

# Block Ciphers and Data Encryption Standard

CSS 322 - Security and Cryptography

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- Block Cipher Principles
- Feistel Structure for Block Ciphers
- DES
  - Simplified DES
  - Real DES
- DES Design Issues

# Block and Stream Ciphers

- Block cipher
  - Encryption algorithm is applied on a fixed size block of information
    - If block too short (e.g. 8 bits) then easy to break if obtain some plaintext, ciphertext pairs
    - If block too long, too complex and inefficient performance
    - Typical size is 64 bits
  - But messages are not usually 64 bits!
    - Block cipher modes (another lecture) allow block encryption algorithm to be applied to many 64 bit blocks
- Stream cipher
  - Encrypt a bit at a time
  - Useful for operating in real-time applications

# Ideal Block Ciphers

- Operates on plaintext block of  $n$  bits
- Produces ciphertext block of  $n$  bits
- $2^n$  different plaintext blocks
  - In order to do decryption, each plaintext must produce unique ciphertext, i.e. must be reversible

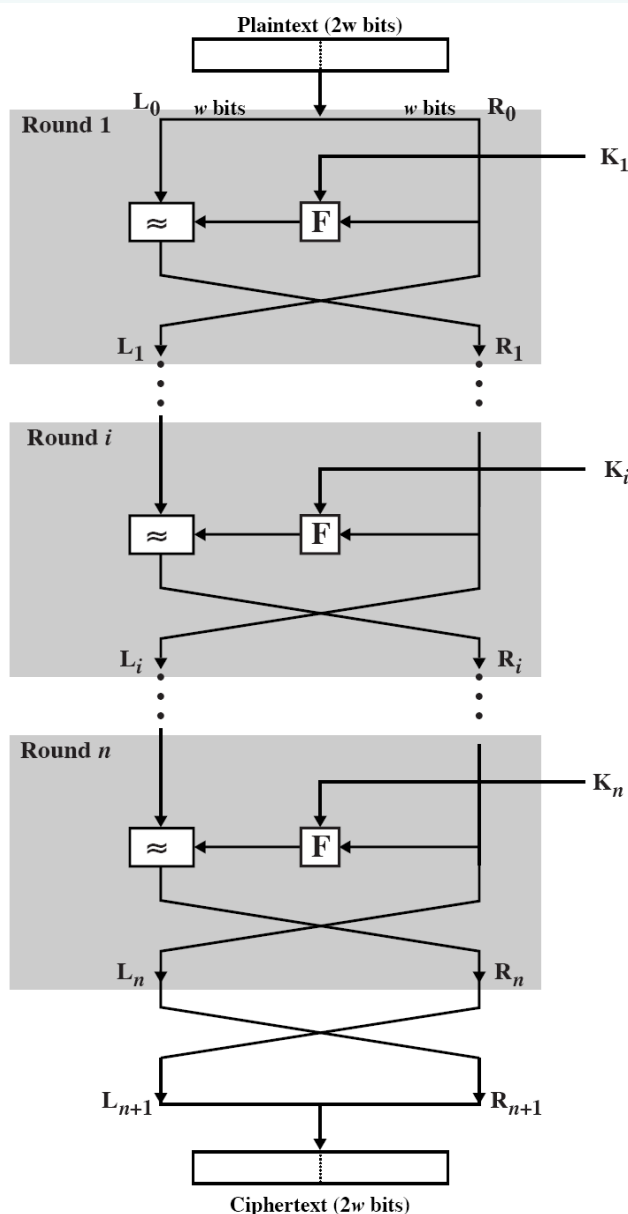
Reversible Mapping		Irreversible Mapping	
Plaintext	Ciphertext	Plaintext	Ciphertext
00	11	00	11
01	10	01	10
10	00	10	01
11	01	11	01

- A  $n$ -bit input maps to  $2^n$  possible input states, the substitution is used to produce  $2^n$  output states, and then mapped to  $n$ -bit output
- But:
  - If  $n$  is small, easy to use statistical analysis of letters etc.
  - If  $n$  is large, then implementation and performance is too complex

# Feistel Structure for Block Ciphers

- In 1975 Feistel proposed a generic cipher that approximates ideal block cipher, but easier to implement
  - Execute two or more simple ciphers in sequence, so that result is cryptographically stronger than the simple ciphers
  - The cipher alternates substitutions and permutations
- Based on concepts of:
  - **Diffusion**: statistical nature of plaintext is reduced in ciphertext, e.g. a plaintext letter affects the value of many ciphertext letters
  - **Confusion**: Make relationship between ciphertext and key as complex as possible, e.g. a complex substitution algorithm

# Feistel Structure



- Plaintext split into halves
- Subkeys generated from Key
- Apply a round function (F) to right half
  - Subkey is parameter
- Apply substitution on left half by XOR with output of F
- Apply permutation by interchanging the halves
- Repeat rounds
- Final output of left and right halves is the ciphertext

# Using the Feistel Structure

- The exact implementation of algorithm based on Feistel structure depends on:
  - Block size: typical is 64 bits (AES uses 128 bits)
    - Larger value leads to more diffusion
  - Key size: 128 bits is common
    - Larger value leads to more confusion and resistance against brute-force attacks
  - Number of rounds: one round is insecure; 16 rounds is common
  - Subkey generation algorithm: should be complex!
  - Round function: should be complex!
- The above have tradeoffs between security and performance
  - More complex and larger leads to lower performance

# Data Encryption Standard

- Symmetric block cipher
  - 56-bit key
  - 64-bit input block
  - 64-bit output block
- One of most used encryption systems in world
- Principles used in DES are used in other systems as well (e.g. 3DES, IDEA)
- We will go through details of operation
  - But first will use Simplified DES as an example of main concepts
  - Note Simplified DES is not used in real world, only developed to help explain DES to students

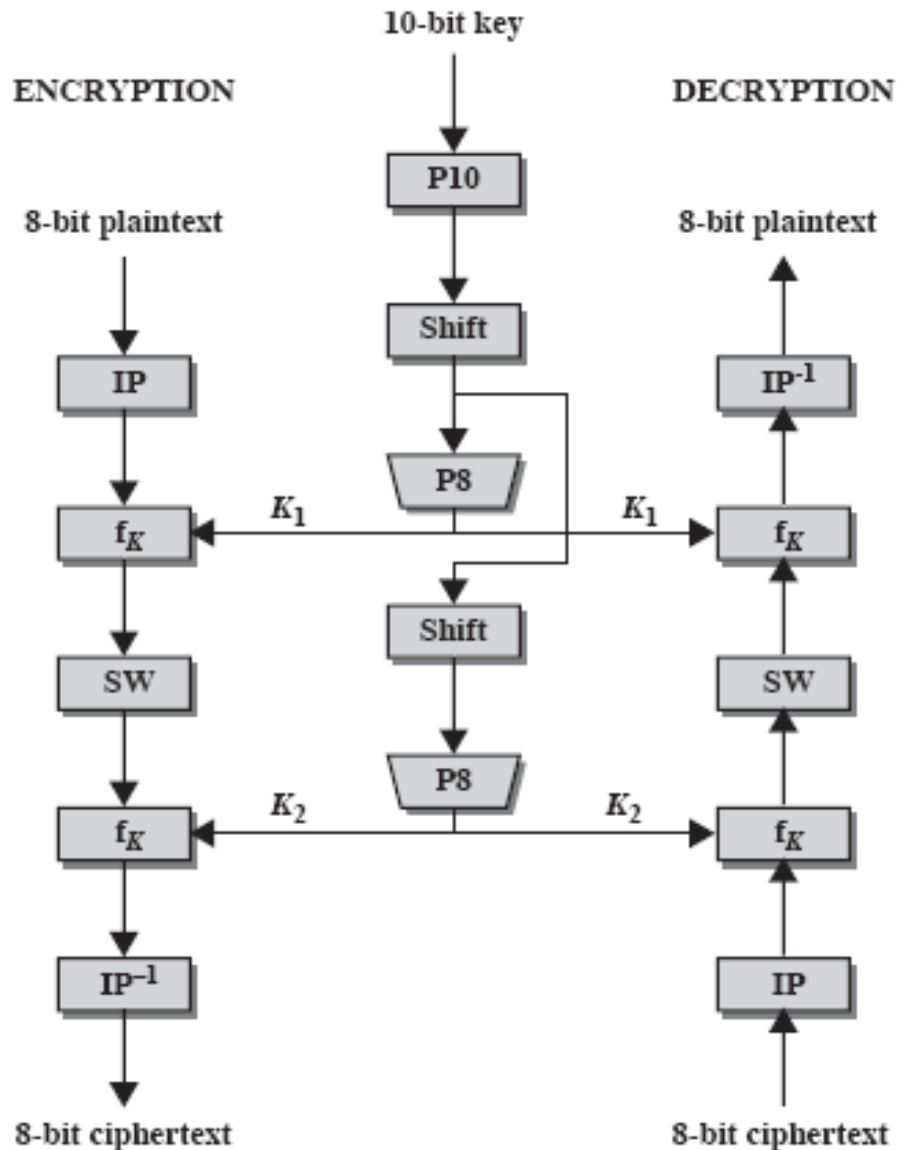


# History of DES

- Published as standard by National Institute of Standards and Technology (NIST) in 1977 (NIST was NBS)
- Designed by IBM (based on Lucifer) with input from NSA
- Why 56-bit key?
  - Actually 64 bits but 8 bits used for parity (error check)
  - Critics suggest 56-bits was just weak enough for NSA to break
- Efficient to implement in hardware, was slow in software
  - Allow more control on implementation and distribution
  - Now feasible to implement in software
- Lack of insight into design of S-Boxes; critics believed NSA may know vulnerabilities so can break DES
- In 1999, NIST recommended Triple DES be used for new systems (DES only for legacy systems)

# Simplified DES (S-DES)

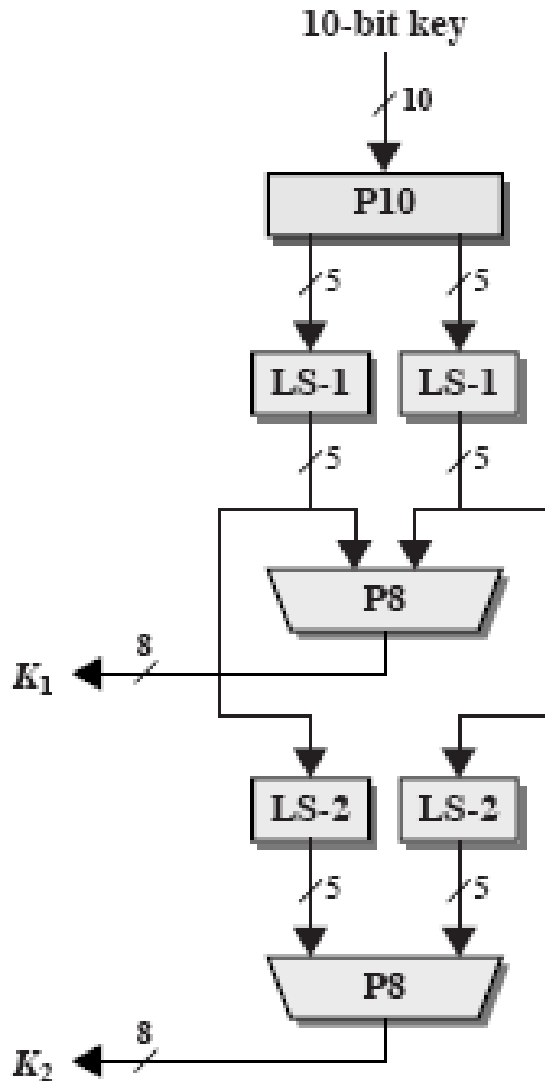
- Plaintext: 8-bit block
- Key: 10-bits
- Ciphertext: 8-bits
- Encryption steps:
  - Initial permutation (IP)
  - Function  $f_k$
  - Switch (SW) halves of data
  - Final permutation ( $IP^{-1}$ )
- Creating keys:
  - Permutation (P10)
  - Shift bits
  - Permutation (P8)



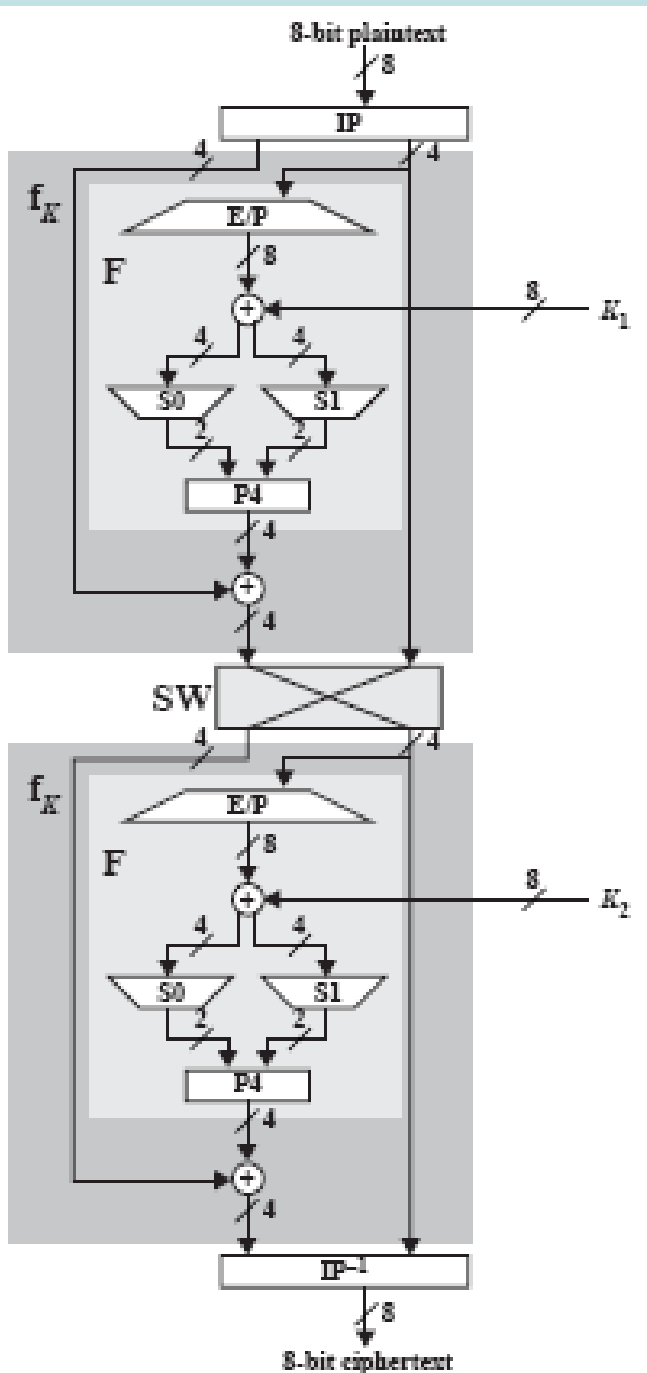
# S-DES Key Generation

- 10-bit key is shared between sender and receiver
- Two 8-bit keys are generated from original 10-bit key and used in encryption and decryption: K1 and K2
  - P10: rearrange bits of 10-bit key  
Input order : 1 2 3 4 5 6 7 8 9 10  
Output order: 3 5 2 7 4 10 1 9 8 6
  - LS1: left shift bits 1 position separately on left and right five bits  
Input order : 1 2 3 4 5 6 7 8 9 10  
Output order: 2 3 4 5 1 7 8 9 10 6
  - P8: pick 8 of 10 bits and re-arrange  
Input order : 1 2 3 4 5 6 7 8 9 10  
Output order: 6 3 7 4 8 5 10 9
  - LS2: left shift bits 2 positions separately on left and right 5 bits  
Input order : 1 2 3 4 5 6 7 8 9 10  
Output order: 3 4 5 1 2 8 9 10 6 7

# S-DES Key Generation



- Example key: 1010000010
- After P10: 1000001100
- After LS1: 00001 11000
- K1 (after P8): 10100100
- After LS2: 00100 00011
- K2 (after P8): 01000011



# S-DES Encryption

- **IP: rearrange 8-bits**  
Output order: 2 6 3 1 4 8 5 7
- **IP<sup>-1</sup>: inverse of IP at end**  
Output order: 4 1 3 5 7 2 8 6
- **SW: Switch left bits with right bits**  
Output order: 5 6 7 8 1 2 3 4
- **Function  $f_k$** 
  - Split input 8 bits into left 4 bits (L) and right 4 bits (R)
  - **E/P: Expand and re-arrange R**  
Output order: 4 1 2 3 2 3 4 1
  - XOR output of E/P with  $K_1$
  - Feed left 4 bits into S-Box S0 and right 4 bits into S-Box S1

# S-Boxes in S-DES

- Each S-Box has a 4 bit input:  $b_1, b_2, b_3, b_4$ 
  - $(b_1, b_4)$  specify the row,  $r$ , of the S-Box
  - $(b_2, b_3)$  specify the column,  $c$ , of the S-Box
  - Output is the entry at  $(r, c)$

$$S_0 = \begin{array}{c} \begin{array}{cccc} & 00 & 01 & 10 & 11 \\ 00 & 01 & 00 & 11 & 10 \\ 01 & 11 & 10 & 01 & 00 \\ 10 & 00 & 10 & 01 & 11 \\ 11 & 11 & 01 & 11 & 10 \end{array} \end{array}$$

$$S_1 = \begin{array}{c} \begin{array}{cccc} & 00 & 01 & 10 & 11 \\ 00 & 00 & 01 & 10 & 11 \\ 01 & 10 & 00 & 01 & 11 \\ 10 & 11 & 00 & 01 & 00 \\ 11 & 10 & 01 & 00 & 11 \end{array} \end{array}$$

- The 4 bits produced by  $S_0$  and  $S_1$  are re-arranged (P4):

Output order: 2 4 3 1

# S-DES Encryption and Decryption

- The output of  $f_k$  is the XOR of L and output of P4
- The output of  $f_k$  and R are input to the switch SW
- Then repeat the entire process but with key  $K_2$
- Finally the output is input to  $IP^{-1}$ , producing the 8-bit ciphertext
- Decryption:
  - Follow same steps as encryption except use  $K_2$  first, and then  $K_1$

# Summary of S-DES

- Educational encryption algorithm

- S-DES expressed as functions:

$$ciphertext = IP^{-1}\left(f_{K_2}\left(SW\left(f_{K_1}\left(IP(plaintext)\right)\right)\right)\right)$$

$$plaintext = IP^{-1}\left(f_{K_1}\left(SW\left(f_{K_2}\left(IP(ciphertext)\right)\right)\right)\right)$$

- Security of S-DES

- 10-bit key, 1024 keys – easy to try every key and analyse plaintext
- If know plaintext and corresponding ciphertext, can we determine the key?
  - Very hard!



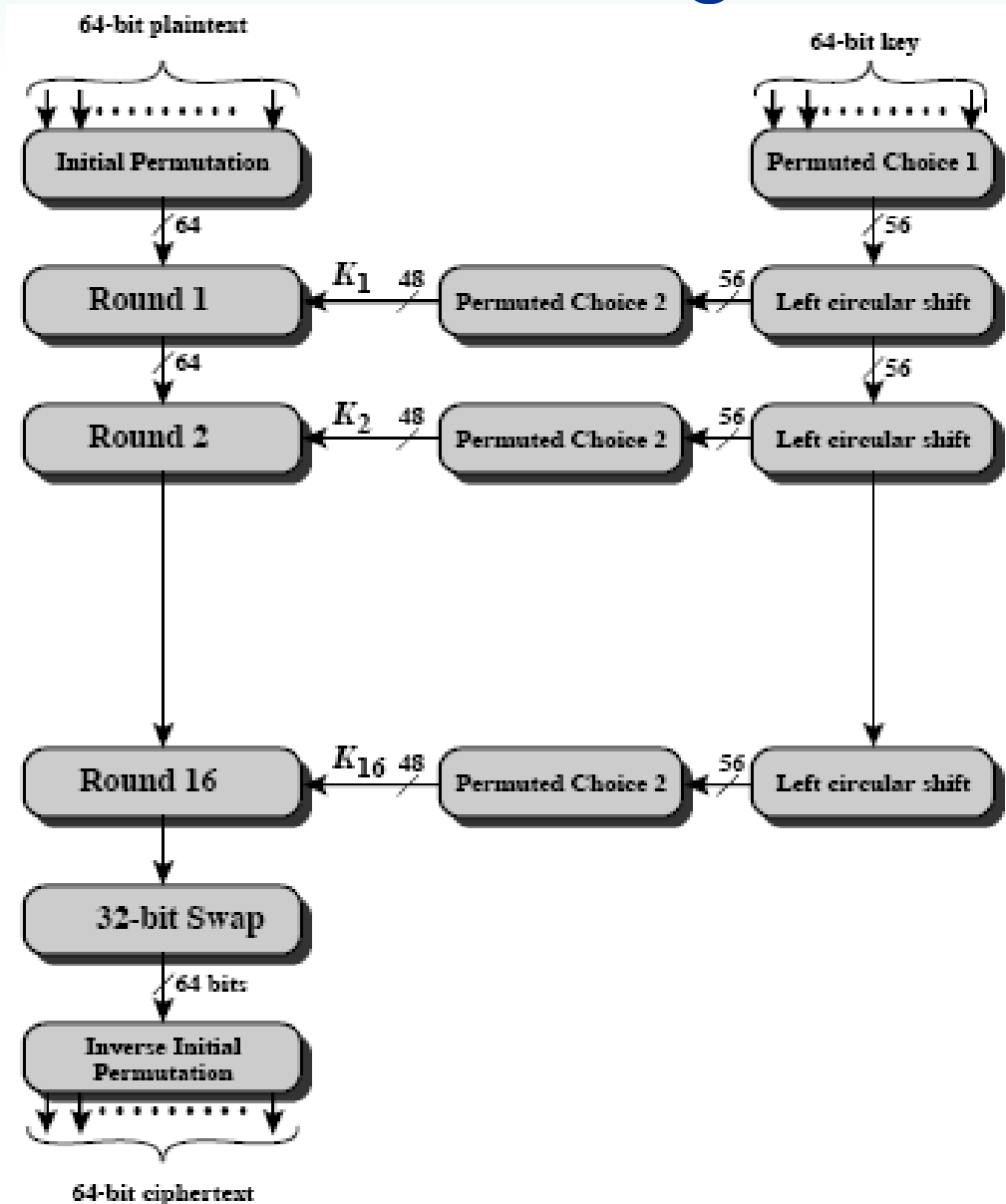
# Comparing DES and S-DES

- |  |   |
|--|---|
| <ul style="list-style-type: none"> <li>• DES</li> <li>• Operates on 64-bit blocks</li> <li>• 56-bit key used             <ul style="list-style-type: none"> <li>– 16 x 48-bit keys are calculated from this 56-bit key</li> </ul> </li> <li>• Initial Permutation, IP of 64 bits</li> <li>• F acts on 32 bits</li> <li>• 8 S-Boxes</li> <li>• 16 rounds</li> </ul> | <ul style="list-style-type: none"> <li>• S-DES</li> <li>• Operates on 8-bits</li> <li>• 10-bit key             <ul style="list-style-type: none"> <li>– 2 x 8-bit keys are calculated from 10-bit key</li> </ul> </li> <li>• IP of 8 bits</li> <li>• F acts on 4 bits</li> <li>• 2 S-Boxes</li> <li>• 2 rounds</li> </ul> |
|--|---|

S-DES 
$$ciphertext = IP^{-1} \left( f_{K_2} \left( SW \left( f_{K_1} \left( IP(plaintext) \right) \right) \right) \right)$$

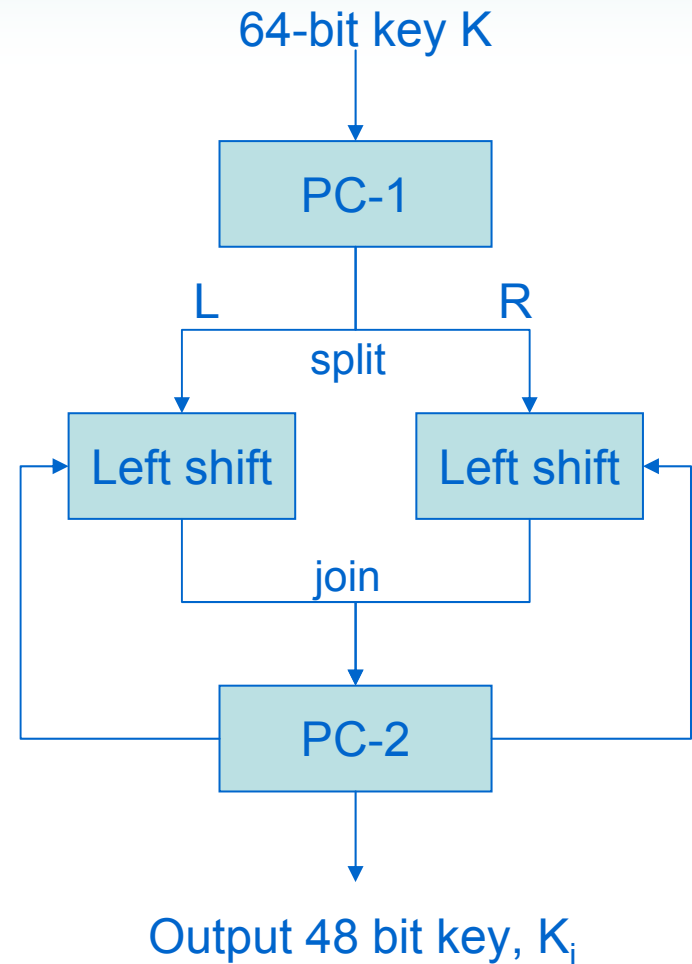
DES 
$$ciphertext = IP^{-1} \left( f_{K_{16}} \left( SW \left( f_{K_{15}} \left( SW \left( \dots \left( SW \left( f_{K_1} \left( IP(plaintext) \right) \right) \right) \right) \right) \right) \right) \right)$$

# Generic DES Algorithm



# DES Key Generation

- Map 64-bit original key (K) to 56-bits (ignore every 8<sup>th</sup> bit which is used for parity check)
- Re-arrange bits according to PC-1, and split into two halves, L and R
  - E.g. bit 1 of L will be the 57<sup>th</sup> bit of K, bit 1 of R will be 63<sup>rd</sup> bit of K
- Apply left shift either 1 or 2 positions (according to round)
- Join and apply PC-2 to produce output key,  $K_i$
- Put Split  $K_i$  and use as input to left shifts for next round



# 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)

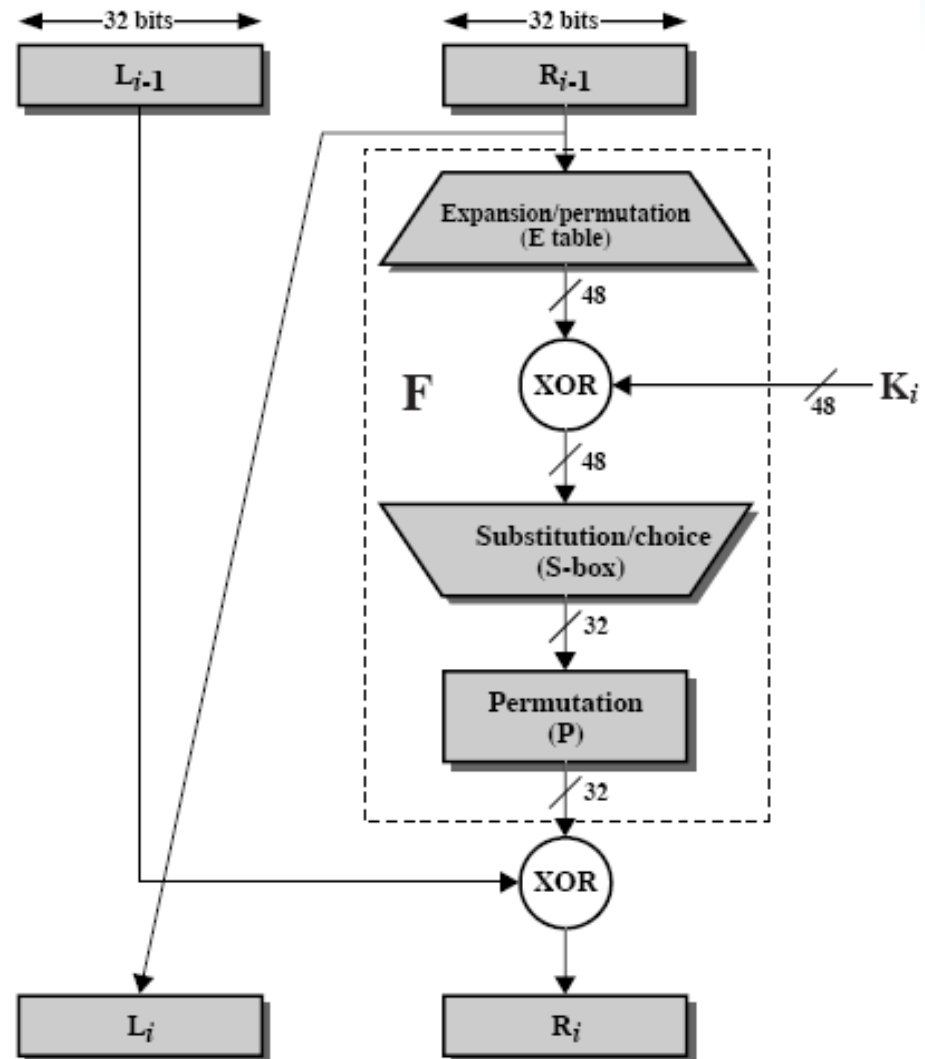
14	17	11	24	1	5	3	28
15	6	21	10	23	19	12	4
26	8	16	7	27	20	13	2
41	52	31	37	47	55	30	40
51	45	33	48	44	49	39	56
34	53	46	42	50	36	29	32

(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

# Single Round of DES

- Split 56-bit block into L and R
- Expand R to 48 bits and permute (re-arrange) using E
- XOR E with  $K_i$
- Split into 8 x 6-bit values and input into 8 S-Boxes
- Join S-Box outputs and permute using P, then XOR with L to produce output of R'
- $L' = R$
- Move to next round using  $L'$  and  $R'$  as input



# DES Permutations

(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

(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

(b) Inverse Initial Permutation (IP<sup>-1</sup>)

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

(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

# DES S-Boxes 1-4

$S_1$

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

# DES S-Boxes 5-8

$S_5$

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



# Some Design Issues with DES

- Avalanche Effect

- Aim: small change in plaintext or key produces large change in ciphertext
- DES achieves this quite well
- Table shows change in ciphertext bits after each round
- Plaintext differ by 1 bit
- Keys differ by 1 bit
- Both cases the output ciphertext differs by more than 30 bits

(a) Change in Plaintext		(b) Change in Key	
Round	Number of bits that differ	Round	Number of bits that differ
0	1	0	0
1	6	1	2
2	21	2	14
3	35	3	28
4	39	4	32
5	34	5	30
6	32	6	32
7	31	7	35
8	29	8	34
9	42	9	40
10	44	10	38
11	32	11	31
12	30	12	33
13	30	13	28
14	26	14	26
15	29	15	34
16	34	16	35

# Some Design Issues with DES

- Initial/Final Permutation (IP and  $IP^{-1}$ ) – why?
  - The initial permutations have no security value
  - The original algorithm that DES was based on did not have these permutations
  - Possible reason for IP: make DES less efficient to implement in software (no longer relevant; software implementations now feasible)
- 56-bit keys,
  - 1 decryption per  $\mu s$ : 1142 years
  - In 1977, estimated cost \$US20m to build machine to break it in 10 hours
  - In 1988, EFF built machine for \$250k that broke DES in 3 days
  - Remember: key searches require ability to identify the plaintext (not so easy in some cases)
  - Triple DES (3DES) uses 128-bit keys

# Some Design Issues with DES

- S-Boxes: why are they designed as they are?
  - How did designers chose the S-Boxes?
    - DES was a closed design process in 1970's. Why? One reason is so designers did not divulge information about known attacks
  - Experience has shown that it looks like a good design (no one has found flaws)
    - Experiments have shown that simple changes (eg. Swap S-Box 3 with S-Box 7) and DES becomes much weaker
  - A lot of research has been conducted on S-Box design and there are some general principles that should be followed