CHAPTER 3

BLOCK CIPHERS AND THE DATA ENCRYPTION STANDARD

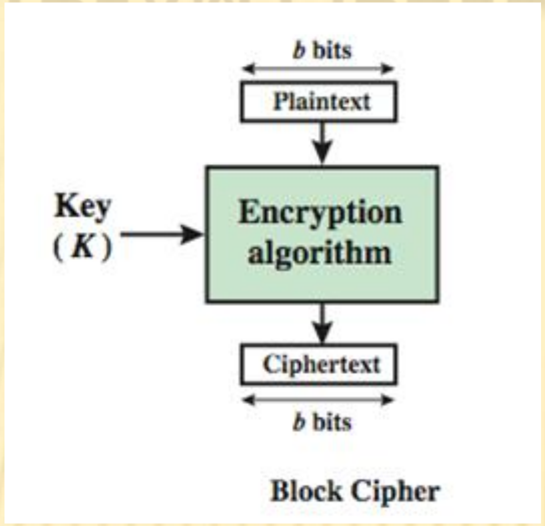
MODERN BLOCK CIPHERS

- The most widely used symmetric cipher : **Data Encryption Standard (DES)**
- DES remains the most important such algorithm although it is replaced by Advanced Encryption Standard (AES).
  - This chapter begins with :
    - Discussion of the general principles of symmetric block ciphers.
    - Next, we cover full DES.
    - A general discussion of block cipher design.

BLOCK VS. STREAM CIPHERS

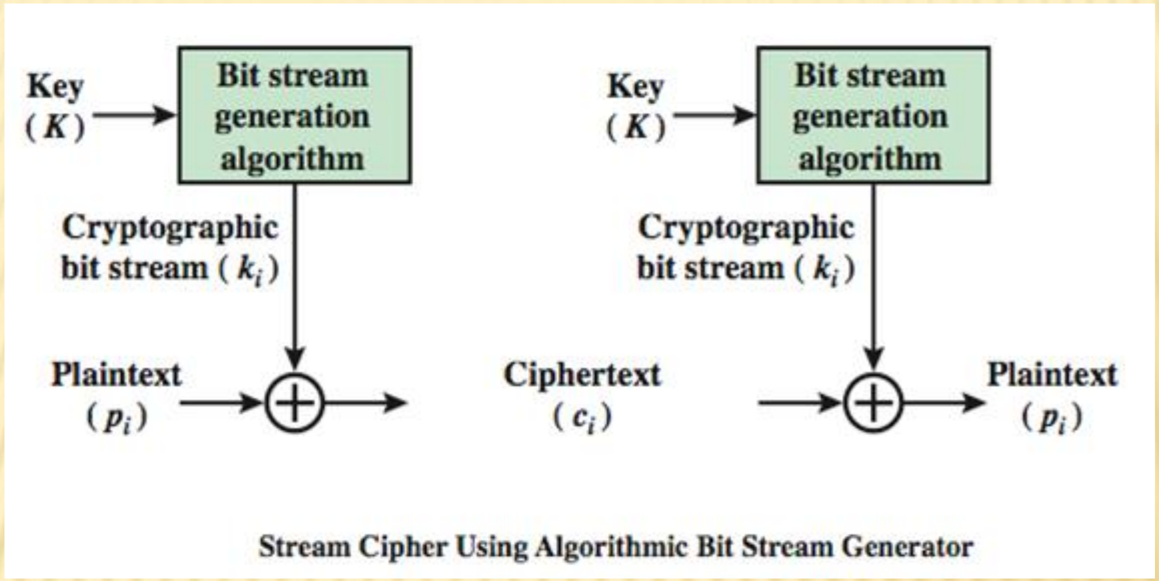
- Block ciphers process messages in blocks or word (number of bits) at a time, then encrypted or decrypted
- Stream ciphers process messages in a bit or byte at a time, then encrypted or decrypted
- many current ciphers are block ciphers
  - ✓ better analyzed
  - ✓ broader range of applications

BLOCK VS. STREAM CIPHERS



- A block cipher is one in which a block of plaintext is treated as a whole and used to produce a ciphertext block of equal length.
- Typically, a block size of 64 or 128 bits is used.

BLOCK VS. STREAM CIPHERS


Key (K)
Bit stream generation algorithm
Cryptographic bit stream (k_i)
Plaintext (p_i)
Key (K)
Bit stream generation algorithm
Cryptographic bit stream (k_i)
Ciphertext (c_i)
Plaintext (p_i)

Stream Cipher Using Algorithmic Bit Stream Generator

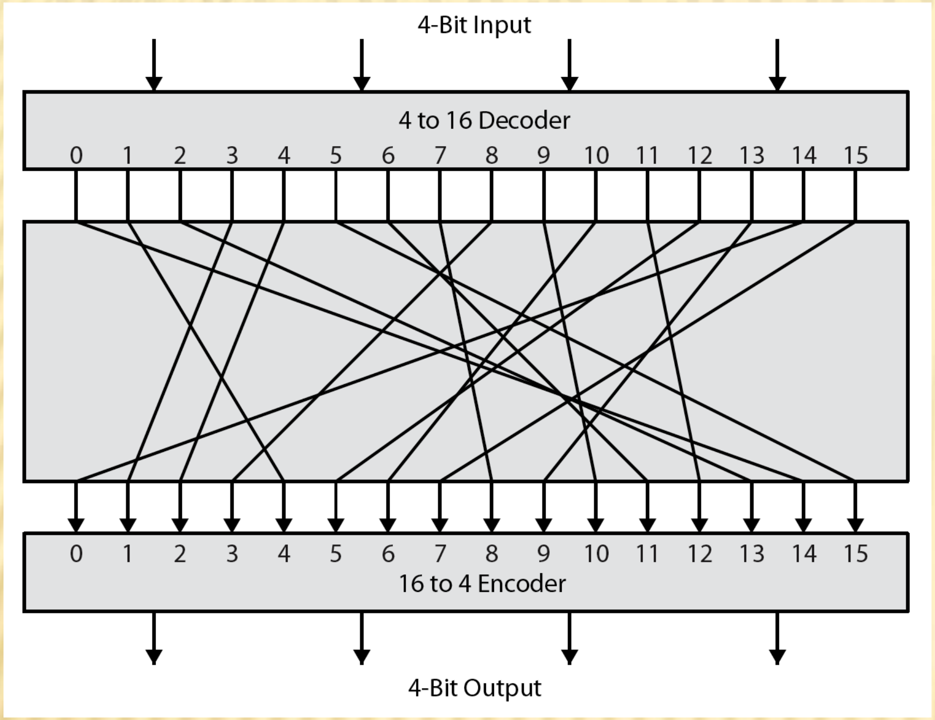
- A stream cipher, the two users share a symmetric encryption key.
- Encrypts a digital data stream one bit or one byte at a time. In which the keystream (k) is as long as the plaintext bit stream (p).
- Ex. , One-time pad version of the Vernam cipher would be used.

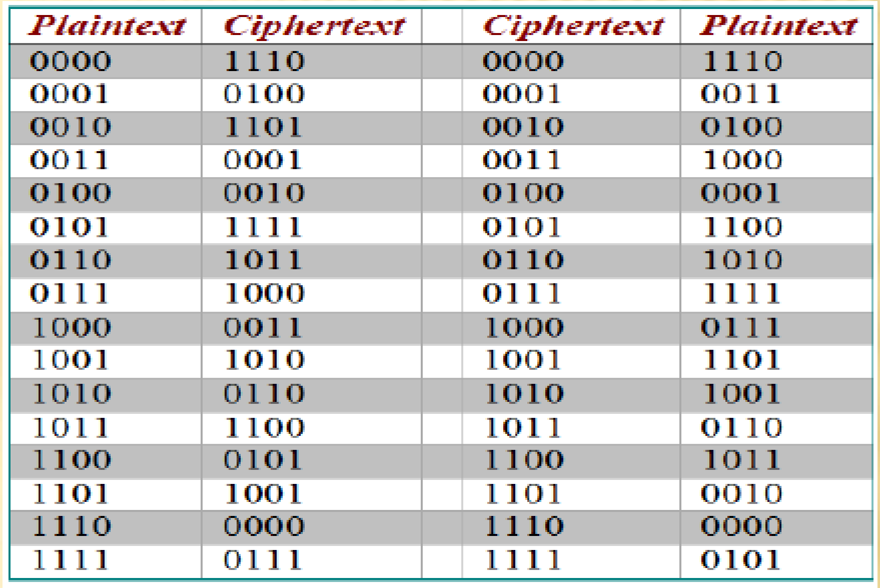
BLOCK CIPHER PRINCIPLES

- Most symmetric block encryption algorithms are based on a structure referred to as a **Feistel block cipher**.
  - The execution of two or more ciphers in sequence, the final result is cryptographically stronger than any of the component ciphers.

- A block cipher operates on a plaintext block of n bits to produce a ciphertext block of n bits.
- Block ciphers look like an extremely large substitution.
- For *n*-bit general substitution block cipher, the size of the key is $n \times 2^n$.
- For a 64-bit block, the key size is $64\text{x } 2^{64}=2^{70}=10^{21}$bits.

IDEAL BLOCK CIPHER





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

Key Length

Key length 16 $\times$ 4 bits = 64 bits

key length is $2^n \times n$

Actual block size is at least 64 bits

Key length will be $2^{64} \times 64 \approx 10^{21}$ bits

Ability to map any plaintext to any ciphertext is the ideal block cipher

CLAUDE SHANNON AND SUBSTITUTION-PERMUTATION CIPHERS

- Claude Shannon introduced idea of substitution-permutation (S-P) networks from basis of modern block ciphers
- S-P nets are based on two primitive cryptographic operations:
  - substitution (S-box):

    Each plaintext element or group of elements is uniquely replaced by a corresponding ciphertext element or group of elements.
  - permutation (P-box) :

    A sequence of plaintext elements is replaced by a permutation of that sequence. That is, no elements are added or deleted or replaced in the sequence, rather the order in which the elements appear in the sequence is changed.
- Provide confusion & diffusion of message & key

CONFUSION AND DIFFUSION

More practically Shannon suggested combining S&P elements to obtain:

- **Diffusion:** makes relationship between plaintext and ciphertext as complex as possible to thwart attempts to deduce the key.

  Message M = m1, m2, m3, …

$$y_n = \left(\sum_{i=1}^{k} m_{n+i}\right) \bmod 26$$

Ciphertext letter y_n results from adding *k* successive plaintext letters (avalanche effect)

- **Confusion:** makes relationship between ciphertext and key as complex as possible to thwart attempts to discover the key

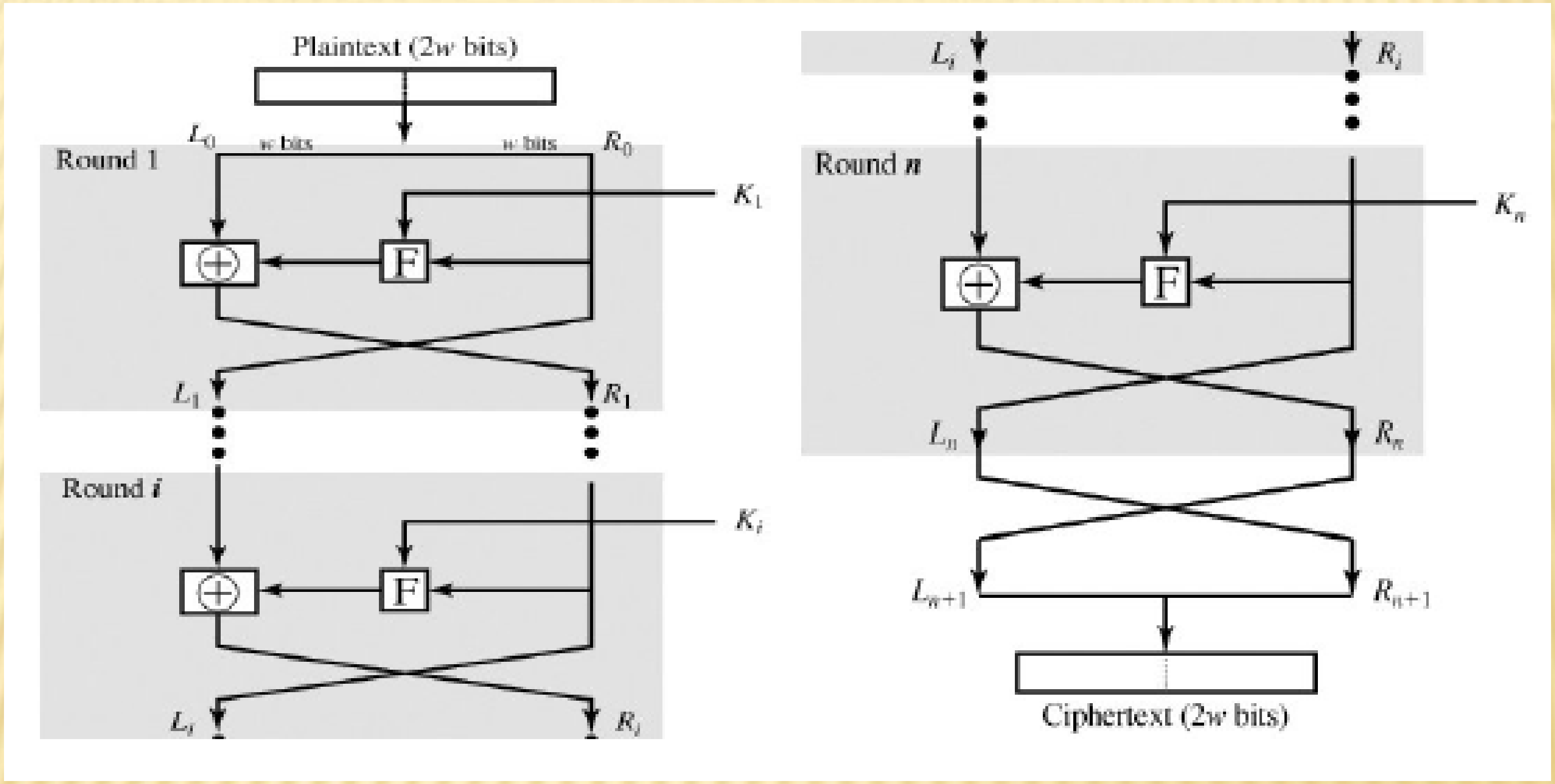
FEISTEL CIPHER STRUCTURE

- It partitions input block into two halves which are processed through multiple rounds which perform a substitution on left data half, based on round function of right half & subkey, and then have permutation swapping halves.
- Implements Shannon’s S-P net concept

FEISTEL CIPHER STRUCTURE

- Input
  - plaintext block of length 2w
  - key K
- Plaintext block divided to L0, R0
- Pass thru *n rounds of processing*
- Each round i has
  - Li-1, Ri-1 derived from previous round
  - subkey Ki derived from overall K

FEISTEL CIPHER STRUCTURE

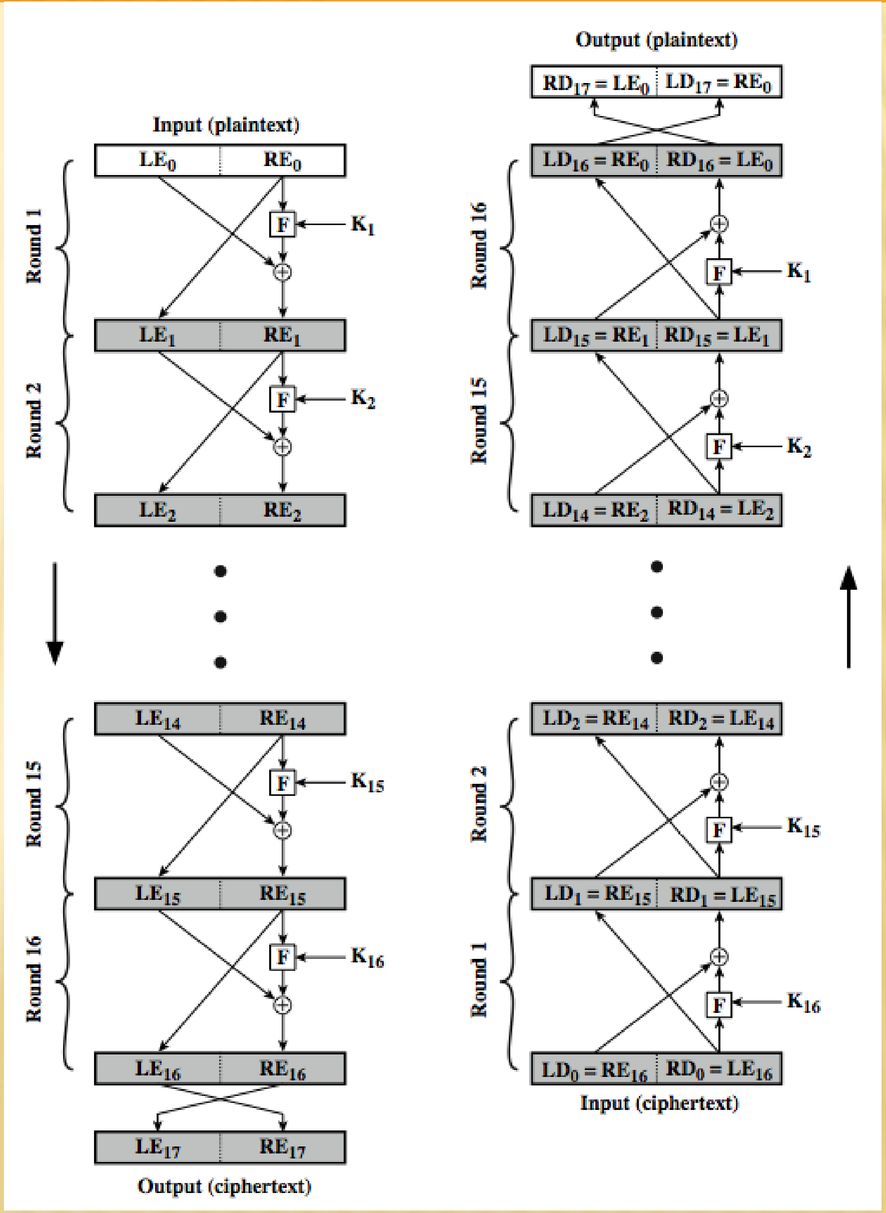


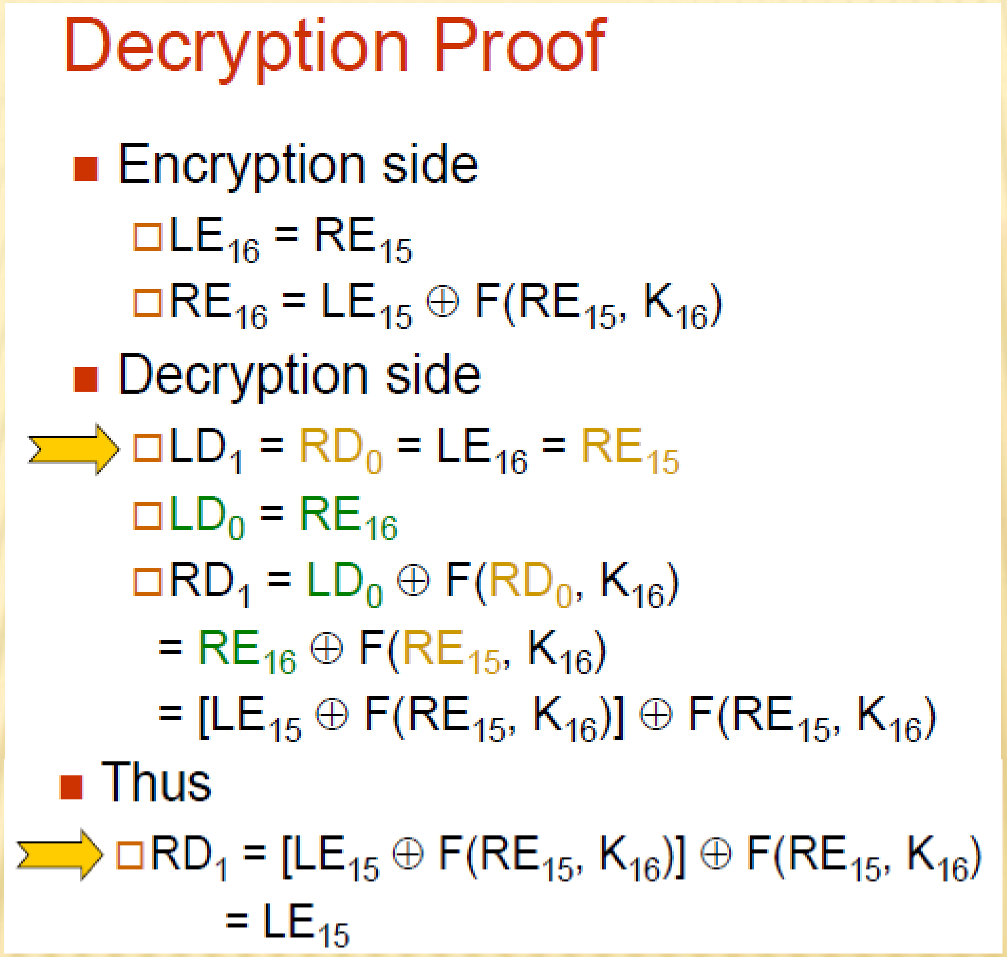
Substitution performed to left half
- apply round function F to right half
- take XOR of output with left half
- F is parameterized by round subkey *Ki*

Permutation of left and right halves
- interchange left and right halves

FEISTEL CIPHER STRUCTURE

- Output of ith encryption round $\rightarrow$ input to (16-i)th decryption round swapped
- $LE_i||RE_i \equiv RD_{16-i}||LD_{16-i}$





Decryption Proof

- Encryption side
  - $LE_{16} = RE_{15}$
  - $RE_{16} = LE_{15} \oplus F(RE_{15}, K_{16})$
- Decryption side
  - $LD_1 = RD_0 = LE_{16} = RE_{15}$
  - $LD_0 = RE_{16}$
  - $RD_1 = LD_0 \oplus F(RD_0, K_{16})$

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

    $= [LE_{15} \oplus F(RE_{15}, K_{16})] \oplus F(RE_{15}, K_{16})$
- Thus
  - $RD_1 = [LE_{15} \oplus F(RE_{15}, K_{16})] \oplus F(RE_{15}, K_{16})$

    $= LE_{15}$

The same algorithm with a reversed key order produces the correct result, noting that 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.

FEISTEL CIPHER DESIGN ELEMENTS

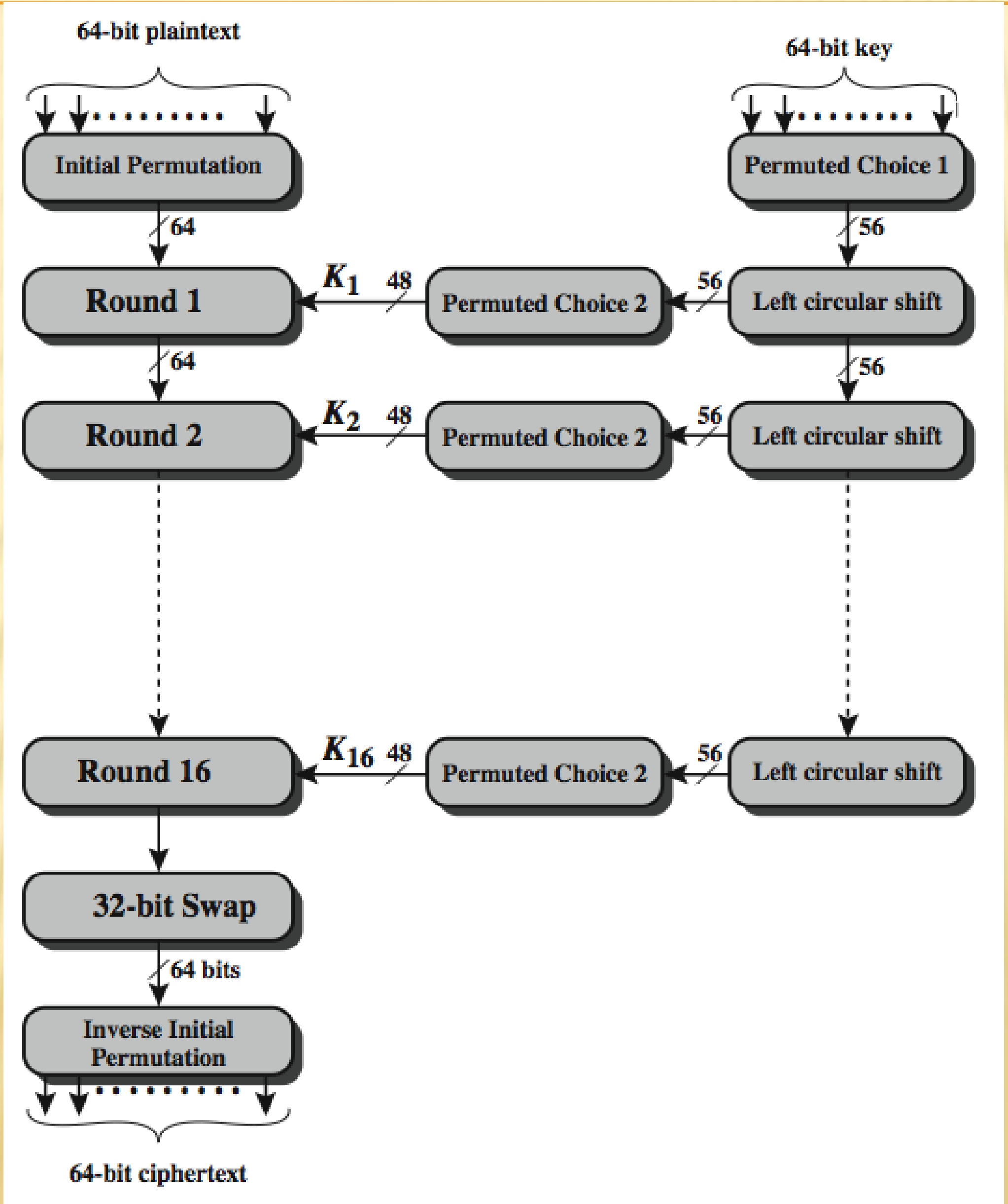
Parameters and Design Features:

- **Block size:** increasing size improves security, but slows cipher - typical: 64 bit, 128 bit AES
- **Key size**: increasing size improves security, but slows cipher - typical: 128 bit
- **Number of rounds** - increasing number improves security, but slows cipher - typical: 16
- **Sub-key generation algorithm**- greater complexity make cryptanalysis harder, but slows cipher
- **Round function** - greater complexity make cryptanalysis harder, but slows cipher
- **Fast software en/decryption** - more recent concern for practical use
- **Ease of analysis** - for easier validation & testing of strength

DATA ENCRYPTION STANDARD (DES)

- The most widely used private key block cipher
- 64-bit plaintext block and 56-bit key
- Exact structure as Feistel except
  - initial permutation of plaintext
  - final permutation of last round’s output

DES ENCRYPTION OVERVIEW



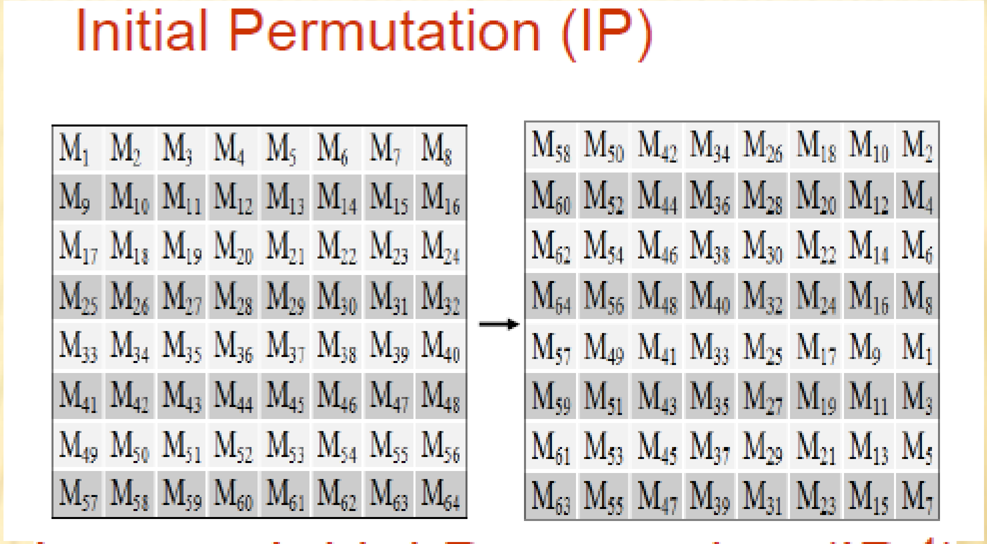
DES ENCRYPTION SCHEME

The overall scheme for DES encryption takes as input 64-bits of data and of key.

- The left side shows the basic process for enciphering a 64-bit data block :
  - an initial permutation (IP) which shuffles the 64-bit input block
  - 16 rounds of a complex key dependent round function involving substitutions & permutations
  - a final permutation, being the inverse of IP

- The right side shows the handling of the 56-bit key :
  - an initial permutation of the key (PC1) which selects 56-bits out of the 64-bits input, in two 28-bit halves
  - 16 stages to generate the 48-bit sub keys using a left circular shift and a permutation of the two 28-bit halves.

THE INITIAL PERMUTATION AND ITS INVERSE ARE DEFINED BY FOLLOWING TABLES

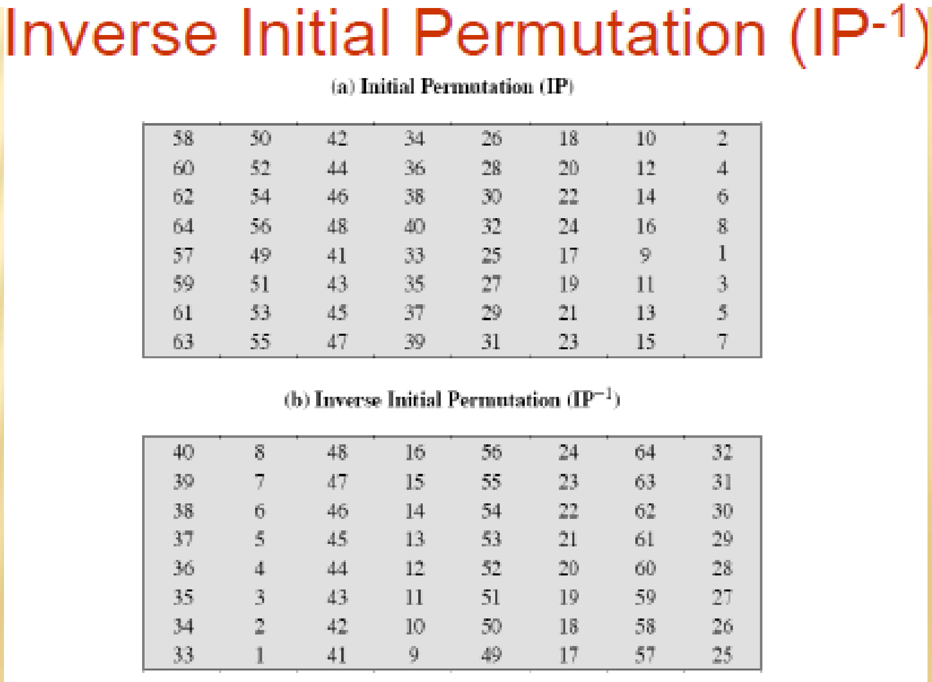


Initial Permutation (IP)

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}

$\rightarrow$

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



Inverse Initial Permutation (IP^{-1})

(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

- The input to a table consists of 64 bits numbered left to right from 1 to 64. The 64 entries in the permutation table contain a permutation of the numbers from 1 to 64. Each entry in the permutation table indicates the position of a numbered input bit in the output, which also consists of 64 bits.
- Note that the bit numbering for DES reflects IBM mainframe practice, and is the opposite of what we now mostly use - so be careful! Numbers from Bit 1 (leftmost, most significant) to bit 32/48/64 etc (rightmost, least significant).
- For example, a 64-bit plaintext value of “675a6967 5e5a6b5a” (written in left & right halves) after permuting with IP becomes “ffb2194d 004df6fb”. Note that example values are specified using hexadecimal.

INITIAL PERMUTATION IP

- IP reorders the input data bits
- even bits to LH half, odd bits to RH half
- quite regular in structure (easy in h/w)
- example:

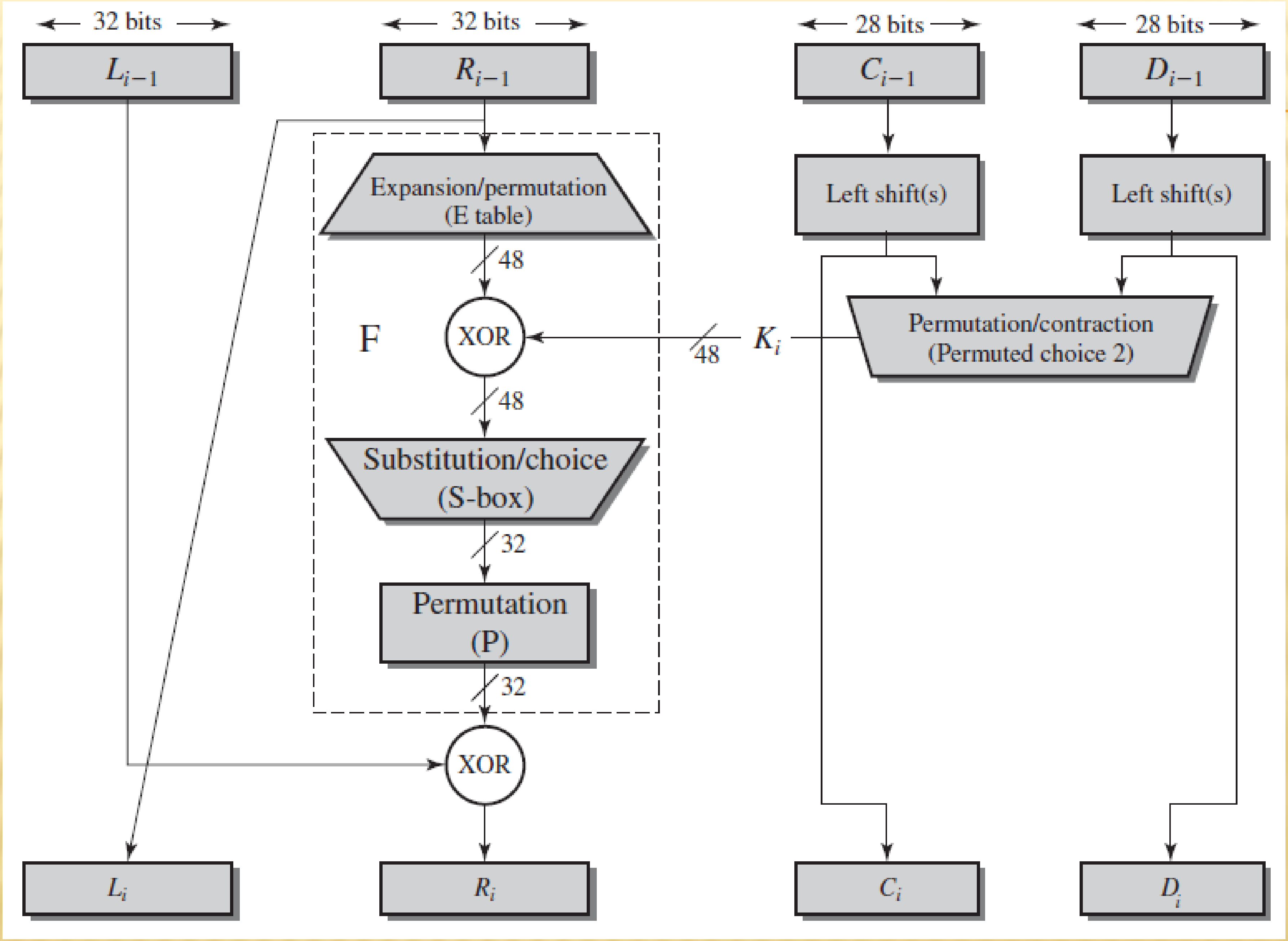
```
IP(675a6967 5e5a6b5a) = (ffb2194d 004df6fb)
```

- Uses two 32-bit L & R halves

  $L_i = R_{i-1}$

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

- 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

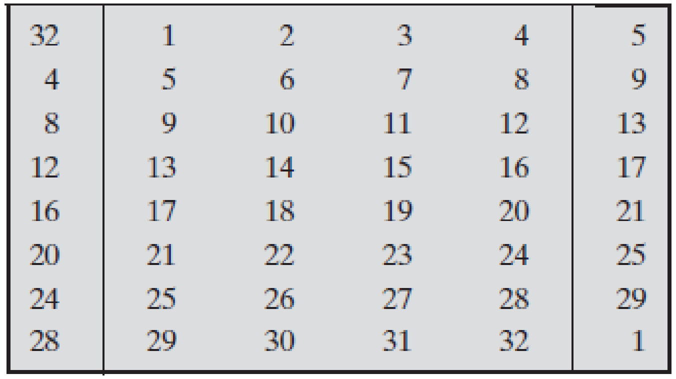

32 bits
32 bits
28 bits
28 bits
L_{i-1}
R_{i-1}
C_{i-1}
D_{i-1}
Expansion/permutation (E table)
Left shift(s)
Left shift(s)
48
F
XOR
48
K_i
Permutation/contraction (Permuted choice 2)
48
Substitution/choice (S-box)
32
Permutation (P)
32
XOR
L_i
R_i
C_i
D_i

DES SINGLE ROUND ALGORITHM

The round key K_i is 48 bits.   The R input is 32 bits.

The internal structure of the DES round function F. The R input is first expanded to 48 bits by using expansion table E that defines a permutation plus an expansion that involves duplication of 16 of the R bits.

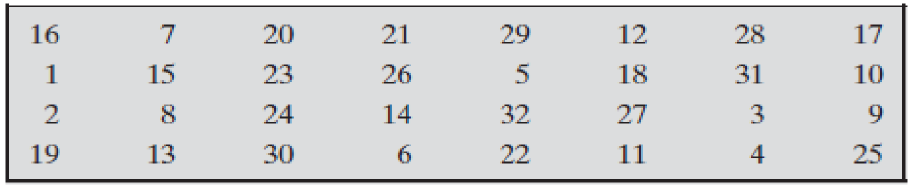
(c) Expansion Permutation (E)



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

The resulting 48 bits are XORed with key K_i . This 48-bit result passes through a substitution function comprising 8 S-boxes which each map 6 input bits to 4 output bits, producing a 32-bit output, which is then permuted by permutation P.

(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

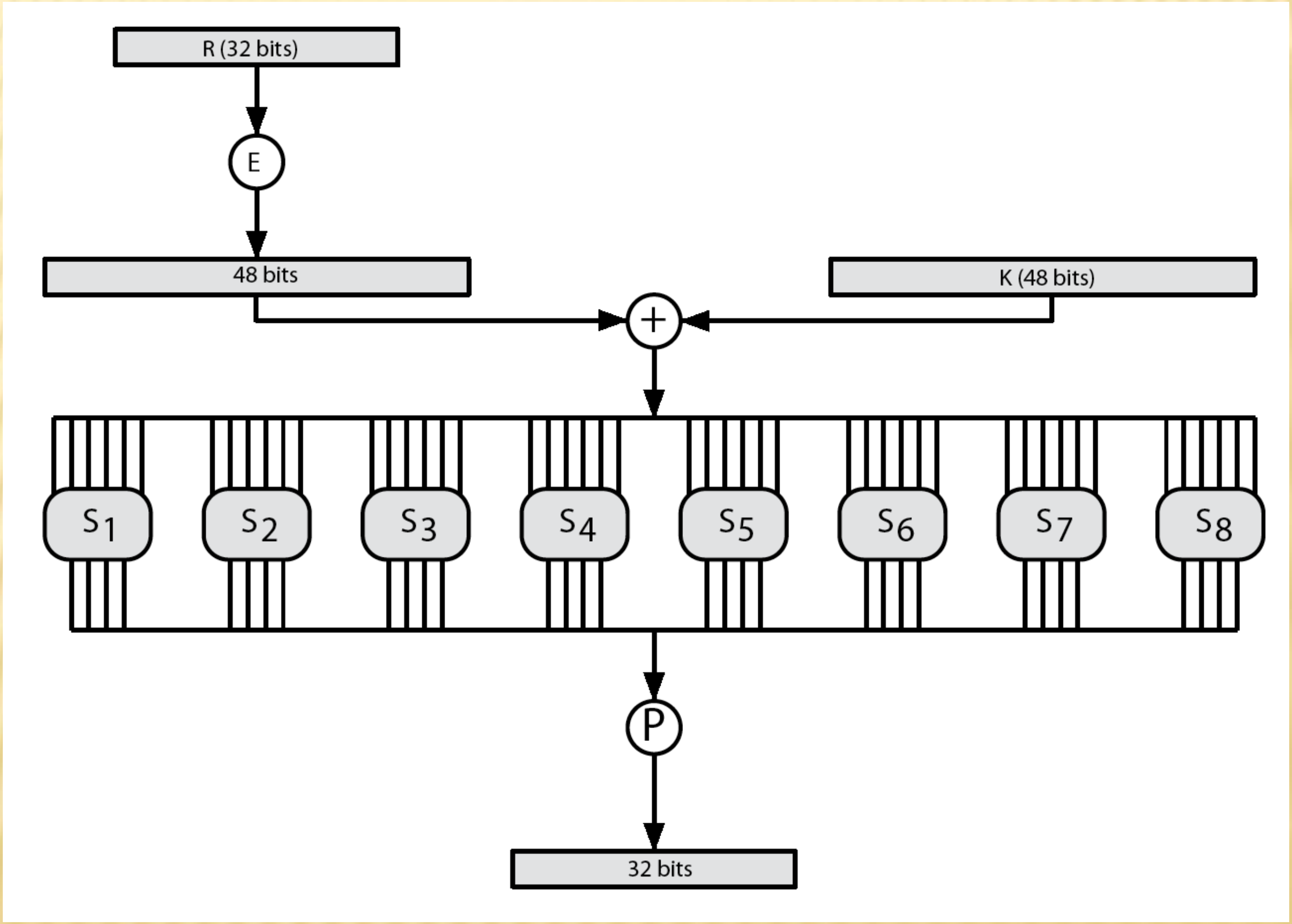
s-boxes provide the “confusion” of data and key values, so each S-box output affects as many S-box inputs in the next round as possible, giving “diffusion”.

SUBSTITUTION BOXES S

- Eight S-boxes which map 6 input to 4 bits out
- each S-box is actually 4 little 4 bit boxes
  - outer bits 1 & 6 (**row** bits) select one row of 4
  - inner bits 2-5 (**col** bits) are substituted
  - result is 8 lots of 4 bits, or 32 bits
- row selection depends on both data & key
  - feature known as autoclaving (autokeying)
- example:

```
S(18 09 12 3d 11 17 38 39) = 5fd25e03
```

DES ROUND STRUCTURE



Discussion: Table 3.3

- The substitution consists of a set of eight S-boxes, each of which accepts 6 bits as input and produces 4 bits as output.

- Table 3.3:
  - The first and last bits of the input to box S*i* form a 2-bit binary number to select one of four substitutions defined by the four rows in the table for S*i*.
  - The middle four bits select one of the sixteen columns. The decimal value in the cell selected by the row and column is then converted to its 4-bit representation to produce the output. For example, in S1, for input 011001, the row is 01 (row 1) and the column is 1100 (column 12). The value in row 1, column 12 is 9, so the output is 1001.

- The example lists 8 6-bit values (ie 18 in hex is 011000 in binary, 09 hex is 001001 binary, 12 hex is 010010 binary, 3d hex is 111101 binary etc), each of which is replaced following the process detailed above using the appropriate S-box. ie
  - S1(011000) lookup row 00 col 1100 in S1 to get 5
  - S2(001001) lookup row 01 col 0100 in S2 to get 15 = f in hex
  - S3(010010) lookup row 00 col 1001 in S3 to get 13 = d in hex
  - S4(111101) lookup row 11 col 1110 in S4 to get 2 etc

DES KEY SCHEDULE

- forms subkeys used in each round
  - Initial permutation of the key (PC1) which selects 56-bits 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 by PC2 for use in round function F
- note practical use issues in h/w vs s/w

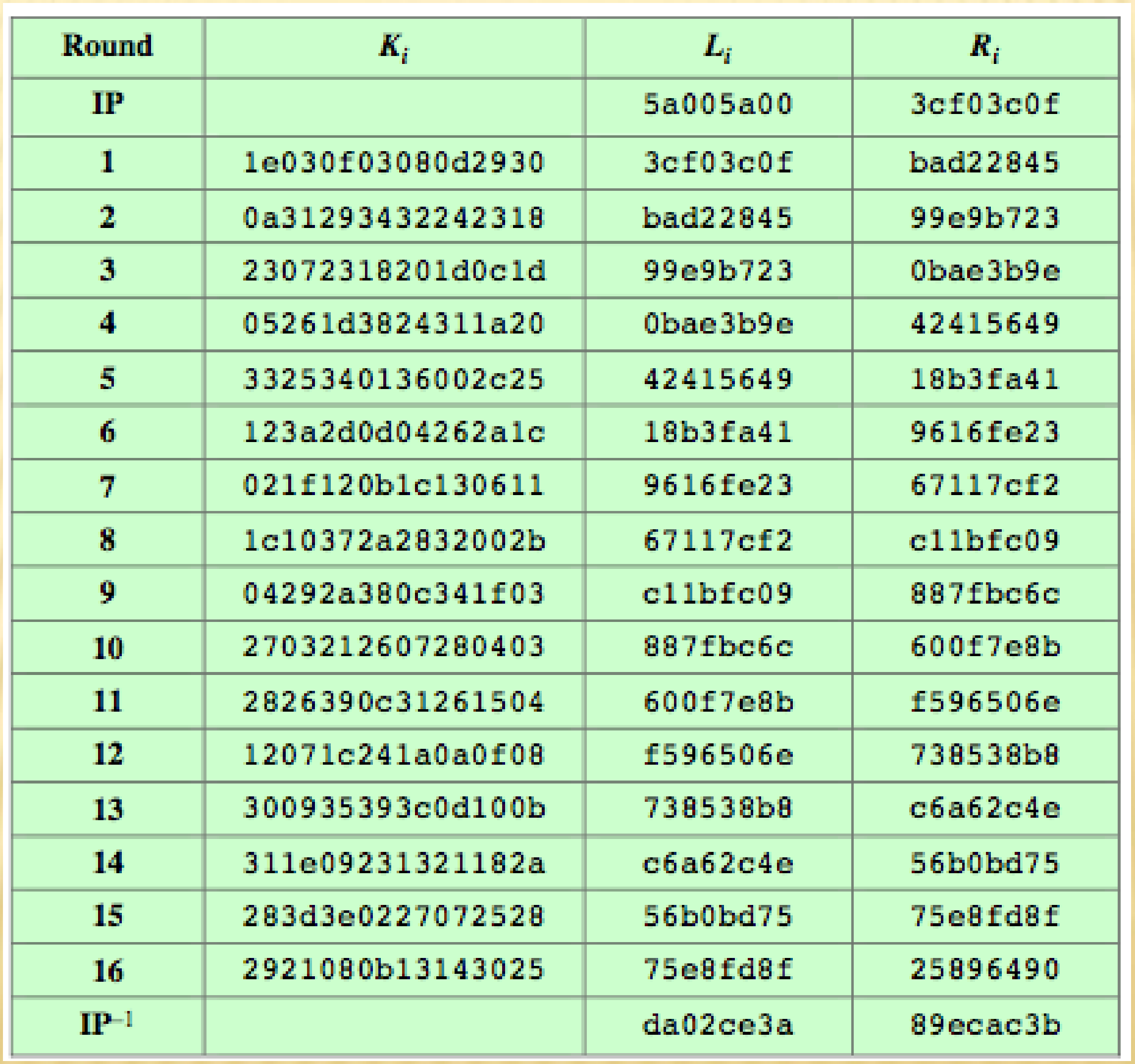
DISCUSSION

- The DES Key Schedule generates the subkeys needed for each data encryption round. A 64-bit key is used as input to the algorithm, though every eighth bit is ignored, as indicated by the lack of shading in Table 3.4a. It is first processed by Permuted Choice One (Stallings Table 3.4b). The resulting 56-bit key is then treated as two 28-bit quantities C & D. In each round, these are separately processed through a circular left shift (rotation) of 1 or 2 bits as shown in Stallings Table 3.4d. These shifted values serve as input to the next round of the key schedule. They also serve as input to Permuted Choice Two (Stallings Table 3.4c), which produces a 48-bit output that serves as input to the round function F.
- The 56 bit key size comes from security considerations as we know now. It was big enough so that an exhaustive key search was about as hard as the best direct attack (a form of differential cryptanalysis called a T-attack, known by the IBM & NSA researchers), but no bigger. The extra 8 bits were then used as parity (error detecting) bits, which makes sense given the original design use for hardware communications links. However we hit an incompatibility with simple s/w implementations since the top bit in each byte is 0 (since ASCII only uses 7 bits), but the DES key schedule throws away the bottom bit! A good implementation needs to be cleverer!

DES DECRYPTION

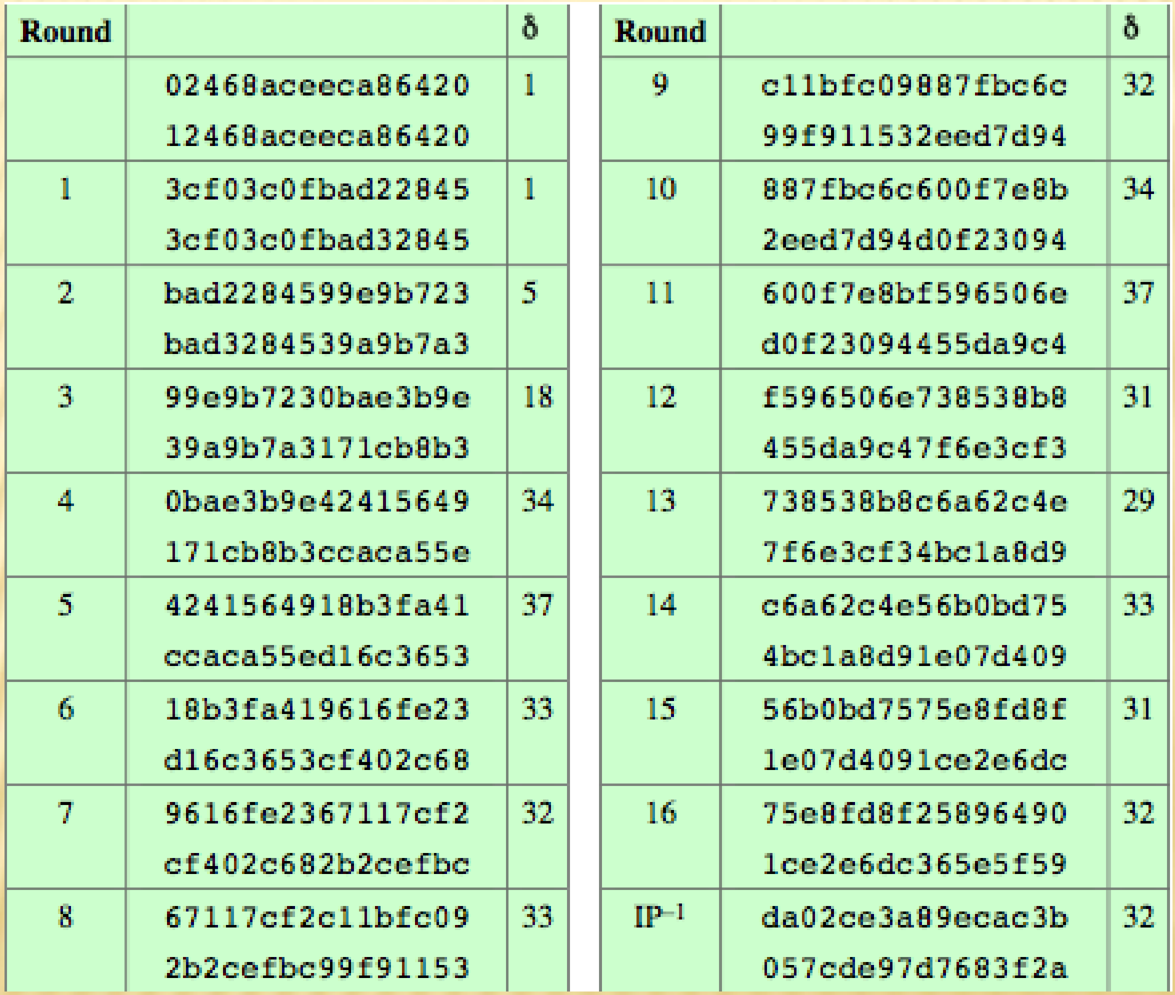
- decrypt must unwind steps of data computation
- with Feistel design, do encryption steps again using subkeys in reverse order (SK16 … SK1)
  - IP undoes final FP step of encryption
  - 1st round with SK16 undoes 16th encrypt round
  - ….
  - 16th round with SK1 undoes 1st encrypt round
  - then final FP undoes initial encryption IP
  - thus recovering original data value

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

AVALANCHE IN DES



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

- key desirable property of encryption alg
- where a change of **one** input or key bit results in changing approx **half** output bits
- making attempts to “home-in” by guessing keys impossible
- DES exhibits strong avalanche

STRENGTH OF DES – KEY SIZE

- 56-bit keys have $2^{56} = 7.2 \times 10^{16}$ values
- brute force search looks hard
- recent advances have shown is possible
  - in 1997 on Internet in a few months
  - in 1998 on dedicated h/w (EFF) in a few days
  - in 1999 above combined in 22hrs!
- still must be able to recognize plaintext
- must now consider alternatives to DES