Generating Graphs Packed With Paths

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Overview

Motivation

Differential and Linear Distinguishers

[BS90]

$$\mathbb{P}_x[E_k(x) + \nabla = E_k(x + \Delta)]$$

[Mat93]

$$\mathbb{P}_x[\langle \alpha, x \rangle = \langle \beta, E_k(x) \rangle]$$

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[Mat93]

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Differential and Linear Distinguishers

In this presentation, focus on linear cryptanalysis (differential largely analogous)

[MY92], [Mat93]

$$\mathbb{P}_x[\langle \alpha, x \rangle = \langle \beta, E_k(x) \rangle]$$

Iterated Ciphers and Trails

$$E_k = E_{k_r}^{(r)} \circ \ldots \circ E_{k_2}^{(2)} \circ E_{k_1}^{(1)}$$

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$$U = (\alpha = u_0, \ldots, u_r = \beta)$$

$$C_{(u_i, u_{i+1})}^{k_i}(i) = 2 \cdot \mathbb{P}_{x \in \mathbb{F}^n}[\langle u_i, x \rangle = \langle u_{i+1}, E_{k_i}^{(i)}(x) \rangle] - 1$$

Hull

Correlation contribution for linear trail[1]:

$$C_U^k = \prod_{i=0}^{r} C_{(u_i, u_{i+1})}^{k_i}(i)$$

[1] under 'Markov cipher assumption'

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$$C_{\alpha,\beta}^k = \sum_{U:(u_0,u_r)=(\alpha,\beta)} C_U^k$$

[1] under 'Markov cipher assumption'

Hull; Expected Linear Potential

For key-alternating ciphers (key-addition in the field):

$$\forall k : (C_U^k)^2 = (C_U)^2 = \prod_{i=0}^{r} (C^k_{(u_i,u_{i+1})}(i))^2$$

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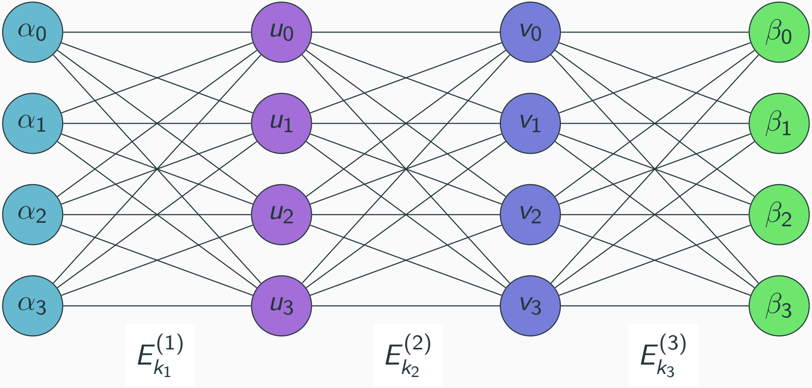
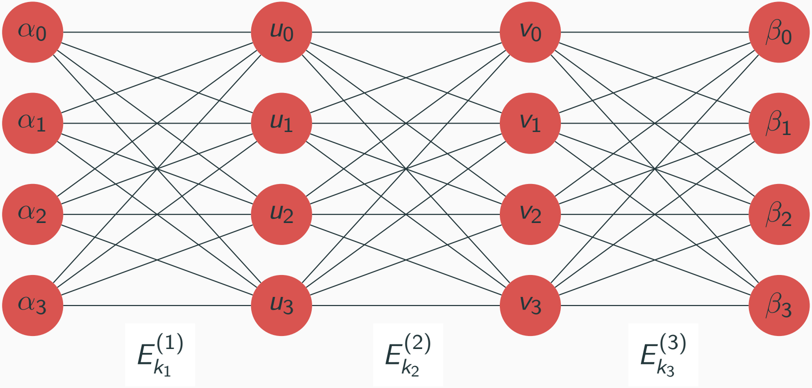
Problem: Current methods usually linear in the number of trails

Linear Cryptanalysis & Graphs

Multistage Graph



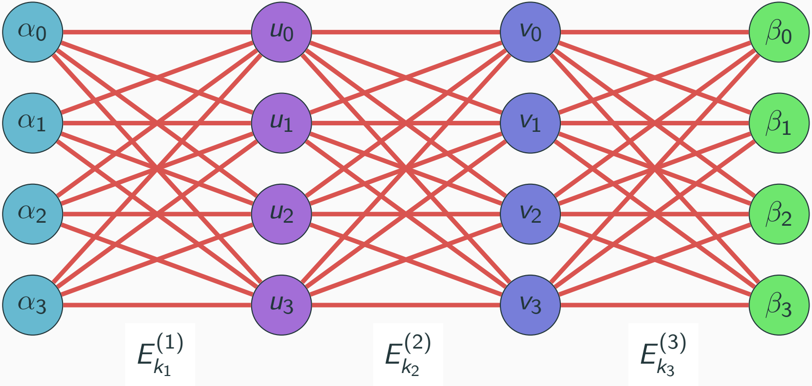
Nodes and Parities



Nodes $\alpha \in \mathbb{F}^n$ represent parities α^* for linear cryptanalysis:

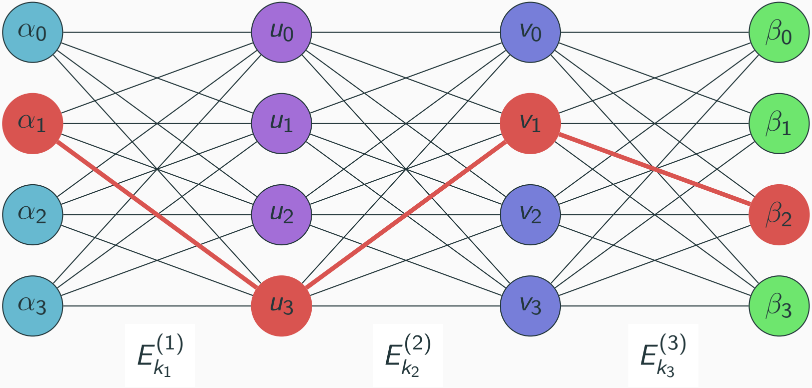
$$\alpha^* : v \mapsto \langle v, \alpha \rangle$$

Edges and Approximations



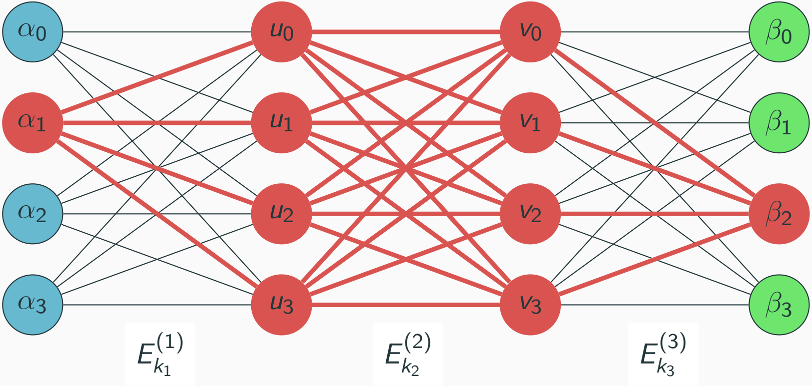
$$I(u \to v) = (C_{(u,v)}^{k})^2$$

Paths and Trails



$$l(v_0 \rightsquigarrow v_r) = \prod_{i=0}^{r-1} l(v_i \to v_{i+1})$$

Hulls as Sets of Paths



$$w_{G_{\mathcal{E}}}(\alpha \diamond \beta) = \sum l(\alpha \rightsquigarrow \beta) = \sum_{v} w_{G_{\mathcal{E}}}(\alpha \diamond v) \cdot l(v \to \beta)$$

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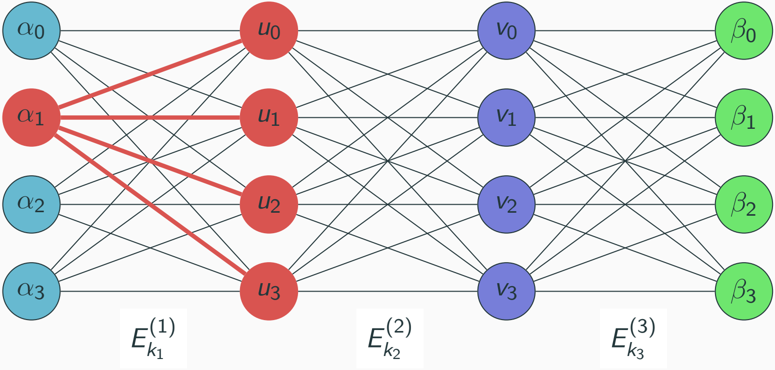

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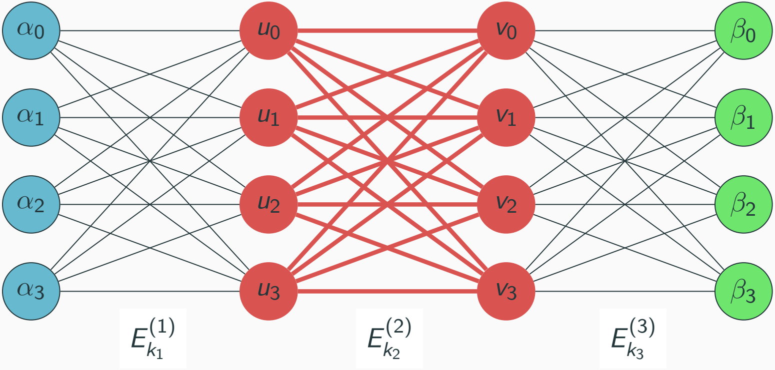

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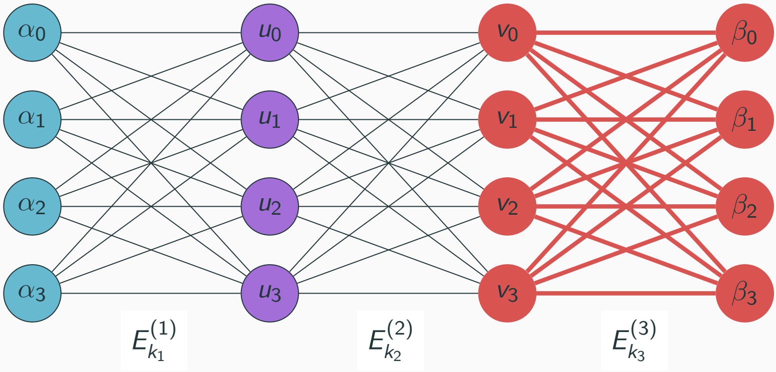

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Suitable Subgraphs

The full graph $G_{\mathcal{E}}$ is too large.

(exponential in the block-size)

Can we find suitable $\bar{G}_{\mathcal{E}} \subset G_{\mathcal{E}}$, that contains the good trails?

i.e. $\max_{\alpha,\beta} w_{\bar{G}_{\mathcal{E}}}(\alpha \diamond \beta)$ is large.

Subgraph Heuristics (for SPN)

Overall Method

1. Pick disjoint ‘families’ of edges

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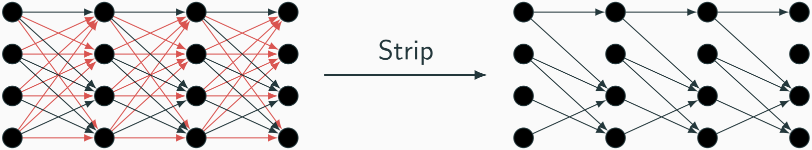
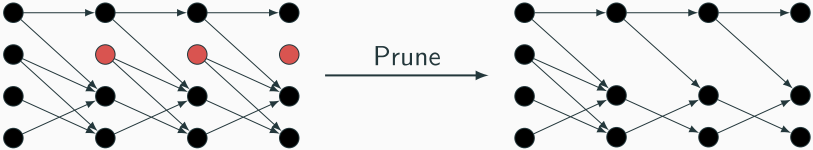
2. Prune the families an ‘approximate’ graph
3. Expand the families to a full graph
4. Remove unneeded vertices & edges in resulting graph

Pruning



$$I(v \to u) = 0$$

Pruning



S-Box Patterns / Families of edges

Example: 16-bit SPN, with four identical 4-bit S-Boxes.

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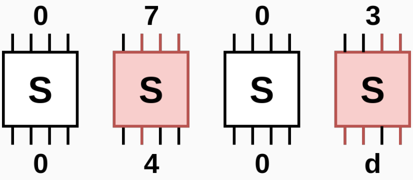
$$\mathrm{Ex}(p) = \{(\texttt{0x0303}, \texttt{0x0d0d}), (\texttt{0x0307}, \texttt{0x0d04}), (\texttt{0x0703}, \texttt{0x040d}), (\texttt{0x0707}, \texttt{0x0404})\}$$



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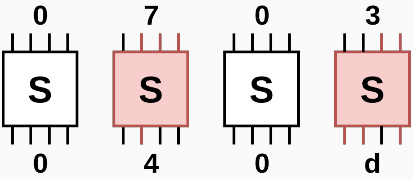
$$\mathsf{Ex}_{in}(p) = \{\texttt{0x0303}, \texttt{0x0307}, \texttt{0x0703}, \texttt{0x0707}\}$$
$$\mathsf{Ex}_{out}(p) = \{\texttt{0x0d0d}, \texttt{0x0d04}, \texttt{0x040d}, \texttt{0x0404}\}$$



Graph Defined By S-Box Pattern Set

Given a set of S-Box patterns $\mathcal{P}$, the graph defined by $\mathcal{P}$:

$$E = \mathrm{Ex}(\mathcal{P}) = \bigcup_{p \in \mathcal{P}} \mathrm{Ex}(p)$$

$$V = \mathrm{Ex}_{in}(\mathcal{P}) \ \cup \ \mathrm{Ex}_{out}(\mathcal{P})$$

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Let $\mathcal{P}$ be a set of S-Box patterns defining our subgraph.

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For intermediate stages:

$$v \notin \mathrm{Ex}_{in}(\mathcal{P}) \cap \mathrm{Ex}_{out}(\mathcal{P}) \implies v \text{ is pruned}$$

Graph Compression

Problem: $\mathrm{Ex}(\mathcal{P})$ too large to store explicitly ($|\mathrm{Ex}(\mathcal{P})| \gg |\mathcal{P}|$)

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Generate an approximation of $\bar{G}_{\mathcal{E}} = \mathrm{Ex}(\mathcal{P})$, by applying a compression function $g_j : \mathbb{F}^n \to \mathbb{F}^{n/j}$ to every vertex.

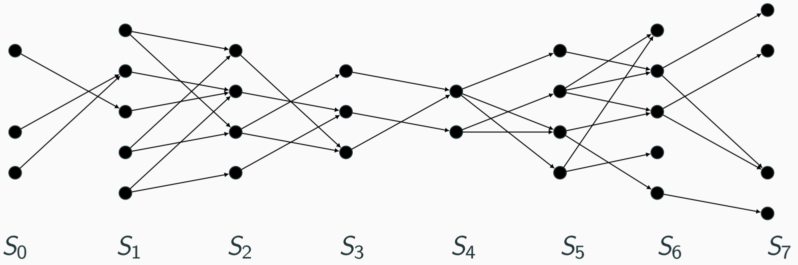
$$u \to v \in \bar{G}_{\mathcal{E}} \implies \hat{g}_j(u) \to \hat{g}_j(v) \in \hat{g}_j(\bar{G}_{\mathcal{E}})$$

Graph Compression

Iteratively refine the compression:

1. Generate a set of patterns $\mathcal{P}$.
2. Pick a $j > 1$ such that j is a power of two:
   2.1 Generate the graph $\hat{g}_j(\bar{G}_{\mathcal{E}})$ from $\mathcal{P}$ and prune.
   2.2 Remove dead patterns from $\mathcal{P}$ according to $\hat{g}_j(\bar{G}_{\mathcal{E}})$.
   2.3 If $j = 2$ then stop. Otherwise set $j = j/2$ and repeat.

Vertex Anchoring



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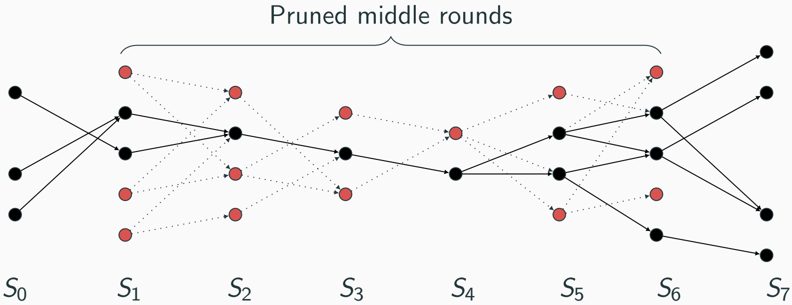

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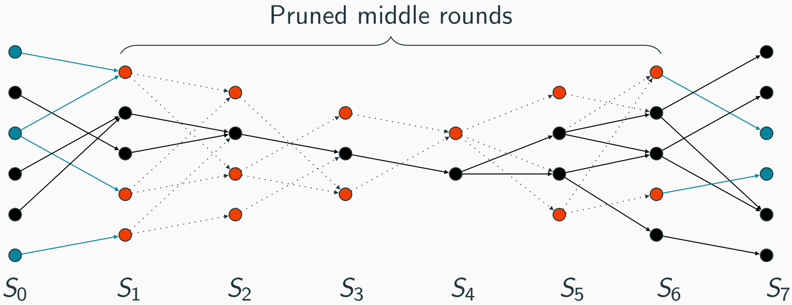


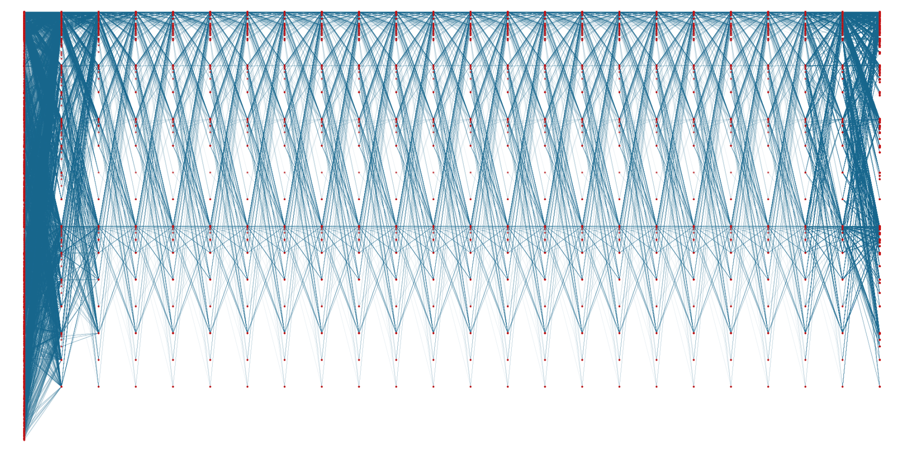
Plots & Results

cryptagraph

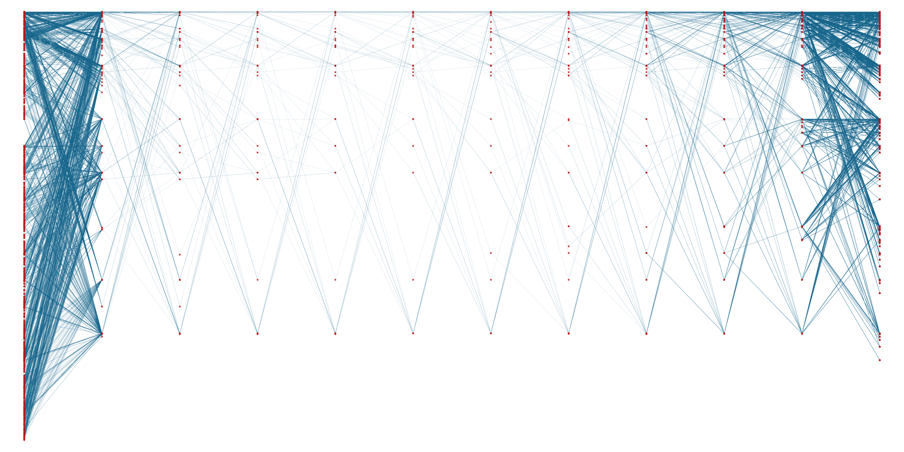
https://gitlab.com/psve/cryptagraph

Plots of subgraphs (for small parameters)

PRESENT [BKL+07]



GIFT [BPP+17]



Linear Results

Cipher (Total rounds, block size)	Rounds	$\lvert\mathcal{A}\rvert$	a	$\lvert\alpha \diamond \beta\rvert$	ELP	T_g	T_s
AES [oST01] (10, 128)	3	$2^{29.9}$	$2^{24.0}$	2^{1}	$2^{-53.36}$	0.0	0.0
	4	$2^{38.8}$	$2^{24.0}$	2^{4}	$2^{-147.88}$	2.5	20.0
EPCBC-48 [YKPH11] (32, 48)	15 † [Bul13]	$2^{26.1}$	–	$2^{31.3}$	$2^{-43.74}$	0.0	0.4
	16 † [Bul13]	$2^{26.1}$	–	$2^{34.0}$	$2^{-46.77}$	0.0	0.4
EPCBC-96 [YKPH11] (32, 96)	31	$2^{27.6}$	–	$2^{63.6}$	$2^{-94.47}$	0.0	0.4
	32	$2^{27.6}$	–	$2^{63.6}$	$2^{-97.59}$	0.0	0.4
Fly [KG16] (20, 64)	8	$2^{32.5}$	–	$2^{6.5}$	$2^{-54.83}$	0.1	6.0
	9	$2^{32.5}$	–	$2^{6.1}$	$2^{-63.00}$	0.2	8.8
GIFT-64 [BPP+17] (28, 64)	11	$2^{31.8}$	–	$2^{5.1}$	$2^{-55.00}$	0.1	8.0
	12	$2^{32.7}$	–	$2^{3.6}$	$2^{-64.00}$	0.2	41.5
Khazad [BR00] (8, 64)	2	$2^{18.3}$	$2^{25.0}$	2^{0}	$2^{-37.97}$	0.0	0.0
	3	$2^{30.1}$	$2^{25.0}$	2^{0}	$2^{-68.01}$	0.2	0.2
KLEIN [GNL11] (12, 64)	5	$2^{30.8}$	$2^{17.0}$	2^{0}	$2^{-46.0}$	0.0	0.0
	6	$2^{39.6}$	$2^{16.9}$	2^{0}	$2^{-66.0}$	0.3	0.0
LED [GPPR11] (32, 64)	4	$2^{24.7}$	2^{25}	2^{2}	$2^{-48.68}$	0.0	0.9
MANTIS_7 [BJK+16] (2 · 8, 64)	2 · 4	$2^{34.3}$	$2^{24.0}$	$2^{15.0}$	$2^{-49.05}$	0.1	0.0
Midori64 [BBI+15] (16, 64)	6	$2^{44.3}$	–	$2^{19.0}$	$2^{-53.02}$	25.9	0.8
	7	$2^{46.5}$	–	$2^{21.9}$	$2^{-62.88}$	53.1	5.5
present [BKL+07] (31, 64)	23 † [Ohk09]	$2^{31.1}$	–	$2^{55.0}$	$2^{-61.00}$	0.1	6.8
	24 † [Ohk09]	$2^{31.1}$	–	$2^{57.9}$	$2^{-63.61}$	0.1	6.9
	25 † [Ohk09]	$2^{31.1}$	–	$2^{60.7}$	$2^{-66.21}$	0.1	6.9
PRIDE [ADK+14] (20, 64)	15	$2^{27.1}$	–	2^{0}	$2^{-58.00}$	0.0	0.0
	16	$2^{37.4}$	–	2^{3}	$2^{-63.99}$	1.8	0.0
PRINCE [BCG+12] (2 · 6, 64)	2 · 3	$2^{18.1}$	–	$2^{2.0}$	$2^{-54.00}$	0.0	0.0
	2 · 4	$2^{38.3}$	–	$2^{6.8}$	$2^{-63.82}$	2.1	0.4
PUFFIN [CHW08] (32, 64)	32	$2^{26.8}$	–	$2^{112.4}$	$2^{-51.90}$	0.0	0.0
QARMA [Ava17] (2 · 8, 64)	2 · 3	$2^{24.8}$	$2^{24.0}$	$2^{5.0}$	$2^{-53.71}$	0.0	0.0
RECTANGLE [ZBL+14] (25, 64)	12 † [ZBL+14]	$2^{31.1}$	–	$2^{15.0}$	$2^{-52.27}$	0.1	21.1
	13 † [ZBL+14]	$2^{31.1}$	–	$2^{15.9}$	$2^{-58.14}$	0.1	25.9
	14 † [ZBL+14]	$2^{31.1}$	–	$2^{18.3}$	$2^{-62.98}$	0.1	31.1
SKINNY-64 [BJK+16] (32, 64)	8	$2^{41.4}$	$2^{23.7}$	$2^{34.4}$	$2^{-50.46}$	0.7	50.7
	9	$2^{41.4}$	$2^{23.9}$	$2^{31.3}$	$2^{-69.83}$	0.4	8.9

Differential Results

Cipher (Total rounds, block size)	Rounds	$\lvert\mathcal{D}\rvert$	a	$\lvert\Delta \diamond \nabla\rvert$	EDP	T_g	T_s
AES [oST01] (10, 128)	3	$2^{18.7}$	$2^{24.0}$	2^{0}	$2^{-54.00}$	0.0	0.0
	4	$2^{36.9}$	$2^{24.0}$	2^{0}	$2^{-150.00}$	0.7	0.3
EPCBC-48 [YKPH11] (32, 48)	13	$2^{28.4}$	–	$2^{21.2}$	$2^{-43.86}$	0.1	13.7
	14	$2^{28.4}$	–	$2^{20.4}$	$2^{-47.65}$	0.1	14.0
EPCBC-96 [YKPH11] (32, 96)	20	$2^{32.8}$	–	$2^{16.9}$	$2^{-92.73}$	1.1	21.6
	21	$2^{32.8}$	–	$2^{19.9}$	$2^{-97.78}$	1.1	22.6
Fly [KG16] (20, 64)	8	$2^{31.6}$	–	$2^{4.9}$	$2^{-55.76}$	0.1	2.6
	9	$2^{33.2}$	–	$2^{7.3}$	$2^{-63.35}$	0.2	17.8
GIFT-64 [BPP+17] (28, 64)	12 † [ZDY18]	$2^{22.4}$	–	$2^{3.3}$	$2^{-56.57}$	0.0	0.0
	13	$2^{22.4}$	–	$2^{3.6}$	$2^{-60.42}$	0.0	0.0
Khazad [BR00] (8, 64)	2	$2^{25.8}$	$2^{24.8}$	2^{0}	$2^{-45.42}$	0.0	0.0
	3	$2^{25.8}$	$2^{25.0}$	2^{0}	$2^{-81.66}$	0.0	0.0
KLEIN [GNL11] (12, 64)	5	$2^{30.8}$	$2^{17.0}$	$2^{1.0}$	$2^{-45.91}$	0.0	0.0
	6	$2^{39.7}$	$2^{24.0}$	$2^{1.0}$	$2^{-69.00}$	0.3	6.4
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MANTIS_7 [BJK+16] (2 · 8, 64)	2 · 4	$2^{37.7}$	–	$2^{18.6}$	$2^{-47.98}$	0.9	0.1
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	7	$2^{42.2}$	$2^{23.9}$	$2^{22.8}$	$2^{-61.22}$	1.0	0.9
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	16 † [Abd12]	$2^{30.3}$	–	$2^{28.9}$	$2^{-61.80}$	0.1	18.0
	17	$2^{30.3}$	–	$2^{32.9}$	$2^{-63.52}$	0.1	18.8
PRIDE [ADK+14] (20, 64)	15	$2^{35.9}$	$2^{23.6}$	$2^{5.0}$	$2^{-58.00}$	0.5	36.5
	16	$2^{35.9}$	$2^{23.6}$	$2^{17.4}$	$2^{-63.99}$	0.5	44.1
PRINCE [BCG+12] (2 · 6, 64)	2 · 3 † [CFG+14]	$2^{14.0}$	2^{19}	2^{1}	$2^{-55.91}$	0.0	0.0
	2 · 4	$2^{38.7}$	–	$2^{9.0}$	$2^{-67.32}$	3.0	1.0
PUFFIN [CHW08] (32, 64)	32	$2^{26.0}$	–	$2^{63.7}$	$2^{-59.63}$	0.0	0.0
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	15 † [ZBL+14]	$2^{31.1}$	–	$2^{18.2}$	$2^{-65.64}$	0.1	50.2
SKINNY-64 [BJK+16] (32, 64)	8	$2^{39.4}$	$2^{24.0}$	$2^{31.0}$	$2^{-50.72}$	0.2	15.0
	9	$2^{41.7}$	$2^{23.8}$	$2^{31.2}$	$2^{-69.64}$	0.4	6.4

Cipher(Total rounds, block size)	Rounds	$\lvert\mathcal{A}\rvert$	a	$\lvert\alpha \diamond \beta\rvert$	ELP	T_g	T_s
EPCBC-48 [YKPH11] (32, 48)	15 † [Bul13]	$2^{26.1}$	–	$2^{31.3}$	$2^{-43.74}$	0.0	0.4
	16 † [Bul13]	$2^{26.1}$	–	$2^{34.0}$	$2^{-46.77}$	0.0	0.4
EPCBC-96 [YKPH11] (32, 96)	31	$2^{27.6}$	–	$2^{63.6}$	$2^{-94.47}$	0.0	0.4
	32	$2^{27.6}$	–	$2^{63.6}$	$2^{-97.59}$	0.0	0.4
PRESENT [BKL+07] (31, 64)	23 † [Ohk09]	$2^{31.1}$	–	$2^{55.0}$	$2^{-61.00}$	0.1	6.8
	24 † [Ohk09]	$2^{31.1}$	–	$2^{57.9}$	$2^{-63.61}$	0.1	6.9
	25 † [Ohk09]	$2^{31.1}$	–	$2^{60.7}$	$2^{-66.21}$	0.1	6.9
PUFFIN [CHW08] (32, 64)	32	$2^{26.8}$	–	$2^{112.4}$	$2^{-51.90}$	0.0	0.0
RECTANGLE [ZBL+14] (25, 64)	12 † [ZBL+14]	$2^{31.1}$	–	$2^{15.0}$	$2^{-52.27}$	0.1	21.1
	13 † [ZBL+14]	$2^{31.1}$	–	$2^{15.9}$	$2^{-58.14}$	0.1	25.9
	14 † [ZBL+14]	$2^{31.1}$	–	$2^{18.3}$	$2^{-62.98}$	0.1	31.1
Cipher(Total rounds, block size)	**Rounds**	$\lvert\mathcal{D}\rvert$	a	$\lvert\Delta \diamond \nabla\rvert$	**EDP**	T_g	T_s
EPCBC-48 [YKPH11] (32, 48)	13	$2^{28.4}$	–	$2^{21.2}$	$2^{-43.86}$	0.1	13.7
	14	$2^{28.4}$	–	$2^{20.4}$	$2^{-47.65}$	0.1	14.0
EPCBC-96 [YKPH11] (32, 96)	20	$2^{32.8}$	–	$2^{16.9}$	$2^{-92.73}$	1.1	21.6
	21	$2^{32.8}$	–	$2^{19.9}$	$2^{-97.78}$	1.1	22.6
PRESENT [BKL+07] (31, 64)	15	$2^{30.3}$	–	$2^{27.2}$	$2^{-58.00}$	0.1	16.2
	16 † [Abd12]	$2^{30.3}$	–	$2^{28.9}$	$2^{-61.80}$	0.1	18.0
	17	$2^{30.3}$	–	$2^{32.9}$	$2^{-63.52}$	0.1	18.8
PUFFIN [CHW08] (32, 64)	32	$2^{26.0}$	–	$2^{63.7}$	$2^{-59.63}$	0.0	0.0
RECTANGLE [ZBL+14] (25, 64)	13 † [ZBL+14]	$2^{31.1}$	–	$2^{15.3}$	$2^{-55.64}$	0.1	32.2
	14 † [ZBL+14]	$2^{31.1}$	–	$2^{15.9}$	$2^{-60.64}$	0.1	41.3
	15 † [ZBL+14]	$2^{31.1}$	–	$2^{18.2}$	$2^{-65.64}$	0.1	50.2

Future Work

Support for ARX ciphers.

Support for ARX ciphers.

Better heuristics for Feistel networks.

cryptagraph

https://gitlab.com/psve/cryptagraph