Meet-in-the-Middle Attacks Revisited: Key-recovery, Collision, and Preimage Attacks

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August 5, 2021

Outline

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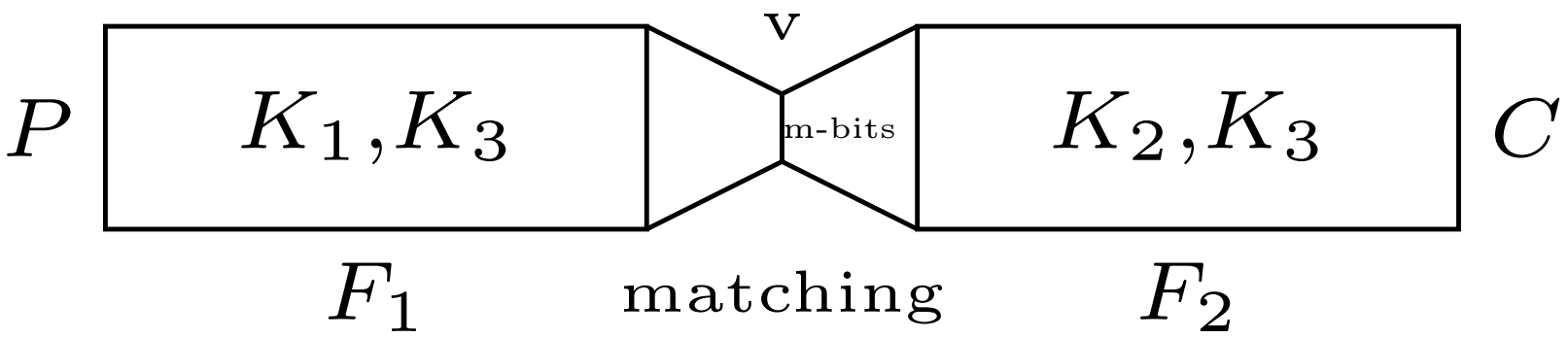
3-Subset Meet-in-the-Middle Attack

1. MITM Stage: Filter out some wrong key candidates and reduce the key space
2. Key Testing Stage: Test the surviving key candidates in a brute force manner.



3-Subset Meet-in-the-Middla Attack

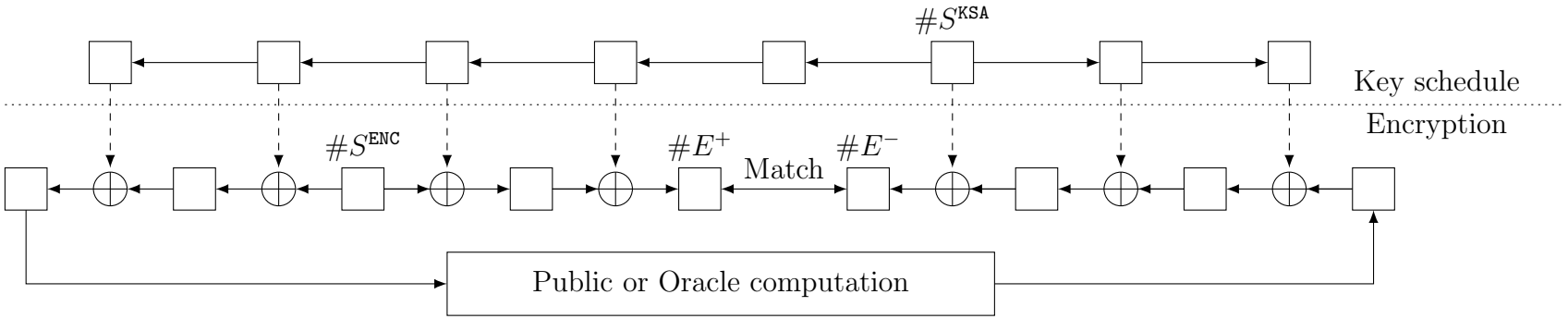
- block size: n-bit key size: l-bit.
  $K = K_1||K_2||K_3$, they are independent.
- m-bit($m < n$) of v can compute by $F_1(P)$ without knowing K_2 and ${F_2}^{-1}(C)$ without knowing K_1.
- $2^{|K_3|}(2^{|K_1|+|K_2|-m}) = 2^{|K|-m} = 2^{l-m}$ remained.
- test the surviving key candidates using some plaintext/ciphertext pairs.

The total computation complexity is estimated as

$$T = \underbrace{2^{|K_3|}(2^{|K_1|} + 2^{|K_2|})}_{MITM\ stage} + \underbrace{(2^{l-m} + 2^{l-m-n} + 2^{l-m-2n} + \cdots)}_{Key\ testing\ stage}.$$

A Formal Description of the MITM Technique

At EUROCRYPT 2021, the MITM preimage attacks on AES-like hashing was throughly modeled as constrained optimization problems by Bao et al.



- Forward chunk: $(\#S^{\mathtt{ENC}}, \#S^{\mathtt{KSA}}) \rightarrow \#E^{+}$
- Backward chunk: $(\#S^{\mathtt{ENC}}, \#S^{\mathtt{KSA}}) \rightarrow \#E^{-}$
- Partial match: $\#E^{+} \leftrightarrow \#E^{-}$

A Formal Description of the MITM Technique

the cells of $(\#S^{\mathtt{ENC}}, \#S^{\mathtt{KSA}})$ are partitioned into different subsets with different meanings:

- neutral words of forward chunk: ■.
- neutral words of backward chunk: ■.
- known constants: ■.
- unknown words in both the forward and backward chunk: □.

A Formal Description of the MITM Technique

- The initial DoF for the forward computation: the number of ■ in $(\#S^{\mathtt{ENC}}, \#S^{\mathtt{KSA}})$, defined as λ^+.
- The initial DoF for the backward computation: the number of ■ in $(\#S^{\mathtt{ENC}}, \#S^{\mathtt{KSA}})$, defined as λ^-.
- Accumulated DoF consumed in forward chunk: denoted by σ^-
- Accumulated DoF consumed in backward chunk: denoted by σ^+

The remaining degree of freedom(DoF) of forward and backward computation denoted by DoF^+ and DoF^-, the degree of match is denoted by DoM.
So $DoF^+ = \lambda^+ - \sigma^+$, $DoF^- = \lambda^- - \sigma^-$. The objective is to maximize $min\{DoF^+, DoF^-, DoM\}$.

Outline

Automatic MITM Key-recovery Attacks

Divide λ^+ to $\lambda^+_{\mathtt{ENC}}$ and $\lambda^+_{\mathtt{KSA}}$ which from $\#S^{\mathtt{ENC}}$ and $\#S^{\mathtt{KSA}}$.
Divide σ^+ to $\sigma^+_{\mathtt{ENC}}$ and $\sigma^+_{\mathtt{KSA}}$ which is the accumulated DoF be consumed from $\#S^{\mathtt{ENC}}$ and $\#S^{\mathtt{KSA}}$.

Two requirements

In MITM key-recovery attack, the full key space must be tested and we prefer not to exhaust the full codebook.

1. $\lambda^+_{\mathtt{ENC}}$ and $\lambda^-_{\mathtt{ENC}}$ should be used up, $\lambda^+_{\mathtt{KSA}}$ and $\lambda^-_{\mathtt{KSA}}$ cannot be depleted.
2. there is at least one ■ cell in the plaintext state.

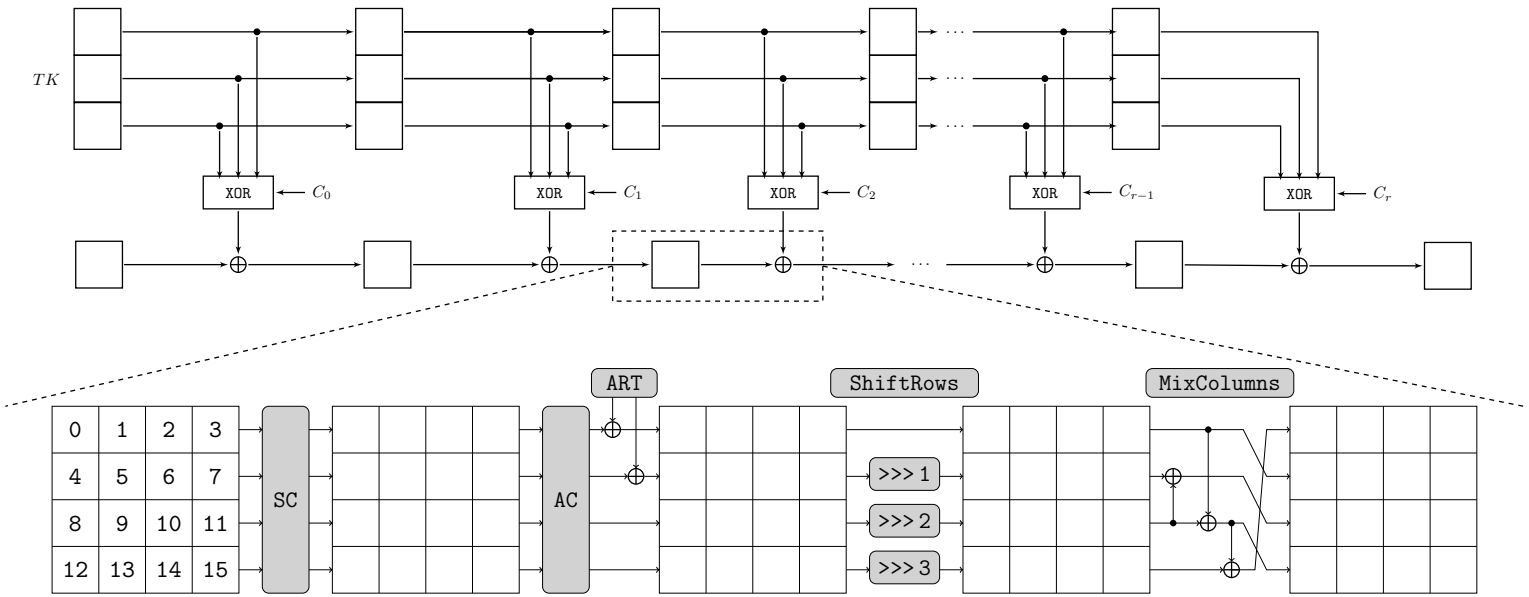
Then we have $\lambda^+_{\mathtt{ENC}} - \sigma^+_{\mathtt{ENC}} = 0$, $\lambda^-_{\mathtt{ENC}} - \sigma^-_{\mathtt{ENC}} = 0$

$$\lambda^+_{\mathtt{KSA}} - \sigma^+_{\mathtt{KSA}} >= 1,\ \lambda^-_{\mathtt{KSA}} - \sigma^-_{\mathtt{KSA}} >= 1$$

so $\mathrm{DoF}^+ = \lambda^+_{\mathtt{KSA}} - \sigma^+_{\mathtt{KSA}}$, $\mathrm{DoF}^- = \lambda^-_{\mathtt{KSA}} - \sigma^-_{\mathtt{KSA}}$

Outline

Specifications of Skinny



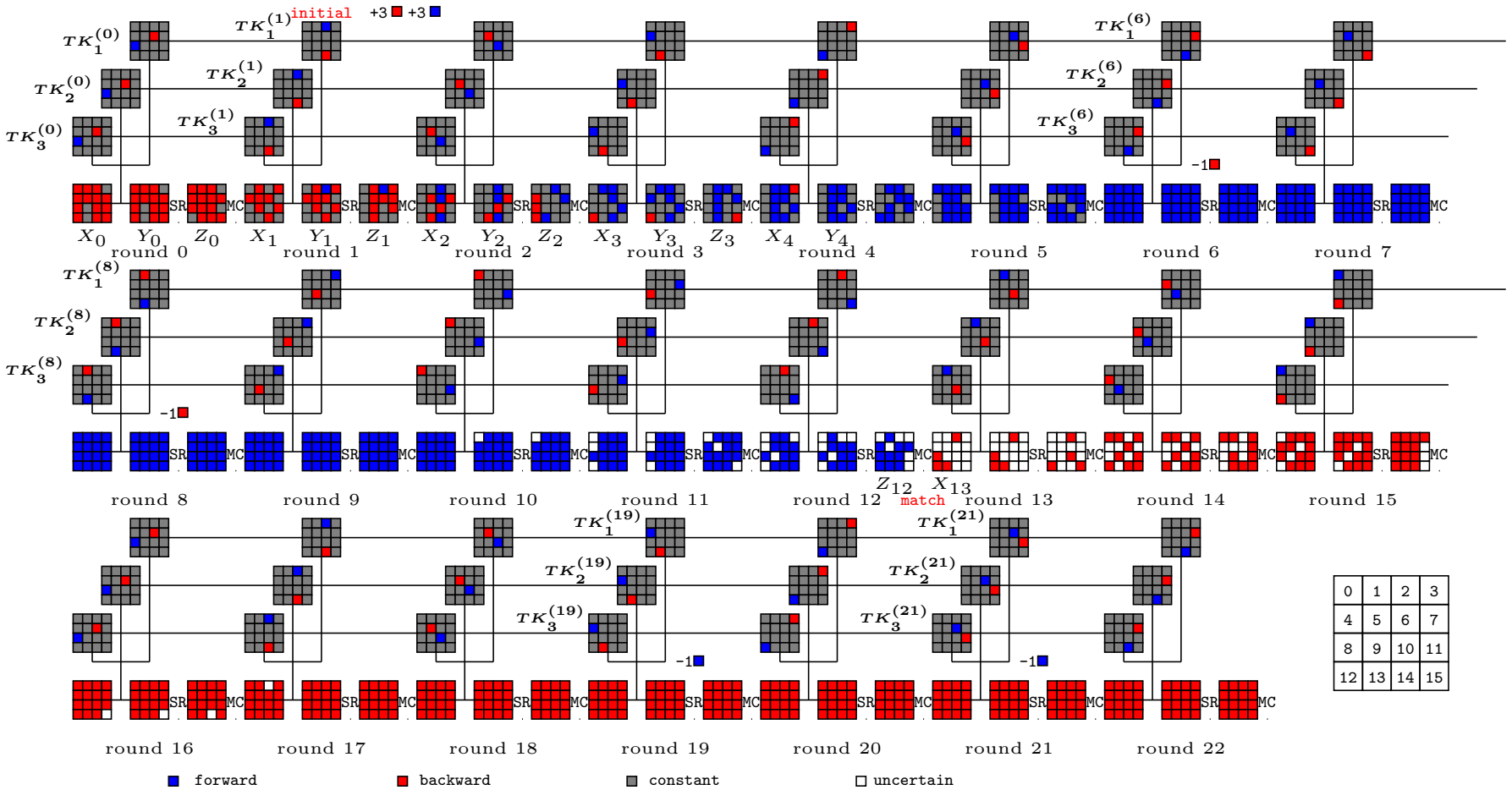
In each round, the state is updated with five operations: `SubCells (SC)`, `AddConstants (AC)`, `AddRoundTweakey (ART)`, `ShiftRows (SR)` and `MixColumns (MC)`.

Programming the MITM Attacks on SKINNY-n-3n with MILP

- Objective function: $max\{\min\{\mathrm{DoF}^+, \mathrm{DoF}^-, \mathrm{DoM}\}\}$
- Constraints for the Starting States: each cell in $(\#S^{\mathtt{ENC}}, \#S^{\mathtt{KSA}})$, $\alpha_i = 1$ if it is Blue and $\beta_i = 1$ it is Red. $\lambda^+_{\mathtt{ENC}} = \sum_i \alpha_i^{\mathtt{ENC}}$, $\lambda^+_{\mathtt{KSA}} = \sum_i \alpha_i^{\mathtt{KSA}}$, $\lambda^-_{\mathtt{ENC}} = \sum_i \beta_i^{\mathtt{ENC}}$, $\lambda^-_{\mathtt{KSA}} = \sum_i \beta_i^{\mathtt{KSA}}$
- Constraints for the Ending States: enumerate all possible patterns and convert it to linear inequalities.
- Constraints Imposed by the Computation Paths: Build rules for XOR, ART and MC.

$$\begin{cases} \lambda^+_{\mathtt{ENC}} - \sigma^+_{\mathtt{ENC}} = 0, \quad \lambda^-_{\mathtt{ENC}} - \sigma^-_{\mathtt{ENC}} = 0 \\ \mathrm{DoF}^+ = \lambda^+_{\mathtt{KSA}} - \sigma^+_{\mathtt{KSA}} \geq 1, \quad \mathrm{DoF}^- = \lambda^-_{\mathtt{KSA}} - \sigma^-_{\mathtt{KSA}} \geq 1 \end{cases}.$$

The MITM Key-recovery Attack on SKINNY-n-3n



The MITM Key-recovery Attack on SKINNY-n-3n

1 $X_0[3, 9, 13] \leftarrow 0$, $X_1[0, 2, 8, 10, 13] \leftarrow 0$, $X_2[1, 3, 9, 11] \leftarrow 0$, $Y_2[5] \leftarrow 0$, $X_3[0, 8] \leftarrow 0$, $Y_4[3] \leftarrow 0$

2 Collecting structure of plaintext-ciphertext pairs and store them in table H, which traverses the non-constant 16-3=13 cells in the plaintext.

3 **for** *All possilbe values of the* ■ *cells in* $(TK_1^{(0)}, TK_2^{(0)}, TK_3^{(0)})$ **do**

4 for $(a_1, a_2, b_1, b_2) \in \mathbb{F}_2^{4w}$ **do**

5 $Y_0[3] \leftarrow TK_1^{(0)}[3] \oplus TK_2^{(0)}[3] \oplus TK_3^{(0)}[3]$, $Y_0[9, 13] \leftarrow X_0[9, 13]$, $Z_0[3, 11, 12] \leftarrow Y_0[3, 9, 13]$, $X_1[12] \leftarrow X_1[0] \oplus Z_0[12]$, $X_1[7] \leftarrow Z_0[3]$, $X_1[15] \leftarrow Z_0[3] \oplus Z_0[11]$, $X_2[15] \leftarrow X_2[3] \oplus Z_1[15]$, $X_3[4] \leftarrow Z_2[0]$

6 Derive the solution space of the ■ cells in the TK by

7 $$TK_1^{(6)}[7] \oplus TK_2^{(6)}[7] \oplus TK_3^{(6)}[7] = a_1$$

8 $$TK_1^{(8)}[1] \oplus TK_2^{(8)}[1] \oplus TK_3^{(8)}[1] = a_2$$

9 Derive the solution space of the ■ cells in the TK by

10 $$TK_1^{(19)}[4] \oplus TK_2^{(19)}[4] \oplus TK_3^{(19)}[4] = b_1$$

11 $$TK_1^{(21)}[6] \oplus TK_2^{(21)}[6] \oplus TK_3^{(21)}[6] = b_2$$

12 Initialize L to be an empty hash table

13 **for** *the value in the solution space of* ■ *cells in* TK **do**

14 Compute $X_{13}[8]$ along the backward computation path: $X_4 \rightarrow X_0 \rightarrow E_K(X_0) \rightarrow X_{13}$ by accessing H

15 Insert relative information into L indexed by $X_{13}[8]$

16 **end**

17 **for** *the value in the solution space of* ■ *cells in* TK **do**

18 Compute $Z_{12}[4]$ and $Z_{12}[8]$ along the forward computation path: $X_1 \rightarrow Z_{12}$

19 **for** *Candidate keys in* $L[Z_{12}[4] \oplus Z_{12}[8]]$ **do**

20 Test the guessed key with several plaintext-ciphertext pairs

21 **end**

22 **end**

23 **end**

24 **end**

A summary of SKINNY and ForkSkinny

SKINNY							
Version	Rounds	Data	Time	Memory	Attack	Setting	Ref.
64-192	22	$2^{47.84}$	$2^{183.97}$	$2^{74.84}$	ID	SK	[16]
	23	2^{52}	2^{188}	2^{4}	MITM	SK	Ours
128-384	22	2^{96}	$2^{382.46}$	$2^{330.99}$	DS-MITM	SK	[15]
	22	$2^{92.22}$	$2^{373.48}$	$2^{147.22}$	ID	SK	[16]
	23	2^{104}	2^{376}	2^{8}	MITM	SK	Ours
ForkSkinny							
64-192	24	2^{52}	2^{188}	2^{4}	MITM	SK	Ours
128-384	24	2^{104}	2^{376}	2^{8}	MITM	SK	Ours
128-256	24	$2^{122.5}$	$2^{124.5}$	$2^{97.5}$	ID	RK	[2]
	26	2^{127}	$2^{250.3}$	2^{160}	ID	RK	[2]

Outline

Computing the solution spaces of nonlinear constrained neutral words

- In MITM attack on Skinny, we have to solve two systems of equations. It is easy to compute if they are linear.
- For nonlinear constrained neutral words, We present a table based technique to solve it.

Algorithm 1: Computing the solution spaces of the neutral words

Input: $(\#S^{\mathrm{ENC}}[\mathcal{G}^{\mathrm{ENC}}], \#S^{\mathrm{KSA}}[\mathcal{G}^{\mathrm{KSA}}]) \in \mathbb{F}_2^{w\cdot(|\mathcal{G}^{\mathrm{ENC}}|+|\mathcal{G}^{\mathrm{KSA}}|)}$
Output: V, U

$V \leftarrow [\,]$, $U \leftarrow [\,]$
for $(\#S^{\mathrm{ENC}}[\mathcal{B}^{\mathrm{ENC}}], \#S^{\mathrm{KSA}}[\mathcal{B}^{\mathrm{KSA}}]) \in \mathbb{F}_2^{w\cdot(|\mathcal{B}^{\mathrm{ENC}}|+|\mathcal{B}^{\mathrm{KSA}}|)}$ **do**
  $\boldsymbol{v} \leftarrow \boldsymbol{\pi}^{+}(\#S^{\mathrm{ENC}}[\mathcal{G}^{\mathrm{ENC}}], \#S^{\mathrm{KSA}}[\mathcal{G}^{\mathrm{KSA}}], \#S^{\mathrm{ENC}}[\mathcal{B}^{\mathrm{ENC}}], \#S^{\mathrm{KSA}}[\mathcal{B}^{\mathrm{KSA}}])$
  Insert $(\#S^{\mathrm{ENC}}[\mathcal{B}^{\mathrm{ENC}}], \#S^{\mathrm{KSA}}[\mathcal{B}^{\mathrm{KSA}}])$ into V at index $\boldsymbol{v}$
end
for $(\#S^{\mathrm{ENC}}[\mathcal{R}^{\mathrm{ENC}}], \#S^{\mathrm{KSA}}[\mathcal{R}^{\mathrm{KSA}}]) \in \mathbb{F}_2^{w\cdot(|\mathcal{R}^{\mathrm{ENC}}|+|\mathcal{R}^{\mathrm{KSA}}|)}$ **do**
  $\boldsymbol{u} \leftarrow \boldsymbol{\pi}^{-}(\#S^{\mathrm{ENC}}[\mathcal{G}^{\mathrm{ENC}}], \#S^{\mathrm{KSA}}[\mathcal{G}^{\mathrm{KSA}}], \#S^{\mathrm{ENC}}[\mathcal{R}^{\mathrm{ENC}}], \#S^{\mathrm{KSA}}[\mathcal{R}^{\mathrm{KSA}}])$
  Insert $(\#S^{\mathrm{ENC}}[\mathcal{R}^{\mathrm{ENC}}], \#S^{\mathrm{KSA}}[\mathcal{R}^{\mathrm{KSA}}])$ into U at index $\boldsymbol{u}$
end

MITM preimage attack on AES-like hashing with non-linearly constrained neutral words

Applying the technique to the MITM preimage attack can deal with nonlinearly constrained neutral words.

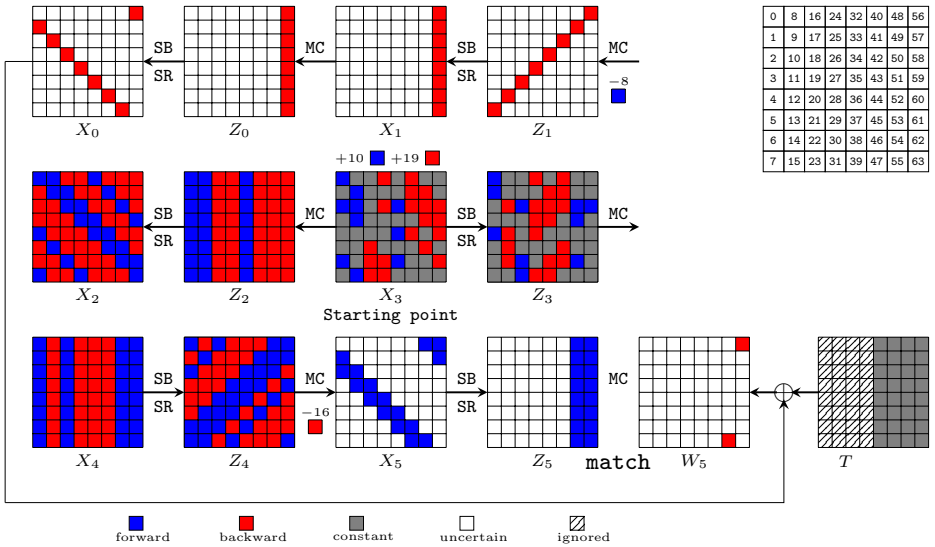
Algorithm 2: The framework of the MITM preimage attack on AES-like hashing with non-linearly constrained neutral words

```
for (#S^ENC[G^ENC], #S^KSA[G^KSA]) ∈ 𝔾 ⊆ 𝔽_2^{w·(|G^ENC|+|G^KSA|)} do
    Call Algorithm 1 to build V, U
    for c^+ = (a_1, ··· , a_{l+}) ∈ 𝔽_2^{w·l^+} do
        for c^- = (b_1, ··· , b_{l-}) ∈ 𝔽_2^{w·l^-} do
            L ← [ ]
            for (#S^ENC[B^ENC], #S^KSA[B^KSA]) ∈ V[c^+] do
                Compute E^+[M^+] along the forward computation path
                Insert (#S^ENC[B^ENC], #S^KSA[B^KSA]) into L indexed by E^+[M^+]
            end

            for (#S^ENC[R^KSA], #S^KSA[R^KSA]) ∈ U[c^-], do
                Compute E^-[M^-] along the backward computation path

                for (#S^ENC[B^ENC], #S^KSA[B^KSA]) ∈ L[E^-[M^-]] do
                    Reconstruct the (candidate) message X
                    if X is a preimage then
                        Output X and Stop.
                    end
                end
            end
        end
    end
end
```

Preimage attack on 6-round output transformation of Grøstl-256



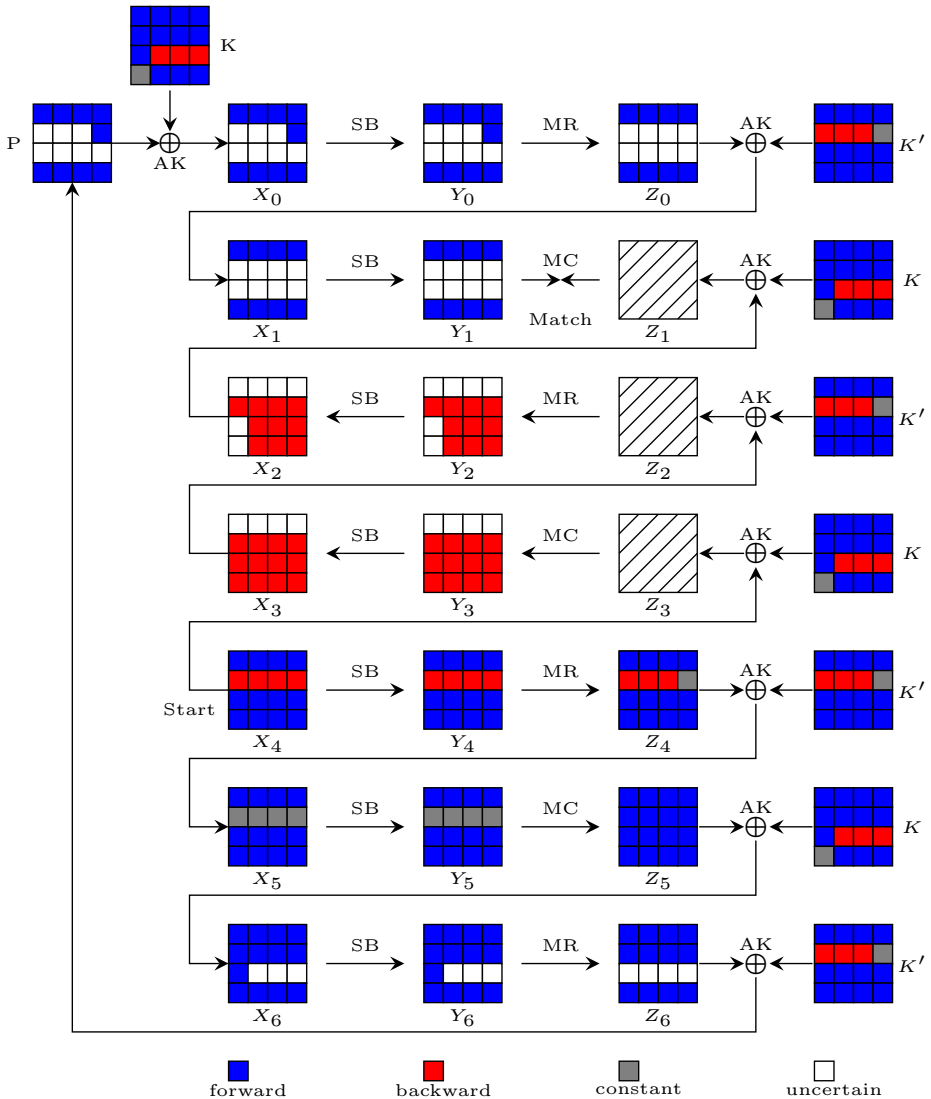
0	8	16	24	32	40	48	56
1	9	17	25	33	41	49	57
2	10	18	26	34	42	50	58
3	11	19	27	35	43	51	59
4	12	20	28	36	44	52	60
5	13	21	29	37	45	53	61
6	14	22	30	38	46	54	62
7	15	23	31	39	47	55	63

Time complexity:

$$(2^8)^{32-10} + (2^8)^{32-19} + (2^8)^{32-\min(2,\ 3,\ 2)} \approx 2^{240}$$

Memory complexity: $(2^8)^{10} + (2^8)^{19} + (2^8)^{\min(2,\ 3)} \approx 2^{152}$

The 7-round MITM attack on Saturnin-Hash



Time complexity

$$(2^{16})^{16-\min(6,\ 3,\ 3)} \approx 2^{208}.$$

Memory complexity:

$$(2^{16})^3 = 2^{48}$$

.

Outline

MITM-based collision attack

- t-cell partial target preimage attack: can produce a message whose hash value is a random element in a given subspace.
- If there is an algorithm that can produce a different t-cell partial target preimage. We can find a collision by running the algorithm $2^{w(h-t)/2}$ times.
- Given an MITM characteristic, the framework for a collision attack is described in the following algorithm.

MITM-based collision attack

Algorithm 3: The framework of the MITM collision attack on AES-like hashing with non-linearly constrained starting states

```
1  Setting the selected t cells of #T to constants
2  H ← [ ]
3  for (#S^ENC[G^ENC], #S^KSA[G^KSA]) ∈ G ⊆ F_2^{w·(|G^ENC|+|G^KSA|)} do
4      V ← [ ], U ← [ ]
5      Call Algorithm 1 to populate V and U
6      for c^+ = (a_1, ··· , a_{l+}) ∈ F_2^{w·l+} do
7          for c^- = (b_1, ··· , b_{l-}) ∈ F_2^{w·l-} do
8              L ← [ ]
9              for (#S^ENC[B^ENC], #S^KSA[B^KSA]) ∈ V[c^+] do
10                 Compute E^+[M^+] along the forward computation path
11                 Insert (#S^ENC[B^ENC], #S^KSA[B^KSA]) into L indexed by E^+[M^+]
12             end
13             for (#S^ENC[R^KSA], #S^KSA[R^KSA]) ∈ U[c^-], do
14                 Compute E^-[M^-] along the backward computation path
15                 for (#S^ENC[B^ENC], #S^KSA[B^KSA]) ∈ L[E^-[M^-]] do
16                     Reconstruct the (candidate) message X
17                     if X is a t-cell partial target preimage then
18                         Insert X into H indexed by the hash value of X
19                         Stop when there is a collision
20                     end
21                 end
22             end
23         end
```

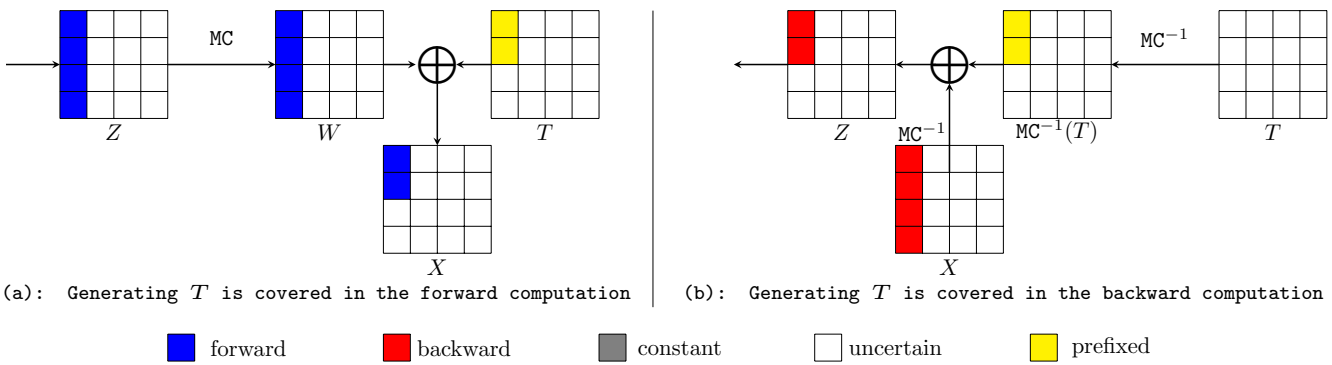
Automatic Search for MITM-based Collision Attacks

The time complexity is about $(2^w)^{\frac{h}{2}-\min\{\mathrm{DoF}^+-\frac{t}{2},\ \mathrm{DoF}^--\frac{t}{2},\ m-\frac{t}{2},\ \frac{t}{2}\}}$

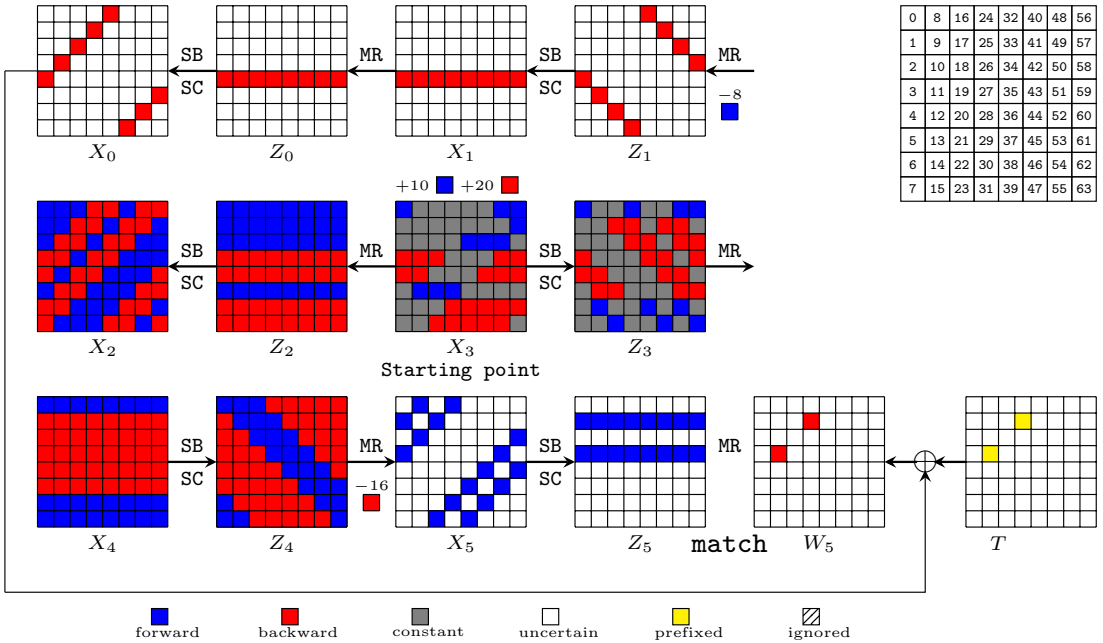
The objective function of the model is to maximize

$$\min(\mathrm{DoF}^+ - \frac{t}{2}, \mathrm{DoF}^- - \frac{t}{2}, m - \frac{t}{2}, \frac{t}{2})$$

- The matching point is placed at the last round: we can ignore the coloring information of T.
- The matching point is not at the last round: we can regard the ■ cells as ■ cells.



Collision attack on 6-round WHIRLPOOL



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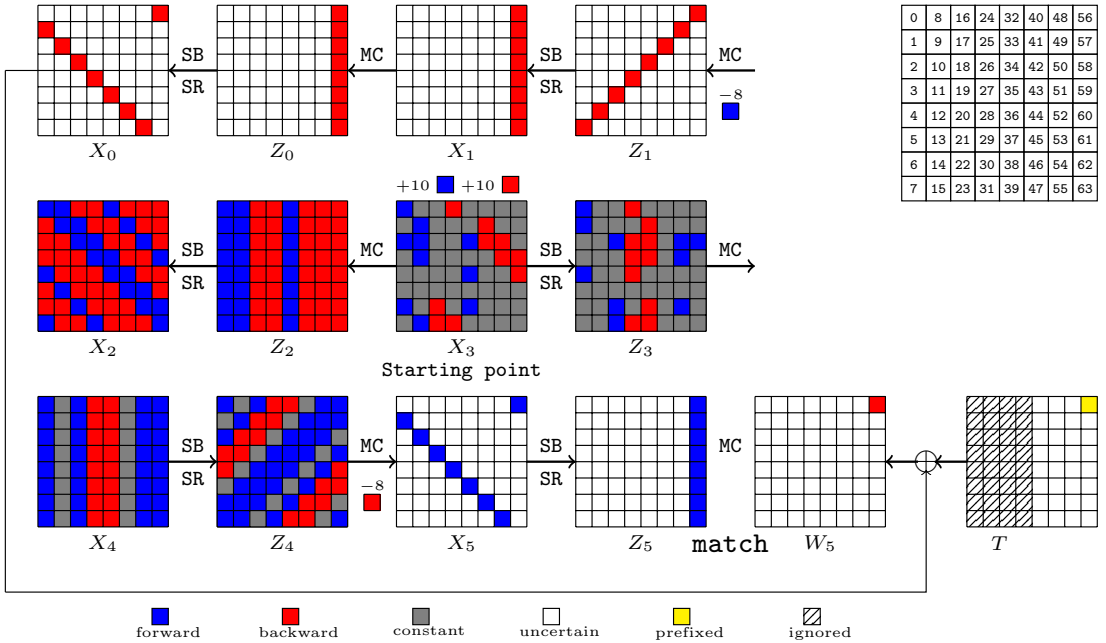
4	12	20	28	36	44	52	60
5	13	21	29	37	45	53	61
6	14	22	30	38	46	54	62
7	15	23	31	39	47	55	63

The time complexity is

$$(2^8)^{\frac{64}{2}-(10-\frac{2}{2})}+(2^8)^{\frac{64}{2}-(20-\frac{2}{2})}+(2^8)^{\frac{64}{2}-\min\{2-\frac{2}{2},\ 4-\frac{2}{2},\ 2-\frac{2}{2},\ \frac{2}{2}\}} \approx 2^{248}$$

The memory complexity is about 2^{248}.

Collision attack on 6-round Grøstl-256 output transformation



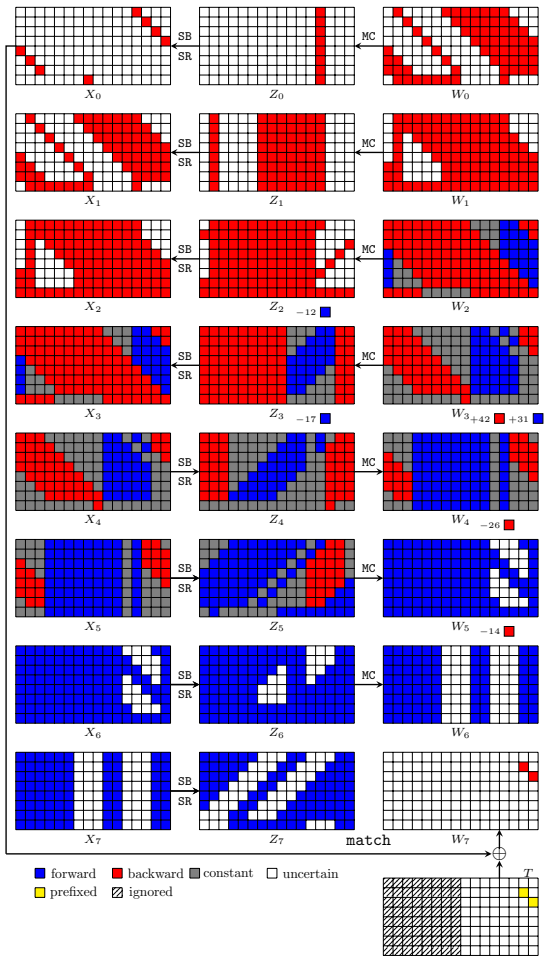
$\mathrm{DoF}^+ = \lambda^+ - l^+ = 2$, $\mathrm{DoF}^- = \lambda^- - l^- = 2$, $m = 1$, and $t = 1$.

The time complexity:

$$(2^8)^{10} + (2^8)^{10} + (2^8)^{\frac{32}{2} - \min\{2-\frac{1}{2},\ 2-\frac{1}{2},\ 1-\frac{1}{2},\ \frac{1}{2}\}} \approx 2^{124}.$$

The memory complexity is about: 2^{124}.

Collision attack on 8-round Grøstl-512 output transformation



$$\mathrm{DoF}^+ = \lambda^+ - l^+ = 2,$$
$$\mathrm{DoF}^- = \lambda^- - l^- = 2,\ m = 2$$
and $t = 2$
The time complexity

$$(2^8)^{\frac{64}{2}-(14-\frac{2}{2})} + (2^8)^{\frac{64}{2}-(16-\frac{2}{2})} + (2^8)^{\frac{64}{2}-\min\{2-\frac{2}{2},\ 2-\frac{2}{2},\ 2-\frac{2}{2},\ \frac{2}{2}\}} \approx 2^{248}$$

The memory cost: 2^{248}.

A Summary of the results

Target	Attack	Rounds	Time	Memory	Setting	Ref.
WHIRLPOOL						
Hash function	Collision	4	2^{120}	2^{16}	Classic	[9]
		5	2^{120}	2^{64}	Classic	[5, 8]
		6	2^{228}	-	Quantum	[6]
		6	2^{248}	2^{248}	Classic	Ours
	Preimage	5	2^{504}	2^{8}	Classic	[11]
		5	$2^{481.5}$	2^{64}		[17]
		6	2^{481}	2^{256}		[13]
Compression function	(Semi-) free-start	5	2^{120}	2^{16}	Classic	[9]
		7	2^{184}	2^{8}		[8]
		8	2^{120}	2^{8}		[13]
Grøstl-256						
Hash function	Collision	3	2^{64}	-	Classic	[14]
		5	2^{120}	2^{64}		[10]
	Pseudo preimage	5	$2^{244.8}$	2^{230}	Classic	[17]
		6	2^{252}	2^{251}		Ours
Compression function	Semi-free-start	6	2^{112}	2^{64}	Classic	[14]
Output Transformation	Preimage	5	2^{206}	2^{48}	Classic	[17]
		6	2^{240}	2^{152}		Ours
	Collision	6	2^{124}	2^{124}	Classic	Ours
Grøstl-512						
Hash function Compression function Output Transformation	Collision	5	2^{240}	2^{64}	Quantum	[4]
		7	2^{152}	2^{56}	Classic	[12]
		8	2^{248}	2^{248}	Classic	Ours
Hash function	Pseudo preimage	8	$2^{507.3}$	2^{507}	Classic	[17]
Saturnin-Hash						
Compression function Hash function	Preimage	7	2^{208}	2^{48}	Classic	Ours
		7	2^{232}	2^{48}		
SKINNY-128-384, Romulus-H, and AES hashing mode						
SKINNY-128-384-DM/MMO	Preimage	23	2^{120}	2^{8}	Classic	Ours
Romulus-H		23	2^{248}	2^{8}		Ours
AES-256		9	2^{120}	2^{8}		[1]
AES-256		10	2^{120}	2^{56}		Ours
Romulus-H compression function	Free-start	23	2^{124}	2^{124}		Ours

Thank you

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