Cryptanalysis of PRESENT-like ciphers with secret S-boxes

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FSE 2011

Cryptanalysis of Maya

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Outline

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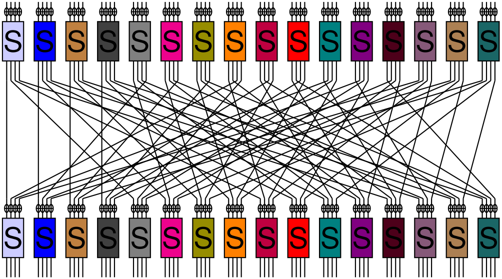
Maya



- 64 bit block size
- key-dependent 4-bit Sbox
- fixed bit permutation
- round keys
- 16 rounds

A more efficient variant of PRESENT.

Outline

Our Contribution

Main Result

In this talk we explain how to break Maya with a complexity of $\approx 2^{37}$.

Technique: Differential attack with a twist.

Idea

Use good differentials without knowing them.

Differential Attack on Maya

- We cannot specify characteristics
- Thus: no characteristic to be followed

$$\begin{matrix}(x||r)\\(y||r)\end{matrix} \longrightarrow \boxed{E_{K_1}} \xrightarrow{\Delta?} \boxed{E_{K_2}} \xrightarrow{\Delta?} \boxed{E_{K_3}} \quad \cdots \quad \boxed{E_{K_r}} \longrightarrow \Delta\gamma$$

Differential Attack on Maya

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- Thus: no characteristic to be followed

$$\begin{matrix}(x||r)\\(y||r)\end{matrix} \rightarrow \boxed{E_{K_1}} \xrightarrow{\Delta ?} \boxed{E_{K_2}} \xrightarrow{\Delta ?} \boxed{E_{K_3}} \cdots \boxed{E_{K_r}} \rightarrow \Delta\gamma$$

Use relative information:

$$\begin{matrix}(x||r)\\(y||r)\end{matrix} \rightarrow \boxed{E_{K_1}} \xrightarrow{\Delta\alpha} \boxed{E_{K_2}} \xrightarrow{\Delta ?} \boxed{E_{K_3}} \cdots \boxed{E_{K_r}} \rightarrow \Delta\gamma$$

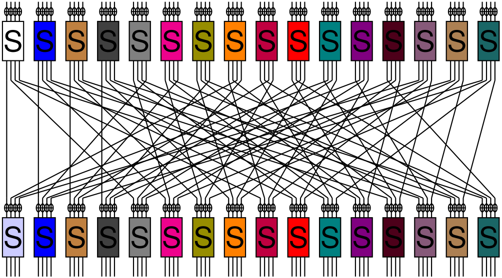
$$\begin{matrix}(x'||r)\\(y'||r)\end{matrix} \rightarrow \boxed{E_{K_1}} \xrightarrow{\Delta\alpha'} \boxed{E_{K_2}} \xrightarrow{\Delta ?} \boxed{E_{K_3}} \cdots \boxed{E_{K_r}} \rightarrow \Delta\gamma'$$

Informally: Compare distribution of $\Delta\gamma$ and $\Delta\gamma'$: Learn something about $\Delta\alpha$ and/or $\Delta\alpha'$.

Left Most Sbox

Remark

We focus on the leftmost Sbox in the first round. Other Sboxes similar.



- try to recover the white Sbox
- using differentials
- with a twist

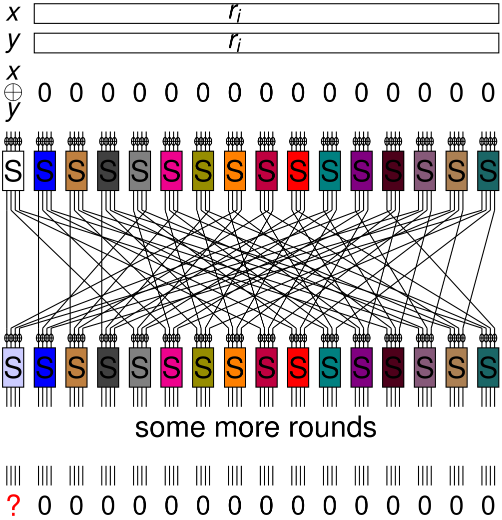
The basic idea to recover the Sboxes

- Fix two inputs $x \neq y \in \mathbb{F}_2^4$ to the leftmost Sbox S.
- Estimate the probability of

$$(x \oplus y)||0^{60} \rightarrow ?||0^{60}$$

using counters for each pair (x, y).

The basic idea in a picture



- Fix x, y
- Encrypt pair $(x|r_i, y|r_i)$, $0 \leq i < N$.
- Count how often only first Sbox active in the output

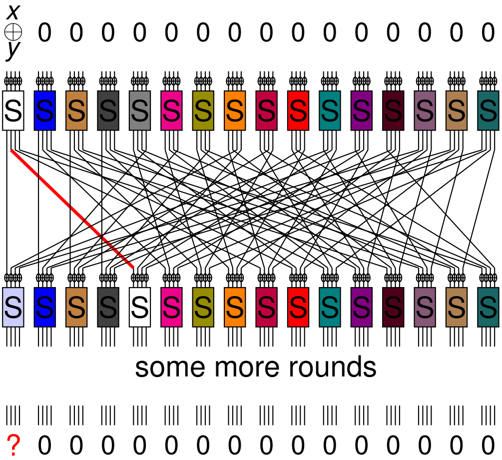
First Assumption

Assumption

The smaller the hamming weight of $S(x) \oplus S(y)$ is, the higher the counter.

The highest counters correspond to one bit differences $S(x) \oplus S(y)$. This will tell us something about the Sbox.

First Assumption in a Picture

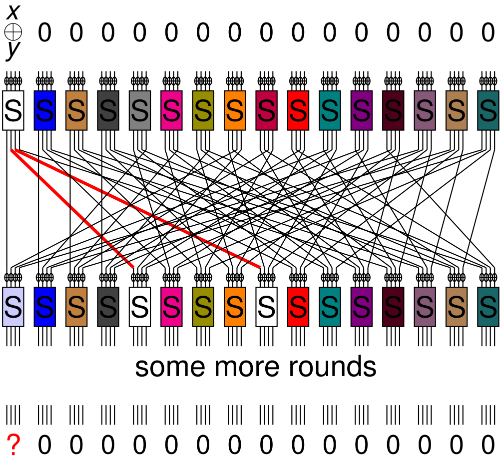


- x, y with one bit output difference

  $$\mathrm{wt}(S(x)+S(y)) = 1$$

- One active Sboxes in the second round

First Assumption in a Picture



- x, y with two bit output difference

  $$\mathrm{wt}(S(x)+S(y)) = 2$$

- Two active Sboxes in the second round

A bit more precise

- Encrypt structures $\star || r_i$, $\star$ runs through all 4 bit values and $r_i \in \mathbb{F}_2^{60}$ is random and fixed. $0 \leq i < Ns$.
- For each pair $\{x, y\}$ with $x \neq y \in \mathbb{F}_2^4$ we have a counter

$$C(\{x, y\}) = \sharp\{r_i \,|Enc(x||r_i) \oplus Enc(y||r_i) =?||0^{64}\}$$

Assumption

The highest counters $C(\{x, y\})$ correspond to x, y such that $\mathrm{wt}(S(x) \oplus S(y)) = 1$.

For the rest: Examples only!

Example

$$C(\{x,y\}) = \sharp\{r_i \mid Enc(x||r_i) \oplus Enc(y||r_i) =?||0^{64}\}$$

(sorted and only the 24 highest values out of 120)

$C(x,y)$	273	265	264	263	261	261	253	243
$\{x,y\}$	(b,9)	(7,2)	(d,a)	(6,5)	(3,1)	(f,8)	(e,4)	(c,0)
$C(x,y)$	163	157	139	136	119	114	102	95
$\{x,y\}$	(a,6)	(8,4)	(2,0)	(9,1)	(f,e)	(d,5)	(c,7)	(b,3)
$C(x,y)$	11	8	8	7	6	6	5	5
$\{x,y\}$	(8,0)	(8,3)	(f,4)	(e,7)	(4,2)	(5,2)	(6,1)	(a,9)

Do the highest counters $C(\{x,y\})$ correspond to x, y such that $\mathrm{wt}(S(x) \oplus S(y)) = 1$?

Example for the counters

$C(x,y)$	273	265	264	263	261	261	253	243
$\{x,y\}$	(b,9)	(7,2)	(d,a)	(6,5)	(3,1)	(f,8)	(e,4)	(c,0)
$\mathrm{wt}(S(x) \oplus S(y))$	1	1	1	1	1	1	1	1
$C(x,y)$	163	157	139	136	119	114	102	95
$\{x,y\}$	(a,6)	(8,4)	(2,0)	(9,1)	(f,e)	(d,5)	(c,7)	(b,3)
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$\mathrm{wt}(S(x) \oplus S(y))$	2	2	1	3	2	1	2	2

The assumption is fulfilled! But there is more...

Probabilities of Differentials

Assumption

The probability of a (truncated) differential depends on the (second round) input difference.

Implication for the counters $C(\{x, y\})$: High counters should correspond to the same output difference.

Example for the counters

$C(x,y)$	273	265	264	263	261	261	253	243
$\{x,y\}$	(b,9)	(7,2)	(d,a)	(6,5)	(3,1)	(f,8)	(e,4)	(c,0)
$\mathrm{wt}(S(x) \oplus S(y))$	1	1	1	1	1	1	1	1
$S(x) \oplus S(y)$	4	4	4	4	4	4	4	4
$C(x,y)$	163	157	139	136	119	114	102	95
$\{x,y\}$	(a,6)	(8,4)	(2,0)	(9,1)	(f,e)	(d,5)	(c,7)	(b,3)
$\mathrm{wt}(S(x) \oplus S(y))$	1	1	1	1	1	1	1	1
$S(x) \oplus S(y)$	2	2	2	2	2	2	2	2
$C(x,y)$	11	8	8	7	6	6	5	5
$\{x,y\}$	(8,0)	(8,3)	(f,4)	(e,7)	(4,2)	(5,2)	(6,1)	(a,9)
$\mathrm{wt}(S(x) \oplus S(y))$	2	2	1	3	2	1	2	2
$S(x) \oplus S(y)$	5	6	8	7	5	8	5	5

Example for the counters

$C(x,y)$	273	265	264	263	261	261	253	243
$\{x,y\}$	(b,9)	(7,2)	(d,a)	(6,5)	(3,1)	(f,8)	(e,4)	(c,0)
$\mathrm{wt}(S(x) \oplus S(y))$	1	1	1	1	1	1	1	1
$S(x) \oplus S(y)$	4	4	4	4	4	4	4	4

- The highest 8 counters correspond to 8 pairs with the same output difference.
- There are exactly 8 such pairs, so we learn them all.
- We do not know the exact difference.
- But we assume it is of hamming weight one.

Recovering the Sbox

Remark

That is a lot(?) of information about the Sbox!

We learn up to 4 sets

$$D_e = \{\{x, y\} \mid S(x) \oplus S(y) = e\}$$

- Still too many possibilities!
- Learning all 4 sets is difficult.

Attack the Inverse

We learn up to 4 sets

$$D_e = \{\{x, y\} \mid S(x) \oplus S(y) = e\}$$

Even better

We can do the attack upside down!

We learn up to 4 sets

$$E_f = \{\{x, y\} \mid S^{-1}(x) \oplus S^{-1}(y) = f\}$$

Experimental Fact

Given two sets D_e and one set E_f: Often only one possible Sbox.

Some Improvements

Improvements over the basic idea:

- Relaxed truncated differentials
- Detect errors, i.e. discard wrong sets

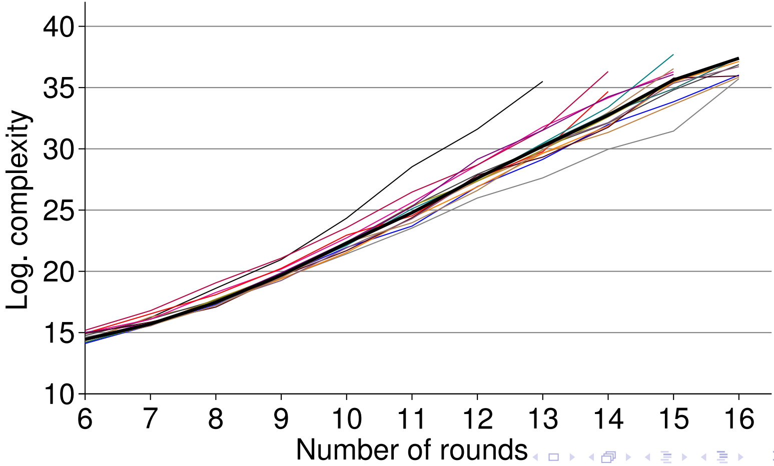
Details in the paper

Crucial

Those make the difference between a practical and a theoretical attack.

Outline

Experimental Complexity of the Attack



Conclusions

- Practical attack on Maya
- Applies to a broader class
- Up to 28 rounds: not secure
- Technique: Twist on truncated differentials
- Mathematical model of the complexity in the paper

The End

Thanks a lot!