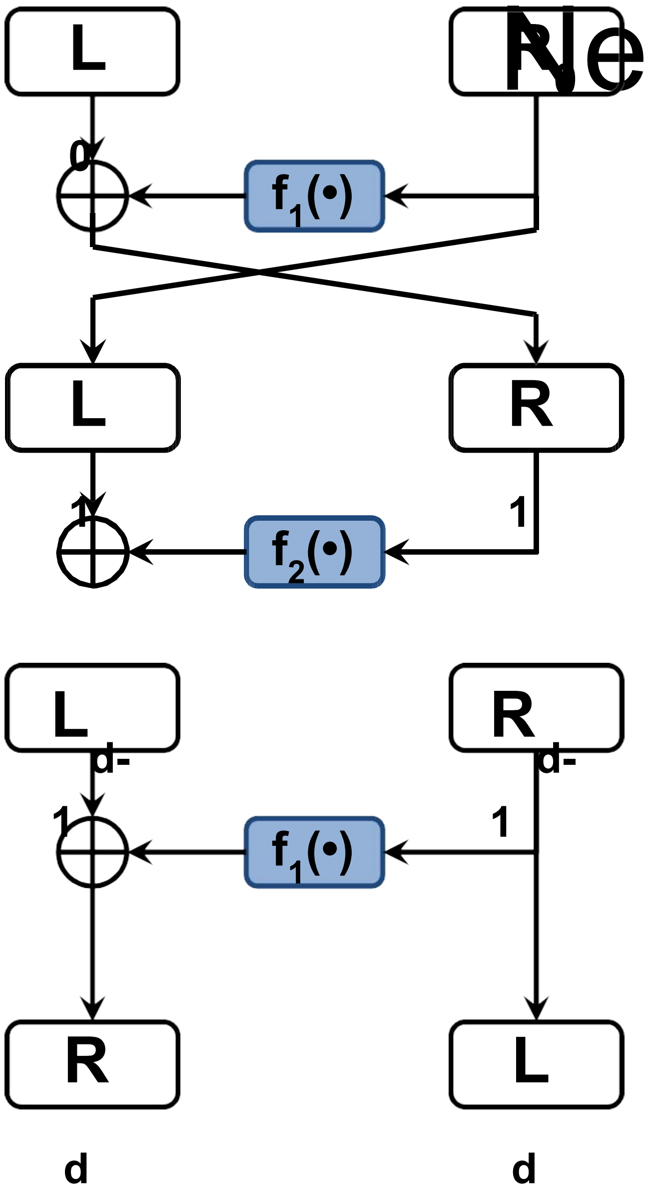
Data Encryption Standard (DES)

Feistel Network

- Several block ciphers are based on the structure proposed by *Feistel* in 1973
- A *Feistel Network* is fully specified given
  - the *block size*: $n = 2w$
  - *number of rounds*: d
  - d *round functions* $f_1, \ldots, f_d$: $\{0,1\}^w$ € $\{0,1\}^w$
- Used in DES, IDEA, RC5 (Rivest's Cipher n. 5), and many other block ciphers.
- Not used in AES

Feistel Network



- **Encryption**:
  - $L_1 = R_0$ $R_1 = L_0 \oplus f_1(R_0)$
  - $L_2 = R_1$ $R_2 = L_1 \oplus f_2(R_1)$

    …
  - $L_d = R_{d-1}$ $R_d = L_{d-1} \oplus f_d(R_{d-1})$
- **Decryption**:
  - $R_{d-1} = L_d$ $L_{d-1} = R_d \oplus f_d(L_d)$

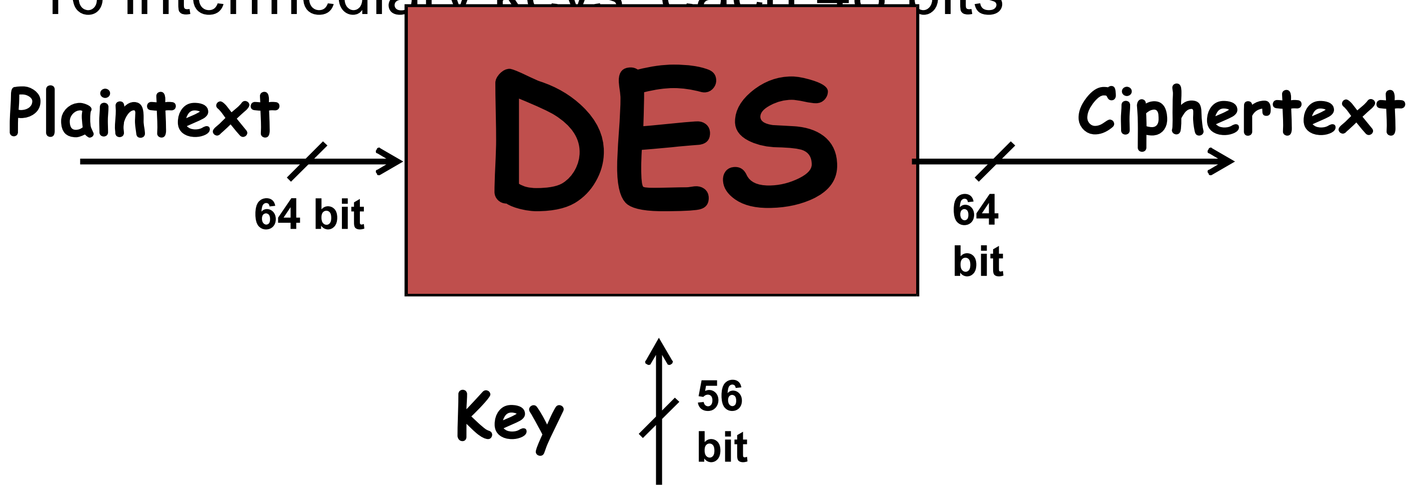
    …
  - $R_0 = L_1$; $L_0 = R_1 \oplus f_1(L_1)$

A Word About NIST and Standards

- “Founded in 1901 NIST, the *National Institute of Standards and Technology*, (former NBS) is a non- regulatory federal agency within the U.S. Commerce Department’s Technology Administration.
- NIST‘s mission is to develop and promote measurement, standards, and technology to enhance productivity, facilitate trade, and improve the quality of life.”
- Cryptographic Standards & Applications.
- Federal Information Processing Standards (FIPS): define security standards

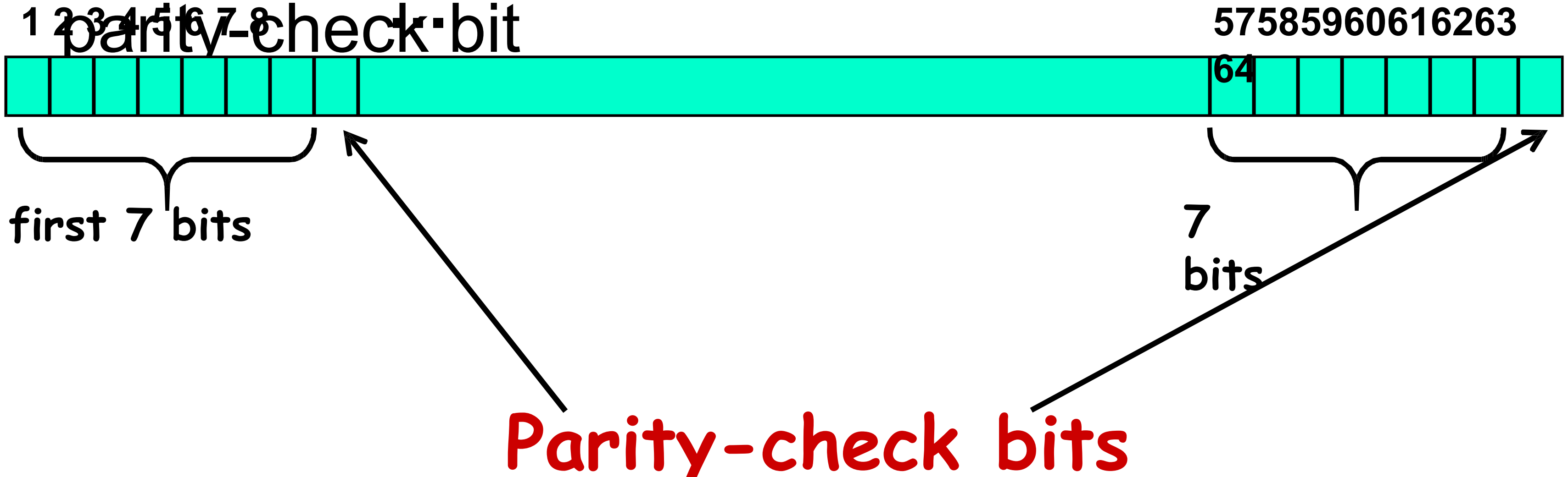
DES Features

- Features:
  - Block size = 64 bits
  - Key size = 56 bits (in reality, 64 bits, but 8 are used as parity-check bits for error control, see next slide)
  - Number of rounds = 16
  - 16 intermediary keys, each 48 bits



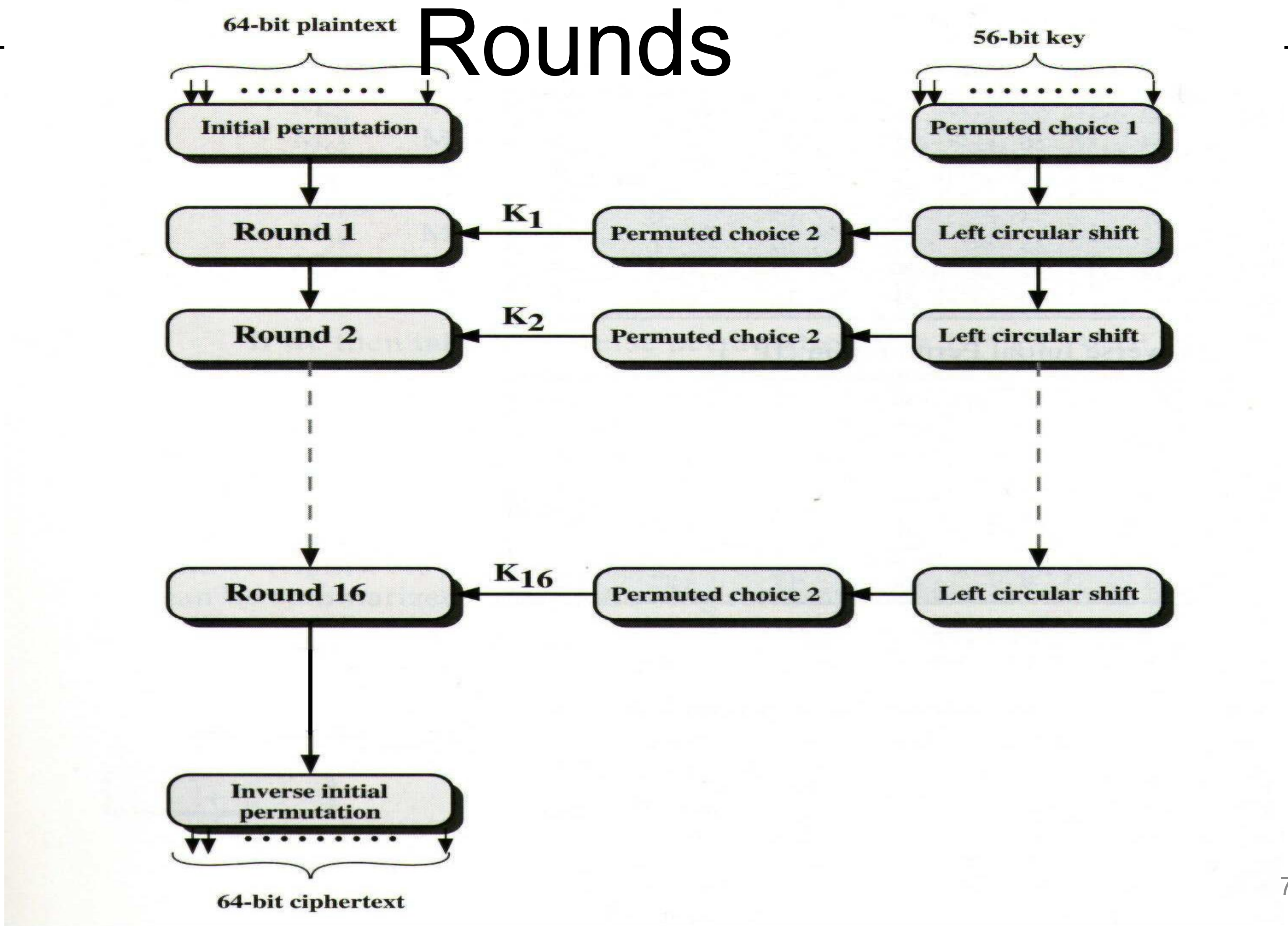
Key length in DES

- In the DES specification, the key length is 64 bit:
- 8 bytes; in each byte, the 8th bit is a parity-check bit



Each parity-check bit is the XOR of the previous 7 bits

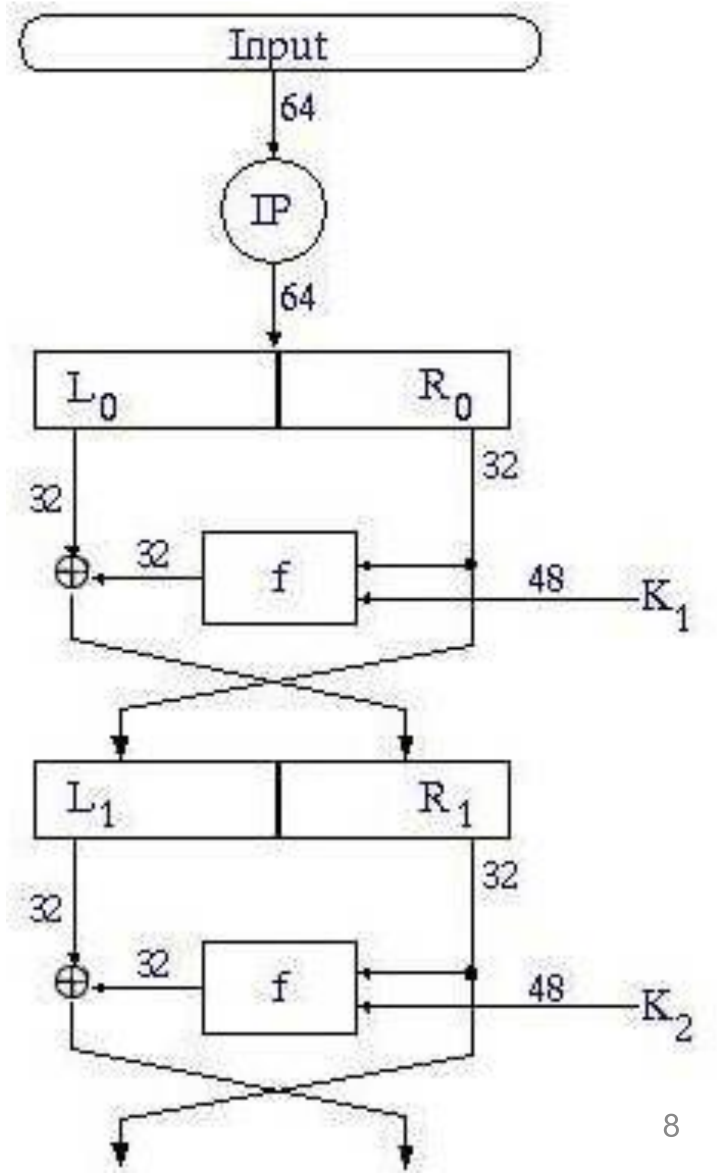
DES Rounds


64-bit plaintext
56-bit key
Initial permutation
Permuted choice 1
Round 1
K_1
Permuted choice 2
Left circular shift
Round 2
K_2
Permuted choice 2
Left circular shift
Round 16
K_{16}
Permuted choice 2
Left circular shift
Inverse initial permutation
64-bit ciphertext

Details

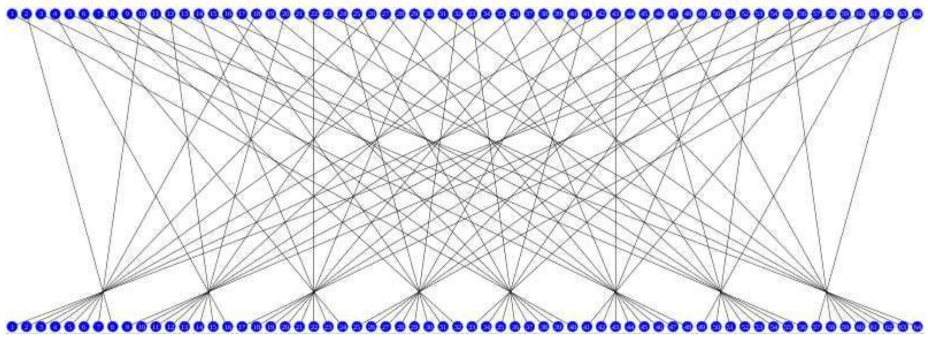
- $IP(x) = L_0R_0$
- $L_i = R_{i-1}$
- $R_i = L_{i-1} \oplus f(R_{i-1}, K_i)$
- $y = IP^{-1}(R_{16}L_{16})$

Note: IP means Initial Permutation



Initial Permutation (IP)

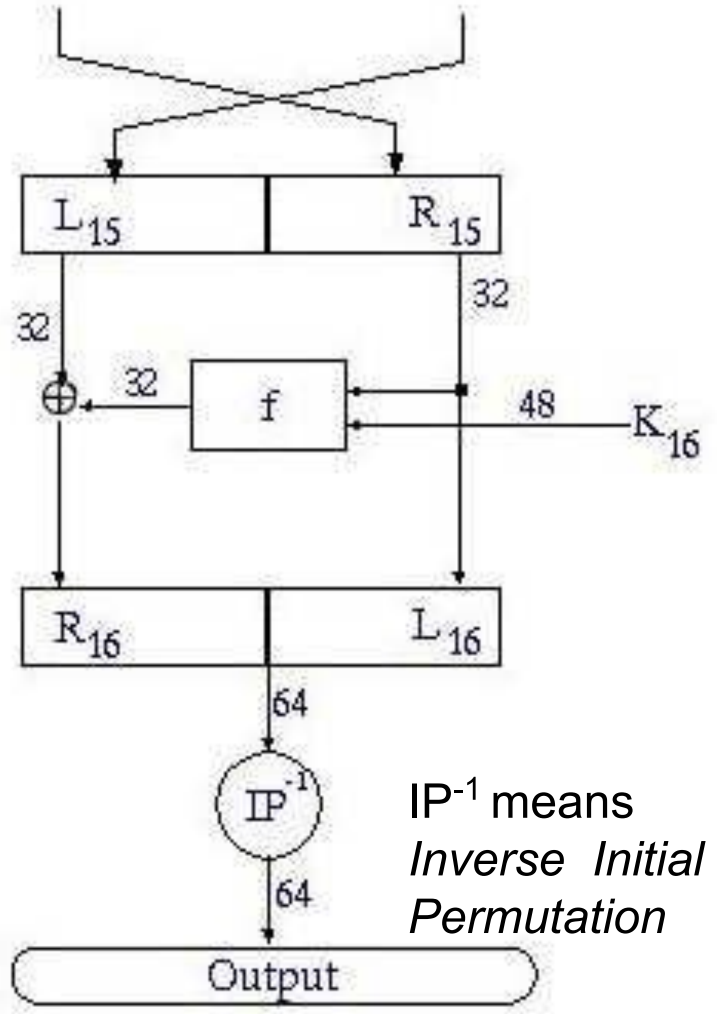
58	50	42	34	26	18	10	2
60	52	44	36	28	20	12	4
62	54	46	38	30	22	14	6
64	56	48	40	32	24	16	8
57	49	41	33	25	17	9	1
59	51	43	35	27	19	11	3
61	53	45	37	29	21	13	5
63	55	47	39	31	23	15	7



- This table specifies the input permutation on a 64-bit block.
- The meaning is as follows:
  - the first bit of the output is taken from the 58th bit of the input; the second bit from the 50th bit, and so on, with the last bit of the output taken from the 7th bit of the input.
- This information is presented as a table for ease of presentation:
  - it is a vector, not a matrix.

DES Rounds

- $IP(x) = L_0R_0$
- $L_i = R_{i-1}$
- $R_i = L_{i-1} \oplus f(R_{i-1}, K_i)$
- $y = IP^{-1}(R_{16}L_{16})$
- Note that, as usual:
  - $R_{16} = L_{15} \oplus f(R_{15}, K_{16})$
  - $L_{16} = R_{15}$
- … but they are *switched* in the pre-output

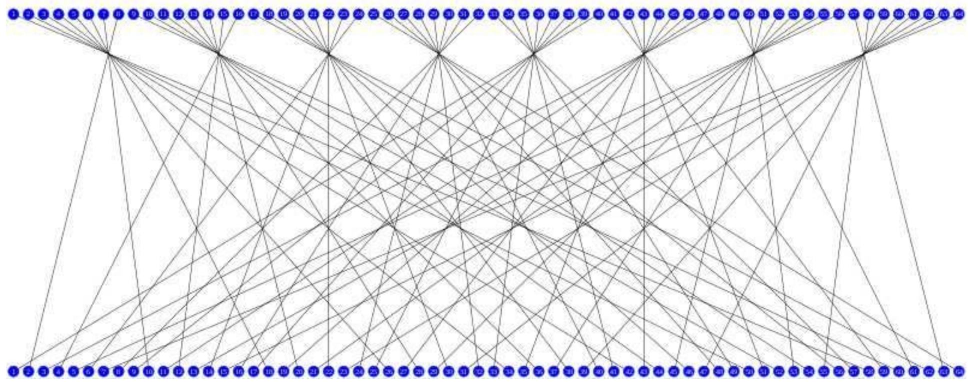


y

IP^{-1} means *Inverse Initial Permutation*

Final Permutation (IP^{-1})

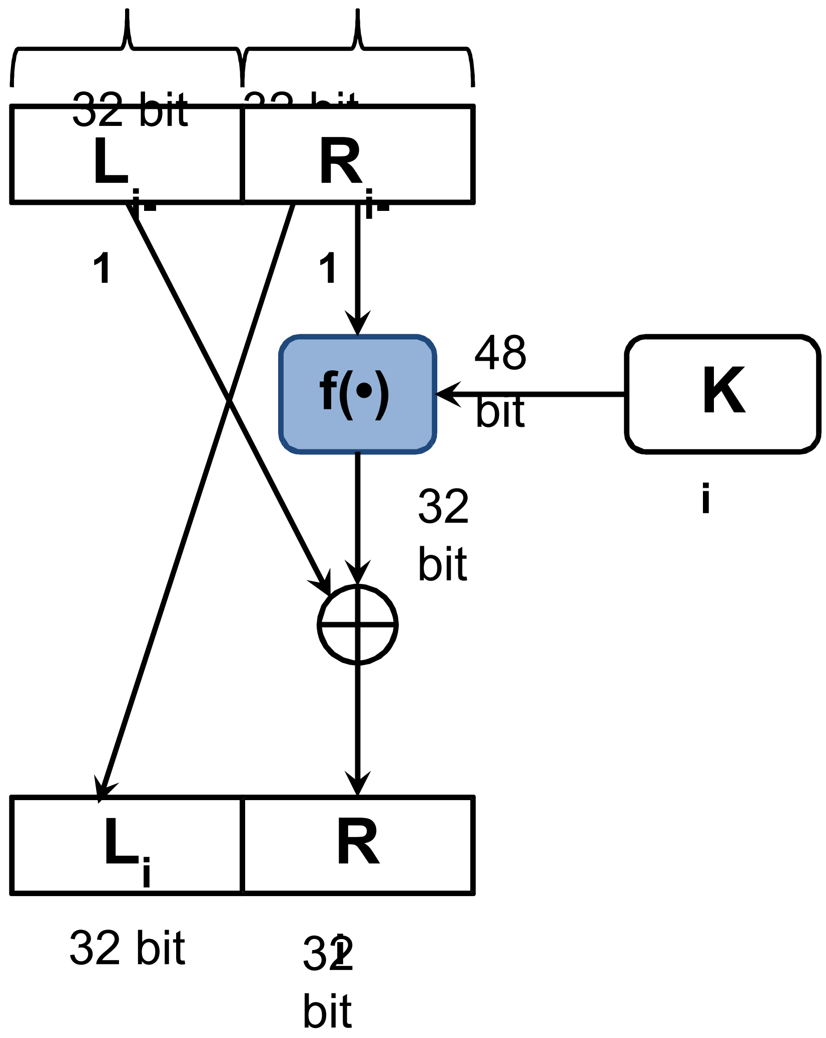
40	8	48	16	56	24	64	32
39	7	47	15	55	23	63	31
38	6	46	14	54	22	62	30
37	5	45	13	53	21	61	29
36	4	44	12	52	20	60	28
35	3	43	11	51	19	59	27
34	2	42	10	50	18	58	26
33	1	41	9	49	17	57	25



- The final permutation is the *inverse* of the initial permutation; the table is interpreted similarly.
  - That is, the output of the *Final Permutation* has bit 40 of the preoutput block as its first bit, bit 8 as its second bit, and so on, until bit 25 of the preoutput block is the last bit of the output.

DES Round i

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

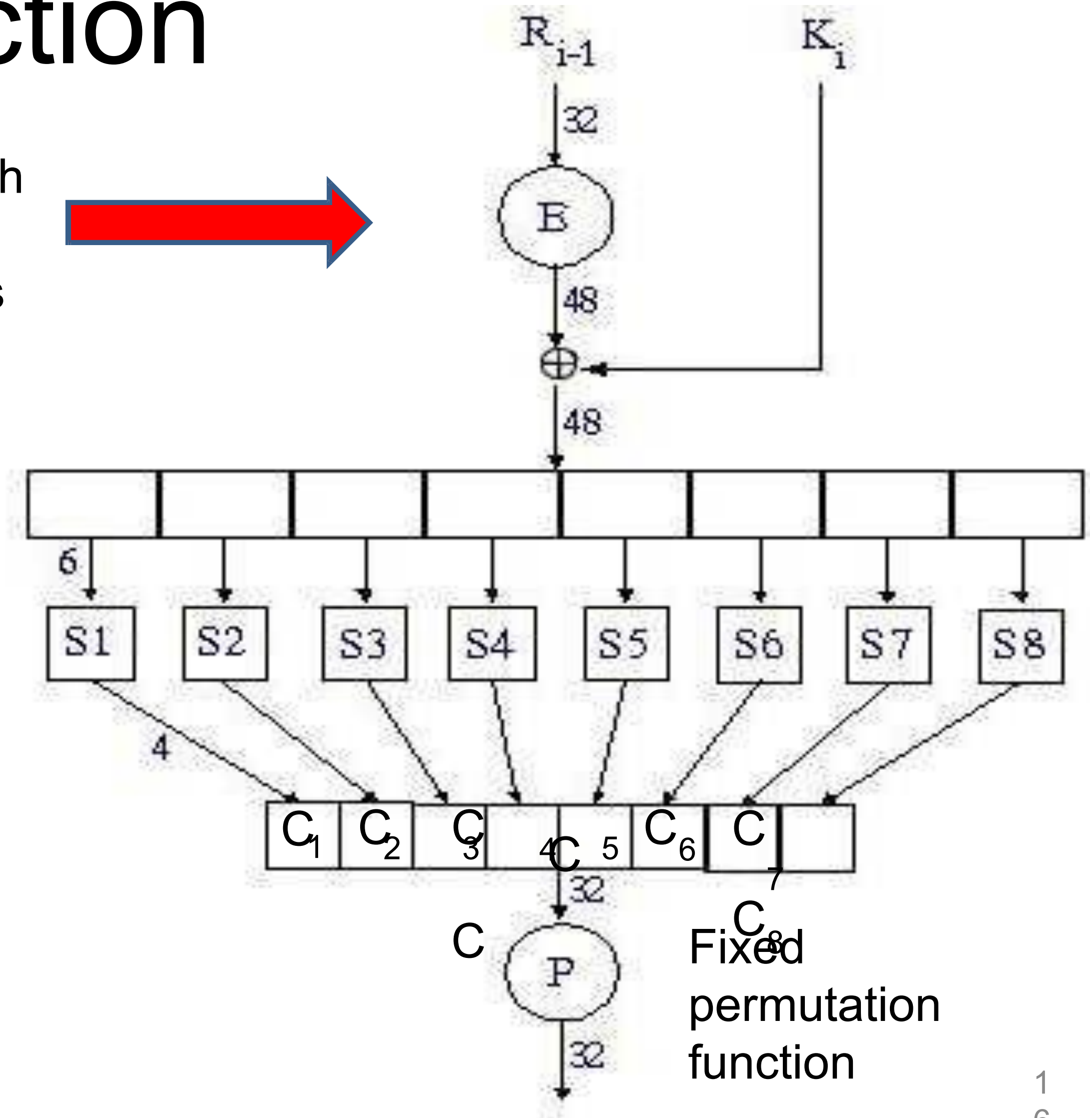


DES "f(•)" Function

E is an *expansion function* which takes a block of 32 bits as input and produces a block of 48 bits as output

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

16 bits appear twice, in the expansion

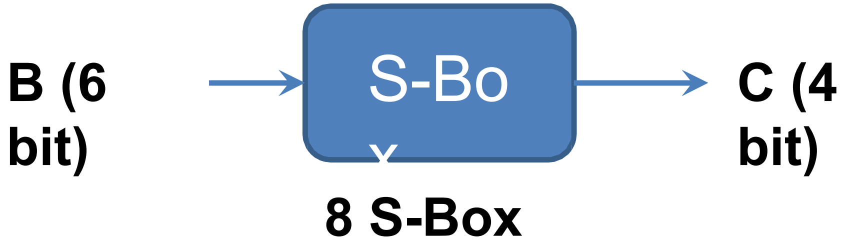


Fixed permutation function

S-boxes

- S-boxes are the only *non-linear* elements in DES design

Each of the unique selection functions $\mathbf{S_1,S_2,\ldots,S_8}$, takes a 6-bit block as input and yields a 4-bit block as output



- S = matrix 4x16, values from 0 to 15
- B (6 bit long) = $b_1b_2b_3b_4b_5b_6$
  - b_1b_6 € r = row of the matrix (2 bits: 0,1,2,3)
  - $b_2b_3b_4b_5$ € c = column of the matrix (4 bits:0,1,...15)
- C (4 bit long) = Binary representation of S(r, c)

Example (S1)

Row #	S_1 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15 Column #
0	14	4	13	1	2	15	11	8	3	10	6	12	5	9	0	7
1	0	15	7	4	14	2	13	1	10	6	12	11	9	5	3	8
2	4	1	14	8	13	6	2	11	15	12	9	7	3	10	5	0
3	15	12	8	2	4	9	1	7	5	11	3	14	10	0	6	13

S(i, j) <16, can be represented with 4 bits

Example: B =101111

b_1b_6 = 11 = row 3

$b_2b_3b_4b_5$= 0111 = column 7

C=7=<u>0111</u>

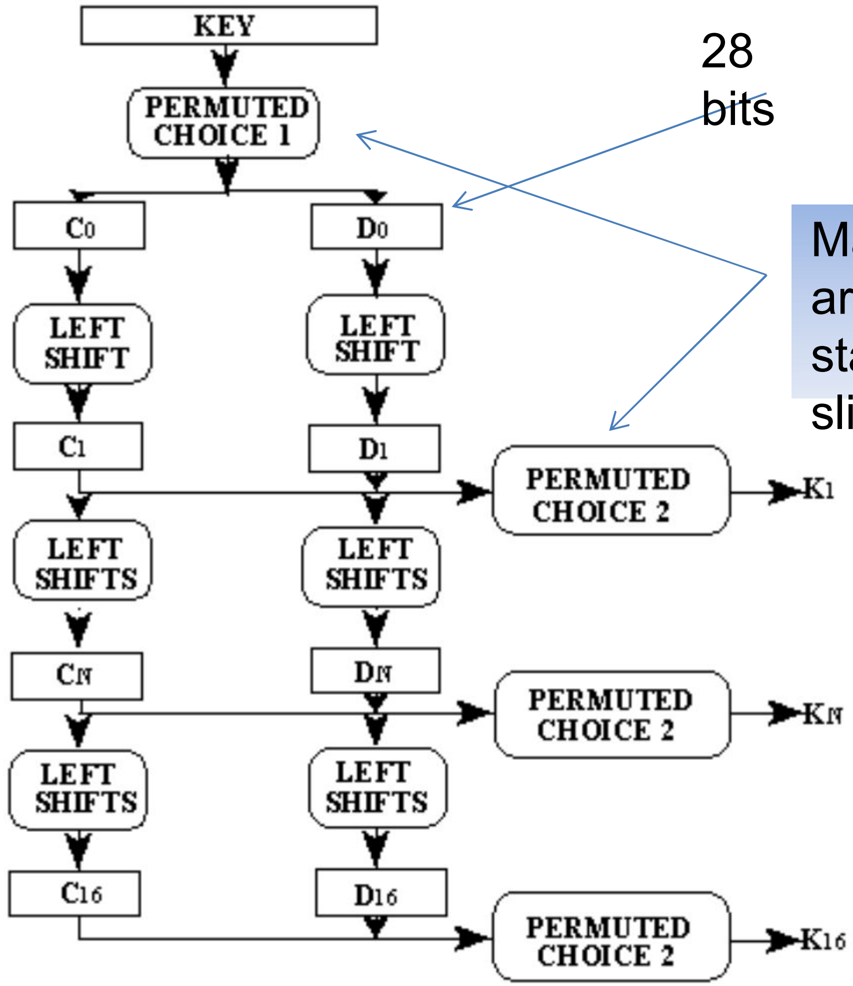
Another example: B=011011, C=?

DES Key Generation (K_1 – K_{16})

64 bit key (including parity-check bits)

28 bits

28 bits



Matrix PC-1 and PC-2 are given by the standard (see next slide)

48 bits

$C_i=LS_i(C_{i-1})$
$D_i=LS_i(D_{i-1})$
$K_i=PC\text{-}2(C_i D_i)$
LS=Left Shift
-shift *one* position if i=1,2,9 or 16
-shift *two* positions otherwise

DES Permuted Choice 1 and 2 (PC-1, PC-2)

Parity-check bits (namely, bits 8,16, 4,32,40,48,56,64) are not chosen, they do not appear in **PC-1**

Left						
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
Right						
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

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

PC-2 selects the 48-bit subkey for each round from the 56-bit key-schedule state

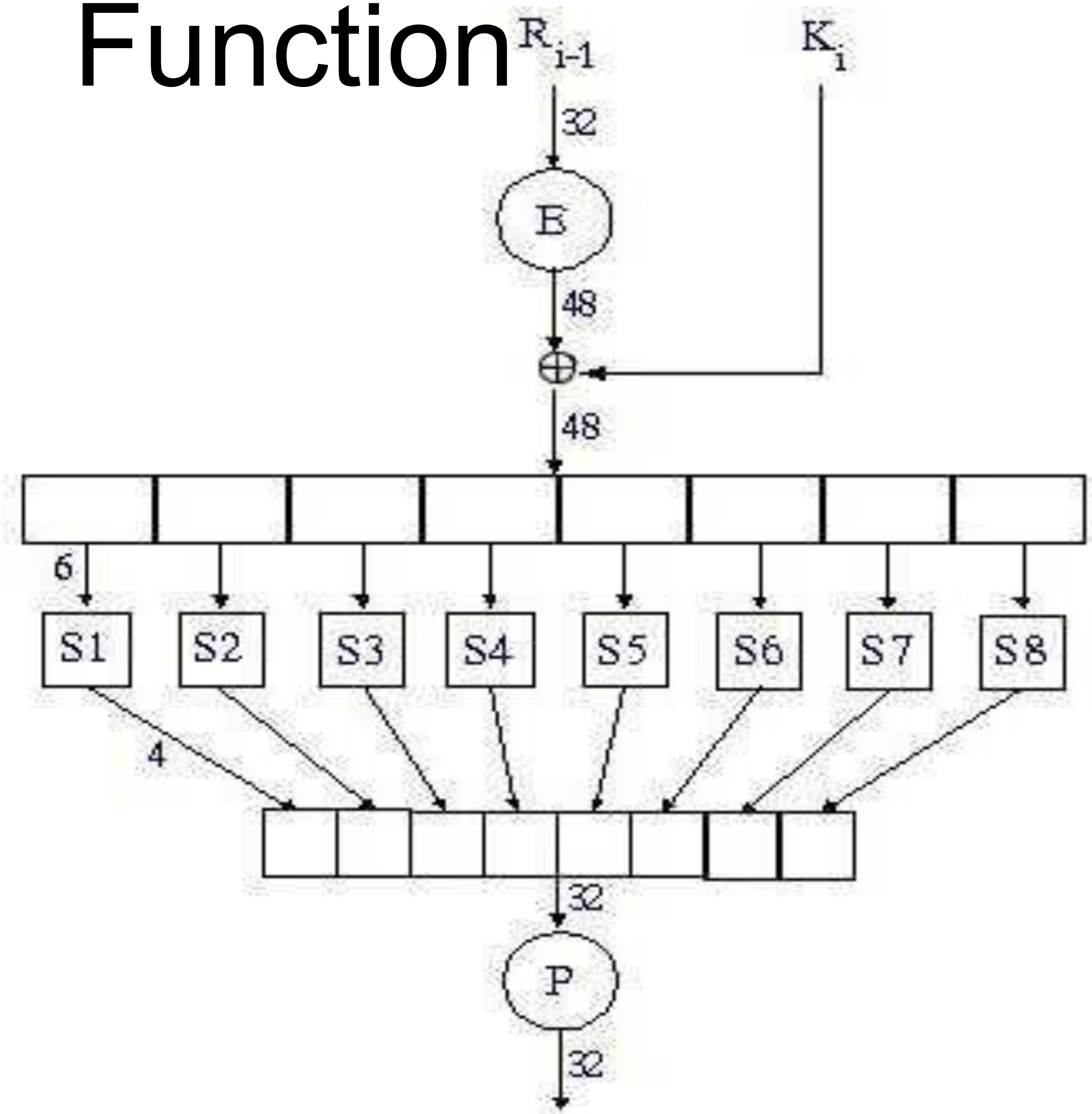
DES Weak Keys

- DES uses 16 48-bits keys generated from a master 56- bit key (64 bits if we consider also parity bits)
- Weak keys: keys make the same sub-key to be generated in more than one round.
- Result: reduce cipher complexity
- Weak keys can be avoided at key generation.
- DES has 4 weak keys
  - 01010101 01010101
  - FEFEFEFE FEFEFEFE
  - E0E0E0E0 F1F1F1F1
  - 1F1F1F1F 0E0E0E0E

DES Decryption

- Decryption uses the same algorithm as encryption, except that the subkeys K_1, K_2, …K_{16} are applied in reversed order

DES “f(•)” Function



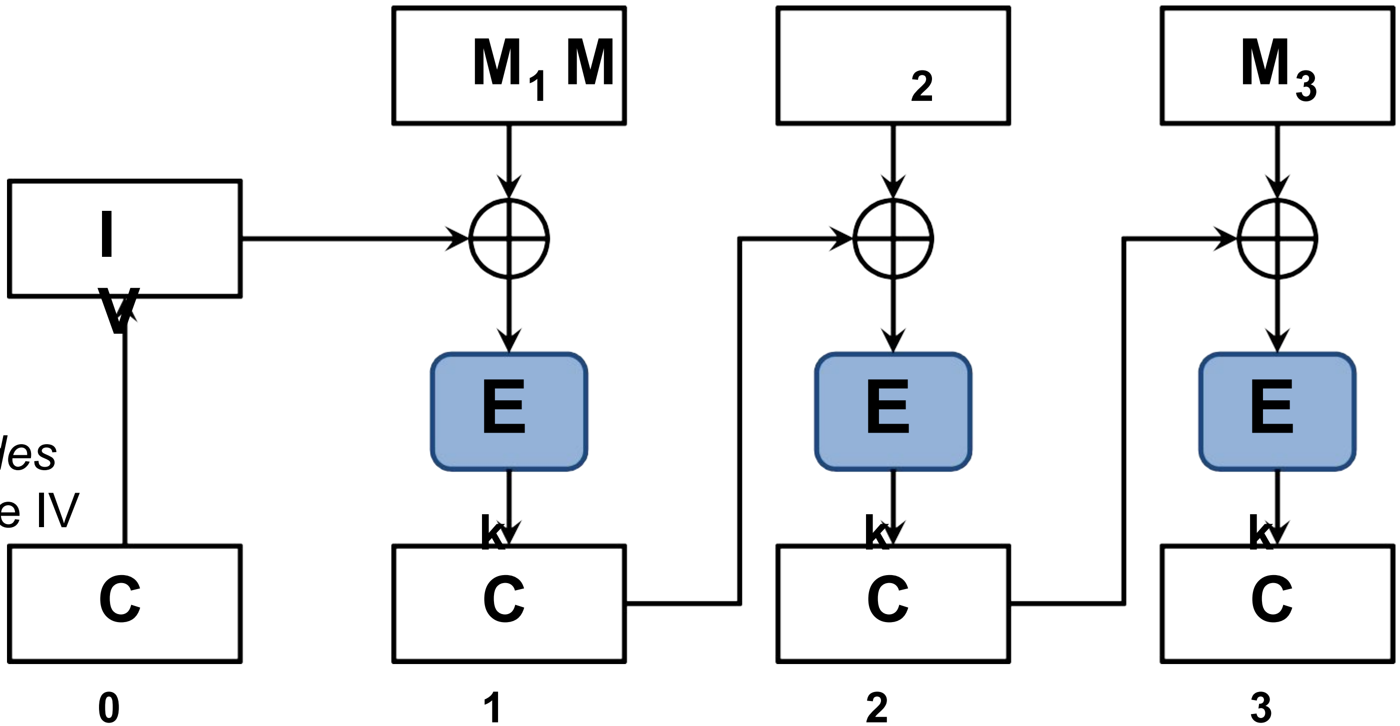
Salt

- 12-bit Salt is chosen randomly, stored with the password
- Salt creates 4096 different DES functionings: if the ith bit of the salt is set (non-zero), then the bits i and i+24 of the output of the expansion function are swapped.
- Result: same password will have different encryptions in the password file

DES Encryption Modes: CBC

- **Cipher Block Chaining** (**<u>CBC</u>**): *next* input depends upon *previous* output
- **Encryption**: $C_i = E_k(M_i \oplus C_{i-1})$, with C_0=IV
- **Decryption**: $M_i = C_{i-1} \oplus D_k(C_i)$, with C_0=IV

E_k = DES encryption function
D_k = DES decryption function



C_0 *coincides* with the IV

Properties of CBC

- Randomized encryption: repeated text gets mapped to different encrypted data.
  - can be proven to be "secure" assuming that the block cipher has desirable properties and that ***random IV's*** are used

- A ciphertext block depends on all preceding plaintext blocks; reorder affects decryption

- Errors in one block propagate to two blocks
  - one bit error in C_j affects all bits in M_j and one bit in M_{j+1}

- Sequential encryption, cannot use parallel hardware

Usage: chooses random IV and protects the integrity of IV

Observation:

if $\mathbf{C_i = C_j}$ then $E_k(M_i \oplus C_{i-1}) = E_k(M_j \oplus C_{j-1})$; thus $\mathbf{M_i \oplus C_{i-1} = M_j \oplus C_{j-1}}$

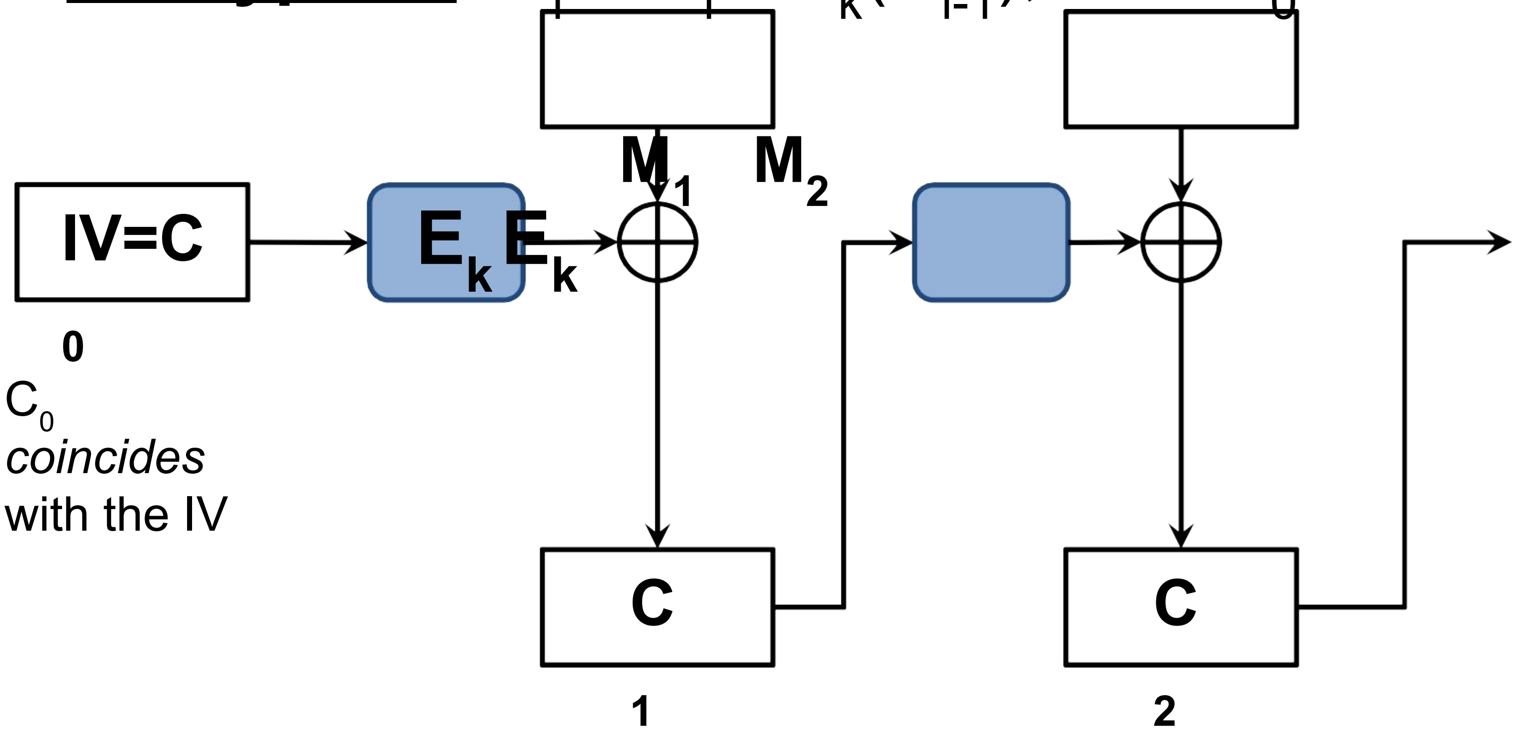
thus $\mathbf{M_i \oplus M_j = C_{i-1} \oplus C_{j-1}}$

Use DES to construct Stream Ciphers

- **Cipher Feedback (CFB)**
- **Output Feedback (OFB)**
- **Counter Mode (CTR)**
- Common properties:
  - uses only the encryption function E_k of the cipher both for encryption and for decryption
  - malleable: possible to make predictable bit changes

Encryption Modes: CFB

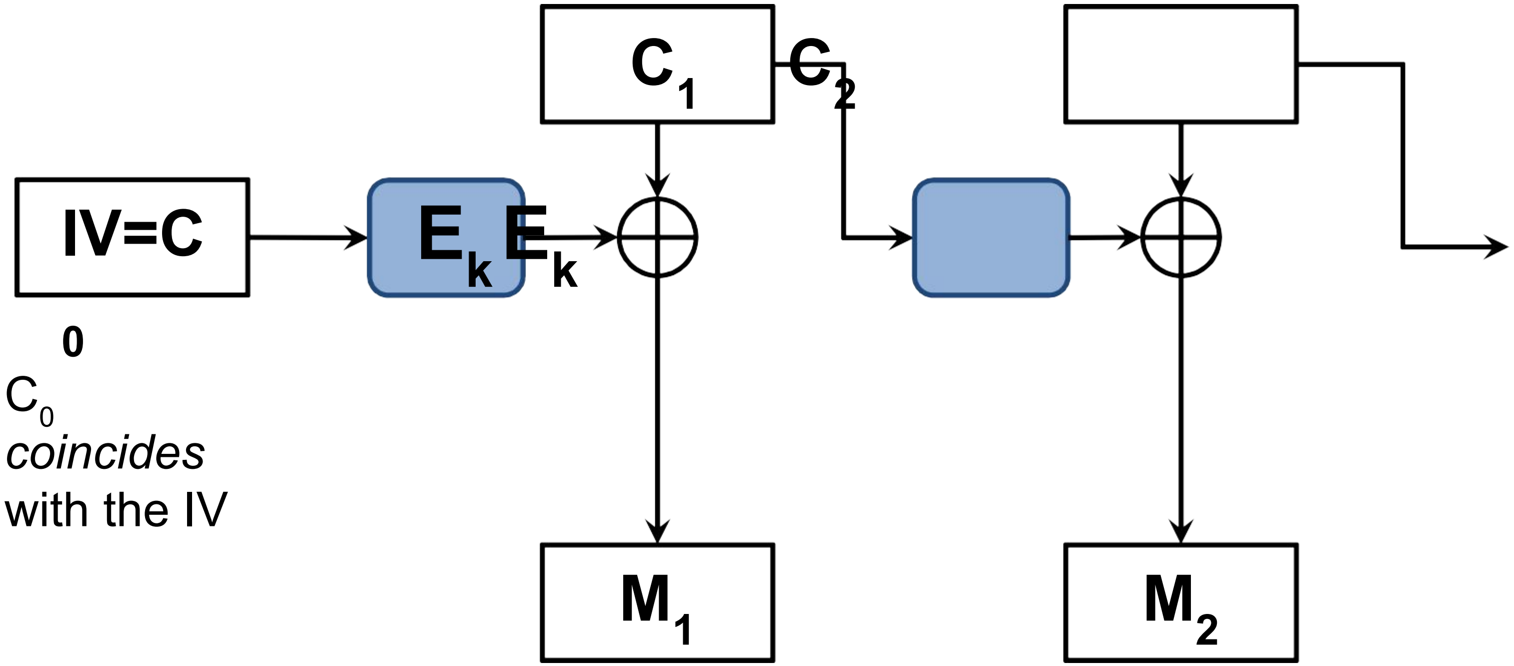
- **Cipher Feedback** (**CFB**): the message is XORed with the feedback of encrypting the previous block
- **<u>Encryption</u>**: $C_i = M_i \oplus E_k(C_{i-1})$, with C_0=IV



C_0 *coincides* with the IV

Encryption Modes: CFB

- **Decryption**: $M_i = C_i \oplus E_k(C_{i-1})$, with C_0=IV
- The *same* encryption function E_k is used here also for decryption



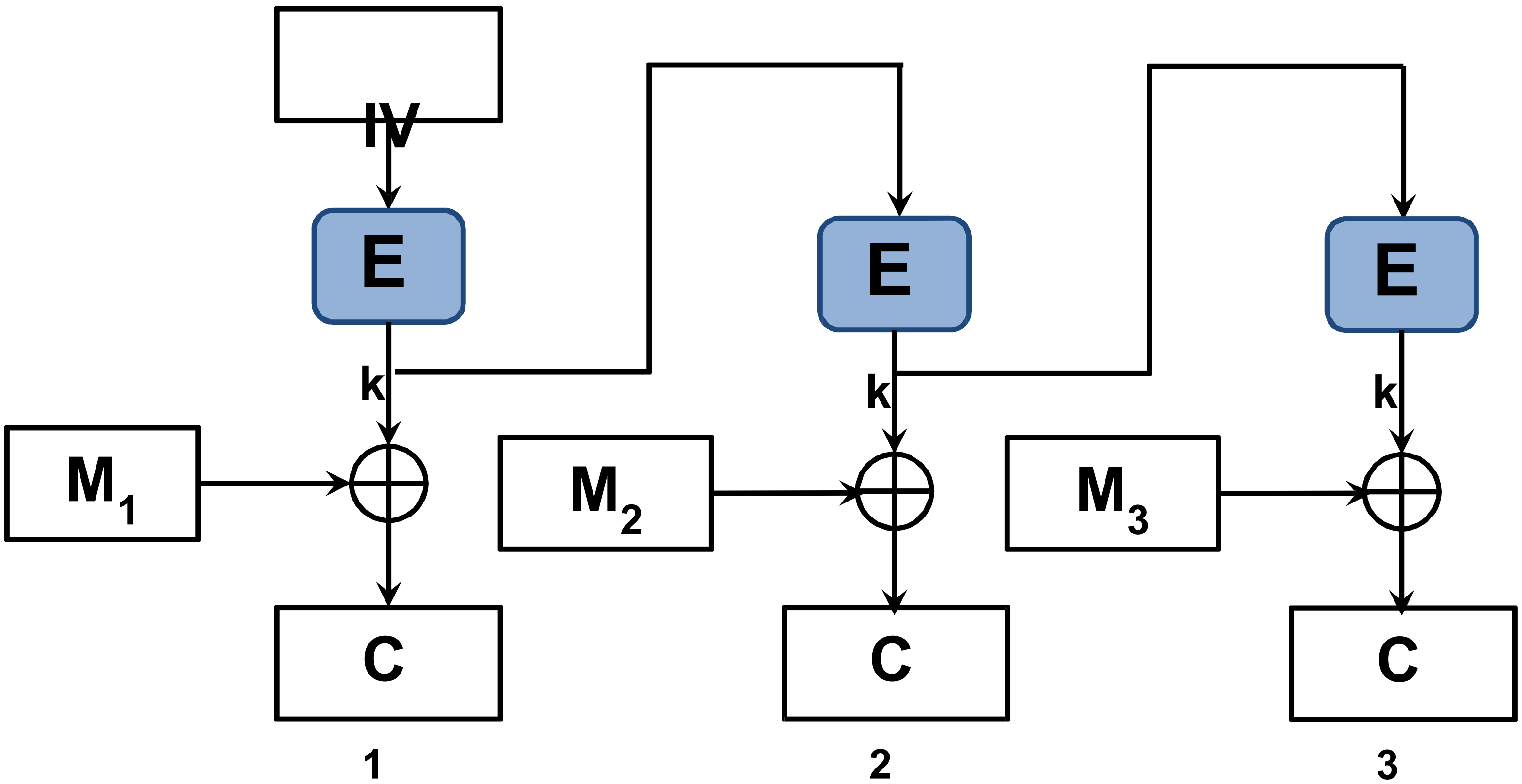
C_0 *coincides* with the IV

Properties of CFB

- Randomized encryption
- A ciphertext block depends on all preceding plaintext blocks; reorder affects decryption
- Errors propagate for several blocks after the error, but the mode is self-synchronizing (like CBC).
- Decreased throughput.
  - Can vary the number of bits feed back, trading off throughput for ease of use
- Sequential encryption

Encryption Modes: OFB

- **Output Feedback (OFB)**:
  – constructs a Pseudo Random Number Generator using DES E_k function



Properties of OFB

- Randomized encryption

- Sequential encryption, but pre-processing possible

- Error propagation limited

- Subject to limitations of stream ciphers

Encryption Modes: CTR

- **Counter Mode** (**CTR**): Another way to construct PRNG using DES

  counter

  - **Encryption**: $C_i = M_i \oplus E_k[\text{nonce} + i]$
  - nonce= number used only once

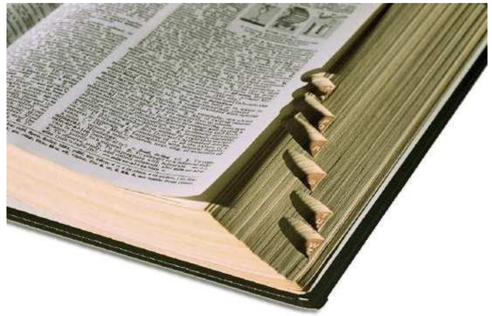
    (equivalent to an IV=Initialization

    Vector)
  - **Decryption**: $M_i = C_i \oplus E_k[\text{nonce} + i]$
  - Sender and receiver share: nonce (does *not* need to be secret) and the secret key *k*.

Properties of CTR

- *Software and hardware efficiency*: different blocks can be encrypted in parallel.
- *Preprocessing*: the encryption part can be done offline and when the message is known, just do the XOR.
- *Random access*: decryption of a block can be done in random order, very useful for hard-disk encryption.
- *Messages of arbitrary length*: ciphertext is the same length with the plaintext (i.e.,

Cryptanalysis of DES



- **Dictionary attack:**

- Each plaintext may result in 2^{64} different ciphertexts, but there are only 2^{56} possible different key values.
- Encrypt the known plaintext with all possible keys.
- Keep a *look up table* of size 2^{56}
- Given a Plaintext/Ciphertext pair (P,C), look up C in the table

Meet-in-the-Middle Attack

- To improve the security of a *block cipher*, one might get the (naive) idea to simply use two independent keys to encrypt the data twice.
- **$C = E_{K2} [E_{K1} [P]]$**
- Naively, one might think that this would *square*
  the security of the double-encryption scheme.
- In fact, an exhaustive search of all possible *combinations* of keys would take 2^{2n} attempts (if each key K1, K2 is n bits long), compared

DES Strength Against Various Attacks

Attack Method	Known	Chosen	Storage Complexity	Processing Complexity
Exhaustive precomputation	-	1	2^{56}	1
Exhaustive search	1	-	Negligible	2^{55}
Linear cryptanalysis	2^{43}	-	For texts	2^{43}
	2^{38}	-		2^{50}
Differential cryptanalysis	-	2^{47}	For texts	2^{47}
	2^{55}	-		2^{55}

The weakest point of DES remains the size of the key (56 bits)!

How to Improve Block Ciphers

- Variable key length
- Mixed operators: use more than one arithmetic and/or Boolean; this can provide non-linearity
- Data dependent rotation
- Key-dependent S-boxes
- Lengthy key schedule algorithm
- Variable plaintext/ciphertext block length
- Variable number of rounds
- Operation on both data halves each round
- Variable *f()* function (varies from round to round)
- Key-dependent rotation