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Implementation of the Data Encryption Standard Using PIC17C42

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INTRODUCTION

In January 1977, The United States government adopted a product cipher developed by IBM as its official encryption standard [1]. This algorithm, called the Data Encryption Standard (DES), has been adopted as a worldwide standard for data encryption by ISO (International Standards Organization) [2, 3]. This application note describes the implementation of the DES algorithm on PIC17C42.

THE DATA ENCRYPTION STANDARD

The DES algorithm is a substitution cipher which takes a block of 64 bits of input (plaintext) into a unique block of 64 bits of output (ciphertext), under the control of a 64-bit key, which is known only to the people intended to read the message. In this system, plaintext information is divided into several blocks which are then operated upon independently to generate a sequence of ciphertext blocks. The basic idea behind DES is to build a strong system out of simple, individually weak, components. The DES encryption system is based on a system of transpositions and permutations. The permutation box or P-box, is used to transpose, or map a sequence of input values to another sequence of values of the same length. Substitutions are performed by what are called S-boxes. A combination of the S-boxes and P-boxes can be viewed as a decoder/coder operation, where the output is simply a linear mapping of the input values. Each combination of the S-box and P-box comprises a single weak component of the algorithm. By including a sufficiently large number of stages in the product cipher, the output can be made to be a nonlinear function of the input.

The mapping of input to output is one-to-one and invertible, since the encrypted messages can be decrypted. The DES has three distinct components: key schedule, cipher function, and invertibility.

KEY SCHEDULE

The DES uses a 64-bit key for encryption and decryption process. Initially, the original 64-bit key is reduced to 56-bit by ignoring every eighth bit. In general these bits are used as parity bits to make sure that there were no errors when entering the key or during key transmission. After the 56-bit key is extracted a different 48-bit key, referred to as subkey, is generated for each of the 16 rounds of the DES. These keys, K_i, are determined as shown in Figure 1. The 56-bit key is divided into two 28-bit halves C_i and D_i which are then shifted left by either 1 or 2 digits, depending on the round. Table 1 shows the number of circular left shifts for C_i and D_i halves. After the shifting operation, 48 out of the 56 bits are selected. Since this operation permutes the order of the bits as well as selecting a subset of the original bits, it is called compression permutation or permuted choice. The permuted choice 1 and permuted choice 2 matrices are shown in Figure 2 and Figure 3 respectively.

TABLE 1: LEFT SHIFTS FOR KEY GENERATION

Iteration	# of left shifts
1	1
2	1
3	2
4	2
5	2
6	2
7	2
8	2
9	1
10	2
11	2
12	2
13	2
14	2
15	2
16	1

FIGURE 1: KEY GENERATION

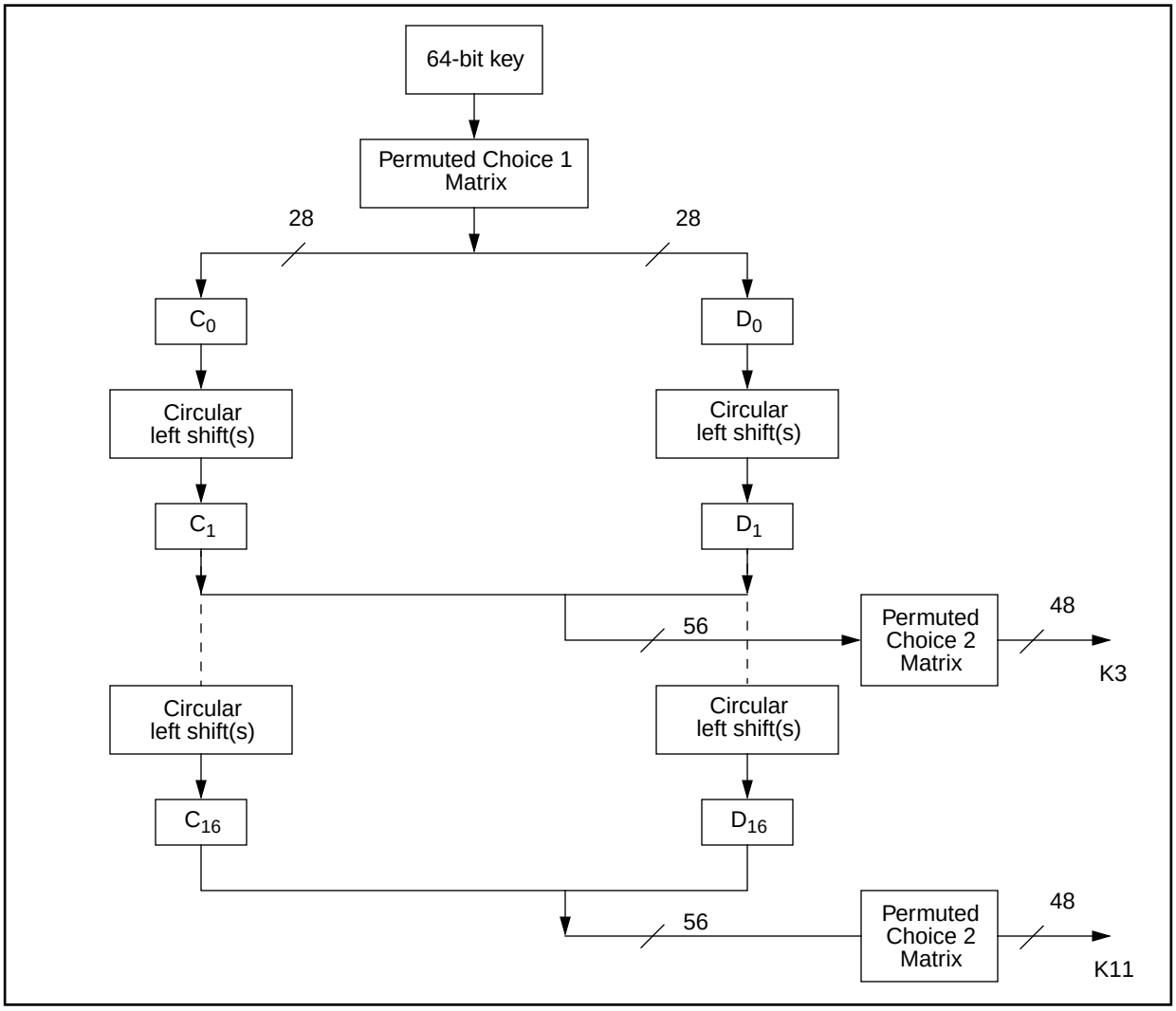


FIGURE 2: PERMUTED CHOICE 1 MATRIX

57	49	41	33	25	17	9	1
58	50	42	34	26	18	10	2
59	51	43	35	27	19	11	3
60	52	44	36	63	55	47	39
31	23	15	7	62	54	46	38
30	22	14	6	61	53	45	37

FIGURE 3: PERMUTED CHOICE 2 MATRIX

14	17	11	24	1	5	3	28
15	6	21	10	23	19	12	4
26	8	16	7	27	20	13	2
41	52	31	37	47	55	30	40
51	45	33	48	44	49	39	56
34	53	46	42	50	36	29	32

CIPHER FUNCTION

The strength of the DES is based on the cipher function component. This is a fixed, highly nonlinear function which guarantees that each bit of the ciphertext depend on every bit of the plaintext and every bit of the key.

After an initial permutation, the 64-bit block of plaintext is broken into a right half and left half, each 32 bits long. This step is followed by 16 identical rounds of operation, called function *f*, that combines the data with a 48-bit key, K_i. At each stage *i*, the inputs are the left block L_{i-1} and the right block R_{i-1} of the previous stage, and the outputs are the left shift block L_i and right block R_i of this stage. The outputs of L_i and R_i of each stage are computed from L_{i-1} and R_{i-1}, and a subkey K_i that is generated from the encryption key. In other words a round of the DES can be shown as:

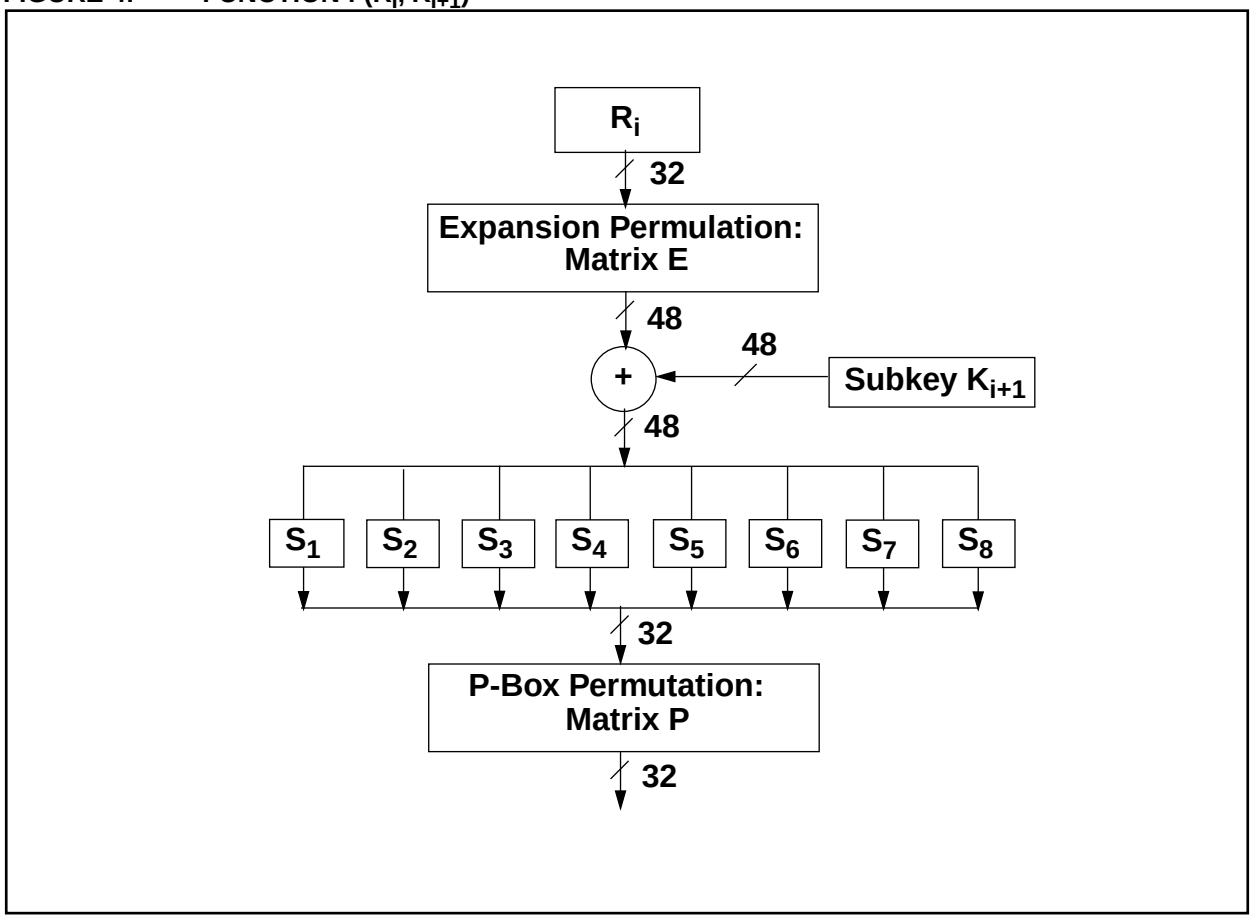
$$L_i = R_i$$

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

All the complexity of the DES algorithm lies in the function f, as shown in Figure 4. The function has four steps that are carried out in sequence. First a 48-bit number, *E*, is constructed by expanding the 32-bit previous right value, R_{i-1}, according to a fixed transposition and duplication rule. Then, K_i and R_{i-1} are XORed together, generating a 48-bit result. This output is then partitioned into eight groups of 6-bits each, each of which is fed into a different S-box or substitution box. The S-boxes generate four instead of six outputs. In other words, the 64-bit input is mapped into a 32-bit output. Each S-box is a table of 4 rows and 16 columns. Each entry in the box is a 4-bit number. The six input bits of the S-box specify under which row and column number to look for the output. Figure 7 shows the 8 S-boxes.

The six input bits specify an entry in the Sbox in a particular fashion as follows: the first and last bits of the sequence, taken together, represent a number between 0 and 3 (row entry), while the middle 4-bits represent a number between 0 and 15 (column entry). The output is simply the entry that corresponds to the (row, column) entry. For example, that the input to the first S-box is the binary sequence `110010`. The first and last bits combine to form 10 which corresponds to the third row of the S-box. The middle 4-bits are combined to form `1001` which corresponds to the ninth column of the for `110010`. The substitution boxes are the most critical step in the DES algorithm and more than anything else give DES its security.

FIGURE 4: FUNCTION f (R_I, K_{I+1})



Finally, the last stage consists of a permutation stage that generates a 32-bit output. After the 16 rounds, the left and right halves are joined, and a final permutation generates the ciphertext. The final permutation is the inverse of the initial permutation. Figure 10 shows a block diagram of the enciphering portion of the algorithm. The reverse process of deciphering is shown in Figure 11. The initial permutation and inverse initial permutation matrices in Figure 10 are shown in Figure 8 and Figure 9. Where the algorithm requires bit manipulation of a stream of data according to a matrix, the matrix is read from left to right, top to bottom, and interpreted as the bit position in the output block. For example, the initial permutation matrix transposes bit1 to bit58, bit2 to bit50, bit3 to bit42, etc.

INVERTIBILITY

The DES cipher function is not necessarily invertible, meaning to decode a message, it is not necessary to recover the input to the cipher function from its output and a knowledge of the key. In fact the cipher function must be highly nonlinear to be resistant to plaintext attack (a method used for breaking a given algorithm). Invertibility of the DES is that one half-word of the output is precisely the bit configuration which was used to encode the other half, with the aid of the particular stage subkey. Therefore, by using the subkeys in reverse order, the encryption process can be reversed. This is really the reason that one half-word is always passed through unchanged - to provide the means of decrypting the other half-word.

PIC17C42 IMPLEMENTATION OF DES

CPU processing is required to generate the encryption key into the DES subkeys. The 64-bit encryption key is reduced to 56-bits, by ignoring every eighth bit, usually used as parity bit.

The majority of the DES code is for the Implementation of the permutation of the block of bits. The 56-bits of the key, stored in K1 through K8, scrambled-bit output is stored in the eight bytes D0-D7. The scrambling is accomplished by constructing D0-D7, one bit at a time. This is accomplished by initializing the D0 to D7 locations to a known state (cleared). Then the 64-bits of plain text are processed through the Initial Permutation Matrix (IP), which permutes the plain text and divides the information into two 32-bit blocks.

The use of Indirect addressing and the PICmicro™ single word instructions allows tight efficient coding of the DES algorithm. These bit testing capabilities allows the same code structure to generate the different subkey blocks. This permutation macro looks like:

```
Permute   Macro     KEY,TEST,BIT
          BTFS C    KEY,TEST,BIT
          BSF       INDOF0,BIT
          endm
```

Where KEY is the DES key and TEST is the bit is the KEY being tested. If the KEY<TEST> bit is set, then the bit position (BIT) in the data location pointed to by INDF0 is set.

The main algorithm requires that the 16 subkeys, each 48-bits long, be generated. These 16 subkeys are then used at the 16 stages of the algorithm.

Using the generated subkeys, the incoming stream of bits can be encrypted or decrypted. Table 2 shows the requirements of the DES algorithm.

TABLE 2: DES ALGORITHM REQUIREMENTS

		Execution time	
Function	Program Memory words	Instruction cycles	ms
Key management and subkey generation	382	2729	0.436
Encryption	789	7714	1.234

A bit rate of about 51 Kbps baud can be achieved, with a device utilization of 100%. This makes the PIC17C42 a price/performance leader for DES algorithms.

CONCLUSION

We have demonstrated the implementation of the DES algorithm on the PIC17C42 microcontroller. The 160 ns cycle time of the PIC17C42 makes possible a half-duplex rate of 51 Kbps for the DES. This rate is as good or superior to other implementations of the algorithm. The high performance of the PIC17C42 provides a low-cost alternative to many dedicated solutions resulting in minimum system cost because of the programmability of the device.

References

1. NBS FIPS PUB 46, “Data Encryption Standard,” National Bureau of Standards, US Department of Commerce, January 1977.
2. SO DIS 8730, “Banking Requirements for Message Authentication (Wholesale),” Association for Payment Clearing Services, London, July 1987.
3. ISO DIS 8732, “Banking Key Management (Wholesale),” Association for Payment Clearing Services, London, December 1987.

FIGURE 5: MATRIX E

32	1	2	3	4	5	4	5
6	7	8	9	8	9	10	11
12	13	12	13	14	15	16	17
16	17	18	19	20	21	20	21
22	23	24	25	24	25	26	27
28	29	28	29	30	31	32	1

FIGURE 6: MATRIX P

16	7	20	21	29	12	28	17
1	15	23	26	5	18	31	10
2	8	24	14	32	27	3	9
19	13	30	6	22	11	4	25

FIGURE 7: S MATRICES

```
/* S1 */
14  4 13  1  2 15 11  8  3 10  6 12  5  9  0  7
 0 15  7  4 14  2 13  1 10  6 12 11  9  5  3  8
 4  1 14  8 13  6  2 11 15 12  9  7  3 10  5  0
15 12  8  2  4  9  1  7  5 11  3 14 10  0  6 13

/* S2 */
15  1  8 14  6 11  3  4  9  7  2 13 12  0  5 10
 3 13  4  7 15  2  8 14 12  0  1 10  6  9 11  5
 0 14  7 11 10  4 13  1  5  8 12  6  9  3  2 15
13  8 10  1  3 15  4  2 11  6  7 12  0  5 14  9

/* S3 */
10  0  9 14  6  3 15  5  1 13 12  7 11  4  2  8
13  7  0  9  3  4  6 10  2  8  5 14 12 11 15  1
13  6  4  9  8 15  3  0 11  1  2 12  5 10 14  7
 1 10 13  0  6  9  8  7  4 15 14  3 11  5  2 12

/* S4 */
 7 13 14  3  0  6  9 10  1  2  8  5 11 12  4 15
13  8 11  5  6 15  0  3  4  7  2 12  1 10 14  9
10  6  9  0 12 11  7 13 15  1  3 14  5  2  8  4
 3 15  0  6 10  1 13  8  9  4  5 11 12  7  2 14

/* S5 */
 2 12  4  1  7 10 11  6  8  5  3 15 13  0 14  9
14 11  2 12  4  7 13  1  5  0 15 10  3  9  8  6
 4  2  1 11 10 13  7  8 15  9 12  5  6  3  0 14
11  8 12  7  1 14  2 13  6 15  0  9 10  4  5  3
```

FIGURE 7: S matrices (CONT.)

```
/* S6 */
12  1 10 15  9  2  6  8  0 13  3  4 14  7  5 11
10 15  4  2  7 12  9  5  6  1 13 14  0 11  3  8
 9 14 15  5  2  8 12  3  7  0  4 10  1 13 11  6
 4  3  2 12  9  5 15 10 11 14  1  7  6  0  8 13

/* S7 */
 4 11  2 14 15  0  8 13  3 12  9  7  5 10  6  1
13  0 11  7  4  9  1 10 14  3  5 12  2 15  8  6
 1  4 11 13 12  3  7 14 10 15  6  8  0  5  9  2
 6 11 13  8  1  4 10  7  9  5  0 15 14  2  3 12

/* S8 */
13  2  8  4  6 15 11  1 10  9  3 14  5  0 12  7
 1 15 13  8 10  3  7  4 12  5  6 11  0 14  9  2
 7 11  4  1  9 12 14  2  0  6 10 13 15  3  5  8
 2  1 14  7  4 10  8 13 15 12  9  0  3  5  6 11
```

FIGURE 8: INITIAL PERMUTATION MATRIX

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

FIGURE 9: INVERSE PERMUTATION MATRIX

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

FIGURE 10: DES ENCRYPTION BLOCK DIAGRAM

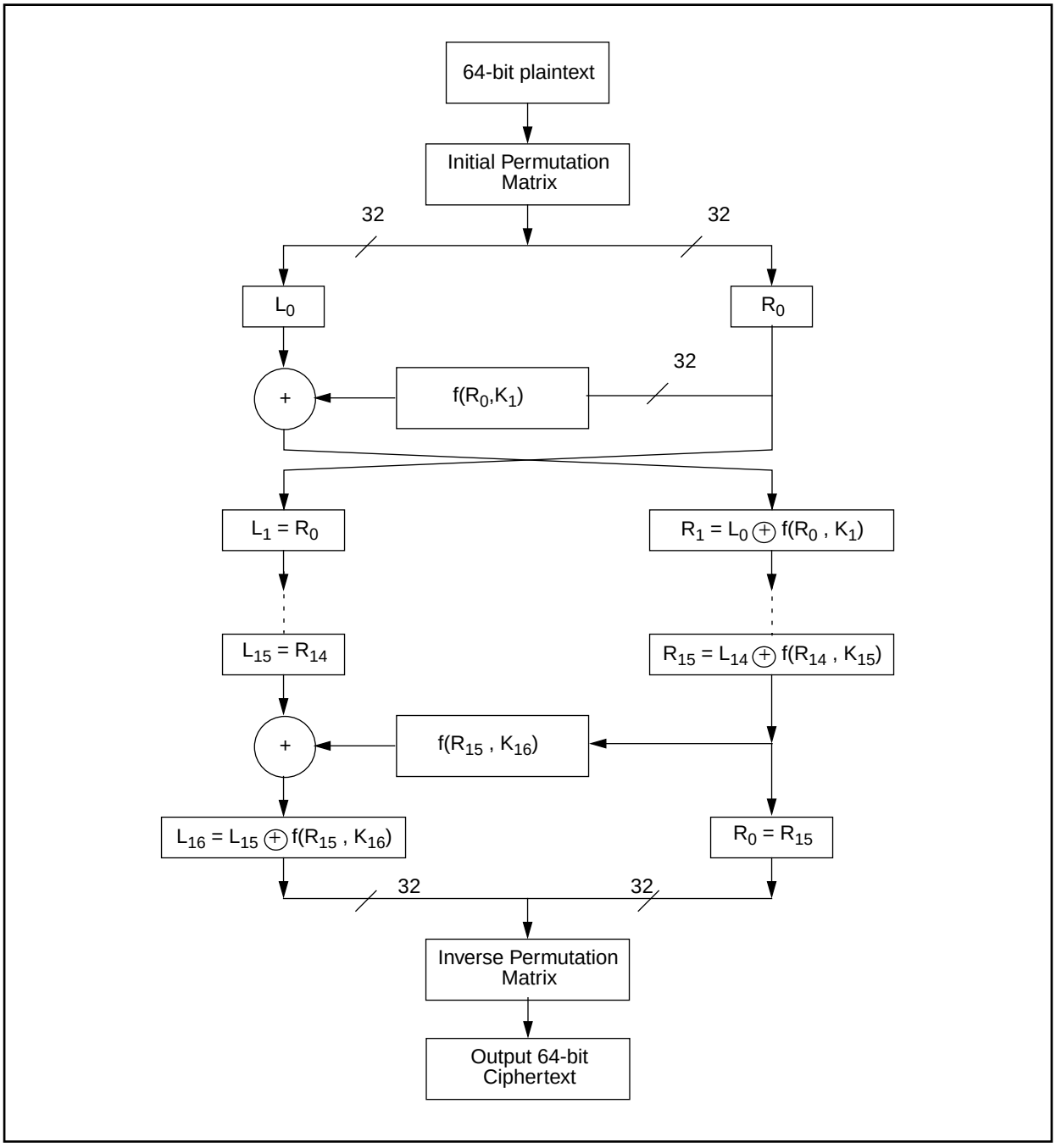
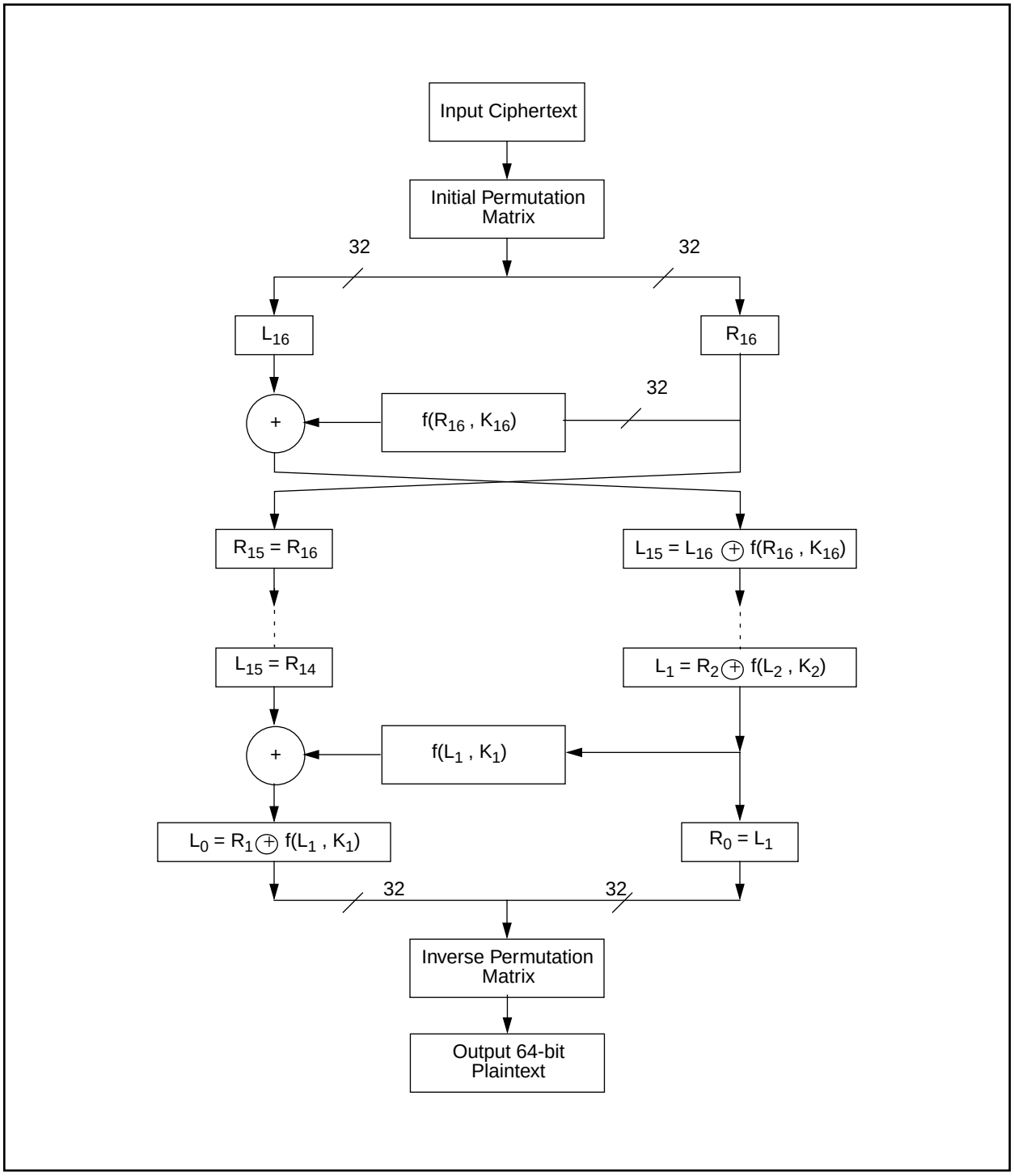


FIGURE 11: DES DECRYPTION BLOCK DIAGRAM



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