
Information security — Lightweight cryptography —

Part 2: Block ciphers

Sécurité de l'information — Cryptographie pour environnements contraints —

Partie 2: Chiffrements par blocs





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Foreword

ISO (the International Organization for Standardization) and IEC (the International Electrotechnical Commission) form the specialized system for worldwide standardization. National bodies that are members of ISO or IEC participate in the development of International Standards through technical committees established by the respective organization to deal with particular fields of technical activity. ISO and IEC technical committees collaborate in fields of mutual interest. Other international organizations, governmental and non-governmental, in liaison with ISO and IEC, also take part in the work.

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This document was prepared by Technical Committee ISO/IEC JTC 1, *Information technology*, Subcommittee SC 27, *Information security, cybersecurity and privacy protection*.

This second edition cancels and replaces the first edition (ISO/IEC 29192-2:2012), which has been technically revised.

The main changes compared to the previous edition are as follows:

- the LEA algorithm has been added to [6.3](#);
- numerical examples and feature tables of LEA have been added to [B.3](#) and [Annex C](#).

A list of all parts in the ISO/IEC 29192 series can be found on the ISO website.

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Introduction

ISO/IEC 29192-1 specifies the requirements for lightweight cryptography.

A block cipher maps blocks of n bits to blocks of n bits, under the control of a key of k bits.

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Information security — Lightweight cryptography —

Part 2: Block ciphers

1 Scope

This document specifies three block ciphers suitable for applications requiring lightweight cryptographic implementations:

- PRESENT: a lightweight block cipher with a block size of 64 bits and a key size of 80 or 128 bits;
- CLEFIA: a lightweight block cipher with a block size of 128 bits and a key size of 128, 192 or 256 bits;
- LEA: a lightweight block cipher with a block size of 128 bits and a key size of 128, 192 or 256 bits.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <http://www.electropedia.org/>

3.1

block

string of bits of defined length

[SOURCE: ISO/IEC 18033-1:2015, 2.8]

3.2

block cipher

symmetric encipherment system with the property that the encryption algorithm operates on a *block* (3.1) of *plaintext* (3.6), i.e. a string of bits of a defined length, to yield a block of *ciphertext* (3.3)

[SOURCE: ISO/IEC 18033-1:2015, 2.9]

3.3

ciphertext

data which has been transformed to hide its information content

[SOURCE: ISO/IEC 10116:2017, 3.2]

3.4

key

sequence of symbols that controls the operation of a cryptographic transformation (e.g. encipherment, decipherment)

[SOURCE: ISO/IEC 18033-1:2015, 2.27]

3.5

***n*-bit block cipher**

block cipher (3.2) with the property that *plaintext* (3.6) blocks and *ciphertext* (3.3) blocks are *n* bits in length

[SOURCE: ISO/IEC 18033-1:2015, 2.29]

3.6

plaintext

unenciphered information

[SOURCE: ISO/IEC 9798-1:2010, 3.19]

3.7

round key

sequence of symbols derived from the *key* (3.4) using the key schedule, and used to control the transformation in each round of the *block cipher* (3.2)

4 Symbols

0x a prefix for a binary string in hexadecimal notation

|| concatenation of bit strings

$a \leftarrow b$ updating a value of *a* by a value of *b*

$\oplus$ bitwise exclusive-OR operation

5 Lightweight block cipher with a block size of 64 bits

5.1 General

In this clause, a 64-bit lightweight block cipher is specified: PRESENT in 5.2.

[Annex A](#) defines the object identifiers which shall be used to identify the algorithm specified in [Clause 5](#). [Annex B](#) provides numerical examples of the block ciphers described in this document. [Annex C](#) summarizes the lightweight properties of the block ciphers described in this document. [Annex D](#) gives a limit on the number of block cipher encryption operations that should be performed using a single key.

5.2 PRESENT

5.2.1 PRESENT algorithm

The PRESENT algorithm^[10] is a symmetric block cipher that can process data blocks of 64 bits, using a key of length 80 or 128 bits. The cipher is referred to as PRESENT-80 or PRESENT-128 when using an 80-bit or 128-bit key respectively.

5.2.2 PRESENT specific notation

$K_i = k_{63}^i \dots k_0^i$ 64-bit round key that is used in round *i*

k_b^i bit *b* of round key K_i

$K = k_{79} \dots k_0$ 80-bit key register

k_b bit *b* of key register *K*

$STATE$	64-bit internal state
b_i	bit i of the current $STATE$
w_i	4-bit word where $0 \leq i \leq 15$

5.2.3 PRESENT encryption

The PRESENT block cipher consists of 31 "rounds", i.e. 31 applications of a sequence of simple transformations. A pseudocode description of the complete encryption algorithm is provided in [Figure 1](#), where $STATE$ denotes the internal state. The individual transformations used by the algorithm are defined in [5.2.5](#). Each round of the algorithm uses a distinct round key K_i ($1 \leq i \leq 31$), derived as specified in [5.2.6](#). Two consecutive rounds of the algorithm are shown for illustrative purposes in [Figure 2](#).

```

generateRoundKeys()
for  $i = 1$  to 31 do

    addRoundKey( $STATE, K_i$ )
    sBoxLayer( $STATE$ )
    pLayer( $STATE$ )
end for
addRoundKey( $STATE, K_{32}$ )

```

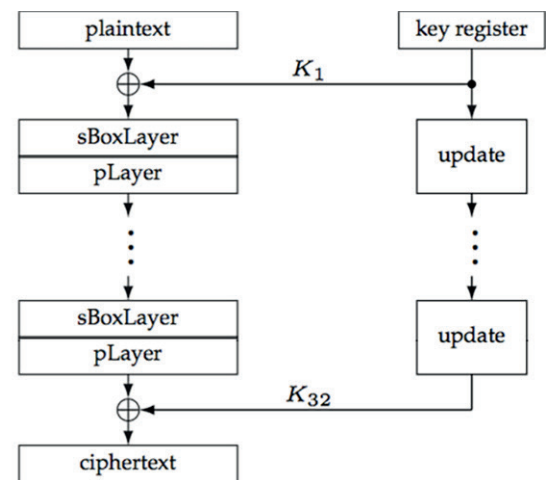


Figure 1 — The encryption procedure of PRESENT

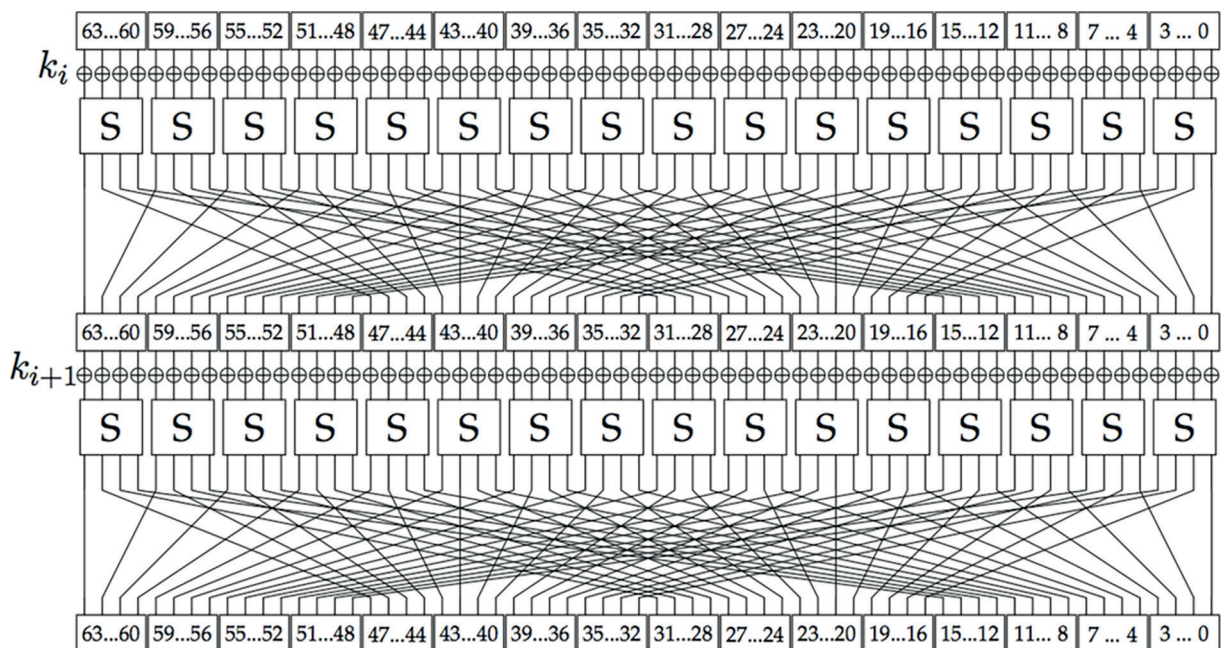


Figure 2 — Two rounds of PRESENT

5.2.4 PRESENT decryption

The complete PRESENT decryption algorithm is given in Figure 3. The individual transformations used by the algorithm are defined in 5.2.5. Each round of the algorithm uses a distinct round key K_i ($1 \leq i \leq 31$), derived as specified in 5.2.6.

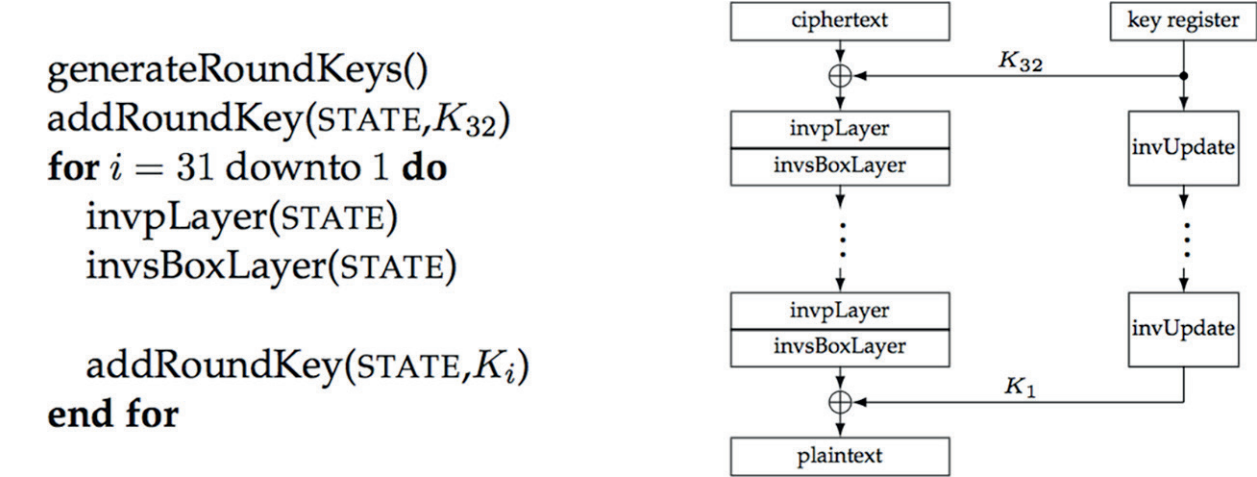


Figure 3 — The decryption procedure of PRESENT

5.2.5 PRESENT transformations

5.2.5.1 addRoundKey

Given round key $K_i = k_{63}^i \dots k_0^i$ for $1 \leq i \leq 32$ and current $STATE\ b_{63} \dots b_0$, **addRoundKey** consists of the operation for $0 \leq j \leq 63$, $b_j \leftarrow b_j \oplus k_j^i$.

5.2.5.2 sBoxLayer

The non-linear **sBoxLayer** of the encryption process of PRESENT uses a single 4-bit to 4-bit S-box S which is applied 16 times in parallel in each round. The S-box transforms the input x to an output $S(x)$ as given in hexadecimal notation in Table 1.

Table 1 — PRESENT S-box

x	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
$S(x)$	C	5	6	B	9	0	A	D	3	E	F	8	4	7	1	2

For **sBoxLayer** the current $STATE\ b_{63} \dots b_0$ is considered as sixteen 4-bit words $w_{15} \dots w_0$ where $w_i = b_{4*i+3} \parallel b_{4*i+2} \parallel b_{4*i+1} \parallel b_{4*i}$ for $0 \leq i \leq 15$ and the output nibble $S(w_i)$ provides the updated state values as a concatenation $S(w_{15}) \parallel S(w_{14}) \parallel \dots \parallel S(w_0)$.

5.2.5.3 invsBoxLayer

The S-box used in the decryption procedure of PRESENT is the inverse of the 4-bit to 4-bit S-box S that is described in 5.2.5.2. The inverse S-box transforms the input x to an output $S^{-1}(x)$ as given in hexadecimal notation in Table 2.

Table 2 — PRESENT inverse S-box

x	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
$S^{-1}(x)$	5	E	F	8	C	1	2	D	B	4	6	3	0	7	9	A

5.2.5.4 pLayer

The bit permutation **pLayer** used in the encryption routine of PRESENT is given by [Table 3](#). Bit i of *STATE* is moved to bit position $P(i)$.

Table 3 — PRESENT permutation layer pLayer

i	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$P(i)$	0	16	32	48	1	17	33	49	2	18	34	50	3	19	35	51
i	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
$P(i)$	4	20	36	52	5	21	37	53	6	22	38	54	7	23	39	55
i	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47
$P(i)$	8	24	40	56	9	25	41	57	10	26	42	58	11	27	43	59
i	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63
$P(i)$	12	28	44	60	13	29	45	61	14	30	46	62	15	31	47	63

5.2.5.5 invpLayer

The inverse permutation layer **invpLayer** used in the decryption routine of PRESENT is given by [Table 4](#). Bit i of *STATE* is moved to bit position $P^{-1}(i)$.

Table 4 — PRESENT inverse permutation Layer invpLayer

i	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$P^{-1}(i)$	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60
i	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
$P^{-1}(i)$	1	5	9	13	17	21	25	29	33	37	41	45	49	53	57	61
i	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47
$P^{-1}(i)$	2	6	10	14	18	22	26	30	34	38	42	46	50	54	58	62
i	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63
$P^{-1}(i)$	3	7	11	15	19	23	27	31	35	39	43	47	51	55	59	63

5.2.6 PRESENT key schedule

5.2.6.1 PRESENT-80 and PRESENT-128

PRESENT can take keys of either 80 or 128 bits. In [5.2.6.2](#), the version with an 80-bit key (PRESENT-80) and in [5.2.6.3](#) the 128-bit version (PRESENT-128) is described.

5.2.6.2 80-bit key for PRESENT-80

The user-supplied key is stored in a key register K and represented as $k_{79}k_{78} \dots k_0$. At round i the 64-bit round key $K_i = k_{63}^i k_{62}^i \dots k_0^i$ consists of the 64 leftmost bits of the current contents of register K . Thus at round i , K_i is as follows:

$$K_i = k_{63}^i k_{62}^i \dots k_0^i = k_{79} k_{78} \dots k_{16}$$

After extracting the round key K_i , the key register $K = k_{79}k_{78} \dots k_0$ is updated as follows.

- 1) $k_{79}k_{78} \dots k_1 k_0 \leftarrow k_{18}k_{17} \dots k_{20}k_{19}$
- 2) $k_{79}k_{78}k_{77}k_{76} \leftarrow S[k_{79}k_{78}k_{77}k_{76}]$
- 3) $k_{19}k_{18}k_{17}k_{16}k_{15} \leftarrow k_{19}k_{18}k_{17}k_{16}k_{15} \oplus \text{round_counter}$

In words, the key register is rotated by 61 bit positions to the left, the left-most four bits are passed through the PRESENT S-box, and the *round_counter* value i is exclusive-ORed with bits $k_{19}k_{18}k_{17}k_{16}k_{15}$ of K where the least significant bit of *round_counter* is on the right. The rounds are numbered from $1 \leq i \leq 31$ and *round_counter* = i . Figure 4 depicts the key schedule for PRESENT-80 graphically.

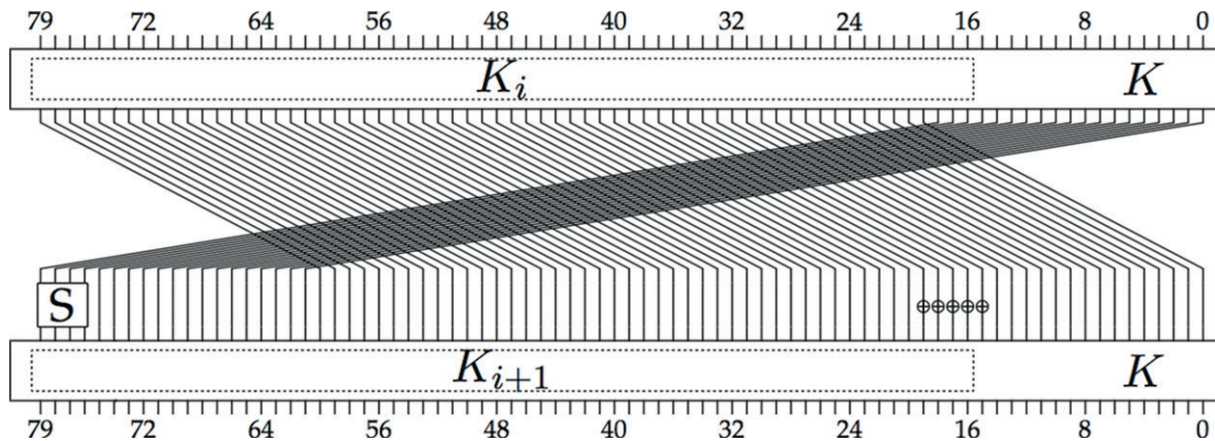


Figure 4 — PRESENT-80 key schedule

5.2.6.3 128-bit key for PRESENT-128

Similar to the 80-bit variant the user-supplied key is stored initially in a key register K and is represented as $k_{127}k_{126} \dots k_0$. At round i the 64-bit round key $K_i = k_{63}^i k_{62}^i \dots k_0^i$ consists of the 64 leftmost bits of the current contents of register K . Thus at round i , K_i is as follows:

$$K_i = k_{63}^i k_{62}^i \dots k_0^i = k_{127} k_{126} \dots k_{64}$$

After extracting the round key K_i , the key register $K = k_{127}k_{126} \dots k_0$ is updated as follows.

- 1) $k_{127}k_{126} \dots k_1 k_0 \leftarrow k_{66}k_{65} \dots k_{68}k_{67}$
- 2) $k_{127}k_{126}k_{125}k_{124} \leftarrow S[k_{127}k_{126}k_{125}k_{124}]$
- 3) $k_{123}k_{122}k_{121}k_{120} \leftarrow S[k_{123}k_{122}k_{121}k_{120}]$
- 4) $k_{66}k_{65}k_{64}k_{63}k_{62} \leftarrow k_{66}k_{65}k_{64}k_{63}k_{62} \oplus \text{round_counter}$

In words, the key register is rotated by 61 bit positions to the left, the left-most eight bits are passed through the PRESENT S-box, and the *round_counter* value i is exclusive-ORed with bits $k_{66}k_{65}k_{64}k_{63}k_{62}$

of K where the least significant bit of *round_counter* is on the right. The rounds are numbered from $1 \leq i \leq 31$ and *round_counter* = i . Figure 5 depicts the key schedule for PRESENT-128 graphically.

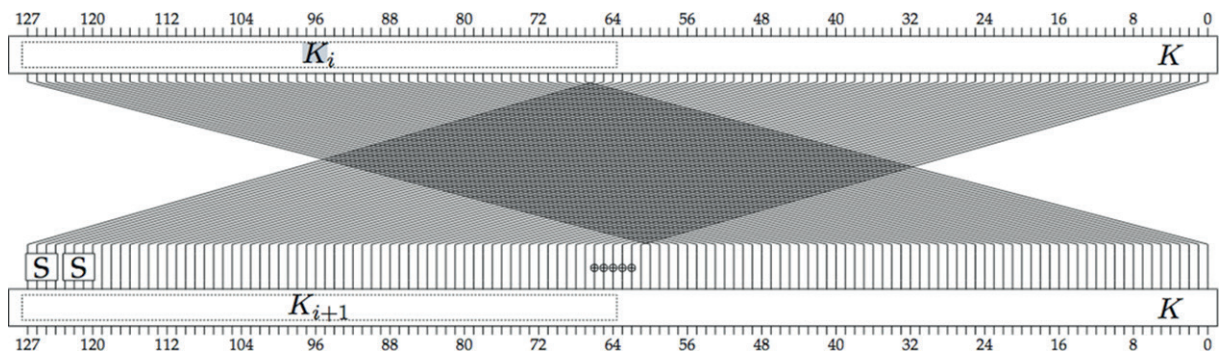


Figure 5 — PRESENT-128 key schedule

6 Lightweight block ciphers with a block size of 128 bits

6.1 General

In this clause, two 128-bit lightweight block ciphers are specified: CLEFIA in 6.2 and LEA in 6.3.

Annex A defines the object identifiers which shall be used to identify the algorithms specified in Clause 6. Annex B provides numerical examples of the block ciphers described in this document. Annex C summarizes the lightweight properties of the block ciphers described in this document. Annex D gives a limit on the number of block cipher encryption operations that should be performed using a single key.

6.2 CLEFIA

6.2.1 CLEFIA algorithm

The CLEFIA algorithm^[15] is a symmetric block cipher that can process data blocks of 128 bits using a cipher key of length 128, 192, or 256 bits. The number of rounds is 18, 22 and 26 for CLEFIA with 128-bit, 192-bit and 256-bit keys, respectively. The total number of round keys depends on the key length. The CLEFIA encryption and decryption functions require 36, 44 and 52 round keys for 128-bit, 192-bit and 256-bit keys, respectively.

6.2.2 CLEFIA specific notation

$a_{(b)}$	bit string of bit length b
$\{0,1\}^n$	a set of n -bit binary strings
$\cdot$	multiplication in $GF(2^n)$
$\lll i$	i -bit left cyclic shift operation
$\sim a$	bitwise complement of bit string a
Σ^n	n times operations of the DoubleSwap function Σ

6.2.3 CLEFIA encryption

The encryption process of CLEFIA is based on the 4-branch r -round generalized Feistel structure $GFN_{4,r}$. Let $P, C \in \{0,1\}^{128}$ be a plaintext and a ciphertext. Let $P_i, C_i \in \{0,1\}^{32}$ ($0 \leq i < 4$) be divided plaintexts

and ciphertexts where $P = P_0 \parallel P_1 \parallel P_2 \parallel P_3$ and $C = C_0 \parallel C_1 \parallel C_2 \parallel C_3$. Let $WK_0, WK_1, WK_2, WK_3 \in \{0,1\}^{32}$ be whitening keys and $RK_i \in \{0,1\}^{32}$ ($0 \leq i < 2r$) be round keys provided by the key schedule. Then, r -round encryption function ENC_r is defined as follows:

ENC_r :

- 1) $T_0 \parallel T_1 \parallel T_2 \parallel T_3 \leftarrow P_0 \parallel (P_1 \oplus WK_0) \parallel P_2 \parallel (P_3 \oplus WK_1)$
- 2) $T_0 \parallel T_1 \parallel T_2 \parallel T_3 \leftarrow GFN_{4,r}(RK_0, \dots, RK_{2r-1}, T_0, T_1, T_2, T_3)$
- 3) $C_0 \parallel C_1 \parallel C_2 \parallel C_3 \leftarrow T_0 \parallel (T_1 \oplus WK_2) \parallel T_2 \parallel (T_3 \oplus WK_3)$

6.2.4 CLEFIA decryption

The decryption function DEC_r is defined as follows:

DEC_r :

- 1) $T_0 \parallel T_1 \parallel T_2 \parallel T_3 \leftarrow C_0 \parallel (C_1 \oplus WK_2) \parallel C_2 \parallel (C_3 \oplus WK_3)$
- 2) $T_0 \parallel T_1 \parallel T_2 \parallel T_3 \leftarrow GFN_{4,r}^{-1}(RK_0, \dots, RK_{2r-1}, T_0, T_1, T_2, T_3)$
- 3) $P_0 \parallel P_1 \parallel P_2 \parallel P_3 \leftarrow T_0 \parallel (T_1 \oplus WK_0) \parallel T_2 \parallel (T_3 \oplus WK_1)$

[Figure 6](#) illustrates both ENC_r and DEC_r .

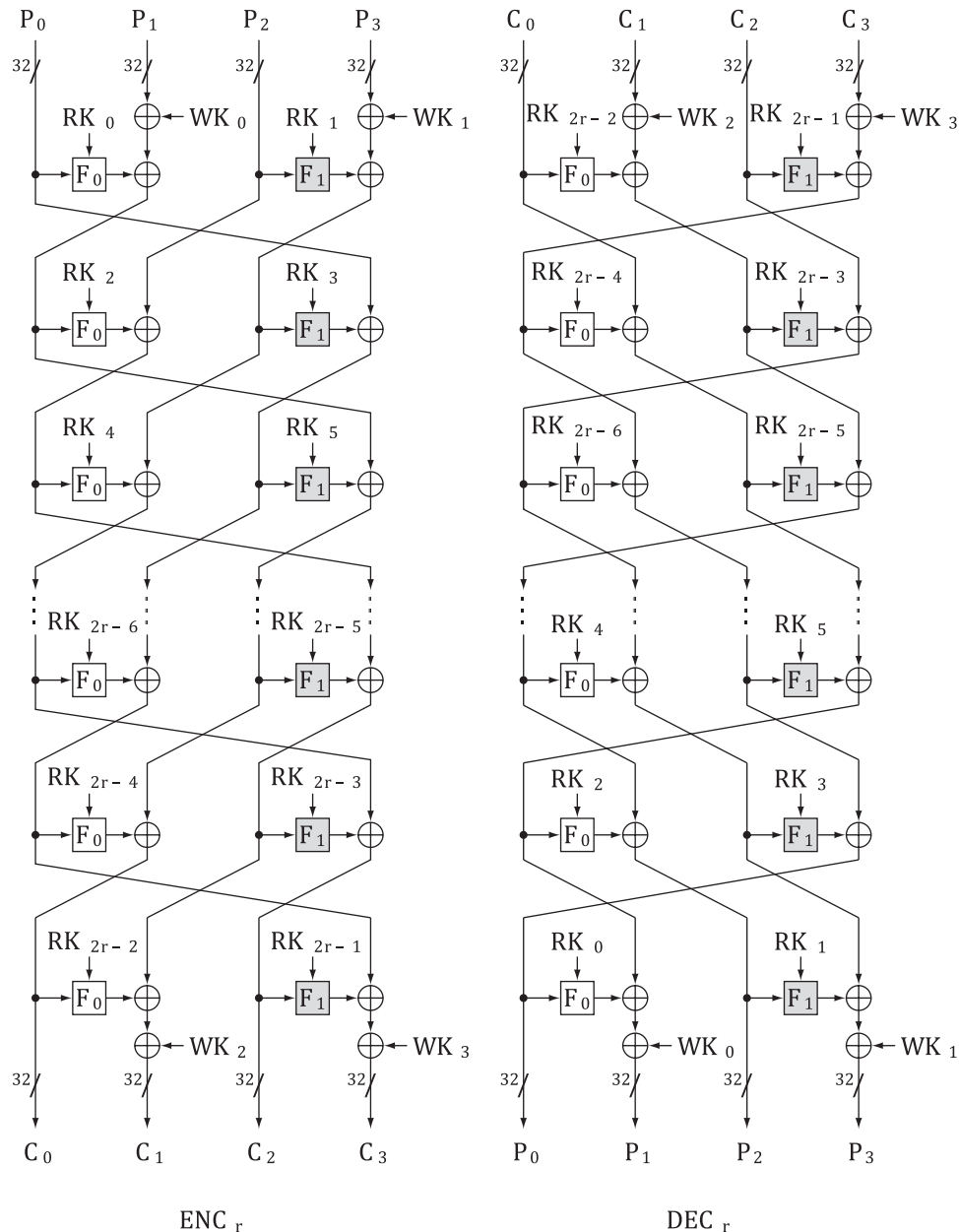


Figure 6 — The encryption procedure and the decryption procedure of CLEFIA

6.2.5 CLEFIA building blocks

6.2.5.1 $GFN_{d,r}$

The fundamental structure of CLEFIA is a generalized Feistel structure. This structure is employed in both a data processing part and a key schedule part.

CLEFIA uses a 4-branch and an 8-branch generalized Feistel network. The 4-branch generalized Feistel network is used in the data processing part and the key schedule for a 128-bit key. The 8-branch generalized Feistel network is applied in the key schedule for a 192-bit/256-bit key. Let $GFN_{d,r}$ denote the d -branch r -round generalized Feistel network employed in CLEFIA. $GFN_{d,r}$ uses two different 32-bit F-functions F_0 and F_1 .

For d pairs of 32-bit input X_i and output Y_i ($0 \leq i < d$), and $dr/2$ 32-bit round keys RK_i ($0 \leq i < dr/2$), $GFN_{d,r}$ ($d = 4, 8$) and the inverse function $GFN_{d,r}^{-1}$ ($d = 4$) are defined as follows.

$GFN_{4,r}$:

- 1) $T_0 \parallel T_1 \parallel T_2 \parallel T_3 \leftarrow X_0 \parallel X_1 \parallel X_2 \parallel X_3$
- 2) For $i = 0$ to $r - 1$ do the following:
 - 2.1) $T_1 \leftarrow T_1 \oplus F_0(RK_{2i}, T_0)$
 $T_3 \leftarrow T_3 \oplus F_1(RK_{2i+1}, T_2)$
 - 2.2) $T_0 \parallel T_1 \parallel T_2 \parallel T_3 \leftarrow T_1 \parallel T_2 \parallel T_3 \parallel T_0$
- 3) $Y_0 \parallel Y_1 \parallel Y_2 \parallel Y_3 \leftarrow T_3 \parallel T_0 \parallel T_1 \parallel T_2$

$GFN_{8,r}$:

- 1) $T_0 \parallel T_1 \parallel \dots \parallel T_7 \leftarrow X_0 \parallel X_1 \parallel \dots \parallel X_7$
- 2) For $i = 0$ to $r - 1$ do the following:
 - 2.1) $T_1 \leftarrow T_1 \oplus F_0(RK_{4i}, T_0)$
 $T_3 \leftarrow T_3 \oplus F_1(RK_{4i+1}, T_2)$
 $T_5 \leftarrow T_5 \oplus F_0(RK_{4i+2}, T_4)$
 $T_7 \leftarrow T_7 \oplus F_1(RK_{4i+3}, T_6)$
 - 2.2) $T_0 \parallel T_1 \parallel \dots \parallel T_6 \parallel T_7 \leftarrow T_1 \parallel T_2 \parallel \dots \parallel T_7 \parallel T_0$
- 3) $Y_0 \parallel Y_1 \parallel \dots \parallel Y_6 \parallel Y_7 \leftarrow T_7 \parallel T_0 \parallel \dots \parallel T_5 \parallel T_6$

The inverse function $GFN_{4,r}^{-1}$ is obtained by changing the order of RK_i and the direction of word rotation at 2.2) and 3) in $GFN_{4,r}$.

$GFN_{4,r}^{-1}$:

- 1) $T_0 \parallel T_1 \parallel T_2 \parallel T_3 \leftarrow X_0 \parallel X_1 \parallel X_2 \parallel X_3$
- 2) For $i = 0$ to $r - 1$ do the following:
 - 2.1) $T_1 \leftarrow T_1 \oplus F_0(RK_{2(r-i)-2}, T_0)$
 $T_3 \leftarrow T_3 \oplus F_1(RK_{2(r-i)-1}, T_2)$
 - 2.2) $T_0 \parallel T_1 \parallel T_2 \parallel T_3 \leftarrow T_3 \parallel T_0 \parallel T_1 \parallel T_2$
- 3) $Y_0 \parallel Y_1 \parallel Y_2 \parallel Y_3 \leftarrow T_1 \parallel T_2 \parallel T_3 \parallel T_0$

6.2.5.2 F-functions

Two F-functions F_0 and F_1 used in $GFN_{d,r}$ are defined as follows:

$F_0 : (RK_{(32)}, X_{(32)}) \mapsto Y_{(32)}$

- 1) $V \leftarrow RK \oplus x$
- 2) Let $V = V_0 \parallel V_1 \parallel V_2 \parallel V_3$, $V_i \in \{0,1\}^8$.
 $V_0 \leftarrow S_0(V_0)$
 $V_1 \leftarrow S_1(V_1)$

$$V_2 \leftarrow S_0(V_2)$$

$$V_3 \leftarrow S_1(V_3)$$

3) Let $y = y_0 \parallel y_1 \parallel y_2 \parallel y_3$, $y_i \in \{0,1\}^8$.

$$\begin{pmatrix} y_0 \\ y_1 \\ y_2 \\ y_3 \end{pmatrix} \leftarrow M_0 \begin{pmatrix} V_0 \\ V_1 \\ V_2 \\ V_3 \end{pmatrix}$$

$$F_1 : (RK_{(32)}, x_{(32)}) \mapsto y_{(32)}$$

1) $V \leftarrow RK \oplus x$

2) Let $V = V_0 \parallel V_1 \parallel V_2 \parallel V_3$, $V_i \in \{0,1\}^8$.

$$V_0 \leftarrow S_1(V_0)$$

$$V_1 \leftarrow S_0(V_1)$$

$$V_2 \leftarrow S_1(V_2)$$

$$V_3 \leftarrow S_0(V_3)$$

3) Let $y = y_0 \parallel y_1 \parallel y_2 \parallel y_3$, $y_i \in \{0,1\}^8$.

$$\begin{pmatrix} y_0 \\ y_1 \\ y_2 \\ y_3 \end{pmatrix} \leftarrow M_1 \begin{pmatrix} V_0 \\ V_1 \\ V_2 \\ V_3 \end{pmatrix}$$

S_0 and S_1 are nonlinear 8-bit S-boxes described in 6.2.5.3, and M_0 and M_1 are 4×4 diffusion matrices described in 6.2.5.4. In each F-function two S-boxes and a matrix are used, but the S-boxes are used in a different order and the matrices differ. Figure 7 shows a graphical representation of the F-functions.

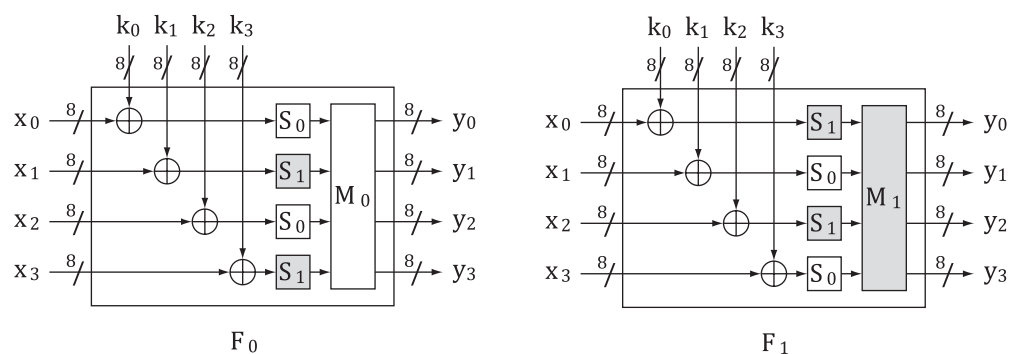


Figure 7 — F-functions

6.2.5.3 S-boxes

CLEFIA employs two different types of 8-bit S-boxes S_0 and S_1 : S_0 is based on four 4-bit random S-boxes, and S_1 is based on the inverse function over $GF(2^8)$.

Tables 5 and 6 show the output values of S_0 and S_1 , respectively. In these tables all values are expressed in a hexadecimal notation. For an 8-bit input of an S-box, the upper 4 bits indicate a row and the lower

4 bits indicate a column. For example, if a value $0xab$ is input, $0x7e$ is output by S_0 because it is on the cross line of the row indexed by 'a.' and the column indexed by 'b'.

Table 5 — S_0

	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	.a	.b	.c	.d	.e	.f
0.	57	49	d1	c6	2f	33	74	fb	95	6d	82	ea	0e	b0	a8	1c
1.	28	d0	4b	92	5c	ee	85	b1	c4	0a	76	3d	63	f9	17	af
2.	bf	a1	19	65	f7	7a	32	20	06	ce	e4	83	9d	5b	4c	d8
3.	42	5d	2e	e8	d4	9b	0f	13	3c	89	67	c0	71	aa	b6	f5
4.	a4	be	fd	8c	12	00	97	da	78	e1	cf	6b	39	43	55	26
5.	30	98	cc	dd	eb	54	b3	8f	4e	16	fa	22	a5	77	09	61
6.	d6	2a	53	37	45	c1	6c	ae	ef	70	08	99	8b	1d	f2	b4
7.	e9	c7	9f	4a	31	25	fe	7c	d3	a2	bd	56	14	88	60	0b
8.	cd	e2	34	50	9e	dc	11	05	2b	b7	a9	48	ff	66	8a	73
9.	03	75	86	f1	6a	a7	40	c2	b9	2c	db	1f	58	94	3e	ed
a.	fc	1b	a0	04	b8	8d	e6	59	62	93	35	7e	ca	21	df	47
b.	15	f3	ba	7f	a6	69	c8	4d	87	3b	9c	01	e0	de	24	52
c.	7b	0c	68	1e	80	b2	5a	e7	ad	d5	23	f4	46	3f	91	c9
d.	6e	84	72	bb	0d	18	d9	96	f0	5f	41	ac	27	c5	e3	3a
e.	81	6f	07	a3	79	f6	2d	38	1a	44	5e	b5	d2	ec	cb	90
f.	9a	36	e5	29	c3	4f	ab	64	51	f8	10	d7	bc	02	7d	8e

Table 6 — S_1

	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	.a	.b	.c	.d	.e	.f
0.	6c	da	c3	e9	4e	9d	0a	3d	b8	36	b4	38	13	34	0c	d9
1.	bf	74	94	8f	b7	9c	e5	dc	9e	07	49	4f	98	2c	b0	93
2.	12	eb	cd	b3	92	e7	41	60	e3	21	27	3b	e6	19	d2	0e
3.	91	11	c7	3f	2a	8e	a1	bc	2b	c8	c5	0f	5b	f3	87	8b
4.	fb	f5	de	20	c6	a7	84	ce	d8	65	51	c9	a4	ef	43	53
5.	25	5d	9b	31	e8	3e	0d	d7	80	ff	69	8a	ba	0b	73	5c
6.	6e	54	15	62	f6	35	30	52	a3	16	d3	28	32	fa	aa	5e
7.	cf	ea	ed	78	33	58	09	7b	63	c0	c1	46	1e	df	a9	99
8.	55	04	c4	86	39	77	82	ec	40	18	90	97	59	dd	83	1f
9.	9a	37	06	24	64	7c	a5	56	48	08	85	d0	61	26	ca	6f
a.	7e	6a	b6	71	a0	70	05	d1	45	8c	23	1c	f0	ee	89	ad
b.	7a	4b	c2	2f	db	5a	4d	76	67	17	2d	f4	cb	b1	4a	a8
c.	b5	22	47	3a	d5	10	4c	72	cc	00	f9	e0	fd	e2	fe	ae
d.	f8	5f	ab	f1	1b	42	81	d6	be	44	29	a6	57	b9	af	f2
e.	d4	75	66	bb	68	9f	50	02	01	3c	7f	8d	1a	88	bd	ac
f.	f7	e4	79	96	a2	fc	6d	b2	6b	03	e1	2e	7d	14	95	1d

a) S-box S_0

$S_0 : \{0,1\}^8 \rightarrow \{0,1\}^8 : x \mapsto y = S_0(x)$ is generated by combining four 4-bit S-boxes SS_0 , SS_1 , SS_2 and SS_3 in the following way. The values of these S-boxes are defined in [Table 7](#).

- 1) $t_0 \leftarrow SS_0(x_0), t_1 \leftarrow SS_1(x_1)$, where $x = x_0 \parallel x_1, x_i \in \{0,1\}^4$
- 2) $u_0 \leftarrow t_0 \oplus_{0 \times 2} t_1, u_1 \leftarrow_{0 \times 2} t_0 \oplus t_1$
- 3) $y_0 \leftarrow SS_2(u_0), y_1 \leftarrow SS_3(u_1)$, where $y = y_0 \parallel y_1, y_i \in \{0,1\}^4$

The multiplication in $_{0 \times 2} t_i$ is performed in $GF(2^4)$ defined by the lexicographically first primitive polynomial $z^4 + z + 1$. Figure 8 shows the construction of S_0 .

Table 7 — SS_i ($0 \leq i < 4$)

x	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
$SS_0(x)$	e	6	c	a	8	7	2	f	b	1	4	0	5	9	d	3
$SS_1(x)$	6	4	0	d	2	b	a	3	9	c	e	f	8	7	5	1
$SS_2(x)$	b	8	5	e	a	6	4	c	f	7	2	3	1	0	d	9
$SS_3(x)$	a	2	6	d	3	4	5	e	0	7	8	9	b	f	c	1

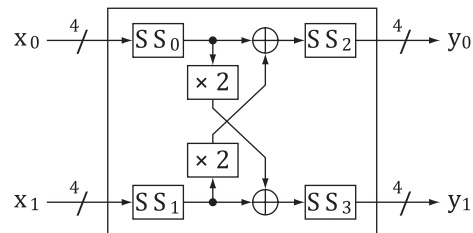


Figure 8 — S_0

b) S-box S_1

$S_1 : \{0,1\}^8 \rightarrow \{0,1\}^8 : x \mapsto y = S_1(x)$ is defined as follows:

$$y = \begin{cases} g((f(x))^{-1}) & \text{if } f(x) \neq 0 \\ g(0) & \text{if } f(x) = 0 \end{cases}$$

The inverse function is performed in $GF(2^8)$ defined by a primitive polynomial $z^8 + z^4 + z^3 + z^2 + 1$ ($=0x11d$). f and g are affine transformations over $GF(2)$, which are defined as follows.

$$f : \{0,1\}^8 \rightarrow \{0,1\}^8 : x \mapsto y = f(x),$$

$$\begin{pmatrix} y_0 \\ y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \\ y_6 \\ y_7 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \end{pmatrix} \oplus \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \\ 1 \\ 1 \\ 1 \\ 0 \end{pmatrix}$$

$$g : \{0,1\}^8 \rightarrow \{0,1\}^8 : x \mapsto y = g(x),$$

$$\begin{pmatrix} y_0 \\ y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \\ y_6 \\ y_7 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \end{pmatrix} \oplus \begin{pmatrix} 0 \\ 1 \\ 1 \\ 0 \\ 1 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

Here, $x = x_0 \parallel x_1 \parallel x_2 \parallel x_3 \parallel x_4 \parallel x_5 \parallel x_6 \parallel x_7$ and $y = y_0 \parallel y_1 \parallel y_2 \parallel y_3 \parallel y_4 \parallel y_5 \parallel y_6 \parallel y_7$, $x_i, y_i \in \{0,1\}$. The constants in f and g can be represented as $0 \times 1e$ and 0×69 , respectively.

6.2.5.4 Diffusion matrices

The matrices M_0 and M_1 are defined as follows.

$$M_0 = \begin{pmatrix} 01 & 02 & 04 & 06 \\ 02 & 01 & 06 & 04 \\ 04 & 06 & 01 & 02 \\ 06 & 04 & 02 & 01 \end{pmatrix}, M_1 = \begin{pmatrix} 01 & 08 & 02 & 0a \\ 08 & 01 & 0a & 02 \\ 02 & 0a & 01 & 08 \\ 0a & 02 & 08 & 01 \end{pmatrix}$$

The multiplications of a matrix and a vector are performed in $GF(2^8)$ defined by the lexicographically first primitive polynomial $z^8 + z^4 + z^3 + z^2 + 1$ ($=0 \times 11d$).

6.2.6 CLEFIA key schedule

6.2.6.1 Overall structure

The key schedule of CLEFIA supports 128, 192 and 256-bit keys and outputs whitening keys WK_i ($0 \leq i < 4$) and round keys RK_j ($0 \leq j < 2r$) for the data processing part. Let K be the key and L be an intermediate key. The key schedule consists of the following two steps.

- 1) Generating L from K .
- 2) Expanding K and L (Generating WK_i and RK_j).

To generate L from K , the key schedule for a 128-bit key uses a 128-bit permutation $GFN_{4,12}$, while the key schedules for 192/256-bit keys use a 256-bit permutation $GFN_{8,10}$.