Lightweight Encryption Algorithm
- LEA -

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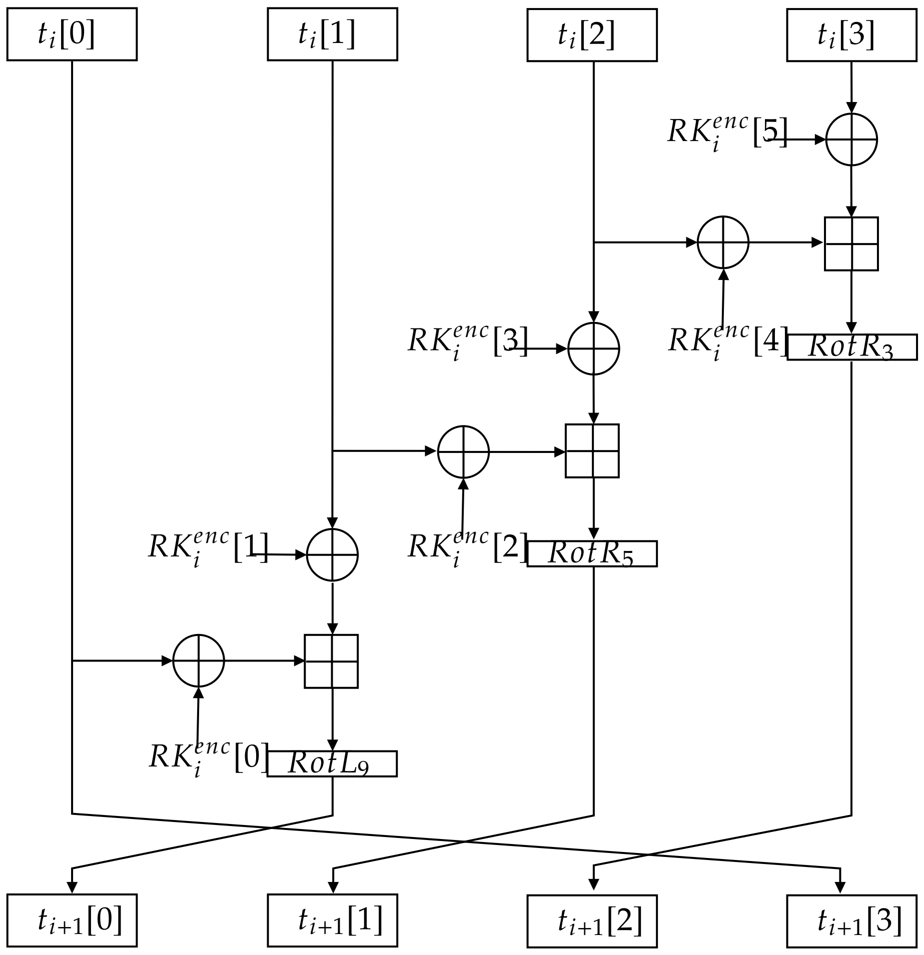

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List of Symbols

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Chapter 1

LEA: Implementation in Little-Endian

1.1 Specification

Table 1.1: Specification Comparison between AES and LEA Block Ciphers

Specification	**AES**	**LEA**
Block Size (bits)	128	128
Key Size (bits)	128/192/256	128/192/256
Structure	Substitution-Permutation Network	Generalized Feistel Network
Rounds	10/12/14 (depends on key size)	24/28/32 (depends on key size)
Design Year	1998	2013

Table 1.2: Parameters of the Block Cipher LEA (1-word = 32-bit)

Algorithms	Block Size (N_b-byte)	Key Length (N_k-byte)	Number of Rounds (N_r)	Round-Key Length (byte)	Total Size of Round-Keys (($N_r * 192$)-bit)
LEA-128	16(4-word)	16(4-word)	24	24	4608 (144-word)
LEA-192	16(4-word)	24(6-word)	28	24	5376 (168-word)
LEA-256	16(4-word)	32(8-word)	32	24	6144 (192-word)

1.2 State Representation

Let $\mathsf{state}[0], \mathsf{state}[1], \ldots$ be representation of arrays of bytes. Note that

$$\mathsf{state}[i] := \{input_{8i}, input_{8i+1}, \ldots, input_{8i+7}\} \in \mathbb{F}_{2^8}$$

for $input_i \in \mathbb{F}_2$. For example, $\mathsf{state}[0] = \{input_0, input_1, \ldots, input_7\}$.

The 128-bit plaintext P of LEA is represented as an array of four 32-bit words $P[0], P[1], P[2]$ and $P[3]$. Then

$$P[i] = \mathsf{state}[4i+3] \,\|\, \mathsf{state}[4i+2] \,\|\, \mathsf{state}[4i+1] \,\|\, \mathsf{state}[4i] \quad \text{for} \quad 0 \leq i \leq 3.$$

Here, $P[i] \in \mathbb{F}_{2^{32=8\cdot 4}}$The key K of LEA is also represented as the same way.

Table 1.3: Representations for words, bytes, and bits

Input Bit Sequence	24	···	31	16	···	23	8	···	15	0	···	7
Word Number	0											
Byte Number	3			2			1			0		
Bit Numbers in Word	31	···										1

Example 1.1.

128-bit Input String	`0x0f1e2d3c4b5a69788796a5b4c3d2e1f0`			
Split into Words	0x0f1e2d3c $P[0]$	0x4b5a6978 $P[1]$	0x8796a5b4 $P[2]$	0xc3d2e1f0 $P[3]$
$P[0]$ **(Word)**	0x0f1e2d3c			
$P[0]$ **(Bit)**	0b 0000:1111:0001:1110:0010:1101:0011:1010			
Split into Bytes	0x0f state[3]	0x1e state[2]	0x2d state[1]	0x3c state[0]
state[0] **(Byte)**	0x3c			
Split into Bits	1111:0000 24 ··· 31	- 16 ··· 23	- 8 ··· 15	- 0 ··· 7

```c
void stringToWordArray(const char* hexString, u32* wordArray) {
    size_t length = strlen(hexString);
    for (size_t i = 0; i < length; i += 8) {
        sscanf(&hexString[i], "%8x", &wordArray[i / 8]);
    }
}

const char* inputString = "0f1e2d3c4b5a69788796a5b4c3d2e1f0";
u32 key[4];
stringToWordArray(inputString, key);
```

```
(gdb) x/16xb key
0x7fffffffd9c0: 0x3c   0x2d   0x1e   0x0f   0x78   0x69   0x5a   0x4b
0x7fffffffd9c8: 0xb4   0xa5   0x96   0x87   0xf0   0xe1   0xd2   0xc3
```

1.3 Key Schedule

$$\text{KeySchedule}^{\text{enc}}_{128} : \{0,1\}^{128=8\cdot16} \longrightarrow \{0,1\}^{4608=192\cdot24}$$

$$\text{KeySchedule}^{\text{enc}}_{192} : \{0,1\}^{192=8\cdot24} \longrightarrow \{0,1\}^{5376=192\cdot28}$$

$$\text{KeySchedule}^{\text{enc}}_{256} : \{0,1\}^{256=8\cdot32} \longrightarrow \{0,1\}^{6144=192\cdot24}$$

1.3.1 Round Constant

The constant $\delta[i] \in \mathbb{F}_{2^{32}}$ ($i \in \{1,\dots,7\}$) is as follows:

i	$\delta[i]$	value
0	$\delta[0]$	`0xc3efe9db`
1	$\delta[1]$	`0x44626b02`
2	$\delta[2]$	`0x79e27c8a`
3	$\delta[3]$	`0x78df30ec`
4	$\delta[4]$	`0x715ea49e`
5	$\delta[5]$	`0xc785da0a`
6	$\delta[6]$	`0xe04ef22a`
7	$\delta[7]$	`0xe5c40957`

1.3.2 Rotation Function

Algorithm 1: Rotation to Left and Right

```
/* RotL : $\{0,1\}^{32} \times \{0,1\}^{32} \to \{0,1\}^{32}$ */
Function RotL(value, shift):
    return (value $\ll$ shift) | (value $\gg$ (32 − shift));
end

/* RotR : $\{0,1\}^{32} \times \{0,1\}^{32} \to \{0,1\}^{32}$ */
Function RotR(value, shift):
    return (value $\gg$ shift) | (value $\ll$ (32 − shift));
end
```

1.3.3 Encryption Key Schedule of LEA-128

Algorithm 2: Encryption Key Schedule (LEA-128)

```
Input: User-key UK = UK[0] || UK[1] || UK[2] || UK[3] (UK[$i$] $\in \{0,1\}^{32}$)
Output: Encryption Round-keys $\{RK_i^{enc}\}_{i=0}^{23}$ ($RK_i^{enc} \in \{0,1\}^{192}$)
/* UK $\in \{0,1\}^{128}$ is 16-byte and $\{RK_i^{enc}\}_{i=0}^{23} \in \{0,1\}^{4608}$ is 576-byte */
for $i = 0$ to 3 do
    $T[i]$ = UK[$i$]                                    // $T = T[0] \| \cdots \| T[3] \in \{0,1\}^{128=32*4}$
end
for $i = 0$ to 23 do
    $T[0] \leftarrow$ RotL($T[0] \boxplus$ RotL($\delta[i \bmod 4], i+0$), 1)     // $T[i] \in \{0,1\}^{32}$
    $T[1] \leftarrow$ RotL($T[1] \boxplus$ RotL($\delta[i \bmod 4], i+1$), 3)
    $T[2] \leftarrow$ RotL($T[2] \boxplus$ RotL($\delta[i \bmod 4], i+2$), 6)
    $T[3] \leftarrow$ RotL($T[3] \boxplus$ RotL($\delta[i \bmod 4], i+3$), 11)
    $RK_i^{enc} \leftarrow T[0] \| T[1] \| T[2] \| T[1] \| T[3] \| T[1]$      // $RK_i^{enc} \in \{0,1\}^{196=32*6}$
end
return $\{RK_i^{enc}\}_{i=0}^{23}$
```

1.3.4 Decryption Key Schedule of LEA-128

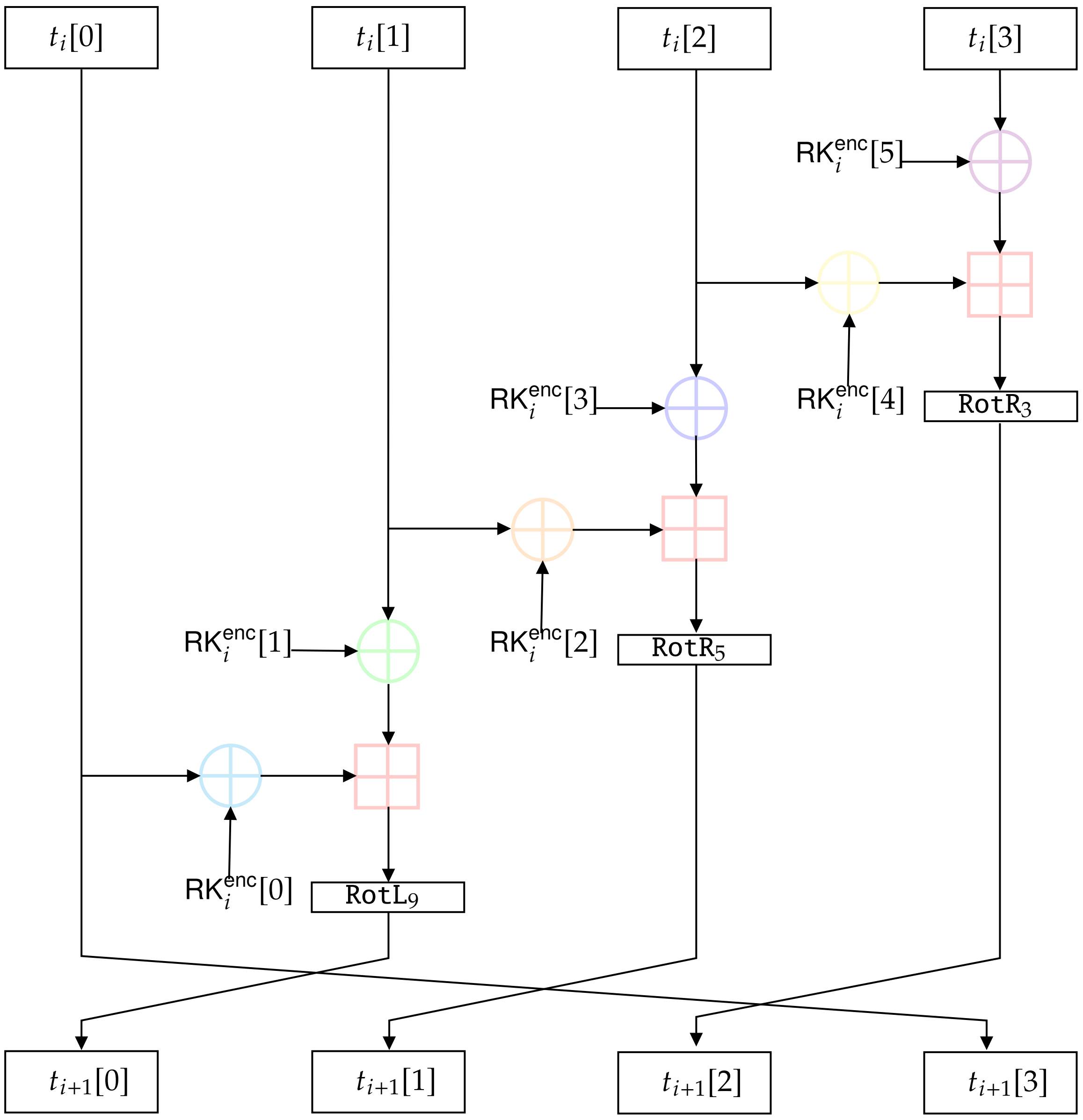
Algorithm 3: Decryption Key Schedule (LEA-128)

```
Input: User-key $\mathsf{UK} = \mathsf{UK}[0] \| \mathsf{UK}[1] \| \mathsf{UK}[2] \| \mathsf{UK}[3]$ ($\mathsf{UK}[i] \in \{0, 1\}^{32}$)
Output: Decryption Round-keys $\{\mathsf{RK}_i^{\mathsf{dec}}\}_{i=0}^{23}$ ($\mathsf{RK}_i^{\mathsf{dec}} \in \{0, 1\}^{192}$)
/* $\mathsf{UK} \in \{0, 1\}^{128}$ is 16-byte and $\left\{\mathsf{RK}_i^{\mathsf{dec}}\right\}_{i=0}^{23} \in \{0, 1\}^{4608}$ is 576-byte */
for $i = 0$ to $3$ do
    $T[i] = \mathsf{UK}[i]$        // $T = T[0] \| \cdots \| T[3] \in \{0, 1\}^{128=32*4}$
end
for $i = 0$ to $23$ do
    $T[0] \leftarrow \mathtt{RotL}(T[0] \boxplus \mathtt{RotL}(\delta[i \bmod 4], i + 0), 1)$        // $T[i] \in \{0, 1\}^{32}$
    $T[1] \leftarrow \mathtt{RotL}(T[1] \boxplus \mathtt{RotL}(\delta[i \bmod 4], i + 1), 3)$
    $T[2] \leftarrow \mathtt{RotL}(T[2] \boxplus \mathtt{RotL}(\delta[i \bmod 4], i + 2), 6)$
    $T[3] \leftarrow \mathtt{RotL}(T[3] \boxplus \mathtt{RotL}(\delta[i \bmod 4], i + 3), 11)$
    $\mathsf{RK}_{\mathbf{23-i}}^{\mathsf{dec}} \leftarrow T[0] \| T[1] \| T[2] \| T[1] \| T[3] \| T[1]$        // $\mathsf{RK}_i^{\mathsf{dec}} \in \{0, 1\}^{196=32*6}$
end
return $\left\{\mathsf{RK}_i^{\mathsf{dec}}\right\}_{i=0}^{23}$
```

1.4 Encryption of LEA-128

Algorithm 4: Encryption of LEA-128

```
Input: block src = src[0] || src[1] || src[2] || src[3] $\in \{0, 1\}^{128=32*4}$ and $\{\mathsf{RK}_i^{\mathsf{enc}}\}_{i=0}^{N_r-1=23}$
Output: block dst = dsc[0] || dsc[1] || dsc[2] || dsc[3] $\in \{0, 1\}^{128=32*4}$
1 $t_0 = t[0] \| t[1] \| t[2] \| t[3] \leftarrow$ src
2 for $i = 0$ to 23 do
3     $tmp \leftarrow t[0]$
4     $t_{i+1}[0] \leftarrow \mathtt{RotL}(\ t_i[0] \oplus \mathsf{RK}_i^{\mathsf{enc}}[0] \boxplus (t_i[1] \oplus \mathsf{RK}_i^{\mathsf{enc}}[1])\ , 9)$
5     $t_{i+1}[1] \leftarrow \mathtt{RotR}(\ t_i[1] \oplus \mathsf{RK}_i^{\mathsf{enc}}[2] \boxplus (t_i[2] \oplus \mathsf{RK}_i^{\mathsf{enc}}[3])\ , 5)$
6     $t_{i+1}[2] \leftarrow \mathtt{RotR}(\ t_i[2] \oplus \mathsf{RK}_i^{\mathsf{enc}}[4] \boxplus (t_i[3] \oplus \mathsf{RK}_i^{\mathsf{enc}}[5])\ , 3)$
7     $t_{i+1}[3] \leftarrow tmp$
8 end
9 return dst $\leftarrow t_{N_r}$
```



$t_i[0]$
$t_i[1]$
$t_i[2]$
$t_i[3]$
$\mathsf{RK}_i^{\mathsf{enc}}[5]$
$\mathsf{RK}_i^{\mathsf{enc}}[3]$
$\mathsf{RK}_i^{\mathsf{enc}}[4]$
RotR3
$\mathsf{RK}_i^{\mathsf{enc}}[1]$
$\mathsf{RK}_i^{\mathsf{enc}}[2]$
RotR5
$\mathsf{RK}_i^{\mathsf{enc}}[0]$
RotL9
$t_{i+1}[0]$
$t_{i+1}[1]$
$t_{i+1}[2]$
$t_{i+1}[3]$

1.5 Decryption of LEA-128

Algorithm 5: Encryption of LEA-128

```
Input: block src = src[0] || src[1] || src[2] || src[3] ∈ $\{0, 1\}^{128=32*4}$ and $\{\mathsf{RK}_i^{\mathsf{enc}}\}_{i=0}^{N_r-1=23}$
Output: block dst = dsc[0] || dsc[1] || dsc[2] || dsc[3] ∈ $\{0, 1\}^{128=32*4}$
1 $t_0 = t[0] \| t[1] \| t[2] \| t[3] \leftarrow \mathsf{src}$
2 for $i = 0$ to 23 do
3     $tmp \leftarrow t[0]$
4     $t_{i+1}[0] \leftarrow \mathtt{RotL}(t_i[0] \oplus \mathsf{RK}_i^{\mathsf{enc}}[0] \boxplus (t_i[1] \oplus \mathsf{RK}_i^{\mathsf{enc}}[1]), 9)$
5     $t_{i+1}[1] \leftarrow \mathtt{RotR}(t_i[1] \oplus \mathsf{RK}_i^{\mathsf{enc}}[2] \boxplus (t_i[2] \oplus \mathsf{RK}_i^{\mathsf{enc}}[3]), 5)$
6     $t_{i+1}[2] \leftarrow \mathtt{RotR}(t_i[2] \oplus \mathsf{RK}_i^{\mathsf{enc}}[4] \boxplus (t_i[3] \oplus \mathsf{RK}_i^{\mathsf{enc}}[5]), 3)$
7     $t_{i+1}[3] \leftarrow tmp$
8 end
9 return dst $\leftarrow t_{N_r}$
```

Algorithm 6: Decryption of LEA-128

```
Input: block src ∈ $\{0, 1\}^{128=8*16}$, decryption round-keys $\{\mathsf{RK}_i^{\mathsf{dec}}\}_{i=0}^{N_r-1=23}$
Output: block dst ∈ $\{0, 1\}^{128=8*16}$
1 $t_0 \leftarrow \mathsf{src}$
2 for $i = 0$ to $N_r - 1$ do
3     $t_{i+1}[0] \leftarrow t_i[3]$
4     $t_{i+1}[1] \leftarrow (\mathtt{RotR}(t_i[0], 9) \boxminus (t_{i+1}[0] \oplus \mathsf{RK}_i^{\mathsf{dec}}[0])) \oplus \mathsf{RK}_i^{\mathsf{dec}}[1]$
5     $t_{i+1}[2] \leftarrow (\mathtt{RotL}(t_i[1], 5) \boxminus (t_{i+1}[1] \oplus \mathsf{RK}_i^{\mathsf{dec}}[2])) \oplus \mathsf{RK}_i^{\mathsf{dec}}[3]$
6     $t_{i+1}[3] \leftarrow (\mathtt{RotL}(t_i[2], 3) \boxminus (t_{i+1}[2] \oplus \mathsf{RK}_i^{\mathsf{dec}}[4])) \oplus \mathsf{RK}_i^{\mathsf{dec}}[5]$
7 end
8 return dst $\leftarrow t_{N_r}$
```

Chapter 2

Modes of Operation

Table 2.1: Comparison of Modes

Mode	Integrity	Authentication	EncryptBlk	DecryptBlk	Padding	IV	$\lvert P\rvert \overset{?}{=} \lvert C\rvert$
ECB	O	X	O	O	O	X	$\lvert P\rvert < \lvert C\rvert$
CBC	O	X	O	O	O	O	$\lvert P\rvert < \lvert C\rvert$
OFB	O	X	O	X	X	O	$\lvert P\rvert = \lvert C\rvert$
CFB	O	X	O	X	X	O	$\lvert P\rvert = \lvert C\rvert$
CTR	O	X	O	X	X	O	$\lvert P\rvert = \lvert C\rvert$
CBC-CS	O	X	O	O	X	O	$\lvert P\rvert = \lvert C\rvert$

2.1 Padding

Block ciphers require input lengths to be a multiple of the block size. Padding is used to extend the last block of plaintext to the required length. Without proper padding, the encryption process may be insecure or infeasible.

There are several padding schemes used in practice, such as:

Table 2.2: Padding Standards in Block Ciphers

Standard Name	**Padding Method**
PKCS#7	Pad with bytes all the same value as the number of padding bytes `...dd	dd dd dd dd dd dd dd dd dd dd dd dd 04 04 04 04 |`
ANSI X9.23	Pad with zeros, last byte is the number of padding bytes `...dd	dd dd dd dd dd dd dd dd dd dd dd 00 00 00 00 05 |`
ISO/IEC 7816-4	First byte is ’80’ (hex), followed by zeros `...dd	dd dd dd dd dd dd dd dd dd dd 80 00 00 00 00 00 |`
ISO 10126	Pad with random bytes, last byte is the number of padding bytes `...dd	dd dd dd dd dd dd dd dd dd dd 2e 49 1b c1 aa 06 |`

2.1.1 PKCS#7

```c
void PKCS7_PAD(u32* block, size_t block_len, size_t input_len) {
    if (block_len < input_len) {
        fprintf(stderr,
            "Block length must be greater than input length.\n");
        return;
    }

    u8 padding_value = block_len - input_len;
    for (size_t i = input_len; i < block_len; ++i) {
        block[i] = padding_value;
    }
}
```

2.2 ECB (Electronic CodeBook)

Algorithm 7: Electronic CodeBook

```
Input: $K$ and $P = P_1 \| \cdots \| P_N$ $(P_i \in \{0, 1\}^n)$
Output: $C = C_1 \| \cdots \| C_N$ $(C_i \in \{0, 1\}^n)$
1 for $i \leftarrow 1$ to $N$ do
2     $C_i \leftarrow \text{EncryptBlk}(K, P_i)$;
3 end
4 return $C = C_1 \| \cdots \| C_N$;
```

```
Input: $K$ and $C = C_1 \| \cdots \| C_N$ $(C_i \in \{0, 1\}^n)$
Output: $P = P_1 \| \cdots \| P_N$ $(P_i \in \{0, 1\}^n)$
1 for $i \leftarrow 1$ to $N$ do
2     $P_i \leftarrow \text{DecryptBlk}(K, C_i)$;
3 end
4 return $C = C_1 \| \cdots \| C_N$;
```

Chapter 3

Mode of Operations Validation System (MOVS)

3.1 Known Answer Test (KAT)

- Variable Key KAT
- Variable Text KAT

3.2 Multi-block Message Test (MMT)

3.3 Monte Carlo Test (MCT)

Appendix A

Additional Data A

A.1 Substitution-BOX