CRYPTOGRAPHIC TOOLS

Symmetric Key Cipher

Symmetric Encryption

- The universal technique for providing confidentiality for transmitted or stored data
- Also referred to as conventional encryption or single-key encryption
- Two requirements for secure use:
  - Need a strong encryption algorithm
  - Sender and receiver must have obtained copies of the secret key in a secure fashion and must keep the key secure

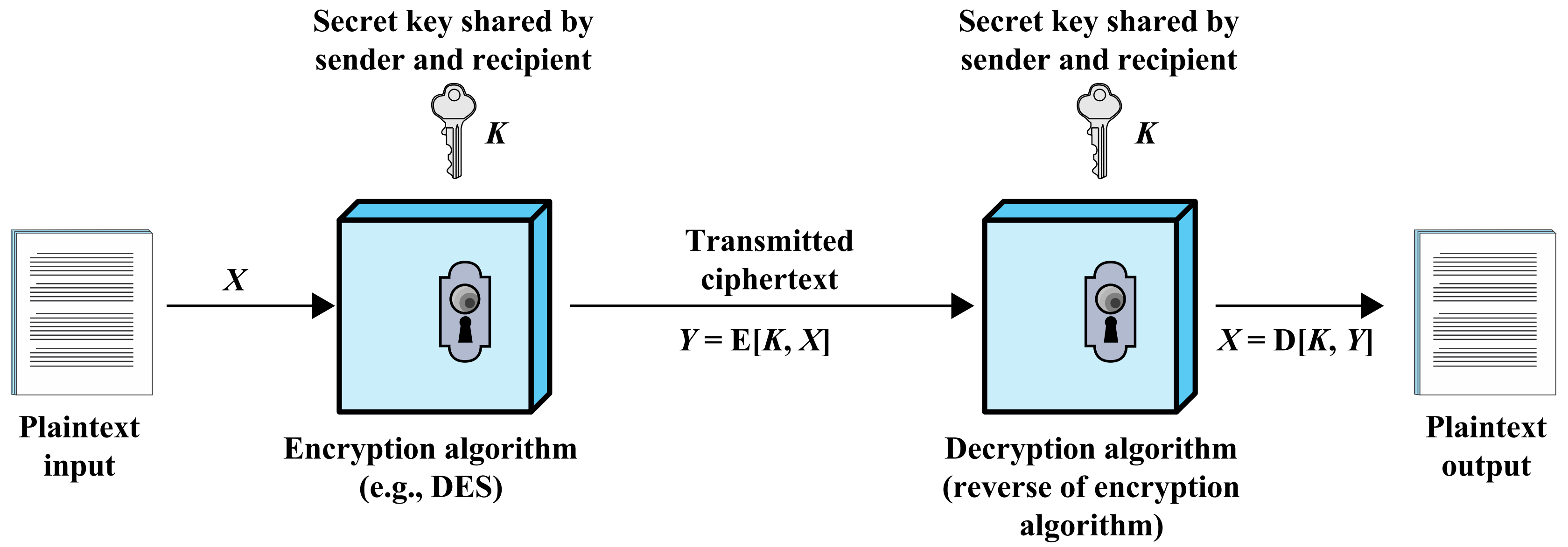


Figure 2.1 Simplified Model of Symmetric Encryption

Attacking Symmetric Encryption

Cryptanalytic Attacks

- Rely on:
  - Nature of the algorithm
  - Some knowledge of the general characteristics of the plaintext
  - Some sample plaintext-ciphertext pairs
- Exploits the characteristics of the algorithm to attempt to deduce a specific plaintext or the key being used
  - If it is successful all future and past messages encrypted with that key are compromised

Brute-Force Attacks

- Try all possible keys on some cipher text until an intelligible translation into plaintext is obtained
  - On average half of all possible keys must be tried to achieve success

	DES	Triple DES	AES
Plaintext block size (bits)	64	64	128
Ciphertext block size (bits)	64	64	128
Key size (bits)	56	112 or 168	128, 192, or 256

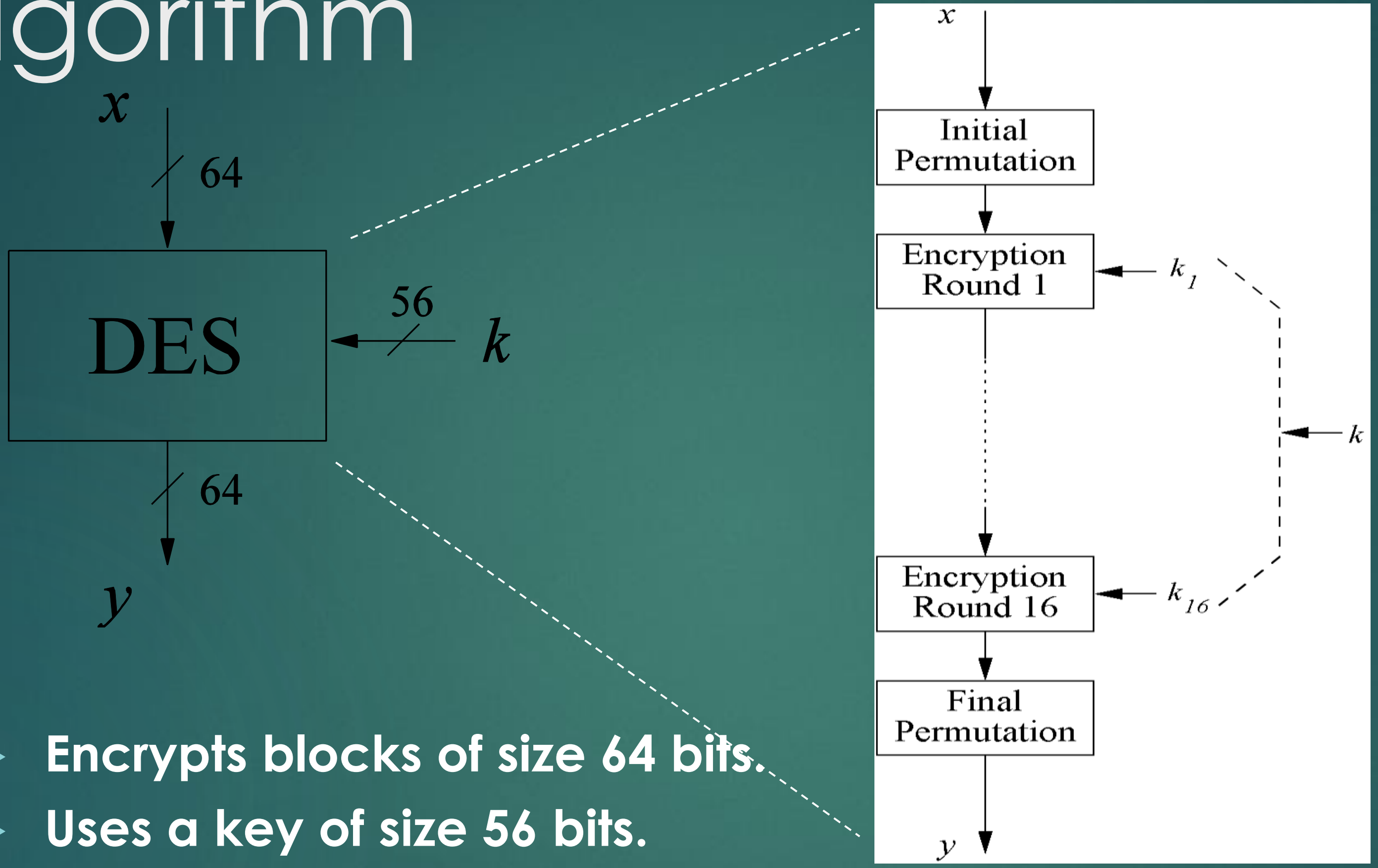
DES = Data Encryption Standard
AES = Advanced Encryption Standard

Comparison of Three Popular Symmetric Encryption Algorithms

Data Encryption Standard(DES)

- Until recently was the most widely used encryption scheme
  - FIPS PUB 46
  - Referred to as the Data Encryption Algorithm (DEA)
  - Uses 64-bit plaintext block and 56 bit key to produce a 64-bit ciphertext block
- Strength concerns:
  - Concerns about the algorithm itself
    - DES is the most studied encryption algorithm in existence
  - Concerns about the use of a 56-bit key
    - The speed of commercial off-the-shelf processors makes this key length woefully inadequate

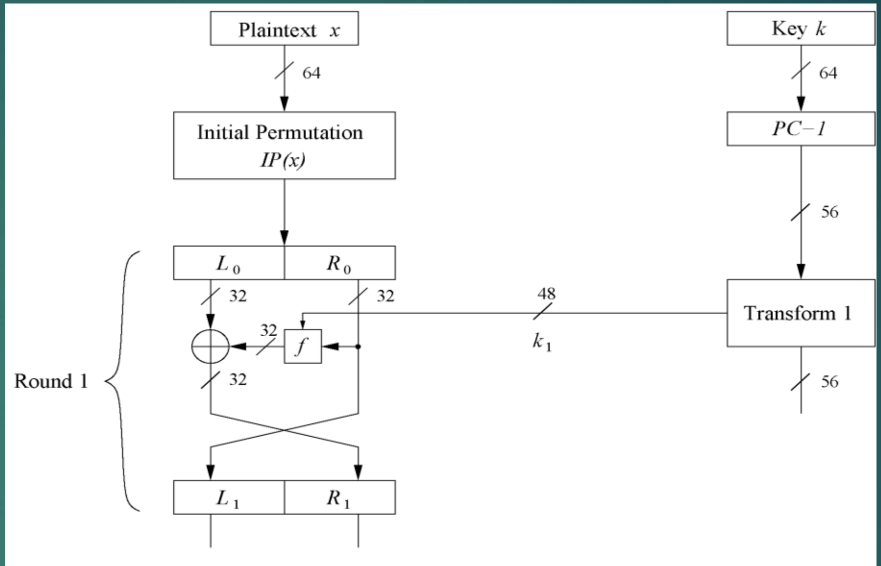
Overview of the DES Algorithm



- **Encrypts blocks of size 64 bits.**
- **Uses a key of size 56 bits.**
- Symmetric cipher: uses same key for encryption and decryption
- Uses 16 rounds which all perform the identical operation
- Different subkey in each round derived from main key

The DES Feistel Network

- DES structure is a *Feistel network*
- Advantage: encryption and decryption differ only in keyschedule

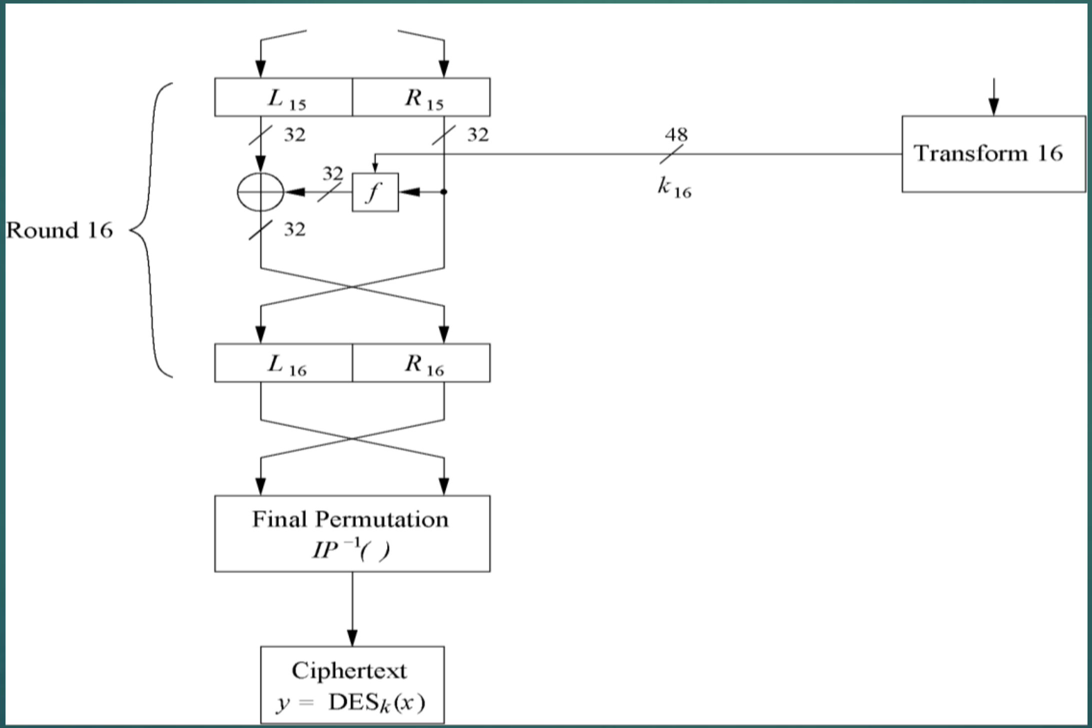


- Bitwise initial permutation, then 16 rounds
  1. Plaintext is split into 32-bit halves L_i and R_i
  2. R_i is fed into the function *f*, the output of which is then XORed with L_i
  3. Left and right half are swapped
- Rounds can be expressed as:

$$L_i = R_{i-1},$$
$$R_i = L_{i-1} \oplus f(R_{i-1}, k_i)$$

The DES Feistel Network

- L and R swapped again at the end of the cipher, i.e., after round 16 followed by a final permutation

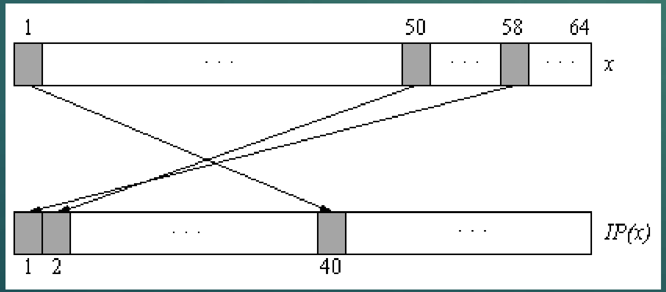


Initial and Final Permutation

- Bitwise Permutations.
- Inverse operations.
- Described by tables *IP* and *IP*$^{-1}$.

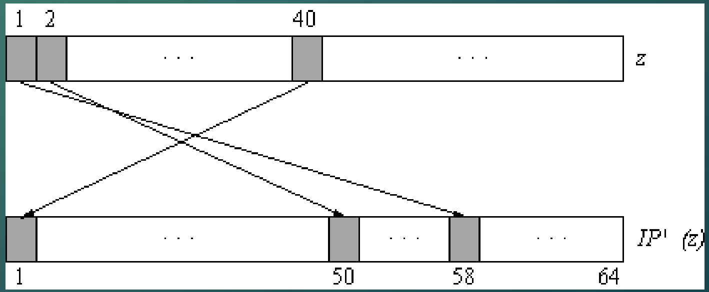
Initial Permutation

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



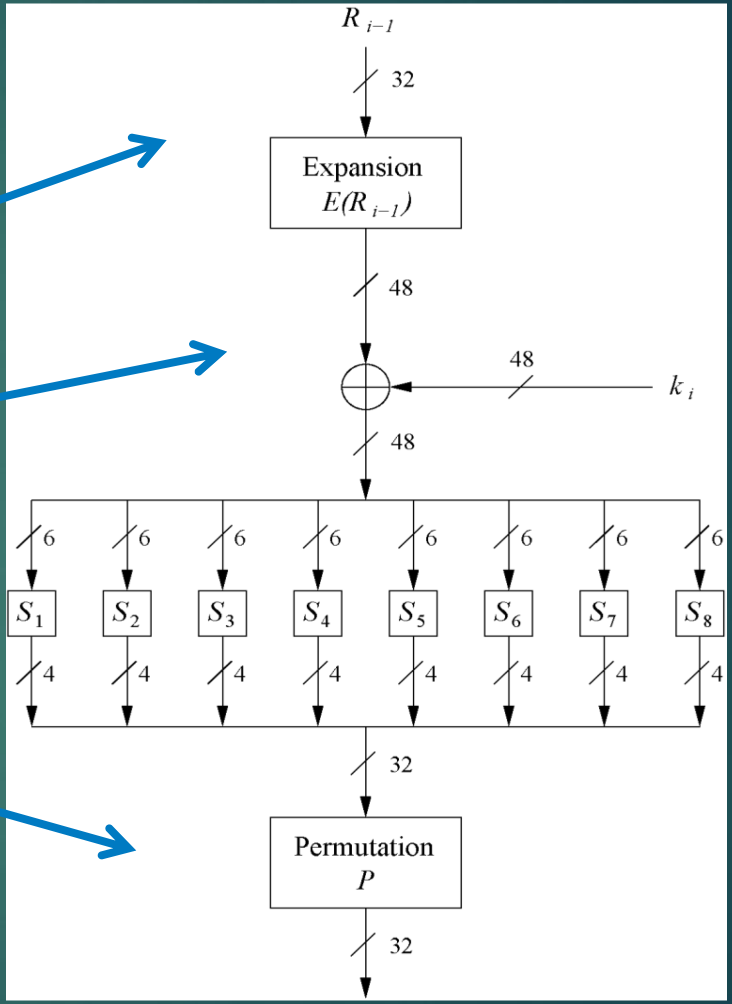
Final Permutation

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



The f-Function

- **main operation of DES**
- *f*-Function inputs: R_{i-1} and round key k_i
- **4 Steps**:
  1. Expansion *E*
  2. XOR with round key
  3. S-box substitution
  4. Permutation

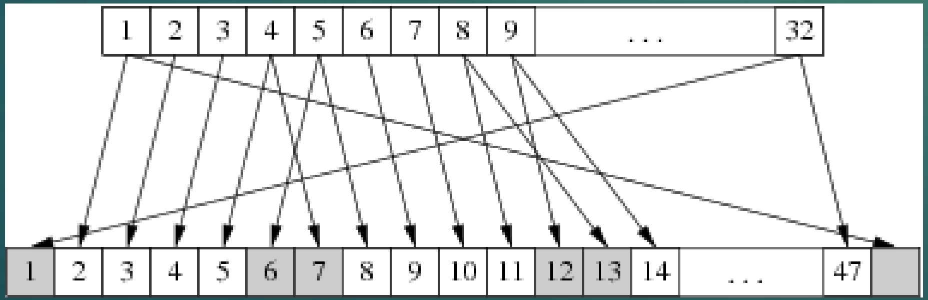


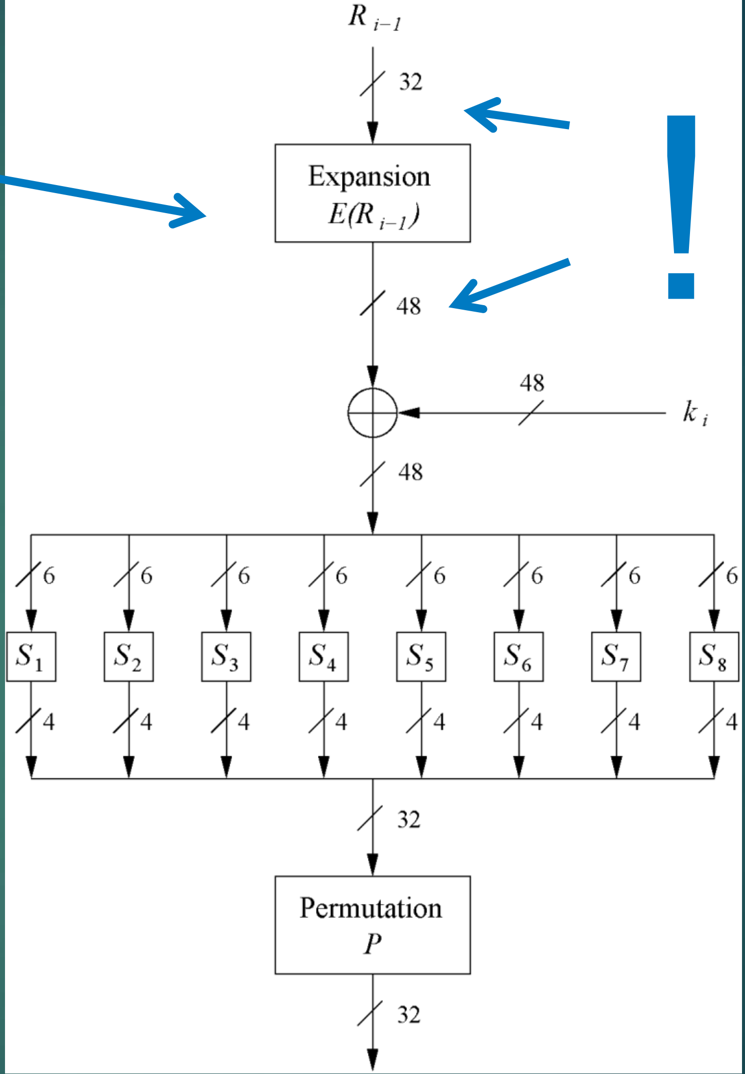
The Expansion Function E

1. **Expansion *E***

- **main purpose: increases diffusion**

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

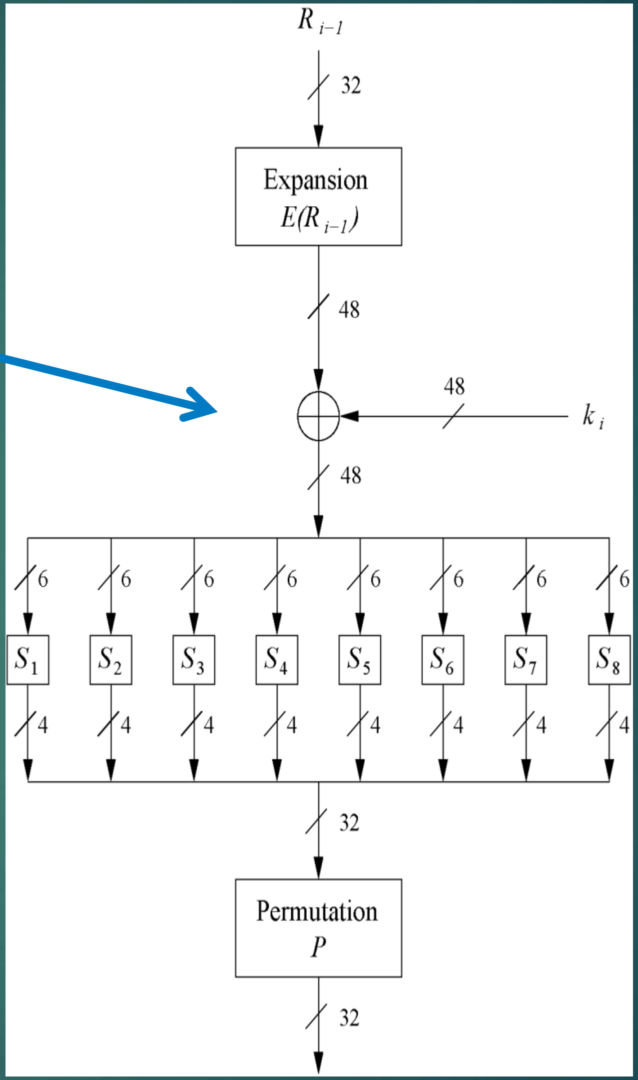




Add Round Key

2. **XOR Round Key**

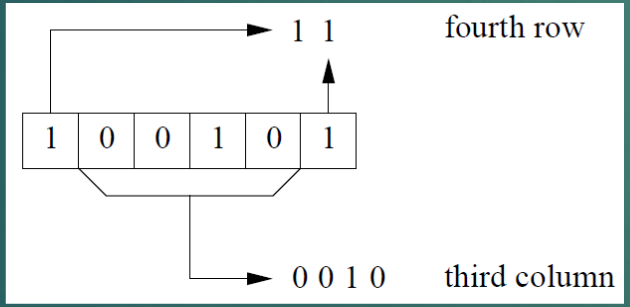
- **Bitwise XOR of the round key and the output of the expansion function *E***
- **Round keys are derived from the main key in the DES keyschedule (in a few slides)**



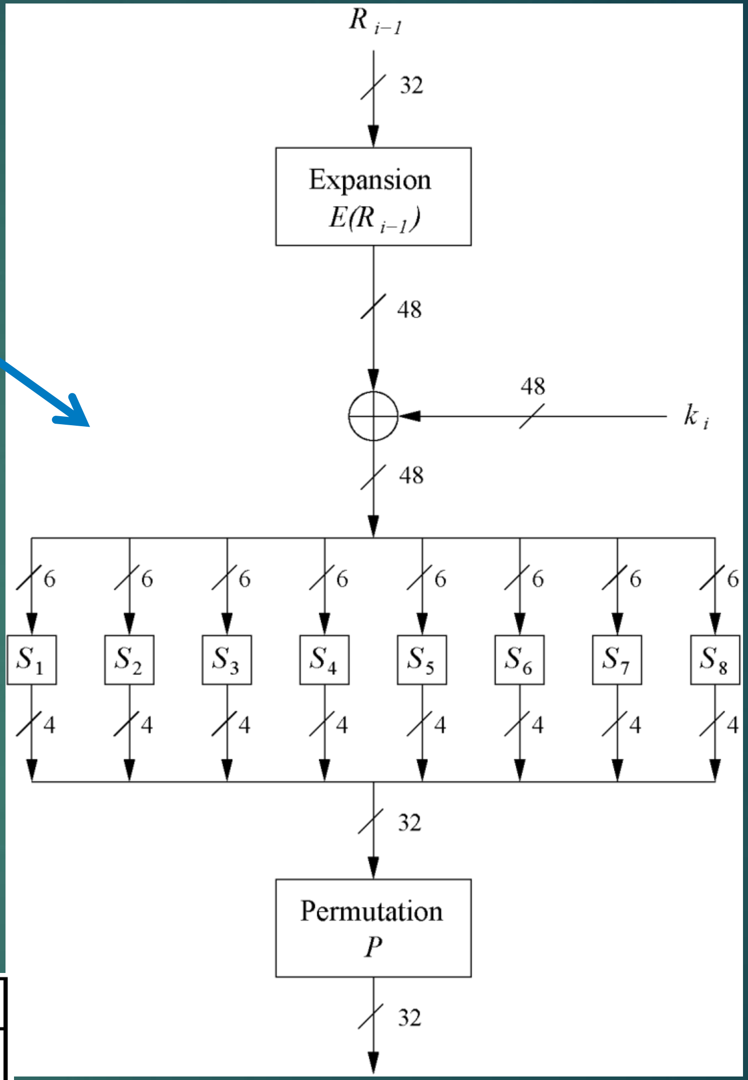
The DES S-Boxes

3. **S-Box substitution**

- Eight substitution tables.
- 6 bits of input, 4 bits of output.
- Non-linear and resistant to differential cryptanalysis.
- Crucial element for DES security!
- Find all S-Box tables and S-Box design criteria in *Understanding Cryptography* Chapter 3.



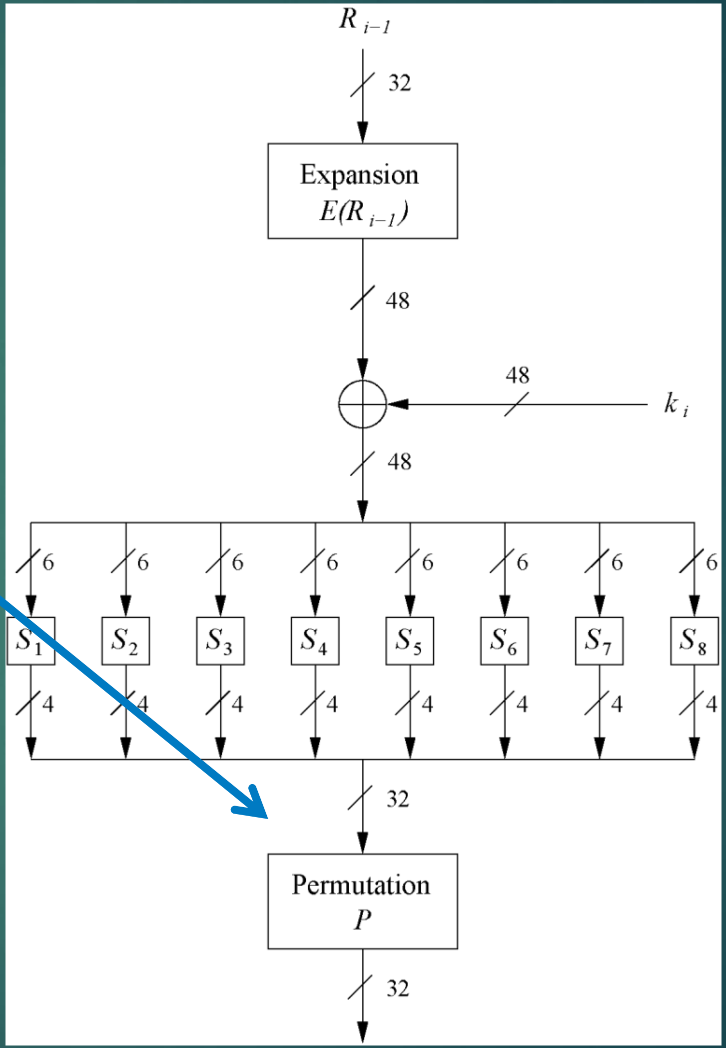
S_1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	14	04	13	01	02	15	11	08	03	10	06	12	05	09	00	07
1	00	15	07	04	14	02	13	01	10	06	12	11	09	05	03	08
2	04	01	14	08	13	06	02	11	15	12	09	07	03	10	05	00
3	15	12	08	02	04	09	01	07	05	11	03	14	10	00	06	13



The Permutation P

4. **Permutation P**
   - Bitwise permutation.
   - Introduces diffusion.
   - Output bits of one S-Box effect several S-Boxes in next round
   - Diffusion by E, S-Boxes and P guarantees that after Round 5 every bit is a function of each key bit and each plaintext bit.

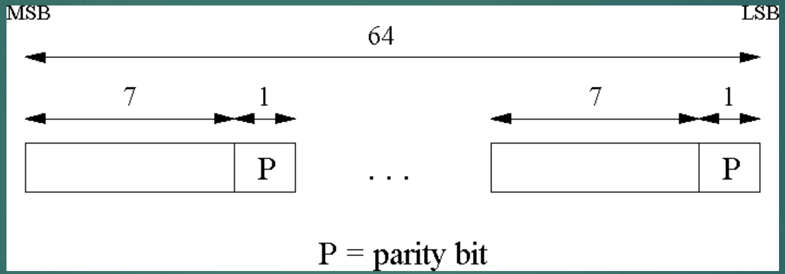
P							
16	7	20	21	29	12	28	17
1	15	23	26	5	18	31	10
2	8	24	14	32	27	3	9
19	13	30	6	22	11	4	25



Key Schedule (1)

- Derives 16 round keys (or *subkeys*) k_i of 48 bits each from the original 56 bit key.
- The input key size of the DES is 64 bit: **56 bit key** and 8 bit parity:

!



- **Parity bits are removed** in a first **permuted choice** *PC-1*:
(note that the bits 8, 16, 24, 32, 40, 48, 56 and 64 are not used at all)

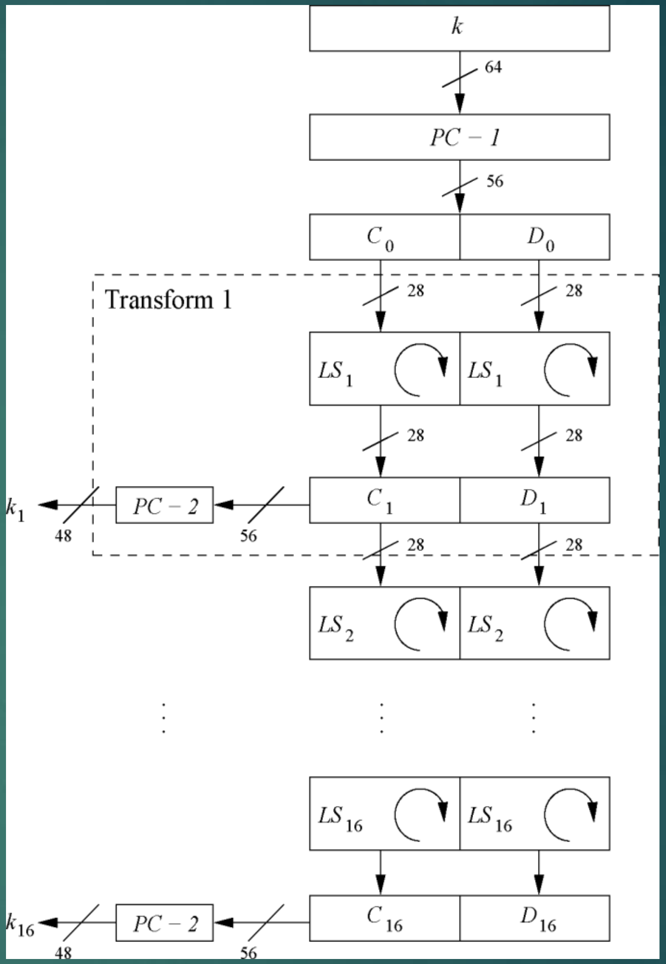
PC − 1							
57	49	41	33	25	17	9	1
58	50	42	34	26	18	10	2
59	51	43	35	27	19	11	3
60	52	44	36	63	55	47	39
31	23	15	7	62	54	46	38
30	22	14	6	61	53	45	37
29	21	13	5	28	20	12	4

Key Schedule (2)

- Split key into 28-bit halves C_0 and D_0.
- In **rounds *i* = 1, 2, 9 ,16,** the two halves are each rotated left by **one bit**.
- In **all other rounds** where the two halves are each rotated left by **two bits**.
- *In each round i permuted choice **PC-2*** selects a permuted subset of 48 bits of C_i and D_i as round key k_i, i.e. **each k_i is a permutation of k**!

$PC-2$							
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

- **Note:** The total number of rotations:
  $4 \times 1 + 12 \times 2 = 28 \Rightarrow D_0 = D_{16}$ and $C_0 = C_{16}$!



Key size (bits)	**Cipher**	**Number of Alternative Keys**	**Time Required at 10^9 decryptions/s**	**Time Required at 10^{13} decryptions/s**
56	DES	$2^{56} \approx 7.2 \leftrightarrow 10^{16}$	2^{55} ns = 1.125 years	1 hour
128	AES	$2^{128} \approx 3.4 \leftrightarrow 10^{38}$	2^{127} ns = $5.3 \leftrightarrow 10^{21}$ years	$5.3 \leftrightarrow 10^{17}$ years
168	Triple DES	$2^{168} \approx 3.7 \leftrightarrow 10^{50}$	2^{167} ns = $5.8 \leftrightarrow 10^{33}$ years	$5.8 \leftrightarrow 10^{29}$ years
192	AES	$2^{192} \approx 6.3 \leftrightarrow 10^{57}$	2^{191} ns = $9.8 \leftrightarrow 10^{40}$ years	$9.8 \leftrightarrow 10^{36}$ years
256	AES	$2^{256} \approx 1.2 \leftrightarrow 10^{77}$	2^{255} ns = $1.8 \leftrightarrow 10^{60}$ years	$1.8 \leftrightarrow 10^{56}$ years

Average Time Required for Exhaustive Key Search

Triple DES (3DES)

- Repeats basic DES algorithm three times using either two or three unique keys
- First standardized for use in financial applications in ANSI standard X9.17 in 1985
- Attractions:
  - 168-bit key length overcomes the vulnerability to brute-force attack of DES
  - Underlying encryption algorithm is the same as in DES
- Drawbacks:
  - Algorithm is sluggish in software
  - Uses a 64-bit block size

Advanced Encryption Standard (AES)

Needed a replacement for 3DES

- 3DES was not reasonable for long term use

NIST called for proposals for a new AES in 1997

- Should have a security strength equal to or better than 3DES
- Significantly improved efficiency
- Symmetric block cipher
- 128 bit data and 128/192/256 bit keys

Selected Rijndael in November 2001

- Published as FIPS 197

Practical Security Issues

- Typically symmetric encryption is applied to a unit of data larger than a single 64-bit or 128-bit block
- Electronic codebook (ECB) mode is the simplest approach to multiple-block encryption
    - Each block of plaintext is encrypted using the same key
    - Cryptanalysts may be able to exploit regularities in the plaintext
- Modes of operation
    - Alternative techniques developed to increase the security of symmetric block encryption for large sequences
    - Overcomes the weaknesses of ECB

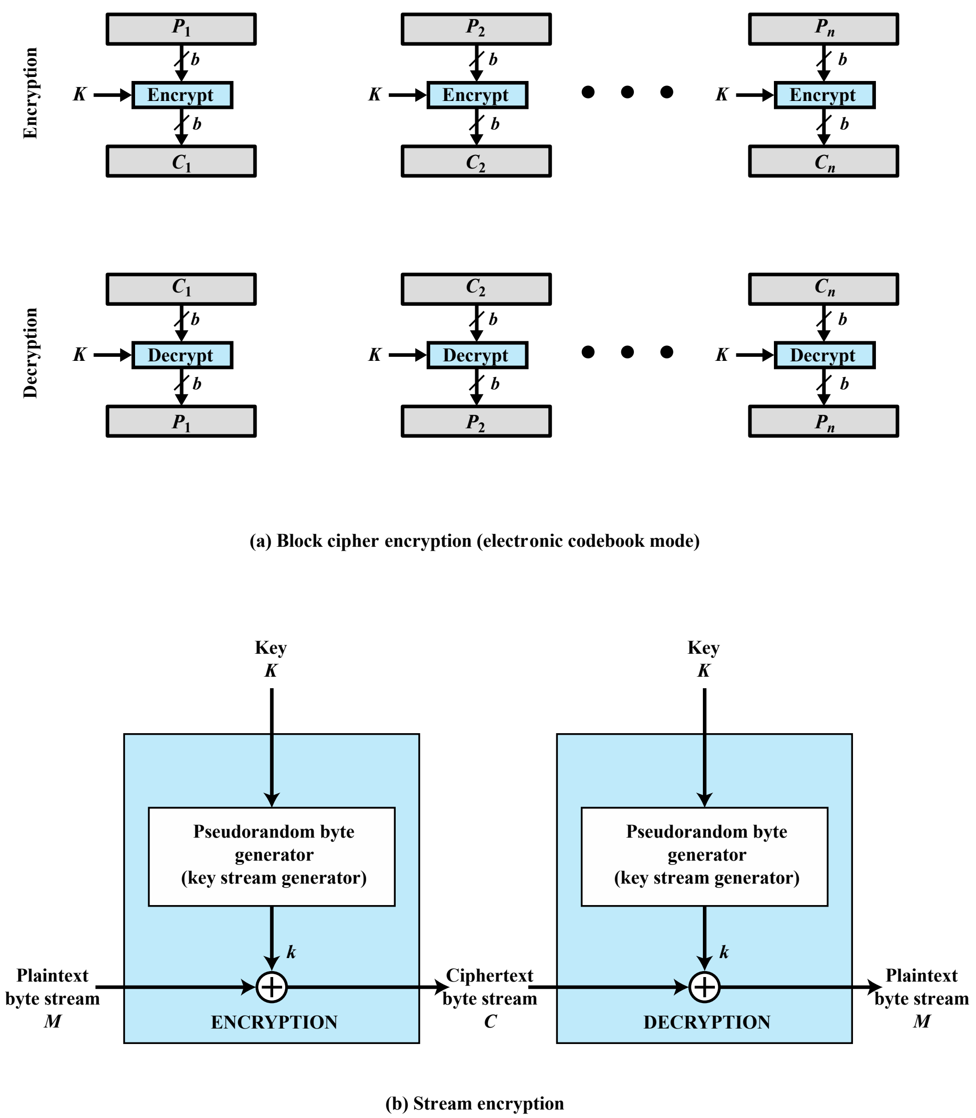


Figure 2.2 Types of Symmetric Encryption

Block & Stream Ciphers

Block Cipher

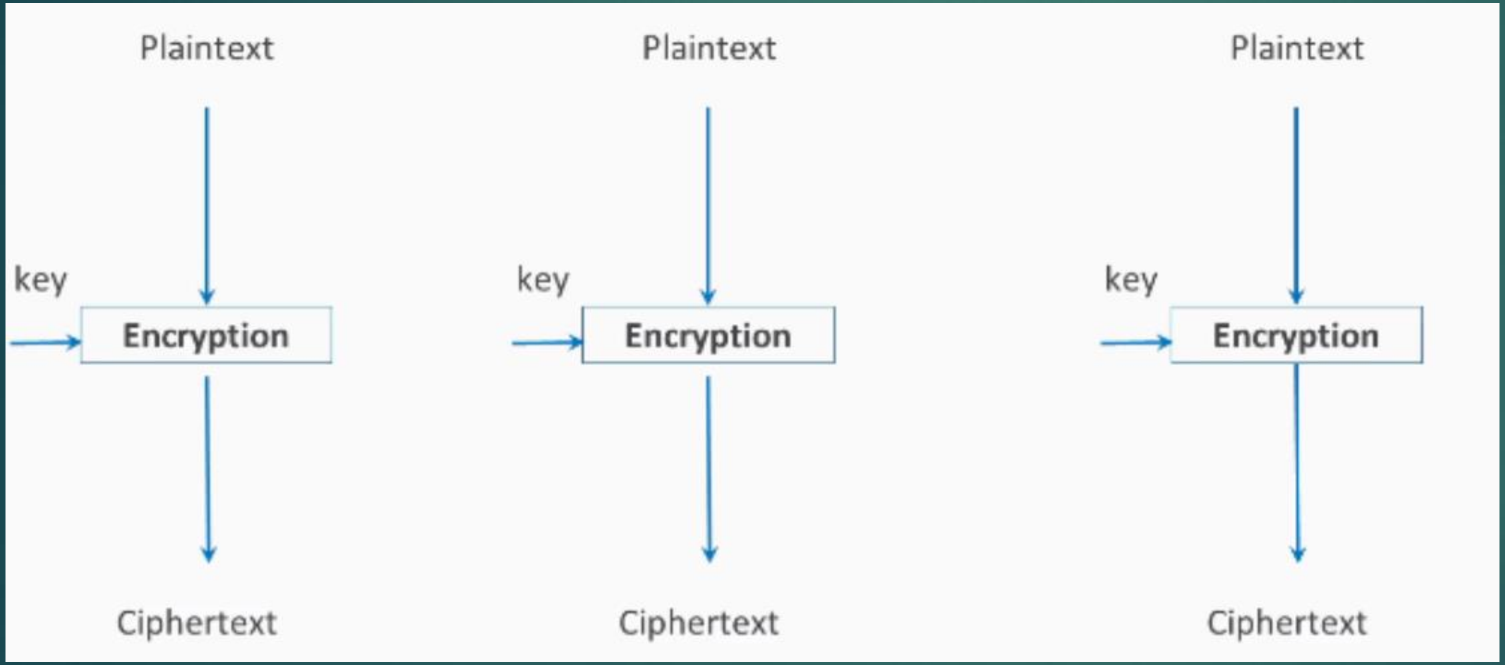
- Processes the input one block of elements at a time
- Produces an output block for each input block
- Can reuse keys
- More common

Stream Cipher

- Processes the input elements continuously
- Produces output one element at a time
- Primary advantage is that they are almost always faster and use far less code
- Encrypts plaintext one byte at a time
- Pseudorandom stream is one that is unpredictable without knowledge of the input key

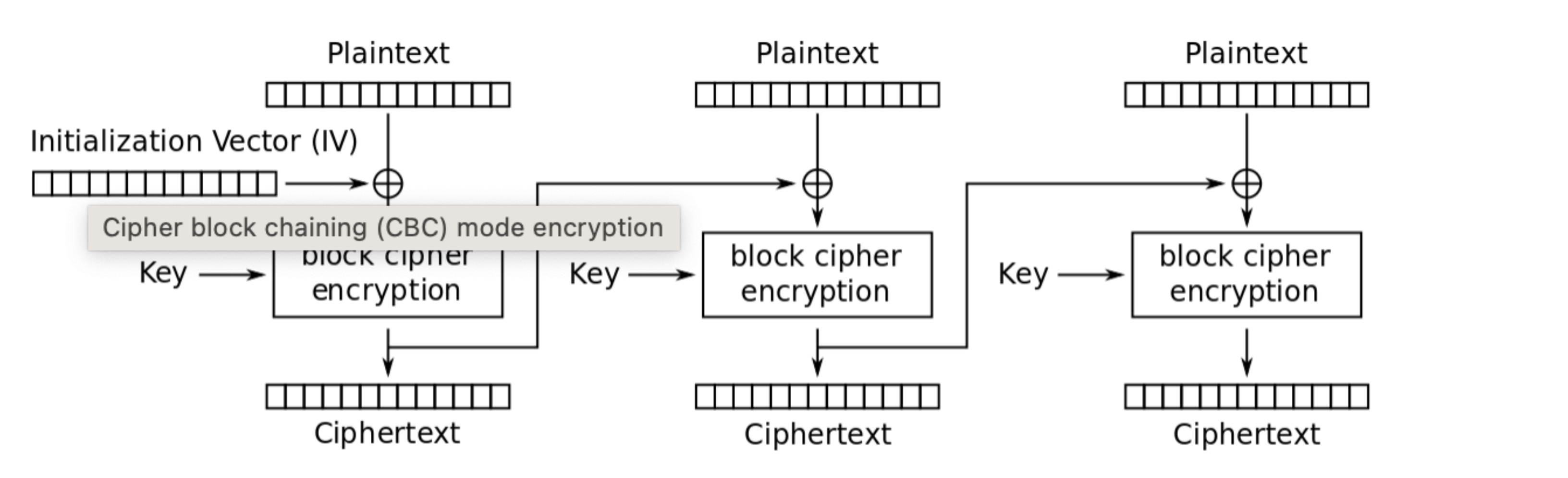
Mode of Encryption

ECB (Electronic Code Book): Plain text messages are divided into sub-blocks each of 64 bits. Then each sub-block is encrypted independently



Mode of Encryption

CBC (Cipher Blocker Chaining): One in which a sequence of bits are encrypted as a single unit, or block, with a cipher key applied to the entire block



Cipher Block Chaining (CBC) mode encryption