Khazad-Block-Cipher

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Abstract. This paper contains a detailed report on the KHAZAD cipher. This paper gives a brief history of the KHAZAD cipher followed by some features of the cipher like block size, key size, etc. The implementation of the KHAZAD cipher is also mentioned in this paper and it contains a detailed description of the key expansion algorithm, general round structure of the cipher, the encryption algorithm, the decryption algorithm, and the code in python for the cipher implementation. This paper also has details about the s-box of KHAZAD and various attacks on the cipher like differential attack, integral attack, etc. on a round reduced variant of the KHAZAD cipher. Finally, it also contains the details about the security and key features of the cipher and the brownie point for our work done.

Keywords: encryption, decryption, integral, differential

1 Introduction

KHAZAD is a symmetrical block cipher developed by two cryptographers: Belgian Vincent Reimen (author of the cipher Rijndael) and Brazilian Paulo Barreto. [Wik]
KHAZAD was presented at the European competition of cryptographic primitives NESSIE in 2000.
Key Size: 128 bits
Block Size: 64 bit (8 bytes)

The predecessor of the KHAZAD algorithm is considered to be the SHARK code developed in 1995 by Vincent Rayman and Joan Dimen. The authors of KHAZAD claim that the algorithm is based on the strategy of developing cryptographically stable encryption algorithms (Wide-Trail strategy), proposed by Joan Dimen.

The KHAZAD algorithm has conservative parameters and is designed to replace existing ciphers with a 64-bit block, such as IDEA and DES, providing a higher level of security at high execution speeds.

Involution transformations are widely used in ciphers, which minimizes the difference between encryption and decryption algorithms.
[Bar]

Name	**KHAZAD**
Number of rounds	**8**
Schedule (extension) of the key	**The Feistel scheme**
Unreduced polynomial of the field GF(2^8)	$x^8 + x^4 + x^3 + x^2 + 1$
Implementation of the S-box	**Recursive P - and Q-miniblocks**
Implementation of the mixing matrix	**Involutional MDS code**

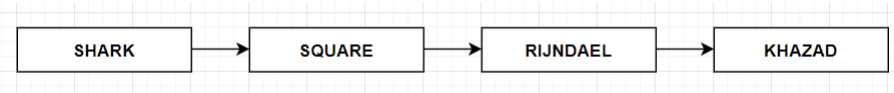
2 Main Result

2.1 Brief Description

It's an block cipher that has a single variant block size of 64 bits with a key of single variant of size 128 bits. The input data block is served as a string of 8 bytes.

The S-box and the mixing matrix are chosen in a way which ensures that the process of encryption and decryption are the same, except the round connections.

KHAZAD, like the AES algorithm (Rijndael), is from a family of block ciphers which are formed from the SHARK cipher.



2.2 The Implementation Algorithm :

- Apply key extension algorithm to the key results in a set of round keys.
- The algorithm have 8 rounds, each of which consists of 3 stages:
  1. *Nonlinear Transformation* γ
  2. *Linear Transformation* θ
  3. *Adding a round key* σ
- Set of round keys k_0 ... k_8 obtained by applying to the encryption key K key extension procedures.
- Before the first round $\sigma(k_0)$ is performed.
- Operation θ is not performed in the last round.

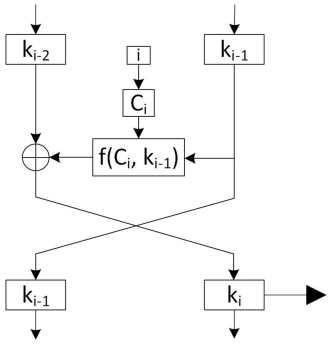
2.3 Key Expansion

- 128-bit (16-byte) key K is divided into 2 equal parts:
- k_{-1} - older 8 bytes (from the 15th to the 8th)
- k_{-2} - lower 8 bytes (from the 7th to the 0th)
- Keys $k_0 \ldots k_8$ calculated according to the Feistel scheme :
- $k_i = f(C_i, k_{i-1}) \oplus k_{i-2}$

Here:

$f(x, y)$ - round function of the algorithm with the input block x and the key y.

C_i - 64-bit constant, j which byte is $C_i^j = S(8i + j)$



2.4 General Round Structure

2.4.1 Nonlinear transformation

Denoted as γ. In each round, the input block is divided into smaller blocks of 8 bytes, which are independently subjected to nonlinear transformation (change), i.e. pass in parallel through the same S-blocks (each S-block - 8x8 bits, i.e. 8 bits at the input and 8 bits at the output).

Replacement blocks in the source and modified (tweaked) ciphers are different. The substitution unit is selected so that the nonlinear transformation is involutionary, i.e. $\gamma = \gamma^{-1}$ *or* $\gamma(\gamma(x)) = x$.

2.4.2 Linear transformation

Denoted by θ. An 8-byte row of data is multiplied byte by byte to a fixed matrix H size 8 x 8, and byte multiplication is performed in the Galois field $GF(2^8)$ with a polynomial that is not given $x^8 + x^4 + x^3 + x^2 + 1$ $(0x11D)$.[BR00]

$$\theta(x) = x \times H \quad \text{where}$$

$$H = \begin{bmatrix} 01_x & 03_x & 04_x & 05_x & 06_x & 08_x & 0B_x & 07_x \\ 03_x & 01_x & 05_x & 04_x & 08_x & 06_x & 07_x & 0B_x \\ 04_x & 05_x & 01_x & 03_x & 0B_x & 07_x & 06_x & 08_x \\ 05_x & 04_x & 03_x & 01_x & 07_x & 0B_x & 08_x & 06_x \\ 06_x & 08_x & 0B_x & 07_x & 01_x & 03_x & 04_x & 05_x \\ 08_x & 06_x & 07_x & 0B_x & 03_x & 01_x & 05_x & 04_x \\ 0B_x & 07_x & 06_x & 08_x & 04_x & 05_x & 01_x & 03_x \\ 07_x & 0B_x & 08_x & 06_x & 05_x & 04_x & 03_x & 01_x \end{bmatrix},$$

2.4.3 Adding a round key

A 64-bit XOR operation is performed on the 64-bit data block & the 64-bit round key . A 64-bit data block is been xored with a round key of 64 bits calculated using key expansion algorithm based on Fiestal scheme.

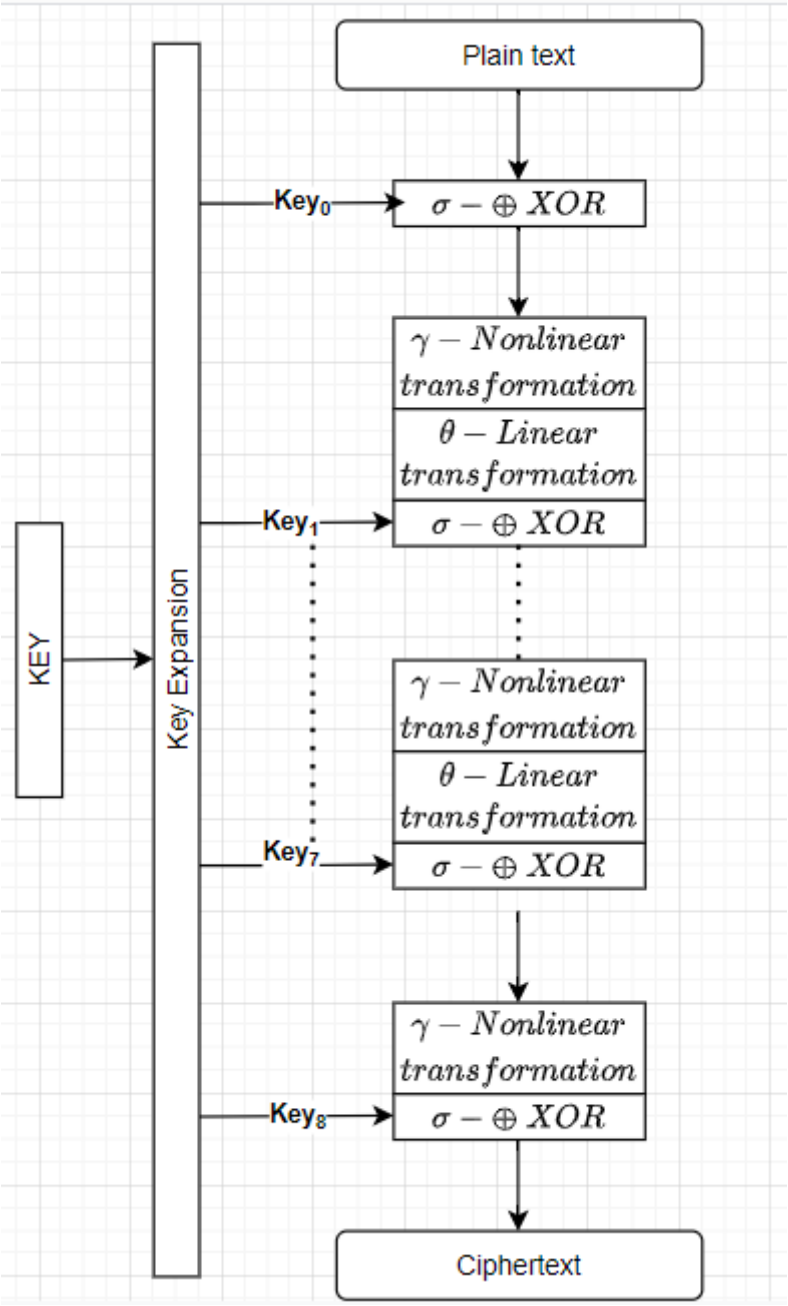
$$\text{For } i^{th}\ round\ :\ \sigma(x_i) = x_{i-1} \oplus k_{i-1}$$

2.5 The Encryption and Decryption Algorithm

2.5.1 Encryption Algorithm

The encryption algorithm is explained below with the help of figure, the figure give good overview of how different layers have been working in course of 8 rounds.

$$\alpha_8[K^0,\ \ldots\ K^8] = \sigma[K^8].\gamma.\left(Round_1^7\right).\sigma[K^0])$$

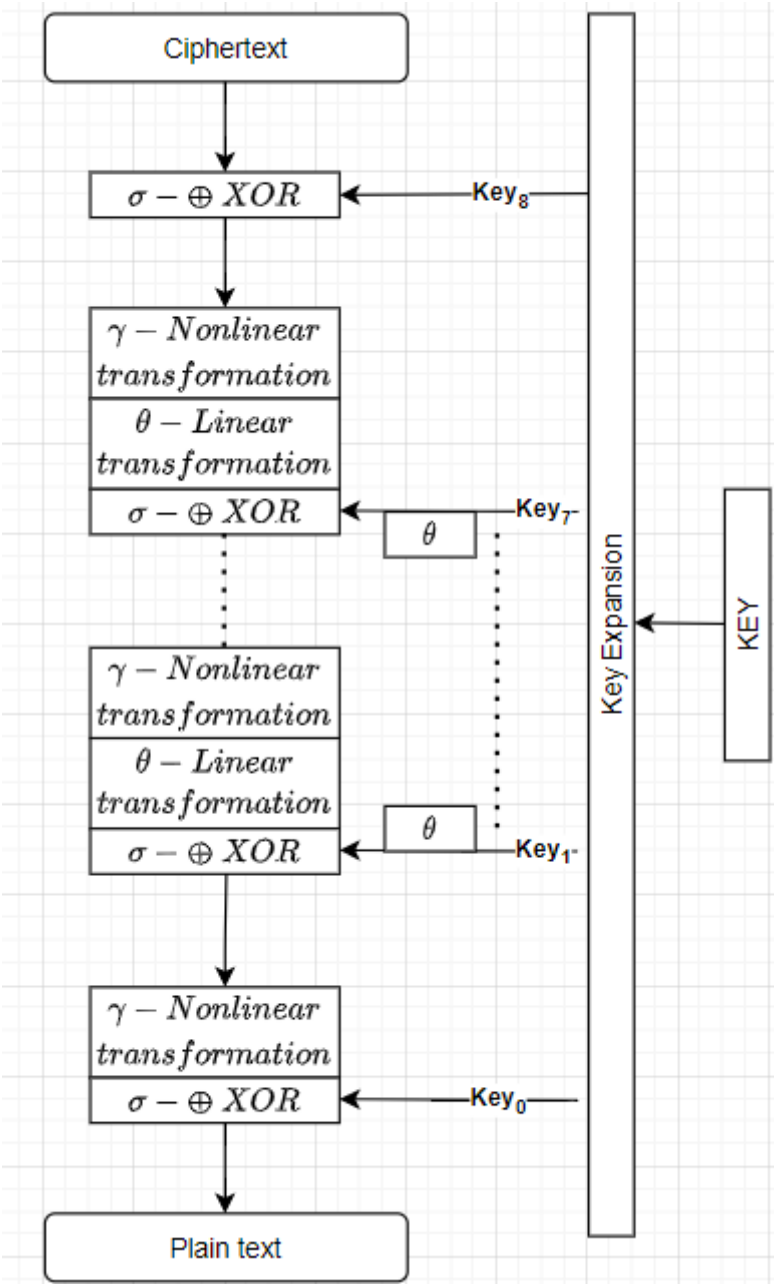


The Encryption Algorithm

2.5.2 Decryption Algorithm

The decryption algorithm is explained below with the help of figure, the figure give good overview of how different layers have been working in course of 8 rounds.

$$\alpha_8[K^8, \ \ldots \ K^0] = \sigma[K^0].\gamma.\left(Round_7^1\right).\sigma[K^8])$$



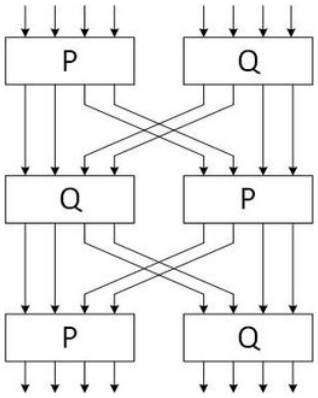
The Decryption Algorithm

2.6 The Creation of S-box

In the original version of the cipher (KHAZAD-0) tabular replacement was represented by a classic S-block.
The bool type definition $GF(2)^n \longrightarrow$ GF(2) is called Zhegalkin polynomial. The nonlinear order function f is called the order of Zhegalkin's polynomial, i.e. the maximum of the orders of its members.
The KHAZAD-0 cipher uses a pseudo random generated S-block that meets the following requirements :

- must be an involution
- δ-value might not be over 8×2^{-8}
- λ-value might not be over 16×2^{-16}
- nonlinear order ν should be a maximum, namely equal to 7

In the modified version of the cipher, the S-block 8x8 is modified and represented by a recursive structure consisting of mini-blocks P and Q, each of which is a small replacement block with 4 bits at the input and output (4x4).
Recursive structure of the replacement unit in the modified KHAZAD cipher:[BR00]



This structure of P - and Q-miniblocks is equivalent to the S-block with the following substitution table:

Correspondence of output values to inputs for mini-block P [Bar]

u	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
P (u)	3	F	E	0	5	4	B	C	D	A	9	6	7	8	2	1

Correspondence of output values to inputs for mini-block Q [Bar]

u	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
Q (u)	9	E	5	6	A	2	3	C	F	0	4	D	7	B	1	8

The final KHAZAD S-box [BR00]

	00_x	01_x	02_x	03_x	04_x	05_x	06_x	07_x	08_x	09_x	$0A_x$	$0B_x$	$0C_x$	$0D_x$	$0E_x$	$0F_x$
00_x	BA_x	54_x	$2F_x$	74_x	53_x	$D3_x$	$D2_x$	$4D_x$	50_x	AC_x	$8D_x$	BF_x	70_x	52_x	$9A_x$	$4C_x$
10_x	EA_x	$D5_x$	97_x	$D1_x$	33_x	51_x	$5B_x$	$A6_x$	DE_x	48_x	$A8_x$	99_x	DB_x	32_x	$B7_x$	FC_x
20_x	$E3_x$	$9E_x$	91_x	$9B_x$	$E2_x$	BB_x	41_x	$6E_x$	$A5_x$	CB_x	$6B_x$	95_x	$A1_x$	$F3_x$	$B1_x$	02_x
30_x	CC_x	$C4_x$	$1D_x$	14_x	$C3_x$	63_x	DA_x	$5D_x$	$5F_x$	DC_x	$7D_x$	CD_x	$7F_x$	$5A_x$	$6C_x$	$5C_x$
40_x	$F7_x$	26_x	FF_x	ED_x	$E8_x$	$9D_x$	$6F_x$	$8E_x$	19_x	$A0_x$	$F0_x$	89_x	$0F_x$	07_x	AF_x	FB_x
50_x	08_x	15_x	$0D_x$	04_x	01_x	64_x	DF_x	76_x	79_x	DD_x	$3D_x$	16_x	$3F_x$	37_x	$6D_x$	38_x
60_x	$B9_x$	73_x	$E9_x$	35_x	55_x	71_x	$7B_x$	$8C_x$	72_x	88_x	$F6_x$	$2A_x$	$3E_x$	$5E_x$	27_x	46_x
70_x	$0C_x$	65_x	68_x	61_x	03_x	$C1_x$	57_x	$D6_x$	$D9_x$	58_x	$D8_x$	66_x	$D7_x$	$3A_x$	$C8_x$	$3C_x$
80_x	FA_x	96_x	$A7_x$	98_x	EC_x	$B8_x$	$C7_x$	AE_x	69_x	$4B_x$	AB_x	$A9_x$	67_x	$0A_x$	47_x	$F2_x$
90_x	$B5_x$	22_x	$E5_x$	EE_x	BE_x	$2B_x$	81_x	12_x	83_x	$1B_x$	$0E_x$	23_x	$F5_x$	45_x	21_x	CE_x
$A0_x$	49_x	$2C_x$	$F9_x$	$E6_x$	$B6_x$	28_x	17_x	82_x	$1A_x$	$8B_x$	FE_x	$8A_x$	09_x	$C9_x$	87_x	$4E_x$
$B0_x$	$E1_x$	$2E_x$	$E4_x$	$E0_x$	EB_x	90_x	$A4_x$	$1E_x$	85_x	60_x	00_x	25_x	$F4_x$	$F1_x$	94_x	$0B_x$
$C0_x$	$E7_x$	75_x	EF_x	34_x	31_x	$D4_x$	$D0_x$	86_x	$7E_x$	AD_x	FD_x	29_x	30_x	$3B_x$	$9F_x$	$F8_x$
$D0_x$	$C6_x$	13_x	06_x	05_x	$C5_x$	11_x	77_x	$7C_x$	$7A_x$	78_x	36_x	$1C_x$	39_x	59_x	18_x	56_x
$E0_x$	$B3_x$	$B0_x$	24_x	20_x	$B2_x$	92_x	$A3_x$	$C0_x$	44_x	62_x	10_x	$B4_x$	84_x	43_x	93_x	$C2_x$
$F0_x$	$4A_x$	BD_x	$8F_x$	$2D_x$	BC_x	$9C_x$	$6A_x$	40_x	CF_x	$A2_x$	80_x	$4F_x$	$1F_x$	CA_x	AA_x	42_x

2.7 Code Implementation

The code file for implementation is provided in the same *github* repository, the test vectors are also provided for the same.

```
def roundfunction(p,k):
    #gamma (sbox)
    c = [0 for i in range(8)]
    for i in range(8):
        c[i]= sbox[p[i]]
    #theta (linear transformation)
    d = [0 for i in range(8)]
    H = [ [1,3,4,5,6,8,0xB,7],
     [3,1,5,4,8,6,7,0xB],
     [4,5,1,3,0xB,7,6,8],
     [5,4,3,1,7,0xB,8,6],
     [6,8,0xB,7,1,3,4,5],
     [8,6,7,0xB,3,1,5,4],
     [0xB,7,6,8,4,5,1,3],
     [7,0xB,8,6,5,4,3,1] ]
    for i in range(8):
        s=0
        for j in range(8):
            s^= c[j]*H[j][i]
        d[i] =s % 256

    #sigma (xor with key)
    e = [0 for i in range(8)]
    e = xor(d,k)
    return e
```

(a) The code snippet for round structure

```
def KeyExpansion(K_1,K_2):
    #First K0, K1 we separately find using K-1 and K-2
    keys1 = []
    C = findC(0)
    k = roundfunction(C,K_1)
    l = xor(k,K_2)
    keys1.append(l)
    Ct = findC(1)
    kt = roundfunction(Ct,keys1[0])
    lt = xor(kt,K_1)
    keys1.append(lt)
    # for i in 2 to 16 we use a loop
    for i in range(2,9):
        Cs = findC(i)
        ks = roundfunction(Cs,keys1[i-1])
        ls = xor(ks,keys1[i-2])
        keys1.append(l)
    return keys1
```

(b) The code snippet for key expansion algorithm

```
def Encrypt(plaintext,keys):
    # initial key xor with key[0]
    pt = xor(plaintext,keys[0])

    # 1-7 full rounds
    pt1 = roundfunction(pt,keys[1])
    pt2 = roundfunction(pt1,keys[2])
    pt3 = roundfunction(pt2,keys[3])
    pt4 = roundfunction(pt3,keys[4])
    pt5 = roundfunction(pt4,keys[5])
    pt6 = roundfunction(pt5,keys[6])
    pt7 = roundfunction(pt6,keys[7])

    # last round (no theta operation)
    #gamma (sbox)
    cipher = [0 for i in range(8)]
    for i in range(8):
        cipher[i]= sbox[pt7[i]]

    #sigma (key xor with last key)
    e = [0 for i in range(8)]
    e = xor(cipher,keys[8])

    #returning the ciphertext in hex string
    cip = ""
    for i in range(8):
        a = hex(e[i])
        if(len(a)==4):
            cip+=a[2:4]
        else:
            cip+="0"+a[2]
    return cip
```

(c) The code snippet for encryption algorithm

Figure 1: Implementation code snippets

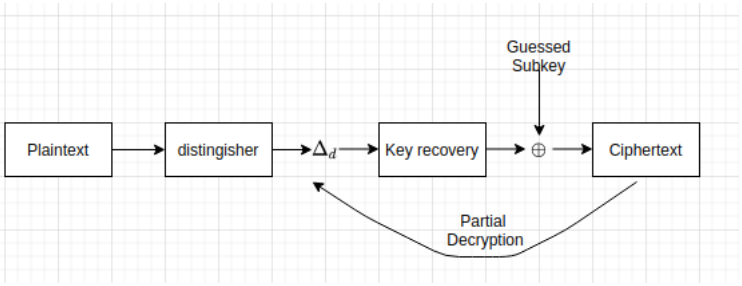
2.8 Attacks

The group of ciphers which include Shark, Square, Rijndael, Anubis and Khazad are made in such a way that as far as differential attack and attacks like linear attacks are concerned, it is very unusual to be successful for these ciphers on their full versions.

2.8.1 Differential attack

A differential attack exists for a 3 rounds Khazad cipher but its time complexity is very large as compared to 3 round integral attack which is discussed below. The effect of each round on the message block due to different layers is shown below:

The attack would follow this strategy:

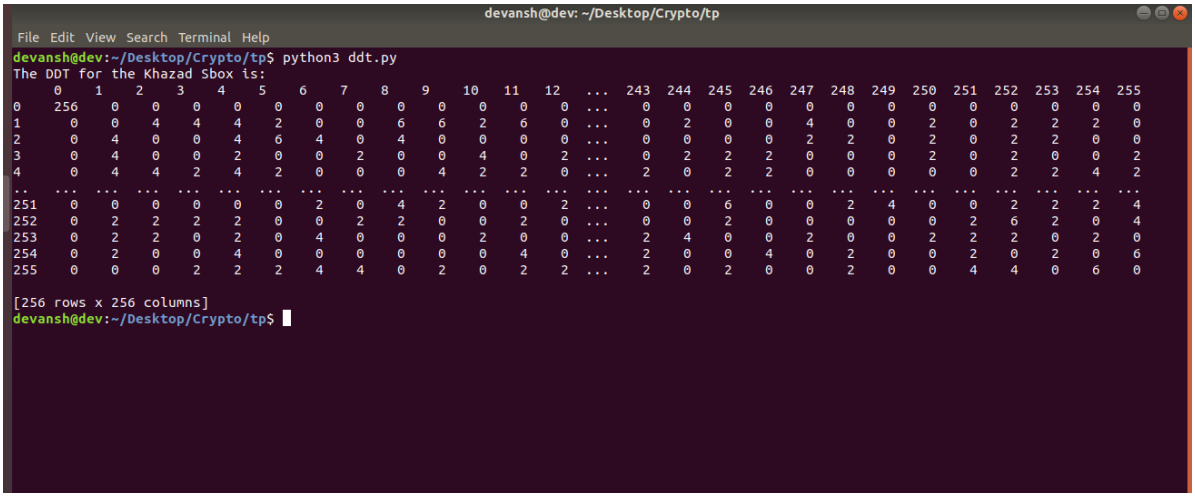


So after guessing 8 bytes of key or guessing subkey there would be at max 2^{64} possible guesses for 8 bytes of subkey, therefore the time complexity achieved would be 2^{64}

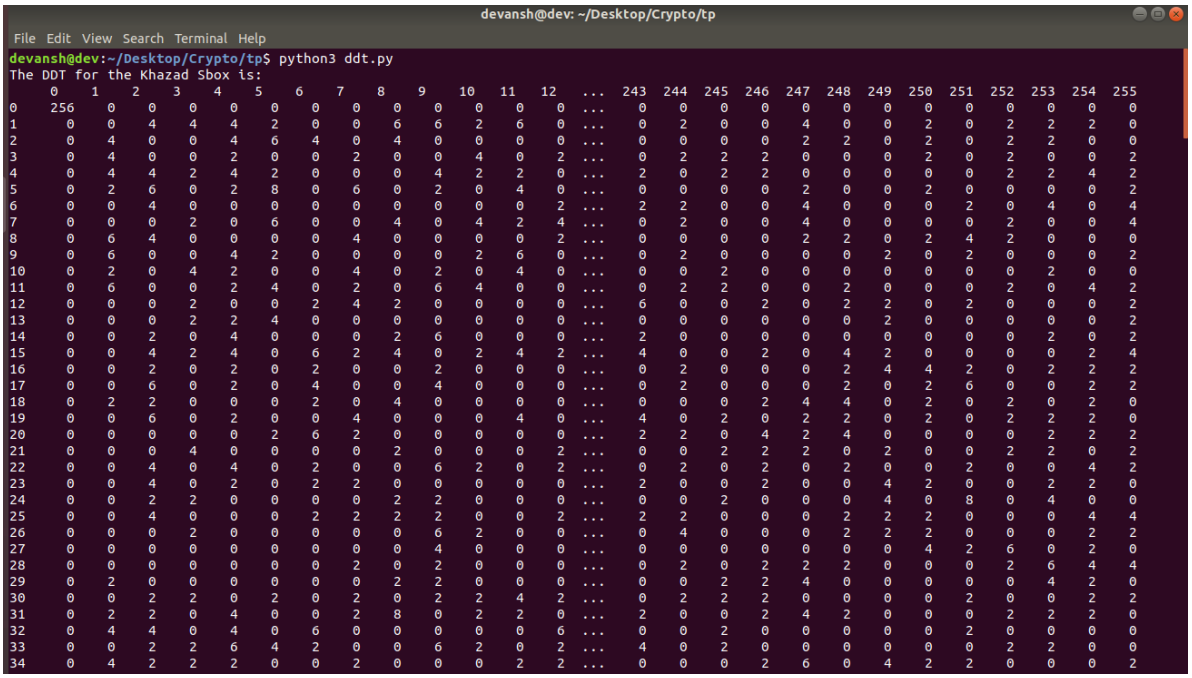
Attack Type	Rounds	Time
differential attack	3	2^{64}

2.8.2 DDT

The DDT for s-box of KHAZAD can be created similar to how it was created for other block ciphers.



The horizontal view



The center view

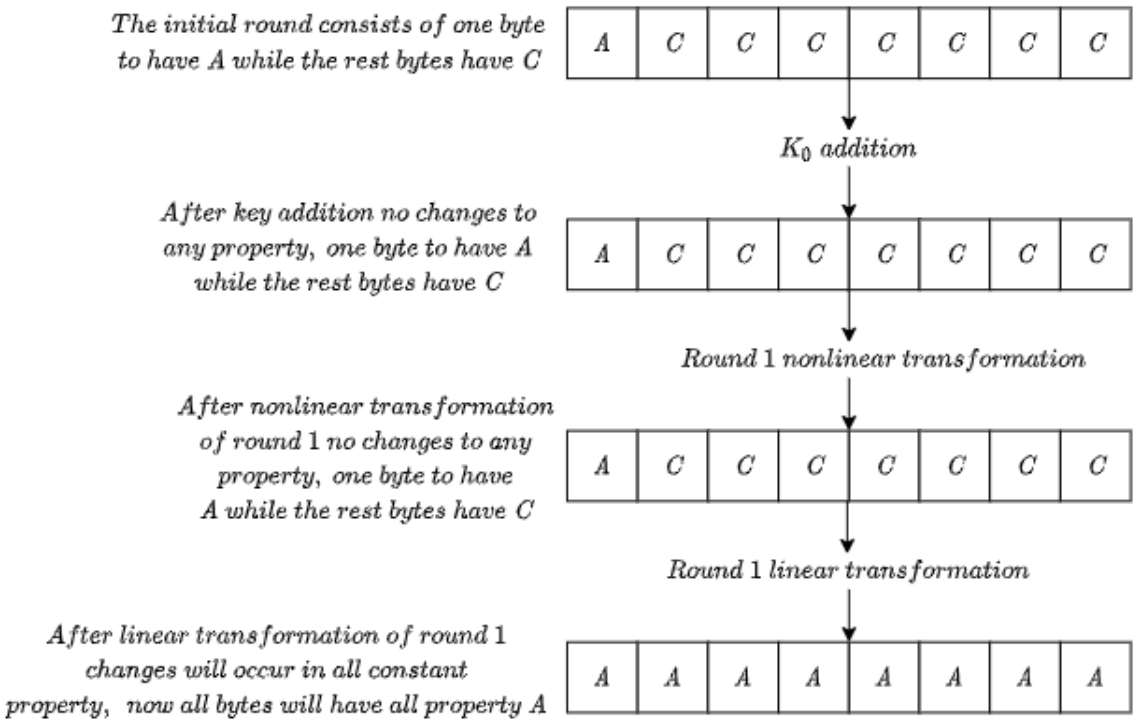
There were around 100 s-box transitions like 5 -> 5 , 4 -> 2E, 7 -> 86 having the best probability equal to $\frac{8}{16} = 0.5$. Any of the byte can be taken accordingly for differential attack.

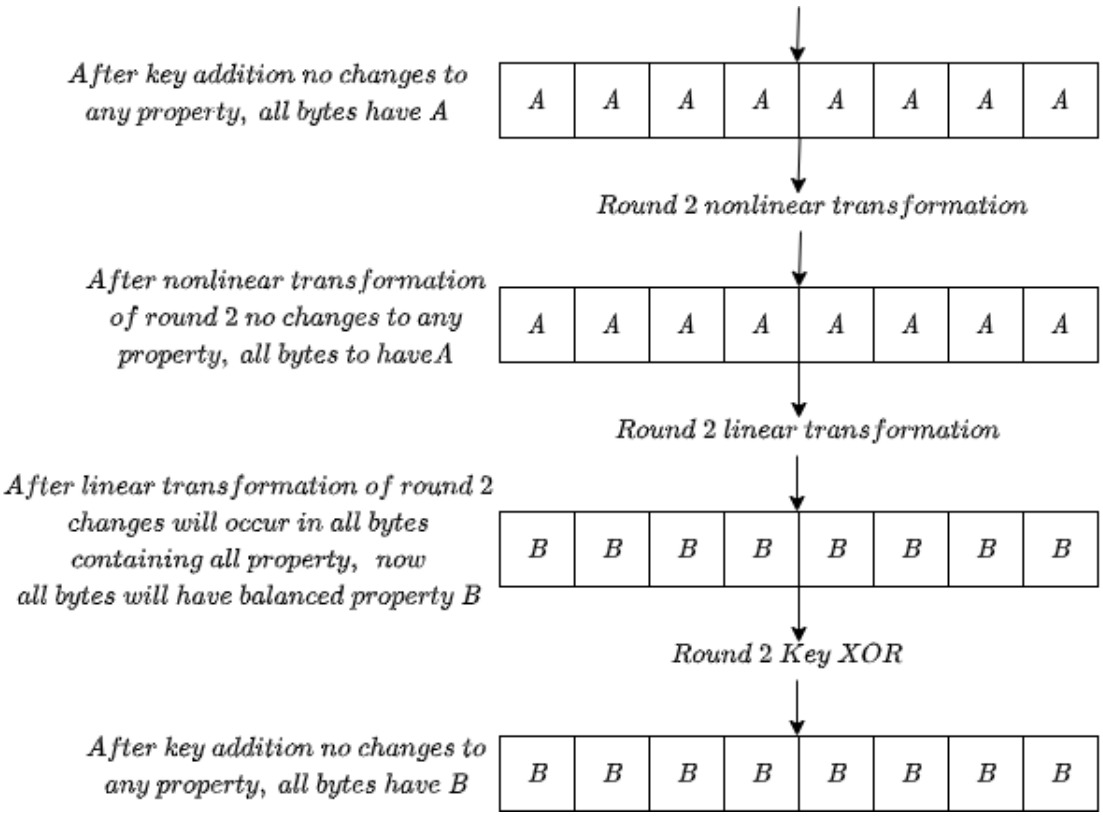
2.8.3 The Integral attack

Also known as the **The Square Attack**. The integral attack consists of the following properties. The attack is set on a 256 plaintexts, such that the first byte takes all 256 possible values while other bytes have constant values.

- **The All property :** The All property is the byte in which all values come once among the texts in the set. It is denoted by ***A***.
- **The Constant property :** The constant property refers to the byte in which all texts in the set have the same value. It is denoted by ***C***.
- **The Balanced property :** Also called the 0-sum property, the balanced property refers to the byte in which sum of all the texts in the set is ZERO. It is denoted by ***B***.

The integral attack on Khazad cipher is explained in the below figure :[Mul03]





So we can say that all bytes in our plaintexts will have balanced property after 2 rounds. Considering the fact that there will be no H-box or linear transformation in the last round, the corresponding subkey bytes can be guessed separately to do a complete 3-rounds attack here.
The complexity of this attack will be nearly 2^{16} sbox looks and 2^9 plaintexts selections. Also we can increase this attack to 4 rounds by guessing the other subkey and this will increase time complexity by 2^{64}.
So far we have seen two variants of integral attacks on Khazad in which one is 3 round integral attack where complexity is :

Attack Type	Rounds	Time	Space
integral attack-1	3	2^{16}	2^9

The second one is 4 round integral attack where we guess the other subkey.

Attack Type	Rounds	Time	Space
integral attack-2	4	2^{80}	2^9

2.9 Other Attacks

2.9.1 Improved Integral attack

[BR00] The improved integral attack is basically an extension of integral attack up to 5 rounds and is having following time complexity.[Mul03]

Attack Type	Rounds	Time	Space
integral attack-3(improved)	5	2^{91}	2^{64}

With the use of key-scheduling algorithm and algebraic properties of round structure, this attack was made possible for 5 round KHAZAD in a very impressive time and space complexity.

2.9.2 Weak Keys Attack

[BR00] There are various new attacks on Khazad one of which is weak keys attack. The one of better cryptanalytic result on 5-rounds Khazad cipher is the of 2^{64} weak keys identified where it can be broken with 2^{43} steps of analysis using 2^{38} encryption blocks.

Attack Type	Rounds	Time	Space
Weak Keys	5	2^{43}	2^{38}

2.9.3 Interpolation attacks

[BR00] This attack generally give benefit using the cipher components having simple algebraic structures like the structure of s-box etc.,that can be used as combined to give polynomial in feasible complexity.The way s-box of KHAZAD is created,and enforcing the effect of the diffusion layer, makes an attack of this type infeasible.

2.9.4 The boomerang attack

[BR00] The boomerang attack require ciphers whose encryption and decryption efficiency is different; this is not the case for KHAZAD, as it have involution structure.

2.10 Security

KHAZAD's crypto-resistance is equal to a block cipher with the given block and key lengths.
The motive of KHAZAD cipher was to achieve a K-secure and Hermetic secrecy.

Major security highlights of KHAZAD are :

- The most effective attack to find the KHAZAD cipher key is a full search.
- In KHAZAD, retrieving information about some Plain-Cipher text pairs from any given Plain-Cipher text pair is as efficient as using complete key search to determine the key.
- The approximate complexity of the key search by the full search method is directly dependent on the bit length of the key and is equal to 2^{127} applications of KHAZAD.

2.11 Key-Features

- It is observed that KHAZAD is much better than most of the modern available ciphers as far as compatibility is concerned.
- It is a very fast cipher and it avoids using excessive storage space for all of its code and tables.
- It does not have uncommon and expensive instruction built for a processor. This is the reason it is good for most platforms.
- The maths included in the creation algorithm is not complex and easy to understand.
- Since the key schedule is similar to the round function, we don't require any extra storage.

2.12 Brownie Point

- We implemented the key expansion algorithm and the code implementation of the cipher in python language which was not found anywhere and was solely done by us.
- We created several figures using draw.io which would be helpful for the people who wants to understand KHAZAD implementation algorithm and basic attacks on it. These figures were not available online and was solely done by us.

References

[Bar] Paulo S. L. M. Barreto. The khazad block cipher. https://web.archive.org/web/20171011071731/http://www.larc.usp.br/~pbarreto/KhazadPage.html.

[BR00] Paulo Barreto and Vincent Rijmen. The khazad legacy-level block cipher. 01 2000.

[Mul03] Frédéric Muller. A new attack against khazad. In Chi-Sung Laih, editor, *Advances in Cryptology - ASIACRYPT 2003*, pages 347–358, Berlin, Heidelberg, 2003. Springer Berlin Heidelberg.

[Wik] Wikipedia. Wikipedia-khazad. https://en.wikipedia.org/wiki/KHAZAD.