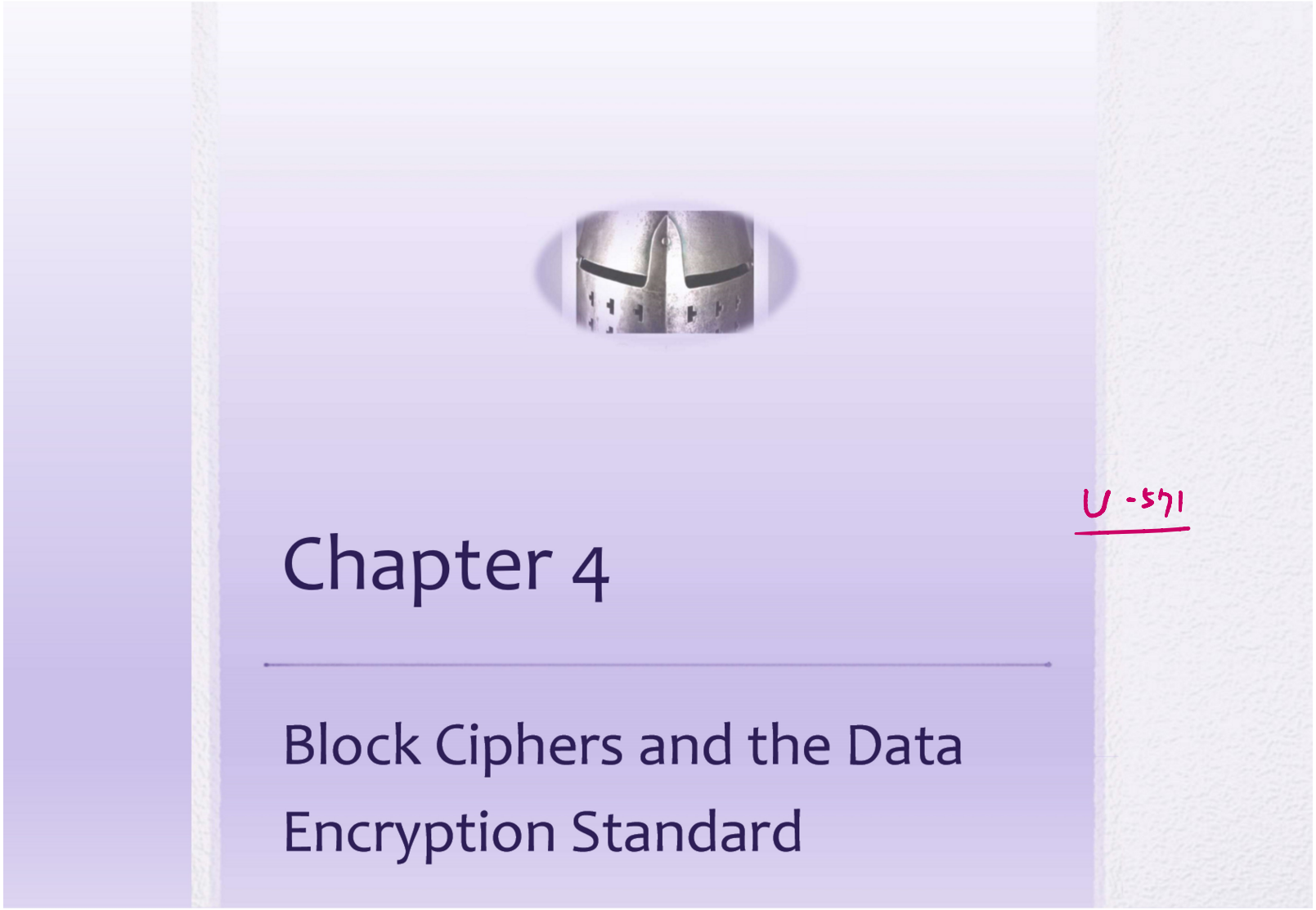
列印成品

2024年2月14日　　上午 10:18



Stream cipher

- Encrypt plaintext bit by bit or byte by byte
- Each unit is encrypted with a different key

$$E(k_i, p_i) = c_i, 1 \leq i \leq m$$

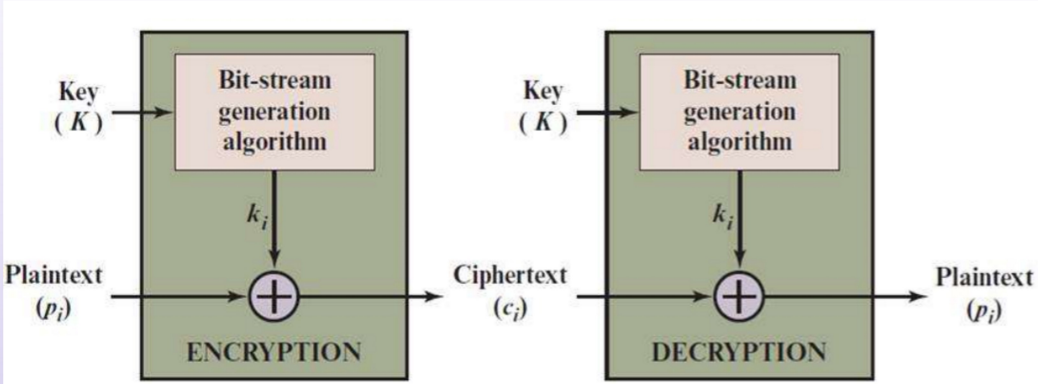
- Examples
  - Vernam cipher
  - One-time pad
  - Autokeyed Vigenère cipher
  - Stream ciphers used in 4G/5G
    - SNOW 3G
    - AES-CTR
    - ZUC: 16-stage Linear Feedback Shift Register (LFSR)

Block cipher

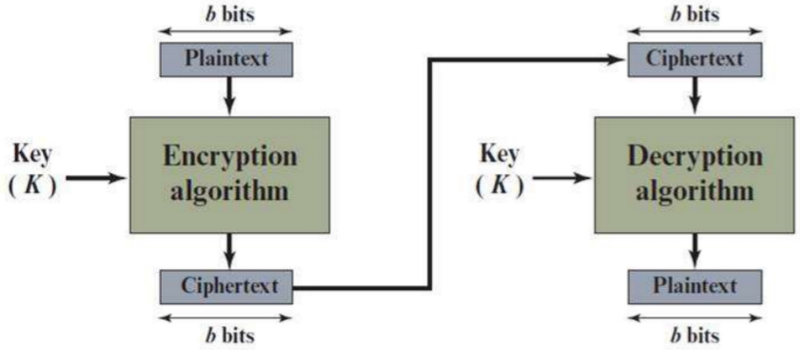
- Encrypt plaintext block by block, typically, 128 bits
- Each unit is encrypted with the same key

$$E(k, p_i) = c_i, 1 \leq i \leq m$$

- Examples
  - Playfair cipher
  - Hill cipher
  - DES
  - AES

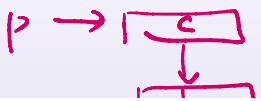


(a) Stream cipher using algorithmic bit-stream generator

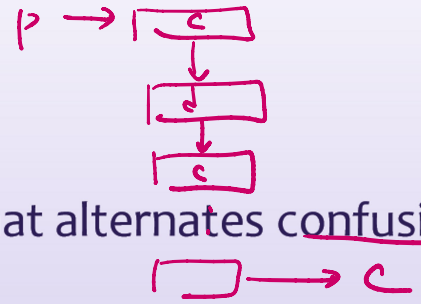


(b) Block cipher

Design principles



Design principles

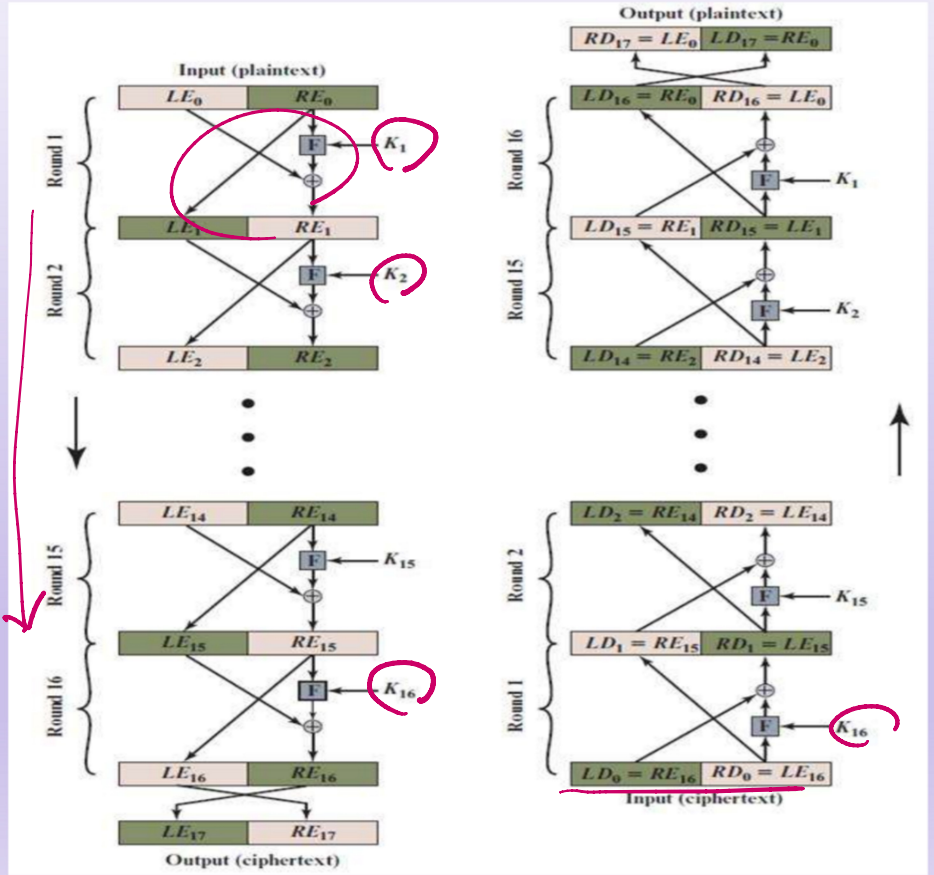


- Claude Shannon
  - propose ***product cipher*** that alternates confusion and diffusion functions
  - each component introduces some level of security
  - accumulate full security from small security of each function
- Horst Feistel
  - propose a structure for easy encryption/decryption no matter what core functions are used
  - focus on design of secure core functions
  - components are substitution and permutation functions
  - Feistel structure is a practical realization of Shannon's principle

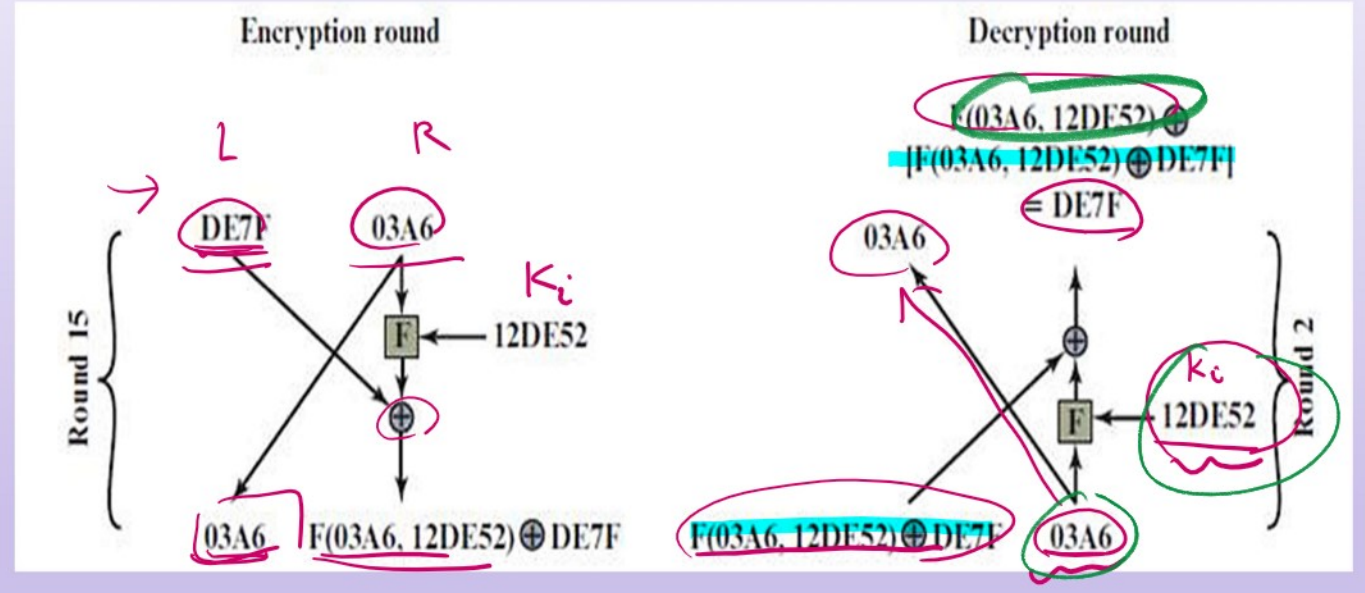
Diffusion and Confusion

- To counter “statistical analysis”
- Confusion
  - Complicate statistics relationship between of ciphertext and key
  - Even if the attacker gets some statistics of ciphertext, key is still too complex to deduce
- Diffusion
  - The statistical structure of the plaintext is dissipated into long-range statistics of ciphertext
  - Each plaintext digit affects many ciphertext digits

Feistel structure: 16 rounds



Feistel structure: one round



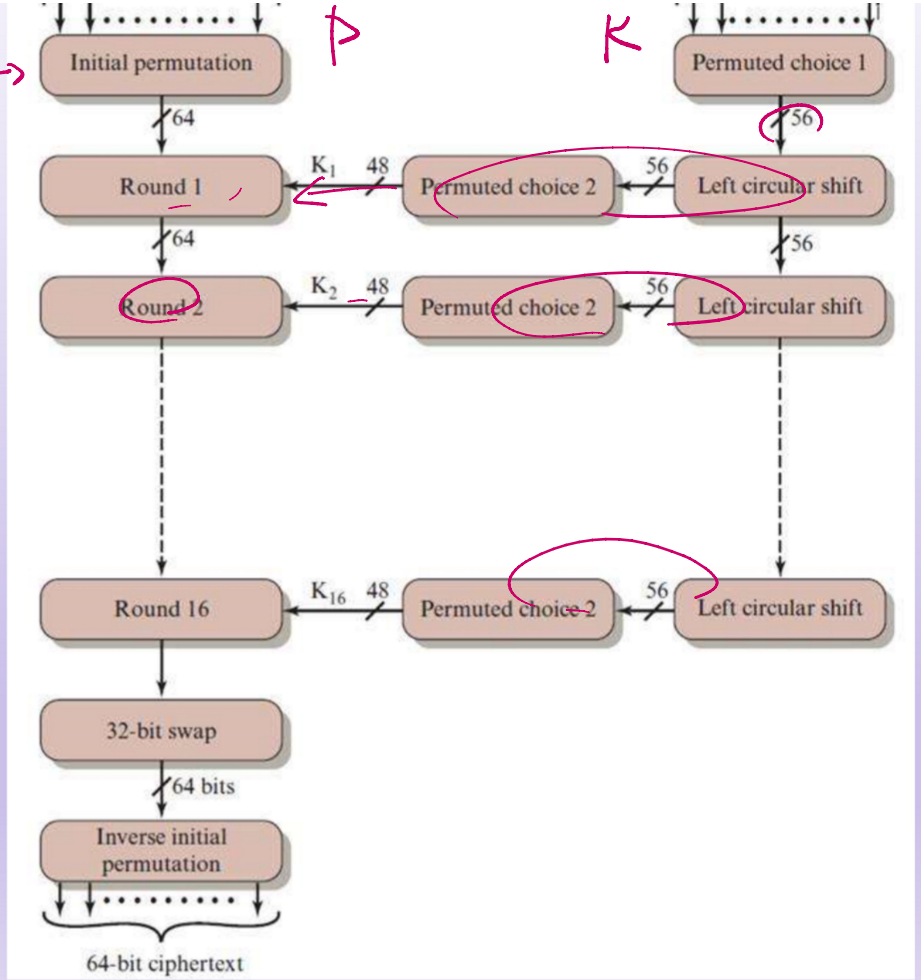
Feistel cipher: design features

- Block size
  - Larger block sizes mean greater security, but reduce encryption/decryption speed
- Key size
  - Larger key size means greater security, but decrease encryption/decryption speed
- Number of rounds
  - Multiple rounds offer increasing security, but decrease encryption/decryption speed
- Subkey generation algorithm
  - Greater complexity of subkey generation lead to greater difficulty of cryptanalysis

- Round function F
  - Greater complexity means greater resistance to cryptanalysis
- Fast software encryption/decryption
- Ease of analysis
  - Easy explanation enhances understanding of cipher. This leads to comprehensive analysis. More analysis means higher security

Data Encryption Standard (DES)

- FIPS-46, National Bureau of Standards (now NIST) ,1977
- Data Encryption Algorithm (DEA)
  - Plaintext, ciphertext: 64 bits
  - Key size: 56 bits
  - 16 rounds
  - Feistel cipher
- Replaced by Advanced Encryption Standard (AES) in 2001, FIPS 197


Initial permutation
64
Round 1
K_1
48
Permuted choice 2
56
Left circular shift
64
56
Round 2
K_2
48
Permuted choice 2
56
Left circular shift
Round 16
K_{16}
48
Permuted choice 2
56
Left circular shift
32-bit swap
64 bits
Inverse initial permutation
64-bit ciphertext
Permuted choice 1
56

DES : initial permutation

- Initial permutation: IP (64 bits → 64 bits)
- Final permutation: IP^{-1} (64 bits → 64 bits)

1 2 ... 64

IP

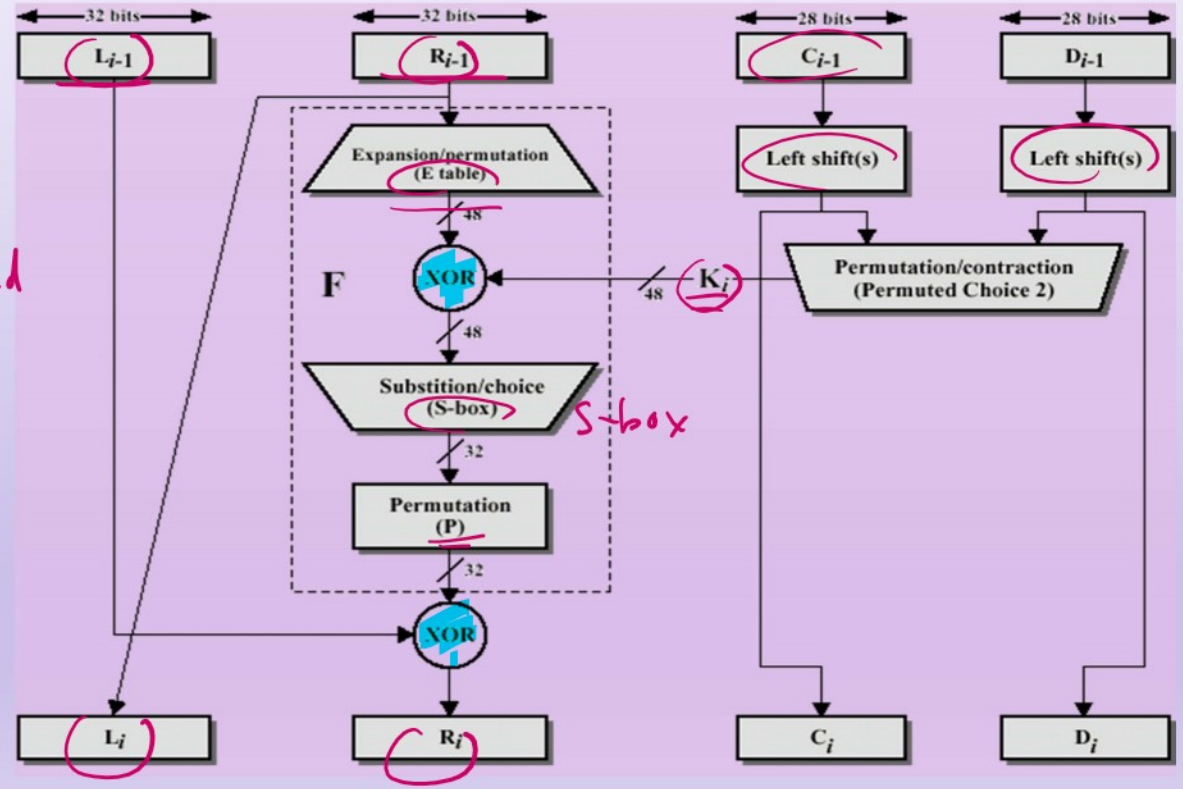
58	50	42	34	26	18	10	2
60	52	44	36	28	20	12	4
62	54	46	38	30	22	14	6
64	56	48	40	32	24	16	8
57	49	41	33	25	17	9	1
59	51	43	35	27	19	11	3
61	53	45	37	29	21	13	5
63	55	47	39	31	23	15	7

IP^{-1}

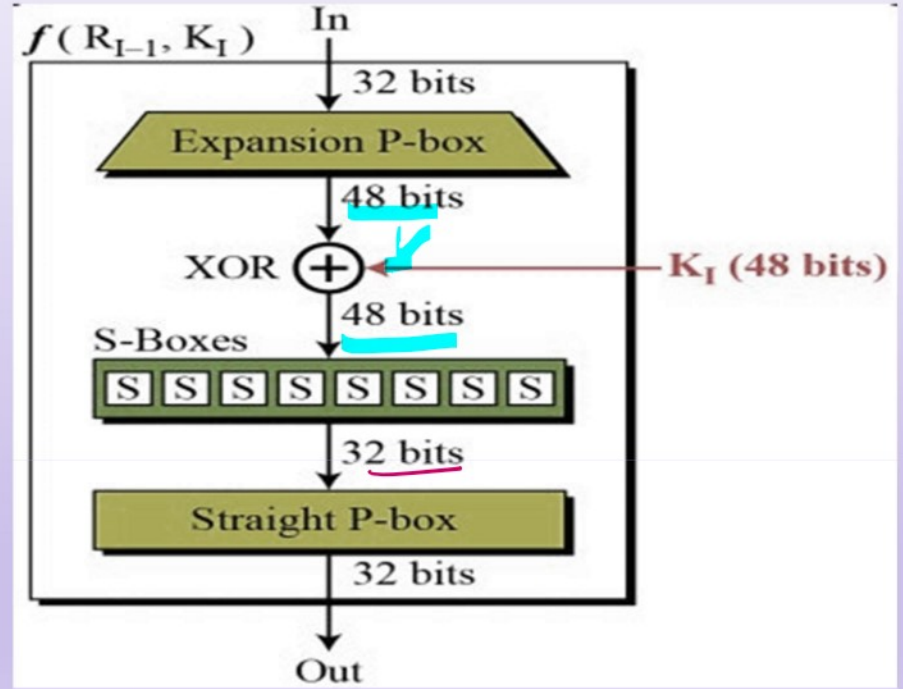
40	8	48	16	56	24	64	32
39	7	47	15	55	23	63	31
38	6	46	14	54	22	62	30
37	5	45	13	53	21	61	29
36	4	44	12	52	20	60	28
35	3	43	11	51	19	59	27
34	2	42	10	50	18	58	26
33	1	41	9	49	17	57	25

DES: single round

Feistel structure ith round



DES: f function



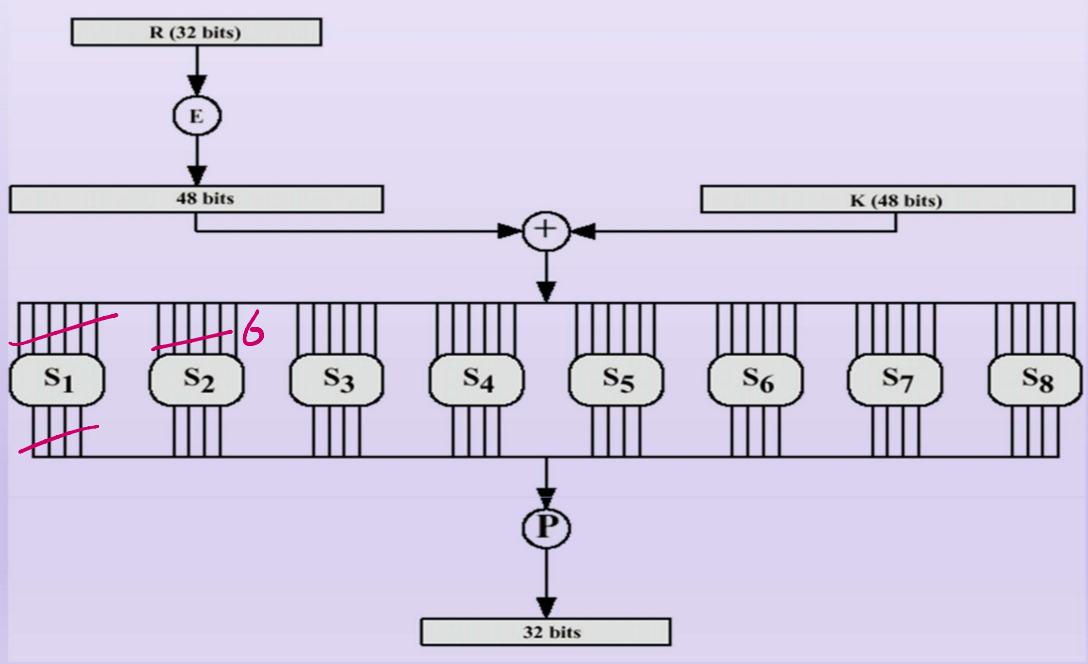
DES: expansion function E

- Expansion permutation E: 32 bits→48bits
- Input bits: 1 2 3 … 32

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

DES: S-box

- The only non-linear relation between input and output



$b_1\ b_2\ b_3\ b_4\ b_5\ b_6$

i	$b_2\ b_3\ b_4\ b_5$															
	S_i															
$b_1\ b_6$	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

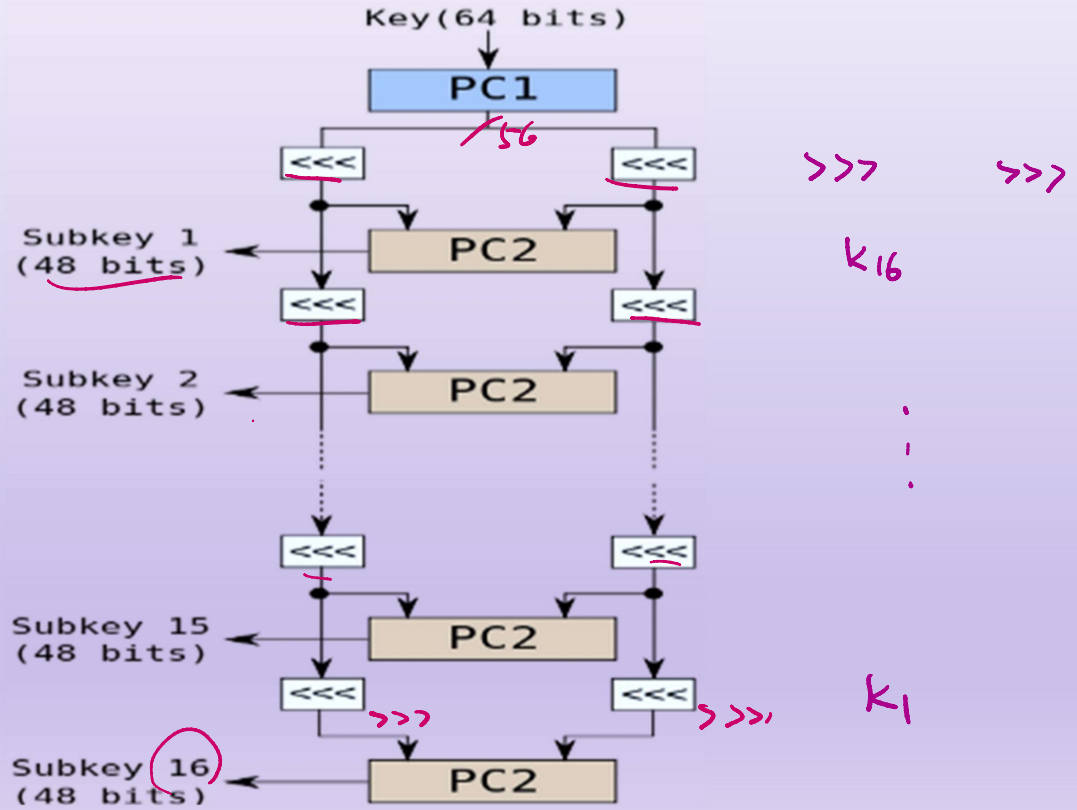
1	14	4	13	1	2	15	11	8	3	10	6	12	5	9	0	7
	0	15	7	4	14	2	13	1	10	6	12	11	9	5	3	8
	4	1	14	8	13	6	2	11	15	12	9	7	3	10	5	0
	15	12	8	2	4	9	1	7	5	11	3	14	10	0	6	13
2	15	1	8	14	6	11	3	4	9	7	2	13	12	0	5	10
	3	13	4	7	15	2	8	14	12	0	1	10	6	9	11	5
	0	14	7	11	10	4	13	1	5	8	12	6	9	3	2	15
	13	8	10	1	3	15	4	2	11	6	7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

DES: permutation function P

- Permutation function P: $32\ bits \rightarrow 32\ bits$

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 scheduling



Key scheduling

(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) 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

- 28 positions in total
  → re-position after 16 rounds
- Decryption: shift right

(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 Example

Round	Ki	Li	Ri
IP		5a005a00 L_0	3cf03c0f R_0

DES Example

plaintext:
02468aceeca86420

key:
0f1571c947d9e859

ciphertext:
da02cd3a89ecac3b

Round	K_i	L_i	R_i
IP		5a005a00	3cf03c0f
1	1e030f03080d2930	3cf03c0f	bad22845
2	0a31293432242318	bad22845	99e9b723
3	23072318201d0c1d	99e9b723	0bae3b9e
4	05261d3824311a20	0bae3b9e	42415649
5	3325340136002c25	42415649	18b3fa41
6	123a2d0d04262a1c	18b3fa41	9616fe23
7	021f120b1c130611	9616fe23	67117cf2
8	1c10372a2832002b	67117cf2	c11bfc09
9	04292a380c341f03	c11bfc09	887fbc6c
10	2703212607280403	887fbc6c	600f7e8b
11	2826390c31261504	600f7e8b	f596506e
12	12071c241a0a0f08	f596506e	738538b8
13	300935393c0d100b	738538b8	c6a62c4e
14	311e09231321182a	c6a62c4e	56b0bd75
15	283d3e0227072528	56b0bd75	75e8fd8f
16	2921080b13143025	75e8fd8f	25896490
IP–1		da02ce3a	89ecac3b

DES security

- The core of security is the non-linear mapping of S-boxes
- Key size: to defend the brute-force attack

- The core of security is the non-linear mapping of S-boxes
- Key size: to defend the brute-force attack
- Avalanche effect
- Bit independence effect

linear

$$y_i = f(x_1, x_2, \cdots, x_n) = \sum_{i=1}^{n} b_i x_i$$

$$y_i = f(x_1, x_2, \cdots, x_n) \text{ (permutation)} = x_j$$

$$y_i = f(x_1 \cdots, x_n) \quad (\text{XOR}) = x_j \oplus x_k \oplus x_l$$

Avalanche effect

- A small change in either plaintext or key should produce a significant change in ciphertext
- In particular, one bit change in either plaintext or key
  ⇒ half bits change in ciphertext

Fast avalanche effect

- Example: alternate the first bit of plaintext
- δ: number of different bits

Round		δ
	02468aceeca86420 12468aceeca86420	1
1	3cf03c0fbad22845 3cf03c0fbad32845	1
2	bad2284599e9b723 bad3284539a9b7a3	5
3	99e9b7230bae3b9e 39a9b7a3171cb8b3	18
4	0bae3b9e42415649 171cb8b3ccaca55e	34
5	4241564918b3fa41 ccaca55ed16c3653	37
6	18b3fa419616fe23 d16c3653cf402c68	33
7	9616fe2367117cf2 cf402c682b2cefbc	32
8	67117cf2c11bfc09 2b2cefbc99f91153	33

Round		δ
9	c11bfc09887fbc6c 99f911532eed7d94	32
10	887fbc6c600f7e8b 2eed7d94d0f23094	34
11	600f7e8bf596506e d0f23094455da9c4	37
12	f596506e738538b8 455da9c47f6e3cf3	31
13	738538b8c6a62c4e 7f6e3cf34bc1a8d9	29
14	c6a62c4e56b0bd75 4bc1a8d91e07d409	33
15	56b0bd7575e8fd8f 1e07d4091ce2e6dc	31
16	75e8fd8f25896490 1ce2e6dc365e5f59	32
IP–1	da02ce3a89ecac3b 057cde97d7683f2a	32

Exhaustive key search

0.0005 second

Exhaustive key search

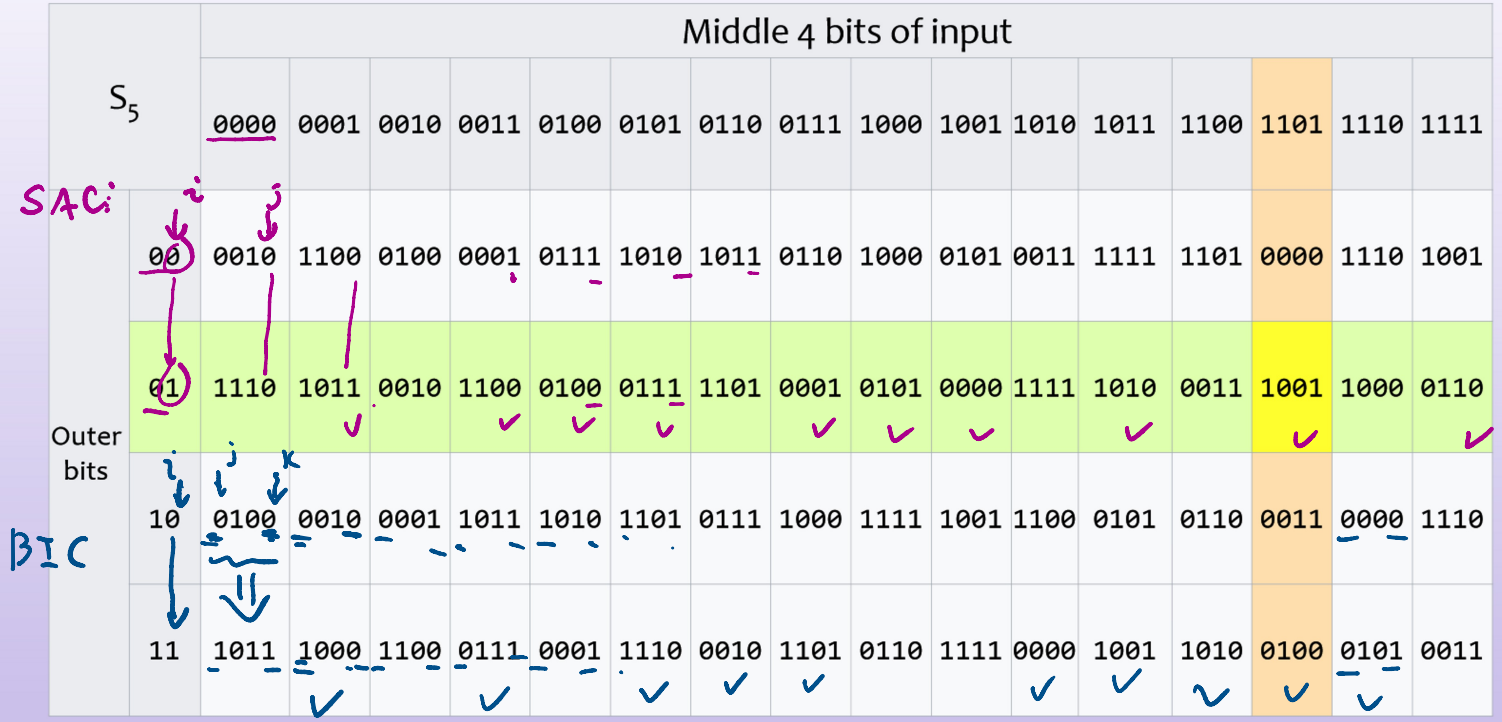
0.0005 second

Key size (bits)	Cipher	Number of keys	Time required at 10^9 decryptions/s	Time required at 10^{13} decryptions/s
56	DES	$2^{56} \approx 7.2 \times 10^{16}$	1.125 years	1 hour
128	AES	$2^{128} \approx 3.4 \times 10^{38}$	5.3×10^{21} years	5.3×10^{17} years
168	Triple DES	$2^{168} \approx 3.7 \times 10^{50}$	5.8×10^{33} years	5.8×10^{29} years
192	AES	$2^{192} \approx 6.3 \times 10^{57}$	9.8×10^{40} years	9.8×10^{36} years
256	AES	$2^{256} \approx 1.2 \times 10^{77}$	1.8×10^{60} years	1.8×10^{56} years
26 characters	Monoalphabetic	$26! \approx 4 \times 10^{26}$	6.3×10^{9} years	6.3×10^{6} years

$2^{112} \approx 10^{34}$

S-box security

- Strict avalanche criterion (SAC)
  - When an input ***bit i*** is inverted, an output ***bit j*** of an S-box changes with probability 0.5
- Bit independence criterion (BIC)
  - When an input ***bit i*** is inverted, output ***bits j and k*** change independently, for all i, j and k


Middle 4 bits of input
S_5
0000 0001 0010 0011 0100 0101 0110 0111 1000 1001 1010 1011 1100 1101 1110 1111
Outer bits
00 0010 1100 0100 0001 0111 1010 1011 0110 1000 0101 0011 1111 1101 0000 1110 1001
01 1110 1011 0010 1100 0100 0111 1101 0001 0101 0000 1111 1010 0011 1001 1000 0110
10 0100 0010 0001 1011 1010 1101 0111 1000 1111 1001 1100 0101 0110 0011 0000 1110
11 1011 1000 1100 0111 0001 1110 0010 1101 0110 1111 0000 1001 1010 0100 0101 0011

Key schedule

- One subkey is generated in each round
- It is difficult to deduce individual subkeys and the main key from a subkey
- Meet the SAC and BIC conditions

DES: weakness

- Key complementation:
  $$C = DES(P, K) \Rightarrow \bar{C} = DES(\bar{P}, \bar{K})$$
- Differential cryptanalysis
  - $\Delta x = P1 \oplus P2$ and $\Delta y = S(P1) \oplus S(P2)$ have some relation
  - Chosen plaintext attack: need ~~247~~ pair of plaintexts and ~~237~~ DES calls
  - Significantly less than ~~255~~ exhaustive key search.
- 16 rounds are the boundary for current known attacks
- 56-bit is too small in current technology
  - Quantum computers reduces the key search to 2^{28}
  - Should use 3DES with 112-bit keys at least

Triple DES: EDE-DES

2-EDE-DES

3-EDE-DES

Triple DES: EDE-DES