# Analytical Approach for Data Encryption Standard Algorithm

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**Abstract**—Although it was first developed and studied in the late 1970s and early 1977s, the Data Encryption Standard (DES) algorithm has grown in popularity. There are two causes for this occurrence. First, the DES algorithm's complex mathematical structure allows it to serve as the theoretical foundation for a wide variety of applications. Second, the encryption technique works quite well in practice for a variety of applications when implemented correctly. In this paper, we undertake a thorough and practical review of the theoretical aspects of this sort of encryption algorithm and demonstrate how they have been implemented by executing multiple encryption configurations.

Keywords—data encryption standard, cryptography, S-box, bit rotation, symmetric cipher

# 1 Introduction

The Data Encryption Standard (DES) is a standard technique for securing computer and telecommunication data. The National Bureau of Standards (now the National Institute of Standards and Technology) first adopted this standard in 1977 as FIPS Pub 46 [1, 2]. DES is a block cipher of the Feistel type that operates on 64-bit data blocks with a 56-bit key [3, 4]. Feistel ciphers use numerous rounds to decipher a block of bits by independently processing its left and right halves. To be invertible, a Feistel cipher just requires that the function (f) used to operate on the half-blocks of data bits be invertible, which is an intriguing property in and of itself. Because it executes both substitutions and permutations, the function f in the Data Encryption Algorithm is a product cipher. The Data Encryption Standard (DES) is an example of a symmetric block cipher [5, 6]. Each 64-bit block of plaintext is converted into ciphertext using a 56-bit key. The 56-bit key used to encipher the text is the same key used to decrypt it. The only variation between encryption and decryption is in the formation of sub-keys, therefore the key and algorithm are the same in both cases. Permutations, initial and inverse initial, and 16 comparable rounds of permutations, summing, and bit-wise manipulations are used in DES's processing of input blocks. The initial permutation merely passes input bits to different processing locations. The second bit, for example, is routed to location 33, and bit 55 is routed to place two. This rerouting is clearly explained in FIPS Pub-46. The inverse initial permutation is simply the opposite of the initial permutation. The block is processed in 16 iterations between the initial and inverse initial permutations. The DES algorithm's block diagram is presented in Figure 1 [5, 7-9].

This paper is structured as follows. In Section 2 we review the theory of DES algorithm with simple example. In section 3 illustrates the evaluation of the DES algorithm. Section 4 concludes the conclusion.

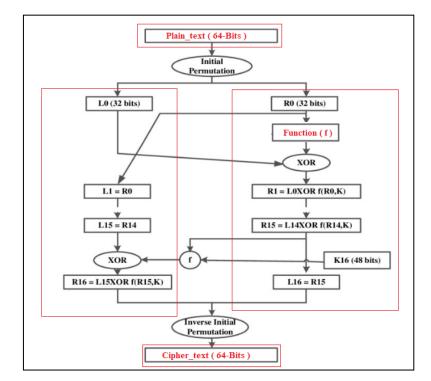


Fig. 1. Block diagram of DES algorithm

# 2 DES Processes – Example

The DES algorithm encrypts messages in blocks of 64 bits, which is equivalent to 16 hexadecimal digits. The "keys" that DES employs to encrypt data are reportedly 16 hexadecimal digits long, or 64 bits. The DES algorithm uses a 56-bit key, but discards every eighth bit as noise. In any event, 64-bits (i.e., 16 Hexadecimal digits) is the round number based on which DES is structured. DES algorithm is based on the fundamental parts: Subkeys generation and encryption process[10, 11]. These parts are explained in the following subsections bellow.

#### 2.1 Sub keys generator

This phase make a 16 sub-keys, each with a length of 48-bits. The Sub-key generation process based on sequential steps:

Let K be the Hexadecimal key K = 133457799BBCDFF1.

1. Convert the *K* to the binary key based on Figure 2 as illustrated in Table 1 and Figure 3.

Range	Group	HEX	Binary
[1-2]	1	13	00010011
[3-4]	2	34	00110100
[5-6]	3	57	01010111
[7-8]	4	79	01111001
[9-10]	5	9B	10011011
[11-12]	6	BC	10111100
[13-14]	7	DF	11011111
[15-16]	8	F1	11110001

 Table 1. Key representation - Binary

1	<pre>my_hexdata = "133457799BBCDFF1"</pre>
2	
3	<pre>scale = 16 ## equals to hexadecimal</pre>
4	
5	num_of_bits = 8
6	
7	<pre>bin(int(my_hexdata, scale))[2:].zfill(num_of_bits)</pre>

Fig. 2. Convert key to binary sequence

_	K	ley	/ =	0	00	1(	00	)11	00	)11	01	00	01	01	01	11	01	111	100	)11	00	011	01	11	01	11	100	)11	01	11	11	11	11	00	01	
In	35	34	33	32	31	13	50	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
I	0	0	1	1	0	(	)	1	1	1	1	0	1	1	1	0	1	0	1	0	0	0	1	0	1	1	0	0	1	1	0	0	1	0	0	0
Ľ		Chu	en Ke					64	63	62	61	60	59	58	57	56	55	54	53	52	51	50	49	48	47	46	45	44	43	42	41	40	39	38	37	36
Ш		GIV	en Ke	:y- 04	-DIts			1	0	0	0	1	1	1	1	1	1	1	1	1	0	1	1	0	0	1	1	1	1	0	1	1	1	0	1	1

Fig. 3. 64-Bits key length

2. Key permutation to 56-Bits length

The 64-bit key is permuted according to the Table 2 to generate a 56-Bit. As the first number in the table, "57" indicates that the 57th bit of the original key is the new starting point for the permuted key. The second bit of the permuted key is the original key's 49th bit. Bit 4 of the original key is now the final bit of the permuted key. Remember that the permuted key only contains 56-bits of the original key as shown in Figure 4.

1	5 2	3	31	39	47	- 55	63	36	44	52	60	3	11	19	27	35	43	51	59	2	10	18	26	34	42	50	- 58	1	9	17	25	33	41	49	57
		1	0	1	0	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	1	1	0	0	1	1	0	0	0	0	1	1	1	1
Г						Porm	nted I	Cor Fr	5-Bits						4	12	20	28	5	13	21	29	37	45	53	61	6	14	22	30	38	46	54	62	7
I .						reim	ateu 1	acy-o	-Dits						1	1	1	1	0	0	0	1	1	1	1	0	0	1	1	0	0	1	1	0	1

Fig. 4. 56-Bits permuted key

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	29
21	13	5	28	20	12	4

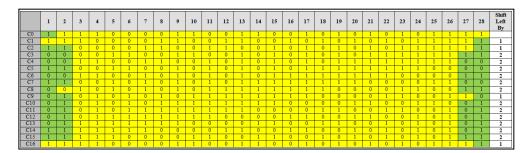
Table 2. Index permutation

3. Split the permuted key into 2 blocks (i.e., C<sub>0</sub> and D<sub>0</sub>), each block 28-Bits as shown in Figure 5.

	co	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
· ·	0	1	1	1	1	0	0	0	0	1	1	0	0	1	1	0	0	1	0	1	0	1	0	1	0	1	1	1	1
1	D0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
	00	0	1	0	1	0	1	0	1	0	1	1	0	0	1	1	0	0	1	1	1	1	0	0	0	1	1	1	1

Fig. 5. 28-Bits each block

4. Shift each block based on the shift left value to generate 16-Subkeys as shown in Figure 6 and 7.



**Fig. 6.** Result of the shift left operation -Right block

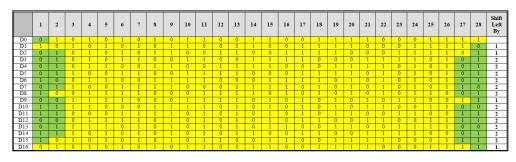


Fig. 7. Result of the shift left operation - Left block

5. Recombine  $C_n$  and  $D_n$  to generate 16- Sub keys each sub key size is 56-Bits as shown in Figure 8.

						-											1		
$\frac{1}{1}$ $\frac{2}{1}$	3	4	0	0	7	8	9	10 0	0	12	13	14 0	15 0	16 1	17 1	18 19 1 0	20	21	22         23         24         25         26         27         28         29         30         31         32         33         34         35           1         0         1         1         1         1         0
36 37	38	39	40	41	42	43	44	45	46	47	48	49	50	51		53 54	55	56	
0 1	1	0	0	1	1	0	0	1	1	1	1	0	0	0	1		1	0	Key No.1 – 56-Bits
1 2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		18 19	20	21	22 23 24 25 26 27 28 <b>29</b> 30 31 32 33 34 35
1 1	0	0	0	0	1	1	0	0	1	1	0	0	1	0		) 1	0	1	0 1 1 1 1 1 1 0 1 0 1 0 1 0
36 37 1 1	38	39 0	40	41	42	43 0	44	45	46	47	48	49 0	50 0	51		53 54 1 1	55	56	Key No.2- 56-Bits
1 2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		18 19	20	21	
0 0	0	0	1	1	0	0	1	1	0	0	1	0	1	0		0 1	0	1	1 1 1 1 1 1 1 1 1 0 1 0 1 0 1 1 1
36 37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53 54	55	56	
0 0	1	1	0	0	1	1	1	1	0	0	0	1	1	1		0 1	0	1	Key No.3- 56-Bits
1 2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		18 19	20	21	22 23 24 25 26 27 28 <b>29</b> 30 31 32 33 34 35
0 0 36 37	1 38	1 39	0 40	0 41	1 42	1	0 44	0 45	1 46	0 47	1 48	0 49	1 50	0	1 ( 52 :		1 55	1	1 1 1 1 1 0 0 0 1 0 1 1 0 <b>0</b>
1 1	0	0	40	41	42	43	44 0	45	40	47	40	49	1	51 0	1 (		0	56	Key No.4- 56-Bits
1 1	V	V	1	1	1	1	V	V	V	1	1	1	1	V	1		V	1	
1 2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		8 19	20	21	22 23 24 25 26 27 28 <b>29</b> 30 31 32 33 34 35
1 1 36 37	0	0 39	1 40	1 41	0 42	0 43	1 44	0 45	1 46	0 47	1 48	0 49	1 50	0 51	1 1 52 5	3 54	1 55	1 56	1 1 1 0 0 0 0 0 1 1 0 0 1 <b>1</b>
0 0	38	1	40	41	42	43	44 0	45	40	4/	48	0	1	0	1 0		0	20	Key No.5- 56-Bits
1 2	3	4	5	6	7	S	9	10	11	12	13	14	15	16		8 19	20	21	22 23 24 25 26 27 28 29 30 31 32 33 34 35
0 0	1	1	0		1	0	1	0	1	0	1	0	1	1	1 1		1	1	1 0 0 0 0 1 1 1 0 0 1 1 0 0
36 37	38	39	40		42	43	44	45	46	47	48	49	50	51		3 54	55	56	V No 6 56 Bits
1 1	1	1	0		0	1	1	1	1	0	1	0	1	0	1 0		0	1	Key No.6- 56-Bits
1 2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		8 19	20	21	22 23 24 25 26 27 28 <b>29</b> 30 31 32 33 34 35
1 1 36 37	0	0 39	1 40	0 41	1 42	0 43	1 44	0 45	1 46	0 47	1 48	1 49	1 50	1 51	1 1 52 5	3 54	1 55	0	0 0 0 1 1 0 0 0 1 1 0 0 1 1
1 1	0	0	0		1	1	1	0	1	0	1	0	1	0	1 0		1	0	Key No. 7– 56-Bits
1 2	3	4	5	6	7	8	9	10	11	12	13	14		16	17 1		20	21	22 23 24 25 26 27 28 29 30 31 32 33 34 35
0 0	1		1		1	0	1	0	1	1	1	1	1	1	1 1		0	0	0 1 1 0 0 1 1 1 0 0 1 1 1 1
36 37	38	39	40	41	42	43	44	45	46	47	48	49	50	51		3 54	55	56	Wee No. 9. 56 Pite
	0	1	1	1	1	0	1	0	1	0	1	0	1	0	1 1	0	0	1	
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0 0	,				1	· .		v	1	•		•		•		v	V	1	Key No.5- 50-Dits
		-	5	6	7	8	•									-			
1 2	3	4	5	6 1	7	8 1	9	10	11	12	13	14	15	16	17 1	8 19	20	21	22 23 24 25 26 27 28 <b>29</b> 30 31 32 33 34 35
0 0 1 2 0 1 36 37		-	5 0 40	6	7 0 42	8	9 0 44		11	12	13	14	15		17 1 1 (	-			22         23         24         25         26         27         28         29         30         31         32         33         34         35           1         1         0         0         1         1         0         0         1         1         1         1         0
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$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	3 0 38 1 3 0 38	4 1 39 1 4 1 39	5 0 40 1 5 0 40	6 1 41 1 6 1 41	7 0 42 0 7 0 42	8 1 43 1 8 1 43	9 0 44 0 9 1 44	10 1 45 1 10 1 45	11 1 46 0 11 1 46	12 1 47 1 12 1 47	13 1 48 0 13 1 48	14 1 49 1 14 1 49	15 1 50 0 15 1 50	16 1 51 1 16 0 51	17 1 1 0 52 5 1 0 17 1 0 0 52 5	18         19           0         0           53         54           0         0           18         19           0         0           53         54           53         54	20 0 55 1 20 1 55	21 0 56 1 21 1 56	22         23         24         25         26         27         28         29         30         31         32         33         34         35           1         1         0         0         1         1         0         0         1         1         1         0         0           VEW No.9-56-Bits           22         23         24         25         26         27         28         29         30         31         32         33         34         35           22         23         24         25         26         27         28         29         30         31         32         33         34         35           0         0         1         1         1         0         <
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Fig. 8. Sub keys – 56-Bits length

6. Key permutation to 48-Bits length The 56-bit key is permuted according to the Table 3 to generate a 48-bit as shown in Figure 9.

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

 Table 3. Index permutation to 48-bits length

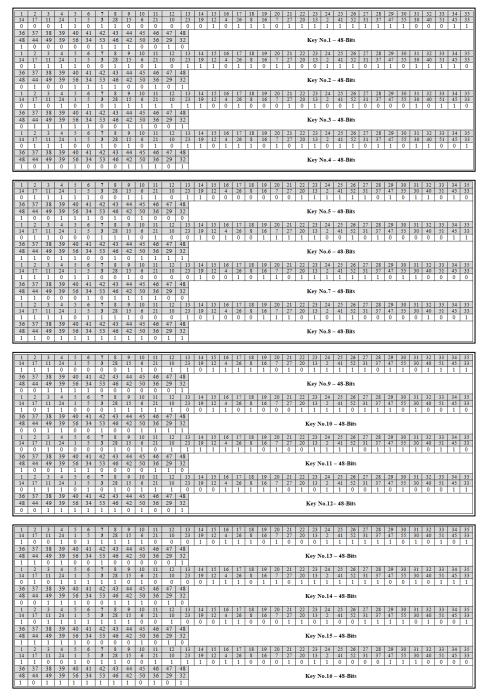


Fig. 9. 16-Sub keys – 48-Bits key length for each sub key

As soon as this phase is completed, we have generated the sub keys K<sub>n</sub>, for 1≤n≤16, by applying the permutation structure based on Table 3 to each of the joined C<sub>n</sub>D<sub>n</sub> pairs. Now let's take a look at the actual message (i.e., Plaintext) by applying the second phase (i.e., Encryption process).

#### 2.2 **Encryption process**

Now let's take a look at the actual message (i.e., plaintext) by applying the second phase (i.e., Encryption process). The encryption process based on sequential steps: Let plaintext be the Hexadecimal M = 0123456789ABCDEF.

1. Convert the Plaintext to the binary key based on Figure 10 as illustrated in Table 4 and Figure 11.

Range	Group	HEX	Binary
[1-2]	1	01	00000001
[3-4]	3	23	00100011
[5-6]	5	45	01000101
[7-8]	7	67	01100111
[9-10]	9	89	10001001
[11-12]	11	AB	10101011
[13-14]	13	CD	11001101
[15-16]	15	EF	11101111

Table 4. Key binary representation

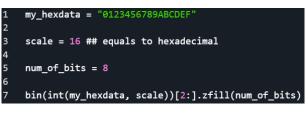


Fig. 10. Convert message to binary sequence

N	Лe	SSa	ıge	e is	s 0	000	000	001	10(	)1(	000	)11	01	00	01	01	01	10	01	11	100	)01	.00	)11	01	01	01	11	10	01	10	11	11(	)11	11
- [	35	34	33	32	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
	0	0	1	1	1	1	0	0	1	1	0	1	0	1	0	0	0	1	0	1	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0
					-Bits		64	63	62	61	60	59	58	57	56	55	54	53	52	51	50	49	48	47	46	45	44	43	42	41	40	39	38	37	36
		Plai	ntext	- 04	-Bits		1	1	1	1	0	1	1	1	1	0	1	1	0	0	1	1	1	1	0	1	0	1	0	1	1	0	0	1	0

Fig. 11. Plaintext- 64-Bits length

2. Plain-text initial permutation

Initially, the 6-bits that make up the message data M are shuffled around. Each entry in Table 5 indicates how the bits have been rearranged from their original order. M's 58th bit is now the first bit. As a result, bit 50 of M is now bit 2. As for M, the seventh bit is the very last one as shown in Figure 12.

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

Table 5. Initial permutation

3	5 34	33	32	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
4	1 49	57	8	16	24	32	40	48	56	64	6	14	22	30	38	46	54	62	4	12	20	28	36	44	53	60	2	10	18	26	34	42	50	58
1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1
						64	63	62	61	60	59	58	57	56	55	54	53	52	51	50	49	48	47	46	45	44	43	42	41	40	39	38	37	36
F	Permuta	ited Pl	a inte:	ct-64-	Bits	7	15	23	31	39	47	55	63	5	13	21	29	37	45	53	61	3	11	19	27	35	43	51	59	1	9	17	25	33
						0	1	0	1	0	1	0	1	0	0	0	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	0	0	

Fig. 12. Result of the initial permutation

 $3. \ L_n \ and \ R_n$ 

Here, DES split the permuted message (See Figure 12) into two halves, each of which consists of 32-bits (i.e., Left and Right) as shown in Figure 13.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	
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	Left
1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	0	0	1	1	1	1	1	1	1	1	L <sub>0</sub>
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	<b>D</b> . 1.
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	Right Ro
1	1	1	1	0	0	0	0	1	0	1	0	1	0	1	0	1	1	1	1	0	0	0	0	1	0	1	0	1	0	1	0	R <sub>0</sub>

Fig. 13. Left and right parts	Fig.	13.	Left	and	right	parts
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Now, perform DES structure to generate  $L_0$  to  $L_{16}$  and  $R_0$  to  $R_{16}$  based on the following formula:

 $L_n = R_{n-1}$ 

 $R_n = L_{n-1} \text{ XOR } F(R_{n-1}, K_n)$ 

$L_1$	L1=R <sub>1-1</sub>	$L_1 = R_0$
<b>R</b> <sub>1</sub>	$R_1 = L_{1-1} \text{ XOR } F(R_{1-1}, K_1)$	$R1=L_0 XOR F(R_0, K_1)$
$L_2$	$L_2 = R_{2-1}$	$L_2=R_1$
<b>R</b> <sub>2</sub>	$R_1 = L_{2-1} \text{ XOR } F(R_{2-1}, K_2)$	$R_2 = L_1 \text{ XOR } F(R_1, K_2)$
L <sub>3</sub>	$L_3 = R_{3-1}$	$L_3=R_2$
R <sub>3</sub>	R <sub>3</sub> =L <sub>3-1</sub> XOR F(R <sub>3-1</sub> , K <sub>3</sub> )	$R_3=L_2 XOR F(R_2, K_3)$
•		
L <sub>15</sub>	$L_{15} = R_{15-1}$	$L_{15} = R_{14}$
R <sub>15</sub>	R <sub>15</sub> =L <sub>15-1</sub> XOR F(R <sub>15-1</sub> , K <sub>15</sub> )	R <sub>15</sub> =L <sub>15</sub> XOR F(R <sub>14</sub> , K <sub>15</sub> )
L <sub>16</sub>	$L_{16} = R_{16-1}$	$L_{16} = R_{15}$
R <sub>16</sub>	R <sub>16</sub> =L <sub>16-1</sub> XOR F(R <sub>16-1</sub> , K <sub>16</sub> )	$R_{16} = L_{15} \text{ XOR F}(R_{15}, K_{16})$

The Implementation process for 2-rounds to generate  $L_1$  and  $R_1$  as follow:

Figure 14 displayed L<sub>1</sub>. To find R1, we get R0 = 32-Bits and K1 = 48- Bits. DES algorithm expands R0 to be 48-Bits based on Table 6 (i.e., Bit-selection). Table 6, repeats some of the bits in  $R_{n-1}$  to expand 32-bit to 48-bits as shown in Figure 15.

1	1	2	3	- 4	5	6	7	8	9	10	- 11	12	13	- 14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	T
1	L	1	1	1	0	0	0	0	1	0	1	0	1	0	1	0	1	1	1	1	0	0	0	0	1	0	1	0	1	0	1	0	L1

Fig. 14. L1 32-bits length

Table 6. Bit-selection

32	1	2	3	4	5
8	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

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
32	1	2	3	4	5	8	5	6	7	8	9	8	9	10	11	12	13	12	13	14	15	16	17	
0	1	1	1	1	0	1	0	0	0	0	1	0	1	0	1	0	1	0	1	0	1	0	1	Expanded (R0)
25	26	27	28	29	30	31	32	33	34	35	36	37	- 38	39	40	41	42	43	44	45	46	47	48	48-Bits
16	17	18	19	20	21	20	21	22	23	24	25	24	25	26	27	28	29	28	29	30	31	32	1	
0	1	1	1	1	0	1	0	0	0	0	1	0	1	0	1	0	1	0	1	0	1	0	1	

Fig. 15. Expanded R<sub>0</sub> to 48-bits length

In Figure 16, the expanded R0 is XORed with the Sub key No.1 (See Figure 9)

	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
	17	16	15	14	13	12	13	12	11	10	9	8	9	8	7	6	5	8	5	4	3	2	1	32
Expanded (R0)	1	0	1	0	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	1	1	1	0
48-Bits	48	47	46	45	44	43	42	41	40	39	38	37	36	35	34	33	32	31	30	29	28	27	26	25
	1	32	31	30	29	28	29	28	27	26	25	24	25	24	23	22	21	20	21	20	19	18	17	16
	1	0	1	0	1	0	1	0	1	0	1	0	1	0	0	0	0	1	0	1	1	1	1	0
	24	00	22	01	20	10	10	17	16	1.0	14	10	10	11	10	0	0	-		~	4	0		-
	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	/	6	2	4	3	2	1
Key 1	1	1	1	1	0	1	1	1	0	1	0	0	0	0	0	0	1	1	0	1	1	0	0	0
48-Bits	48	47	46	45	44	43	42	41	40	39	38	37	36	35	34	33	32	31	30	29	28	27	26	25
	0	1	0	0	1	1	1	0	0	0	0	0	1	1	1	0	0	0	1	1	1	1	1	1
	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
[Expanded (R0)] XOR	0	1	0	1	1	1	0	1	1	1	1	0	1	0	0	0	1	0	0	0	0	1	1	0
[Key 1]	48	47	46	45	44	43	42	41	40	39	38	37	36	35	34	33	32	31	30	29	28	27	26	25
[Key 1]	1	1	1	0	0	1	0	0	1	0	1	0	0	1	1	0	0	1	1	0	0	0	0	1

Fig. 16. Result of XOR operation

As can be seen in Figure 17, the XORed data has been partitioned into 8 groups, each of which consists of 6-bits.

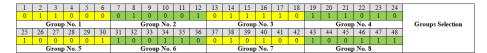


Fig. 17. Group selection

DES uses six-bit groups as addresses in "S-boxes" as shown in Figure 18. Each six-bit group gives an S-box address. A 4-bit number is at that address. This 4-bit number replaces 6 bits. The eight groups of 6-bits are turned into eight groups of 4-bits (S-box outputs) for 32 bits. S-box value is determined as shown in Table 7.

0         14         4         13         1         2         15         11         8         3         10         6         12         5         9         0           1         0         15         7         4         14         2         13         1         10         6         12         11         9         5         3	0 7	-				10		0	1	0	2	4	- 3	2	1	0	No.
1 0 15 7 4 14 2 13 1 10 6 12 11 9 5 3		0	9	5	12	6	10	3	8	11	15	2	1		4	14	0
	3 8	3	5	9	11	12	6	10	1		2	14	4	7		0	1
2 4 1 14 8 13 6 2 11 15 12 9 7 3 10 5	5 0	5	10	3	7	9	12	15	11	2	6	13	8	14	1	4	2
3 15 12 8 2 4 9 1 7 5 11 3 14 10 0 6	6 13	6	0	10	14	3	11	5	7	1	9	4	2				3
S1-Box- Group No. 1							o. 1	oup No	x– Gro	S1-Bo							

No.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	15	1	8	14	6	11	3	4	9	7	2	13	12	0	5	10
1	3	13	4	7	15	2	8	14	12	0	1	10	6	9	11	5
2	0	14	7	11	10	4	13	1	5	8	12	6	9	3	2	15
3	13	8	10	1	3	15	4	2	11	6	7	12	0	5	14	9
						5	S2-Box	x – Gro	oup No	o. 2						

No.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	10	0	9	14	6	3	15	5	1	13	12	7	11	4	2	8
1	13	7	0	9	3	4	6	10	2	8	5	14	12	11	15	1
2	13	6	4	9	8	15	3	0	11	1	2	12	5	10	14	7
3	1	10	13	0	6	9	8	7	4	15	14	3	11	5	2	12
							S3-Bo	x- Gro	oup No	5.3						

No.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	7	13	14	3	0	6	9	10	1	2	8	5	11	12	4	15
1	13	8	11	5	6	15	0	3	4	7	2	12	1	10	14	9
2	10	6	9	0	12	11	7	13	15	1	3	14	5	2	8	4
3	3	15	0	6	10	1	13	8	9	4	5	11	12	7	2	14
							S4-Bo	x– Gro	oup No	o. 4						

No.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	2	12	4	1	7	10	11	6	8	5	3	15	13	0	14	9
1	14	11	2	12	4	7	13	1	5	0	15	10	3	9	8	6
2	4	2	1	11	10	13	7	8	15	9	12	5	6	3	0	14
3	11	8	12	7	1	14	2	13	6	15	0	9	10	4	5	3
							S5-Bo	x– Gro	oup No	5.5						

No.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	12	1	10	15	9	2	6	8	0	13	3	4	14	7	5	11
1	10	15	4	2	7	12	9	5	6	1	13	141	0	11	3	8
2	9	14	15	5	2	8	12	3	7	0	4	10	1	13	11	6
3	4	3	2	12	9	5	15	10	11	14	1	7	6	0	8	13
							S6-Bo	x- Gr	oup N	o. 6						

No.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	4	11	2	14	15	0	8	13	3	12	9	7	5	10	6	1
1	13	0	11	7	4	9	1	10	14	3	5	12	2	15	8	6
2	1	4	11	13	12	3	7	14	10	15	6	8	0	5	9	2
3	6	11	13	8	1	4	10	7	9	5	0	15	14	2	3	12
							S7-Bo	x– Gro	oup No	o. 7						

No.	0	1	2	3	4	- 5	6	7	8	9	10	11	12	13	14	15
0	13	2	8	4	6	15	11	1	10	9	3	141	5	0	12	7
1	1	15	13	8	10	3	7	4	12	5	6	11	0	14	9	2
2	7	11	4	1	9	12	14	2	0	6	10	13	15	3	5	8
3	2	1	14	7	4	10	8	13	15	12	9	0	3	5	6	11
							S8-Bo	x– Gr	oup No	o. 8						

Fig. 18. S-Box for each group

Group No.	Binary Representation	Binary	Decimal	S-Box Intersection	S-Box
Group No.1	011000				(See Figure 18)
Row	First & Last-Bit (2-Bits)	00	0	5	S1 – Box-Group
Column	In Between (4-Bits)	1100	12		No. 1
Group No.2	010001				(See Figure 18)
Row	First & Last-Bit (2-Bits)	01	1	12	S2 - Box-Group
Column	In Between (4-Bits)	1000	8		No. 2
Group No.3	011110				(See Figure 16)S3
Row	First & Last-Bit (2-Bits)	00	0	8	– Box-Group No.
Column	In Between (4-Bits)	1111	15		3
Group No.4	111010				(See Figure 18)
Row	First & Last-Bit (2-Bits)	10	2	2	S4 – Box-Group
Column	In Between (4-Bits)	1101	13		No. 4
Group No.5	100001				(See Figure 18)
Row	First & Last-Bit (2-Bits)	11	3	11	S5 – Box-Group
Column	In Between (4-Bits)	0000	0		No. 5
Group No.6	100110				(See Figure 18)
Row	First & Last-Bit (2-Bits)	10	2	5	S6 – Box-Group
Column	In Between (4-Bits)	0011	3		No. 6
Group No.7	010100				(See Figure 18)
Row	First & Last-Bit (2-Bits)	00	0	9	S7–Box-Group
Column	In Between (4-Bits)	1010	10		No. 7
Group No.8	100111				(See Figure 18)
Row	First & Last-Bit (2-Bits)	11	3	7	S8 – Box-Group
Column	In Between (4-Bits)	0011	3		No. 8

# Table 7. S-box utilization

Figure 19 displays the result derived from the preceding table (Table 7).

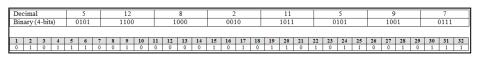


Fig. 19. Binary representation of the obtained result

# 4. Function (f)

The final step in calculating f is to permute the S-box output using Table 8 to achieve the final value of f as shown in Figure 20.

Table 8. Index permutation

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

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
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
0	0	1	0	0	0	1	1	0	1	0	0	1	0	1	0	1	0	1	0	1	0	0	1	1	0	1	1	1	0	1	1

Fig. 20. F(R<sub>0</sub>, K<sub>1</sub>)

 $R_1=L_0$  XOR  $F(R_0, K_1)$ , we got the result in Figure 21 to represent  $R_1$ .

1		2	3	4	5	<u>6</u> 0	7	8 1	9 0	10	11 0	12 0	13	14 0	15	16 0	17	18 0	19 1	20 0	21	22 0	23 0	24	25	26 0	27	28 1	29 1	30 0	31 1	32	F(R <sub>0</sub> , K <sub>1</sub> )
	_																																
1		2	3	4	5	6	7	8	9	10	0	0	13	0	0	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	$\mathbf{L}_{0}$
1		2	3	4	5	6	7	8 1	9 0	10	11	12	13	14 0	15	16 0	17 0	18	19	20	21	22	23 0	24	25 0	26	27	28	29 0	30	31 0	32 0	R1

### Fig. 21. R1

Repeating the preceding steps yields  $L_{16}$  and  $R_{16}$  as indicated in Figure 22.

1	T	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	T
0		1	0	0	0	0	1	1	0	1	0	0	0	0	1	0	0	0	1	1	0	0	1	0	0	0	1	1	0	1	0	0	L16
1		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	n
0		0	0	0	1	0	1	0	0	1	0	0	1	1	0	0	1	1	0	1	1	0	0	1	1	0	0	1	0	1	0	1	R16

#### Fig. 22. L16 and R16

5. Re-combine  $L_{16}$  and  $R_{16}$ 

We have the blocks  $L_{16}$  and  $R_{16}$  at the end of the sixteenth round. The two blocks are then reversed into the 64-bit block (i.e.,  $R_{16}L_{16}$ ) as shown in Figure 23.

Г	35	34	33	32	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
Г	0	1	0	1	0	1	0	1	0	0	1	1	0	0	1	1	0	1	1	0	0	1	1	0	0	1	0	0	1	0	1	0	0	0	0
Г							64	63	62	61	60	59	58	57	56	55	54	53	52	51	50	49	48	47	46	45	44	43	42	41	40	39	38	37	36
L			R <sub>16</sub>	L16			0	0	1	0	1	1	0	0	0	1	0	0	1	1	0	0	0	1	0	0	0	0	1	0	1	1	0	0	0

Fig. 23. R<sub>16</sub>L<sub>16</sub>

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

Table 9. Initial permutation - Inverse

Finally, utilize Table 9's for final Permutation as shown in Table 9 and Figure 24.

35	34	33	32	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
44	4	36	29	61	21	53	13	45	5	37	30	62	22	54	14	46	6	38	31	63	23	55	15	47	7	39	32	64	24	56	16	48	8	40
0	0	0	0	0	1	0	1	0	1	0	1	1	0	0	1	0	0	0	0	0	0	1	0	1	1	1	1	0	1	0	0	0	0	1
						64	63	62	61	60	59	58	57	56	55	54	53	52	51	50	49	48	47	46	45	44	43	42	41	40	39	38	37	36
	Cip	her te	xt-64	-Bits		25	57	17	49	9	41	1	33	26	58	18	50	10	42	2	34	27	59	19	51	11	43	3	35	28	60	20	52	12
						1	0	1	0	0	0	0	0	0	0	1	0	1	1	0	1	0	1	0	1	0	0	0	0	1	1	1	1	0

Fig. 24.Binary representation of the Cipher text -64-Bits

If we express the result as a Hexadecimal, we get the value as shown in Table 10 for both plain and cipher texts.

Table 10.	HEX data rep	resentation for	r Plain and	Cipher texts
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DATA	HEXADECIMAL Number	SIZE
Plaintext	0123456789ABCDEF	16 * 4 = 64- Bits
Cipher text	85E813540F0AB405	16 * 4 = 64- Bits

To make it clear, we have outlined how DES algorithm operates to convert plain text to cipher text in Figures 25, 26, and 27.

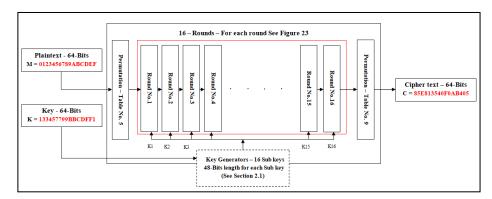
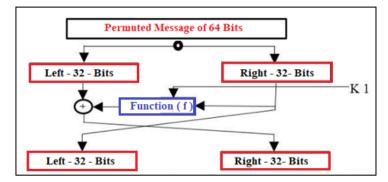


Fig. 25. Steps of DES algorithm



R0 - 32 - Bits Expand to 48-Bits 48 - Bits K1 - 48 - Bits S1 S2 S3 S4 S5 S6 S7 S8 Permutation 32 - Bits

Fig. 26. DES-For each round

**Fig. 27.** Function  $F(R_{n-1}, K_n)$ 

# **3** Evaluation

Data Encryption Standard (i.e., DES) is an obsolete symmetric key encryption technique[12]. It was implemented by government entities in 1977 to safeguard sensitive information and was officially decommissioned in 2005 [13, 14]. The initial specification was developed by IBM's researchers in the early 1970s. Afterwards, in 1977, it became an official Federal Information Processing Standard (i.e., FIPS) for the encryption of commercial and sensitive but unclassified government computer data by the U.S. National Bureau of Standards, now known as the National Institute of Standards and Technology, or NIST[6, 15, 16]. The United States government first allowed the public release of DES, an encryption algorithm. In doing so, it secured its rapid adoption by sectors like the financial sector, which required robust encryption. Due to

its ease of use, DES was also implemented in many embedded devices, such as smart cards, SIM cards, modems, and routers [17-19].

Brute-force attacks, in which each possible key is tried in turn until the correct one is discovered, are the most fundamental way to break any cipher[20]. The number of potential keys, and hence the viability of this form of attack, is directly proportional to the key length as shown in Table 11 [7, 16, 21]. A maximum of 256 or nearly 72 quadrillion, attempts would be needed to find the correct key, given that the effective DES key length is 56 bits. This is insufficient to prevent modern computers from breaking through DES-protected data using brute force[22]. Through the early to middle 1990s, DES was still the de facto standard for secure data transmission. While this may seem like a long time, in 1998, a computer created by the Electronic Frontier Foundation (i.e., EFF) deciphered a DES-encoded communication in just 56 hours. The next year, EFF reduced the decryption time to 22 hours by harnessing the power of thousands of networked computers. The extended version of DES, known as Triple-DES (i.e., TDES or 3-DES), will be used in government and finance for many years to come. The differences and similarities between DES and Triple-DES are shown in Table 12 [14, 23-29].

Key size - Bits	Quantity of alternate keys	Decryption time - 1 /µs
168	$2^{168} = 3.7 \text{ x} 10^{50}$	$2^{167}\mu s = 5.9 \text{ x } 10^{36} \text{ years}$
128	$2^{128} = 3.4 \text{ x} 10^{38}$	$2^{127}\mu s = 5.4 \text{ x} 10^{24} \text{ years}$
56	$2^{56} = 7.2 \text{ x } 10^{16}$	$2^{55}\mu s = 1142$ years
32	$2^{32} = 4.3 \times 10^9$	$2^{31}\mu s = 35.8 minutes$

 Table 11.
 Total Key-Search Time: an Average Estimate

Feature	DES	Triple-DES
Created by / Year	IBM - 1975	IBM - 1978
Key size	56 - Bits	(168 or 112) - Bits
Number of rounds	16	48
Number of Sub keys	16	48
Key generations	Permute Shift	Permute Shift
Block size	64 – Bits	64 – Bits
Mathematical operations	S-Boxes- Fixed, XOR	S-Boxes- Fixed, XOR
Cipher type	Block cipher - Symmetric	Block cipher - Symmetric
Attack	Broken in 1998 - Brute-force	No known Attack
Security level	Not Secure Enough	Adequate Security
Speed	Slow	Very Slow

Table 12. DES and Triple-DES - Comparison

# 4 Conclusion

In this paper we have attempted to present the theory of Data Encryption Standard (i.e., DES) algorithm from the simplest to the most sophisticated concept. It has been

our purposes to focus on the practical explanation of the basic mathematics and how DES algorithm it could be implemented in practice in real world system because a correct comprehension of the encryption algorithm leads to an understanding of the pros and cons, which allows for modernization and the development of a new encryption algorithm that operates more efficiently.

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