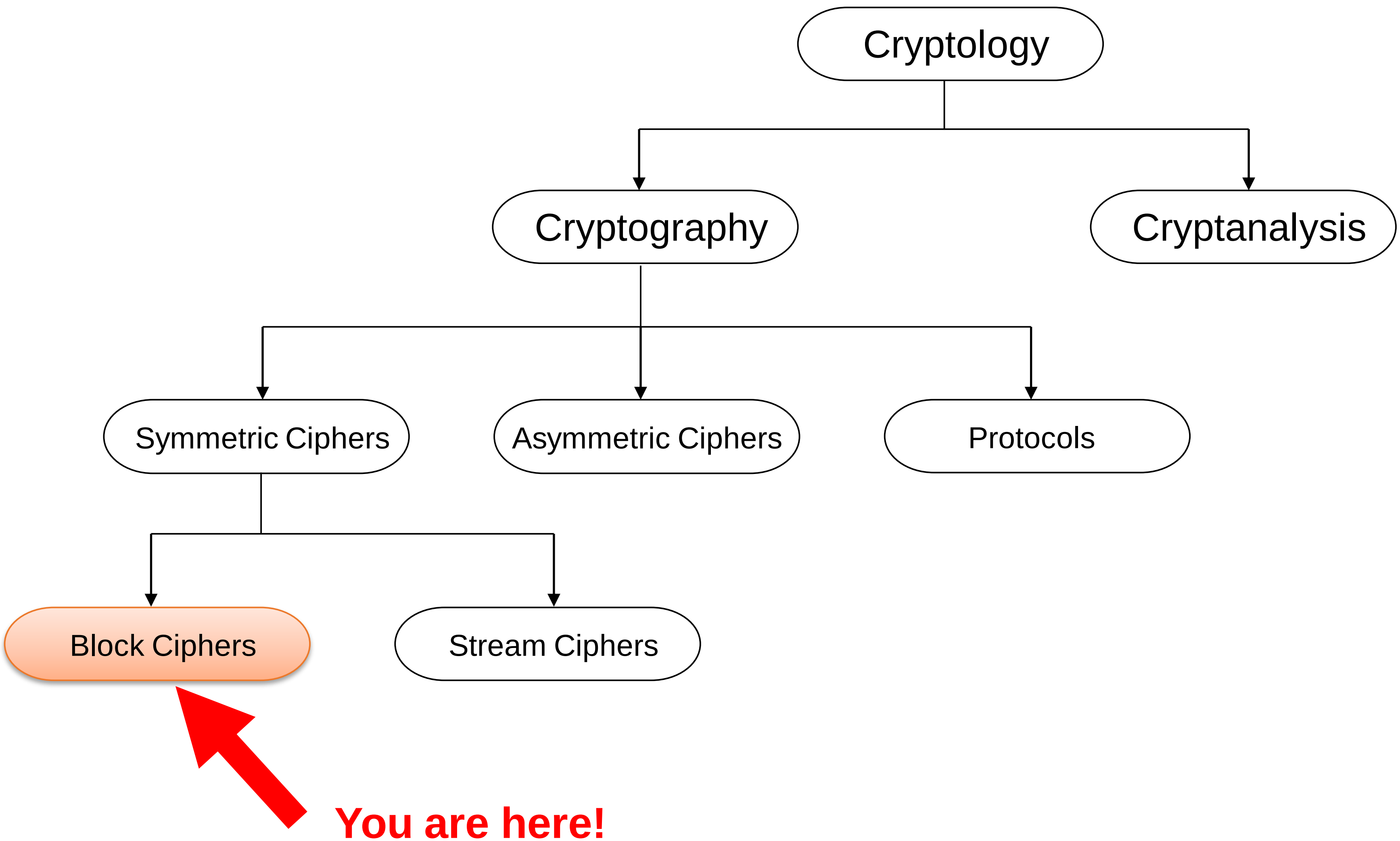
Data Encryption Standard
DES

Outline

1. Introduction to DES
2. Overview of DES Algorithm
3. Internal Structure of DES
4. Security of DES

Introduction to DES

Classification of DES in the Field of Cryptology



DES Facts

- Data Encryption Standard (DES) encrypts **blocks of size 64 bits**
- Developed by **IBM** based on the cipher *Lucifer* under influence of the *National Security Agency* (NSA)
- **Standardized 1977** by the **National Bureau of Standards** (NBS) today called *National Institute of Standards and Technology* (NIST)
- Most popular **block cipher** until 2000
- By far best studied symmetric algorithm
- Nowadays considered insecure due to the small **key length of 56 bit**
- **But: 3DES yields very secure cipher**, still widely used today.
- Replaced by the *Advanced Encryption Standard* (**AES**) in 2000

Block Cipher Primitives: Confusion and Diffusion

Claude Shannon established that two primitive operations are required to build strong encryption algorithms:

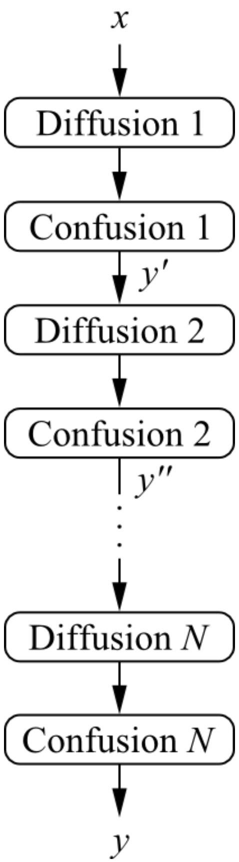
1. **Confusion:** An encryption operation where the **relationship between key and ciphertext is obscured**
   - Commonly achieved using **substitution**
   - Small change in key → large change in ciphertext

2. **Diffusion:** An encryption operation where the **influence of one plaintext symbol is spread over many ciphertext symbols** with the goal of hiding statistical properties of the plaintext

- Commonly achieved using **bit permutation**
- Small change in message → large change in ciphertext
- Hides patterns within the message

- Concatenate both confusion and diffusion elements to build so called *product ciphers*

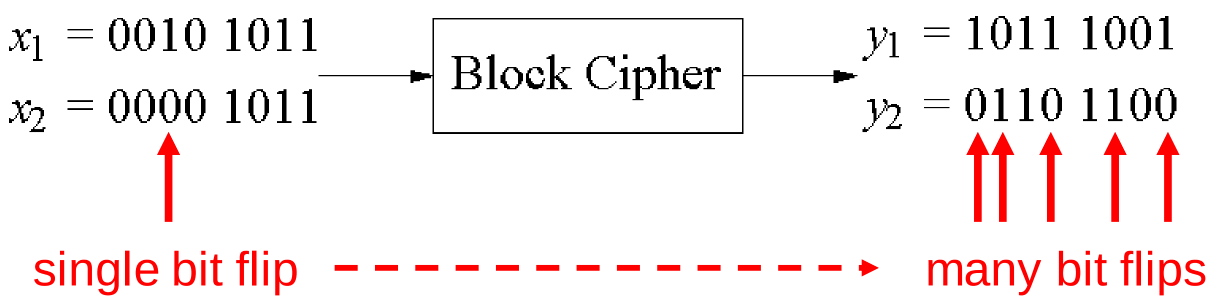
Product Ciphers



- Most of today's block ciphers are *product ciphers* as they consist of rounds which are applied repeatedly to the data

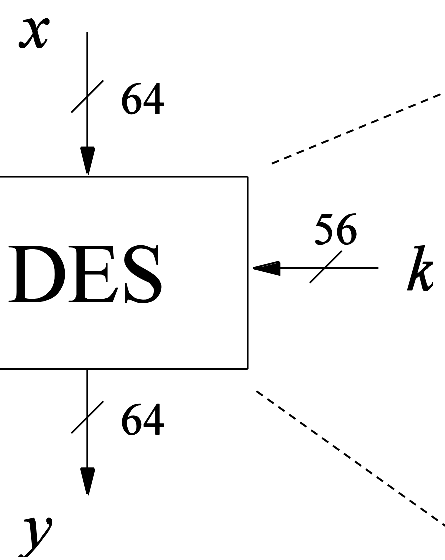
- Can reach excellent diffusion: **changing of one bit of plaintext results** *on average* in the **change of half the output bits**

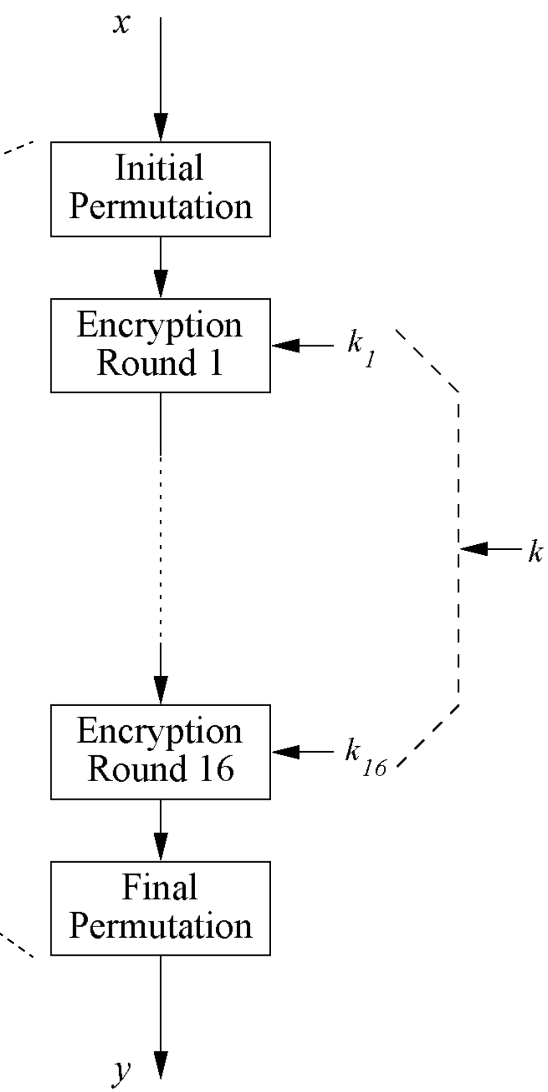
Example:



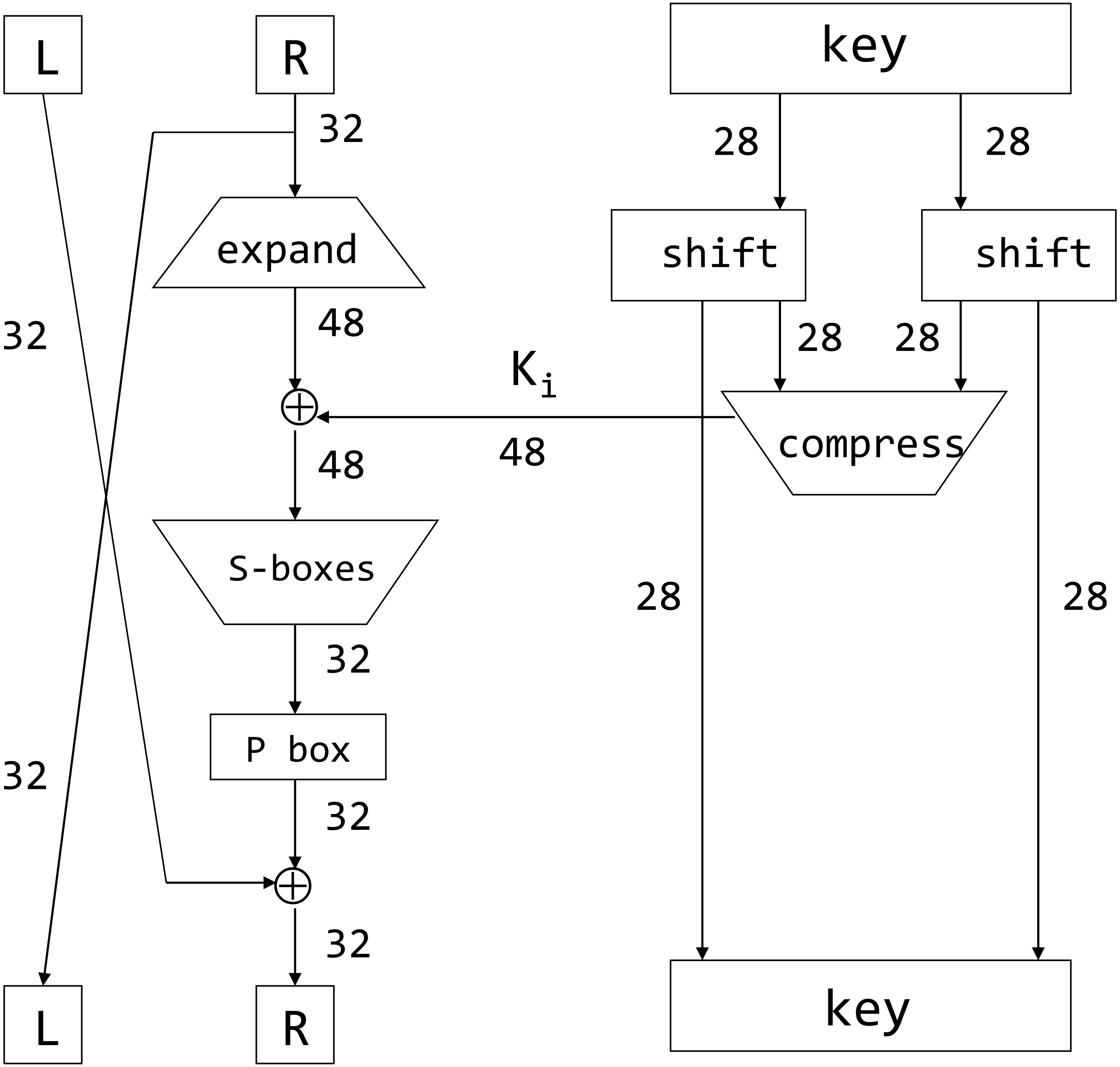
Overview of DES Algorithm

Overview of DES Algorithm





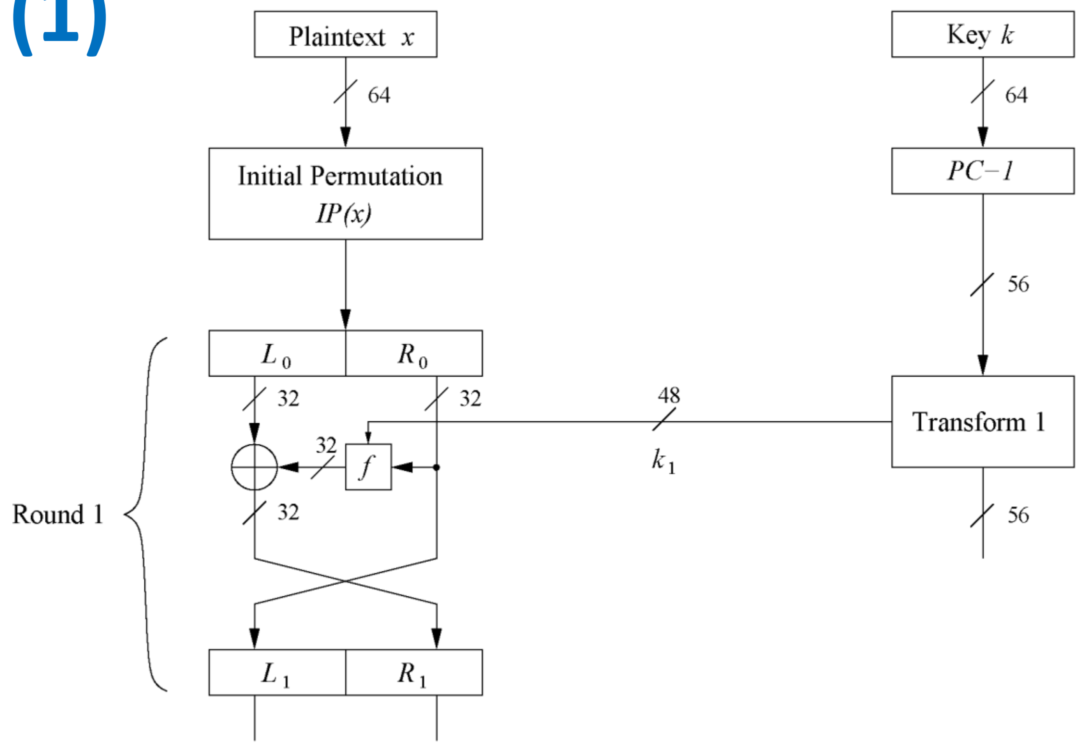
- **Encrypts blocks of size 64 bits**
- **Uses a key of size 56 bits**
- Symmetric cipher: uses same key for encryption and decryption
- Uses **16 rounds** which all perform identical operation
- Different subkey in each round derived from main key
- Each round uses a generated ***subkey*** and the ***output*** of previous round



One Round of DES

DES Feistel Network (1)

- DES structure is a *Feistel network* - an approach adopted by many block ciphers
- Advantage: encryption and decryption differ only in keyschedule



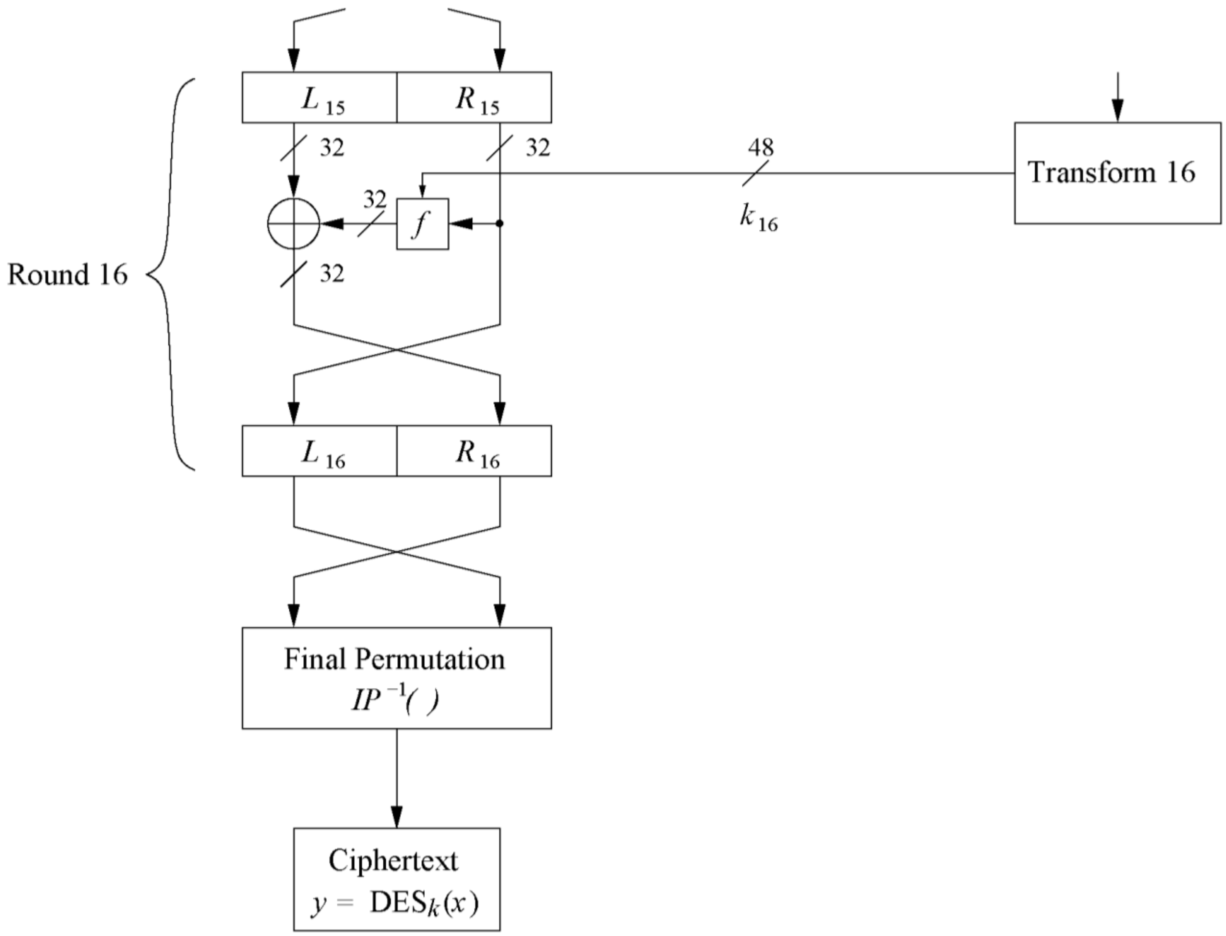
- Bitwise initial permutation, then 16 rounds
  1. Plaintext is split into 32-bit halves L_i and R_i
  2. R_i is fed into the **function *f***, the output of which is then XORed with L_i
  3. Left and right half are swapped
- Rounds can be expressed as:

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

$$R_i = L_{i-1} \oplus f(R_{i-1}, k_i)$$

The DES Feistel Network (2)

- L and R swapped again at the end of the cipher, i.e., after round 16 followed by a **final permutation**



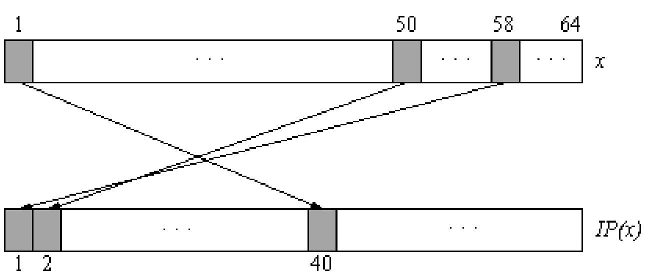
Internal Structure of DES

Initial and Final Permutation

- Bitwise Permutations
- Described by tables *IP* and *IP*$^{-1}$

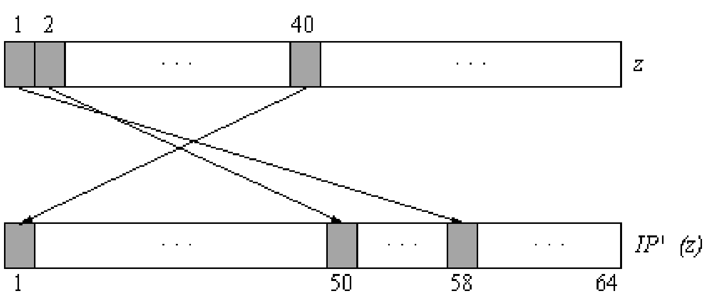
Initial Permutation

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



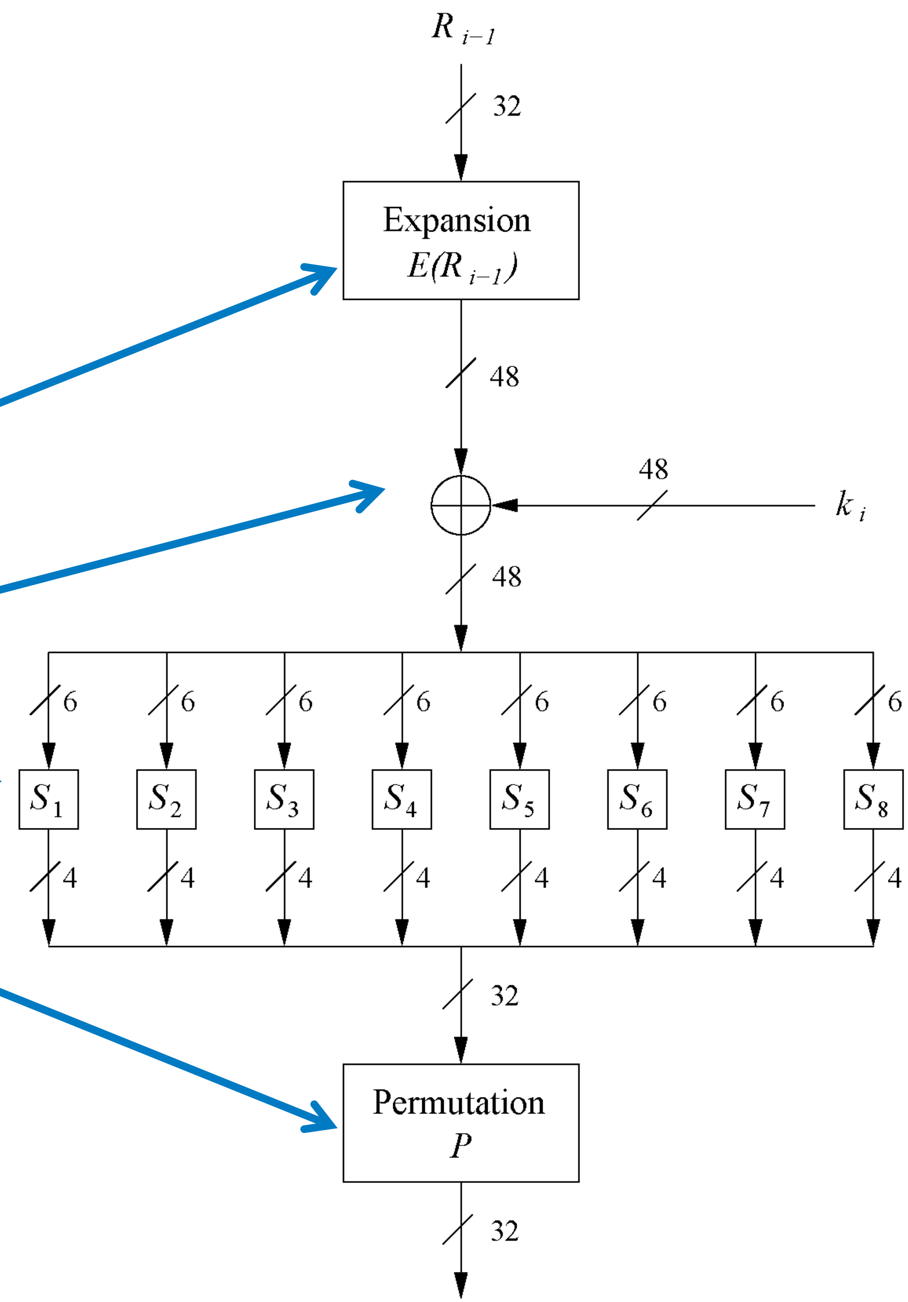
Final Permutation

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



The f-Function

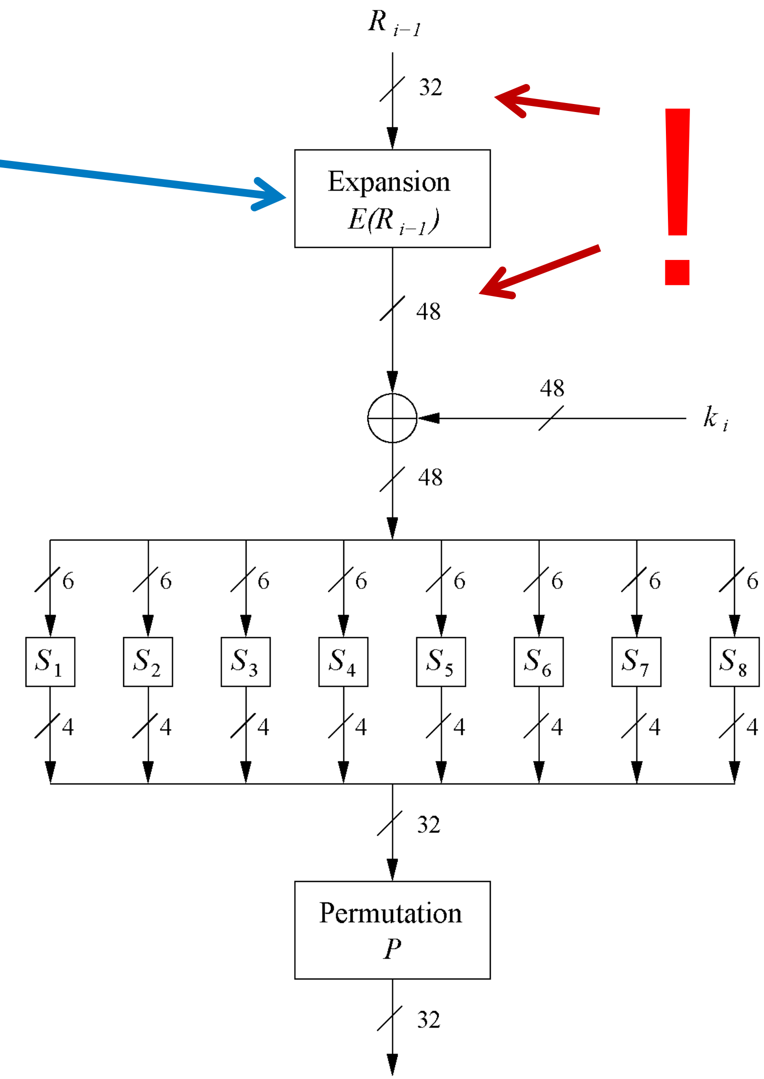
- **Main operation of DES**
- *f*-Function inputs:
  R_{i-1} and round key k_i
- **4 Steps**:
  1. Expansion *E*
  2. XOR with round key
  3. S-box substitution
  4. Permutation



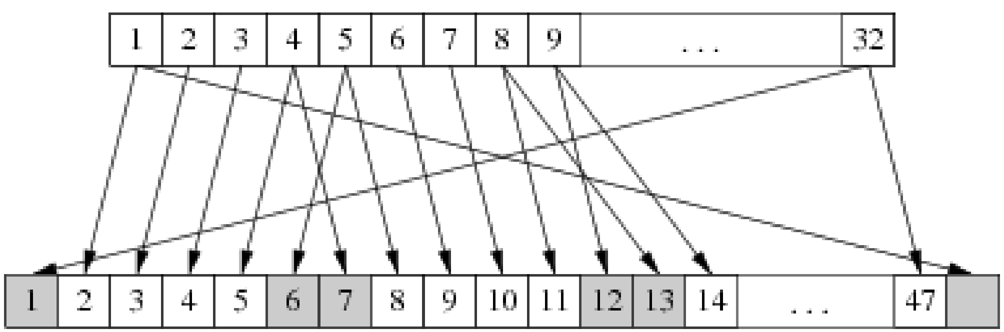
The Expansion Function E

1. Expansion *E*

- main purpose: **increases diffusion**



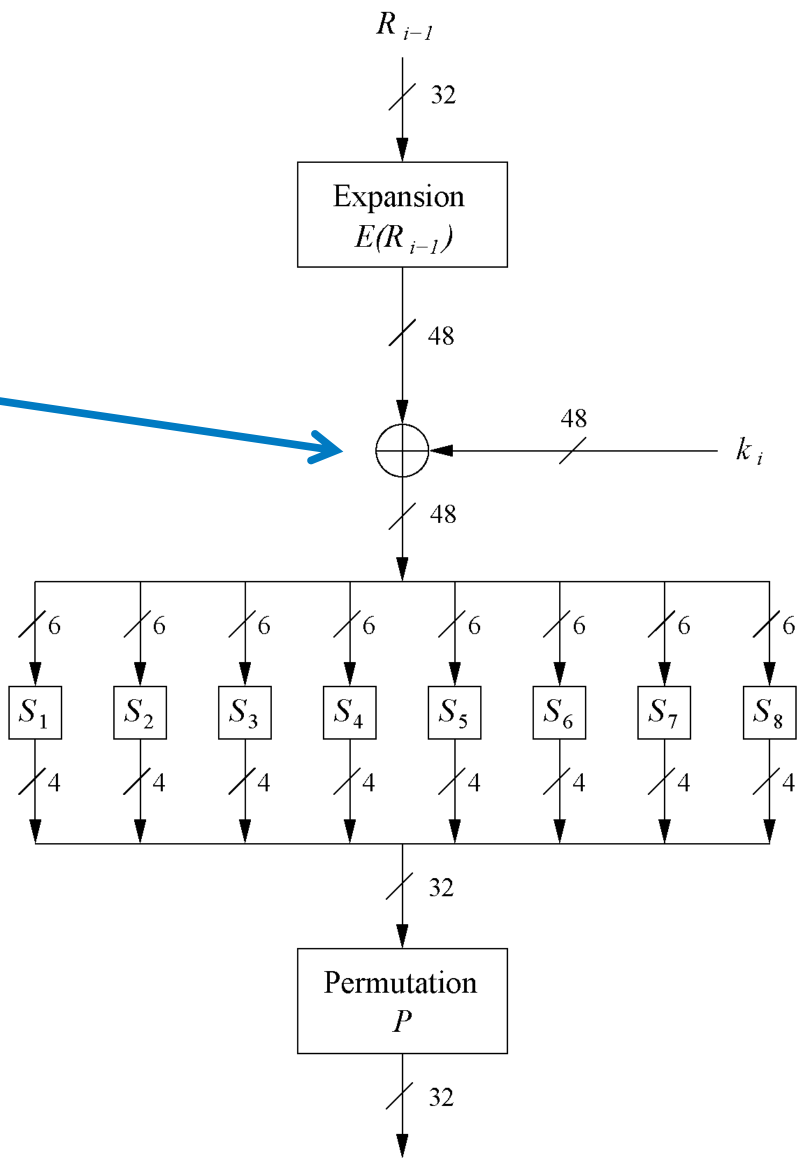
E					
32	1	2	3	4	5
4	5	6	7	8	9
8	9	10	11	12	13
12	13	14	15	16	17
16	17	18	19	20	21
20	21	22	23	24	25
24	25	26	27	28	29
28	29	30	31	32	1



XOR Round Key

2. XOR Round Key

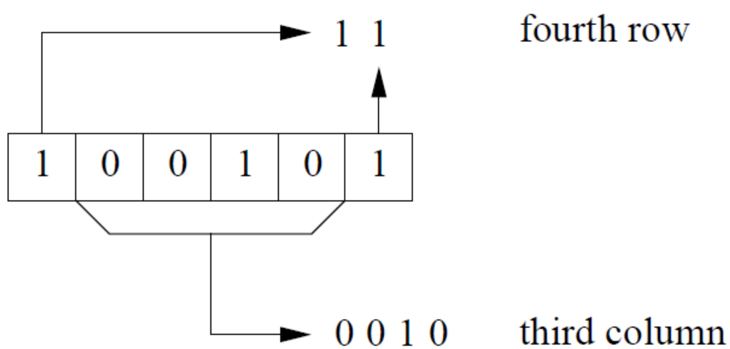
- Bitwise XOR of the round key and the output of the expansion function *E*
- Round keys are derived from the main key in the DES keyschedule (in a few slides)

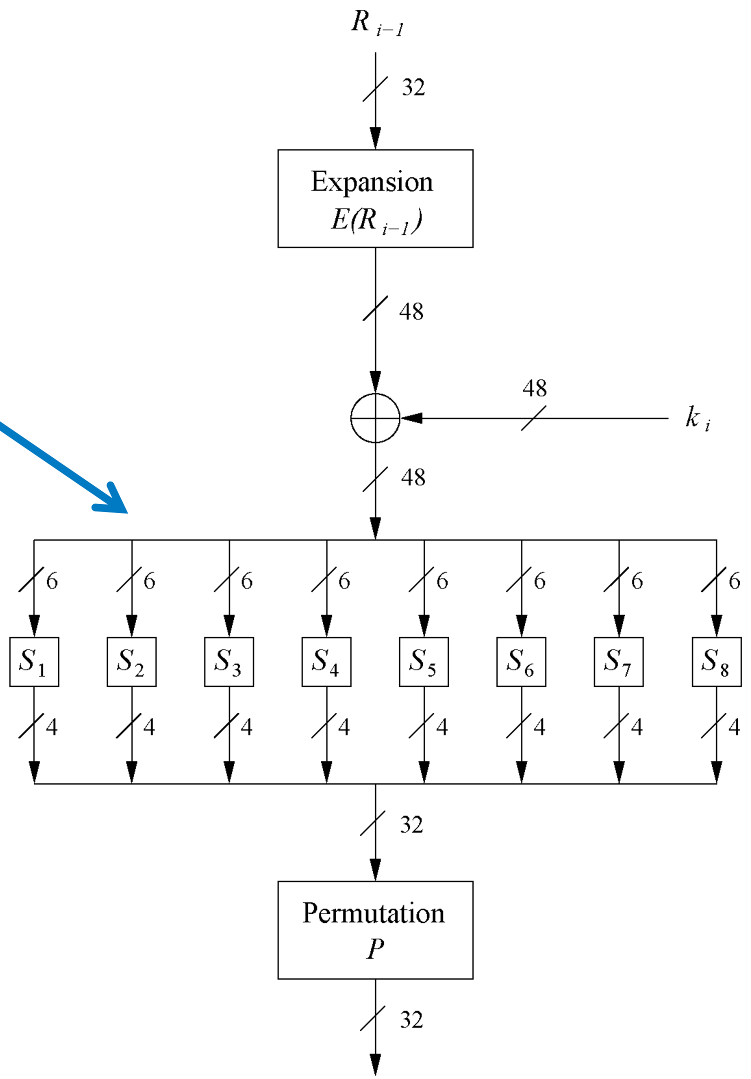


The DES S-Boxes

3. S-Box substitution

- Eight substitution tables
- Each S-box maps 6 bits of input
  to 4 bits of output
- Non-linear and resistant to differential cryptanalysis
- **Crucial element for DES security!**



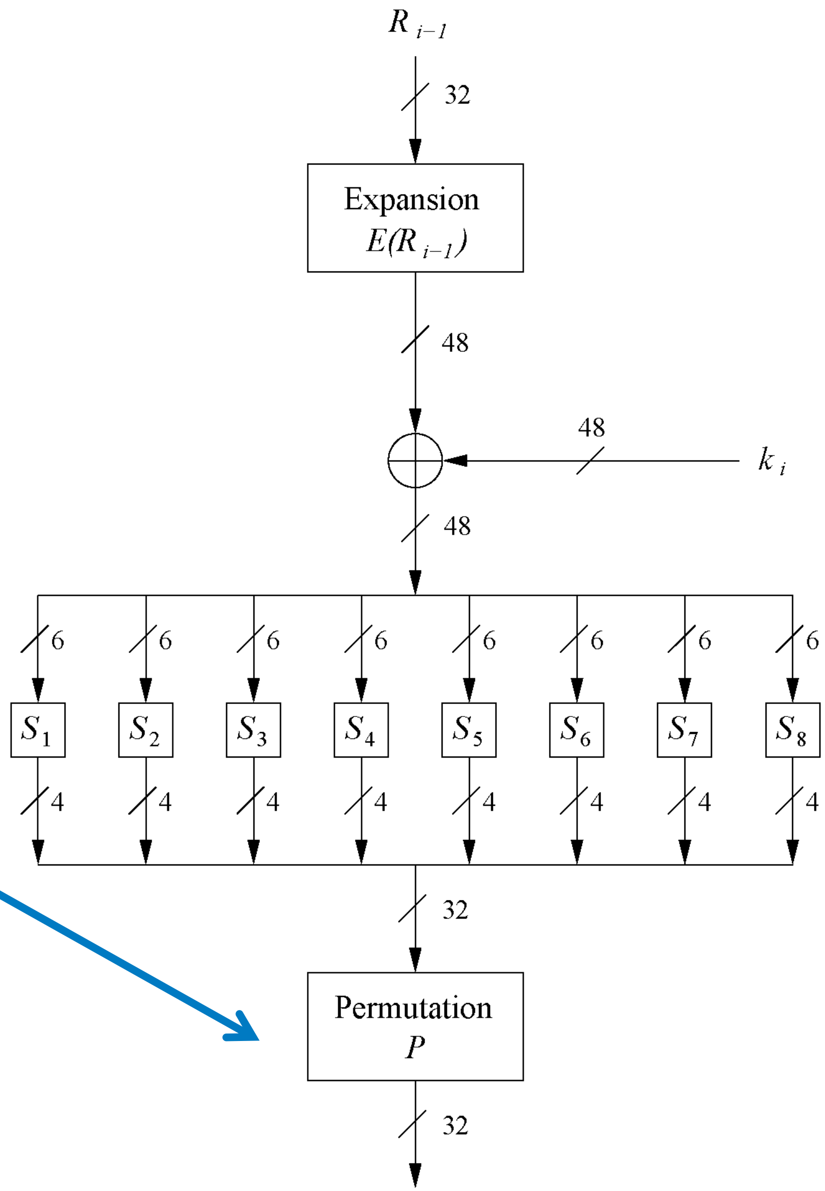


S_1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	14	04	13	01	02	15	11	08	03	10	06	12	05	09	00	07
1	00	15	07	04	14	02	13	01	10	06	12	11	09	05	03	08
2	04	01	14	08	13	06	02	11	15	12	09	07	03	10	05	00
3	15	12	08	02	04	09	01	07	05	11	03	14	10	00	06	13

The Permutation P

4. Permutation P

- Bitwise permutation
- Introduces diffusion
- Output bits of one S-Box effect several S-Boxes in next round

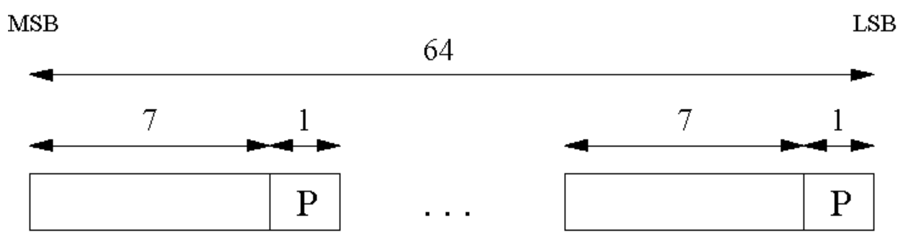


P							
16	7	20	21	29	12	28	17
1	15	23	26	5	18	31	10
2	8	24	14	32	27	3	9
19	13	30	6	22	11	4	25

Key Schedule (1)

- Derives 16 round keys (or *subkeys*) k_i of 48 bits each from the original 56 bit key
- The input key size of the DES is 64 bit: **56 bit key** and 8 bit parity:

!



P = parity bit

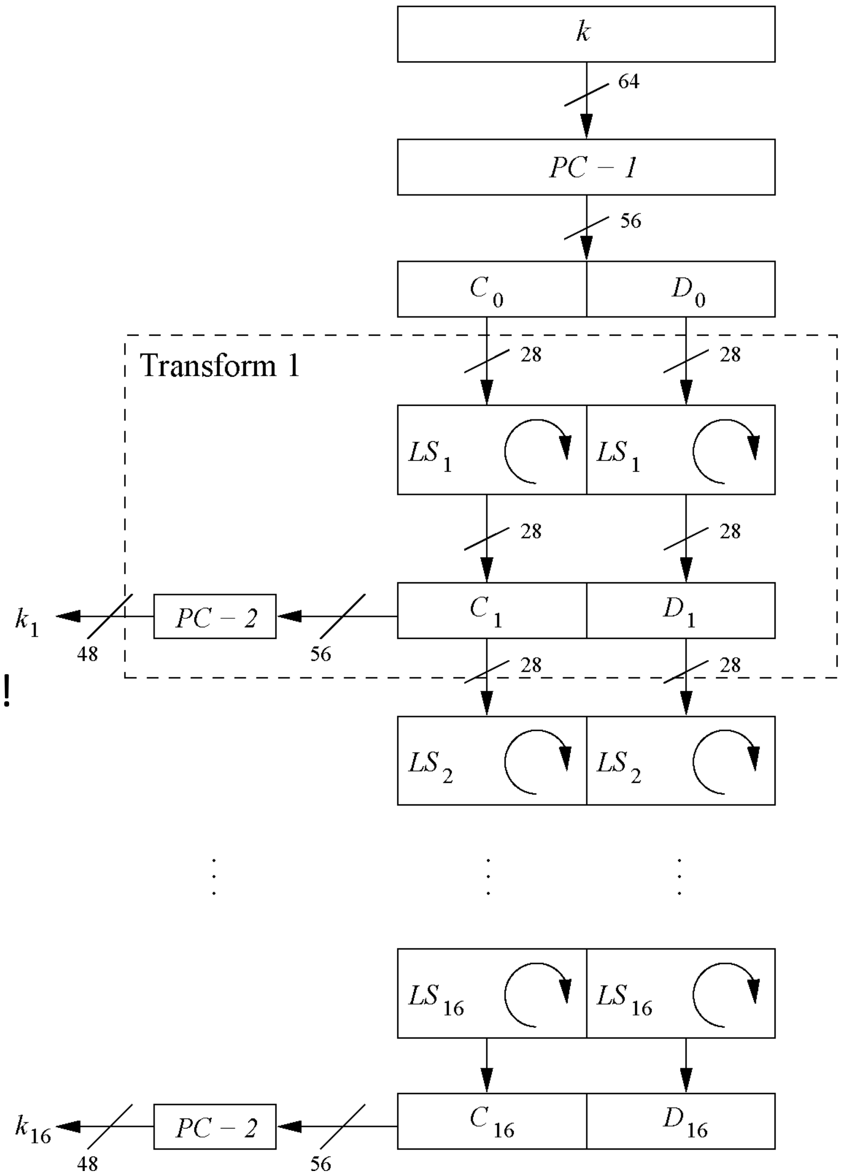
- **Parity bits are removed** in a first **permuted choice** *PC-1*:
  (note that the bits 8, 16, 24, 32, 40, 48, 56 and 64 are not used at all)

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

Key Schedule (2)

- Split key into 28-bit halves C_0 and D_0
- In **rounds *i* = 1, 2, 9 ,16,** the two halves are each rotated left by **one bit**
- In **all other rounds** where the two halves are each rotated left by **two bits**
- *In each round i permuted choice **PC-2*** selects a permuted subset of 48 bits of C_i and D_i as round key k_i, i.e. **each k_i is a permutation of k**!

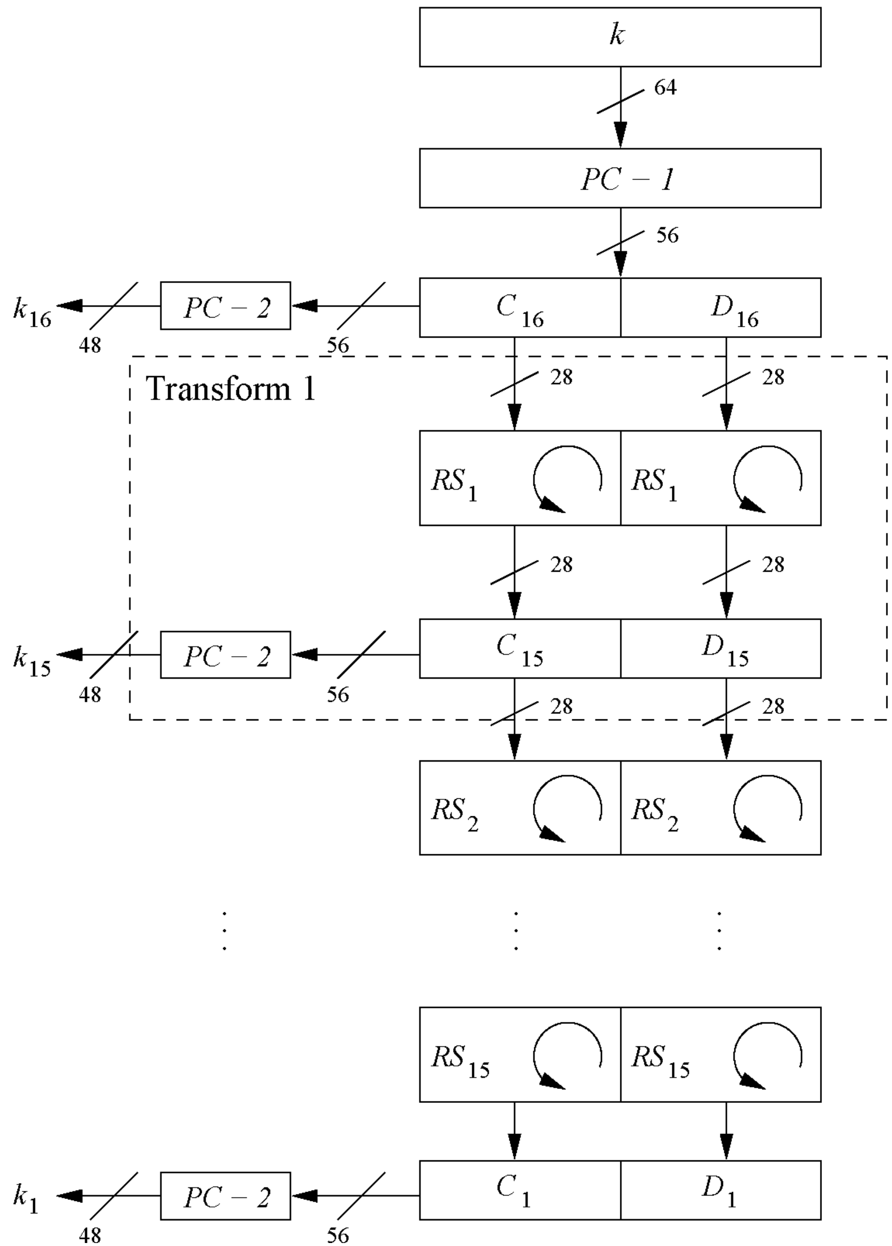
$PC-2$							
14	17	11	24	1	5	3	28
15	6	21	10	23	19	12	4
26	8	16	7	27	20	13	2
41	52	31	37	47	55	30	40
51	45	33	48	44	49	39	56
34	53	46	42	50	36	29	32



- **Note:** The total number of rotations: 4 x 1 + 12 x 2 = 28 $\Rightarrow D_0 = D_{16}$ and $C_0 = C_{16}$!

Decryption

- In **Feistel ciphers** only the keyschedule has to be modified for decryption
- Generate the same 16 round keys in reverse order
- **Reversed key schedule:**
  As D_0=D_{16} and C_0=C_{16} the first round key can be generated by applying *PC-2* right after *PC-1* (no rotation here!).
  All other rotations of *C* and *D* can be reversed to reproduce the other round keys resulting in:
  - No rotation in round 1.
  - One bit rotation **to the right** in rounds 2, 9 and 16.
  - Two bit rotations **to the right** in all other rounds.



Security of DES

Back

Security of DES

- **After proposal of DES two major criticisms arose:**
  1. Key space is too small (2^{56} keys)
  2. S-box design criteria have been kept secret: Are there any hidden analytical attacks (*backdoors*), only known to the NSA?

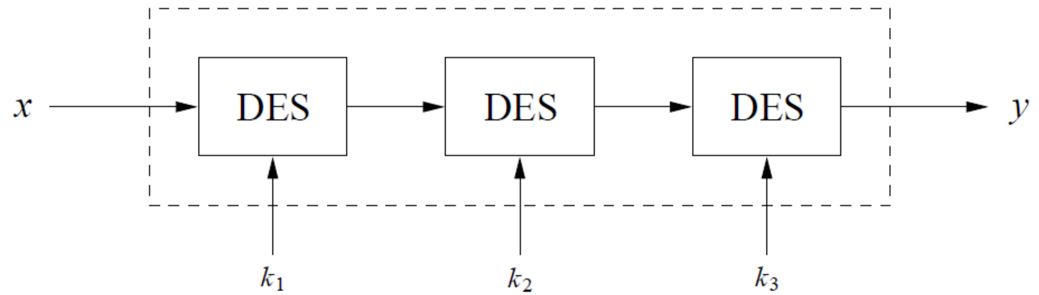
- **Analytical Attacks:** DES is highly resistent to both *differential* and *linear cryptanalysis*, which have been published years later than the DES. This means IBM and NSA had been aware of these attacks for 15 years!
  So far there is no known analytical attack which breaks DES in realistic scenarios.

- **Exhaustive key search:** For a given pair of plaintext-ciphertext (x, y) test all 2^{56} keys until the condition $DES_k^{-1}(x)=y$ is fulfilled.
  $\Rightarrow$ Relatively easy given today's computer technology!

Triple DES – 3DES

- Triple encryption applies the DES cipher algorithm three times to each data block
- Protect against brute-force attacks without the need to design a completely new block cipher algorithm (just by effective key length up to 168 bits)

$$y = DES_{k_3}(DES_{k_2}(DES_{k_1}(x)))$$



- No practical attack known today.
- Used in many legacy applications such as in banking systems.

Alternatives to DES

Algorithm	I/O Bit	key lengths	remarks
AES	128	128/192/256	DES "replacement", worldwide used standard
Triple DES	64	112 (effective)	conservative choice
Mars	128	128/192/256	AES finalist
RC6	128	128/192/256	AES finalist
Serpent	128	128/192/256	AES finalist
Twofish	128	128/192/256	AES finalist
IDEA	64	128	(Patented till 2011)

Summary

- DES was the dominant symmetric encryption algorithm from the mid-1970s to the mid-1990s. Since 56-bit keys are no longer secure, the Advanced Encryption Standard (AES) was created

- Standard DES with 56-bit key length can be broken relatively easily nowadays through an exhaustive key search

- DES is robust against known analytical attacks. Security depends heavily on S-boxes

- By encrypting with DES three times in a row, triple DES (3DES) is created, against which no practical attack is currently known

- The "default" symmetric cipher is nowadays often **AES**