CS458/CS558 Introduction to Computer Security

Transposition Ciphers

- Consider classical transposition or permutation ciphers
- Hide the message by rearranging the letter order without altering the actual letters used

Rail Fence cipher

- Write message letters out diagonally over a number of rows
- Then read the letters row by row
- Encrypt the message "meet me after the toga party" with a rail fence of depth 2

```
m e m a t r h t g p r y
 e t e f e t e o a a t
```

Ciphertext: MEMATRHTGPRYETEFETEOAAT

- Think: how to encrypt the above message using rail fence cipher of depth 3?

Rail Fence cipher

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```
m   t   a   e   h   o   p   t
 e   m   f   r   e   g   a   y
   e   e   t   t   t   a   r
```

Ciphertext: MTAEHOPTEMFREGAYEETTTAR

- How to decrypt a ciphertext with 3 rows?

ciphertext: CPEERYOURCIMTSUT

Rail Fence cipher: Decryption

- Example:

ciphertext: **CPEERYOURCIMTSUT**

|row| = 3

- **|cipher| = 16**
- **16/3= 5, 16 mod 3 = 1 ➔**

1st row: 5+1 = 6 letters

2nd row: 5 letters, 3rd row: 5 letters

```
C P E E R Y
 O U R C I
  M T S U T
```

➔ Plaintext: **computersecurity**

Rail Fence cipher: Decryption

- How to decrypt a ciphertext
  - Let |**row**| be the number of rows
  - Compute the length of the ciphertext |**cipher**|
  - Compute the number of letters of each row
  - Write down the ciphertext row by row
  - Read the ciphertext diagonally

Row Transposition Ciphers

- A more complex transposition
- Write letters of message out in rows over a specified number of columns
- Then reorder the columns according to some key before reading off the rows

Read the 3rd column

```
Key:        3 4 2 1 5 6 7
Plaintext:  a t t a c k p
            o s t p o n e
            d u n t i l t
            w o a m x y z
Ciphertext:
TTNAAPTMTSUOAODWCOIXKNLYPETZ
```

Row Transposition Ciphers

- A more complex transposition
- Write letters of message out in rows over a specified number of columns
- Then reorder the columns according to some key before reading off the rows

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Plaintext:  a t t a c k p
            o s t p o n e
            d u n t i l t
            w o a m x y z
Ciphertext:TTNAAPTMTSUOAODWCOIXKNLYPETZ
```

- how to decrypt a ciphertext using the above key?
  ciphertext: ATHNIERIPTSISORPNSOCZ

Row Transposition Ciphers: Decryption

- How to decrypt a ciphertext?
  ciphertext: ATHNIERIPTSISORPNSOCZ
  - |cipher| = 21, |key| = 7 → |row| = 3

```
Key:         3 4 2 1 5 6 7
Ciphertext:  T R A N S P O
             S I T I O N C
             I P H E R S Z
Plaintext:  transpositionciphers
```

Product Ciphers

- Ciphers using substitutions or transpositions are not secure because of language characteristics
- Hence consider using several ciphers in succession to make harder
  - Two substitutions make a more complex substitution
  - Two transpositions make a more complex transposition
  - But a substitution followed by a transposition makes a much harder cipher
    - This is bridge from classical to modern ciphers

Chapter 3
Block Ciphers and the Data Encryption Standard (DES)

Block Ciphers

- Block ciphers: 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
  - Many current ciphers are block ciphers
  - Broader range of applications
  - DES (Data Encryption Standard): one of the most widely used cryptographic algorithms, especially in financial applications.

Block Cipher Principles

- A block cipher operates on a plaintext block of n bits to produce a ciphertext block of n bits.
- There are possible different plaintext blocks.

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- There are 2^n possible different plaintext blocks
- For the encryption to be reversible (for decryption to be possible), each must produce a unique ciphertext block
- Reversible:

Plaintext	Ciphertext
00	11
01	10
10	00
11	01

Block Cipher Principles

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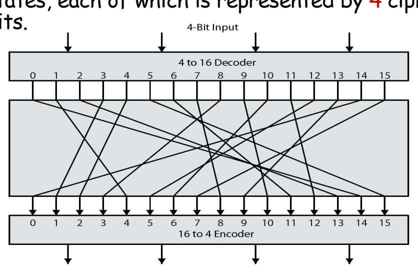
- There are 2^n possible different plaintext blocks,
- for the encryption to be reversible (for decryption to be possible), each must produce a unique ciphertext black
- Irreversible:

Plaintext	Ciphertext
00	11
01	10
10	00
11	00

Ideal Block Cipher

- The logic of a general substitution cipher for n=4
  - A 4-bit input produces one of 16 possible input states, which is mapped into a unique one of 16 possible output states, each of which is represented by 4 ciphertext bits.



Ideal Block Cipher

- Ideal block cipher: allows for maximum number of possible encryption mappings from the plaintext block.
  - n bits → possible mappings

Ideal Block Cipher

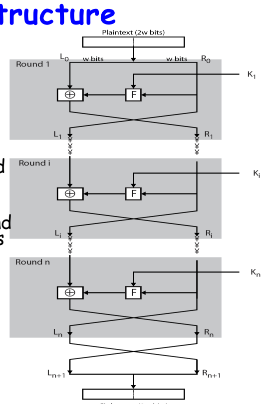
- Ideal block cipher: allows for maximum number of possible encryption mappings from the plaintext block.
  - n bits ➔ $2^n!$ possible mappings
  - Impractical when n is large
    - Each mapping constitutes a key
    - n=64 ➔ the key size is > $63*2^{63}$ -- not practical.

The Feistel Cipher

- The Feistel cipher: approximate the ideal block cipher by utilizing the concept of a product cipher
  - Develop a block cipher with a key length of k bits and a block length of n bits, allowing a total of 2^k possible mappings (rather than $2^n!$ Mappings)
  - Alternates substitution and permutation
- Most symmetric block ciphers are based on a Feistel Cipher Structure

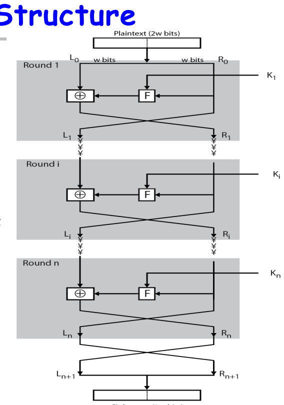
Feistel Cipher Structure

- Inputs: a plaintext block of length 2w bits and a key K.
- The plaintext block is divided into two halves L_0, R_0
  - Pass through n rounds of processing and then combined to produce the ciphertext block
  - Each round i has inputs L_{i-1} and R_{i-1} derived from the previous round, as well as a subkey K_i derived from K.
  - In general, K_i are different from K and from each other.



Feistel Cipher Structure

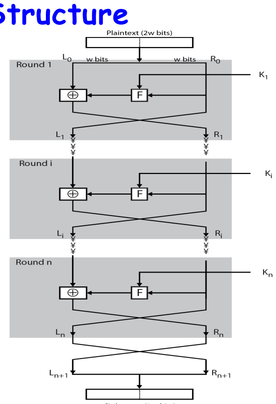
- A substitution is applied to the left half
  - Applying a round function F to the right half of the data. F is parameterized by the round subkey K_i
  - Then take the exclusive-OR (XOR) of the output of F and the left half of the data.
- A permutation is then performed that exchanges the two halves of the data.



Feistel Cipher Structure

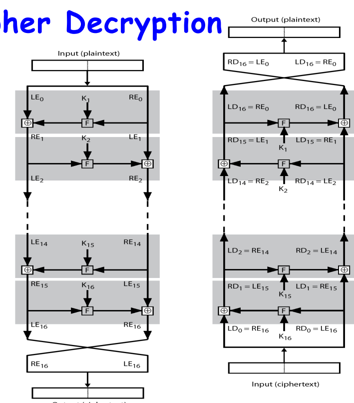
$$L_i = R_{i-1}$$

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



Feistel Cipher Decryption

- Same as the encryption process
- Except that the subkeys K_i are used in reverse order: K_n in the first round,..., k_1 in the last round.



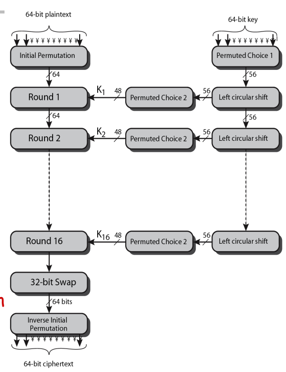
Data Encryption Standard (DES)

Data Encryption Standard (DES)

- Most widely used block cipher in world
- Developed in 1974 by IBM and the U.S. government
- The algorithm transforms 64-bit input in a series of steps into a 64-bit output.
- The same steps, with the same key, are used to reverse the encryption.
- Use of DES has flourished, especially in financial applications

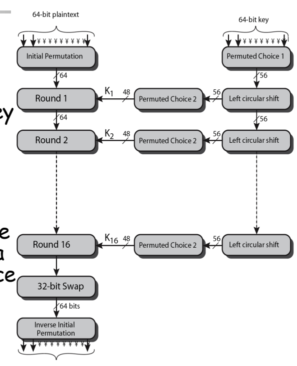
DES Encryption Overview

- The plaintext passes through an initial permutation (IP) that rearranges the bits to produce the permuted input
- Then passes through 16 rounds of the same function, which involves both permutation and substitution function
- The left and right halves of the output of the last round are swapped, which is then passed through a permutation that is the inverse of IP to produce the 64-bit ciphertext



DES Encryption Overview

- 64-bit key is passed through a permutation function.
- For each 16 round, a subkey K_i is produced by the combination of a left circular shift and a permutation.
- Permutation function is the same for each round, but a different subkey is produce because of the repeated shifts of key bits



Initial Permutation (IP)

Input:

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_{34}	M_{35}	M_{36}	M_{37}	M_{38}
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}

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 (IP)

Output:

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

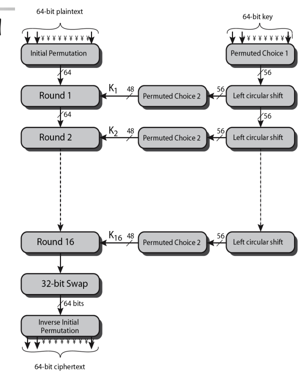
Example

Input: 00100….0

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

DES Encryption Overview

- The 64-bit key is passed through a permutation function.



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

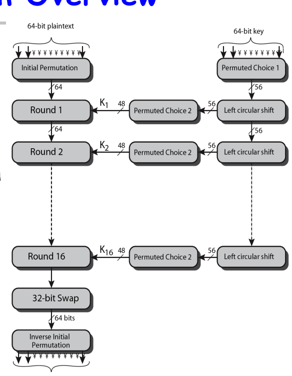
Example

Input: 00100001….0

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 Encryption Overview

- For each 16 round, a subkey K_i is produced by the combination of a left circular shift and a permutation.
- The permutation function is the same for each round, but a different subkey is produce because of the repeated shifts of the key bits



Schedule of Left Circular Shifts

- The output of PC-1 is then treated as two 28 bits quantities, labeled C_1 and D_1.
- At each round, C_i and D_i are separately subjected to a circular left shift, of 1 or 2 bits.

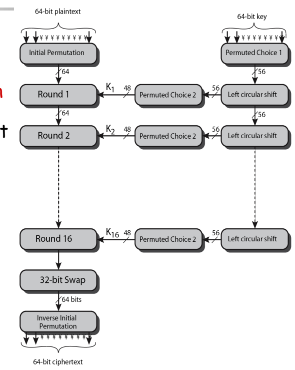
Round number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Bits rotated	1	1	2	2	2	2	2	2	1	2	2	2	2	2	2	1

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

DES Encryption Overview

- The left and right halves of the output of the last round are swapped, which is then passed through a permutation that is the inverse of IP to produce the 64-bit ciphertext
  - $IP^{-1}(IP(M)) = M$



Inverse Initial Permutation (IP^{-1})

Input:

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}

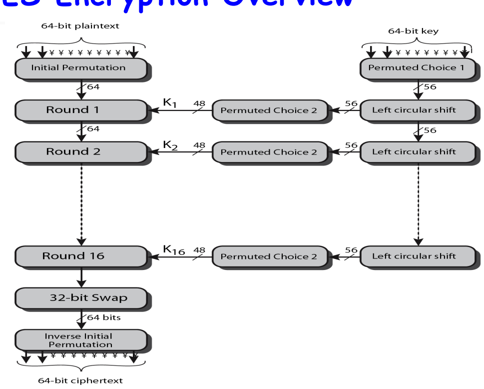
40	8	48	16	56	24	64	32
39	7	47	15	55	23	63	31
38	6	46	14	54	22	62	30
37	5	45	13	53	21	61	29
36	4	44	12	52	20	60	28
35	3	43	11	51	19	59	27
34	2	42	10	50	18	58	26
33	1	41	9	49	17	57	25

Inverse Initial Permutation (IP^{-1})

Output:

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_{34}	M_{35}	M_{36}	M_{37}	M_{38}
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}

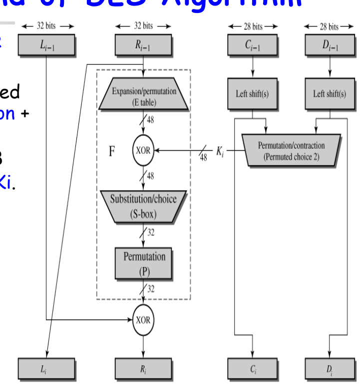
DES Encryption Overview



Single Round of DES Algorithm

- Uses two 32-bit L & R halves. Ki: 48 bits

1. The R input is expanded to 48 bits (permutation + duplication of 16 of R bits); the resulting 48 bits are XORed with Ki.



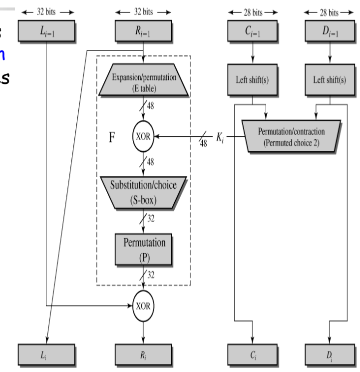
Expanded Permutation (E)

Input: 0011000….0

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

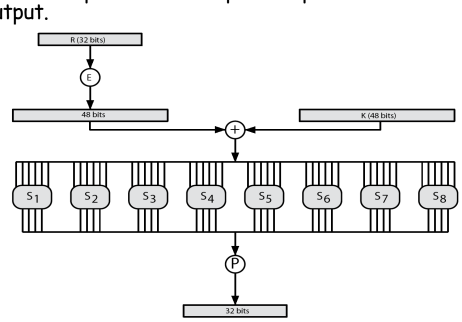
Single Round of DES Algorithm

2. The 48-bits then pass through a substitution function that produces 32-bit output.



S-Boxes

- The substitution consists of a set of 8 S-boxes, each of which accepts 6 bits as input and produces 4 bits as output.



S-Boxes

- The substitution consists of a set of 8 S-boxes, each of which accepts 6 bits as input and produces 4 bits as output.
  - The first and last bits of the input to S_i form a 2-bit binary number to select one of 4 substitutions defined by the four rows (0, 1, 2, 3) in the table for S_i.
  - The middle 4 bits select one of 16 columns (0-15).
  - E.g. in S_1, input 011001

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

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  - The middle 4 bits select one of 16 columns (0-15).
  - E.g. in S_1, input 011001
    - The row is 01 (row 1)
    - The column is 1100 (column 12)
    - The value is 9 – output is 1001.

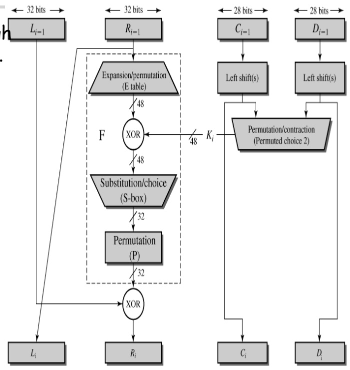
14	4	13	1	2	15	11	8	3	10	6	12	5	9	0	7
0	15	7	4	14	2	13	1	10	6	12	11	9	5	3	8
4	1	14	8	13	6	2	11	15	12	9	7	3	10	5	0
15	12	8	2	4	9	1	7	5	11	3	14	10	0	6	13

S-Box: Design Criteria

- The design of the round function focuses on the design of s-boxes and on the permutation P.
- The design was primarily aimed at thwarting differential cryptanalysis.
  - Any change to the input to an S-box should result in random-looking changes to the output
  - No output bit of any S-box should be too close a linear function of the input bits

Single Round of DES Algorithm

3. The 32-bit pass through a permutation function.



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

- The four output bits from each S-box affect six different S-boxes on the next round.

Expanded Permutation (E)

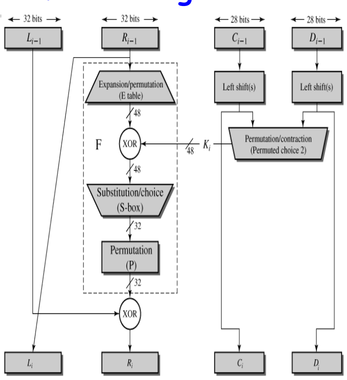
32	1	2	3	4	5
4	5	6	7	8	9
8	9	10	11	12	13
12	13	14	15	16	17
16	[illegible]	18	19	20	21
20	[illegible]	22	23	24	25
24	25	26	27	28	29
28	29	30	31	32	1

Single Round of DES Algorithm

- As for any Feistel cipher,

$L_i = R_{i-1}$

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



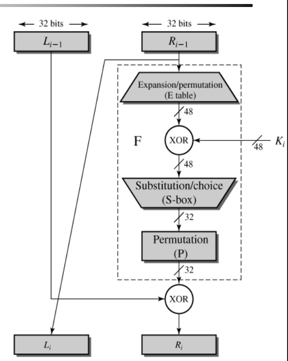
DES Decryption

- As with any Feistel cipher, decryption uses the same algorithm as encryption, except that the application of the subkeys is reversed.

Attacks on 1-Round DES

A Simple Attack on 1-Round DES

- Assumption: the attacker has plaintext-ciphertext Pairs (P1,C1),…,(Pn,Cn)
- Goal: to discover the sub-key K1

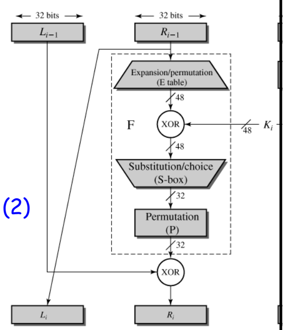


A Simple Attack on 1-Round DES

P1 = (L0, R0)
C1 = (L1, R1)

R0 ➔ output of E table (1)

R1 and L0 ➔
output of P table ➔
output of S-box ➔
4 possible inputs of each S-box (2)



A Simple Attack on 1-Round DES

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

output of P table ➔ output of S-box

E.g. the output of P table: 1010000…0

Output of s1:

A Simple Attack on 1-Round DES

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

output of P table ➔ output of S-box

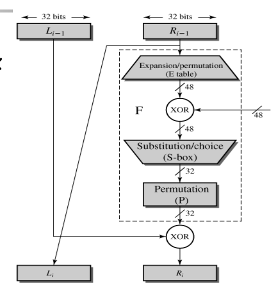
E.g. the output of P table: 1010000…0

Output of s1: (the 16th bit and 20th bit are 1; others are 0)

A Simple Attack on 1-Round DES

output of S-box ➔
4 possible inputs of each S-box

E.g. Output of S1: 0000

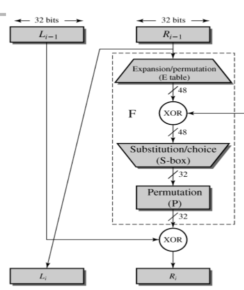


14	4	13	1	2	15	11	8	3	10	6	12	5	9	0	7
0	15	7	4	14	2	13	1	10	6	12	11	9	5	3	8
4	1	14	8	13	6	2	11	15	12	9	7	3	10	5	0
15	12	8	2	4	9	1	7	5	11	3	14	10	0	6	13

A Simple Attack on 1-Round DES

output of S-box ➔
4 possible inputs of each S-box

E.g. Output of S1: 0000
Input of S1:
011100 (row 0 column 14)
000001 (row 1 column 0)
111110 (row 2 column 15)
111011 (row 3 column 13)

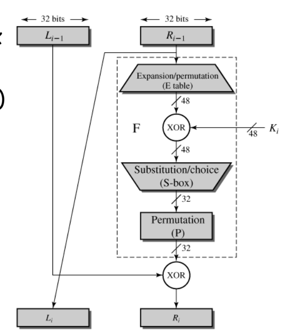


14	4	13	1	2	15	11	8	3	10	6	12	5	9	0	7
0	15	7	4	14	2	13	1	10	6	12	11	9	5	3	8
4	1	14	8	13	6	2	11	15	12	9	7	3	10	5	0
15	12	8	2	4	9	1	7	5	11	3	14	10	0	6	13

A Simple Attack on 1-Round DES

output of E table &
4 possible inputs of each S-box
➔ 4 possible values for
each K1j, where K1 = (K11 .. K18)

Try other plaintext-ciphertext
pairs until K1 is discovered



Avalanche Effect

- Avalanche Effect:
  - Desirable property of any encryption algorithm.
  - Small change in either the plaintext or the key should produce a significant change in the ciphertext.
  - Change in 1 bit of the plaintext or the key should produce a change in many bits of the ciphertext.
- Making attempts of guessing keys impossible
- DES exhibits strong avalanche

Avalanche Effect

- Two plaintexts:
  - P1:

00000000 00000000
00000000 00000000
00000000 00000000
00000000 00000000

  - P2:

10000000 00000000 00000000
00000000 00000000 00000000
00000000 00000000

- Key K:
  - 0000001 1001011 0100100
    1100010 0011100 0011000
    0011100 0110010

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

Avalanche Effect

- One plaintext P:
  - 01101000 10000101
    00101111 01111010
    00010011 01110110
    11101011 10100100
- Two keys:
  - K1

1110010 1111011 1101111
0011000 0011101 0000100
0110001 1101110

  - K2

0110010 1111011 1101111
0011000 0011101 0000100
0110001 1101110

(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

DES – Key Size

- 56-bit keys have $2^{56} = 7.2 \times 10^{16}$ values
- Brute force search looks hard
  - assume: half of the key space has to be searched, a single machine performing one DES encryption per microsecond would take more than a thousand years to break the cipher
- Recent advances have shown is possible
  - In 1977, Diffie and Hellman: technology existed to build a parallel machine with 1 million encryption devices; each performs one encryption per microsecond ➔ 10 hours
  - In 1998, Electronic Frontier Foundation (EFF) had broken a DES encryption using a computer built for less than $250K. The attack took less than 3 days.

- S-Box Modifications and Their Effect in DES-like Encryption Systems

http://www.sans.org/reading_room/whitepapers/vpns/s-box-modifications-effect-des-like-encryption-systems_768