

# Linear Cryptanalysis of FEAL-4

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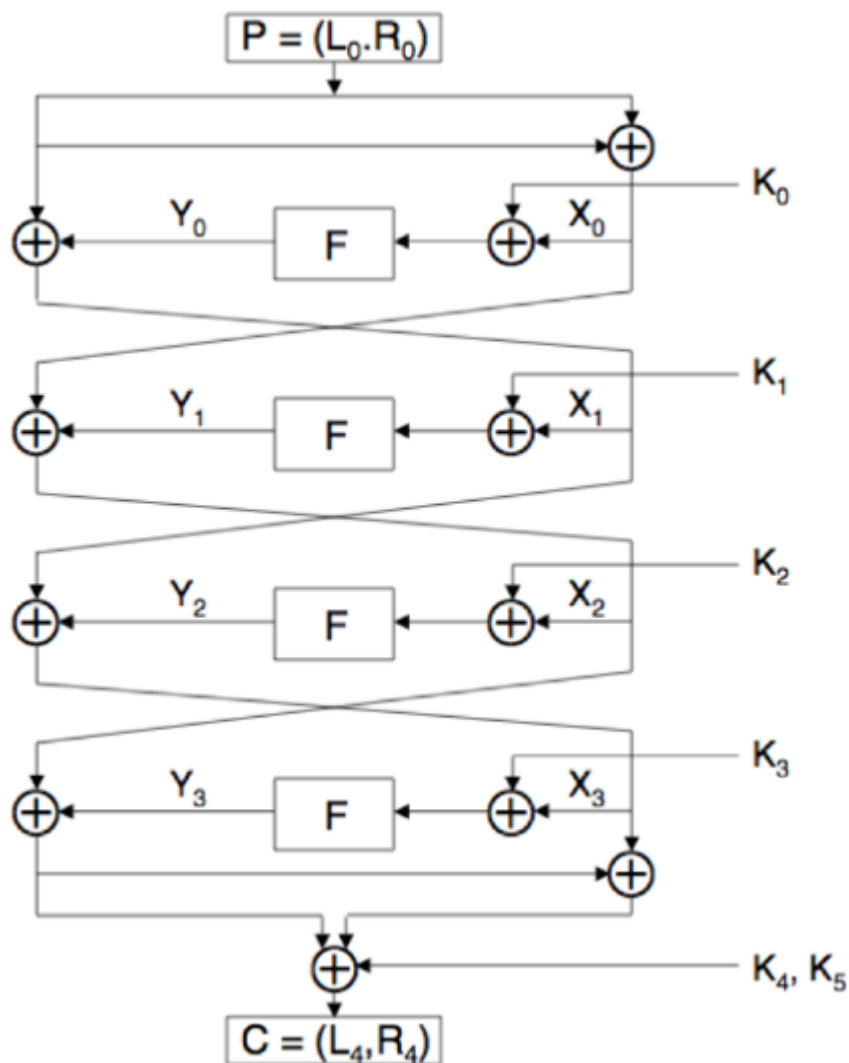
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**Signed Name:** Róisín Ní Bhriain

**Date:** 27-11-2023

## Diagram



## Optimised Formula for inner bits/outer bits

```
int j = 0;
boolean moveOn = false;
int key = 0;

// optimised version of the original function - move on if its not equal to the first result
for ( int i = 0; i < Math.pow(2, 12); i++ ) {

    key = sortBits( i );
    dividePairs( 0 );
    j = calcInnerConst( key );

    int k = 0;
    for ( k = 1; k < PAIRS_LENGTH; k++ ) {
```

```

        dividePairs( k );

        if ( j != calcInnerConstK0( key ) ) {

            moveOn = true;
            k = PAIRS_LENGTH;

        }

    }

    if ( !moveOn ) {
        outerValues( key ); // or next key
    } else {
        moveOn = false;
    }

}

```

This is the optimised formula I used to ensure that the algorithm didn't waste time cycling through any of the pairs that had already failed for that key.

## Precalculations

This section details the calculations I did to work out the constants (as well as some other useful calculations:

### Y Values

```

Y0 = f( L0 ⊕ R0 ⊕ K0 )
Y1 = f( L0 ⊕ Y0 ⊕ K1 )
Y2 = f( L0 ⊕ R0 ⊕ Y1 ⊕ K2 )
Y3 = f( L0 ⊕ Y0 ⊕ Y2 ⊕ K3 )

```

### Possible Constants Calculations (in bold)

With the relation  $L4 = X0 \oplus Y1 \oplus Y3 \oplus K4$

**Const1:  $S23, 29( L0 \oplus R0 \oplus L4 ) \oplus S31( L4 \oplus R4 \oplus L0 ) \oplus S31(F( L0 \oplus R0 \oplus K0 )$**   
(from Video)

**$a = S23, 29( L0 \oplus R0 \oplus L4 ) \oplus S31( L4 \oplus R4 \oplus L0 ) \oplus S31(F( Y )$**

We find:

$S13(L4) = S13(X0) \oplus S13(Y1) \oplus S13(Y3) \oplus S13(K4)$

$S13(X0) = S13(L0 \oplus R0)$

$S13(Y3) = S7,15,23,31(X) \oplus 1$   
 $= S7,15,23,31(L4 \oplus K4 \oplus R4 \oplus K5 \oplus K3) \oplus 1$   
 $= S7,15,23,31(L4 \oplus R4) \oplus S7,15,23,31(K4 \oplus K5 \oplus K3) \oplus 1$

$S13(Y1) = S13 F(X1 \oplus K1)$

$$\begin{aligned}
 &= S13 F(L0 \oplus Y0 \oplus K1) \\
 &= S7,15,23,31(K1) \oplus S7,15,23,31(Y0) \oplus S7,15,23,31(L0) \oplus 1 \\
 \\ 
 S7,15,23,31(Y0) &= S7,15,23,31 F(X0 \oplus K0) \\
 &= S7,15,23,31 F(L0 \oplus R0 \oplus K0) \\
 \\ 
 \text{Const2} &= S13(L0 \oplus R0 \oplus L4) \oplus S7,15,23,31(L0 \oplus L4 \oplus R4) \oplus S7,15,23,31 F(L0 \oplus R0 \oplus K0) \\
 \\ 
 a &= S13(L0 \oplus R0 \oplus L4) \oplus S7,15,23,31(L0 \oplus L4 \oplus R4) \oplus S7,15,23,31 F(Y)
 \end{aligned}$$

Using these constants & the y formulas we can figure out a constant for each key.

## Key Zero

Using the constant from the video in the Future Learn notes we can begin the attack on Key Zero's inner bits 10...15 and 18...23.

$$a = S5, 13, 21(L0 \oplus R0 \oplus L4) \oplus S15(L0 \oplus L4 \oplus R4) \oplus S15(Y0)$$

Using an optimised version of the provided formula for checking if the const is correct we cycle through all possible values for the inner bits and use check if the value remains the same for all of the key pairs. If it does not remain the same then we skip to the next possible value, if it reaches the last key pair then this is a possible value.

For the outer bits I used the same optimised formula with the constant from above:

$$a = S13(L0 \oplus R0 \oplus L4) \oplus S7,15,23,31(L0 \oplus L4 \oplus R4) \oplus S7,15,23,31(F(Y0))$$

This left me with 16 options for the key:

### Results

```

SUCCESS Inner Values K0: 200400
SUCCESS Inner Values K0: 200500
SUCCESS: 25050c09
SUCCESS: 25054c49
SUCCESS: 25058c89
SUCCESS: 2505ccc9
SUCCESS: 65450c09
SUCCESS: 65454c49
SUCCESS: 65458c89
SUCCESS: 6545ccc9
SUCCESS: a5850c09
SUCCESS: a5854c49
SUCCESS: a5858c89
SUCCESS: a585ccc9
SUCCESS: e5c50c09
SUCCESS: e5c54c49
SUCCESS: e5c58c89
SUCCESS: e5c5ccc9==
    
```

## Key One

Using the same method as for key 0 we attack the inner 12 bits first. This is done using the following constant (similar to the one from Key 0 but following the diagram):

$$a = S_{5,13,21}(L_0 \oplus L_4 \oplus R_4) \oplus S_{15}(Y_1)$$

The outer bits use the same formula with the constant:

$$a = S_{13}(L_0 \oplus R_4 \oplus L_4) \oplus S_{7,15,23,31}(F(Y_1))$$

Which leaves us with 64 options for key 1:

```
SUCCESS Inner Values K1: 370800
SUCCESS K1: 2f983b33
SUCCESS K1: 2f987b73
SUCCESS K1: 2f98bbb3
SUCCESS K1: 2f98fbf3
SUCCESS K1: 6fd83b33
SUCCESS K1: 6fd87b73
SUCCESS K1: 6fd8bbb3
...
```

## Key Two

Using the same method as for key 0 we attack the inner 12 bits first. This is done using the following constant:

$$a = S_{5,13,21}(L_0 \oplus R_0 \oplus L_4) \oplus S_{15}(Y_2)$$

The outer bits use the same formula with the constant (from the above calculations):

$$a = S_{13}(L_0 \oplus R_0 \oplus L_4) \oplus S_{7,15,23,31}(F(Y_2))$$

As well as a second constant (as it was large):

$$a = S_{23,29}(L_0 \oplus R_0 \oplus L_4) \oplus S_{31}(F(Y_2))$$

Which leaves us with 128 key options:

```
SUCCESS K2: 3615ce19
SUCCESS K2: 36158e59
SUCCESS K2: 36154e99
SUCCESS K2: 36150ed9
SUCCESS K2: 7655ce19
SUCCESS K2: 76558e59
SUCCESS K2: 76554e99
SUCCESS K2: 76550ed9
SUCCESS K2: b695ce19
SUCCESS K2: b6958e59
SUCCESS K2: b6954e99
SUCCESS K2: b6950ed9
```

...

## Key Three

Using the same method as for key 0 we attack the inner 12 bits first. This is done using the following constant:

$$a = S5,13,21(L0 \oplus L4 \oplus R4) \oplus S15(L0 \oplus R0 \oplus L4) \oplus S15(Y3)$$

The outer bits use the same formula with the constant (from the above calculations):

$$a = S23, S29(L0 \oplus R4 \oplus L4) \oplus S31(L0 \oplus R0 \oplus L4) \oplus S31(Y3)$$

And I used a second constant to get more bits:

$$a = S13(L0 \oplus R4 \oplus L4) \oplus S7, 15, 23, 31(L0 \oplus R0 \oplus L4) \oplus S7, 15, 23, 31(Y3)$$

```
SUCCESS K3: 1c339c15
SUCCESS K3: 1c33dc55
SUCCESS K3: 1c331c95
SUCCESS K3: 1c335cd5
SUCCESS K3: 5c739c15
SUCCESS K3: 5c73dc55
SUCCESS K3: 5c731c95
SUCCESS K3: 5c735cd5
...
```

## Key Four

This key uses a simple equation from the diagram:

$$L0 \oplus R0 \oplus Y1 \oplus Y3 \oplus L4 = K4$$

## Key Five

This key also uses a simple equation from the diagram:

$$L0 \oplus R0 \oplus Y1 \oplus Y3 \oplus L0 \oplus Y0 \oplus Y2 \oplus R4$$

Eliminating L0 we can simplify this to:

$$R0 \oplus Y1 \oplus Y3 \oplus Y0 \oplus Y2 \oplus R4$$

## Final Set of Keys:

```
Key zero:    0x65454c49
Key one:     0x6fd87b73
Key two:     0x76558e59
Key three:   0x1c339c15
Key four:    0x4e673d7e
Key five:    0xfe0fb8a4
```

```
Key zero:    0x65454c49
Key one:     0x6fd87b73
Key two:     0x76558e59
Key three:   0x1c331c95
Key four:    0x4e673d7c
Key five:    0xfe0fb8a6
Key zero:    0x65454c49
Key one:     0x6fd87b73
Key two:     0x76558e59
Key three:   0x9cb39c15
Key four:    0x4c673d7e
Key five:    0xfc0fb8a4
...
```

To get the final set of keys I looped through the pairs and checked that the encrypted plaintext values matched the ciphertext pairs. I then planned to save the keys in an arraylist of the matching keys.

Then I could pick out the common bits of each one using a formula:

```
for ( int i = 0; i < 32; i++ ) {
    int bit = returnBit( keys.get( 0 ).keyOne, i );
    int j = 0;
    for ( j = 1; j < keys.size(); j++ ) {
        if ( bit != returnBit( keys.get( j ).keyOne, i ) ) break;
    }
    if ( j == keys.size() ) System.out.print(bit);
    else System.out.print("?");
}
```

I did not have enough time to finish picking out the bits but I have attached the results in the appendix.

Key 0: 11100101110001011100110011001001  
Unsure Bits : 0/8/16/24

Key 1: 11101101010110001111101111110001  
Unsure Bits: 0/1/6/8/9/10/16/17/24/25/30

Key 2: ?11101?0?1010101??001110??0110?1  
Unsure Bits: 0/1/6/8/9/16/17/24/25/30

Key 3: ??0111?0??110011??011100??0101?1  
Unsure Bits:

Key 4:

Key 5:



The biggest problem I had was figuring out the key outer bit organisation - once I had this done the constants I had before were usable.

## APPENDIX

```
Key zero:    0x65454c49
Key one:     0x6fd87b73
Key two:     0x76558e59
Key three:   0x1c339c15
Key four:    0x4e673d7e
Key five:    0xfe0fb8a4
Key zero:    0x65454c49
Key one:     0x6fd87b73
Key two:     0x76558e59
Key three:   0x1c331c95
Key four:    0x4e673d7c
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Key four:    0x4c673d7e
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Key three:   0x9cb31c95
Key four:    0x4c673d7c
Key five:    0xfc0fb8a6
Key zero:    0x65454c49
Key one:     0x6fd87b73
Key two:     0x76550ed9
Key three:   0x1c339c17
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Key two:     0x76550ed9
Key three:   0x9cb31c97
Key four:    0x4c673d7c
Key five:    0xfc0fb8a4
```

```
Key zero: 0x65454c49
Key one: 0x6fd87b73
Key two: 0xf6d58e59
Key three: 0x1e339c15
Key four: 0x4e673d7e
Key five: 0xfc0fb8a4
Key zero: 0x65454c49
Key one: 0x6fd87b73
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Key two: 0xf6d50ed9
Key three: 0x9eb31c97
Key four: 0x4c673d7c
Key five: 0xfe0fb8a4
Key zero: 0x65454c49
Key one: 0x6fd8fbf3
Key two: 0x76558e5b
Key three: 0x1c339c15
Key four: 0x4e673d7c
```

```
Key five: 0xfe0fb8a6
Key zero: 0x65454c49
Key one: 0x6fd8fbf3
Key two: 0x76558e5b
Key three: 0x1c331c95
Key four: 0x4e673d7e
Key five: 0xfe0fb8a4
Key zero: 0x65454c49
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Key three: 0x1e331c95
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Key two: 0xf4d58e5b
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Key three: 0x9eb31c95
Key four: 0x4e673d7e
Key five: 0xfc0fb8a4
Key zero: 0x65454c49
Key one: 0xef58fbf3
Key two: 0xf4d50edb
Key three: 0x1e339c17
Key four: 0x4c673d7c
Key five: 0xfe0fb8a4
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Key zero: 0x65454c49
Key one: 0xef58fbf3
Key two: 0xf4d50edb
Key three: 0x1e331c97
Key four: 0x4c673d7e
Key five: 0xfe0fb8a6
Key zero: 0x65454c49
Key one: 0xef58fbf3
Key two: 0xf4d50edb
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Key five: 0xfc0fb8a6
Key zero: 0x6545ccc9
Key one: 0x6fd87b71
Key two: 0x76558e59
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Key four: 0x4e673d7e
Key five: 0xfe0fb8a6
Key zero: 0x6545ccc9
Key one: 0x6fd87b71
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Key four: 0x4e673d7e
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Key zero: 0x6545ccc9
Key one: 0x6fd87b71
Key two: 0x76550ed9
Key three: 0x1c331c95
Key four: 0x4e673d7c
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Key five: 0xfe0fb8a6
Key zero: 0x6545ccc9
Key one: 0x6fd87b71
Key two: 0x76550ed9
Key three: 0x9cb39c15
Key four: 0x4c673d7e
Key five: 0xfc0fb8a4
Key zero: 0x6545ccc9
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Key four: 0x4c673d7e
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Key five:  0xfe0fb8a4
Key zero:  0x6545ccc9
Key one:    0xef587b71
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Key four:     0x4c673d7e
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Key two: 0x74550ed9
Key three: 0x9eb31c97
Key four: 0x4e673d7c
Key five: 0xfc0fb8a4
Key zero: 0xe5c54c49
Key one: 0xed587b73
Key two: 0xf4d58e59
Key three: 0x1c339c15
Key four: 0x4c673d7e
Key five: 0xfc0fb8a4
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Key two: 0xf4d58e59
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