Cybersecurity MSc: Applied Cryptography

2023-24

1st Project: Enhanced DES (E-DES)

October 3, 2023 Due date: November 5, 2023

Changelog

- v1.0 Initial version.
- v1.1 Fixed errors in the indexes used to compute input values for S-Boxes.
- v1.2 Added figure to show how S-Boxes are used.

1 Introduction

DES is a milestone in the universe of symmetric block ciphers. However, due to the time at which it was conceived, it became obsolete due to two factors: slowness and reduced key size. The slowness is mainly due to bit operations performed in software, namely permutations. The original dimension of the key, of only 56 bit, was indeed considered by several people to be too short at the time of the algorithm standardization.

In this project we want to explore a variant of DES, so-called E-DES. This variant uses less operations to implement a cipher with a DES resemblance, namely it uses solely Feistel Networks and S-Boxes. S-Boxes are a normal building block in many ciphers, and DES is no exception. However, DES uses static S-Boxes, an option that often raises concerns about hidden cryptanalysis trapdoors. In E-DES we will use variable, key-dependent S-Boxes. Furthermore, E-DES will use longer, 256-bit keys.

2 Homework

The work consists on implementing a variant of DES (E-DES), which will be similar to DES but with a longer, 256-bit key and faster functions on the Feistel networks (16, as in DES). The input and output blocks must have the same size, 64 bits.

The (normally unidirectional) function used in each Feistel Network should be implemented exclusively by an S-Box. All 16 S-Boxes should be different and not generated from each other. In other words, they should be generated from the key, the generation process should not allow to discover an S-Box from the value of any of the 15 other, and S-Boxes cannot be equal. Finally, it should not be easy to discover the key from any subset of the S-Boxes.

The values of the 16 S-Boxes should be deterministically computed only once, during the key set-up, in order to speed-up encryptions and decryptions. Do not use language-dependent shuffling features, such as in Python, because you do not know how they operate (usually, they use some degree of randomness).

The totality of the 16 S-Boxes must have exactly 16 equal byte values, but these do not need to be equally distributed by all S-Boxes. For instance, one S-Box can have many zero values, and another one no zero values, but the totallity of the S-Boxes must have exactly 16 zeros.

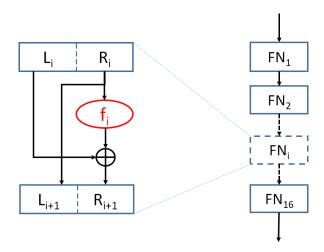


Figure 1: Overview of E-DES, with 16 Feistel Networks. Each f_i function is implemented by a different S-Box. Unlike DES, there is no initial and final bit permutations.

The values in each S-Box are the output for a byte-long input. Each S-Box must be used to transform all individual bytes presented as input for the function used on the respective Feistel Network.

Since S-Boxes will be used to transform 4-byte values a byte at the time, the algorithm to increase the entropy introduced by each S-Box within an f function should be the following (see Figure 2):

- The output byte in the lowest memory address (offset 0) should be the output of the S-Box for the input byte in the higher memory address (offset 3);
- The output byte in the next memory address (offset 1) should be the output of the S-Box for an input with the sum modulo 256 of the two input bytes in the higher memory addresses (offsets 2 and 3);
- The output byte in the next memory address (offset 2) should be the output of the S-Box for an input with the sum modulo 256 of the three input bytes in the higher memory addresses (offsets 1, 2 and 3);
- The output byte in the highest memory address (offset 3) should be the output of the S-Box for an input with the sum modulo 256 of the four input bytes.

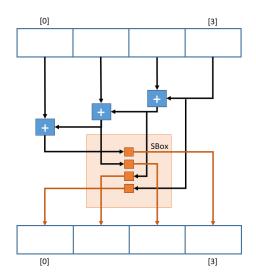


Figure 2: Overview of byte transformations with an S-Box in E-DES.

In C, an f function for a given S-Box should work as follows:

```
uint8_t SBox[256];
uint8_t in[4];
uint8_t out[4];
uint8_t index = in[3];
out[0] = sbox[index];
index = (index ^ in[2]);
out[1] = sbox[index];
index = (index ^ in[1]);
out[2] = sbox[index];
index = (index ^ in[0]);
out[3] = sbox[index];
```

Note that the 4-byte input and output values of the f functions only process half the bytes of the input and output of Feistel networks used in E-DES (which deal with 64-bit input/output values).

2.1 Applications

Besides implementing E-DES in a module (or library), you should implement two applications, encrypt and decrypt. These should receive one textual password as argument, which will be used to generate the 256-bit key of E-DES. An option should also be available to default to the normal DES.

The applications should process the input from stdin and produce a result to stdout. E-DES (or DES) should be used to process the input in ECB mode with a PKCS#7 padding.

Each of these applications must be implemented in two different languages, say A and B. You should be able to encrypt with a program written in A and decrypt with a program written in B; and vice-versa.

Create a third application, speed, to evaluate the relative performance of your E-DES implementation and one or more library implementation of DES. For that, allocate a 4KiB buffer (a memory page), fill it with random values (you can use /dev/urandom for that), and evaluate the time it takes to encrypt and decrypt the buffer with DES (from the library) and E-DES (both in ECB mode). Perform at least 100 000 measurements of each operation, and present the lowest values observed for each (i.e. the maximum achievable speed). For each measurement, use new, random keys. For accurate timing you can use the Linux system call clock_gettime function, which provides a nanosecond precision. Note that the measurements must encompass only encryptions and decryptions, and not DES or E-DES key-related set-up operations.

For improving the accuracy of measurements, it is advised to use some degree of loop unrolling for reducing the relative weight of cycle-related branching along the measurement. With the C language, loop unrolling can be easily achieved by means of preprocessor macros.

2.2 Library implementations of DES in Linux

In C, you can use these library implementations:

- The OpenSSL crypto library;
- The Nettle library.

In C++, you can use this library implementations:

• The Crypto++ library.

In Java, you can use these library implementations:

- The Java Runtime Environment;
- IAIK JCE:
- Bouncy Castle Crypto Library.

In Python, you can use these library implementations:

- Cryptography;
- PyCrypto.

3 Evaluation

The project will be evaluated as follows:

- Implementation of E-DES (in any two different languages): 40%;
- Implementation of the applications (in any two languages): 10% for encrypt, 10% for decrypt, 10% for speed;
- Written report, with a complete explanations of the strategies followed and the results achieved: 30%

4 Homework delivery

Send your code to the course teachers through Elearning (a submission link will be provided). Include a small report, with no more than 6 pages, describing the implementation (not a complete copy of the code developed!). Code snippets may be used to illustrate your implementation.

Every piece of code imported from anywhere must be stated in the report and in the code itself. Failure to do so will be penalised.

5 Test vectors

With the following S-Boxes (defined in C):

```
0 x 0 1
                                                                                                                                  0 \times 04 .
 0x08
                0 \times 08
                                0 \times 09 \\ 0 \times 11
                                                 0 \times 09
                                                                 0 \times 0 a \\ 0 \times 12
                                                                                  \begin{smallmatrix}0&x&0&a\\0&x&1&2\end{smallmatrix}
                                                                                                  0 \times 0 b
                                                                                                                  0x0b,
0x13,
                                                                                                                                  \begin{array}{c} 0 \ x \ 0 \ c \\ 0 \ x \ 1 \ 4 \end{array}
                                                                                                                                                   \begin{array}{c} 0 \ x \ 0 \ c \\ 0 \ x \ 1 \ 4 \end{array}
                                                                                                                                                                   0 \times 0 d,
0 \times 15,
                                                                                                                                                                                   \begin{array}{c} 0 \ x \ 0 \ d \\ 0 \ x \ 1 \ 5 \end{array}
                                                                                                                                                                                                   0 x 0 e
0 x 16
                                                                                                                                                                                                                    0 \times 0 e
                                                                                                                                                                                                                                    0 \times 0 f
0 \times 17
                                                                                                                                                                                                                                                    \begin{array}{c} 0 \ x \ 0 \ f \\ 0 \ x \ 1 \ 7 \end{array}
                                                                                                                                                                                                                    0 x 1 6
                 0 x 1 0
0x18,
                0 \times 18
                                0 \times 19
                                                 0 \times 19
                                                                 0 \times 1 a
                                                                                  0 \times 1 a
                                                                                                  0 \times 1 h
                                                                                                                   0 x 1 b
                                                                                                                                  0 \times 1 c
                                                                                                                                                   0 \times 1 c
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 0 x 20 ,
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                0 \times 20
                                0 \times 21
                                                                 0x22,
                                                                                  0 \ge 22
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                0 \times 28
                                0 \times 29
                                                 0 \times 29
                                                                 0 \times 2 a
                                                                                  0 \times 2a
                                                                                                   0 \times 2 b
                                                                                                                   0 \times 2b
                                                                                                                                  0 \times 2 c
                                                                                                                                                   0 \times 2c
                                                                                                                                                                   0 x 2 d .
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                 0 \times 30
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0x38.
                0 \times 38
                                0 \times 39
                                                  0 \times 39
                                                                 0 \times 3 a
                                                                                  0 \times 3 a
                                                                                                  0x3b.
                                                                                                                   0x3b.
                                                                                                                                  0 \times 3 c
                                                                                                                                                   0 \times 3 c
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                                                                                                                                                                                                                                    0 \times 3 f
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                                0 \ge 41
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0 \times 48
                 0 \times 48
                                0 \times 49
                                                  0 \times 49
                                                                 0 \times 4 a
                                                                                  0 \times 4 a
                                                                                                   0 \times 4 b
                                                                                                                   0 \times 4 h
                                                                                                                                  0 \times 4 c
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                                                                                                                                                                   0 \times 4 d
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                0 \times 58
                                0 \times 59
                                                  0 \times 59
                                                                 0 \times 5 a
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                                                                                                                   0 \times 5 b
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0x68.
                0 \times 68
                                0 \times 69
                                                 0 \times 69
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                                                                                  0 \times 6 a
                                                                                                  0 x 6 b
                                                                                                                   0x6b.
                                                                                                                                  0 x 6 c
                                                                                                                                                   0 \times 6 c
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                                                                                                                                                                                   0 \times 6 d
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                                0 \times 79
                                                 0 \times 79
                                                                 0 \times 7 a
                                                                                  0 \times 7 a
                                                                                                  0 \times 7 b
                                                                                                                   0 \times 7 b
                                                                                                                                  0 \times 7 c
                                                                                                                                                   0 \times 7 c
                                                                                                                                                                   0 \times 7 d,
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          SBox_0
0, 0x80
                                = \{ 0 \times 81 \}
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                                0 \times 89
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                                0 \times 91
                                                  0 \times 91
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                                0 \times b1
                                                 0 \times b 1
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                                                                                                                                                                                   0 \times b5
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                                0 \times b9
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 0 \times b 8
                                                  0 \times b 9
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0x10,
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                 0 \times 18
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                                                                                  0 \times 1 a
                                                                                                                   0x1b,
                                                                                                                                  0 \ge 1 \ \mathrm{c}
                                                                                                                                                   0 \ge 1 \ \mathrm{c}
                                                                                                                                                                   0 x 1 d,
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                                                                                                                                                                                                                    0 \times 1 e
                                                                                                   0 \times 1 b
 0 \times 20 .
                 0 \times 20
                                0 \times 21
                                                  0 \times 21
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                                                  0 x 2 9
                                 0 \times 29
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0x30.
                0 \times 30
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                                                                                  0\,\mathrm{x}\,3\,\mathrm{a}
 0x38,
                0 \times 38
                                0\,\mathrm{x}\,3\,9
                                                  0 \times 39
                                                                 0~\mathrm{x}\,3\,\mathrm{a}
                                                                                                   0 \times 3 b
                                                                                                                   0x3b,
                                                                                                                                  0х3с,
                                                                                                                                                   0 \times 3 c
                                                                                                                                                                   0 \times 3 d,
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                                0 \times 41
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                                                                                                                                                                                                                                    0 \times 47
                                                                 0 \ge 4 \ \mathrm{a}
                                                                                                                   0 x 4b ,
0x50,
                                                                                                                  0 \times 53, 0 \times 5b,
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                0 \times 50
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                                                                                                                                                                  0x65.
                                                                                                                                                                                   0 \times 65
                                                                                                                                                                                                    0x66.
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0x69,
                                                                               0x6b, 0x6b, 0x6c, 0x6c, 0x6d, 0x6d, 0x6e, 0x73, 0x73, 0x74, 0x74, 0x75, 0x75, 0x76,
                                                                                                                                                                                           0 \times 6 f,
0 \times 68 , 0 \times 68 ,
                                       0 \times 69, 0 \times 6a,
                                                                  0 \times 6a,
0 \times 72,
                                                                                                                                                                0x6e, 0x6e, 0x6f
0x76, 0x76, 0x77
0 \times 70, 0 \times 70,
                          0 \times 71 ,
                                        0 \times 71 ,
                                                     0 \times 72,
                                                                                                                                                                                                         0 \times 77
                                                                                                                        0х7с,
                                                                                                                                                                             0x7e,
0 x 78
             0 \times 78
                          0 \times 79
                                        0x79,
                                                     0 x 7 a ,
                                                                   0x7a,
                                                                                0x7b,
                                                                                              0x7b,
                                                                                                           0 x7c,
                                                                                                                                     0x7d, 0x7d,
                                                                                                                                                                0 \times 7e,
                                                                                                                                                                                           0 x 7 f
                                                                                                                                                                                                         0 \times 7 f
        SBox
                    0\dot{4}
0 \times 80,
             0 \times 80,
                          0 \times 81
                                        0 \times 81
                                                     0 \times 82 .
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                                                                                                                                                                                                         0 \times 87
                                                                                              0x8b,
             0 \times 88
                                        0 \times 89
                                                     0 x 8a,
                                                                                                                                                   0x8d
0x88,
                          0 \times 89
                                                                   0x8a,
                                                                                 0x8b,
                                                                                                           0x8c,
                                                                                                                         0x8c,
                                                                                                                                      0 x8d,
                                                                                                                                                                 0x8e,
                                                                                                                                                                              0x8e,
                                                                                                                                                                                            0 x 8 f
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0x90,
             0 x 9 0
                          0 \times 91
                                        0 \times 91
                                                     0 \times 92
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0 x 98,
                                        0 \times 99
                                                                                 0х9ь,
                                                                                              0х9ь,
                                                                                                                                                                 0х9е,
                                                                                                                                                                                                         0 x 9 f
             0 \times 98
                          0x99,
                                                     0 x 9 a ,
                                                                   0 \times 9 a
                                                                                                           0х9с
                                                                                                                         0 x 9 c ,
                                                                                                                                      0 x 9 d ,
                                                                                                                                                   0 \times 9 d
                                                                                                                                                                              0x9e,
                                                                                                                                                                                            0 x 9 f
0 \times a0
             0 \times a 0
                          0 \times a.1
                                        0 \times a.1
                                                     0 \times a.2
                                                                   0 \times a2
                                                                                 0 \times a.3
                                                                                              0 \times a.3
                                                                                                           0 \times a \cdot 4
                                                                                                                         0 \times a.4
                                                                                                                                      0 \times a.5
                                                                                                                                                   0 \times a.5
                                                                                                                                                                 0 \times a.6
                                                                                                                                                                              0 x a 6 .
                                                                                                                                                                                            0 \times a.7
                                                                                                                                                                                                         0 \times a.7
             0 \times a 8
                                        0 x a 9
                                                     0 \times aa ,
                                                                   0 x aa .
                                                                                                           0 хас
                                                                                                                         0 x ac ,
                                                                                                                                                   0 \, \mathrm{xad}
                                                                                                                                                                 0 xae ,
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                                                                                                                                                                                            0 \times a f
                           0 \times a9
                                                                                              0\,\mathrm{x}\,\mathrm{ab} ,
                                                                                                                                      0 xad,
0 xa8.
                                                                                 0 \times a b
                                                                                                                                                                                                         0 \times af
0xb0,
                                        0xb1,
                                                                                                                                      0xb5,
                                                                                 0xb3,
                                                                                                                                                                 0xb6,
                                                                                                                                                                              0xb6
             0 \times b0.
                          0 \times b1
                                                     0 \times b2.
                                                                   0 \times b2
                                                                                              0 \times b3.
                                                                                                           0 \times b4
                                                                                                                        0 x b 4.
                                                                                                                                                   0 \times b5
                                                                                                                                                                                           0 \times b7
                                                                                                                                                                                                         0 \times b7
                                                     0 \, \mathrm{xba} ,
                                                                                                           0 \times bc ,
             0 \times b8
                           0xb9,
                                        0xb9,
                                                                   0xba
                                                                                 0xbb,
                                                                                              0xbb,
                                                                                                                         0 xbc,
                                                                                                                                      0xbd,
                                                                                                                                                   0 xbd,
                                                                                                                                                                 0xbe,
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 0xb8,
0 \times c0
             0 \times c0
                          0 \times c1
                                        0 \times c1
                                                     0 \times c2
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                                                                                                                         Охсс
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                                                                                                                                                                              Охсе,
0 \times d0,
             0 \times d0.
                          0 \times d1
                                        0xd1.
                                                     0 \times d2.
                                                                   0 \times d2
                                                                                 0xd3.
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                                                                                                                                                                                                         0 \times d7
                                                                                                                                      0xdd,
             0 \times d8
                           0 x d9
                                        0 x d 9 .
                                                     0 \, x \, d \, a ,
                                                                   0 \times da,
                                                                                 0xdb.
                                                                                              0xdb.
                                                                                                           0xdc.
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0 x e 0 .
             0 \times e0.
                          0 x e 1
                                        0 x e 1 .
                                                     0 x e 2 .
                                                                   0 x e 2 .
                                                                                 0 \times e3
                                                                                              0 \times e3.
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                                                     0 \times ea,
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             0 \times e^8
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0 \times f0,
             0 \times f0,
                          0 \times f1,
                                        0 \times f1
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                                                                   0 \times f2,
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             0 x f8
                          0 \times f9
                                        0 x f9,
                                                     0 x fa,
                                                                   0xfa,
                                                                                 0xfb,
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                                                                                                                         0 xfc,
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        SBox_0
0, 0x00
                    0.5
0 \times 00,
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                          0 x 0 1,
                                        0 \times 01
                                                     0x02,
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0 \times 08.
             0x08.
                          0x09.
                                        0 \times 09.
                                                     0 \times 0 a.
                                                                   0 \times 0 a.
                                                                                0x0b.
                                                                                              0x0b.
                                                                                                           0 x 0 c .
                                                                                                                        0 x 0 c.
                                                                                                                                      0 \times 0 d, 0 \times 0 d
                                                                                                                                                                 0x0e.
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                                                                                                                                                                                                         0 \times 0 f
                                                                                                           0x14,
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0x18,
             0 \times 18
                          0 \times 19
                                        0 \times 19
                                                     0 \times 1 a
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                                                                                 0 \times 1 b
                                                                                              0x1b,
                                                                                                           0 \times 1 c
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0 \times 20,
                                                     0 x 2 2 ,
                                                                                                                                      0 \times 25,
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0 x 28 .
             0 \times 28
                          0 \times 29 .
                                        0 \times 29
                                                     0 x 2 a .
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                                                                                 0x2b.
                                                                                                           0 x 2 c .
                                                                                                                        0 x 2 c .
                                                                                                                                      0 \times 2d. 0 \times 2d
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                                                                                                                                                                              0 x 2 e .
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0 \times 30,
             0 \times 30
                          0 \times 31
                                        0 \times 31
                                                     0 \times 32,
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                                                                                 0 x 33,
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0 x 38 .
             0 x 38 .
                          0 \times 39.
                                        0 \times 39 .
                                                     0 x 3 a .
                                                                   0 \times 3 a
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                                                                                                           0 x 3 c .
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                                                                                                                                                                                                         0 \times 3 f
                                                                                                                                      0 x 45,
0 x 40
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             0 \times 40
                          0 \times 41
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0 x 48,
             0 x 48,
                          0 \times 49
                                        0 \times 49
                                                     0 x 4 a ,
                                                                   0 \times 4 a
                                                                                 0x4b,
                                                                                              0x4b,
                                                                                                           0 x 4 c ,
                                                                                                                         0 x 4 c ,
                                                                                                                                      0x4d, 0x4d
                                                                                                                                                                 0 x 4 e ,
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             0 x 50,
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                          0 \times 51
                                                                                 0x53,
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0 \times 50,
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                                                                                                                                      0x5d, 0x5d
                                                                                                                                                                                           0 \times 5 f
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             0 \times 58,
                          0 \times 59,
                                        0 \times 59
                                                     0 \times 5 a,
                                                                   0 \times 5 a
                                                                                 0x5b,
                                                                                              0x5b,
0 \times 58,
                                                                                                           0 x 5 c ,
                                                                                                                         0х5с
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0 \times 60,
             0 \times 60
                                                     0 \times 62,
                                                                                             0x63,
0x6b,
                                                                                                           0 \times 64 ,
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                                                                                                                                                                              0\,\mathrm{x}\,6\,6
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                          0 \times 61
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             0 \times 68,
                                                     0x6a,
                                                                                                                                      0x6d, 0x6d
0 \times 68,
                          0 \times 69
                                        0 \times 69
                                                                   0x6a.
                                                                                 0x6b,
                                                                                                           0x6c,
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                                                                                                                                                                 0x6e,
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0 x 70 ,
            0 x 7 0 ,
                                                     0 x 7 2 ,
                                                                                 0x73
                                                                                              0 x 73,
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                                        0 \times 71
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             0 x 7 8
                                                                                                                                     0x7d, 0x7d,
                          0 \times 79,
                                                    0 \times 7 a ,
                                                                  0 \times 7a,
                                                                                0x7b, 0x7b,
                                                                                                                        0 \times 7 c ,
                                                                                                                                                                              0\,\mathrm{x}\,7\,\mathrm{e} ,
0x78
                                        0x79.
                                                                                                           0 x 7 c ,
                                                                                                                                                                0 \times 7e,
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8_t SBox_06
0x80, 0x80,
                          = \{ 0 \times 81 
                                                                   0x82.
                                                                                 0x83.
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                                        0x89,
                                                                                 0x8b,
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                                                                                                           0x8c.
0x88,
             0 \times 88
                          0 x 8 9
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                                                                   0 x 8a
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0 x 9 0 ,
                                        0 \times 91
                                                     0 x 9 2 ,
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             0 \times 90
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0 \times 98
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                                                                                 0 \times 9 b
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                                                                                                                                                                                                         0 \times 9 f
             0 \times a 0
                                        0 \times a 1
                                                                   0 \times a2
                                                                                                           0 \times a 4
                                                                                                                         0 x a 4
                                                                                                                                                                 0 x a6,
0 \times a 0
                           0 \times a 1
                                                     0 \times a \cdot 2
                                                                                 0 x a 3
                                                                                              0 \times a3 ,
                                                                                                                                      0 \times a5,
                                                                                                                                                   0 \times a5
                                                                                                                                                                              0 \times a 6
                                                                                                                                                                                            0 \times a7
                                                                                                                                                                                                         0 \times a7
                                                                                                                                      0 xad,
                                                                                              Oxab,
\begin{array}{c} 0\,\mathrm{x}\,\mathrm{a}\,8\ , \\ 0\,\mathrm{x}\,\mathrm{b}\,0\ , \end{array}
             0 \times a.8
                          0 \times a.9
                                        0 \times a.9
                                                     0 \times a a
                                                                   0 \times a.a.
                                                                                 0 \times a \cdot b
                                                                                                           0 \, \mathrm{xac}
                                                                                                                         0 \times ac
                                                                                                                                                   0 xad
                                                                                                                                                                 0 \times a.e.
                                                                                                                                                                              0 \times a.e
                                                                                                                                                                                            0 \times a f
                                                                                                                                                                                                         0 \times af
             0xb0,
                          0 x b 1
                                                                   0xb2,
                                                                                              0xb3,
                                                                                                           0xb4,
                                                                                                                         0xb4,
                                                                                                                                      0xb5,
                                                                                                                                                   0 \times b5
                                                                                                                                                                 0xb6,
                                                                                                                                                                              0xb6,
                                        0 x b 1
                                                     0 \times b2
                                                                                 0xb3,
                                                                                                                                                                                            0 \times b7
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0 \times b = 8
             0 \times b8
                          0 \times h9
                                        0 \times b9
                                                     0 \times b =
                                                                   0xha
                                                                                 0 \times bb
                                                                                              0 \times b \cdot b
                                                                                                           0 \times b c
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                                                                                                                                                                                                         0 \times b f
                                                     0 x c 2
             0 \times c 0
                           0 \times c 1
                                        0 x c 1
                                                                   0 \times c 2
                                                                                 0 x c 3
                                                                                              0 \times c3,
                                                                                                           0 \times c 4
                                                                                                                         0 \ge 4
                                                                                                                                      0 x c 5 ,
                                                                                                                                                   0 x c 5
                                                                                                                                                                 0 x c 6 ,
                                                                                                                                                                              0 \times c6
                                                                                                                                                                                            0 x c 7
0\,\mathrm{xc}\,8 ,
                                                                                                                                      0 \times cd,
                                                                                                                                                                              0 x ce,
             0 \times c8
                          0 \times c9
                                        0 \times c9
                                                     0xca.
                                                                   0 \times ca
                                                                                 0 \times cb
                                                                                              0xcb,
                                                                                                           0 \times cc
                                                                                                                        0 \times cc
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                                                                                                                                                                                           0 \times cf
                                                                                                                                                                                                         0 \times cf
                           0 \times d1
                                        0 \times d1
                                                     0 x d 2 .
                                                                   0xd2.
                                                                                              0 \times d3
                                                                                                           0 x d 4 .
                                                                                                                                      0 x d 5 .
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                                                                                 0 \times d3
0xd8.
             0 x d8.
                          0 x d9.
                                        0 x d 9.
                                                     0xda.
                                                                   0 \times da
                                                                                 0xdb.
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                           0\ge 1
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             0 \times e 0
                                        0 \times e1
                                                     0 \ge 2 ,
                                                                   0 \times e 2
                                                                                              0 \times e3,
                                                                                                                                                                 0 xe6,
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0 \times e8.
             0 \times e8
                          0 \times e9
                                        0 \times e9
                                                     0 xea.
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                                                                                 0 \times eb
                                                                                              0 xeb.
                                                                                                           0 xec.
                                                                                                                         0 \times ec
                                                                                                                                      0 xed, 0 xed
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             0 \times f0,
                          0 \times f1
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                                                                                 0 \times f3
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                          0 x f9.
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        SBox 08
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                                                                                 0xa3,
                                                                                                                                      0 \times a5,
             0 \times a \cdot 0
                          0 \times a 1
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                                                     0 \times a.2
                                                                   0 \times a2
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                                        0 x c 1 ,
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                          0 \times c1
                                                     0 \times c2.
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0x70,
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                                                                                                                                                                 0 \times 76
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                                                                                              0x7b,
            0 \times 78,
                                        0 x 79 .
                                                     0\,\mathrm{x}\,7\,\mathrm{a} ,
                          0 \times 79 .
                                                                   0 \times 7a,
                                                                                0x7b,
                                                                                                                        0 x 7 c,
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                                                                                                           0 x 7 c,
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8 t SBox 10
0x80, 0x80,
0x88, 0x88,
uint8
                                          0 x 8 1
                                                                       , 0x82,
                                                           0 \times 81
                                                                                            0 \times 82,
                                                                                                             0x83, 0x83, 0x84,
                                                                                                                                                              0 \times 84, 0 \times 85, 0 \times 85,
                                                                                                                                                                                                               0x86, 0x86, 0x87
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                                                           0 x 89 ,
                                                                           0x8a,
                                                                                            0x8a,
                                                                                                             0x8b,
                                                                                                                             0x8b,
                                                                                                                                                                              0 x 8 d ,
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                                                                                                                                                                                                                                0x8e,
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0 x 9 4 ,
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                                          0 \times 89
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          0 x 9 0
                          0 x 90 .
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                                          0 \times a 1
                                                            0 \times a 1
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          0 \times a0,
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                          0xa8
                                          0 \times a 9
                                                           0 \times a 9
                                                                            0 vaa
                                                                                            0 \times aa
                                                                                                             0 xab
                                                                                                                             Oxab
                                                                                                                                              0 vac
                                                                                                                                                               0 \times ac
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          0xa8,
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          0xb0,
                                                                                                                                                                                                                                 0xb6,
                          0 \times b0
                                          0xb1
                                                            0xb1,
                                                                            0 \times b 2
                                                                                            0xb2,
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          0 \times b = 8
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                                          0 \times b9
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                                                                            0 \times c2 ,
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          0 \times c0.
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                                                                                                                             0xcb,
          0 \times c8, 0 \times d0,
                          0 \times c8
                                          0 \times c9
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          0 x e 8 ,
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                                                                                                                             0 xeb,
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                          0 \times e8
                                          0 \times e9
                                                                            0 xea.
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          0 \times f8
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                                          0 x f9.
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                    \begin{array}{c}
\text{SBox} & 11 \\
\text{SBox} & \overline{000}, \\
\text{SB
                                          0 x 0 1.
                                                           0x01,
          0 \times 00, 0 \times 08,
                                                                            0 \times 02,
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                          0 \times 0 8
                                          0 \times 09
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                                                                                                              0 x 0 b
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          0 \times 20 .
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                                                                           0\,x\,6\,a
                                                                                                                             0x6b,
                                                                                                                                             0x6c,
0x74,
                                                                                                                                                                                                                0х6е,
                          0 \times 68
                                          0 \times 69
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          0 \times 78
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                         0 \times 80,
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          0x88.
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          0xb8.
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                                           0 \times b9
                                                            0xb9.
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                                                                            0 x 32.
                                                                                            0 \times 32 .
                                                                                                             0 \times 33.
                                                                                                                             0 x 3 3 .
                                                                                                                                              0 \times 34
                                                                                                                                                               0 \times 34
                                                                                                                                                                               0 \times 35 . 0 \times 35
                                                                                                                                                                                                                0 \times 36 .
                                                                                                                                                                                                                                0 \times 36 .
                                                                                                                                                                                                                                                 0 \times 37
                                                                                                                                                                                                                                                                  0 \times 37
                                                                                                                                                                               0 x 3 d ,
                                                                                                                                                                                               0 \times 3 d
          0 \times 38
                          0 \times 38
                                          0 \times 39
                                                           0 \times 39
                                                                            0 x 3 a ,
                                                                                            0 \times 3 a
                                                                                                              0 \times 3 b
                                                                                                                             0x3b,
                                                                                                                                              0 x 3 c ,
                                                                                                                                                               0 \times 3 c
                                                                                                                                                                                                                0 x 3 e ,
                                                                                                                                                                                                                                 0 x 3 e
                                                                                                                                                                                                                                                 0 \times 3 f
                                                                                                                                                                                                                                                                  0 \times 3 f
          0 x 40,
                          0 \times 40,
                                          0 \times 41
                                                           0 \times 41
                                                                            0 x 42,
                                                                                            0 \times 42,
                                                                                                             0 x 43,
                                                                                                                             0 \times 43,
                                                                                                                                              0 x 44,
                                                                                                                                                               0 x 44,
                                                                                                                                                                               0 \times 45,
                                                                                                                                                                                               0 \times 45
                                                                                                                                                                                                                0 x 46,
                                                                                                                                                                                                                                0 \times 46,
                                                                                                                                                                                                                                                 0 \times 47
                                                                                                                                                                                                                                                                  0 \times 47
                                                                                                                                                                               0 x 4 d ,
                                                                                                             0 x 4 b
                                                                                                                                              0 x 4 c
                                          0 \times 49
                                                           0 \times 49
                                                                                            0 \times 4 a
                                                                                                                             0 \times 4 b
                                                                                                                                                                                                0 \times 4 d
                                                                                                                                                                                                                                                 0 \times 4 f
          0 \times 48
                          0 \times 48
                                                                            0 \times 4 a
                                                                                                                                                               0 \times 4 c
                                                                                                                                                                                                                0 \times 4e
                                                                                                                                                                                                                                 0 \times 4e
                                                                                                                                                                                                                                                                  0 \times 4 f
          0 \times 50,
                          0 \times 50
                                          0 \times 51,
                                                           0 \times 51
                                                                            0 \times 52,
                                                                                            0 \times 52
                                                                                                             0 \times 53,
                                                                                                                             0 \times 53,
                                                                                                                                              0 \times 54,
                                                                                                                                                               0 \times 54
                                                                                                                                                                               0 \times 55,
                                                                                                                                                                                               0 \times 55
                                                                                                                                                                                                                0 \times 56,
                                                                                                                                                                                                                                0 \times 56
                                                                                                                                                                                                                                                 0 \times 57
                                                                                                                                                                                                                                                                  0 \times 57
                                                                                                                                                                               0 x 5 d ,
                                                                                                                                                                                                                                 0 x 5 e
                                                                                                                                                                                                                                                                  0 \times 5 f
                          0 \times 58
                                          0 \times 59
                                                           0 \times 59
                                                                                            0 \times 5 a
                                                                                                             0 \times 5 b
                                                                                                                             0 \times 5 b
                                                                                                                                              0х5с,
                                                                                                                                                                                                0 \times 5 d
                                                                                                                                                                                                                                                 0 \times 5 f
          0 \times 58
                                                                            0 \times 5 a
                                                                                                                                                               0 \times 5 c
                          0x60,
                                                                            0 \times 62.
                                                                                            0x62.
                                                                                                                             0 \times 63.
                                                                                                                                              0x64.
                                                                                                                                                                                                                0x66.
                                                                                                                                                                                                                                0x66.
          0 \times 60 .
                                          0 \times 61.
                                                           0 \times 61
                                                                                                             0 \times 63.
                                                                                                                                                               0x64.
                                                                                                                                                                               0 \times 65 .
                                                                                                                                                                                               0 \times 65
                                                                                                                                                                                                                                                 0 \times 67
                                                                                                                                                                                                                                                                  0 \times 67
                                                                                                                                                                               0 x 6 d ,
          0 \times 68
                          0 \times 68
                                          0 \times 69
                                                           0 \times 69
                                                                            0 x 6 a
                                                                                            0 \times 6 a
                                                                                                             0 \times 6 b
                                                                                                                             0x6b,
                                                                                                                                              0 x 6 c
                                                                                                                                                              0 x 6 c
                                                                                                                                                                                               0 \times 6 d
                                                                                                                                                                                                                0х6е
                                                                                                                                                                                                                                0х6е
                                                                                                                                                                                                                                                 0 \times 6 f
                                                                                                                                                                                                                                                                  0 \times 6 f
                          0 \times 70,
                                                           0 \times 71,
                                                                            0 \times 72,
                                                                                            0 \times 72,
                                                                                                             0 \times 73,
                                                                                                                             0x73,
                                                                                                                                              0 \times 74,
                                                                                                                                                              0 \times 74,
                                                                                                                                                                               0 \times 75,
                                                                                                                                                                                               0 \times 75,
                                                                                                                                                                                                                0x76,
                                                                                                                                                                                                                                0 \times 76,
          0 \times 70,
                                          0 \times 71,
                                                                                                                                                                                                                                                 0 \times 77
                                                                                                                                                                                                                                                                  0 \times 77
                          0 \times 78
                                          0 \times 79,
                                                           0 x 79 .
                                                                            0 x 7 a ,
                                                                                            0 \times 7a,
                                                                                                             0x7b,
                                                                                                                             0x7b,
                                                                                                                                              0 x7c,
                                                                                                                                                              0 x 7 c ,
                                                                                                                                                                               0 x 7 d ,
                                                                                                                                                                                               0 \times 7 d
                                                                                                                                                                                                                                0x7e,
                                                                                                                                                                                                                                                 0 x 7 f
                                                                                                                                                                                                                                                                 0 \times 7 f
          0 \times 78
                                                                                                                                                                                                                0x7e,
                    SBox
                                  16
          0x80,
                         0 \times 80,
                                                           0x81,
                                                                                                                                                                                                                0 x 86,
                                          0 x 81.
                                                                           0\,x\,8\,2\ ,\quad 0\,x\,8\,2\ ,
                                                                                                             0 \times 83,
                                                                                                                            0 \times 83 , 0 \times 84 ,
                                                                                                                                                              0x84, 0x85, 0x85,
                                                                                                                                                                                                                                0x86, 0x87,
                                                                                                                                                                                                                                                                 0 \times 87
          0x88, 0x88,
                                          0x89, 0x89, 0x8a, 0x8a, 0x8b, 0x8b, 0x8c,
                                                                                                                                                              0x8c, 0x8d, 0x8d, 0x8e,
                                                                                                                                                                                                                                0x8e, 0x8f, 0x8f.
```

```
\begin{array}{c} 0 \times 90 \ , \\ 0 \times 98 \ , \end{array}
                   0 \times 90,
0 \times 98,
                                       0 \times 91,
0 \times 99,
                                                           \begin{array}{c} 0 \times 91 \ , \\ 0 \times 99 \ , \end{array}
                                                                               \begin{array}{c} 0 \times 92 \ , \\ 0 \times 9a \ , \end{array}
                                                                                                   \begin{array}{c} 0 \times 92 \ , \\ 0 \times 9a \ , \end{array}
                                                                                                                       0x93,
0x9b,
                                                                                                                                           \begin{array}{c} 0 \times 93 , \\ 0 \times 9b , \end{array}
                                                                                                                                                               \begin{array}{c} 0 \times 94 \ , \\ 0 \times 9c \ , \end{array}
                                                                                                                                                                                  \begin{array}{c} 0 \times 94 \ , \\ 0 \times 9c \ , \end{array}
                                                                                                                                                                                                      0 \times 95, 0 \times 95, 0 \times 9d,
                                                                                                                                                                                                                                              0 x 96 ,
0 x 9 e ,
                                                                                                                                                                                                                                                                   \begin{array}{c} 0 \, x \, 9 \, 6 \; , \\ 0 \, x \, 9 \, e \; , \end{array}
                                                                                                                                                                                                                                                                                      0 \times 97,
0 \times 9f,
                                                                                                                                                                                                                                                                                                          0 \times 97
0 \times 9f
\begin{array}{c} 0 \times a0 \ , \\ 0 \times a8 \ , \end{array}
                   0 \times a0,
                                                                                                                                                                                                      0 \times a5, 0 \times ad,
                                       0 x a 1 ,
                                                            0\;\mathrm{x}\,\mathrm{a}\,1
                                                                                0 \times a2 ,
                                                                                                   0 \times a2 ,
                                                                                                                       0 \times a3 ,
                                                                                                                                           0 \times a3 ,
                                                                                                                                                               0 \times a4,
                                                                                                                                                                                   0 \times a4 ,
                                                                                                                                                                                                                           0 x a5,
                                                                                                                                                                                                                                               0xa6,
                                                                                                                                                                                                                                                                   0xa6,
                                                                                                                                                                                                                                                                                      0 \times a7
                   0 xa8,
                                       0 xa9,
                                                           0 x a 9 ,
                                                                                0 xaa ,
                                                                                                   0 x aa ,
                                                                                                                                           0 x ab ,
                                                                                                                                                               0 xac,
                                                                                                                                                                                   0 xac,
                                                                                                                                                                                                                           0 xad,
                                                                                                                                                                                                                                               0 xae,
                                                                                                                                                                                                                                                                   0 xae ,
                                                                                                                                                                                                                                                                                       0 \times af,
                                                                                                                        0xab,
                                                                                                                       0xb3,
                                                                                                                                                                                                       0 \times b5,
                                                                                                                                                                                                                                                                   0xb6
0 \times b0,
                   0 \times b0
                                       0 \times b1
                                                           0 \times b 1
                                                                                0 \times b 2,
                                                                                                   0xb2,
                                                                                                                                           0xb3,
                                                                                                                                                               0 \times b4,
                                                                                                                                                                                   0xb4,
                                                                                                                                                                                                                           0 \times b5
                                                                                                                                                                                                                                               0xb6,
                                                                                                                                                                                                                                                                                      0 \times b7
                                                                                                                                                                                                                                                                                                           0 \times b7
                                                                                                                                           0xbb,
                   0 x b 8
                                       0xb9,
                                                            0xb9,
                                                                                0xba,
                                                                                                   0xba,
                                                                                                                                                               0xbc,
                                                                                                                                                                                   0xbc,
                                                                                                                                                                                                       0xbd,
                                                                                                                                                                                                                          0xbd,
                                                                                                                                                                                                                                                                   0xbe,
                                                                                                                                                                                                                                                                                      0 \times b f
                                                                                                                                                                                                                                                                                                           0 \times b f
0xb8,
                                                                                                                        0xbb,
                                                                                                                                                                                                                                               0xbe,
                   0 \times c0
0 \times c0 ,
                                       0 x c 1 ,
                                                           0 \times c1, 0 \times c9,
                                                                                0 \times c2,
                                                                                                   0 \times c2,
                                                                                                                        0 \times c3,
                                                                                                                                           0 \times c3,
                                                                                                                                                               0 \times c4
                                                                                                                                                                                   0 \times c4
                                                                                                                                                                                                       0 \times c5,
                                                                                                                                                                                                                           0 \ge 5
                                                                                                                                                                                                                                               0xc6,
                                                                                                                                                                                                                                                                   0 \times c6,
                                                                                                                                                                                                                                                                                      0 \times c7
                                       0 x c 9 ,
                                                                                                   0 \times ca
                                                                                                                                                                                                                                                                                                           0 x c f
0 xc8,
                   0 \times c 8
                                                                                0 x ca,
                                                                                                                        0xcb,
                                                                                                                                           0xcb,
                                                                                                                                                               0 хсс
                                                                                                                                                                                    0xcc,
                                                                                                                                                                                                       0 xcd,
                                                                                                                                                                                                                           0 \times cd
                                                                                                                                                                                                                                               0xce,
                                                                                                                                                                                                                                                                   0xce,
                                                                                                                                                                                                                                                                                      0 \times cf
                                                                               0 \times d2,
0 \times da,
                                                                                                                                                               0 x d 4 ,
0 x d c ,
                                                                                                                                                                                                                          0 x d 5 ,
0 \times d0,
                   0 x d0,
                                       0 \times d1
                                                            0 \times d1
                                                                                                   0xd2,
                                                                                                                        0xd3,
                                                                                                                                           0xd3,
                                                                                                                                                                                   0 x d4,
                                                                                                                                                                                                       0 \times d5,
                                                                                                                                                                                                                                               0xd6,
                                                                                                                                                                                                                                                                   0xd6,
                                                                                                                                                                                                                                                                                      0 \times d7
0 x d8,
                   0 x d8,
                                       0 x d 9
                                                                                                   0xda,
                                                                                                                                           0xdb,
                                                                                                                                                                                                                                                                                       0 \times df
                                                            0 \times d9,
                                                                                                                        0xdb,
                                                                                                                                                                                   0xdc,
                                                                                                                                                                                                       0 xdd,
                                                                                                                                                                                                                                               0xde,
                                                                                                                                                                                                                                                                   0 x d e ,
                                                                                                                                                                                                                                                                                                           0 \times d f
\begin{array}{c} 0 \times e \, 0 \ , \\ 0 \times e \, 8 \ , \end{array}
                                       \begin{array}{c} 0 \times e1 \\ 0 \times e9 \end{array}
                                                           \begin{array}{c} 0 \ x \ e \ 1 \ , \\ 0 \ x \ e \ 9 \ , \end{array}
                                                                               \begin{array}{c} 0 \ x \ e \ 2 \ , \\ 0 \ x \ e \ a \ , \end{array}
                                                                                                                       \begin{array}{c} 0 \ x \, e \, 3 \ , \\ 0 \ x \, e \, b \ , \end{array}
                                                                                                                                           \begin{array}{c} 0 \ \text{xe} \, 3 \ , \\ 0 \ \text{xe} \, b \ , \end{array}
                                                                                                                                                                                                      \begin{array}{c} 0 \ x \ e \ 5 \ , \\ 0 \ x \ e \ d \ , \end{array}
                                                                                                                                                                                                                          0 \times e5, 0 \times ed,
                                                                                                                                                                                                                                                                                      \begin{array}{c} 0 \ x \, e \, 7 \ , \\ 0 \ x \, e \, f \ , \end{array}
                                                                                                                                                                                                                                                                                                          0 x e 7 ,
0 x e f ,
                   0 \times e 0
                                                                                                   0 \ge 2
                                                                                                                                                               0 \ge 4
                                                                                                                                                                                   0 \times e4,
                                                                                                                                                                                                                                               0 \times e6,
                                                                                                                                                                                                                                                                   0 \times e6,
                   0 x e 8 ,
                                                                                                   0 xea,
                                                                                                                                                               0 xec,
                                                                                                                                                                                                                                               0 xee,
                                                                                                                                                                                                                                                                   Охее,
                                                                                                                                                                                    0 xec ,
                                                                                                                                           0 x f3,
0 x f0 ,
0 x f8 ,
                                                                               0 x f2
                                                                                                                                                                                                      \begin{array}{c} 0 \text{ x f5} \\ 0 \text{ x fd} \end{array}
                                                                                                                                                                                                                                                                   \begin{array}{c} 0 \times f6 \ , \\ 0 \times fe \ , \end{array}
                   0 \times f0
                                       0 \times f1
                                                            0 \times f1
                                                                                                   0 \times f2
                                                                                                                        0 \times f3
                                                                                                                                                               0 \times f4
                                                                                                                                                                                   0 \times f4
                                                                                                                                                                                                                           0 \times f5
                                                                                                                                                                                                                                               0 \times f6
                                                                                                                                                                                                                                                                                      0 \times f7
```

you should obtain the following outputs on a cipher operation (all values in hexadecimal):

Input bytes (LSB on the left)								Output bytes (LSB on the left)							
01	00	00	00	00	00	00	00	3c	58	2b	44	04	4b	5f	1c
00	01	00	00	00	00	00	00	3d	55	20	41	06	4e	69	64
00	00	01	00	00	00	00	00	3d	59	2b	47	05	45	58	19
00	00	00	01	00	00	00	00	3c	5b	21	43	07	4c	6c	63
00	00	00	00	01	00	00	00	3a	53	19	48	0c	6a	60	7c
00	00	00	00	00	01	00	00	3f	15	18	62	1d	0c	7f	62
00	00	00	00	00	00	01	00	3e	28	12	7e	12	7a	63	7c
00	00	00	00	00	00	00	01	02	6d	16	4b	0d	6a	26	6c

6 References

- $\bullet \ \ Data \ Encryption \ Standard, \ \texttt{https://en.wikipedia.org/wiki/Data_Encryption_Standard}$
- Feistel Cipher, https://en.wikipedia.org/wiki/Feistel_cipher