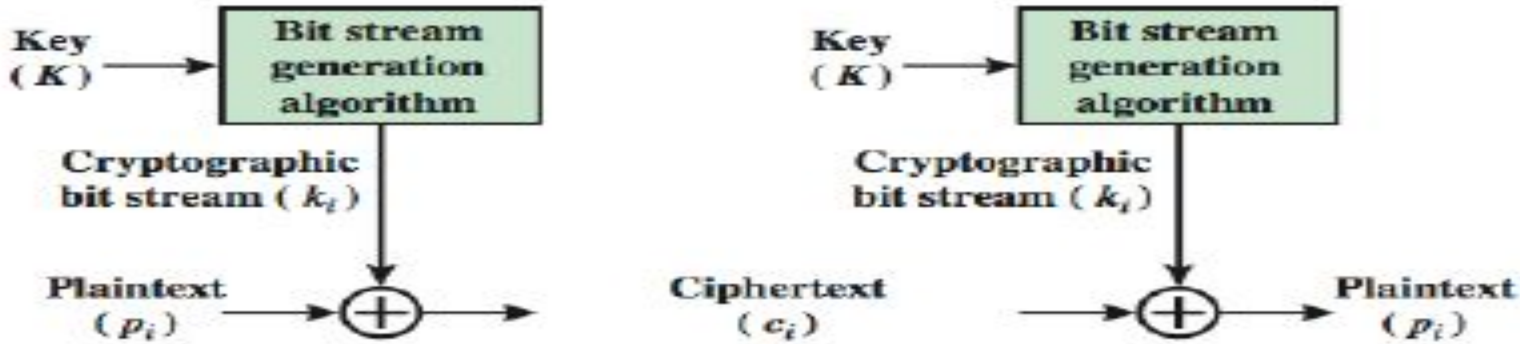
CSE4137: Cryptography and Security

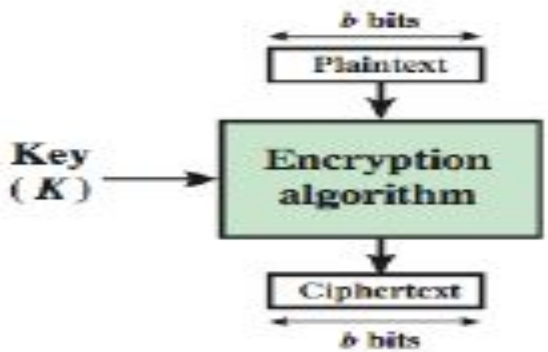
Lecture 7

Block Cipher and The Data Encryption Standard

Block vs Stream Cipher



(a) Stream Cipher Using Algorithmic Bit Stream Generator



(b) Block Cipher

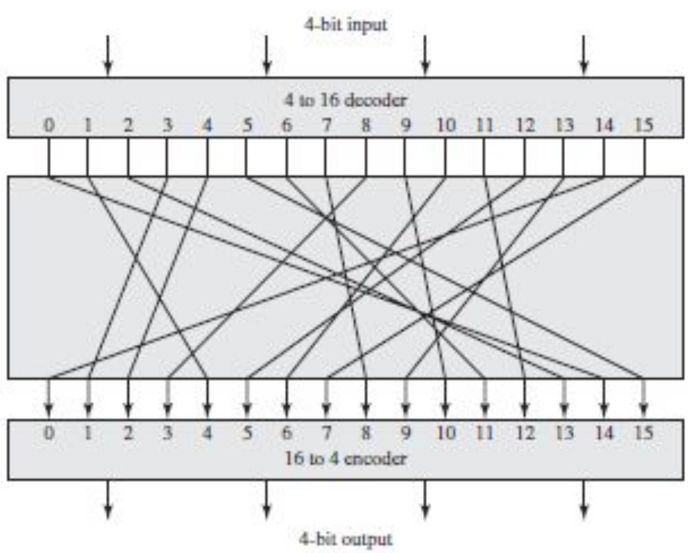
Block vs Stream Cipher

- **<u>Block Cipher:</u>**
  - block ciphers process messages in blocks, each of which is then en/decrypted
  - typically a block size of 64 bits or 128 bits are used.
- **<u>Stream Cipher:</u>**
  - stream ciphers process messages a bit or a byte at a time when en/decrypted

- Many current ciphers are block ciphers
  - better analyzed
  - broader range of applications

Ideal Block Cipher

- In a modern block cipher, a block of ***N*** bits from the plaintext is replaced with a block of ***N*** bits to produce the ciphertext.
- In an ideal block cipher, the relationship between the input blocks and the output block is completely random. But it must be invertible for decryption to work.



Plaintext	Ciphertext
0000	1110
0001	0100
0010	1101
0011	0001
0100	0010
0101	1111
0110	1011
0111	1000
1000	0011
1001	1010
1010	0110
1011	1100
1100	0101
1101	1001
1110	0000
1111	0111

Ciphertext	Plaintext
0000	1110
0001	0011
0010	0100
0011	1000
0100	0001
0101	1100
0110	1010
0111	1111
1000	0111
1001	1101
1010	1001
1011	0110
1100	1011
1101	0010
1110	0000
1111	0101

The Size of the Encryption Key for the Ideal Block Cipher

- The encryption key for the ideal block cipher is the codebook itself, meaning the table that shows the relationship between the input blocks and the output blocks
- With a 64-bit block, we can think of each possible input block as 1 of 2^{64} integers and for each such integer we can specify an output 64-bit block. The size of the codebook will be of size $64 \times 2^{64} \approx 10^{21}$.
- For small block size, ideal block cipher is prone to statistical analysis.

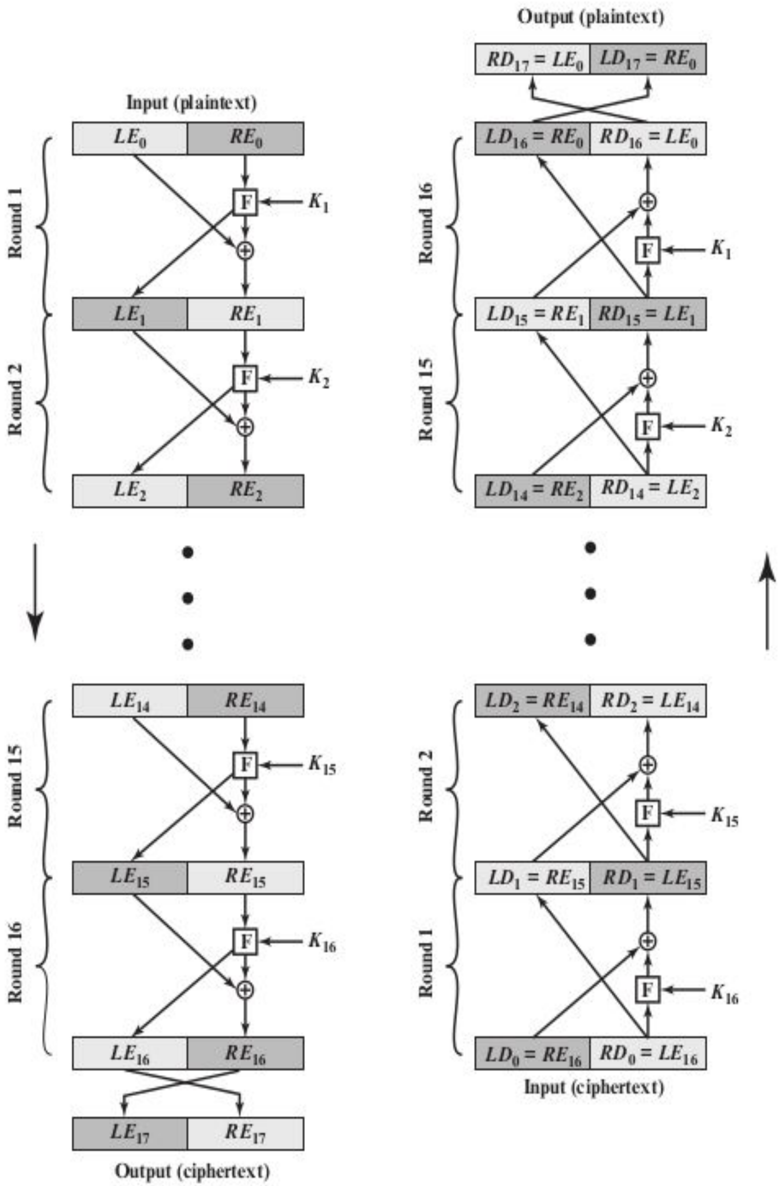
The Feistel Cipher Structure

- Named after the IBM cryptographer Horst Feistel and first implemented in the Lucifer cipher by Horst Feistel and Don Copper smith.
- It is based on Shannon’s proposal of 1945, is the structure used by many significant symmetric block ciphers currently in use.
- The idea is to develop a product cipher that alternates ***confusion*** and ***diffusion*** functions.
- A cryptographic system based on Feistel structure uses the same basic algorithm for both encryption and decryption.

Confusion and Diffusion

- Cipher needs to completely obscure statistical properties of original message.
- a one-time pad does this
- more practically Shannon suggested combining *substitution* and *permutation* to obtain:
- **Diffusion** – dissipates statistical structure of plaintext over bulk of ciphertext
- **Confusion** – makes relationship between ciphertext and key as complex as possible.

Feistel Cipher Structure



- ✔ Input to the encryption algorithm
  - ✔ A plaintext block of 2w bits divided into two halves L_0 and R_0.
  - ✔ A Key K
- ✔ N=16 round of processing (although any number can be used).
  - ✔ Round i has input L_{i-1} and R_{i-l} and Key K_i different from K and each other.
- ✔Round function has same structure but is parameterized by K_i.
- ✔Round function performed substitution function on the left half of the data. This is followed by a permutation that interchange the two halves of the data.
- ✔The structure is a particular form of the Substition-Permutation Network (SPN).

Feistel Decryption Algorithm

- ✔ At every round, the intermediate value of the decryption process is equal to the corresponding value of the encryption process with the two halves of the value swapped.
- ✔ Output of the last round of encryption = RE_{16} || LE_{16} = ciphertext = Input to the first round of decryption process.
  - ✔ Result of encryption of 16th Round:

$$LE_{16} = RE_{15}$$
$$RE_{16} = LE_{15} \oplus F(RE_{15}, K_{16})$$

  - ✔ On the decryption side:

$$LD_1 = RD_0 = LE_{16} = RE_{15}$$
$$\begin{aligned} RD_1 &= LD_0 \oplus F(RD_0, K_{16}) \\ &= RE_{16} \oplus F(RE_{15}, K_{16}) \\ &= [LE_{15} \oplus F(RE_{15}, K_{16})] \oplus F(RE_{15}, K_{16}) \end{aligned}$$

- ✔ Derivation does not require F to be a reversible function.

Feistel Cipher Design Elements

- Block size
- Key size
- Number of rounds
- Subkey generation algorithm
- Round function
- Fast software en/decryption
- Ease of analysis

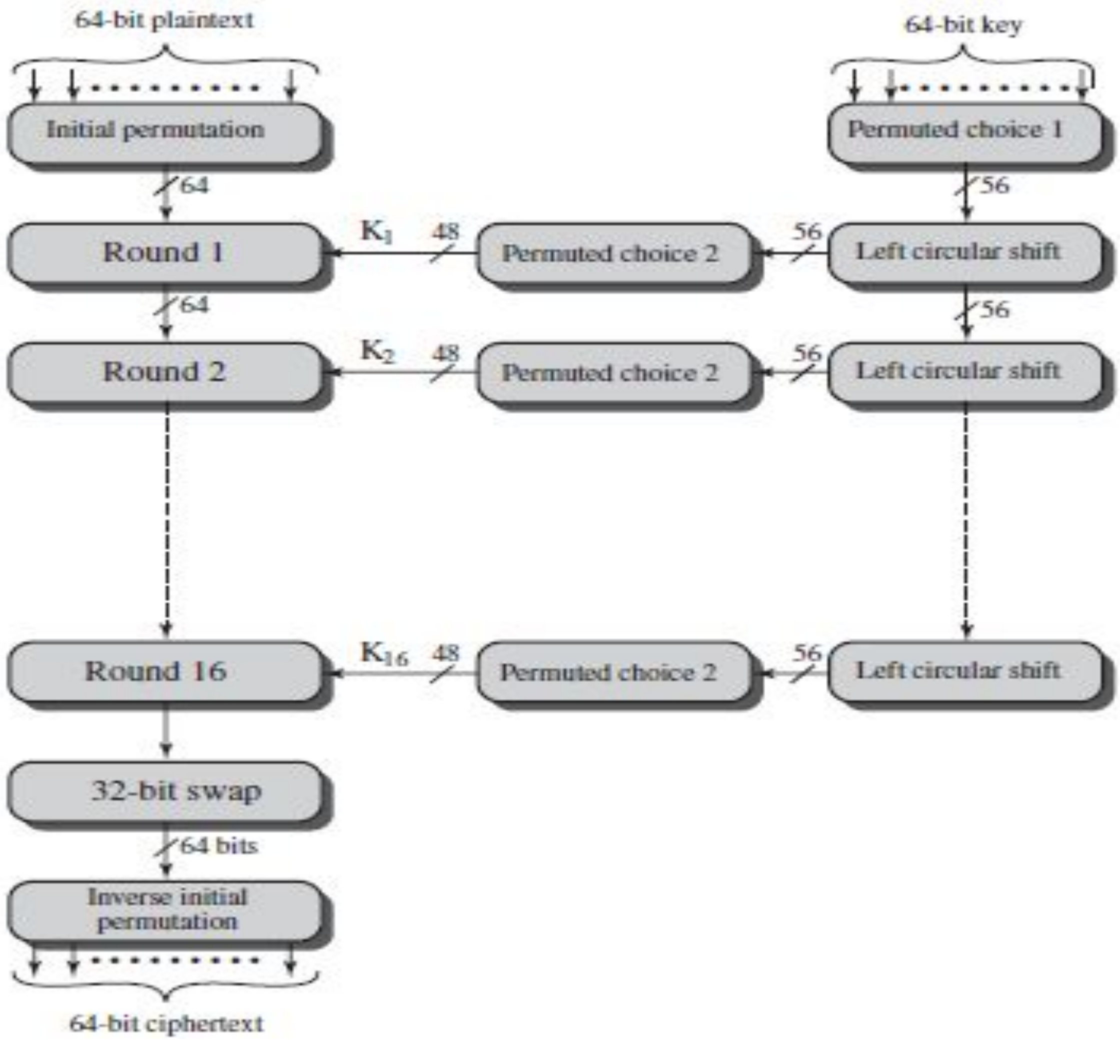
Data Encryption Standard (DES)

- Most widely used block cipher.
- Adopted in 1977 by NBS (now NIST)
  - as FIPS PUB 46
- Encrypts 64-bit data using 56-bit key
- IBM developed Lucifer cipher
  - by team led by Feistel in late 60's
  - used 64-bit data blocks with 128-bit key
- Then redeveloped as a commercial cipher
- In 1973 NBS issued request for proposals for a national cipher standard
- IBM submitted their revised Lucifer which was eventually accepted as the DES.

DES Design Controversy

- Although DES standard is public
- Was considerable controversy over design
  - in choice of 56-bit key (vs Lucifer 128-bit)
  - and because design criteria were classified
- Subsequent events and public analysis show in fact design was appropriate
- Use of DES has flourished
  - especially in financial applications
  - still standardized for legacy application use

DES Encryption Overview



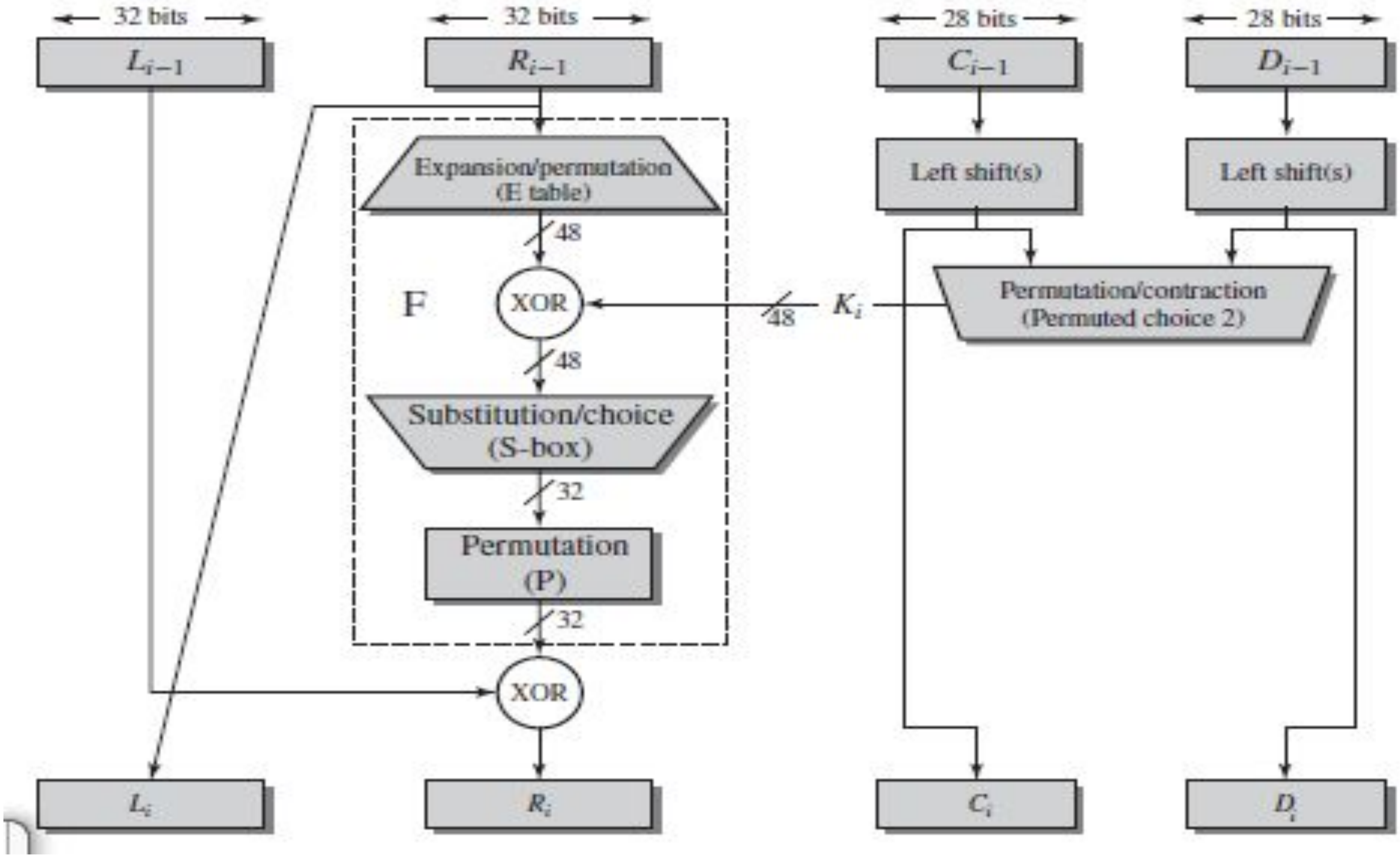
DES Round Structure

- Uses two 32-bit L & R halves
- As for any Feistel cipher can described as:

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

- F takes 32-bit R half and 48-bit subkey:
  - expands R to 48-bits using perm E
  - adds to subkey using XOR
  - passes through 8 S-boxes to get 32-bit result
  - finally permutes using 32-bit perm P

DES Round Structure



Initial Permutation and Inverse Initial Permutation

(a) 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

(b) Inverse Initial 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

$M=IP^{-1}(IP(M))=IP^{-1}(X)$

M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8
M_9	M_{10}	M_{11}	M_{12}	M_{13}	M_{14}	M_{15}	M_{16}
M_{17}	M_{18}	M_{19}	M_{20}	M_{21}	M_{22}	M_{23}	M_{24}
M_{25}	M_{26}	M_{27}	M_{28}	M_{29}	M_{30}	M_{31}	M_{32}
M_{33}	M_{34}	M_{35}	M_{36}	M_{37}	M_{38}	M_{39}	M_{40}
M_{41}	M_{42}	M_{43}	M_{44}	M_{45}	M_{46}	M_{47}	M_{48}
M_{49}	M_{50}	M_{51}	M_{52}	M_{53}	M_{54}	M_{55}	M_{56}
M_{57}	M_{58}	M_{59}	M_{60}	M_{61}	M_{62}	M_{63}	M_{64}

$X=IP(M)$

M_{58}	M_{50}	M_{42}	M_{34}	M_{26}	M_{18}	M_{10}	M_2
M_{60}	M_{52}	M_{44}	M_{36}	M_{28}	M_{20}	M_{12}	M_4
M_{62}	M_{54}	M_{46}	M_{38}	M_{30}	M_{22}	M_{14}	M_6
M_{64}	M_{56}	M_{48}	M_{40}	M_{32}	M_{24}	M_{16}	M_8
M_{57}	M_{49}	M_{41}	M_{33}	M_{25}	M_{17}	M_9	M_1
M_{59}	M_{51}	M_{43}	M_{35}	M_{27}	M_{19}	M_{11}	M_3
M_{61}	M_{53}	M_{45}	M_{37}	M_{29}	M_{21}	M_{13}	M_5
M_{63}	M_{55}	M_{47}	M_{39}	M_{31}	M_{23}	M_{15}	M_7

Expansion and Permutation

(c) Expansion Permutation (E)

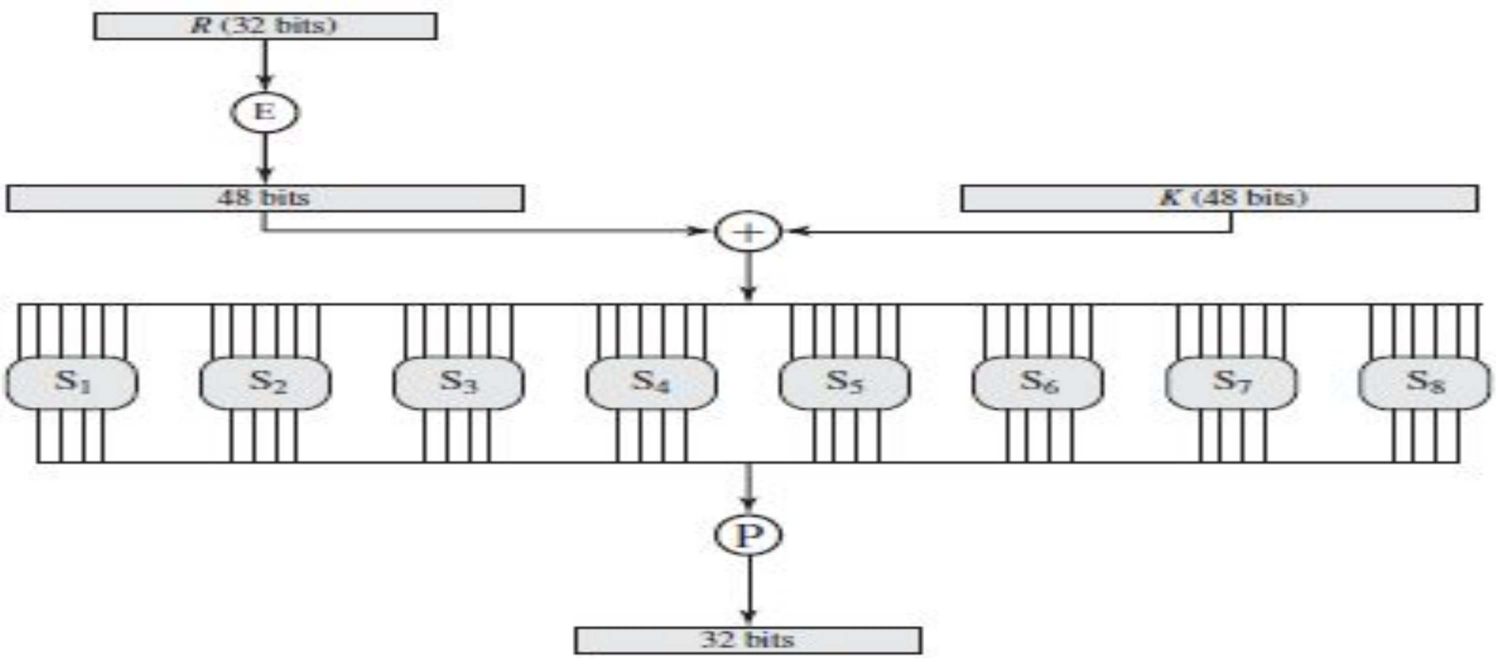
32	1	2	3	4	5
4	5	6	7	8	9
8	9	10	11	12	13
12	13	14	15	16	17
16	17	18	19	20	21
20	21	22	23	24	25
24	25	26	27	28	29
28	29	30	31	32	1

(d) Permutation Function (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

Substitution Boxes S

- Have eight S-boxes which map 6 to 4 bits
  - – outer bits 1 & 6 (**row** bits) select 1 row of 4
  - – inner bits 2-5 (**col** bits) are substituted
  - – result is 8 lots of 4 bits, or 32 bits



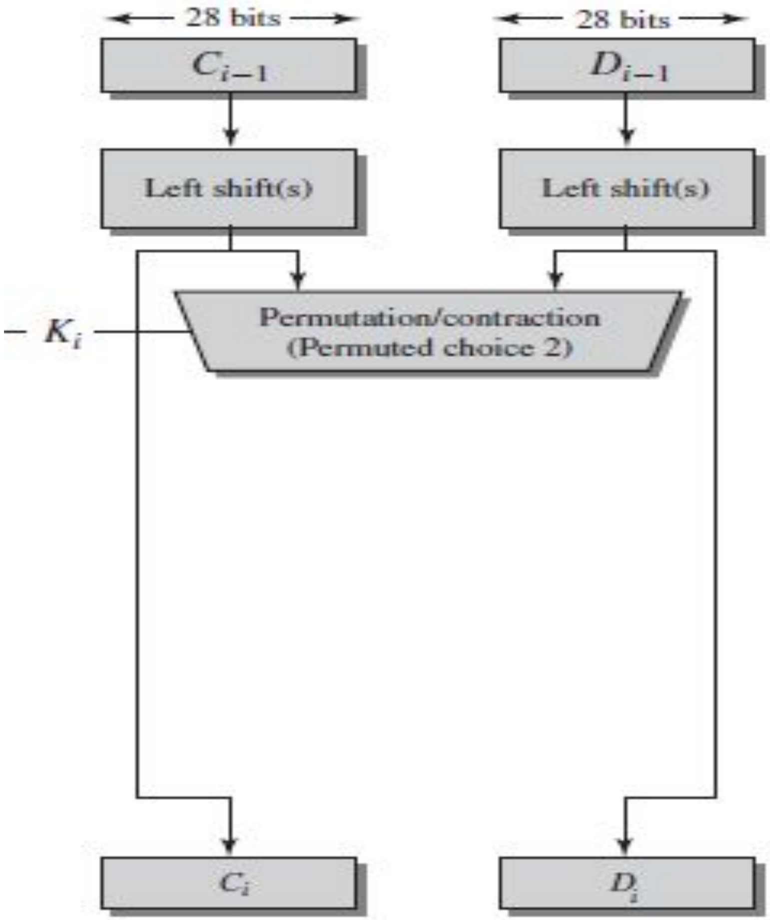
Substitution Boxes S

S_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_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_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_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_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_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_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_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 Key Schedule

- Forms subkeys used in each round
  - initial permutation of the key (P) which discards every 8th bit to selects 56-bits.
  - Selected 56 bits are divided in two 28-bit halves
- 16 stages consisting of:
  - rotating **each half** separately either 1 or 2 places depending on the **key rotation schedule** K
  - selecting 24-bits from each half & permuting them

DES Key Generation



(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

(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

A DES Example

Table 3.5 DES Example

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

Plaintext:	02468aceeca86420
Key:	0f1571c947d9e859
Ciphertext:	da02ce3a89ecac3b

Avalanche Effect

- Key desirable property of encryption algorithm.
- Where a change of **one** input or key bit results in changing many bits of the output (ciphertext)
- Small change may provide a way to reduce the size of the plaintext or key space to be searched.
- DES exhibits strong avalanche

Table 3.6 Avalanche Effect in DES: Change in Plaintext

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

Avalanche Effect

Table 3.7 Avalanche Effect in DES: Change in Key

Round		δ
	02468aceeca86420 02468aceeca86420	0
1	3cf03c0fbad22845 3cf03c0f9ad628c5	3
2	bad2284599e9b723 9ad628c59939136b	11
3	99e9b7230bae3b9e 9939136b768067b7	25
4	0bae3b9e42415649 768067b75a8807c5	29
5	4241564918b3fa41 5a8807c5488dbe94	26
6	18b3fa419616fe23 488dbe94aba7fe53	26
7	9616fe2367117cf2 aba7fe53177d21e4	27
8	67117cf2c11bfc09 177d21e4548f1de4	32

Round		δ
9	c11bfc09887fbc6c 548f1de471f64dfd	34
10	887fbc6c600f7e8b 71f64dfd4279876c	36
11	600f7e8bf596506e 4279876c399fdc0d	32
12	f596506e738538b8 399fdc0d6d208dbb	28
13	738538b8c6a62c4e 6d208dbbb9bdeeaa	33
14	c6a62c4e56b0bd75 b9bdeeaad2c3a56f	30
15	56b0bd7575e8fd8f d2c3a56f2765c1fb	33
16	75e8fd8f25896490 2765c1fb01263dc4	30
IP^{-1}	da02ce3a89ecac3b ee92b50606b62b0b	30

Strength of DES

- **Key Size:**

Table 5 Average Time Required for Exhaustive Key Search

Key Size (bits)	Cipher	Number of Alternative Keys	Time Required at 10^9 Decryptions/s	Time Required at 10^{13} Decryptions/s
56	DES	$2^{56} \approx 7.2 \times 10^{16}$	2^{55} ns = 1.125 years	1 hour
128	AES	$2^{128} \approx 3.4 \times 10^{38}$	2^{127} ns = 5.3×10^{21} years	5.3×10^{17} years
168	Triple DES	$2^{168} \approx 3.7 \times 10^{50}$	2^{167} ns = 5.8×10^{33} years	5.8×10^{29} years
192	AES	$2^{192} \approx 6.3 \times 10^{57}$	2^{191} ns = 9.8×10^{40} years	9.8×10^{36} years
256	AES	$2^{256} \approx 1.2 \times 10^{77}$	2^{255} ns = 1.8×10^{60} years	1.8×10^{56} years
26 characters (permutation)	Monoalphabetic	$2! = 4 \times 10^{26}$	2×10^{26} ns = 6.3×10^{9} years	6.3×10^{6} years

- **The nature of the DES Algorithm.**
- **Timing Attacks**

Block Cipher Design

- Basic principles still like Feistel's in 1970's
- **Number of rounds:**

  – more is better.

  - General requirement is to make known cryptanalytic effort requires greater effort than a brute-force key attack.
- **Function F:**

  – provides "confusion".

  - should be non-linear (difficult to approximate with a set of linear equations).

  - Strict avalanche criterion (SAC)- an output bit ***j***

- ✔ Chapter 4 of William Stalling book (7th Edition).
- ✔ Chapter 3 of William Stalling book (5th Edition)