S-Box Reverse-Engineering

Boolean Functions, American/Russian Standards, and Butterflies

Léo Perrin

Based on joint works with Biryukov, Canteaut, Duval and Udovenko

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CECC'18

informatics mathematics

Outline

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Symmetric Cryptography

There are many **symmetric** algorithms! Hash functions, MACs...

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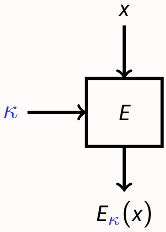
- Input: n-bit block x
- Parameter: k-bit key κ
- Output: n-bit block $E_\kappa(x)$
- Symmetry: E and E^{-1} use the same κ



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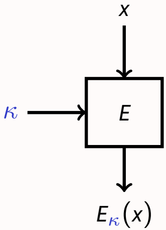


Properties needed:

Diffusion Confusion No cryptanalysis!

No Cryptanalysis?

Let us look at a typical cryptanalysis technique: the differential attack.

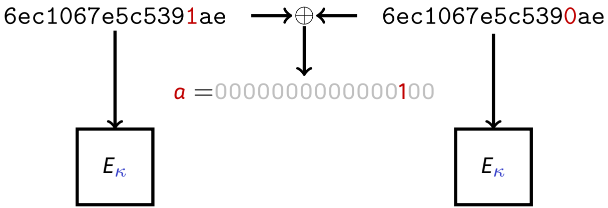
Differential Attacks

$$\texttt{6ec1067e5c5391ae} \longrightarrow \oplus \longleftarrow \texttt{6ec1067e5c5390ae}$$

$$\downarrow$$

$$a = 0000000000000100$$

Differential Attacks



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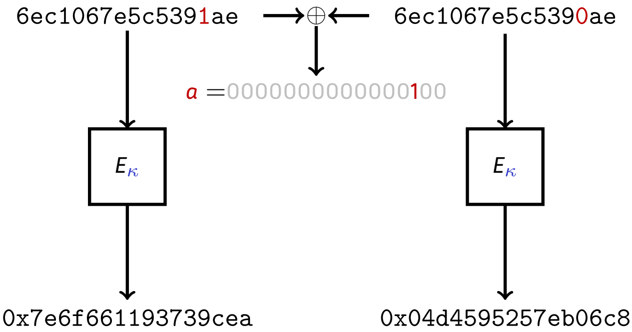

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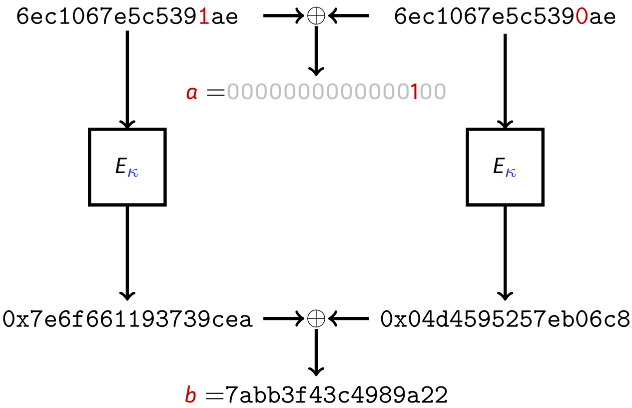

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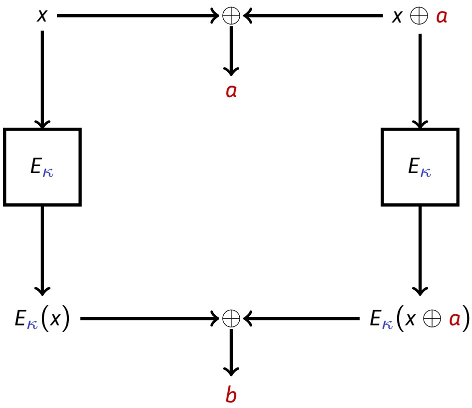

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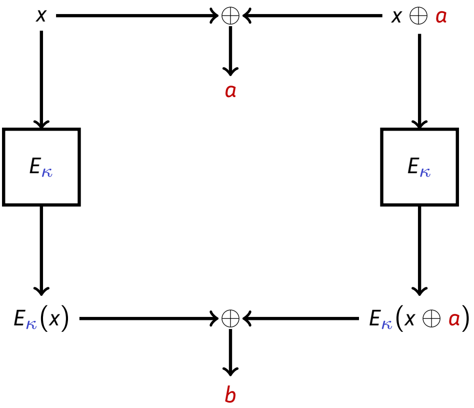

Differential Attack

If there are many x such that $E_\kappa(x) \oplus E_\kappa(x \oplus a) = b$, then the cipher is **not secure**.

Basic Block Cipher Structure

How do we build block ciphers that prevent such attacks (as well as others)?

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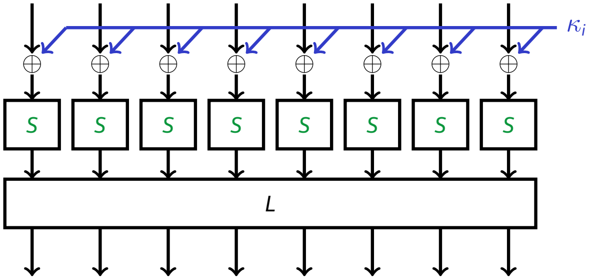

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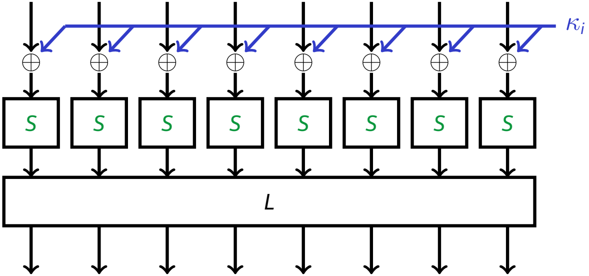

Substitution-Permutation Network

Such a block cipher iterates the round function above several times. S is the **S**ubstitution **B**ox (S-Box).

The S-Box (1/2)

π' = (252, 238, 221, 17, 207, 110, 49, 22, 251, 196, 250, 218, 35, 197, 4, 77, 233, 119, 240, 219, 147, 46, 153, 186, 23, 54, 241. 187, 20, 205, 95, 193, 249, 24, 101, 90, 226, 92, 239, 33, 129, 28, 60, 66, 139, 1, 142, 79, 5, 132, 2, 174, 227, 106, 143, 160, 6, 11, 237, 152, 127, 212, 211, 31, 235, 52, 44, 81, 234, 200, 72, 171, 242, 42, 104, 162, 253, 58, 206, 204, 181, 112, 14, 86, 8, 12, 118, 18, 191, 114, 19, 71, 156, 183, 93, 135, 21, 161, 150, 41, 16, 123, 154, 199, 243, 145, 120, 111, 157, 158, 178, 177, 50, 117, 25, 61, 255, 53, 138, 126, 109, 84, 198, 128, 195, 189, 13, 87, 223, 245, 36, 169, 62, 168, 67, 201, 215, 121, 214, 246, 124, 34, 185, 3, 224, 15, 236, 222, 122, 148, 176, 188, 220, 232, 40, 80, 78, 51, 10, 74, 167, 151, 96, 115, 30, 0, 98, 68, 26, 184, 56, 130, 100, 159, 38, 65, 173, 69, 70, 146, 39, 94, 85, 47, 140, 163, 165, 125, 105, 213, 149, 59, 7, 88, 179, 64, 134, 172, 29, 247, 48, 55, 107, 228, 136, 217, 231, 137, 225, 27, 131, 73, 76, 63, 248, 254, 141, 83, 170, 144, 202, 216, 133, 97, 32, 113, 103, 164, 45, 43, 9, 91, 203, 155, 37, 208, 190, 229, 108, 82, 89, 166, 116, 210, 230, 244, 180, 192, 209, 102, 175, 194, 57, 75, 99, 182).

The S-Box π of the latest Russian standards, Kuznyechik (BC) and Streebog (HF).

The S-Box (2/2)

Importance of the S-Box

If S is such that

$$S(x) \oplus S(x \oplus a) = b$$

does not have many solutions x for all (a, b) then the cipher may be proved secure against differential attacks.

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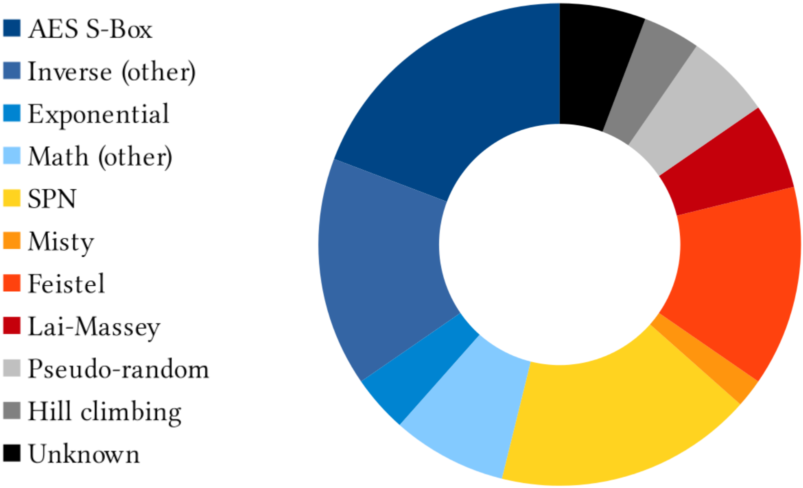
In academic papers presenting new block ciphers, the choice of S is carefully explained.

S-Box Design

- AES S-Box
- Inverse (other)
- Exponential
- Math (other)
- SPN
- Misty
- Feistel
- Lai-Massey
- Pseudo-random
- Hill climbing
- Unknown

S-Box Design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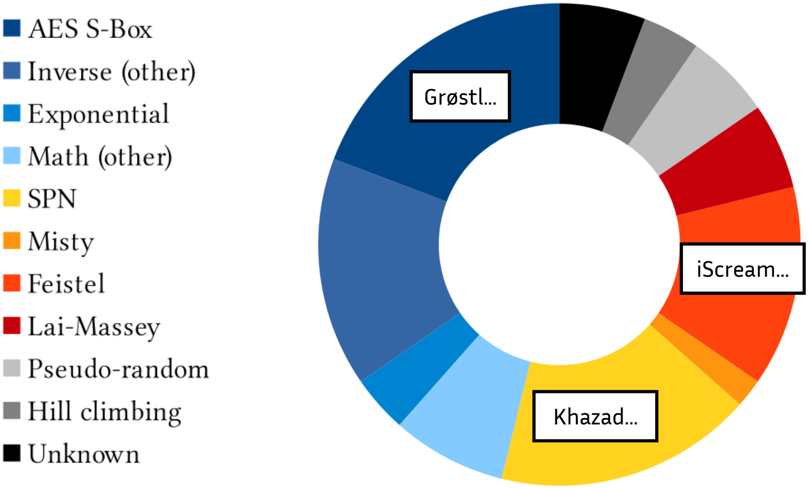
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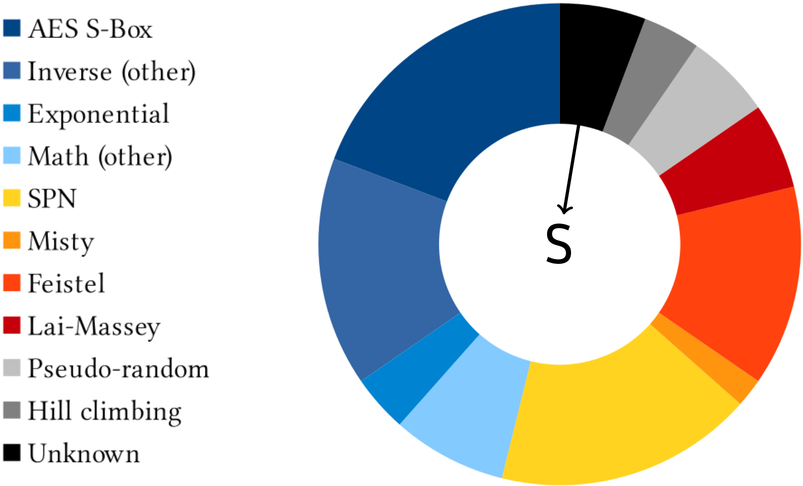
Grøstl...
iScream...
Khazad...

S-Box Reverse-Engineering



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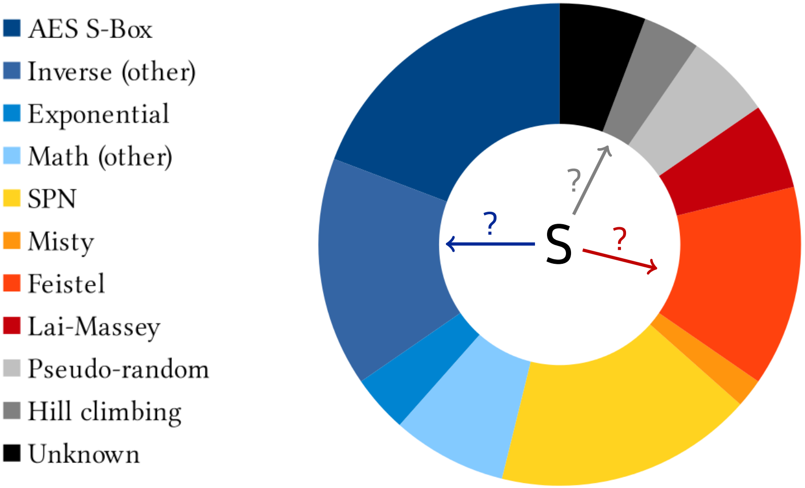

Motivation (1/3)

A malicious designer can easily hide a structure in an S-Box.

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To keep an advantage in implementation (WB crypto)...

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A malicious designer can easily hide a structure in an S-Box.

To keep an advantage in implementation (WB crypto)...
... or an advantage in cryptanalysis (backdoor).

Motivation (2/3)

Definition (Kleptography)

The study of trapdoored cryptography is called kleptography (term introduced by Jung and Young).

S-Box based backdoors in the literature

- Rijmen, V., & Preneel, B. (1997). *A family of trapdoor ciphers*. FSE'97.
- Patterson, K. (1999). *Imprimitive Permutation Groups and Trapdoors in Iterated Block Ciphers*. FSE'99.
- Blondeau, C., Civino, R., & Sala, M. (2017). *Differential Attacks: Using Alternative Operations*. `eprint` report 2017/610.
- Bannier, A., & Filiol, E. (2017). *Partition-based trapdoor ciphers*. InTech'17.

Motivation (3/3)

Even without malicious intent, an unexpected structure can be a problem.

$\Longrightarrow$ We need tools to *reverse-engineer* S-Boxes!

Outline

Summary

We can recover parts of the design process of an S-Box using some statistics.

1. The two tables (basics of Boolean functions for cryptography)
2. A satistical tool based on the two tables
3. Application to NSA's Skipjack

The Two Tables

Let $S : \mathbb{F}_2^n \to \mathbb{F}_2^n$ be an S-Box.

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Definition (DDT)

The *Difference Distribution Table* of S is a matrix of size $2^n \times 2^n$ such that

$$\mathrm{DDT}[a, b] = \#\{x \in \mathbb{F}_2^n \mid S(x \oplus a) \oplus S(x) = b\}.$$

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Definition (LAT)

The *Linear Approximations Table* of S is a matrix of size $2^n \times 2^n$ such that

$$\mathrm{LAT}[a, b] = \#\{x \in \mathbb{F}_2^n \mid x \cdot a = S(x) \cdot b\} - 2^{n-1}.$$

Example

$$S = [4, 2, 1, 6, 0, 5, 7, 3]$$

The DDT of S.

$$\begin{bmatrix} 8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 2 & 2 & 2 \\ 0 & 0 & 0 & 0 & 2 & 2 & 2 & 2 \\ 0 & 0 & 4 & 4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 2 & 2 & 2 \\ 0 & 4 & 4 & 0 & 0 & 0 & 0 & 0 \\ 0 & 4 & 0 & 4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 2 & 2 & 2 \end{bmatrix}$$

The LAT of S.

$$\begin{bmatrix} 4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 2 & 0 & 0 & 2 & -2 \\ 0 & 2 & 2 & 0 & 0 & 2 & -2 & 0 \\ 0 & 2 & 0 & 2 & 0 & -2 & 0 & 2 \\ 0 & 2 & 0 & -2 & 0 & -2 & 0 & -2 \\ 0 & -2 & 2 & 0 & 0 & -2 & -2 & 0 \\ 0 & 0 & -2 & 2 & 0 & 0 & -2 & -2 \\ 0 & 0 & 0 & 0 & -4 & 0 & 0 & 0 \end{bmatrix}$$

Coefficient Distribution in the DDT

If an n-bit S-Box is bijective, then its DDT coefficients behave like independent and identically distributed random variables following a Poisson distribution:

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- Always even, ≥ 0
- Typically between 0 and 16.
- Lower is better.

Coefficient Distribution in the LAT

If an n-bit S-Box is bijective, then its LAT coefficients behave like independent and identically distributed random variables following this distribution:

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- Always even, signed.
- Typically between -40 and 40.
- Lower absolute value is better.

Looking Only at the Maximum

δ	$\log_2\left(\Pr\left[\max(\mathrm{DDT}) \leq \delta\right]\right)$
14	-0.006
12	-0.094
10	-1.329
8	-16.148
6	-164.466
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DDT

ℓ	$\log_2\left(\Pr\left[\max(\mathrm{LAT}) \leq \ell\right]\right)$
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LAT

Probability that the maximum coefficient in the DDT/LAT of an 8-bit permutation is at most equal to a certain threshold.

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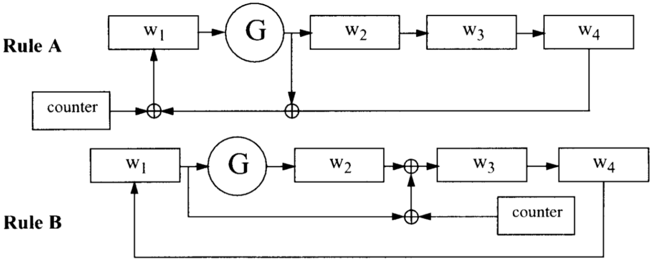
What is Skipjack? (1/2)

Type	Block cipher
Bloc	64 bits
Key	80 bits
Authors	NSA
Publication	1998



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- Skipjack was supposed to be secret...
- ... but eventually published in 1998.
- Skipjack was to be used by the *Clipper Chip*,
- It uses an 8×8 S-Box (F) specified only by its LUT.

Reverse-Engineering F

For Skipjack's F, $\max(\text{LAT}) = 28$ and $\#28 = 3$.

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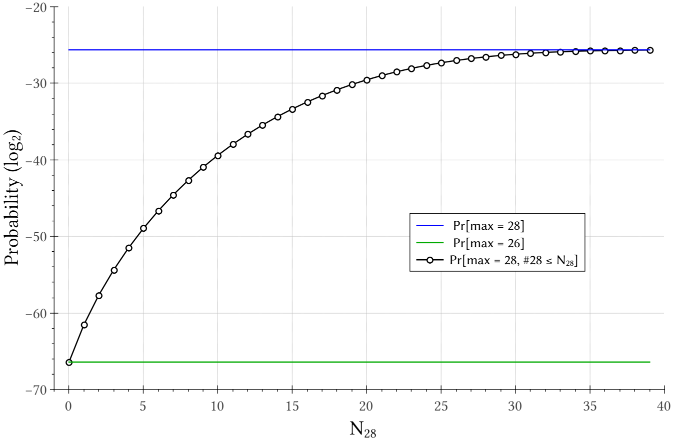

Reverse-Engineering F

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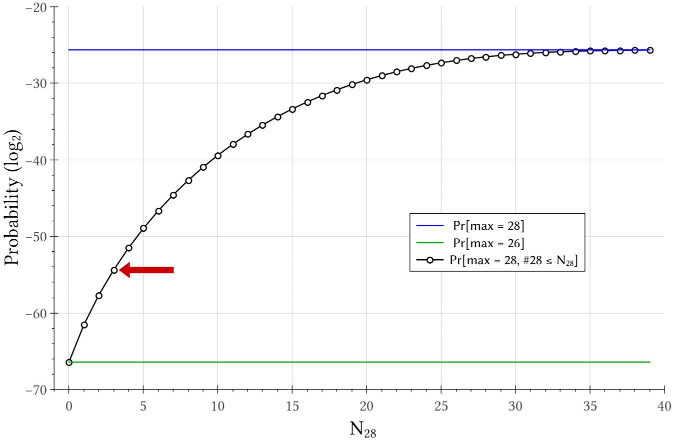

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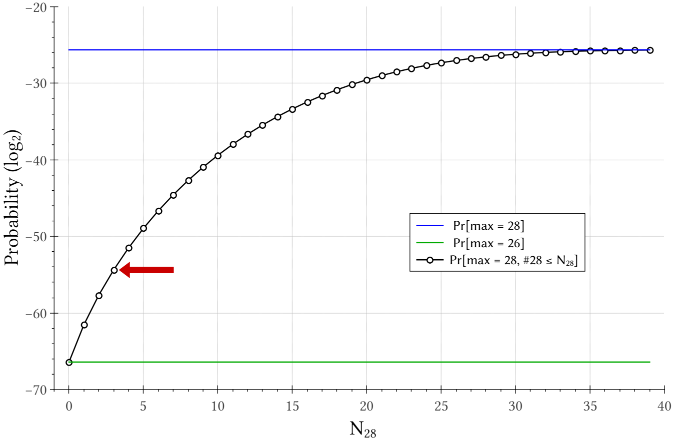

$$\Pr\left[\max(\text{LAT}) = 28 \text{ and } \#28 \leq 3\right] \approx 2^{-55}$$

What Can We Deduce?

- F has not been picked uniformly at random.
- F has not been picked among a feasibly large set of random S-Boxes.
- Its linear properties were optimized (though poorly).

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The S-Box of Skipjack was built using a dedicated algorithm.

Timeline

Jun 98 Declassification of Skipjack

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Timeline

1987	Initial design of Skipjack
Aug 90	(CRYPTO) Gilbert et al. use linear relations for key recovery (FEAL)
Aug 91	(CRYPTO) Attack against FEAL using linear relations between key, plaintext and ciphertext
May 92	(EUROCRYPT) Other attack against FEAL using linear relations between key, plaintext and ciphertext
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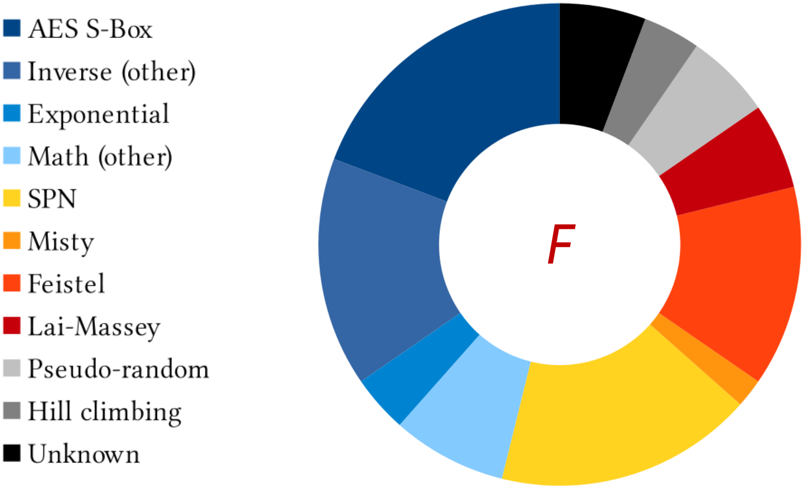

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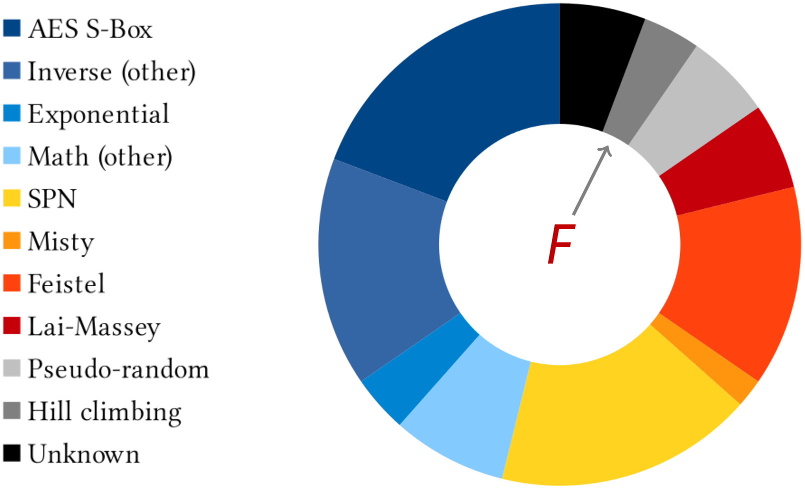

Outline

Summary

We can recover an actual decomposition using patterns in the LAT.

1. Our target, the S-Box of Kuznyechik and Streebog
2. TU-decomposition: what is it and how to apply it to Kuznyechik

Kuznyechik/Stribog

Stribog

Type	Hash function
Publication	2012

Kuznyechik

Type	Block cipher
Publication	2015

Kuznyechik/Stribog

Stribog

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Kuznyechik

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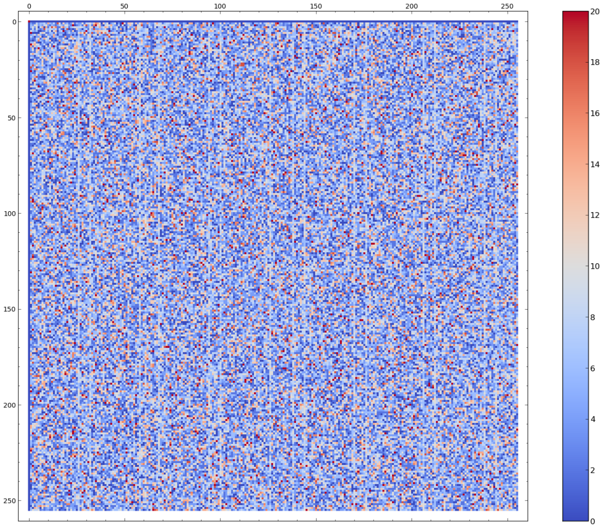
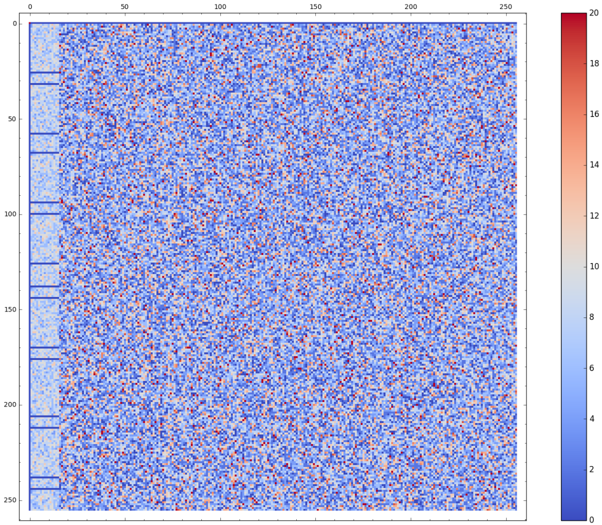
Common ground

- Both are standard symmetric primitives in Russia.
- Both were designed by the FSB (TC26).
- Both use the same 8×8 S-Box, π.

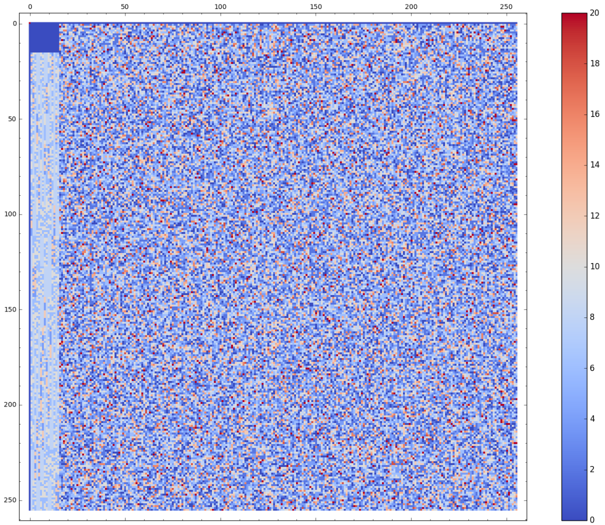
The LAT of π



The LAT of η (reordered columns)



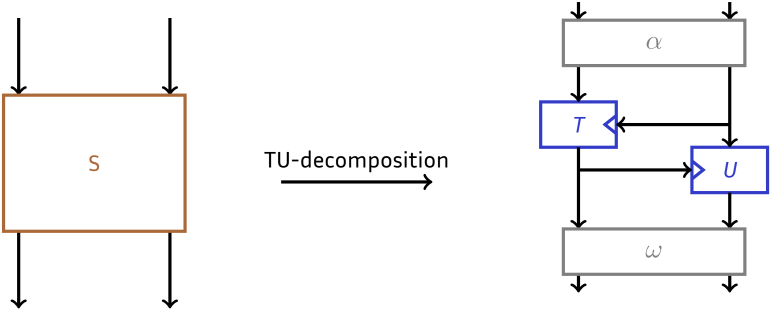
The LAT of $\eta \circ \pi \circ \mu$



The TU-Decomposition

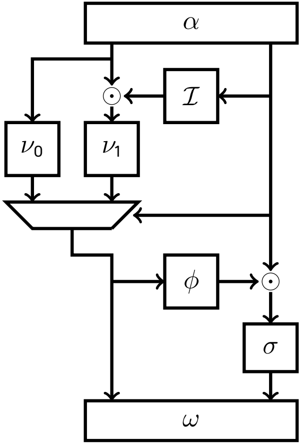
Definition

The TU-decomposition is a decomposition algorithm working against S-Boxes with vector spaces of zeroes in their LAT.



T and U are mini-block ciphers ; μ and η are linear permutations.

Final Decomposition Number 1



$\odot$ Multiplication in $\mathbb{F}_{2^4}$

α Linear permutation

$\mathcal{I}$ Inversion in $\mathbb{F}_{2^4}$

ν_0, ν_1, σ 4×4 permutations

ϕ 4×4 function

ω Linear permutation

Hardware Performance

Structure	Area (μm^2)	Delay (ns)
Naive implementation	3889.6	362.52
Feistel-like	1534.7	61.53
Multiplications-first	1530.3	54.01
Feistel-like (with tweaked MUX)	1530.1	46.11

Conclusion for Kuznyechik/Stribog?

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Belarussian inspiration

- The last standard of Belarus (BelT) uses an 8-bit S-box,
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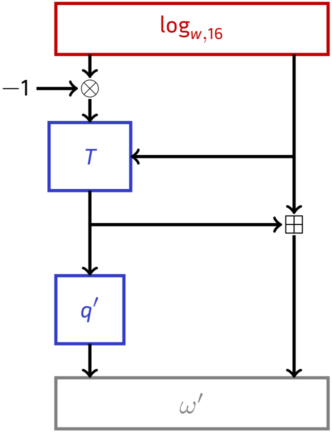
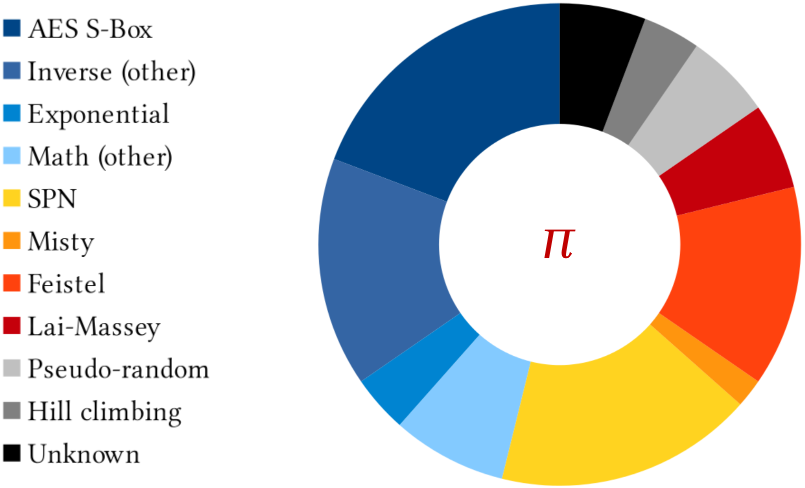
- ... based on a finite field exponential!

Final Decomposition Number 2 (!)

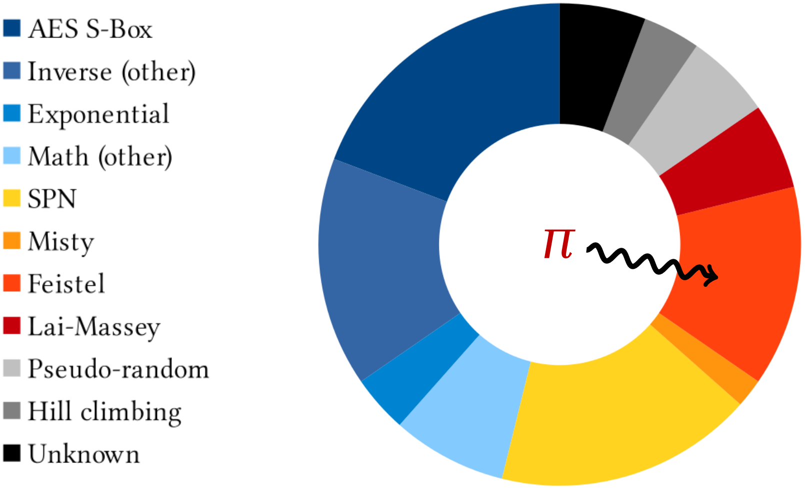


	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
T_0	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
T_1	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
T_2	0	1	2	3	4	5	6	7	8	9	a	b	c	d	f	e
T_3	0	1	2	3	4	5	6	7	8	9	a	b	c	f	d	e
T_4	0	1	2	3	4	5	6	7	8	9	a	b	f	c	d	e
T_5	0	1	2	3	4	5	6	7	8	9	a	f	b	c	d	e
T_6	0	1	2	3	4	5	6	7	8	9	f	a	b	c	d	e
T_7	0	1	2	3	4	5	6	7	8	f	9	a	b	c	d	e
T_8	0	1	2	3	4	5	6	7	f	8	9	a	b	c	d	e
T_9	0	1	2	3	4	5	6	f	7	8	9	a	b	c	d	e
T_a	0	1	2	3	4	5	f	6	7	8	9	a	b	c	d	e
T_b	0	1	2	3	4	f	5	6	7	8	9	a	b	c	d	e
T_c	0	1	2	3	f	4	5	6	7	8	9	a	b	c	d	e
T_d	0	1	2	f	3	4	5	6	7	8	9	a	b	c	d	e
T_e	0	1	f	2	3	4	5	6	7	8	9	a	b	c	d	e
T_f	0	f	1	2	3	4	5	6	7	8	9	a	b	c	d	e

Conclusion on Kuznyechik/Stribog



Conclusion on Kuznyechik/Stribog



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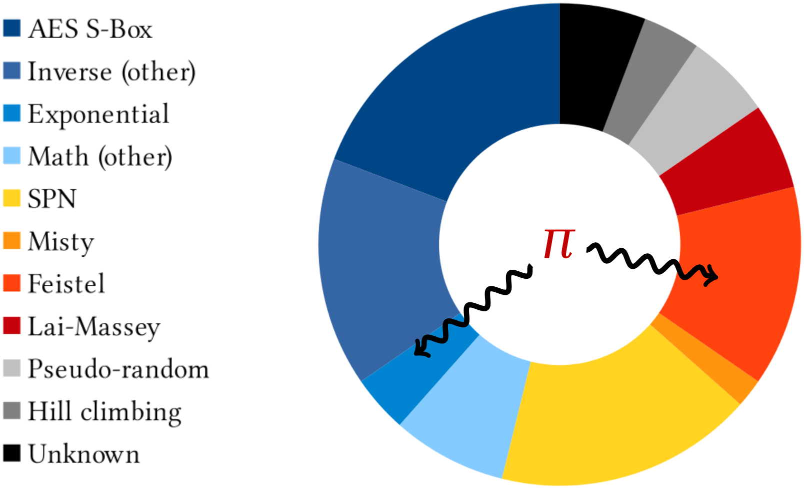

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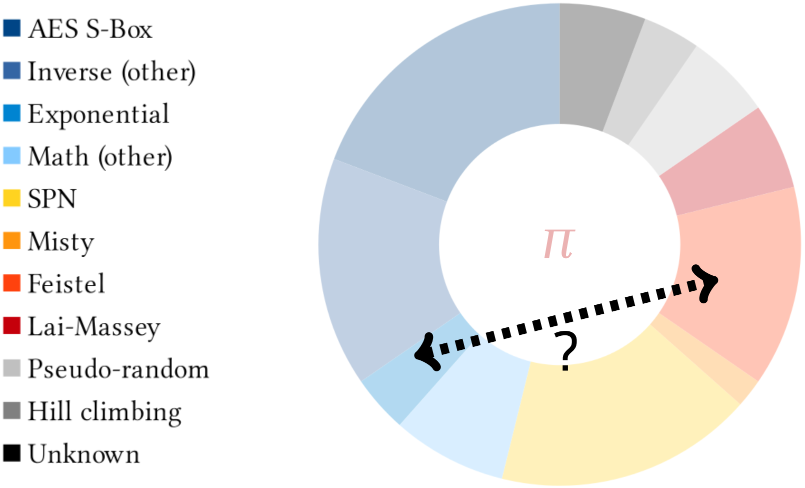

Outline

Summary

We can obtain new mathematical results using reverse-engineering techniques.

1. The big APN problem and its only known solution
2. Decomposing and generalizing this solution as butterflies

NSUCRYPTO (Olympiad in Cryptography)

Siberian Student's Olympiad in Cryptography with International participation — 2014

Second round NSUCRYPTO November 17-24

Task 2. «An APN Permutation»

"Try to find an APN permutation on 8 variables or prove that it doesn't exist."

`https://nsucrypto.nsu.ru/`

The Big APN Problem

Definition (APN function)

A function $S : \mathbb{F}_2^n \rightarrow \mathbb{F}_2^n$ is Almost Perfect Non-linear (APN) if

$$S(x \oplus a) \oplus S(x) = b$$

has 0 or 2 solutions for all $a \neq 0$ and for all b.

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Big APN Problem

Are there APN permutations operating on $\mathbb{F}_2^n$ where n is even?

Dillon et al.'s Permutation

Only One Known Solution!

For $n = 6$, Dillon et al. found an APN permutation.

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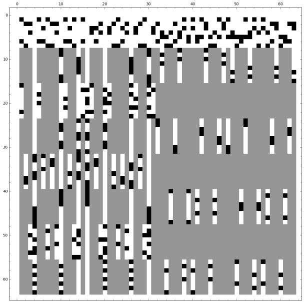

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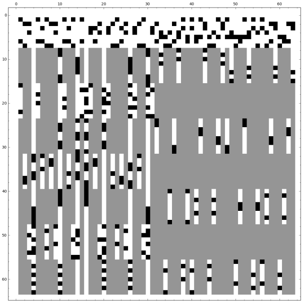

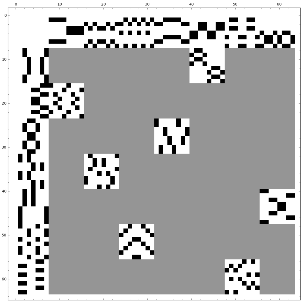

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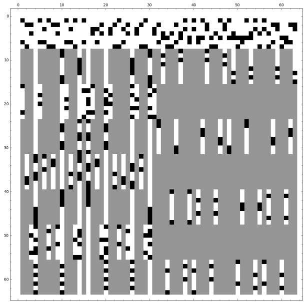
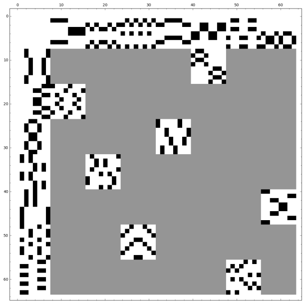
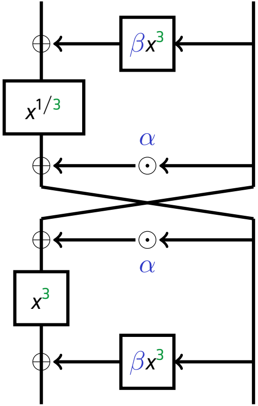




It is possible to make a TU-decomposition!

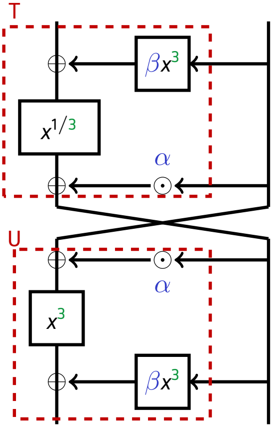
On the Butterfly Structure



Definition (Open Butterfly $H^3_{\alpha,\beta}$)

This permutation is an open butterfly.

On the Butterfly Structure



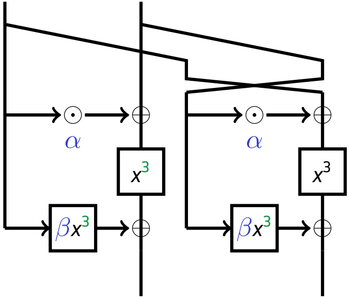
Definition (Open Butterfly $H^3_{\alpha,\beta}$)

This permutation is an open butterfly.

Lemma

Dillon's permutation is affine-equivalent to $H^3_{w,1}$, *where* $Tr(w) = 0$.

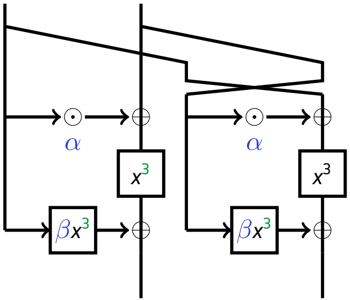
Closed Butterflies



Definition (Closed butterfly $V^3_{\alpha,\beta}$)

This quadratic function is a closed butterfly.

Closed Butterflies



Definition (Closed butterfly $V^3_{\alpha,\beta}$)

This quadratic function is a closed butterfly.

Lemma (Equivalence)

Open and closed butterflies with the same parameters are CCZ-equivalent.

Some Properties of Butterflies

Theorem (Properties of butterflies)

Let $V^3_{\alpha,\beta}$ and $H^3_{\alpha,\beta}$ be butterflies operating on $2n$ bits, n odd. Then:

- $\deg\left(V^3_{\alpha,\beta}\right) = 2$,
- *if* $n = 3$, $Tr(\alpha) = 0$ *and* $\beta + \alpha^3 \in \{\alpha, 1/\alpha\}$, *then*
$$\max(DDT) = \mathbf{2},\ \max(\mathcal{W}) = 2^{n+1} \text{ and } \deg\left(H^3_{\alpha,\beta}\right) = n+1\,,$$
- *if* $\beta = (1+\alpha)^3$, *then*
$$\max(DDT) = 2^{n+1},\ \max(\mathcal{W}) = 2^{(3n+1)/2} \text{ and } \deg\left(H^3_{\alpha,\beta}\right) = n\,,$$
- *otherwise,*
$$\max(DDT) = 4,\ \max(\mathcal{W}) = 2^{n+1} \text{ and } \deg\left(H^3_{\alpha,\beta}\right) \in \{n, n+1\}$$
and $\deg\left(H^3_{\alpha,\beta}\right) = n$ *if and only if*
$$1 + \alpha\beta + \alpha^4 = (\beta + \alpha + \alpha^3)^2\,.$$

Outline

Open Problem

Cellular Message Encryption Algorithm

From Wikipedia, the free encyclopedia

In cryptography, the **Cellular Message Encryption Algorithm** (**CMEA**) is a block cipher which was used for securing mobile phones in the United States. CMEA is one of four cryptographic primitives specified in a Telecommunications Industry Association (TIA) standard, and is designed to encrypt the control channel, rather than the voice data. In 1997, a group of cryptographers published attacks on the cipher showing it had several weaknesses which give it a trivial effective strength of a 24-bit to 32-bit cipher.[1]

CMEA

General	
Designers	James A. Reeds III
First published	1991
Cipher detail	
Key sizes	64 bits
Block sizes	16-64 bits
Rounds	3

Open Problem

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A hidden structure!

CMEA uses an 8-bit (non-bijective) S-Box... With a TU-decomposition!

What is its actual structure?

Conclusion

1. Cryptographers use mathematics but mathematicians could also use crypto!

Conclusion

1. Cryptographers use mathematics but mathematicians could also use crypto!

2. If you design a cipher, justify every step of your design.

Conclusion

1. Cryptographers use mathematics but mathematicians could also use crypto!
2. If you design a cipher, justify every step of your design.
3. If you choose a cipher, demand a full design explanation.

The Last S-Box

14	11	60	6d	e9	10	e3	2	b	90	d	17	c5	b0	9f	c5
d8	da	be	22	8	f3	4	a9	fe	f3	f5	fc	bc	30	be	26
bb	88	85	46	f4	2e	e	fd	76	fe	b0	11	4e	de	35	bb
30	4b	30	d6	dd	df	df	d4	90	7a	d8	8c	6a	89	30	39
e9	1	da	d2	85	87	d3	d4	ba	2b	d4	9f	9c	38	8c	55
d3	86	bb	db	ec	e0	46	48	bf	46	1b	1c	d7	d9	1b	e0
23	d4	d7	7f	16	3f	3	3	44	c3	59	10	2a	da	ed	e9
8e	d8	d1	db	cb	cb	c3	c7	38	22	34	3d	db	85	23	7c
24	d1	d8	2e	fc	44	8	38	c8	c7	39	4c	5f	56	2a	cf
d0	e9	d2	68	e4	e3	e9	13	e2	c	97	e4	60	29	d7	9b
d9	16	24	94	b3	e3	4c	4c	4f	39	e0	4b	bc	2c	d3	94
81	96	93	84	91	d0	2e	d6	d2	2b	78	ef	d6	9e	7b	72
ad	c4	68	92	7a	d2	5	2b	1e	d0	dc	b1	22	3f	c3	c3
88	b1	8d	b5	e3	4e	d7	81	3	15	17	25	4e	65	88	4e
e4	3b	81	81	fa	1	1d	4	22	0	6	1	27	68	27	2e
3b	83	c7	cc	25	9b	d8	d5	1c	1f	e5	59	7f	3f	3f	ef

Conclusion