CHAPTER 3. BLOCK CIPHERS AND THE DATA ENCRYPTION STANDARD

- A **block cipher** is an encryption/decryption scheme in which a block of plaintext is treated as a whole and used to produce a ciphertext block of equal length.
- A **stream cipher** is one that encrypts a digital data stream one bit or one byte at a time.

The Feistel Cipher

Feistel cipher 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.

Diffusion and Confusion

Diffusion is the statistical structure of the plaintext is ***dissipated*** into long-range statistics of the ciphertext. This is achieved by having each plaintext digit affect the value of many ciphertext digits; generally this is equivalent to having each ciphertext digit be affected by many plaintext digits.

Confusion seeks to make the relationship between the statistics of the ciphertext and the value of the encryption key as complex as possible, again to thwart attempts to discover the key.

Feistel Cipher Structure

- The inputs to the encryption algorithm are a plaintext block of length 2w bits and a key K. The plaintext block is divided into two halves, L_0 and R_0.
- The two halves of the data pass through n rounds of processing and then combine to produce the ciphertext block.
- Each round i has as inputs L_{i-1} and R_{i-1}, derived from the previous round, as well as a subkey K_i, derived from the overall K.

- In general, the subkeys K_i are different from K and from each other.

A **substitution** is performed on the left half of the data. This is done by applying a *round function* F to the right half of the data and then taking the exclusive-OR of the output of that function and the left half of the data. Following this substitution, a **permutation** is performed that consists of the interchange of the two halves of the data.

The exact realization of a Feistel network depends on the choice of the following parameters and design features:

Block size: Larger block sizes mean greater security, but reduced encryption/decryption speed for a given algorithm.

Key size: Larger key size means greater security but may decrease encryption/decryption speed. The greater security is achieved by greater resistance to brute-force attacks and greater confusion.

- **Number of rounds:** The essence of the Feistel cipher is that a single round offers inadequate security but that multiple rounds offer increasing security. A typical size is 16 rounds.
- **Subkey generation algorithm:** Greater complexity in this algorithm should lead to greater difficulty of cryptanalysis.
- **Round function:** Again, greater complexity generally means greater resistance to cryptanalysis.

There are two other considerations in the design of a Feistel cipher: •

- **Fast software encryption/decryption:** The speed of execution of the algorithm becomes a concern.
- **Ease of analysis:** if the algorithm can be concisely and clearly explained, it is easier to analyze that algorithm for cryptanalytic vulnerabilities

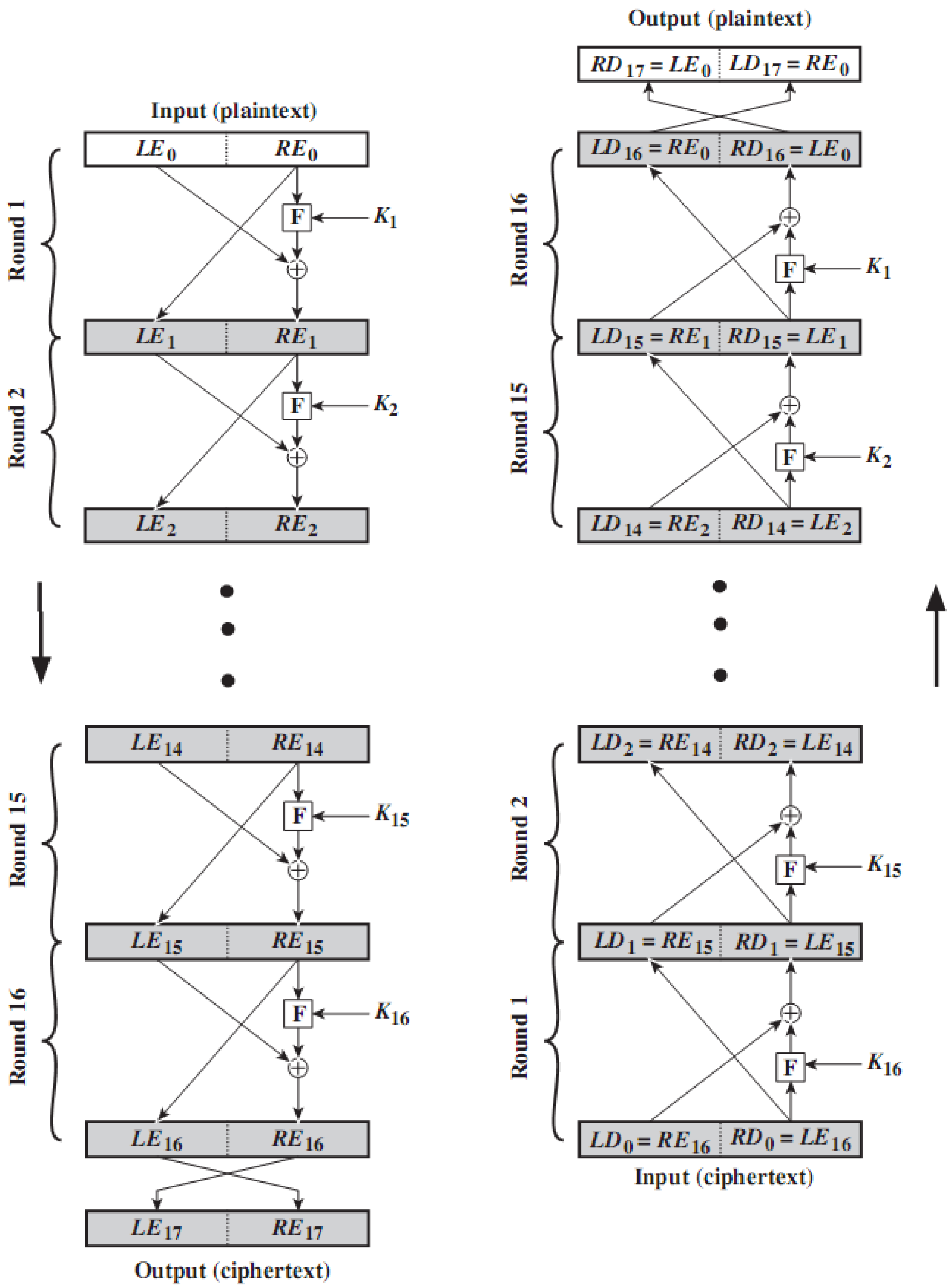

Figure 3.3 Feistel Encryption and Decryption (16 rounds)

Feistel Decryption Algorithm

The process of decryption with a Feistel cipher is essentially the same as the encryption process. The rule is as follows: Use the ciphertext as input to the algorithm, but use the subkeys K_i in reverse order. That is, use K_n in the first round, K_{n-1} in the second round, and so on until K_1 is used in the last round.

Now we would like to show that the output of the first round of the decryption process is equal to a 32-bit swap of the input to the sixteenth round of the encryption process. First, consider the encryption process. We see that

$LE_{16} = RE_{15}$

$RE_{16} = LE_{15} \text{ x } F(RE_{15}, K_{16})$

On the decryption side,

$LD_1 = RD_0 = LE_{16} = RE_{15}$

$RD_1 = LD_0 \text{ x } F(RD_0, K_{16})$

$= RE_{16} \text{ x } F(RE_{15}, K_{16})$

$= [LE_{15} \text{ x } F(RE_{15}, K_{16})] \text{ x } F(RE_{15}, K_{16})$

The XOR has the following properties:

$[A \text{ x } B] \text{ x } C = A \text{ x } [B \text{ x } C]$

$D \text{ x } D = 0$

$E \text{ x } 0 = E$

Thus, we have $LD_1 = RE_{15}$ and $RD_1 = LE_{15}$. Therefore, the output of the first round of the decryption process is $LE_{15}||RE_{15}$, which is the 32-bit swap of the input to the sixteenth round of the encryption. This correspondence holds all the way through the 16 iterations, as is easily shown. We can cast this process in general terms. For the ith iteration of the encryption algorithm,

$LE_i = RE_{i-1}$

$RE_i = LE_{i-1} \text{ x } F(RE_{i-1}, K_i)$

Rearranging terms,

$RE_{i-1} = LE_i$

$LE_{i-1} = RE_i \text{ x } F(RE_{i-1}, K_{i2} = RE_i \text{ x } F(LE_i, K_i)$

3.2. The Data Encryption Standard

The most widely used encryption scheme is based on the Data Encryption Standard (DES) adopted in 1977 by the National Institute of Standards and Technology (NIST).

The algorithm itself is referred to as the Data Encryption Algorithm (DEA). For DES, data are encrypted in **64-bit blocks using a 56-bit key.** The algorithm transforms 64-bit input in a series of steps into a 64-bit output. The same steps, with the same key, are used to reverse the encryption.

DES Encryption

As with any encryption scheme, there are two inputs to the encryption function: the **plaintext** to be encrypted and **the key.** In this case, the plaintext must be 64 bits in length and the key is 56 bits in length.

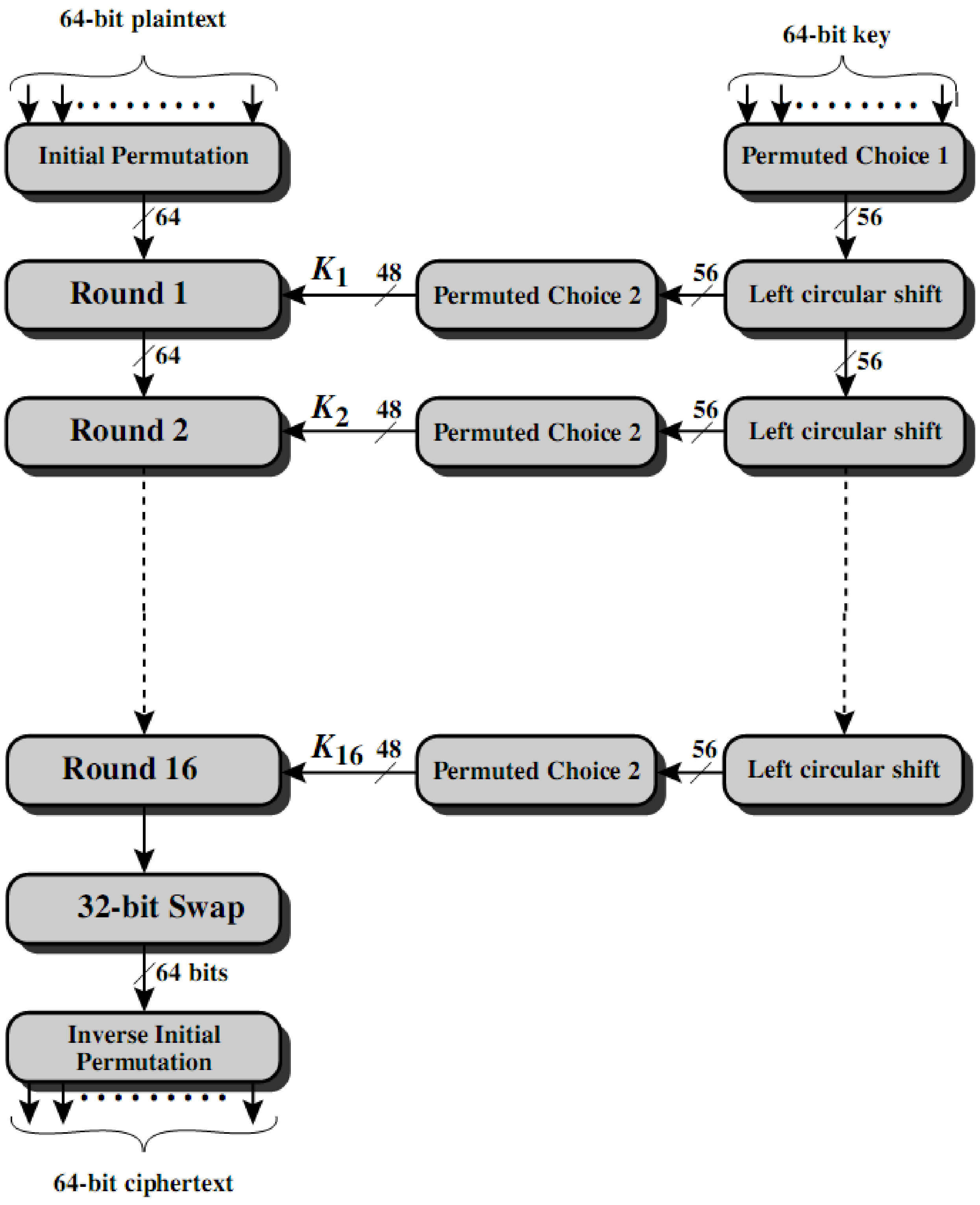

Figure 3.4 General Depiction of DES Encryption Algorithm

Looking at the left-hand side of the figure, the processing of the plaintext proceeds in three phases.

1. The 64-bit plaintext passes through an **initial permutation (IP)** that rearranges the bits to produce the permuted input. This is followed by a phase consisting of **16 rounds** of the same function, which involves both permutation and substitution functions.
2. The output of the last (sixteenth) round consists of 64 bits that are a function of the input plaintext and the key. The left and right halves of the output are **swapped** to produce the *preoutput*.
3. Finally, the preoutput is passed through a permutation **(IP^{-1})** that is the inverse of the initial permutation function, to produce the 64-bit ciphertext. With the exception of the initial and final permutations, DES has the exact structure of a Feistel cipher

The right-hand portion shows the way in which the 56-bit key is used. Initially, the key is passed through a permutation function. Then, for each of the 16 rounds, a ***subkey*** (K_i) is produced by the combination of a left circular shift and a permutation. The permutation function is the same for each round, but a different subkey is produced because of the repeated shifts of the key bits.

<u>**Initial Permutation IP:**</u>

- First step of the data computation
- IP reorders the input data bits
- Even bits to LH half, Odd bits to RH half
- Quite regular in structure (easy in h/w)

- see text Table 3.2 for all permutation functions(IP, IP^{-1},E,P)

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

(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

(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

(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

Details of Single Round:

- The left and right halves of each 64-bit intermediate value are treated as separate 32-bit quantities, labeled L (left) and R (right).
- the overall processing at each round can be summarized in the following formulas:

$$L_i = R_{i-1}$$

$$R_i = L_{i-1} \text{ x } F(R_{i-1}, K_i)$$

- The round key K_i is 48 bits. The R input is 32 bits. This R input is first expanded to 48 bits by using a table that defines a permutation plus an expansion that involves duplication of 16 of the R bits.
- The resulting 48 bits are XORed with K_i. This 48-bit result passes through a substitution function that produces a 32-bit output.
- The substitution consists of a set of eight S-boxes, each of which accepts 6 bits as input and produces 4 bits as output.
- The first and last bits of the input to box S_i form a 2-bit binary number to select one of four substitutions defined by the four rows in the table for S_i. The middle four bits select one of the sixteen columns.
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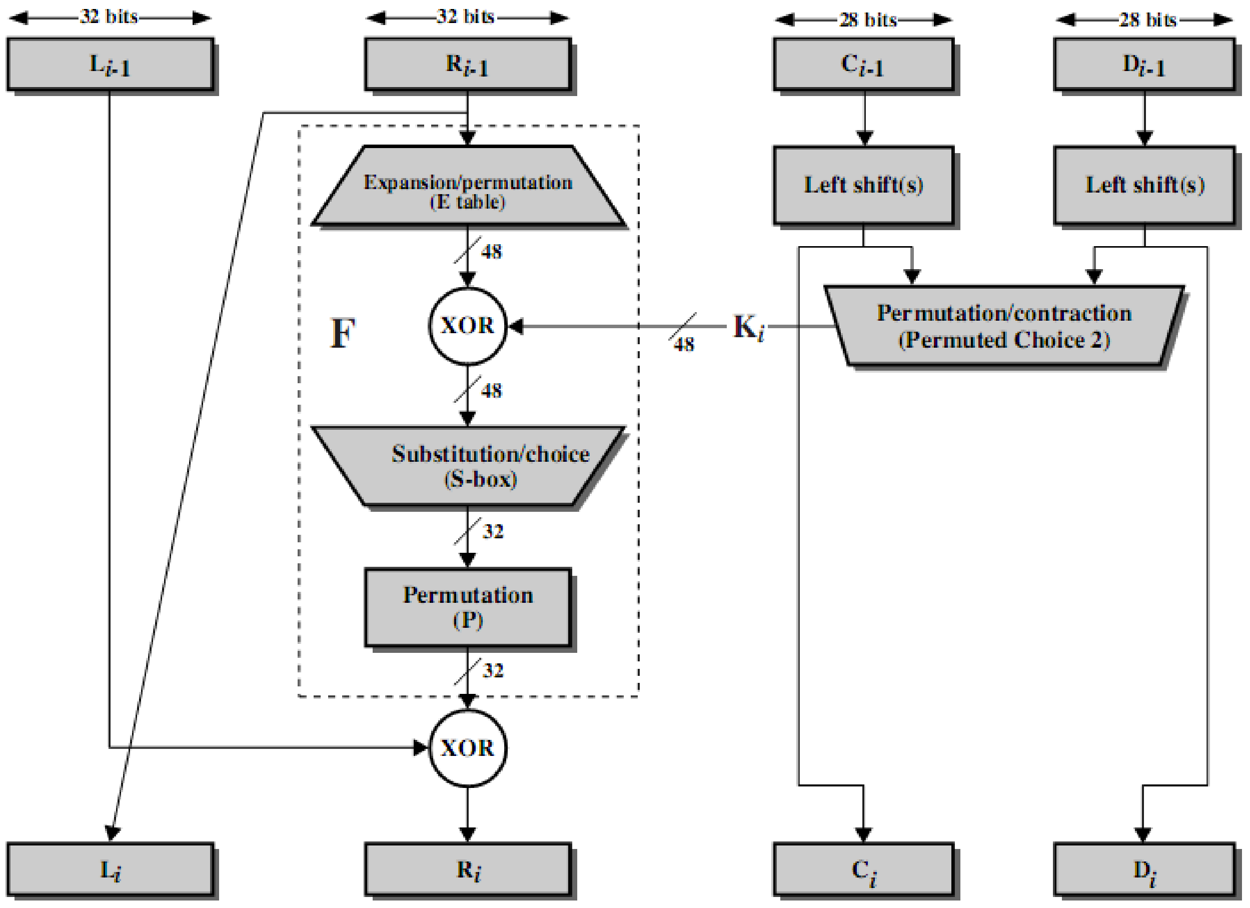
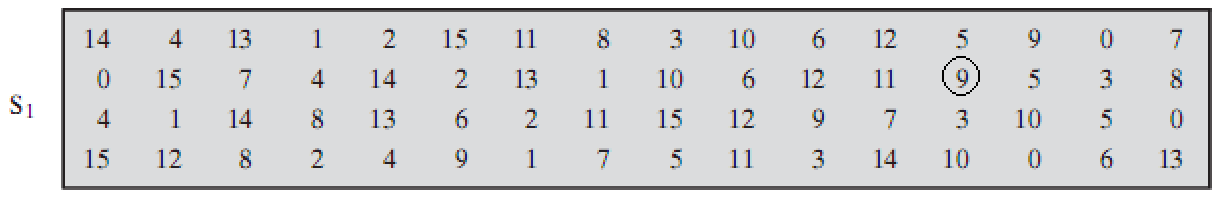


Figure 3.5 Single Round of DES Algorithm

- The decimal value in the cell selected by the row and column is then converted to its 4-bit representation to produce the output. For example, in S_1 for input 011001, the row is 01 (row 1) and the column is 1100 (column 12). The value in row 1, column 12 is 9, so the output is 1001.

Table 3.3 Definition of DES S-Boxes



	14	4	13	1	2	15	11	8	3	10	6	12	5	9	0	7
S_1	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

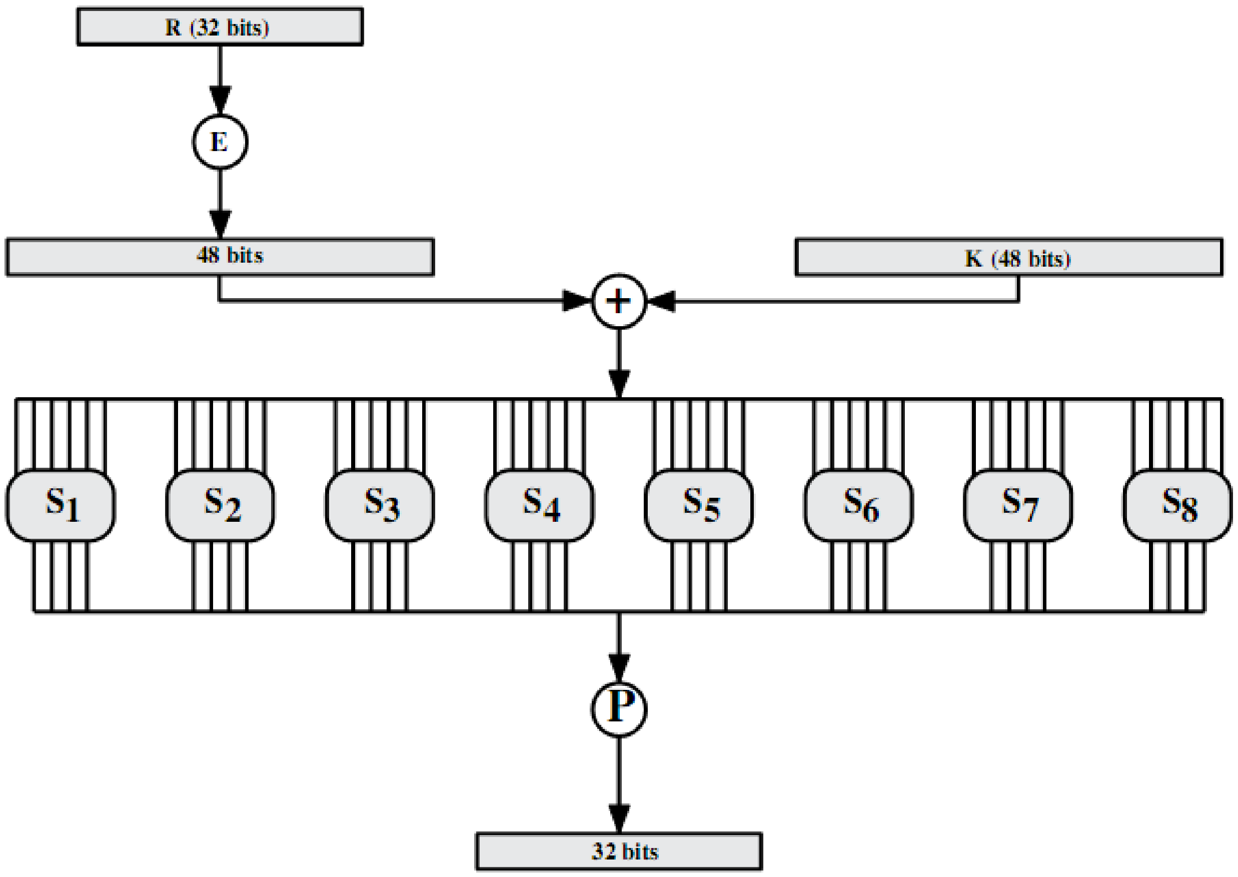


Figure 3.6 Calculation of F(R, K)

K EY GENERATION :

- Returning to Figures 3.5 and 3.6, we see that a 64-bit key is used as input to the algorithm.
- The bits of the key are numbered from 1 through 64;every eighth bit is ignored, as indicated by the lack of shading in Table 3.4a.
- The key is first subjected to a permutation governed by a table labeled Permuted Choice One (Table 3.4b).
- The resulting 56-bit key is then treated as two 28-bit quantities, labeled C_0 and D_0. At each round, C_{i-1} and D_{i-1} are separately subjected to a circular left shift or (rotation) of 1 or 2 bits,as governed by Table 3.4d.

- These shifted values serve as input to the next round. They also serve as input to the part labeled Permuted Choice Two (Table 3.4c), which produces a 48-bit output that serves as input to the function $F(R_{i-1},K_i)$.

Table 3.4 DES Key Schedule Calculation

(a) Input Key

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) 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

(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

(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

The Avalanche Effect

A change in one bit of the plaintext or one bit of the key should produce a change in many bits of the ciphertext. If the change were small, this might provide a way to reduce the size of the plaintext or key space to be searched.

3.3. The Strength of DES:

The Use of 56-Bit Keys

- With a key length of 56 bits, there are 2^{56} possible keys, which is approximately 7.2×10^{16}. So a brute-force attack appears impractical.
- Assuming that, on average, half the key space has to be searched, a single machine performing one DES encryption per microsecond would take more than a thousand years to break the cipher.
- If the message is just plain text in English, then the task of recognizing English would have to be automated.
- If the text message has been compressed before encryption, then recognition is more difficult. And if the message is some more general type of data, such as a numerical file, and this has been compressed, the problem becomes even more difficult to automate.
- Thus, to supplement the brute-force approach, some degree of knowledge about the expected plaintext is needed.

The Nature of the DES Algorithm

Another concern is the possibility that cryptanalysis is possible by exploiting the characteristics of the DES algorithm.

Timing Attacks

A timing attack is one in which information about the key or the plaintext is obtained by **observing how long it takes** a given implementation to perform decryptions on various ciphertexts. This is a long way from knowing the actual key, but it is an intriguing first step.

3.4. Differential and Linear Cryptanalysis

Differential Cryptanalysis

One of the most significant advances in cryptanalysis in recent years is differential cryptanalysis. In this section, we discuss the technique and its applicability to DES.The differential cryptanalysis attack is complex. The rationale behind differential cryptanalysis is to observe the behavior of pairs of text blocks evolving along each round of the cipher, instead of observing the evolution of a single text block.

Consider the original plaintext block **m** to consist of two halves **m_0, m_1**. Each round of DES maps the right-hand input into the left-hand output and sets the right-hand output to be a function of the left-hand input and the subkey for this round. So, at each round, only one new 32-bit block is created. If we label each new block

m_1 ($2 \le i \le 17$), then the intermediate message halves are related as follows:

$$\mathbf{m_{i+1} = m_{i-1} \oplus f(m_i, K_i), i = 1, 2, ..., 16}$$

In differential cryptanalysis, we start with two messages, **m** and **m'**, with a known XOR difference **$\Delta m = m \oplus m'$**, and consider the difference between the intermediate message halves: **$m_i = m_i \oplus m_i'$** Then we have:

$$\begin{aligned}\Delta m_{i+1} &= m_{i+1} \oplus m'_{i+1} \\ &= [m_{i-1} \oplus \mathrm{f}(m_i, K_i)] \oplus [m'_{i-1} \oplus \mathrm{f}(m'_i, K_i)] \\ &= \Delta m_{i-1} \oplus [\mathrm{f}(m_i, K_i) \oplus \mathrm{f}(m'_i, K_i)]\end{aligned}$$

This attack is known as **Differential Cryptanalysis** because the analysis compares **differences** between two related encryptions, and looks for a **known difference in** leading to a **known difference out** with some (pretty small but still significant) probability. If a number of such differences are determined, it is feasible to determine the subkey used in the function f.

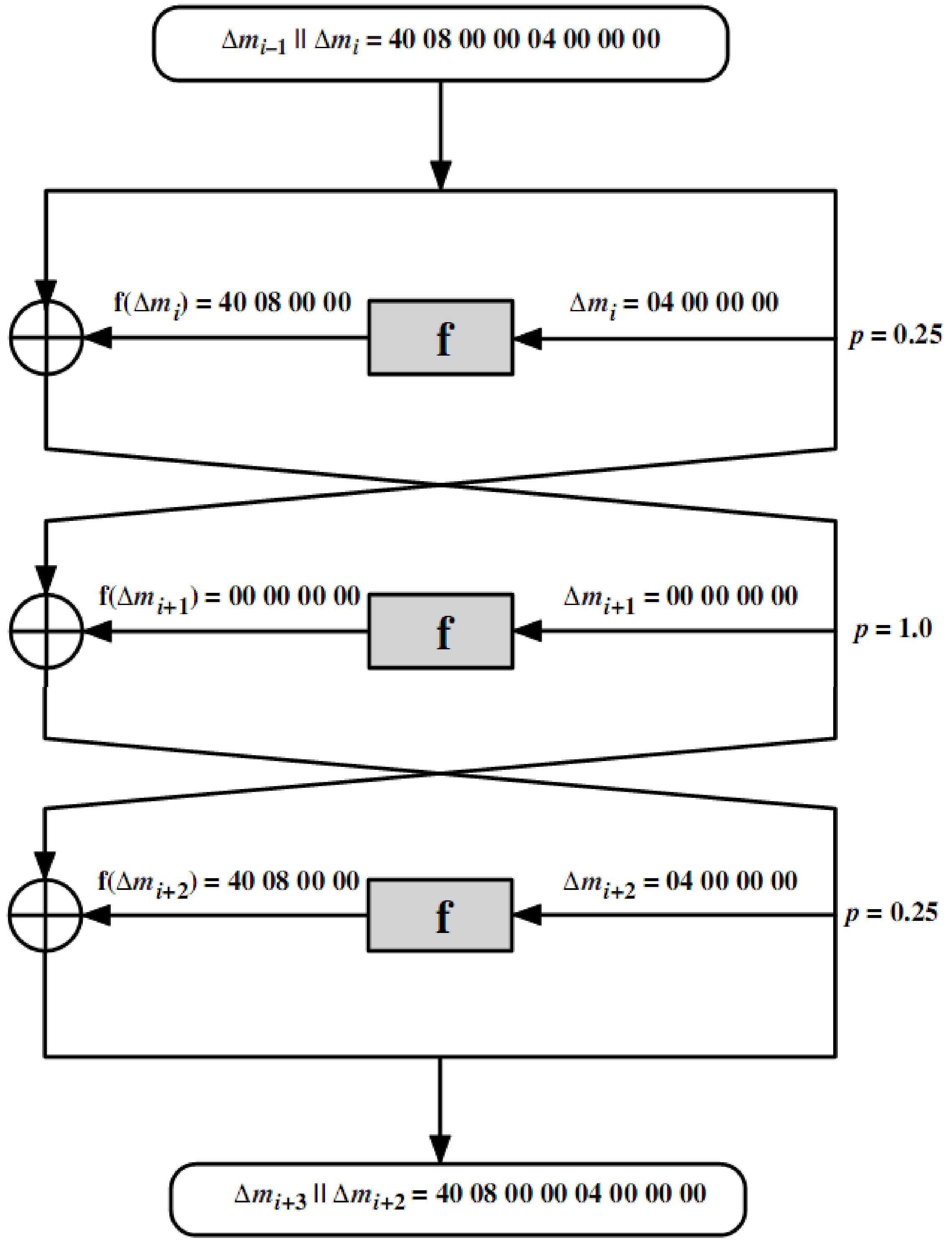

$\Delta m_{i-1} \| \Delta m_i$ = 40 08 00 00 04 00 00 00
f(Δm_i) = 40 08 00 00
f
Δm_i = 04 00 00 00
p = 0.25
f(Δm_{i+1}) = 00 00 00 00
f
Δm_{i+1} = 00 00 00 00
p = 1.0
f(Δm_{i+2}) = 40 08 00 00
f
Δm_{i+2} = 04 00 00 00
p = 0.25
$\Delta m_{i+3} \| \Delta m_{i+2}$ = 40 08 00 00 04 00 00 00

Figure 3.7 Differential Propagation through Three Round of DES (numbers in hexadecimal)

The overall strategy of differential cryptanalysis is based on these considerations for a single round. The procedure is to begin with two plaintext messages m and m' with a given difference and trace through a probable pattern of differences after each round to yield a probable difference for the ciphertext. You submit **m** and **m'** for encryption to determine the actual difference under the unknown key and compare the result to the probable difference. If there is a match, then suspect that all the probable patterns at all the intermediate rounds are correct. With that assumption, can make some deductions about the key bits. This procedure must be repeated many times to determine all the key bits.

Linear Cryptanalysis

A more recent development is linear cryptanalysis. This attack is based on finding linear approximations to describe the transformations performed in DES. This method can find a DES key given 243 known plaintexts, as compared to 247 chosen plaintexts for differential cryptanalysis. Although this is a minor improvement, because it may be easier to acquire known plaintext rather than chosen plaintext, it still leaves linear cryptanalysis infeasible as an attack on DES. Again, this attack uses structure not seen before. So far, little work has been done by other groups to validate the linear cryptanalytic approach.

3.4. Block Cipher Design Principles

There are three critical aspects of block cipher design:

- The number of rounds,
- Design of the function F,
- Key scheduling.

The number of rounds

- The greater the number of rounds, the more difficult it is to perform cryptanalysis, even for a relatively weak F.
- The criterion should be that the number of rounds is chosen so that known cryptanalytic efforts require greater effort than a simple brute-force key search attack.
- If DES had 15 or fewer rounds, differential cryptanalysis would require less effort than brute-force key search.

Design of the function F

- The function F provides the element of confusion in a Feistel cipher, want it to be difficult to "unscramble" the substitution performed by F.
- One obvious criterion is that F be nonlinear. The more nonlinear F, the more difficult any type of cryptanalysis will be.
- One of the most intense areas of research in the field of symmetric block ciphers is that of S-box design. Would like any change to the input vector to an S-box to result in random-looking changes to the output. The relationship should be nonlinear and difficult to approximate with linear functions.

Key scheduling

- A final area of block cipher design, and one that has received less attention than S-box design, is the key schedule algorithm. With any Feistel block cipher, the key schedule is used to generate a subkey for each round.
- Would like to **select subkeys to maximize the difficulty** of deducing individual subkeys and the difficulty of working back to the main key. The key schedule should guarantee key/ciphertext Strict Avalanche Criterion and Bit Independence Criterion.