Information Security
CS3002

Lecture 5
2nd September 2024

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Feistel Cipher

- Feistel proposed that we can approximate the ideal block cipher by utilizing the concept of a product cipher.

- The essence of the approach is to develop a block cipher with a key length of k bits and a block length of n bits, allowing a total of 2^k possible transformations, rather than the $2^n!$ transformations available with the ideal block cipher.

- He proposed the use of a cipher that alternates substitutions and permutations.

- Feistel's is a practical application of a proposal by Claude Shannon.

Claude Shannon and Substitution-Permutation Ciphers

- Claude Shannon introduced idea of substitution-permutation (S-P) networks in 1949 paper
- Form basis of modern block ciphers
- S-P nets are based on the two primitive cryptographic operations :
  - *substitution* (S-box)
  - *permutation* (P-box)
- provide *confusion* & *diffusion* of message & key

Confusion and Diffusion

- Confusion: An encryption operation where the relationship between key and ciphertext is obscured.
    - Today, a common element for achieving confusion is substitution, which is found in both AES and DES
- Diffusion: An encryption operation where the influence of one plaintext symbol is spread over many ciphertext symbols with the goal of hiding statistical properties of the plaintext.
    - A simple diffusion element is the bit permutation, which is frequently use

Credit: Chapter 3 of Understanding Cryptography by Christof Paar and Jan Pelzl

Feistel Cipher Structure

- Input
  - plaintext block of length $2w$
  - key K
- Plaintext block divided to L_0, R_0
- Pass through n rounds of processing
- Each round i has
  - L_{i-1}, R_{i-1} derived from previous round
  - subkey K_i derived from overall K

Feistel encryption and decryption
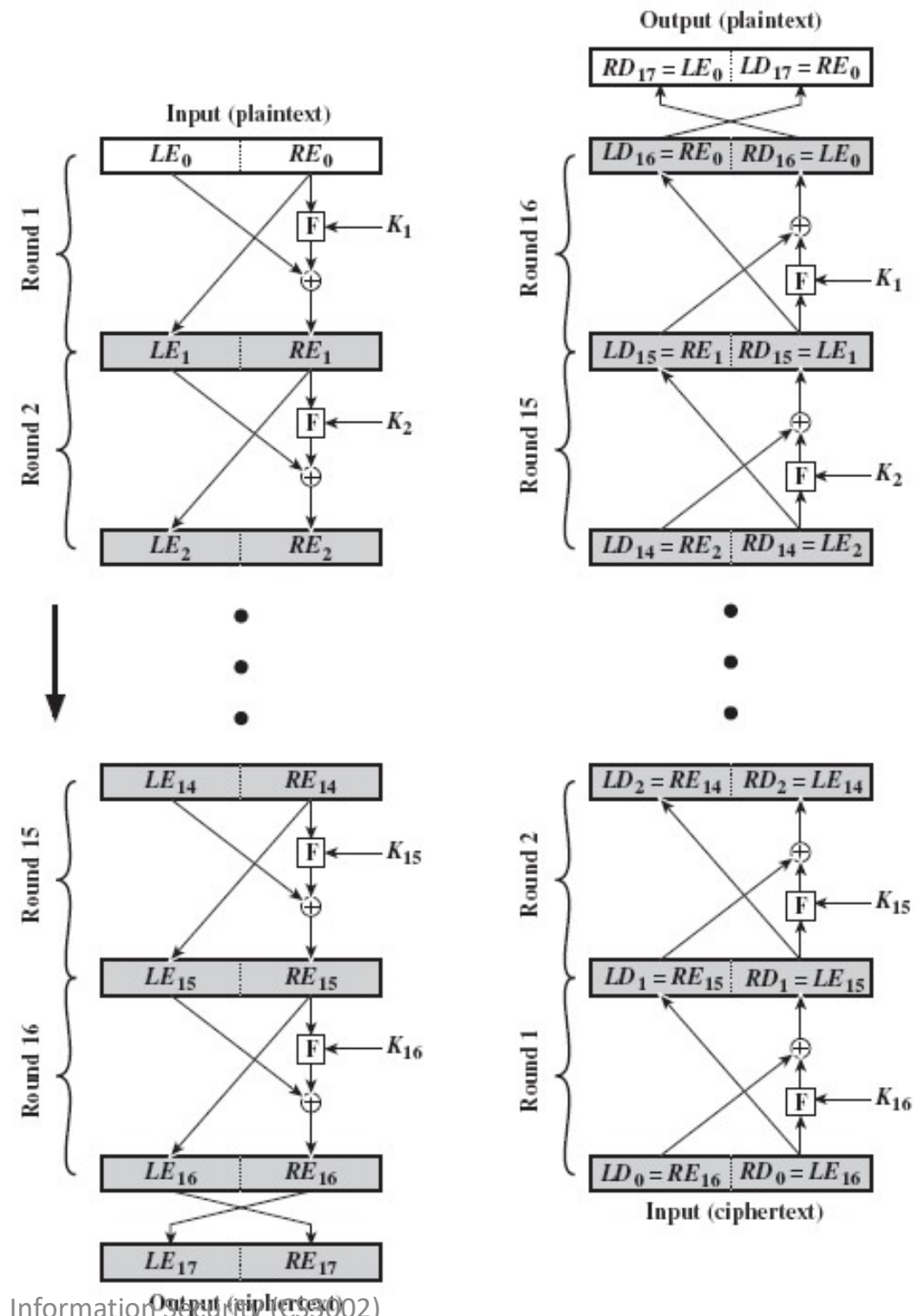
Feistel Cipher Structure

- Substitution
  - Apply round function F to right half.
  - Take XOR of output with left half.
  - F is parameterized by round subkey K_i.
- Permutation
  - Interchange left and right halves.

Design Parameters (1/3)

- Block size
  - Larger: greater security (diffusion)
  - Smaller: faster encryption, decryption
  - Typical: 64 bit, 128 bit
- Key size
  - Larger: greater security (brute-force resist)
  - Smaller: faster encryption, decryption
  - Typical: 128 bit

Design Parameters (2/3)

- Number of rounds
  - Multiple rounds increase security
  - Typical: 16
- Subkey generation algorithm
  - Complexity makes cryptanalysis difficult
- Round function
  - Complexity makes cryptanalysis difficult

Design Parameters (3/3)

- Speed of execution
  - Required for embedded systems
- Ease of analysis
  - Algorithm easy to understand is easy to identify vulnerabilities

Feistel Cipher Decryption

- Ciphertext is used as input
- Use subkeys K_i in reverse order
- Same algorithm is used
- Notation
  - LE_i : left half in encryption algorithm
  - RE_i : right half in encryption algorithm
  - LD_i : left half in decryption algorithm
  - RD_i : right half in decryption algorithm

Feistel Cipher Decryption

- Output of ith encryption round $\rightarrow$ input to i^{th} decryption round swapped
- $LE_i || RE_i \equiv RD_{16-i} || LD_{16-i}$

Feistel Cipher Decryption

Output (plaintext)

$RD_{17} = LE_0 \quad LD_{17} = RE_0$

Input (plaintext)

$LE_0 \quad RE_0$

Round 1

$F \leftarrow K_1$

$LE_1 \quad RE_1$

Round 2

$F \leftarrow K_2$

$LE_2 \quad RE_2$

Round 16

$LD_{16} = RE_0 \quad RD_{16} = LE_0$

$F \leftarrow K_1$

$LD_{15} = RE_1 \quad RD_{15} = LE_1$

Round 15

$F \leftarrow K_2$

$LD_{14} = RE_2 \quad RD_{14} = LE_2$

$LE_{14} \quad RE_{14}$

Round 15

$F \leftarrow K_{15}$

$LE_{15} \quad RE_{15}$

Round 16

$F \leftarrow K_{16}$

$LE_{16} \quad RE_{16}$

$LE_{17} \quad RE_{17}$

Output (ciphertext)

$LD_2 = RE_{14} \quad RD_2 = LE_{14}$

Round 2

$F \leftarrow K_{15}$

$LD_1 = RE_{15} \quad RD_1 = LE_{15}$

Round 1

$F \leftarrow K_{16}$

$LD_0 = RE_{16} \quad RD_0 = LE_{16}$
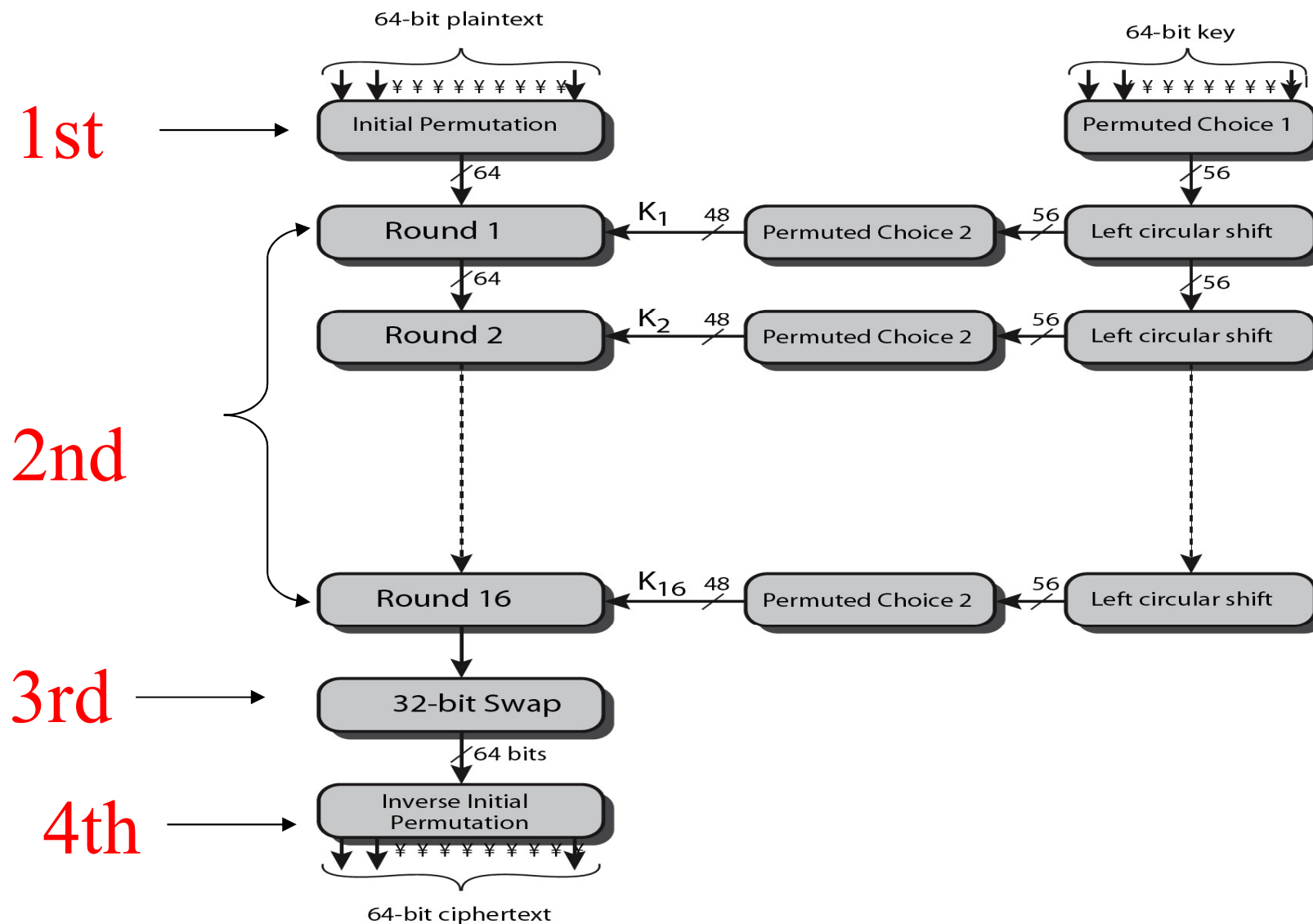
Input (ciphertext)

3
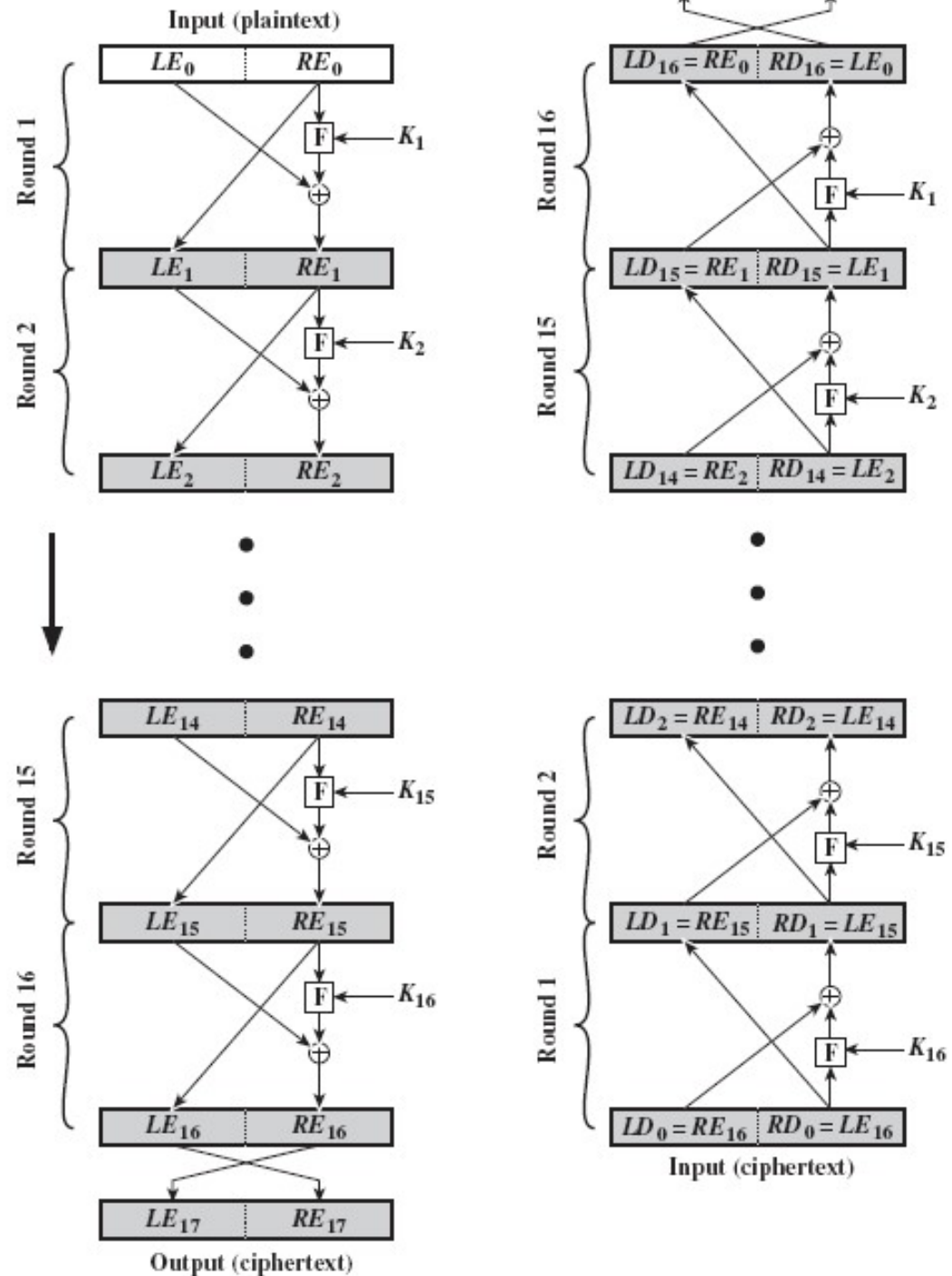
Data Encryption Standard (DES)

Data Encryption Standard (DES)

- Most widely used block cipher in world
- Adopted in 1977 by NBS (now NIST)
  - as FIPS PUB 46
- Encrypts 64-bit data using 64-bit key
- Exact structure as Feistel except
  - Initial permutation of plaintext
  - Final permutation of last round's out

DES Encryption Overview
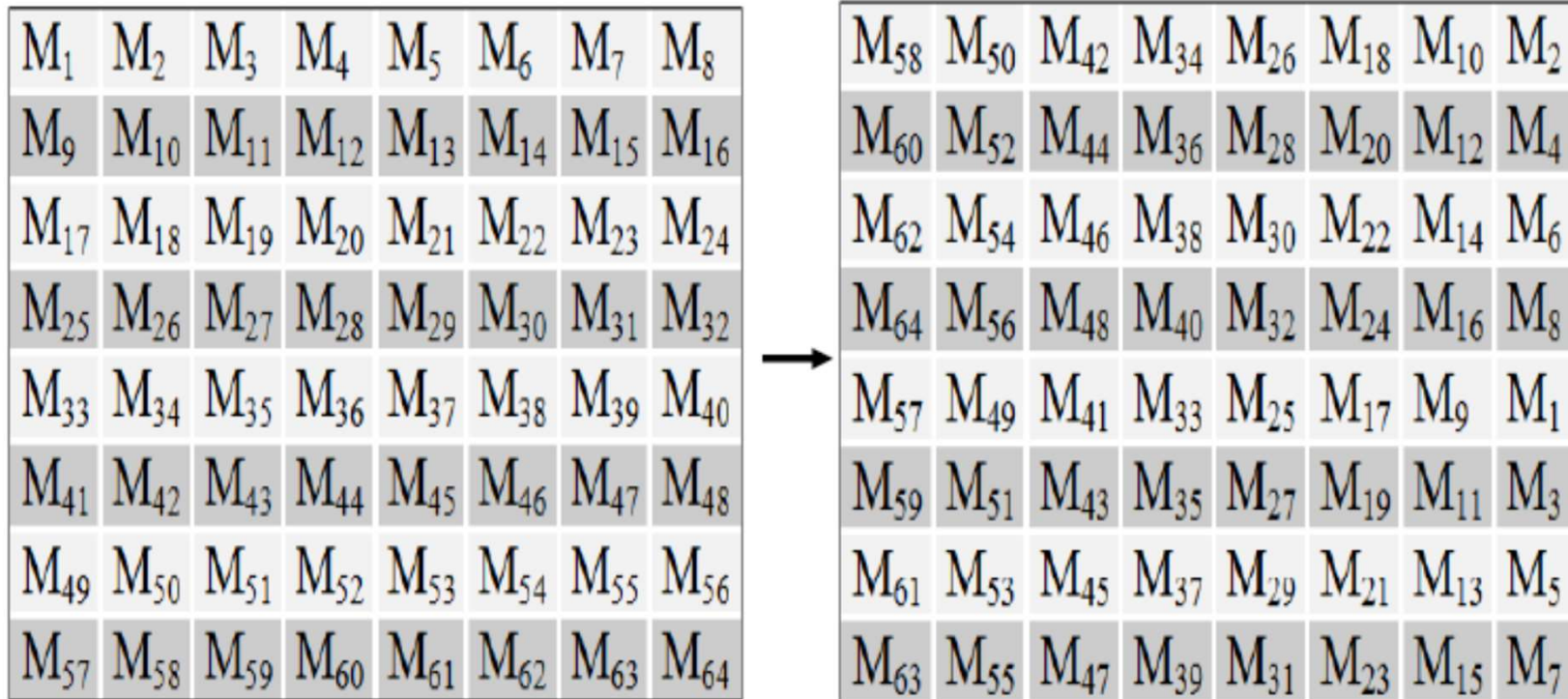
DES Encryption Four Phases

- 64 bit plaintext pass thru initial permutation (IP).
  - Rearrange bit to produce permuted input.

- Followed by 16 rounds of same function.
  - Involve permutation & substitution functions.

- Output of last round swapped (LH, RH) to produce preoutput.

- Preoutput pass thru a permutation (IP^{-1}).
  - Inverse of IP to produce 64 bit ciphertext.

Initial Permutation (IP) 1st

M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8
M_9	M_{10}	M_{11}	M_{12}	M_{13}	M_{14}	M_{15}	M_{16}
M_{17}	M_{18}	M_{19}	M_{20}	M_{21}	M_{22}	M_{23}	M_{24}
M_{25}	M_{26}	M_{27}	M_{28}	M_{29}	M_{30}	M_{31}	M_{32}
M_{33}	M_{34}	M_{35}	M_{36}	M_{37}	M_{38}	M_{39}	M_{40}
M_{41}	M_{42}	M_{43}	M_{44}	M_{45}	M_{46}	M_{47}	M_{48}
M_{49}	M_{50}	M_{51}	M_{52}	M_{53}	M_{54}	M_{55}	M_{56}
M_{57}	M_{58}	M_{59}	M_{60}	M_{61}	M_{62}	M_{63}	M_{64}

→

M_{58}	M_{50}	M_{42}	M_{34}	M_{26}	M_{18}	M_{10}	M_2
M_{60}	M_{52}	M_{44}	M_{36}	M_{28}	M_{20}	M_{12}	M_4
M_{62}	M_{54}	M_{46}	M_{38}	M_{30}	M_{22}	M_{14}	M_6
M_{64}	M_{56}	M_{48}	M_{40}	M_{32}	M_{24}	M_{16}	M_8
M_{57}	M_{49}	M_{41}	M_{33}	M_{25}	M_{17}	M_9	M_1
M_{59}	M_{51}	M_{43}	M_{35}	M_{27}	M_{19}	M_{11}	M_3
M_{61}	M_{53}	M_{45}	M_{37}	M_{29}	M_{21}	M_{13}	M_5
M_{63}	M_{55}	M_{47}	M_{39}	M_{31}	M_{23}	M_{15}	M_7

example:

IP(675a6967 5e5a6b5a) = (ffb2194d 004df6fb)

verify (?)

Inverse Initial Permutation (IP^{-1})

(a) Initial Permutation (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

1st

(b) Inverse Initial Permutation (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

4th

Details of Single Round   2nd

- Left and right halves of 64 bits are separated into two 32-bit parts L,R
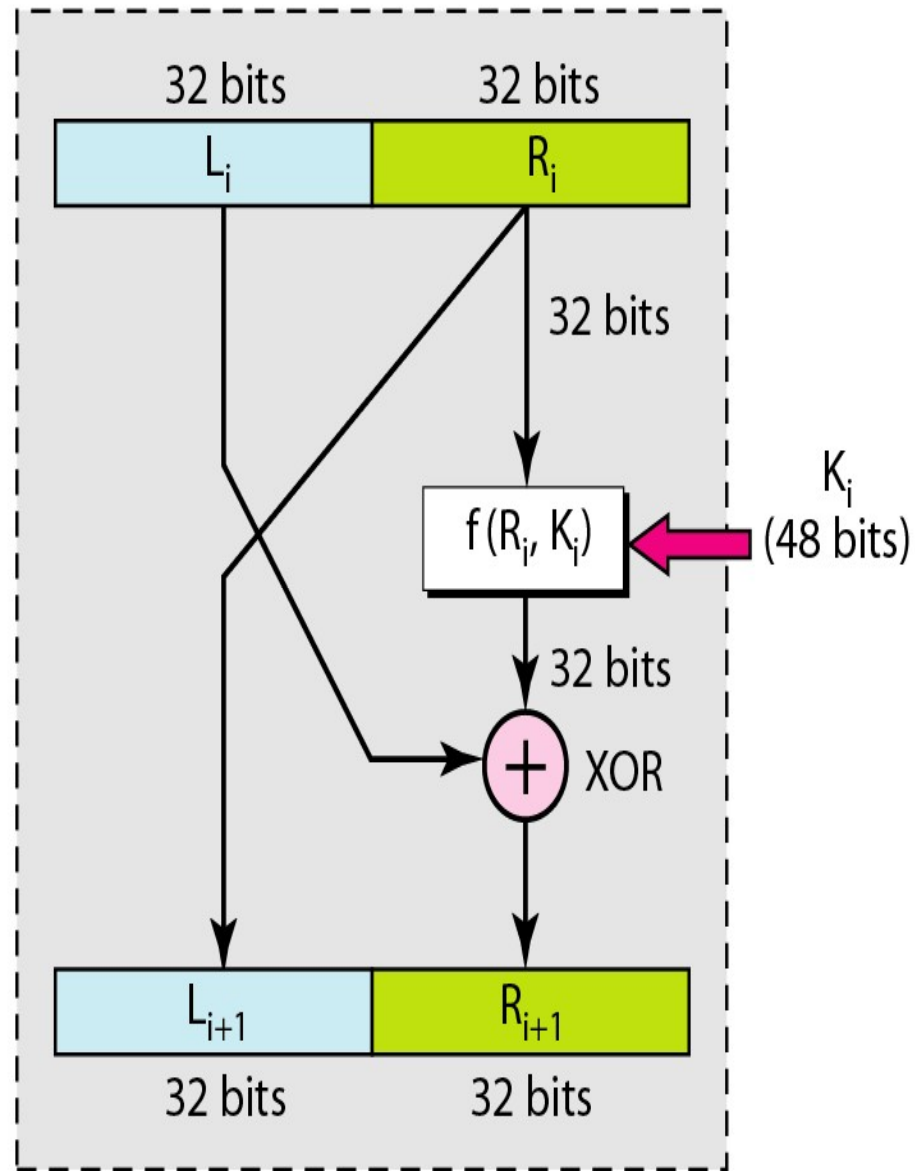
$$L_i = R_{i-1}$$
$$R_i = L_{i-1} \oplus F(R_{i-1}, K_i)$$

- R is expanded to 48 bits using permutation E
- Resulting 48 bits are XORed with K_i
- 48 bit result passes thru substitution function F
  - (8 S-boxes) producing 32-bit output
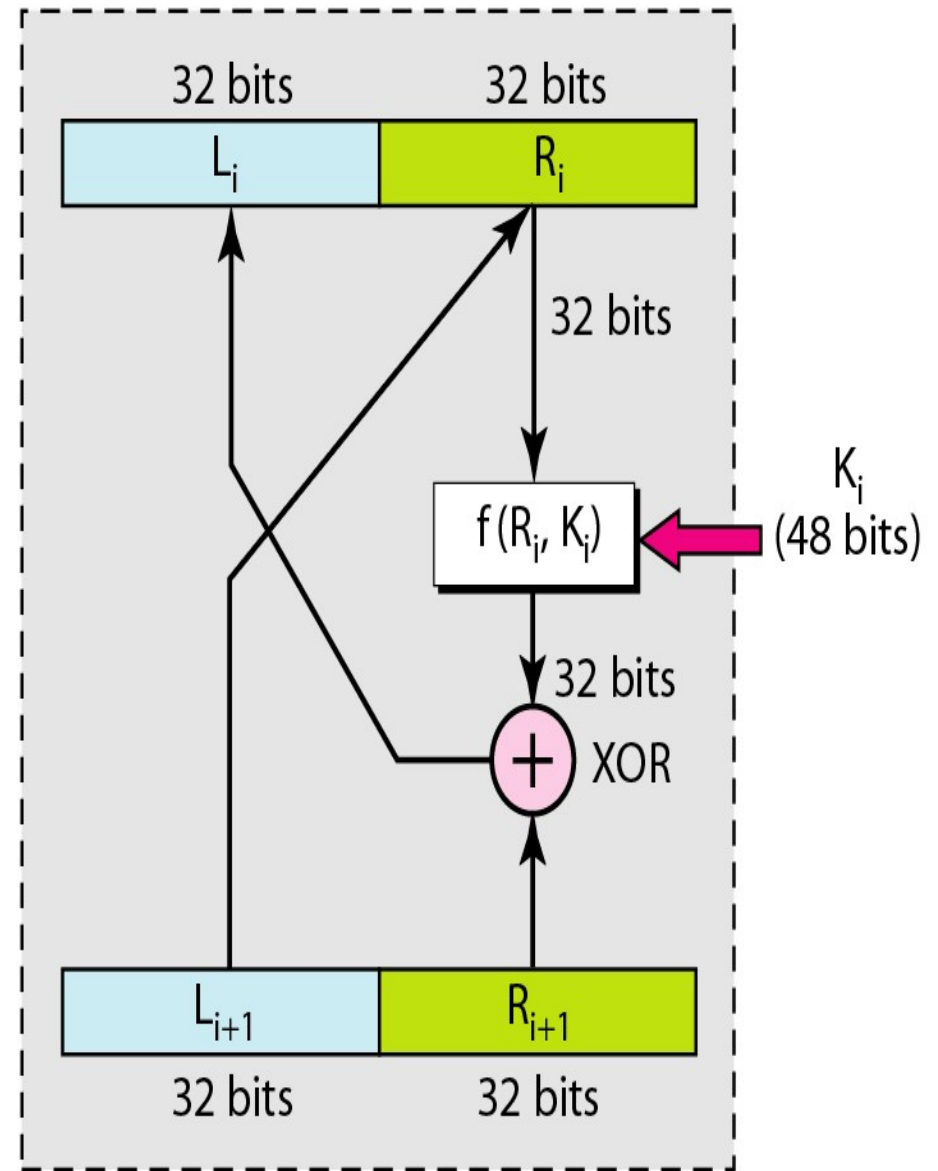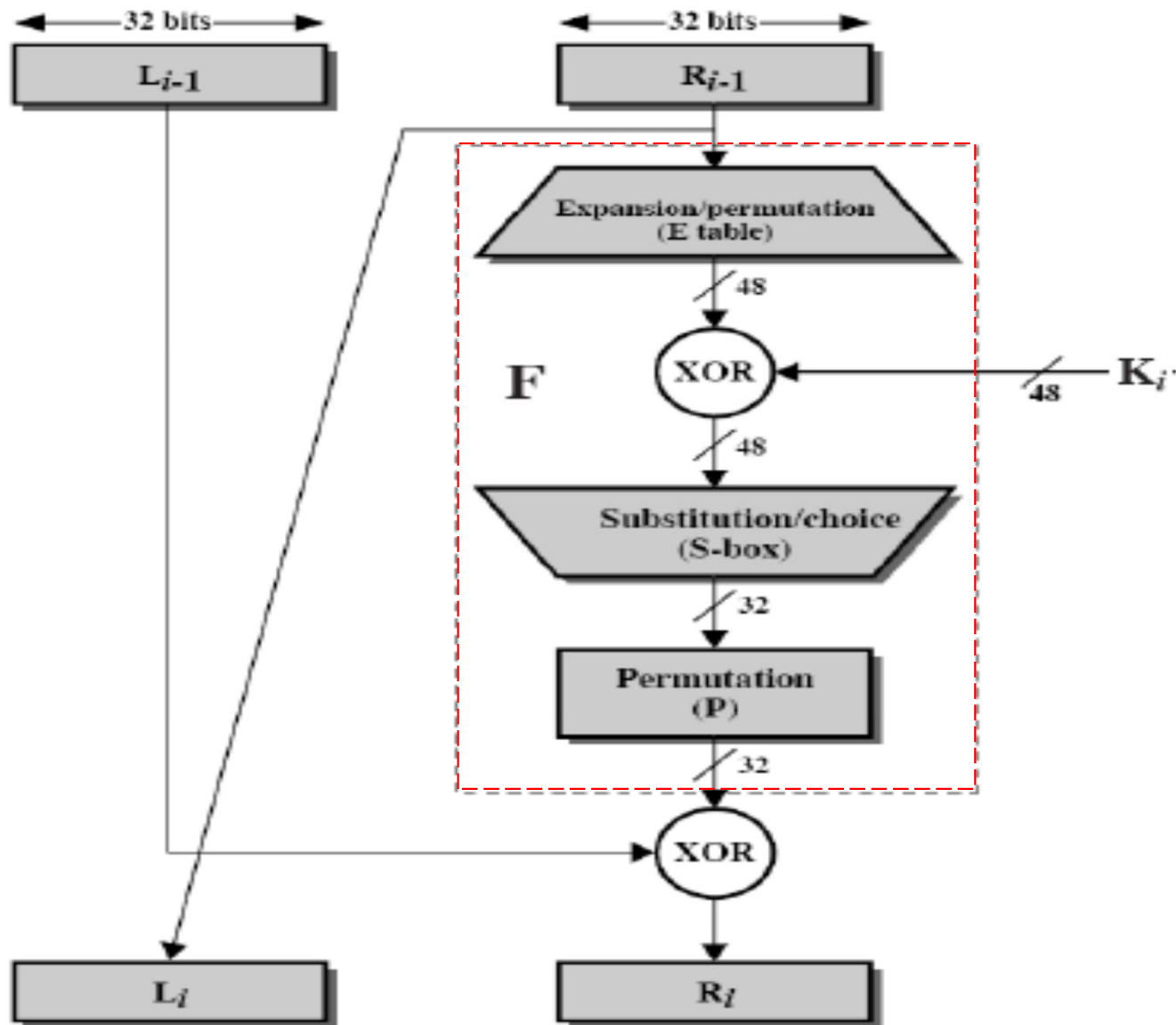- Output is permuted using permutation function P
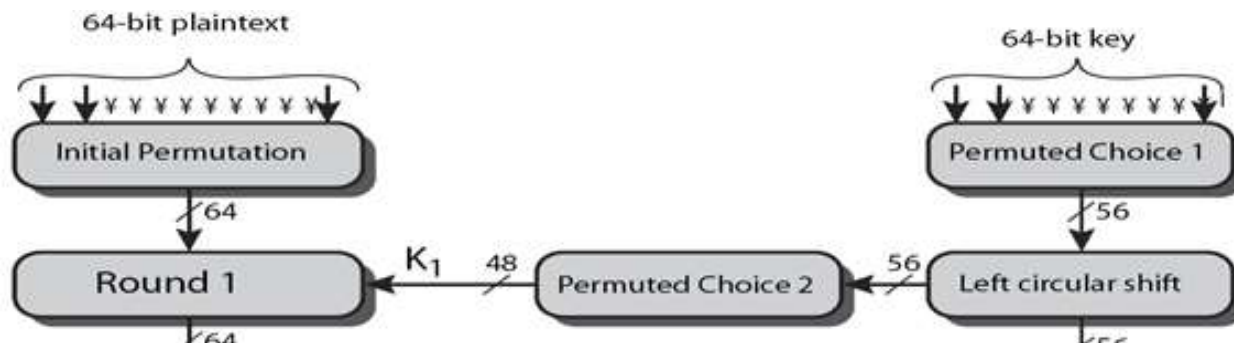
One round in DES

a. Encryption round

b. Decryption round

Details of Single Round

Permutation Tables E, P

(c) Expansion Permutation (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

(d) Permutation Function (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

Roles of S-boxes

- 8 s-boxes, each has 6 bits input, 4 bits out.
- Outer 2 bits (1,6) used to select row.
- Inner 4 bits (2-5) used to select column.
- Decimal value of cell converted to 4 bits out.
  - Note that decimal values are [0-15].
- 8 4-bit groups produce 32 bit output.
- Row selection depends on both data & key.
  - Feature known as autoclaving (auto-keying).

Role of S-Boxes (cont.)
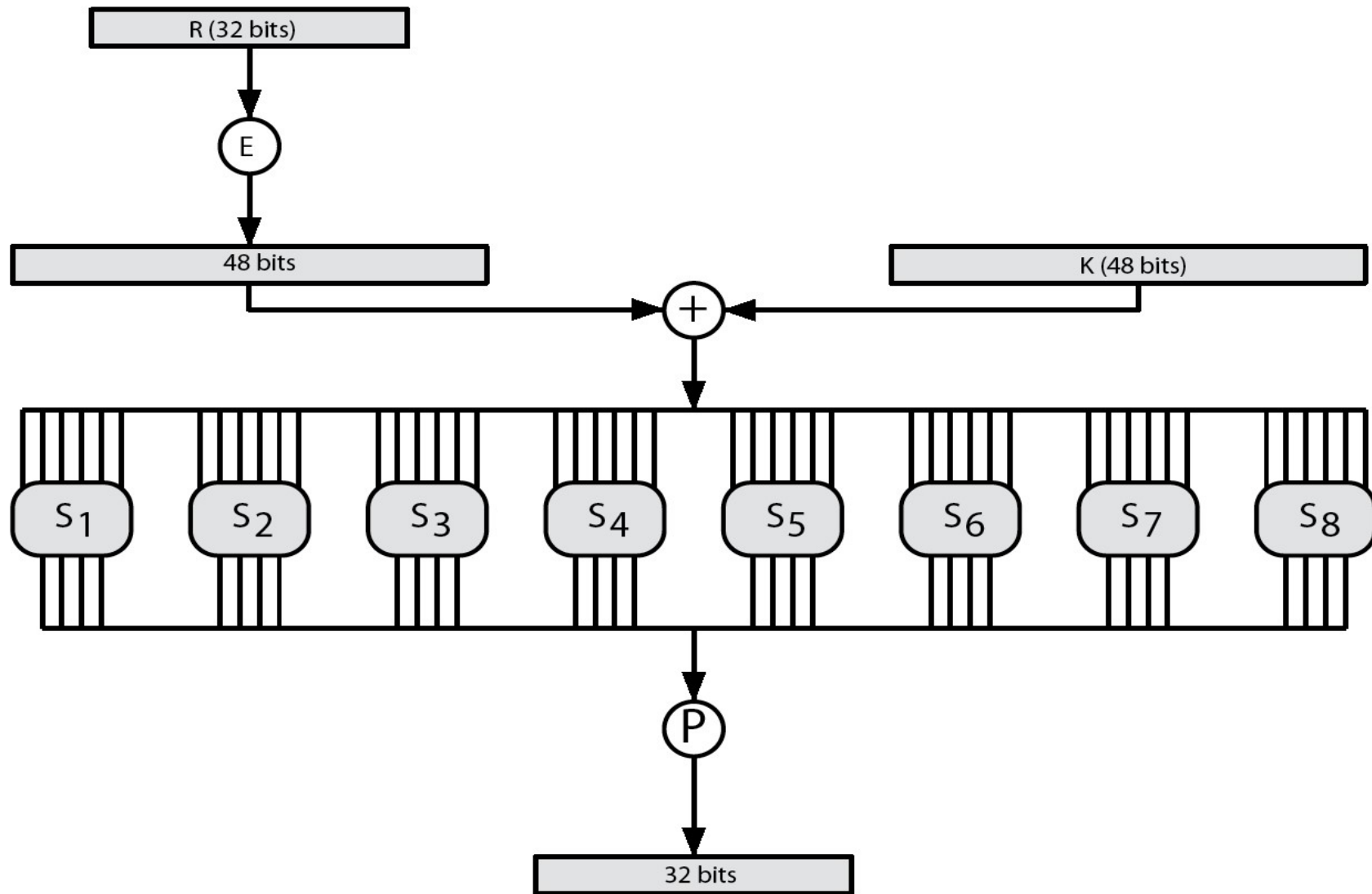
Role of S-Boxes

s_1	14	4	13	1	2	15	11	8	3	10	6	12	5	9	0	7
	0	15	7	4	14	2	13	1	10	6	12	11	9	5	3	8
	4	1	14	8	13	6	2	11	15	12	9	7	3	10	5	0
	15	12	8	2	4	9	1	7	5	11	3	14	10	0	6	13

s_2	15	1	8	14	6	11	3	4	9	7	2	13	12	0	5	10
	3	13	4	7	15	2	8	14	12	0	1	10	6	9	11	5
	0	14	7	11	10	4	13	1	5	8	12	6	9	3	2	15
	13	8	10	1	3	15	4	2	11	6	7	12	0	5	14	9

s_3	10	0	9	14	6	3	15	5	1	13	12	7	11	4	2	8
	13	7	0	9	3	4	6	10	2	8	5	14	12	11	15	1
	13	6	4	9	8	15	3	0	11	1	2	12	5	10	14	7
	1	10	13	0	6	9	8	7	4	15	14	3	11	5	2	12

Example

- Using S1
- Input: 011001
- Row is 01: (1)
- Column 1100: (12)
- Value of row 1, column 12 is 9
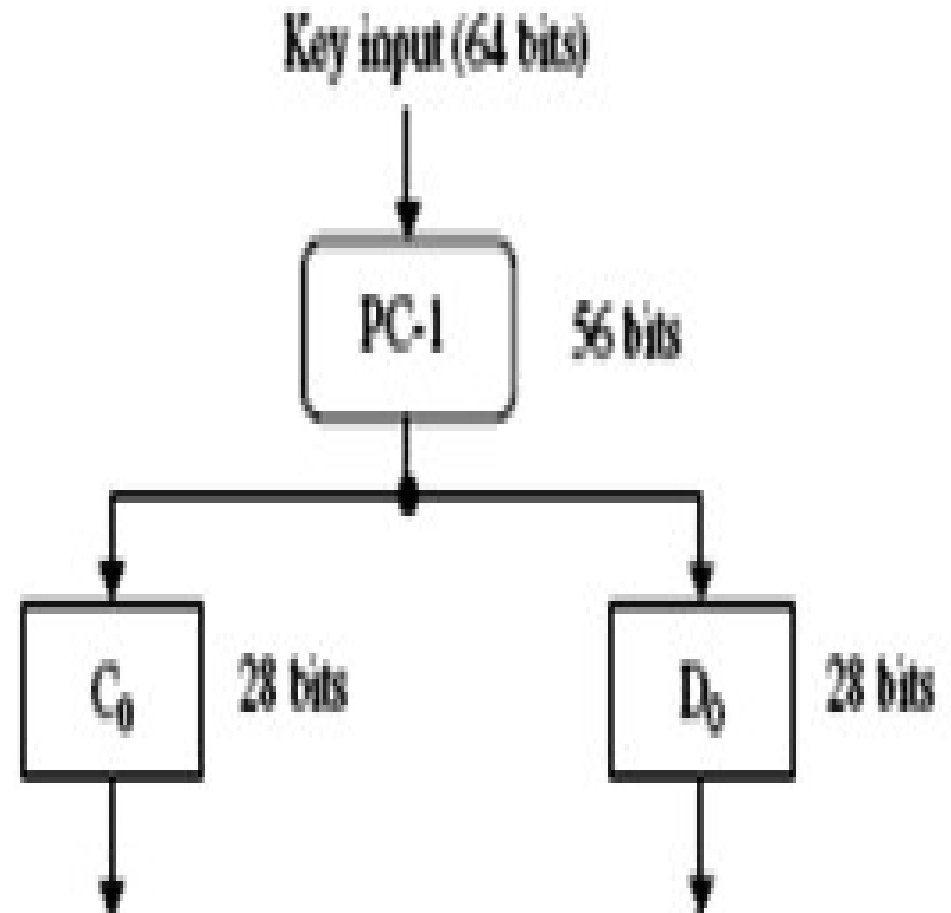- Output is 1001

Key Generation in DES

DES Encryption Overview
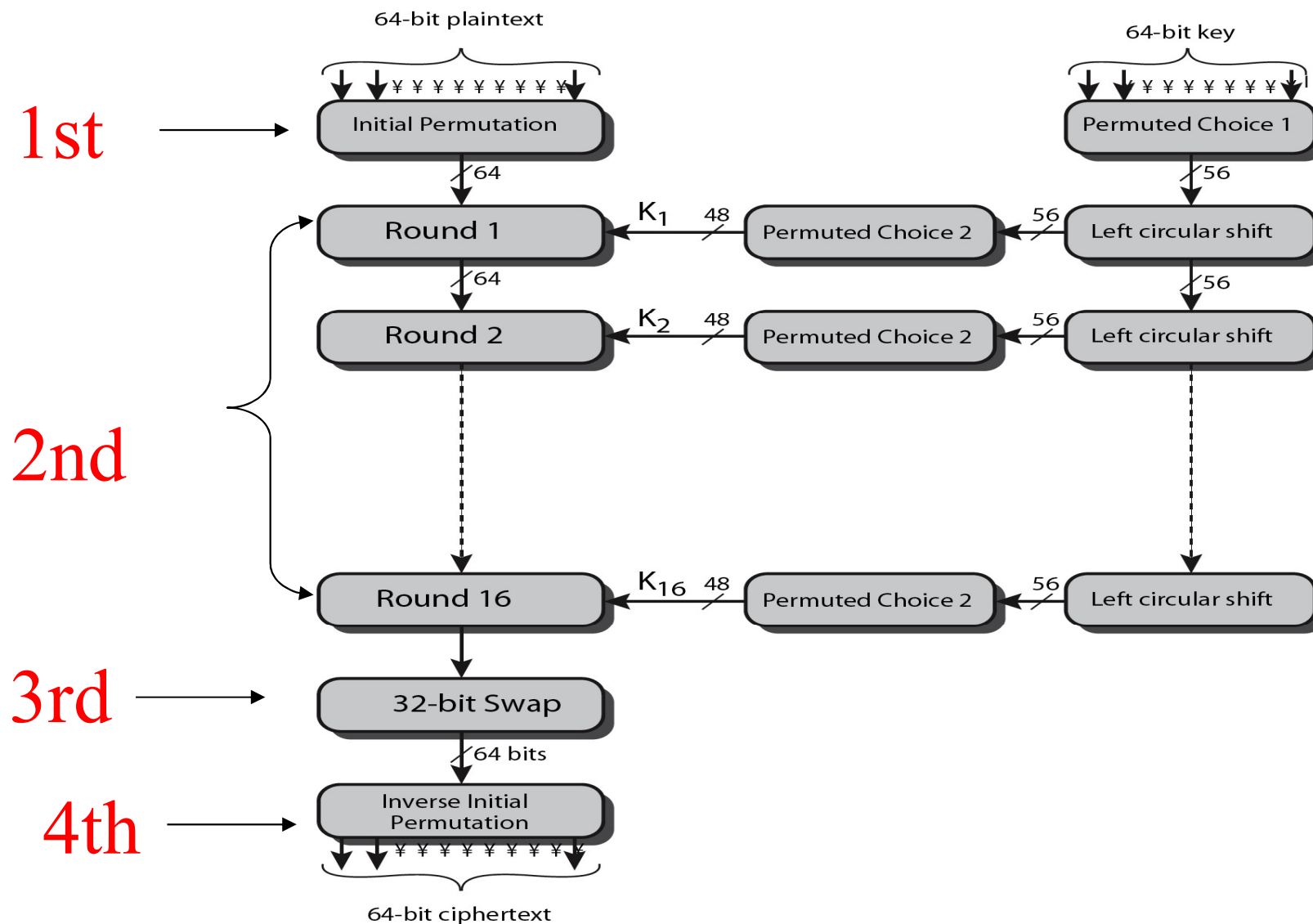
Key Generation (1/6)

- 64-bit key used as input (8 × 8 table)

- 8th bit in each row is ignored $\rightarrow$ 56 bits

- Key is permuted using table PC-1

- Resulting 56 bits separated into two 28-bit parts C_0, D_0

Key Generation (2/6)

Key Generation (3/6)

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	27	28	29	30	31	32
33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48
49	50	51	52	53	54	55	56
57	58	59	60	61	62	63	64

(b) Permuted Choice One (PC-1)

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
14	6	61	53	45	37	29
21	13	5	28	20	12	4

Key Generation (4/6)

- Each round
  - Circular left shift c_{i-1}, d_{i-1} of 1 or 2 bits (table)
  - Shifted values go to next round
  - Also used as input to table PC-2
  - PC-2 produce 48-bit output k_i used in $f(r_{i-1}, k_i)$

Key Generation (5/6)

Internet Security: Cryptographic Principles, Algorithms and Protocols, P-61
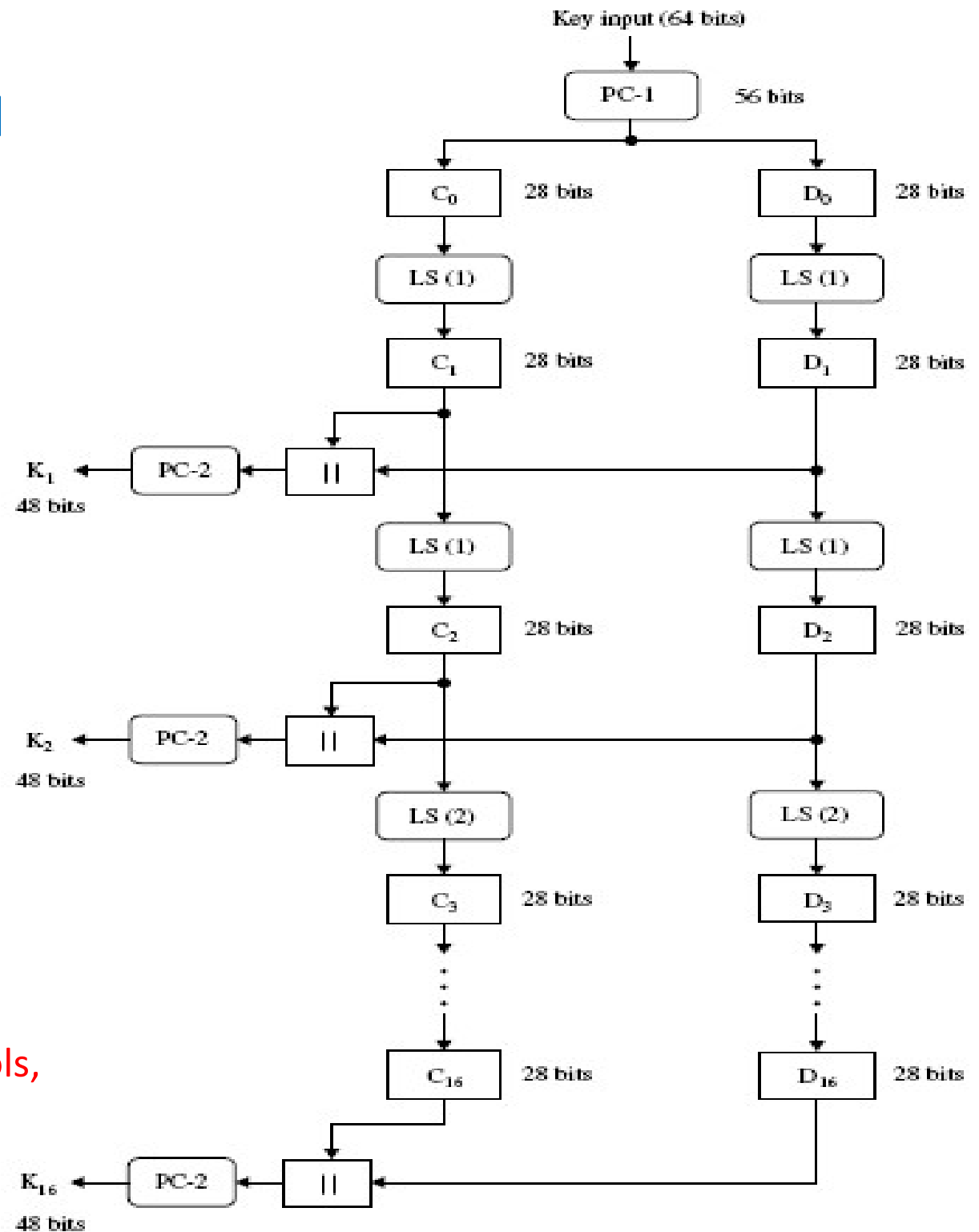
Key Generation (6/6)

(c) Permuted Choice Two (PC-2)

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

(d) Schedule of Left Shifts

Round number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Bits rotated	1	1	2	2	2	2	2	2	1	2	2	2	2	2	2	1

DES Decryption

- Decrypt must unwind steps of data computation.
- With Feistel design, do encryption steps again using subkeys in reverse order (SK_{16} ... SK_1).
    - IP undoes final FP step of encryption
    - 1st round with SK_{16} undoes 16th encrypt round
    - ....
    - 16th round with SK_1 undoes 1st encrypt round
    - then final FP undoes initial encryption IP
    - thus recovering original data value

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 (EFF) in a few days .
  - in 1999 above combined in 22hrs!
- Still must be able to recognize plaintext
- Must now consider alternatives to DES