

Near-Collisions for Round-Reduced Skein and BLAKE

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Abstract. The SHA-3 competition organized by NIST [1] aims to find a new hash standard as a replacement of SHA-2. Till now, 14 submissions have been selected as the second round candidates, including Skein and BLAKE, both of which have components based on modular addition, rotation and bitwise XOR (ARX). In this paper, we propose improved near-collision attacks on round-reduced Skein and BLAKE. The attacks are based on linear differentials of the modular additions. The computational complexity of near-collision attacks on 4-round and 5-round BLAKE-64 are 2^7 and 2^{162} respectively, and the attacks on 24-round Skein-256, 24-round Skein-512 and 24-round Skein-1024 have a complexity of 2^{60} , 2^{230} and 2^{395} respectively.

Key words: Hash function, Near-collision, SHA-3 candidates, Skein, BLAKE

1 Introduction

Hash function, a very important component in cryptology, is a function of creating a short digest for a message of arbitrary length. The classical security requirements for such a function are preimage resistance, second-preimage resistance and collision resistance. In other words, it should be impossible to find a collision in less hash computations than birthday attack, or a (second)-preimage in less hash computations than brute force attack.

In recent years, the popular hash functions (MD4, MD5, RIPEMD, SHA-0 and SHA-1) have been seriously attacked [2–5]. As a response to advances in the cryptanalysis of hash functions, NIST launched a public competition to develop a new hash function called SHA-3. Till now, 14 submissions have been selected as the second round candidates.

Skein and BLAKE are two of the second round candidates of SHA-3. Skein uses the UBI chaining mode, while BLAKE uses HAIFA approach. Both of them are of the ARX (Addition-Rotate-XOR) type. More specifically, their design primitives use only addition, rotation and XOR.

Previous works studied the linear differential trails of non-linear operations such as boolean functions and modular additions. Linear differential trails can be constructed to find near-collisions of these hash functions [7, 9, 10, 13]. Recently,

linear differential attacks have been applied to many SHA-3 candidates, such as EnRUPt, CubeHash, MD6, and BLAKE [8–10].

In this paper, we further study the linear differential techniques and propose near-collision attacks on round-reduced Skein and BLAKE. Our strategy to find optimal linear differential trails can be described in three steps. First, linear approximations of Skein and BLAKE is constructed. In this step, all the addition modulo 2^{64} components of Skein and BLAKE are approximated by bitwise XOR of the inputs. Second, a difference with low hamming weight in some intermediate state as a starting point is placed. Third, the difference above propagates in both forward and backward directions until the probability becomes too little to obtain near collisions. Table 1 summarizes our attack along with the previously known ones on round-reduced Skein and BLAKE.

Table 1. Comparison of results on Skein and BLAKE

Target	Rounds	Time	Memory	Type	Authors
Skein-512	17	2^{24}	-	434-bit near-collision	[12]
Skein-256	24	2^{60}	-	236-bit near-collision	✓
Skein-512	24	2^{230}	-	374-bit near-collision	✓
Skein-1024	24	2^{395}	-	740-bit near-collision	✓
BLAKE-32	4	2^{42}	-	216-bit near-collision	[13]
BLAKE-64	4	2^7	-	400-bit near-collision	✓
BLAKE-64	5	2^{162}	-	336-bit near-collision	✓

The paper is organized as follows. In Section 2, we describe Skein and BLAKE hash functions. In Section 3, we apply the linear differential technique to Skein-256, Skein-512 and Skein-1024 and present a near-collision for Skein’s compression function with round-reduced Threefish-256, Threefish-512 and Threefish-1024. In Section 4, we apply the linear differential technique to BLAKE-64 and obtain a near-collision for round-reduced BLAKE-64. Finally, Section 5 summarizes this paper.

2 Description of Skein and BLAKE

2.1 Skein

Skein is a family of hash functions based on the tweakable block cipher Threefish, which has equal block and key size of either 256, 512, or 1,024 bits. The MMO (Matyas-Meyer-Oseas) mode is used to construct the Skein compression function from Threefish. The format specification of the tweak and a padding scheme defines the so-called Unique Block Iteration (UBI) chaining mode. UBI is used for IV generation, message compression, and as output transformation.

Threefish consists of a number of similar rounds, which is based on three simple operations: Addition modulo 2^{64} , Rotation and XOR. The intermediate

state of Threefish is organized as a number of 64-bit words. The letter Δ stands for a difference in the most significant bit (MSB), i.e., $\Delta = 0x8000000000000000$. Subkeys are derived from the cipher key K and tweak $T = (t_0, t_1)$ through a simple key schedule.

Let N_w denote the number of words in the key and the plaintext block, N_r be the number of rounds. For Threefish-256, $N_w = 4$ and $N_r = 72$. Let $v_{d,i}$ be the value of the i th word of the encryption state after d rounds. The procedure of Threefish-256 encryption is:

1. $(v_{0,0}, v_{0,1}, \dots, v_{0,N_w-1}) := (p_0, p_1, \dots, p_{N_w-1})$, where (p_0, p_1, p_2, p_3) is the 256-bit plaintext.

2. For each round, we have

$$e_{d,i} := \begin{cases} (v_{d,i} + k_{d/4,i}) \bmod 2^{64} & \text{if } d \bmod 4 = 0, \\ v_{d,i} & \text{otherwise.} \end{cases}$$

Where $k_{d/4,i}$ is the i -th word of the subkey added to the d -th round. For $i = 0, 1, \dots, N_w - 1$, $d = 0, 1, \dots, N_r - 1$.

3. Mixing and word permutations followed:

$$\begin{aligned} (f_{d,2j}, f_{d,2j+1}) &:= \text{MIX}_{d,j}(e_{d,2j}, e_{d,2j+1}), & j &= 0, \dots, N_w/2 - 1, \\ v_{d+1,i} &:= f_{d,\pi(i)}, & i &= 0, \dots, N_w - 1, \end{aligned}$$

where the MIX operation depicted in Figure 1 transforms two of these 64-bit words and is common to all Threefish variants, with $R_{d,i}$ rotation constant depending on the Threefish block size, the round index d and the position of the two 64-bit words i in the Threefish state. The permutation $\pi(\cdot)$ and the rotation constant $R_{d,i}$ can be referred to [14].

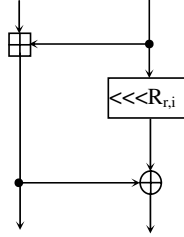


Fig. 1. The MIX function

After N_r rounds, the ciphertext $C = (c_0, c_1, \dots, c_{N_w-1})$ is given as follows:

$$c_i := (v_{N_r,i} + k_{N_r/4,i}) \bmod 2^{64} \quad \text{for } i = 0, 1, \dots, N_w - 1.$$

The s -th keying ($d = 4s$) uses subkeys $k_{s,0}, \dots, k_{s,N_w-1}$. These are derived from the key k_0, \dots, k_{N_w-1} and from the tweak t_0, t_1 as follows:

$$\begin{aligned}
k_{s,i} &:= k_{(s+i) \bmod (N_w+1)} && \text{for } i = 0, \dots, N_w - 4 \\
k_{s,i} &:= k_{(s+i) \bmod (N_w+1)} + t_{s \bmod 3} && \text{for } i = N_w - 3 \\
k_{s,i} &:= k_{(s+i) \bmod (N_w+1)} + t_{(s+1) \bmod 3} && \text{for } i = N_w - 2 \\
k_{s,i} &:= k_{(s+i) \bmod (N_w+1)} + s && \text{for } i = N_w - 1
\end{aligned}$$

where $k_{N_w} := \lfloor 2^{64}/3 \rfloor \oplus \bigoplus_{i=0}^{N_w-1} k_i$ and $t_2 := t_0 \oplus t_1$.

2.2 BLAKE

The BLAKE family of hash functions has been designed by Aumasson et al. [11] and follows HAIFA structure [6] with internal wide-pipe design strategy. Two versions of BLAKE are available: a 32-bit version (BLAKE-32) for message digests of 224 bits and 256 bits, and a 64-bit version (BLAKE-64) for message digests of 384 bits and 512 bits. Since we work on near-collisions of BLAKE-64 in this paper, we will only focus on BLAKE-64 in the following.

BLAKE-64 operates on a large inner state v which is represented as a 4×4 matrix of words. The compression function consists of three steps: Initialization, 14 iterations of Rounds and Finalization as illustrated in Figure 2.

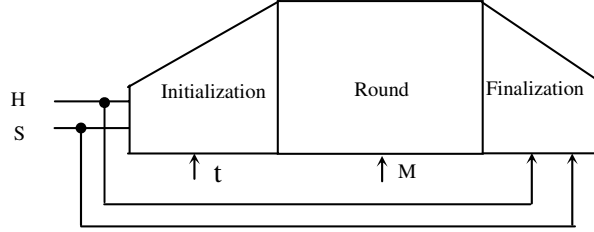


Fig. 2. Overall Structure of Compression Function of BLAKE-64

During the First step, the inner state v is initialized from 8 words of the chaining value $h = h_0, \dots, h_7$, 4 words of the salt S and 2 words of block index (t_0, t_1) as follows:

$$\begin{pmatrix} v_0 & v_1 & v_2 & v_3 \\ v_4 & v_5 & v_6 & v_7 \\ v_8 & v_9 & v_{10} & v_{11} \\ v_{12} & v_{13} & v_{14} & v_{15} \end{pmatrix} \leftarrow \begin{pmatrix} h_0 & h_1 & h_2 & h_3 \\ h_4 & h_5 & h_6 & h_7 \\ s_0 \oplus c_0 & s_1 \oplus c_1 & s_2 \oplus c_2 & s_3 \oplus c_3 \\ t_0 \oplus c_4 & t_0 \oplus c_5 & t_1 \oplus c_6 & t_1 \oplus c_7 \end{pmatrix}$$

Then, a series of 14 rounds is performed. Each of these rounds is based on the stream cipher ChaCha [15] and consists of the eight round-dependent transformations G_0, \dots, G_7 illustrated in Figure 3, where σ_r is a fixed permutation

used in round r , M_s are message blocks and C_s are round-dependent constants. The $G_i(0 \leq i \leq 7)$ function takes 4 registers and 2 message words as input and outputs the updated 4 registers. A column step and diagonal step update the four columns and the four diagonals of matrix v respectively as follows:

$$\begin{array}{cccc} G_0(v_0, v_4, v_8, v_{12}) & G_1(v_1, v_5, v_9, v_{13}) & G_2(v_2, v_6, v_{10}, v_{14}) & G_3(v_3, v_7, v_{11}, v_{15}) \\ G_4(v_0, v_5, v_{10}, v_{15}) & G_5(v_1, v_6, v_{11}, v_{12}) & G_6(v_2, v_7, v_8, v_{13}) & G_7(v_3, v_4, v_9, v_{14}) \end{array}$$

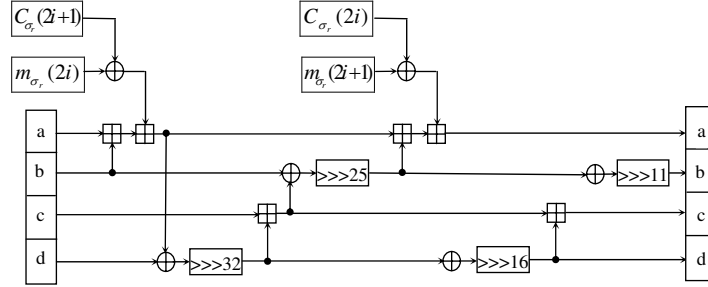


Fig. 3. The G function of BLAKE-64 for index i

In the last step, the new chaining value $h' = h'_0, \dots, h'_7$ is computed from the internal state v and the previous chain value h (Finalization step):

$$\begin{array}{l|l} h'_0 \leftarrow h_0 \oplus s_0 \oplus v_0 \oplus v_8 & h'_4 \leftarrow h_4 \oplus s_4 \oplus v_4 \oplus v_{12} \\ h'_1 \leftarrow h_1 \oplus s_1 \oplus v_1 \oplus v_9 & h'_5 \leftarrow h_5 \oplus s_5 \oplus v_5 \oplus v_{13} \\ h'_2 \leftarrow h_2 \oplus s_2 \oplus v_2 \oplus v_{10} & h'_6 \leftarrow h_6 \oplus s_6 \oplus v_6 \oplus v_{14} \\ h'_3 \leftarrow h_3 \oplus s_3 \oplus v_3 \oplus v_{11} & h'_7 \leftarrow h_7 \oplus s_7 \oplus v_7 \oplus v_{15} \end{array}$$

3 Near-Collisions for the Round-Reduced Compression Function of Skein

Skein is based on the UBI (Unique Block Iteration) chaining mode that uses Threefish to build a compression function. The compression function outputs $E_k(t, m) \oplus m$, where E is Threefish.

Since the MIX function is the only non-linear component in the Threefish block cipher, the first step is to linearize the MIX function to obtain linear approximations of the Compression Function of Skein. To Linearize the MIX function, We replace the modular addition with XOR. The linearized MIX function is illustrated in Figure 4.

3.1 Near Collisions for the Compression Function of Skein-256

After linearizing the Compression Function of Skein-256, we need to choose the starting point. Since Skein-256 has 72 rounds, there are $72 \approx 2^6$ possible choices.

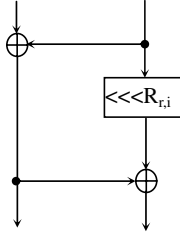


Fig. 4. linearized MIX function in Threefish

Then we place one or two bits of differences in the message blocks and certain round of the intermediate state at the starting point. Since compression function of Skein-256 uses 256-bit message and 256-bit state, there are $\binom{512}{1} + \binom{512}{2} \approx 2^{17}$ choices of positions for the one or two bits above. Therefore, the search space is less than 2^{23} , which can be explored exhaustively.

Our aim is to find one path with the highest probability in the search space. As introduced in [9], we can calculate probability of one differential trail by counting hamming weight in the differences. We search for 24-round differential trail and the results are introduced as follows.

The difference Δ in k_2, k_3, t_0 and t_1 gives a difference $(0, 0, 0, \Delta)$ at the third subkey, and $(0, 0, 0, 0)$ after the fourth. And the difference in the state of round 20 is canceled out at the third subkey which is then turned into an eight-round local collision from round 21 to round 28. After 24 rounds, the hamming weight of the difference becomes too large to obtain near collisions. In the 35-th round, after adding the final subkey and feedforward value, one obtains a collision on $256 - 20 = 236$ bits. Table 2 shows the corresponding differential trail of the key and the tweak from the 12-th round to the 35-th round. And Table 3 presents the corresponding trail from the 12-th round to the 35-th round. In the table, the probability for all rounds are given, except for the first round, which are indicated with M as we will use message modification techniques to make sure the first round of the trail fulfills.

The message modification are applied to the most expensive part in our trail, namely the first round. Freedom degrees in chaining value and the message can be used to fulfill the first round of the trail. We use techniques introduced in [9] to derive sufficient conditions for each modular addition of the first round of the trail. Then the message block and the chaining value are chosen according to the conditions.

3.2 Near Collisions for the Compression Function of Skein-512 and Skein-1024

Ideas for near collision attacks on other version of Skein is similar to the one of Skein-256. So we skip explanations here. In Table 4 and Table 5, we propose difference in the key schedule of Skein-512 and Skein-1024. The differential trails for them are illustrated in Table 6 and Table 7 in the appendix.

Table 2. Details of the subkeys and of their differences of Skein-256, given a difference in k_2 , k_3 , t_0 and t_1 .

Rd	d	$k_{s,0}$	$k_{s,1}$	$k_{s,2}$	$k_{s,3}$
3	12	k_3	$k_4 + t_2$	$k_0 + t_0$	k_1
		Δ	Δ	Δ	0
4	16	k_4	$k_0 + t_0$	$k_1 + t_1$	k_2
		0	Δ	0	Δ
5	20	k_0	$k_1 + t_1$	$k_2 + t_2$	k_3
		0	0	0	Δ
6	24	k_1	$k_2 + t_2$	$k_3 + t_0$	k_4
		0	0	0	0
7	28	k_2	$k_3 + t_0$	$k_4 + t_1$	k_0
		Δ	0	0	0
8	32	k_3	$k_4 + t_1$	$k_0 + t_2$	k_1
		Δ	0	Δ	0
9	36	k_4	$k_0 + t_2$	$k_1 + t_0$	k_2
		0	Δ	Δ	Δ

Table 3. Differential trail used for near collision of 24-round Skein-256, with probability of 2^{-60} .

Rd	Difference	Pr
12	2a0344037023028a 60c217767a8a8080 ee8002206ae20266 7e23020a22014e01	-
13	c0a3442714a300aa 4ac153750aa9820a 4ea102204ac10264 10a3002a48e34c67	M
14	8a2246035a02028a 8a6217521e0a82a0 1e02020a0a620642 5e02020a02224e03	M
15	8040414144008002 004051514408802a 4000000000404041 4000000008404841	M
16	0000000000080028 8000101000080028 0010104008002800 0000000008000800	M
17	0000101000000020 0000101000000000 0010104000000000 8010104000002000	2^{-27}
18	0000000000000020 0000000000000020 0000004000002000 8000000000002000	2^{-7}
19	0000000000000000 0000000000000000 0000004000000000 8000004000000000	2^{-3}
20	0000000000000000 0000000000000000 0000000000000000 8000000000000000	2^{-1}
	no differences in round 21 - 28	1
29	0000000000000000 8000000000000000 8000000080000000 0000000000000000	1
30	0000000000000000 8000000000000000 8000000000000000 8000000080000000	2^{-1}
31	0000000000000000 8000000000000000 8000000000000000 0000000080000000	2^{-1}
32	8000000000000000 8000000000000000 8000000000000000 8000000080000000	2^{-1}
33	8000000080000000 8000000000000000 8000000000000000 8000000080000000	2^{-2}
34	0000000080002000 0000000080000000 0000800080008000 0000000080000000	2^{-2}
35	2000a00020008000 0000000000002000 0000800020002000 0000800000008000	2^{-5}
36	200008002800a000 2000a0002000a000 80008000a0008000 000000002000a000	2^{-10}

Table 4. Details of the subkeys and of their differences of Skein-512, given a difference in k_4 , k_5 and t_0 (leading to a differences in t_2).

Rd	d	$k_{s,0}$	$k_{s,1}$	$k_{s,2}$	$k_{s,3}$	$k_{s,4}$	$k_{s,5}$	$k_{s,6}$	$k_{s,7}$
5	20	k_5	k_6	k_7	k_8	k_0	$k_1 + t_2$	$k_2 + t_0$	$k_3 + 5$
		Δ	0	0	0	0	Δ	Δ	0
6	24	k_6	k_7	k_8	k_0	k_1	$k_2 + t_0$	$k_3 + t_1$	$k_4 + 6$
		0	0	0	0	0	Δ	0	Δ
7	28	k_7	k_8	k_0	k_1	k_2	$k_3 + t_1$	$k_4 + t_2$	$k_5 + 7$
		0	0	0	0	0	0	0	Δ
8	32	k_8	k_0	k_1	k_2	k_3	$k_4 + t_2$	$k_5 + t_0$	$k_6 + 8$
		0	0	0	0	0	0	0	0
9	36	k_0	k_1	k_2	k_3	k_4	$k_5 + t_0$	$k_6 + t_1$	$k_7 + 9$
		0	0	0	0	Δ	0	0	0
10	40	k_1	k_2	k_3	k_4	k_5	$k_6 + t_1$	$k_7 + t_2$	$k_8 + 10$
		0	0	0	Δ	Δ	0	Δ	0

Table 5. Details of the subkeys and of their differences of Skein-1024, given a difference in k_0 , k_2 and t_1 (leading to a differences in t_2).

Rd	d	$k_{s,0}$	$k_{s,1}$	$k_{s,2}$	$k_{s,3}$	$k_{s,4}$	$k_{s,5}$	$k_{s,6}$	$k_{s,7}$	$k_{s,8}$	$k_{s,9}$	$k_{s,10}$	$k_{s,11}$	$k_{s,12}$	$k_{s,13}$	$k_{s,14}$	$k_{s,15}$
0	0	k_0	k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8	k_9	k_{10}	k_{11}	k_{12}	$k_{13} + t_0$	$k_{14} + t_1$	k_{15}
		Δ	0	Δ	0	0	0	0	0	0	0	0	0	0	0	0	0
1	4	k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8	k_9	k_{10}	k_{11}	k_{12}	k_{13}	$k_{14} + t_1$	$k_{15} + t_2$	k_0
		0	Δ	0	0	0	0	0	0	0	0	0	0	0	Δ	Δ	0
2	8	k_2	k_3	k_4	k_5	k_6	k_7	k_8	k_9	k_{10}	k_{11}	k_{12}	k_{13}	k_{14}	$k_{15} + t_2$	$k_0 + t_0$	k_1
		Δ	0	0	0	0	0	0	0	0	0	0	0	0	Δ	0	Δ
3	12	k_3	k_4	k_5	k_6	k_7	k_8	k_9	k_{10}	k_{11}	k_{12}	k_{13}	k_{14}	k_{15}	$k_0 + t_0$	$k_1 + t_1$	k_2
		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	16	k_4	k_5	k_6	k_7	k_8	k_9	k_{10}	k_{11}	k_{12}	k_{13}	k_{14}	k_{15}	k_0	$k_1 + t_1$	$k_2 + t_2$	k_3
		0	0	0	0	0	0	0	0	0	0	0	0	0	0	Δ	Δ
5	20	k_5	k_6	k_7	k_8	k_9	k_{10}	k_{11}	k_{12}	k_{13}	k_{14}	k_{15}	k_0	k_1	$k_2 + t_2$	$k_3 + t_0$	k_4
		0	0	0	0	0	0	0	0	0	0	0	0	Δ	Δ	Δ	0

4 Near Collisions for Round-Reduced BLAKE-64

4.1 Linearizing G function

In order to linearize the G function, modular additions are replaced with XORs. Near collision attack for 4-round BLAKE-32 in [13] also uses the linearization technique. The cyclic rotation constants in BLAKE-32 are 16,12,8,7. Notice that three of the constants 16,12 and 8 have a greatest common divisor 4, so difference $0xAAAAAAAA$ is cyclic invariant with these rotation constants, where A is a 4-bit value. In the linearized BLAKE-32, if all differences in registers are restricted to this pattern, cyclic rotations difference $\ggg 16, \ggg 12$ and $\ggg 8$ can be removed. If zero differences pass through $\ggg 7$, the only possible difference pattern in registers is either $0xAAAAAAAA$ or zero which can be indicated as 1-bit value. So the linear differential trails with this difference pattern form a small space of size 2^{32} , which can be searched by brute force. The linear differential trail in [13] is the best one in this space. But this attack doesn't work on BLAKE-64, because the cyclic rotation constants are different. BLAKE-64 uses the number of rotations 32, 25, 16 and 11. Two of them are not multiples of 4, which implies more restrictions of the differential trail.

To obtain near collisions for BLAKE-64, we have to release the restrictions. This can be done in two ways: either by using non-linear differential trail instead of linear one, or still by using linear differential trail but releasing restrictions on the differential pattern. In this paper, we use linear differential trail and try to release restrictions on the differential pattern. Instead of using cyclic invariant differences, we use a random difference of hamming weight less than or equal to two in the intermediate states. We find a 4-round differential trail with probability of only 2^{-7} and a 5-round differential trail with probability of 2^{-162} for BLAKE-64.

Since we intend to release restrictions on the differential pattern, the cyclic invariant differential pattern in previous works is not used. So the cyclic rotations can not be removed. The linearized G function is illustrated in Figure 5.

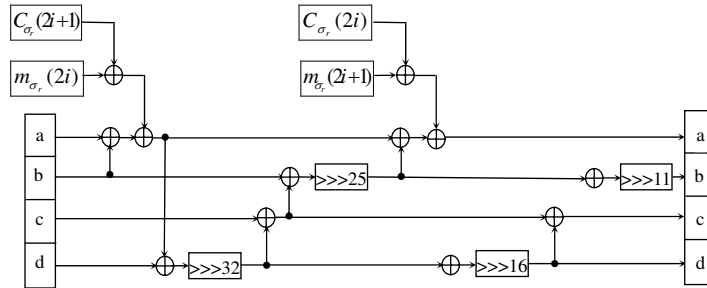


Fig. 5. linearized G function in BLAKE-64

4.2 Searching for Differential Trails with High Probability

we need to choose the starting point after linearizing G function. Since BLAKE-64 has 14 rounds, there are less than 2^4 possible choices. Then we place one or two bits of differences in the message blocks and certain round of the intermediate state at the starting point. Since compression function of BLAKE-64 uses 1024-bit message and 1024-bit state, there are $\binom{2048}{1} + \binom{2048}{2} \approx 2^{21}$ choices of positions for the pair of bits. Therefore, the search space is less than 2^{25} , which can be explored exhaustively.

Our aim is to find one path with the highest probability in the search space. Furthermore, following Section 3.1, we calculate probability of one differential trail by counting hamming weight in the differences. We search for 4-round and 5-round differential trail and the results are introduced in the following sections.

4.3 4-round Near Collision

We search with the configuration where differences are in $M[14] = 0x80000000$ 00000000 and $V[0,3,4,7,8,9,11,12,13,15]$ and find that a starting point at round 7 leads to a linear differential trail whose total hamming weight is equal to 7 only. We don't need to count for the last round, since it can be fulfilled by message modifications with similar techniques used in attacks on Skein.

So, This trail can be fulfilled with probability of 2^{-7} . Complexity of this attack is 2^7 with no memory requirements. With assumption that no differences in the salt value, this configuration has a final collision on $512 - 112 = 400$ bits after the finalization. Table 8 in the appendix demonstrates how differences propagate in intermediate chaining values from round 7 to 10.

4.4 5-Round Near Collision

Then we search for 5-round differential trails, with the configuration where differences are placed in $M[11] = 0x8000000000000000$ and $V[0 \sim 15]$. We find that a starting point at round 6 leads to a linear differential trail whose total hamming weight is 162. This trail with probability of 2^{-162} is illustrated in Table 9 of the appendix, which leads to a $512 - 176 = 336$ -bit collision after feedforward. The message modifications are also applied to the last round.

5 Conclusion

In this paper, we revisited the linear differential techniques and applied it to two ARX-based hash functions: Skein and BLAKE. Our attacks include near-collision attacks on 24-round Skein-256, Skein-512 and Skein-1024, 4-round and 5-round BLAKE-64. Future works might apply some non-linear differences for integer addition besides XOR differences to improve our results.

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A Differential Trails of Round-Reduced Skein and BLAKE

Table 6. Differential trail used for near collision of 24-round Skein-512, with probability of 2^{-230} .

Rd	Difference	Pr
20	177363f900ab3668 36ed5b708e227114 55bc1c3e7881275c 4e65052fe03ee6b3 8ca8e770541856b3 36a6043068ef74e1 821adaa76647acf8 d0857e4c77f10cb0	-
21	1bd9191198bfc1ef 0af0294dc0abc1a1 3a0ee3403cf72252 2e074b0908d70142 d29fa4eb11b6a048 a21e22e38124a488 a19e38898e89477c 811420858c004114	M
22	1409a84934202310 1400884920202110 70818608909204c0 6181000c80a00440 208a180c02890668 080a080c02002648 1129305c5814004e 110110541804004c	M
23	1100860410320080 1100040410220080 2880100000892020 2080100040882200 0028200840100002 00a0200800100000 0009200014000200 0001000010000200	M
24	0800000040010220 0080000440000220 0088000040000002 0008000000000002 0008200004000000 8008200000000000 0000820000100000 8000820000000000	M
25	0080000040000000 0000000040000000 0000000004000000 0000000004000000 0000000000100000 0000000000100000 0880000400010000 0080000000010000	2^{-43}
26	0000000000000000 0000000000000000 0000000000000000 0000000000000000 0800000400000000 0800000000000000 0080000000000000 0080000000000000	2^{-8}
27	0000000000000000 0000000000000000 0000000400000000 0000000400000000 0000000000000000 0000000000000000 0000000000000000 0000000000000000	2^{-3}
28	0000000000000000 0000000000000000 0000000000000000 0000000000000000 0000000000000000 0000000000000000 0000000000000000 8000000000000000	2^{-1}
	no differences in round 29 - 36	1
37	0000000000000000 0000000000000000 8000000000000000 0000000000000000 0000000000000000 8000000000000000 0000000000000000 0000000000000000	1
38	8000000000000000 0000000000000000 8000000000000000 0000000000000000 0000000000000000 8000000000002000 0000000000000000 8000000000000000	1
39	8000000000000000 8000000000000000 8000000000002000 8000020000000000 8000000000000000 8000000080000000 8000000000000000 8000000000000000	2^{-1}
40	0000020000002000 0000000100000000 0000000080000000 0000020000000000 0000000000000000 0000020008002000 0000000000000000 0000020004002010	2^{-3}
41	8000020008000000 0002020100002000 8000020008002000 80100a0004012012 8000020004002010 0002020008000000 0000020100002000 800102000c000000	2^{-24}
42	001008000c010012 8400000148002004 800200000c002010 800100410c812006 800100010c002000 000200000c200010 8002000108002000 4035082018010810	2^{-26}
43	0003004100810016 8412980104082816 8003000100202010 c0b300010a85381c c037082110012810 4203010100002010 8410080144012016 400e004300031914	2^{-47}
44	40b000000aa5180c b413905054a42025 8234092010010800 c592826243021882 c41e084244023902 8236082430311810 8411984004892800 308981660aa70d06	2^{-74}

Table 7. Differential trail used for near collision of Skein-1024, of probability 2^{-395} .

Rd	Difference				Pr
0	19784dd0abac34ae 724160f9f7774d 9e01dc1568d478f3 c56a33799988135a	195468f0130f00ce 354b6cea52cf6b59 6c62c73d18ea1df5 4620157d0e931057	1866a2c424af0b54 b7e8d028e7ee826b 9c52d04d61b020b8 fc472494ac63eae4	fc2f300ca644975c c80d060ce08aa6aa 90f0436baf866419 7839420c8263b374	-
1	802c2520b8a33460 7fe5d624076424c1 0ca29326ce3644a1 047e66982e005990	90a426309a23906a 8a75cc2a06056541 2cb0b22284625484 0c66e64166434521	644992c882eb9c08 470a0c13a9281c14 834a2604971b030d f2631b28703e6506	dc0982c082ca8b08 4808081729281800 824806001000038d 703f2a2076ba6008	M
2	108803102280a40a 0f02040480000414 01022004871b0080 825c31080684050e	90a0038028009409 0d02000480000410 03022000840b9080 805c30080404000a	b840100800211700 f5901a0e01614180 081880d948431cb1 201221044a541025	9841100800000508 5510300601614100 8818005151400c81 201220804810002c	M
3	802800900a803003 a0802a0800000080 8000808819031030 0000018402441009	0020008008801003 80a2220800000000 0000008018030030 0000008000041009	2001000000211208 0200040000000004 0200010002800504 0200000403109000	0001000000201208 0200040000000000 02000000800100 0000000403109000	M
4	8008001002002000 000000000000004 0000010002000404 0200000000000000	8000001002002000 000000000000004 0000010002000004 8200000000000000	2000000000010000 2022080000000080 0000010402400000 8000800801001000	2000000000000000 6012000000000080 0000000402400000 0000800001000000	M
5	8008000000000000 4030080000000000 0000010000000000 0000008000010000	0008000002000000 0010080000000000 0000010000000000 000000000000010000	0000000000010000 0000000000000000 0000000000000000 0000000000000400	0000000000010000 0000000000000000 0000000000000000 0000000000000400	2^{-71}
6	8000000002000000 0000000000000000 0000000000000000 0000000000000000	0000000002000000 0000000000000000 0000000000000000 0000000000000000	0000000000000000 4020000000000000 0000008000000000 0000000000000000	0000000000000000 4000000000000000 0000008000000000 0000000000000000	2^{-11}
7	8000000000000000 0020000000000000 0000000000000000 0000000000000000	0000000000000000 0020000000000000 0000000000000000 0000000000000000	0000000000000000 0000000000000000 0000000000000000 0000000000000000	0000000000000000 0000000000000000 0000000000000000 0000000000000000	2^{-4}
8	8000000000000000 0000000000000000 0000000000000000 0000000000000000	0000000000000000 0000000000000000 0000000000000000 8000000000000000	0000000000000000 0000000000000000 0000000000000000 0000000000000000	0000000000000000 0000000000000000 0000000000000000 8000000000000000	2^{-1}
	no differences in round 9 - 16				1
17	0000000000000000 0000000000000000 0000000000000000 0000000000000000	0000000000000000 0000000000000000 0000000000000000 0000000000000000	0000000000000000 0000000000000000 0000000000000000 0000000000000000	0000000000000000 0000000200000000 0000000000000000 0000000000000000	1
18	0000000000000000 0000000020000000 0000000000000000 0000000000000000	0000000000000000 0000000000000000 0000000000000000 0000000000000000	0000000000000000 0000000000000000 0000000000000000 0000000000000000	0000000000000000 0000000000000000 0000000000000000 0000000000000000	2^{-1}
19	0000000000000000 0000000000000000 0000000000000000 0000000000000000	1000020020000100 0000000000000000 0000000000000000 0000000020000000	0000000000000000 0000000200000000 0000000000000000 1000000200000000	0000000000000000 0000000000000000 0000000000000000 0000000000000000	2^{-3}
20	1000020020000100 0000000020000000 0000000000000000 1000000200000000	0000000000000000 0000000000000000 0000000020000000 0000000000000000	0000000000000000 0000000000000000 0000000200000000 0000000000000000	0000000200002000 1000000200000000 0000000000000000 1002022020040140	2^{-8}
21	1000020020000100 1000000200000000 0000000200000000 9002022020040140	0000000220000000 0000000200000000 1000800020010000 0000000200000000	0000000200002000 0000000200000000 1000000200000000 0000000200000000	1000020020000000 9800820024004100 8000800200002000 1000020020000100	2^{-42}
22	1000020200000100 9800820004004100 9000080000000200 1000020000000100	1008800200110001 d010080100040200 9004420414016102 1000000000200000	1000020000000200 1000000000000000 9002022000040140 1000800000010000	90020220000401c0 1002022000040140 9000020040000a00 1002220200000100	2^{-39}
23	0008820000110101 0002022000040140 0002002040040b40 0002a20200010100	00406a455417732b 40100020000c0b41 0a02823011040160 48c09a0905044702	80020020000403c0 48108a0104044300 0000020000200100 00044a0414016302	8000024000200100 0000a22204450500 80120722400c0b40 800a821100101109	2^{-74}
24	0048e8455406722a 4810282300414600 80120522402c0a40 800ec8151411720b	aa28a11141401c20 e8020762a4640bc1 6010282611516428 015212002008060a	00020260002402c0 4012020000080a01 48c2380b05054602 0a00821051000a20	59d3e3128076d6216 a02cdb150115500b 0082066200240bc0 6a0dbbc52272d726a	2^{-141}

Table 8. Differential trail used for near collision of 4-round BLAKE-64, with probability of 2^{-7} .

Rd	Difference				Pr
7	8000000080000000	0000000000000000	0000000000000000	0000000010000000	-
	8000000080000000	0000000000000000	0000000000000000	8000000010000000	
	8000800080008000	8000000000000000	0000000000000000	8000000000000000	
	0000800000008000	0000000080000000	0000000000000000	8000000000000000	
8	0000000000000000	8000000000000000	0000000000000000	0000000000000000	2^{-6}
	0000000000000000	0000000000000000	0000000000000000	0000000000000000	
	0000000000000000	0000000000000000	0000000000000000	0000000000000000	
9	0000000000000000	0000000000000000	0000000000000000	0000000000000000	1
	0000000000000000	0000000000000000	0000000000000000	0000000000000000	
	0000000000000000	0000000000000000	0000000000000000	0000000000000000	
10	0000000000000000	8000000000000000	0000000000000000	0000000000000000	2^{-1}
	0000000000000000	0000000000000000	0000010000000000	0000000000000000	
	0000000000000000	0000000000000000	0000000000000000	0000800000000000	
	0000800000000000	0000000000000000	0000000000000000	0000000000000000	
11	2844001000142010	8201020000412240	2800084400402804	8054000008040810	M
	0080088102810a80	0a80008400800284	0804000008004004	0080009500900885	
	2004a84080040000	0000001408100804	2000280400100054	2000004102400041	
	2001820000410240	a004280088440800	0010800400108004	2800285400400854	

Table 9. Differential trail used for near collision of 5-round BLAKE-64, with probability of 2^{-162} .

Rd	Difference				Pr
6	9500550115001500	1000408080004480	8002800881008400	0508050005080500	-
	9108910191089180	9000008800000080	0002000881000400	9008040800080400	
	0000840880008408	0000000080008000	8008000884008400	9400840084000000	
	0408c00804088088	0000c00800004400	8500000080088000	1000050810008100	
7	8000000001000000	8000000080000000	8000000000000000	0000000000000000	2^{-155}
	8000000001000000	8000000080000000	0000000000000000	0000000000000000	
	8000000000000000	8000800080008000	8000000000000000	0000000000000000	
8	0000000000000000	0000000000000000	8000000000000000	0000000000000000	2^{-6}
	0000000000000000	0000000000000000	0000000000000000	0000000000000000	
	0000000000000000	0000000000000000	0000000000000000	0000000000000000	
9	0000000000000000	0000000000000000	0000000000000000	0000000000000000	1
	0000000000000000	0000000000000000	0000000000000000	0000000000000000	
	0000000000000000	0000000000000000	0000000000000000	0000000000000000	
10	8000000000000000	0000000000000000	0000000000000000	0000000000000000	2^{-1}
	0000000000000000	0000001000000000	0000000000000000	0000000000000000	
	0000000000000000	0000000000000000	0000800000000000	0000000000000000	
	0000000000000000	0000000000000000	0000000000000000	0000800000000000	
11	8201020000412240	a800084400402804	0054000008040850	2844001000142010	M
	0a80008400800284	0804000008004004	0080008500900885	0880009102910a90	
	0040801488108804	2000280400100054	2000004102400041	2004284080040000	
	a004a80088440800	0050000400100004	2800285400400854	2001820000410240	