Improved Rectangle Attacks on SKINNY and CRAFT

Hosein Hadipour Nasour Bagheri Ling Song

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Outline

1 Boomerang and Sandwich Distinguishers

2 Our Method To Find Sandwich Distinguishers

3 BCT Framework and Our New Tools

4 Application to CRAFT

5 Application to SKINNY

6 Conclusion

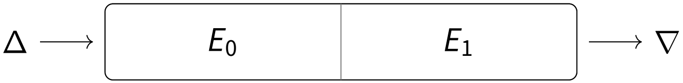
Boomerang and Sandwich Distinguishers

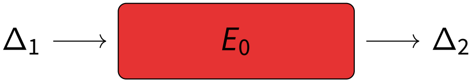
Long Weak Differentials V.S. Two Short Strong Differentials

$$\begin{tikzcd}\Delta \arrow[r] & \boxed{E : \mathbb{F}_2^n \to \mathbb{F}_2^n} \arrow[r] & \nabla\end{tikzcd}$$

$$0 \lnsim \Pr\{\Delta \xrightarrow{E} \nabla\} \lll 2^{-n}$$

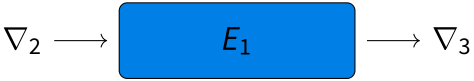
Long Weak Differentials V.S. Two Short Strong Differentials





$$p = \Pr\{\Delta_1 \xrightarrow{E_0} \Delta_2\}$$

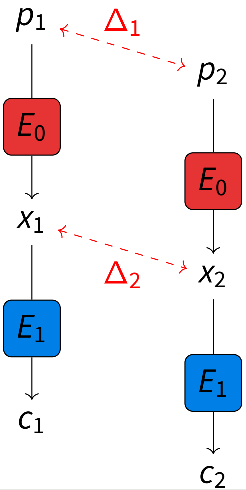
$$q = \Pr\{\nabla_2 \xrightarrow{E_1} \nabla_3\}$$



$$p^2q^2 \ggg 2^{-n}$$

Combine Two Short Differentials in ACPC Setting [Wag99]

$$\Pr\{\Delta_1 \xrightarrow{E_0} \Delta_2\} = p$$



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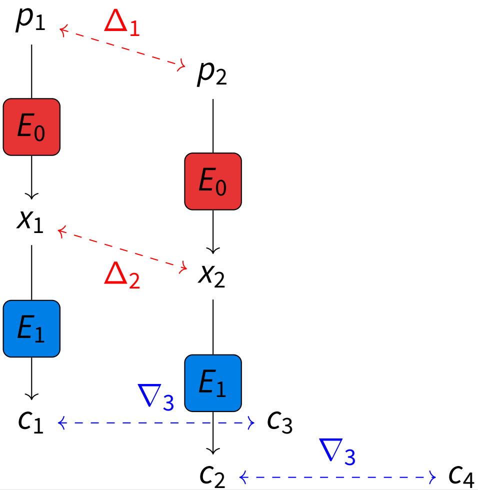

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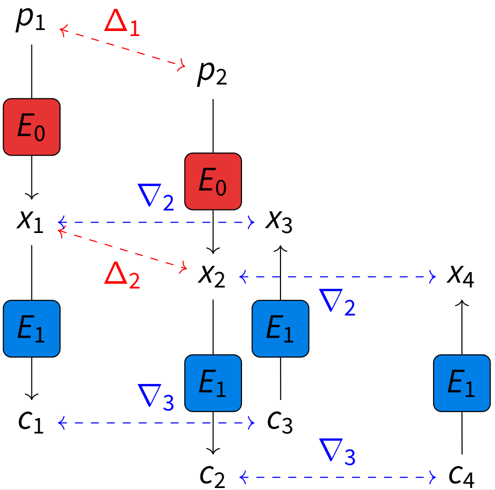
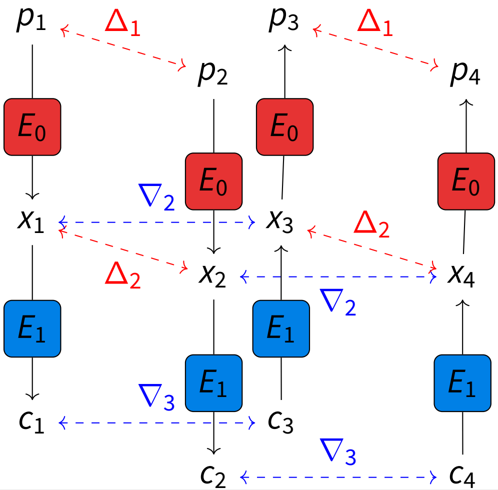


Combine Two Short Differentials in ACPC Setting [Wag99]

$$\Pr\{p_3 \oplus p_4 = \Delta_1\} = p^2 \times q^2$$



Upper and Lower Parts are Not Independent in Practice!

From the attacker’s perspective:

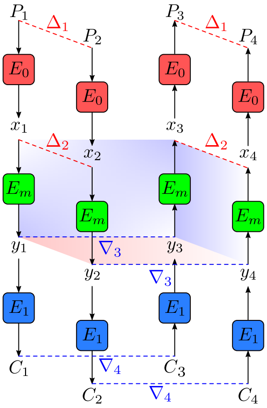
✓ Dependency can have a positive effect

- Feistel Switch [Wag99]
- Ladder Switch and S-box Switch [BK09]

⚠ Dependency can have a **negative** effect

- Inconsistency between the upper and lower trail [Mur11]

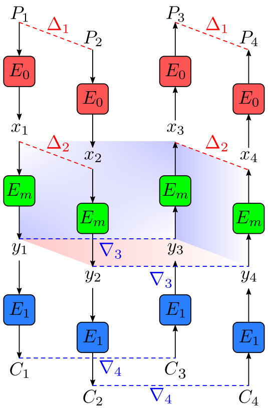
Sandwich Distinguisher [DKS10; DKS14]

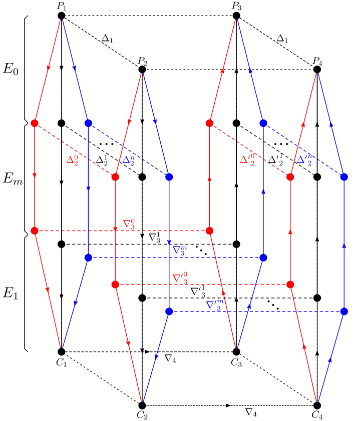


$$\Pr(P_3 \oplus P_4 = \Delta_1) \approx p^2 \times r \times q^2$$

$$r = r(\Delta_2, \nabla_3) = \Pr\{E_m^{-1}(E_m(x) \oplus \nabla_3) \oplus E_m^{-1}(E_m(x \oplus \Delta_2) \oplus \nabla_3) = \Delta_2\}$$

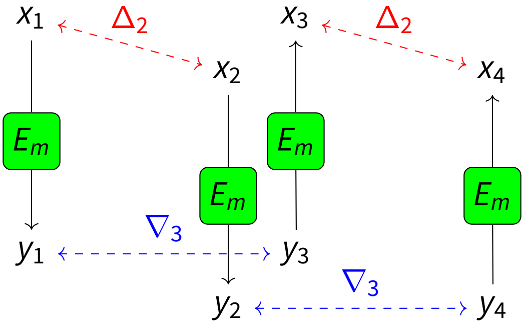
Sandwich Distinguisher [DKS10; DKS14]





$$\Pr\left(P_3 \oplus P_4 = \Delta_1\right) = \sum_{\Delta_2,\Delta'_2,\nabla_3,\nabla'_3} p_{\nabla 3} \times p_{\nabla'_3} \times r(\Delta_2,\Delta'_2,\nabla_3,\nabla'_3) \times q_{\nabla_3} \times q_{\nabla'_3}$$

Ladder Switch



$$r = r(\Delta_2, \nabla_3) = \Pr\{E_m^{-1}(E_m(x) \oplus \nabla_3) \oplus E_m^{-1}(E_m(x \oplus \Delta_2) \oplus \nabla_3) = \Delta_2\}$$

$$\Delta_2 = 0 \implies r = r(0, \nabla_3) = 1$$

$$\nabla_3 = 0 \implies r = r(\Delta_2, 0) = 1$$

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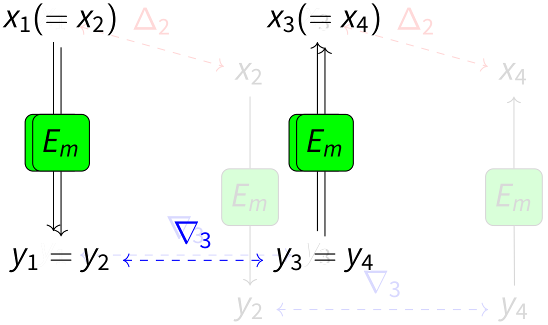

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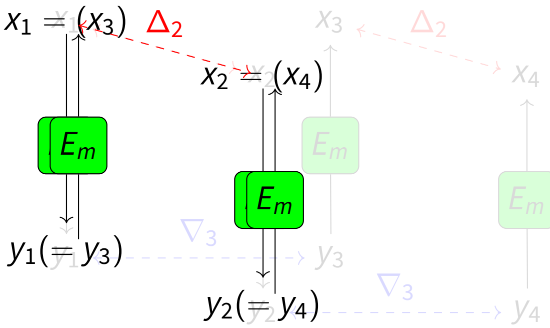

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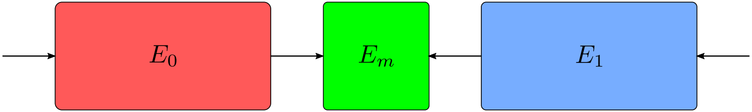
Effective Parameters in p^2q^2r for SPN Ciphers

- ✓ p is mostly determined by the number of active S-boxes in E_0
- ✓ q is mostly determined by the number of active S-boxes in E_1
- ✓ r is mostly determined by the number of common active S-boxes in E_m
- ⚠ Active S-boxes in E_0, E_1 are more expensive than common active S-boxes in E_m



Our Method To Find Sandwich Distinguishers

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Our method consists of 3 main steps:

- Find the truncated upper and lower trails minimizing:
  - number of active S-boxes in outer parts
  - and number of common active S-boxes in the middle part
- Instantiate the discovered truncated trails with concrete differential trails
- Compute p, q and r to derive the entire probability, i.e., p^2q^2r

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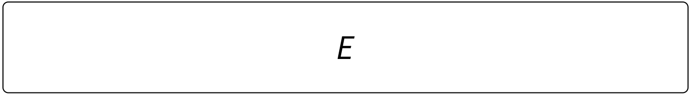
Finding Appropriate Truncated Upper and Lower Trails



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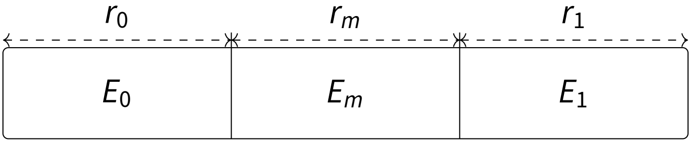

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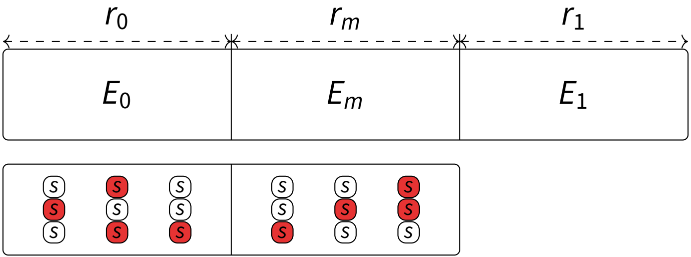

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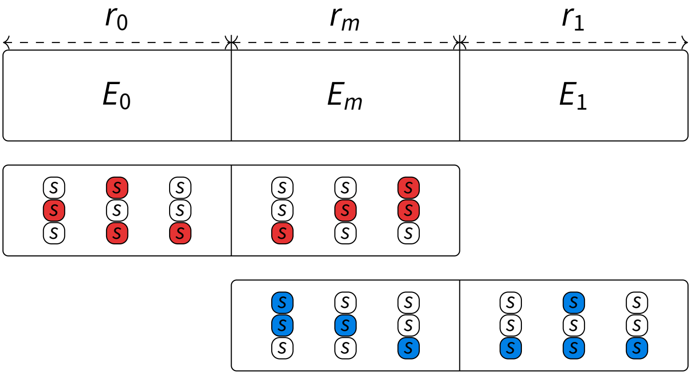

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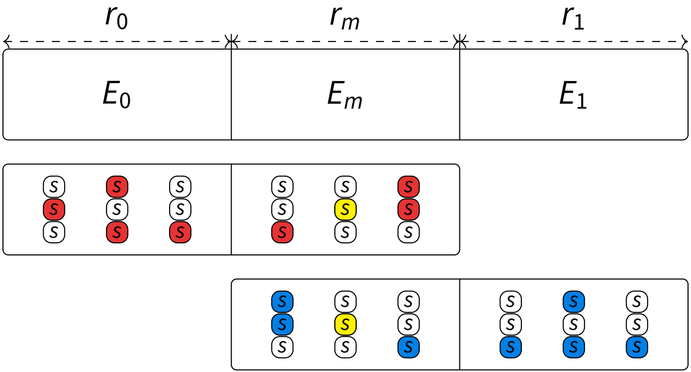
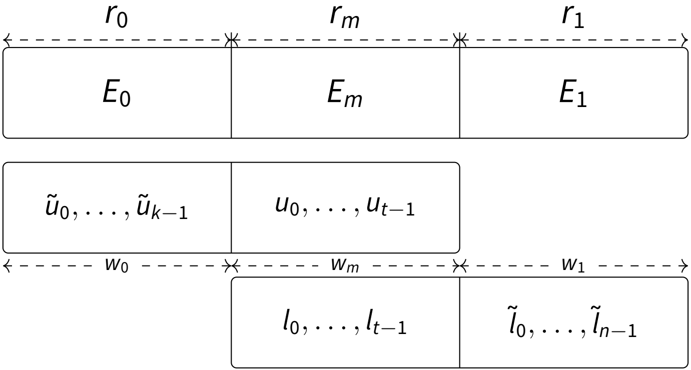


$$\color{red}{u_i} - s_i \geq 0,\ \color{blue}{\ell_i} - s_i \geq 0,\ -\color{red}{u_i} - \color{blue}{\ell_i} + s_i \geq -1$$

Finding Appropriate Truncated Upper and Lower Trails

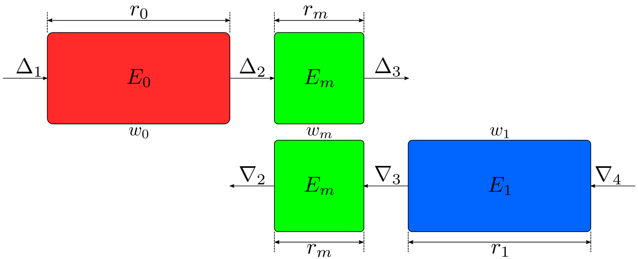


$$\min \sum_{i=0}^{k-1} w_0 \cdot \tilde{u}_i + \sum_{j=0}^{t-1} w_m \cdot s_j + \sum_{k=0}^{n-1} w_1 \cdot \tilde{l}_k.$$

$$u_i - s_i \geq 0,\ \ \ell_i - s_i \geq 0,\ \ -u_i - \ell_i + s_i \geq -1.$$

Instantiating Truncated Trails with Concrete Differentials

- We Instantiate the first and last parts with concrete bit-wise differentials
- To compute *p*, *q* and *r* we fix the differences at only four positions
- ⚠ **Our distinguishers do not rely on differential characteristics for** E_0, E_1, E_m



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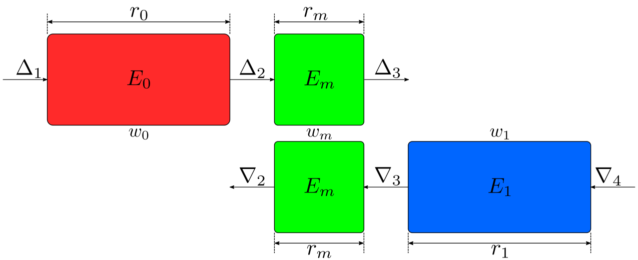

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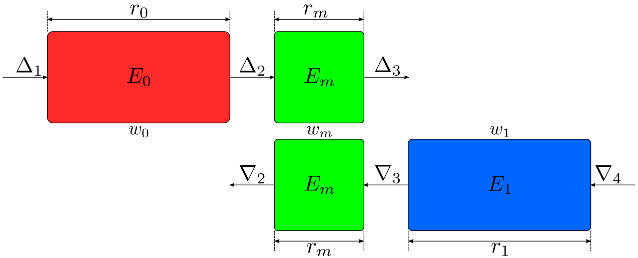

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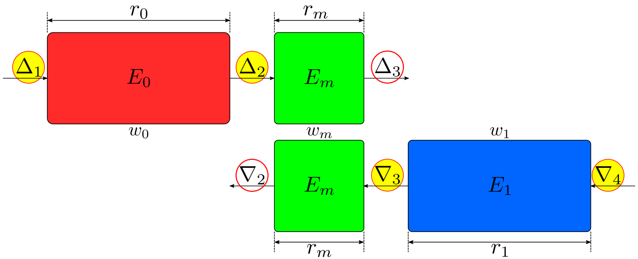
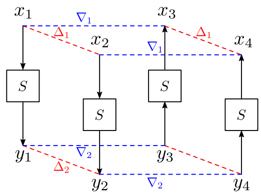


BCT Framework And Our New Tools

BCT Framework



Δ_1 Δ_2

∇_1 ∇_2

- $\mathcal{X}_{\mathrm{DDT}}(\Delta_1, \Delta_2) = \{x : S(x) \oplus S(x \oplus \Delta_1) = \Delta_2\}, \quad \mathrm{DDT}(\Delta_1, \Delta_2) = \#\mathcal{X}_{\mathrm{DDT}}(\Delta_1, \Delta_2)$
- $\mathcal{X}_{\mathrm{BCT}}(\Delta_1, \nabla_2) = \{x : S^{-1}(S(x) \oplus \nabla_2) \oplus S^{-1}(S(x \oplus \Delta_1) \oplus \nabla_2) = \Delta_1\}$, $\mathrm{BCT}(\Delta_1, \nabla_2) = \#\mathcal{X}_{\mathrm{BCT}}(\Delta_1, \nabla_2)$ [Cid+18]
- $\mathrm{UBCT}(\Delta_1, \Delta_2, \nabla_2) = \#\{x : x \in \mathcal{X}_{\mathrm{BCT}}(\Delta_1, \nabla_2) \cap \mathcal{X}_{\mathrm{DDT}}(\Delta_1, \Delta_2)\}$ [WP19]
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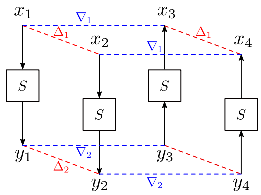
BCT Framework



$$\Delta_1 \longrightarrow \Delta_2$$

$$\nabla_1 \longrightarrow \nabla_2$$

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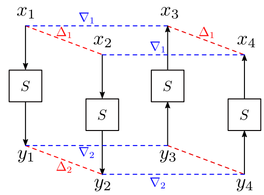

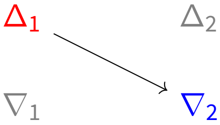

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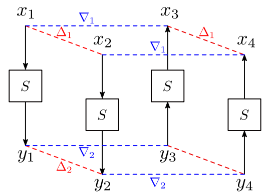

$$\begin{tikzcd}
\Delta_1 \arrow[r] \arrow[dr] & \Delta_2 \\
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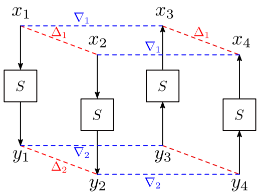

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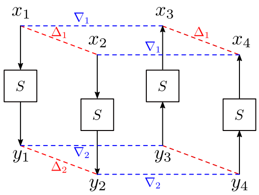

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Double Boomerang Connectivity Table (DBCT)

$$\begin{tikzcd}
\Delta_1 \arrow[r] \arrow[dr] & \Delta_2 \arrow[dr] & \\
& * \arrow[r] & \nabla_3
\end{tikzcd}$$

- ✓ $\mathtt{DBCT}^{\vdash}(\Delta_1, \Delta_2, \nabla_3) = \sum_{\nabla_2} \mathtt{UBCT}(\Delta_1, \nabla_2, \Delta_2) \cdot \mathtt{LBCT}(\Delta_2, \nabla_3, \nabla_2)$

- ✓ $\mathtt{DBCT}^{\dashv}(\Delta_1, \nabla_2, \nabla_3) = \sum_{\Delta_2} \mathtt{UBCT}(\Delta_1, \nabla_2, \Delta_2) \cdot \mathtt{LBCT}(\Delta_2, \nabla_3, \nabla_2)$.

- ✓ $\mathtt{DBCT}(\Delta_1, \nabla_3) = \sum_{\Delta_2} \mathtt{DBCT}^{\vdash}(\Delta_1, \Delta_2, \nabla_3) = \sum_{\nabla_2} \mathtt{DBCT}^{\dashv}(\Delta_1, \nabla_2, \nabla_3)$.

Double Boomerang Connectivity Table ($\mathtt{DBCT}$)

$$\begin{tikzcd}
\Delta_1 \arrow[r] \arrow[dr] & * \arrow[dr] & \\
& \nabla_2 \arrow[r] & \nabla_3
\end{tikzcd}$$

✓ $\mathtt{DBCT}^{\vdash}(\Delta_1, \Delta_2, \nabla_3) = \sum_{\nabla_2} \mathtt{UBCT}(\Delta_1, \nabla_2, \Delta_2) \cdot \mathtt{LBCT}(\Delta_2, \nabla_3, \nabla_2)$

✓ $\mathtt{DBCT}^{\dashv}(\Delta_1, \nabla_2, \nabla_3) = \sum_{\Delta_2} \mathtt{UBCT}(\Delta_1, \nabla_2, \Delta_2) \cdot \mathtt{LBCT}(\Delta_2, \nabla_3, \nabla_2)$.

✓ $\mathtt{DBCT}(\Delta_1, \nabla_3) = \sum_{\Delta_2} \mathtt{DBCT}^{\vdash}(\Delta_1, \Delta_2, \nabla_3) = \sum_{\nabla_2} \mathtt{DBCT}^{\dashv}(\Delta_1, \nabla_2, \nabla_3)$.

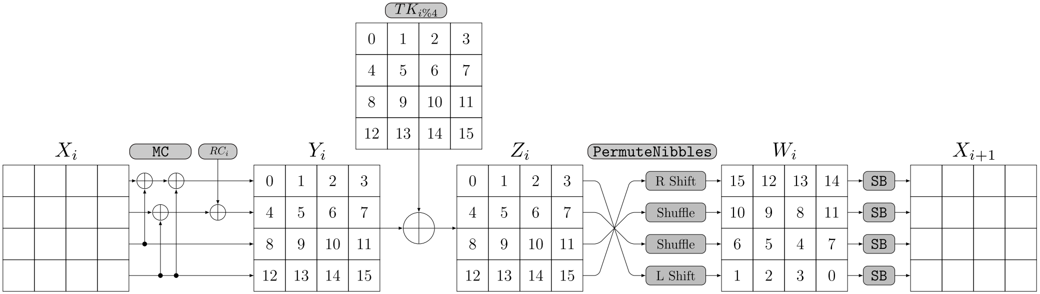
Double Boomerang Connectivity Table ($\mathtt{DBCT}$)

$$\begin{tikzcd}
\Delta_1 \arrow[r] \arrow[dr] & * \arrow[dr] & \\
& * \arrow[r] & \nabla_3
\end{tikzcd}$$

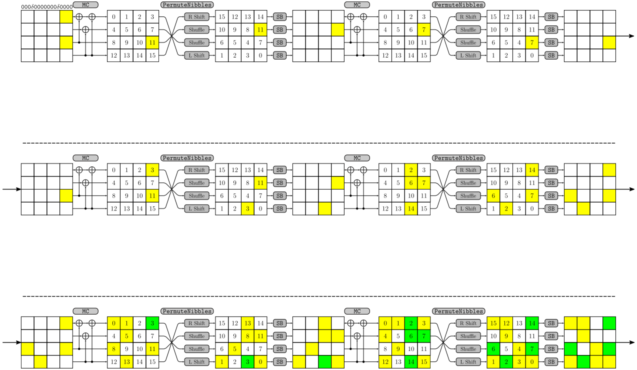
- $\mathtt{DBCT}^{\vdash}(\Delta_1, \Delta_2, \nabla_3) = \sum_{\nabla_2} \mathtt{UBCT}(\Delta_1, \nabla_2, \Delta_2) \cdot \mathtt{LBCT}(\Delta_2, \nabla_3, \nabla_2)$
- $\mathtt{DBCT}^{\dashv}(\Delta_1, \nabla_2, \nabla_3) = \sum_{\Delta_2} \mathtt{UBCT}(\Delta_1, \nabla_2, \Delta_2) \cdot \mathtt{LBCT}(\Delta_2, \nabla_3, \nabla_2).$
- $\mathtt{DBCT}(\Delta_1, \nabla_3) = \sum_{\Delta_2} \mathtt{DBCT}^{\vdash}(\Delta_1, \Delta_2, \nabla_3) = \sum_{\nabla_2} \mathtt{DBCT}^{\dashv}(\Delta_1, \nabla_2, \nabla_3).$

Application to CRAFT

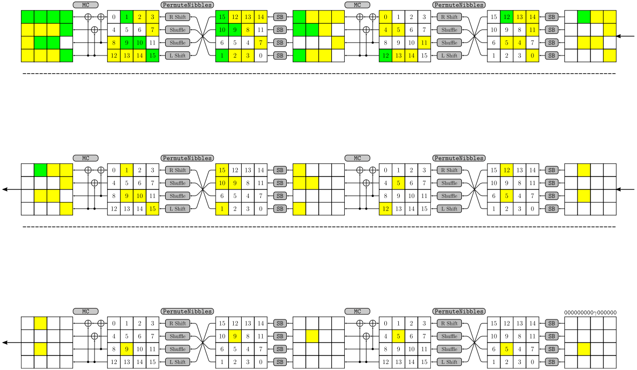
CRAFT [Bei+19]


$TK_{i\%4}$
0 1 2 3
4 5 6 7
8 9 10 11
12 13 14 15
X_i
MC
RC_i
Y_i
0 1 2 3
4 5 6 7
8 9 10 11
12 13 14 15
Z_i
0 1 2 3
4 5 6 7
8 9 10 11
12 13 14 15
PermuteNibbles
R Shift
Shuffle
Shuffle
L Shift
W_i
15 12 13 14
10 9 8 11
6 5 4 7
1 2 3 0
SB
SB
SB
SB
X_{i+1}

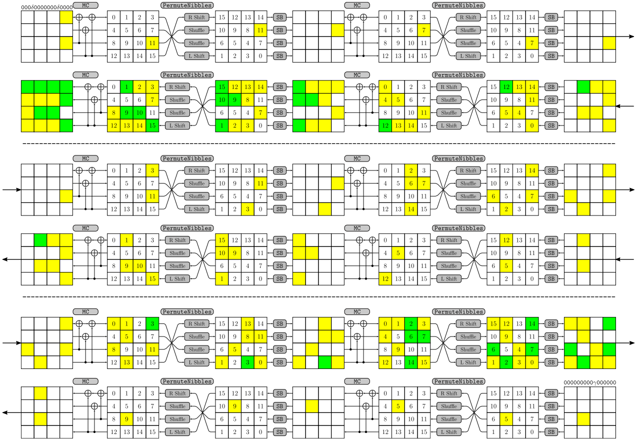
A 6-round ST Deterministic Distinguisher for CRAFT



A 6-round ST Deterministic Distinguisher for CRAFT

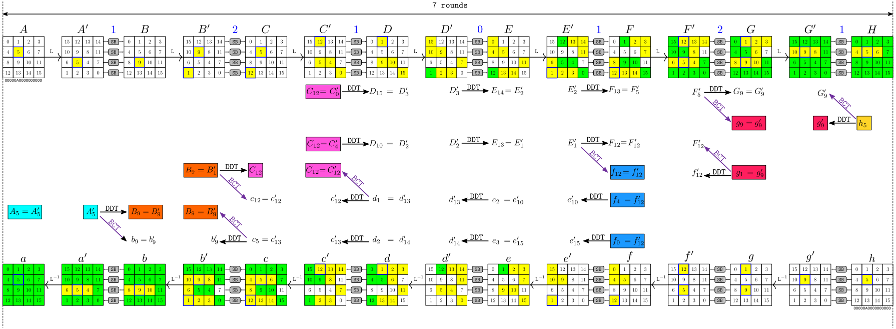


A 6-round ST Deterministic Distinguisher for CRAFT

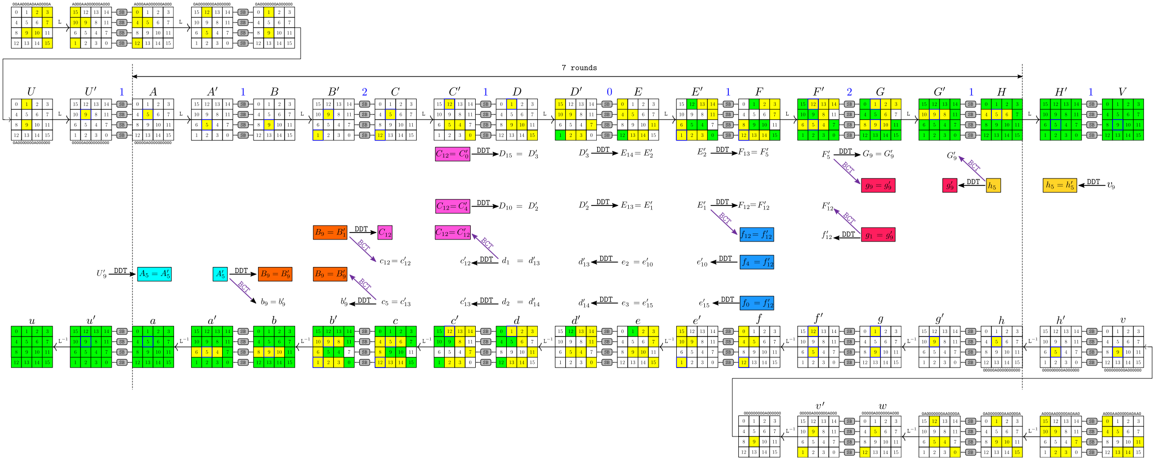


$\Pr = 1$

A 7-round Distinguisher (Extendable up to 14 rounds)


7 rounds
A
A′
1
B
B′
2
C
C′
1
D
D′
0
E
E′
1
F
F′
2
G
G′
1
H
L
SB
0000A0000000000
$C_{12} = C'_0$ DDT $D_{15} = D'_3$
D'_3 DDT $E_{14} = E'_2$
E'_2 DDT $F_{13} = F'_5$
F'_5 DDT $G_9 = G'_9$
BCT
$g_9 = g'_9$
G'_9
BCT
g'_9 DDT h_5
$C_{12} = C'_4$ DDT $D_{10} = D'_2$
D'_2 DDT $E_{13} = E'_1$
E'_1 DDT $F_{12} = F'_{12}$
BCT
$f_{12} = f'_{12}$
F'_{12}
BCT
f'_{12} DDT $g_1 = g'_9$
$B_9 = B'_1$ DDT C_{12}
BCT
$c_{12} = c'_{12}$
$C_{12} = C'_{12}$
BCT
c'_{12} DDT $d_1 = d'_{13}$
d'_{13} DDT $e_2 = e'_{10}$
e'_{10} DDT $f_4 = f'_{12}$
$A_5 = A'_5$
A'_5 DDT $B_9 = B'_9$
BCT
$b_9 = b'_9$
$B_9 = B'_9$
BCT
b'_9 DDT $c_5 = c'_{13}$
c'_{13} DDT $d_2 = d'_{14}$
d'_{14} DDT $e_3 = e'_{15}$
e'_{15} DDT $f_0 = f'_{12}$
a
a′
b
b′
c
c′
d
d′
e
e′
f
f′
g
g′
h
L^{-1}
SB
0000A0000000000

A 7-round Distinguisher (Extendable up to 14 rounds)

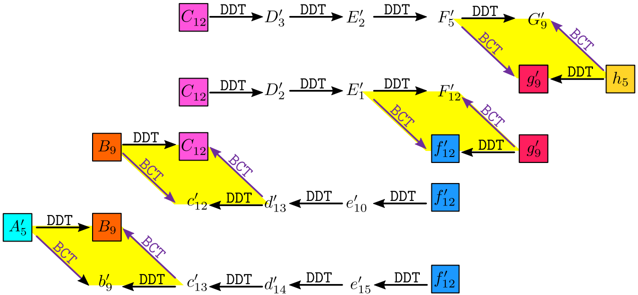


00AA000A0AA0000A
A000AA000000A000
0A0000000A000000
7 rounds
U
U′
1
A
A′
1
B
B′
2
C
C′
1
D
D′
0
E
E′
1
F
F′
2
G
G′
1
H
H′
1
V
L
SB
$C_{12} = C'_0 \xrightarrow{DDT} D_{15} = D'_3$
$D'_3 \xrightarrow{DDT} E_{14} = E'_2$
$E'_2 \xrightarrow{DDT} F_{13} = F'_5$
$F'_5 \xrightarrow{DDT} G_9 = G'_9$
G'_9
BCT
$g_9 = g'_9$
$g'_9 \xleftarrow{DDT} h_5$
$h_5 = h'_5 \xleftarrow{DDT} v_9$
$C_{12} = C'_4 \xrightarrow{DDT} D_{10} = D'_2$
$D'_2 \xrightarrow{DDT} E_{13} = E'_1$
$E'_1 \xrightarrow{DDT} F_{12} = F'_{12}$
F'_{12}
$f_{12} = f'_{12}$
$g_1 = g'_9$
$f'_{12} \xleftarrow{DDT} g_1 = g'_9$
$B_9 = B'_1 \xrightarrow{DDT} C_{12}$
$C_{12} = C'_{12}$
$c_{12} = c'_{12}$
$c'_{12} \xleftarrow{DDT} d_1 = d'_{13}$
$d'_{13} \xleftarrow{DDT} e_2 = e'_{10}$
$e'_{10} \xleftarrow{DDT} f_4 = f'_{12}$
$U'_9 \xrightarrow{DDT} A_5 = A'_5$
$A'_5 \xrightarrow{DDT} B_9 = B'_9$
$B_9 = B'_9$
$b_9 = b'_9$
$b'_9 \xleftarrow{DDT} c_5 = c'_{13}$
$c'_{13} \xleftarrow{DDT} d_2 = d'_{14}$
$d'_{14} \xleftarrow{DDT} e_3 = e'_{15}$
$e'_{15} \xleftarrow{DDT} f_0 = f'_{12}$
u
u′
a
a′
b
b′
c
c′
d
d′
e
e′
f
f′
g
g′
h
h′
v
L^{-1}
0A0000000000000
00000A0000000000
000000000A000000
00000A000000A000
0A0000000AA0000A
A000AA00000A0AA0
v′
w

Hosein Hadipour, Nasour Bagheri, Ling Song

FSE 2022

A 7-round Distinguisher (Extendable up to 14 rounds)



$$\mathrm{DBCT_{total}} = \mathrm{DBCT}^{\vdash}(A_5, B_9, c_5) \cdot \mathrm{DBCT}^{\vdash}(B_9, C_{12}, d_1) \cdot \mathrm{DBCT}^{\dashv}(E'_1, f'_{12}, g'_9) \cdot \mathrm{DBCT}^{\dashv}(F'_5, g'_9, h_5)$$

$$\mathrm{Pr_{total}} = \mathrm{Pr}(d_1 \xleftarrow{2\ \mathrm{DDT}} f'_{12}) \cdot \mathrm{Pr}(c_5 \xleftarrow{3\ \mathrm{DDT}} f'_{12}) \cdot \mathrm{Pr}(C_{12} \xrightarrow{2\ \mathrm{DDT}} E'_1) \cdot \mathrm{Pr}(C_{12} \xrightarrow{3\ \mathrm{DDT}} F'_5)$$

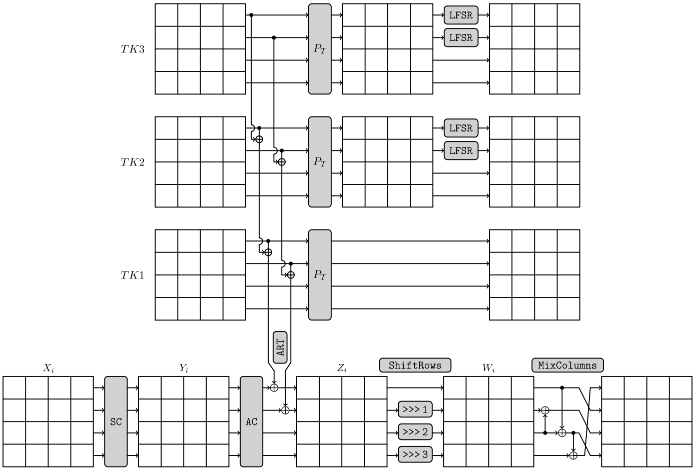
$$r = 2^{-8 \cdot n} \cdot \sum_{B_9} \sum_{C_{12}} \sum_{g'_9} \sum_{f'_{12}} \sum_{c_5} \sum_{d_1} \sum_{E'_1} \sum_{F'_5} \mathrm{DBCT_{total}} \cdot \mathrm{Pr_{total}}.$$

Summary of Our Distinguishers for CRAFT

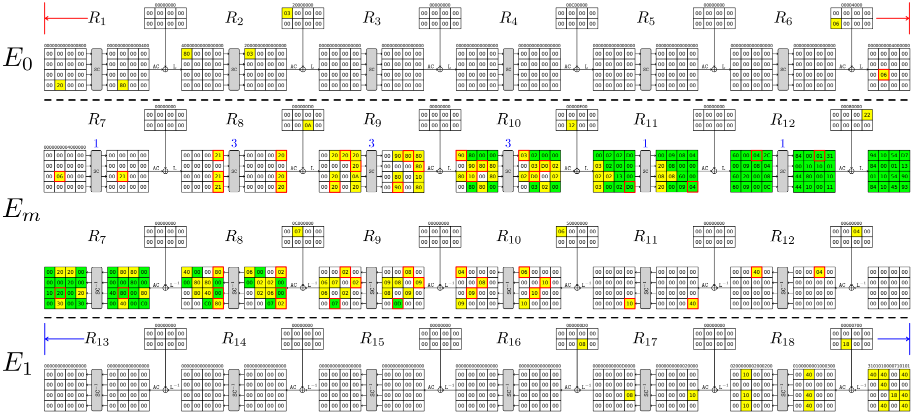
Distinguisher Type	# Rounds	Probability	Reference
ST-Differential	9	$2^{-40.20}$	[Had+19]
	10	$2^{-44.89}$	
	11	$2^{-49.79}$	
	12	$2^{-54.48}$	
	13	$2^{-59.13}$	
	14	$2^{-63.80}$	
ST-Boomerang	6	**1**	This Paper
	7	**2^{-4}**	
	8	**2^{-8}**	
	9	**$2^{-14.76}$**	
	10	**$2^{-19.83}$**	
	11	**$2^{-24.90}$**	
	12	**$2^{-34.89}$**	
	13	$2^{-44.89}$	
	14	$2^{-55.85}$	

Application to SKINNY

SKINNY [Bei+16]



18-round Practical Sandwich Distinguisher for SKINNY-128-256



$$p = 2^{-3}$$

$$r = 2^{-20.19}$$

$$q = 2^{-7.29}$$

$$p^2q^2r = 2^{-40.77} \ggg 2^{-77.83}$$

Summary of Our Distinguishers for SKINNY

Version	n	#Rounds	Probability	
			Our Distinguisher	[SQH19]
SKINNY-n-$2n$	64	17	$\mathbf{2^{-26.54}}$(II)	$2^{-29.78}$
		18	$\mathbf{2^{-37.90}}$(II)	$2^{-45.14}$
		19	$\mathbf{2^{-51.08}}$(II)	$2^{-65.62}$
	128	18	$\mathbf{2^{-40.77}}$ (II)	$2^{-77.83}$
		19	$\mathbf{2^{-58.33}}$ (II)	$2^{-97.53}$
		20	$\mathbf{2^{-85.31}}$ (I)	$2^{-128.65}$
		21	$\mathbf{2^{-114.07}}$ (II)	$2^{-171.77}$
SKINNY-n-$3n$	64	22	$\mathbf{2^{-38.84}}$ (I)	$2^{-42.98}$
		23	$\mathbf{2^{-52.84}}$ (I)	$2^{-67.36}$
	128	22	$\mathbf{2^{-40.57}}$ (I)	$2^{-48.30}$
		23	$\mathbf{2^{-56.47}}$ (I)	$2^{-75.86}$
		24	$\mathbf{2^{-87.39}}$ (I)	$2^{-107.86}$
		25	$\mathbf{2^{-116.59}}$ (I)	$2^{-141.66}$

Summary of Our Key Recovery Attacks

Scheme	#rounds	Data	Memory	Time	Attack	P_s	Reference
SKINNY-64-128	23/36	$2^{60.54}$	$2^{60.9}$	$2^{120.7}$	Rectangle	0.977	This paper
SKINNY-64-192	29/40	$2^{61.42}$	2^{80}	2^{178}	Rectangle	0.977	This paper
SKINNY-128-256	24/48	$2^{125.21}$	$2^{125.54}$	$2^{209.85}$	Rectangle	0.977	This paper
SKINNY-128-384	30/56	$2^{125.29}$	$2^{125.8}$	$2^{361.68}$	Rectangle	0.977	This paper
CRAFT	18/32	$2^{60.92}$	2^{84}	$2^{101.7}$	Rectangle	0.977	This paper
SKINNY-64-128	23/36	$2^{62.47}$	2^{124}	$2^{125.91}$	Impossible	1	[LGS17]
SKINNY-64-192	27/40	$2^{63.5}$	2^{80}	$2^{165.5}$	Rectangle	0.916	[LGS17]
SKINNY-128-256	23/48	$2^{124.47}$	2^{248}	$2^{251.47}$	Impossible	1	[LGS17]
SKINNY-128-384	28/56	2^{122}	$2^{122.32}$	$2^{315.25}$	Rectangle	0.8315	[Zha+20]

Conclusion

Our Main Contributions

- ✓ We introduced a heuristic method to search for sandwich distinguishers
- ✓ We introduced new tools in BCT framework (DBCT, ...)
- ✓ We significantly improved the rectangle attacks on SKINNY and CRAFT

Thanks for your attention!

https://github.com/hadipourh/Boomerang

Bibliography I

[Bei+16] Christof Beierle et al. **The SKINNY Family of Block Ciphers and Its Low-Latency Variant MANTIS.** CRYPTO (2). Vol. 9815. Lecture Notes in Computer Science. Springer, 2016, pp. 123–153.

[Bei+19] Christof Beierle et al. **CRAFT: Lightweight Tweakable Block Cipher with Efficient Protection Against DFA Attacks.** *IACR Trans. Symmetric Cryptol.* 2019.1 (2019), pp. 5–45.

[BK09] Alex Biryukov and Dmitry Khovratovich. **Related-Key Cryptanalysis of the Full AES-192 and AES-256.** ASIACRYPT. Vol. 5912. Lecture Notes in Computer Science. Springer, 2009, pp. 1–18.

[Cid+18] Carlos Cid et al. **Boomerang Connectivity Table: A New Cryptanalysis Tool.** EUROCRYPT (2). Vol. 10821. Lecture Notes in Computer Science. Springer, 2018, pp. 683–714.

[DKS10] Orr Dunkelman, Nathan Keller, and Adi Shamir. **A Practical-Time Related-Key Attack on the KASUMI Cryptosystem Used in GSM and 3G Telephony.** CRYPTO. Vol. 6223. Lecture Notes in Computer Science. Springer, 2010, pp. 393–410.

[DKS14] Orr Dunkelman, Nathan Keller, and Adi Shamir. **A Practical-Time Related-Key Attack on the KASUMI Cryptosystem Used in GSM and 3G Telephony.** *J. Cryptol.* 27.4 (2014), pp. 824–849.

Bibliography II

[Had+19] Hosein Hadipour et al. **Comprehensive security analysis of CRAFT.** *IACR Trans. Symmetric Cryptol.* 2019.4 (2019), pp. 290–317.

[LGS17] Guozhen Liu, Mohona Ghosh, and Ling Song. **Security Analysis of SKINNY under Related-Tweakey Settings.** *IACR Transactions on Symmetric Cryptology* 2017.3 (Sept. 2017). `https://tosc.iacr.org/index.php/ToSC/article/view/765`, pp. 37–72. DOI: `10.13154/tosc.v2017.i3.37-72`.

[Mur11] Sean Murphy. **The Return of the Cryptographic Boomerang.** *IEEE Trans. Inf. Theory* 57.4 (2011), pp. 2517–2521.

[SQH19] Ling Song, Xianrui Qin, and Lei Hu. **Boomerang Connectivity Table Revisited. Application to SKINNY and AES.** *IACR Trans. Symmetric Cryptol.* 2019.1 (2019), pp. 118–141.

[Wag99] David A. Wagner. **The Boomerang Attack.** FSE. Vol. 1636. Lecture Notes in Computer Science. Springer, 1999, pp. 156–170.

[WP19] Haoyang Wang and Thomas Peyrin. **Boomerang Switch in Multiple Rounds. Application to AES Variants and Deoxys.** *IACR Trans. Symmetric Cryptol.* 2019.1 (2019), pp. 142–169.

Bibliography III

[Zha+20] Boxin Zhao et al. **Generalized related-key rectangle attacks on block ciphers with linear key schedule: applications to SKINNY and GIFT**. *Designs, Codes and Cryptography* 88.6 (2020), pp. 1103–1126.