How to Analyse an S-box, and, in the Process, Prove the Russian Standardizing Agency Wrong

Léo Perrin
Based on joint works with Biryukov, Bonnetain, Canteaut, Duval, Tian and Udovenko

June 26, 2019
University of Rostock

informatics mathematics

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).

From ↑ to ↓

$$\pi : \begin{cases} \mathbb{F}_{2^8} & \to \mathbb{F}_{2^8} \\ 0 & \mapsto \kappa(0)\,, \\ \left(\alpha^{2^m+1}\right)^j & \mapsto \kappa(2^m - j), \ \text{for } 1 \leq j \leq 2^m - 1\,, \\ \alpha^{i+(2^m+1)j} & \mapsto \kappa(2^m - i) \oplus \left(\alpha^{2^m+1}\right)^{s(j)}, \ \text{for } 0 < i, 0 \leq j < 2^m - 1\,. \end{cases}$$

From Russia with Love, Terence Young et al. (1963).

Outline

1 Introduction: S-Boxes and Standardization

2 TU-Decomposition, a Russian God and a Grasshoper

3 The Final Structure in the Russian S-box

4 Conclusion

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Plan of this Section

1 Introduction: S-Boxes and Standardization
- Basics of Symmetric Cryptography
- Block Cipher Design
- How Standardization (Doesn't) Work

2 TU-Decomposition, a Russian God and a Grasshoper

3 The Final Structure in the Russian S-box

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Symmetric Cryptography

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

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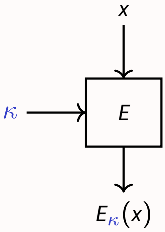
Definition (Block Cipher)

- 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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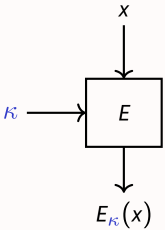


Properties needed:

Diffusion

Confusion

No cryptanalysis!

No Cryptanalysis?

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

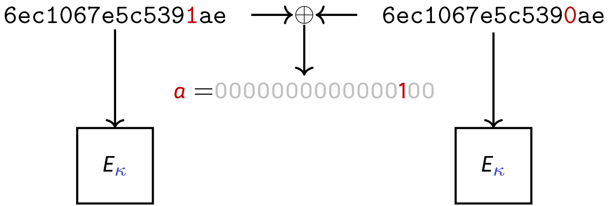
Differential Attacks

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

$$\downarrow$$

$$a = 0000000000000100$$

Differential Attacks



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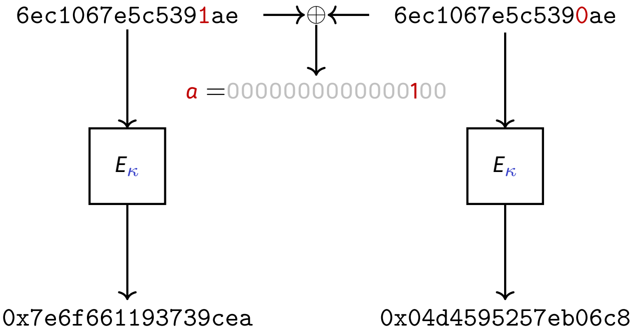

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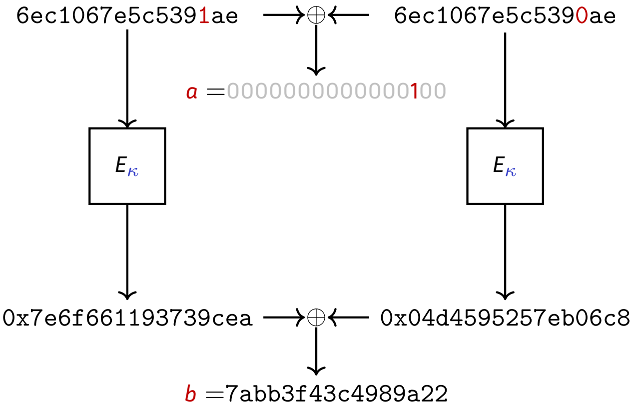

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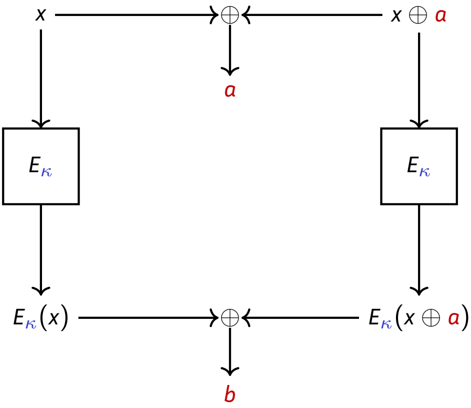

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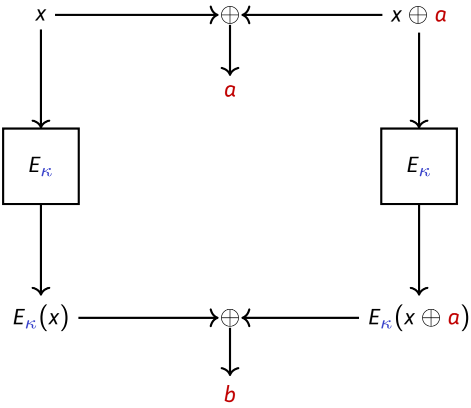

Differential Attack

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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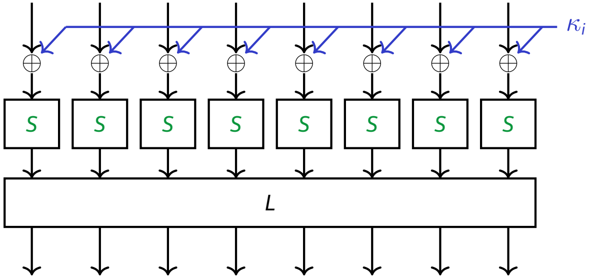

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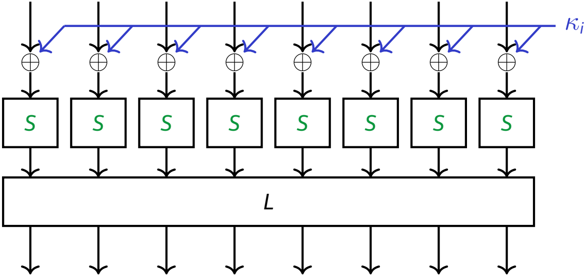

Substitution-Permutation Network

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.

The S-Box (2/2)

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

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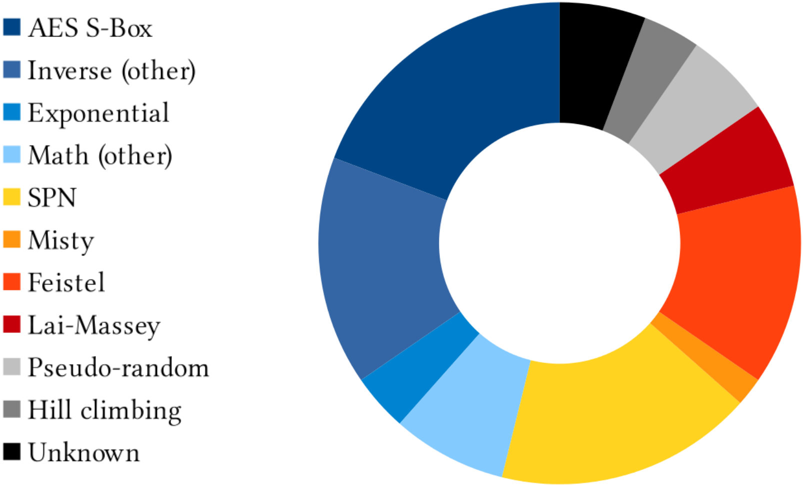
In academic papers presenting new block ciphers, the choice of S is carefully explained.

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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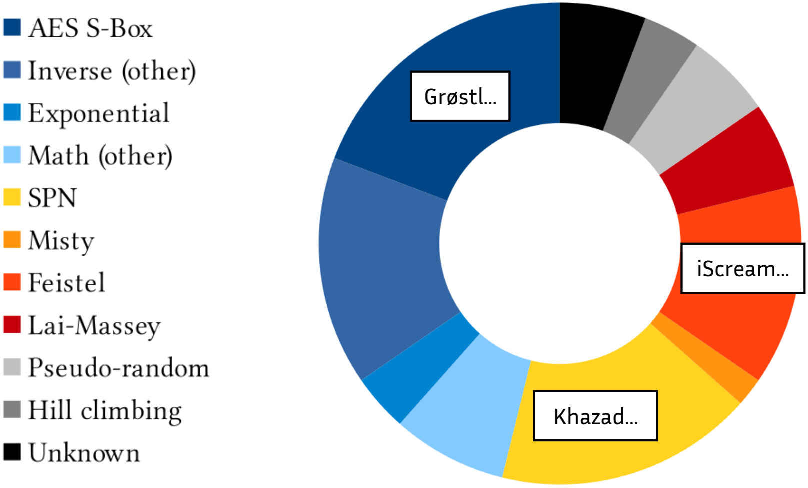
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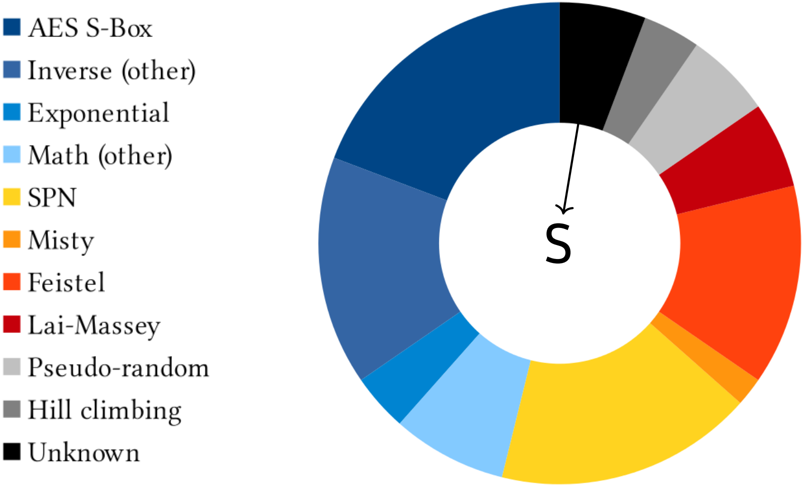
Grøstl...
iScream...
Khazad...

S-Box Reverse-Engineering



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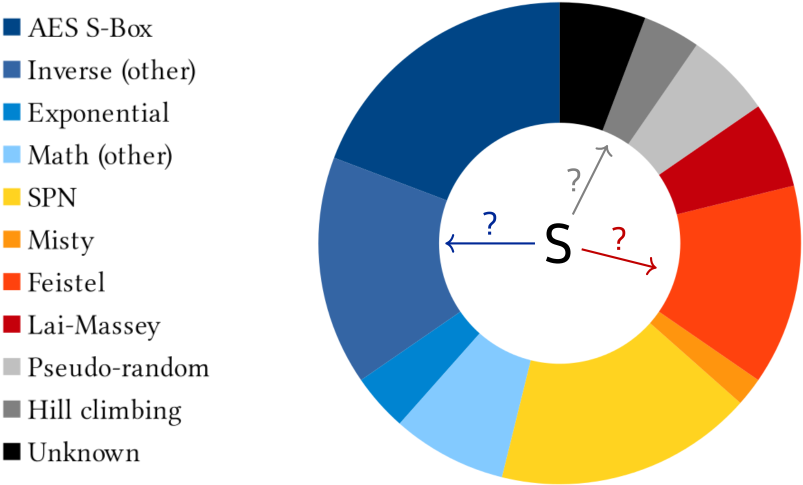

Life Cycle of a Cryptographic Primitive

Fundamental Research

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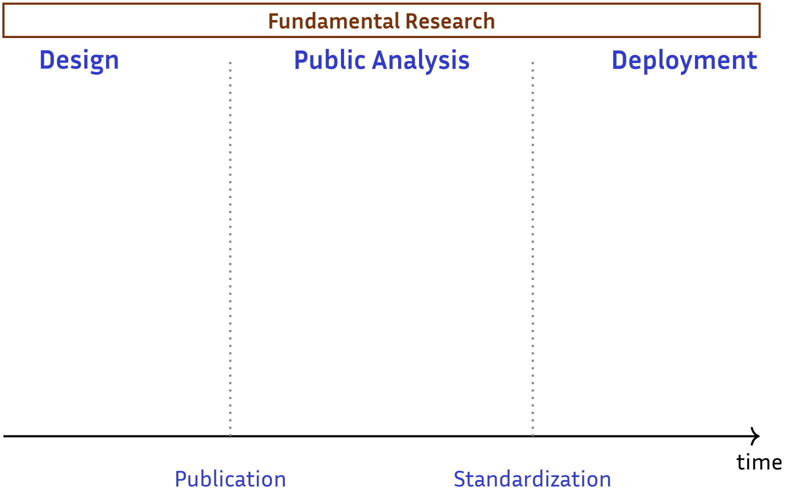

Life Cycle of a Cryptographic Primitive

Fundamental Research

Design
Small teams

Public Analysis
Academic community

Deployment
Industry

time

Publication
Conf., competition

Standardization
NIST, ISO, IETF...

Life Cycle of a Cryptographic Primitive

Fundamental Research

Design

Small teams

- Scope statement
- Algorithm specification
- Design choices justifications
- Security analysis

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Design	**Public Analysis**	**Deployment**
Small teams	*Academic community*	*Industry*
■ Scope statement ■ Algorithm specification ■ Design choices justifications ■ Security analysis	Try and break published algorithms	

time

Publication	**Standardization**
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Academic community

Try and break published algorithms

Unbroken algorithms are eventually trusted

Deployment

Industry

time

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Small teams

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Public Analysis
Academic community

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Deployment
Industry

Implements algorithms in actual products...
...unless a new attack is found

time

Publication
Conf., competition

Standardization
NIST, ISO, IETF...

Breaking the Pipeline

Fundamental Research

Design

Small teams

- Scope statement
- Algorithm specification
- Design choices justifications
- Security analysis

Public Analysis

Academic community

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Deployment

Industry

Implements algorithms in actual products

time

Publication

Standardization

Breaking the Pipeline

Fundamental Research

Design	**Public Analysis**	**Deployment**
~~*Small teams*~~	*Academic community*	*Industry*
???		Implements algorithms in actual products

~~Publication~~ Standardization time

Breaking the Pipeline

Fundamental Research

Design	**Public Analysis**	**Deployment**
Small teams	*Academic community*	*Industry*

Hidden defect?

Publication — Standardization — time

Outline

1 Introduction: S-Boxes and Standardization

2 TU-Decomposition, a Russian God and a Grasshoper

3 The Final Structure in the Russian S-box

4 Conclusion

Plan of this Section

1 Introduction: S-Boxes and Standardization

2 TU-Decomposition, a Russian God and a Grasshoper
- The Two Tables
- Streebog and Kuznyechik
- Decomposing the Mysterious S-Box

3 The Final Structure in the Russian S-box

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The Two Tables

Let $S : \mathbb{F}_2^n \rightarrow \mathbb{F}_2^n$ 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

$$\begin{aligned}\mathrm{LAT}[a, b] &= \#\{x \in \mathbb{F}_2^n \mid x \cdot a = S(x) \cdot b\} - 2^{n-1} \\ &= \frac{1}{2} \times \sum_{x \in \mathbb{F}_2^n} (-1)^{a \cdot x + b \cdot S(x)}\end{aligned}$$

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.

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

Coding Time! (Basics)

1. Computing the DDT and LAT.
2. Differential uniformity, linearity.
3. What do DDT coefficients mean?
4. What do LAT coefficients mean?
5. Permutation vs. function

Coding Time! (Bigger S-box)

1. Using the `sage.crypto.sboxes` module.
2. The AES S-box: differential uniformity, etc
3. The Jackon Pollock representation
4. Comparison with a random permutation

Kuznyechik/Stribog

Stribog

Type Hash function

Publication 2012

Kuznyechik

Type Block cipher

Publication 2015

Kuznyechik/Stribog

Stribog

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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.

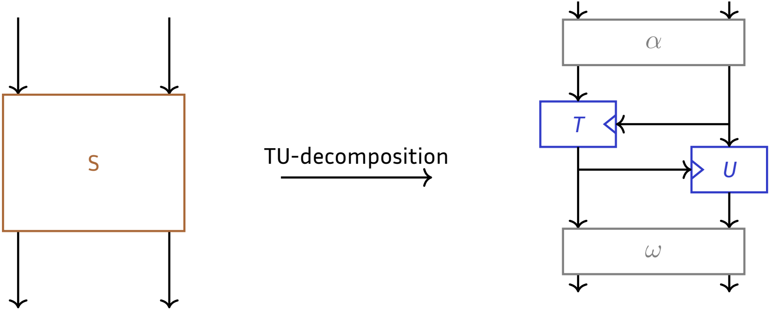
Coding Time!

1. JP representation of the LAT of π
2. Reordering the columns
3. Reordering both rows and columns with linear permutations
4. Deduce an interesting permutation $L' \circ \pi \circ L$
5. Notice the **integral distinguisher**

The TU-Decomposition

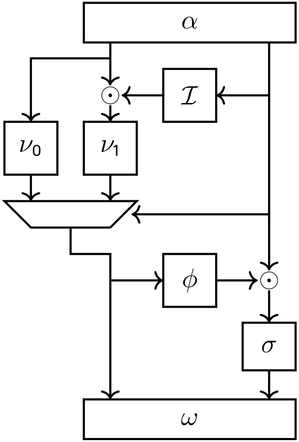
Definition

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?

The Russian S-Box was built like a strange Feistel...

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Belarussian inspiration

- The last standard of Belarus (BelT) uses an 8-bit S-box,
- somewhat similar to π...

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- somewhat similar to π...
- ... based on a finite field exponential!

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Plan of this Section

1 Introduction: S-Boxes and Standardization

2 TU-Decomposition, a Russian God and a Grasshoper

3 The Final Structure in the Russian S-box
- Generation Process
- Cryptographic Properties

4 Conclusion

Timeline

July 2012	GOST standardization of Streebog
Aug. 2013	RFC for Streebog (RFC6986)
June 2015	GOST standardization of Kuznyechik
Mar. 2016	RFC for Kuznyechik (RFC7801)

[1] A. Biryukov, L. Perrin, A. Udovenko. *Reverse-engineering the S-box of Streebog, Kuznyechik and STRIBOBr1.* EUROCRYPT'16

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A Third and Final Decomposition: the TKlog

π is a TKlog!

π operates on $\mathbb{F}_{2^{2m}}$ where $m = 4$ using:

- α: a generator of $\mathbb{F}_{2^{2m}}$,
- κ: an affine function $\mathbb{F}_2^m \to \mathbb{F}_{2^{2m}}$ with $\kappa(\mathbb{F}_2^m) \oplus \mathbb{F}_{2^m} = \mathbb{F}_{2^{2m}}$,
- s: a permutation of $\mathbb{Z}/(2^m - 1)\mathbb{Z}$;

it works as follows:

$$\begin{cases} \pi(0) & = \kappa(0)\,, \\ \pi\left(\left(\alpha^{2^m+1}\right)^j\right) & = \kappa(2^m - j), \text{ for } 1 \leq j \leq 2^m - 1\,, \\ \pi\left(\alpha^{i+(2^m+1)j}\right) & = \kappa(2^m - i) \oplus \left(\alpha^{2^m+1}\right)^{s(j)}, \text{ for } 0 < i, 0 \leq j < 2^m - 1\,. \end{cases}$$

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From the Designers, at ISO

questioned is the S-box π. This S-box was chosen from Streebog hash-function and it was synthesized in 2007. Note that through many years of cryptanalysis no weakness of this S-box was found. The S-box π was obtained by pseudo-random search and the following properties were taken into account.

[...]

No secret structure was enforced during construction of the S-box. At the same time, it is obvious that for any transformation a lot of representations are possible (see, for example, a lot of AES S-box representations).

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questioned is the S-box π. This S-box was chosen from Streebog hash-function and it was synthesized in 2007. Note that through many years of cryptanalysis no weakness of this S-box was found. The S-box π was obtained by pseudo-random search and the following properties were taken into account.

[...]

No secret structure was enforced during construction of the S-box. At the same time, it is obvious that for any transformation a lot of representations are possible (see, for example, a lot of AES S-box representations).

Everything is wrong except for the green part.

The Russian S-box is too simple

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p(x){unsigned char*k="@`rFTDVbpPB
vdtfR@\xacp?\xe2>4\xa6\xe9{z\xe3q
5\xa7\xe8",a=2,l=0,b=17;while(x&&
(l++,a^x))a=2*a^a/128*29;return l
%b?k[l%b]^k[b+l/b]^b:k[l/b]^188;}
```

- 165 ASCII characters that fit on 7 bits: this program is 1155-bit long
- It is **impossible** that all 2^{1684} 8-bit permutations have an implementation this short!

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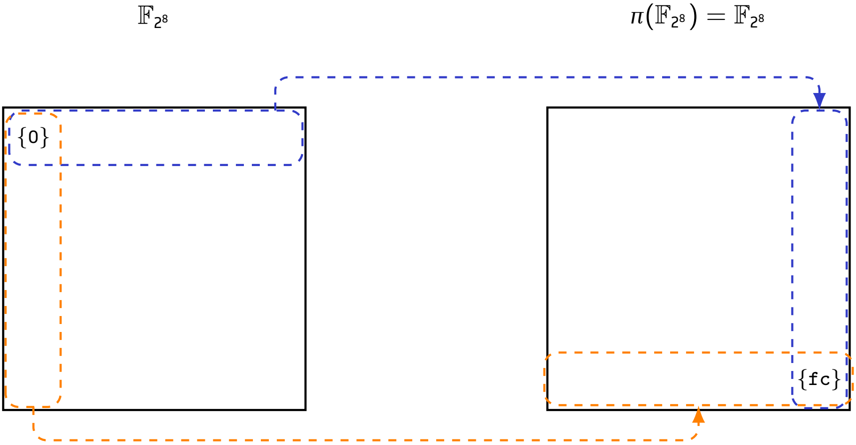
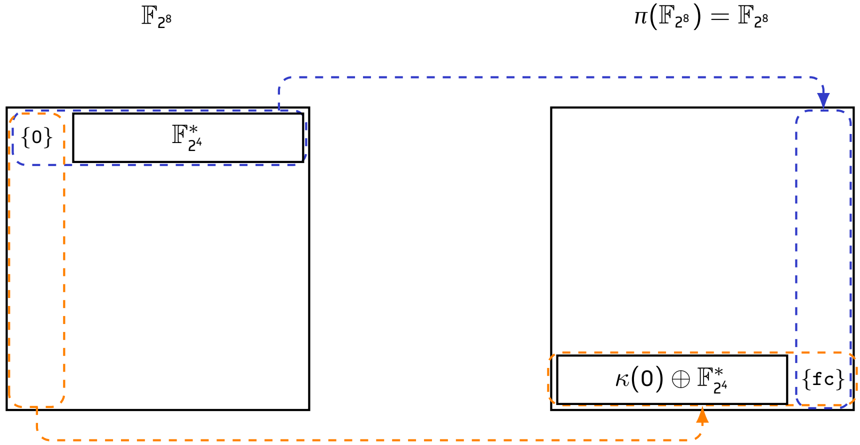
https://codegolf.stackexchange.com/questions/186498/proving-that-a-russian-cryptographic-standard-is-too-structured

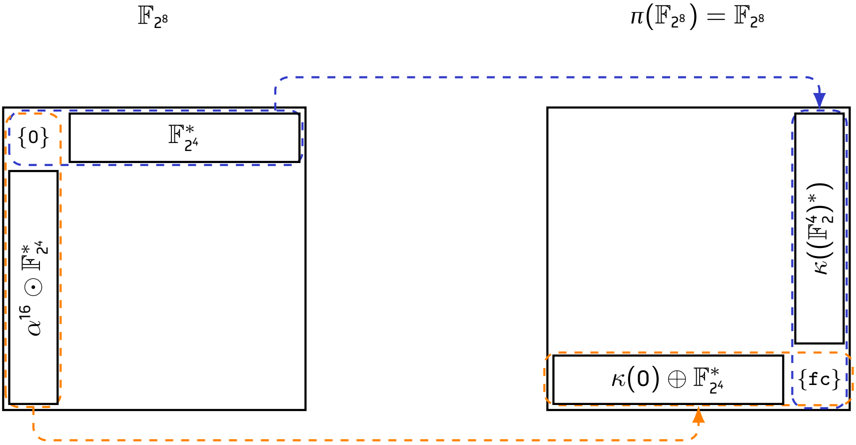
Cosets to Cosets



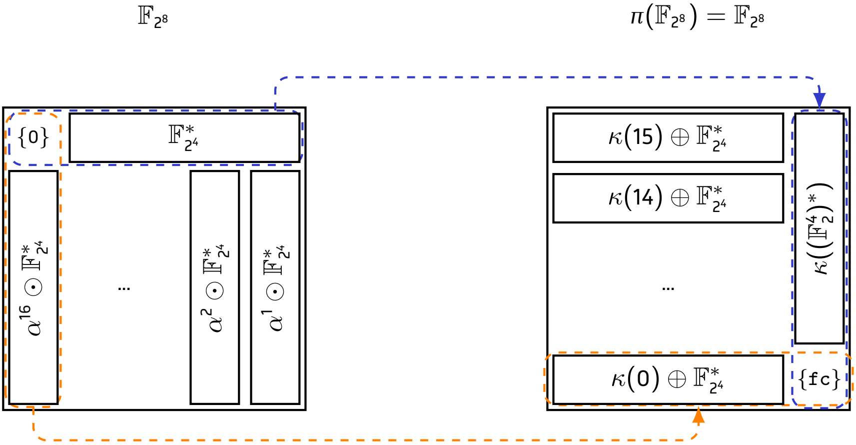
Cosets to Cosets



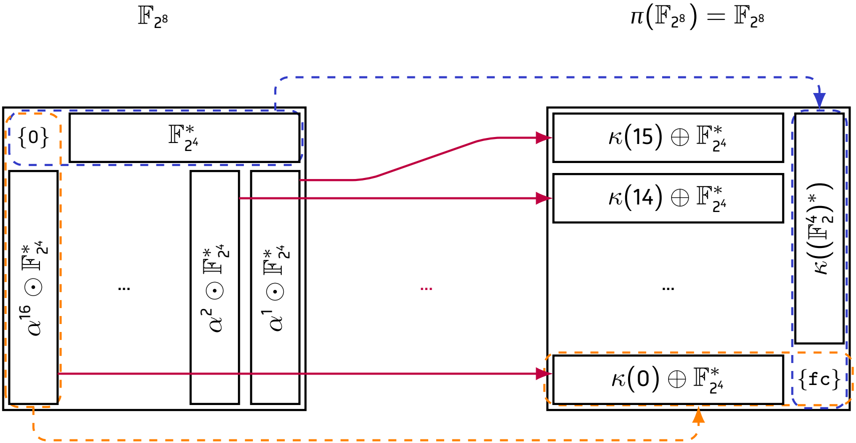
Cosets to Cosets



Cosets to Cosets

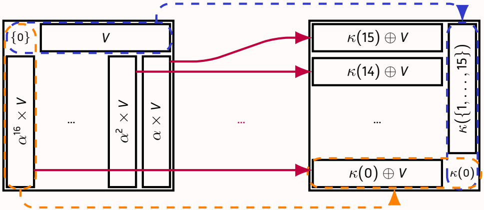


Cosets to Cosets

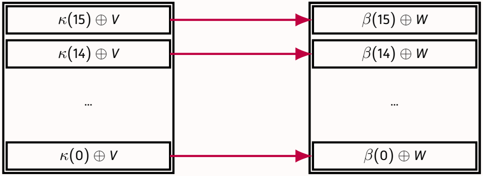


Why it is Worrying

Russia's π



Backdoored S-box



Outline

1 Introduction: S-Boxes and Standardization

2 TU-Decomposition, a Russian God and a Grasshoper

3 The Final Structure in the Russian S-box

4 Conclusion

Plan of this Section

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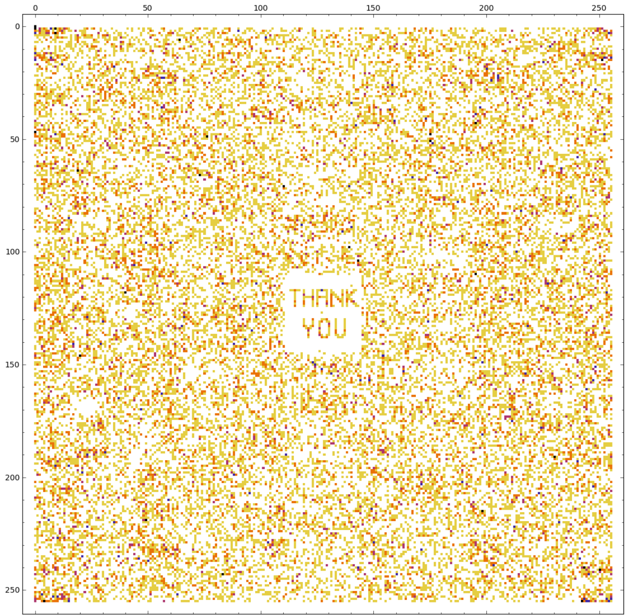
1. Cryptographers use mathematics but mathematicians could also use crypto!
2. If you design a cipher, justify every step of your design.
3. If you choose a cipher, demand a full design explanation.

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


0
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THANK
YOU