# Ceng 471 Cryptography

## *Symmetrical Cryptosystems*
## *DES*

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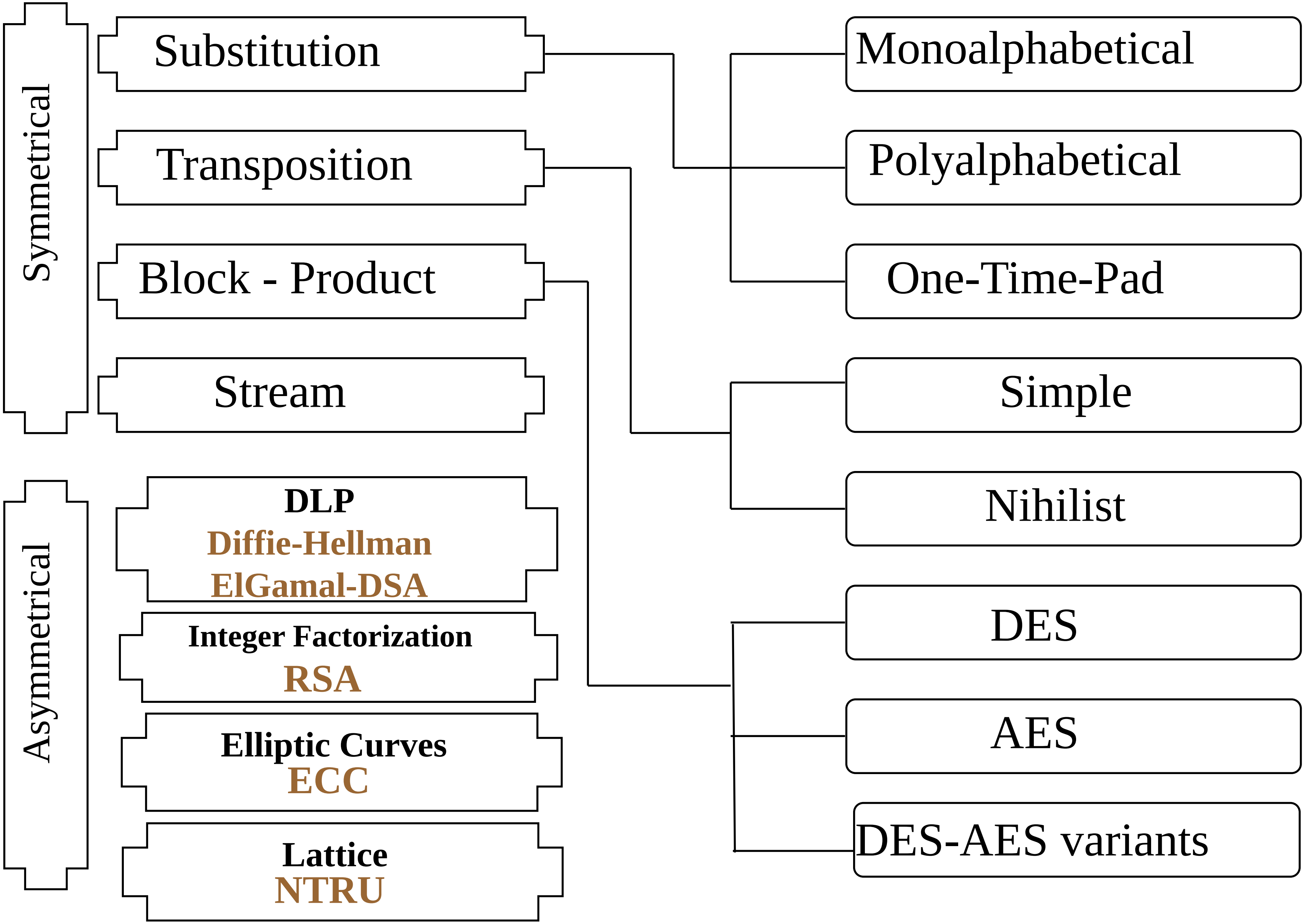
**Reference Book:** Introduction to Cryptography with Coding Theory 2nd Ed., W.Trappe, L. Washington

**Reference Presentations:**

Lecture slides of Assoc. Prof. Dr. Ahmet Koltuksuz for "Symmetric Cryptography".

Lecture slides by Lawrie Brown for " Cryptography and Network Security", 5/e, by William Stallings, Chapter 3.

# Introduction



# Symmetric Cryptography

Symmetrical

Substitution

Ceasar Cipher, 60 B.C.

**Plaintext**

Encryption

**C=P+n (mod k)**

**Ciphertext**

n=5, k=26 ( English )

**S-M-I-T-H** → → **X-R-N-Y-M**

| A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T | U | V | W | X | Y | Z |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 |

# Symmetric Cryptography

Symmetrical

Substitution

Monoalphabetical Substitution

- MCRKHAT LNBDEFGI J ZPOYSÖUŞÇİĞÜV
- ABCÇDE FGĞHI İ JKLMNOÖPRSŞTUÜVYZ

- Plaintext : TÜRKİYE
- Ciphertext : ŞİSGEÜA

# Symmetric Cryptography

Symmetrical

## Substitution

### Polylphabetical Substitution: Vigenere Table

| | A | B | C | Ç | D | E | F | G | Ğ | H | I | İ | J | K | L | M | N | O | Ö | P | R | S | Ş | T | U | Ü | V | Y | Z | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **A** | A | B | C | Ç | D | E | F | G | Ğ | H | I | İ | J | K | L | M | N | O | Ö | P | R | S | Ş | T | U | Ü | V | Y | Z | **00** |
| **B** | B | C | Ç | D | E | F | G | Ğ | H | I | İ | J | K | L | M | N | O | Ö | P | R | S | Ş | T | U | Ü | V | Y | Z | A | **01** |
| **C** | C | Ç | D | E | F | G | Ğ | H | I | İ | J | K | L | M | N | O | Ö | P | R | S | Ş | T | U | Ü | V | Y | Z | A | B | **02** |
| **Ç** | Ç | D | E | F | G | Ğ | H | I | İ | J | K | L | M | N | O | Ö | P | R | S | Ş | T | U | Ü | V | Y | Z | A | B | C | **03** |
| **D** | D | E | F | G | Ğ | H | I | İ | J | K | L | M | N | O | Ö | P | R | S | Ş | T | U | Ü | V | Y | Z | A | B | C | Ç | **04** |
| **E** | E | F | G | Ğ | H | I | İ | J | K | L | M | N | O | Ö | P | R | S | Ş | T | U | Ü | V | Y | Z | A | B | C | Ç | D | **05** |
| **F** | F | G | Ğ | H | I | İ | J | K | L | M | N | O | Ö | P | R | S | Ş | T | U | Ü | V | Y | Z | A | B | C | Ç | D | E | **06** |
| **G** | G | Ğ | H | I | İ | J | K | L | M | N | O | Ö | P | R | S | Ş | T | U | Ü | V | Y | Z | A | B | C | Ç | D | E | F | **07** |
| **Ğ** | Ğ | H | I | İ | J | K | L | M | N | O | Ö | P | R | S | Ş | T | U | Ü | V | Y | Z | A | B | C | Ç | D | E | F | G | **08** |
| **H** | H | I | İ | J | K | L | M | N | O | Ö | P | R | S | Ş | T | U | Ü | V | Y | Z | A | B | C | Ç | D | E | F | G | Ğ | **09** |
| **I** | I | İ | J | K | L | M | N | O | Ö | P | R | S | Ş | T | U | Ü | V | Y | Z | A | B | C | Ç | D | E | F | G | Ğ | H | **10** |
| **İ** | İ | J | K | L | M | N | O | Ö | P | R | S | Ş | T | U | Ü | V | Y | Z | A | B | C | Ç | D | E | F | G | Ğ | H | I | **11** |
| **J** | J | K | L | M | N | O | Ö | P | R | S | Ş | T | U | Ü | V | Y | Z | A | B | C | Ç | D | E | F | G | Ğ | H | I | İ | **12** |
| **K** | K | L | M | N | O | Ö | P | R | S | Ş | T | U | Ü | V | Y | Z | A | B | C | Ç | D | E | F | G | Ğ | H | I | İ | J | **13** |
| **L** | L | M | N | O | Ö | P | R | S | Ş | T | U | Ü | V | Y | Z | A | B | C | Ç | D | E | F | G | Ğ | H | I | İ | J | K | **14** |
| **M** | M | N | O | Ö | P | R | S | Ş | T | U | Ü | V | Y | Z | A | B | C | Ç | D | E | F | G | Ğ | H | I | İ | J | K | L | **15** |
| **N** | N | O | Ö | P | R | S | Ş | T | U | Ü | V | Y | Z | A | B | C | Ç | D | E | F | G | Ğ | H | I | İ | J | K | L | M | **16** |
| **O** | O | Ö | P | R | S | Ş | T | U | Ü | V | Y | Z | A | B | C | Ç | D | E | F | G | Ğ | H | I | İ | J | K | L | M | N | **17** |
| **Ö** | Ö | P | R | S | Ş | T | U | Ü | V | Y | Z | A | B | C | Ç | D | E | F | G | Ğ | H | I | İ | J | K | L | M | N | O | **18** |
| **P** | P | R | S | Ş | T | U | Ü | V | Y | Z | A | B | C | Ç | D | E | F | G | Ğ | H | I | İ | J | K | L | M | N | O | Ö | **19** |
| **R** | R | S | Ş | T | U | Ü | V | Y | Z | A | B | C | Ç | D | E | F | G | Ğ | H | I | İ | J | K | L | M | N | O | Ö | P | **20** |
| **S** | S | Ş | T | U | Ü | V | Y | Z | A | B | C | Ç | D | E | F | G | Ğ | H | I | I | J | K | L | M | N | O | Ö | P | R | **21** |
| **Ş** | Ş | T | U | Ü | V | Y | Z | A | B | C | Ç | D | E | F | G | Ğ | H | I | İ | J | K | L | M | N | O | Ö | P | R | S | **22** |
| **T** | T | U | Ü | V | Y | Z | A | B | C | Ç | D | E | F | G | Ğ | H | I | İ | J | K | L | M | N | O | Ö | P | R | S | Ş | **23** |
| **U** | U | Ü | V | Y | Z | A | B | C | Ç | D | E | F | G | Ğ | H | I | İ | J | K | L | M | N | O | Ö | P | R | S | Ş | T | **24** |
| **Ü** | Ü | V | Y | Z | A | B | C | Ç | D | E | F | G | Ğ | H | I | İ | J | K | L | M | N | O | Ö | P | R | S | Ş | T | U | **25** |
| **V** | V | Y | Z | A | B | C | Ç | D | E | F | G | Ğ | H | I | İ | J | K | L | M | N | O | Ö | P | R | S | Ş | T | U | Ü | **26** |
| **Y** | Y | Z | A | B | C | Ç | D | E | F | G | Ğ | H | I | İ | J | K | L | M | N | O | Ö | P | R | S | Ş | T | U | Ü | V | **27** |
| **Z** | Z | A | B | C | Ç | D | E | F | G | Ğ | H | I | İ | J | K | L | M | N | O | Ö | P | R | S | Ş | T | U | Ü | V | Y | **28** |

Plaintext:TÜRKİYE

T=00

Ü=01

R=02

K=03

İ=04

Y=05

E=06

Ciphertext:TVŞNMÇİ

# Symmetric Cryptography

Symmetrical

## Substitution

One Time Pad, Vernam Cipher, 1926

### Step #1: Digitize the Alphabet

| A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T | U | V | W | X | Y | Z |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 |

### Step #2: Encryption

| | | | | | | |
|---|---|---|---|---|---|---|
| Plaintext | : | **H** | **E** | **L** | **L** | **O** |
| (1) Digitalization | : | **8** | **5** | **12** | **12** | **15** |
| (2) Random Numbers | : | **12** | **48** | **28** | **32** | **80** |
| Summation of 1 & 2 | : | **20** | **53** | **40** | **44** | **95** |
| Modulus 26 | : | **20** | **1** | **14** | **18** | **17** |
| Ciphertext | : | **T** | **A** | **N** | **R** | **Q** |

# Symmetric Cryptography

Symmetrical

Substitution

One Time Pad, Vernam Cipher, 1926

- The only mathematically proven unbreakable cipher. Proven by **Shannon**.
- With the conditions of :The length of the key should be equal to that of the length of the message.
- Each key should only be used once.
- Thus very popular with the intelligence agencies.

# Symmetric Cryptography

Symmetrical

Transposition: Permutation

Simple Permutation

| | | |
|---|---|---|
| Plaintext | : KRİPTOGRAFİ | |
| Index | : 1 2 3 4 5 6 | |
| Permutation (key) | : 4 3 6 2 5 1 | |
| Encryption | : K R İ P T O | G R A F İ - |
| | 1 2 3 4 5 6 | 1 2 3 4 5 6 |
| | 4 3 6 2 5 1 | 4 3 6 2 5 1 |
| Ciphertext | : P İ O R T K | F A - R İ G |

# Symmetric Cryptography
# Modern Block Ciphers

- now look at modern block ciphers
- one of the most widely used types of cryptographic algorithms
- provide secrecy services
- focus on DES (Data Encryption Standard)

  to illustrate block cipher design principles

# DES History

- IBM developed Lucifer cipher
  - by team led by Horst Feistel in late 60’s
  - used 64-bit data blocks with 128-bit key
- then redeveloped as a commercial cipher with input from NSA and others
- in 1973 NBS issued request for proposals for a national cipher standard for unclassified computer data
- IBM submitted their revised Lucifer which was eventually accepted as the DES

# Data Encryption Standard (DES)

- Used in most EFT and EFTPOS from banking industry
  - It was reconfirmed as a standard for 5 years twice
  - Currently 3DES is recommended
- DES became a federal standard in November 76
  - adopted in 1977 by National Bureau of Standards - NBS (now NIST – National Institutes of Standards and Technologies)
    - As Federal Information Processing Standard 46 - FIPS PUB 46
  - ANSI X3.92-1981 (hardware + software)
  - ANSI X3.106-1983 (modes of operation)
  - Australia AS2805.5-1985
- encrypts 64-bit data using 56-bit key

# DES Design Criteria

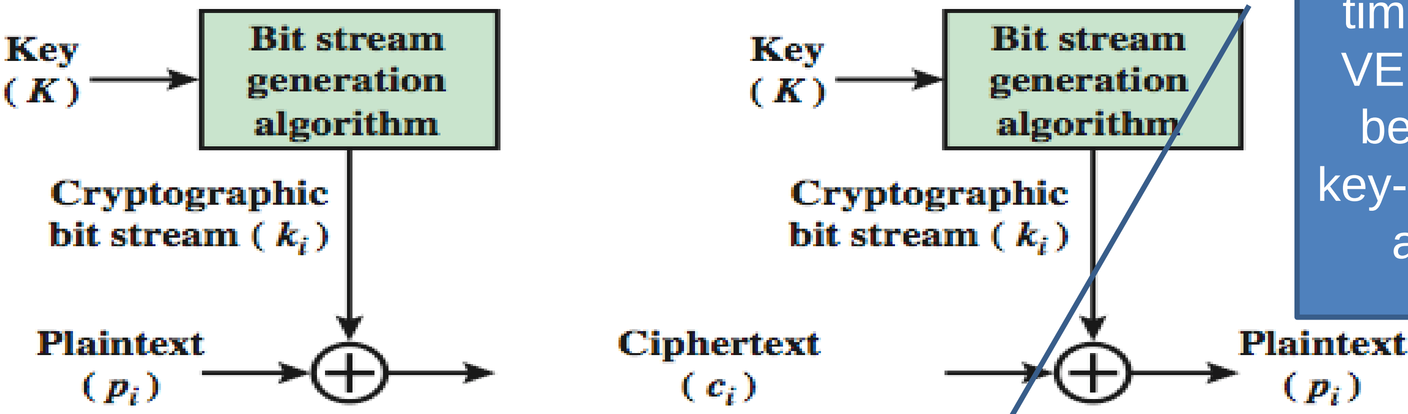
- The standard is public, the design criteria is classified
- One of the biggest controversies is the key size (56 bits)
  - W Diffie, M Hellman "Exhaustive Cryptanalysis of the NBS Data Encryption Standard" IEEE Computer 10(6), June 1977, pp74-84
  - M Hellman "DES will be totally insecure within ten years" IEEE Spectrum 16(7), Jul 1979, pp 31-41
- Another controversy: is there a back door?

# Block vs Stream Ciphers

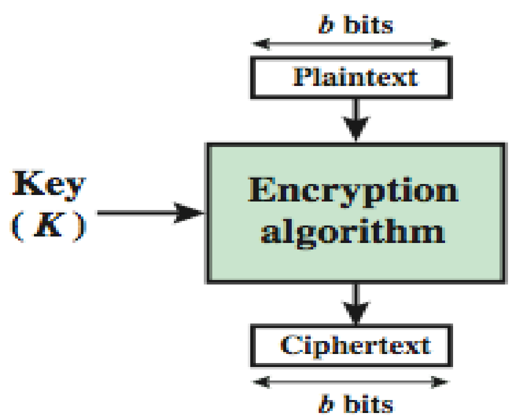
- Block ciphers process messages in blocks, each of which is then en/decrypted
- Like a substitution on very big characters
  - 64-bits or more
- Stream ciphers process messages a bit or byte at a time when en/decrypting
- Many current ciphers are block ciphers
  - better analyzed
  - broader range of applications

# Block vs Stream Ciphers

In the ideal case, a one-time pad version of the VERNAM cipher would be used, in which the key-stream (k ) is as long as the plaintext bit stream (p).




(a) Stream Cipher Using Algorithmic Bit Stream Generator




(b) Block Cipher

# Block Cipher Principles

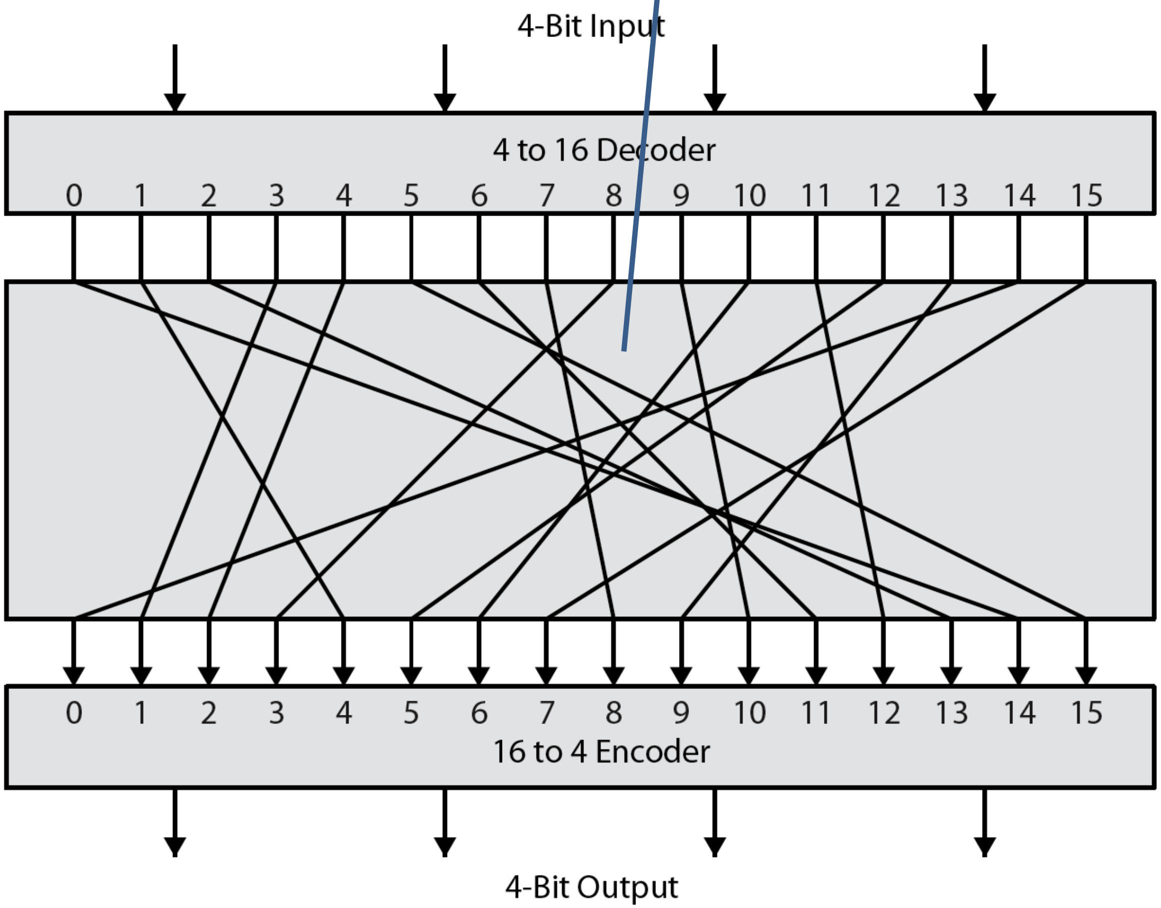
- A block cipher operates on a plaintext block of n bits to produce a ciphertext block of n bits,
- most symmetric block ciphers are based on a **Feistel Cipher Structure.**
- needed since must be able to **decrypt** ciphertext to recover messages efficiently
- block ciphers look like an extremely large substitution
- would need table of $2^{64}$ entries for a 64-bit block
  - In general, for an *n*-bit general substitution block cipher, the size of the key is $n \times 2^n$. For a 64-bit block, which is a desirable length to thwart statistical attacks, the key size is $64 \times 2^{64} = 2^{70} = 10^{21}$ bits.
- instead create from smaller building blocks
- using idea of **a product cipher**

# Ideal Block Cipher

The encryption and decryption mappings can be defined by a tabulation

A 4-bit input produces one of 16 possible input states, which is mapped by the substitution cipher into a unique one of 16 possible output states, each of which is represented by 4 ciphertext bits.

It illustrates a tiny 4-bit substitution to show that each possible input can be arbitrarily mapped to any output - which is why its complexity grows so rapidly.




The encryption and decryption mappings can be defined by a tabulation, as shown in this Figure.

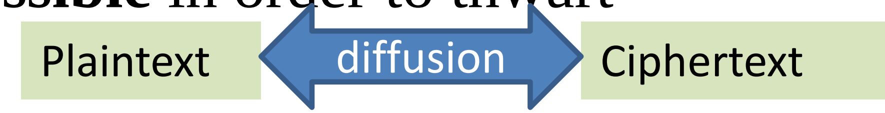
# Claude Shannon and Substitution-Permutation Ciphers

- The concept of a product cipher, which is the execution of two or more simple ciphers in sequence in such a way that the final result or product is cryptographically stronger than any of the component ciphers.
- Claude Shannon introduced idea of substitution-permutation (S-P) networks in 1949 paper.
- This form basis of modern block ciphers.
- S-P nets are based on the two primitive cryptographic operations seen before:
  - *substitution* (S-box)
  - *permutation* (P-box)

  Critically, it was the technique of layering groups of S-boxes separated by a larger P-box to form the S-P network, a complex form of a product cipher.
- provide *confusion* & *diffusion* of message & key

# Confusion and Diffusion

- Cipher needs to completely obscure statistical properties of original message,
- A one-time pad does this.
- More practically Shannon suggested combining S & P elements to obtain:
  - **diffusion** – The mechanism of diffusion seeks to **make the statistical relationship between the plaintext and ciphertext as complex as possible** in order to thwart attempts to deduce the key.




  - **confusion** – makes **relationship between ciphertext and key as complex as possible**


- At the simplest level, **diffusion is achieved through numerous permutations** and **confusions is achieved through the XOR operation**.

# Confusion and Diffusion

- Good confusion can only be achieved


  - when each character of the ciphertext depends on several parts of the key, and
  - this dependence appears to be random to the observer.

Ciphers that do not offer much confusion (such as Vigen`ere cipher) are vulnerable to frequency analysis.

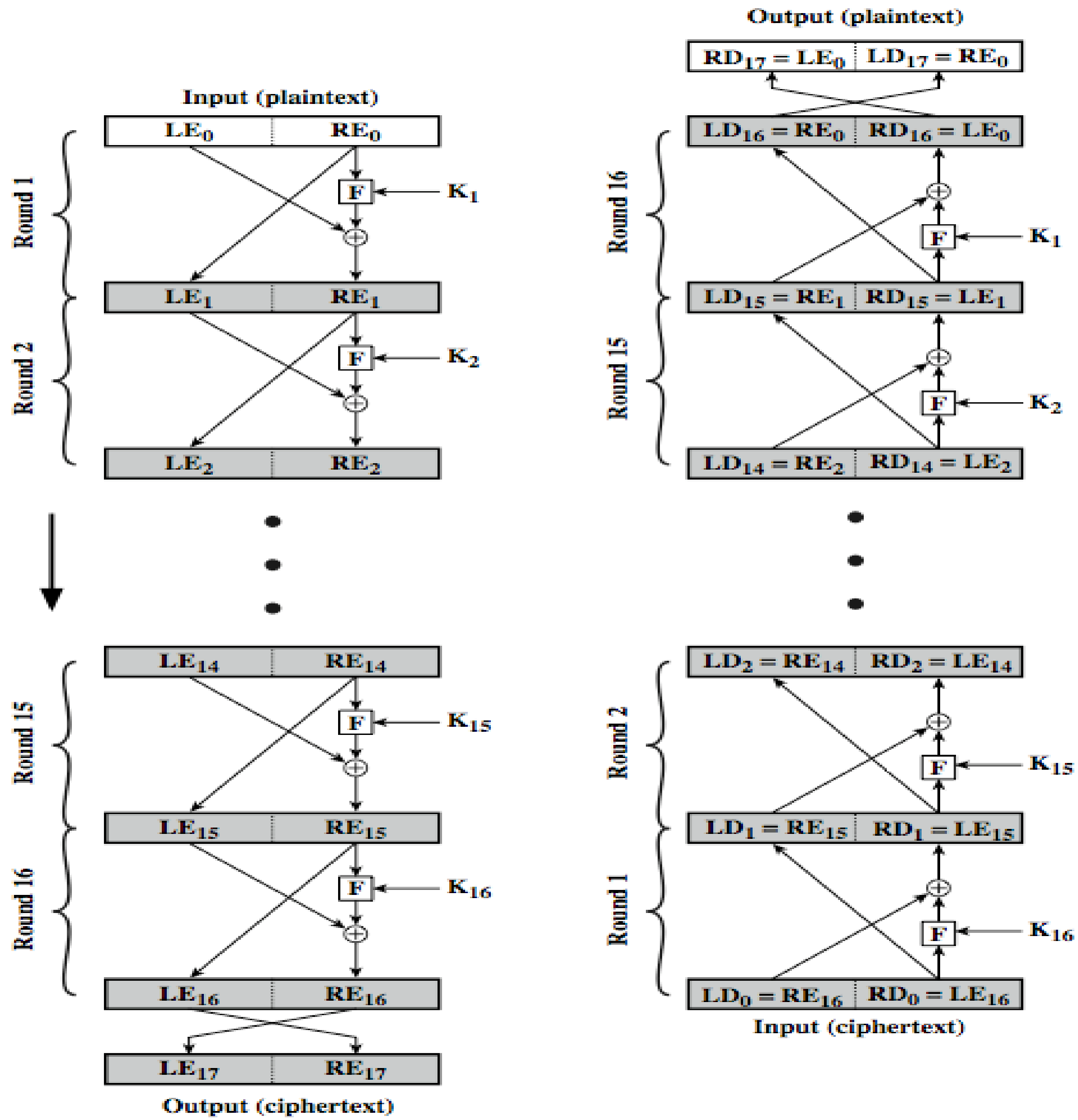
# Confusion and Diffusion


- Good diffusion spreads the influence of a single plaintext letter over many ciphertext letters.
  - In terms of the frequency statistics of letters, diagrams, etc. in the plaintext, diffusion randomly spreads them across several characters in the ciphertext.
  - This means that much more ciphertexts are needed to do a meaningful statistical attack on the cipher.

# Feistel Cipher Structure

- Horst Feistel; working at IBM Thomas J Watson Research Labs devised the **feistel cipher** (early 70`s)
  - **His main contributions** was the invention of a suitable structure which adapted Shannon's S-P network in an easily inverted structure.
- partitions input block into two halves
  - process through multiple rounds which
  - perform a substitution on left data half
  - based on round function of right half & subkey
  - then have permutation swapping halves
- Essentially the same h/w or s/w is used for both encryption and decryption, with just a slight change in how the keys are used. One layer of S-boxes and the following P-box are used to form the round function.

# Feistel Cipher Structure

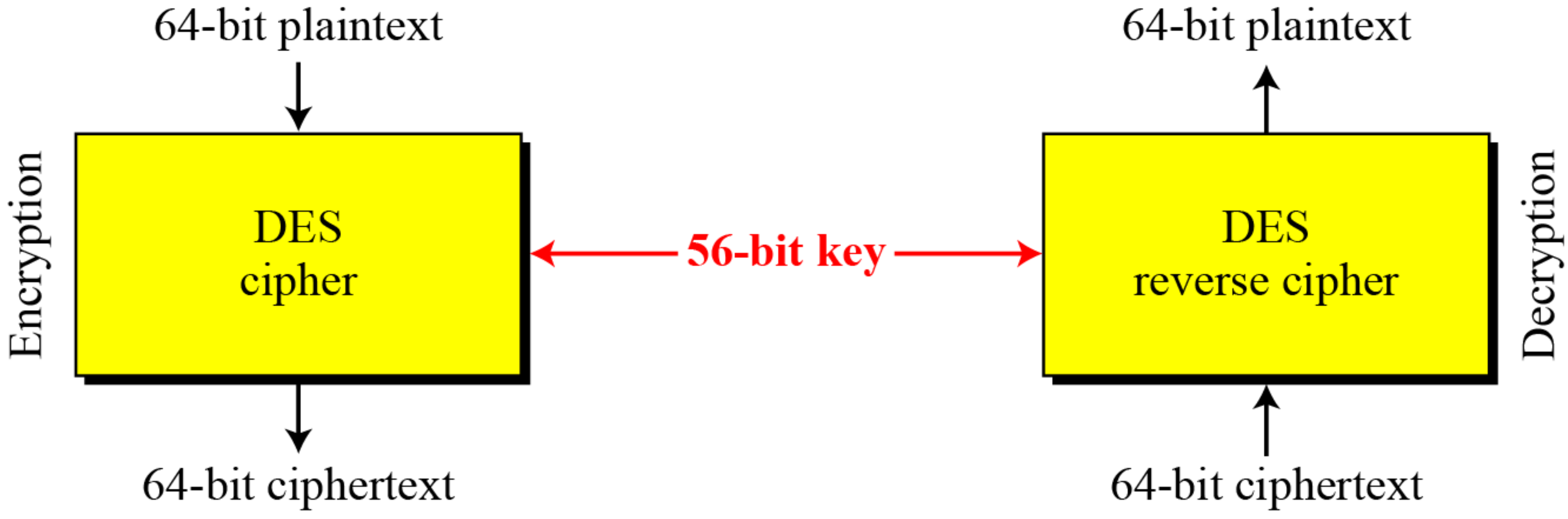


# Feistel Cipher Design Elements

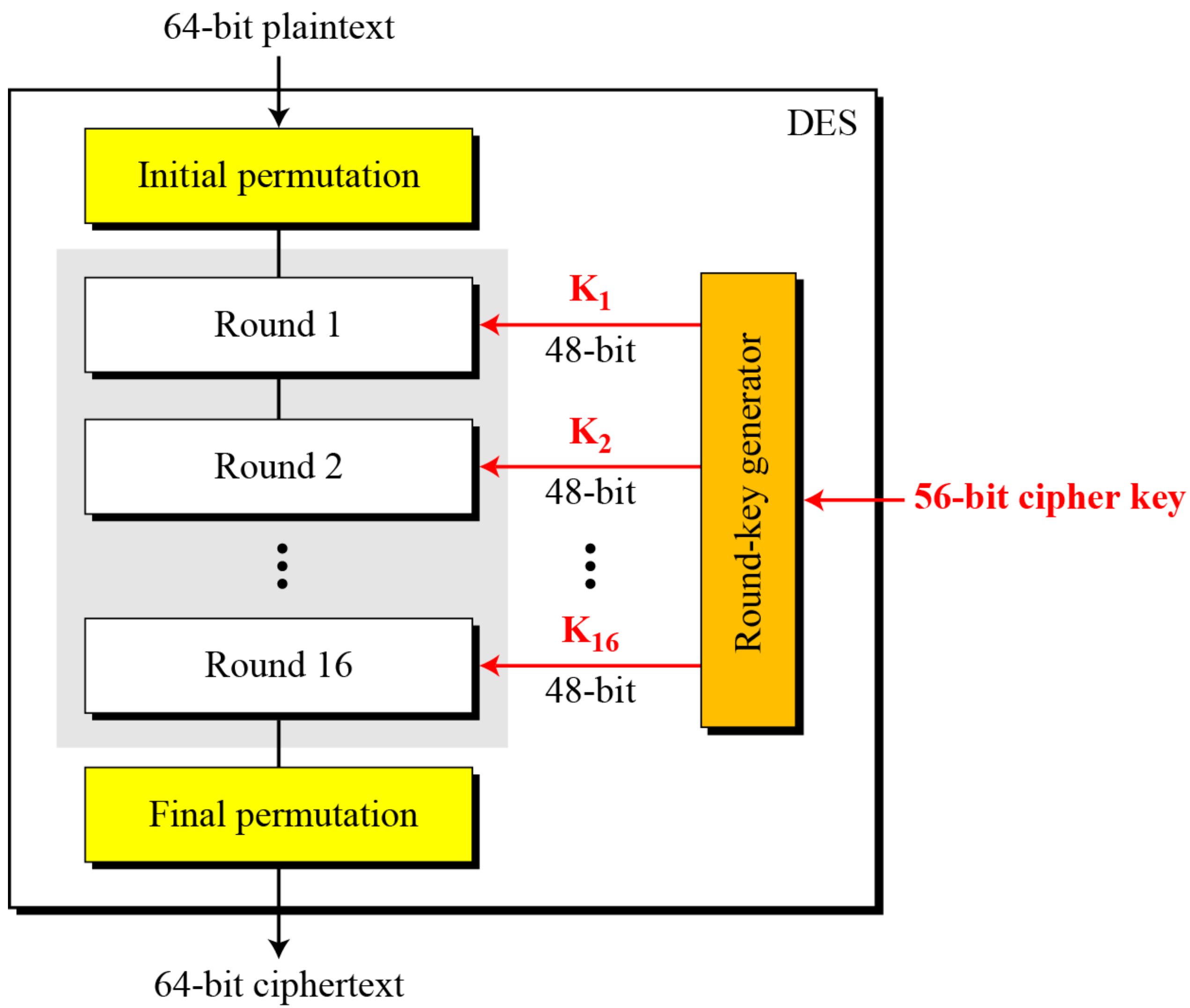
- **block size**; - increasing size improves security, but slows cipher
- **key size;** increasing size improves security, makes exhaustive key searching harder, but may slow cipher
- **number of rounds;** increasing number improves security, but slows cipher
- **subkey generation algorithm;** greater complexity can make analysis harder, but slows cipher
- **round function;** greater complexity can make analysis harder, but slows cipher
- **fast software en/decryption;** more recent concern for practical use
- **ease of analysis;** for easier validation & testing of strength

# DES is a block cipher

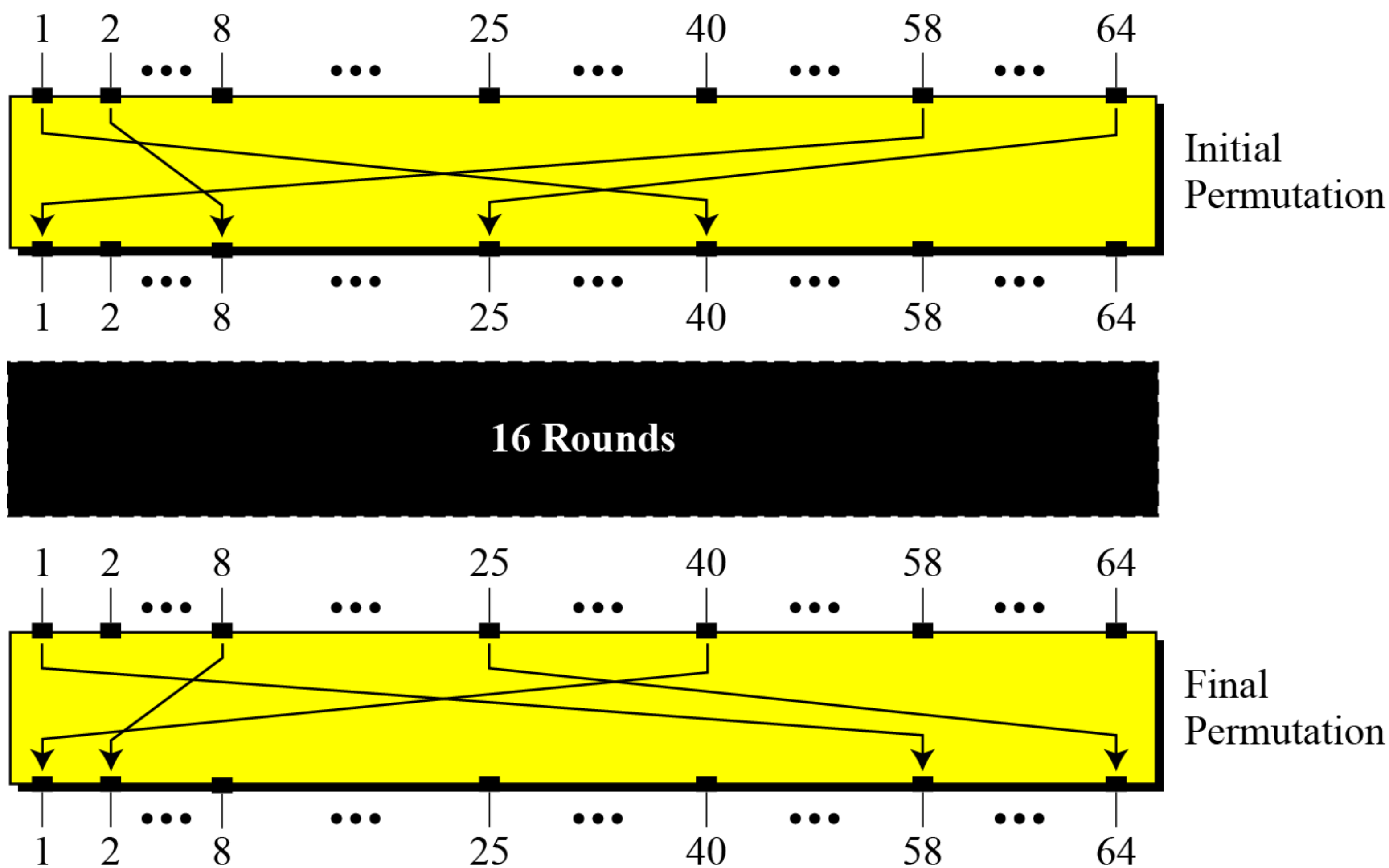
- *Encryption and decryption with DES*



# General structure of DES



# Initial and final permutation steps in DES



# Initial and final permutation tables

1st bit is permuted to 40th bit position.
58th bit is permuted to 1st bit position

40th bit is permuted to 1th bit position.

*Initial Permutation*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 58 | 50 | 42 | 34 | 26 | 18 | 10 | 02 |
| 60 | 52 | 44 | 36 | 28 | 20 | 12 | 04 |
| 62 | 54 | 46 | 38 | 30 | 22 | 14 | 06 |
| 64 | 56 | 48 | 40 | 32 | 24 | 16 | 08 |
| 57 | 49 | 41 | 33 | 25 | 17 | 09 | 01 |
| 59 | 51 | 43 | 35 | 27 | 19 | 11 | 03 |
| 61 | 53 | 45 | 37 | 29 | 21 | 13 | 05 |
| 63 | 55 | 47 | 39 | 31 | 23 | 15 | 07 |

*Final Permutation*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 40 | 08 | 48 | 16 | 56 | 24 | 64 | 32 |
| 39 | 07 | 47 | 15 | 55 | 23 | 63 | 31 |
| 38 | 06 | 46 | 14 | 54 | 22 | 62 | 30 |
| 37 | 05 | 45 | 13 | 53 | 21 | 61 | 29 |
| 36 | 04 | 44 | 12 | 52 | 20 | 60 | 28 |
| 35 | 03 | 43 | 11 | 51 | 19 | 59 | 27 |
| 34 | 02 | 42 | 10 | 50 | 18 | 58 | 26 |
| 33 | 01 | 41 | 09 | 49 | 17 | 57 | 25 |

# Example 1/a

Find the output of the initial permutation box when the input is given in hexadecimal as:

0x0000 0080 0000 0002

## Solution

Only bit 25 and bit 63 are 1s; the other bits are 0s. In the final permutation, bit 25 becomes bit 64 and bit 63 becomes bit 15. The result is

| **0000** | **0000** |
|---|---|
| 0000 | 0000 |
| 0000 | 0000 |
| 1000 | 0000 |
| 0000 | 0000 |
| 0000 | 0000 |
| 0000 | 0000 |
| 0000 | 0010 |

| **0000** | **0000** |
|---|---|
| 0000 | 0010 |
| 0000 | 0000 |
| 0000 | 0000 |
| 0000 | 0000 |
| 0000 | 0000 |
| 0000 | 0000 |
| 0000 | 0001 |

*Initial Permutation*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 58 | 50 | 42 | 34 | 26 | 18 | 10 | 02 |
| 60 | 52 | 44 | 36 | 28 | 20 | 12 | 04 |
| 62 | 54 | 46 | 38 | 30 | 22 | 14 | 06 |
| 64 | 56 | 48 | 40 | 32 | 24 | 16 | 08 |
| 57 | 49 | 41 | 33 | 25 | 17 | 09 | 01 |
| 59 | 51 | 43 | 35 | 27 | 19 | 11 | 03 |
| 61 | 53 | 45 | 37 | 29 | 21 | 13 | 05 |
| 63 | 55 | 47 | 39 | 31 | 23 | 15 | 07 |

0x0002 0000 0000 0001

## Example 1/b

Prove that the initial and final permutations are the inverse of each other by finding the output of the final permutation if the input is

0x0002 0000 0000 0001

**Solution**

The input has only two 1s; the output must also have only two 1s. Using tables, we can find the output related to these two bits. Bit 15 in the input becomes bit 63 in the output. Bit 64 in the input becomes bit 25 in the output. So the output has only two 1s, bit 25 and bit 63. The result in hexadecimal is

0x0000 0080 0000 0002

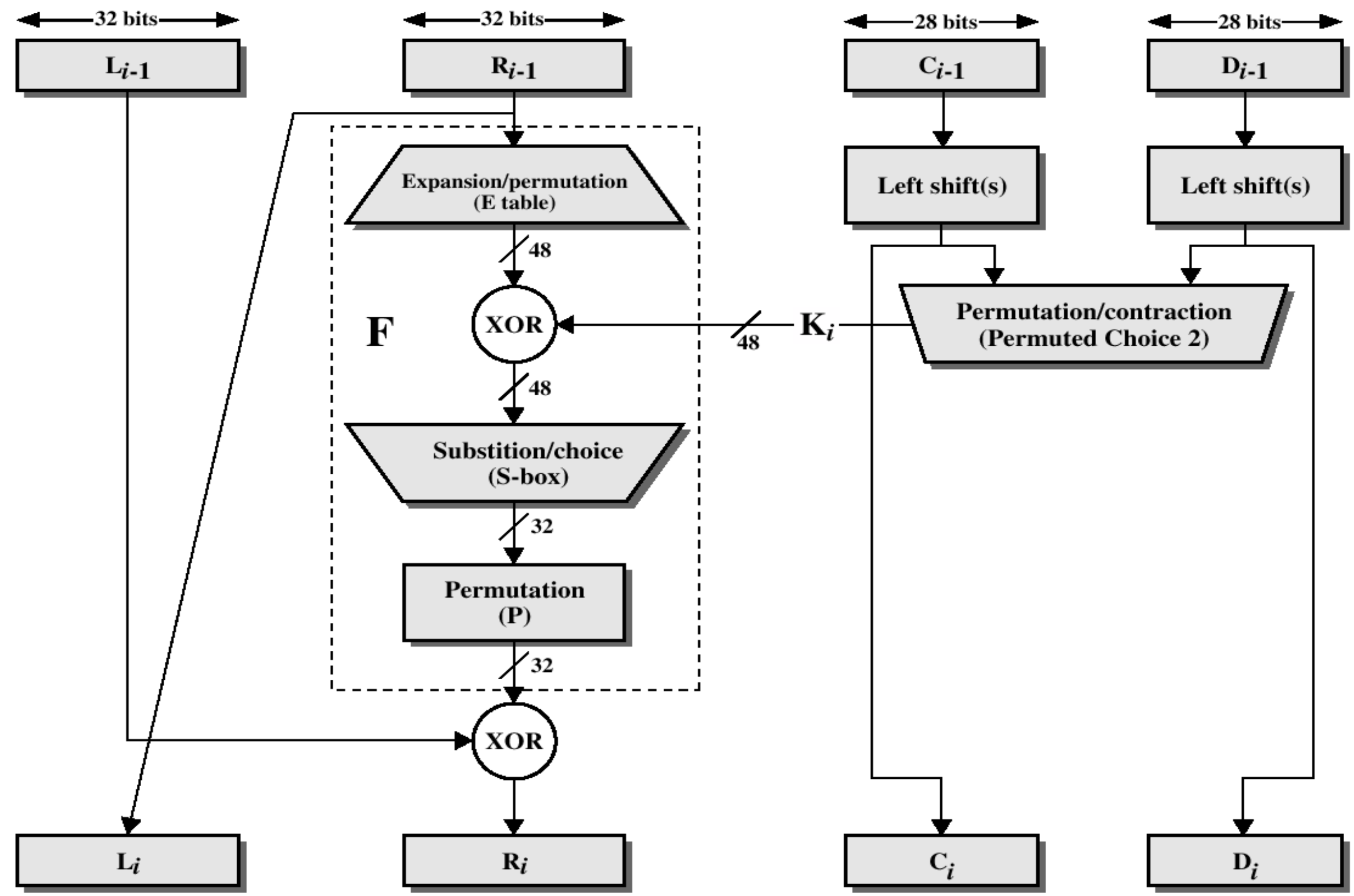
| *Final Permutation* | | | | | | | |
|---|---|---|---|---|---|---|---|
| 40 | 08 | 48 | 16 | 56 | 24 | 64 | 32 |
| 39 | 07 | 47 | 15 | 55 | 23 | 63 | 31 |
| 38 | 06 | 46 | 14 | 54 | 22 | 62 | 30 |
| 37 | 05 | 45 | 13 | 53 | 21 | 61 | 29 |
| 36 | 04 | 44 | 12 | 52 | 20 | 60 | 28 |
| 35 | 03 | 43 | 11 | 51 | 19 | 59 | 27 |
| 34 | 02 | 42 | 10 | 50 | 18 | 58 | 26 |
| 33 | 01 | 41 | 09 | 49 | 17 | 57 | 25 |

*Note*

**The initial and final permutations are straight P-boxes that are inverses of each other.**
**They have no cryptography significance in DES.**

Symmetrical

# Block:DES-1977

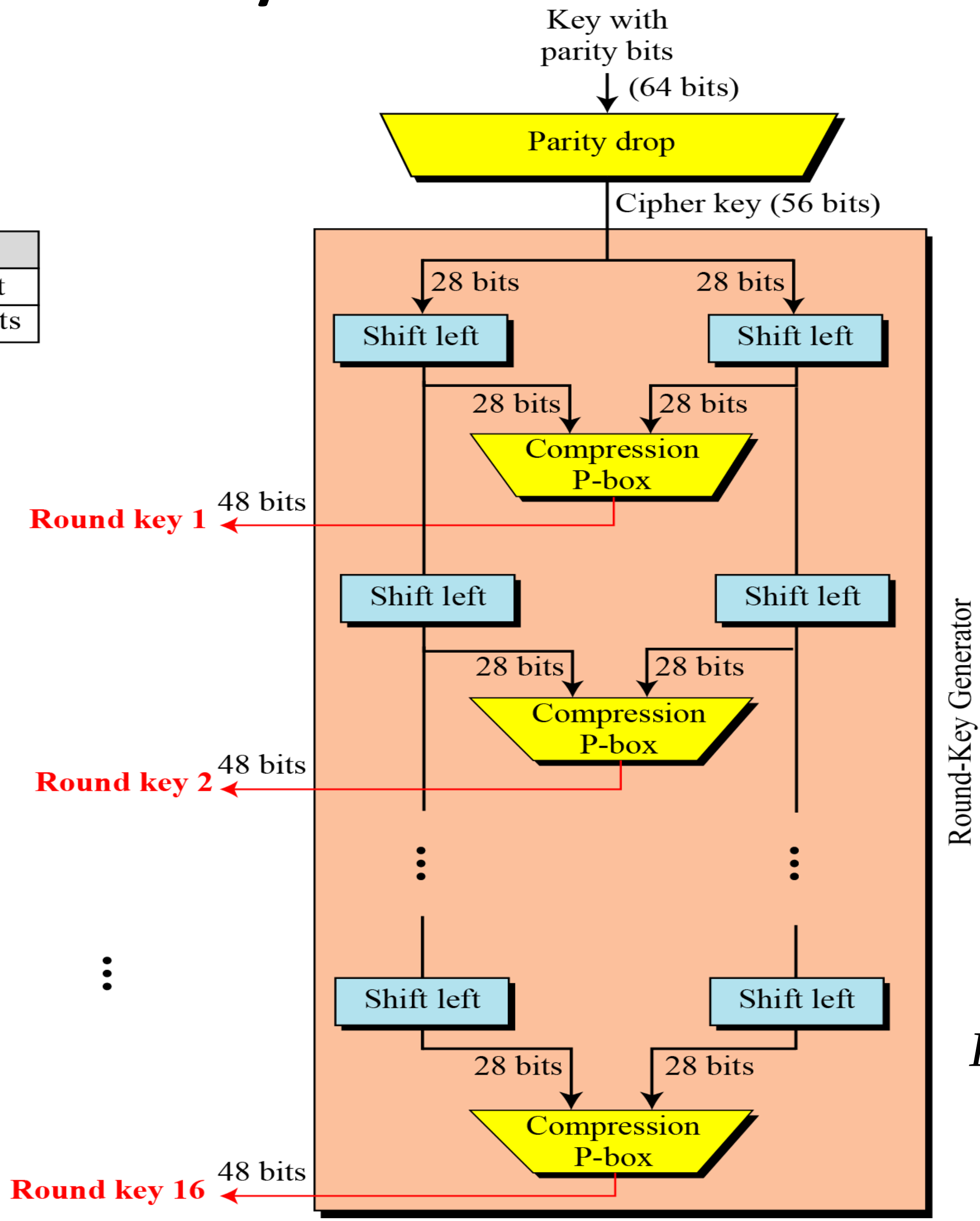



**Single Round of DES Algorithm**

# Key Generation

Shifting

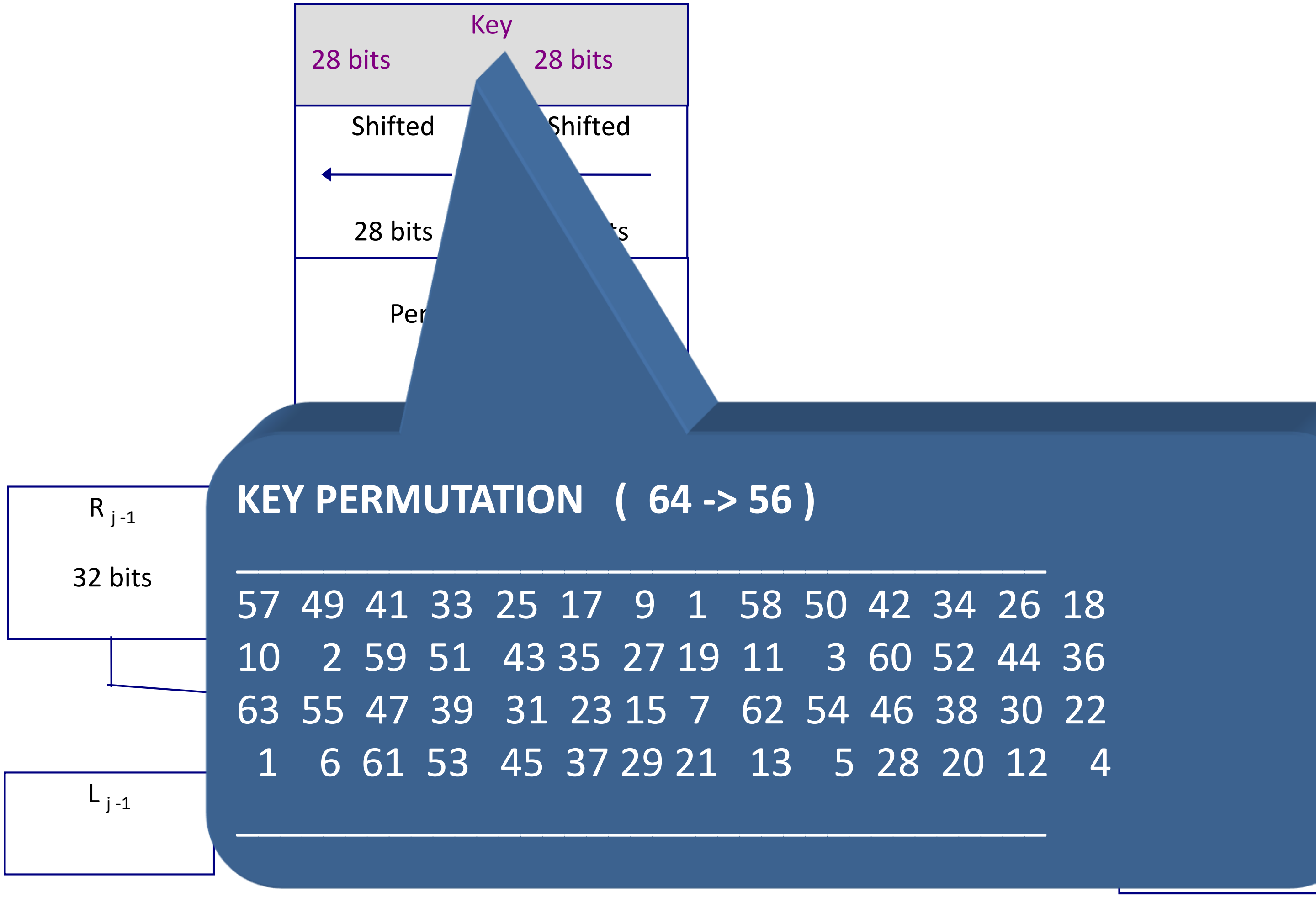
| Rounds | Shift |
|---|---|
| 1, 2, 9, 16 | one bit |
| Others | two bits |




*Key generation*

Symmetrical

# Block:DES-1977

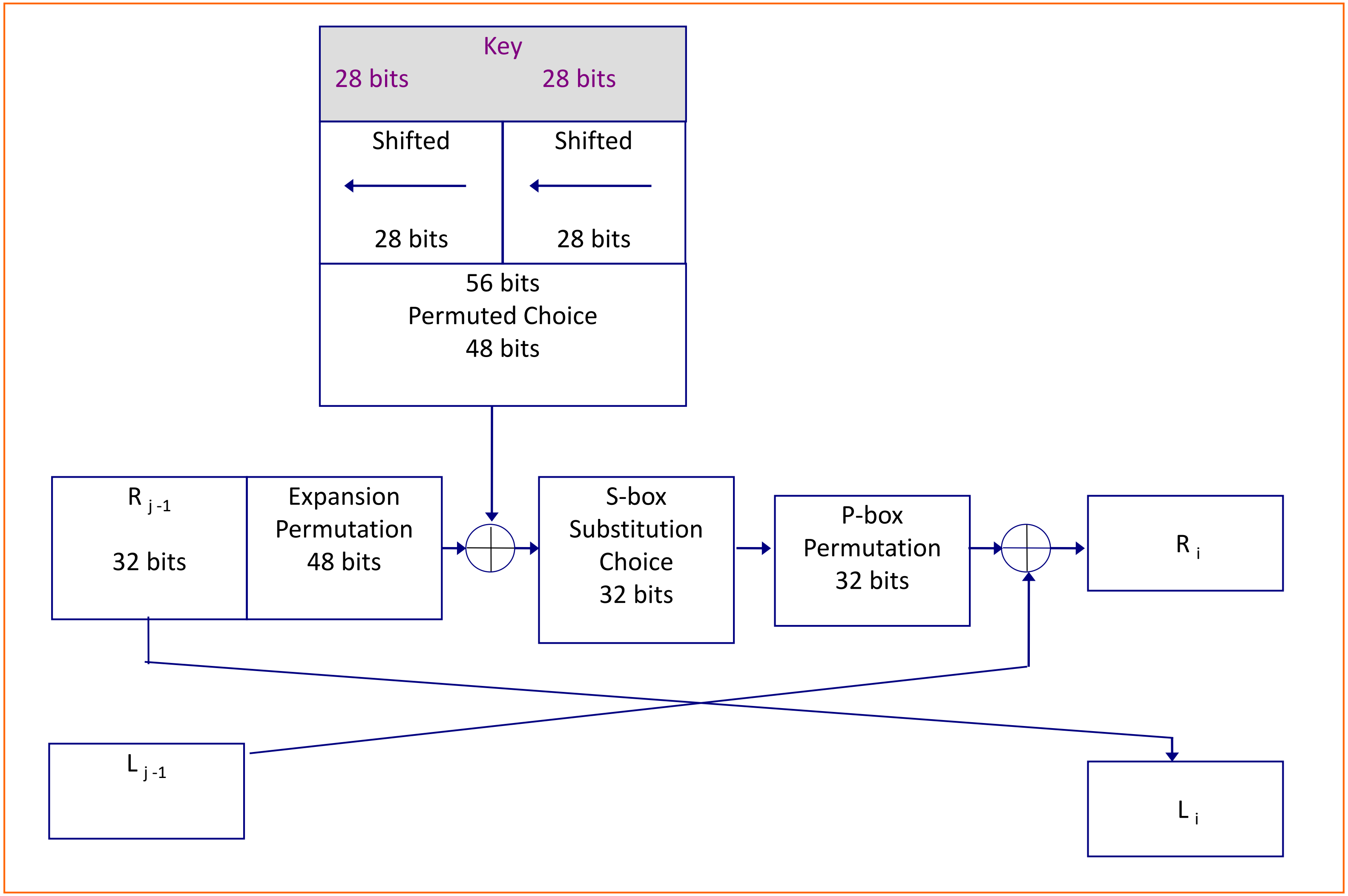



**KEY PERMUTATION ( 64 -> 56 )**

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

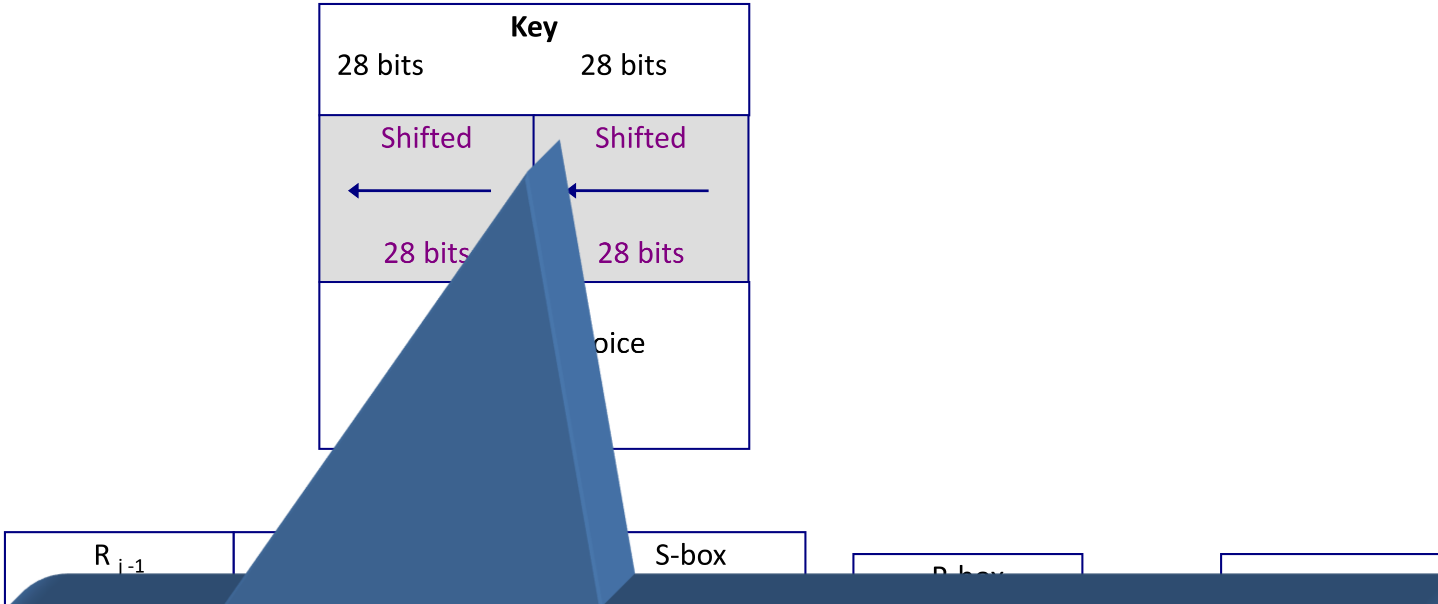
Symmetrical

# Block:DES-1977



Symmetrical

# Block:DES-1977

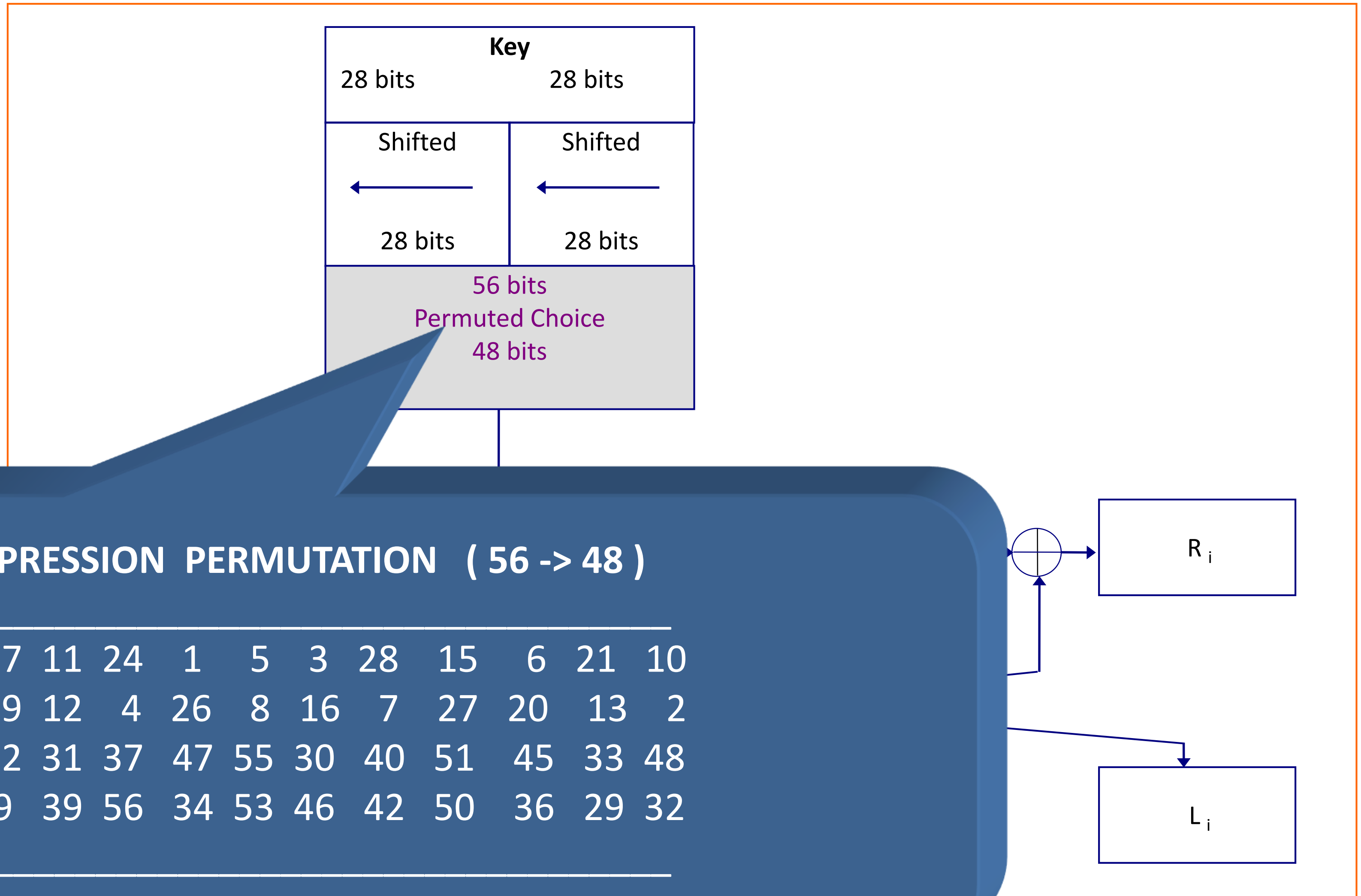



**KEY SHIFTS PER ROUND**

| Round | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # of shifts | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 1 |

Symmetrical

# Block:DES-1977

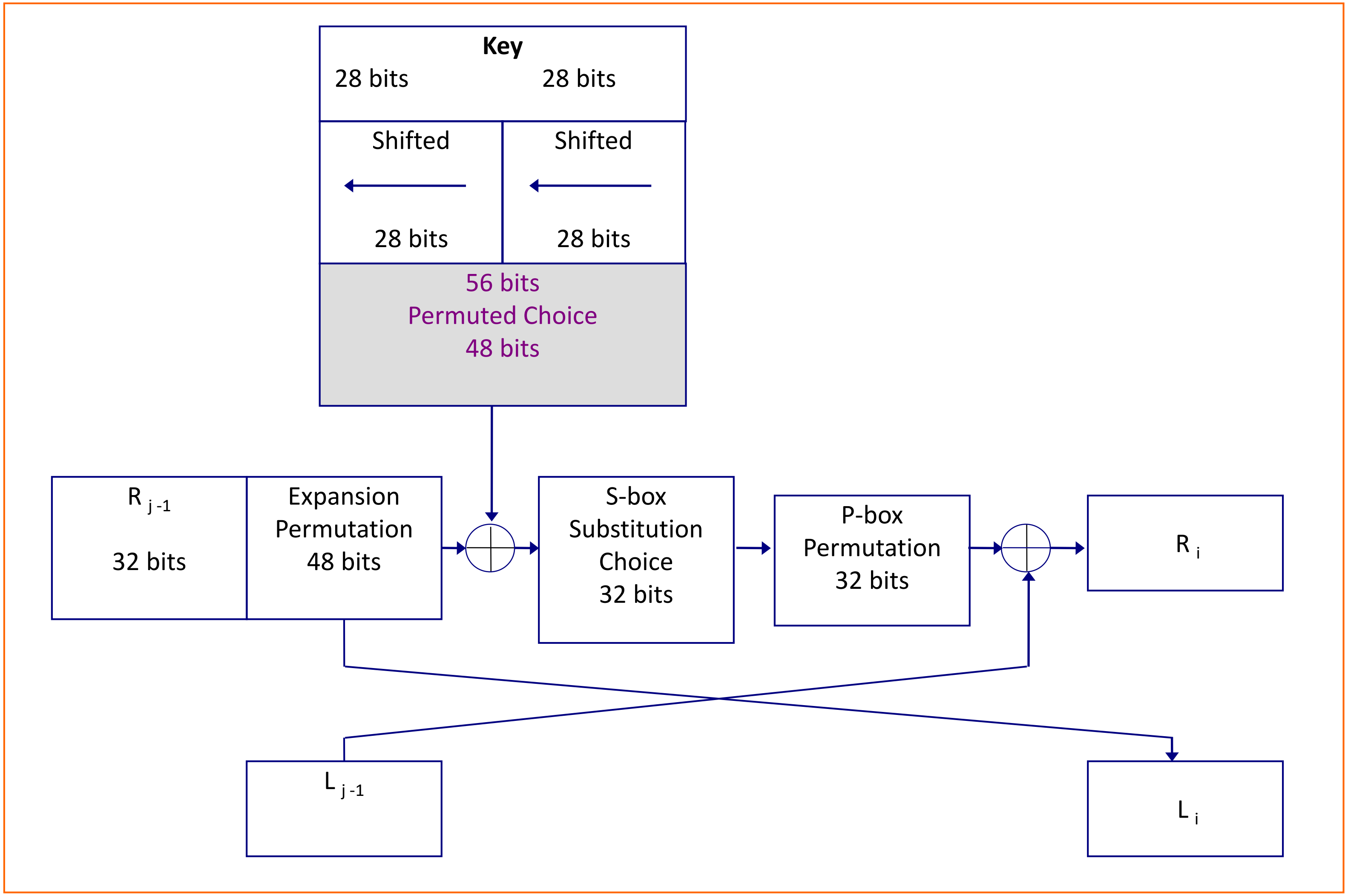



**COMPRESSION PERMUTATION ( 56 -> 48 )**

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 14 | 17 | 11 | 24 | 1 | 5 | 3 | 28 | 15 | 6 | 21 | 10 |
| 23 | 19 | 12 | 4 | 26 | 8 | 16 | 7 | 27 | 20 | 13 | 2 |
| 41 | 52 | 31 | 37 | 47 | 55 | 30 | 40 | 51 | 45 | 33 | 48 |
| 44 | 49 | 39 | 56 | 34 | 53 | 46 | 42 | 50 | 36 | 29 | 32 |

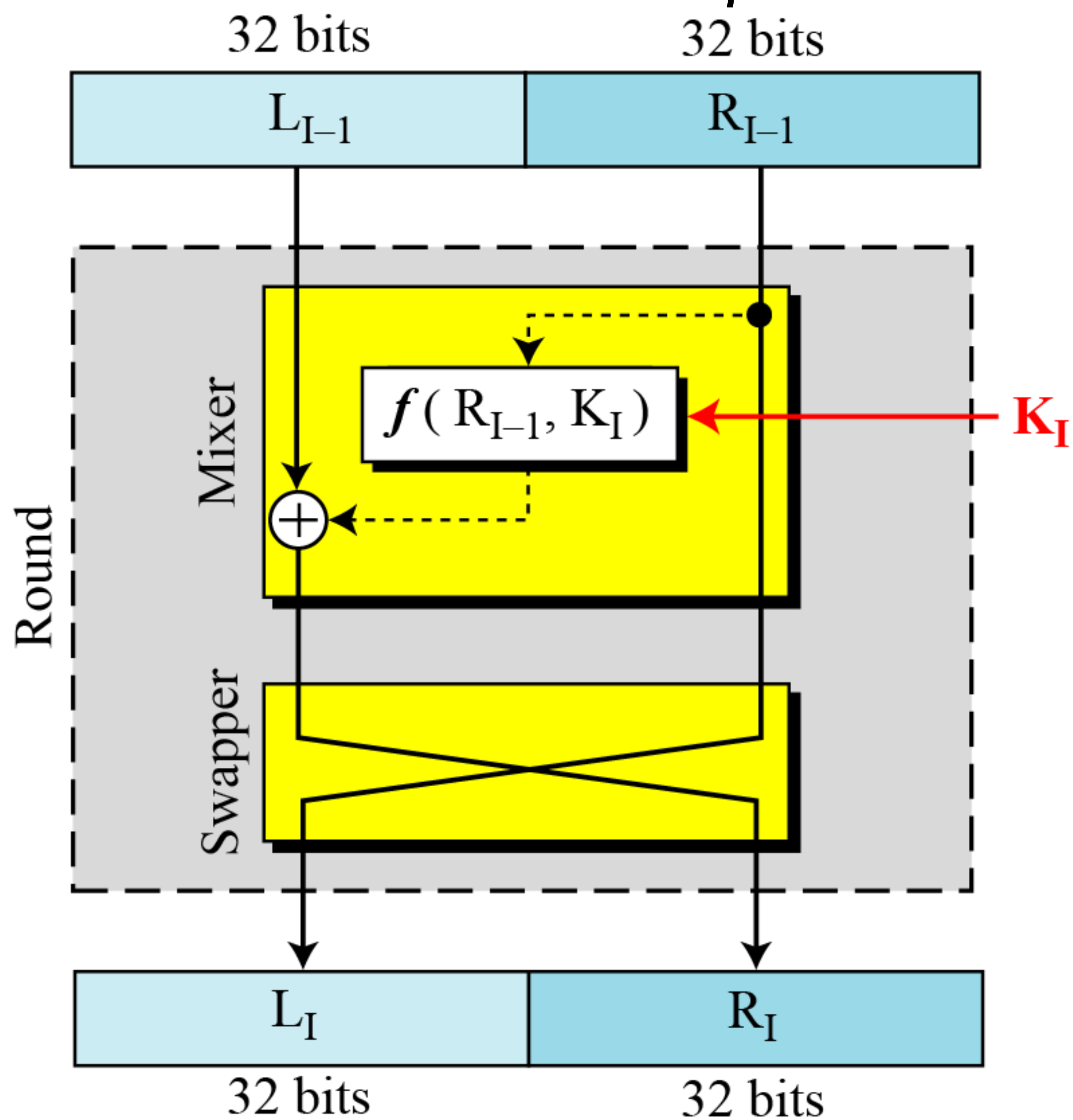
Symmetrical

# Block:DES-1977



# DES Rounds

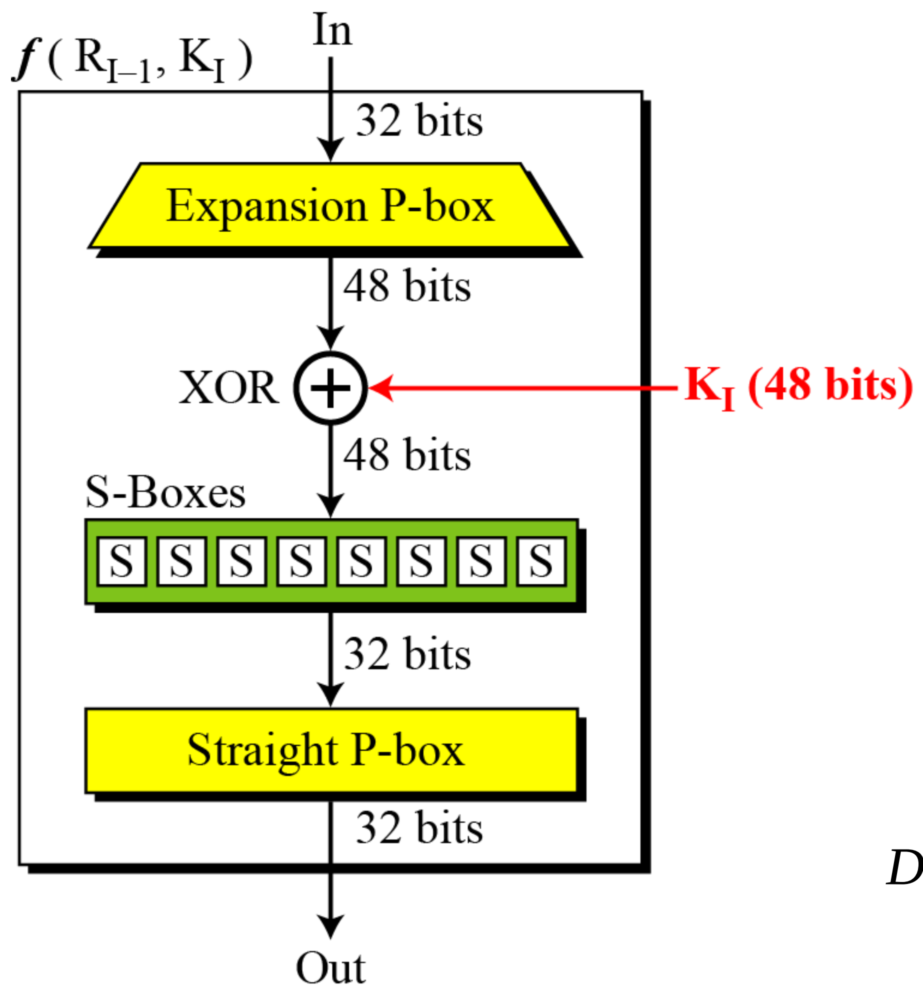
*DES uses 16 rounds. Each round of DES is a Feistel cipher.*




*A round in DES (encryption site)*

# DES Function

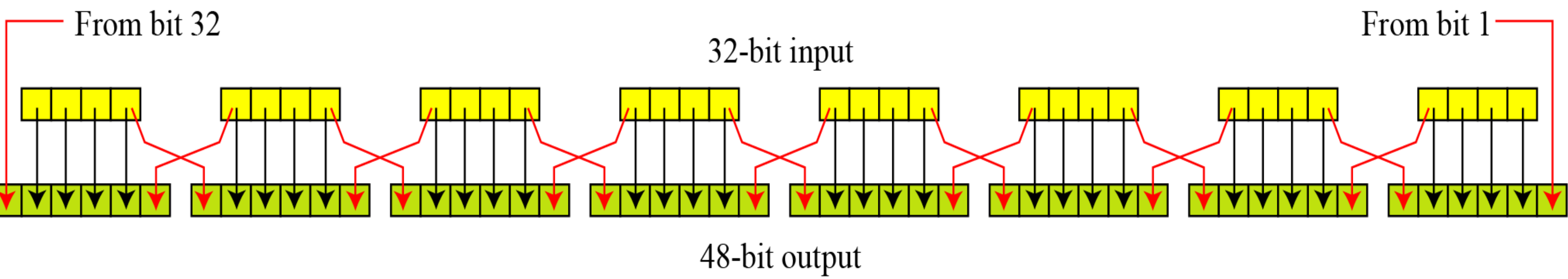
The heart of DES is the DES function. The DES function applies a 48-bit key to the rightmost 32 bits to produce a 32-bit output.




*DES function*

# Expansion P-box

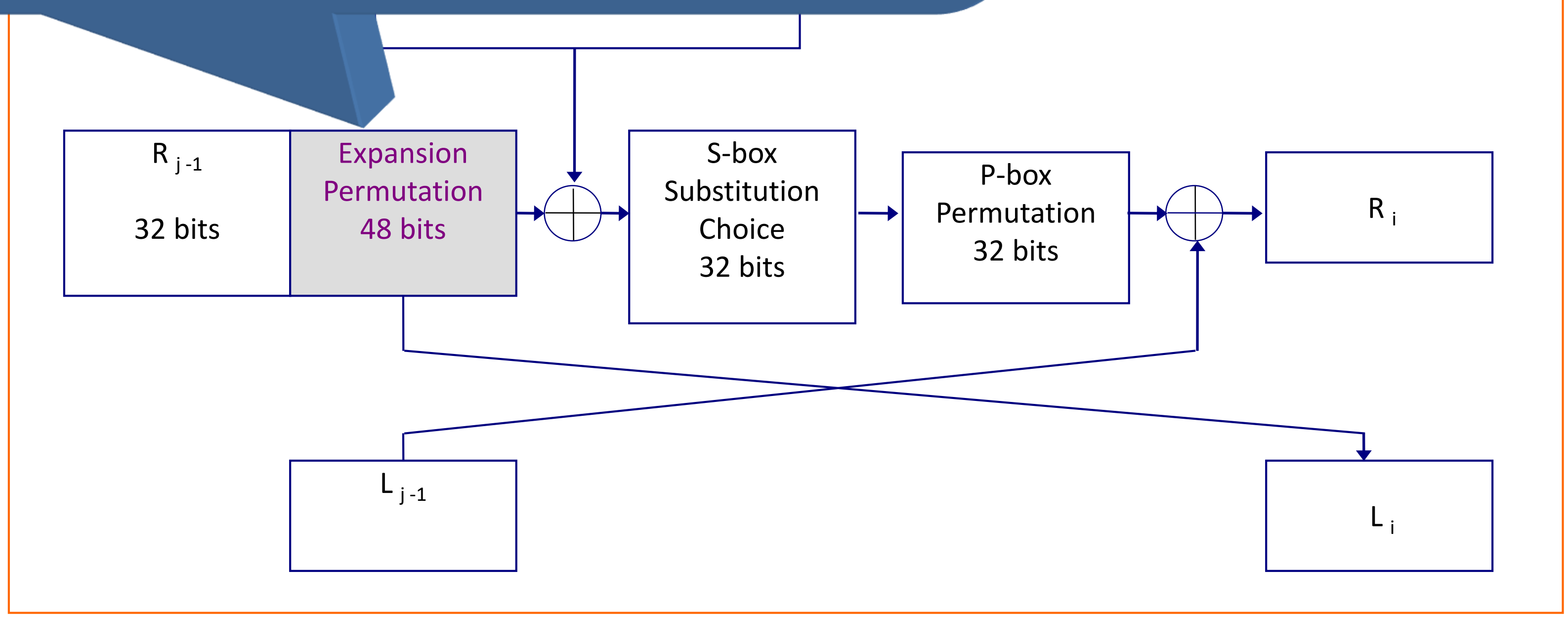
Since $R_{I-1}$ is a 32-bit input and $K_I$ is a 48-bit key, we first need to expand $R_{I-1}$ to 48 bits.




*Expansion permutation*

**EXPANSION PERMUTATION ( 32 -> 48 )**

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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 | |
| 17 | 24 | 25 | 26 | 27 | 28 | 29 | 28 | 29 | 30 | 31 | 32 | 1 |



# XOR

Whitener (XOR)

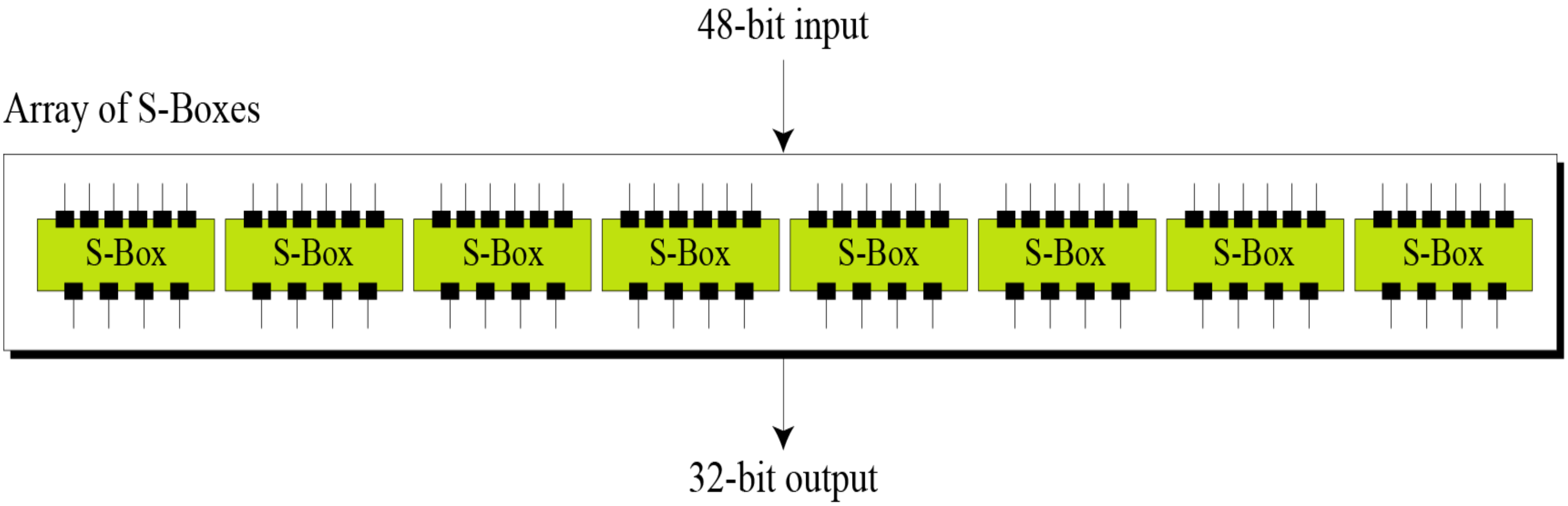
After the expansion permutation, DES uses the XOR operation on the expanded right section and the round key.

Note that both **the right section and the key are 48-bits in length**. Also note that **the round key is used only in this operation**.

# S-Boxes

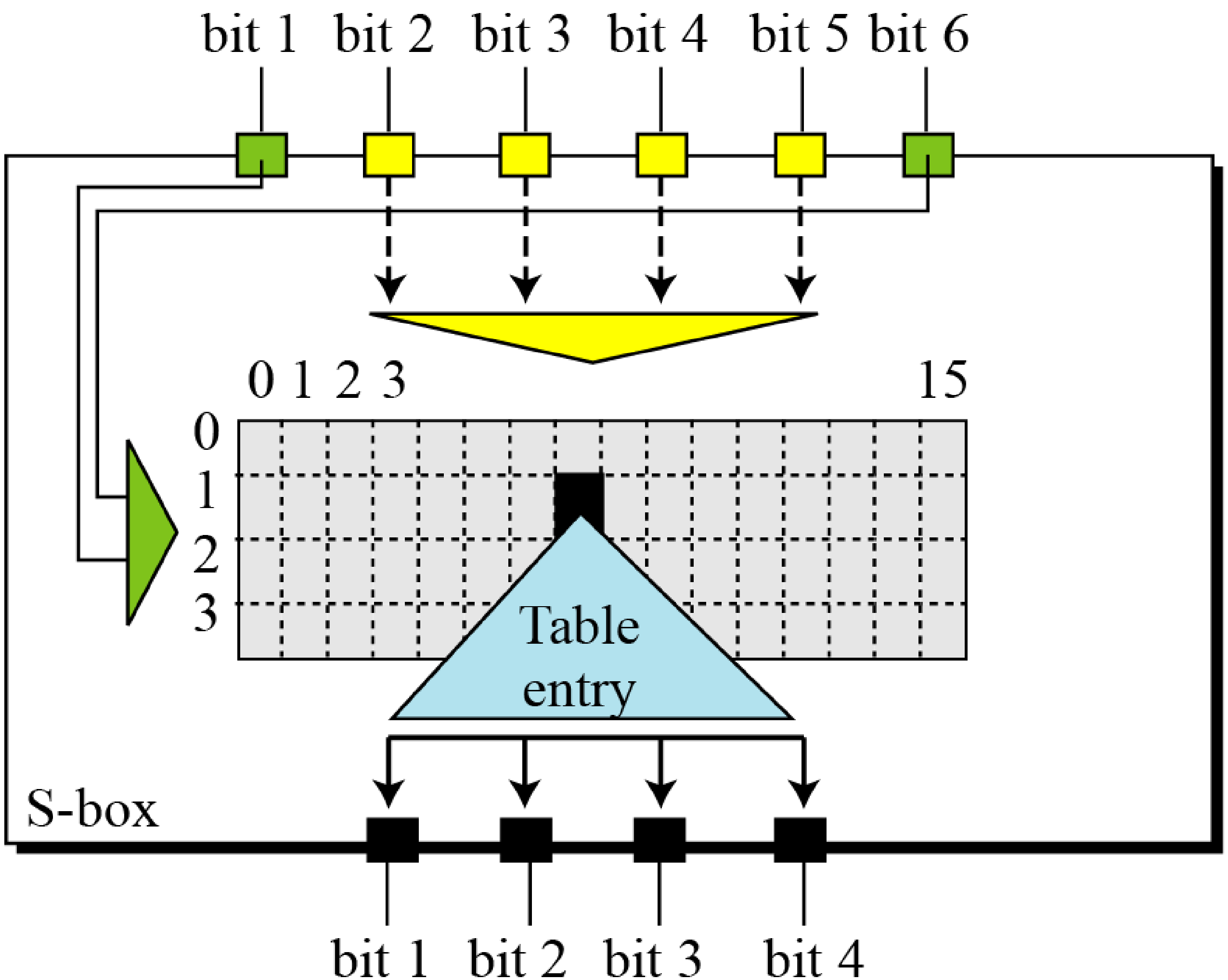
The S-boxes do the **real mixing (confusion).**

DES uses 8 S-boxes, each with a 6-bit input and a 4-bit output.




*S-boxes*

# S-Box Rule



bit 1
bit 2
bit 3
bit 4
bit 5
bit 6
0 1 2 3
15
0
1
2
3
Table entry
S-box
bit 1
bit 2
bit 3
bit 4

*** s1 ***

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 14 | 4 | 13 | 1 | 2 | 15 | 11 | 8 | 3 | 10 | 6 | 12 | 5 | 9 |
| 0 | 15 | 7 | 4 | 14 | 2 | 13 | 1 | 10 | 6 | 12 | 11 | 9 | 5 |
| 4 | 1 | 14 | 8 | 13 | 6 | 2 | 11 | 15 | 12 | 9 | 7 | 3 | 10 |
| 15 | 12 | 8 | 2 | 4 | 9 | 1 | 7 | 5 | 11 | 3 | 14 | 10 | 0 |

*** s2 ***

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 15 | 1 | 8 | 14 | 6 | 11 | 3 | 4 | 9 | 7 | 2 | 13 | 12 | 0 |
| 3 | 13 | 4 | 7 | 15 | 2 | 8 | 14 | 12 | 0 | 1 | 10 | 6 | |
| 0 | 14 | 7 | 11 | 10 | 4 | 13 | 1 | 5 | 8 | 12 | 6 | | |
| 13 | 8 | 10 | 1 | 3 | 15 | 4 | 2 | 11 | 6 | 7 | 12 | | |

*** s3 ***

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | 0 | 9 | 14 | 6 | 3 | 15 | 5 | 1 | 13 | 12 | | | |
| 13 | 7 | 0 | 9 | 3 | 4 | 6 | 10 | 2 | 8 | | | | |
| 13 | 6 | 4 | 9 | 8 | 15 | 3 | 0 | 11 | 1 | | | | |
| 1 | 10 | 13 | 0 | 6 | 9 | 8 | 7 | 4 | 15 | | | | |

*** s4 ***

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | 13 | 14 | 3 | 0 | 6 | 9 | 10 | 1 | 2 | | | | |
| 13 | 8 | 11 | 5 | 6 | 15 | 0 | 3 | 4 | 7 | | | | |
| 10 | 6 | 9 | 0 | 12 | 11 | 7 | 13 | 15 | 1 | 3 | | | |
| 3 | 15 | 0 | 6 | 10 | 1 | 13 | 8 | 9 | 4 | 5 | | | |

*** s5 ***

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 12 | 4 | 1 | 7 | 10 | 11 | 6 | 8 | 5 | | | | |
| 14 | 11 | 2 | 12 | 4 | 7 | 13 | 1 | 5 | 0 | | 10 | 3 | 9 |
| 4 | 2 | 1 | 11 | 10 | 13 | 7 | 8 | 15 | 9 | 12 | 5 | 6 | 3 |
| 11 | 8 | 12 | 7 | 1 | 14 | 2 | 13 | 6 | 15 | 0 | 9 | 10 | 4 |

*** s6 ***

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 | 1 | 10 | 15 | 9 | 2 | 6 | 8 | 0 | 13 | 3 | 4 | 14 | 7 |
| 10 | 15 | 4 | 2 | 7 | 12 | 9 | 5 | 6 | 1 | 13 | 14 | 0 | 11 |
| 9 | 14 | 15 | 5 | 2 | 8 | 12 | 3 | 7 | 0 | 4 | 10 | 1 | 13 |
| 4 | 3 | 2 | 12 | 9 | 5 | 15 | 10 | 11 | 14 | 1 | 7 | 6 | 0 |

*** s7 ***

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | 11 | 2 | 14 | 15 | 0 | 8 | 13 | 3 | 12 | 9 | 7 | 5 | 10 |
| 13 | 0 | 11 | 7 | 4 | 9 | 1 | 10 | 14 | 3 | 5 | 12 | 2 | 15 |
| 1 | 4 | 11 | 13 | 12 | 3 | 7 | 14 | 10 | 15 | 6 | 8 | 0 | 5 |
| 6 | 11 | 13 | 8 | 1 | 4 | 10 | 7 | 9 | 5 | 0 | 15 | 14 | 2 |

*** s8 ***

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 13 | 2 | 8 | 4 | 6 | 15 | 11 | 1 | 10 | 9 | 3 | 14 | 5 | 0 |
| 1 | 15 | 13 | 8 | 10 | 3 | 7 | 4 | 12 | 5 | 6 | 11 | 0 | 14 |
| 7 | 11 | 4 | 1 | 9 | 12 | 14 | 2 | 0 | 6 | 10 | 13 | 15 | 3 |
| 2 | 1 | 14 | 7 | 4 | 10 | 8 | 13 | 15 | 12 | 9 | 0 | 3 | 5 |

$(15)_{10} = (1111)_2$

**EXAMPLE S-BOX USAGE:**

INPUT TO THE 5th. S-BOX IS ==> 110011

01 1

ST BITS

NS 3rd. ROW

K BITS

ORM 1001

(9) WHICH MEANS 9th. COLUMN

2 10

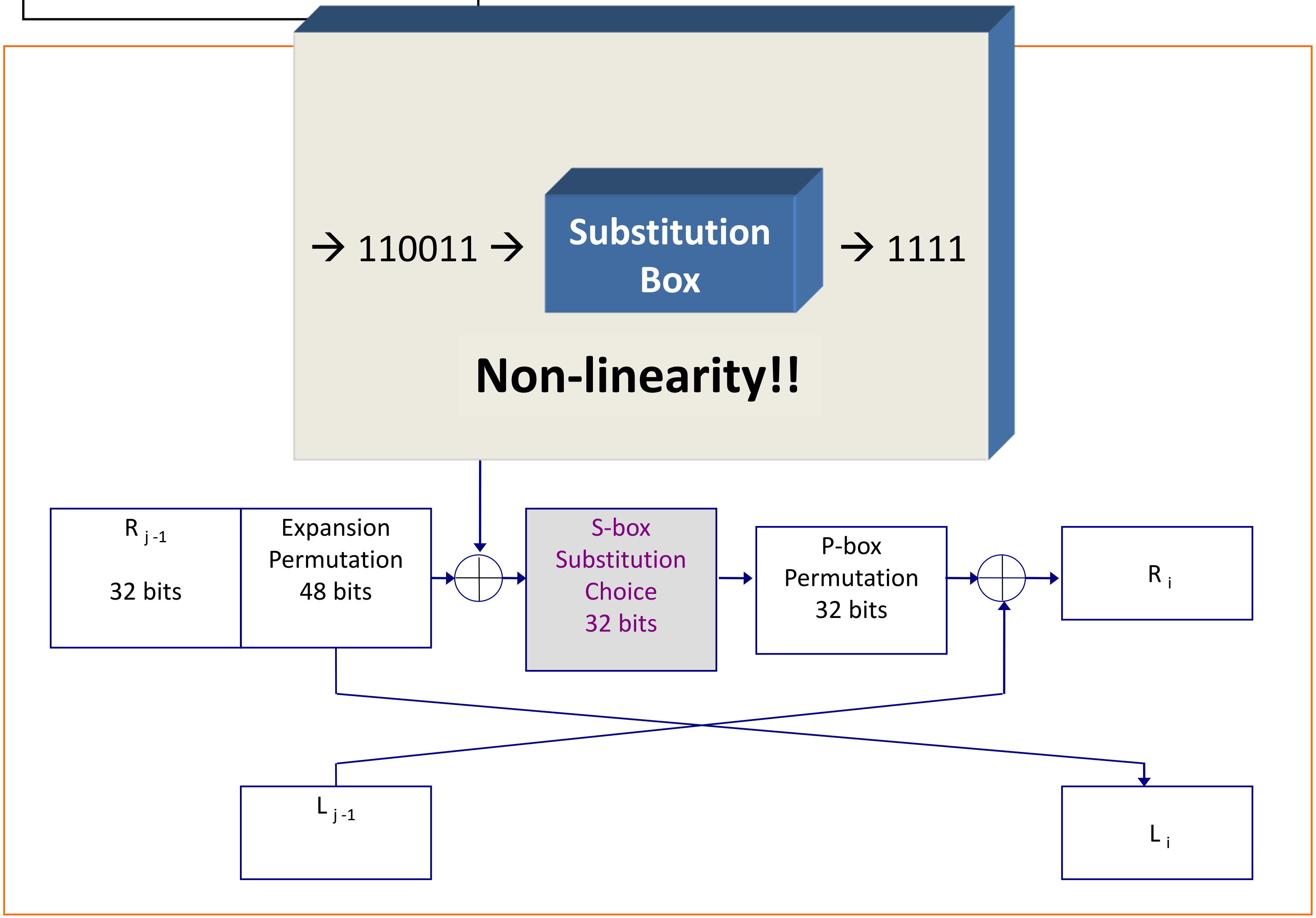
3rd. ROW, 9th. COLUMN OF THE 5th. S-BOX IS ==> 15, AND SO

$(15)_{10} = (1111)_2$

SO THE VALUE **1111** IS SUBSTITUED FOR **110011**

Symmetrical

# Block:DES-1977



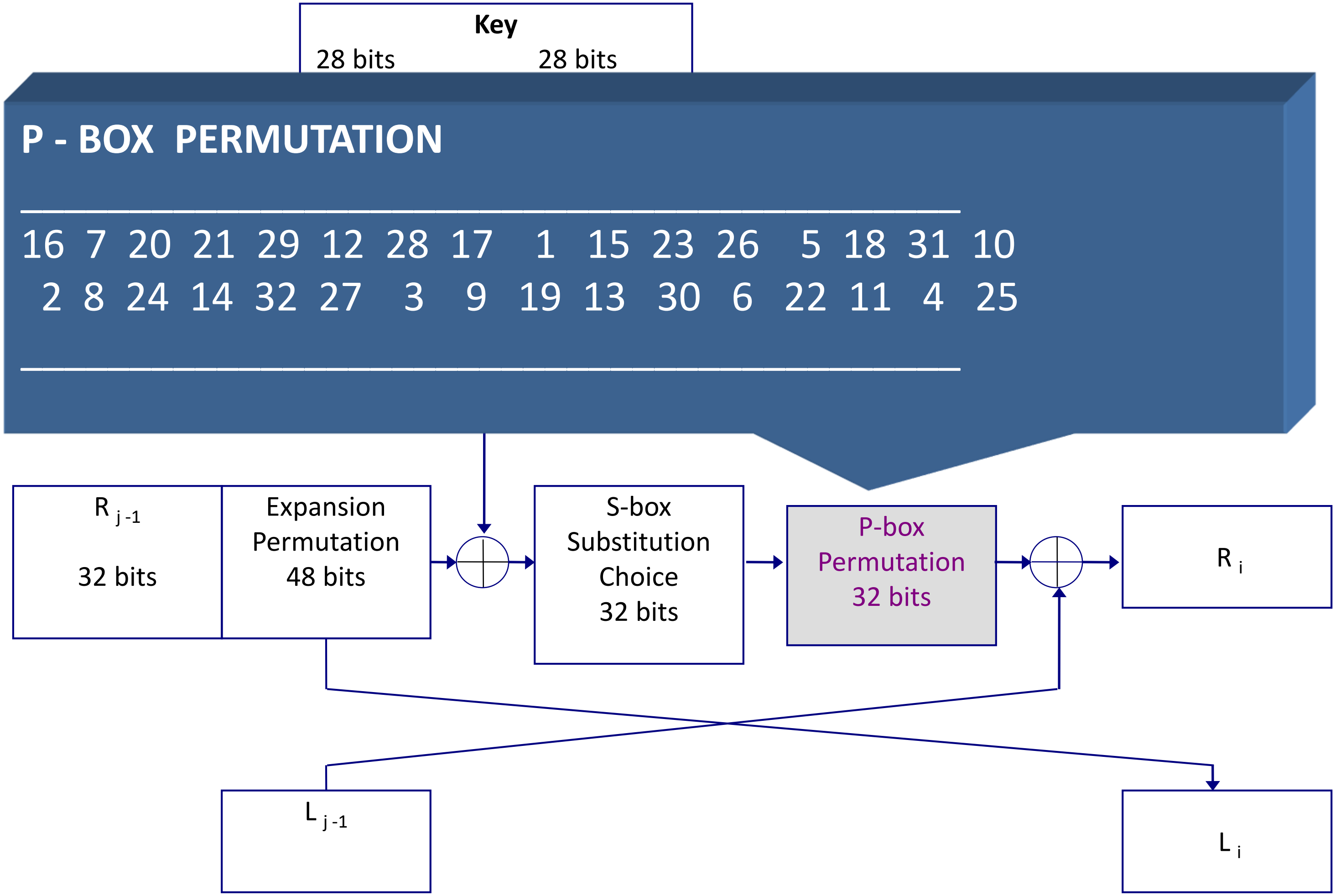
Symmetrix

Symmetrical

# Block:DES-1977

## P - BOX PERMUTATION

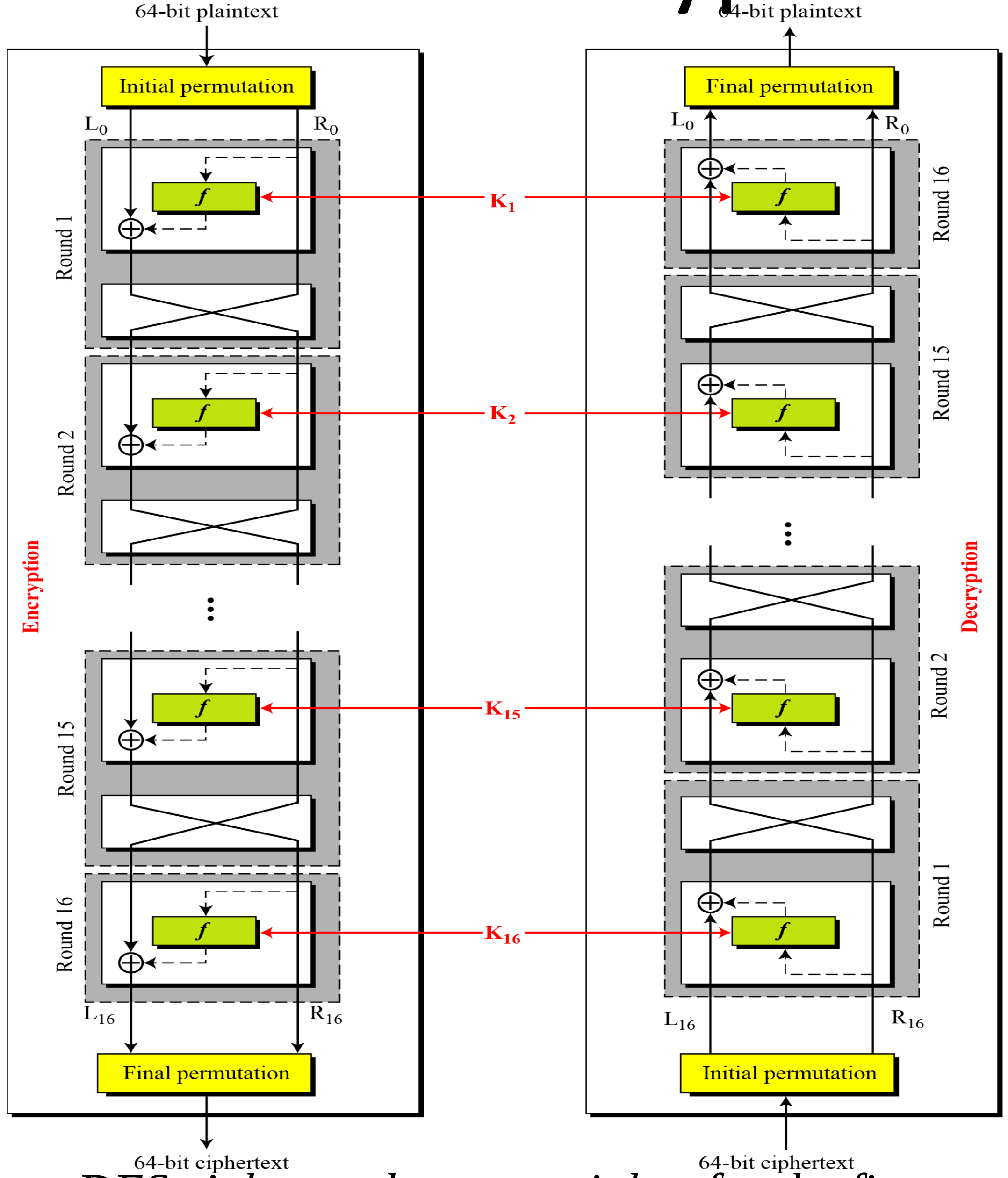
| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 16 | 7 | 20 | 21 | 29 | 12 | 28 | 17 | 1 | 15 | 23 | 26 | 5 | 18 | 31 | 10 |
| 2 | 8 | 24 | 14 | 32 | 27 | 3 | 9 | 19 | 13 | 30 | 6 | 22 | 11 | 4 | 25 |



# DES Decryption

- Decrypt must unwind steps of data computation
- With feistel design, do encryption steps again using subkeys in reverse order (SK16 … SK1)
  - IP undoes final FP step of encryption
  - 1st round with SK16 undoes 16th encrypt round
  - ….
  - 16th round with SK1 undoes 1st encrypt round
  - Then final FP undoes initial encryption IP
  - Thus recovering original data value

# DES Decryption




*DES cipher and reverse cipher for the first approach*

# Example 2

We choose a random plaintext block and a random key, and determine what the ciphertext block would be (all in hexadecimal):

Plaintext: 123456ABCD132536 Key: AABB09182736CCDD
CipherText: C0B7A8D05F3A829C

Table *Trace of data for Example 2*

| *Plaintext:* 123456ABCD132536 | | | |
|---|---|---|---|
| *After initial permutation:* 14A7D67818CA18AD<br>After splitting: $L_0$=14A7D678 $R_0$=18CA18AD | | | |
| *Round* | *Left* | *Right* | *Round Key* |
| *Round 1* | 18CA18AD | 5A78E394 | 194CD072DE8C |
| *Round 2* | 5A78E394 | 4A1210F6 | 4568581ABCCE |
| *Round 3* | 4A1210F6 | B8089591 | 06EDA4ACF5B5 |
| *Round 4* | B8089591 | 236779C2 | DA2D032B6EE3 |

# Example 2

Table *Trace of data for Example 2(Continue)*

| | | | |
|---|---|---|---|
| *Round 5* | 236779C2 | A15A4B87 | 69A629FEC913 |
| *Round 6* | A15A4B87 | 2E8F9C65 | C1948E87475E |
| *Round 7* | 2E8F9C65 | A9FC20A3 | 708AD2DDB3C0 |
| *Round 8* | A9FC20A3 | 308BEE97 | 34F822F0C66D |
| *Round 9* | 308BEE97 | 10AF9D37 | 84BB4473DCCC |
| *Round 10* | 10AF9D37 | 6CA6CB20 | 02765708B5BF |
| *Round 11* | 6CA6CB20 | FF3C485F | 6D5560AF7CA5 |
| *Round 12* | FF3C485F | 22A5963B | C2C1E96A4BF3 |
| *Round 13* | 22A5963B | 387CCDAA | 99C31397C91F |
| *Round 14* | 387CCDAA | BD2DD2AB | 251B8BC717D0 |
| *Round 15* | BD2DD2AB | CF26B472 | 3330C5D9A36D |
| *Round 16* | 19BA9212 | CF26B472 | 181C5D75C66D |
| *After combination:* 19BA9212CF26B472 | | | |
| *Ciphertext:* C0B7A8D05F3A829C *(after final permutation)* | | | |

# Example 3

Let us see how Bob, at the destination, can decipher the ciphertext received from Alice using the same key. Table shows some interesting points.

| | | | |
|---|---|---|---|
| *Ciphertext:* C0B7A8D05F3A829C | | | |
| *After initial permutation:* 19BA9212CF26B472<br>After splitting: $L_0$=19BA9212 $R_0$=CF26B472 | | | |
| *Round* | *Left* | *Right* | *Round Key* |
| *Round 1* | CF26B472 | BD2DD2AB | 181C5D75C66D |
| *Round 2* | BD2DD2AB | 387CCDAA | 3330C5D9A36D |
| . . . | . . . | . . . | . . . |
| *Round 15* | 5A78E394 | 18CA18AD | 4568581ABCCE |
| *Round 16* | 14A7D678 | 18CA18AD | 194CD072DE8C |
| After combination: 14A7D67818CA18AD | | | |
| Plaintext:123456ABCD132536 (after final permutation) | | | |

**Animation Link:** [http://www.cs.bham.ac.uk/research/projects/lemsys/DES/DESPage.jsp](http://www.cs.bham.ac.uk/research/projects/lemsys/DES/DESPage.jsp)

# DES Example

**Plaintext:** 02468aceeca86420
**Key:** 0f1571c947d9e859
**Ciphertext:** da02ce3a89ecac3b

The first row shows the 32-bit values of the left and right halves of data after the initial permutation.
The next 16 rows show the results after each round.

Also shown is the value of the 48-bit subkey generated for each round.

The final row shows the left and right-hand values after the inverse initial permutation. These two values combined form the ciphertext.

| Round | $K_i$ | $L_i$ | $R_i$ |
|---|---|---|---|
| IP | | 5a005a00 | 3cf03c0f |
| 1 | 1e030f03080d2930 | 3cf03c0f | bad22845 |
| 2 | 0a31293432242318 | bad22845 | 99e9b723 |
| 3 | 23072318201d0c1d | 99e9b723 | 0bae3b9e |
| 4 | 05261d3824311a20 | 0bae3b9e | 42415649 |
| 5 | 3325340136002c25 | 42415649 | 18b3fa41 |
| 6 | 123a2d0d04262a1c | 18b3fa41 | 9616fe23 |
| 7 | 021f120b1c130611 | 9616fe23 | 67117cf2 |
| 8 | 1c10372a2832002b | 67117cf2 | c11bfc09 |
| 9 | 04292a380c341f03 | c11bfc09 | 887fbc6c |
| 10 | 2703212607280403 | 887fbc6c | 600f7e8b |
| 11 | 2826390c31261504 | 600f7e8b | f596506e |
| 12 | 12071c241a0a0f08 | f596506e | 738538b8 |
| 13 | 300935393c0d100b | 738538b8 | c6a62c4e |
| 14 | 311e09231321182a | c6a62c4e | 56b0bd75 |
| 15 | 283d3e0227072528 | 56b0bd75 | 75e8fd8f |
| 16 | 2921080b13143025 | 75e8fd8f | 25896490 |
| $IP^{-1}$ | | da02ce3a | 89ecac3b |

# Avalanche Effect

A desirable property of any encryption algorithm is that **a small change in either the plaintext or the key should produce a significant change in the ciphertext.**

- Key desirable property of encryption algorithm
- Where a change of **one** input or key bit results in changing approx **half** output bits
- Making attempts to “home-in” by guessing keys impossible
- DES exhibits strong avalanche

# Avalanche in DES

Table shows the result when the fourth bit of the plaintext is changed.
The plaintext is 12468aceeca86420.
The second column shows the intermediate 64-bit values at the end of each round for the two plaintexts.
The third column shows the number of bits that differ between the two intermediate values.
The table shows that after just three rounds, 18 bits differ between the two blocks.

| Round | | δ |
|---|---|---|
| | 02468aceeca86420<br>12468aceeca86420 | 1 |
| 1 | 3cf03c0fbad22845<br>3cf03c0fbad32845 | 1 |
| 2 | bad2284599e9b723<br>bad3284539a9b7a3 | 5 |
| 3 | 99e9b7230bae3b9e<br>39a9b7a3171cb8b3 | 18 |
| 4 | 0bae3b9e42415649<br>171cb8b3ccaca55e | 34 |
| 5 | 4241564918b3fa41<br>ccaca55ed16c3653 | 37 |
| 6 | 18b3fa419616fe23<br>d16c3653cf402c68 | 33 |
| 7 | 9616fe2367117cf2<br>cf402c682b2cefbc | 32 |
| 8 | 67117cf2c11bfc09<br>2b2cefbc99f91153 | 33 |

| Round | | δ |
|---|---|---|
| 9 | c11bfc09887fbc6c<br>99f911532eed7d94 | 32 |
| 10 | 887fbc6c600f7e8b<br>2eed7d94d0f23094 | 34 |
| 11 | 600f7e8bf596506e<br>d0f23094455da9c4 | 37 |
| 12 | f596506e738538b8<br>455da9c47f6e3cf3 | 31 |
| 13 | 738538b8c6a62c4e<br>7f6e3cf34bc1a8d9 | 29 |
| 14 | c6a62c4e56b0bd75<br>4bc1a8d91e07d409 | 33 |
| 15 | 56b0bd7575e8fd8f<br>1e07d4091ce2e6dc | 31 |
| 16 | 75e8fd8f25896490<br>1ce2e6dc365e5f59 | 32 |
| $IP^{-1}$ | da02ce3a89ecac3b<br>057cde97d7683f2a | 32 |

# Completeness Effect

Completeness effect means that each bit of the ciphertext needs to depend on many bits on the plaintext.

# An Exercise

**Q.** Explain why the cipher $e_k(m) = k \oplus m$ and $d_k(c) = k \oplus c$ defined by XOR of bit strings is not secure against a chosen plaintext attack.

Demonstrate your attack by finding the private key used to encrypt the 16-bit ciphertext $c = 1001010001010111$ if you know that the corresponding plaintext is $p=0010010000101100$.

**A.**

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| c | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 1 |
| **k** | **1** | **0** | **1** | **1** | **0** | **0** | **0** | **0** | **0** | **1** | **1** | **0** | **1** | **0** | **1** | **1** |
| p | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 0 |

# DES Weaknesses

During the last few years critics have found some weaknesses in DES.

## Weaknesses in Cipher Design

1. Weaknesses in S-boxes
2. Weaknesses in P-boxes
3. Weaknesses in Key

**Table 6.18** *Weak keys*

| *Keys before parities drop (64 bits)* | *Actual key (56 bits)* |
|---|---|
| 0101 0101 0101 0101 | 0000000 0000000 |
| 1F1F 1F1F 0E0E 0E0E | 0000000 FFFFFFF |
| E0E0 E0E0 F1F1 F1F1 | FFFFFFF 0000000 |
| FEFE FEFE FEFE FEFE | FFFFFFF FFFFFFF |

# Strength of DES – Key Size

- 56-bit keys have $2^{56} = 7.2 \times 10^{16}$ values
- brute force search looks hard
- recent advances have shown is possible
  - in 1997 on Internet in a few months
  - in 1998 on dedicated h/w (Electronic Frontier Foundation –EFF, "DES cracker" machine, $250,000) in a few days
  - in 1999 above combined in 22hrs!
- still must be able to recognize plaintext
- must now consider alternatives to DES

# Example – DES Weaknesses

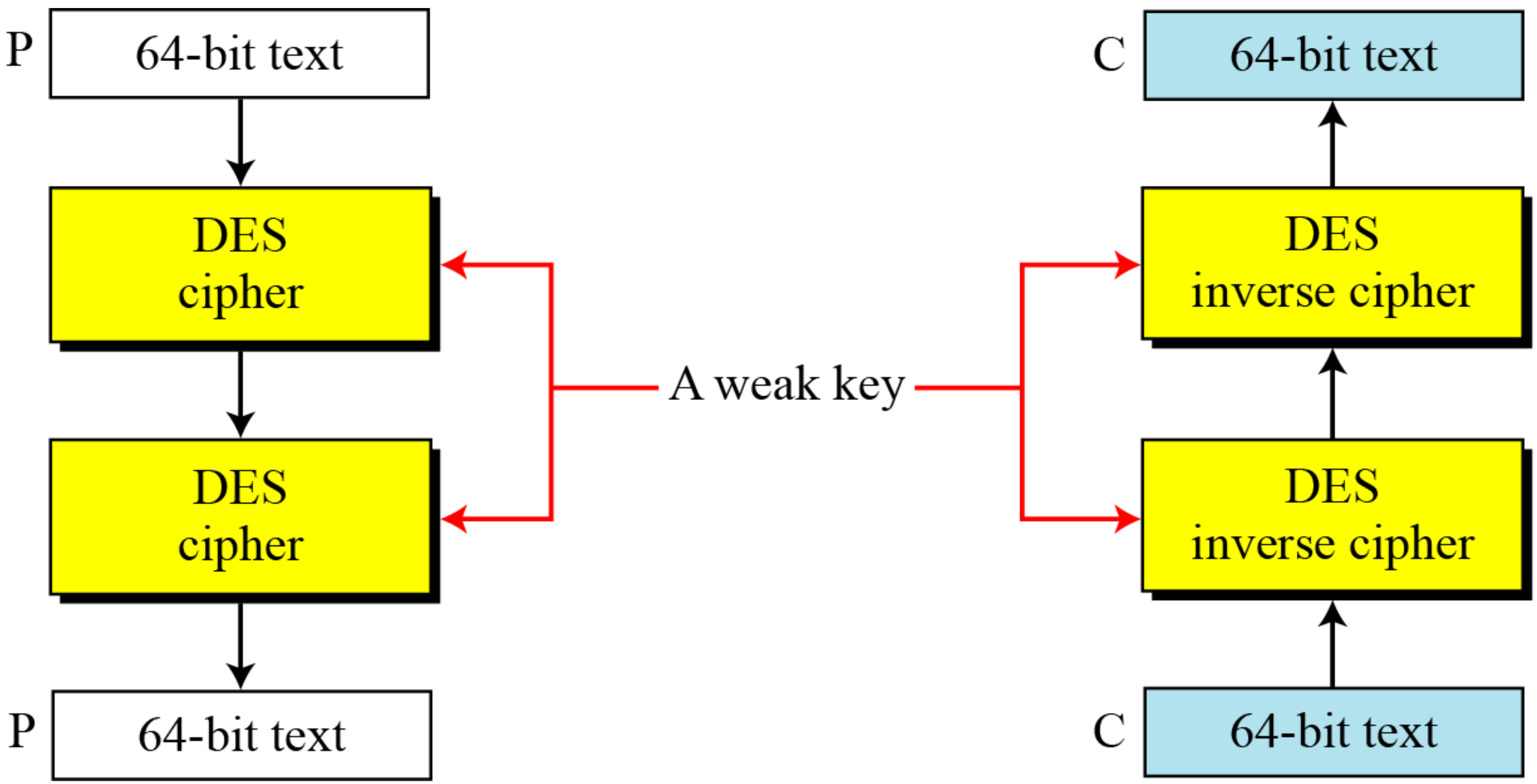
Let us try the first weak key in the Table to encrypt a block two times. After two encryptions with the same key the original plaintext block is created. Note that we have used the encryption algorithm two times, not one encryption followed by another decryption.

Key: 0x0101010101010101
Plaintext: *0x1234567887654321*    Ciphertext: 0x814FE938589154F7

Key: 0x0101010101010101
Plaintext: 0x814FE938589154F7    Ciphertext: *0x1234567887654321*

# Example – DES Weaknesses

*Double encryption and decryption with a weak key*



# Example – DES Weaknesses

**Table 6.19** *Semi-weak keys*

| *First key in the pair* | *Second key in the pair* |
|---|---|
| 01FE 01FE 01FE 01FE | FE01 FE01 FE01 FE01 |
| 1FE0 1FE0 0EF1 0EF1 | E01F E01F F10E F10E |
| 01E0 01E1 01F1 01F1 | E001 E001 F101 F101 |
| 1FFE 1FFE 0EFE 0EFE | FE1F FE1F FE0E FE0E |
| 011F 011F 010E 010E | 1F01 1F01 0E01 0E01 |
| E0FE E0FE F1FE F1FE | FEE0 FEE0 FEF1 FEF1 |

# Example – DES Weaknesses

| | | |
|---|---|---|
| *Round key 1* | 9153E54319BD | 6EAC1ABCE642 |
| *Round key 2* | 6EAC1ABCE642 | 9153E54319BD |
| *Round key 3* | 6EAC1ABCE642 | 9153E54319BD |
| *Round key 4* | 6EAC1ABCE642 | 9153E54319BD |
| *Round key 5* | 6EAC1ABCE642 | 9153E54319BD |
| *Round key 6* | 6EAC1ABCE642 | 9153E54319BD |
| *Round key 7* | 6EAC1ABCE642 | 9153E54319BD |
| *Round key 8* | 6EAC1ABCE642 | 9153E54319BD |
| *Round key 9* | 9153E54319BD | 6EAC1ABCE642 |
| *Round key 10* | 9153E54319BD | 6EAC1ABCE642 |
| *Round key 11* | 9153E54319BD | 6EAC1ABCE642 |
| *Round key 12* | 9153E54319BD | 6EAC1ABCE642 |
| *Round key 13* | 9153E54319BD | 6EAC1ABCE642 |
| *Round key 14* | 9153E54319BD | 6EAC1ABCE642 |
| *Round key 15* | 9153E54319BD | 6EAC1ABCE642 |
| *Round key 16* | 6EAC1ABCE642 | 9153E54319BD |

# Security of DES

- Now have several analytic attacks on DES
- These utilise some deep structure of the cipher
  - by gathering information about encryptions
  - can eventually recover some/all of the sub-key bits
  - if necessary then exhaustively search for the rest
- Generally these are statistical attacks
  - differential cryptanalysis
  - linear cryptanalysis
  - related key attacks

# Brute-Force Attack

We have discussed the weakness of short cipher key in DES.

Combining this weakness with the key complement weakness, it is clear that DES can be broken using $2^{55}$ encryptions.

# Multiple Encryption with DES

- In 2001, NIST published the Advanced Encryption Standard (AES) to replace DES.
- But users in commerce and finance are not ready to give up on DES.
- As a temporary solution to DES's security problem, one may encrypt a message (with DES) multiple times using multiple keys:
  - 2DES is not much securer than the regular DES
  - So, 3DES with either 2 or 3 keys is used

# 3DES with 2 keys

- A straightforward implementation would be:

$$c := E_{k_1}\left(E_{k_2}\left(E_{k_1}(m)\right)\right)$$

- In practice: $c := E_{k_1}\left(D_{k_2}\left(E_{k_1}(m)\right)\right)$
  - Also referred to as EDE encryption
- Reason: if $k_1 = k_2$, then 3DES $=$ 1DES.
  Thus, a 3DES software can be used as a single-DES.
- Standardized in ANSI X9.17 & ISO 8732.
- No practical attacks are known.

## 3DES with 3 keys

- Encryption: $c := E_{k_3}\left(D_{k_2}\left(E_{k_1}(m)\right)\right).$
- If $k_1 = k_3,$ it becomes 3DES with 2 keys.
- If $k_1 = k_2 = k_3,$ it becomes the regular DES.
- So, it is backward compatible with both 3DES with 2 keys and the regular DES.
- Some internet applications adopt 3DES with three keys; e.g. PGP and S / MIME.

# Summary

- Have considered:
  - Block vs stream ciphers
  - Feistel cipher design & structure
  - DES
    - details
    - strength
  - DES attack types
  - DES implementation types