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CRYPTOGRAPHY AND SECURITY

LABORATORY WORK #4

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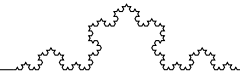
Block Ciphers. DES

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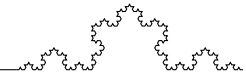


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1 Introduction

Blocks ciphers are a type of ciphers which encode a fixed size block. They are more used in modern cryptography than stream ciphers due to their enhanced security features. Block ciphers operate on fixed-size blocks of plaintext, transforming them into ciphertext using a symmetric key. This lab focuses on Data Encryption Standard (DES) cipher only.

2 DES Cipher

DES ciphers is a symmetric-key algorithm for the encryption of digital data. It was developed in the early 1970s at IBM and later adopted as a federal standard in the United States.

DES operates on 64-bit blocks of data using a 56-bit key. However, the key is often represented as a 64-bit value, with every eighth bit used for parity checking and not for encryption. In other words, in the result the KEY is permuted to 56 bits.

The steps of DES encryption are as follows [2] [3]:

- Divide the message into 64 blocks. Let's call each block M .
- Apply an initial permutation (IP) to each block M .
- Split the permuted block into two halves: left (L) and right (R), each 32 bits.
- Perform 16 rounds of processing, where in each round:
 1. we set $L_i = R_{i-1}$
 2. we set $R_i = L_{i-1} \oplus f(R_{i-1}, K_i)$, where K_i is the subkey for round i , generated from the main key using a key schedule algorithm, and f is a complex function involving expansion, substitution using S-boxes, and permutation.
- In the last round, with L_{16} and R_{16} we make a swap, so the final output before the last permutation is $R_{16}L_{16}$.
- Apply the final permutation (IP^{-1}) to the combined block to produce C .
- The cipher text is then outputted in necessary format

Despite its historical significance, DES is no longer considered secure for many applications due to its relatively short key length, which makes it vulnerable to brute-force attacks. Modern encryption standards, such as the Advanced Encryption Standard (AES), have largely replaced DES in most applications. For example, new ciphers like Triple DES (3DES) apply the DES algorithm three times to each data block, effectively increasing the key length and enhancing security.



3 Implementation of DES Cipher

My task: (2.11): From L_{16} and R_{16} compute C (ciphertext) and output in hex format.

Unfortunately, due to missread of the lab instructions, I implemented the full algorithm instead of some part of it. Thus, I will describe the full algorithms, because I don't want the work to go to waste.

The DES cipher was implemented in Kotlin. The source code can be found in GitHub repository [1]. In this laboratory work, I implemented both encryption and decryption functions of the DES. I have core function like encrypt and decrypt data block, which are used in DesIO module, which provides additional functionality like encrypting/decrypting hex strings, plaintext in ascii and etc.

3.1 Main datatypes

In my implementation, I mostly used BooleanArray to represent bits. For example, 64-bit block is represented as BooleanArray of size 64, where each element is either true (1) or false (0). This representation allows for easy manipulation of individual bits during the various transformations required by the DES algorithm. The input or output can be presented in different formats like hex string, ascii string or byteArray, but internally all data is converted to BooleanArray for processing.

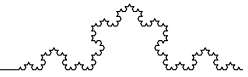
3.2 Tables

DES algorithm relies on several predefined tables for permutations and substitutions. These tables are crucial for the various transformations that occur during the encryption and decryption processes. In Kotlin, they are represented as intArrays with the exception of S-boxes, which are represented as 2D arrays.

For example, this is how PC_1 table is presented in the code:

```
1 val PC_1 = intArrayOf(  
2     57, 49, 41, 33, 25, 17, 9,  
3     1, 58, 50, 42, 34, 26, 18,  
4     10, 2, 59, 51, 43, 35, 27,  
5     19, 11, 3, 60, 52, 44, 36,  
6     63, 55, 47, 39, 31, 23, 15,  
7     7, 62, 54, 46, 38, 30, 22,  
8     14, 6, 61, 53, 45, 37, 29,  
9     21, 13, 5, 28, 20, 12, 4  
10 )
```

Listing 1: Table PC_1



Most of the tables are simple permutation tables but S Boxes. The method of applying S Box is presented below:

```

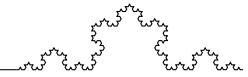
1 fun apply_S_box(block: BooleanArray, boxNumber: Int):
  BooleanArray {
2
3   val row = (if (block[0]) 2 else 0) + (if (block[5]) 1 else
4     0)
5   val column = (if (block[1]) 8 else 0) +
6     (if (block[2]) 4 else 0) +
7     (if (block[3]) 2 else 0) +
8     (if (block[4]) 1 else 0)
9
10  val value = S_BOXES[boxNumber - 1][row][column]
11
12  return BooleanArray(4) { bit ->
13    (value shr (3 - bit) and 1) == 1 // 2bit => 0110 -> 0011
14    -> 0001 = 1 => (~, ~, 1, ~)
15  }
16 }
```

Listing 2: Table PC1

Now, let's describe the main functions of DES implementation.

```

1 fun BooleanArray.encryptDesBlock(key: BooleanArray):
  BooleanArray {
2
3   val mPermuted = applyPermutation(IP, this) // keeps size, 64
4     bits
5
6   val L0 = mPermuted.sliceArray(0..31) // 32 bits
7   val R0 = mPermuted.sliceArray(32..63) // 32 bits
8
9   var LCurrent = L0
10  var RCurrent = R0
11
12  val KList = getKList(key, loggerActive);
13
14  for (i in 1..16) {
```



```

15     val fRezult = f(RCurrent, KList[i-1])
16
17     val RNext = LCurrent xor fRezult
18
19     val LNext = RCurrent
20
21     LCurrent = LNext
22     RCurrent = RNext
23 }
24
25 val C = getCfromL16R16(LCurrent, RCurrent, loggerActive);
26
27 return C
28 }
```

Listing 3: Encryption

In *3rd* line we get the message with initial permutation applied. Then in lines *5th* and *6th* we split the message into left and right parts. Then, in *11th* line we get the list of Keys $1 \dots 16$ with given key. The function is shown later.

Then, we have a loop, where we iterate through 16 rounds.

As we have theoretically, $L_i = R_{i-1}$; $R_i = L_i \oplus f(R_i, K_i)$

For each i we have:

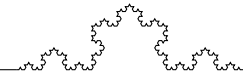
- compute fRezult (15th line)
- Compute $R_{\text{Next}} = L_{\text{Current}} \text{ xor } f_{\text{Rezult}}$ (17th line)
- Set $L_{\text{Next}} = R_{\text{Current}}$ (19th line)
- Update LCurrent and RCurrent for the next iteration (21st and 22nd lines)

And finally, with L_{16} and R_{16} we apply the final permutation and get the ciphertext.

Now, I'll show how the f is defined:

```

1 internal fun f(Rn: BooleanArray, Kn_plus_1: BooleanArray):
   BooleanArray {
2
3     val R_E_permuted = applyPermutation(E, Rn) // extends R to
       48 bits
4
5     val R_Permuted_XOR_ed = R_E_permuted xor Kn_plus_1
```



```

6      val B_blocks = R Permuted_XOR_ed.toList().chunked(6).map {
7          it.toBooleanArray() } // 48 -> 8 blocks of 6 bits
8
9      val sBoxOutput = B_blocks.mapIndexed { i, b ->
10
11          val sBox = S_BOXES[i]
12          val sResult = apply_S_box(b, i + 1)
13          sResult.toList()
14
15      }.flatten().toBooleanArray()
16
17      val PPermRezult = applyPermutation(P, sBoxOutput)
18      return PPermRezult
19  }

```

Listing 4: Function f

Mathematically, the function f can be described as follows:

- Expand the 32-bit input R_n to 48 bits using the
- XOR the expanded R_n with the 48-bit subkey K_{n+1} .
- Divide the 48-bit result into eight 6-bit blocks.
- For each 6-bit block, use the corresponding S-box to substitute it with a 4-bit block.
- Concatenate the eight 4-bit blocks to form a 32-bit block.
- Apply a P permutation to the 32-bit block to produce the output of the function f.

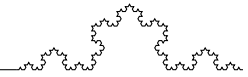
And since my task was specifically to get C from L16 and R16, I will show it too.

```

1  fun main() {
2      val M = "0123456789ABCDEF"
3      val K = randomBooleanArray(64).toHexString();
4      println("M: $M")
5      println("K: $K")
6      val enc = M.hexToBooleanArray().encryptDesBlock(K.
7          hexToBooleanArray(), true)
8      println("C: ${enc.toHexString()}")
9  }

```

Listing 5: from L16 and R16 get C



The process is quite simple: L16 and R16 are swapped and then the final permutation is applied.

4 Demonstration

To show the implementation of the algorithm, I'll encrypt and decrypt a simple hex encoded block.

```

1 fun main() {
2     val M = "0123456789ABCDEF"
3     val K = randomBooleanArray(64).toHexString();
4     println("M: $M")
5     println("K: $K")
6     val enc = M.hexToBooleanArray().encryptDesBlock(K.
7         hexToBooleanArray(), true)
8     println("C: ${enc.toHexString()}")
9 }

```

Listing 6: Main code

Now, let's see the output for the encryption:

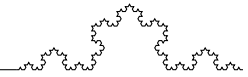
```

1 ms  12:07:11: Executing ':lab4.BlockEncryptionKt.main()'...

M: 0123456789ABCDEF
K: 37A210B3EEF576B0
Step: Permute m
M: 0000000100100011010001010110011110001001101010111100110111101111
Table IP:
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
M permuted: 11001100000000001100110011111111111000010101011110000101010
Step: Get L0, R0
L0 = 11001100000000001100110011111111
R0 = 11110000101010101111000010101010
Step: Getting subkeys.
Making K+
Permutation table PC_1 =
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

```

Figure 1: Encryption step 1



```

19 13 30 6 22 11 4 25
Permutation result: 11111010101111011000110010010011
f = 11111010101111011000110010010011
L15 = 1010010110001001010101101111010
R16 = L15 xor f result
R16 = 01011111001101001101101001101001
L16 = R15 = 10010010110101110110001011010110
Step: From L16 and R16, get C
Got L16 = 10010010110101110110001011010110, R16 = 01011111001101001101101001101001
R16L16 = 0101111100110100110110100110100110010010110101110110001011010110
Permutation table IP^-1 =
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 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
C = 0110000111101110011100100100010111110110000110010110111110100110
C: 61EE7245F6196FA6
12:07:12: Execution finished ':lab4.BlockEncryptionKt.main()'.
lab4 > BlockEncryption.kt

```

Figure 2: Encryption step final

As one can see, the hex encoded block 0123456789ABCDEF with key 37A210B3EEF576B0 is encrypted to 61EE7245F6196FA6.

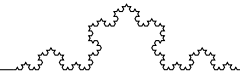
The final step, getting C from L0 and R16 is outputted above.

5 Conclusion

In this laboratory work, I have implemented the DES cipher in Kotlin. The implementation includes both encryption and decryption functions, along with necessary data transformations. Even though DES format is considered insecure for modern applications, understanding its structure and operation provides valuable insights into symmetric-key cryptography. The implementation demonstrates the key concepts of block ciphers, including permutations, substitutions, and key scheduling.

References

- [1] GitHub repository <https://github.com/TimurCravtov/CryptographyAndSecurityLabs>
- [2] DES illustrated <https://page.math.tu-berlin.de/~kant/teaching/hess/krypto-ws2006/des.htm>



[3] Lecture Notes CS