Modern Symmetric Key Ciphers

Part II: Fiestel Ciphers and the DES

THE
UNIVERSITY
OF UTAH

Priyank Kalla
Professor
Electrical & Computer Engineering

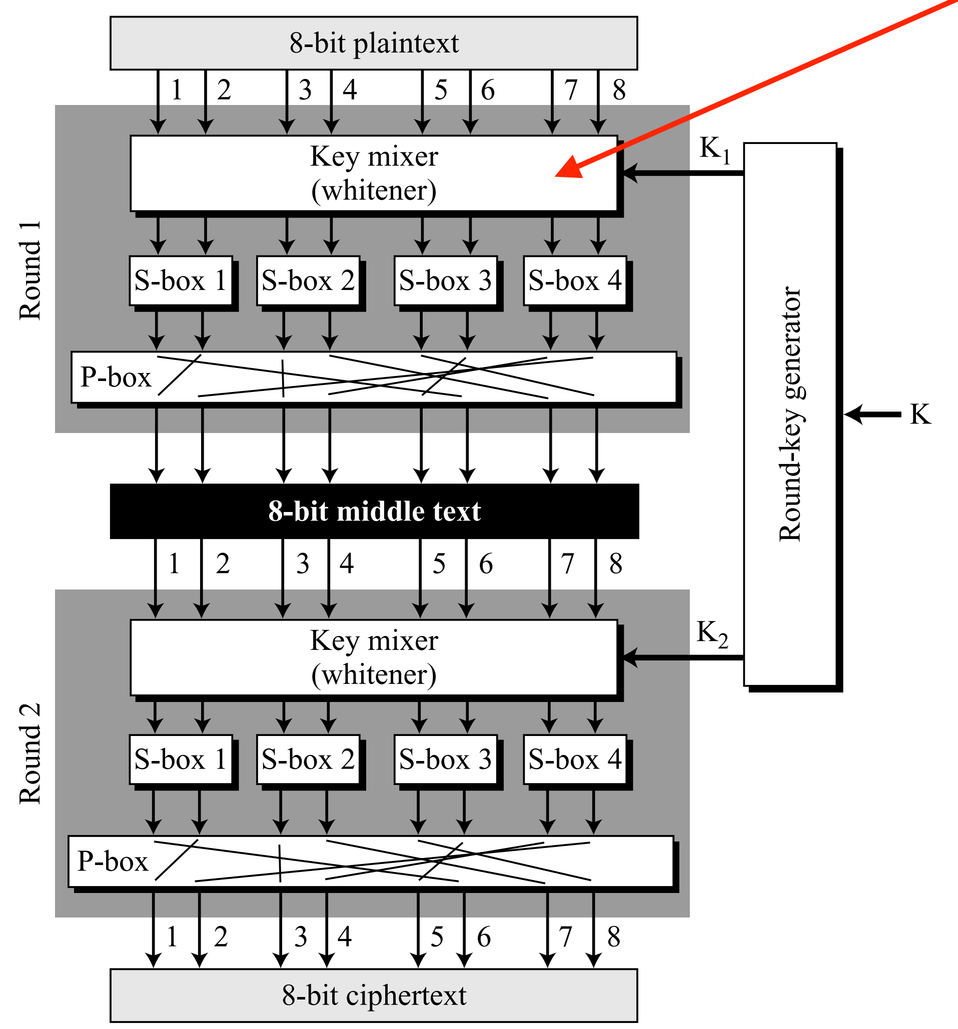
Product Ciphers

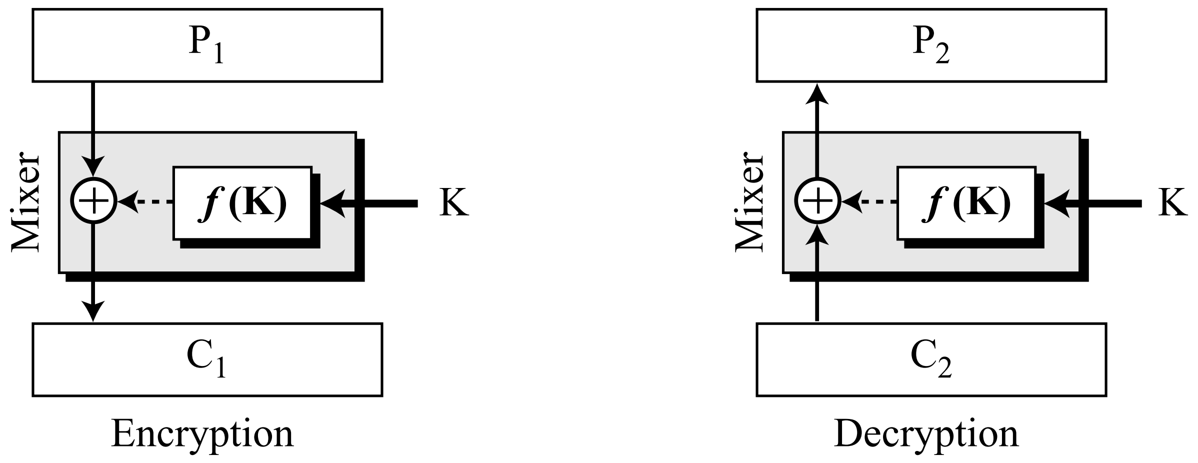
- Product Cipher: Combines S-Boxes, P-Boxes and Mixers, and may use multiple rounds for encipherment
- Two types of Product Ciphers
  - Feistel Cipher: Includes invertible and noninvertible components
  - DES = Feistel Cipher (uses non-invertible mixers and compression P-Boxes)
  - Non-Feistel Cipher: Includes only invertible components
  - AES = Non-Feistel Cipher

Example Product Cipher

Key Mixer: P[7:0] XOR K1[7:0]

A product cipher made of two rounds





- Mixer: Use a non-invertible function $f(K)$: can be linear or polynomial in $\mathbb{F}_{2^k}$

- But the Mixer is “self-invertible”:

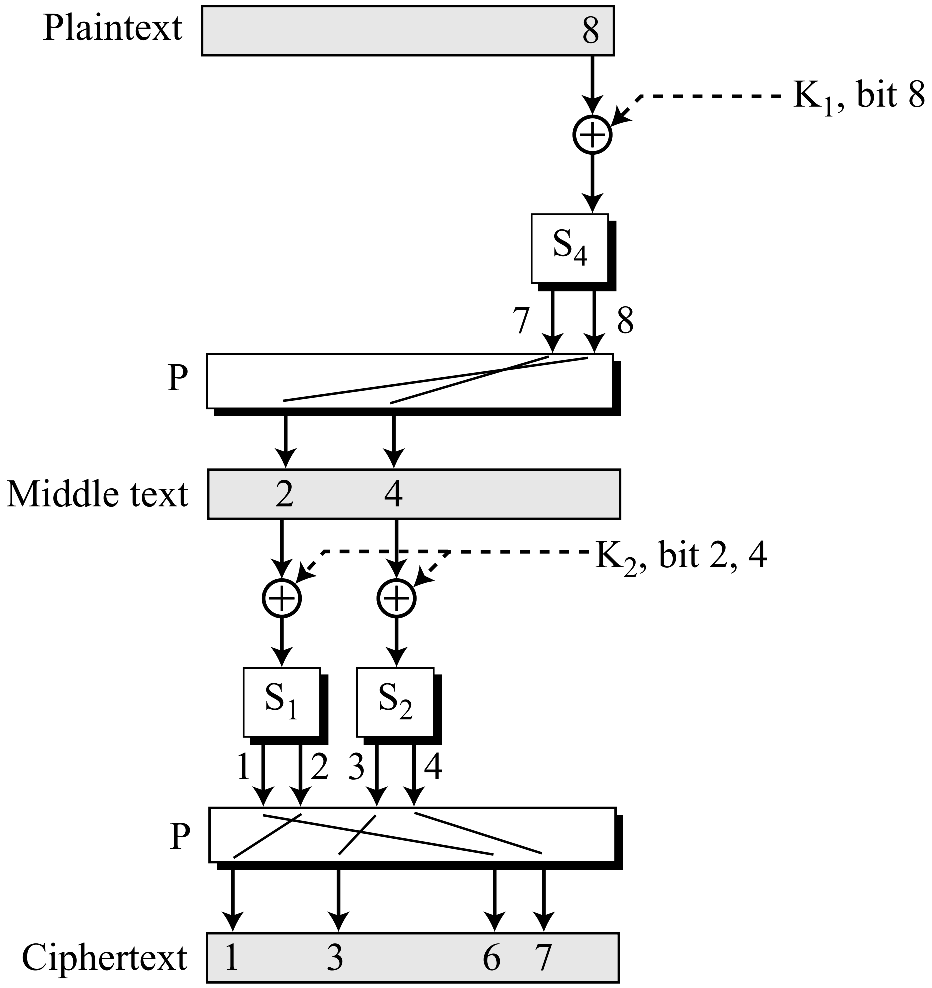
$$C = P \oplus f(K)$$

- $$P = C \oplus f(K)$$

Encryption: $C_1 = P_1 \oplus f(K)$

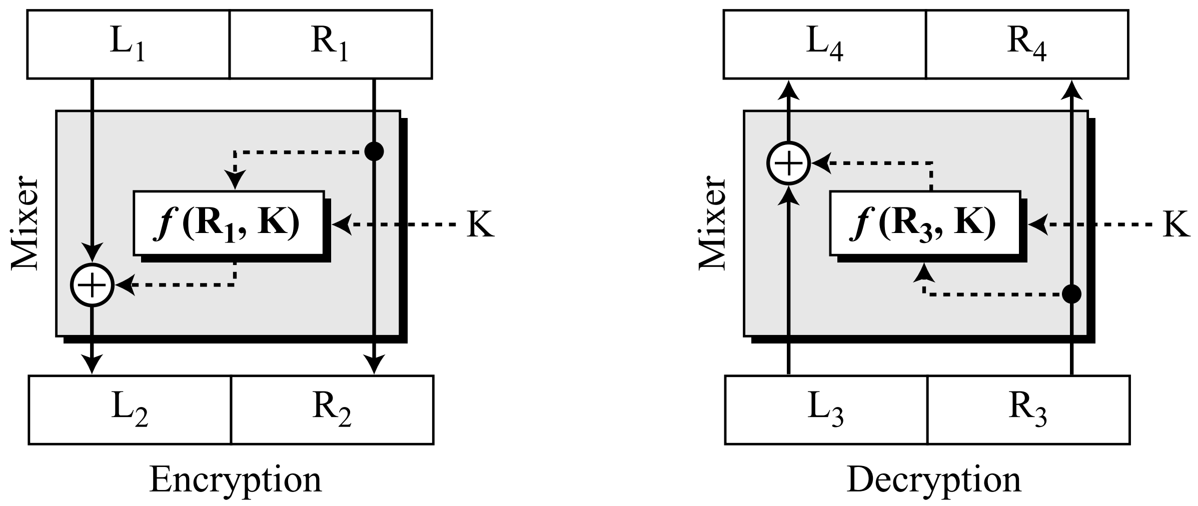
Decryption: $P_2 = C_2 \oplus f(K) = C_1 \oplus f(K) = P_1 \oplus f(K) \oplus f(K) = P_1 \oplus\ (00\ldots0) = P_1$

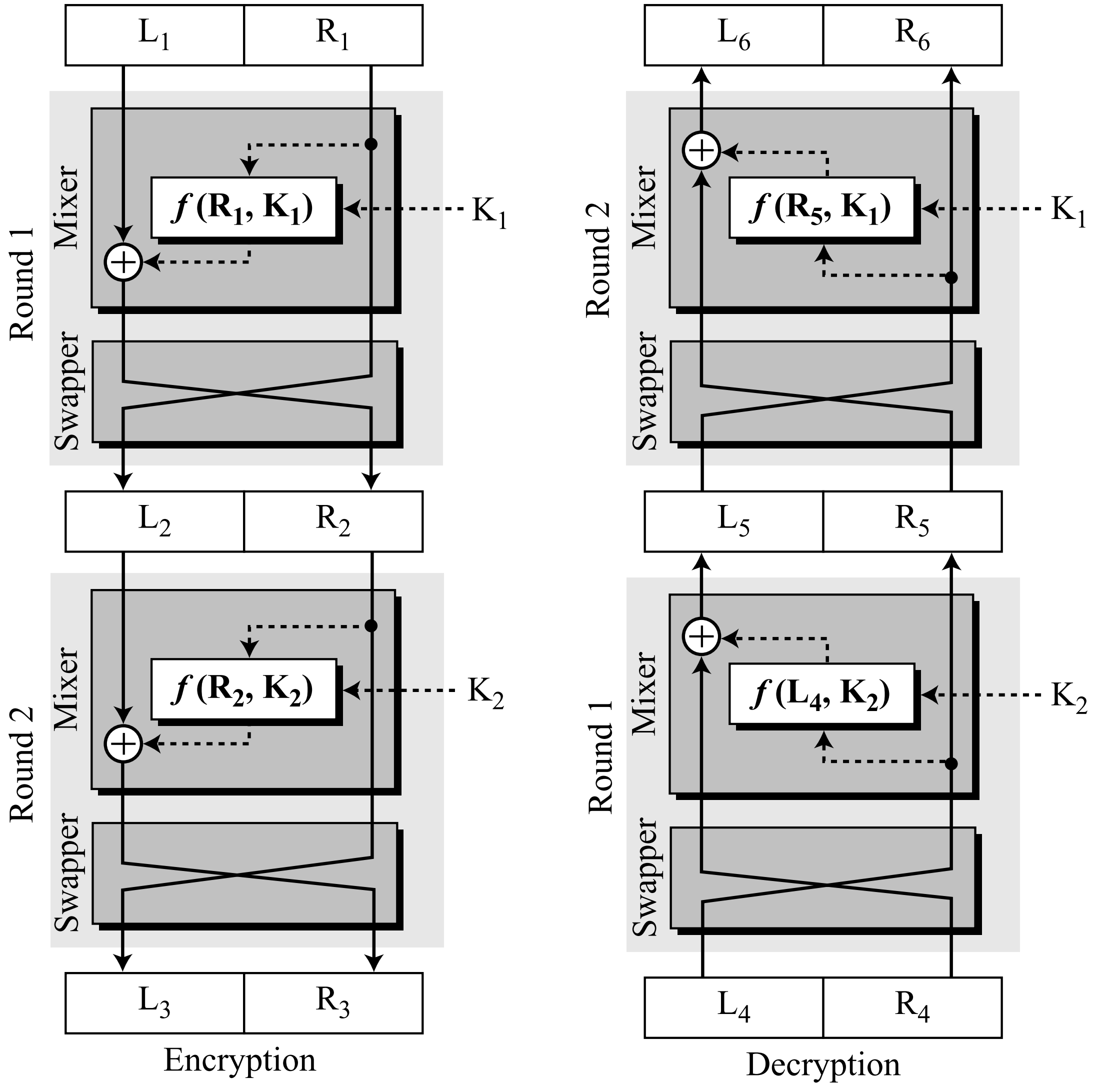
Example of Diffusion and Confusion



- Diffusion:
  - Bit-8 in P has affected bits 1, 3, 6,7 in C
  - Similarly, each bit in C is affected by several bits in P
- Confusion:
  - Bits 1, 3, 6, 7 in C affected by bit 8 in K_1 and bits 2, 4 in K_2

An Example Product Cipher: Feistel Cipher

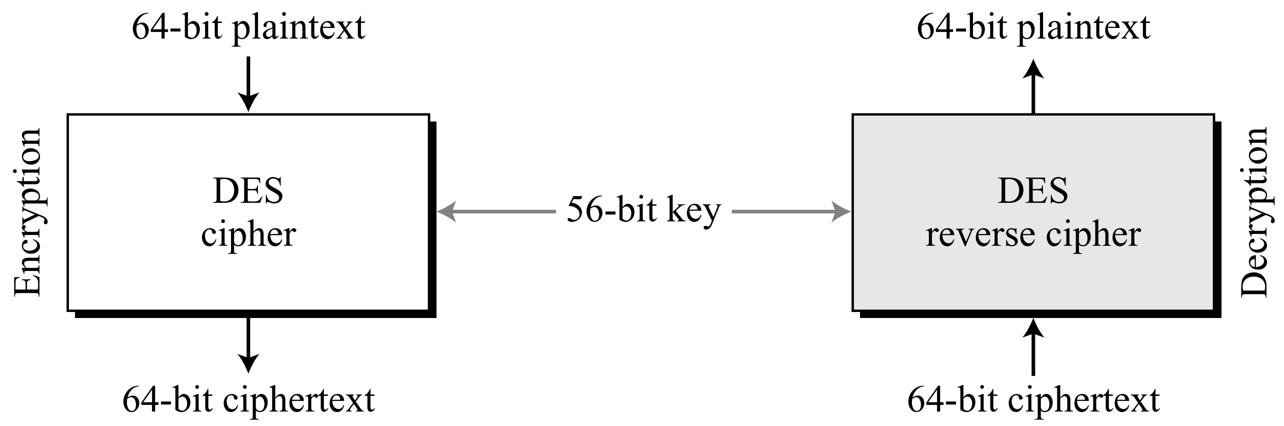




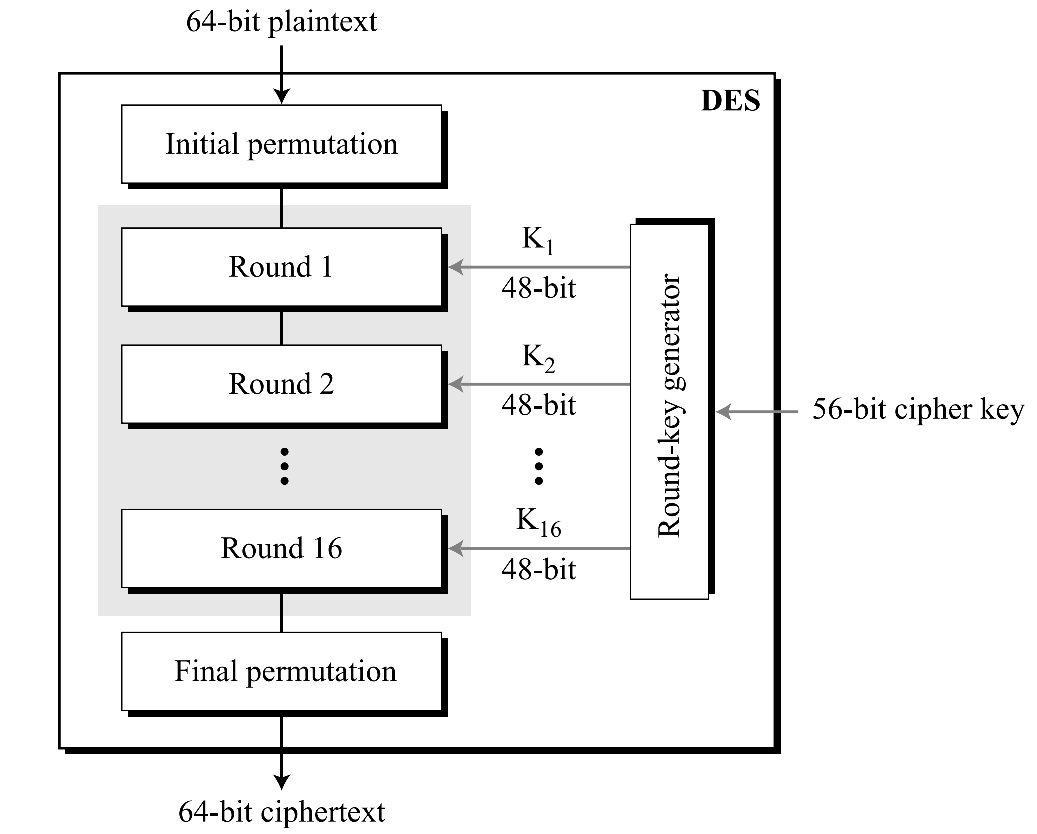
- $L_3 = L_2, R_3 = R_2$

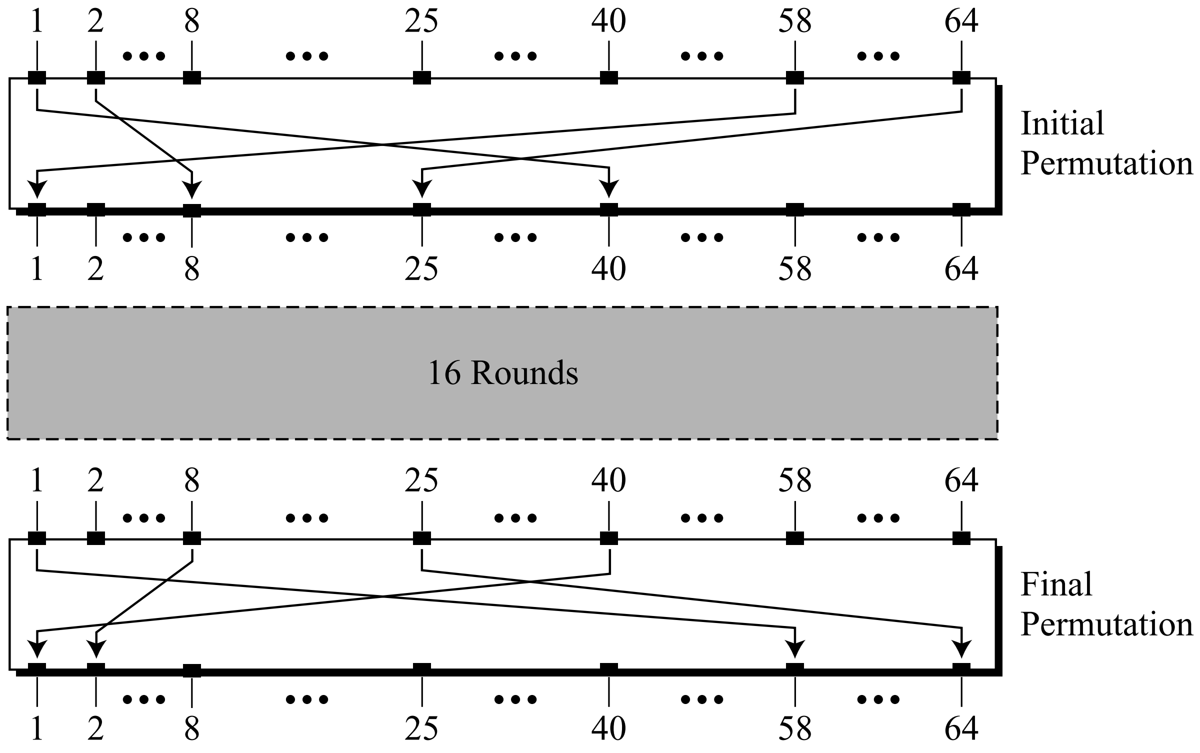
Data Encryption Standard (DES)

- DES was published by NIST ~1977, original proposal by IBM
- 64-bit block cipher (64-bit data block), and 56-bit key
- Proof (by IBM?) that the 56-bit partial size key cipher is not a subgroup of the full size key



High-Level Structure of DES





Initial Permutation	*Final Permutation*
58 50 42 34 26 18 10 02	40 08 48 16 56 24 64 32
60 52 44 36 28 20 12 04	39 07 47 15 55 23 63 31
62 54 46 38 30 22 14 06	38 06 46 14 54 22 62 30
64 56 48 40 32 24 16 08	37 05 45 13 53 21 61 29
57 49 41 33 25 17 09 01	36 04 44 12 52 20 60 28
59 51 43 35 27 19 11 03	35 03 43 11 51 19 59 27
61 53 45 37 29 21 13 05	34 02 42 10 50 18 58 26
63 55 47 39 31 23 15 07	33 01 41 09 49 17 57 25

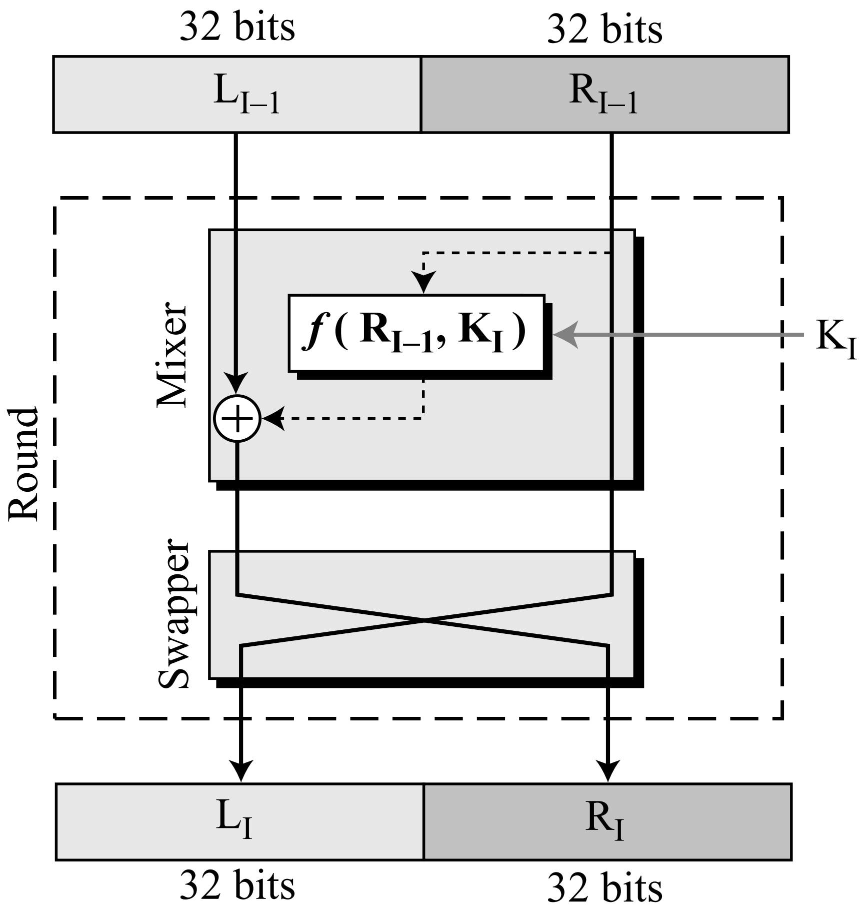
- Output bit 1 = input bit 58, and so on…

- There's been debate on the security significance of initial and final permutations — don't seem to add to security

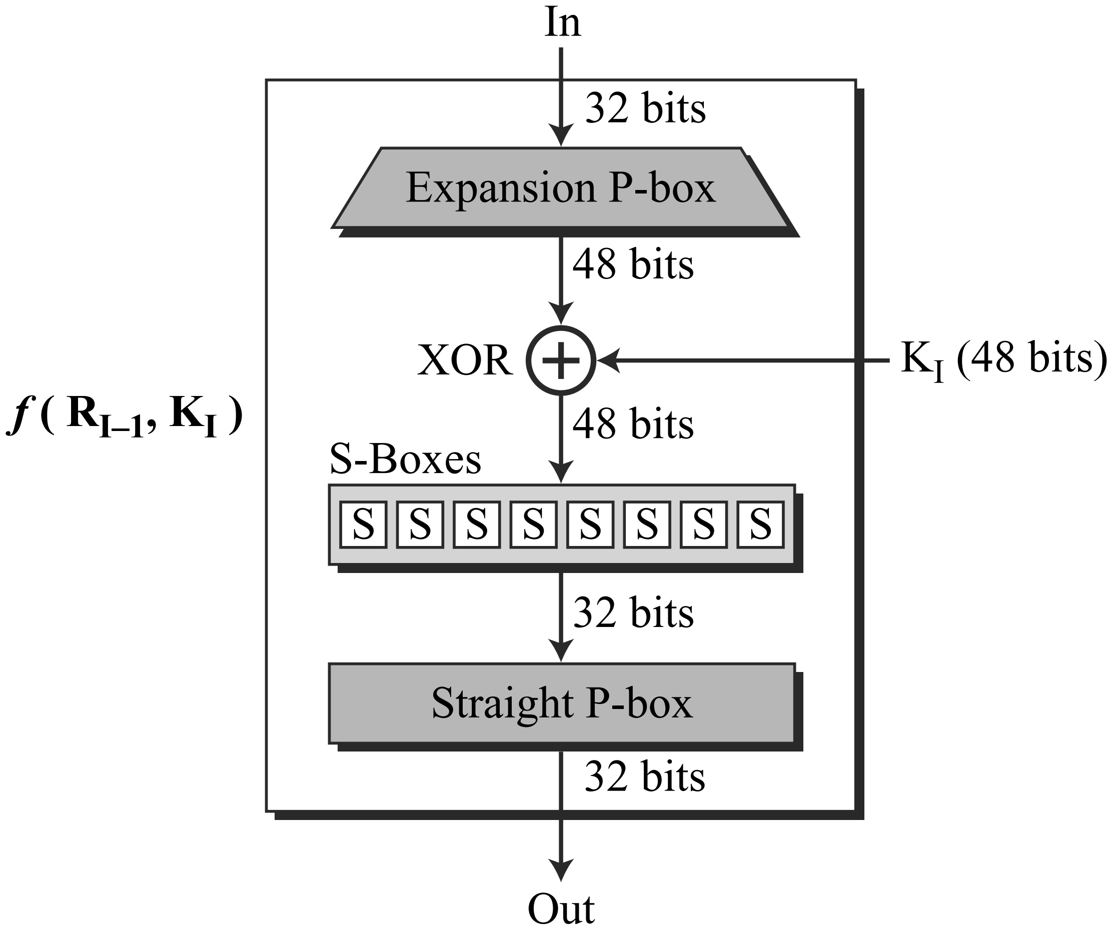
- Each DES Round = Feistel Cipher

- 16 DES Rounds

DES Round & Mixer Function



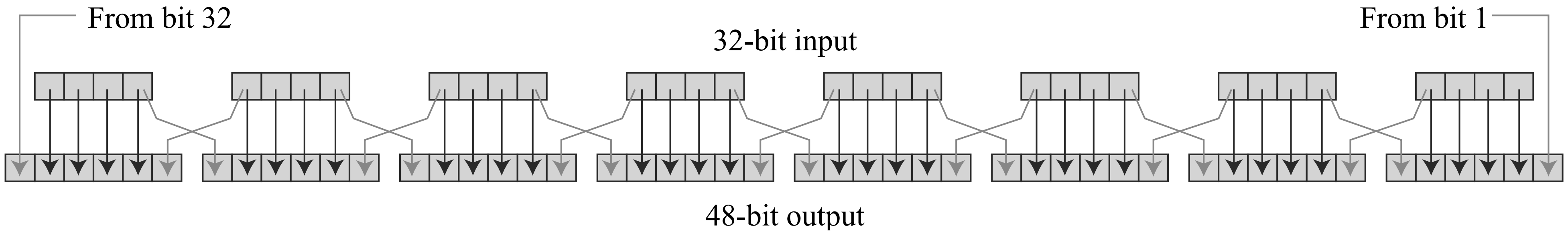
A Round in DES



The Mixer Function in DES

- The Expansion P-Box has a specified table (routing)
- Each of the 8 S-boxes has a separate 6-bit → 4-bit table
- The last P-box is also a permutation table (routing)

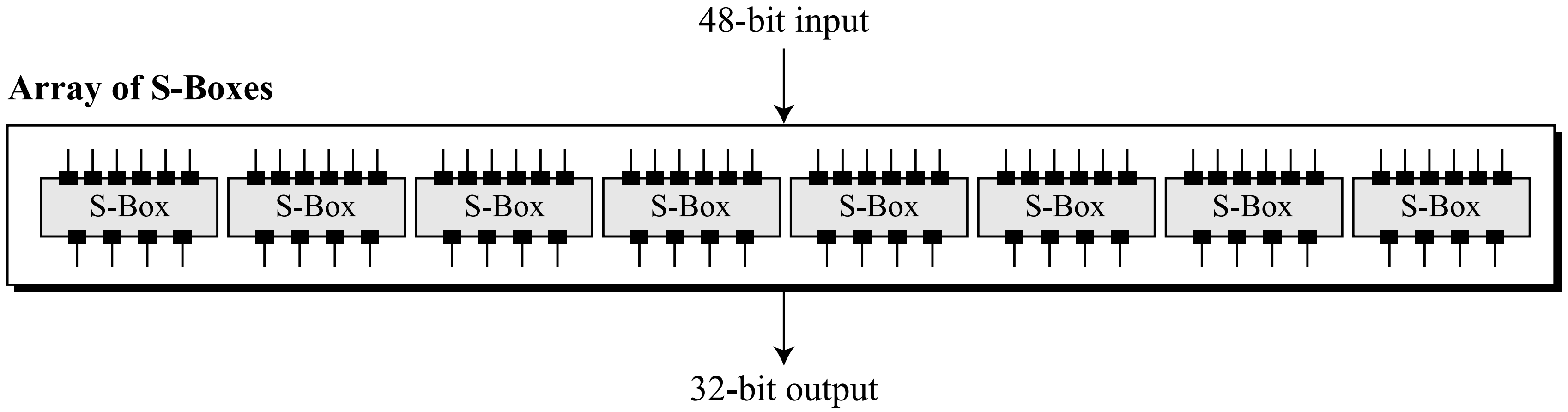
Details of DES Function: Expansion P-Box

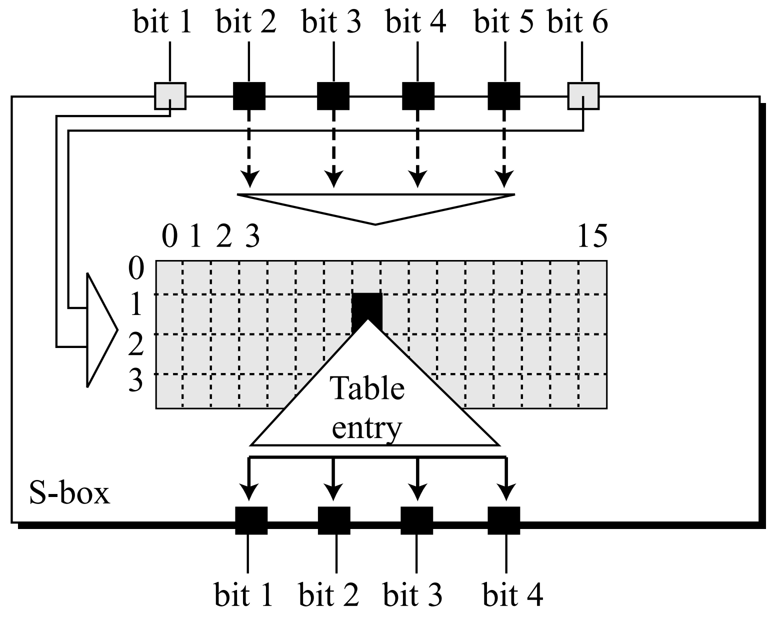


32	01	02	03	04	05
04	05	06	07	08	09
08	09	10	11	12	13
12	13	14	15	16	17
16	17	18	19	20	21
20	21	22	23	24	25
24	25	26	27	28	29
28	29	30	31	32	01

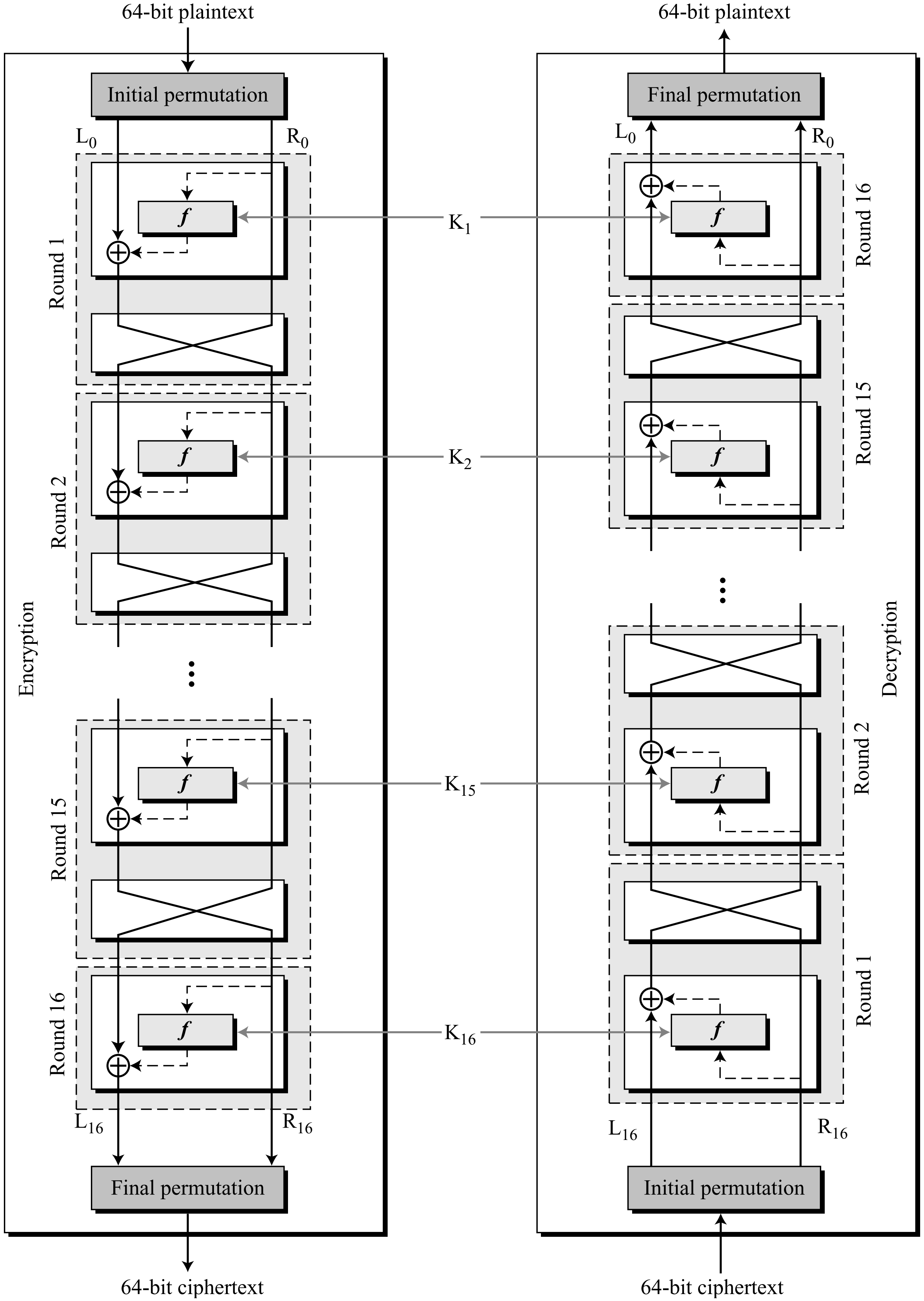
- The Expansion Permutation P-Box of the DES function
- It’s just wiring…

Details of DES Function: S-Boxes





- Each S-Box is a different polynomial function: $\mathbb{F}_{2^6} \to \mathbb{F}_{2^4}$
- Or as a truth table of a 6-input, 4 output Boolean function: $\mathbb{B}^6 \to \mathbb{B}^4$
- Each of the 8 truth tables are different — are provided in the DES Spec



- The Final DES Cipher and Reverse Cipher

- Round 16 does not have a swap

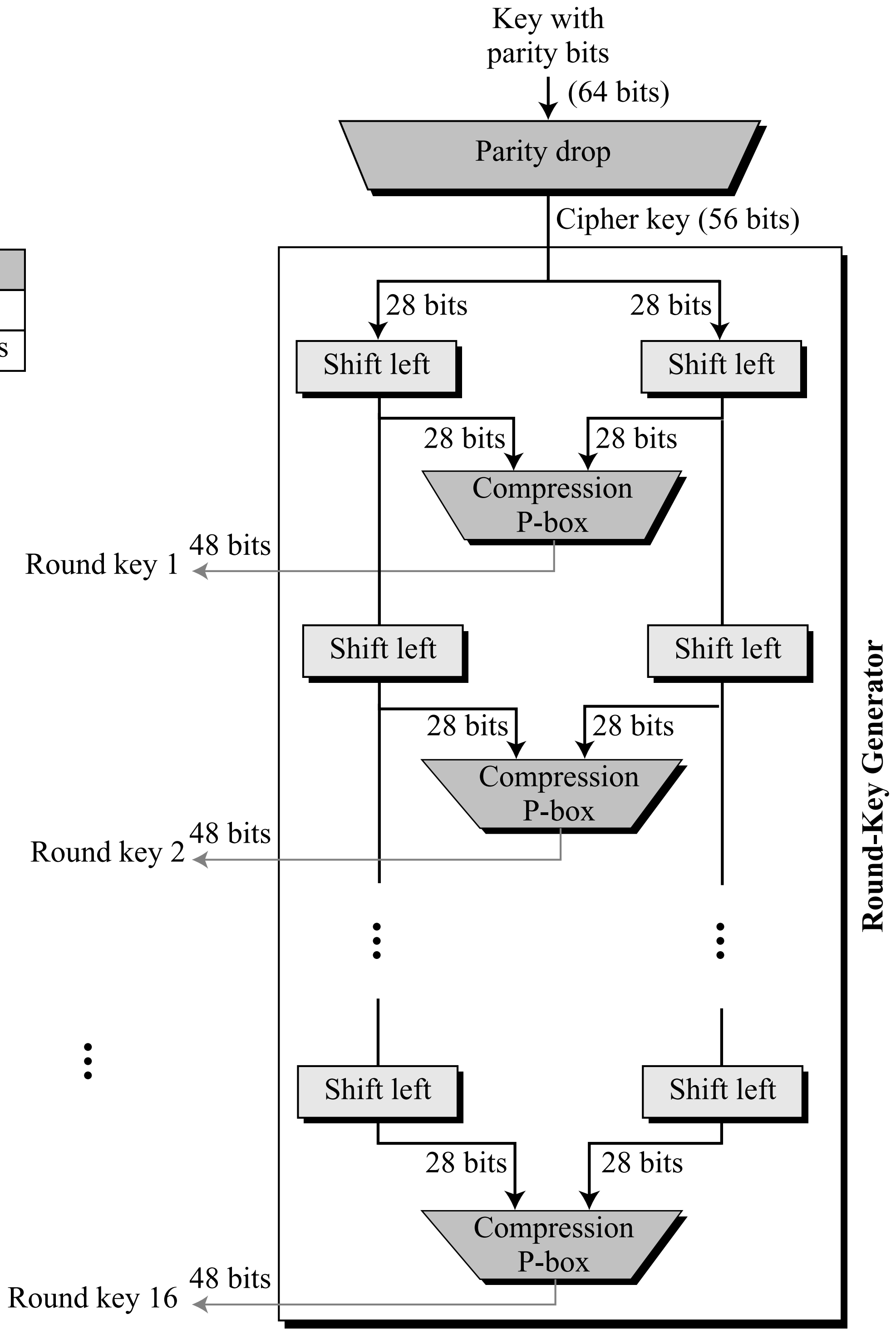
Key Generation for Each Round

- Key Generator takes a 56-bit Key (K)
- Keys are usually provided with 8 parity bits: Adds 8 parity bits to get 64-bit key after every 7 key bits
- These parity bits are dropped before the real key generation
- Generates 16 48-bit Keys (K1, …, K16) from K

Key Generation View

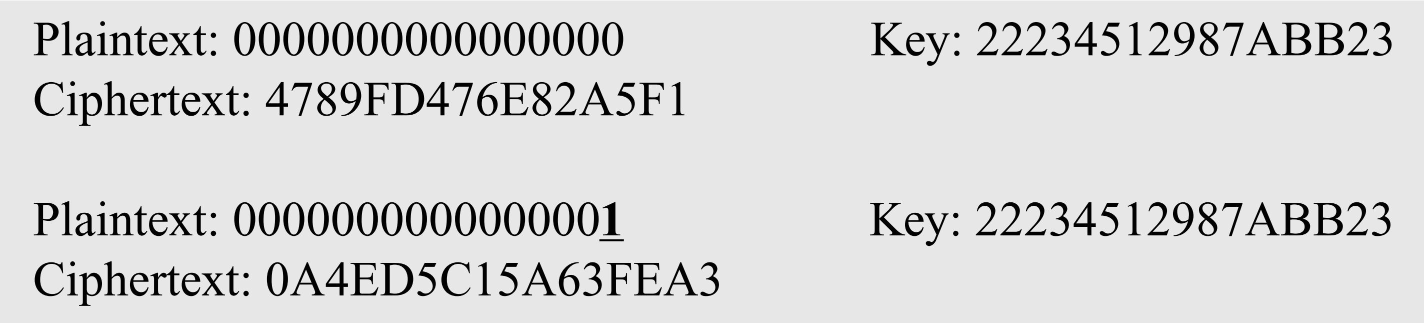
Shifting

Rounds	Shift
1, 2, 9, 16	one bit
Others	two bits



- Shifts = circular shifts
- All compression P-Box Truth Tables are specified
- Verilog Code for DES is available on the internet
- Never been a good HW problem :)
- I have a DES.blif logic circuit (which can transformed into Verilog)

Other Aspects of DES

- IBM released the design rationale for choices of DES blocks ~1994, as well as their effects
- Avalanche effects: Small change in input, significant change in the output:
- 

  Plaintext: 0000000000000000 Key: 22234512987ABB23
  Ciphertext: 4789FD476E82A5F1

  Plaintext: 000000000000000**1** Key: 22234512987ABB23
  Ciphertext: 0A4ED5C15A63FEA3

- Each bit in C depends on various bits of P
- Various publications have also found weaknesses in DES
- Significant criticism came about Key size & Weak Keys: Will study them next week