Cryptanalysis of SKINNY in the Framework of the SKINNY 2018-2019 Cryptanalysis Competition

Patrick Derbez[1], Virginie Lallemand[2], Aleksei Udovenko[3]

[1]Univ Rennes, CNRS, IRISA, France

[2]Université de Lorraine, CNRS, Inria, France

[3]SnT and CSC, University of Luxembourg, Luxembourg

SAC 2019

Problem

Given a set of 2^{20} **messages**, **practically** recover the 128-bit keys of reduced versions of SKINNY-64-128 and SKINNY-128-128

$$\text{Skinny}-n-k$$

block size

key size

Overview of SKINNY

SKINNY [BJK+16]

The SKINNY family of block ciphers and its low-latency variant MANTIS
Beierle, Jean, Kölbl, Leander, Moradi, Peyrin, Sasaki, Sasdrich, Sim
Crypto 2016

- Performs as well as Simon
- Follows the Tweakey Framework [JNP14] :

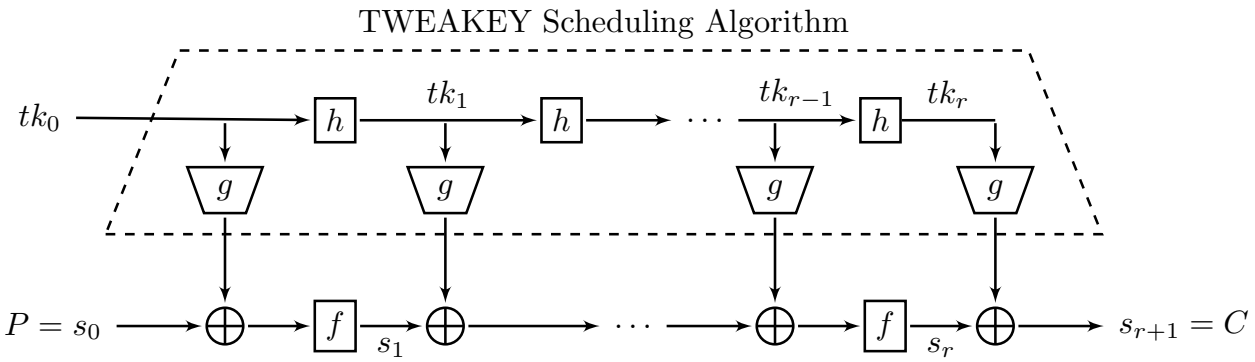
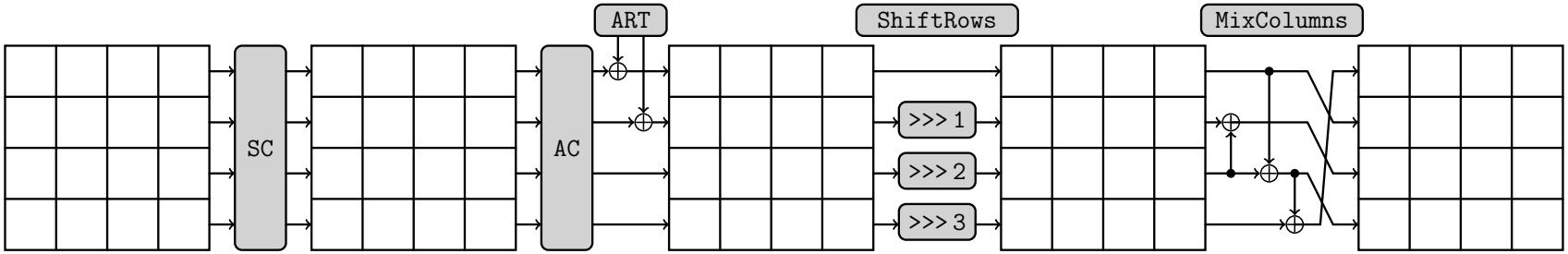


Figure credits: TikZ for Cryptographers [Jea16]

Skinny round function



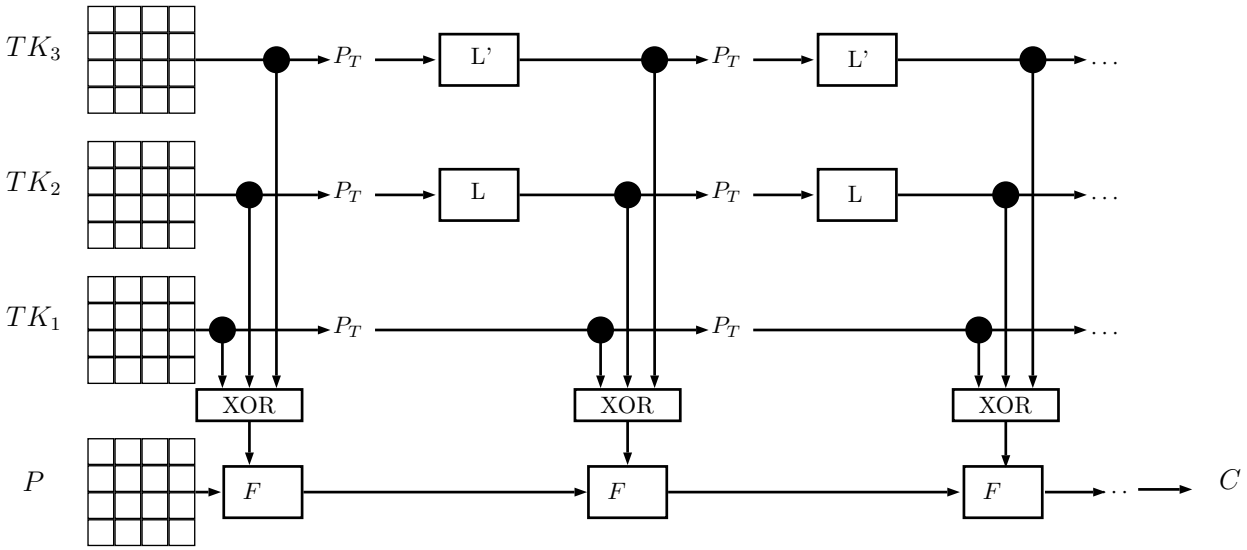
- Block size of 64 or 128 bits
- Tweakey added on the first two lines of the state, **after** SC
- Binary diffusion matrix

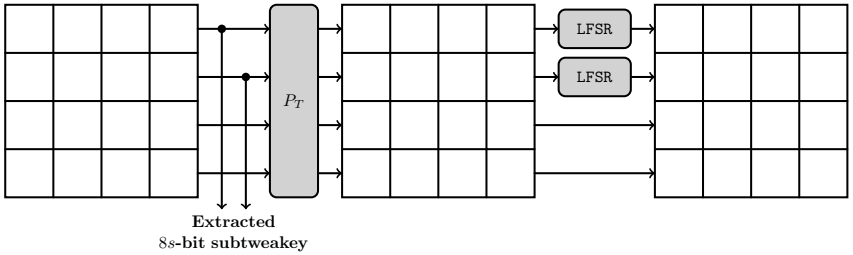
MixColumns Matrix:

$$M = \begin{pmatrix} 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 \end{pmatrix}$$

Figure credits: TikZ for Cryptographers [Jea16]

Skinny Tweakey Schedule





	Tweakey blocks		
block size	1	2	3
$n = 64$	32	36	40
$n = 128$	40	48	56

Figure credits: TikZ for Cryptographers [Jea16]

The SKINNY Competition

The SKINNY 2018-2019 Cryptanalysis Competition

2016 – 2017 Attack small-scaled variants SKINNY-64-128 ($\geq$ 18 rounds), and of SKINNY-128-128 ($\geq$ 22 rounds): [ABC+17] [LGS17] single-key and related-key attacks

2017 – 2018 Similar, except with higher number of rounds

2018 – 2019 More practical scenario:
Provided:

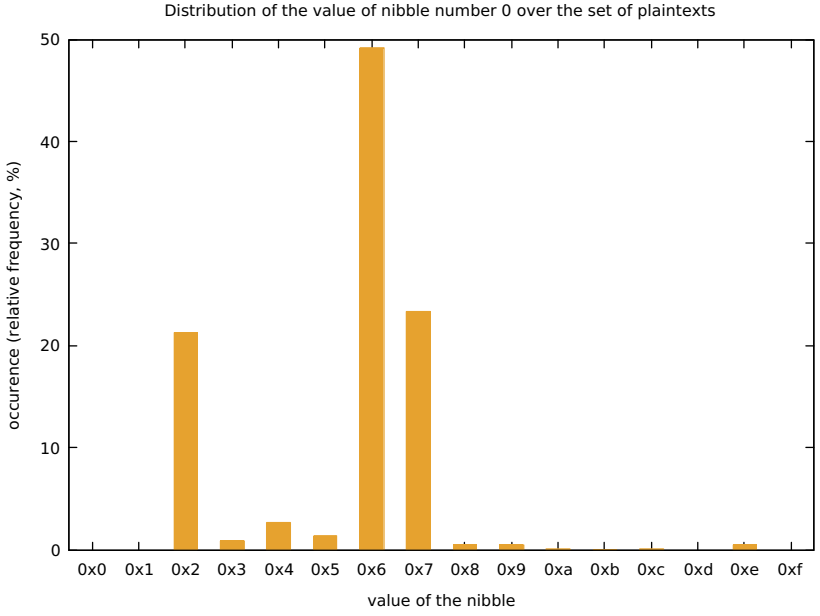
- Set of 2^{20} (plaintexts, ciphertexts) encrypted under a single and secret key
- Sample C code

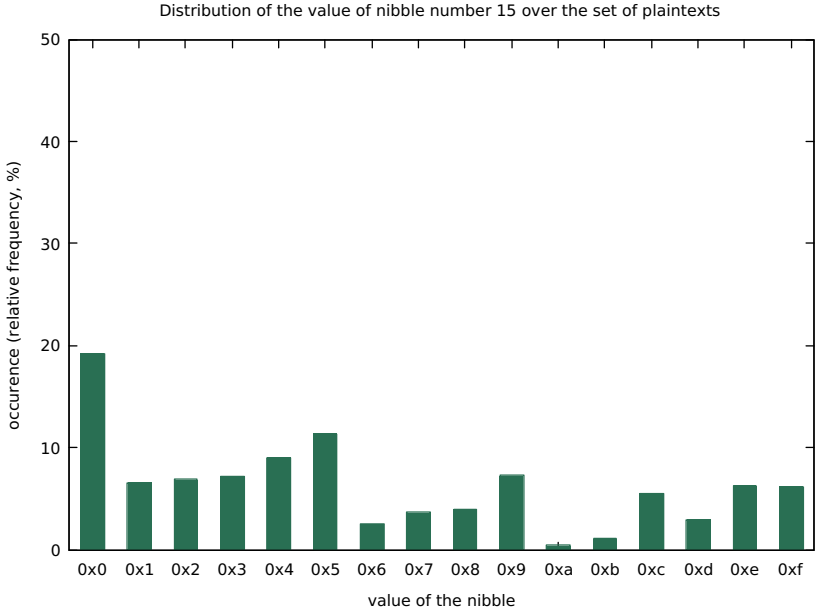
Return the key

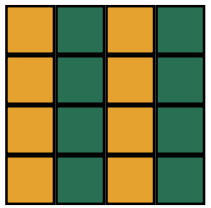
On the Provided Messages

Bias on the Provided Messages

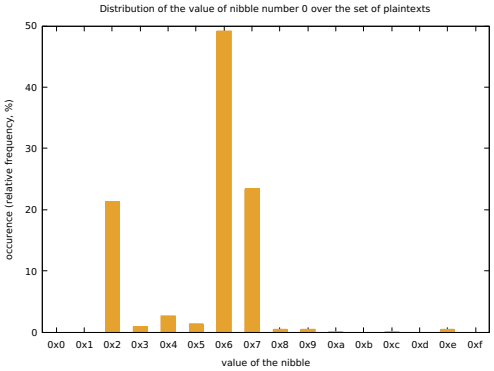
Distribution of the value of nibble 0 (left) and of nibble 15 (right) of the plaintexts for the 12-round attack on SKINNY-64-128

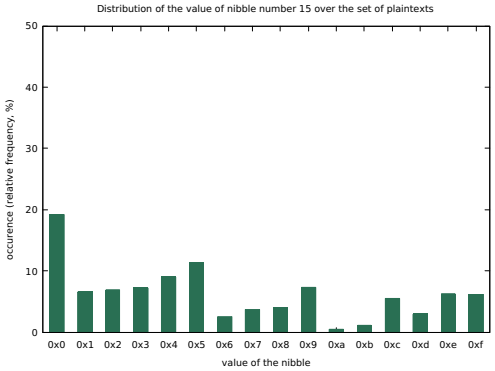




$P =$ 

Recalling the ASCII/UTF8 encoding





	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
⋮								...								
2	space	!	”	#	$	%	&	‘	(	)	*	+	,	-	.	/
3	0	1	2	3	4	5	6	7	8	9	:	;	¡	=	¿	?
4	@	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
5	P	Q	R	S	T	U	V	W	X	Y	Z	[	\	]	ˆ	_
6	`	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o
7	p	q	r	s	t	u	v	w	x	y	z	{	—	}	˜	
⋮																

The Plaintexts actually come from English Novels!

> *Project Gutenberg's Alice's Adventures in Wonderland, by Lewis Carroll This eBook is for the use of anyone anywhere at no cost and with almost no restrictions whatsoever.*

And few lines later:

> *[...] when suddenly a White Rabbit with pink eyes ran close by her. There was nothing so VERY remarkable in that; nor did Alice think it so VERY much out of the way to hear the Rabbit say to itself, 'Oh dear! Oh dear! I shall be late!'*

Other data sets correspond to other books (for instance Metamorphosis, by Franz Kafka or The Prince, by Nicolo Machiavelli).

Possible Attacks?

Given our specific set:

- We expect pairs that differ only in few cells
- A **differential** attack seems possible
- Still, we expect that only little data is exploitable: look for **truncated**, high probability distinguisher

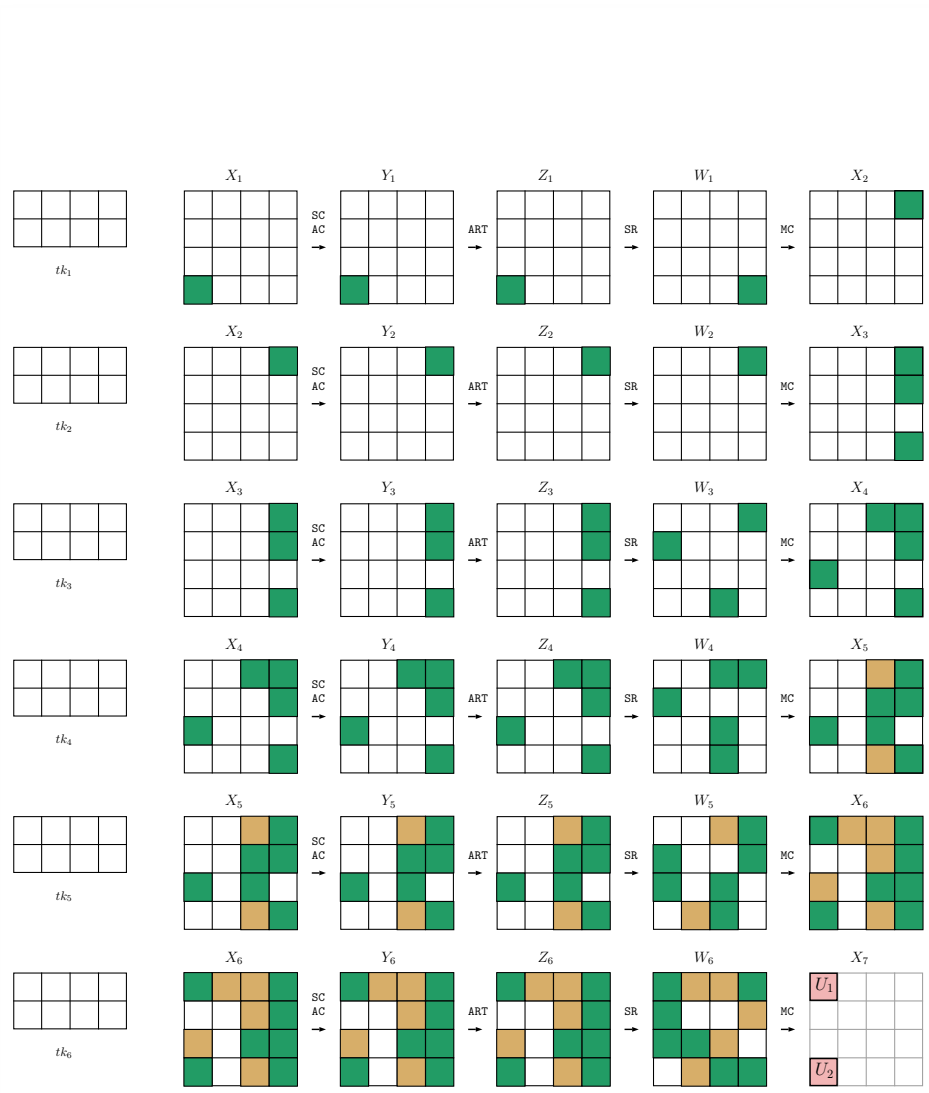
Our Attacks

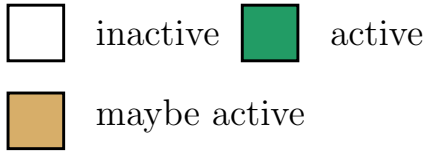
Our Attack on 12-round SKINNY-64-128

- **6 rounds** of truncated differential of **probability 1**
- **1 round** prepended for **free**
- **5 rounds** of key recovery

Total complexity: $2^{51.95}$ basic operations, 32 pairs, 256G memory

Probability 1 Distinguisher over 7 rounds

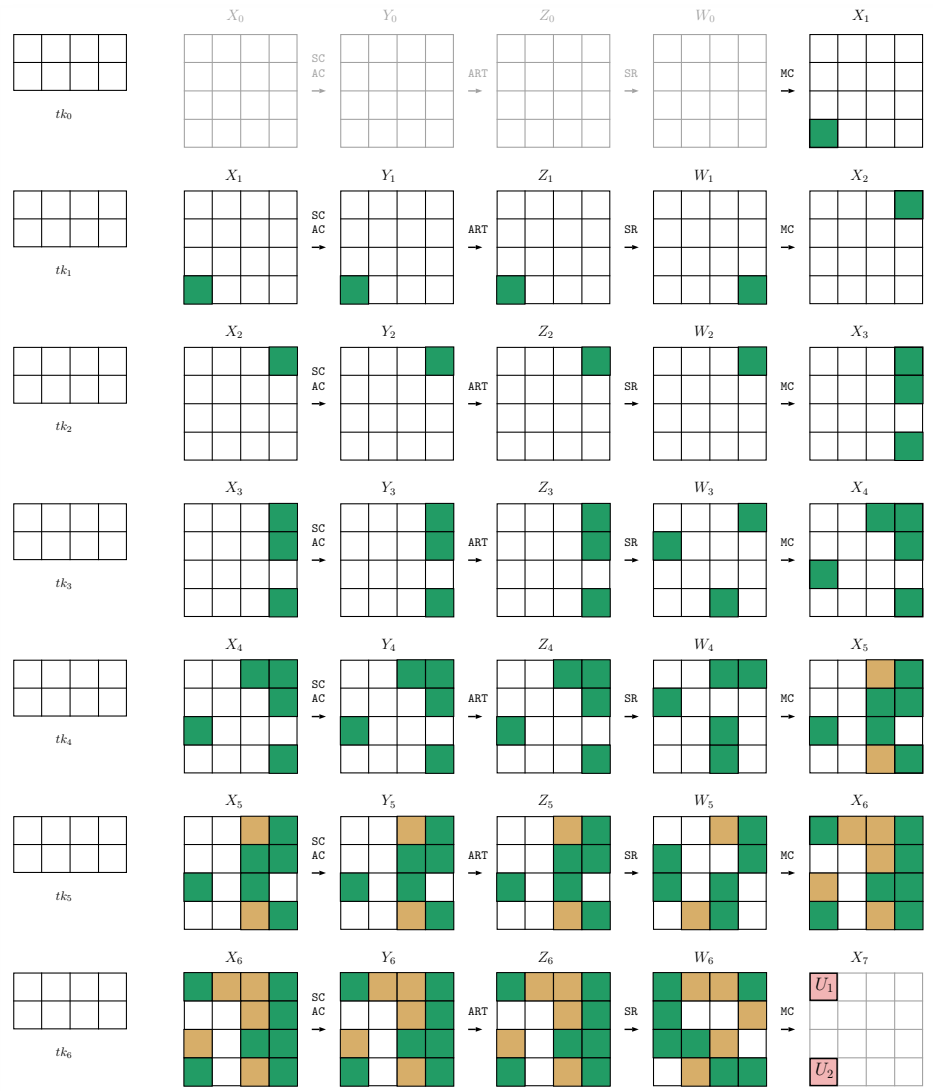




- Truncated differential of probability 1
- If only $X_1[12]$ is active, $X_7[0] = X_7[12]$:

$$\begin{pmatrix} 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 \end{pmatrix} \times \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ 0 \end{pmatrix} = \begin{matrix} x_1 + x_3 \\ x_1 \\ x_2 + x_3 \\ x_1 + x_3 \end{matrix}$$

Probability 1 Distinguisher over 7 rounds



inactive active

maybe active

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- 1 round for free from ARK position

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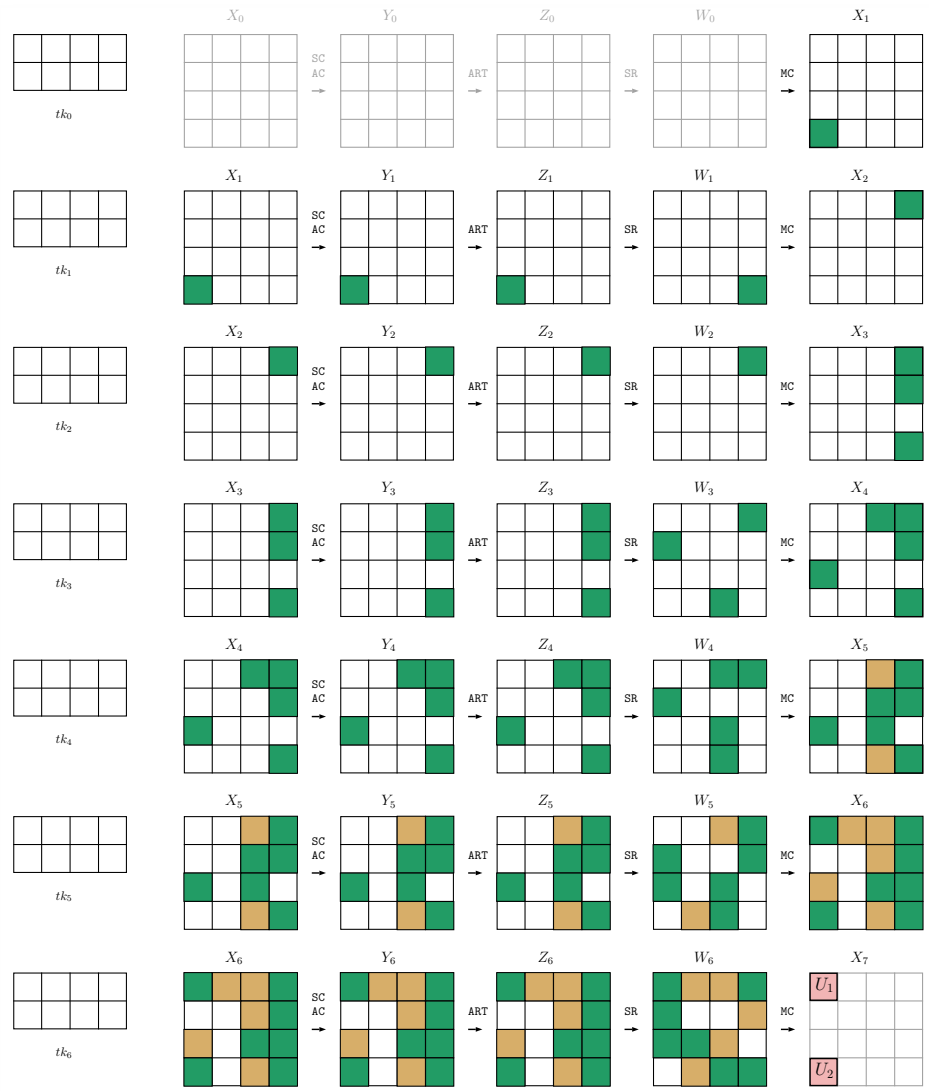

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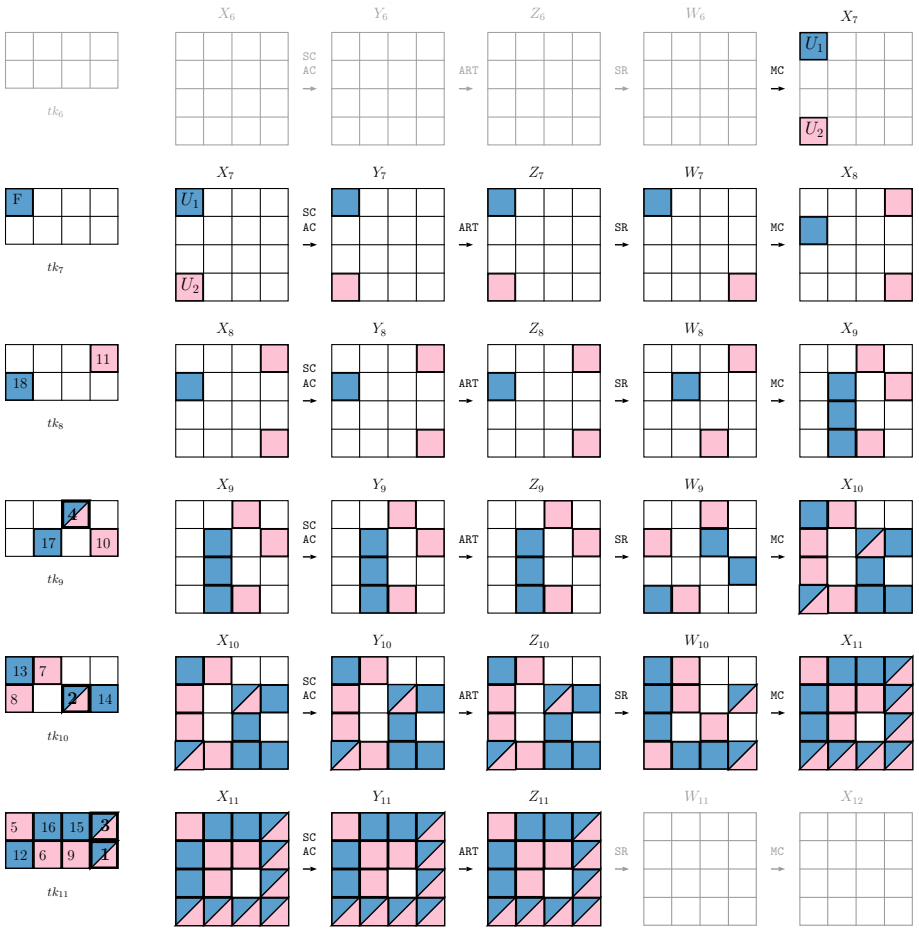
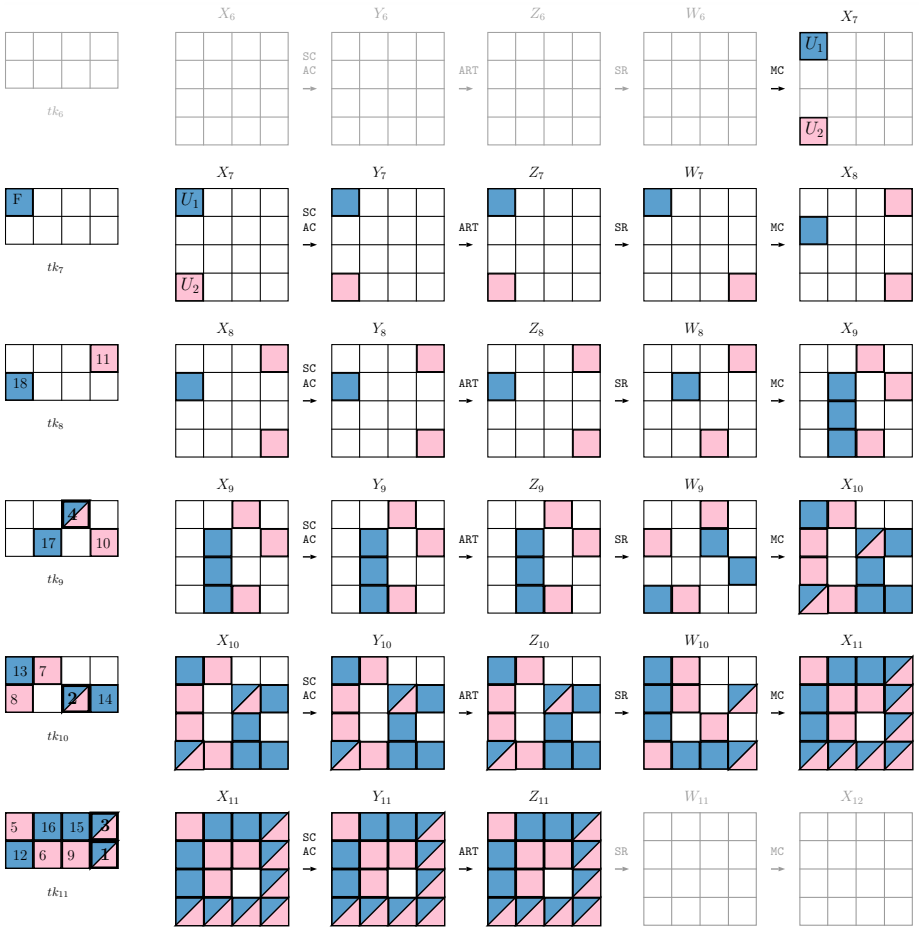
- 1 round for free from ARK position
- In the provided set, 57 pairs follow this trail

Adding 5 rounds of Key Recovery



- in blue the nibbles that are required to compute $X_7[0]$
- in pink the nibbles that are required to compute $X_7[12]$
- total of 19 nibbles, 4 in common

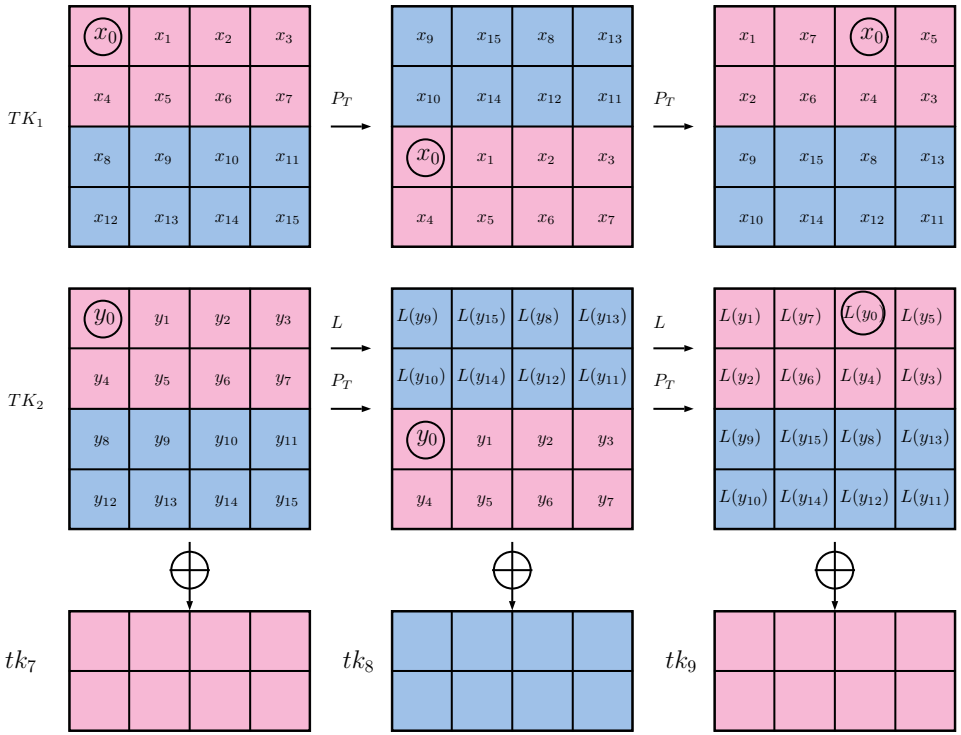
Adding 5 rounds of Key Recovery



- in blue the nibbles that are required to compute $X_7[0]$
- in pink the nibbles that are required to compute $X_7[12]$
- total of 19 nibbles, 4 in common

1 guess can be saved!

Linear Equations in the TweaKey Schedule (TK2)



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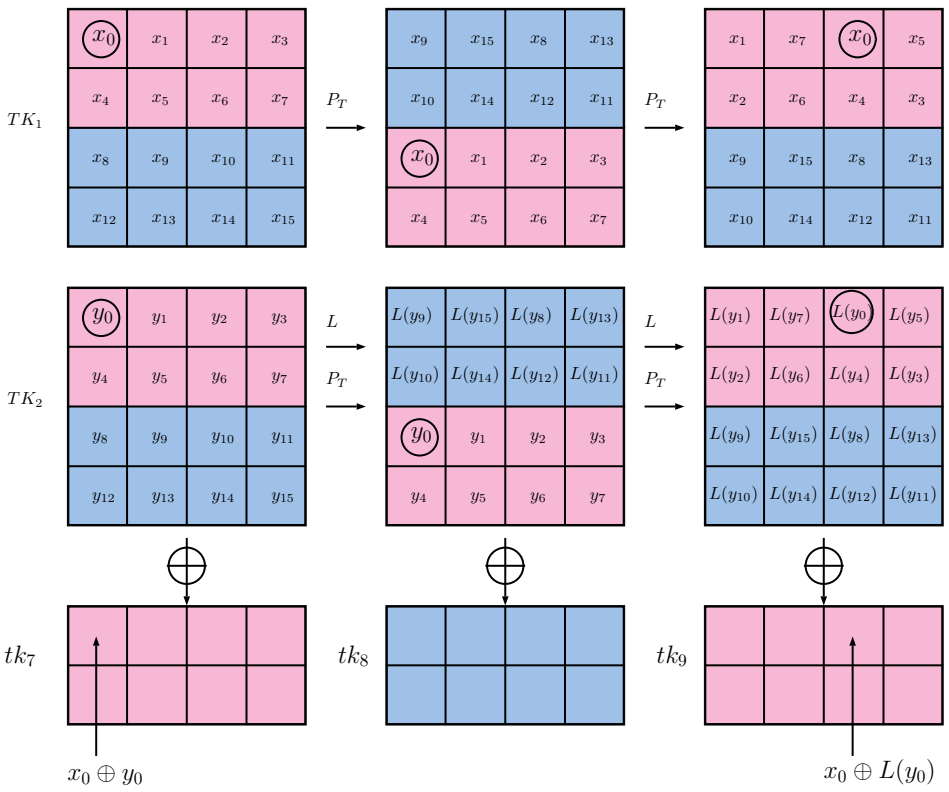
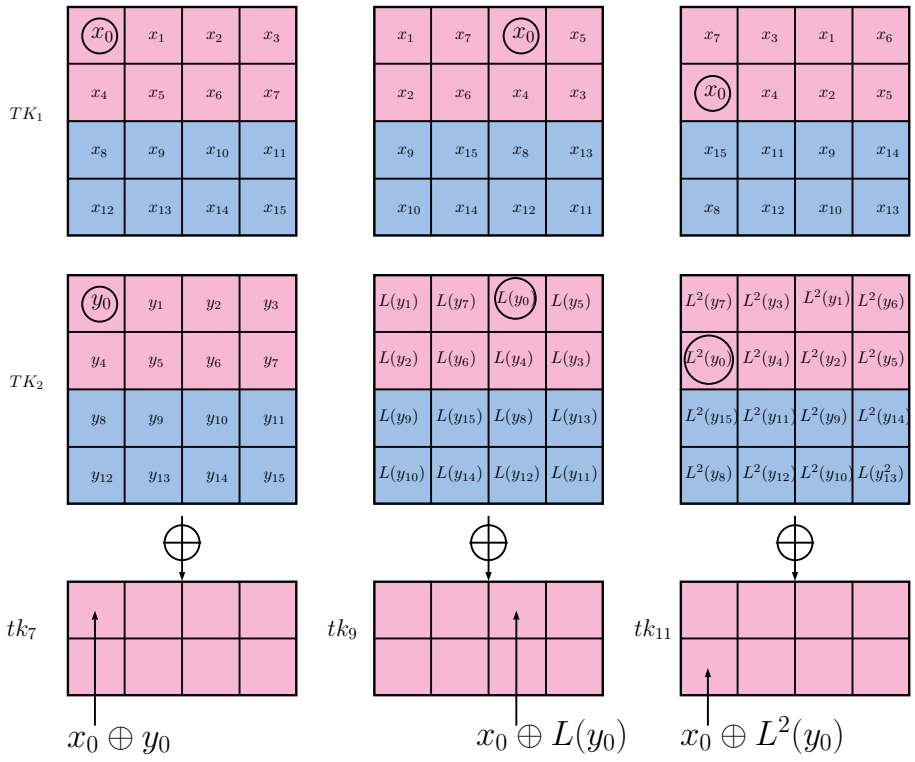


- Tweakey nibbles stay 'aligned' in TK1 and TK2 (e.g. x_0 and y_0)

Linear Equations in the TweaKey Schedule (TK2)



- Focus on odd rounds:
  - $tk_7[0] = x_0 \oplus y_0$
  - $tk_9[2] = x_0 \oplus L(y_0)$
  - $tk_{11}[4] = x_0 \oplus L^2(y_0)$

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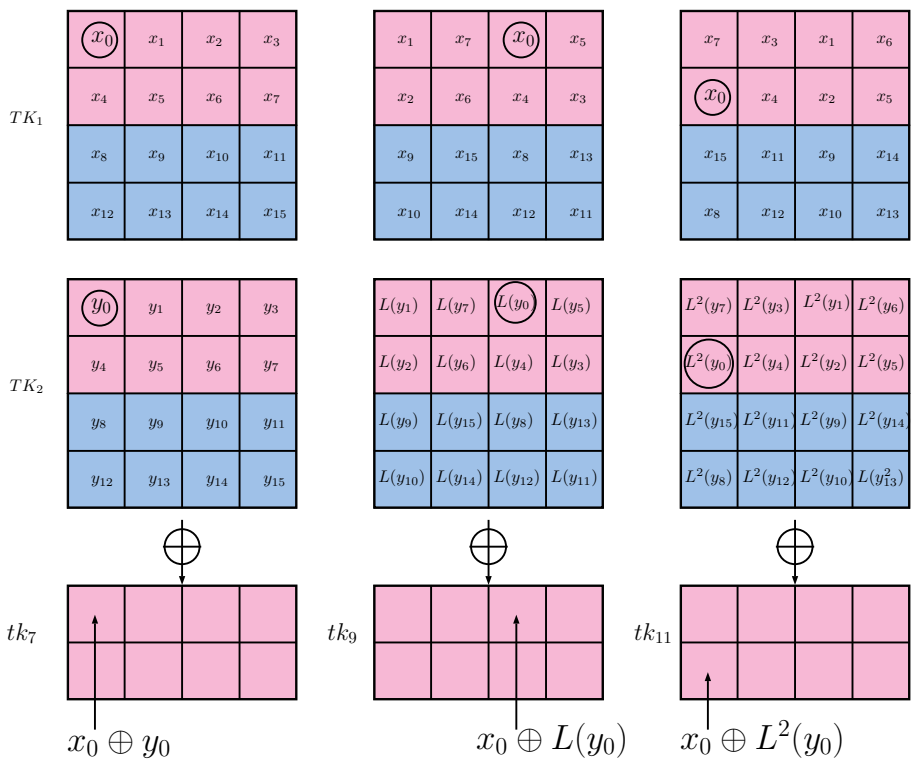

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- $tk_7[0] = L^{-1}(tk_9[2] \oplus tk_{11}[4]) \oplus tk_9[2]$

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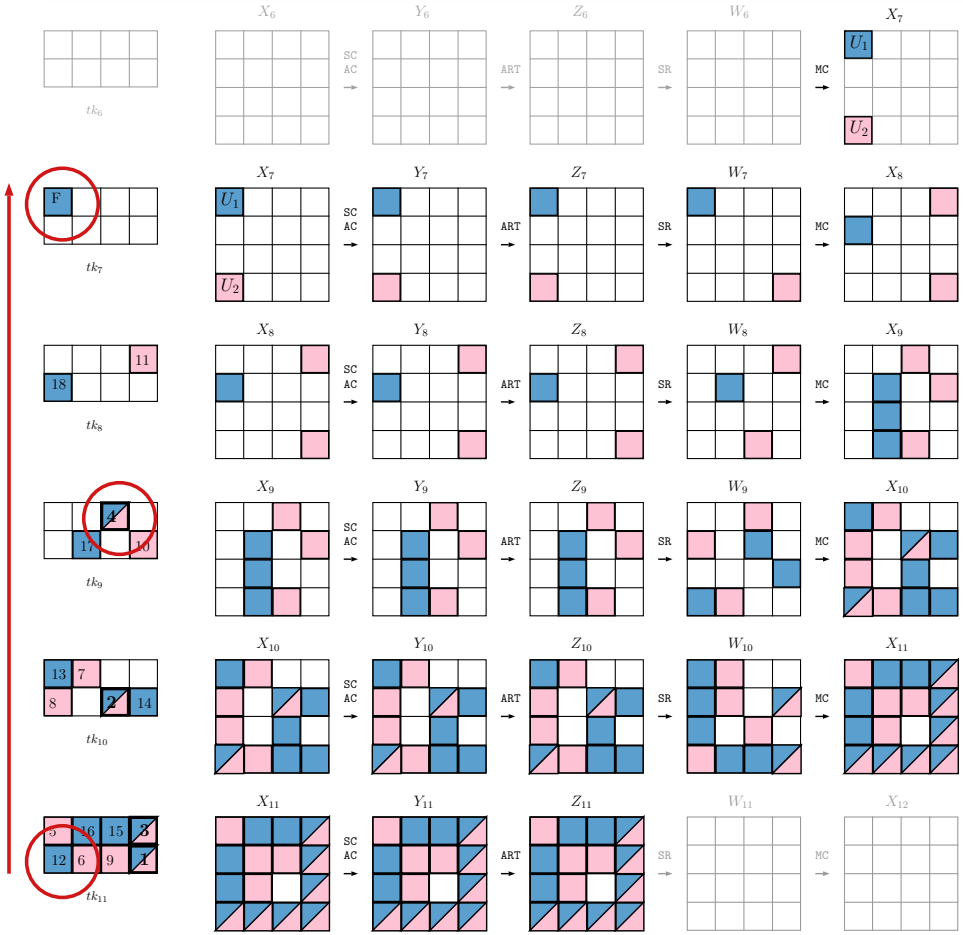

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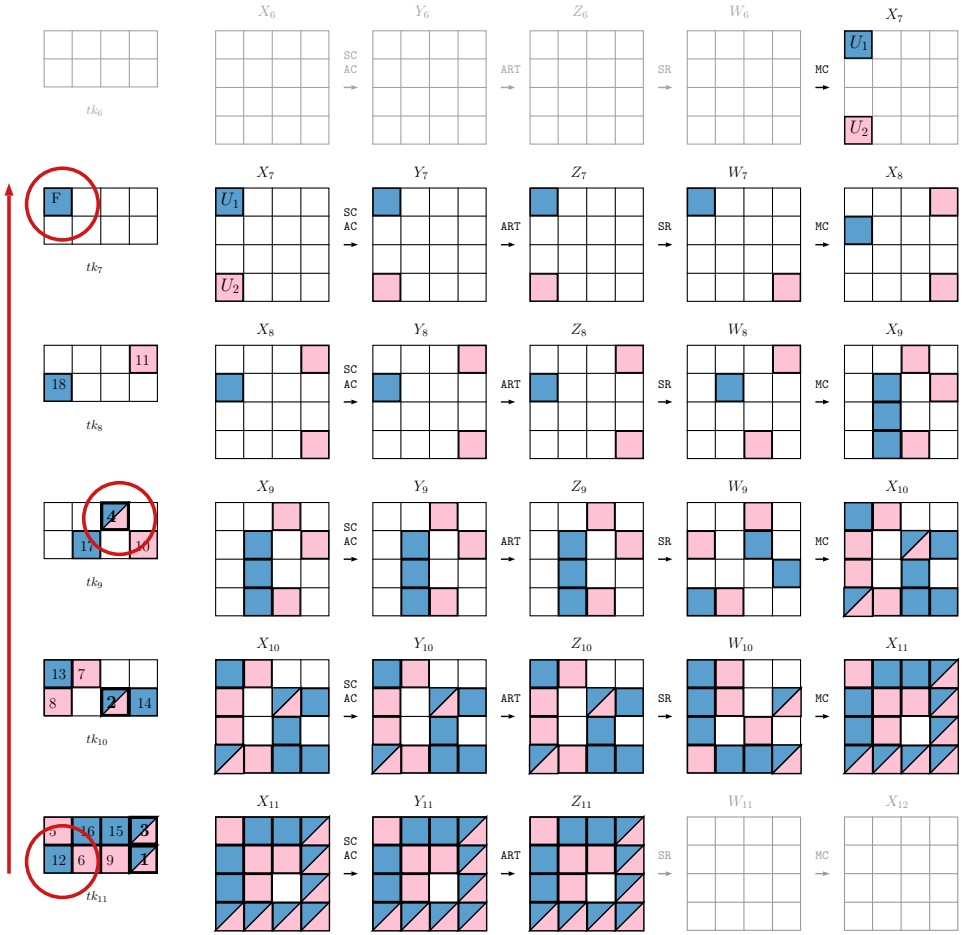

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- $tk_7[0] = L^{-1}(tk_9[2] \oplus tk_{11}[4]) \oplus tk_9[2]$

$\rightarrow$ If $tk_9[2]$ and $tk_{11}[4]$ are known, $tk_7[0]$ can be deduced

Implementation of the Attack

57 pairs available, 32 used

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Guess $tk_{11}[7], tk_{10}[6], tk_{11}[3]$ and $tk_9[2]$ 

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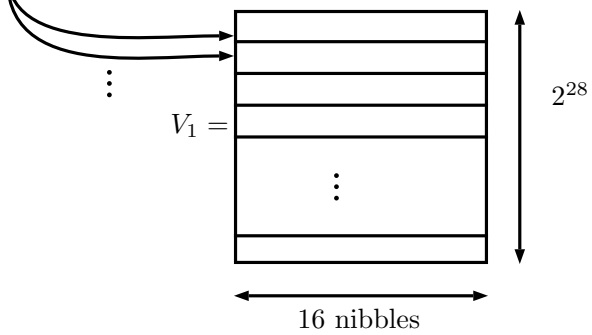
Guess $tk_{11}[4], tk_{10}[0], tk_{10}[7], tk_{11}[2]$, $tk_{11}[1], tk_9[5]$ and $tk_8[4]$



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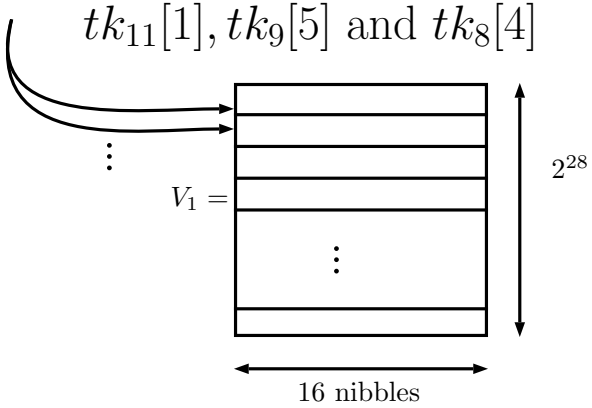
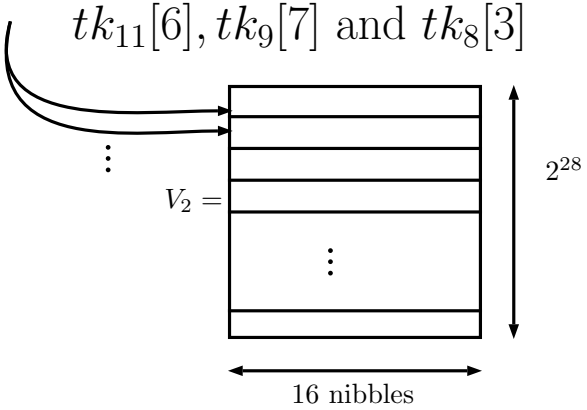


Guess $tk_{11}[0], tk_{11}[5], tk_{10}[1], tk_{10}[4], tk_{11}[6], tk_9[7]$ and $tk_8[3]$



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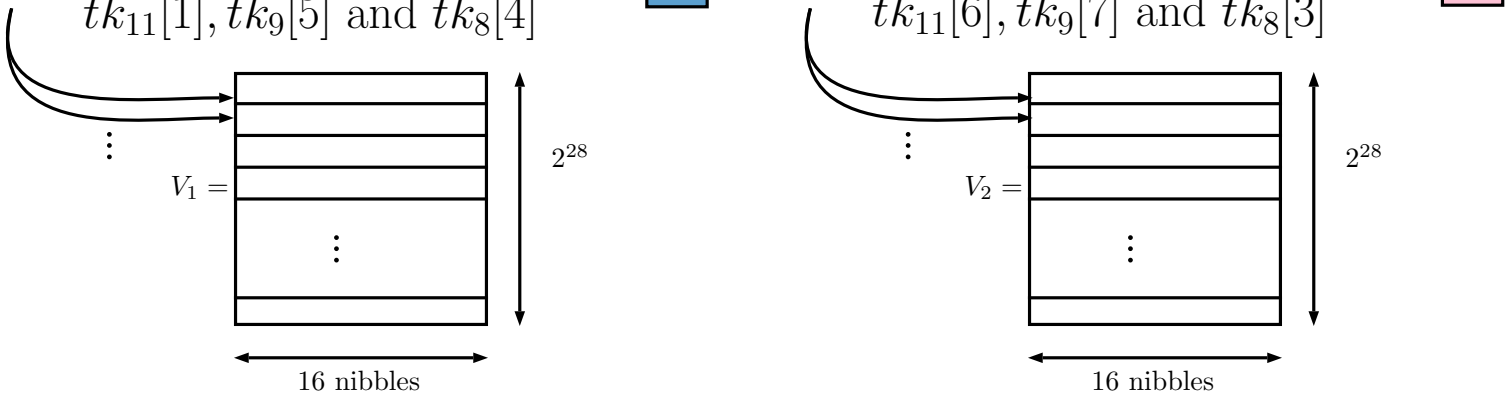

Sort and Merge V_1 and V_2 : $2^{28} \times 2^{28} \times 2^{-64} = 2^{-8}$

2^8 values of $tk_{11}[7], tk_{10}[6], tk_{11}[3]$ and $tk_9[2]$ survive

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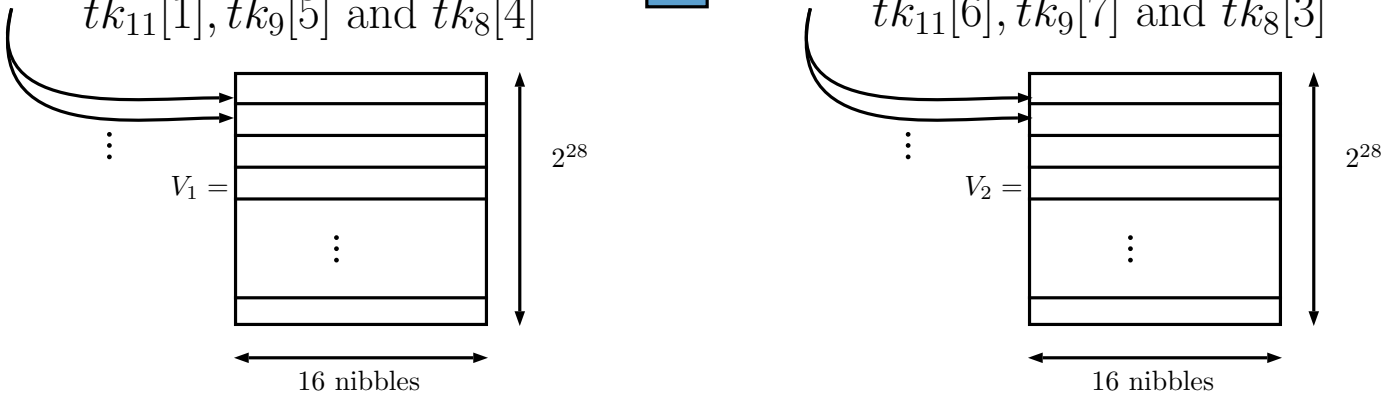

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for these, repeat with 32 pairs

obtain tk_{11}

Implementation of the Attack

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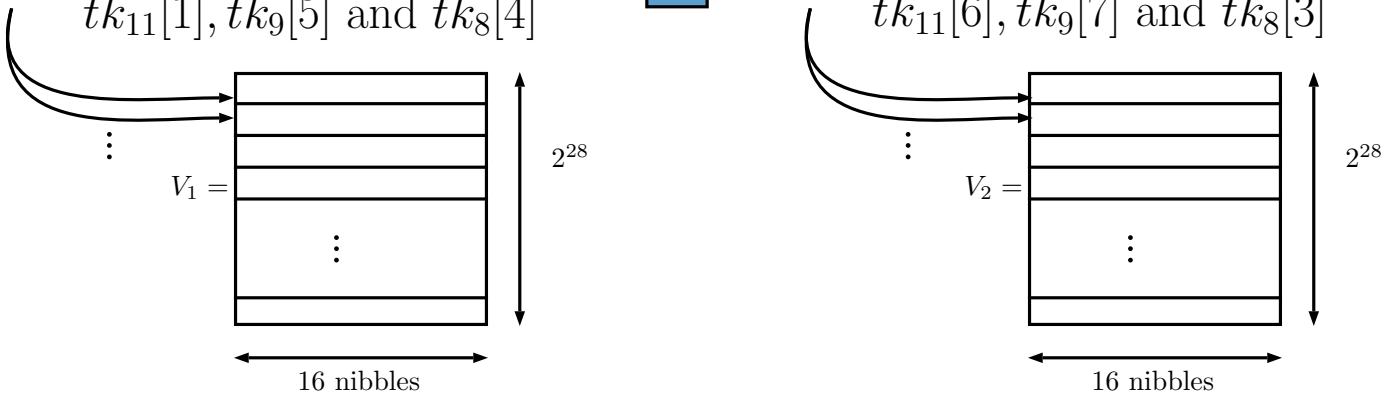

Sort and Merge V_1 and V_2 : $2^{28} \times 2^{28} \times 2^{-64} = 2^{-8}$
2^8 values of $tk_{11}[7], tk_{10}[6], tk_{11}[3]$ and $tk_9[2]$ survive
for these, repeat with 32 pairs
obtain tk_{11}

$$2^{16} \times (2 \times 32 \times 2^{28} + 2 \times 28 \times 2^{28} + 2^{-8} \times 2 \times 64 \times 2^{28}) \approx 2^{51.95} \text{ op.}$$

Implementation of the Attack

57 pairs available, 32 used

Guess $tk_{11}[7], tk_{10}[6], tk_{11}[3]$ and $tk_9[2]$

Guess $tk_{11}[4], tk_{10}[0], tk_{10}[7], tk_{11}[2], tk_{11}[1], tk_9[5]$ and $tk_8[4]$

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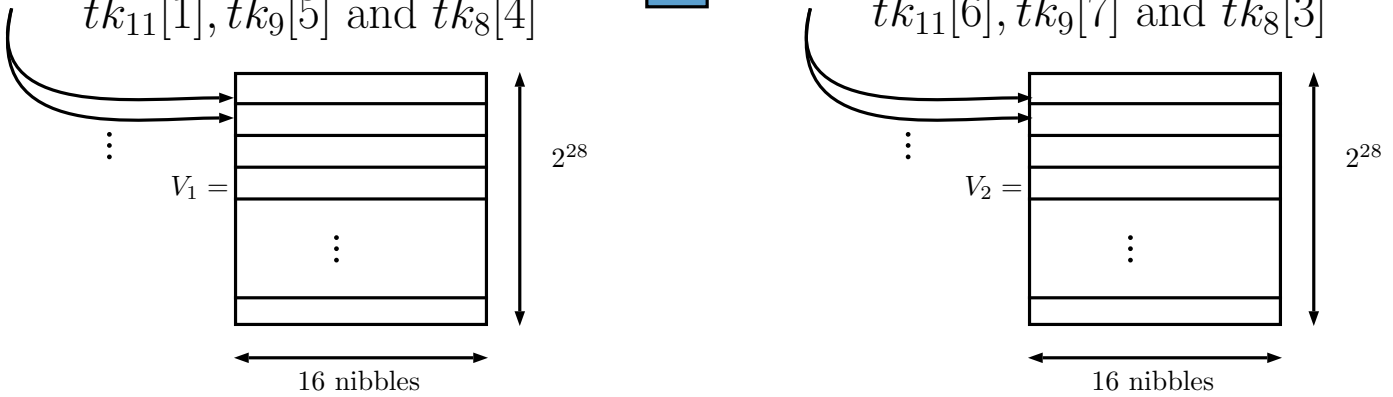

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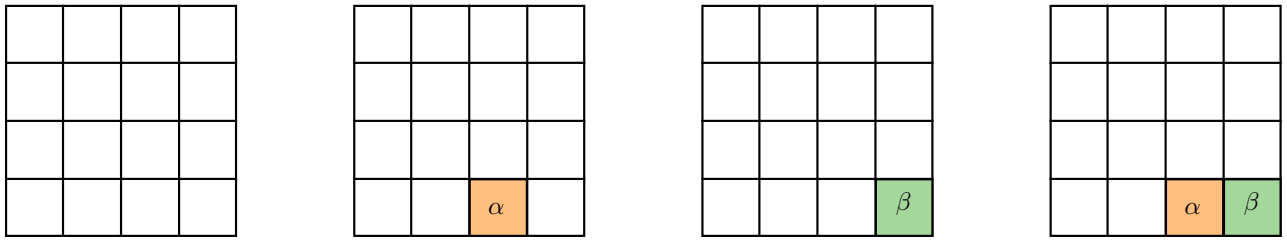
2^8 values of $tk_{11}[7], tk_{10}[6], tk_{11}[3]$ and $tk_9[2]$ survive
for these, repeat with 32 pairs
obtain tk_{11}

114 CPU days, 256 GB of memory required

Our Attack on 10-round SKINNY-128-128

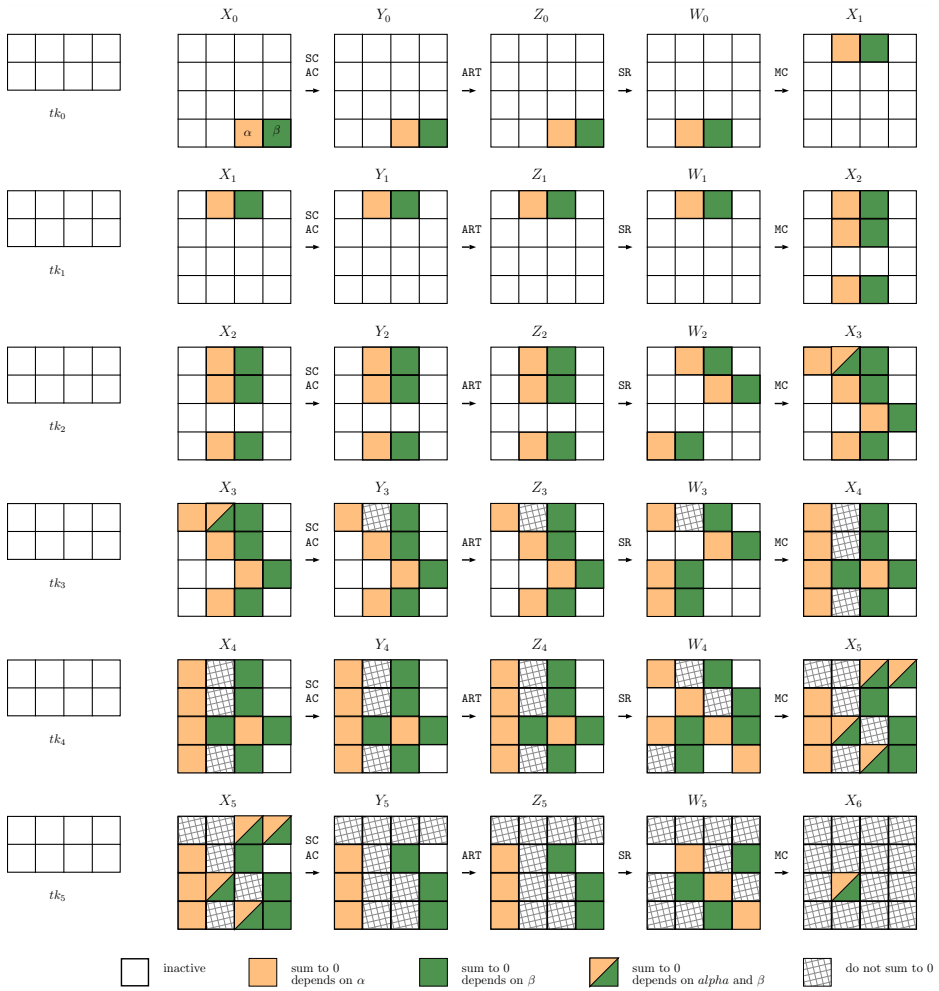
Second order differential [Lai94, Knu95]

- (first-order) differentials consider difference between 2 messages
- (second-order) differentials consider difference between 2^2 messages



After encryption over **6 rounds**, the values obtained for cell 9 sum to 0

Probability 1 Distinguisher over 6 Rounds



- follow the propagation of α (orange) and of β (green)

$$\begin{pmatrix} 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 \end{pmatrix} \times \begin{matrix} \\ x_2 \\ x_3 \\ \\ \end{matrix}$$

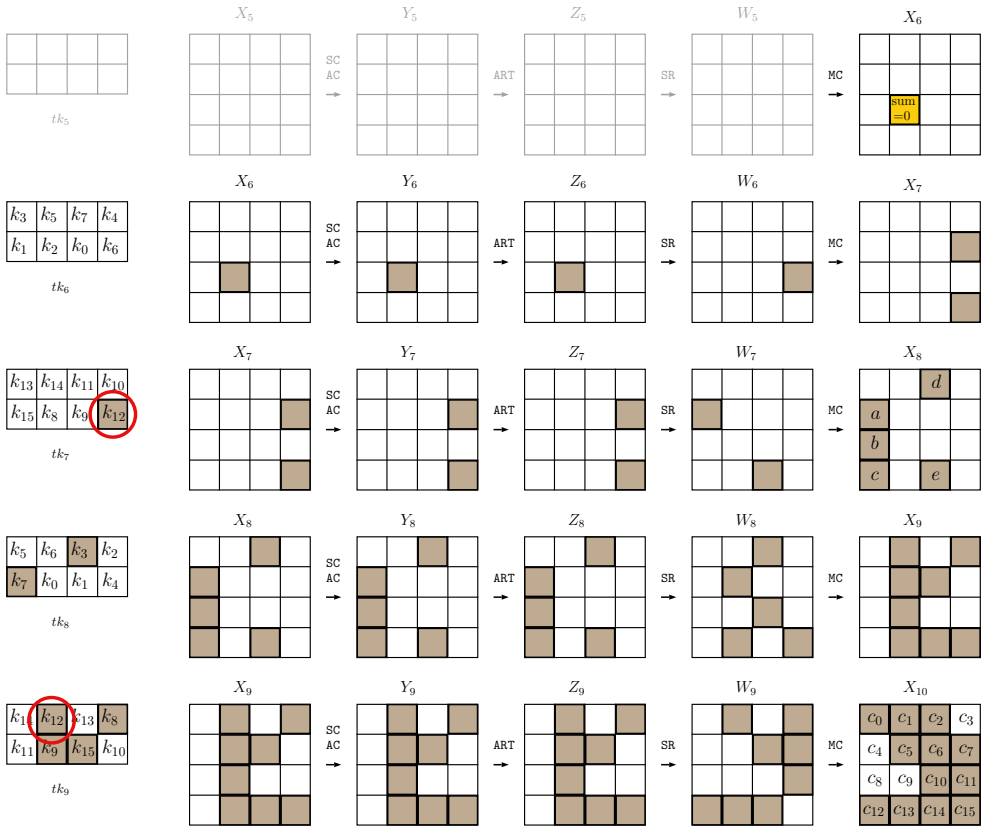
$$\begin{pmatrix} 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 \end{pmatrix} \times \begin{matrix} \\ x_2 + f(\alpha) \\ x_3 \\ \\ \end{matrix}$$

$$\begin{pmatrix} 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 \end{pmatrix} \times \begin{matrix} \\ x_2 \\ x_3 + g(\beta) \\ \\ \end{matrix}$$

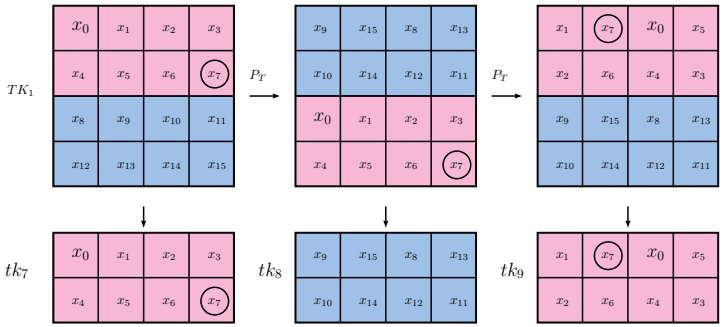
$$\begin{pmatrix} 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 \end{pmatrix} \times \begin{matrix} \\ x_2 + f(\alpha) \\ x_3 + g(\beta) \\ \\ \end{matrix}$$

$$\bigoplus \qquad = \begin{matrix} \\ \\ 0 \\ \\ \end{matrix}$$

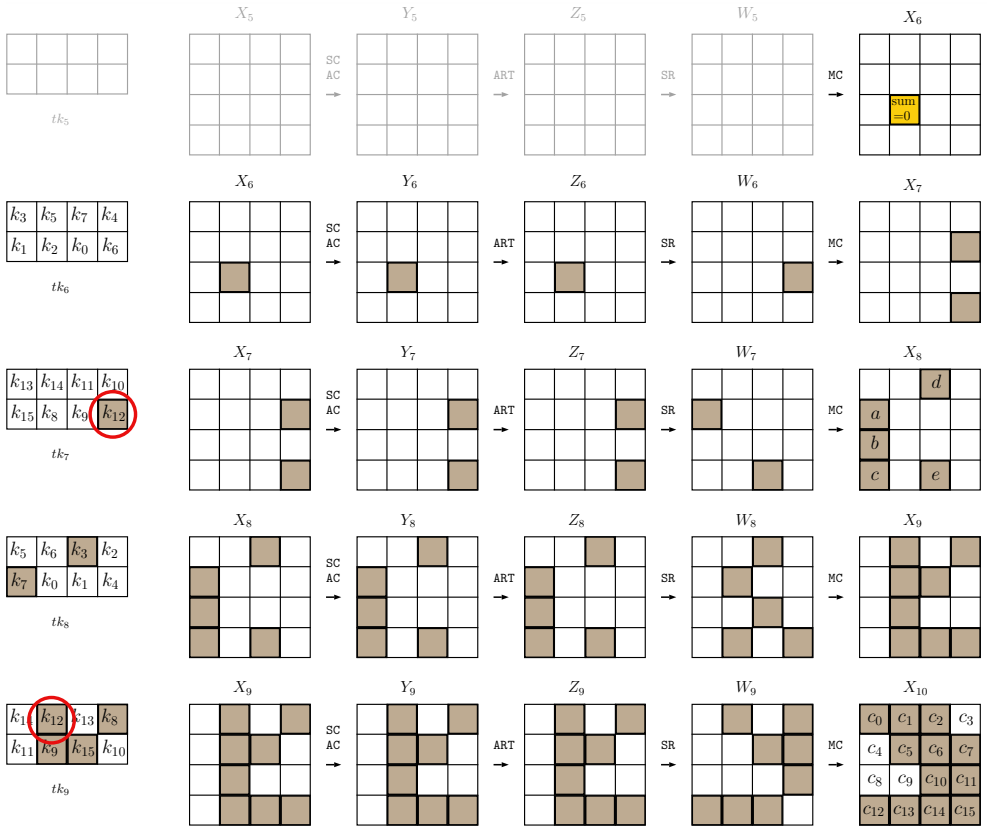
Adding 4 rounds of Key Recovery



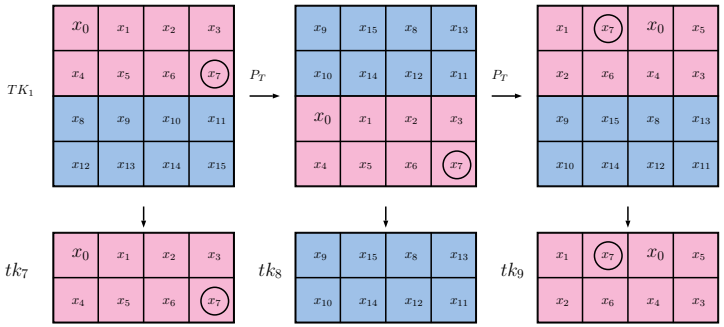
- 7 key bytes involved, 6 unique



Adding 4 rounds of Key Recovery



- 7 key bytes involved, 6 unique



- Guess 6 bytes of key, invert rounds and check that $X_6[9]$ sums to 0
- 6 quadruples are sufficient

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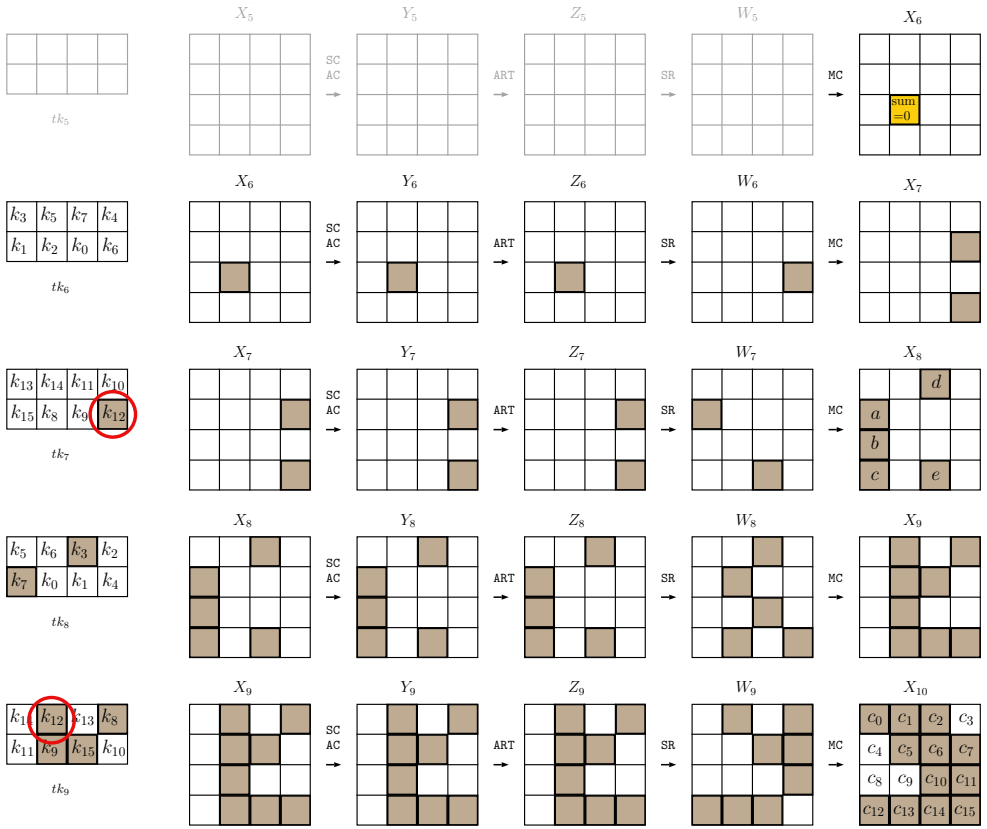

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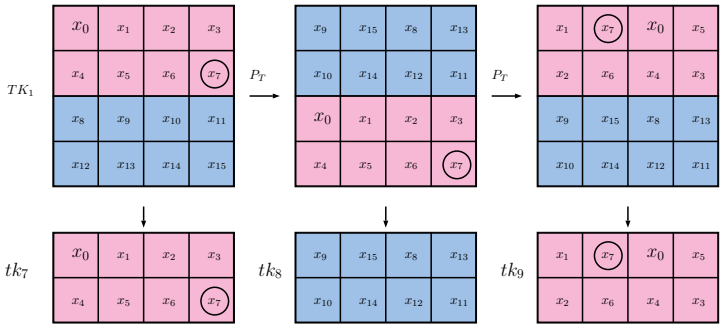

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2^{52} operations, 32 CPU days, 24 messages, 0.5 GB of memory

Conclusion

- We showed that 12-round SKINNY-64-128 and 10-round SKINNY-128-128 can be attacked in practical time

Version	Rounds	Technique	Data	Time	Memory
SKINNY-64-128	12	Trunc. diff.	64	$2^{51.95}$	256 GB
SKINNY-128-128	10	2nd-order T.diff	24	2^{52}	0.5 GB

- So far these are the best attacks of the challenge
- The challenge is still open and names will still be added to the list for winning any challenge.

Source code available at: http://skinnysac19.gforge.inria.fr/

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Thank you for your attention

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