Independent Submission
Request for Comments: 6114
Category: Informational
ISSN: 2070-1721
March 2011
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The 128-Bit Blockcipher CLEFIA

Abstract

This document describes the specification of the blockcipher CLEFIA. CLEFIA is a 128-bit blockcipher, with key lengths of 128, 192, and 256 bits, which is compatible with the interface of the Advanced Encryption Standard (AES). The algorithm of CLEFIA was published in 2007, and its security has been scrutinized in the public community. CLEFIA is one of the new-generation lightweight blockcipher algorithms designed after AES. Among them, CLEFIA offers high performance in software and hardware as well as lightweight implementation in hardware. CLEFIA will be of benefit to the Internet, which will be connected to more distributed and constrained devices.

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1. Introduction

Due to the widespread use of the Internet, devices with limited capabilities, e.g., wireless sensors, are connected to the network. In order to realize enough security for the network, cryptographic technologies suitable for such constrained devices are very important. This recent technology is called "lightweight cryptography", and the demand for lightweight cryptography is increasing.

In order to satisfy these needs, a 128-bit blockcipher, CLEFIA, was designed based on state-of-the-art techniques [FSE07]. CLEFIA is a 128-bit blockcipher, with key lengths of 128, 192, and 256 bits, which is compatible with the interface of AES [FIPS-197]. Since the cipher algorithm was published in 2007, its security has been scrutinized in the public community, but no security weaknesses have been reported so far.

CLEFIA is a lightweight blockcipher, since it can be implemented within 3 Kgates using a 0.13-um standard Complementary Metal Oxide Semiconductor (CMOS) Application-Specific Integrated Circuit (ASIC) library. Many of the lightweight cryptographic algorithms sacrifice security and/or speed; however, CLEFIA provides high-level security of 128, 192, and 256 bits and high performance in software and hardware. CLEFIA will be of benefit to the Internet, which will be connected to more distributed and resource-constrained devices.

CLEFIA is proposed in ISO/IEC 29192-2 [ISO29192-2] and the CRYPTREC project for the revision of the e-Government recommended ciphers list in Japan [CRYPTREC].

Further information about CLEFIA, including reference implementation, test vectors, and security and performance evaluation, is available from http://www.sony.net/clefia/.

2. Notations

This section describes mathematical notations, conventions, and symbols used throughout this document.

```
0x                : A prefix for a binary string in hexadecimal form
a|b or (a|b)      : Concatenation of a and b
(a,b) or (a b)    : Vector style representation of a|b
a <- b            : Updating a value of a by a value of b
trans(a)          : Transposition of a vector or a matrix a
a XOR b           : Bitwise exclusive-OR operation
```

```
~a             : Logical negation
a <<< b        : b-bit left cyclic shift operation
a ^ b          : a raised to the power of b
a * b          : Multiplication in GF(2^n) over a defined polynomial
```

3. CLEFIA Algorithm

The CLEFIA algorithm consists of two parts: a data processing part and a key scheduling part. The data processing part of CLEFIA consists of functions ENCr for encryption and DECr for decryption. The encryption/decryption process is as follows:

Step 1. Key scheduling
Step 2. Encrypting/decrypting each block of data using ENCr/DECr

The process of the key scheduling is described in Section 6, and the definitions of ENCr and DECr are explained in Section 5. CLEFIA supports 128-bit, 192-bit, and 256-bit keys, and the key scheduling and ENCr/DECr should be appropriately selected for its key length.

4. CLEFIA Building Blocks

4.1. GFN_{d,r}

We first define the function GFN_{d,r}, which is a fundamental structure for CLEFIA, and then define a data processing part and a key scheduling 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 scheduling for a 128-bit key. The 8-branch generalized Feistel network is applied in the key scheduling for a 192-bit/256-bit key. We denote the d-branch r-round generalized Feistel network employed in CLEFIA as GFN_{d,r}.

For d pairs of 32-bit inputs Xi and outputs Yi (0 <= i < d), and dr/2 32-bit round keys RK_{i} (0 <= i < dr/2), GFN_{d,r} (d = 4,8) is defined as follows.

```
   GFN_{4,r}(RK_{0}, ..., RK_{2r-1}, X0, X1, X2, X3)

         input : 32-bit round keys RK_{0}, ..., RK_{2r-1},
                 32-bit data X0, X1, X2, X3,

         output: 32-bit data Y0, Y1, Y2, Y3

      Step 1. T0 | T1 | T2 | T3 <- X0 | X1 | X2 | X3

      Step 2. For i = 0 to r - 1 do the following:

         Step 2.1. T1 <- T1 XOR F0(RK_{2i},T0),
                   T3 <- T3 XOR F1(RK_{2i + 1}, T2)

         Step 2.2. T0 | T1 | T2 | T3 <- T1 | T2 | T3 | T0

      Step 3. Y0 | Y1 | Y2 | Y3 <- T3 | T0 | T1 | T2

   GFN_{8,r}(RK_{0}, ..., RK_{4r-1}, X0, X1, ..., X7)

         input : 32-bit round keys RK_{0}, ..., RK_{4r-1},
                 32-bit data X0, X1, X2, X3, X4, X5, X6, X7,

         output: 32-bit data Y0, Y1, Y2, Y3, Y4, Y5, Y6, Y7

      Step 1. T0 | T1 | ... | T7 <- X0 | X1 | ... | X7

      Step 2. For i = 0 to r - 1 do the following:

         Step 2.1. T1 <- T1 XOR F0(RK_{4i}, T0),
                   T3 <- T3 XOR F1(RK_{4i + 1}, T2),
                   T5 <- T5 XOR F0(RK_{4i + 2}, T4),
                   T7 <- T7 XOR F1(RK_{4i + 3}, T6)

         Step 2.2. T0 | T1 | ... | T6 | T7 <- T1 | T2 | ... | T7 | T0

      Step 3. Y0 | Y1 | ... | Y6 | Y7 <- T7 | T0 | ... | T5 | T6
```

The inverse function GFNINV_{4,r} is obtained by changing the order of RK_{i} and the direction of word rotation at Step 2.2 and Step 3 in GFN_{4,r}.

```
   GFNINV_{4,r}(RK_{0}, ..., RK_{2r-1}, X0, X1, X2, X3)

         input : 32-bit round keys RK_{0}, ..., RK_{2r-1},
                 32-bit data X0, X1, X2, X3,

         output: 32-bit data Y0, Y1, Y2, Y3

      Step 1. T0 | T1 | T2 | T3 <- X0 | X1 | X2 | X3

      Step 2. For i = 0 to r - 1 do the following:

         Step 2.1. T1 <- T1 XOR F0(RK_{2(r - i) - 2}, T0),
                   T3 <- T3 XOR F1(RK_{2(r - i) - 1}, T2)

         Step 2.2. T0 | T1 | T2 | T3 <- T3 | T0 | T1 | T2

      Step 3. Y0 | Y1 | Y2 | Y3 <- T1 | T2 | T3 | T0
```

4.2. F-Functions

Two F-functions F0 and F1 used in GFN_{d,r} are defined as follows:

```
   F0(RK, x)

         input : 32-bit round key RK, 32-bit data x,

         output: 32-bit data y

      Step 1. T <- RK XOR x

      Step 2. Let T = T0 | T1 | T2 | T3, where Ti is 8-bit data,
              T0 <- S0(T0),
              T1 <- S1(T1),
              T2 <- S0(T2),
              T3 <- S1(T3)

      Step 3. Let y = y0 | y1 | y2 | y3, where yi is 8-bit data,
              y <- M0 trans((T0, T1, T2, T3))
```

```
   F1(RK, x)

         input : 32-bit round key RK, 32-bit data x,

         output: 32-bit data y

      Step 1. T <- RK XOR x

      Step 2. Let T = T0 | T1 | T2 | T3, where Ti is 8-bit data,
              T0 <- S1(T0),
              T1 <- S0(T1),
              T2 <- S1(T2),
              T3 <- S0(T3)

      Step 3. Let y = y0 | y1 | y2 | y3, where yi is 8-bit data,
              y <- M1 trans((T0, T1, T2, T3))
```

S0 and S1 are nonlinear 8-bit S-boxes, and M0 and M1 are 4x4 diffusion matrices described in the following section. In each F-function, two S-boxes are used in the different order, and a different matrix is used.

4.3. S-Boxes

CLEFIA employs two different types of 8-bit S-boxes: S0 is based on four 4-bit S-boxes, and S1 is based on the inverse function over GF(2^8) [CLEFIA1].

Tables 1 and 2 show the output values of S0 and S1, respectively. In these tables, all values are expressed in hexadecimal form. 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 S0 because it is on the cross line of the row indexed by "a." and the column indexed by ".b".

Table 1: S-Box S0

	.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 2: S-Box S1

	.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

4.4. Diffusion Matrices

The multiplications of a diffusion matrix M0 or M1, and a vector T in Section 4.2, are obtained as follows.

y = M0 trans((T0, T1, T2, T3)):

```
y0 =          T0  XOR (0x02 * T1) XOR (0x04 * T2) XOR (0x06 * T3),
y1 = (0x02 * T0) XOR          T1  XOR (0x06 * T2) XOR (0x04 * T3),
y2 = (0x04 * T0) XOR (0x06 * T1) XOR          T2  XOR (0x02 * T3),
y3 = (0x06 * T0) XOR (0x04 * T1) XOR (0x02 * T2) XOR          T3
```

y = M1 trans((T0, T1, T2, T3)):

```
y0 =          T0  XOR (0x08 * T1) XOR (0x02 * T2) XOR (0x0a * T3),
y1 = (0x08 * T0) XOR          T1  XOR (0x0a * T2) XOR (0x02 * T3),
y2 = (0x02 * T0) XOR (0x0a * T1) XOR          T2  XOR (0x08 * T3),
y3 = (0x0a * T0) XOR (0x02 * T1) XOR (0x08 * T2) XOR          T3
```

In the above equations, * denotes a multiplication in GF(2^8) defined by the lexicographically first primitive polynomial z^8 + z^4 + z^3 + z^2 + 1. The constants 0x02, 0x04, 0x06, 0x08, and 0x0a are represented in hexadecimal form of finite field polynomials. For example, 0x02 identifies the finite field element z. 8-bit data Ti is also interpreted as a finite field element.

The mathematical background of two diffusion matrices and their choices are explained in [CLEFIA2].

5. Data Processing Part

5.1. Encryption/Decryption

The data processing part of CLEFIA consists of ENCr for encryption and DECr for decryption. ENCr and DECr are based on the 4-branch generalized Feistel structure GFN_{4,r}. Let P,C be 128-bit plaintext and ciphertext, and let Pi, Ci (0 <= i < 4) be divided 32-bit plaintexts and ciphertexts where P = P0 | P1 | P2 | P3 and C = C0 | C1 | C2 | C3, and let WK0, WK1, WK2, WK3 be 32-bit whitening keys and RK_{i} (0 <= i < 2r) be 32-bit round keys provided by the key scheduling part. Then, r-round encryption function ENCr is defined as follows:

```
      Step 1. T0 | T1 | T2 | T3 <- P0 | (P1 XOR WK0) | P2 | (P3 XOR WK1)

      Step 2. T0 | T1 | T2 | T3
                    <- GFN_{4,r}(RK_{0}, ..., RK_{2r-1}, T0, T1, T2, T3)

      Step 3. C0 | C1 | C2 | C3 <- T0 | (T1 XOR WK2) | T2 | (T3 XOR WK3)
```

The decryption function DECr is defined as follows:

```
      Step 1. T0 | T1 | T2 | T3 <- C0 | (C1 XOR WK2) | C2 | (C3 XOR WK3)

      Step 2. T0 | T1 | T2 | T3
                 <- GFNINV_{4,r}(RK_{0}, ..., RK_{2r-1}, T0, T1, T2, T3)

      Step 3. P0 | P1 | P2 | P3 <- T0 | (T1 XOR WK0) | T2 | (T3 XOR WK1)
```

5.2. The Numbers of Rounds

The number of rounds, r, is 18, 22, and 26 for 128-bit, 192-bit, and 256-bit keys, respectively. The total number of RK_{i} depends on the key length. The data processing part requires 36, 44, and 52 round keys for 128-bit, 192-bit, and 256-bit keys, respectively.

6. Key Scheduling Part

The key scheduling part of CLEFIA supports 128-bit, 192-bit, and 256-bit keys and outputs whitening keys WKi (0 <= i < 4) and round keys RK_{j} (0 <= j < 2r) for the data processing part.

6.1. DoubleSwap Function

We first define the DoubleSwap function, which is used in the key scheduling part.

The DoubleSwap Function Sigma(X):

For 128-bit data X,

```
   Y = Sigma(X)
     = X[7-63] | X[121-127] | X[0-6] | X[64-120],
```

where X[a-b] denotes a bit string cut from the a-th bit to the b-th bit of X. Bit 0 is the most significant bit.

6.2. Overall Structure

The key scheduling part of CLEFIA provides whitening keys and round keys for the data processing part. Let K be the key and L be an intermediate key, and the key scheduling part consists of the following two steps.

1. Generating L from K.
2. Expanding K and L (Generating WKi 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}.

6.3. Key Scheduling for a 128-Bit Key

The 128-bit intermediate key L is generated by applying GFN_{4,12}, which takes twenty-four 32-bit constant values CON_128[i] (0 <= i < 24) as round keys and K = K0 | K1 | K2 | K3 as an input. Then, K and L are used to generate WKi (0 <= i < 4) and RK_{j} (0 <= j < 36) in the following steps. In the latter part, thirty-six 32-bit constant values CON_128[i] (24 <= i < 60) are used. The generation steps of CON_128[i] are explained in Section 6.6.

(Generating L from K)

```
   Step 1. L <- GFN_{4,12}(CON_128[0], ..., CON_128[23], K0, ..., K3)
```

(Expanding K and L)

```
   Step 2. WK0 | WK1 | WK2 | WK3 <- K

   Step 3. For i = 0 to 8 do the following:
        T <- L XOR (CON_128[24 + 4i] | CON_128[24 + 4i + 1]
                   | CON_128[24 + 4i + 2] | CON_128[24 + 4i + 3])
        L <- Sigma(L)
        if i is odd: T <- T XOR K
        RK_{4i} | RK_{4i + 1} | RK_{4i + 2} | RK_{4i + 3} <- T
```

6.4. Key Scheduling for a 192-Bit Key

Two 128-bit values KL and KR are generated from a 192-bit key K = K0 | K1 | K2 | K3 | K4 | K5, where Ki is 32-bit data. Then, two 128-bit values LL and LR are generated by applying GFN_{8,10}, which takes CON_192[i] (0 <= i < 40) as round keys and KL|KR as a 256-bit input.

Then, KL,KR and LL,LR are used to generate WKi (0 <= i < 4) and RK_{j} (0 <= j < 44) in the following steps. In the latter part, forty-four 32-bit constant values CON_192[i] (40 <= i < 84) are used.

The following steps show the 192-bit/256-bit key scheduling. For the 192-bit key scheduling, the value of k is set as 192.

6.5. Key Scheduling for a 256-Bit Key

The key scheduling for a 256-bit key is almost the same as that for a 192-bit key, except for constant values, the required number of RKi, and the initialization of KR.

For a 256-bit key, the value of k is set as 256, and the steps are almost the same as in the 192-bit key case. The difference is that we use CON_256[i](0 <= i < 40) as round keys to generate LL and LR, and then to generate RK_{j} (0 <= j < 52), we use fifty-two 32-bit constant values CON_256[i](40 <= i < 92).

(Generating LL,LR from KL,KR for a k-bit key)

```
   Step 1. Set k = 192 or k = 256

   Step 2. If k = 192   :
                  KL <- K0 | K1 | K2 | K3, KR <- K4 | K5 | ~K0 | ~K1
           else if k = 256 :
                  KL <- K0 | K1 | K2 | K3, KR <- K4 | K5 | K6 | K7

   Step 3. Let KL = KL0 | KL1 | KL2 | KL3
               KR = KR0 | KR1 | KR2 | KR3
               LL|LR <-
               GFN_{8,10}(CON_k[0] , ..., CON_k[39],
                                  KL0, ..., KL3, KR0, ..., KR3)
```

(Expanding KL,KR and LL,LR for a k-bit key)

```
   Step 4. WK0 | WK1 | WK2 | WK3 <- KL XOR KR
```

```
      Step 5. For i = 0 to 10 (if k = 192),
                                 or 12 (if k = 256) do the following:

                  If (i mod 4) = 0 or 1:
                      T <- LL XOR (CON_k[40 + 4i] | CON_k[40 + 4i + 1]
                              | CON_k[40 + 4i + 2] | CON_k[40 + 4i + 3])
                      LL <- Sigma(LL)
                      if i is odd: T <- T XOR KR
                  else:
                      T <- LR XOR (CON_k[40 + 4i] | CON_k[40 + 4i + 1]
                              | CON_k[40 + 4i + 2] | CON_k[40 + 4i + 3])
                      LR <- Sigma(LR)
                      if i is odd: T <- T XOR KL

                  RK_{4i} | RK_{4i + 1} | RK_{4i + 2} | RK_{4i + 3} <- T
```

6.6. Constant Values

32-bit constant values CON_k[i] are used in the key scheduling algorithm. We need 60, 84, and 92 constant values for 128-bit, 192-bit, and 256-bit keys, respectively. Let P(16) = 0xb7e1 (= (e-2)2^16) and Q(16) = 0x243f (= (pi-3)2^16), where e is the base of the natural logarithm (2.71828...) and pi is the circle ratio (3.14159...). CON_k[i], for k = 128,192,256, are generated as follows (see Table 3 for the repetition numbers l_k and the initial values IV_k).

```
      Step 1. T_k[0] <- IV_k

      Step 2. For i = 0 to l_k - 1 do the following:

         Step 2.1. CON_k[2i] <- (T_k[i] XOR P) | (~T_k[i] <<< 1)

         Step 2.2. CON_k[2i + 1] <- (~T_k[i] XOR Q) | (T_k[i] <<< 8)

         Step 2.3. T_k[i + 1] <- T_k[i] * (0x0002^{-1})
```

In Step 2.3, the multiplications are performed in the field GF(2^16) defined by a primitive polynomial z^16 + z^15 + z^13 + z^11 + z^5 + z^4 + 1 (=0x1a831). 0x0002^{-1} denotes the multiplicative inverse of the finite field element z. The selection criteria of IV and the primitive polynomial are shown in [CLEFIA1].

Table 3: Required Numbers of Constant Values

k	# of CON_k[i]	l_k	IV_k
128	60	30	0x428a
192	84	42	0x7137
256	92	46	0xb5c0

Tables 4-6 show the values of T_k[i](k = 128,192,256), and Tables 7-9 show the values of CON_k[i](k = 128,192,256).

Table 4: T_128[i]

i	0	1	2	3	4	5	6	7
T_128[i]	428a	2145	c4ba	625d	e536	729b	ed55	a2b2
i	8	9	10	11	12	13	14	15
T_128[i]	5159	fcb4	7e5a	3f2d	cb8e	65c7	e6fb	a765
i	16	17	18	19	20	21	22	23
T_128[i]	87aa	43d5	f5f2	7af9	e964	74b2	3a59	c934
i	24	25	26	27	28	29		
T_128[i]	649a	324d	cd3e	669f	e757	a7b3		

Table 5: T_192[i]

i	0	1	2	3	4	5	6	7
T_192[i]	7137	ec83	a259	8534	429a	214d	c4be	625f
i	8	9	10	11	12	13	14	15
T_192[i]	e537	a683	8759	97b4	4bda	25ed	c6ee	6377
i	16	17	18	19	20	21	22	23
T_192[i]	e5a3	a6c9	877c	43be	21df	c4f7	b663	8f29
i	24	25	26	27	28	29	30	31
T_192[i]	938c	49c6	24e3	c669	b72c	5b96	2dcb	c2fd
i	32	33	34	35	36	37	38	39
T_192[i]	b566	5ab3	f941	a8b8	545c	2a2e	1517	de93
i	40	41						
T_192[i]	bb51	89b0						

Table 6: T_256[i]

```
   i       0    1    2    3    4    5    6    7
T_256[i] b5c0 5ae0 2d70 16b8 0b5c 05ae 02d7 d573
   i       8    9   10   11   12   13   14   15
T_256[i] bea1 8b48 45a4 22d2 1169 dcac 6e56 372b
   i      16   17   18   19   20   21   22   23
T_256[i] cf8d b3de 59ef f8ef a86f 802f 940f 9e1f
   i      24   25   26   27   28   29   30   31
T_256[i] 9b17 9993 98d1 9870 4c38 261c 130e 0987
   i      32   33   34   35   36   37   38   39
T_256[i] d0db bc75 8a22 4511 f690 7b48 3da4 1ed2
   i      40   41   42   43   44   45
T_256[i] 0f69 d3ac 69d6 34eb ce6d b32e
```

Table 7: CON_128[i] (0 <= i < 60)

```
   i             0        1        2        3
CON_128[i] f56b7aeb 994a8a42 96a4bd75 fa854521
   i             4        5        6        7
CON_128[i] 735b768a 1f7abac4 d5bc3b45 b99d5d62
   i             8        9       10       11
CON_128[i] 52d73592 3ef636e5 c57a1ac9 a95b9b72
   i            12       13       14       15
CON_128[i] 5ab42554 369555ed 1553ba9a 7972b2a2
   i            16       17       18       19
CON_128[i] e6b85d4d 8a995951 4b550696 2774b4fc
   i            20       21       22       23
CON_128[i] c9bb034b a59a5a7e 88cc81a5 e4ed2d3f
   i            24       25       26       27
CON_128[i] 7c6f68e2 104e8ecb d2263471 be07c765
   i            28       29       30       31
CON_128[i] 511a3208 3d3bfbe6 1084b134 7ca565a7
   i            32       33       34       35
CON_128[i] 304bf0aa 5c6aaa87 f4347855 9815d543
   i            36       37       38       39
CON_128[i] 4213141a 2e32f2f5 cd180a0d a139f97a
   i            40       41       42       43
CON_128[i] 5e852d36 32a464e9 c353169b af72b274
   i            44       45       46       47
CON_128[i] 8db88b4d e199593a 7ed56d96 12f434c9
   i            48       49       50       51
CON_128[i] d37b36cb bf5a9a64 85ac9b65 e98d4d32
   i            52       53       54       55
CON_128[i] 7adf6582 16fe3ecd d17e32c1 bd5f9f66
   i            56       57       58       59
CON_128[i] 50b63150 3c9757e7 1052b098 7c73b3a7
```

Table 8: CON_192[i] (0 <= i < 84)

i	0	1	2	3
CON_192[i]	c6d61d91	aaf73771	5b6226f8	374383ec
i	4	5	6	7
CON_192[i]	15b8bb4c	799959a2	32d5f596	5ef43485
i	8	9	10	11
CON_192[i]	f57b7acb	995a9a42	96acbd65	fa8d4d21
i	12	13	14	15
CON_192[i]	735f7682	1f7ebec4	d5be3b41	b99f5f62
i	16	17	18	19
CON_192[i]	52d63590	3ef737e5	1162b2f8	7d4383a6
i	20	21	22	23
CON_192[i]	30b8f14c	5c995987	2055d096	4c74b497
i	24	25	26	27
CON_192[i]	fc3b684b	901ada4b	920cb425	fe2ded25
i	28	29	30	31
CON_192[i]	710f7222	1d2eeec6	d4963911	b8b77763
i	32	33	34	35
CON_192[i]	524234b8	3e63a3e5	1128b26c	7d09c9a6
i	36	37	38	39
CON_192[i]	309df106	5cbc7c87	f45f7883	987ebe43
i	40	41	42	43
CON_192[i]	963ebc41	fa1fdf21	73167610	1f37f7c4
i	44	45	46	47
CON_192[i]	01829338	6da363b6	38c8e1ac	54e9298f
i	48	49	50	51
CON_192[i]	246dd8e6	484c8c93	fe276c73	9206c649
i	52	53	54	55
CON_192[i]	9302b639	ff23e324	7188732c	1da969c6
i	56	57	58	59
CON_192[i]	00cd91a6	6cec2cb7	ec7748d3	8056965b
i	60	61	62	63
CON_192[i]	9a2aa469	f60bcb2d	751c7a04	193dfdc2
i	64	65	66	67
CON_192[i]	02879532	6ea666b5	ed524a99	8173b35a
i	68	69	70	71
CON_192[i]	4ea00d7c	228141f9	1f59ae8e	7378b8a8
i	72	73	74	75
CON_192[i]	e3bd5747	8f9c5c54	9dcfaba3	f1ee2e2a
i	76	77	78	79
CON_192[i]	a2f6d5d1	ced71715	697242d8	055393de
i	80	81	82	83
CON_192[i]	0cb0895c	609151bb	3e51ec9e	5270b089

Table 9: CON_256[i] (0 <= i < 92)

i	0	1	2	3
CON_256[i]	0221947e	6e00c0b5	ed014a3f	8120e05a
i	4	5	6	7
CON_256[i]	9a91a51f	f6b0702d	a159d28f	cd78b816
i	8	9	10	11
CON_256[i]	bcbde947	d09c5c0b	b24ff4a3	de6eae05
i	12	13	14	15
CON_256[i]	b536fa51	d917d702	62925518	0eb373d5
i	16	17	18	19
CON_256[i]	094082bc	6561a1be	3ca9e96e	5088488b
i	20	21	22	23
CON_256[i]	f24574b7	9e64a445	9533ba5b	f912d222
i	24	25	26	27
CON_256[i]	a688dd2d	caa96911	6b4d46a6	076cacdc
i	28	29	30	31
CON_256[i]	d9b72353	b596566e	80ca91a9	eceb2b37
i	32	33	34	35
CON_256[i]	786c60e4	144d8dcf	043f9842	681edeb3
i	36	37	38	39
CON_256[i]	ee0e4c21	822fef59	4f0e0e20	232feff8
i	40	41	42	43
CON_256[i]	1f8eaf20	73af6fa8	37ceffa0	5bef2f80
i	44	45	46	47
CON_256[i]	23eed7e0	4fcf0f94	29fec3c0	45df1f9e
i	48	49	50	51
CON_256[i]	2cf6c9d0	40d7179b	2e72ccd8	42539399
i	52	53	54	55
CON_256[i]	2f30ce5c	4311d198	2f91cf1e	43b07098
i	56	57	58	59
CON_256[i]	fbd9678f	97f8384c	91fdb3c7	fddc1c26
i	60	61	62	63
CON_256[i]	a4efd9e3	c8ce0e13	be66ecf1	d2478709
i	64	65	66	67
CON_256[i]	673a5e48	0b1bdbd0	0b948714	67b575bc
i	68	69	70	71
CON_256[i]	3dc3ebba	51e2228a	f2f075dd	9ed11145
i	72	73	74	75
CON_256[i]	417112de	2d5090f6	cca9096f	a088487b
i	76	77	78	79
CON_256[i]	8a4584b7	e664a43d	a933c25b	c512d21e
i	80	81	82	83
CON_256[i]	b888e12d	d4a9690f	644d58a6	086cacd3
i	84	85	86	87
CON_256[i]	de372c53	b216d669	830a9629	ef2beb34
i	88	89	90	91
CON_256[i]	798c6324	15ad6dce	04cf99a2	68ee2eb3

7. Security Considerations

The security of CLEFIA has been scrutinized in the public community, but no security weaknesses have been found for full-round CLEFIA to date, neither by the designers nor by independent cryptographers. Security evaluation by the designers is described in [CLEFIA3], and a list of published cryptanalysis results by external cryptographers is available from http://www.sony.net/Products/cryptography/clefia/technical/related_material.html.

8. Informative References

[CLEFIA1] The 128-bit Blockcipher CLEFIA - Algorithm Specification, Revision 1.0, June 1, 2007, Sony Corporation, http://www.sony.net/Products/cryptography/clefia/technical/data/clefia-spec-1.0.pdf.

[CLEFIA2] The 128-bit blockcipher CLEFIA - Design Rationale, Revision 1.0, June 1, 2007, Sony Corporation, http://www.sony.net/Products/cryptography/clefia/technical/data/clefia-design-1.0.pdf.

[CLEFIA3] The 128-bit blockcipher CLEFIA - Security and Performance Evaluations, Revision 1.0, June 1, 2007, Sony Corporation, http://www.sony.net/Products/cryptography/clefia/technical/data/clefia-eval-1.0.pdf.

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[FSE07] Shirai, T., Shibutani, K., Akishita, T., Moriai, S., and T. Iwata, "The 128-bit Blockcipher CLEFIA", proceedings of Fast Software Encryption 2007 - FSE 2007, LNCS 4593, pp. 181-195, Springer-Verlag, 2007.

[ISO29192-2] ISO/IEC 29192-2, "Information technology - Security techniques - Lightweight cryptography - Part 2: Block ciphers", http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=56552.

Appendix A. Test Vectors

In this appendix, we give test vectors of CLEFIA for each key length. The data are expressed in hexadecimal form. For the intermediate values of these vectors, refer to Appendix B.

128-bit key:

```
key        ffeeddcc bbaa9988 77665544 33221100
plaintext  00010203 04050607 08090a0b 0c0d0e0f
ciphertext de2bf2fd 9b74aacd f1298555 459494fd
```

192-bit key:

```
key        ffeeddcc bbaa9988 77665544 33221100
           f0e0d0c0 b0a09080
plaintext  00010203 04050607 08090a0b 0c0d0e0f
ciphertext e2482f64 9f028dc4 80dda184 fde181ad
```

256-bit key:

```
key        ffeeddcc bbaa9988 77665544 33221100
           f0e0d0c0 b0a09080 70605040 30201000
plaintext  00010203 04050607 08090a0b 0c0d0e0f
ciphertext a1397814 289de80c 10da46d1 fa48b38a
```

Appendix B. Test Vectors (Intermediate Values)

128-bit key:

```
key                       ffeeddcc bbaa9988 77665544 33221100
plaintext                 00010203 04050607 08090a0b 0c0d0e0f
ciphertext                de2bf2fd 9b74aacd f1298555 459494fd

L                         8f89a61b 9db9d0f3 93e65627 da0d027e

WK_{0,1,2,3}              ffeeddcc bbaa9988 77665544 33221100
RK_{0,1,2,3}              f3e6cef9 8df75e38 41c06256 640ac51b
RK_{4,5,6,7}              6a27e20a 5a791b90 e8c528dc 00336ea3
RK_{8,9,10,11}            59cd17c4 28565583 312a37cc c08abd77
RK_{12,13,14,15}          7e8e7eec 8be7e949 d3f463d6 a0aad6aa
RK_{16,17,18,19}          e75eb039 0d657eb9 018002e2 9117d009
RK_{20,21,22,23}          9f98d11e babee8cf b0369efa d3aaef0d
RK_{24,25,26,27}          3438f93b f9cea4a0 68df9029 b869b4a7
RK_{28,29,30,31}          24d6406d e74bc550 41c28193 16de4795
RK_{32,33,34,35}          a34a20f5 33265d14 b19d0554 5142f434
```

```
   plaintext                  00010203 04050607 08090a0b 0c0d0e0f
   initial whitening key               ffeeddcc          bbaa9988
   after whitening            00010203 fbebdbcb 08090a0b b7a79787

   Round  1         input     00010203 fbebdbcb 08090a0b b7a79787
          F-function          F0                F1
          input               00010203          08090a0b
          round key           f3e6cef9          8df75e38
          after key add       f3e7ccfa          85fe5433
          after S             290246e1          777de8e8
          after M             547a3193          abf12070

   Round  2         input     af91ea58 08090a0b 1c56b7f7 00010203
          F-function          F0                F1
          input               af91ea58          1c56b7f7
          round key           41c06256          640ac51b
          after key add       ee51880e          785c72ec
          after S             cb5d2b0c          63a5edd2
          after M             f51cebb3          82dfe347

   Round  3         input     fd15e1b8 1c56b7f7 82dee144 af91ea58
          F-function          F0                F1
          input               fd15e1b8          82dee144
          round key           6a27e20a          5a791b90
          after key add       973203b2          d8a7fad4
          after S             c2c7c6c2          be59e10d
          after M             d8dfd8de          e15ea81c

   Round  4         input     c4896f29 82dee144 4ecf4244 fd15e1b8
          F-function          F0                F1
          input               c4896f29          4ecf4244
          round key           e8c528dc          00336ea3
          after key add       2c4c47f5          4efc2ce7
          after S             9da4dafc          43bce638
          after M             b5b28e96          b65c519a

   Round  5         input     376c6fd2 4ecf4244 4b49b022 c4896f29
          F-function          F0                F1
          input               376c6fd2          4b49b022
          round key           59cd17c4          28565583
          after key add       6ea17816          631fe5a1
          after S             f26ad3e5          62af9f1b
          after M             29f08afd          be01d127
```

```
   Round  6         input   673fc8b9 4b49b022 7a88be0e 376c6fd2
          F-function        F0                F1
          input             673fc8b9          7a88be0e
          round key         312a37cc          c08abd77
          after key add     5615ff75          ba020379
          after S           b39c8e58          2dd1e9a2
          after M           5999a79e          0429b329

   Round  7         input   12d017bc 7a88be0e 3345dcfb 673fc8b9
          F-function        F0                F1
          input             12d017bc          3345dcfb
          round key         7e8e7eec          8be7e949
          after key add     6c5e6950          b8a235b2
          after S           8b737025          67a08eba
          after M           6ed11b09          dfd3cd32

   Round  8         input   1459a507 3345dcfb b8ec058b 12d017bc
          F-function        F0                F1
          input             1459a507          b8ec058b
          round key         d3f463d6          a0aad6aa
          after key add     c7adc6d1          1846d321
          after S           e7ee5a5f          9e97f1a1
          after M           8c9d011c          93684eec

   Round  9         input   bfd8dde7 b8ec058b 81b85950 1459a507
          F-function        F0                F1
          input             bfd8dde7          81b85950
          round key         e75eb039          0d657eb9
          after key add     58866dde          8cdd27e9
          after S           4e821daf          59c56044
          after M           e6d6501e          6d5839b4

   Round 10         input   5e3a5595 81b85950 79019cb3 bfd8dde7
          F-function        F0                F1
          input             5e3a5595          79019cb3
          round key         018002e2          9117d009
          after key add     5fba5777          e8164cba
          after S           612d8f7b          0185a49c
          after M           3a1b0e97          b9b479c8

   Round 11         input   bba357c7 79019cb3 066ca42f 5e3a5595
          F-function        F0                F1
          input             bba357c7          066ca42f
          round key         9f98d11e          babee8cf
          after key add     243b86d9          bcd24ce0
          after S           f70f1144          cb72a481
          after M           28974052          4a6700b1
```

```
   Round 12         input   5196dce1 066ca42f 145d5524 bba357c7
          F-function        F0                F1
          input             5196dce1          145d5524
          round key         b0369efa          d3aaef0d
          after key add     e1a0421b          c7f7ba29
          after S           6f7efd4f          72642dce
          after M           ffb5db32          907d3820

   Round 13         input   f9d97f1d 145d5524 2bde6fe7 5196dce1
          F-function        F0                F1
          input             f9d97f1d          2bde6fe7
          round key         3438f93b          f9cea4a0
          after key add     cde18626          d210cb47
          after S           3f751141          ab28e0da
          after M           0a744c28          1c3e38a3

   Round 14         input   1e29190c 2bde6fe7 4da8e442 f9d97f1d
          F-function        F0                F1
          input             1e29190c          4da8e442
          round key         68df9029          b869b4a7
          after key add     76f68925          f5c150e5
          after S           fe6db7e7          fc0c25f6
          after M           aaa2c803          c4315b8d

   Round 15         input   817ca7e4 4da8e442 3de82490 1e29190c
          F-function        F0                F1
          input             817ca7e4          3de82490
          round key         24d6406d          e74bc550
          after key add     a5aae789          daa3e1c0
          after S           8d233818          2904757b
          after M           7bd4cced          eac2f0fb

   Round 16         input   367c28af 3de82490 f4ebe9f7 817ca7e4
          F-function        F0                F1
          input             367c28af          f4ebe9f7
          round key         41c28193          16de4795
          after key add     77bea93c          e235ae62
          after S           7c4a935b          669b8953
          after M           598e6940          c119609f

   Round 17         input   64664dd0 f4ebe9f7 4065c77b 367c28af
          F-function        F0                F1
          input             64664dd0          4065c77b
          round key         a34a20f5          33265d14
          after key add     c72c6d25          73439a6f
          after S           e7e61de7          788c85b4
          after M           2ac01b0a          c755adfa
```

```
   Round 18         input   de2bf2fd 4065c77b f1298555 64664dd0
          F-function        F0                F1
          input             de2bf2fd          f1298555
          round key         b19d0554          5142f434
          after key add     6fb6f7a9          a06b7161
          after S           b44d648c          7e99ea2a
          after M           ac7738f2          12d0c82d

   output                   de2bf2fd ec12ff89 f1298555 76b685fd
   final whitening key               77665544          33221100
   after whitening          de2bf2fd 9b74aacd f1298555 459494fd
   ciphertext               de2bf2fd 9b74aacd f1298555 459494fd


   192-bit key:

   key                      ffeeddcc bbaa9988 77665544 33221100
                            f0e0d0c0 b0a09080
   plaintext                00010203 04050607 08090a0b 0c0d0e0f
   ciphertext               e2482f64 9f028dc4 80dda184 fde181ad

   LL                       db05415a 800082db 7cb8186c d788c5f3
   LR                       1ca9b2e1 b4606829 c92dd35e 2258a432
   WK_{0,1,2,3}             0f0e0d0c 0b0a0908 77777777 77777777
   RK_{0,1,2,3}             4d3bfd1b 7a1f5dfa 0fae6e7c c8bf3237
   RK_{4,5,6,7}             73c2eeb8 dd429ec5 e220b3af c9135e73
   RK_{8,9,10,11}           38c46a07 fc2ce4ba 370abf2d b05e627b
   RK_{12,13,14,15}         38351b2f 74bd6e1e 1b7c7dce 92cfc98e
   RK_{16,17,18,19}         509b31a6 4c5ad53c 6fc2ba33 e1e5c878
   RK_{20,21,22,23}         419a74b9 1dd79e0e 240a33d2 9dabfd09
   RK_{24,25,26,27}         6e3ff82a 74ac3ffd b9696e2e cc0b3a38
   RK_{28,29,30,31}         ed785cbd 9c077c13 04978d83 2ec058ba
   RK_{32,33,34,35}         4bbd5f6a 31fe8de8 b76da574 3a6fa8e7
   RK_{36,37,38,39}         521213ce 4f1f59d8 c13624f6 ee91f6a4
   RK_{40,41,42,43}         17f68fde f6c360a9 6288bc72 c0ad856b

   plaintext                00010203 04050607 08090a0b 0c0d0e0f
   initial whitening key             0f0e0d0c          0b0a0908
   after whitening          00010203 0b0b0b0b 08090a0b 07070707

   Round  1         input   00010203 0b0b0b0b 08090a0b 07070707
          F-function        F0                F1
          input             00010203          08090a0b
          round key         4d3bfd1b          7a1f5dfa
          after key add     4d3aff18          721657f1
          after S           43c58e9e          ed85d736
          after M           b5021a3b          c397f62b
```

```
   Round  2          input    be091130 08090a0b c490f12c 00010203
          F-function          F0                F1
          input               be091130          c490f12c
          round key           0fae6e7c          c8bf3237
          after key add       b1a77f4c          0c2fc31b
          after S             f3d10ba4          13d83a3d
          after M             9fba69c1          6683cae3

   Round  3          input    97b363ca c490f12c 6682c8e0 be091130
          F-function          F0                F1
          input               97b363ca          6682c8e0
          round key           73c2eeb8          dd429ec5
          after key add       e4718d72          bbc05625
          after S             79ea66ed          f47b0d7a
          after M             61c21ea5          120e06e2

   Round  4          input    a552ef89 6682c8e0 ac0717d2 97b363ca
          F-function          F0                F1
          input               a552ef89          ac0717d2
          round key           e220b3af          c9135e73
          after key add       47725c26          651449a1
          after S             daeda541          355c651b
          after M             28a43c63          cb1ab573

   Round  5          input    4e26f483 ac0717d2 5ca9d6b9 a552ef89
          F-function          F0                F1
          input               4e26f483          5ca9d6b9
          round key           38c46a07          fc2ce4ba
          after key add       76e29e84          a0853203
          after S             fe663e39          7edcc7c6
          after M             5ce7dafe          ac7f4e3e

   Round  6          input    f0e0cd2c 5ca9d6b9 092da1b7 4e26f483
          F-function          F0                F1
          input               f0e0cd2c          092da1b7
          round key           370abf2d          b05e627b
          after key add       c7ea7201          b973c3cc
          after S             e77f9fda          174a3a46
          after M             b9869270          8fc7e089

   Round  7          input    e52f44c9 092da1b7 c1e1140a f0e0cd2c
          F-function          F0                F1
          input               e52f44c9          c1e1140a
          round key           38351b2f          74bd6e1e
          after key add       dd1a5fe6          b55c7a14
          after S             c5496150          5aa5c15c
          after M             33d8590f          e62eb913
```

```
   Round  8          input    3af5f8b8 c1e1140a 16ce743f e52f44c9
          F-function          F0                F1
          input               3af5f8b8          16ce743f
          round key           1b7c7dce          92cfc98e
          after key add       21898576          8401bdb1
          after S             a118dc09          3949b1f3
          after M             f091202d          04f9e827

   Round  9          input    31703427 16ce743f e1d6acee 3af5f8b8
          F-function          F0                F1
          input               31703427          e1d6acee
          round key           509b31a6          4c5ad53c
          after key add       61eb0581          ad8c79d2
          after S             2a8d3304          eeffc072
          after M             f9639a90          8bebfe3d

   Round 10          input    efadeeaf e1d6acee b11e0685 31703427
          F-function          F0                F1
          input               efadeeaf          b11e0685
          round key           6fc2ba33          e1e5c878
          after key add       806f549c          50fbcefd
          after S             cd5eeb61          25d7fe02
          after M             a100e35b          26a4e16d

   Round 11          input    40d64fb5 b11e0685 17d4d54a efadeeaf
          F-function          F0                F1
          input               40d64fb5          17d4d54a
          round key           419a74b9          1dd79e0e
          after key add       014c3b0c          0a034b44
          after S             49a4c013          b4c6c912
          after M             51c0208f          f1a2c339

   Round 12          input    e0de260a 17d4d54a 1e0f2d96 40d64fb5
          F-function          F0                F1
          input               e0de260a          1e0f2d96
          round key           240a33d2          9dabfd09
          after key add       c4d415d8          83a4d09f
          after S             801beebe          86b8f8ed
          after M             8a9aef34          3e451646

   Round 13          input    9d4e3a7e 1e0f2d96 7e9359f3 e0de260a
          F-function          F0                F1
          input               9d4e3a7e          7e9359f3
          round key           6e3ff82a          74ac3ffd
          after key add       f371c254          0a3f660e
          after S             29ea68e8          b4f530a8
          after M             17524741          4b8c607e
```

```
   Round 14         input    095d6ad7 7e9359f3 ab524674 9d4e3a7e
          F-function         F0                F1
          input              095d6ad7          ab524674
          round key          b9696e2e          cc0b3a38
          after key add      b03404f9          67597c4c
          after S            152a2f03          52161e39
          after M            f7ee818b          7902f3eb

   Round 15         input    897dd878 ab524674 e44cc995 095d6ad7
          F-function         F0                F1
          input              897dd878          e44cc995
          round key          ed785cbd          9c077c13
          after key add      640584c5          784bb586
          after S            459d9e10          636b5a11
          after M            4034defc          0228bdd4

   Round 16         input    eb669888 e44cc995 0b75d703 897dd878
          F-function         F0                F1
          input              eb669888          0b75d703
          round key          04978d83          2ec058ba
          after key add      eff1150b          25b58fb9
          after S            90e4ee38          e7691f3b
          after M            4a678609          05b2b4a9

   Round 17         input    ae2b4f9c 0b75d703 8ccf6cd1 eb669888
          F-function         F0                F1
          input              ae2b4f9c          8ccf6cd1
          round key          4bbd5f6a          31fe8de8
          after key add      e59610f6          bd31e139
          after S            f6a5286d          b15d7589
          after M            720df49d          bad65e22

   Round 18         input    7978239e 8ccf6cd1 51b0c6aa ae2b4f9c
          F-function         F0                F1
          input              7978239e          51b0c6aa
          round key          b76da574          3a6fa8e7
          after key add      ce1586ea          6bdf6e4d
          after S            919c117f          283aaa43
          after M            ef24fe56          08916103

   Round 19         input    63eb9287 51b0c6aa a6ba2e9f 7978239e
          F-function         F0                F1
          input              63eb9287          a6ba2e9f
          round key          521213ce          4f1f59d8
          after key add      31f98149          e9a57747
          after S            5d03e265          3c8d7bda
          after M            b7464b63          e1d086a7
```

```
   Round 20         input   e6f68dc9 a6ba2e9f 98a8a539 63eb9287
          F-function        F0                F1
          input             e6f68dc9          98a8a539
          round key         c13624f6          ee91f6a4
          after key add     27c0a93f          7639539d
          after S           20b5938b          09893194
          after M           3cae819e          b603c454

   Round 21         input   9a14af01 98a8a539 d5e856d3 e6f68dc9
          F-function        F0                F1
          input             9a14af01          d5e856d3
          round key         17f68fde          f6c360a9
          after key add     8de220df          232b367a
          after S           6666bff2          b383a1bd
          after M           7ae08a5d          662b2c4d

   Round 22         input   e2482f64 d5e856d3 80dda184 9a14af01
          F-function        F0                F1
          input             e2482f64          80dda184
          round key         6288bc72          c0ad856b
          after key add     80c09316          407024ef
          after S           cdb5f1e5          fbe99290
          after M           3d9dac60          108259db

   output                   e2482f64 e875fab3 80dda184 8a96f6da
   final whitening key               77777777          77777777
   after whitening          e2482f64 9f028dc4 80dda184 fde181ad
   ciphertext               e2482f64 9f028dc4 80dda184 fde181ad
```

```
   256-bit key:

   key                       ffeeddcc bbaa9988 77665544 33221100
                             f0e0d0c0 b0a09080 70605040 30201000
   plaintext                 00010203 04050607 08090a0b 0c0d0e0f
   ciphertext                a1397814 289de80c 10da46d1 fa48b38a

   LL                        477e8f09 66ee5378 2cc2be04 bf55e28f
   LR                        d6c10b89 4eeab575 84bd5663 cc933940

   WK_{0,1,2,3}              0f0e0d0c 0b0a0908 07060504 03020100
   RK_{0,1,2,3}              58f02029 15413cd0 1b0c41a4 e4bacd0f
   RK_{4,5,6,7}              6c498393 8846231b 1fc716fc 7c81a45b
   RK_{8,9,10,11}            fa37c259 0e3da2ee aacf9abb 8ec0aad9
   RK_{12,13,14,15}          b05bd737 8de1f2d0 8ffee0f6 b70b47ea
   RK_{16,17,18,19}          581b3e34 03263f89 2f7100cd 05cee171
   RK_{20,21,22,23}          b523d4e9 176d7c44 6d7ba5d7 f797b2f3
   RK_{24,25,26,27}          25d80df2 a646bba2 6a3a95e1 3e3a47f0
   RK_{28,29,30,31}          b304eb20 44f8824e c7557cbc 47401e21
   RK_{32,33,34,35}          d71ff7e9 aca1fb0c 2deff35d 6ca3a830
   RK_{36,37,38,39}          4dd7cfb7 ae71c9f6 4e911fef 90aa95de
   RK_{40,41,42,43}          2c664a7a 8cb5cf6b 14c8de1e 43b9caef
   RK_{44,45,46,47}          568c5a33 07ef7ddd 608dc860 ac9e50f8
   RK_{48,49,50,51}          c0c18358 4f53c80e 33e01cb9 80251e1c

   plaintext                 00010203 04050607 08090a0b 0c0d0e0f
   initial whitening key              0f0e0d0c          0b0a0908
   after whitening           00010203 0b0b0b0b 08090a0b 07070707

   Round  1          input   00010203 0b0b0b0b 08090a0b 07070707
          F-function         F0                F1
          input              00010203          08090a0b
          round key          58f02029          15413cd0
          after key add      58f1222a          1d4836db
          after S            4ee41927          2c78a1ac
          after M            2db2101b          d87ee718

   Round  2          input   26b91b10 08090a0b df79e01f 00010203
          F-function         F0                F1
          input              26b91b10          df79e01f
          round key          1b0c41a4          e4bacd0f
          after key add      3db55ab4          3bc32d10
          after S            aa5afadb          0f1e1928
          after M            317e029c          c0cc96ba
```

```
   Round  3         input   39770897 df79e01f c0cd94b9 26b91b10
          F-function        F0                F1
          input             39770897          c0cd94b9
          round key         6c498393          8846231b
          after key add     553e8b04          488bb7a2
          after S           5487484e          d84876a0
          after M           c3a7ac1d          7ae05884

   Round  4         input   1cde4c02 c0cd94b9 5c594394 39770897
          F-function        F0                F1
          input             1cde4c02          5c594394
          round key         1fc716fc          7c81a45b
          after key add     03195afe          20d8e7cf
          after S           c607fa95          12f002c9
          after M           5edee0ce          4cfb0e90

   Round  5         input   9e137477 5c594394 758c0607 1cde4c02
          F-function        F0                F1
          input             9e137477          758c0607
          round key         fa37c259          0e3da2ee
          after key add     6424b62e          7bb1a4e9
          after S           4592c8d2          46f3a044
          after M           adfd33ae          42450650

   Round  6         input   f1a4703a 758c0607 5e9b4a52 9e137477
          F-function        F0                F1
          input             f1a4703a          5e9b4a52
          round key         aacf9abb          8ec0aad9
          after key add     5b6bea81          d05be08b
          after S           22285e04          f822d448
          after M           0fa52ed4          aa7a0a9c

   Round  7         input   7a2928d3 5e9b4a52 34697eeb f1a4703a
          F-function        F0                F1
          input             7a2928d3          34697eeb
          round key         b05bd737          8de1f2d0
          after key add     ca72ffe4          b9888c3b
          after S           23ed8e68          172b59c0
          after M           8b158630          334e2af2

   Round  8         input   d58ecc62 34697eeb c2ea5ac8 7a2928d3
          F-function        F0                F1
          input             d58ecc62          c2ea5ac8
          round key         8ffee0f6          b70b47ea
          after key add     5a702c94          75e11d22
          after S           facf9d64          586f2c19
          after M           72c2027e          a582d5f0
```

```
Round  9          input   46ab7c95 c2ea5ac8 dfabfd23 d58ecc62
       F-function         F0                F1
       input              46ab7c95          dfabfd23
       round key          581b3e34          03263f89
       after key add      1eb042a1          dc8dc2aa
       after S            177afd6a          57664735
       after M            51d5740a          110287d7

Round 10          input   933f2ec2 dfabfd23 c48c4bb5 46ab7c95
       F-function         F0                F1
       input              933f2ec2          c48c4bb5
       round key          2f7100cd          05cee171
       after key add      bc4e2e0f          c142aac4
       after S            e0434cd9          22fd2380
       after M            a768d32a          b6ae4f2b

Round 11          input   78c32e09 c48c4bb5 f00533be 933f2ec2
       F-function         F0                F1
       input              78c32e09          f00533be
       round key          b523d4e9          176d7c44
       after key add      cde0fae0          e7684ffa
       after S            3fd410d4          02ef5310
       after M            08bd9b01          2fdb3f65

Round 12          input   cc31d0b4 f00533be bce411a7 78c32e09
       F-function         F0                F1
       input              cc31d0b4          bce411a7
       round key          6d7ba5d7          f797b2f3
       after key add      a14a7563          4b73a354
       after S            1b512562          c94a71eb
       after M            7c2c762b          81ca0b59

Round 13          input   8c294595 bce411a7 f9092550 cc31d0b4
       F-function         F0                F1
       input              8c294595          f9092550
       round key          25d80df2          a646bba2
       after key add      a9f14867          5f4f9ef2
       after S            93e47852          5c26cae5
       after M            4a87c858          54bc68d5

Round 14          input   f663d9ff f9092550 988db861 8c294595
       F-function         F0                F1
       input              f663d9ff          988db861
       round key          6a3a95e1          3e3a47f0
       after key add      9c594c1e          a6b7ff91
       after S            58ff39b0          054d1d75
       after M            d82301d4          085d5025
```

```
   Round 15          input    212a2484 988db861 847415b0 f663d9ff
          F-function          F0                F1
          input               212a2484          847415b0
          round key           b304eb20          44f8824e
          after key add       922ecfa4          c08c97fe
          after S             86d2c9a0          b5ff567d
          after M             dbf56073          87e2a6a2

   Round 16          input    4378d812 847415b0 71817f5d 212a2484
          F-function          F0                F1
          input               4378d812          71817f5d
          round key           c7557cbc          47401e21
          after key add       842da4ae          36c1617c
          after S             9e19b889          a10c5414
          after M             6791a3e3          e177d3a8

   Round 17          input    e3e5b653 71817f5d c05df72c 4378d812
          F-function          F0                F1
          input               e3e5b653          c05df72c
          round key           d71ff7e9          aca1fb0c
          after key add       34fa41ba          6cfc0c20
          after S             d4e1be2d          32bc13bf
          after M             2743ef2d          6fec0aab

   Round 18          input    56c29070 c05df72c 2c94d2b9 e3e5b653
          F-function          F0                F1
          input               56c29070          2c94d2b9
          round key           2deff35d          6ca3a830
          after key add       7b2d632d          40377a89
          after S             56193719          fb13c1b7
          after M             ee6316fa          5e3245b7

   Round 19          input    2e3ee1d6 2c94d2b9 bdd7f3e4 56c29070
          F-function          F0                F1
          input               2e3ee1d6          bdd7f3e4
          round key           4dd7cfb7          ae71c9f6
          after key add       63e92e61          13a63a12
          after S             373c4c54          8fe6c54b
          after M             87aab08e          8f8d16f3

   Round 20          input    ab3e6237 bdd7f3e4 d94f8683 2e3ee1d6
          F-function          F0                F1
          input               ab3e6237          d94f8683
          round key           4e911fef          90aa95de
          after key add       e5af7dd8          49e5135d
          after S             f6ad88be          65f68f77
          after M             0889df33          f418c84f
```

```
   Round 21          input   b55e2cd7 d94f8683 da262999 ab3e6237
          F-function         F0                F1
          input              b55e2cd7          da262999
          round key          2c664a7a          8cb5cf6b
          after key add      993866ad          5693e6f2
          after S            2c2b6cee          0df150e5
          after M            8999e772          da5415d2

   Round 22          input   50d661f1 da262999 716a77e5 b55e2cd7
          F-function         F0                F1
          input              50d661f1          716a77e5
          round key          14c8de1e          43b9caef
          after key add      441ebfef          32d3bd0a
          after S            12b052ac          c7bbb182
          after M            f5efd89e          744a9ced

   Round 23          input   2fc9f107 716a77e5 c114b03a 50d661f1
          F-function         F0                F1
          input              2fc9f107          c114b03a
          round key          568c5a33          07ef7ddd
          after key add      7945ab34          c6fbcde7
          after S            a2a77e2a          4cd7e238
          after M            e84f6d9b          ce67e20a

   Round 24          input   99251a7e c114b03a 9eb183fb 2fc9f107
          F-function         F0                F1
          input              99251a7e          9eb183fb
          round key          608dc860          ac9e50f8
          after key add      f9a8d21e          322fd303
          after S            f84572b0          c7d8f1c6
          after M            20634b77          591b3f55

   Round 25          input   e177fb4d 9eb183fb 76d2ce52 99251a7e
          F-function         F0                F1
          input              e177fb4d          76d2ce52
          round key          c0c18358          4f53c80e
          after key add      21b67815          3981065c
          after S            a14dd39c          c8e20aa5
          after M            3f88fbef          89ff5caf

   Round 26          input   a1397814 76d2ce52 10da46d1 e177fb4d
          F-function         F0                F1
          input              a1397814          10da46d1
          round key          33e01cb9          80251e1c
          after key add      92d964ad          90ff58cd
          after S            864445ee          9a8e803f
          after M            5949235a          183d49c7
```

```
output                      a1397814 2f9bed08 10da46d1 f94ab28a
final whitening key                  07060504          03020100
after whitening             a1397814 289de80c 10da46d1 fa48b38a
ciphertext                  a1397814 289de80c 10da46d1 fa48b38a
```

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