CRYPTOGRAPHY AND NETWORK SECURITY

Chapter 2: Block Ciphers, Data Encryption Standard and Advanced Encryption Standard

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The Data Encryption Standard

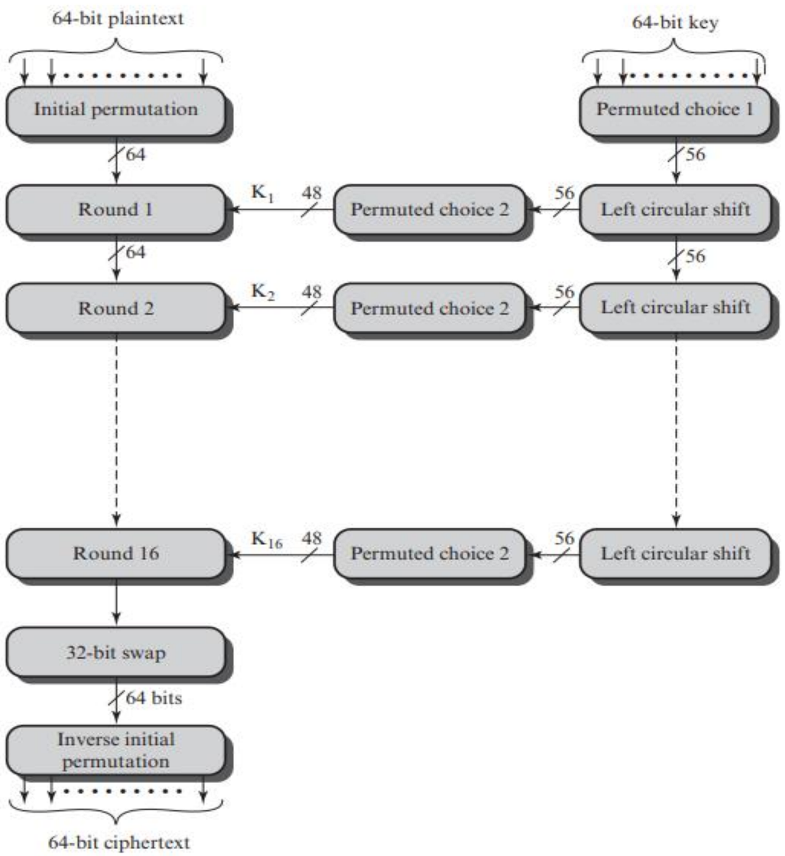


Figure 4.5 General Depiction of DES Encryption Algorithm

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.8 Looking at the left-hand side of the figure, we can see that the processing of the plaintext proceeds in three phases. First, 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 sixteen rounds of the same function, which involves both permutation and substitution functions. 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. 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

Simplified DES

Block Cipher Principles

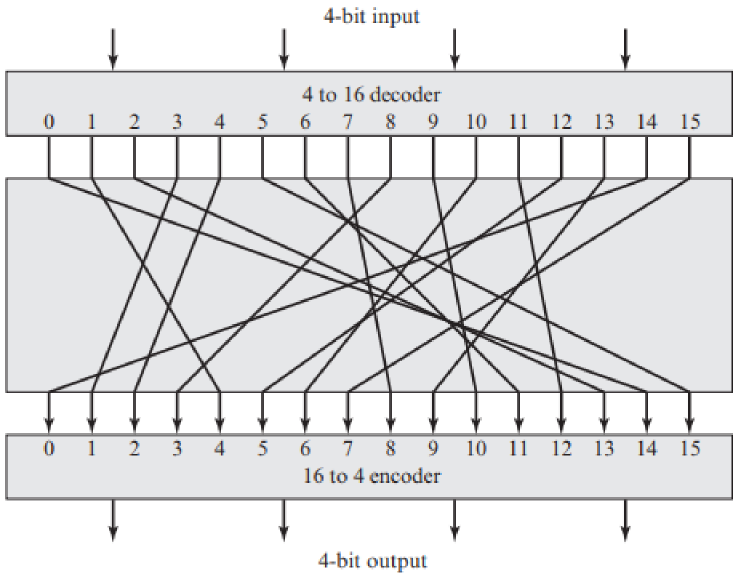


Figure 4.2 General n-bit-n-bit Block Substitution (shown with $n = 4$)

Block Cipher Principles

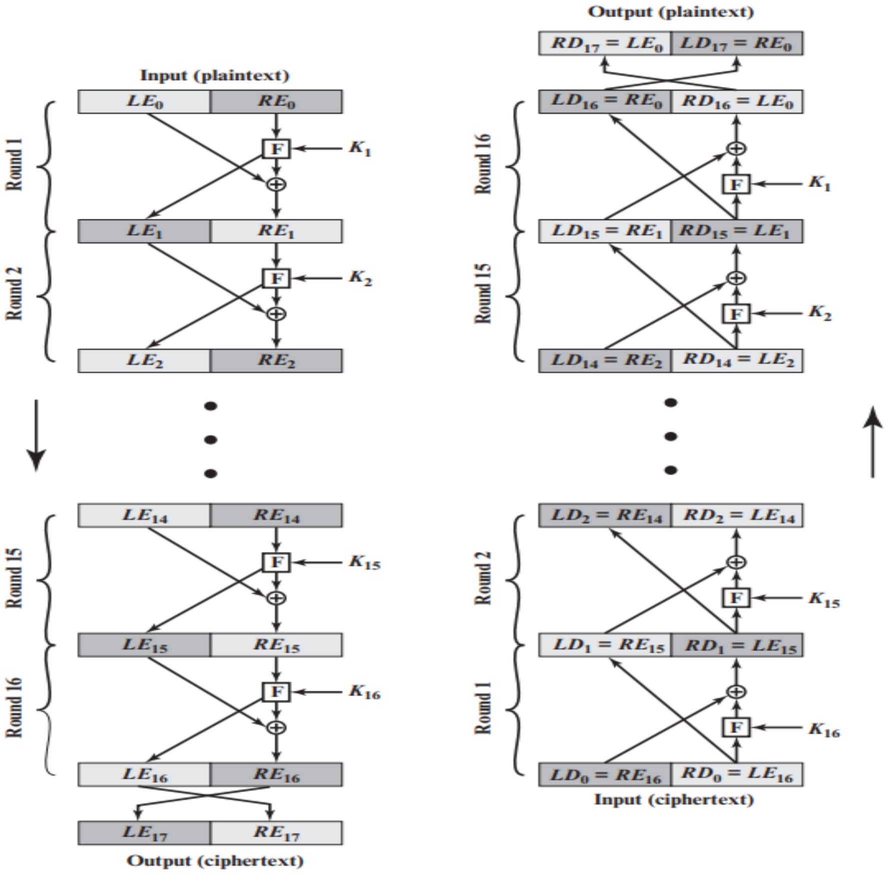


Figure 4.3 Feistel Encryption and Decryption (16 rounds)

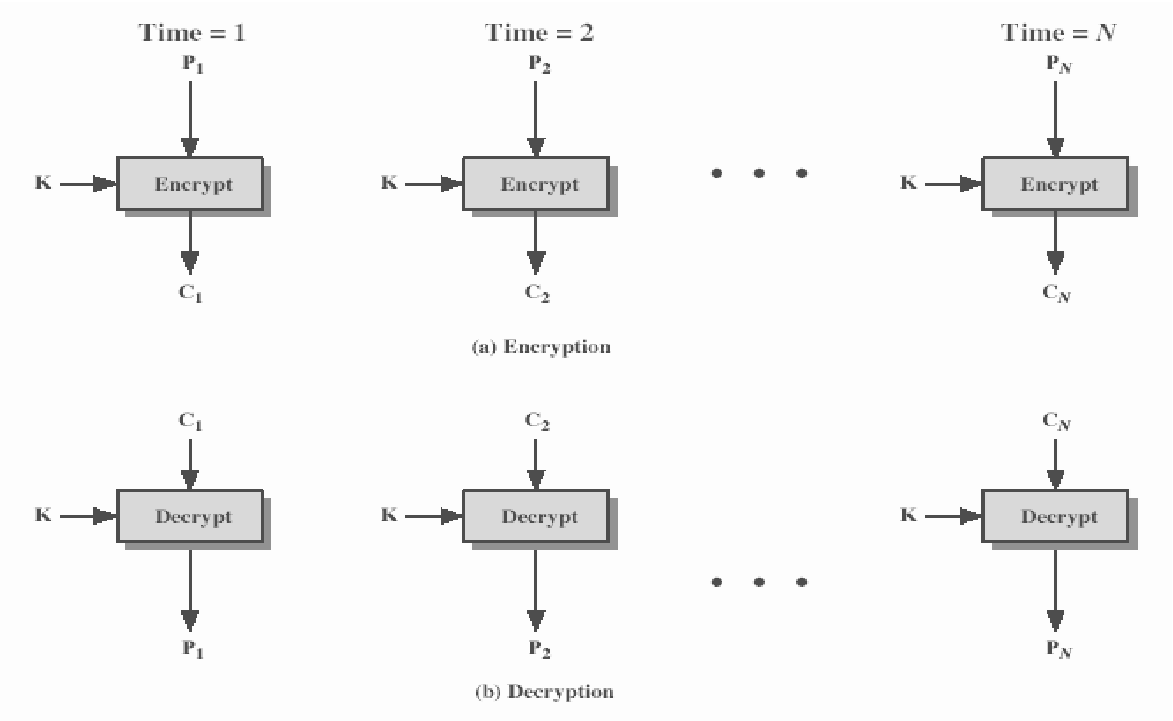
Modes of Operation

- block ciphers encrypt fixed size blocks
  - eg. DES encrypts 64-bit blocks with 56-bit key
- need some way to en/decrypt arbitrary amounts of data in practise
- **ANSI X3.106-1983 Modes of Use** (now FIPS 81) defines 4 possible modes
- subsequently 5 defined for AES & DES
- have **block** and **stream** modes

Electronic Codebook Book (ECB)

- message is broken into independent blocks which are encrypted
- each block is a value which is substituted, like a codebook, hence name
- each block is encoded independently of the other blocks

  $C_i = DES_{K1}(P_i)$
- uses: secure transmission of single values



Advantages And Limitations of ECB

- message repetitions may show in ciphertext
  - if aligned with message block
  - particularly with data such graphics
  - or with messages that change very little, which become a code-book analysis problem
- weakness is due to the encrypted message blocks being independent
- main use is sending a few blocks of data

Advantages and Limitations of CTR

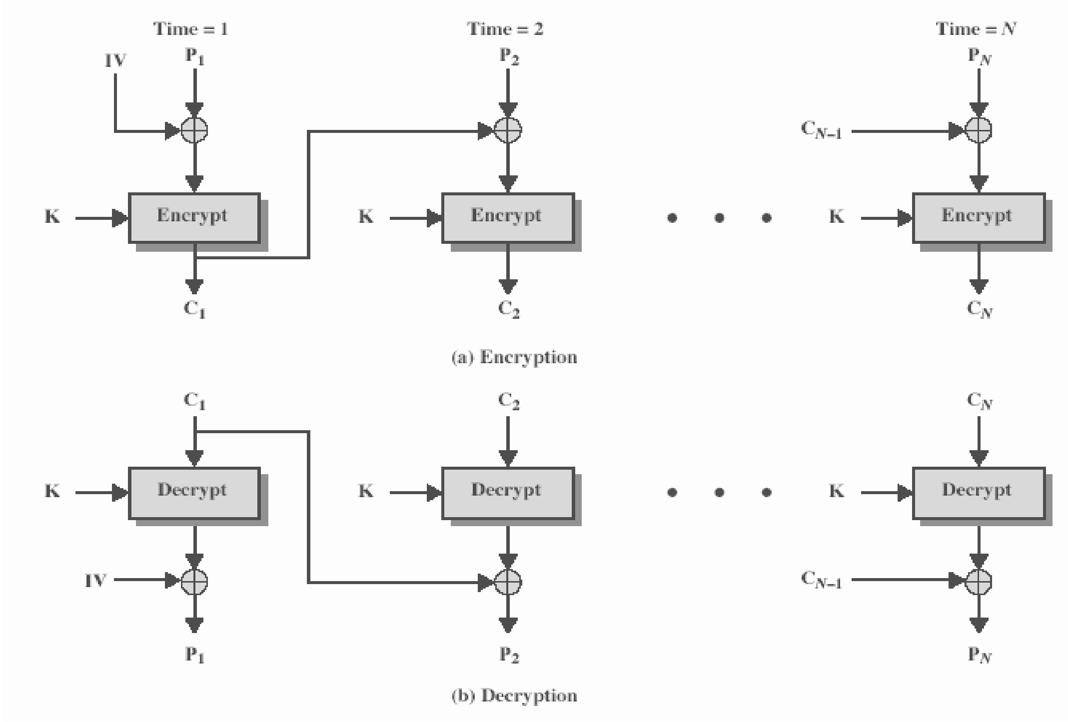
- efficiency
  - can do parallel encryptions in h/w or s/w
  - can preprocess in advance of need
  - good for bursty high speed links
- random access to encrypted data blocks
- provable security (good as other modes)
- but must ensure never reuse key/counter values, otherwise could break (cf OFB)

Cipher Block Chaining (CBC)

- message is broken into blocks
- linked together in encryption operation
- each previous cipher blocks is chained with current plaintext block, hence name
- use Initial Vector (IV) to start process

  $C_i = DES_{K1}(P_i \text{ XOR } C_{i-1})$

  $C_{-1} = IV$
- uses: bulk data encryption, authentication



Advantages and Limitations of CBC

- a ciphertext block depends on **all** blocks before it
- any change to a block affects all following ciphertext blocks
- need **Initialization Vector** (IV)
  - which must be known to sender & receiver
  - if sent in clear, attacker can change bits of first block, and change IV to compensate
  - hence IV must either be a fixed value (as in EFTPOS)
  - or must be sent encrypted in ECB mode before rest of message

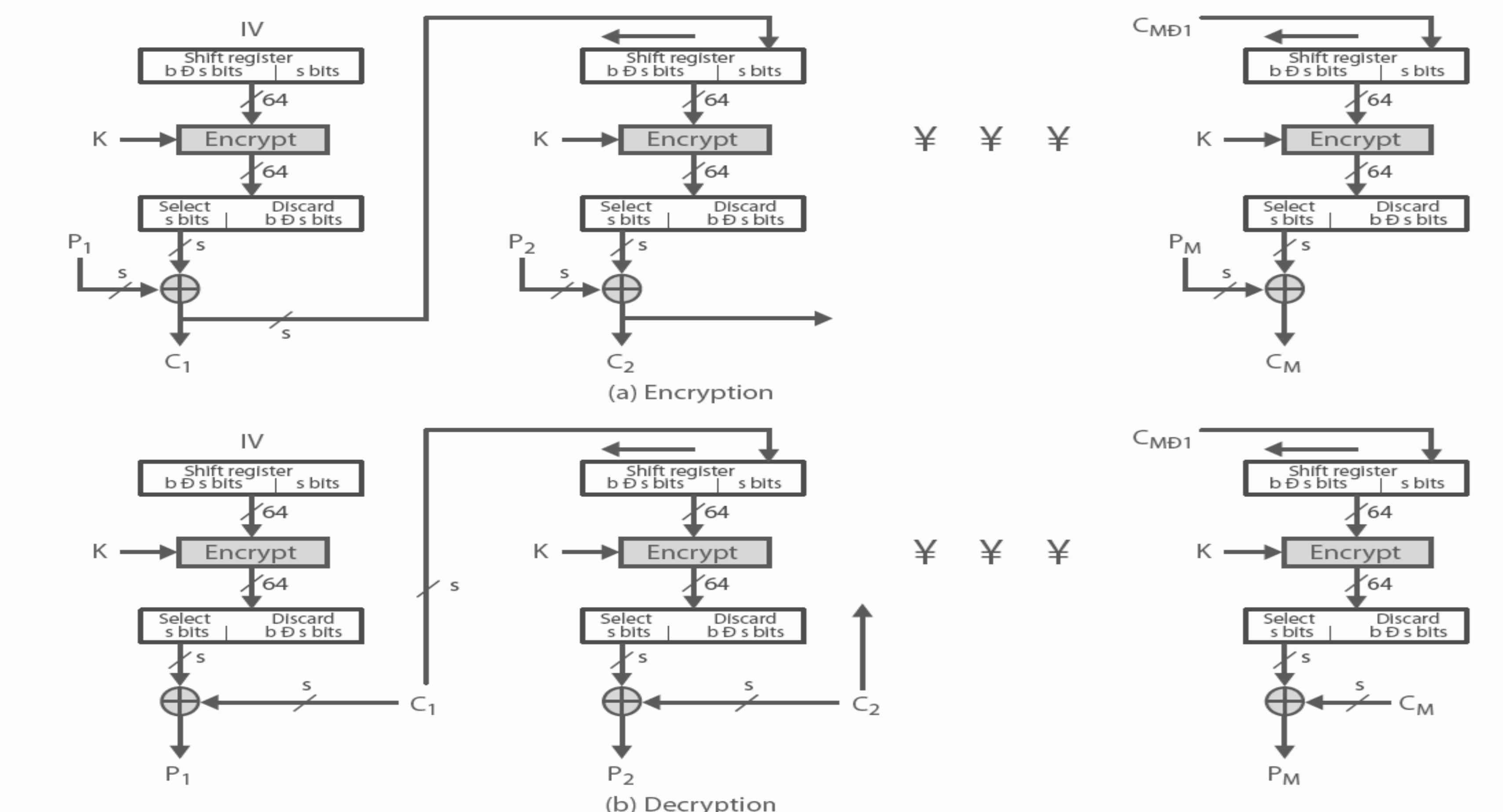
Cipher FeedBack (CFB)

- message is treated as a stream of bits
- added to the output of the block cipher
- result is feed back for next stage (hence name)
- standard allows any number of bit (1,8, 64 or 128 etc) to be feed back
  - denoted CFB-1, CFB-8, CFB-64, CFB-128 etc
- most efficient to use all bits in block (64 or 128)

  $C_i = P_i \text{ XOR } DES_{K1}(C_{i-1})$

  $C_{-1} = IV$
- uses: stream data encryption, authentication

Cipher FeedBack (CFB)



Advantages and Limitations of CFB

- appropriate when data arrives in bits/bytes
- most common stream mode
- limitation is need to stall while do block encryption after every n-bits
- note that the block cipher is used in **encryption** mode at **both** ends
- errors propogate for several blocks after the error

Output FeedBack (OFB)

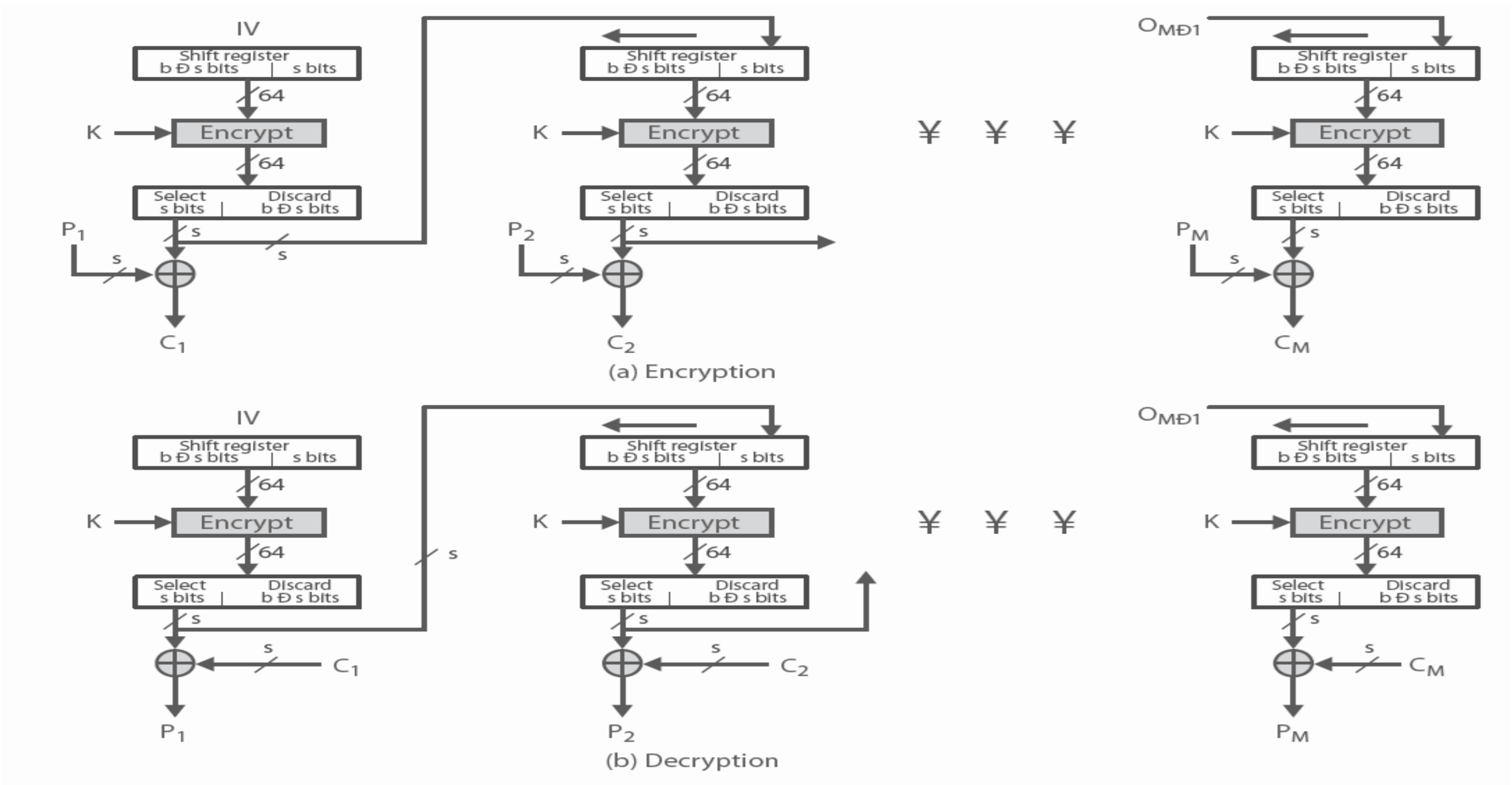
- message is treated as a stream of bits
- output of cipher is added to message
- output is then feed back (hence name)
- feedback is independent of message
- can be computed in advance

  $C_i = P_i \text{ XOR } O_i$

  $O_i = DES_{K1}(O_{i-1})$

  $O_{-1} = IV$
- uses: stream encryption on noisy channels

Output FeedBack (OFB)



(a) Encryption

(b) Decryption

Advantages and Limitations of OFB

- bit errors do not propagate
- more vulnerable to message stream modification
- a variation of a Vernam cipher
  - hence must **never** reuse the same sequence (key+IV)
- sender & receiver must remain in sync
- originally specified with m-bit feedback
- subsequent research has shown that only **full block feedback** (ie CFB-64 or CFB-128) should ever be used

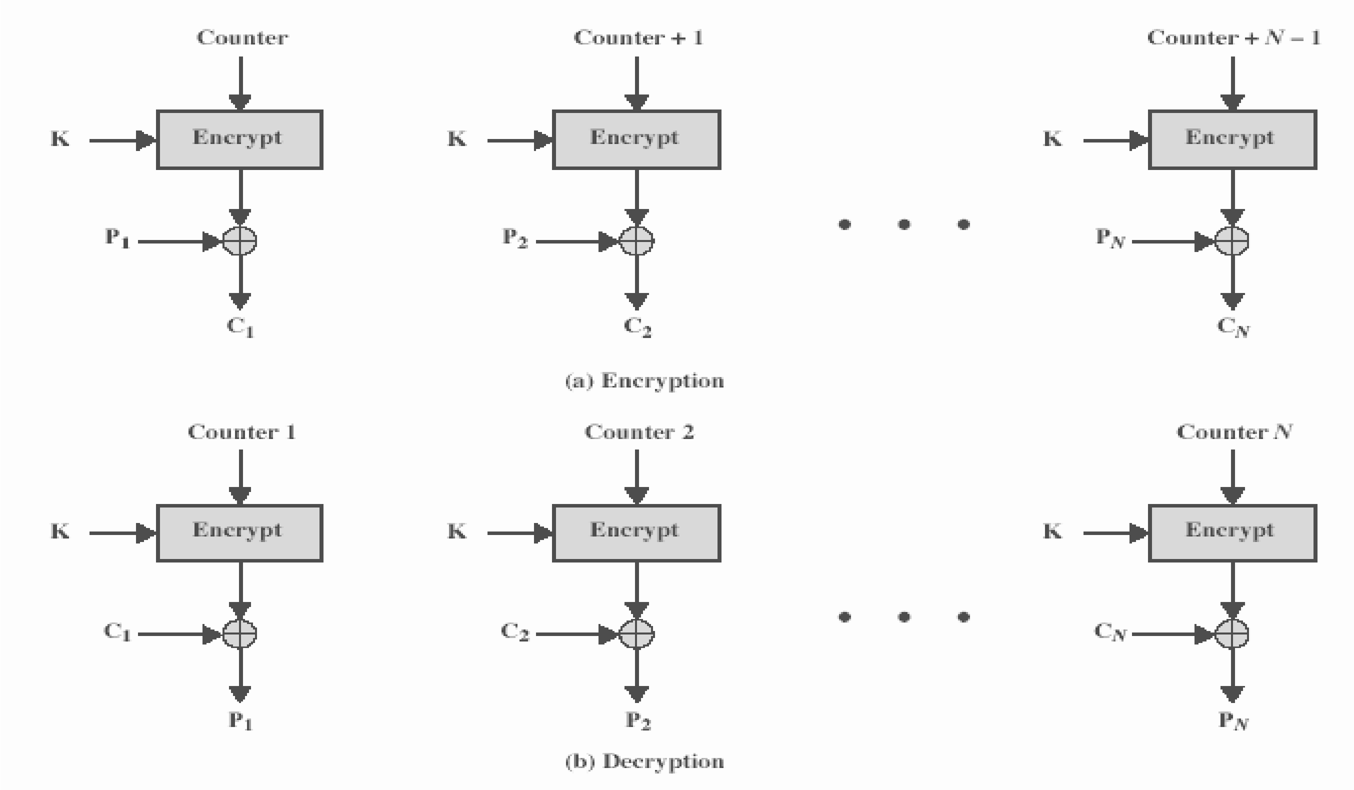
Counter (CTR)

- a “new” mode, though proposed early on
- similar to OFB but encrypts counter value rather than any feedback value
- must have a different key & counter value for every plaintext block (never reused)

  $C_i = P_i \text{ XOR } O_i$

  $O_i = DES_{K1}(i)$
- uses: high-speed network encryptions

Counter (CTR)


Counter
Counter + 1
Counter + N – 1
K
Encrypt
P1
P2
PN
C1
C2
CN
(a) Encryption
Counter 1
Counter 2
Counter N
(b) Decryption

3.4. Differential and Linear Cryptanalysis

For most of its life, the prime concern with DES has been its vulnerability to brute-force attack because of its relatively short (56 bits) key length. However, there has also been interest in finding cryptanalytic attacks on DES. With the increasing popularity of block ciphers with longer key lengths, including triple DES, brute-force attacks have become increasingly impractical. Thus, there has been increased emphasis on cryptanalytic attacks on DES and other symmetric block ciphers. In this section, we provide a brief overview of the two most powerful and promising approaches: differential cryptanalysis 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.

History

Differential cryptanalysis was not reported in the open literature until 1990. The first published effort appears to have been the cryptanalysis of a block cipher called FEAL by Murphy [MURP90]. This was followed by a number of papers by Biham and Shamir, who demonstrated this form of attack on a variety of encryption algorithms and hash functions; their results are summarized in [BIHA93].

The most publicized results for this approach have been those that have application to DES. Differential cryptanalysis is the first published attack that is capable of breaking DES in less than 2^{55} complexity. The scheme, as reported in [BIHA93], can successfully cryptanalyze DES with an effort on the order of 2^{47} encryptions, requiring 2^{47} chosen plaintexts. Although 2^{47} is certainly significantly less than 2^{55} the need for the adversary to find 2^{47} chosen plaintexts makes this attack of only theoretical interest.

Although differential cryptanalysis is a powerful tool, it does not do very well against DES. The reason, according to a member of the IBM team that designed DES [COPP94], is that differential cryptanalysis was known to the team as early as 1974. The need to strengthen DES against attacks using differential cryptanalysis played a large part in the design of the S-boxes and the permutation P. As evidence of the impact of these changes, consider these comparable results reported in [BIHA93]. Differential cryptanalysis of an eight-round LUCIFER algorithm requires only 256 chosen plaintexts, whereas an attack on an eight-round version of DES requires 2^{14} chosen plaintexts.

Differential Cryptanalysis Attack

The differential cryptanalysis attack is complex; [BIHA93] provides a complete description. 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. Here, we provide a brief overview so that you can get the flavor of the attack.

We begin with a change in notation for DES. 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 $m_1 (2 \leq i \leq 17)$, then the intermediate message halves are related as follows:

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

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:

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

Now, suppose that many pairs of inputs to f with the same difference yield the same output difference if the same subkey is used. To put this more precisely, let us say that *X may cause Y with probability p*, if for a fraction p of the pairs in which the input XOR is X, the output XOR equals Y. We want to suppose that there are a number of values of X that have high probability of causing a particular output difference. Therefore, if we know Δm_{i-1} and Δm_i with high probability, then we know Δm_{i+1} with high probability. Furthermore, if a number of such differences are determined, it is feasible to determine the subkey used in the function f.

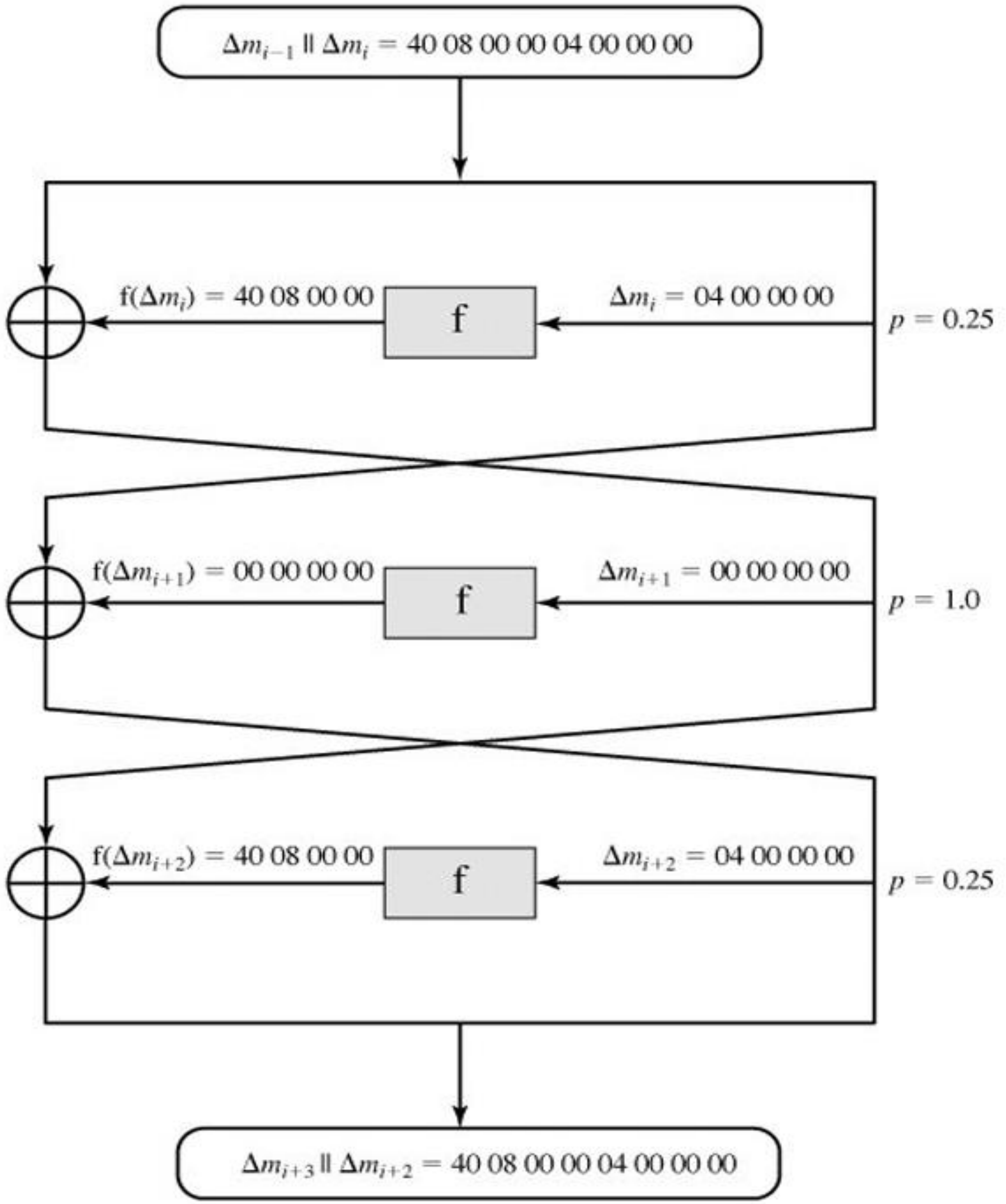
The overall strategy of differential cryptanalysis is based on these considerations for a single round. The procedure is to begin with two plaintext messages m and m' with a given difference and trace through a probable pattern of differences after each round to yield a probable difference for the ciphertext. Actually, there are two probable patterns of differences for the two 32-bit halves: $(\Delta m_{17} || m_{16})$. Next, we 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,

$$E(K, m) \oplus E(K, m') = (\Delta m_{17} || m_{16})$$

then we suspect that all the probable patterns at all the intermediate rounds are correct. With that assumption, we can make some deductions about the key bits. This procedure must be repeated many times to determine all the key bits.

Figure 3.7, based on a figure in [BIHA93], illustrates the propagation of differences through three rounds of DES. The probabilities shown on the right refer to the probability that a given set of intermediate differences will appear as a function of the input differences. Overall, after three rounds the probability that the output difference is as shown is equal to 0.25 x 1 x 0.25 = 0.0625.

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



Linear Cryptanalysis

A more recent development is linear cryptanalysis, described in [MATS93]. This attack is based on finding linear approximations to describe the transformations performed in DES. This method can find a DES key given 2^{43} known plaintexts, as compared to 2^{47} 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. So far, little work has been done by other groups to validate the linear cryptanalytic approach.

We now give a brief summary of the principle on which linear cryptanalysis is based. For a cipher with n-bit plaintext and ciphertext blocks and an m-bit key, let the plaintext block be labeled P[1], ... P[n], the cipher text block C[1], ... C[n], and the key K[1], ... K[m]. Then define

$$A[i, j, \ldots, k] = A[i] \oplus A[j] \oplus \ldots \oplus A[k]$$

The objective of linear cryptanalysis is to find an effective *linear* equation of the form:

$$P[\alpha_1, \alpha_2, \ldots, \alpha_a] \oplus C[\beta_1, \beta_2, \ldots, \beta_b] = K[\gamma_1, \gamma_2, \ldots, \gamma_c]$$

(where $x = 0$ or 1; $1 \leq a, b \leq n$, $1 \leq c \leq m$, and where the α, β and γ terms represent fixed, unique bit locations) that holds with probability $p \neq 0.5$. The further p is from 0.5, the more effective the equation. Once a proposed relation is determined, the procedure is to compute the results of the left-hand side of the preceding equation for a large number of plaintext-ciphertext pairs. If the result is 0 more than half the time, assume $K[\gamma_1, \gamma_2, \ldots, \gamma_c] = 0$. If it is 1 most of the time, assume $K[\gamma_1, \gamma_2, \ldots, \gamma_c] = 1$. This gives us a linear equation on the key bits. Try to get more such relations so that we can solve for the key bits. Because we are dealing with linear equations, the problem can be approached one round of the cipher at a time, with the results combined.