Data Encryption Standard (DES)

↳ Same Data Encryption Algo (DEA)

↳ DES has been a landmark in cryptographic Algorithms.

↳ DES has been used as standard for over two decades.

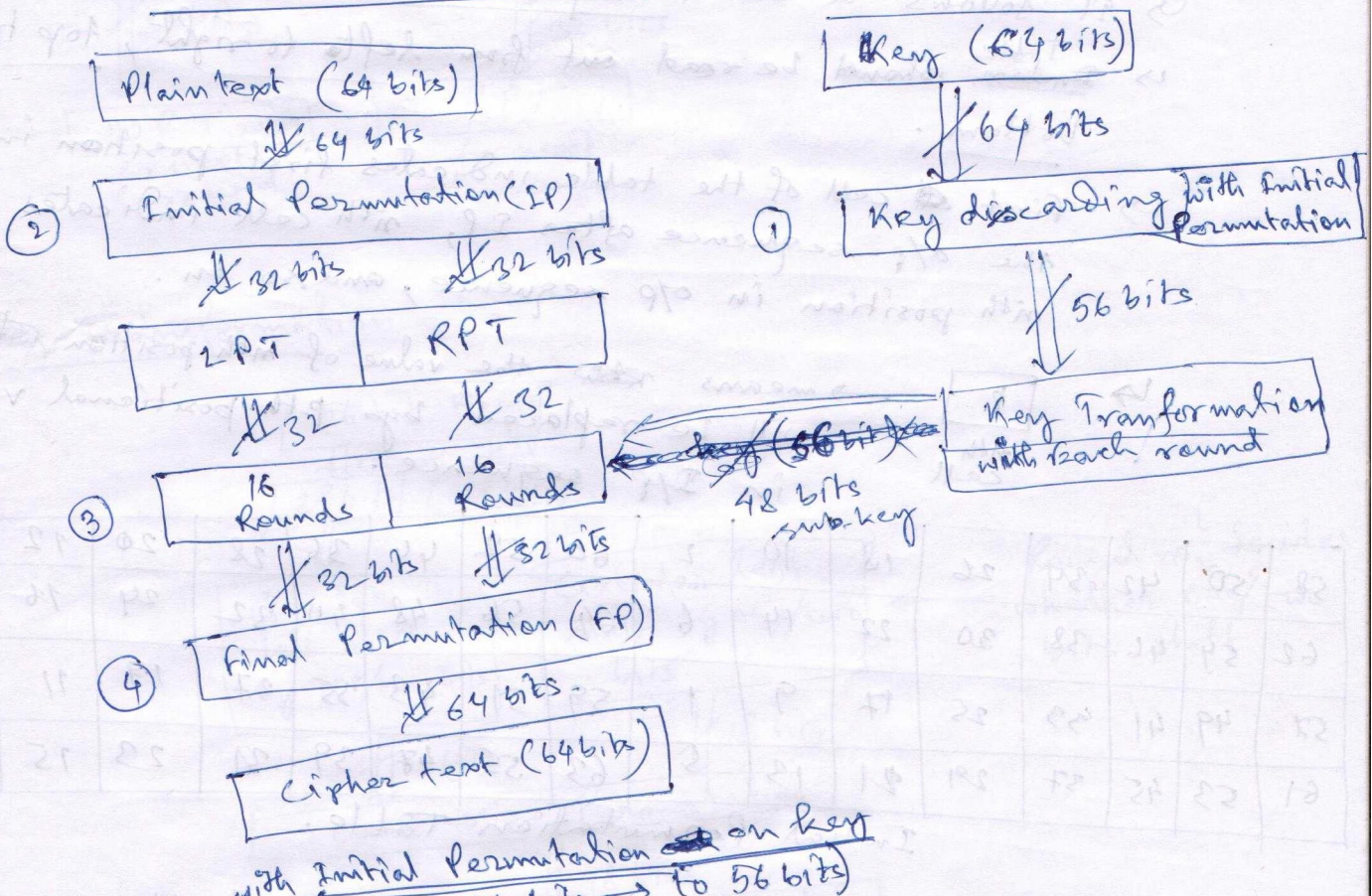
↳ DES has been found & vulnerable against very powerful attack.

Origin IBM's Lucifer

↳ Modified version is DES in 1976.

↳ DES is generally used in ECB, CBC, or CFB mode Block cipher modes.

Broad Level Steps in DES



① Key Discarding: (with Initial Permutation on key (from 64 bits → to 56 bits))

↳ Initial key consists of 64 bits

↳ Then every 8th bit of the key is discarded to produce 56 bit key. So, 8, 16, 24, 32, 40, 48, 56, 64 th bits will be removed. Rest of the bits will remain as it is. Then it will follow permutation using the below table to get 56 bit key.

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

↳ DES is based on two fundamental attributes:

(1) Substitution (also called confusion)
↳ non-linear substitution (e.g. round function in feistel Cipher)

(2) Transposition (also called diffusion)
↳ or, permutation repeatedly.

↳ DES consists of 16 rounds in the middle.

↳ Each round performs the steps of substitution & transposition.

↳ It also uses initial & final permutations.

(2) Initial Permutation (IP)

↳ It runs only once, befor any round.

↳ It follows a transposition table

↳ Table should be read out from left to right, top to bottom.

↳ First cell of the table indicates first position in the o/p sequence after IP, nth cell indicates nth position in o/p sequence, and so on.

↳ [p] (nth cell) → means the value of nth position in o/p will be replaced by pth positional value in IP sequence.

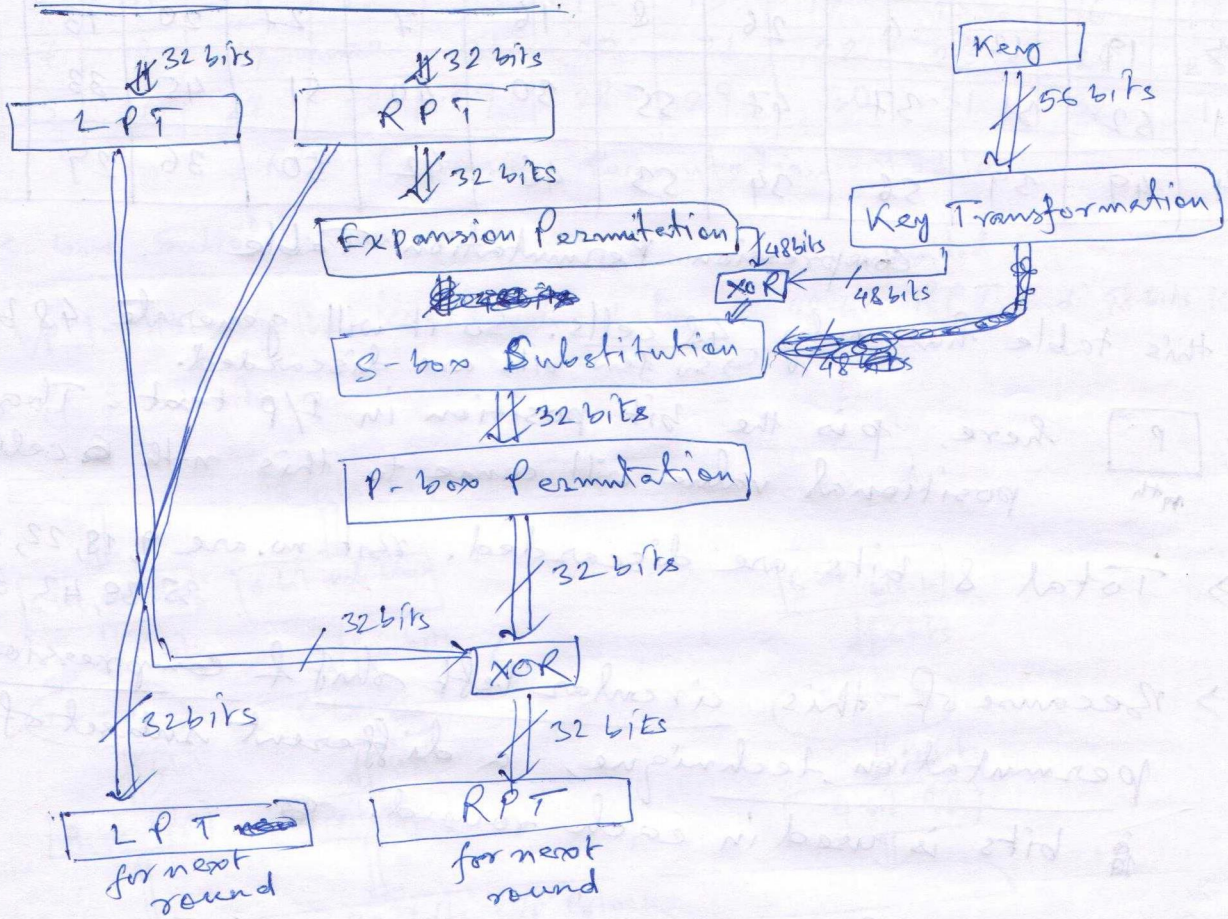
58	50	42	34	26	18	10	2	60	52	44	36	28	20	12	4
62	54	46	38	30	22	14	6	64	56	48	40	32	24	16	8
57	49	41	33	25	17	9	1	59	51	43	35	27	19	11	3
61	53	45	37	29	21	13	5	63	55	47	39	31	23	15	7

Initial Permutation Table.

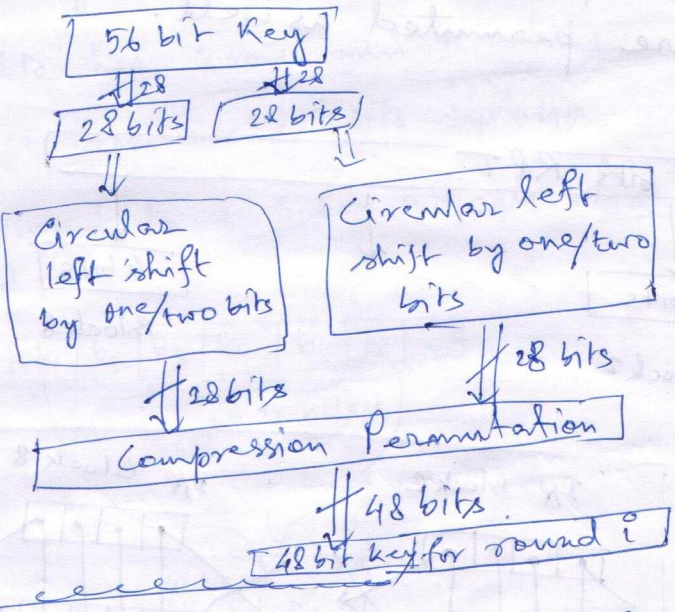
↳ After IP, the resulting 64-bit permuted text block is divided into two half blocks — each contains 32 bits
↳ LPT & RPT

↳ Now, 16 rounds are performed on these two blocks independently.

(3) Details of one Round



(3.1) Key Transformation



Number of key bits shifted per round:

Round No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
No. of bits shifted	1	1	2	2	2	2	2	2	1	2	2	2	2	2	2	1

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

Compression Permutation Table

↳ this table has only 48 cells. So it will generate 48 bits key
↳ so few bits are discarded.

↳ [P] here, p is the bit position in I/p text. That positional value will come to this n-th cell in o/p
n^th

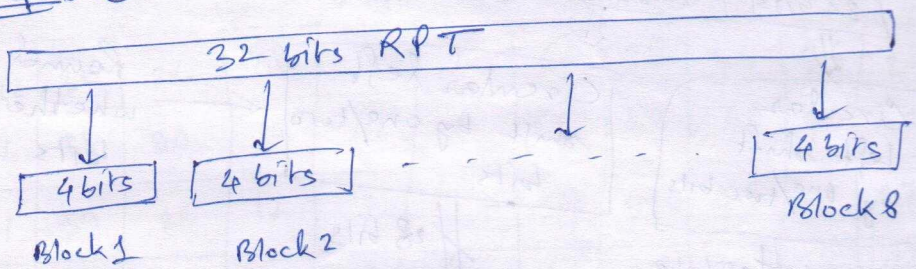
↳ Total 8 bits are discarded. Bit no. are 9, 18, 22, 25, 35, 38, 43, 54

↳ Because of this circular left shift & compression permutation technique, a different subset of key bits is used in each round.

(3.2) Expansion Permutation

↳ the RPT is expanded from 32 bits to 48 bits.
↳ the bits are permuted as well.

Steps - (A)



Steps - (B)

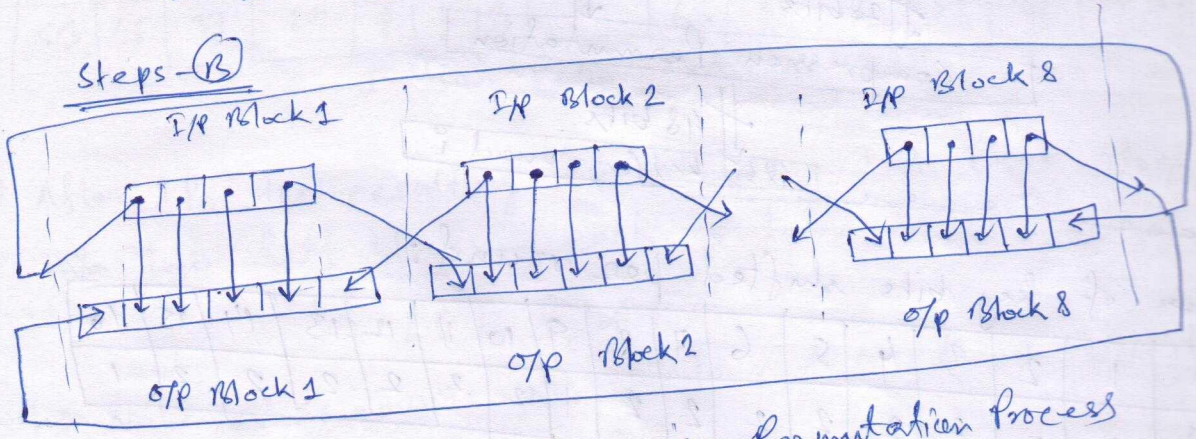


fig: RPT Expansion Permutation Process

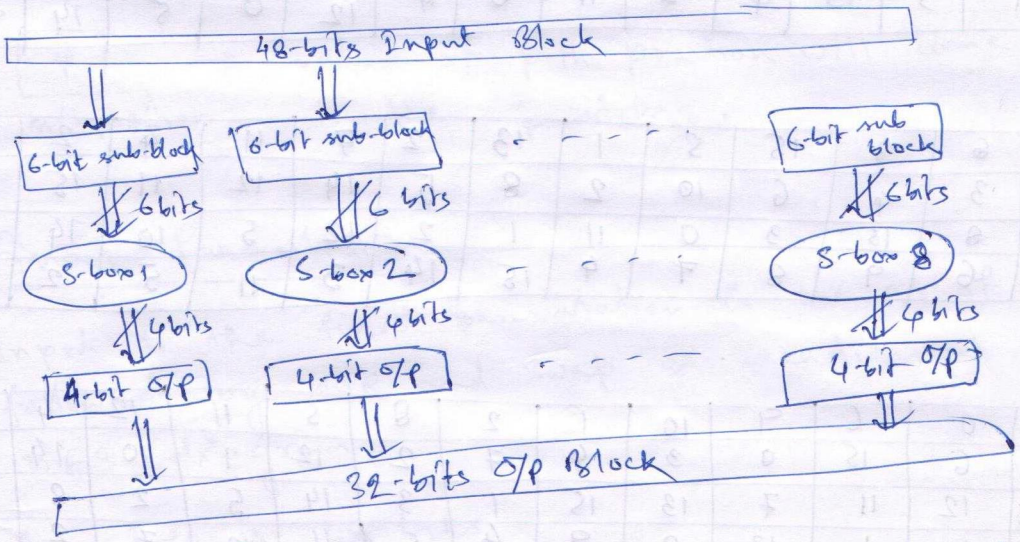
32	1	2	3	4	5	4	5	6	7	8	9
8	9	10	11	12	13	12	13	14	15	16	17
16	17	18	19	20	21	20	21	22	23	24	25
24	25	26	27	28	29	28	29	30	31	32	1

RPT Expansion Permutation Table.

(3.3) S-box Substitution

↳ I/p to this is the XORed value between 48-bits expanded RPT and 48-bits key.

↳ O/p is 32-bits

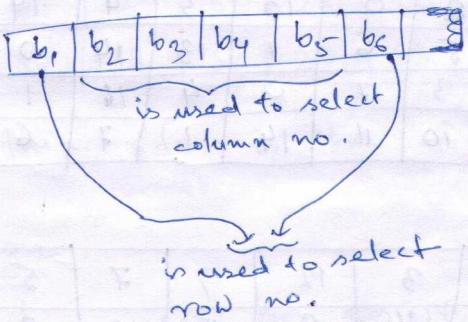


↳ Corresponding to each S-box, we have one substitution table/box.

↳ This table has 4 rows and 16 columns.

represented by 2 bits by 4 bits.

↳ 6 bits input to a S-box indicate which row and column to be selected.



↳ $b_2b_3b_4b_5$

b_1b_6 | p

Let Now, the value in the selected cell is p. Here $0 \le p \le 15$

↳ So, the 4-bits output is the binary equivalent of p.

Note, these tables are substitution table, or box but not the permutation table where the value indicates position.

S-box 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

S-box 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

S-box 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

S-box 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

S-box 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

S-box 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

S-box 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

S-box 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

(3.9) P-box Permutation

↳ from S-box, total 32-bits comes as I/p to P-box for simple permutation following the P-box permutation table.

↳ No expansion or compression are done here.

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

↳ [p] → value of p-th position will come to the n-th position in the O/p string.
(n-th position)

(4) Final Permutation

↳ Input to the final permutation is the O/p of final round followed by XOR and swap as mentioned in the initial DES diagram.

↳ So, I/p is 64 bits

↳ Final permutation is done only once. Sometimes, it is also called Inverse Initial Permutation (IP⁻¹).

↳ It is just a simple transposition of bits following the final Permutation table.

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

↳ O/p of this step is the final 64-bit ciphertext.

DES Decryption

↳ the same algo used for DES encryption also works for decryption.

↳ Only difference is:
  ↳ for encryption, K is divided into $K_1, K_2, K_3 \ldots K_{16}$ for the 16 rounds.
  ↳ for decryption, same sub-keys will be used in reverse order, i.e. the sequence is $K_{16}, K_{15}, \ldots K_1$ for 16 rounds

Analysis About DES

① Key length

↳ DES uses 56-bit key

↳ Thus, 2^{56} possible keys $\approx 7.2 \times 10^{16}$ key need to check

↳ Thus, it seems that brute-force attak is impractical.

Some estimate

↳ A single computer performing one DES encryption per microsecond would require more than 1050 years to break DES.

↳ Another study: A single PC with multicore processor can perform 10^9 ($\approx$1 billion) key combinations per second

↳ Needs $\approx$ 1,125 years to break DES

↳ A contemporary supercomputer can do 10^{13} encryptions per second.

↳ Needs $\approx$ 1 hour to break DES.

② Avalanch Effect:

↳ If we make minor changes to the plaintext or key, then if we get significant changes in ciphertext, it is called avalanch effect.

↳ DES has strong Avalanch effect.

③ Completeness Effect:

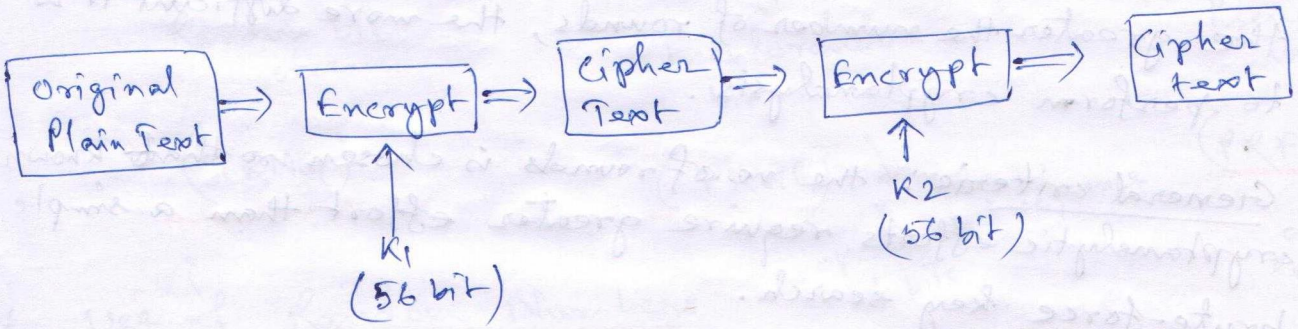
↳ means, each ciphertext bit should depend on more than one plaintext bits.

↳ DES has high completeness effect because of S-box & P-box.

Variations of DES

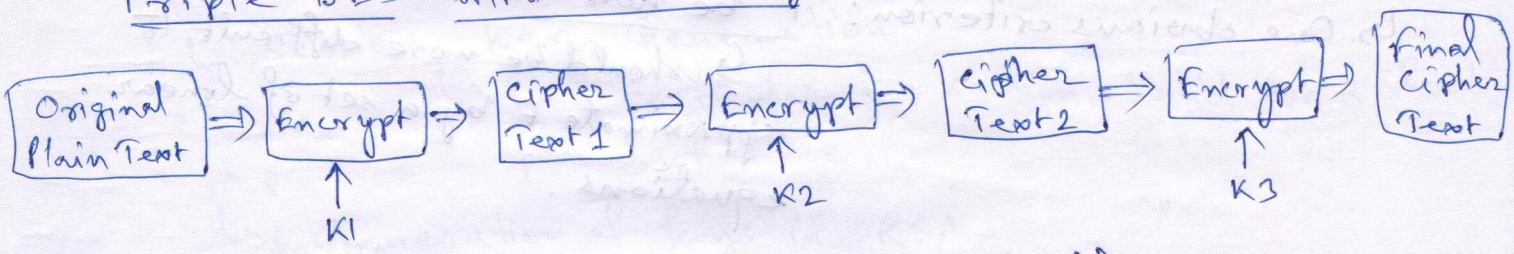
1. Double DES
2. Triple DES
   - → with two keys
   - → with three keys.

Double DES Encryption



↳ In decryption, keys are used in reverse order. i.e. K_2, K_1

Triple DES with three keys

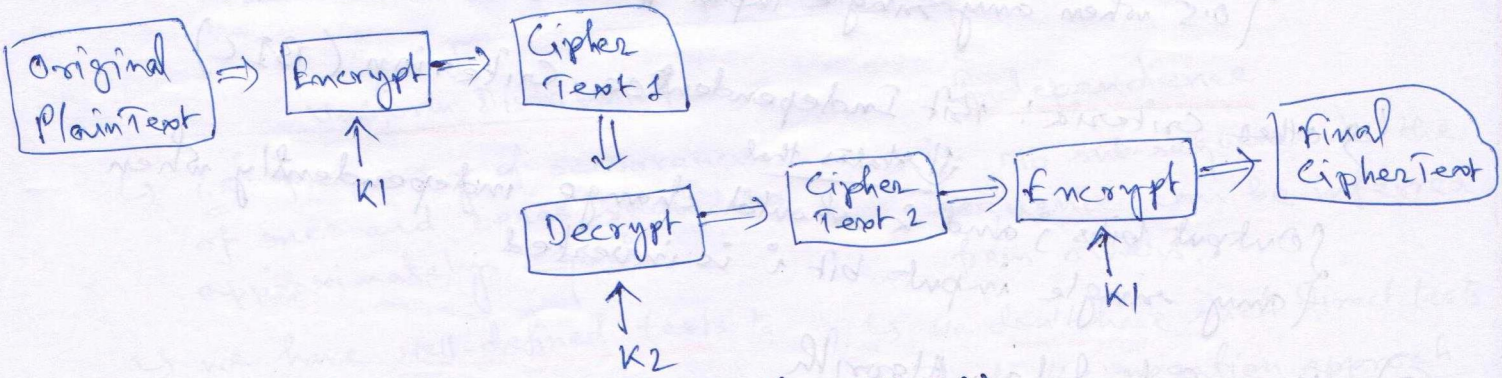


↳ Decryption: $P = D_{K1}(D_{K2}(D_{K3}(C)))$

↳ Dis-advantage: requiring $56 \times 3 = 168$ bits for key

↳ Many Internet-based application adopted this 3DES.
↳ e.g. PGP, S/MIME

Triple DES with two keys



↳ Decryption: $P = D_{K1}(E_{K2}(D_{K1}(C)))$

Block Cipher Design Principles

↳ Three critical aspects of block cipher design
- ① → the number of rounds
- ② → design of the function F
- ③ → key scheduling

① Number of Rounds

↳ the greater the number of rounds, the more difficult it is to perform cryptanalysis.

↳ General criteria: the no. of rounds is chosen so that known cryptanalytic efforts require greater effort than a simple brute-force key search.

② Design of F

↳ The heart of a Feistel Block cipher is this F

↳ One obvious criterion: F be non-linear
↳ should be more difficult to approximate F by a set of linear equations.

↳ other criteria: Good Avalanche properties.

↳ More strict version: Strict Avalanche Criterion (SAC)
⇓ states that
{ Any output bit j of an S-box should change with probability 0.5 when any single input bit i is inverted.

↳ other criteria: Bit Independence Criterion (BIC)
⇓ states that
{ output bits j and k should change independently when any single input bit i is inverted.

③ Key Schedule Algorith

↳ No general criteria yet.
↳ One suggestion: Key schedule should guarantee SAC and BIC.