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Finding the Impossible: Automated Search for Full Impossible-Differential, Zero-Correlation, and Integral Attacks

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Research Gap and Our Contributions

Research gap

- Lack of automatic tool to find full ID/ZC, and integral attacks

Contributions

- Introduced a new CP-based method to find ID/ZC, and integral distinguishers
- Our CP model can be extended to an efficient unified model for key recovery
- Found improved attacks for SKINNY, CRAFT, SKINNYee, and SKINNYe-v2

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Part of Our Result

Cipher	#R	Time	Data	Mem.	Attack	Setting / Model	Ref.
SKINNY-64-192	23	$2^{155.60}$	$2^{73.20}$	2^{138}	Int	180,SK / CP,CT	[Ank+19]
	26	2^{172}	2^{61}	2^{172}	Int	180,SK / CP,CT	This paper
SKINNY-64-128	18	2^{126}	$2^{62.68}$	2^{64}	ZC	STK / KP	[SMB18]
	19	$2^{119.12}$	$2^{62.89}$	2^{49}	ZC	STK / KP	This paper
	20	$2^{97.50}$	$2^{68.40}$	2^{82}	Int	120,SK / CP,CT	[Ank+19]
	22	2^{110}	$2^{57.58}$	2^{108}	Int	120,SK / CP,CT	This paper
SKINNY-128-256	19	$2^{241.80}$	2^{123}	2^{221}	ID	STK / CP	[YQC17]
	19	$2^{219.23}$	$2^{117.86}$	2^{208}	ID	STK / CP	This paper
SKINNY-64-64	14	2^{62}	$2^{62.58}$	2^{64}	ZC	STK / KP	[SMB18]
	16	$2^{62.71}$	$2^{61.35}$	$2^{37.80}$	ZC	STK / KP	This paper
CRAFT	**20**	$2^{120.43}$	$2^{62.89}$	2^{49}	ZC	STK / KP	This paper
	21	$2^{106.53}$	$2^{60.99}$	2^{100}	ID	STK / CP	This paper

Outline

1 Background and the Research Gap

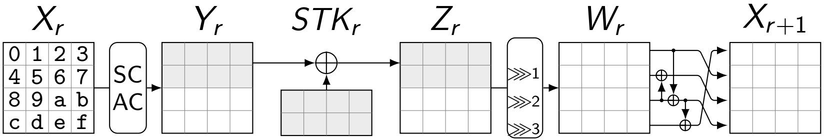
2 Our Method to Search For Distinguisher

3 Our Unified CP Model for Key-Recovery

4 Future Works

Background and the Research Gap

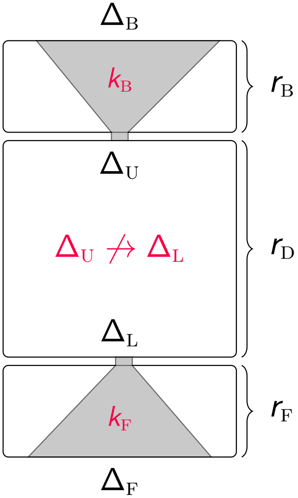
SKINNY Family of Tweakable Block Ciphers [Bei+16]



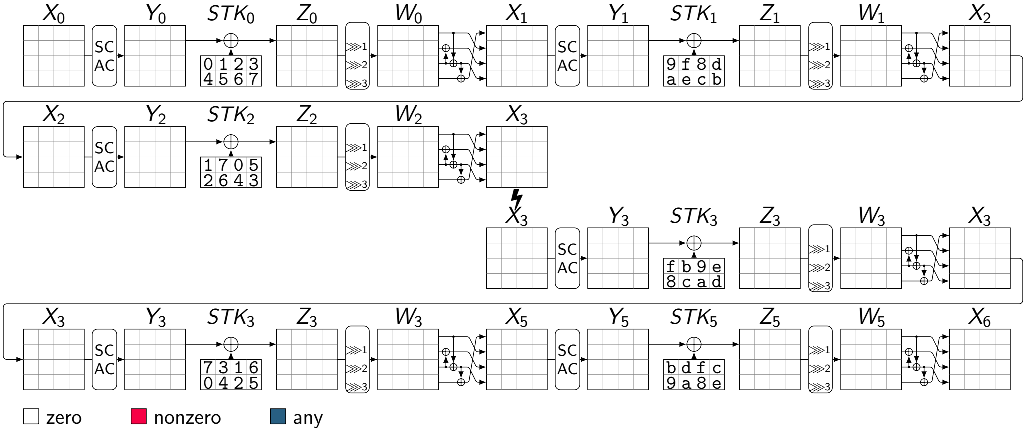
- Introduced in CRYPTO 2016 [Bei+16]
- It has 6 main variants: SKINNY-n-$z \cdot n$, where $n \in \{64, 128\}$, and $z \in \{1, 2, 3\}$
- ISO/IEC 18033-7: SKINNY-64-192, SKINNY-128-256, SKINNY-128-384

Impossible Differential Attack [BBS99; Knu98]

- Find an impossible-differential $\Delta_{\mathrm{U}} \not\to \Delta_{\mathrm{L}}$
- Build a key-recovery attack
  - Create a pool of pairs satisfying $(\Delta_{\mathrm{B}}, \Delta_{\mathrm{F}})$
  - For all $k \in k_{\mathrm{B}} \cup k_{\mathrm{F}}$:
    - If a pair suggests $(\Delta_{\mathrm{U}}, \Delta_{\mathrm{L}})$, discard k
  - Brute force the remaining key candidates



Miss-in-the-Middle Technique [BBS99]



X0 SC AC Y0 STK0 Z0 W0 X1 SC AC Y1 STK1 Z1 W1 X2
0 1 2 3
4 5 6 7
9 f 8 d
a e c b
⋙1 ⋙2 ⋙3
X2 SC AC Y2 STK2 Z2 W2 X3
1 7 0 5
2 6 4 3
X3 SC AC Y3 STK3 Z3 W3 X3
f b 9 e
8 c a d
X3 SC AC Y3 STK3 Z3 W3 X5 SC AC Y5 STK5 Z5 W5 X6
7 3 1 6
0 4 2 5
b d f c
9 a 8 e
□ zero
🟥 nonzero
🟦 any

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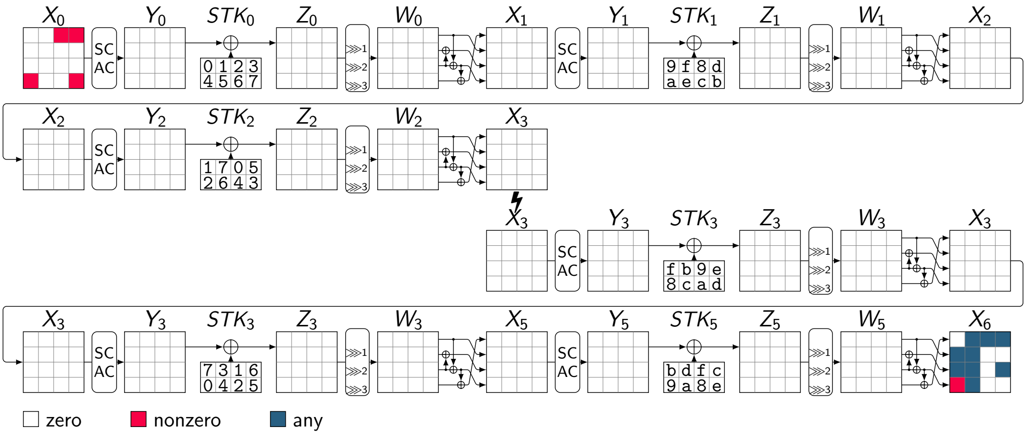

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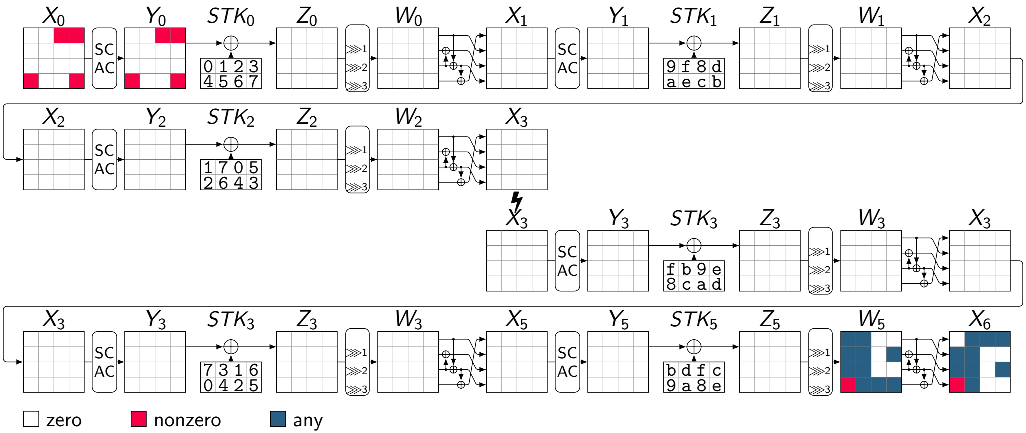

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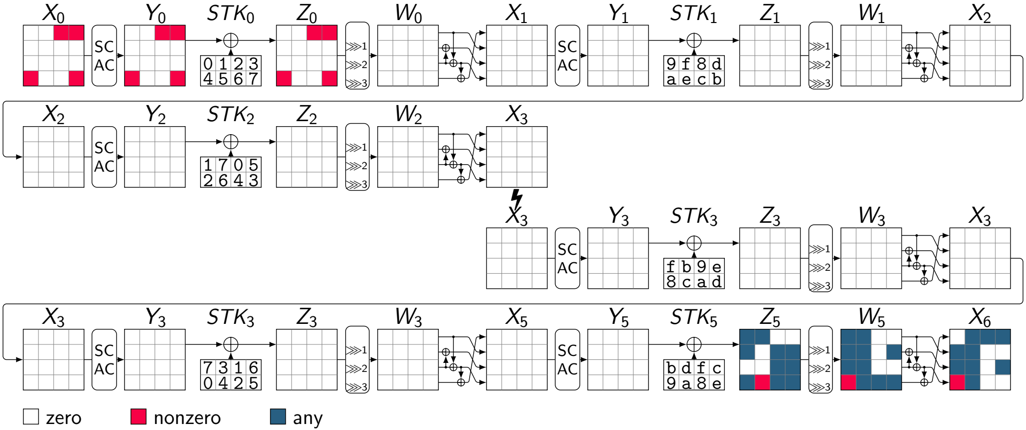
X_0 SC AC Y_0 STK_0 Z_0 ⋙1 ⋙2 ⋙3 W_0 X_1 SC AC Y_1 STK_1 Z_1 ⋙1 ⋙2 ⋙3 W_1 X_2
0 1 2 3
4 5 6 7
9 f 8 d
a e c b
X_2 SC AC Y_2 STK_2 Z_2 ⋙1 ⋙2 ⋙3 W_2 X_3
1 7 0 5
2 6 4 3
X_3 SC AC Y_3 STK_3 Z_3 ⋙1 ⋙2 ⋙3 W_3 X_3
f b 9 e
8 c a d
X_3 SC AC Y_3 STK_3 Z_3 ⋙1 ⋙2 ⋙3 W_3 X_5 SC AC Y_5 STK_5 Z_5 ⋙1 ⋙2 ⋙3 W_5 X_6
7 3 1 6
0 4 2 5
b d f c
9 a 8 e
□ zero
🟥 nonzero
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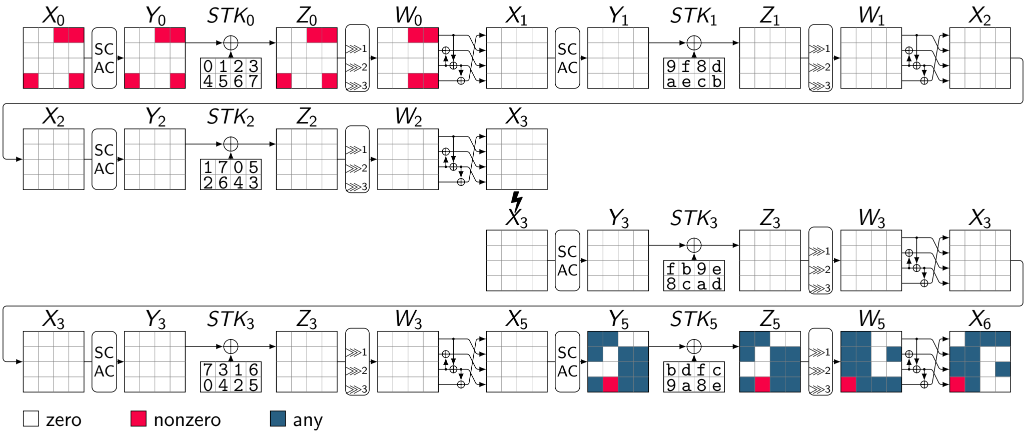
Miss-in-the-Middle Technique [BBS99]


X_0 SC AC Y_0 STK_0 Z_0 W_0 X_1 SC AC Y_1 STK_1 Z_1 W_1 X_2
0 1 2 3
4 5 6 7
9 f 8 d
a e c b
⋙1 ⋙2 ⋙3
X_2 SC AC Y_2 STK_2 Z_2 W_2 X_3
1 7 0 5
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X_3 SC AC Y_3 STK_3 Z_3 W_3 X_3
f b 9 e
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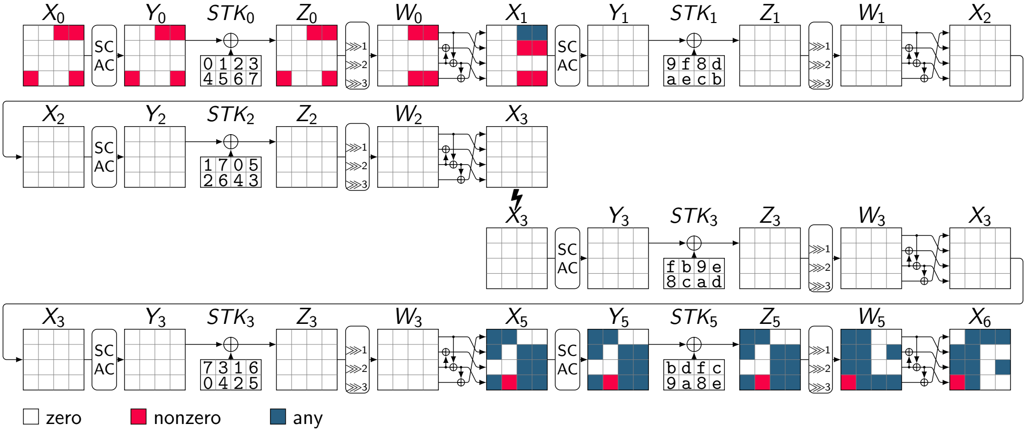

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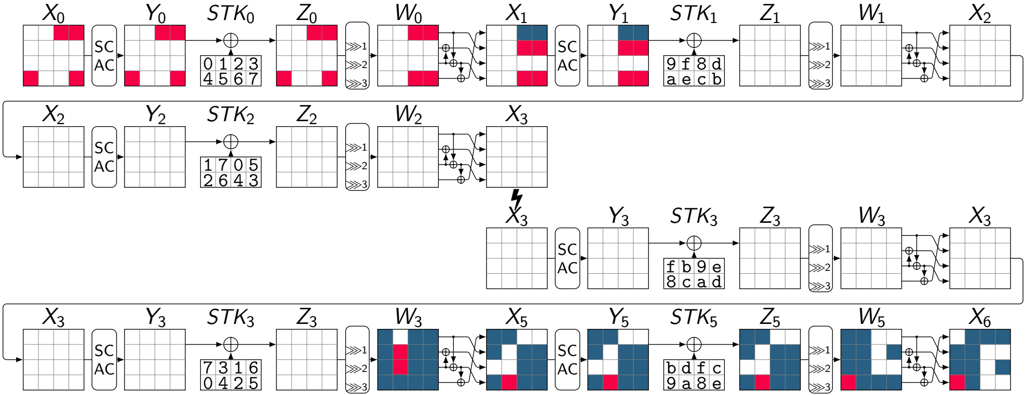

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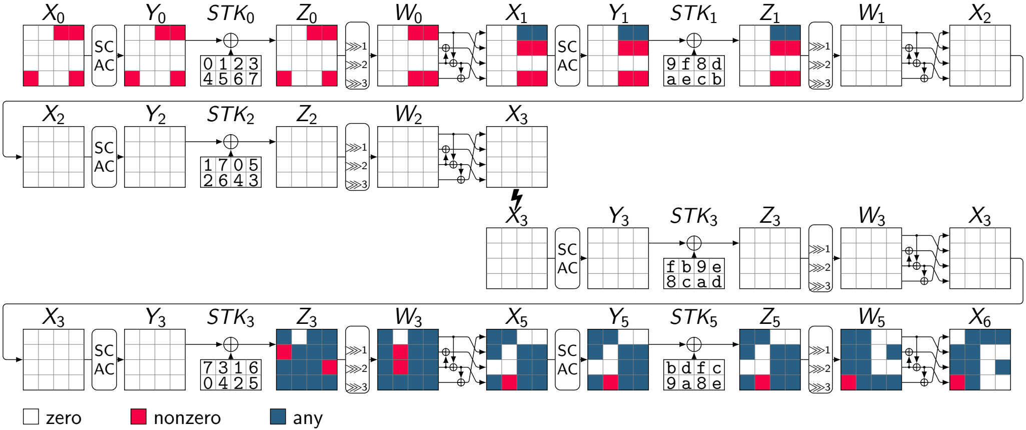
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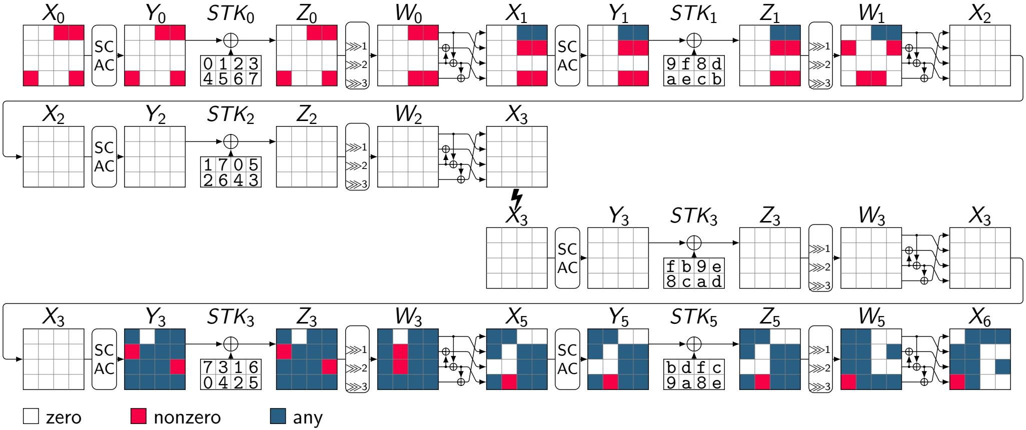

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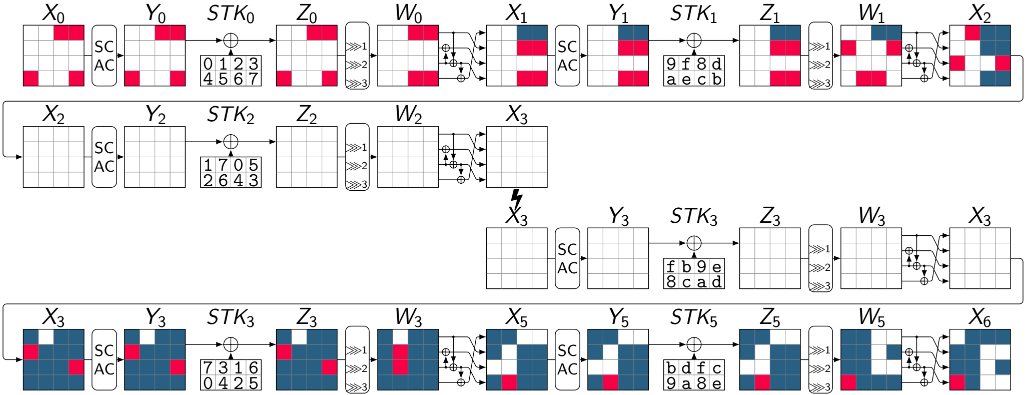

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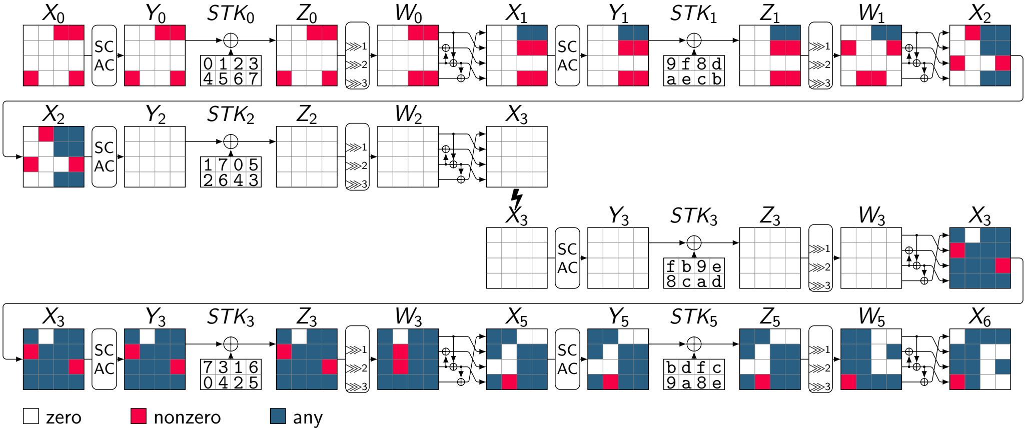

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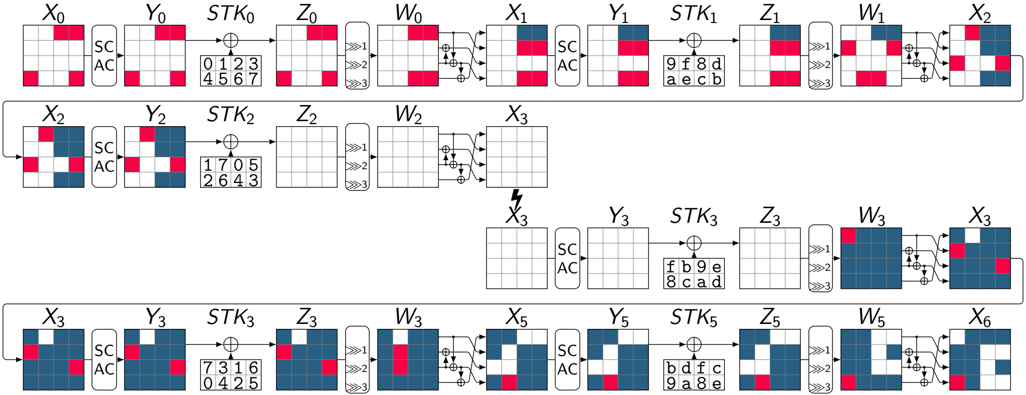

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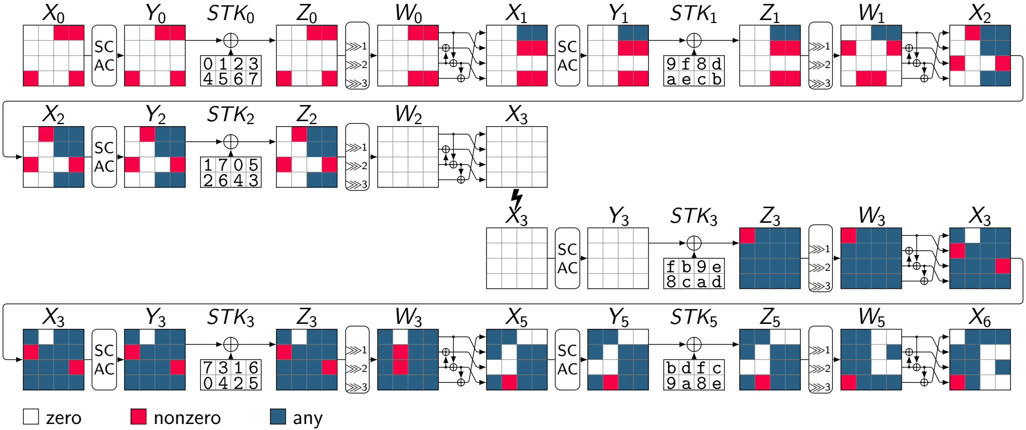

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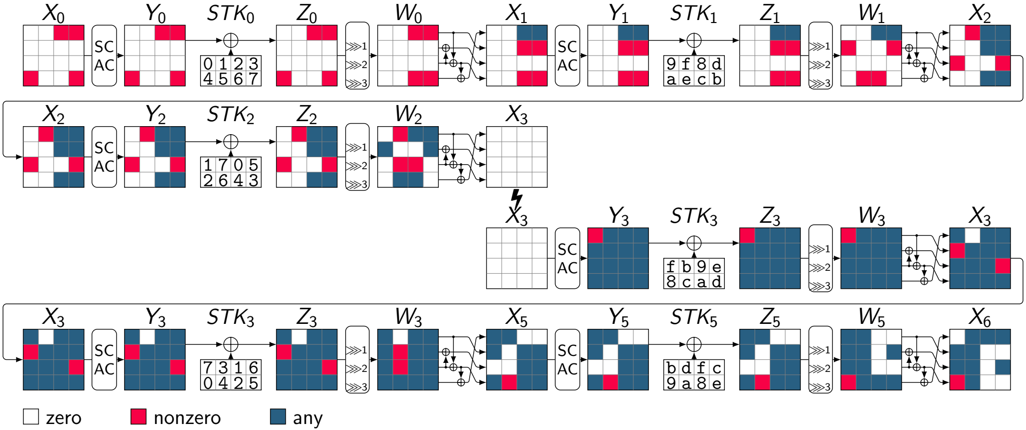

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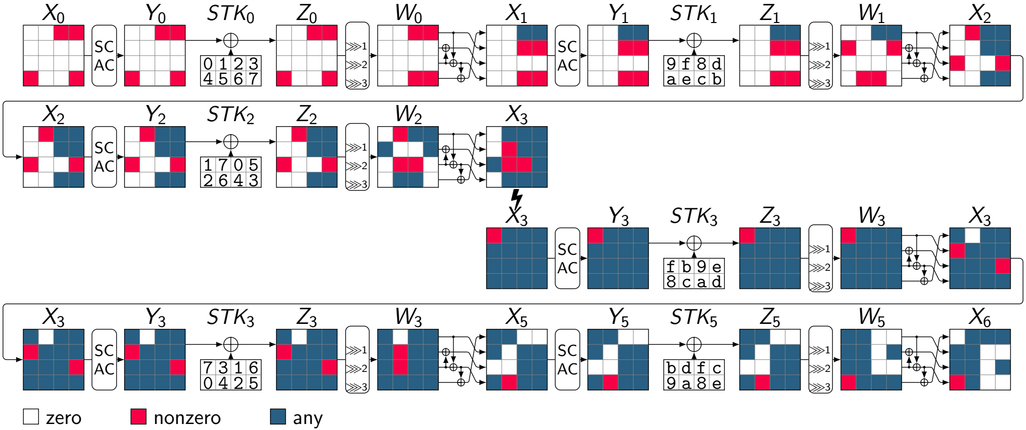
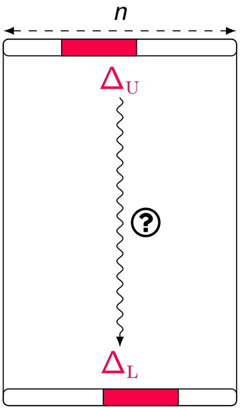


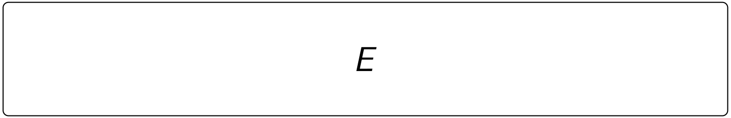
Previous Tools for ID/ZC, and Integral Attacks

- Tools based on dedicated algorithms:
  - CRYPTO 2016 ($\mathcal{DC}$-MITM, ID) [DF16]
- Tools based on general purpose solvers:
  - Eprint 2016 (ID) [Cui+16]
  - ASIACRYPT 2016 (Integral) [Xia+16]
  - EUROCRYPT 2017 (ID, ZC) [ST17]
  - ToSC 2017 (ID, ZC) [Sun+17]
  - ToSC 2020 (ID, ZC) [Sun+20]



Our Method to Search for Distinguishers

Our Method to Search for ID/ZC and Integral Distinguishers



- ✓ $CSP_{\mathrm{U}}(\Delta_{\mathrm{U}}, \Delta'_{\mathrm{U}})$
- ✓ $CSP_{\mathrm{L}}(\Delta_{\mathrm{L}}, \Delta'_{\mathrm{L}})$
- ✓ $CSP_{\mathrm{M}}(\Delta'_{\mathrm{U}}, \Delta'_{\mathrm{L}})$

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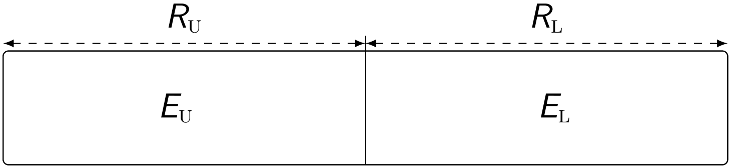

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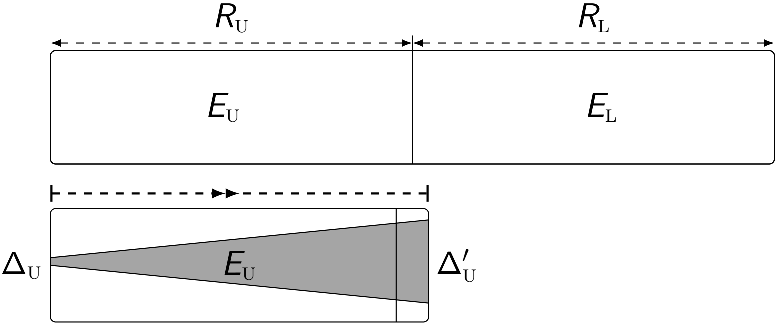

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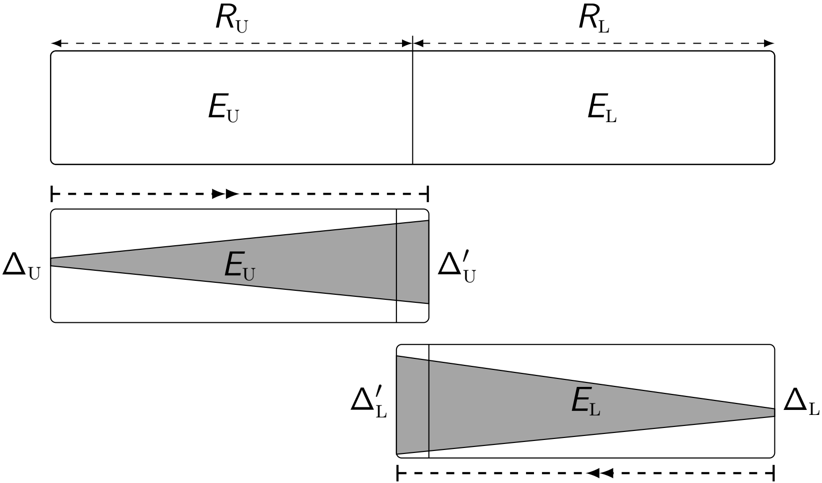

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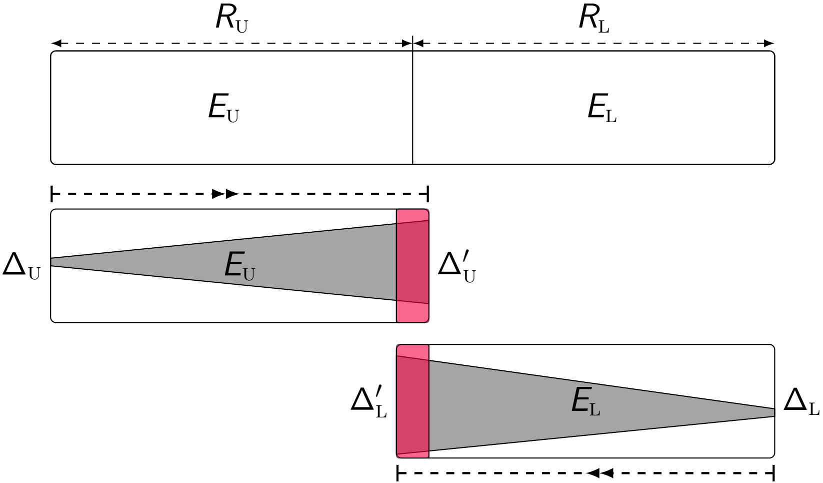

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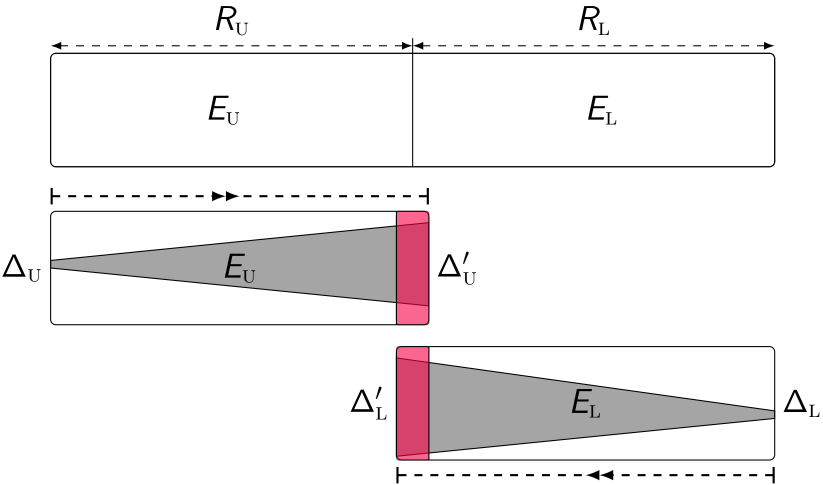


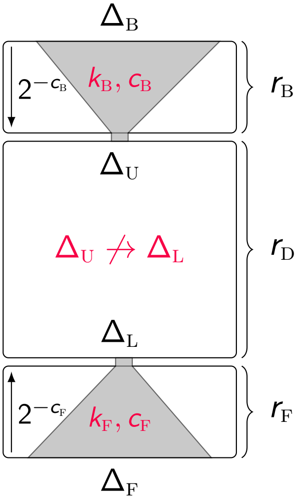
The Advantages of Our Method to Search for Distinguishers

- Based on satisfiability of the CP model
- Any feasible solutions of our CP model is a distinguisher
- We do not fix the input/output of distinguisher
- Extendable to a unified model for key-recovery
  - Find a distinguisher optimized for key-recovery
  - Taking some key-recovery techniques into account, e.g., MitM, and key bridging

Our Unified CP Model for Key-Recovery

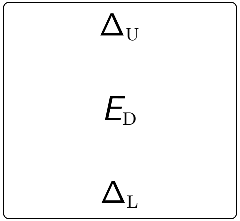
Complexity Analysis of ID Attack [Bou+18; BNS14]

- Number of required pairs: N
- Pair generation: $T_0 = N2^{n+1-|\Delta_{\mathrm{B}}|-|\Delta_{\mathrm{F}}|}$
- Guess-and-filter:
  - $T_1 + T_2 = N + 2^{|k_{\mathrm{B}} \cup k_{\mathrm{F}}|} \frac{N}{2^{c_{\mathrm{B}}+c_{\mathrm{F}}}}$
  - $P = \left(1 - 2^{-(c_{\mathrm{B}}+c_{\mathrm{F}})}\right)^N$
- Exhaustive search: $T_3 = P2^k$
- $T_{tot} = (T_0 + (T_1 + T_2)C_{E'} + T_3)C_E$



Overall View of Our CP Model for Key-Recovery

- Model the distinguisher for E_{D} $(\Delta_{\mathrm{U}}, \Delta_{\mathrm{F}})$
- Model the filters in E_{B}, and E_{F} $(c_{\mathrm{B}}, c_{\mathrm{F}}, \Delta_{\mathrm{B}}, \Delta_{\mathrm{F}})$
- Model the guess-and-determine in E_{B}, and E_{F}
- Model the key bridging
  - Encode $|k_{\mathrm{B}} \cup k_{\mathrm{F}}|$
- Model the complexity formulas
- Objective: `Minimize` the total time complexity



Δ_{U}

E_{D}

Δ_{L}

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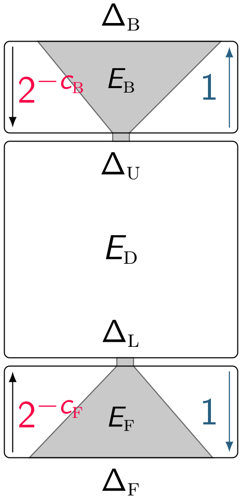

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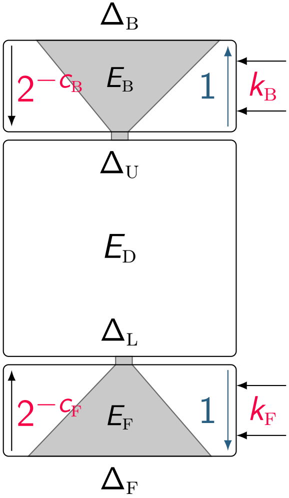

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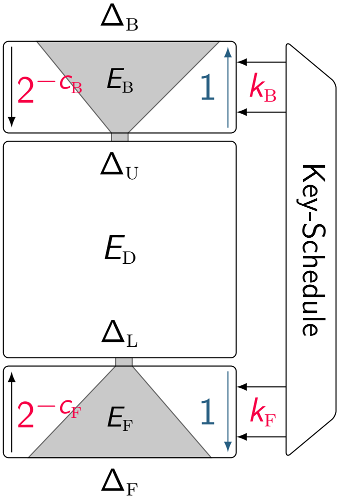

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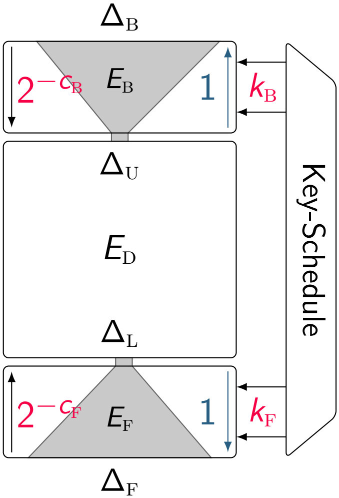

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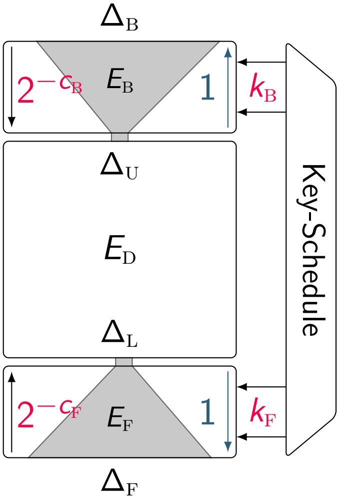
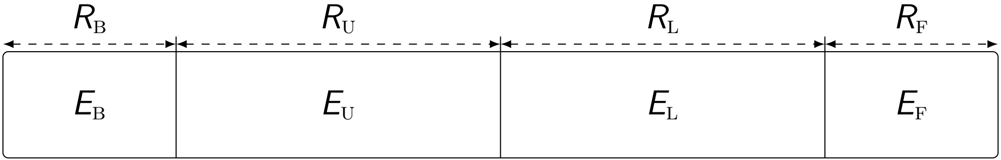


Usage of Our Tool

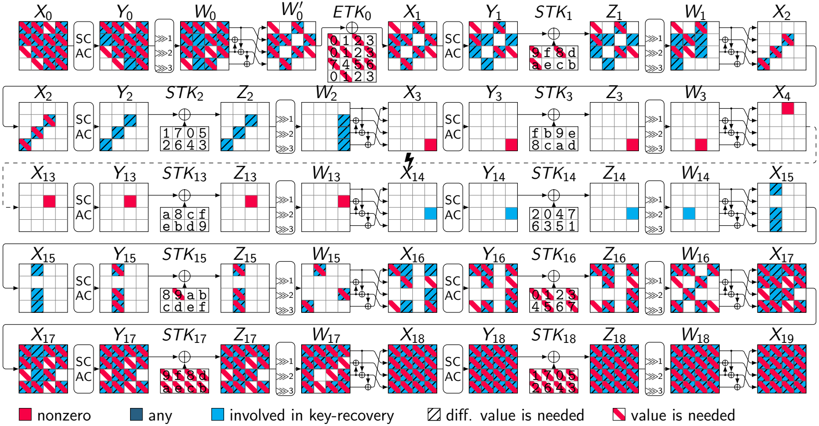
```
python3 attack.py -RB 4 -RU 10 -RL 6 -RF 7
```



- We use MiniZinc [Net+07] to create our CP models
- We use Gurobi [Gur22] and OrTools [PF] as the CP solvers
- Our tool can find the results in a few seconds running on a regular laptop

Example: 19-round ID Attack on SKINNY-n-$2n$

- $|k_{\mathrm{B}} \cup k_{\mathrm{F}}| = 26 \cdot c$
- $c_{\mathrm{B}} = 6 \cdot c$
- $c_{\mathrm{F}} = 15 \cdot c$
- $\Delta_{\mathrm{B}} = 7 \cdot c$
- $\Delta_{\mathrm{F}} = 16 \cdot c$
- $c \in \{4, 8\}$



X0 SC AC Y0 ⋙1 ⋙2 ⋙3 W0 W'0 ETK0 X1 SC AC Y1 STK1 Z1 W1 X2
0 1 2 3
0 1 2 3
7 4 5 6
0 1 2 3
9 f 8 d
a e c b
X2 SC AC Y2 STK2 Z2 W2 X3 SC AC Y3 STK3 Z3 W3 X4
1 7 0 5
2 6 4 3
f b 9 e
8 c a d
X13 SC AC Y13 STK13 Z13 W13 X14 SC AC Y14 STK14 Z14 W14 X15
a 8 c f
e b d 9
2 0 4 7
6 3 5 1
X15 SC AC Y15 STK15 Z15 W15 X16 SC AC Y16 STK16 Z16 W16 X17
8 9 a b
c d e f
0 1 2 3
4 5 6 7
X17 SC AC Y17 STK17 Z17 W17 X18 SC AC Y18 STK18 Z18 W18 X19
9 f 8 d
a e c b
1 7 0 5
2 6 4 3
🟥 nonzero
■ any
🟦 involved in key-recovery
▨ diff. value is needed
▧ value is needed

Part of Our Improved Results for SKINNY

Cipher	#R	Time	Data	Mem.	Attack	Setting / Model	Ref.
SKINNY-64-192	23	$2^{155.60}$	$2^{73.20}$	2^{138}	Int	180,SK / CP,CT	[Ank+19]
	26	2^{172}	2^{61}	2^{172}	Int	180,SK / CP,CT	This paper
SKINNY-128-384	27	2^{378}	$2^{126.03}$	2^{368}	ID	RTK / CP	[LGS17]
	27	$2^{362.61}$	$2^{124.99}$	2^{344}	ID	RTK / CP	This paper
SKINNY-64-128	18	2^{126}	$2^{62.68}$	2^{64}	ZC	STK / KP	[SMB18]
	19	$2^{119.12}$	$2^{62.89}$	2^{49}	ZC	STK / KP	This paper
	20	$2^{97.50}$	$2^{68.40}$	2^{82}	Int	120,SK / CP,CT	[Ank+19]
	22	2^{110}	$2^{57.58}$	2^{108}	Int	120,SK / CP,CT	This paper
SKINNY-128-256	19	$2^{241.80}$	2^{123}	2^{221}	ID	STK / CP	[YQC17]
	19	$2^{219.23}$	$2^{117.86}$	2^{208}	ID	STK / CP	This paper
SKINNY-64-64	14	2^{62}	$2^{62.58}$	2^{64}	ZC	STK / KP	[SMB18]
	16	$2^{62.71}$	$2^{61.35}$	$2^{37.80}$	ZC	STK / KP	This paper

Detecting Flaws in The Previous Attacks Using our Automatic Tools

Invalid Attacks on SKINNY

Cipher	Attack	#R	Setting / Model	Ref.	Flaw
SKINNY-n-n	ID	18	STK / CP	[TAY17]	KR
SKINNY-n-2n	ID	20	STK / CP	[TAY17]	KR
	ZC/Int †	22	SK / CP, CT	[ZCW22]	Dist
SKINNY-n-3n	ID	22	STK / CP	[TAY17]	KR
	ZC/Int †	26	SK / CP, CT	[ZCW22]	Dist

Conclusion

Contributions and Future Works

- Contributions
  - Introduced efficient unified model for finding full ID/ZC/integral attacks
  - Found improved attacks for SKINNY, CRAFT, SKINNYee, and SKINNYe-v2
- Future works
  - Applying our method to other ciphers, e.g., AES, MANTIS, QARMA, etc
  - Creating the bit-oriented version of our method
  - Improving the key-recovery part of our CP models for ZC and integral attacks

: https://github.com/hadipourh/zero

: https://ia.cr/2022/1147

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Zero-Correlation Attack and Its Relation to Integral Attack

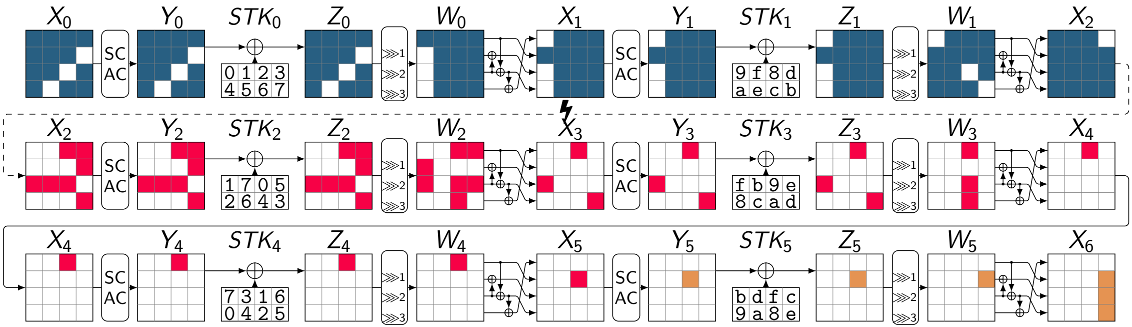
- ZC is the dual of ID in the context of linear cryptanalysis [BR14]
- Multidimensional ZC attack (ASIACRYPT 2012 [Bog+12])

Link Between ZC and Integral Attack [Sun+15]

Let $F : \mathbb{F}_2^n \to \mathbb{F}_2^n$ be a vectorial Boolean function. Assume A is a subspace of $\mathbb{F}_2^n$ and $\beta \in \mathbb{F}_2^n \setminus \{0\}$ such that (α, β) is a ZC approximation for any $\alpha \in A$. Then, for any $\lambda \in \mathbb{F}_2^n$, $\langle \beta, F(x + \lambda) \rangle$ is balanced over the set

$$A^{\perp} = \{x \in \mathbb{F}_2^n \mid \forall\, \alpha \in A : \langle \alpha, x \rangle = 0\}.$$

Example: Conversion of ZC Distinguisher to Integral Distinguisher



🟦 any 🟥 nonzero 🟧 fixed

- $X_0[7, 10, 13]$ takes all possible values and the remaining cells take a fixed value
- $X_6[7] \oplus X_6[11] \oplus X_6[15]$ is balanced