SCIENCE
PASSION
TECHNOLOGY

Improved Rectangle Attacks on SKINNY and CRAFT

Hosein Hadipour Nasour Bagheri Ling Song

FSE 2022 - Athens, Greece

Outline

Boomerang and Sandwich Distinguishers

Long Weak Differentials V.S. Two Short Strong Differentials

$$\Delta \longrightarrow \boxed{E : \mathbb{F}_2^n \to \mathbb{F}_2^n} \longrightarrow \nabla$$

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

Long Weak Differentials V.S. Two Short Strong Differentials

$$\Delta \longrightarrow \boxed{E_0 \mid E_1} \longrightarrow \nabla$$

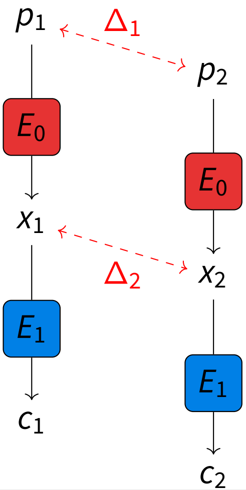
$$\Delta_1 \longrightarrow \boxed{E_0} \longrightarrow \Delta_2 \qquad p = \Pr\{\Delta_1 \xrightarrow{E_0} \Delta_2\}$$

$$q = \Pr\{\nabla_2 \xrightarrow{E_1} \nabla_3\} \qquad \nabla_2 \longrightarrow \boxed{E_1} \longrightarrow \nabla_3$$

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

Combine Two Short Differentials in ACPC Setting [Wag99]

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



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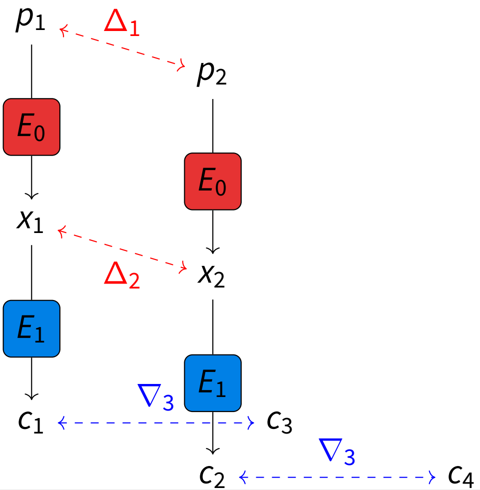

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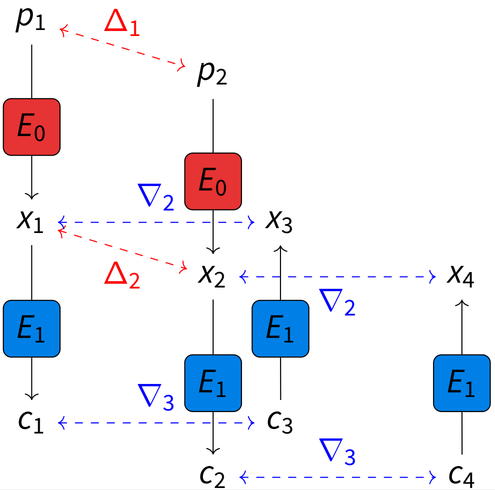
Combine Two Short Differentials in ACPC Setting [Wag99]

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

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



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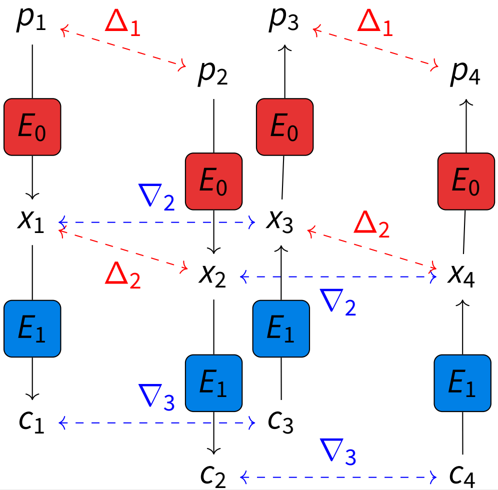
Combine Two Short Differentials in ACPC Setting [Wag99]

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



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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]

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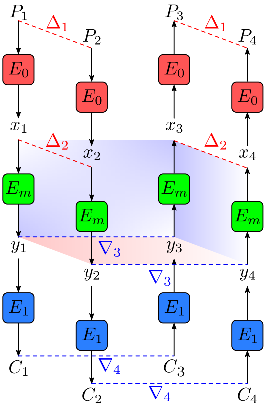
Sandwich Distinguisher [DKS10; DKS14]



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

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

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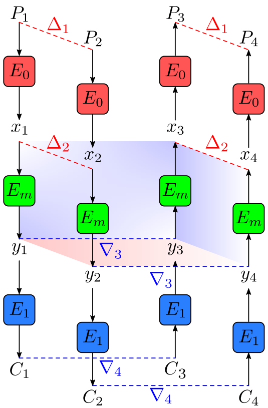

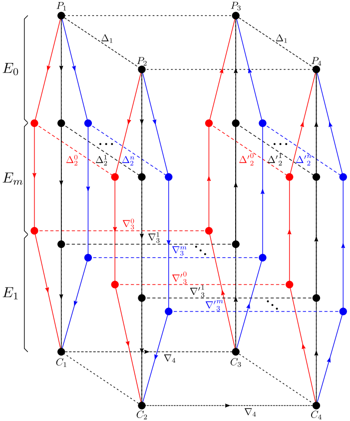

$$\Pr\left(P_3 \oplus P_4 = \Delta_1\right) = \sum_{\Delta_2, \Delta_2', \nabla_3, \nabla_3'} p_{\nabla_3} \times p_{\nabla_3'} \times r(\Delta_2, \Delta_2', \nabla_3, \nabla_3') \times q_{\nabla_3} \times q_{\nabla_3'}$$

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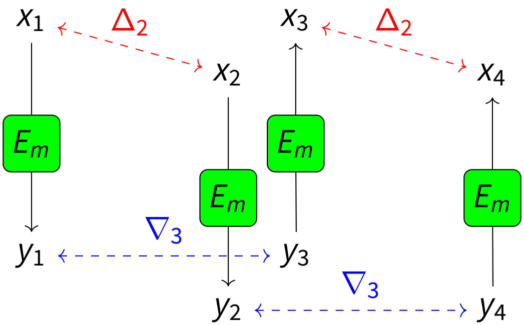
Ladder Switch



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

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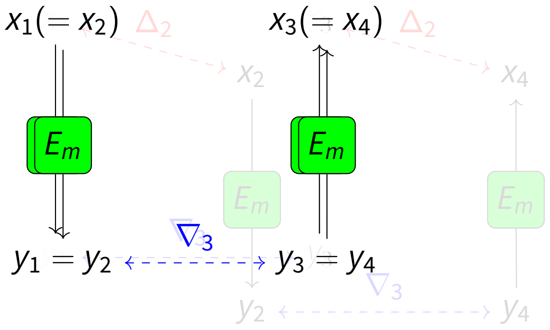

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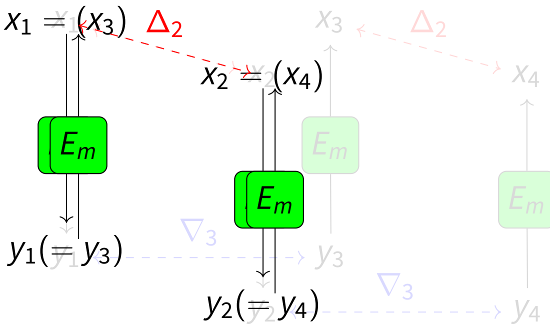

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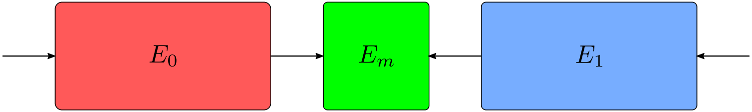
Effective Parameters in p^2q^2r for SPN Ciphers

- 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



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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

$$\boxed{E}$$

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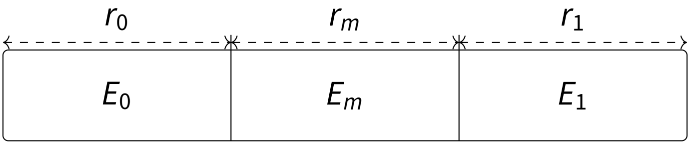

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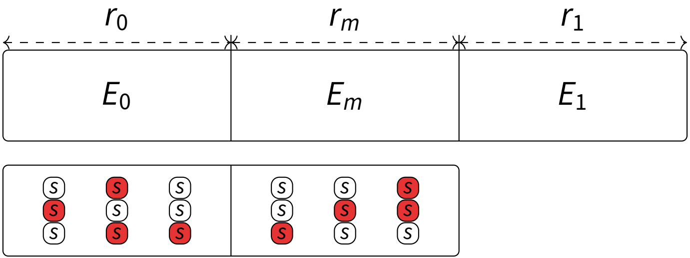

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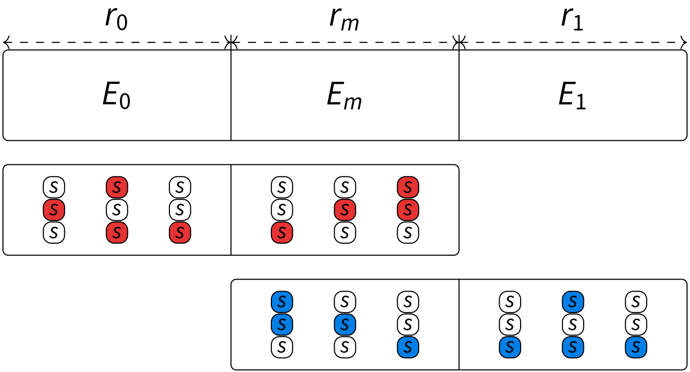

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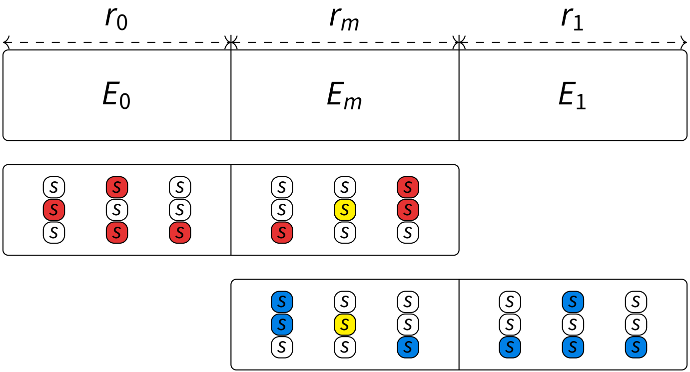

$$u_i - s_i \geq 0, \; \ell_i - s_i \geq 0, \; -u_i - \ell_i + s_i \geq -1$$

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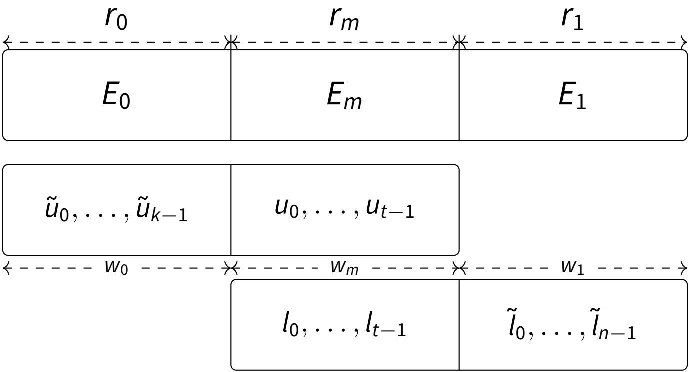
Finding Appropriate Truncated Upper and Lower Trails

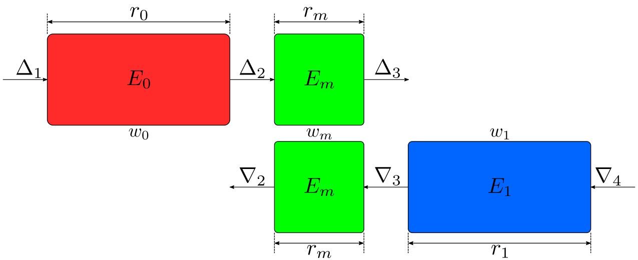


$$\min \sum_{i=0}^{k-1} w_0 \cdot \tilde{u}_i + \sum_{j=0}^{t-1} w_m \cdot s_j + \sum_{k=0}^{n-1} w_1 \cdot \tilde{l}_k.$$

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

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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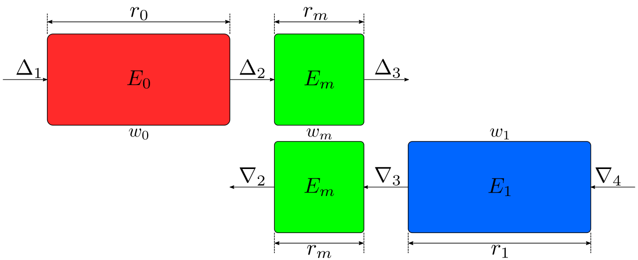

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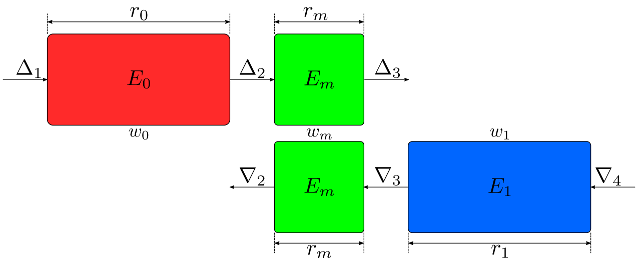

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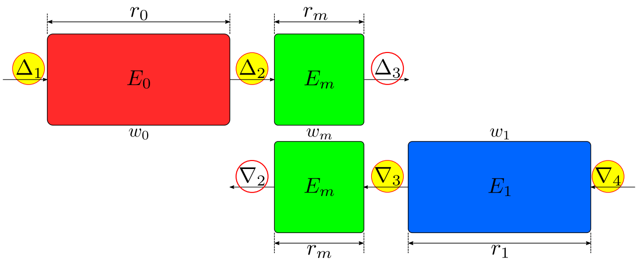

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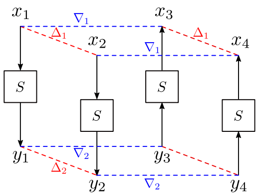
BCT Framework And Our New Tools

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]
- $\mathrm{LBCT}(\Delta_1, \nabla_1, \nabla_2) = \#\{x : x \in \mathcal{X}_{\mathrm{BCT}}(\Delta_1, \nabla_2) \cap \mathcal{X}_{\mathrm{DDT}}(\nabla_1, \nabla_2)\}$ [SQH19]

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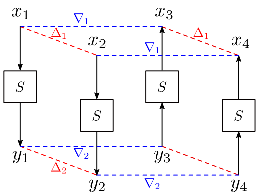
BCT Framework



$$\Delta_1 \longrightarrow \Delta_2$$

$$\nabla_1 \longrightarrow \nabla_2$$

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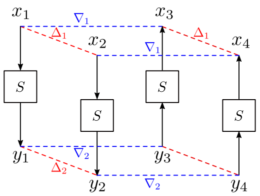

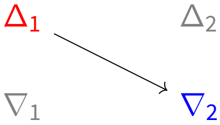

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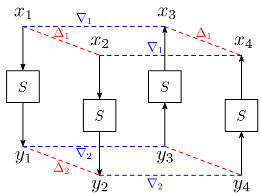

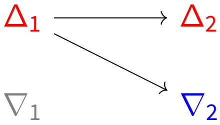

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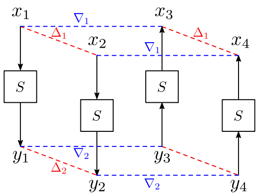

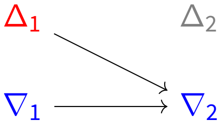

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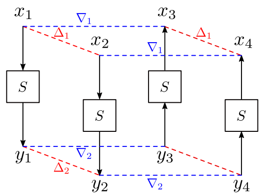

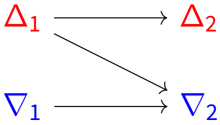

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Double Boomerang Connectivity Table (DBCT)

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

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

Double Boomerang Connectivity Table (DBCT)

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

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

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

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

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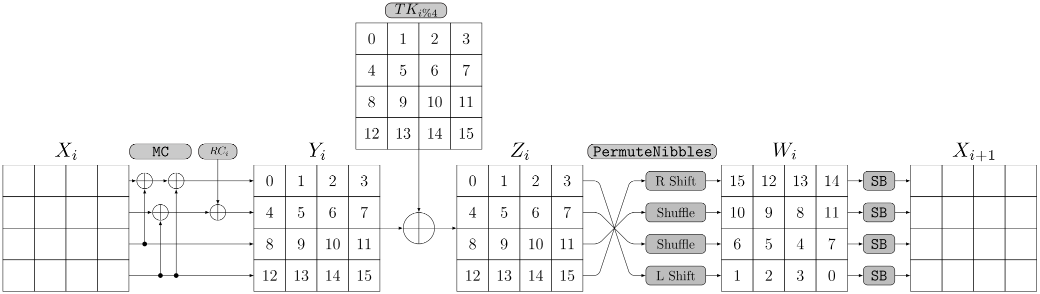
Application to CRAFT

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

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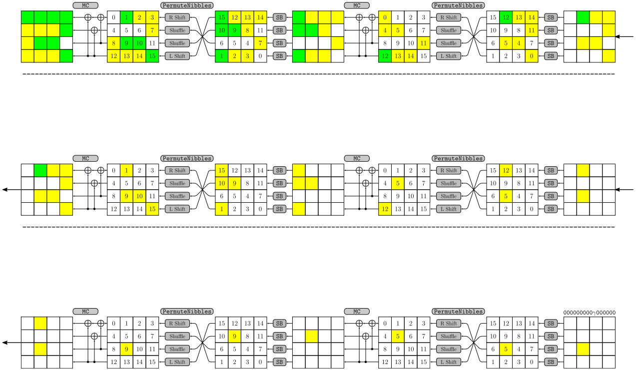
A 6-round ST Deterministic Distinguisher for CRAFT



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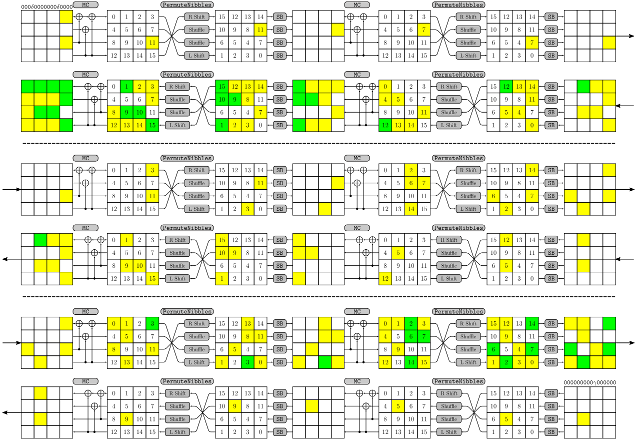
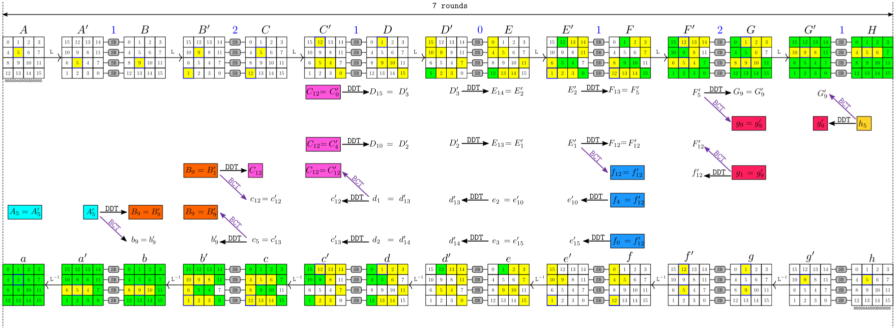
A 6-round ST Deterministic Distinguisher for CRAFT



$\Pr = 1$

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



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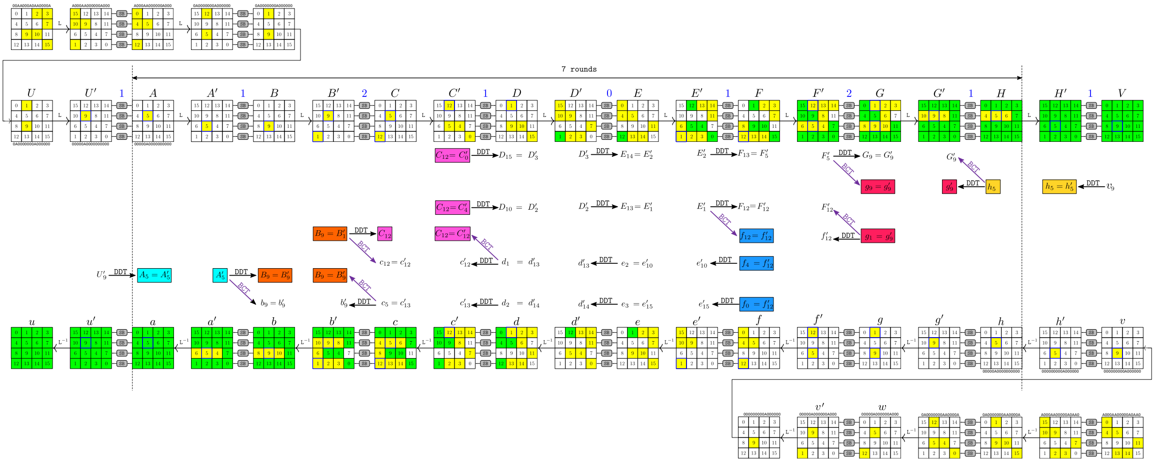
A 7-round Distinguisher (Extendable up to 14 rounds)



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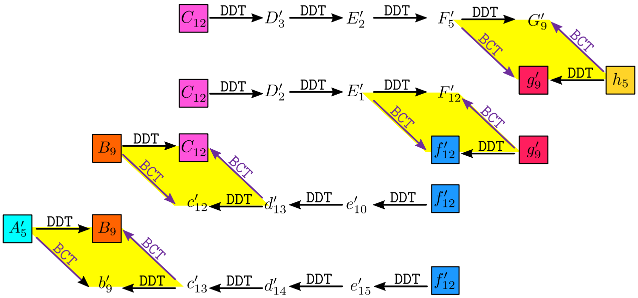
A 7-round Distinguisher (Extendable up to 14 rounds)



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

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

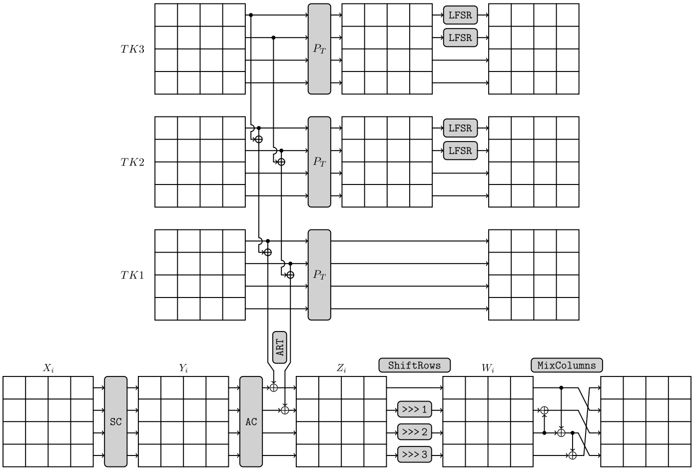
$$r = 2^{-8 \cdot n} \cdot \sum_{B_9} \sum_{C_{12}} \sum_{g'_9} \sum_{f'_{12}} \sum_{c_5} \sum_{d_1} \sum_{E'_1} \sum_{F'_5} \mathrm{DBCT}_{\mathrm{total}} \cdot \mathrm{Pr}_{\mathrm{total}}.$$

Summary of Our Distinguishers for CRAFT

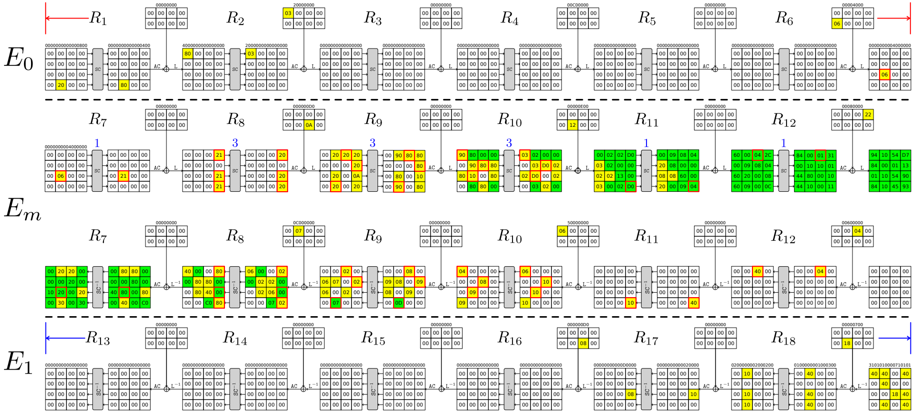
Distinguisher Type	# Rounds	Probability	Reference
ST-Differential	9	$2^{-40.20}$	[Had+19]
	10	$2^{-44.89}$	
	11	$2^{-49.79}$	
	12	$2^{-54.48}$	
	13	$2^{-59.13}$	
	14	$2^{-63.80}$	
ST-Boomerang	6	$\mathbf{1}$	This Paper
	7	$\mathbf{2^{-4}}$	
	8	$\mathbf{2^{-8}}$	
	9	$\mathbf{2^{-14.76}}$	
	10	$\mathbf{2^{-19.83}}$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

Application to SKINNY

SKINNY [Bei+16]



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



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

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

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

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

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Summary of Our Distinguishers for SKINNY

Version	n	#Rounds	Probability: Our Distinguisher	Probability: [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]

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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

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