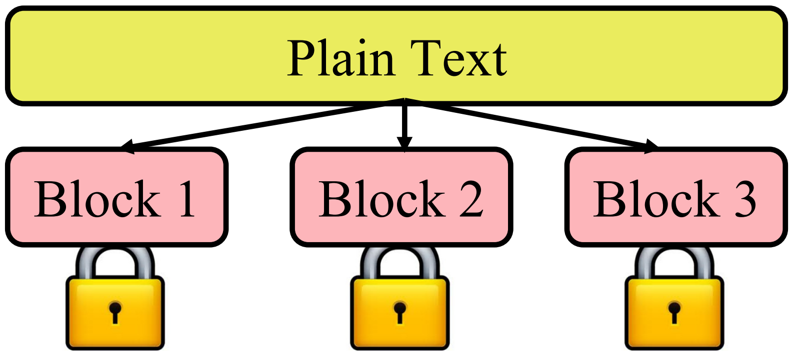
Block Ciphers and DES



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Audio/Video recordings of this lecture are available at:

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1. Block Cipher Principles
2. Data Encryption Standard (DES)
3. Differential and Linear Cryptanalysis
4. Block Cipher Design Principles

These slides are based partly on Lawrie Brown's slides supplied with William Stalling's book "Cryptography and Network Security: Principles and Practice," 6th Ed, 2013.

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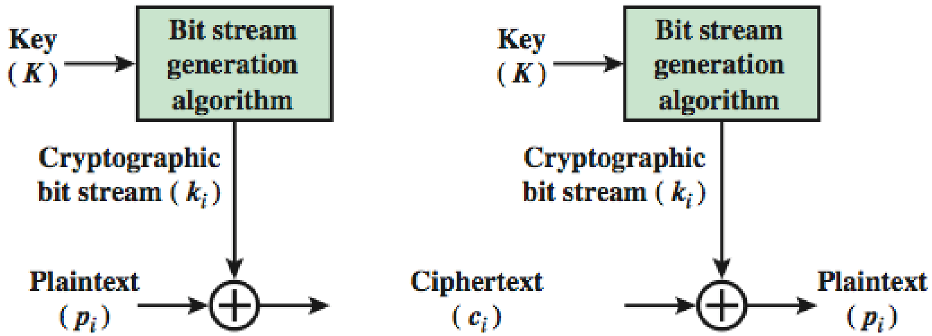
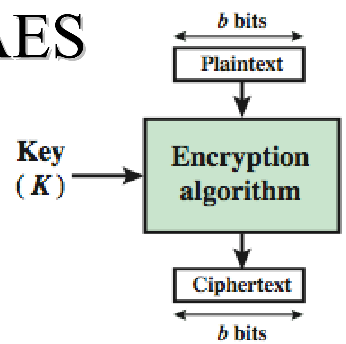
Block vs. Stream Ciphers

- **Stream**: Bits and bytes are processed as they arrive
  Example: RC4



(a) Stream Cipher Using Algorithmic Bit Stream Generator

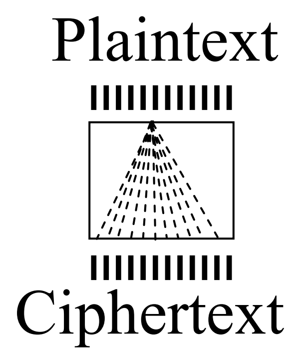
- **Block**: Messages are broken into blocks of 64-bit, 512-bit, …
  Example: DES, AES



(b) Block Cipher

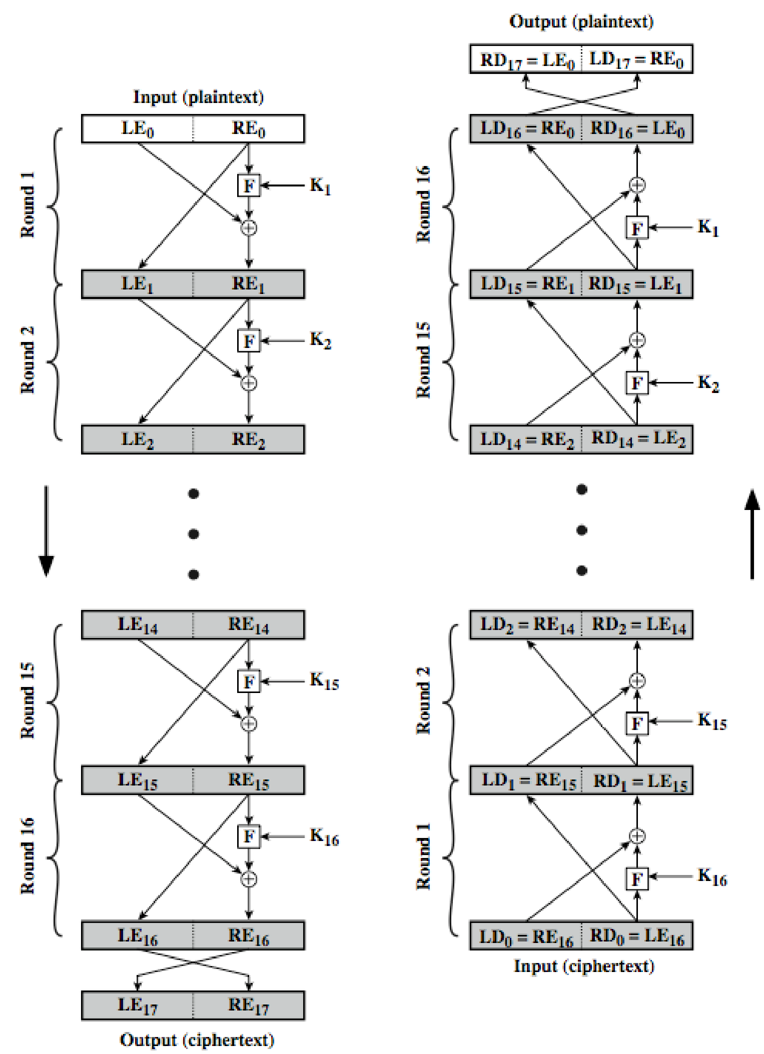
Shannon's S-P Networks

- Claude Shannon introduced idea of substitution-permutation (S-P) networks in his 1949 paper
- Two primitive cryptographic operations:
  - ***Substitution* (S-box)** = Replace n-bits by another n-bits
    ⇒ **Diffusion**: Dissipate statistical structure of plaintext over bulk of ciphertext.
    One bit change in plaintext changes many bits in ciphertext.
    Can not do frequency analysis.
  - ***Permutation* (P-box)** = Bits are rearranged. No bits are added/removed.
    ⇒ **Confusion**: Make relationship between ciphertext and key as complex as possible
- Combination S-P = Product cipher



Feistel Cipher Structure

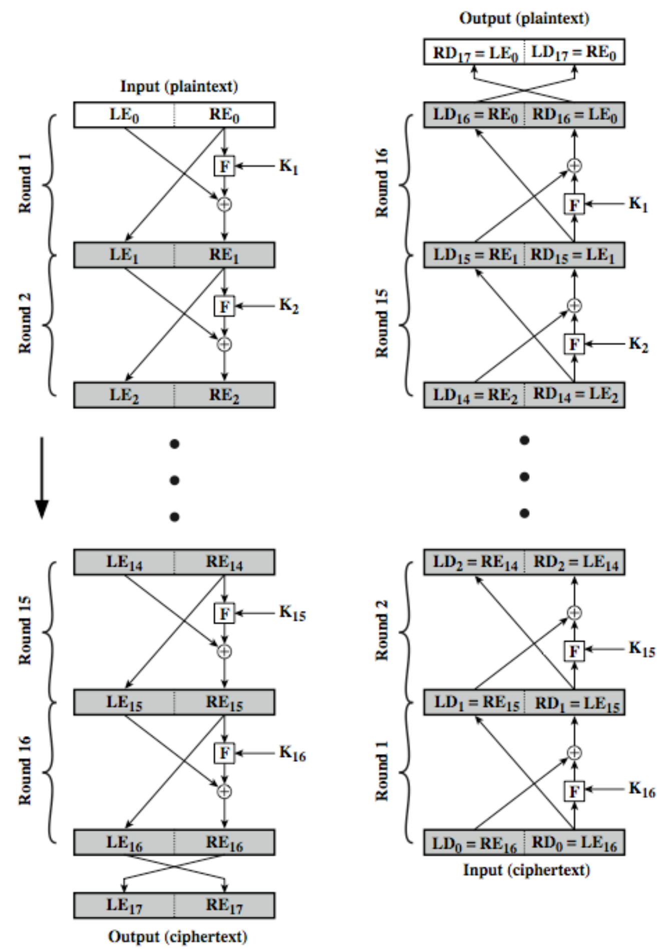
- A practical implementation of Shanon's S-P Networks
- Partitions input block in 2 halves
  - Perform a substitution on left data half based on a function of right half & subkey (Round Function or Mangler function)
  - Then permutation by swapping halves
  - Repeat this "round" of S-P many times
- Invertible



Feistel Cipher Design Elements

Most modern block ciphers are a variation of Feistel Cipher with different:

1. Block size
2. Key size
3. Number of rounds
4. Subkey generation algorithm
5. Round function
6. Fast software en/decryption
7. Ease of analysis



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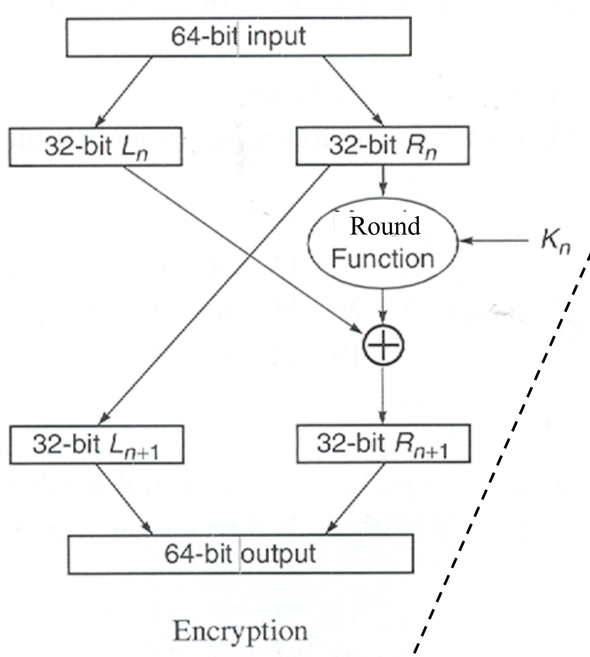
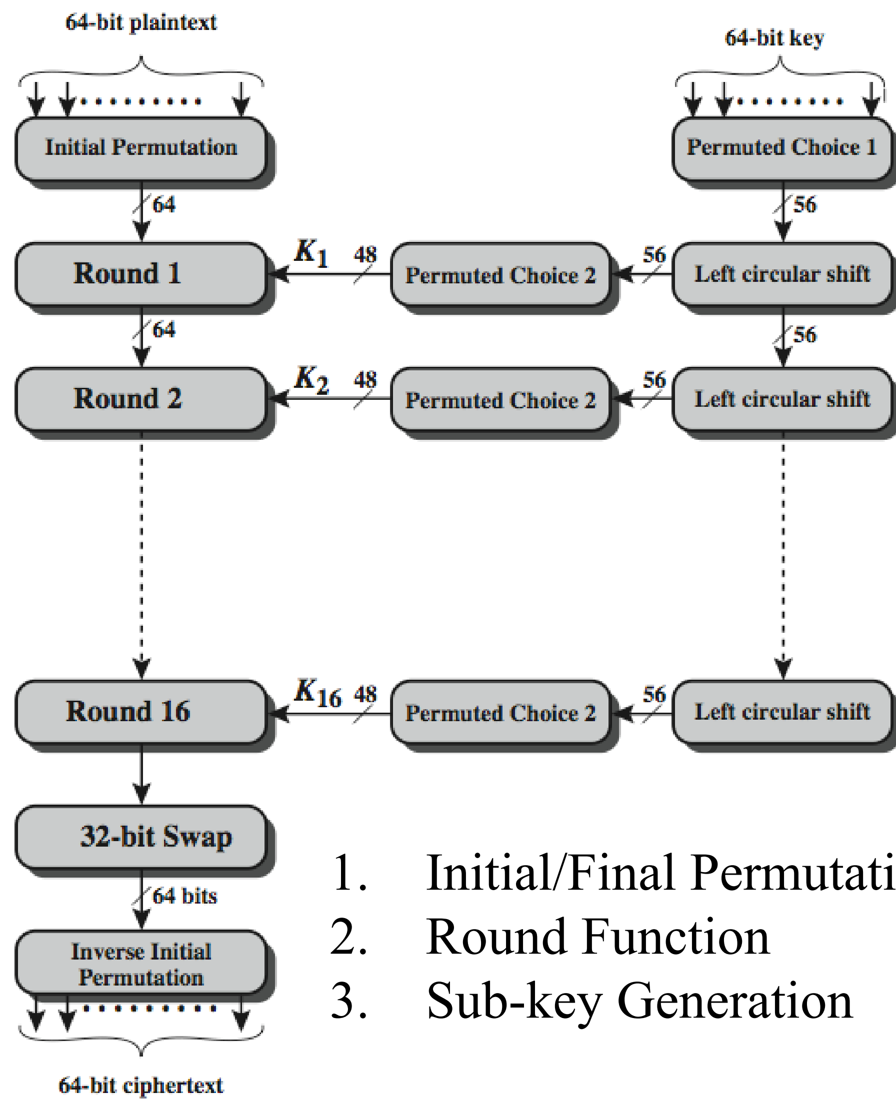
Data Encryption Standard (DES)

- Published by NIST in 1977
- A variation of IBM's Lucifer algorithm developed by Horst Feistel
- For commercial and *unclassified* government applications
- 8 octet (64 bit) key.
  Each octet with 1 odd parity bit ⇒ 56-bit key
- Efficient hardware implementation
- Used in most financial transactions
- Computing power goes up 1 bit every 2 years
- 56-bit was secure in 1977 but is not secure today
- Now we use DES three times ⇒ Triple DES = 3DES

DES Encryption Overview

- 16 rounds using 64-bit block and 48-bit subkey





1. Initial/Final Permutation
2. Round Function
3. Sub-key Generation

1. Initial and Final Permutation

Initial Permutation (IP)

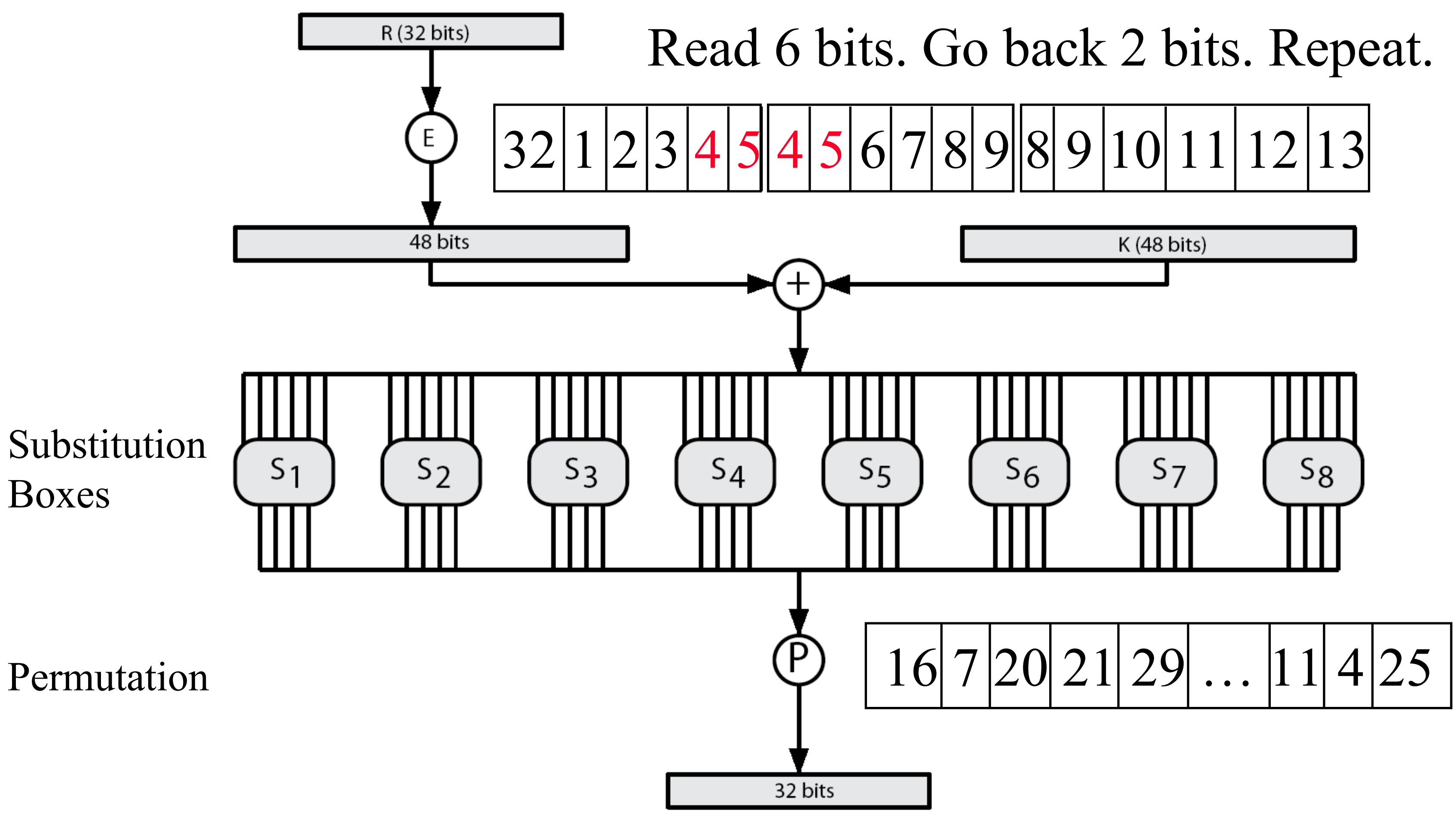
58	50	42	34	26	18	10	2
60	52	44	36	28	20	12	4
62	54	46	38	30	22	14	6
64	56	48	40	32	24	16	8
57	49	41	33	25	17	9	1
59	51	43	35	27	19	11	3
61	53	45	37	29	21	13	5
63	55	47	39	31	23	15	7

Final 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

- Input bit 58 goes to output bit 1
  Input bit 50 goes to output bit 2, …
- Even bits to LH half, odd bits to RH half
- Quite regular in structure (easy in h/w)

2. DES Round Structure



Substitution Boxes

- Map 6 to 4 bits
- Outer bits 1 & 6 (**row** bits) select one row of 4
- Inner bits 2-5 (**column** bits) are substituted
- Example:

Input bits 1 and 6	Input bits 2 thru 5															
↓	0000	0001	0010	0011	0100	0101	0110	0111	1000	1001	1010	1011	1100	1101	1110	1111
00	1110	0100	1101	0001	0010	1111	1011	1000	0011	1010	0110	1100	0101	1001	0000	0111
01	0000	1111	0111	0100	1110	0010	1101	0001	1010	0110	1100	1011	1001	0101	0011	1000
10	0100	0001	1110	1000	1101	0110	0010	1011	1111	1100	1001	0111	0011	1010	0101	0000
11	1111	1100	1000	0010	0100	1001	0001	0111	0101	1011	0011	1110	1010	0000	0110	1101

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3. DES Sub-Key Generation

- Permutation PC1 divides 56-bits in two 28-bit halves
- Rotate **each half** separately either 1 or 2 places depending on the **key rotation schedule** K
- Select 24-bits from each half & permute them by PC2

(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

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DES Decryption

- Decrypt with Feistel design: Do encryption steps again using sub-keys 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

Avalanche Effect

- Key desirable property of encryption algorithm
- A change of **one** input or key bit results in changing approx **half** output bits = **Diffusion**
- Making attempts to "home-in" by guessing keys impossible
- DES exhibits strong avalanche

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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

3+4+3+3+1+0+2+3+2+3+1+2+2+2+1+1=33 bits

Strength of DES

- Bit-wise complement of plaintext with complement of key results in complement of ciphertext
- Brute force search requires 2^{55} keys
- Recent advances have shown, it 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!
- Statistical Attacks:
  - Timing attacks: calculation time depends upon the key. Particularly problematic on smartcards
  - Differential cryptanalysis
  - Linear cryptanalysis

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Differential Cryptanalysis

- Chosen Plaintext attack: Get ciphertext for a given plaintext
- Get the (ΔX, ΔY) pairs, where ΔX is the difference in plaintext and ΔY is the difference in ciphertext
- Some (ΔX, ΔY) pairs are more likely than others, if those pairs are found, some key values are more likely so you can reduce the amount of brute force search
- Straightforward brute force attack on DES requires 2^{55} plaintexts
- Using differential cryptanalysis, DES can be broken with 2^{47} plaintexts.
  But finding appropriate plaintexts takes some trials and so the total amount of effort is $2^{55.1}$ which is more than straight forward brute force attack
  $\Rightarrow$ DES is resistant to differential cryptanalysis

Ref: http://en.wikipedia.org/wiki/Differential_cryptanalysis

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Linear Cryptanalysis

- Bits in plaintext, ciphertext, and keys may have a linear relationship. For example:

$$P1 \oplus P2 \oplus C3 = K2 \oplus K5$$

- In a good cipher, the relationship should hold w probability ½. If any relationship has probability 1, the cipher is easy to break. If any relationship has probability 0, the cipher is easy to break.
- Bias = |Probability of linear relationship – 0.5|
- Find the linear approximation with the highest bias
  ⇒ Helps reduce the brute force search effort.
- This method can be used to find the DES key given 2^{43} plaintexts.

Ref: http://en.wikipedia.org/wiki/Linear_cryptanalysis

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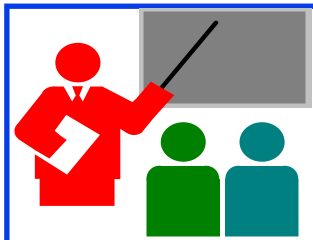
Block Cipher Design Principles

- Nonlinear S-Boxes: Resistant to linear cryptanalysis. Linear approximations between input and output bits of the S-boxes should have minimal bias ⇒ P ≈ ½
- S-Boxes resistant to differential cryptanalysis. All (Input bit difference, output bit difference) pairs should be equally likely.
- Any output bit should change with probability ½ when any input bit is changed (strict avalanche criterion)
- Output bits *j* and *k* should change independently when any input bit *i* is inverted for all *i*, *j*, *k* (bit independence criterion)
- Permutation: Adjacent bits should affect different S-Boxes in the next round ⇒ Increase diffusion
- More rounds are better (but also more computation)



Summary

1. Goal of ciphers is to increase confusion and diffusion.
   Confusion = Complex relationship
   Diffusion = Each input bit affects many output bits
2. Feistel cipher design divides blocks in left and right halves, mangles the right half with a sub-key and swaps the two halves.
3. DES consists of 16 rounds using a 56-bit key from which 48-bit subkeys are generated. Each round uses eight 6x4 S-Boxes followed by permutation.
4. Differential cryptanalysis analyzes frequency of (ΔP, ΔC) pairs. Linear cryptanalysis analyzes frequency of linear relationships among plaintext, ciphertext, and key.
5. Block ciphers should be nonlinear, complex, maximize diffusion.

Homework 3

- Submit answer to Problem 3.11 (One round version of DES)
  Final Answer = F0AAF0AA 5E1CEC63

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