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Improved Rectangle Attacks on SKINNY and CRAFT

Hosein Hadipour Nasour Bagheri Ling Song

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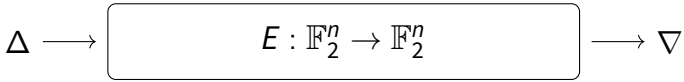
Outline

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



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

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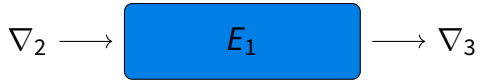
Long Weak Differentials V.S. Two Short Strong Differentials

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

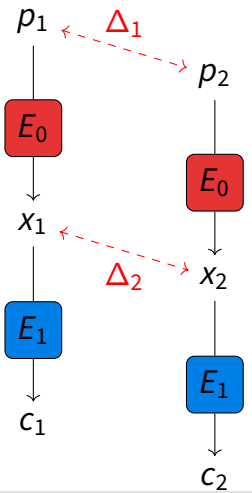
$q = \Pr\{\nabla_2 \xrightarrow{E_1} \nabla_3\}$



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

Combine Two Short Differentials in ACPC Setting [Wag99]

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



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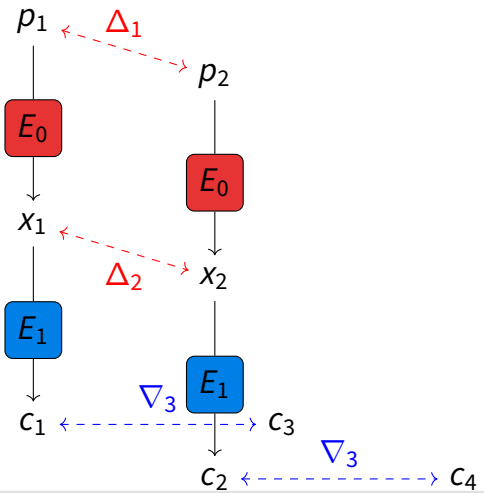

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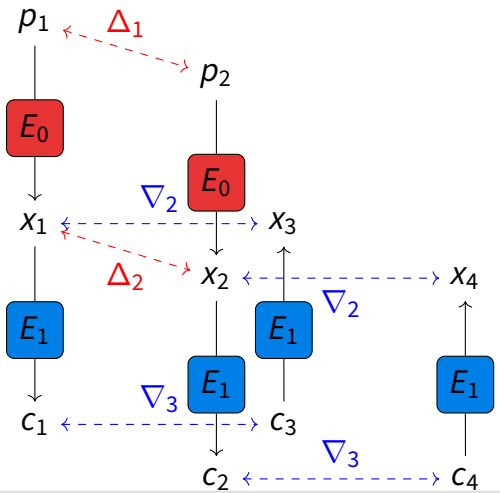
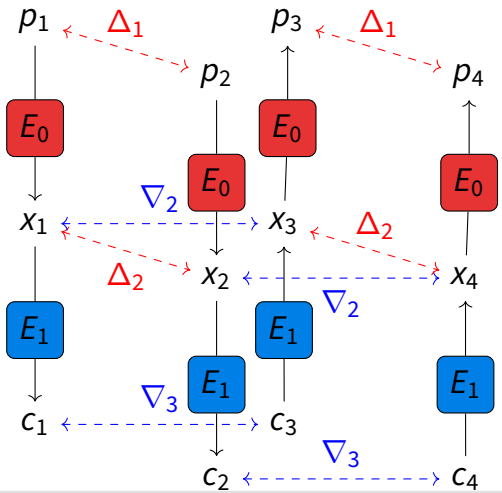


Combine Two Short Differentials in ACPC Setting [Wag99]

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



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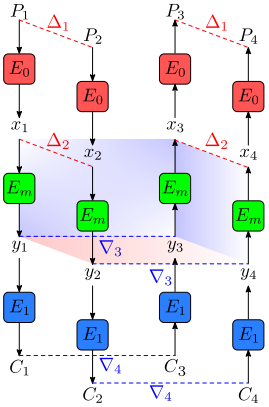
Upper and Lower Parts are Not Independent in Practice!

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]

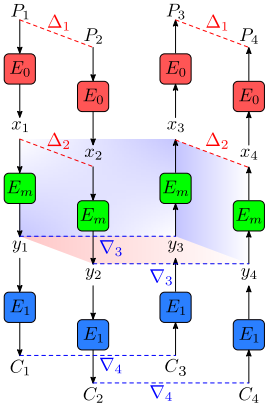
Sandwich Distinguisher [DKS10; DKS14]

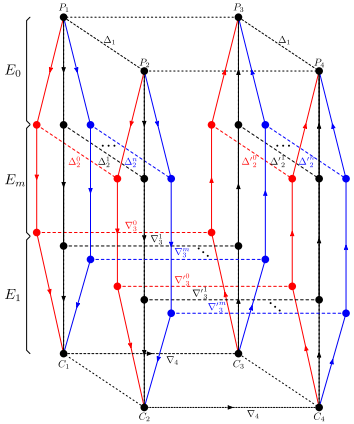


$$\Pr(P_3 \oplus P_4 = \Delta_1) \approx p^2 \times r \times q^2$$

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

Sandwich Distinguisher [DKS10; DKS14]





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

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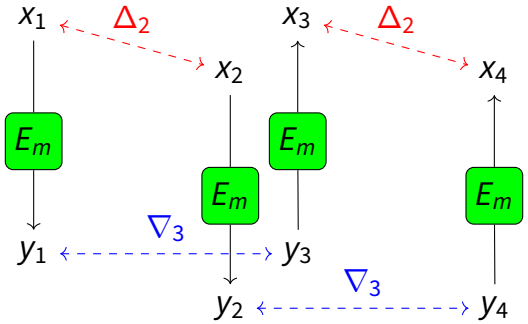
Ladder Switch



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

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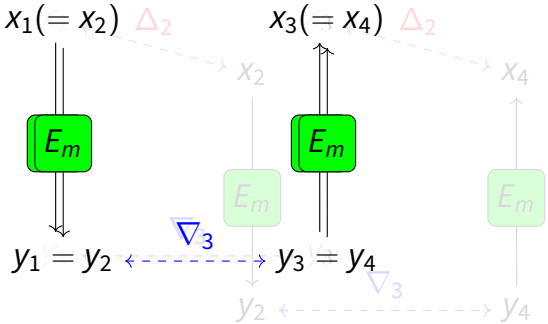

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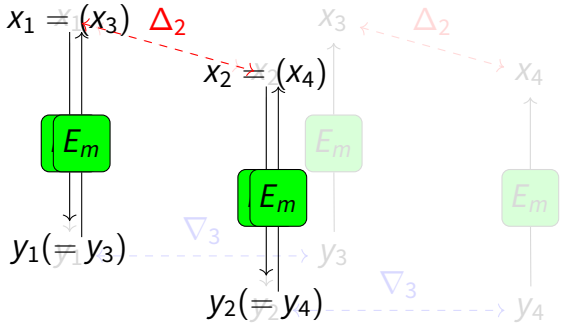

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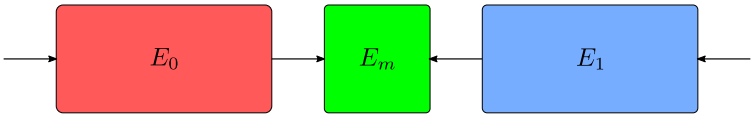
Effective Parameters in p^2q^2r for SPN Ciphers

- 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



Our Method To Find Sandwich Distinguishers

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Our method consists of 3 main steps:

1. 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
2. Instantiate the discovered truncated trails with concrete differential trails
3. Compute p, q and r to derive the entire probability, i.e., p^2q^2r

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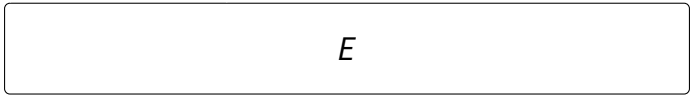
Finding Appropriate Truncated Upper and Lower Trails



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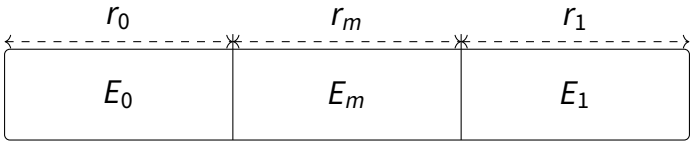

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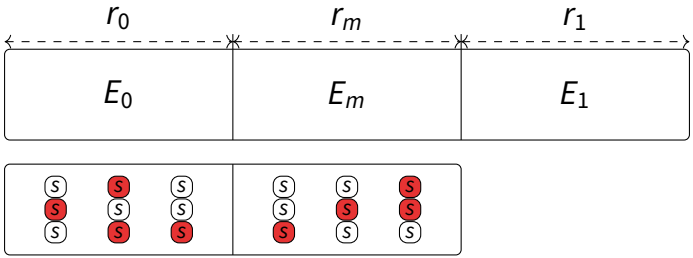

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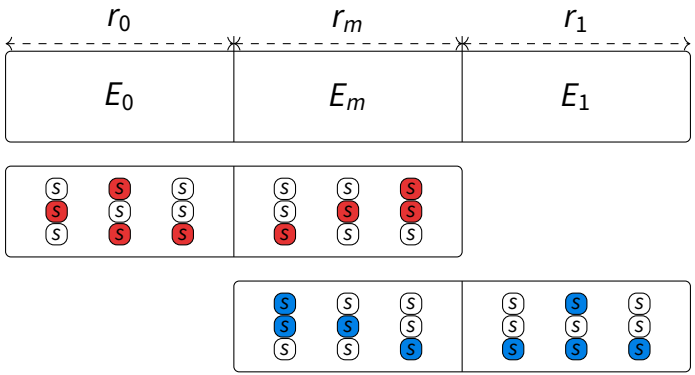

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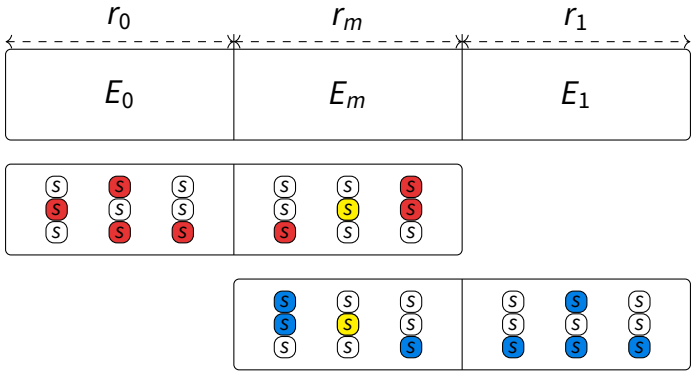

$u_i - s_i \geq 0, \quad \ell_i - s_i \geq 0, \quad -u_i - \ell_i + s_i \geq -1$

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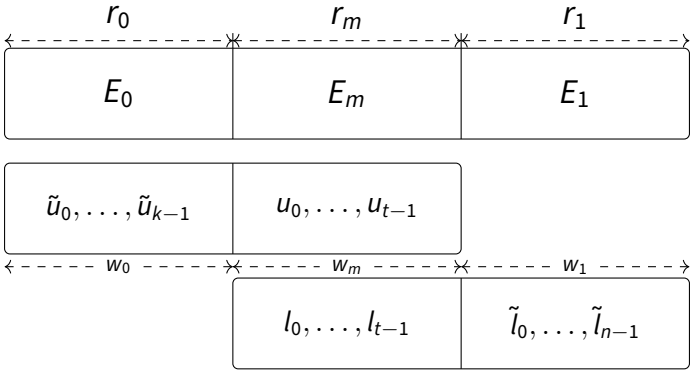

$$\min \sum_{i=0}^{k-1} w_0 \cdot \tilde{u}_i + \sum_{j=0}^{t-1} w_m \cdot s_j + \sum_{k=0}^{n-1} w_1 \cdot \tilde{l}_k.$$

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

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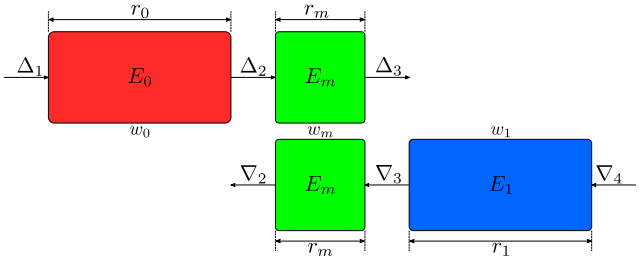
Instantiating Truncated Trails with Concrete Differentials

- 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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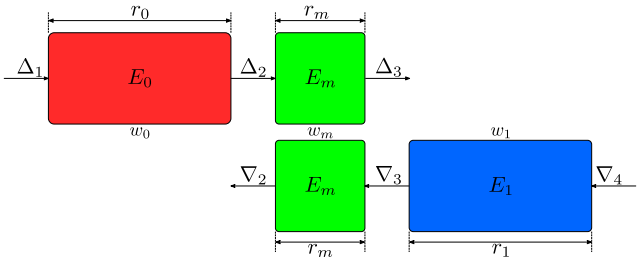

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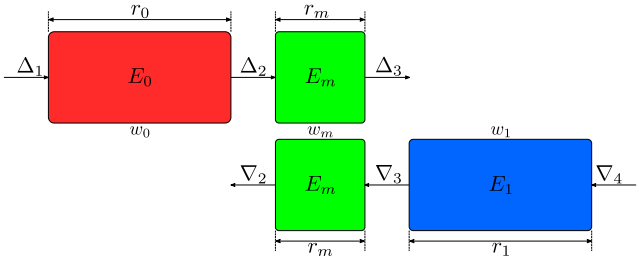

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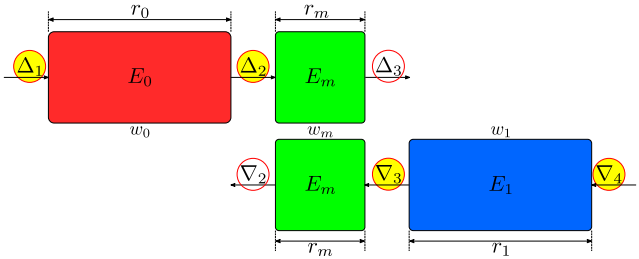
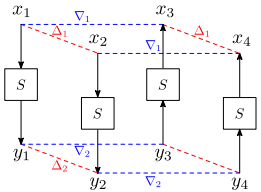


BCT Framework And Our New Tools

BCT Framework



Δ_1 Δ_2

∇_1 ∇_2

- $\mathcal{X}_{\mathrm{DDT}}(\Delta_1, \Delta_2) = \{x : S(x) \oplus S(x \oplus \Delta_1) = \Delta_2\}, \quad \mathrm{DDT}(\Delta_1, \Delta_2) = \#\mathcal{X}_{\mathrm{DDT}}(\Delta_1, \Delta_2)$
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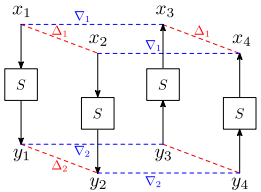
BCT Framework



$$\Delta_1 \longrightarrow \Delta_2$$

$$\nabla_1 \longrightarrow \nabla_2$$

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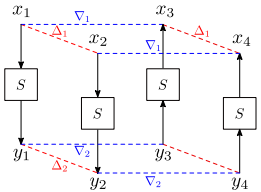

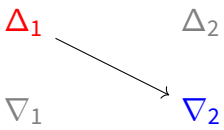

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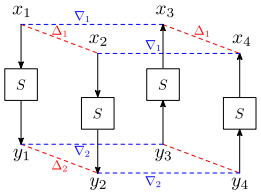
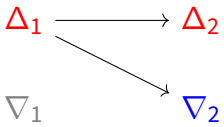
BCT Framework





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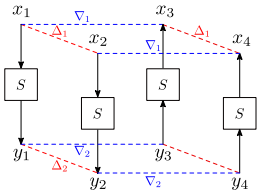
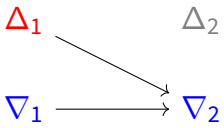
BCT Framework





- $\mathcal{X}_{\mathtt{DDT}}(\Delta_1, \Delta_2) = \{x : S(x) \oplus S(x \oplus \Delta_1) = \Delta_2\}, \quad \mathtt{DDT}(\Delta_1, \Delta_2) = \#\mathcal{X}_{\mathtt{DDT}}(\Delta_1, \Delta_2)$
- $\mathcal{X}_{\mathtt{BCT}}(\Delta_1, \nabla_2) = \{x : S^{-1}(S(x) \oplus \nabla_2) \oplus S^{-1}(S(x \oplus \Delta_1) \oplus \nabla_2) = \Delta_1\}$, $\mathtt{BCT}(\Delta_1, \nabla_2) = \#\mathcal{X}_{\mathtt{BCT}}(\Delta_1, \nabla_2)$ [Cid+18]
- $\mathtt{UBCT}(\Delta_1, \Delta_2, \nabla_2) = \#\{x : x \in \mathcal{X}_{\mathtt{BCT}}(\Delta_1, \nabla_2) \cap \mathcal{X}_{\mathtt{DDT}}(\Delta_1, \Delta_2)\}$ [WP19]
- $\mathtt{LBCT}(\Delta_1, \nabla_1, \nabla_2) = \#\{x : x \in \mathcal{X}_{\mathtt{BCT}}(\Delta_1, \nabla_2) \cap \mathcal{X}_{\mathtt{DDT}}(\nabla_1, \nabla_2)\}$ [SQH19]

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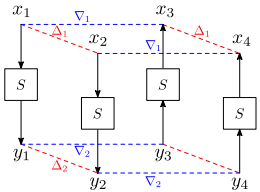
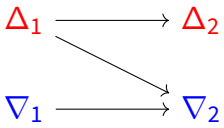
BCT Framework





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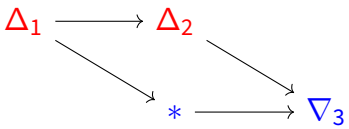
Double Boomerang Connectivity Table (DBCT)



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

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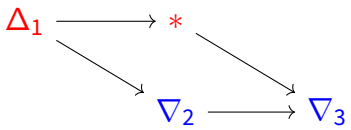
Double Boomerang Connectivity Table (DBCT)



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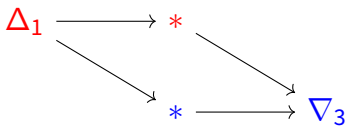
Double Boomerang Connectivity Table (DBCT)



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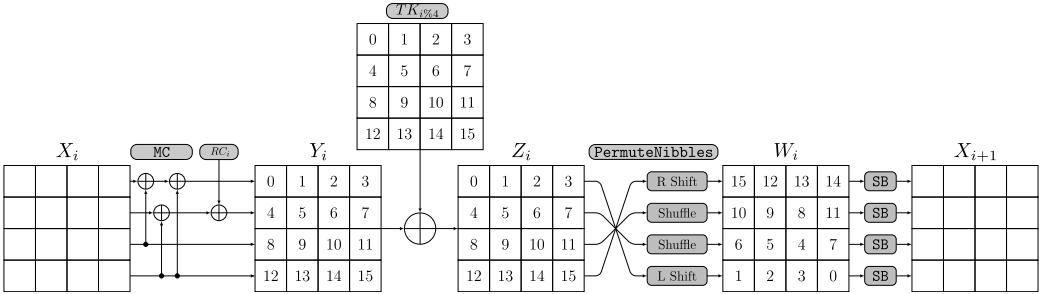
Application to CRAFT

CRAFT [Bei+19]



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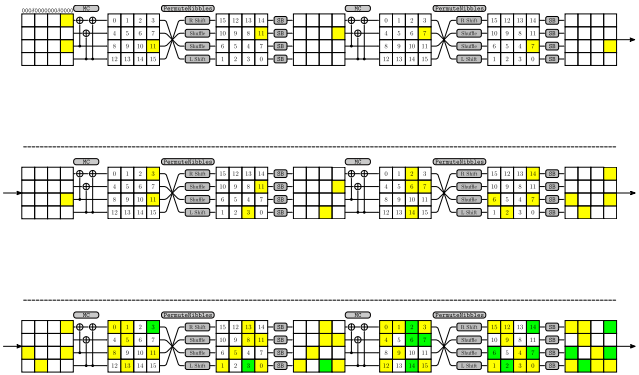
A 6-round ST Deterministic Distinguisher for CRAFT



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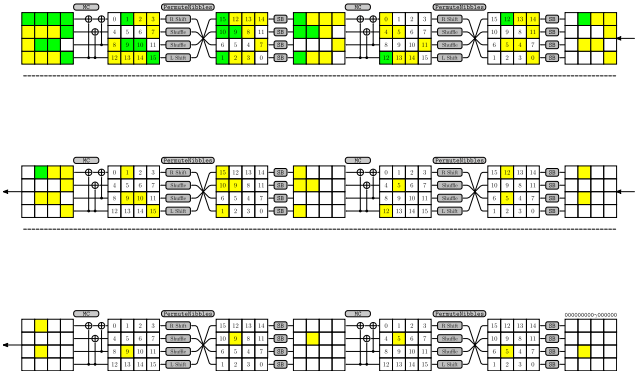
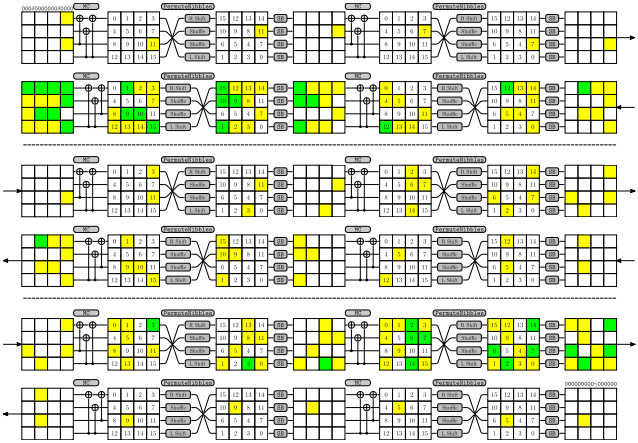
A 6-round ST Deterministic Distinguisher for CRAFT



A 6-round ST Deterministic Distinguisher for CRAFT



$\Pr = 1$

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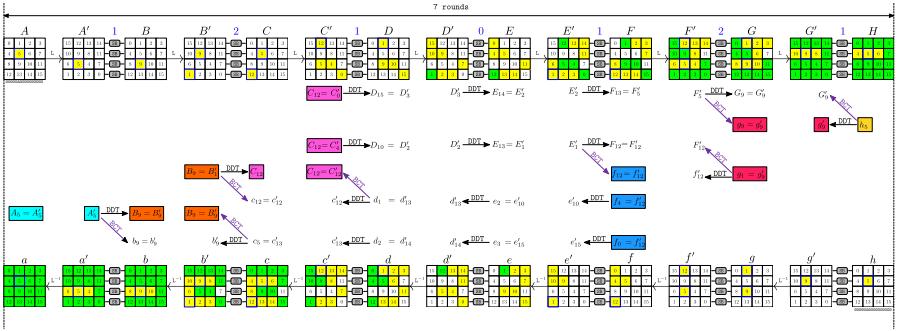
A 7-round Distinguisher (Extendable up to 14 rounds)



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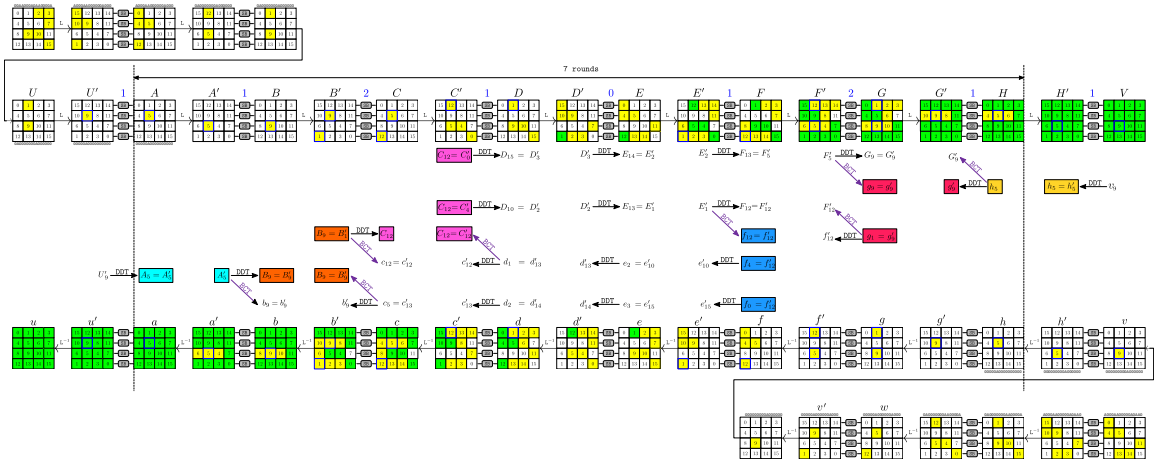
A 7-round Distinguisher (Extendable up to 14 rounds)



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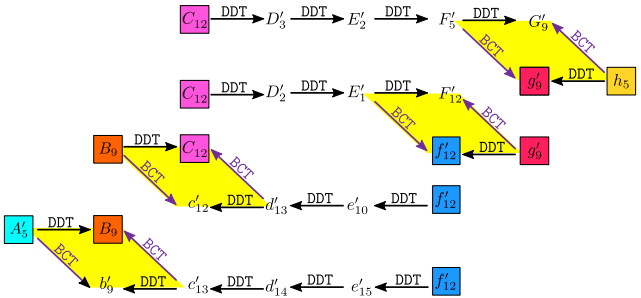
A 7-round Distinguisher (Extendable up to 14 rounds)



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

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

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

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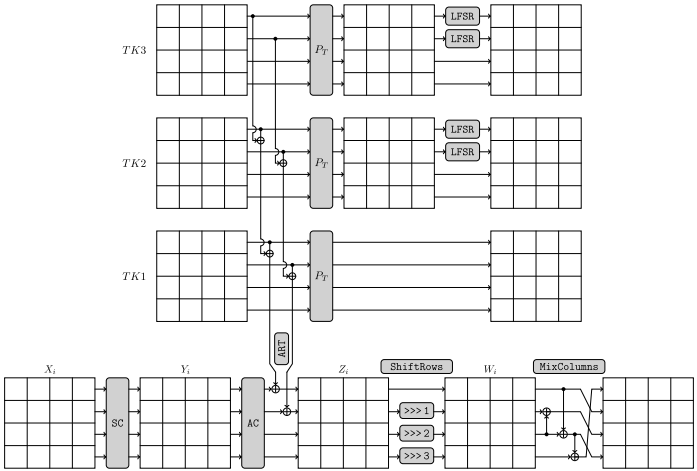
Summary of Our Distinguishers for CRAFT

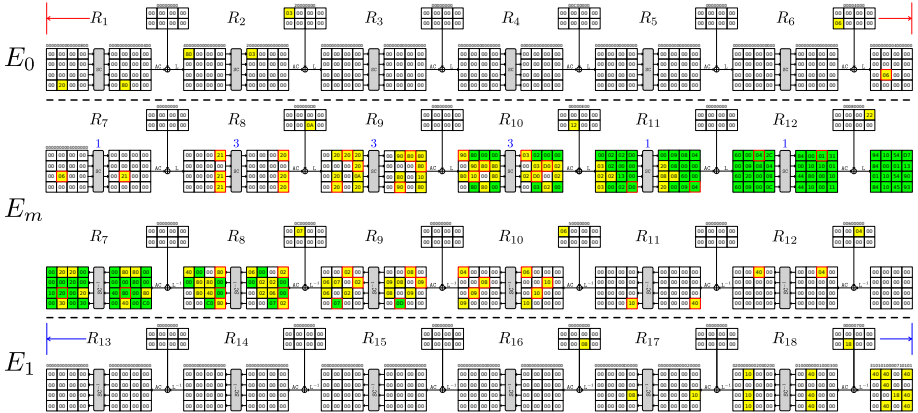
Distinguisher Type	# Rounds	Probability	Reference
ST-Differential	9	$2^{-40.20}$	[Had+19]
	10	$2^{-44.89}$	
	11	$2^{-49.79}$	
	12	$2^{-54.48}$	
	13	$2^{-59.13}$	
	14	$2^{-63.80}$	
ST-Boomerang	6	**1**	This Paper
	7	$\mathbf{2^{-4}}$	
	8	$\mathbf{2^{-8}}$	
	9	$\mathbf{2^{-14.76}}$	
	10	$\mathbf{2^{-19.83}}$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



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

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

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

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

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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

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