Revisiting Differential-Linear Attacks via a Boomerang Perspective

Applications to AES, Ascon, CLEFIA, SKINNY, PRESENT, KNOT, TWINE, WARP, LBlock, Simeck, and SERPENT

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Research Gap and Our Contributions

🔭 Research Gap

- ⊘ How to analytically estimate the correlation of DL distinguishers?
- ⊘ How to (efficiently) find good DL distinguishers?

💎 Contributions

- ✓ Generalizing the DLCT framework [Bar+19] for analytical correlation estimation.
- ✓ Introducing an efficient method to search for DL distinguishers applicable to:
    - ▪ Strongly aligned SPN primitives: AES, SKINNY
    - ▪ Weakly aligned SPN primitives: Ascon, SERPENT, KNOT, PRESENT
    - ▪ Feistel structures: CLEFIA, TWINE, LBlock, LBlock-s, WARP
    - ▪ AndRX designs: Simeck

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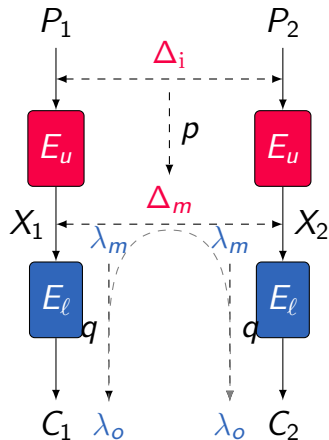 - ▪ AndRX designs: Simeck

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Outline

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Background

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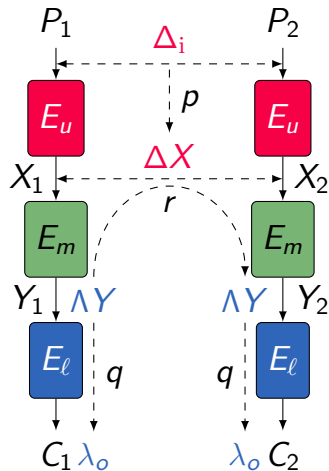CRYPTO 2024 – California, USA

Differential-Linear (DL) Attack [LH94]

- $\mathbb{P}(\Delta_{\mathrm{i}} \xrightarrow{E_u} \Delta_m) = p$

- $\mathbb{C}(\lambda_m \xrightarrow{E_\ell} \lambda_{\mathrm{o}}) = q$

- Assumptions ($\Delta X = X_1 \oplus X_2$):

  1. E_u, and E_ℓ are statistically independent
  2. $\mathbb{P}(\lambda_m \cdot \Delta X = 0) = 1/2$ when $\Delta X \neq \Delta_m$

- $\mathbb{C}(\lambda_{\mathrm{o}} \cdot \Delta C) = (-1)^{\lambda_m \cdot \Delta_m} \cdot pq^2 = \pm pq^2$

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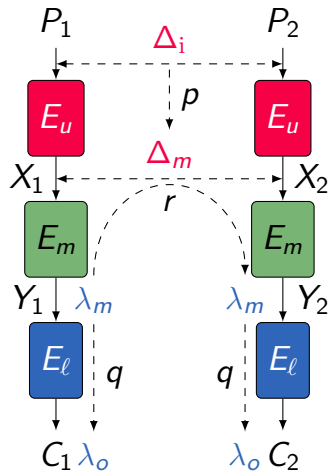CRYPTO 2024 - California, USA

Sandwich Framework for DL Attack [BLN14; DKS14; Bar+19]

- $\mathbb{R}(\Delta X, \Lambda Y) = \mathbb{C}\left(\Lambda Y \cdot E_m(X) \oplus \Lambda Y \cdot E_m(X \oplus \Delta X)\right)$

- $\mathbb{C}(\lambda_o \cdot \Delta C) = \sum_{\Delta X, \Lambda Y} \mathbb{P}(\Delta_i, \Delta X) \cdot \mathbb{R}(\Delta X, \Lambda Y) \cdot \mathbb{C}^2(\Lambda Y, \lambda_o)$

- $\mathbb{P}(\Delta_i \xrightarrow{E_u} \Delta_m) = p$

- $\mathbb{R}(\Delta_m, \lambda_m) = r$

- $\mathbb{C}(\lambda_m \xrightarrow{E_\ell} \lambda_o) = q$

- $\mathbb{C}(\lambda_o \cdot \Delta C) \approx prq^2$

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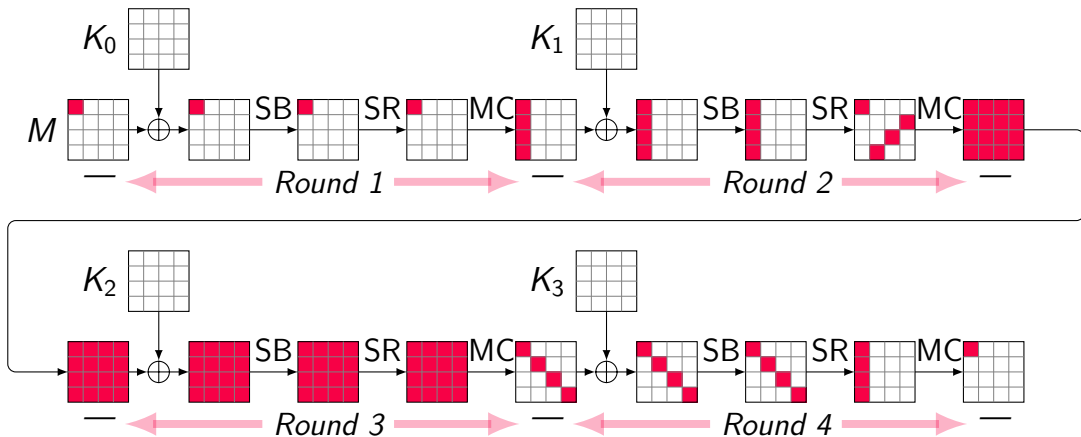
Differential-Linear Connectivity Table (DLCT) [Bar+19]

$$\text{DLCT}_b(\Delta_i, \lambda_o) = \left\{ x \in \mathbb{F}_2^n : \ \lambda_o \cdot S(x) \oplus \lambda_o \cdot S(x \oplus \Delta_i) = b \right\}$$

$$\text{DLCT}(\Delta_i, \lambda_o) = |\text{DLCT}_0(\Delta_i, \lambda_o)| - |\text{DLCT}_1(\Delta_i, \lambda_o)|$$
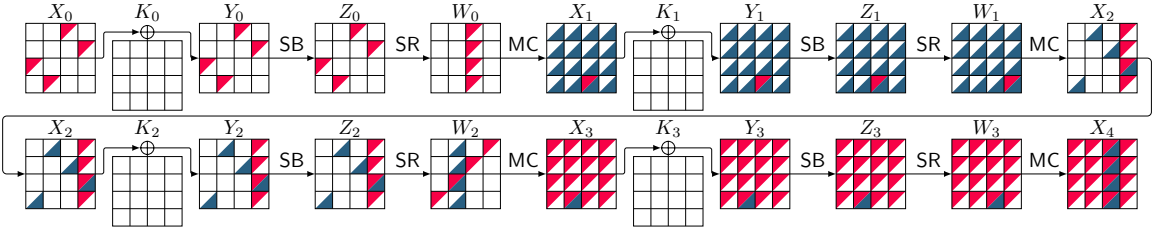
$$\mathbb{C}_{\text{DLCT}}(\Delta_i, \lambda_o) = 2^{-n} \cdot \text{DLCT}(\Delta_i, \lambda_o)$$

Security of AES Against Differential/Linear Attacks

$$\mathbb{P}_{4 \text{ rounds}} \leq 2^{-150}, \ \mathbb{C}^2_{4 \text{ rounds}} \leq 2^{-150}$$

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A 4-round DL Distinguisher for AES

$$r_u = 1, r_m = 3, r_\ell = 0, \ p = 2^{-24.00}, \ r = 2^{-7.66}, q^2 = 1, \ \mathbb{C} = prq^2 = \mathbf{2^{-31.66}}$$

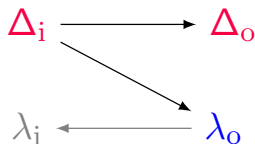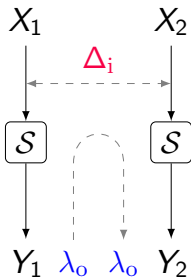|	
ΔX_0 00005200000000f58f000000007b0000	ΔX_1 00000000000000000000000000000b400
ΓX_4 0032000000ab00000066000000980000	-

$$\mathbf{2^{63.32}} \text{ v.s. } 2^{150}$$

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Generalized DLCT Framework

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Upper Differential-Linear Connectivity Table (UDLCT)

$$\mathrm{UDLCT}_b(\Delta_{\mathrm{i}}, \Delta_{\mathrm{o}}, \lambda_{\mathrm{o}}) = \{x \in \mathbb{F}_2^n : \ S(x) \oplus S(x \oplus \Delta_{\mathrm{i}}) = \Delta_{\mathrm{o}} \text{ and } \lambda_{\mathrm{o}} \cdot \Delta_{\mathrm{o}} = b\}$$

$$\mathrm{UDLCT}(\Delta_{\mathrm{i}}, \Delta_{\mathrm{o}}, \lambda_{\mathrm{o}}) = |\mathrm{UDLCT}_0(\Delta_{\mathrm{i}}, \Delta_{\mathrm{o}}, \lambda_{\mathrm{o}})| - |\mathrm{UDLCT}_1(\Delta_{\mathrm{i}}, \Delta_{\mathrm{o}}, \lambda_{\mathrm{o}})|$$

$$\mathbb{C}_{\mathrm{UDLCT}}(\Delta_{\mathrm{i}}, \Delta_{\mathrm{o}}, \lambda_{\mathrm{o}}) = 2^{-n} \cdot \mathrm{UDLCT}(\Delta_{\mathrm{i}}, \Delta_{\mathrm{o}}, \lambda_{\mathrm{o}})$$

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Lower Differential-Linear Connectivity Table (LDLCT)

$$\text{LDLCT}_b(\Delta_i, \lambda_i, \lambda_o) = \{x \in \mathbb{F}_2^n : \; \lambda_i \cdot \Delta_i \oplus \lambda_o \cdot S(x) \oplus \lambda_o \cdot S(x \oplus \Delta_i) = b\}$$

$$\text{LDLCT}(\Delta_i, \lambda_i, \lambda_o) = |\text{LDLCT}_0(\Delta_i, \lambda_i, \lambda_o)| - |\text{LDLCT}_1(\Delta_i, \lambda_i, \lambda_o)|$$

$$\mathbb{C}_{\text{LDLCT}}(\Delta_i, \lambda_i, \lambda_o) = 2^{-n} \cdot \text{LDLCT}(\Delta_i, \lambda_i, \lambda_o)$$

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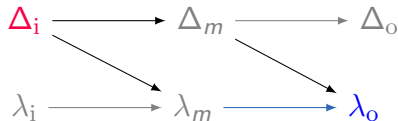# Extended Differential-Linear Connectivity Table (EDLCT)

$$\text{EDLCT}_b(\Delta_i, \Delta_o, \lambda_i, \lambda_o) = \{x \in \mathbb{F}_2^n : \ S(x) \oplus S(x \oplus \Delta_i) = \Delta_o \text{ and } \lambda_i \cdot \Delta_i \oplus \lambda_o \cdot \Delta_o = b\}$$

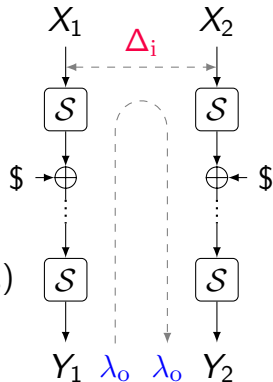$$\text{EDLCT}(\Delta_i, \Delta_o, \lambda_i, \lambda_o) = |\text{EDLCT}_0(\Delta_i, \Delta_o, \lambda_i, \lambda_o)| - |\text{EDLCT}_1(\Delta_i, \Delta_o, \lambda_i, \lambda_o)|$$

$$\mathbb{C}_{\text{EDLCT}}(\Delta_i, \Delta_o, \lambda_i, \lambda_o) = 2^{-n} \cdot \text{EDLCT}(\Delta_i, \Delta_o, \lambda_i, \lambda_o)$$

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Double Differential-Linear Connectivity Table (DDLCT)

$$\mathtt{DDLCT}\left(\Delta_{\mathrm{i}}, \lambda_{\mathrm{o}}\right) = 2^{-n} \cdot \sum_{\Delta_m} \sum_{\lambda_m} \mathtt{UDLCT}\left(\Delta_{\mathrm{i}}, \Delta_m, \lambda_m\right) \cdot \mathtt{LDLCT}\left(\Delta_m, \lambda_m, \lambda_{\mathrm{o}}\right)$$

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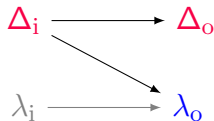
Generalized DLCT Framework (GBCT)

- How to formulate the correaltion for more than 1 round?
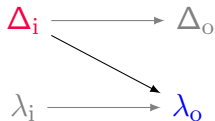
DLCT (Δ_i, λ_o)
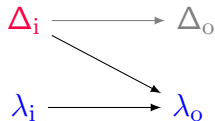
UDLCT $(\Delta_i, \Delta_o, \lambda_o)$

LDLCT $(\Delta_i, \lambda_i, \lambda_o)$

EDLCT $(\Delta_i, \Delta_o, \lambda_i, \lambda_o)$

DDLCT (Δ_i, λ_o)

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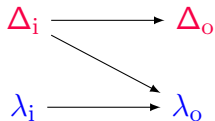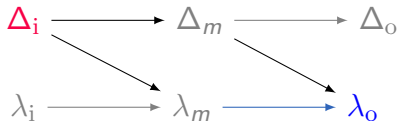
Application of the Generalized DLCT Tables - AES ($\textcolor{red}{\blacksquare}$ differential $\textcolor{blue}{\blacksquare}$ linear)
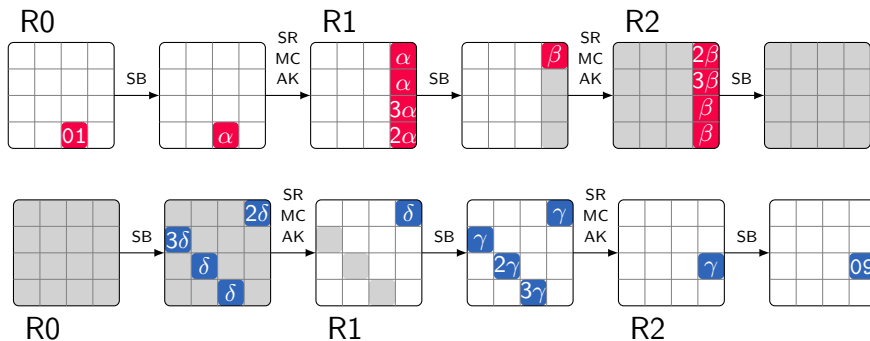
$$\sum_{\alpha, \beta, \gamma, \delta} \mathbb{C}_{\text{UDLCT}}(1, \alpha, \delta) \cdot \mathbb{C}_{\text{EDLCT}}(\alpha, \beta, \delta, \gamma) \cdot \mathbb{C}_{\text{LDLCT}}(\beta, \gamma, 9) = -2^{-7.94}$$

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Application of the Generalized DLCT Tables - TWINE (- differential - linear)
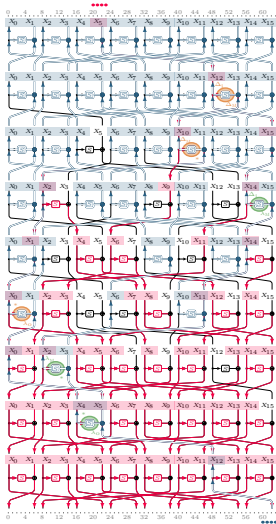
$$\mathbb{C}(\Delta_{\mathrm{i}}, \lambda_{\mathrm{o}}) = \sum_{\Delta_m} \mathbb{P}_{\mathrm{DDT}}(\Delta_{\mathrm{i}}, \Delta_m) \cdot \mathbb{C}_{\mathrm{DDLCT}}(\Delta_m, \lambda_{\mathrm{o}})$$

$$= \sum_{\lambda_m} \mathbb{C}_{\mathrm{DDLCT}}(\Delta_{\mathrm{i}}, \lambda_m) \cdot \mathbb{C}_{\mathrm{LAT}}^2(\lambda_m, \lambda_{\mathrm{o}}).$$

$$\mathbb{C}_{tot}(\Delta_{\mathrm{i}}, \lambda_{\mathrm{o}}) = \mathbb{C}^2(\Delta_{\mathrm{i}}, \lambda_{\mathrm{o}}).$$

Input/Output Differences/Linear-mask	Formula	Exp. Correlation
$(\Delta_{\mathrm{i}}, \lambda_{\mathrm{o}}) = (\mathtt{0xb4}, \mathtt{0x67})$	$-2^{-7.66}$	$-2^{-7.64}$
$(\Delta_{\mathrm{i}}, \lambda_{\mathrm{o}}) = (\mathtt{0x02}, \mathtt{0x02})$	$-2^{-7.92}$	$-2^{-7.93}$
$(\Delta_{\mathrm{i}}, \lambda_{\mathrm{o}}) = (\mathtt{0x55}, \mathtt{0x55})$	$-2^{-7.99}$	$-2^{-7.98}$
$(\Delta_{\mathrm{i}}, \lambda_{\mathrm{o}}) = (\mathtt{0xbf}, \mathtt{0xef})$	$-2^{-8.05}$	$-2^{-8.06}$
$(\Delta_{\mathrm{i}}, \lambda_{\mathrm{o}}) = (\mathtt{0xfe}, \mathtt{0x06})$	$-2^{-8.26}$	$-2^{-8.25}$
$(\Delta_{\mathrm{i}}, \lambda_{\mathrm{o}}) = (\mathtt{0x4b}, \mathtt{0x1a})$	$-2^{-8.43}$	$-2^{-8.44}$

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Differential-Linear Switches and Deterministic Trails

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Cell-Wise and Bit-Wise Switches

x	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
$\mathcal{S}(x)$	4	0	a	7	b	e	1	d	9	f	6	8	5	2	c	3

$\Delta \setminus \lambda$	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
0	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
1	16	0	0	0	-16	0	0	0	0	0	0	0	0	0	0	0
2	16	-8	-8	0	0	0	8	-8	0	-8	0	8	0	0	0	0
3	16	0	-8	-8	0	-8	8	0	0	0	0	0	0	-8	0	8
4	16	0	-8	0	0	0	-8	0	-16	0	8	0	0	0	8	0
5	16	0	-8	0	0	0	-8	0	0	0	8	0	-16	0	8	0
6	16	-8	8	-8	0	0	-8	0	0	-8	0	0	0	0	0	8
7	16	0	8	0	0	-8	-8	-8	0	0	0	8	0	-8	0	0
8	16	0	0	0	-16	0	0	0	-16	0	0	0	16	0	0	0
9	16	-8	0	-8	16	-8	0	-8	0	8	0	-8	0	8	0	-8
a	16	0	0	8	0	8	0	0	0	0	-8	0	0	-8	-8	-8
b	16	8	0	0	0	0	0	8	0	-8	-8	-8	0	0	-8	0
c	16	0	0	-8	0	0	0	-8	16	0	0	-8	0	0	0	-8
d	16	-8	0	0	0	-8	0	0	0	8	0	0	-16	8	0	0
e	16	0	0	0	0	8	0	8	0	0	-8	-8	0	-8	-8	0
f	16	8	0	8	0	0	0	0	0	-8	-8	0	0	0	-8	-8

- Cell-wise switches:
  $\mathrm{DLCT}(\Delta_\mathrm{i}, 0) = \mathrm{DLCT}(0, \lambda_\mathrm{o}) = 2^n$ for all $\Delta_\mathrm{i}, \lambda_\mathrm{o}$

- Bit-wise switches:
  $\mathrm{DLCT}(\Delta_\mathrm{i}, \lambda_\mathrm{o}) = \pm 2^n$ for $\Delta_\mathrm{i}, \lambda_\mathrm{o} \neq 0$

  - Example: $\mathbb{C}(9, 4) = \frac{16}{16}$

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Bit-Wise Switches and Deterministic Trails

x	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
$\mathcal{S}(x)$	4	0	a	7	b	e	1	d	9	f	6	8	5	2	c	3

$\Delta \backslash \lambda$	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
0	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
1	16	0	0	0	-16	0	0	0	0	0	0	0	0	0	0	0
2	16	-8	-8	0	0	0	8	-8	0	-8	0	8	0	0	0	0
3	16	0	-8	-8	0	-8	8	0	0	0	0	0	0	-8	0	8
4	16	0	-8	0	0	0	-8	0	-16	0	8	0	0	0	8	0
5	16	0	-8	0	0	0	-8	0	0	0	8	0	-16	0	8	0
6	16	-8	8	-8	0	0	-8	0	0	-8	0	0	0	0	0	8
7	16	0	8	0	0	-8	-8	-8	0	0	0	8	0	-8	0	0
8	16	0	0	0	-16	0	0	0	-16	0	0	0	16	0	0	0
9	16	-8	0	-8	16	-8	0	-8	0	8	0	-8	0	8	0	-8
a	16	0	0	8	0	8	0	0	0	0	-8	0	0	-8	-8	-8
b	16	8	0	0	0	0	0	8	0	-8	-8	-8	0	0	-8	0
c	16	0	0	-8	0	0	0	-8	16	0	0	-8	0	0	0	-8
d	16	-8	0	0	0	-8	0	0	0	8	0	0	-16	8	0	0
e	16	0	0	0	0	8	0	8	0	0	-8	-8	0	-8	-8	0
f	16	8	0	8	0	0	0	0	0	-8	-8	0	0	0	-8	-8

$$\Delta_i = (0,0,0,1) \xrightarrow{S} \Delta_o = (?,1,?,?)$$

$$\Delta_i = (0,1,0,0) \xrightarrow{S} \Delta_o = (1,?,?,?)$$

$$\Delta_i = (1,0,0,0) \xrightarrow{S} \Delta_o = (1,1,?,?)$$

$$\Delta_i = (1,0,0,1) \xrightarrow{S} \Delta_o = (?,0,?,?)$$

$$\Delta_i = (1,1,0,0) \xrightarrow{S} \Delta_o = (0,?,?,?)$$

$$\lambda_i = (1,?,?,1) \xleftarrow{S} \lambda_o = (0,1,0,0)$$

$$\lambda_i = (1,1,?,?) \xleftarrow{S} \lambda_o = (1,0,0,0)$$

$$\lambda_i = (0,?,?,?) \xleftarrow{S} \lambda_o = (1,1,0,0)$$

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Automatic Tools to Search for DL Distinguishers

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Overview of Our Method to Search for Distinguishers

$$E$$

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Overview of Our Method to Search for Distinguishers

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Overview of Our Method to Search for Distinguishers

• differentially active S-box   • linearly active S-box   • common active S-box

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Overview of Our Method to Search for Distinguishers

- differentially active S-box
- linearly active S-box
- common active S-box

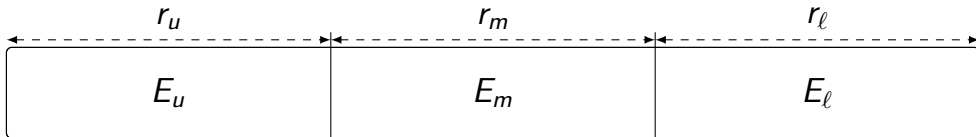**Hosein Hadipour**, Patrick Derbez, Maria Eichlseder
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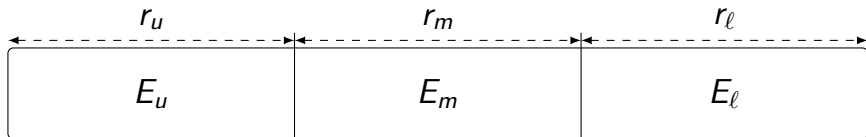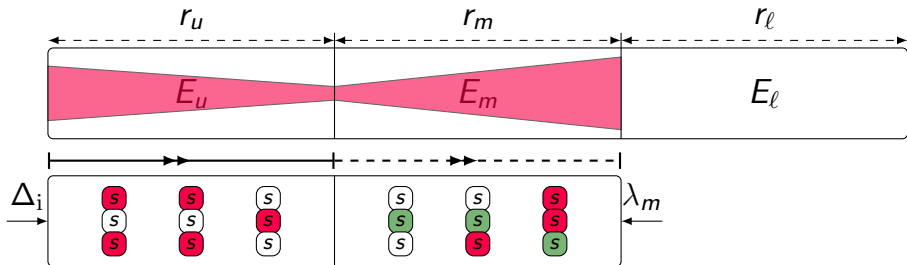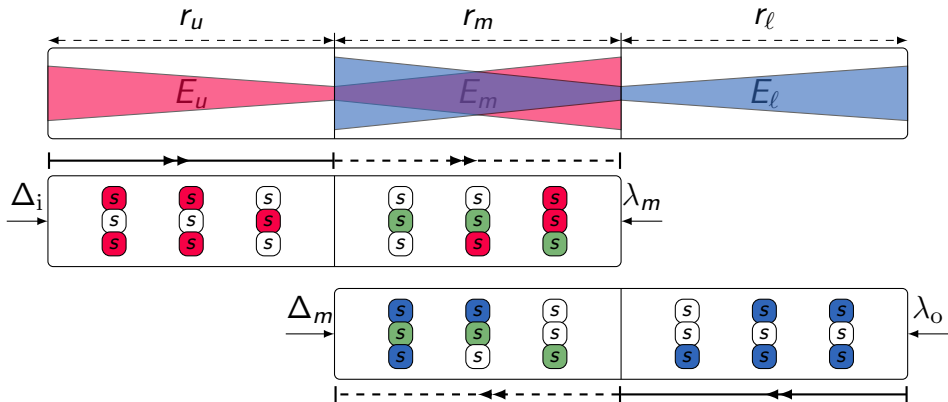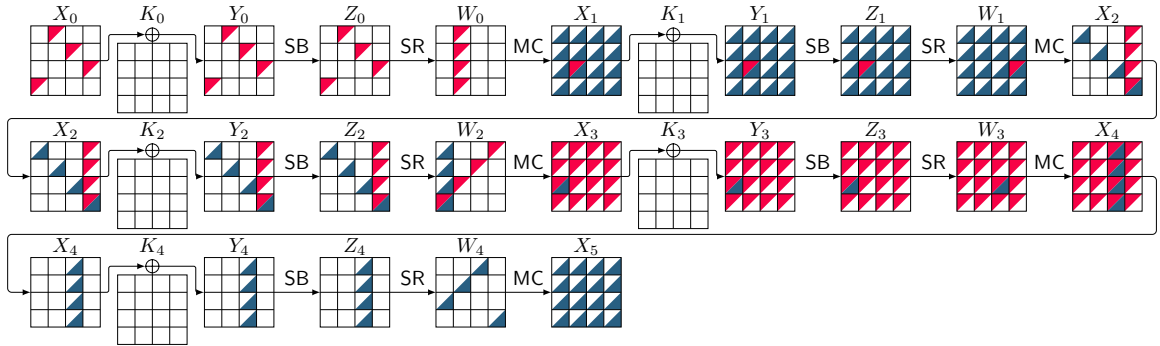
Overview of Our Method to Search for Distinguishers
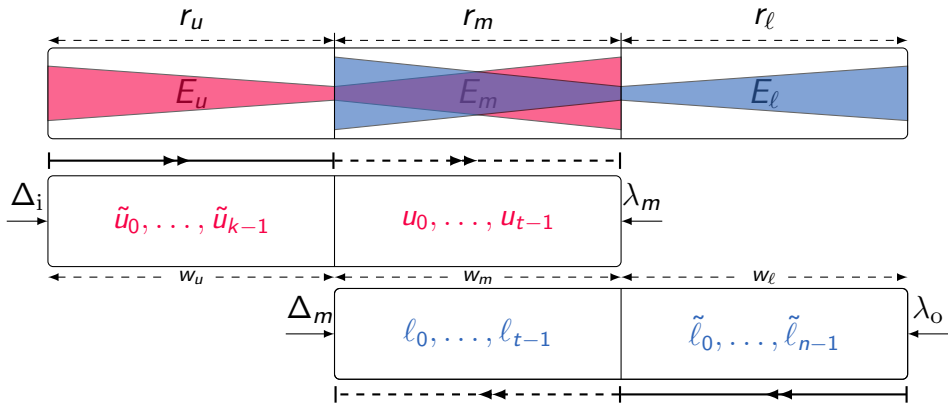
$$\min \left(\sum_{i=0}^{k-1} w_u \cdot \tilde{u}_i + \sum_{j=0}^{t-1} w_m \cdot bool2int \left(\ell_j + u_j = 2 \right) + \sum_{k=0}^{n-1} w_\ell \cdot \tilde{\ell}_k \right)$$

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Usage of Our Tool

```
python3 attack.py -RU 6 -RM 10 -RL 6
```

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Results: A 5-round DL Distinguisher for AES

$$r_0 = 1, r_m = 3, r_1 = 1, \ p = 2^{-24.00}, r = 2^{-7.66}, \ q^2 = 2^{-24.00}, \ prq^2 = 2^{-55.66}$$
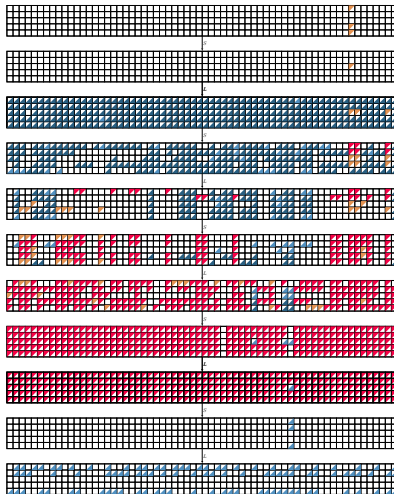
ΔX_0 001c00000000e200000000dfb3000000	ΔX_1 00000000000000000000f7000000000000
ΓX_4 000000000000000006700000000000000	ΓX_5 21d3814d93b1ef228e923507f67383fd

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Results: Application to Ascon-p(active difference ◤ unknown difference ◤ active mask ◤ unknown mask)

$\mathbb{C} = 1$

$\mathbb{C} = 2^{-4.33}$

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Contributions and Future Works

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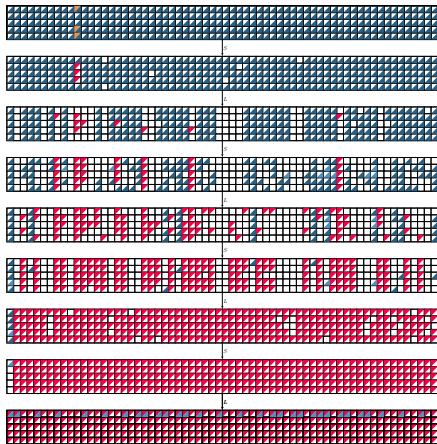
Contributions and Future Works

- Contributions

  ◈ We generalized the `DLCT` framework from one S-box layer to multiple rounds

  ◈ We proposed an automatic tool for finding optimum DL distinguishers

  ◈ We applied our tool to almost any design paradigm

- Future works

  🅰 Extending the application of our tool to other primitives, e.g., ARX

  🅰 Extending our tool to a unified model for finding complete attack (key recovery)

○: https://github.com/hadipourh/DL

▤: https://ia.cr/2024/255

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Properties of Generalized `DLCT` Tables - I

- $\texttt{DLCT}(\Delta_i, \lambda_o) = \sum_{\Delta_o} \texttt{UDLCT}(\Delta_i, \Delta_o, \lambda_o)$

- $\texttt{UDLCT}(\Delta_i, \Delta_o, \lambda_o) = (-1)^{\Delta_o \cdot \lambda_o} \texttt{DDT}(\Delta_i, \Delta_o)$

- $\texttt{LDLCT}(\Delta_i, \lambda_i, \lambda_o) = (-1)^{\Delta_i \cdot \lambda_i} \texttt{DLCT}(\Delta_i, \lambda_o)$

- $\texttt{EDLCT}(\Delta_i, \Delta_o, \lambda_i, \lambda_o) = (-1)^{\lambda_i \cdot \Delta_i \oplus \lambda_o \cdot \Delta_o} \texttt{DDT}(\Delta_i, \Delta_o)$

- $\texttt{LDLCT}(\Delta_i, \lambda_i, \lambda_o) = \sum_{\Delta_o} \texttt{EDLCT}(\Delta_i, \Delta_o, \lambda_i, \lambda_o)$

- $\sum_{\Delta_i} \texttt{LDLCT}(\Delta_i, \lambda_i, \lambda_o) = \texttt{LAT}^2(\lambda_i, \lambda_o)$

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Properties of Generalized DLCT Tables - II

- $\mathrm{DDLCT}(\Delta_\mathrm{i}, \lambda_\mathrm{o}) = 2^{-n} \cdot \sum_{\Delta_m} \sum_{\lambda_m} \mathrm{UDLCT}\left(\Delta_\mathrm{i}, \Delta_m, \lambda_m\right) \cdot \mathrm{LDLCT}\left(\Delta_m, \lambda_m, \lambda_\mathrm{o}\right)$

$$\mathrm{DDLCT}(\Delta_\mathrm{i}, \lambda_\mathrm{o}) = \sum_{\Delta_m} \mathrm{DDT}(\Delta_\mathrm{i}, \Delta_m) \cdot \mathrm{DLCT}(\Delta_m, \lambda_\mathrm{o})$$
$$= 2^{-n} \sum_{\lambda_m} \mathrm{DLCT}(\Delta_\mathrm{i}, \lambda_m) \cdot \mathrm{LAT}^2(\lambda_m, \lambda_\mathrm{o}).$$

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Results: Distinguishers for up to 17 Rounds of TWINE

- Comparing the data complexity of best boomerang and DL distinguishers

# Rounds	Boomerang [HNE22]	Differential-Linear	Gain
5	1	1	1
7	$2^{3.20}$	1	$2^{3.20}$
13	$2^{34.32}$	$2^{27.16}$	$2^{7.16}$
14	$2^{42.25}$	$2^{31.28}$	$2^{10.97}$
15	$2^{51.03}$	$2^{38.98}$	$2^{12.05}$
16	$2^{58.04}$	$2^{47.28}$	$2^{10.76}$
17	-	$2^{59.24}$	-

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Results: Distinguishers for up to 17 Rounds of LBlock

- Comparing the data complexity of best boomerang and DL distinguishers

# Rounds	Boomerang [HNE22]	Differential-Linear	Gain
5	1	1	1
7	$2^{2.97}$	1	$2^{2.97}$
13	$2^{30.28}$	$2^{23.78}$	$2^{6.50}$
14	$2^{38.86}$	$2^{30.34}$	$2^{8.52}$
15	$2^{46.90}$	$2^{38.26}$	$2^{8.64}$
16	$2^{57.16}$	$2^{46.26}$	$2^{10.90}$
17	-	$2^{58.30}$	-

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Results: Distinguishers for up to 8 Rounds of CLEFIA

- Comparing the data complexity of best boomerang and DL distinguishers

# Rounds	Boomerang [HNE22]	Differential-Linear	Gain
3	1	1	1
4	$2^{6.32}$	1	$2^{6.32}$
5	$2^{12.26}$	$2^{5.36}$	$2^{6.90}$
6	$2^{22.45}$	$2^{14.14}$	$2^{8.31}$
7	$2^{32.67}$	$2^{23.50}$	$2^{9.17}$
8	$2^{76.03}$	$2^{66.86}$	$2^{9.17}$

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Results: Application to SERPENT

- 🖳: Experimentally verified

Cipher	#R	$\mathbb{C}$	🖳	Ref.
	3	$\mathbf{2^{-0.68}}$	✓	This work
	4	$2^{-12.75}$		[DIK08]
	4	$\mathbf{2^{-5.54}}$	✓	This work
SERPENT	5	$2^{-16.75}$		[DIK08]
	5	$\mathbf{2^{-11.10}}$	✓	This work
	8	$2^{-39.18}$		This work
	9	$2^{-56.50}$		[DIK08]
	9	$\mathbf{2^{-50.95}}$		This work

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Results: Application to Simeck

- 🖥: Experimentally verified

Cipher	#R	$\mathbb{C}$	🖥	Ref.
	7	**1**	✓	This work
Simeck-32	14	$2^{-16.63}$		[ZWH24]
	14	$\mathbf{2^{-13.92}}$	✓	This work

Cipher	#R	$\mathbb{C}$	🖥	Ref.
	8	**1**	✓	This work
	17	$2^{-22.37}$		[ZWH24]
	17	$\mathbf{2^{-13.89}}$	✓	This work
Simeck-48	18	$2^{-24.75}$		[ZWH24]
	18	$\mathbf{2^{-15.89}}$		This work
	19	$\mathbf{2^{-17.89}}$		This work
	20	$\mathbf{2^{-21.89}}$		This work

Cipher	#R	$\mathbb{C}$	🖥	Ref.
	10	**1**	✓	This work
	24	$2^{-38.13}$		[ZWH24]
	24	$\mathbf{2^{-25.14}}$		This work
Simeck-64	25	$2^{-41.04}$		[ZWH24]
	25	$\mathbf{2^{-27.14}}$		This work
	26	$\mathbf{2^{-30.35}}$		This work