# Chapter 6

# Data Encryption Standard (DES)

# Chapter 6

## Objectives

- To review a short history of DES
- To define the basic structure of DES
- To describe the details of building elements of DES
- To describe the round keys generation process
- To analyze DES

# 6-1 INTRODUCTION

***The Data Encryption Standard (DES) is a symmetric-key block cipher published by the National Institute of Standards and Technology (NIST).***

***Topics discussed in this section:***

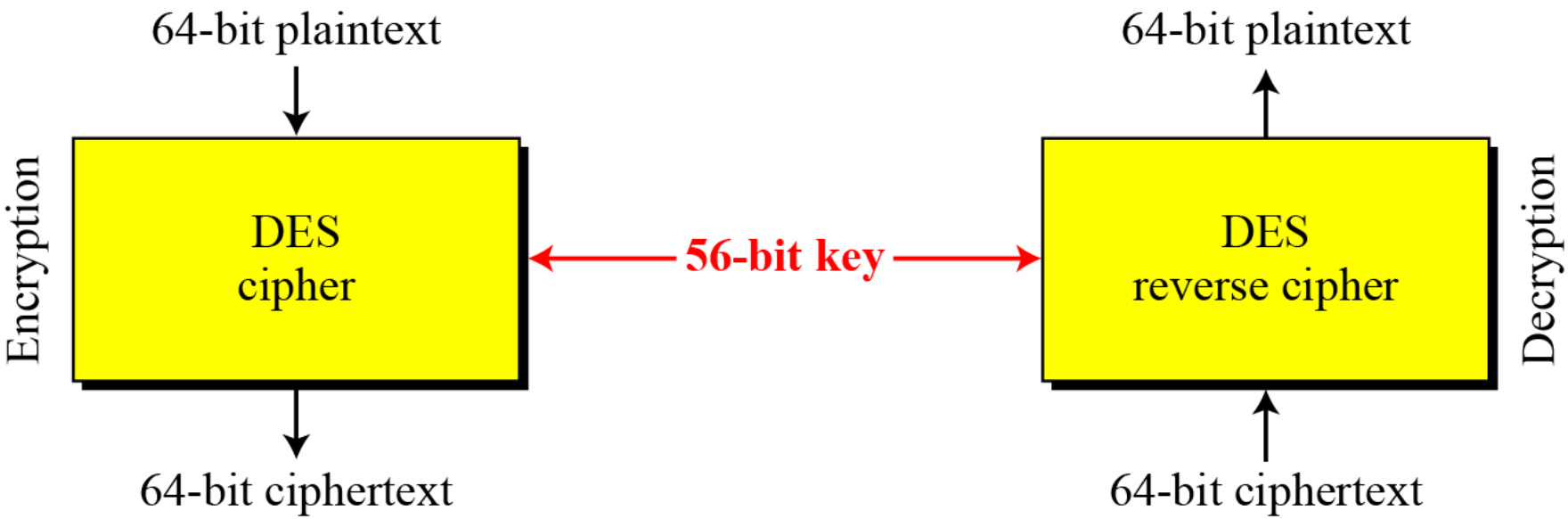
# 6.1.1 History

*In 1973, NIST published a request for proposals for a national symmetric-key cryptosystem. A proposal from IBM, a modification of a project called Lucifer, was accepted as DES. DES was published in the Federal Register in March 1975 as a draft of the Federal Information Processing Standard (FIPS).*

# 6.1.2 Overview

***DES is a block cipher, as shown in Figure 6.1.***

**Figure 6.1** *Encryption and decryption with DES*

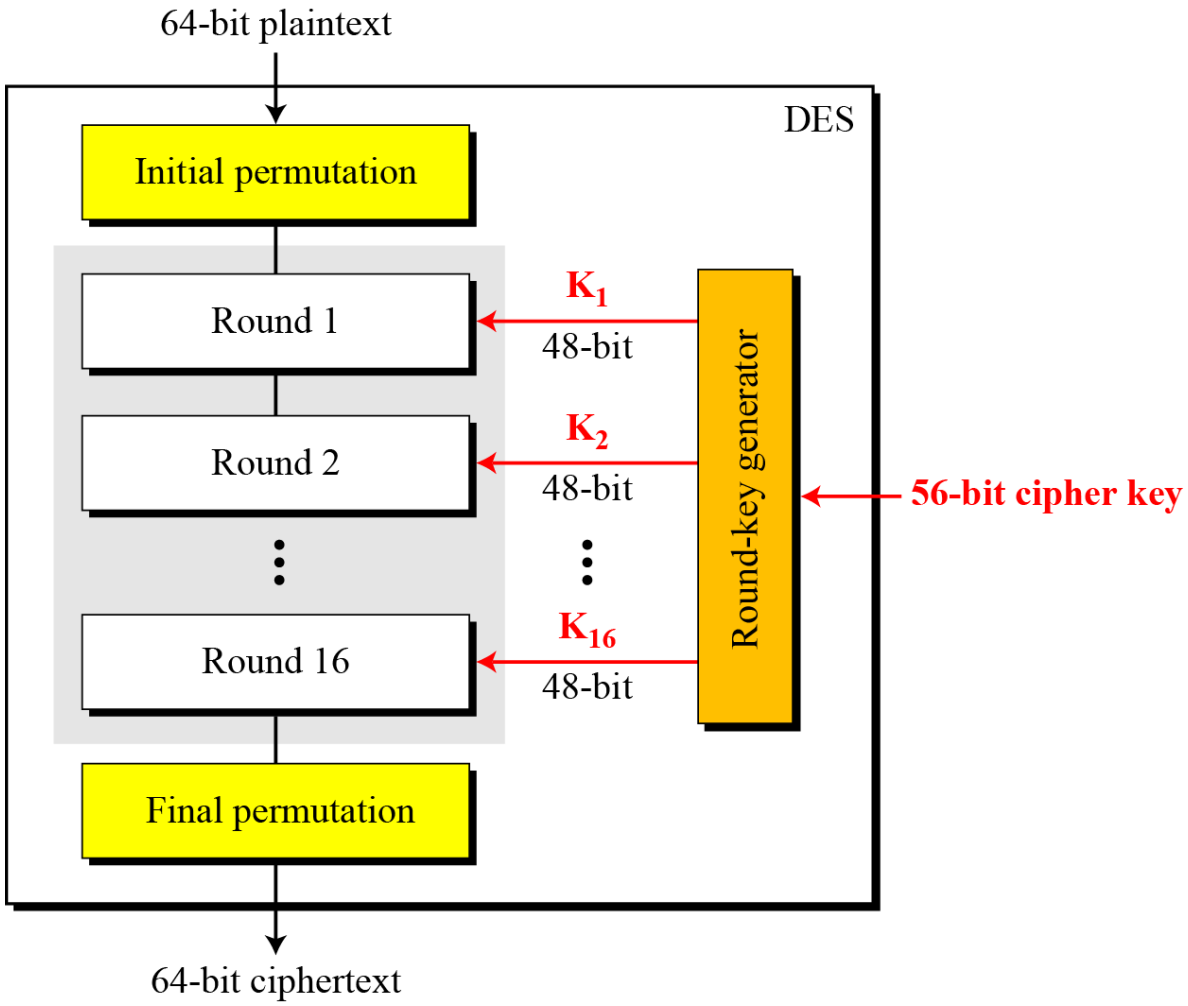


# 6-2 DES STRUCTURE

*The encryption process is made of two permutations (P-boxes), which we call initial and final permutations, and sixteen Feistel rounds.*

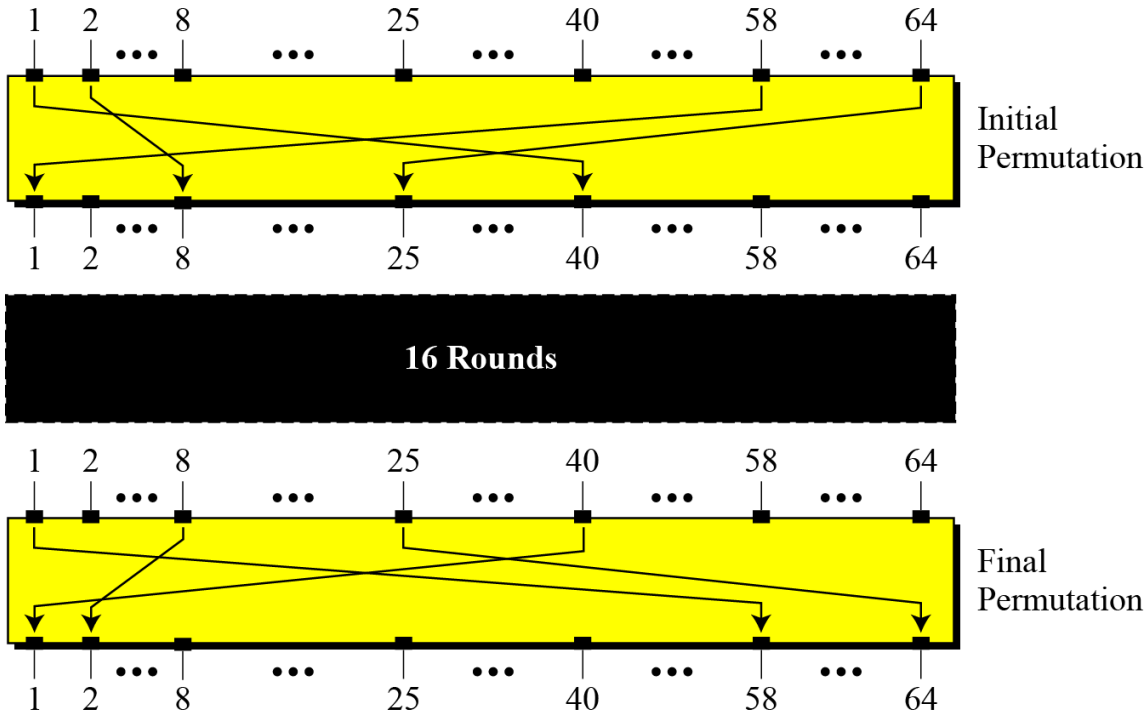
***Topics discussed in this section:***

**Figure 6.2** *General structure of DES*



# 6.2.1 Initial and Final Permutations

**Figure 6.3** *Initial and final permutation steps in DES*



# 6.2.1 Continue

**Table 6.1** *Initial and final permutation tables*

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

# 6.2.1 Continued

**Example 6.1**

**Find the output of the final 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**

0x0002 0000 0000 0001

# 6.2.1 Continued

**Example 6.2**

**Prove that the initial and final permutations are the inverse of each other by finding the output of the initial 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 Table 6.1, 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

*Note*

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

# 6.2.2 Rounds

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

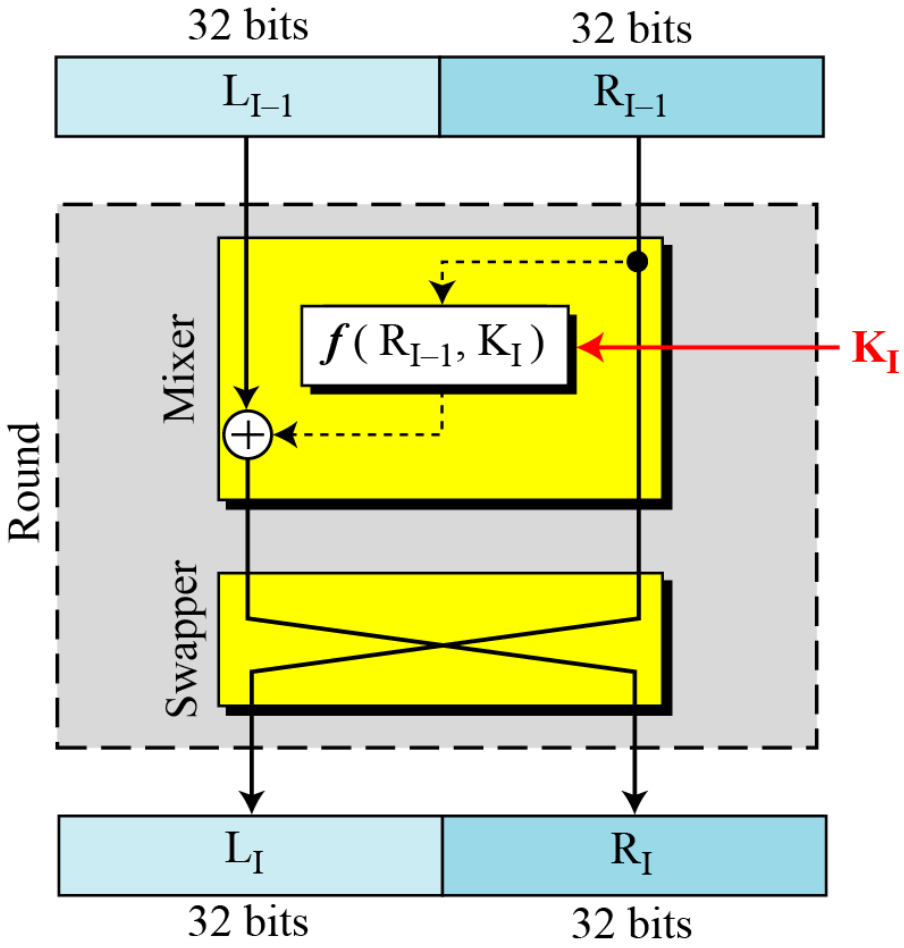



**Figure 6.4**
***A round in DES (encryption site)***

# 6.2.2 Continued

## 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.***

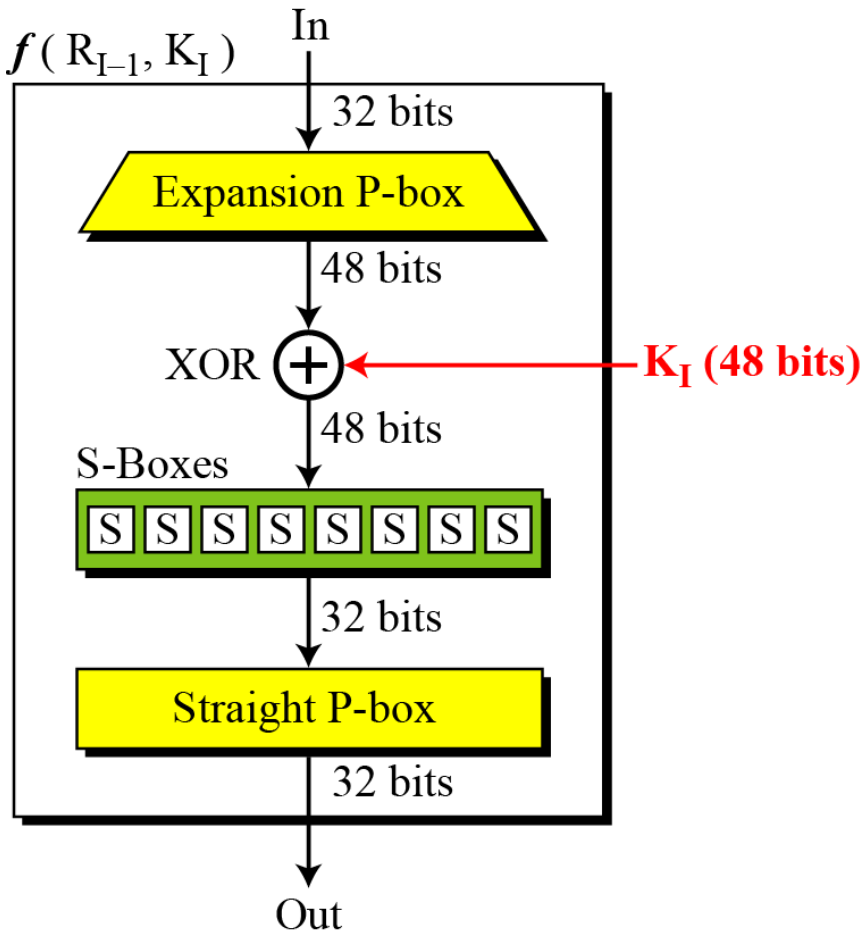
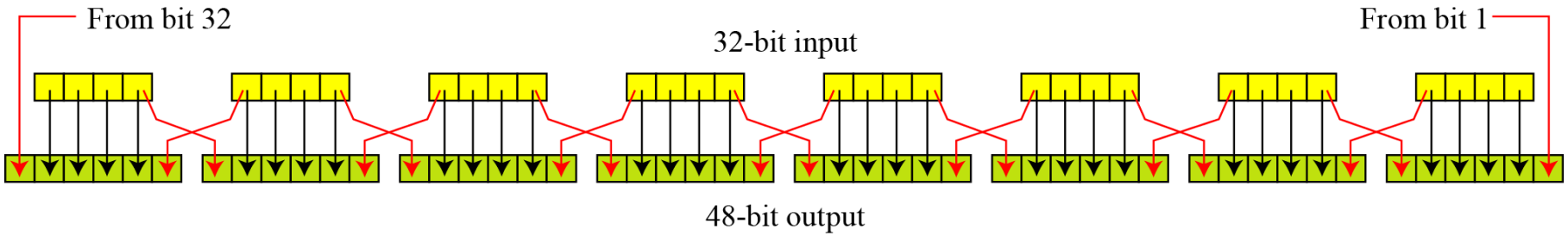



**Figure 6.5**
***DES function***

## 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.***

**Figure 6.6** *Expansion permutation*



# 6.2.2 Continue

***Although the relationship between the input and output can be defined mathematically, DES uses Table 6.2 to define this P-box.***

**Table 6.6** *Expansion P-box table*

| | | | | | |
|---|---|---|---|---|---|
| 32 | 01 | 02 | 03 | 04 | 05 |
| 04 | 05 | 06 | 07 | 08 | 09 |
| 08 | 09 | 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 | 31 | 31 | 32 | 01 |

# 6.2.2 Continue

## *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. See Figure 6.7.*

**Figure 6.7** *S-boxes*

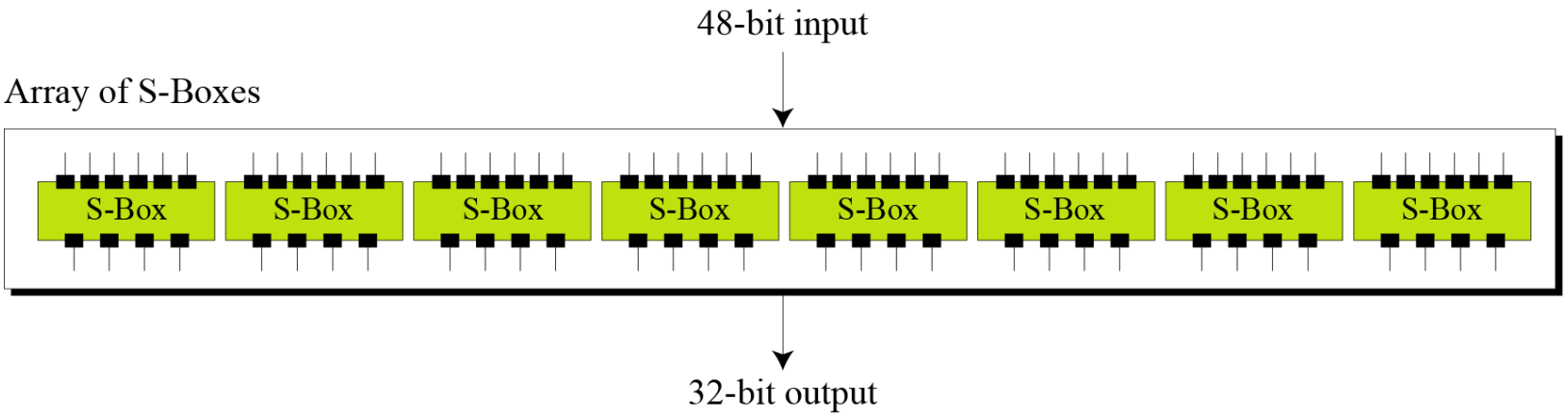
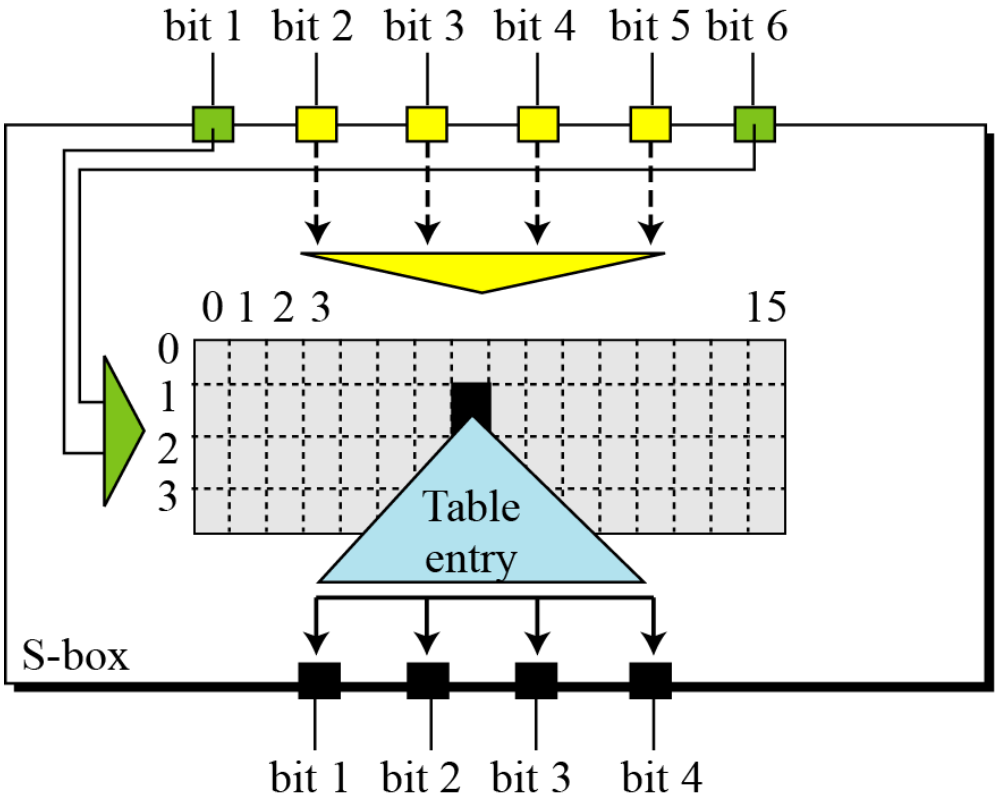


**Figure 6.8** *S-box rule*



# 6.2.2 Continue

***Table 6.3 shows the permutation for S-box 1. For the rest of the boxes see the textbook.***

**Table 6.3** *S-box 1*

| | *0* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* | *11* | *12* | *13* | *14* | *15* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *0* | 14 | 04 | 13 | 01 | 02 | 15 | 11 | 08 | 03 | 10 | 06 | 12 | 05 | 09 | 00 | 07 |
| *1* | 00 | 15 | 07 | 04 | 14 | 02 | 13 | 10 | 03 | 06 | 12 | 11 | 09 | 05 | 03 | 08 |
| *2* | 04 | 01 | 14 | 08 | 13 | 06 | 02 | 11 | 15 | 12 | 09 | 07 | 03 | 10 | 05 | 00 |
| *3* | 15 | 12 | 08 | 02 | 04 | 09 | 01 | 07 | 05 | 11 | 03 | 14 | 10 | 00 | 06 | 13 |

# 6.2.2 Continued

## Example 6.3

**The input to S-box 1 is 100011. What is the output?**

**Solution**

**If we write the first and the sixth bits together, we get 11 in binary, which is 3 in decimal. The remaining bits are 0001 in binary, which is 1 in decimal. We look for the value in row 3, column 1, in Table 6.3 (S-box 1). The result is 12 in decimal, which in binary is 1100. So the input 100011 yields the output 1100.**

## Example 6.4

**The input to S-box 8 is 000000. What is the output?**

**Solution**

**If we write the first and the sixth bits together, we get 00 in binary, which is 0 in decimal. The remaining bits are 0000 in binary, which is 0 in decimal. We look for the value in row 0, column 0, in Table 6.10 (S-box 8). The result is 13 in decimal, which is 1101 in binary. So the input 000000 yields the output 1101.**

## Straight Permutation

**Table 6.11** *Straight permutation table*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 16 | 07 | 20 | 21 | 29 | 12 | 28 | 17 |
| 01 | 15 | 23 | 26 | 05 | 18 | 31 | 10 |
| 02 | 08 | 24 | 14 | 32 | 27 | 03 | 09 |
| 19 | 13 | 30 | 06 | 22 | 11 | 04 | 25 |

# 6.2.3 Cipher and Reverse Cipher

*Using mixers and swappers, we can create the cipher and reverse cipher, each having 16 rounds.*

### *First Approach*

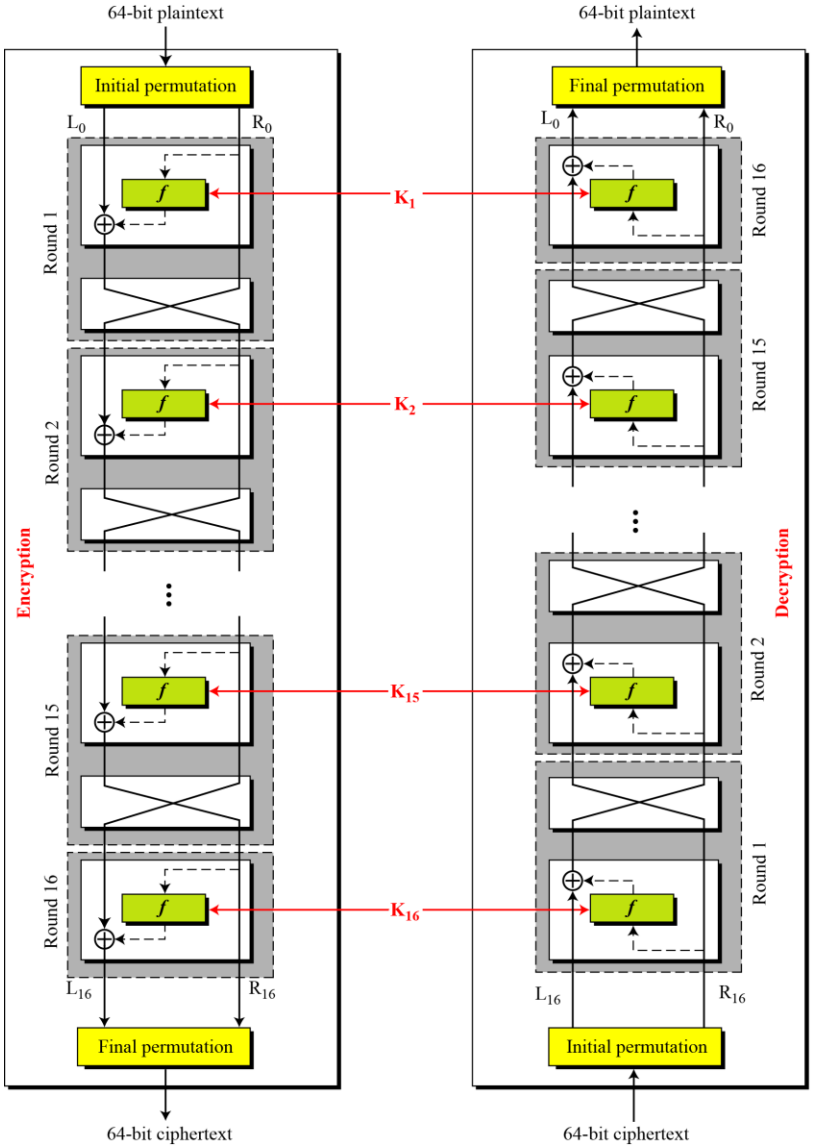
*To achieve this goal, one approach is to make the last round (round 16) different from the others; it has only a mixer and no swapper.*

**Note**

**In the first approach, there is no swapper in the last round.**

# 6.2.3 Continued

## Figure 6.9 *DES cipher and reverse cipher for the first approach*



# 6.2.3 Continued

## Algorithm 6.1 *Pseudocode for DES cipher*

```
Cipher (plainBlock[64], RoundKeys[16, 48], cipherBlock[64])
{
    permute (64, 64, plainBlock, inBlock, InitialPermutationTable)
    split (64, 32, inBlock, leftBlock, rightBlock)
    for (round = 1 to 16)
    {
        mixer (leftBlock, rightBlock, RoundKeys[round])
        if (round!=16) swapper (leftBlock, rightBlock)
    }
    combine (32, 64, leftBlock, rightBlock, outBlock)
    permute (64, 64, outBlock, cipherBlock, FinalPermutationTable)
}
```

## Algorithm 6.1 *Pseudocode for DES cipher* (Continued)

```
mixer (leftBlock[48], rightBlock[48], RoundKey[48])
{
    copy (32, rightBlock, T1)
    function (T1, RoundKey, T2)
    exclusiveOr (32, leftBlock, T2, T3)
    copy (32, T3, rightBlock)
}

swapper (leftBlock[32], rigthBlock[32])
{
    copy (32, leftBlock, T)
    copy (32, rightBlock, leftBlock)
    copy (32, T, rightBlock)
}
```

# 6.2.3 Continued

## Algorithm 6.1 *Pseudocode for DES cipher* (Continued)

```
function (inBlock[32], RoundKey[48], outBlock[32])
{
    permute (32, 48, inBlock, T1, ExpansionPermutationTable)
    exclusiveOr (48, T1, RoundKey, T2)
    substitute (T2, T3, SubstituteTables)
    permute (32, 32, T3, outBlock, StraightPermutationTable)
}
```

# 6.2.3 Continued

## Algorithm 6.1 *Pseudocode for DES cipher* (Continued)

```
substitute (inBlock[32], outBlock[48], SubstitutionTables[8, 4, 16])
{
    for (i = 1 to 8)
    {
        row ← 2 × inBlock[i × 6 + 1] + inBlock [i × 6 + 6]
        col ← 8 × inBlock[i × 6 + 2] + 4 × inBlock[i × 6 + 3] +
              2 × inBlock[i × 6 + 4] + inBlock[i × 6 + 5]

        value = SubstitutionTables [i][row][col]

        outBlock[[i × 4 + 1] ← value / 8;      value ← value mod 8
        outBlock[[i × 4 + 2] ← value / 4;      value ← value mod 4
        outBlock[[i × 4 + 3] ← value / 2;      value ← value mod 2
        outBlock[[i × 4 + 4] ← value
    }
}
```

## Alternative Approach

*We can make all 16 rounds the same by including one swapper to the 16th round and add an extra swapper after that (two swappers cancel the effect of each other).*

## Key Generation

*The round-key generator creates sixteen 48-bit keys out of a 56-bit cipher key.*

# 6.2.3 Continued

Shifting

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

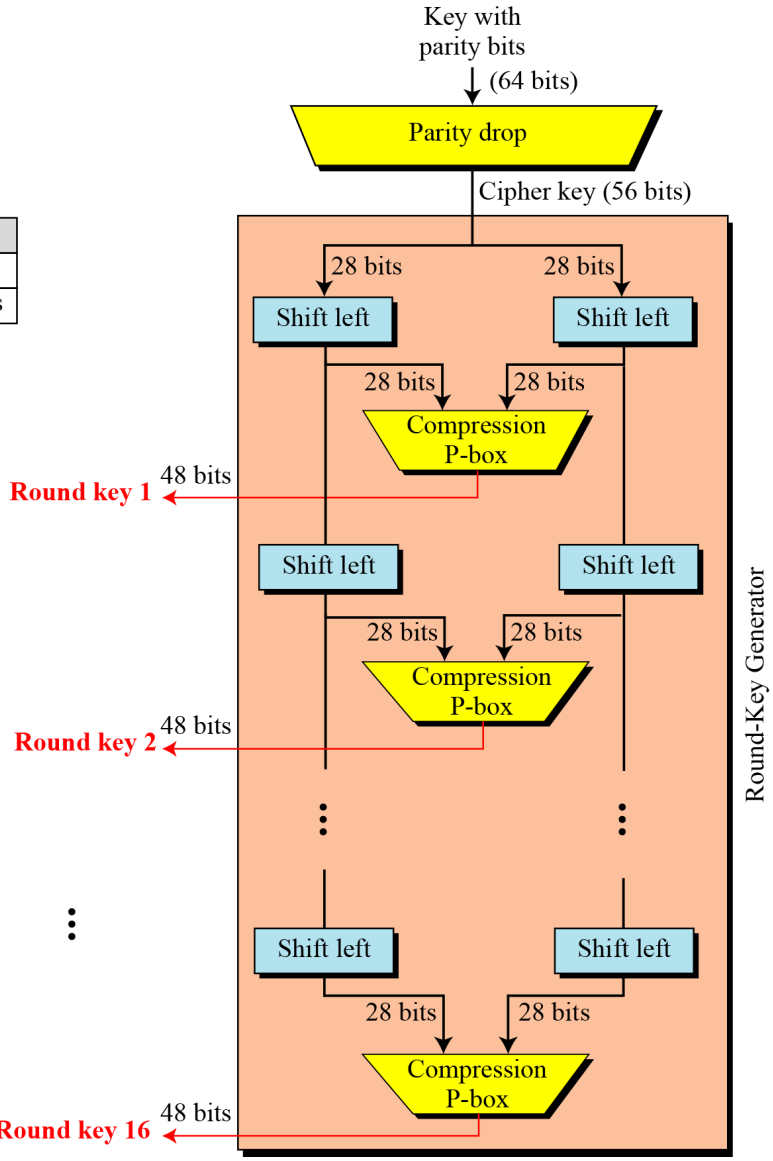



**Figure 6.10**

***Key generation***

# 6.2.3 Continued

## Table 6.12 *Parity-bit drop table*

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

## Table 6.13 *Number of bits shifts*

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

**Table 6.14** *Key-compression table*

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 14 | 17 | 11 | 24 | 01 | 05 | 03 | 28 |
| 15 | 06 | 21 | 10 | 23 | 19 | 12 | 04 |
| 26 | 08 | 16 | 07 | 27 | 20 | 13 | 02 |
| 41 | 52 | 31 | 37 | 47 | 55 | 30 | 40 |
| 51 | 45 | 33 | 48 | 44 | 49 | 39 | 56 |
| 34 | 53 | 46 | 42 | 50 | 36 | 29 | 32 |

# 6.2.3 Continued

## Algorithm 6.2 *Algorithm for round-key generation*

```
Key_Generator (keyWithParities[64], RoundKeys[16, 48], ShiftTable[16])
{
    permute (64, 56, keyWithParities, cipherKey, ParityDropTable)
    split (56, 28, cipherKey, leftKey, rightKey)
    for (round = 1 to 16)
    {
        shiftLeft (leftKey, ShiftTable[round])
        shiftLeft (rightKey, ShiftTable[round])
        combine (28, 56, leftKey, rightKey, preRoundKey)
        permute (56, 48, preRoundKey, RoundKeys[round], KeyCompressionTable)
    }
}
```

# 6.2.3 Continued

**Algorithm 6.2** *Algorithm for round-key generation (Continue)*

```
shiftLeft (block[28], numOfShifts)
{
    for (i = 1 to numOfShifts)
    {
        T ← block[1]
        for (j = 2 to 28)
        {
            block [j−1] ← block [j]
        }
        block[28] ← T
    }
}
```

# 6.2.4 Examples

## Example 6.5

**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 6.15** *Trace of data for Example 6.5*

| *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 |

# 6.2.4 Continued

## Example 6.5 Continued

**Table 6.15** *Trace of data for Example 6.5 (Conintued*

| | | | |
|---|---|---|---|
| *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)* |

# 6.2.4 Continued

## Example 6.6

**Let us see how Bob, at the destination, can decipher the ciphertext received from Alice using the same key. Table 6.16 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) | | | |

# 6-3 DES ANALYSIS

***Critics have used a strong magnifier to analyze DES. Tests have been done to measure the strength of some desired properties in a block cipher.***

***Topics discussed in this section:***

# 6.3.1 Properties

*Two desired properties of a block cipher are the avalanche effect and the completeness.*

**Example 6.7**

**To check the avalanche effect in DES, let us encrypt two plaintext blocks (with the same key) that differ only in one bit and observe the differences in the number of bits in each round.**

Plaintext: 0000000000000000 Key: 22234512987ABB23
Ciphertext: 4789FD476E82A5F1

Plaintext: 0000000000000001 Key: 22234512987ABB23
Ciphertext: 0A4ED5C15A63FEA3

# 6.3.1 Continued

## Example 6.7 Continued

**Although the two plaintext blocks differ only in the rightmost bit, the ciphertext blocks differ in 29 bits. This means that changing approximately 1.5 percent of the plaintext creates a change of approximately 45 percent in the ciphertext.**

**Table 6.17** *Number of bit differences for Example 6.7*

| *Rounds* | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* | *11* | *12* | *13* | *14* | *15* | *16* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bit differences | 1 | 6 | 20 | 29 | 30 | 33 | 32 | 29 | 32 | 39 | 33 | 28 | 30 | 31 | 30 | 29 |

### *Completeness effect*

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

# 6.3.2 Design Criteria

## S-Boxe

*The design provides confusion and diffusion of bits from each round to the next.*

## P-Boxes

*They provide diffusion of bits.*

## Number of Rounds

*DES uses sixteen rounds of Feistel ciphers. the ciphertext is thoroughly a random function of plaintext and ciphertext.*

# 6.3.3 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 |

# 6.3.3 Continued

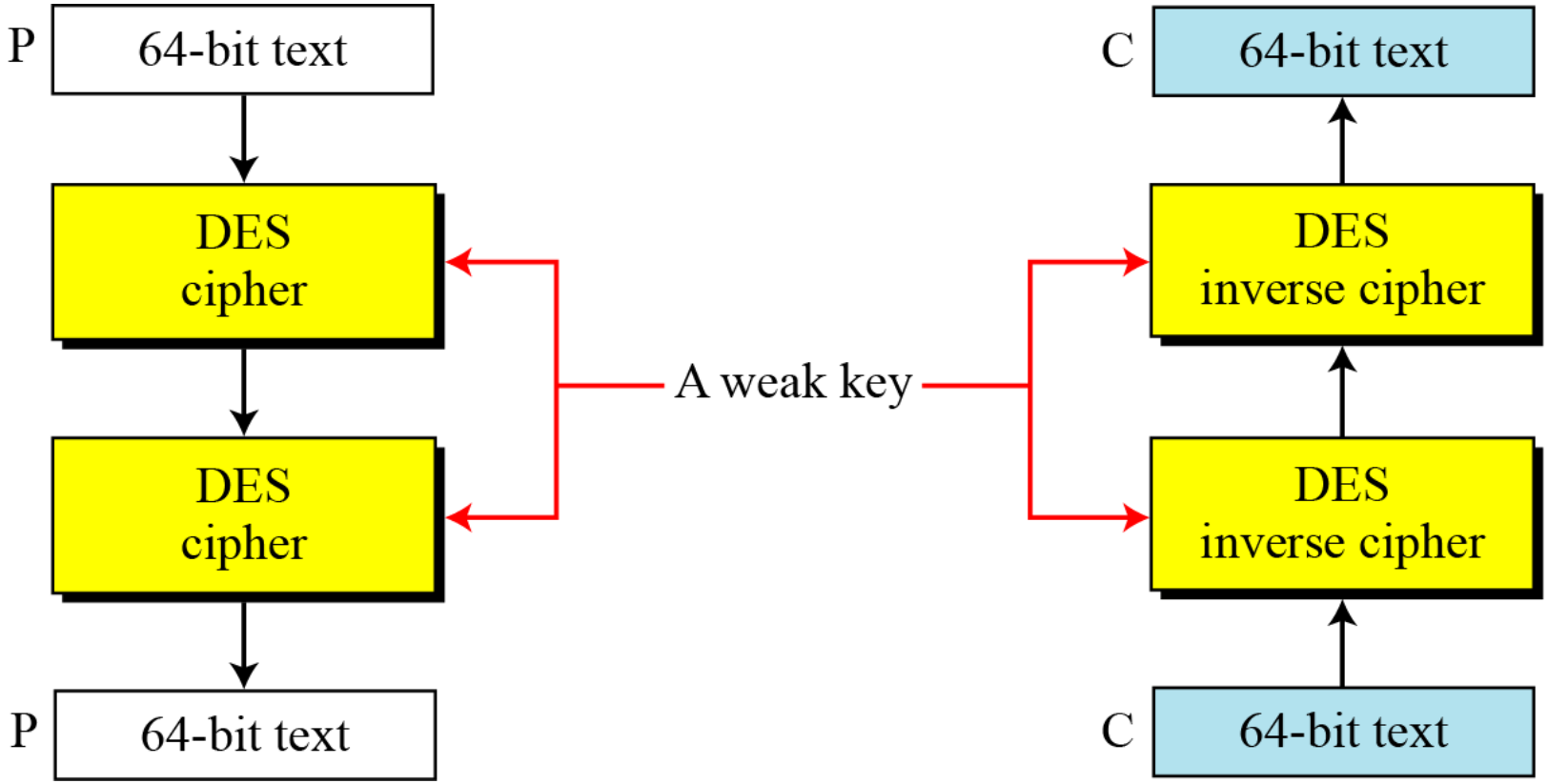
## Example 6.8

**Let us try the first weak key in Table 6.18 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: *0x123456788765432 1* Ciphertext: 0x814FE938589154F7

Key: 0x0101010101010101
Plaintext: 0x814FE938589154F7 Ciphertext: *0x123456788765432 1*

**Figure 6.11** *Double encryption and decryption with a weak key*



# 6.3.3 Continued

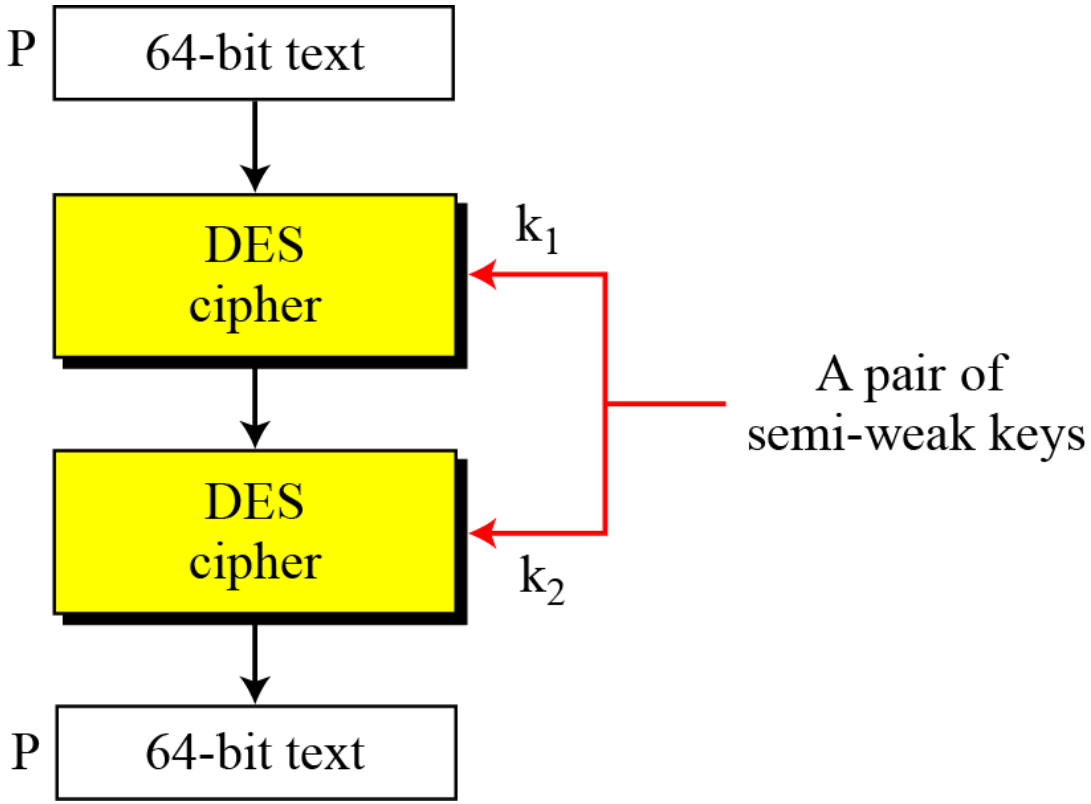
**Table 6.19** *Semi-weak keys*

| *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 |

# 6.3.3 Continued

| | | |
|---|---|---|
| *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 |

**Figure 6.12** *A pair of semi-weak keys in encryption and decryption*



# 6.3.3 Continued

## Example 6.9

**What is the probability of randomly selecting a weak, a semi-weak, or a possible weak key?**

**Solution**

**DES has a key domain of $2^{56}$. The total number of the above keys are 64 (4 + 12 + 48). The probability of choosing one of these keys is $8.8 \times 10^{-16}$, almost impossible.**

# 6.3.3 Continued

**Key Complement** In the key domain ($2^{56}$), definitely half of the keys are *complement* of the other half. A **key complement** can be made by inverting (changing 0 to 1 or 1 to 0) each bit in the key. Does a key complement simplify the job of the cryptanalysis? It happens that it does. Eve can use only half of the possible keys ($2^{55}$) to perform brute-force attack. This is because

$$C = E(K, P) \quad \rightarrow \quad \overline{C} = E(\overline{K}, \overline{P})$$

In other words, if we encrypt the complement of plaintext with the complement of the key, we get the complement of the ciphertext. Eve does not have to test all $2^{56}$ possible keys, she can test only half of them and then complement the result.

# 6.3.3 Continued

## Example 6.10

**Let us test the claim about the complement keys. We have used an arbitrary key and plaintext to find the corresponding ciphertext. If we have the key complement and the plaintext, we can obtain the complement of the previous ciphertext (Table 6.20).**

**Table 6.20** *Results for Example 6.10*

| | *Original* | *Complement* |
|---|---|---|
| Key | 1234123412341234 | EDCBEDCBEDCBEDCB |
| Plaintext | 12345678ABCDEF12 | EDCBA987543210ED |
| Ciphertext | E112BE1DEFC7A367 | 1EED41E210385C98 |

# 6-4 Multiple DES

***The major criticism of DES regards its key length. Fortunately DES is not a group. This means that we can use double or triple DES to increase the key size.***

***Topics discussed in this section:***

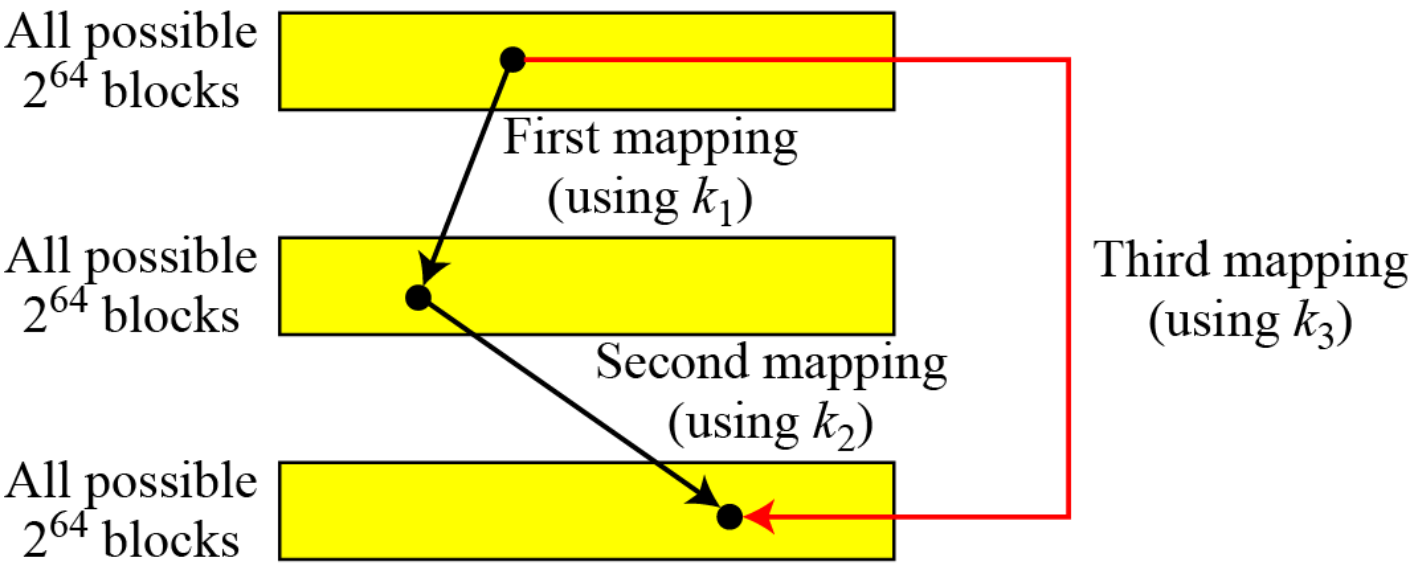
**6.4.1 Double DES**

**6.4.4 Triple DES**

# 6-4 Continued

***A substitution that maps every possible input to every possible output is a group.***

**Figure 6.13** *Composition of mapping*



# 6.4.1 Double DES

*The first approach is to use double DES (2DES).*

### *Meet-in-the-Middle Attack*

*However, using a known-plaintext attack called meet-in-the-middle attack proves that double DES improves this vulnerability slightly (to $2^{57}$ tests), but not tremendously (to $2^{112}$).*

**Figure 6.14** *Meet-in-the-middle attack for double DES*

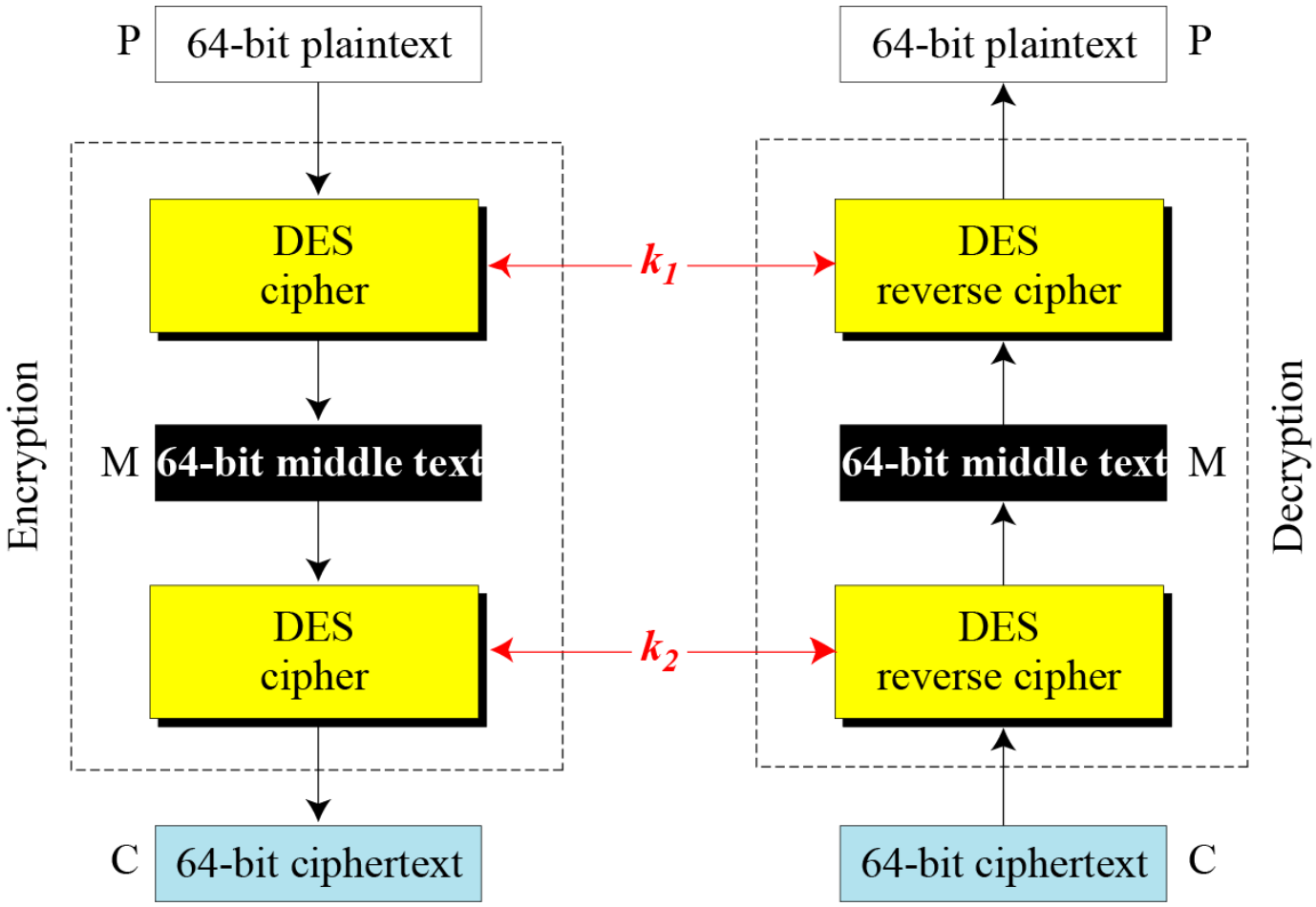
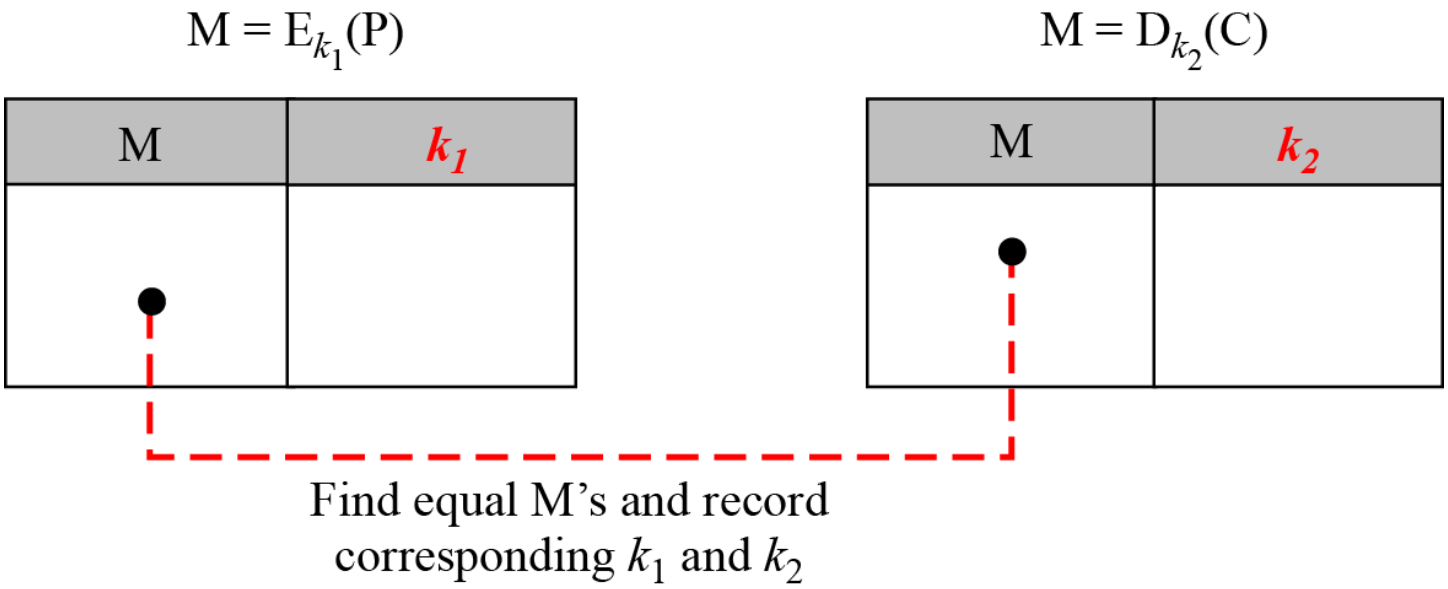
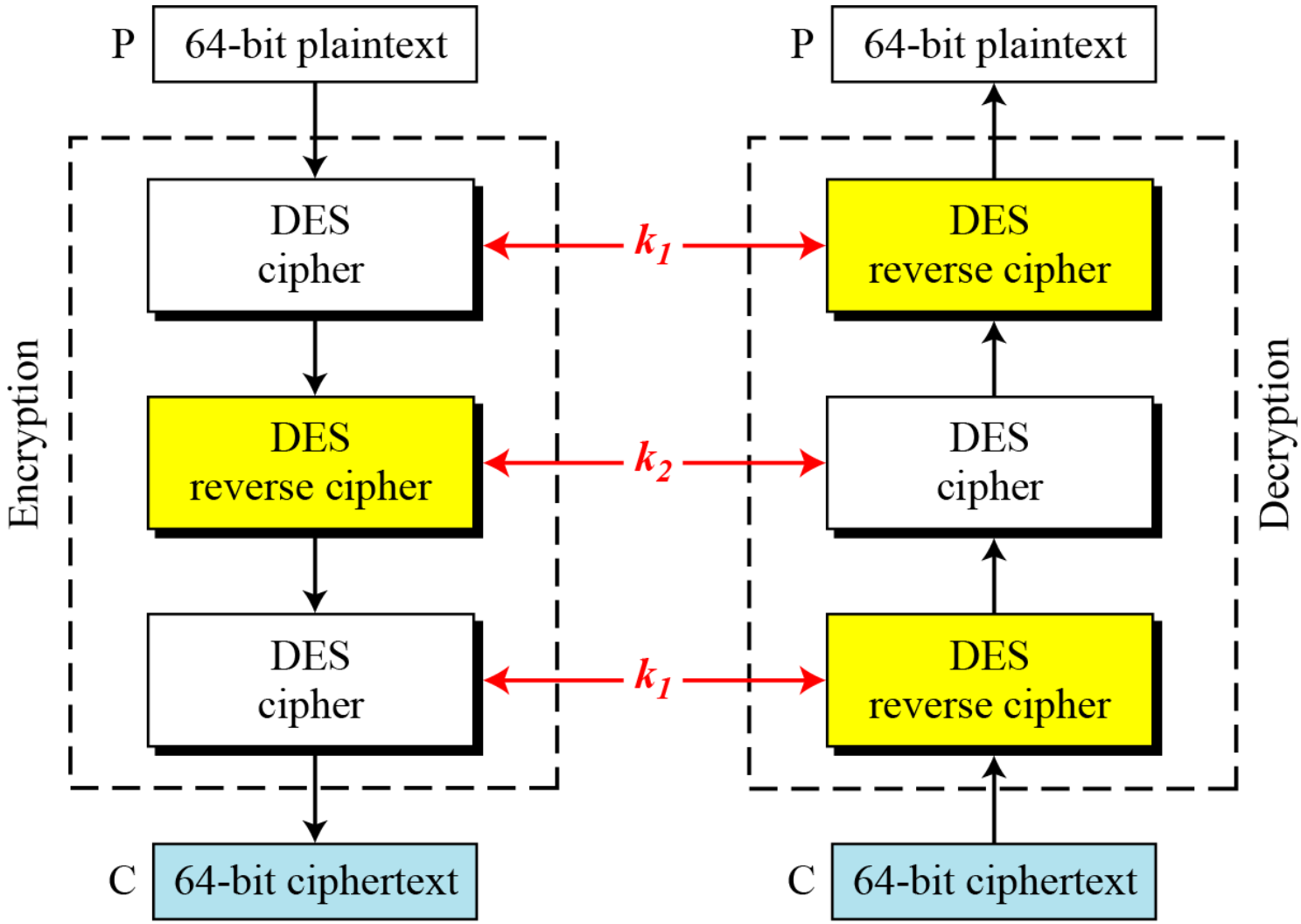


**Figure 6.15** *Tables for meet-in-the-middle attack*



# 6.4.2 Triple DES

**Figure 6.16** *Triple DES with two keys*



# 6.4.2 Continuous

## Triple DES with Three Keys

***The possibility of known-plaintext attacks on triple DES with two keys has enticed some applications to use triple DES with three keys. Triple DES with three keys is used by many applications such as PGP (See Chapter 16).***

# 6-5 Security of DES

*DES, as the first important block cipher, has gone through much scrutiny. Among the attempted attacks, three are of interest: brute-force, differential cryptanalysis, and linear cryptanalysis.*

***Topics discussed in this section:***

# 6.5.1 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.*

# 6.5.2 Differential Cryptanalysis

*It has been revealed that the designers of DES already knew about this type of attack and designed S-boxes and chose 16 as the number of rounds to make DES specifically resistant to this type of attack.*

*Note*

**We show an example of DES differential cryptanalysis in Appendix N.**

# 6.5.3 Linear Cryptanalysis

*Linear cryptanalysis is newer than differential cryptanalysis. DES is more vulnerable to linear cryptanalysis than to differential cryptanalysis. S-boxes are not very resistant to linear cryptanalysis. It has been shown that DES can be broken using $2^{43}$ pairs of known plaintexts. However, from the practical point of view, finding so many pairs is very unlikely.*

**Note**

**We show an example of DES linear cryptanalysis in Appendix N.**