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On nonlinear approximations and the linear hull effect

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joint work with Christof Beierle and Gregor Leander

ASK 2018, Kolkata

Linear approximations

Linear approximations

$$\Pr[\alpha \cdot x + \beta \cdot F(x) = 0] \text{ far from } \frac{1}{2}$$

quantified by:

$$\text{cor}_F(\alpha, \beta) = 2^{-n} \sum_{x \in \mathbb{F}_2^n} (-1)^{\alpha \cdot x + \beta \cdot F(x)}$$

since

$$\Pr[\alpha \cdot x + \beta \cdot F(x) = 0] = \frac{1}{2} (1 + \text{cor}_F(\alpha, \beta))$$

Linear approximations with correlation ± 1

F has a linear approximation with correlation ± 1
iff it has a component of degree 1.

\Rightarrow This never occurs for one-round SPN (except for trivial Sboxes)

An alternative formulation:

$$\text{cor}_F(\alpha, \beta) = -1 + 2^{-n+2} \#\{x \in \langle \alpha \rangle^\perp \text{ such that } F(x) \in \langle \beta \rangle^\perp\}$$

$$\Rightarrow \text{cor}_F(\alpha, \beta) = \pm 1 \text{ iff } F(\langle \alpha \rangle^\perp) = \langle \beta \rangle^\perp \text{ or } \mathbb{F}_2^n \setminus \langle \beta \rangle^\perp.$$

Linear approximations over several rounds [Daemen 95][Nyberg 01]

$$\text{cor}_{G \circ F}(\alpha, \beta) = \sum_{\gamma \in \mathbb{F}_2^n} \text{cor}_F(\alpha, \gamma) \text{cor}_G(\gamma, \beta) .$$

If one dominant trail $(\alpha, \gamma_0, \beta)$:

$$\text{cor}_{G \circ F}(\alpha, \beta) \simeq \text{cor}_F(\alpha, \gamma_0) \text{cor}_G(\gamma_0, \beta) .$$

Otherwise, linear hull effect.

Two-round approximations with correlation ± 1

For a two-round SPN

$$\text{cor}_{L \circ S}(\alpha, \beta) = \sum_{\gamma \in \mathbb{F}_2^n} \text{cor}_S(\alpha, \gamma) \text{cor}_L(\gamma, \beta) = \text{cor}_S(\alpha, L^T(\beta)) .$$

$$\text{cor}_{\mathcal{R} \circ \text{Add}_k \circ \mathcal{R}}(\alpha, \beta) = \sum_{\gamma \in \mathbb{F}_2^n} (-1)^{k \cdot \gamma} \text{cor}_S(\alpha, L^T(\gamma)) \text{cor}_S(\gamma, L^T(\beta)) .$$

Question: can we get a correlation ± 1 for a two-round approximation for some fixed k ?

Nonlinear approximations and invariants

Nonlinear approximations

Let g and h be two balanced Boolean functions of n variables.

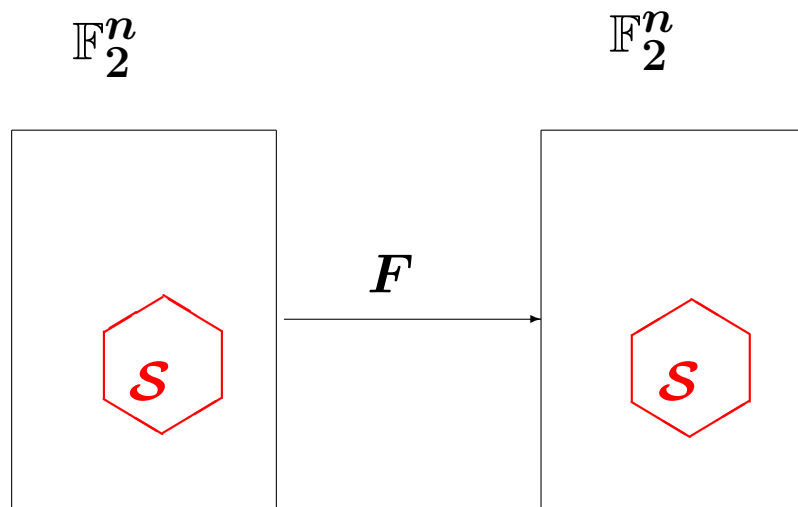
$$\Pr[g(x) + h(F(x)) = 0] \text{ far from } \frac{1}{2}.$$

quantified by:

$$\text{cor}_F(g, h) = 2^{-n} \sum_{x \in \mathbb{F}_2^n} (-1)^{g(x) + h(F(x))}$$

Nonlinear invariants [Todo-Leander-Sasaki 16]

Non-trivial partition of \mathbb{F}_2^n invariant under F :



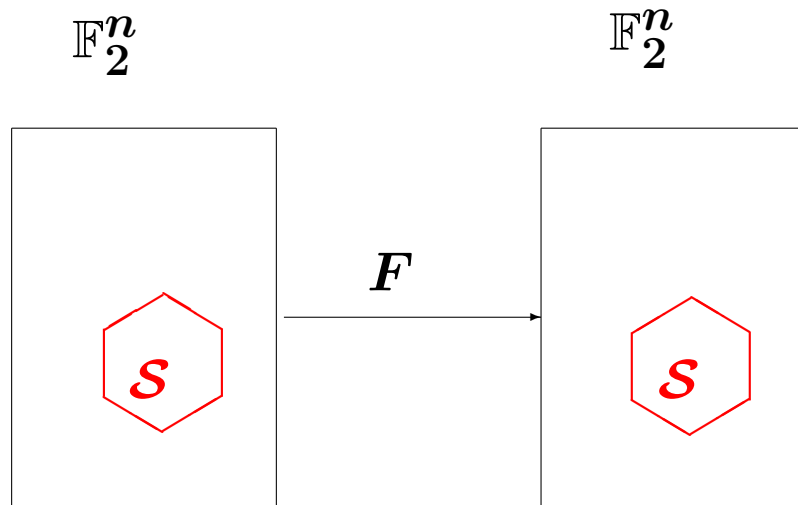
S : any subset of \mathbb{F}_2^n

$$F(S) = S$$

$$\text{or } F(S) = \mathbb{F}_2^n \setminus S$$

The nonlinear invariant attack [Todo-Leander-Sasaki 16]

Non-trivial partition of \mathbb{F}_2^n invariant under F :



S : any subset of \mathbb{F}_2^n

$$F(S) = S$$

$$\text{or } F(S) = \mathbb{F}_2^n \setminus S$$

Equivalently:

Let g be the Boolean function defined by $g(x) := 1$ iff $x \in S$

$$\forall x \in \mathbb{F}_2^n, g(F(x)) = g(x) \text{ or } \forall x \in \mathbb{F}_2^n, g(F(x)) = g(x) + 1$$

Such a g is called an **invariant** for F .

Nonlinear approximations with correlation ± 1

g is an invariant for F if and only if

$$\text{cor}_F(g, g) = 2^{-n} \sum_{x \in \mathbb{F}_2^n} (-1)^{g(x) + g(F(x))} = \pm 1$$

Nonlinear approximations as a combination of linear approximations

$$\text{cor}_F(g, h) = \sum_{\gamma, \gamma' \in \mathbb{F}_2^n} \text{cor}_g(\gamma) \text{cor}_F(\gamma, \gamma') \text{cor}_h(\gamma') .$$

If $g = \ell_\alpha$ and $h = \ell_\beta$, then

$$\text{cor}_F(g, h) = \text{cor}_F(\alpha, \beta) .$$

Otherwise, we gather together several linear approximations.

Nonlinear approximations and the linear hull effect

Transforming nonlinear invariants into linear approximations

Let g be a **balanced** nonlinear invariant for F .

We can always define a permutation \mathcal{G} such that $\alpha \cdot \mathcal{G}(x) = g(x)$.

Then,

$$\begin{aligned} g(x) + g(F(x)) &= \alpha \cdot \mathcal{G}(x) + \alpha \cdot (\mathcal{G} \circ F)(x) \\ &= \alpha \cdot y + \alpha \cdot (\mathcal{G} \circ F \circ \mathcal{G}^{-1})(y) \end{aligned}$$

The **nonlinear** approximation of F defined by (g, g) corresponds to the **linear** approximation (α, α) of $F^{\mathcal{G}, \mathcal{G}^{-1}} = \mathcal{G} \circ F \circ \mathcal{G}^{-1}$.

$$\text{cor}_{F^{\mathcal{G}, \mathcal{G}^{-1}}}(\alpha, \alpha) = \sum_{\gamma_1, \gamma_2 \in \mathbb{F}_2^n} \text{cor}_{\mathcal{G}_\alpha}(\gamma_1) \text{cor}_F(\gamma_1, \gamma_2) \text{cor}_{\mathcal{G}_\alpha}(\gamma_2)$$

The other components of \mathcal{G} do not matter!

\mathcal{G} -shifted trails

$$\begin{aligned} E_{(k_0, \dots, k_t)}^{\mathcal{G}, \mathcal{G}^{-1}} &= \mathcal{G} \circ \mathcal{R}_{k_t} \circ \mathcal{R}_{k_{t-1}} \circ \dots \circ \mathcal{R}_{k_0} \circ \mathcal{G}^{-1} \\ &= \mathcal{R}_{k_t}^{\mathcal{G}, \mathcal{G}^{-1}} \circ \mathcal{R}_{k_{t-1}}^{\mathcal{G}, \mathcal{G}^{-1}} \circ \dots \circ \mathcal{R}_{k_0}^{\mathcal{G}, \mathcal{G}^{-1}}. \end{aligned}$$

$$\text{cor}_{E_{(k_0, \dots, k_t)}^{\mathcal{G}, \mathcal{G}^{-1}}}(\alpha, \beta) = \sum_{\gamma_1, \dots, \gamma_{t-1} \in \mathbb{F}_2^n} \prod_{i=0}^{t-1} \text{cor}_{\mathcal{R}_{k_i}^{\mathcal{G}, \mathcal{G}^{-1}}}(\gamma_i, \gamma_{i+1}).$$

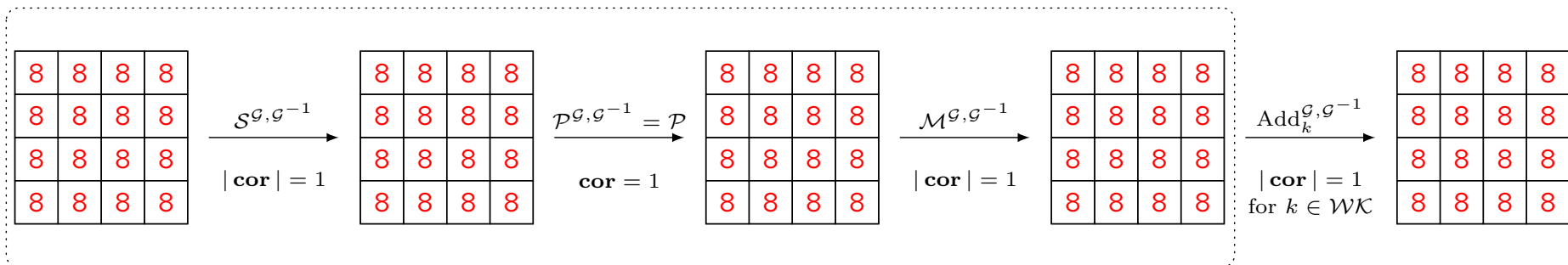
A one-round \mathcal{G} -shifted trail on Midori-64

$\mathcal{G} = (G, \dots, G)$ where G is a bijection on 4 bits such that $\langle 8, G(x) \rangle = g(x)$ with $g(x) = x_3x_2 + x_2 + x_1 + x_0$ invariant for the Sbox, i.e.

$$|\text{cor}_{\mathcal{S}G, G^{-1}}(8, 8)| = 1 .$$

$$|\text{cor}_{\mathcal{M}\mathcal{G}, \mathcal{G}^{-1}}((8, \dots, 8), (8, \dots, 8))| = 1 .$$

\Rightarrow Iterative one-round trail with correlation ± 1 :



A two-round shifted trail on Midori-64 [Beyne 18]

For $g(x) = x_0x_2 + x_0 + x_1 + x_3$ and $\alpha = 0x5$, the Sbox satisfies

$$g(S(x)) + \alpha \cdot x = 1 .$$

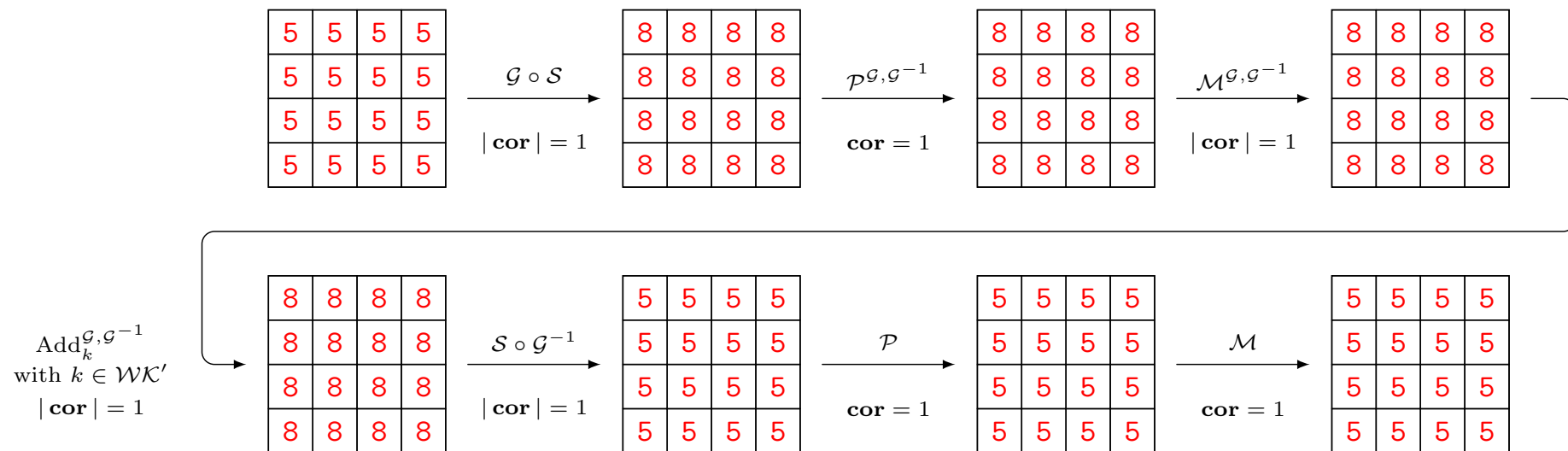
We choose a 4-bit bijection G such that $\langle 8, G(x) \rangle = g(x)$.

Equivalently,

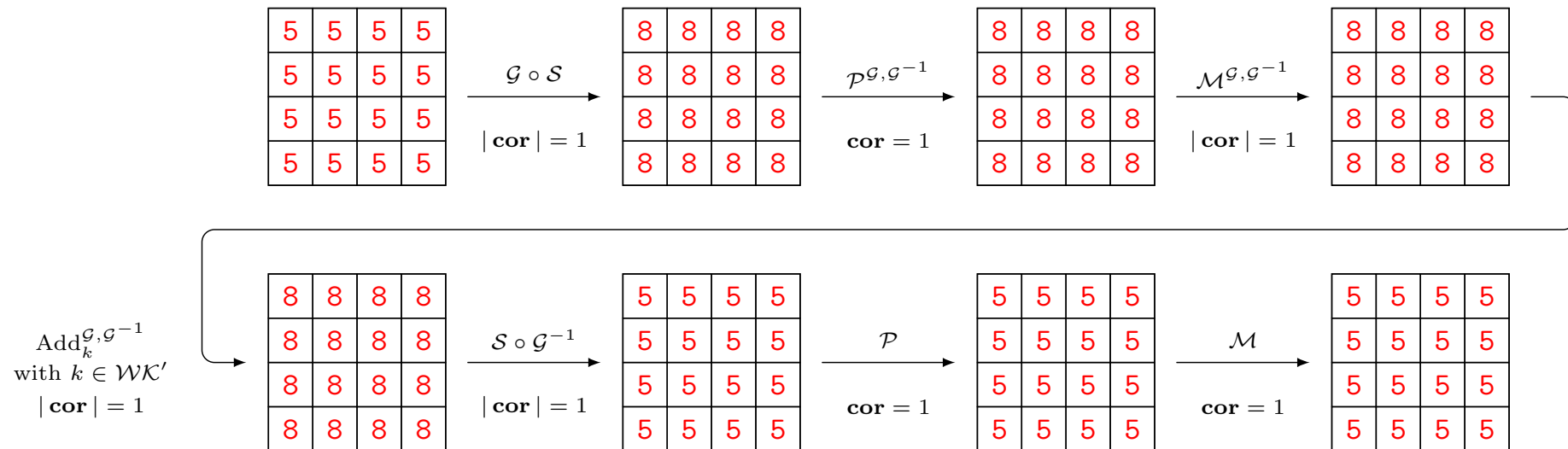
$$\text{cor}_S(\ell_\alpha, g) = \text{cor}_{G \circ S}(\alpha, 8) = -1 .$$

$$|\text{cor}_{\mathcal{M}^{g, g^{-1}}}((8, \dots, 8), (8, \dots, 8))| = 1 .$$

A two-round shifted trail on Midori-64 [Beyne 18]



A two-round shifted trail on Midori-64 [Beyne 18]



This is a two-round **linear** approximation with correlation ± 1 !

A 4-round \mathcal{G} -shifted trail on Midori-64

G is a bijection on 4 bits such that $\langle 8, G(x) \rangle = g(x)$
with $g(x) = x_3x_2x_1 + x_3x_1 + x_3 + x_2 + x_1 + x_0$ invariant for the Sbox:

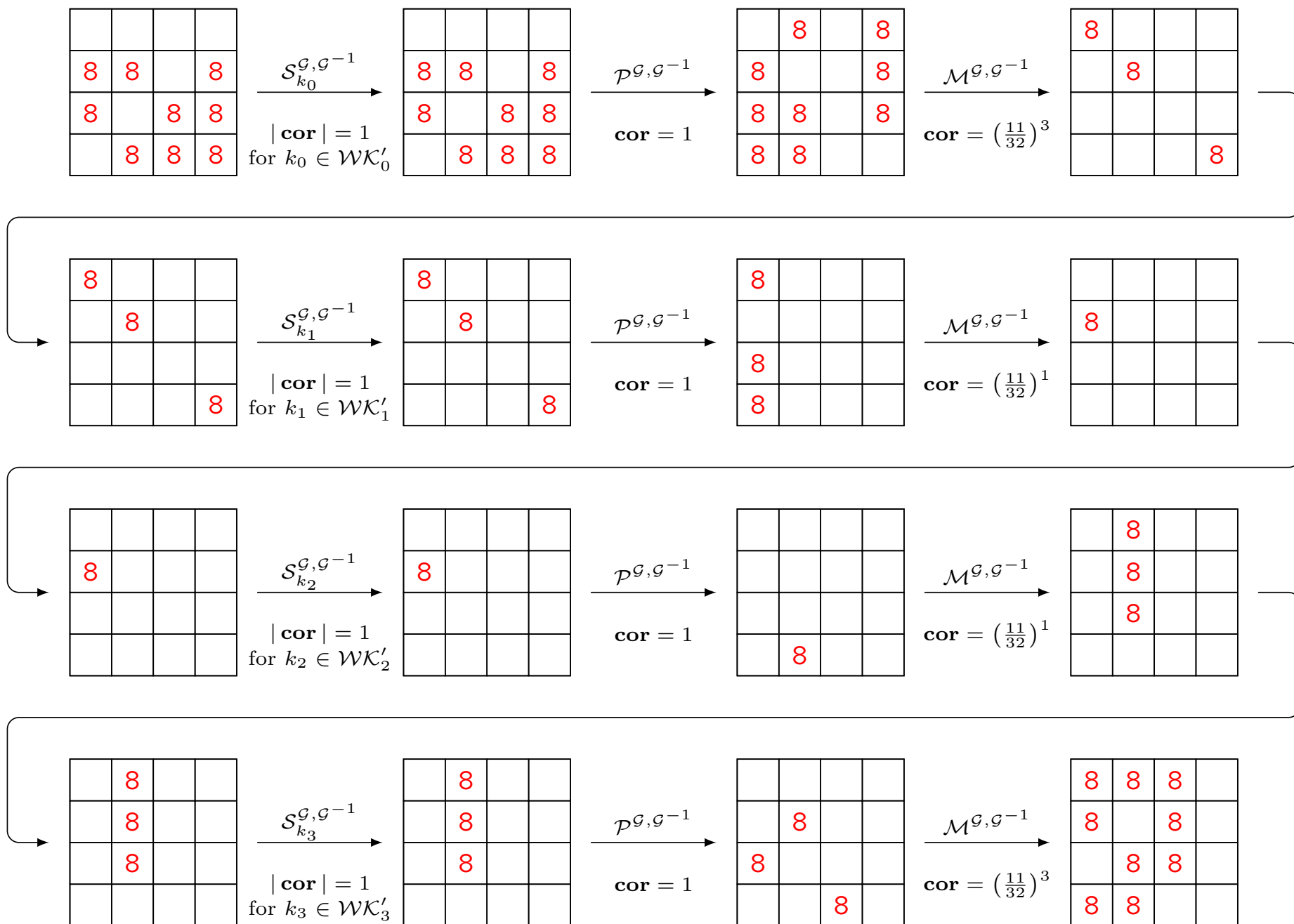
$$|\text{cor}_{SG, G^{-1}}(8, 8)| = 1 .$$

But,

$$|\text{cor}_{MG, G^{-1}}(\alpha, M\alpha)| = \frac{11}{32}$$

if $\alpha \neq (0, 0, 0, 0)$ and all $\alpha_i \in \{0, 8\}$.

A 4-round \mathcal{G} -shifted trail on Midori-64



A 4-round \mathcal{G} -shifted trail on Midori-64

The weak keys are those equal to 0 or 1 in all active cells.

Correlation of the trail:

$$\left(\frac{11}{32}\right)^8 = 2^{-12.325}$$

Correlation of the approximation:

$$\text{cor}_{(\mathcal{R}_{k_3} \circ \dots \circ \mathcal{R}_{k_0})^{\mathcal{G}, \mathcal{G}^{-1}}(\alpha, \alpha)} \simeq 2^{-12.16}$$

What's about the other trails? For the first 2 rounds:

- For $G_1 = [0, 8, c, 4, a, 2, 6, e, 9, 1, d, 5, 3, b, f, 7]$,
35,937 \mathcal{G}_1 -shifted linear trails having a nonzero correlation
- For $G_2 = [0, 9, a, 1, 8, 2, 3, f, c, 4, d, 5, 6, e, b, 7]$,
282,184 \mathcal{G}_2 -shifted linear trails having a nonzero correlation

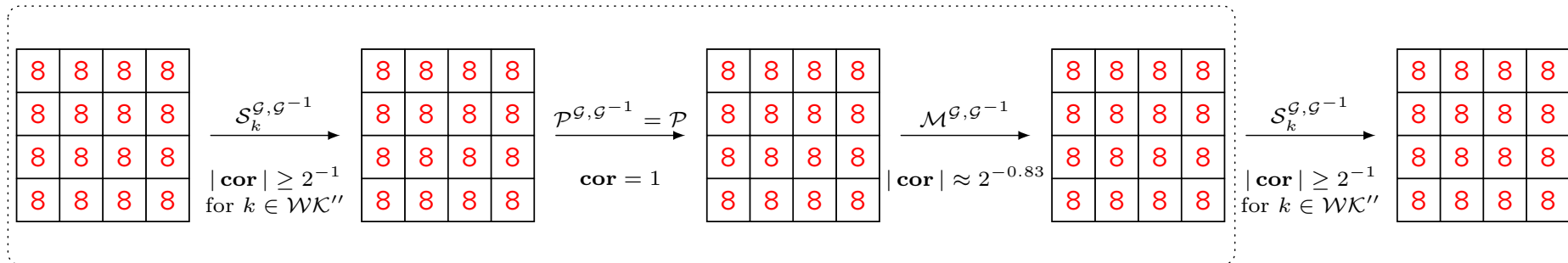
Another 1-round \mathcal{G} -shifted trail on Midori-64

$\mathcal{G} = (G', G, \dots, G)$ where G is a bijection on 4 bits such that
 $\langle 8, G(x) \rangle = g(x)$ with $g(x) = x_3x_2 + x_2 + x_1 + x_0$ invariant for S ,
 $\langle 8, G'(x) \rangle = g'(x)$ with $g'(x) = x_3x_2x_1 + x_3x_1 + x_3 + x_2 + x_1 + x_0$.

$$|\text{cor}_{S_k^{G', G'^{-1}}}(8, 8)| = \begin{cases} 1 & \text{if } k \in \{0, 1\} \\ 2^{-1} & \text{if } k \notin \{0, 1\} \end{cases} .$$

$$|\text{cor}_{\mathcal{M}^{\mathcal{G}, \mathcal{G}^{-1}}}((8, \dots, 8), (8, \dots, 8))| \simeq 2^{-0.83}$$

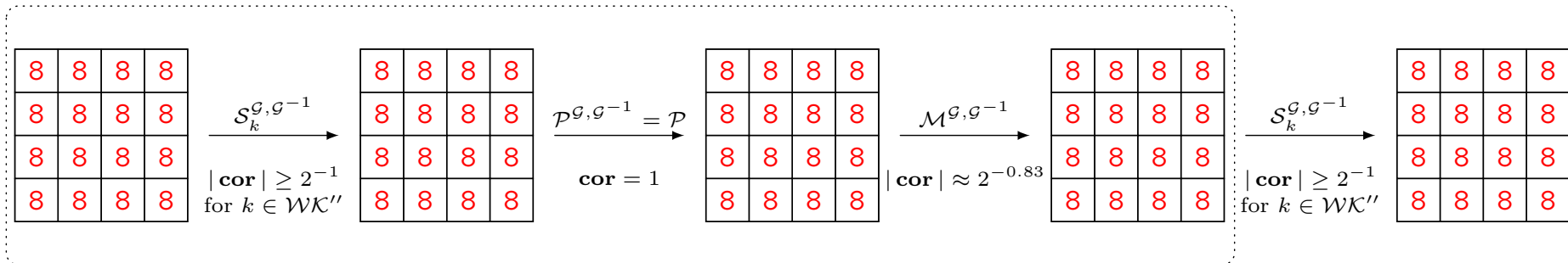
Another 1-round \mathcal{G} -shifted trail on Midori-64



Correlation of the 16-round trail:

$$\geq \left(2^{-1.83}\right)^{16} = 2^{-29.28}$$

Another 1-round \mathcal{G} -shifted trail on Midori-64



Correlation of the 16-round trail:

$$\geq \left(2^{-1.83}\right)^{16} = 2^{-29.28}$$

Correlation over 16 rounds:

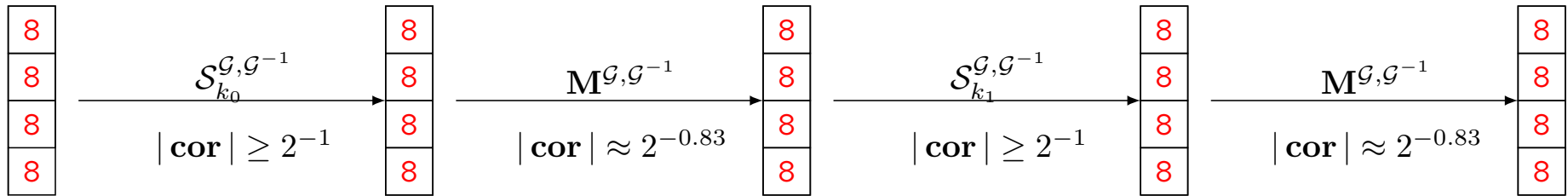
different from the correlation of the trail.

Focus on a single column

$\mathcal{G} = (G', G, G, G)$ with

$$|\text{cor}_{S_k^{G', G'^{-1}}} (8, 8)| = \begin{cases} 1 & \text{if } k \in \{0, 1\} \\ 2^{-1} & \text{if } k \notin \{0, 1\} \end{cases} .$$

$$|\text{cor}_{M^{\mathcal{G}, \mathcal{G}^{-1}}} ((8, 8, 8, 8), (8, 8, 8, 8))| = 2^{-0.83}$$



If $k_1 \in \left(\mathbb{F}_2^4 \setminus \{(0, 0, *, *)\} \right) \times \{(0, 0, *, *)\}^3$,

$$\text{cor}_{\mathcal{R}_{k_1} \circ \mathcal{R}_{k_0}} ((8, 8, 8, 8), (8, 8, 8, 8)) = 0$$

Open problems

- When can we approximate the correlation with a single trail?
- Nonlinear approximations as a method for clustering linear approximations to capture the linear hull effect?
 - How general is this?
 - How can we find the appropriate approximation?