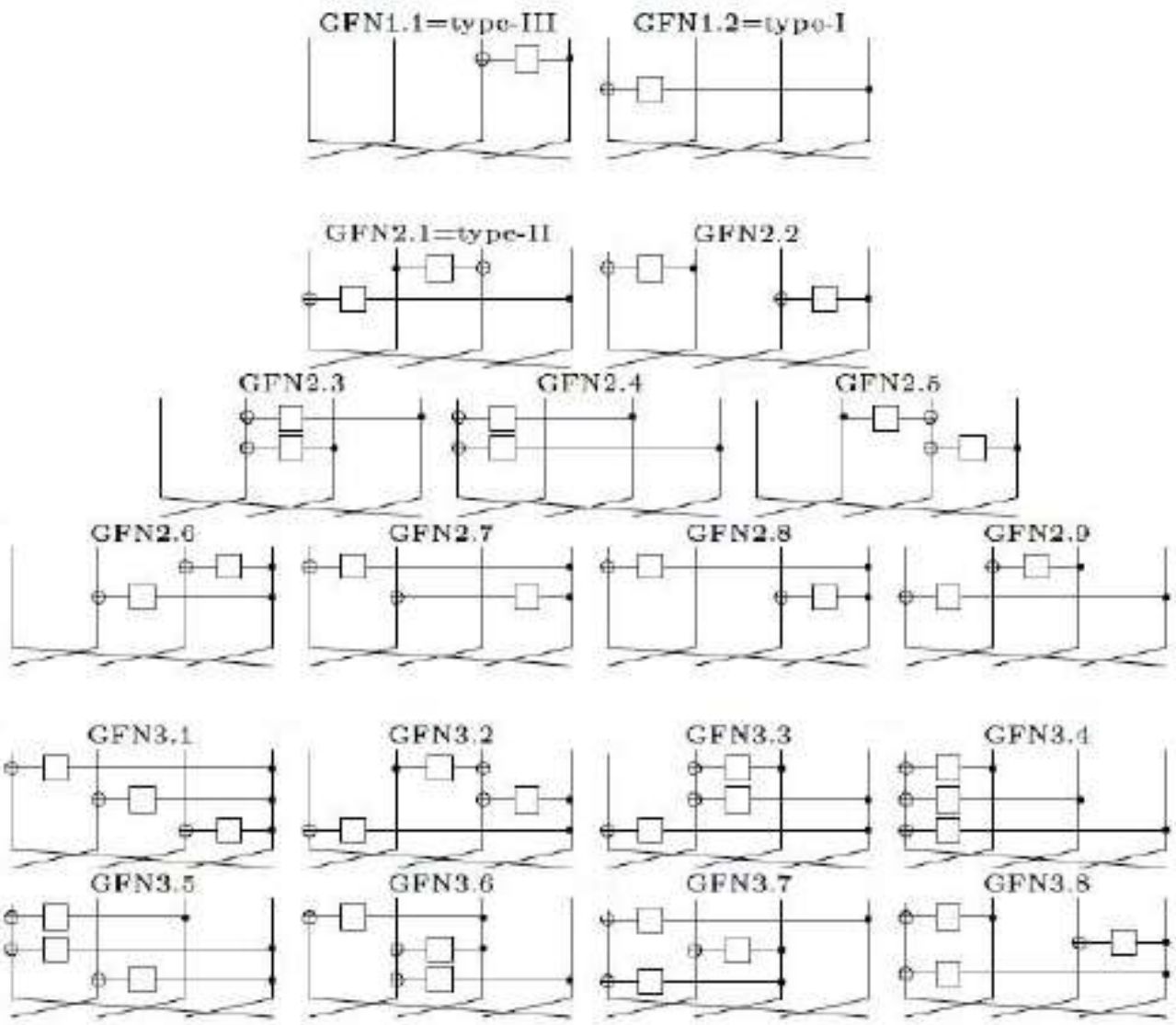



Used in CLEFIA, SHAvite-3, RC6,...

# Balanced and Generalized Feistels



# Classification of 4-line GFNs



# Introduction

| | | |
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| May 1973 | : | NBS issued a call for proposals for a block cipher suitable for federal use |
| Aug 1974 | : | a second call was made |
| | : | DEA (modified Lucifer) was submitted by IBM. |
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| | | |
|---|---|---|
| 2004 | : | NIST withdrew DES |
| 2009 | : | NIST withdrew 2-key TDES |
| until 2030 | : | 3-key TDES |

# Introduction

**DES Development was controversial**

# Introduction

## DES Development was controversial

- NSA secretly involved
- design process was secret
- key length reduced from 128-bit to 56-bit
- two $4 \times 4$ S-boxes to eight $6 \times 4$ S-boxes
- subtle changes to Lucifer algorithm

# DES Numerology

**DES is a Feistel cipher with**

- 64-bit block length
- 56-bit key length
- 16 rounds
- 48-bit of key used in each round

# Encryption Algorithm

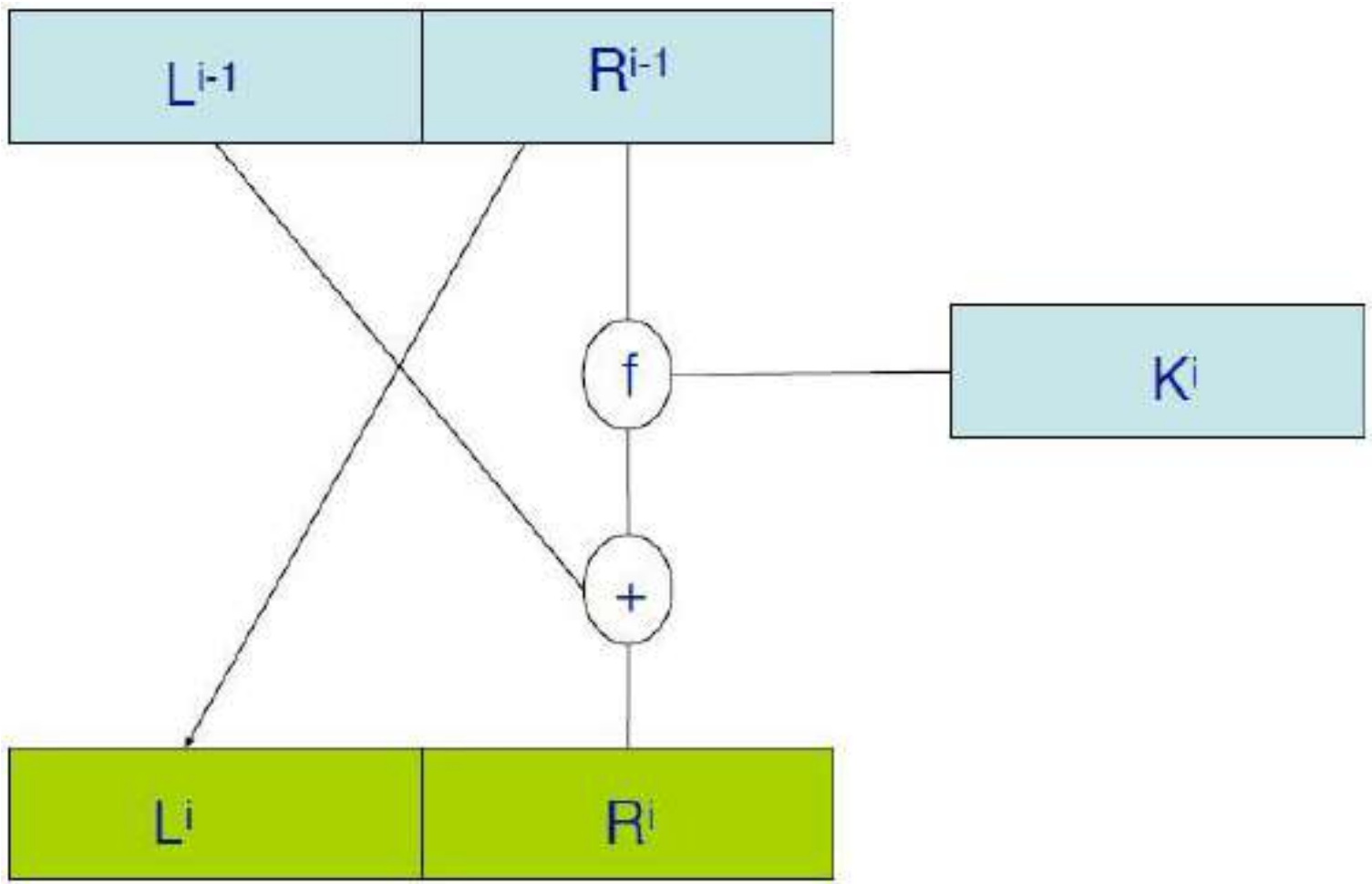
## Initial Permutation IP and Inverse Permutation $IP^{-1}$

| IP | | | | | | | |
|---|---|---|---|---|---|---|---|
| 58 | 50 | 42 | 34 | 26 | 18 | 10 | 2 |
| 60 | 52 | 44 | 36 | 28 | 20 | 12 | 4 |
| 62 | 54 | 46 | 38 | 30 | 22 | 14 | 6 |
| 64 | 56 | 48 | 40 | 32 | 24 | 16 | 8 |
| 57 | 49 | 41 | 33 | 25 | 17 | 9 | 1 |
| 59 | 51 | 43 | 35 | 27 | 19 | 11 | 3 |
| 61 | 53 | 45 | 37 | 29 | 21 | 13 | 5 |
| 63 | 55 | 47 | 39 | 31 | 23 | 15 | 7 |

| $IP^{-1}$ | | | | | | | |
|---|---|---|---|---|---|---|---|
| 40 | 8 | 48 | 16 | 56 | 24 | 64 | 32 |
| 39 | 7 | 47 | 15 | 55 | 23 | 63 | 31 |
| 38 | 6 | 46 | 14 | 54 | 22 | 62 | 30 |
| 37 | 5 | 45 | 13 | 53 | 21 | 61 | 29 |
| 36 | 4 | 44 | 12 | 52 | 20 | 60 | 28 |
| 35 | 3 | 43 | 11 | 51 | 19 | 59 | 27 |
| 34 | 2 | 42 | 10 | 50 | 18 | 58 | 26 |
| 33 | 1 | 41 | 9 | 49 | 17 | 57 | 25 |

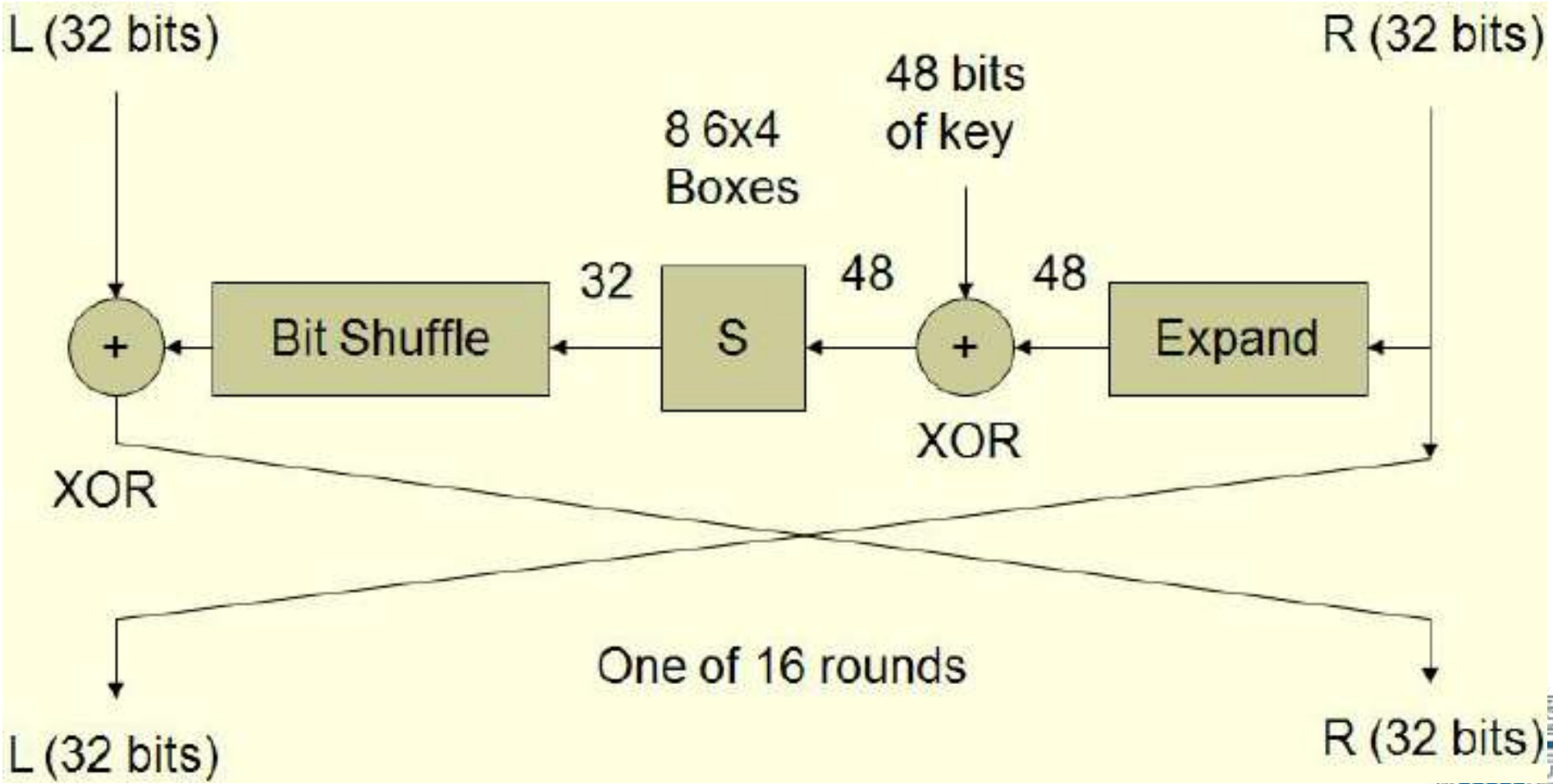
# Encryption Algorithm

## DES Round Function



# Encryption Algorithm

## DES Round Function



# Encryption Algorithm

## Expansion E and Permutation P

| E | | | | | |
|---|---|---|---|---|---|
| 32 | 1 | 2 | 3 | 4 | 5 |
| 4 | 5 | 6 | 7 | 8 | 9 |
| 8 | 9 | 10 | 11 | 12 | 13 |
| 12 | 13 | 14 | 15 | 16 | 17 |
| 16 | 17 | 18 | 19 | 20 | 21 |
| 20 | 21 | 22 | 23 | 24 | 25 |
| 24 | 25 | 26 | 27 | 28 | 29 |
| 28 | 29 | 30 | 31 | 32 | 1 |

| P | | | |
|---|---|---|---|
| 16 | 7 | 20 | 21 |
| 29 | 12 | 28 | 17 |
| 1 | 15 | 23 | 26 |
| 5 | 18 | 31 | 10 |
| 2 | 8 | 24 | 14 |
| 32 | 27 | 3 | 9 |
| 19 | 13 | 30 | 6 |
| 22 | 11 | 4 | 25 |

# Encryption Algorithm

## DES S-boxes

| S1 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | a | b | c | d | e | f |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $p_0$ | e | 4 | d | 1 | 2 | f | b | 8 | 3 | a | 6 | c | 5 | 9 | 0 | 7 |
| $p_1$ | 0 | f | 7 | 4 | e | 2 | d | 1 | a | 6 | c | b | 9 | 5 | 3 | 8 |
| $p_2$ | 4 | 1 | e | 8 | d | 6 | 2 | b | f | c | 9 | 7 | 3 | a | 5 | 0 |
| $p_3$ | f | c | 8 | 2 | 4 | 9 | 1 | 7 | 5 | b | 3 | e | a | 0 | 6 | d |

| S2 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | a | b | c | d | e | f |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $p_0$ | f | 1 | 8 | e | 6 | b | 3 | 4 | 9 | 7 | 2 | d | c | 0 | 5 | a |
| $p_1$ | 3 | d | 4 | 7 | f | 2 | 8 | e | c | 0 | 1 | a | 6 | 9 | b | 5 |
| $p_2$ | 0 | e | 7 | b | a | 4 | d | 1 | 5 | 8 | c | 6 | 9 | 3 | 2 | f |
| $p_3$ | d | 8 | a | 1 | 3 | f | 4 | 2 | b | 6 | 7 | c | 0 | 5 | e | 9 |

| S3 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | a | b | c | d | e | f |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $p_0$ | a | 0 | 9 | e | 6 | 3 | f | 5 | 1 | d | c | 7 | b | 4 | 2 | 8 |
| $p_1$ | d | 7 | 0 | 9 | 3 | 4 | 6 | a | 2 | 8 | 5 | e | c | b | f | 1 |
| $p_2$ | d | 6 | 4 | 9 | 8 | f | 3 | 0 | b | 1 | 2 | c | 5 | a | e | 7 |
| $p_3$ | 1 | a | d | 0 | 6 | 9 | 8 | 7 | 4 | f | e | 3 | b | 5 | 2 | c |

| S4 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | a | b | c | d | e | f |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $p_0$ | 7 | d | e | 3 | 0 | 6 | 9 | a | 1 | 2 | 8 | 5 | b | c | 4 | f |
| $p_1$ | d | 8 | b | 5 | 6 | f | 0 | 3 | 4 | 7 | 2 | c | 1 | a | e | 9 |
| $p_2$ | a | 6 | 9 | 0 | c | b | 7 | d | f | 1 | 3 | e | 5 | 2 | 8 | 4 |
| $p_3$ | 3 | f | 0 | 6 | a | 1 | d | 8 | 9 | 4 | 5 | b | c | 7 | 2 | e |

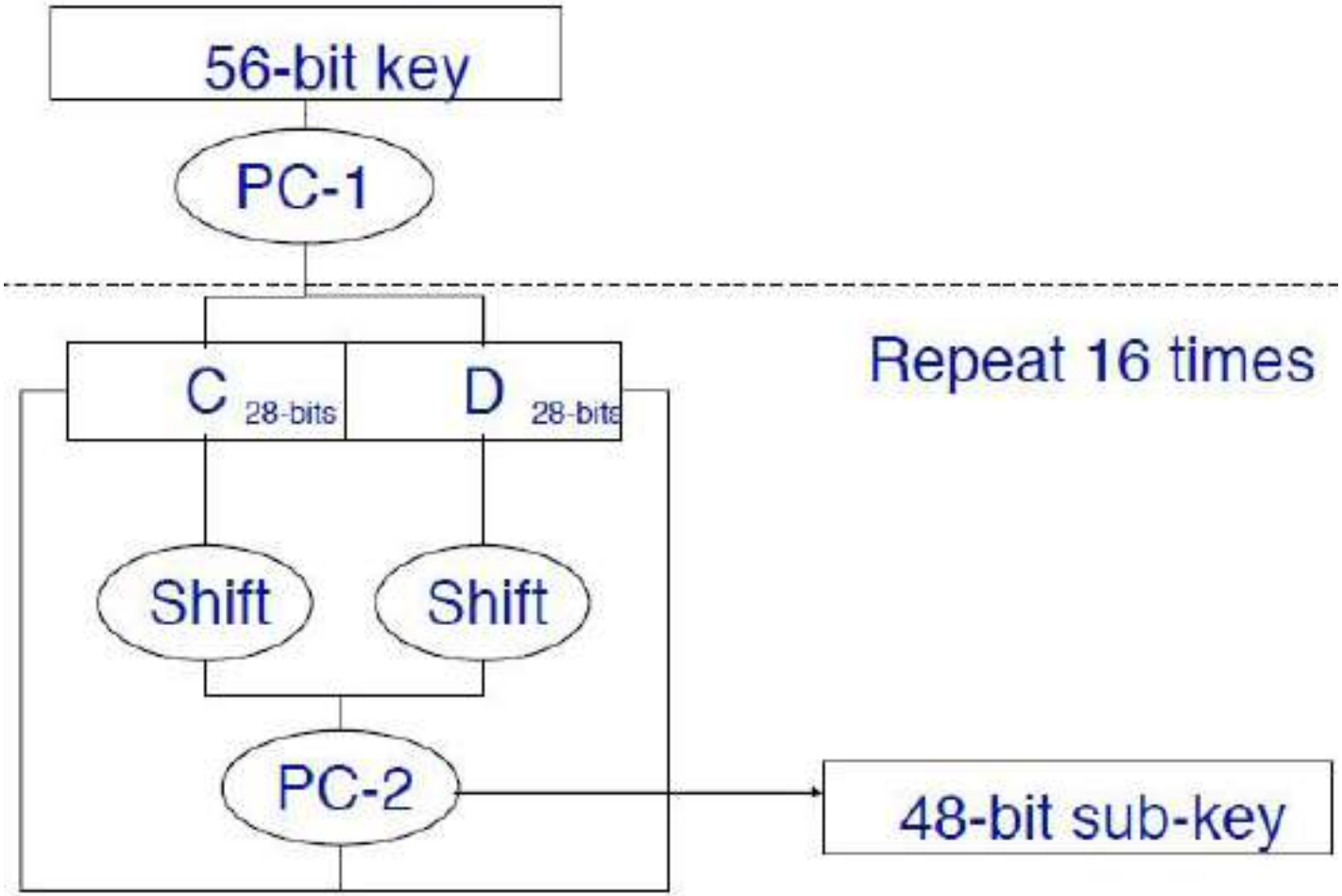
| S5 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | a | b | c | d | e | f |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $p_0$ | 2 | c | 4 | 1 | 7 | a | b | 6 | 8 | 5 | 3 | f | d | 0 | e | 9 |
| $p_1$ | e | b | 2 | c | 4 | 7 | d | 1 | 5 | 0 | f | a | 3 | 9 | 8 | 6 |
| $p_2$ | 4 | 2 | 1 | b | a | d | 7 | 8 | f | 9 | c | 5 | 6 | 3 | 0 | e |
| $p_3$ | b | 8 | c | 7 | 1 | e | 2 | d | 6 | f | 0 | 9 | a | 4 | 5 | 3 |

| S6 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | a | b | c | d | e | f |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $p_0$ | c | 1 | a | f | 9 | 2 | 6 | 8 | 0 | d | 3 | 4 | e | 7 | 5 | b |
| $p_1$ | a | f | 4 | 2 | 7 | c | 9 | 5 | 6 | 1 | d | e | 0 | b | 3 | 8 |
| $p_2$ | 9 | e | f | 5 | 2 | 8 | c | 3 | 7 | 0 | 4 | a | 1 | d | b | 6 |
| $p_3$ | 4 | 3 | 2 | c | 9 | 5 | f | a | b | e | 1 | 7 | 6 | 0 | 8 | d |

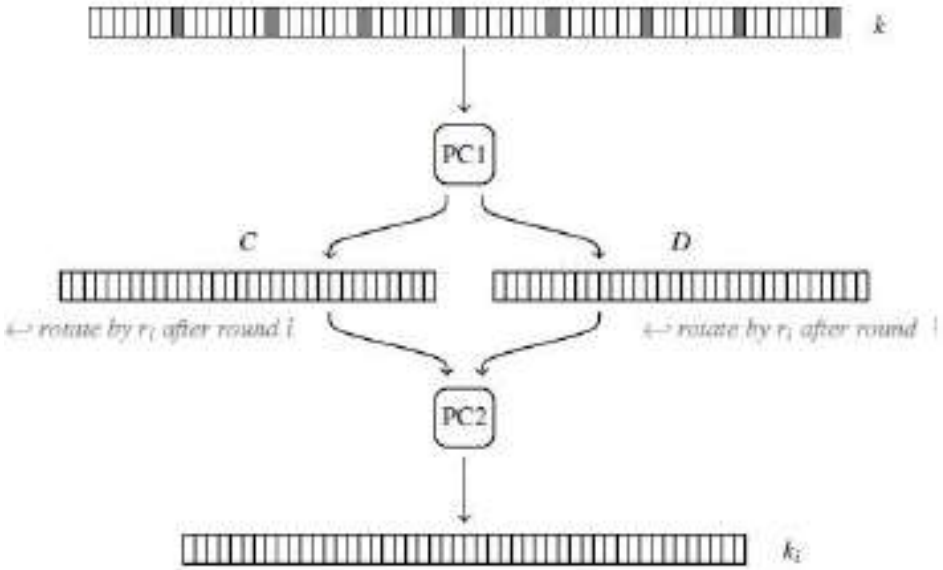
| S7 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | a | b | c | d | e | f |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $p_0$ | 4 | b | 2 | e | f | 0 | 8 | d | 3 | c | 9 | 7 | 5 | a | 6 | 1 |
| $p_1$ | d | 0 | b | 7 | 4 | 9 | 1 | a | e | 3 | 5 | c | 2 | f | 8 | 6 |
| $p_2$ | 1 | 4 | b | d | c | 3 | 7 | e | a | f | 6 | 8 | 0 | 5 | 9 | 2 |
| $p_3$ | 6 | b | d | 8 | 1 | 4 | a | 7 | 9 | 5 | 0 | f | e | 2 | 3 | c |

| S8 | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | a | b | c | d | e | f |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $p_0$ | d | 2 | 8 | 4 | 6 | f | b | 1 | a | 9 | 3 | e | 5 | 0 | c | 7 |
| $p_1$ | 1 | f | d | 8 | a | 3 | 7 | 4 | c | 5 | 6 | b | 0 | e | 9 | 2 |
| $p_2$ | 7 | b | 4 | 1 | 9 | c | e | 2 | 0 | 6 | a | d | f | 3 | 5 | 8 |
| $p_3$ | 2 | 1 | e | 7 | 4 | a | 8 | d | f | c | 9 | 0 | 3 | 5 | 6 | b |

# DES Key Schedule



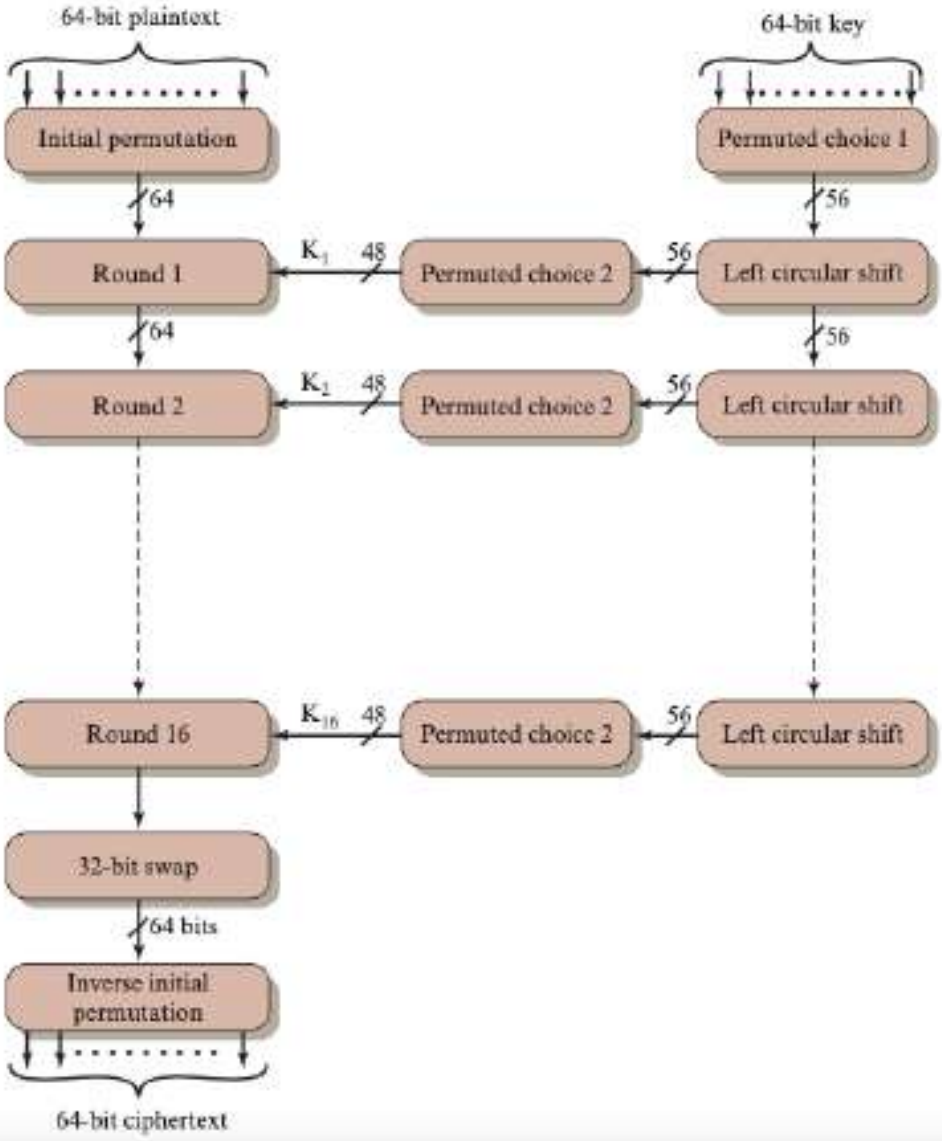
# DES Key Schedule



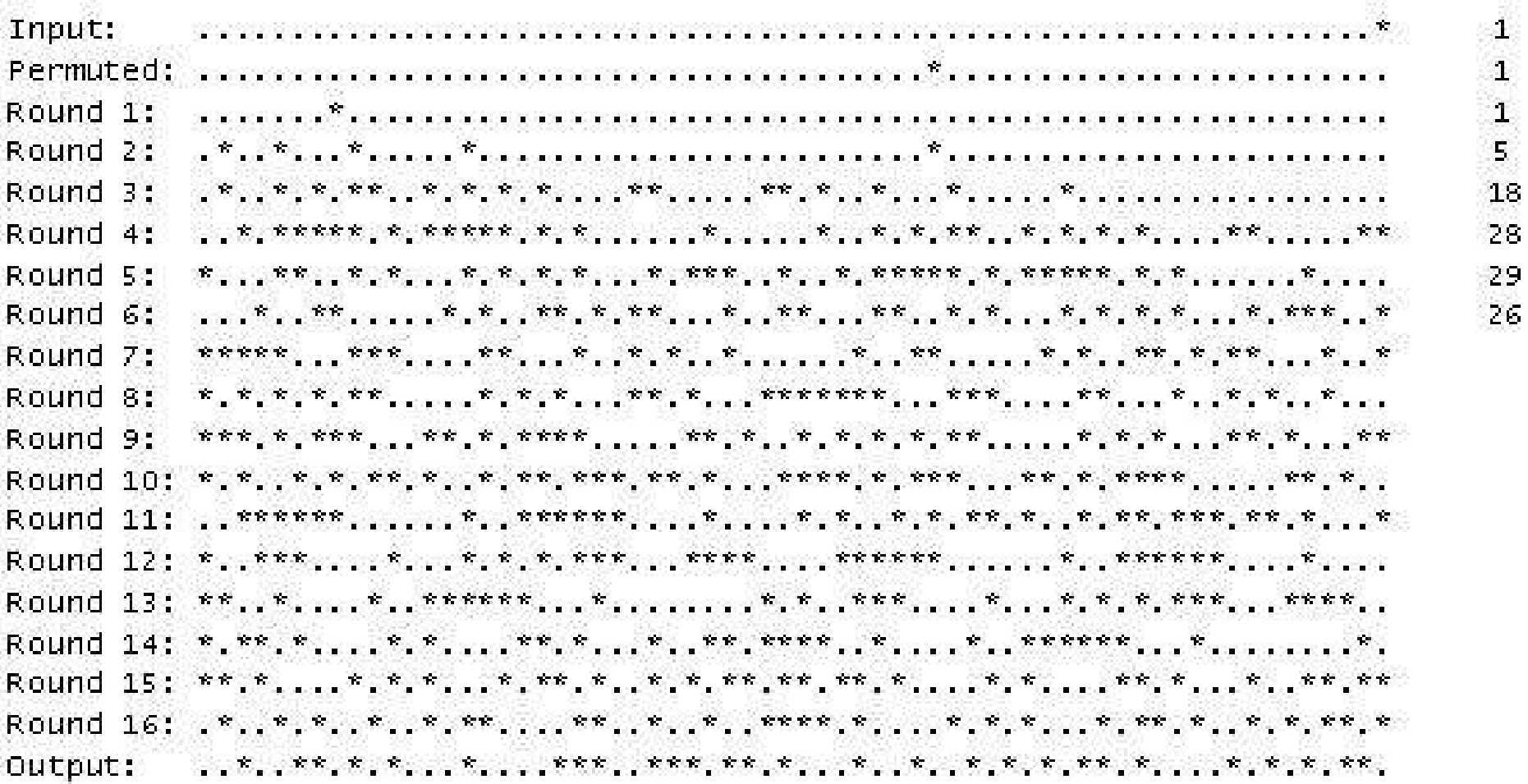

| PC1 | | | | | | | PC2 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 57 | 49 | 41 | 33 | 25 | 17 | 9 | 14 | 17 | 11 | 24 | 1 | 5 | |
| 1 | 58 | 50 | 42 | 34 | 26 | 18 | 3 | 28 | 15 | 6 | 21 | 10 | |
| 10 | 2 | 59 | 51 | 43 | 35 | 27 | 23 | 19 | 12 | 4 | 26 | 8 | |
| 19 | 11 | 3 | 60 | 52 | 44 | 36 | 16 | 7 | 27 | 20 | 13 | 2 | |
| 63 | 55 | 47 | 39 | 31 | 23 | 15 | 41 | 52 | 31 | 37 | 47 | 55 | |
| 7 | 62 | 54 | 46 | 38 | 30 | 22 | 30 | 40 | 51 | 45 | 33 | 48 | |
| 14 | 6 | 61 | 53 | 45 | 37 | 29 | 44 | 49 | 39 | 56 | 34 | 53 | |
| 21 | 13 | 5 | 28 | 20 | 12 | 4 | 46 | 42 | 50 | 36 | 29 | 32 | |

| *round* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $r_i$ | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 1 |

# DES Encryption Algorithm



# DES Diffusion



# Design Criteria of The S-boxes

- No S-box is a linear or affine function of the input.
- Changing 1 bit in the input to an S-box results in changing at least 2 output bits.
- The S-boxes were chosen to minimize the difference between the number of 1's and 0's when any single bit is held constant.
- For any S-box $S$, it holds that $S[x]$ and $S[x \oplus 001100]$ differ in at least 2 bits.
- For any S-box $S$, it holds that $S[x] \neq S[x \oplus 11rs00]$ for any binary values $r$ and $s$.
- If 2 different 48-bit inputs to the 8 S-boxes result in equal outputs, then there must be different inputs to at least 3 neighbouring S-boxes.
- For any S-box it holds for any nonzero 6-bit value $\alpha$ and for any 4-bit value $\beta$, that the number of solutions for $x$ to the equation $S[x] \oplus S[x \oplus \alpha] = \beta$ is at most 16.

# Properties of The $P$ Permutation

- The 4 bits output from an S-box are distributed so that they affect 6 different S-boxes in the following round (4 boxes directly and 2 via the expansion mapping).
- If an output bit from S-box $i$ affects one of the 2 middle input bits to S-box $j$ (in the next round), then an output bit from S-box $i$ cannot affect a middle bit of S-box $i$.
- The middle 6 inputs to 2 neighbouring S-boxes (those not shared by any other S-boxes) are constructed from the outputs from 6 different S-boxes in the previous round.
- The middle 10 input bits to 3 neighbouring S-boxes, 4 bits from the 2 outer S-boxes and 6 from the middle S-box (i.e., those not shared by any other S-boxes), are constructed from the outputs from all S-boxes in the previous round.

# Structural Properties

## Complementation Property

$$\overline{DES_k(m)} = DES_{\bar{k}}(\bar{m}).$$

# Structural Properties

## Weak Keys

### Definition

*A DES key $k$ is said to be weak if the following relationship holds*

$$DES_k(DES_k(m)) = m, \quad \forall\ m.$$

4 weak keys of DES

`0101010101010101` `fefefefefefefefe`

`1f1f1f1f1f1f1f1f` `e0e0e0e0e0e0e0e0`

# Structural Properties

## Semi-Weak Keys

### Definition

*A pair of keys $k_1$ & $k_2$ is said to be semi-weak keys if the following relation satisfies*

$$DES_{k_1}(DES_{k_2}(m)) = m, \quad \forall\ m.$$

## 6 pairs of semi-weak keys of DES

| | | |
|---|---|---|
| 01fe01fe01fe01fe<br>fe01fe01fe01fe01 | 1fe01fe01fe01fe0<br>e01fe01fe01fe01f | 01e001e001e001e0<br>e001e001e001e001 |
| 1ffe1ffe1ffe1ffe<br>fe1ffe1ffe1ffe1f | 011f011f011f011f<br>1f011f011f011f01 | e0fee0fee0fee0fe<br>fee0fee0fee0fee0 |

# Weak Permutation

## Definition

*A permutation $F$ is called a weak permutation if given*

$$y_1 = F_k(x_1) \ \ \& \ \ y_2 = F_k(x_2)$$

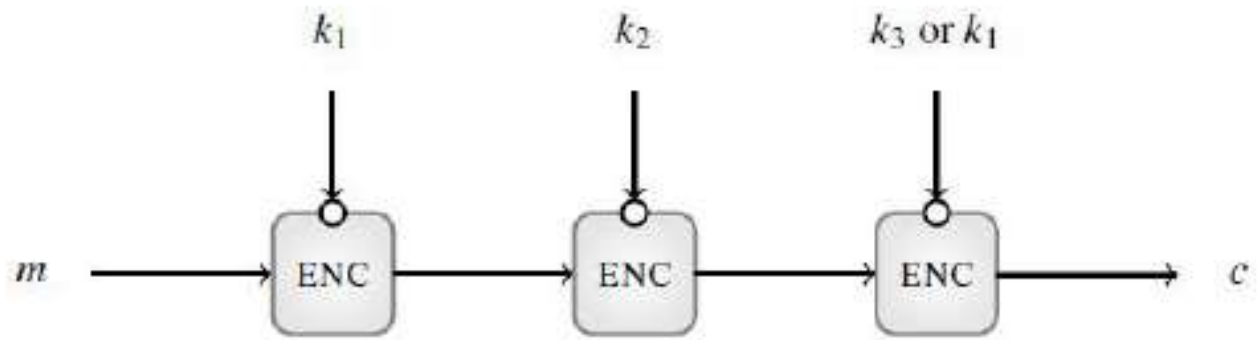
*it is 'easy' to extract the key $k$.*

## Question

*Does 3 rounds of DES form a weak permutation?*

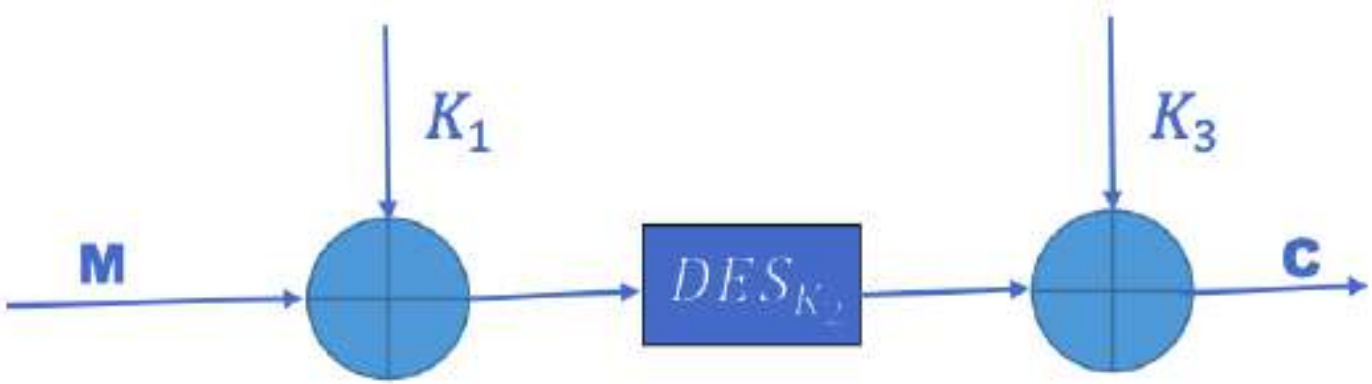
# Common Proposals for Triple Encryption Using a Generic Block Cipher

| | | |
|---|---|---|
| 2-key ENC-DEC-ENC | $EDE_2$ | $c = \text{ENC}_{k_1}(\text{DEC}_{k_2}(\text{ENC}_{k_1}(m)))$ |
| 2-key ENC-ENC-ENC | $EEE_2$ | $c = \text{ENC}_{k_1}(\text{ENC}_{k_2}(\text{ENC}_{k_1}(m)))$ |
| 3-key ENC-DEC-ENC | $EDE_3$ | $c = \text{ENC}_{k_3}(\text{DEC}_{k_2}(\text{ENC}_{k_1}(m)))$ |
| 3-key ENC-ENC-ENC | $EEE_3$ | $c = \text{ENC}_{k_3}(\text{ENC}_{k_2}(\text{ENC}_{k_1}(m)))$ |



# DESX

1. The last algorithm of the DES family is **DESX**
2. This is proposed by Ronald Rivest intended to increase complexity by **applying key whitening**



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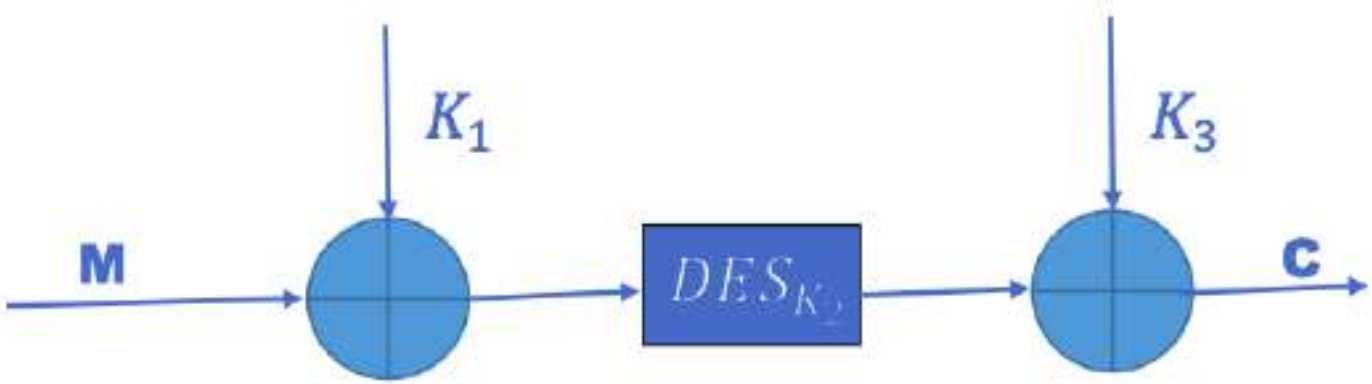


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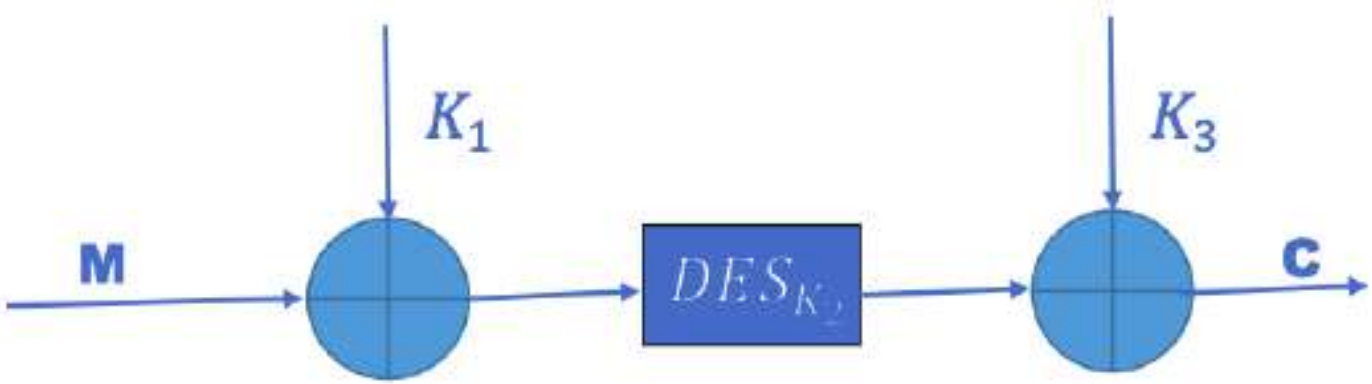


- It requires 184 key bits
- Effective key bits $\approx 118$

# Outline



**Joan Daemen**

**Vincent Rijmen**

# Introduction I

Jan 1997 : NIST announced the initiation.
Sep 1997 : published the final request for candidate nominations.

The functional requirements

- support block length of 128 bits.
- support key length of 128, 192 and 256 bits.
- as secure as T-DES but much more efficient.
- the encryption scheme available on a world wide royalty-free basis.

Aug 1998 : 15 candidates accepted for the $1^{st}$ AES candidate conference.
Mar 1999 : after the $1^{st}$ evaluation NIST selected 5 finalists.

# Introduction II

| | |
|---|---|
| Rijndael | (86) |
| Serpent | (59) |
| RC6 | (31) |
| Mars | (23) |
| Twofish | (13) |

Oct 2000 : NIST announced that Rijndael was "the best overall algorithm for the AES".

Nov 2001 : Dept of Commerce officially declared Rijndael as the AES. (FIPS 197)

May 2002 : AES is effective

# Review of AES

## NIST Requests Public Comments on Several Existing Cryptography Standards and Special Publications

**As part of a periodic review of its cryptography standards and NIST Special Publications, NIST is requesting comments on FIPS 197, SP 800-38A (and Addendum), SP 800-15, SP 800-25, and SP 800-32. Comments are due by June 11, 2021.**

May 10, 2021

NIST is in the process of a periodic review and maintenance of its cryptography standards and NIST Special Publications. A description of the review process is available at the Crypto Publication Review Project page.

Currently, we are reviewing the following publications:

- Federal Information Processing Standard (FIPS) 197, *Advanced Encryption Standard (AES)*, 2001
- NIST Special Publication (SP) 800-38A, *Recommendation for Block Cipher Modes of Operation: Methods and Techniques*, 2001
- NIST SP 800-38A Addendum, *Recommendation for Block Cipher Modes of Operation: Three Variants of Ciphertext Stealing for CBC Mode*, 2010

ORGANIZATIONS

Information Technology Laboratory
Computer Security Division
Cryptographic Technology Group

SIGN UP FOR UPDATES FROM NIST

https://www.nist.gov/news-events/news/2021/05/nist-requests-public-comments-several-existing-cryptography-standards-and

https://csrc.nist.gov/projects/crypto-publication-review-project

# Update of AES

## NIST Updates FIPS 197, Advanced Encryption Standard (AES)

May 09, 2023

Today, NIST has published an update of Federal Information Processing Standards Publication (FIPS) 197, *Advanced Encryption Standard (AES)*. This update makes no technical changes to the algorithm specified in the standard, which was originally published in 2001.

However, this update includes extensive editorial improvements to the original version, including the following:

- The front matter is modernized (e.g., a foreword and abstract are added).
- Terms and symbols are defined more comprehensively and consistently.
- Formatting/typesetting is improved in a variety of ways.
- Unnecessary formalism is removed.
- Diagrams for the three key schedules are included.
- Some references were updated, and additional references are provided.

The changes are documented in greater detail in Appendix D of the updated FIPS. NIST originally proposed to update FIPS 197 in this manner on December 19, 2022. The proposal included the release of a draft of the FIPS update for public comment, as well as a summary of the determination that no technical revisions were necessary. No public comments were received on the proposal nor the draft.

https://csrc.nist.gov/news/2023/nist-updates-fips-197-advanced-encryption-standard

# AES Numerology

**AES is a SPN cipher with**

- 128-bit block length
- 128-, 192- or 256-bit key length
- 10, 12 or 14 rounds

# Mathematical Background

- **Addition (in the field $GF(2^8)$)**

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**Example**

$$57 + 83 = ?$$

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# Mathematical Background

- **Multiplication**
  Multiplication in $GF(2^8)$ corresponds with multiplication of polynomials modulo an irreducible polynomial over $GF(2)$ of degree 8

$$m(x) = x^8 + x^4 + x^3 + x + 1 \text{ or } 11B.$$

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# Mathematical Background

- **Multiplication**
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**Example**

$$57 \times 83 = ?$$

# Mathematical Background

## Choice of Irreducible Polynomial

- AES uses arithmetic in $GF(2^8)$ with the irreducible polynomial $x^8 + x^4 + x^3 + x + 1$.
- There are 30 irreducible polynomials among which 16 are primitive polynomials.
- It is irrelevant whether the irreducible polynomial is primitive or not, due to the isomorphism of all fields of $GF(2^8)$.
- The isomorphism transformation that takes one description of a cipher under an irreducible polynomial to another description with a different irreducible polynomial is linear.
- There is no advantage to select a primitive polynomial over the current polynomial of Rijndael.

# List of 8 Degree Irreducible Polynomials

| | |
|---|---|
| 100011011 | 51 |
| 100011101 | 255 |
| 100101011 | 255 |
| 100101101 | 255 |
| 100111001 | 17 |
| 100111111 | 85 |
| 101001101 | 255 |
| 101011111 | 255 |
| 101100011 | 255 |
| 101100101 | 255 |

# List of 8 Degree Irreducible Polynomials · · ·

| | |
|---|---|
| 101101001 | 255 |
| 101110001 | 255 |
| 101110111 | 85 |
| 101111011 | 85 |
| 110000111 | 255 |
| 110001011 | 85 |
| 110001101 | 255 |
| 110011111 | 51 |
| 110100011 | 85 |
| 110101001 | 255 |

# List of 8 Degree Irreducible Polynomials · · ·

| | |
|---|---|
| 110110001 | 51 |
| 101111101 | 85 |
| 111000011 | 255 |
| 111001111 | 255 |
| 111010111 | 17 |
| 111011101 | 85 |
| 111100111 | 255 |
| 111110011 | 51 |
| 111110101 | 255 |
| 111111001 | 85 |

# Mathematical Background

- **The extended algorithm of Euclid**
  The multiplication defined above is associative and there is an identity element ('$01'$). For any polynomial $b(x)$ of degree at most $7$ over $GF(2)$, the extended algorithm of Euclid can be used to compute polynomials $a(x)$, $c(x)$ such that

$$b(x)a(x) + m(x)c(x) = 1.$$

  It follows that the set of $256$ possible byte values, with the *XOR* as addition and the *multiplication* defined as above has the structure of the finite field $GF(2^8)$.

# Mathematical Background

- **Multiplication by $x$**

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  If we multiply $b(x)$ by the polynomial $x$, we have :

$$b_7x^8 + b_6x^7 + b_5x^6 + b_4x^5 + b_3x^4 + b_2x^3 + b_1x^2 + b_0x$$

- $(x * b(x))$ is obtained by reducing the above result mod $m(x)$.
  i. If $b_7 = 0$, the reduction is identity operation;
  ii. if $b_7 = 1$, $m(x)$ must be subtracted.

**Example**

$$57 \times 13 = 57 \times (01 \oplus 02 \oplus 10)$$

# Mathematical Background

- **Multiplication by $x$**

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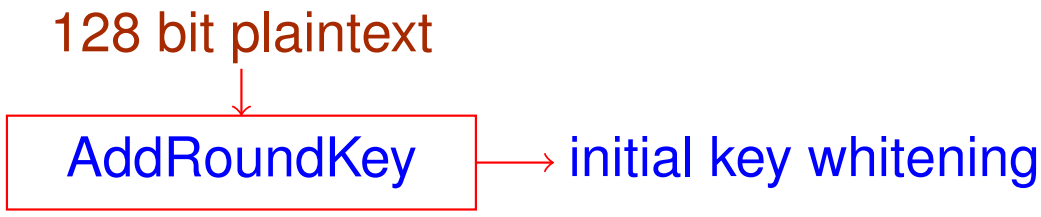
**Example**

$$57 \times 13 = 57 \times (01 \oplus 02 \oplus 10)$$

$$= 57 \oplus AE \oplus 07 = FE.$$

# AES-128-Bit Encryption



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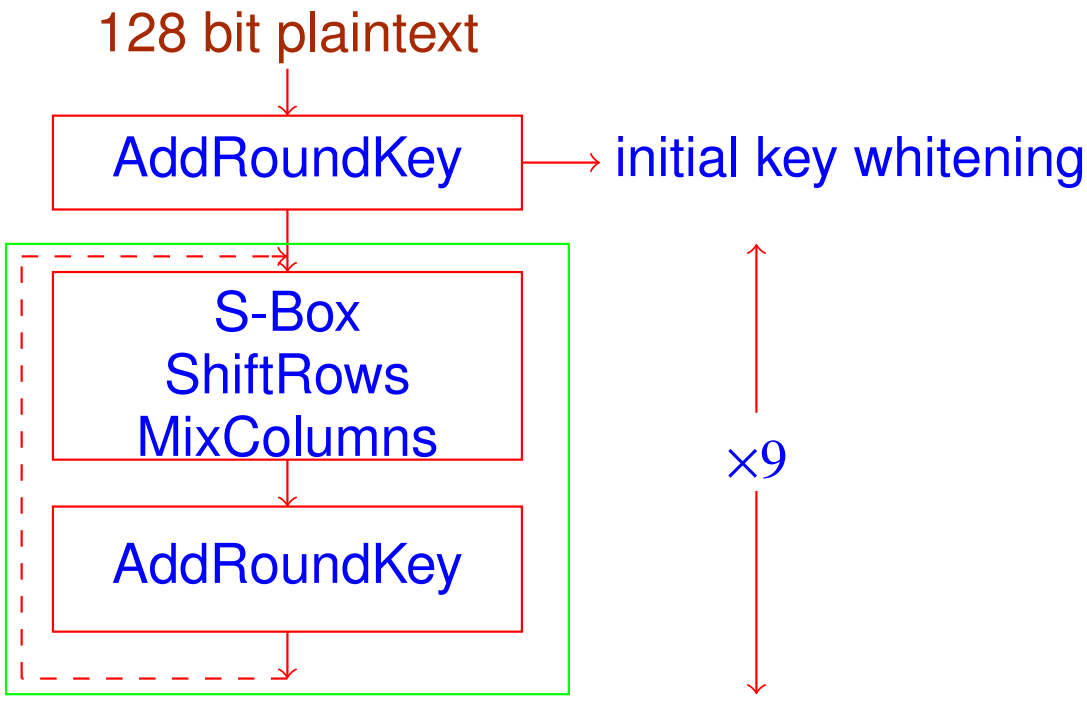
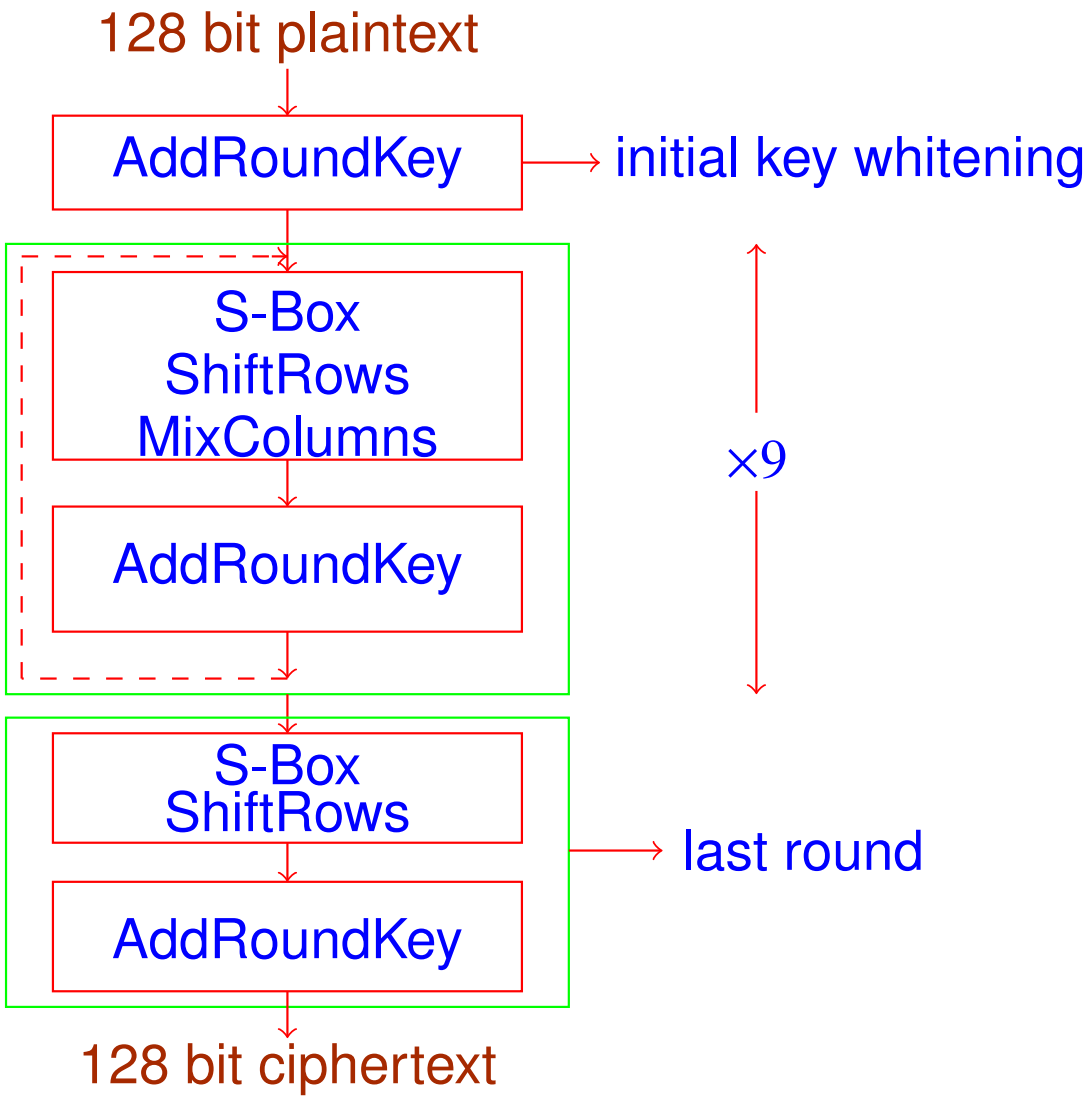
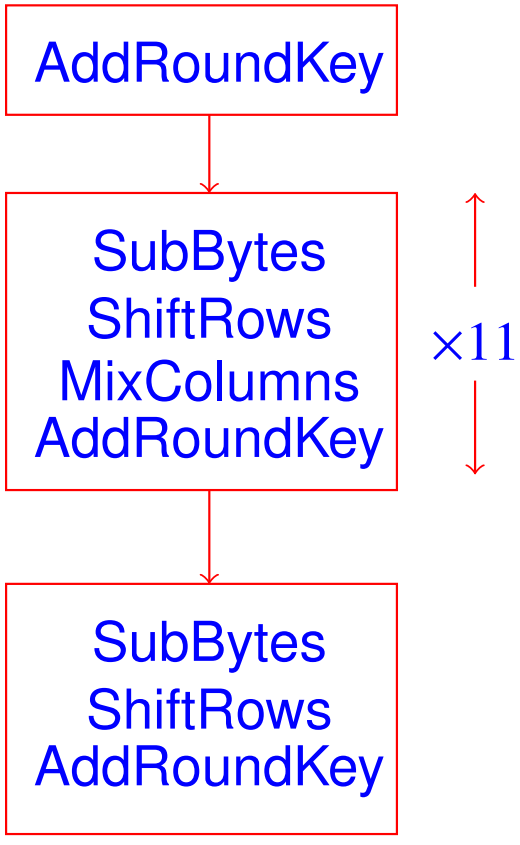


# AES-128-Bit Encryption



# AES-192- & AES-256-Bit Encryption




**AES-192**

C. Cid, S. Murphy & M. Robshaw,
*Algebraic Aspects of the Advanced Encryption Standard*, Springer, 2006.

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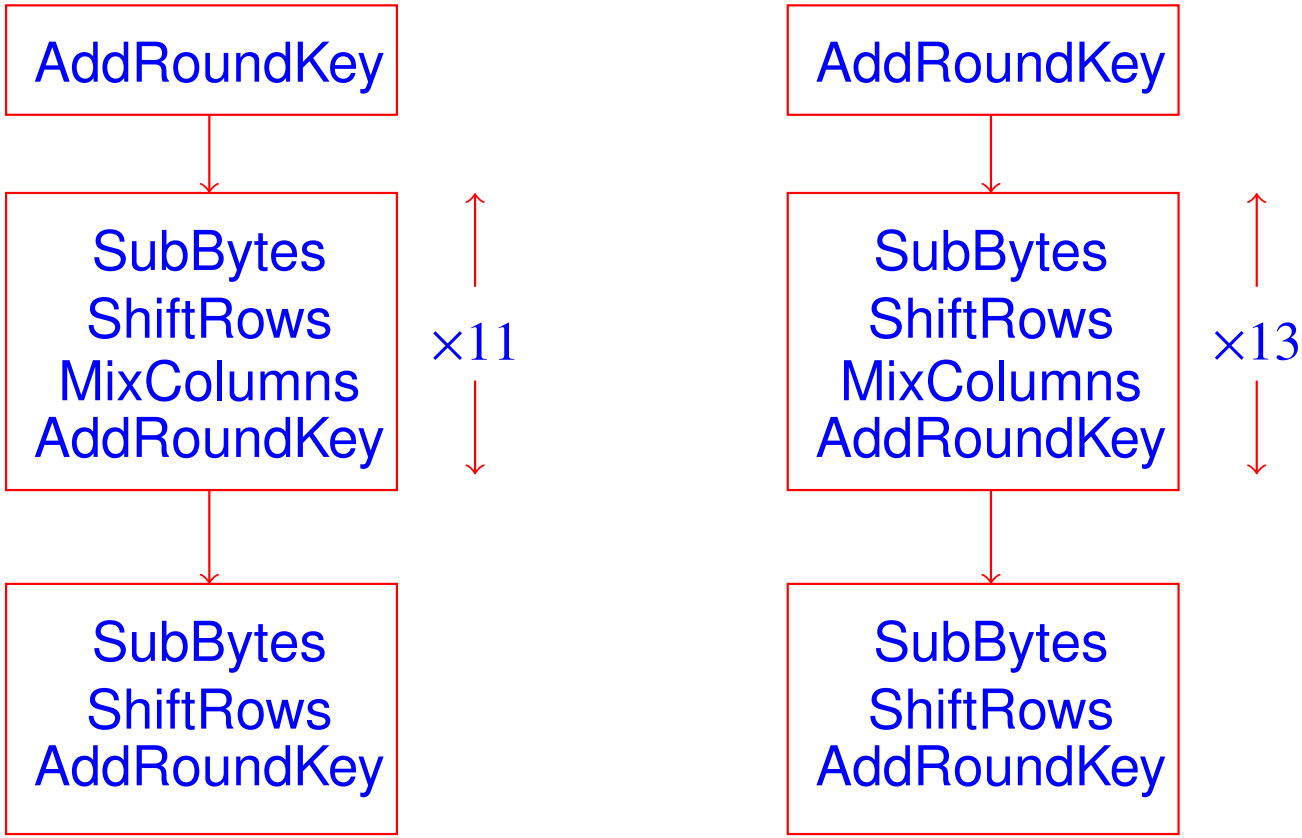


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# AES-128

Plaintext 16 bytes (128 bits)

# AES-128

Plaintext 16 bytes (128 bits)

| | | | |
|---|---|---|---|
| $b_0$ | $b_4$ | $b_8$ | $b_{12}$ |
| $b_1$ | $b_5$ | $b_9$ | $b_{13}$ |
| $b_2$ | $b_6$ | $b_{10}$ | $b_{14}$ |
| $b_3$ | $b_7$ | $b_{11}$ | $b_{15}$ |

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| $b_2$ | $b_6$ | $b_{10}$ | $b_{14}$ |
| $b_3$ | $b_7$ | $b_{11}$ | $b_{15}$ |

$\oplus$

| | | | |
|---|---|---|---|
| $k_0$ | $k_4$ | $k_8$ | $k_{12}$ |
| $k_1$ | $k_5$ | $k_9$ | $k_{13}$ |
| $k_2$ | $k_6$ | $k_{10}$ | $k_{14}$ |
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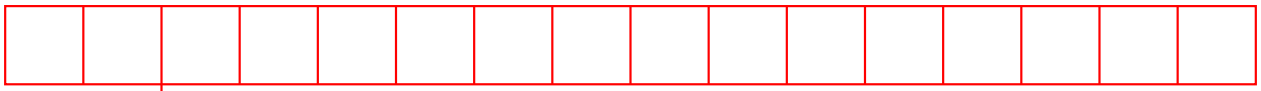

| | | | |
|---|---|---|---|
| $b_0$ | $b_4$ | $b_8$ | $b_{12}$ |
| $b_1$ | $b_5$ | $b_9$ | $b_{13}$ |
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| $b_3$ | $b_7$ | $b_{11}$ | $b_{15}$ |

$\oplus$

| | | | |
|---|---|---|---|
| $k_0$ | $k_4$ | $k_8$ | $k_{12}$ |
| $k_1$ | $k_5$ | $k_9$ | $k_{13}$ |
| $k_2$ | $k_6$ | $k_{10}$ | $k_{14}$ |
| $k_3$ | $k_7$ | $k_{11}$ | $k_{15}$ |

| | | | |
|---|---|---|---|
| $S(b_0 \oplus k_0)$ | $S(b_4 \oplus k_4)$ | $S(b_8 \oplus k_8)$ | $S(b_{12} \oplus k_{12})$ |
| $S(b_1 \oplus k_1)$ | $S(b_5 \oplus k_5)$ | $S(b_9 \oplus k_9)$ | $S(b_{13} \oplus k_{13})$ |
| $S(b_2 \oplus k_2)$ | $S(b_6 \oplus k_6)$ | $S(b_{10} \oplus k_{10})$ | $S(b_{14} \oplus k_{14})$ |
| $S(b_3 \oplus k_3)$ | $S(b_7 \oplus k_7)$ | $S(b_{11} \oplus k_{11})$ | $S(b_{15} \oplus k_{15})$ |

# Design Criteria of AES S-Box

The AES S-Box is the composition of the following 3 functions:

1. $\phi_1 : GF(2^8) \rightarrow GF(2^8)$

$$\begin{array}{lllllll} f & \mapsto & f^{-1} & \text{if} & f & \neq & 0 \\ & \mapsto & 0 & \text{if} & f & = & 0 \end{array}$$

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$$f \mapsto (x^4 + x^3 + x^2 + x + 1).f \mod (x^8 + 1)$$

3. $\phi_2 : GF(2^8) \rightarrow GF(2^8)$

$$f \mapsto (x^6 + x^5 + x + 1) + f$$

**S-box** $= \phi_2 \circ \mathbf{L} \circ \phi_1$.

# AES S-box

| x \ y | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | a | b | c | d | e | f |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 63 | 7c | 77 | 7b | f2 | 6b | 6f | c5 | 30 | 01 | 67 | 2b | fe | d7 | ab | 76 |
| 1 | ca | 82 | c9 | 7d | fa | 59 | 47 | f0 | ad | d4 | a2 | af | 9c | a4 | 72 | c0 |
| 2 | b7 | fd | 93 | 26 | 36 | 3f | f7 | cc | 34 | a5 | e5 | f1 | 71 | d8 | 31 | 15 |
| 3 | 04 | c7 | 23 | c3 | 18 | 96 | 05 | 9a | 07 | 12 | 80 | e2 | eb | 27 | b2 | 75 |
| 4 | 09 | 83 | 2c | 1a | 1b | 6e | 5a | a0 | 52 | 3b | d6 | b3 | 29 | e3 | 2f | 84 |
| 5 | 53 | d1 | 00 | ed | 20 | fc | b1 | 5b | 6a | cb | be | 39 | 4a | 4c | 58 | cf |
| 6 | d0 | ef | aa | fb | 43 | 4d | 33 | 85 | 45 | f9 | 02 | 7f | 50 | 3c | 9f | a8 |
| 7 | 51 | a3 | 40 | 8f | 92 | 9d | 38 | f5 | bc | b6 | da | 21 | 10 | ff | f3 | d2 |
| 8 | cd | 0c | 13 | ec | 5f | 97 | 44 | 17 | c4 | a7 | 7e | 3d | 64 | 5d | 19 | 73 |
| 9 | 60 | 81 | 4f | dc | 22 | 2a | 90 | 88 | 46 | ee | b8 | 14 | de | 5e | 0b | db |
| a | e0 | 32 | 3a | 0a | 49 | 06 | 24 | 5c | c2 | d3 | ac | 62 | 91 | 95 | e4 | 79 |
| b | e7 | c8 | 37 | 6d | 8d | d5 | 4e | a9 | 6c | 56 | f4 | ea | 65 | 7a | ae | 08 |
| c | ba | 78 | 25 | 2e | 1c | a6 | b4 | c6 | e8 | dd | 74 | 1f | 4b | bd | 8b | 8a |
| d | 70 | 3e | b5 | 66 | 48 | 03 | f6 | 0e | 61 | 35 | 57 | b9 | 86 | c1 | 1d | 9e |
| e | e1 | f8 | 98 | 11 | 69 | d9 | 8e | 94 | 9b | 1e | 87 | e9 | ce | 55 | 28 | df |
| f | 8c | a1 | 89 | 0d | bf | e6 | 42 | 68 | 41 | 99 | 2d | 0f | b0 | 54 | bb | 16 |

# AES-128

| | | | |
|---|---|---|---|
| $S(b_0 \oplus k_0)$ | $S(b_4 \oplus k_4)$ | $S(b_8 \oplus k_8)$ | $S(b_{12} \oplus k_{12})$ |
| $S(b_1 \oplus k_1)$ | $S(b_5 \oplus k_5)$ | $S(b_9 \oplus k_9)$ | $S(b_{13} \oplus k_{13})$ |
| $S(b_2 \oplus k_2)$ | $S(b_6 \oplus k_6)$ | $S(b_{10} \oplus k_{10})$ | $S(b_{14} \oplus k_{14})$ |
| $S(b_3 \oplus k_3)$ | $S(b_7 \oplus k_7)$ | $S(b_{11} \oplus k_{11})$ | $S(b_{15} \oplus k_{15})$ |

# AES-128

| | | | |
|---|---|---|---|
| $S(b_0 \oplus k_0)$ | $S(b_4 \oplus k_4)$ | $S(b_8 \oplus k_8)$ | $S(b_{12} \oplus k_{12})$ |
| $S(b_1 \oplus k_1)$ | $S(b_5 \oplus k_5)$ | $S(b_9 \oplus k_9)$ | $S(b_{13} \oplus k_{13})$ |
| $S(b_2 \oplus k_2)$ | $S(b_6 \oplus k_6)$ | $S(b_{10} \oplus k_{10})$ | $S(b_{14} \oplus k_{14})$ |
| $S(b_3 \oplus k_3)$ | $S(b_7 \oplus k_7)$ | $S(b_{11} \oplus k_{11})$ | $S(b_{15} \oplus k_{15})$ |

Apply ShiftRows

| | | | |
|---|---|---|---|
| $S(b_0 \oplus k_0)$ | $S(b_4 \oplus k_4)$ | $S(b_8 \oplus k_8)$ | $S(b_{12} \oplus k_{12})$ |
| $S(b_5 \oplus k_5)$ | $S(b_9 \oplus k_9)$ | $S(b_{13} \oplus k_{13})$ | $S(b_1 \oplus k_1)$ |
| $S(b_{10} \oplus k_{10})$ | $S(b_{14} \oplus k_{14})$ | $S(b_2 \oplus k_2)$ | $S(b_6 \oplus k_6)$ |
| $S(b_{15} \oplus k_{15})$ | $S(b_3 \oplus k_3)$ | $S(b_7 \oplus k_7)$ | $S(b_{11} \oplus k_{11})$ |

# Mix Columns

- In mix columns transformation each column is considered as a polynomial over $GF(2^8)$ of degree 3 and multiplied with a fixed polynomial

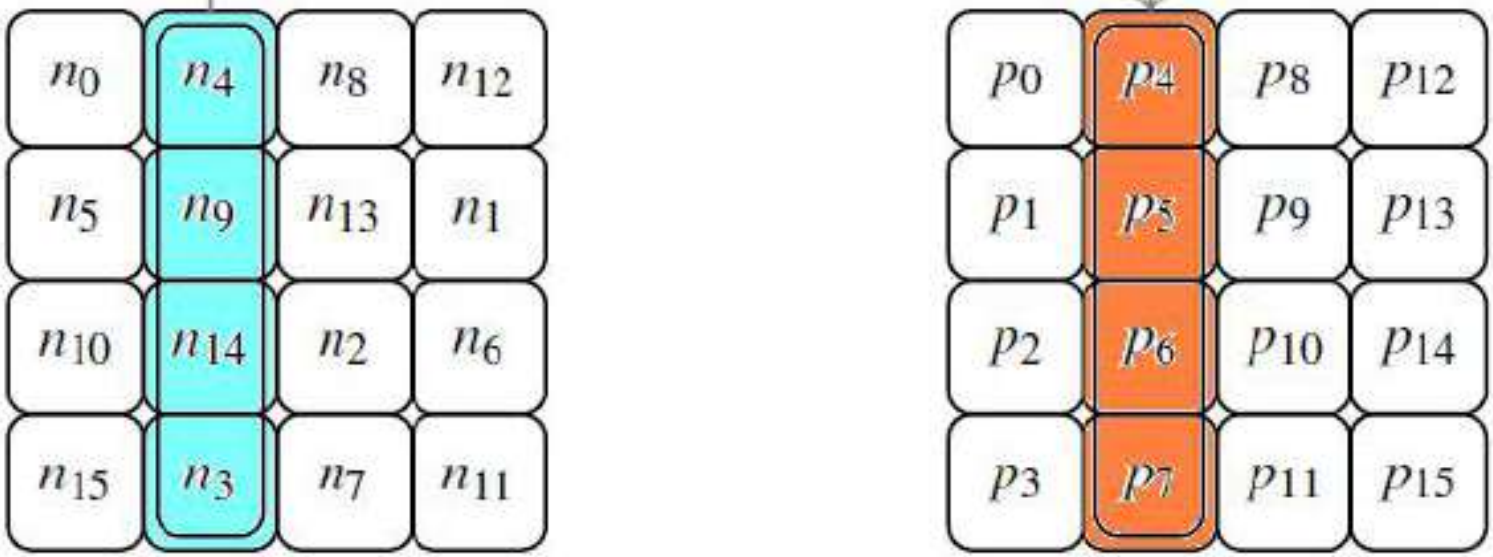
$$03.x^3 + 01.x^2 + 01.x + 02 \ (mod \ x^4 + 1).$$

- Mix columns transformation can also be represented by a matrix $M$ multiplication, where

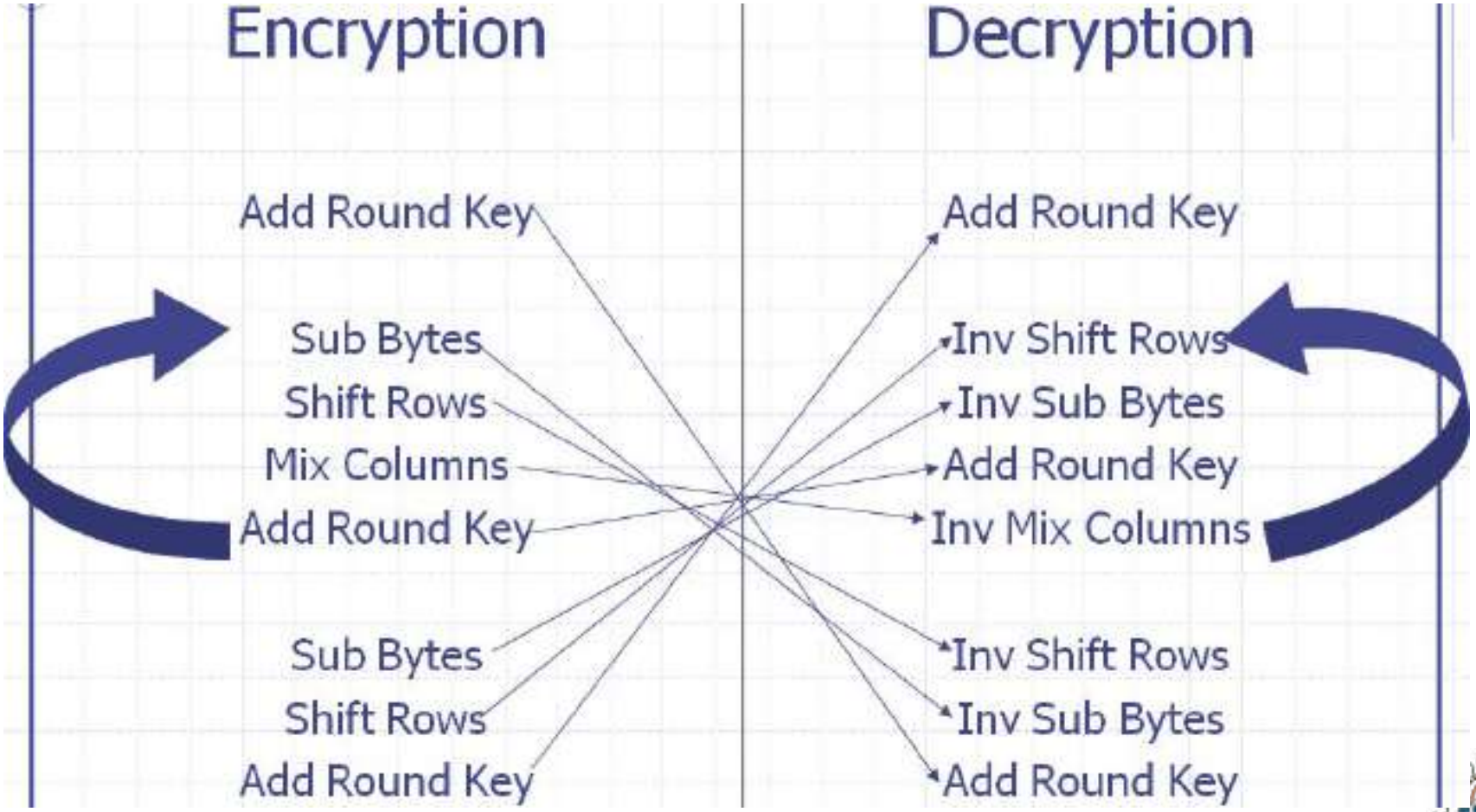
$$M = \begin{pmatrix} 02 & 03 & 01 & 01 \\ 01 & 02 & 03 & 01 \\ 01 & 01 & 02 & 03 \\ 03 & 01 & 01 & 02 \end{pmatrix}$$

# Mix Columns

$$M \cdot \begin{pmatrix} n_4 \\ n_9 \\ n_{14} \\ n_3 \end{pmatrix} = \begin{pmatrix} p_4 \\ p_5 \\ p_6 \\ p_7 \end{pmatrix}$$



# Encryption and Decryption



# Inverse S-box

| $S^{-1}[\cdot]$ | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | a | b | c | d | e | f |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 52 | 09 | 6a | d5 | 30 | 36 | a5 | 38 | bf | 40 | a3 | 9e | 81 | f3 | d7 | fb |
| 1 | 7c | e3 | 39 | 82 | 9b | 2f | ff | 87 | 34 | 8e | 43 | 44 | c4 | de | e9 | cb |
| 2 | 54 | 7b | 94 | 32 | a6 | c2 | 23 | 3d | ee | 4c | 95 | 0b | 42 | fa | c3 | 4e |
| 3 | 08 | 2e | a1 | 66 | 28 | d9 | 24 | b2 | 76 | 5b | a2 | 49 | 6d | 8b | d1 | 25 |
| 4 | 72 | f8 | f6 | 64 | 86 | 68 | 98 | 16 | d4 | a4 | 5c | cc | 5d | 65 | b6 | 92 |
| 5 | 6c | 70 | 48 | 50 | fd | ed | b9 | da | 5e | 15 | 46 | 57 | a7 | 8d | 9d | 84 |
| 6 | 90 | d8 | ab | 00 | 8c | bc | d3 | 0a | f7 | e4 | 58 | 05 | b8 | b3 | 45 | 06 |
| 7 | d0 | 2c | 1e | 8f | ca | 3f | 0f | 02 | c1 | af | bd | 03 | 01 | 13 | 8a | 6b |
| 8 | 3a | 91 | 11 | 41 | 4f | 67 | dc | ea | 97 | f2 | cf | ce | f0 | b4 | e6 | 73 |
| 9 | 96 | ac | 74 | 22 | e7 | ad | 35 | 85 | e2 | f9 | 37 | e8 | 1c | 75 | df | 6e |
| a | 47 | f1 | 1a | 71 | 1d | 29 | c5 | 89 | 6f | b7 | 62 | 0e | aa | 18 | be | 1b |
| b | fc | 56 | 3e | 4b | c6 | d2 | 79 | 20 | 9a | db | c0 | fe | 78 | cd | 5a | f4 |
| c | 1f | dd | a8 | 33 | 88 | 07 | c7 | 31 | b1 | 12 | 10 | 59 | 27 | 80 | ec | 5f |
| d | 60 | 51 | 7f | a9 | 19 | b5 | 4a | 0d | 2d | e5 | 7a | 9f | 93 | c9 | 9c | ef |
| e | a0 | e0 | 3b | 4d | ae | 2a | f5 | b0 | c8 | eb | bb | 3c | 83 | 53 | 99 | 61 |
| f | 17 | 2b | 04 | 7e | ba | 77 | d6 | 26 | e1 | 69 | 14 | 63 | 55 | 21 | 0c | 7d |

# AES Key Schedule

i. It takes a 4-word (128 bits) key and produces a linear array of 44 words (1408 bits).
ii. The key is copied into the $1^{st}$ 4 words of the expanded key.
iii. In the expanded key each added word $W[i]$ depends on $W[i-1]$ and $W[i-4]$.
iv. If $i$ is a multiple of 4 then

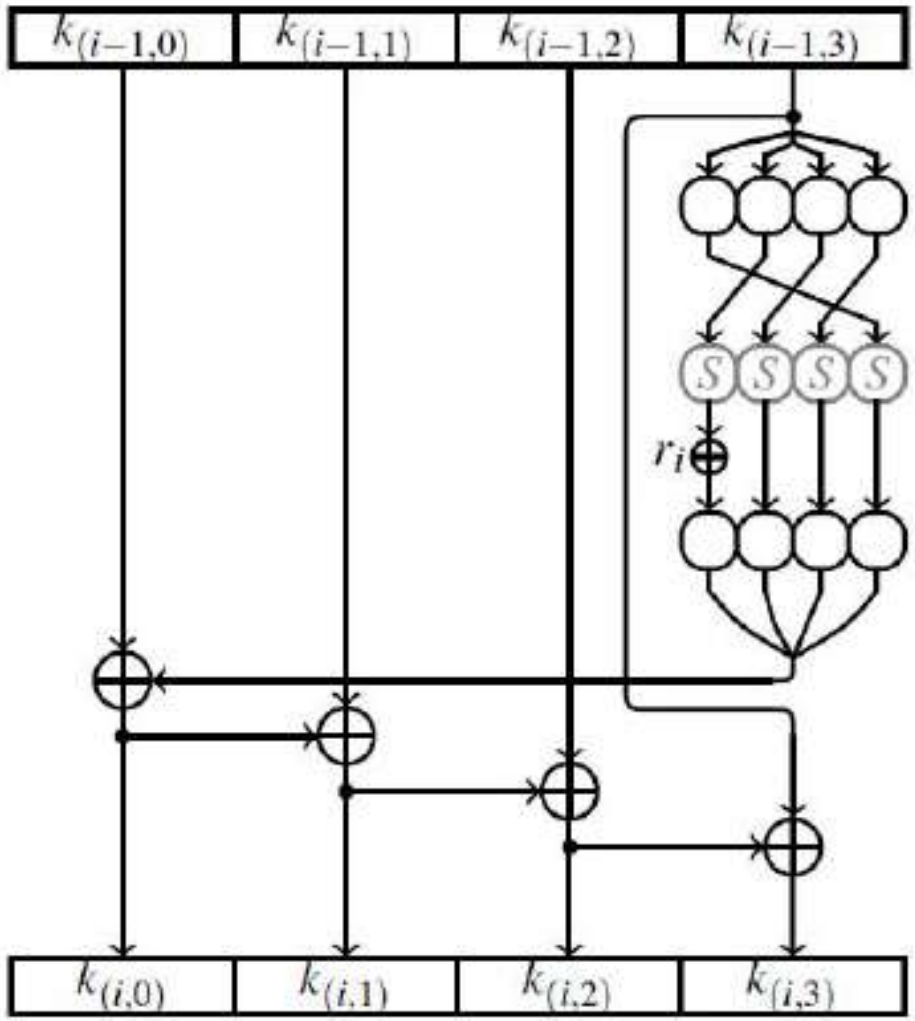
$$W[i] = SubWord(RotWord(W[i-1])) \oplus Rcon[i/4] \oplus W[i-4],$$

where $Rcon[1] = 1$, $Rcon[j] = 2 * Rcon[j-1]$

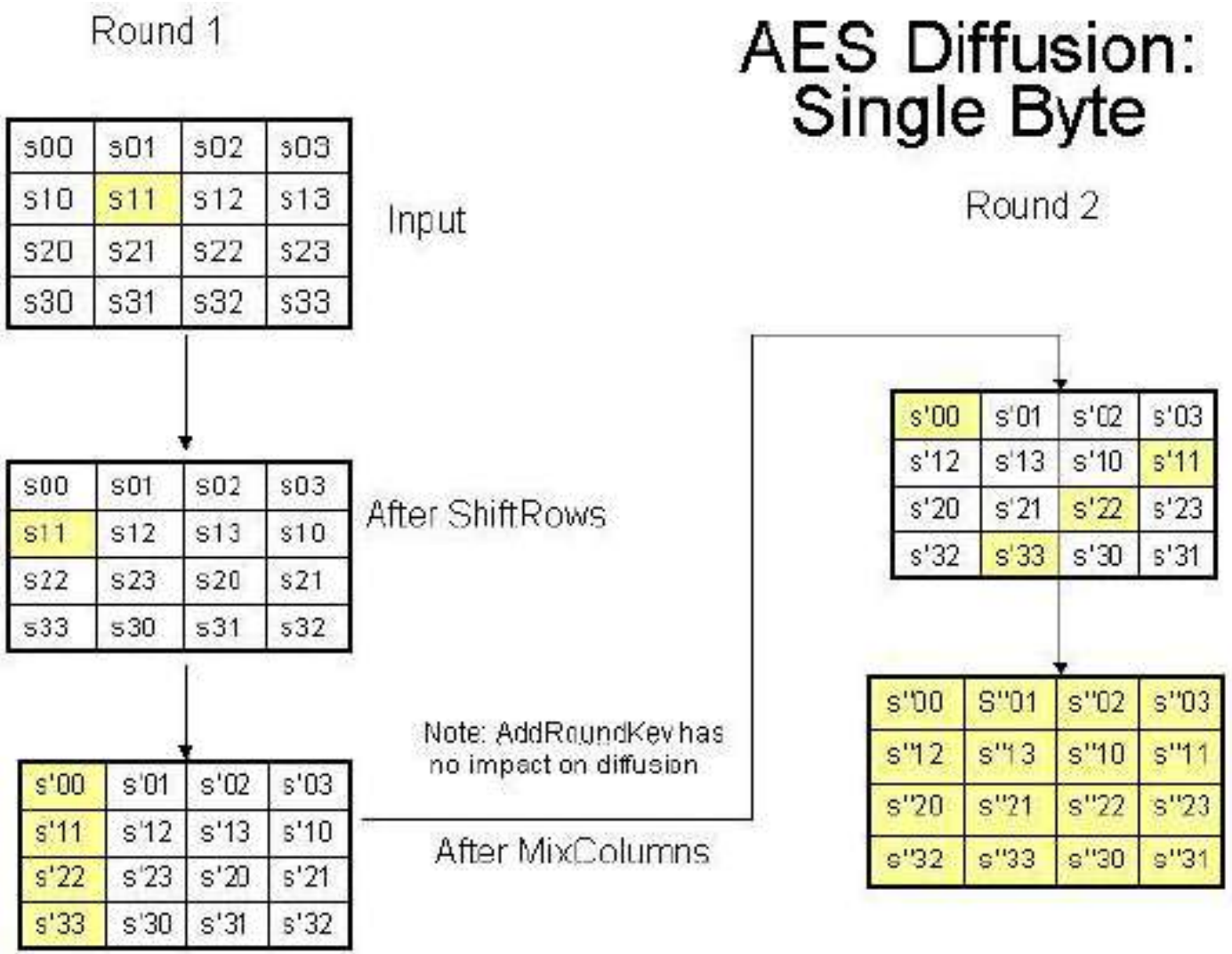
v. Else

$$W[i] = W[i-1] \oplus W[i-4].$$

# Key Schedule



# AES Diffusion



# Design Criteria of S-Box

S-Box is defined over $GF(2^8)$ in the following way

$$y = SBox(x) = \mathbf{A} * x^{-1} + \mathbf{c}, \text{ where}$$

$$\mathbf{A} = \begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 & 0 & 0 & 1 \end{pmatrix} \quad \mathbf{c} = \begin{pmatrix} 0 \\ 1 \\ 1 \\ 0 \\ 0 \\ 0 \\ 1 \\ 1 \end{pmatrix}$$

# Recommended Block Ciphers (ENISA – Nov 2014)

| Primitive | Recommendation | |
|---|---|---|
| | **Legacy** | **Future** |
| AES | ✓ | ✓ |
| Camellia | ✓ | ✓ |

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| DES | × | × |

https://www.enisa.europa.eu/publications/algorithms-key-size-and-parameters-report-2014

# Recommended Block Ciphers

| | |
|---|---|
| Legacy × | Attack exists or security considered not sufficient.<br>Mechanism should be replaced in Fielded products as a matter of urgency. |
| Legacy ✓ | No known weaknesses at present.<br>Better alternatives exist.<br>Lack of security proof or limited key size. |
| Future ✓ | Mechanism is well studied (often with security proof).<br>Expected to remain secure in 10-50 year lifetime. |

# What's Removed in TLS1.3?

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- **Key Exchange and Digital Signature:**
  - Static RSA & Diffie-Hellman (DHE) and DSA
- **Encryption algorithms:**
  - RC4, 3DES, Camellia.
- **Cryptographic Hash algorithms:**
  - MD5, SHA-1, SHA-224
- **Cipher Modes:**
  - AES-CBC (bans all nonAEAD ciphers)

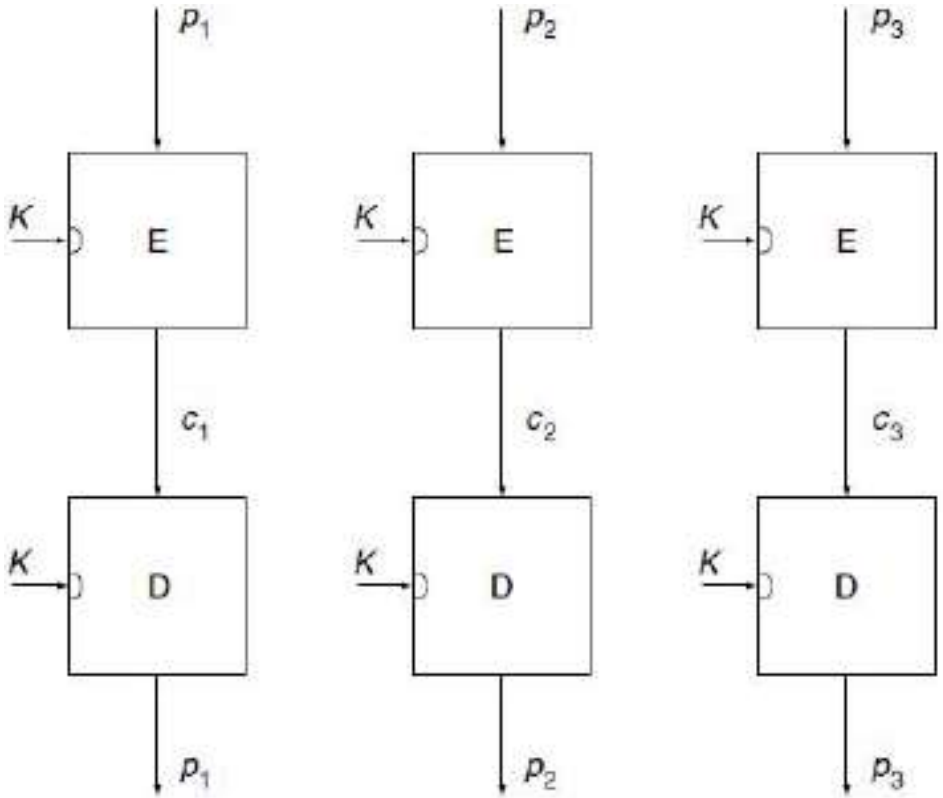
# Outline



# Recommendation of Modes of Operation

- A NIST standard FIPS 800-38A (since 2001)
- This recommendation defines five confidentiality modes of operation for use with an underlying symmetric key block cipher algorithm:
  - Electronic Codebook (ECB),
  - Cipher Block Chaining(CBC),
  - Cipher Feedback (CFB),
  - Output Feedback (OFB), and
  - Counter (CTR).
- Addendum to NIST Special Publication 800-38A for three variants of **ciphertext stealing** for CBC Mode in 2010.

# Electronic Code Book (ECB) Mode




**Encryption** : $c_i = E_K(p_i)$, **Decryption** : $p_i = D_K(c_i)$

# Properties of ECB

- **Advantages**
  i. No block synchronization between sender and receiver is required.
  ii. Bit errors caused by noisy channels only affect the corresponding block but not succeeding blocks.
  iii. Block cipher operating can be parallelized for high-speed implementations.
- **Disadvantages**
  i. Identical plaintexts result in identical ciphertexts.
  ii. An attacker recognizes if the same message has been sent twice.
  iii. Plaintext blocks are encrypted independently of previous blocks.
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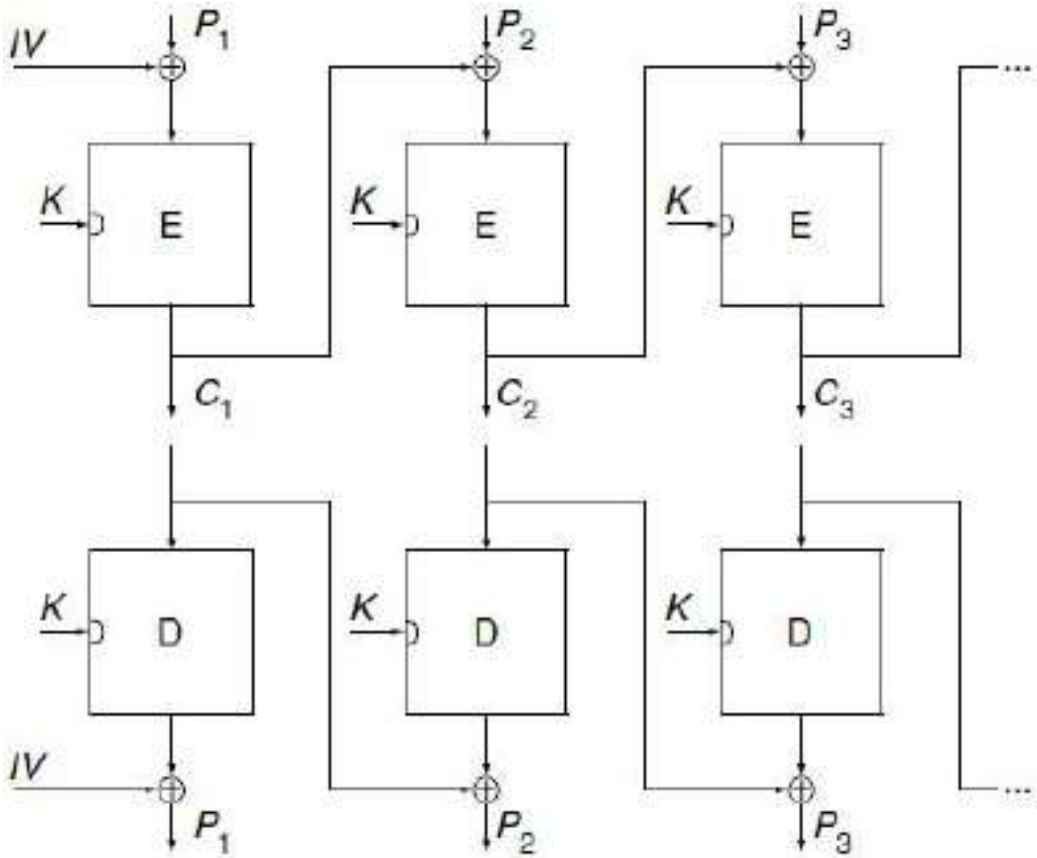
**ECB is insecure and you should not use it!**

# Cipher Block Chaining (CBC)Mode

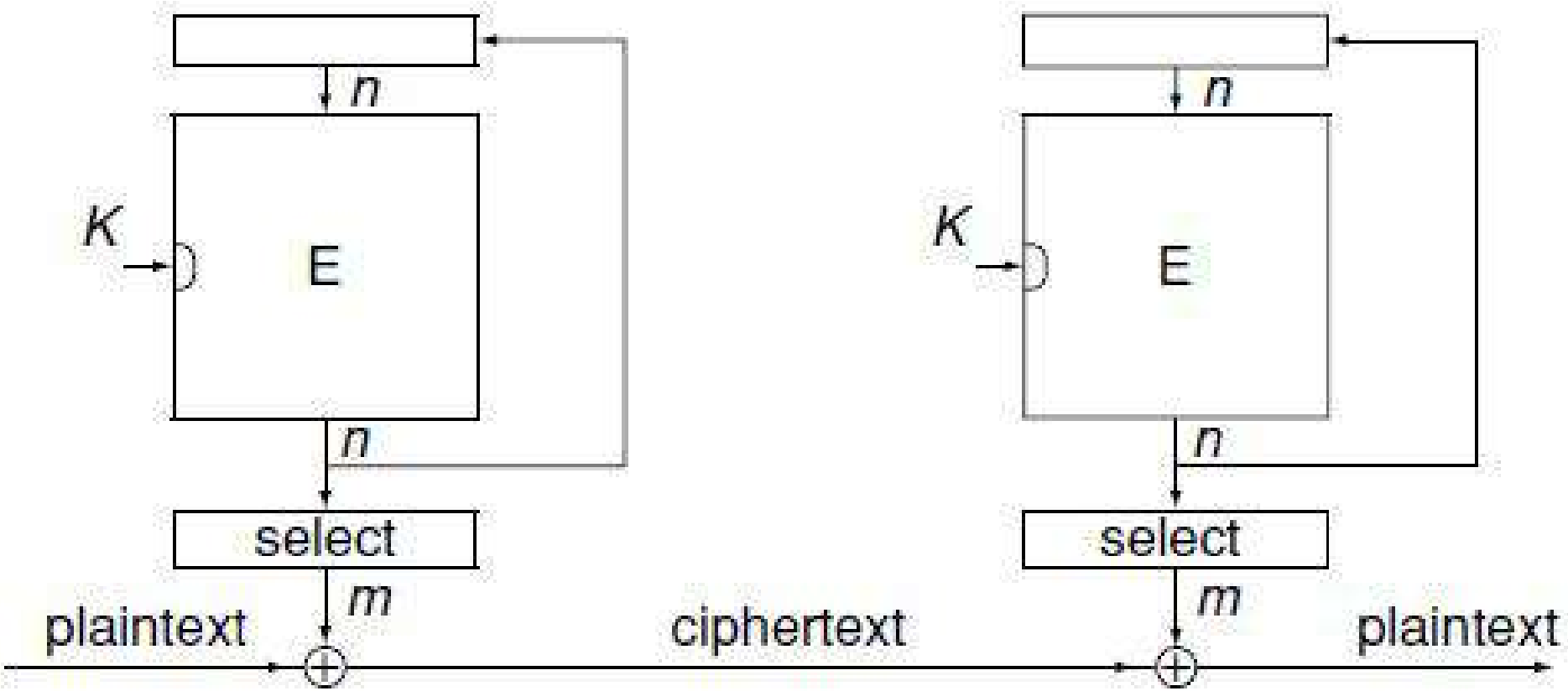



**Encryption** : $c_i = E_K(p_i \oplus c_{i-1})$, **Decryption** : $p_i = D_K(c_i) \oplus c_{i-1}$

# Properties of CBC

- The encryption of all blocks are chained together.
- The encryption is randomized by using an initialization vector $\mathcal{IV}$.
- A single bit error in ciphertext block $c_i$ affects decipherment of blocks $c_i$ and $c_{i+1}$.
  - Block $p'_i$ recovered from $c_i$ is typically totally random, while the recovered plaintext $p'_{i+1}$ has bit errors precisely where $c_i$ did.
- Decryption can be much faster than encryption due to parallelism.
- Padding oracle attack is possible in CBC mode.

# Output FeedBack (OFB) Mode

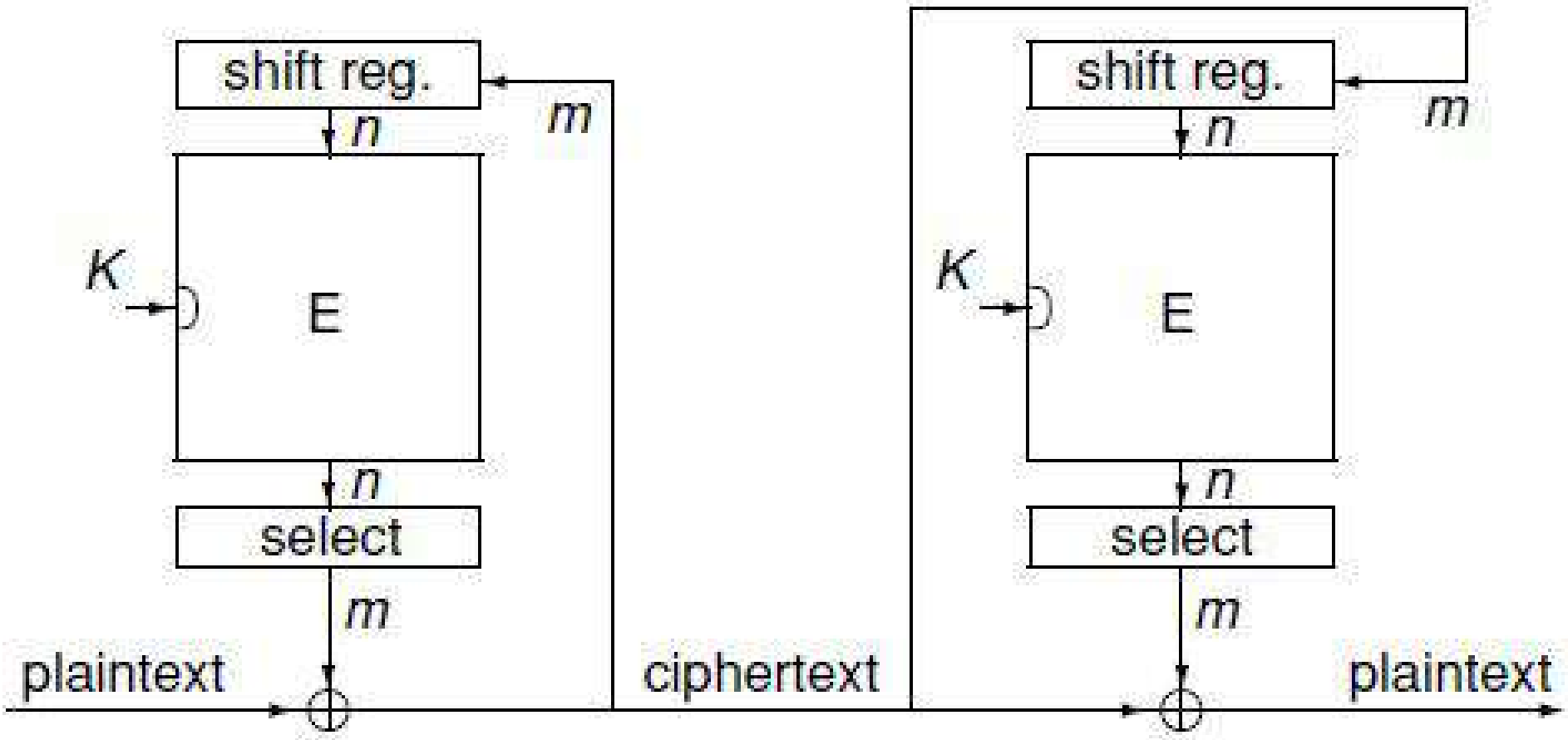



**Encryption** : $c_i = p_i \oplus E_K(k_{i-1})$, **Decryption** : $p_i = c_i \oplus E_K(k_{i-1})$

# Properties of OFB

- It is used to build a synchronous stream cipher from a block cipher.
- The key stream is not generated bitwise but instead in a blockwise fashion.
- One or more bit errors in any ciphertext block $c_i$ affects the decipherment of only that block.
- The $\mathcal{IV}$, which need not be secret, must be changed if an OFB key $K$ is re-used.

# Cipher FeedBack (CFB) Mode

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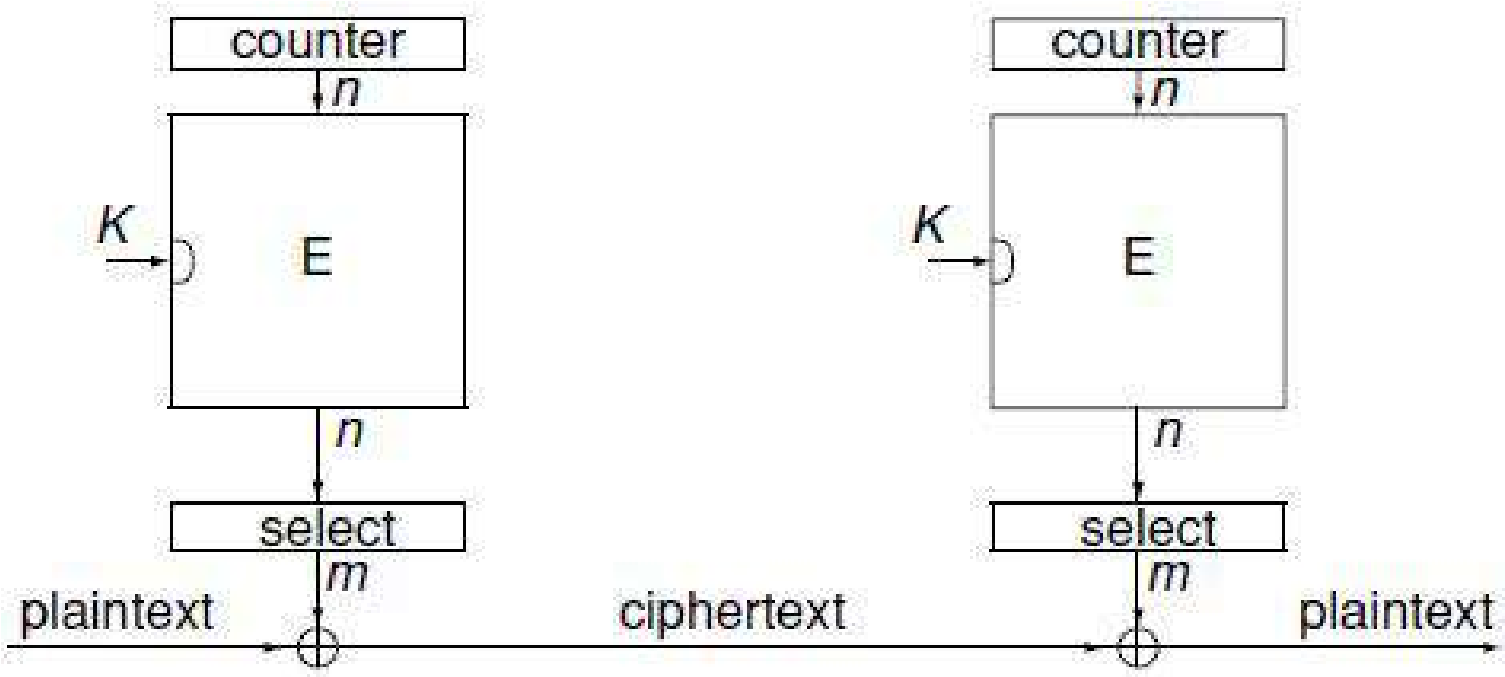
# Properties of CFB

- Since the encryption function $E_K$ is used for both CFB encryption and decryption, the CFB mode must not be used if the block cipher $E$ is a public-key algorithm.
- The CFB mode may be modified
  - to allow processing of plaintext blocks whose size is less than the size of the feedback variable.
- It can be used in situations where short plaintext blocks are to be encrypted.

# CounTeR (CTR) Mode




**Encryption** : $c_i = p_i \oplus E_K(Nonce||CTR)$

**Decryption** : $p_i = c_i \oplus E_k(Nonce||CTR)$

# Properties of CTR

- It uses a block cipher as a *stream cipher*
- The key stream is computed in a blockwise fashion
- Unlike CFB and OFB modes, the CTR mode can be parallelized – desirable for high-speed implementations, e.g., in network routers

# Galois Counter Mode (GCM)

- AES-GCM Authenticated Encryption (proposed by D. McGrew & J. Viega)
  - Designed for high performance (Mainly with a HW viewpoint)
  - This is used for authenticated encryption with associated data (AEAD), and its specialization, GMAC, for generating a MAC on data that is not encrypted.
  - A NIST standard FIPS 800-38D (since 2007)
  - Included in the NSA Suite B Cryptography, IPsec (RFC 4106), IEEE P1619, TLS 1.2, TLS1.3

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  - Encryption is done with AES in CTR mode
  - Authentication tag computations : “Galois Hash"
    - A Carter-Wegman-Shoup universal hash construction: polynomial evaluation over a binary field
    - Uses $GF(2^{128})$ defined by the “lowest" irreducible polynomial

$$g(x) = x^{128} + x^7 + x^2 + x + 1$$

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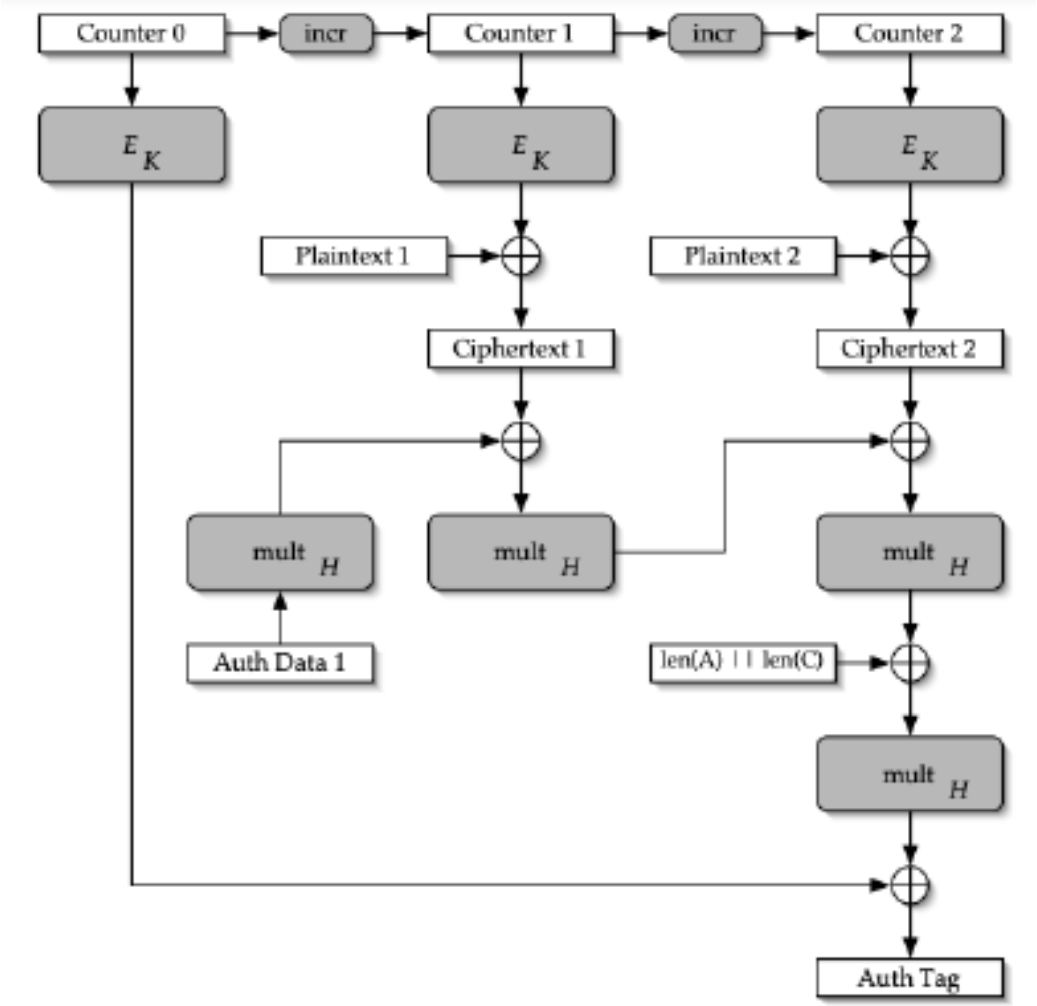
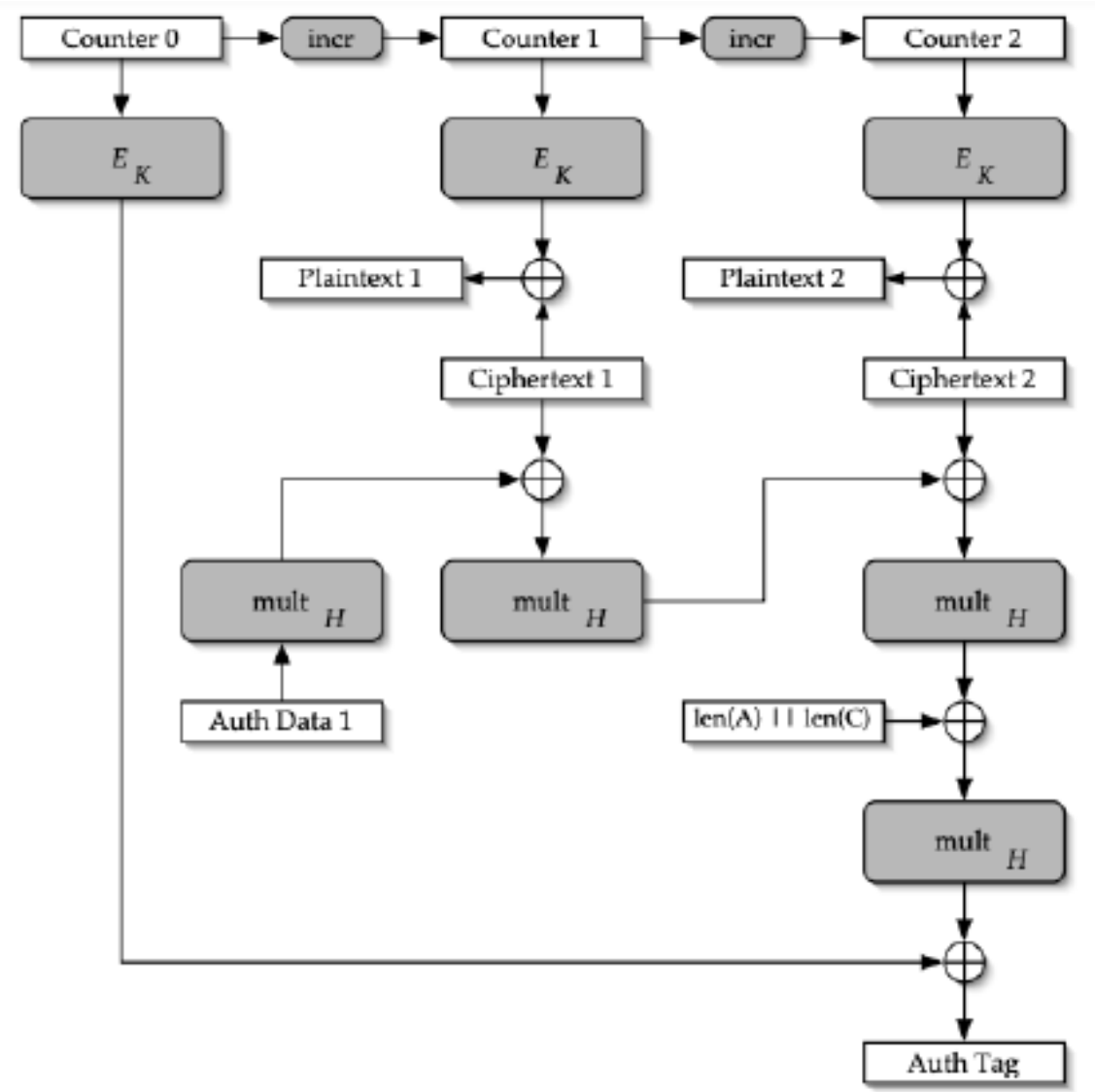
    - Computations based on $GF(2^{128})$ arithmetic

# Galois Counter Mode (GCM) Encryption




$mult_H$ denotes multiplication in $GF(2^{128})$ by the hash key $H = E_K(0^{128})$

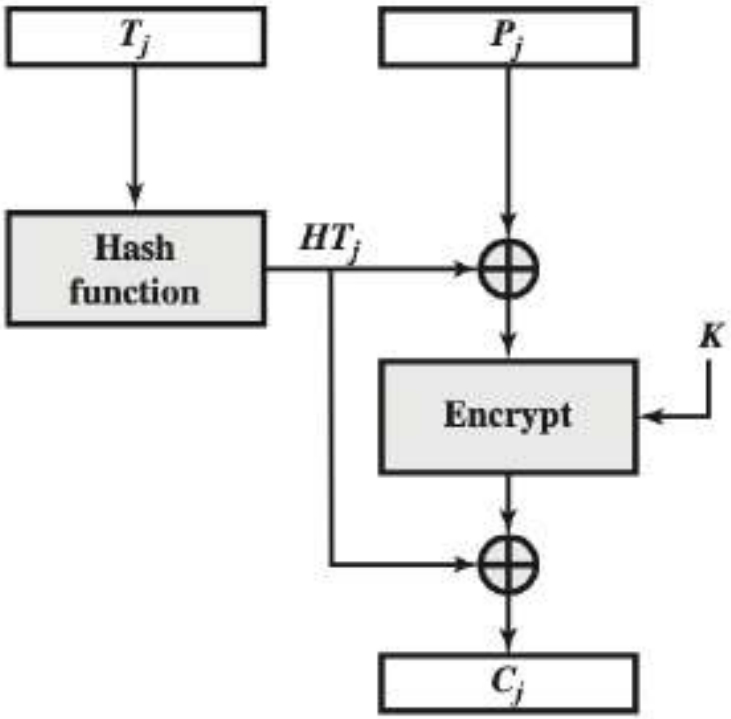
# GCM Decryption

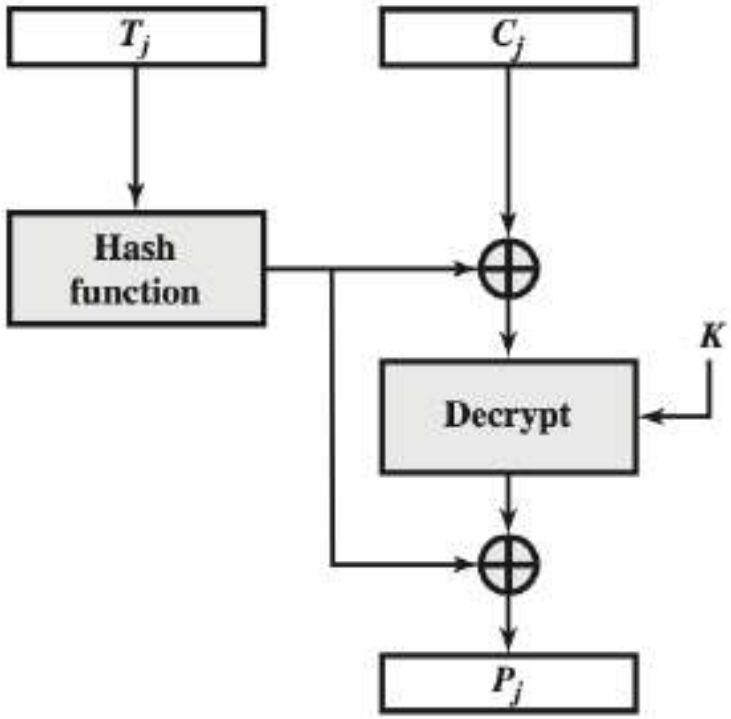


# XTS-AES Mode

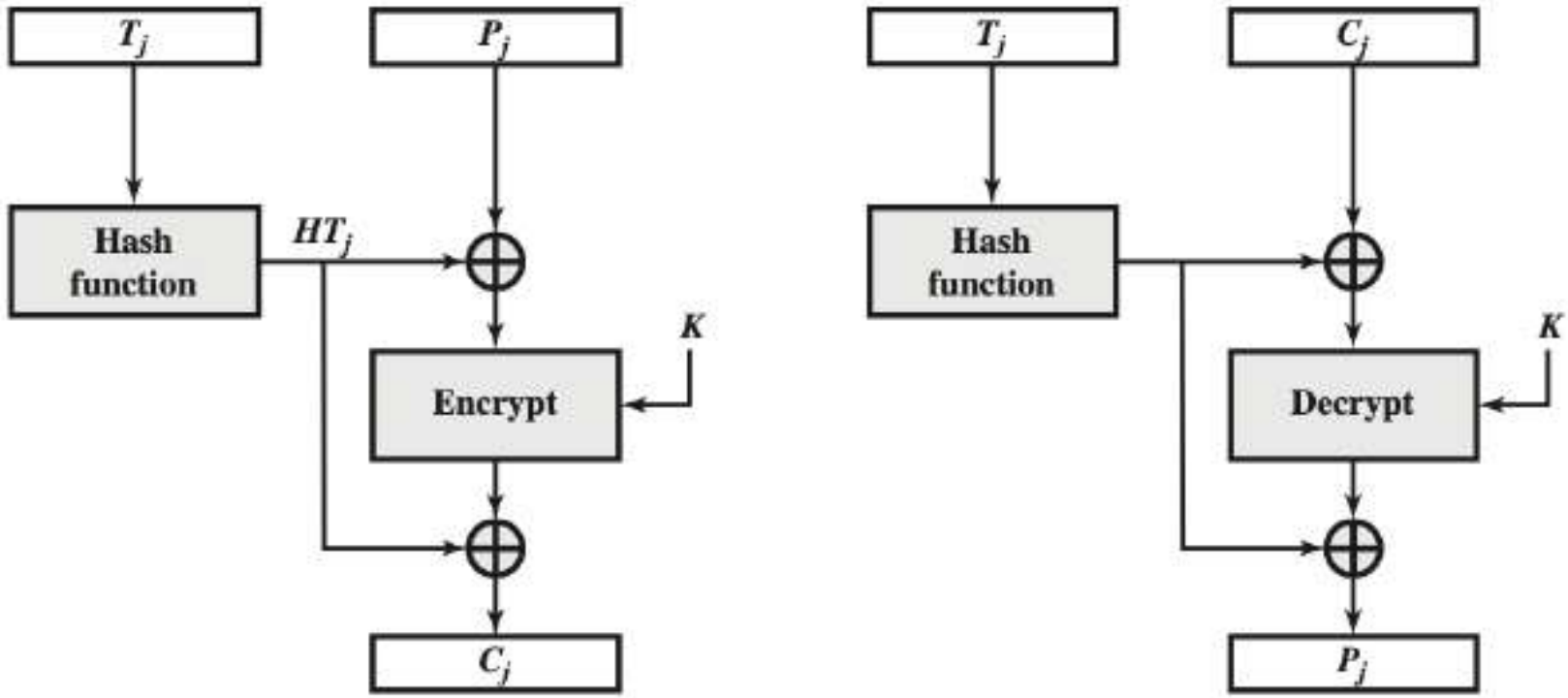
- NIST approved XTS-AES algorithm a mode of operation of the AES algorithm published in 2010 (Std. IEEE 1619-2007).
- **XTS** stands for the **X**EX **T**weakable Block Cipher with Ciphertext **S**tealing
- It was designed for the cryptographic protection of data on storage devices (data at rest).
- It has received widespread industry support.
- It is based on the concept of tweakable block cipher.
- The form of this concept used in XTS-AES was first described by Phillip Rogaway in 2004.

# Tweakable Block Cipher



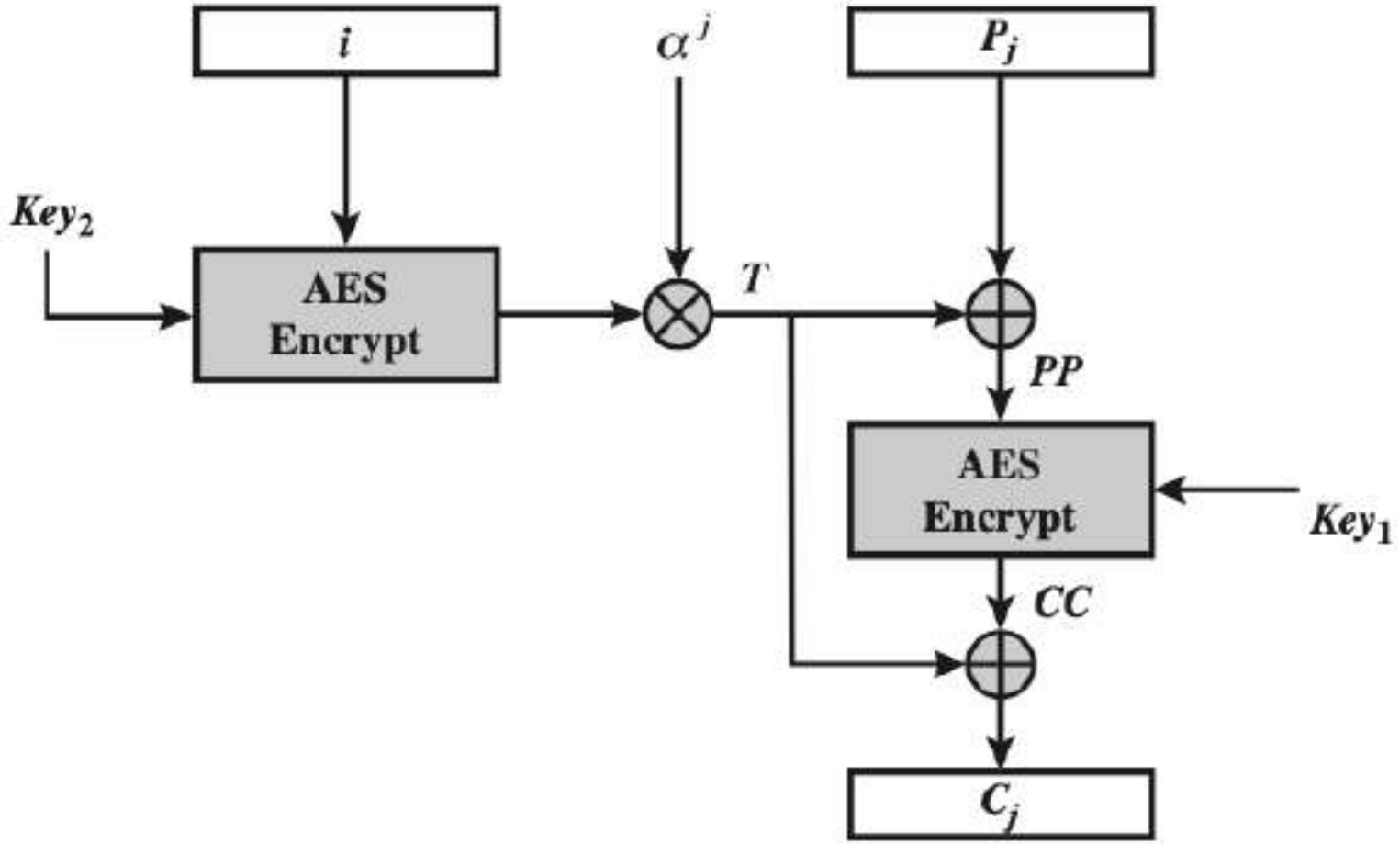
# Tweakable Block Cipher




William Stallings,
*Cryptography and Network Security: Principles and Practice*, Pearson Education Canada, 2020.

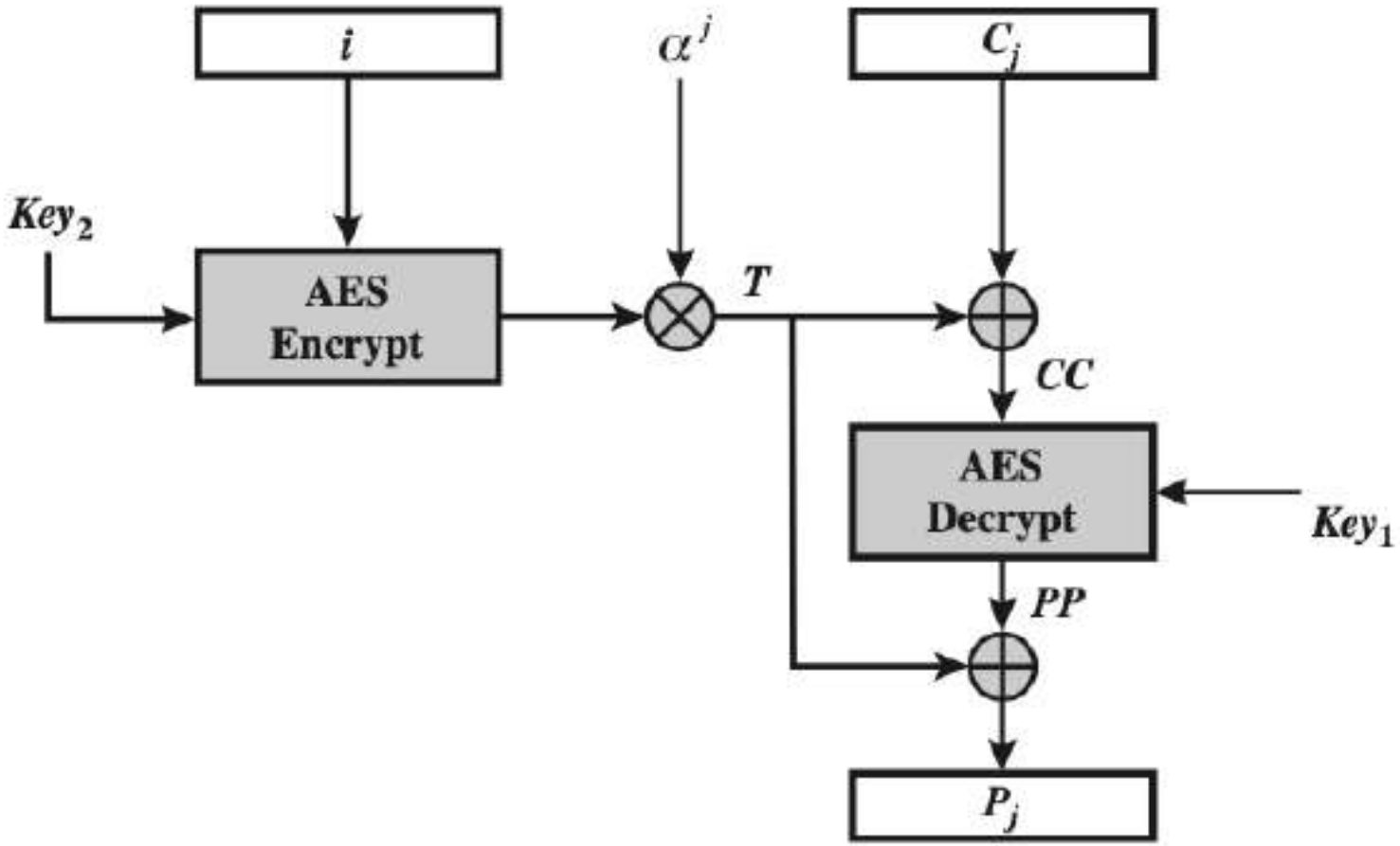
# XTS-AES Mode

## Encryption



# XTS-AES Mode

## Decryption



# The End

**Thanks a lot for your attention!**