How can we ensure that (symmetric) cryptographic primitives are trustworthy?

Léo Perrin

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

June, 2023

University of Rostock

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Why do we care?

Outline

Outline

Plan of this Section

Symmetric Cryptography

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

Symmetric Cryptography

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Definition (Block Cipher)

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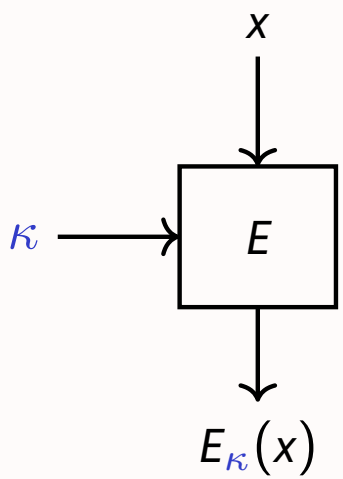
- Output: n-bit block $E_\kappa(x)$
- Symmetry: E and E^{-1} use the same κ



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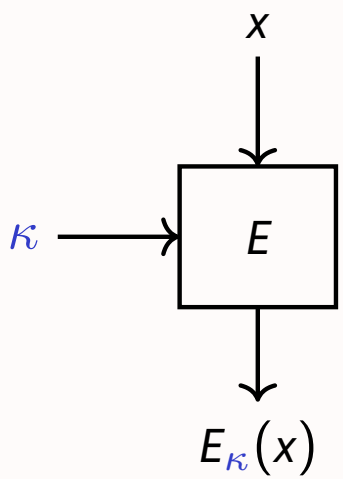


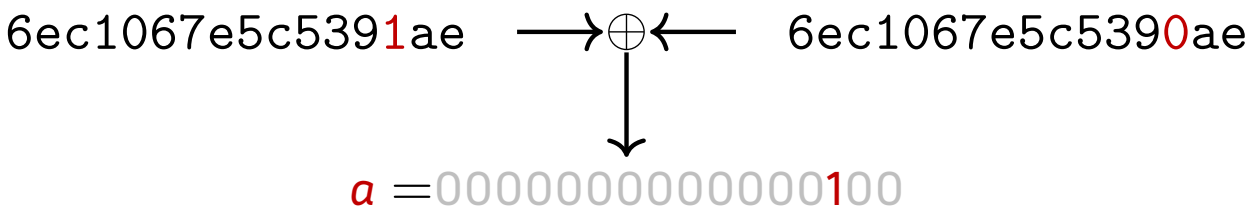
Properties needed:

Diffusion | Confusion | No cryptanalysis!

No Cryptanalysis?

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

Differential Attacks



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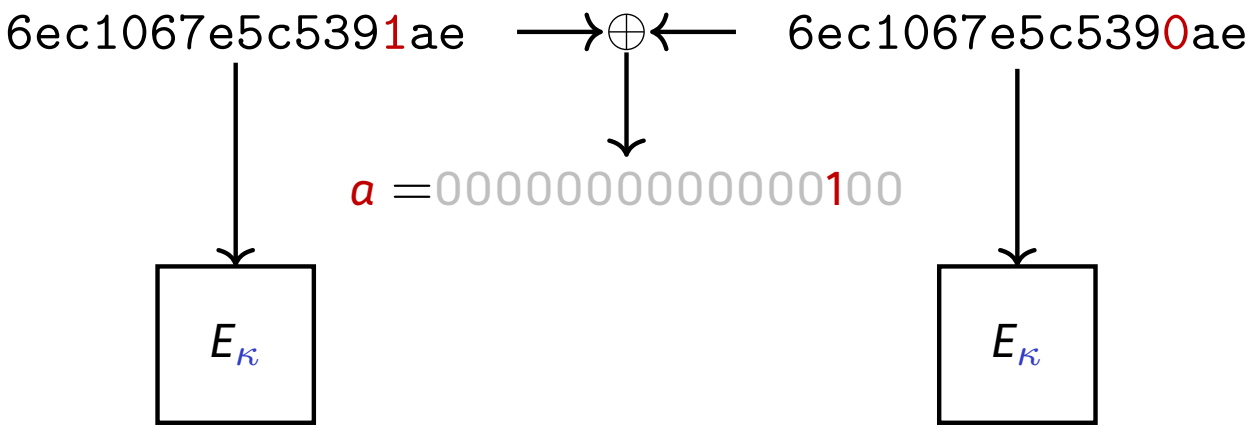

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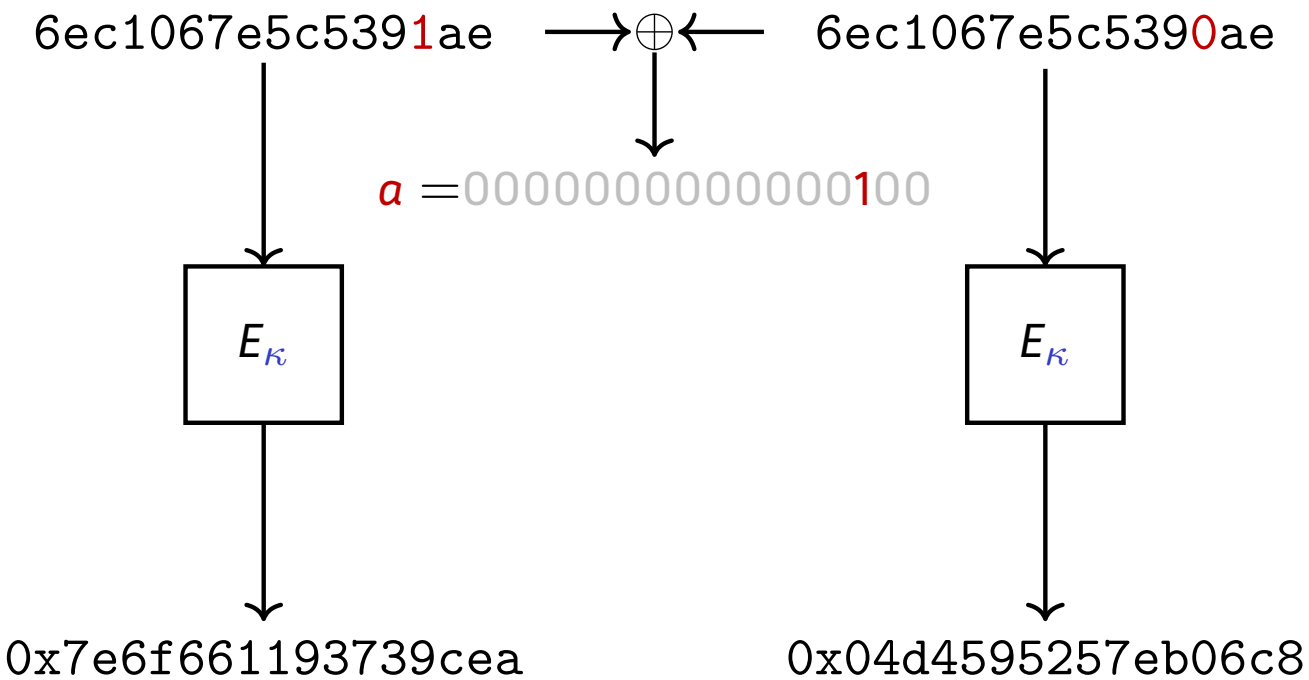

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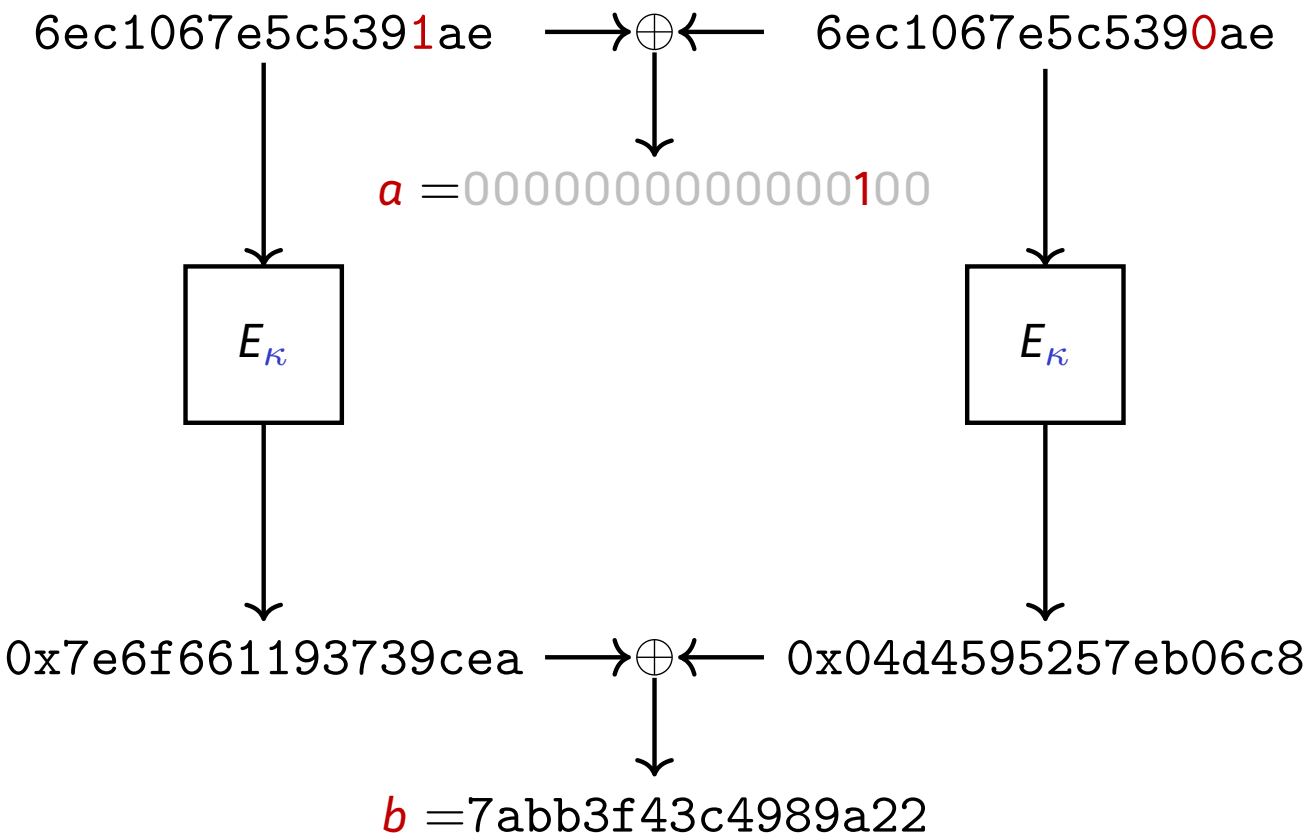

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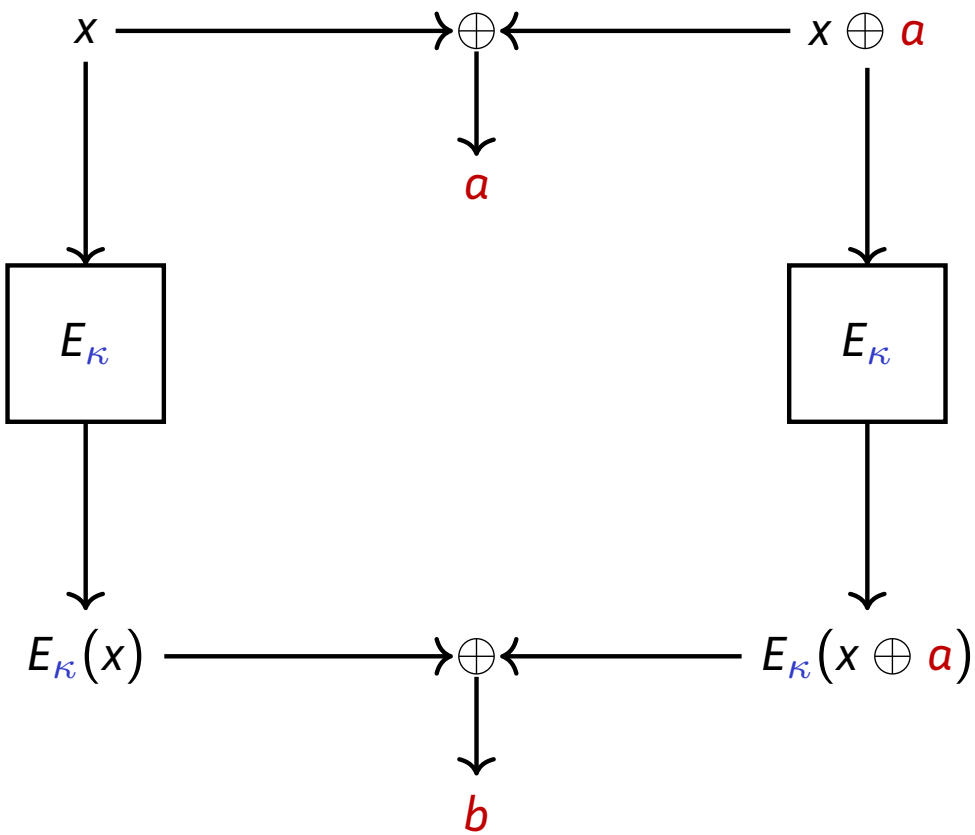

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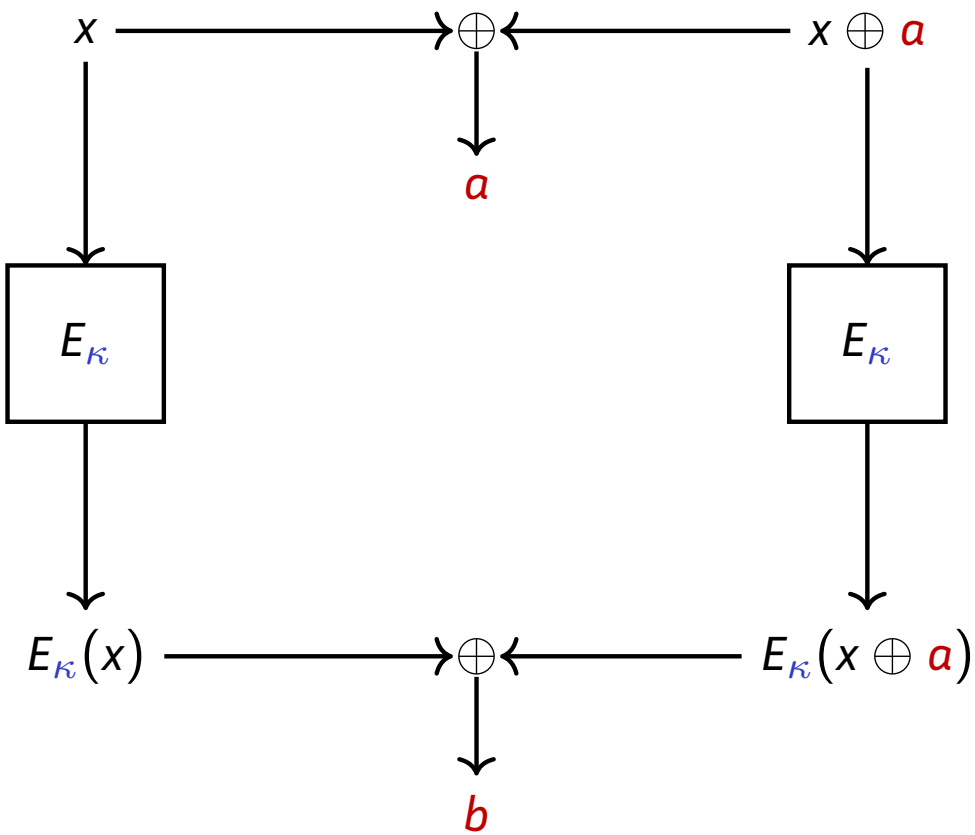

Differential Attack

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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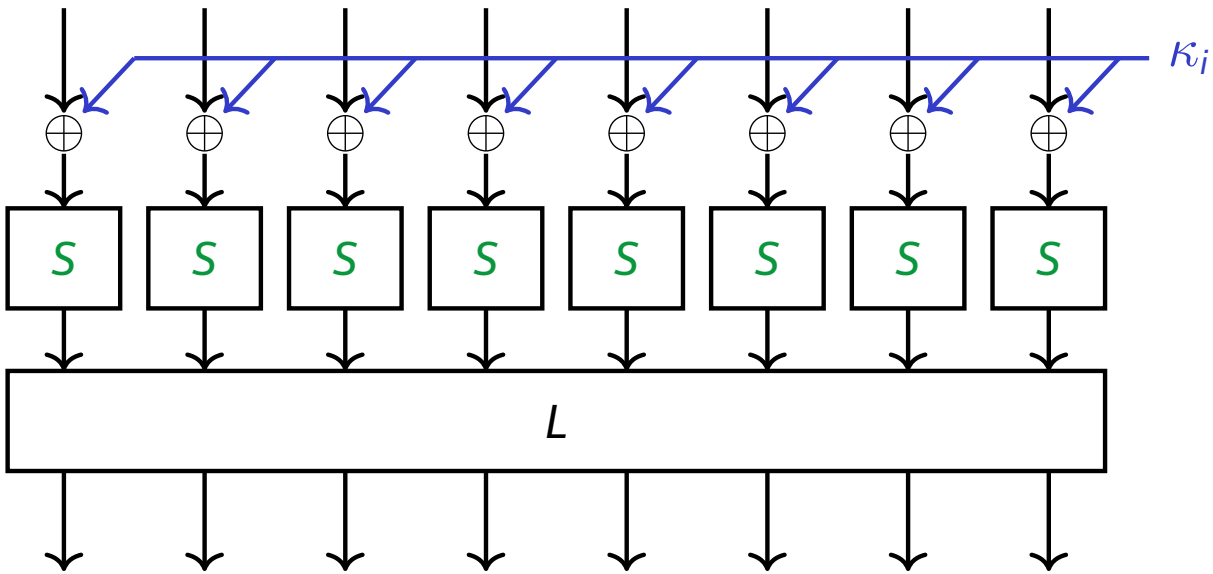

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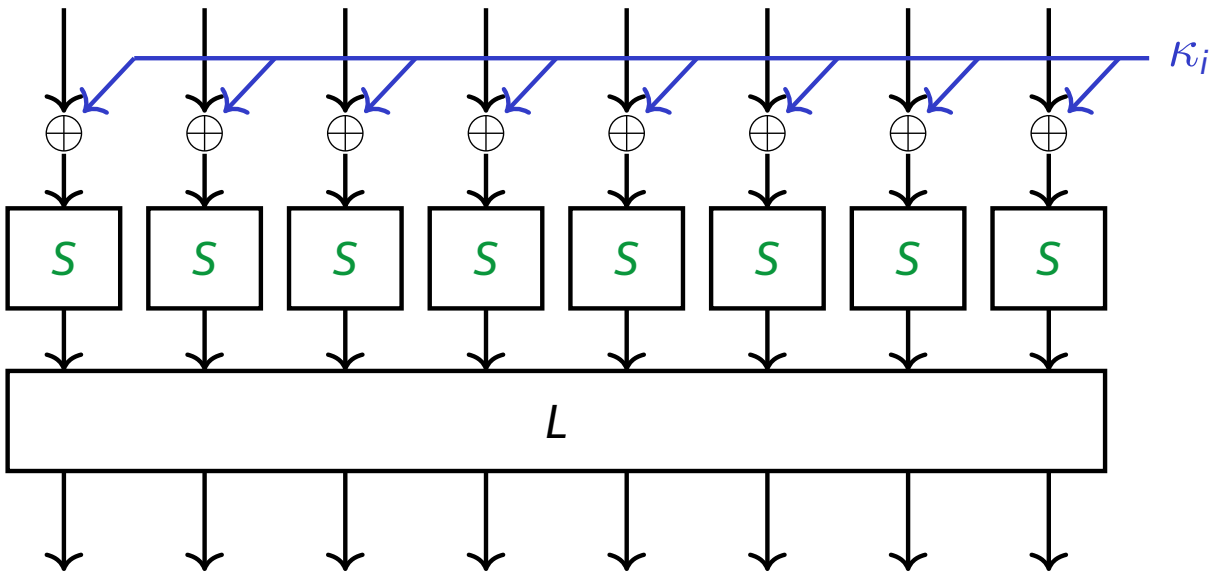

Substitution-Permutation Network

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)

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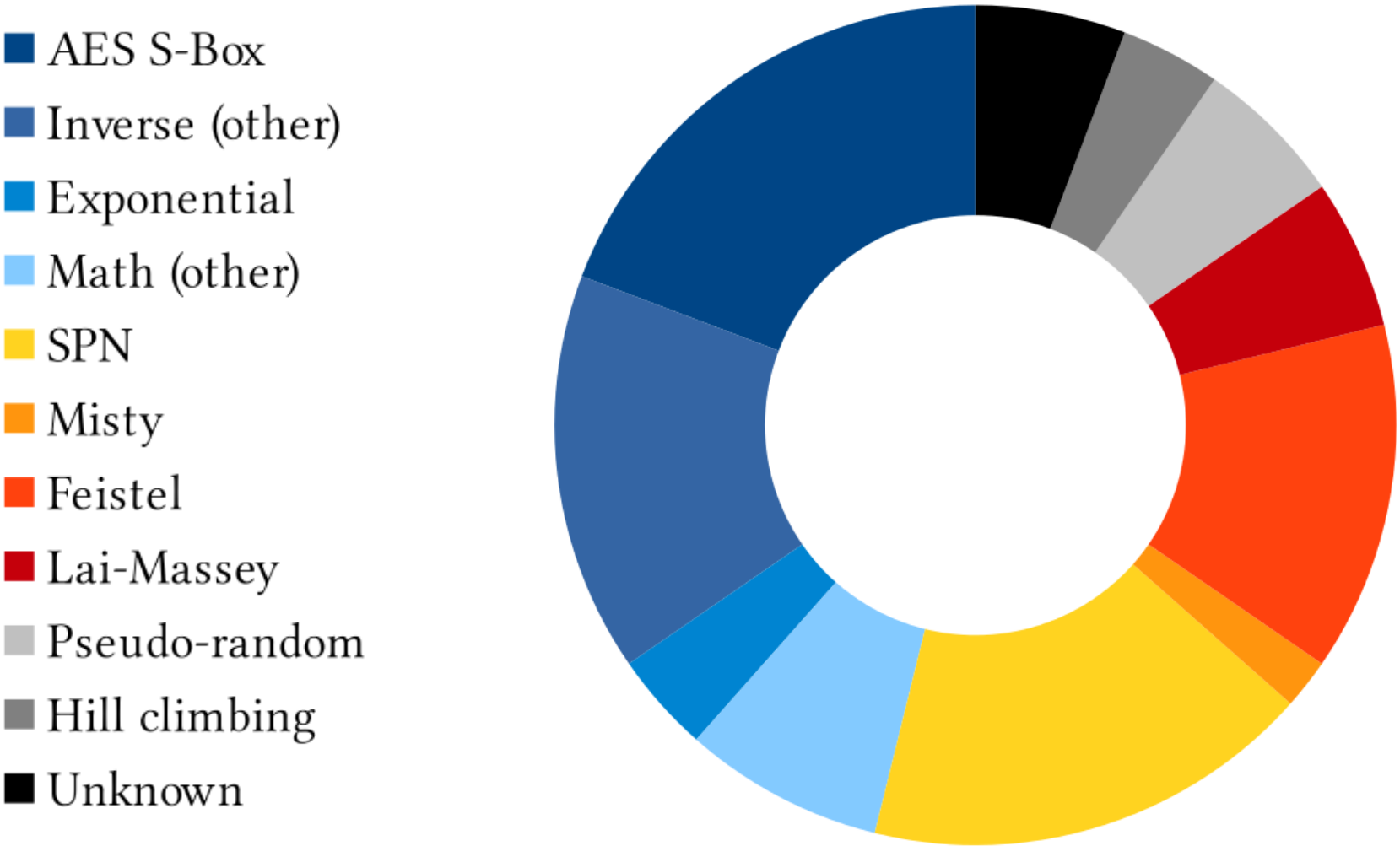
In academic papers presenting new block ciphers, the choice of S is carefully explained.

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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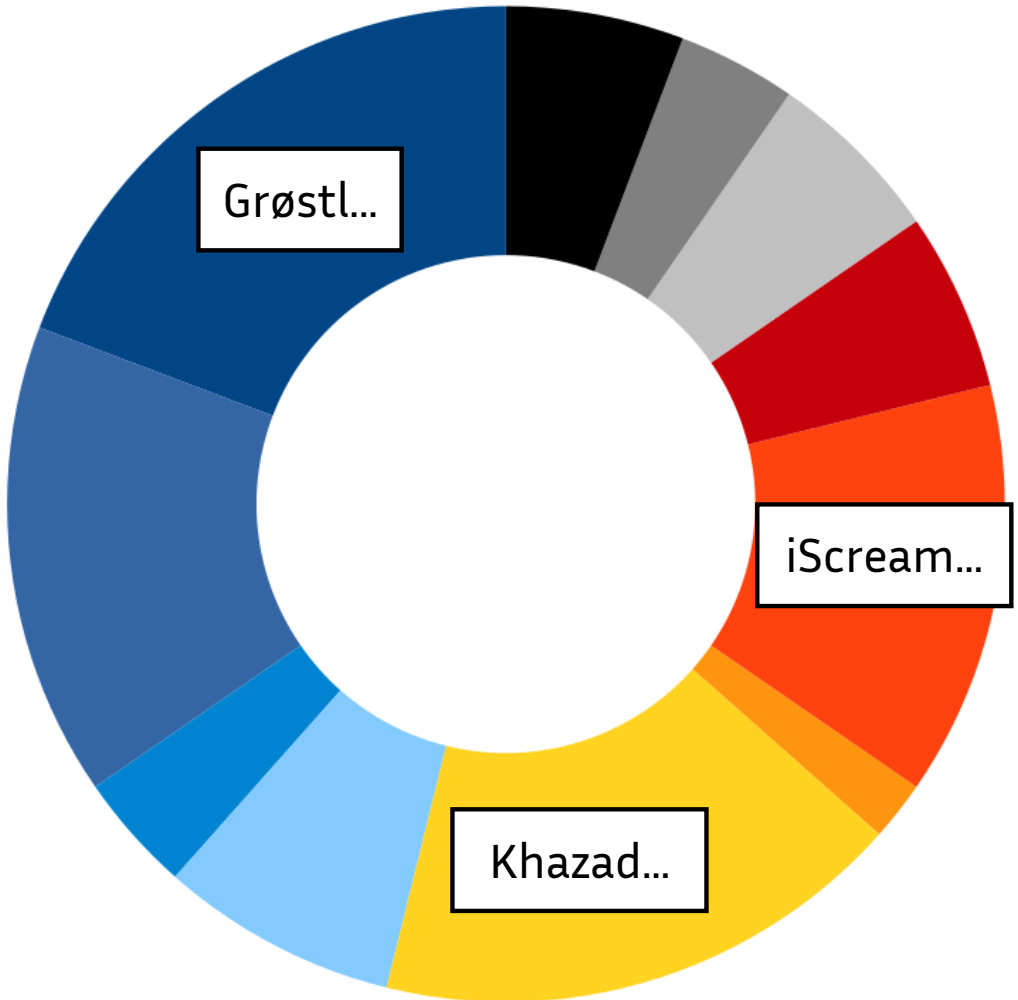


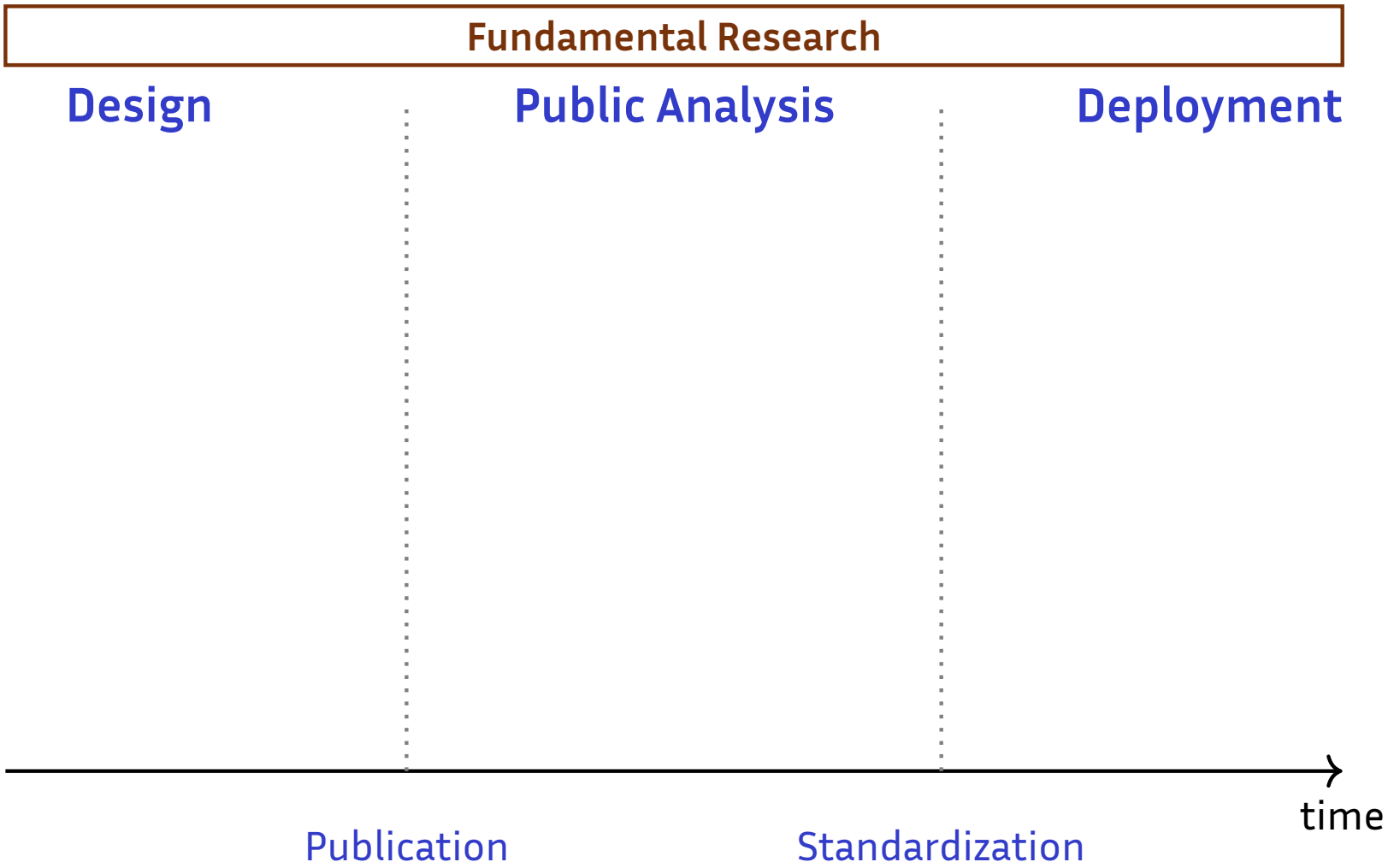
Outline

Plan of this Section

Life Cycle of a Cryptographic Primitive

Fundamental Research

Life Cycle of a Cryptographic Primitive



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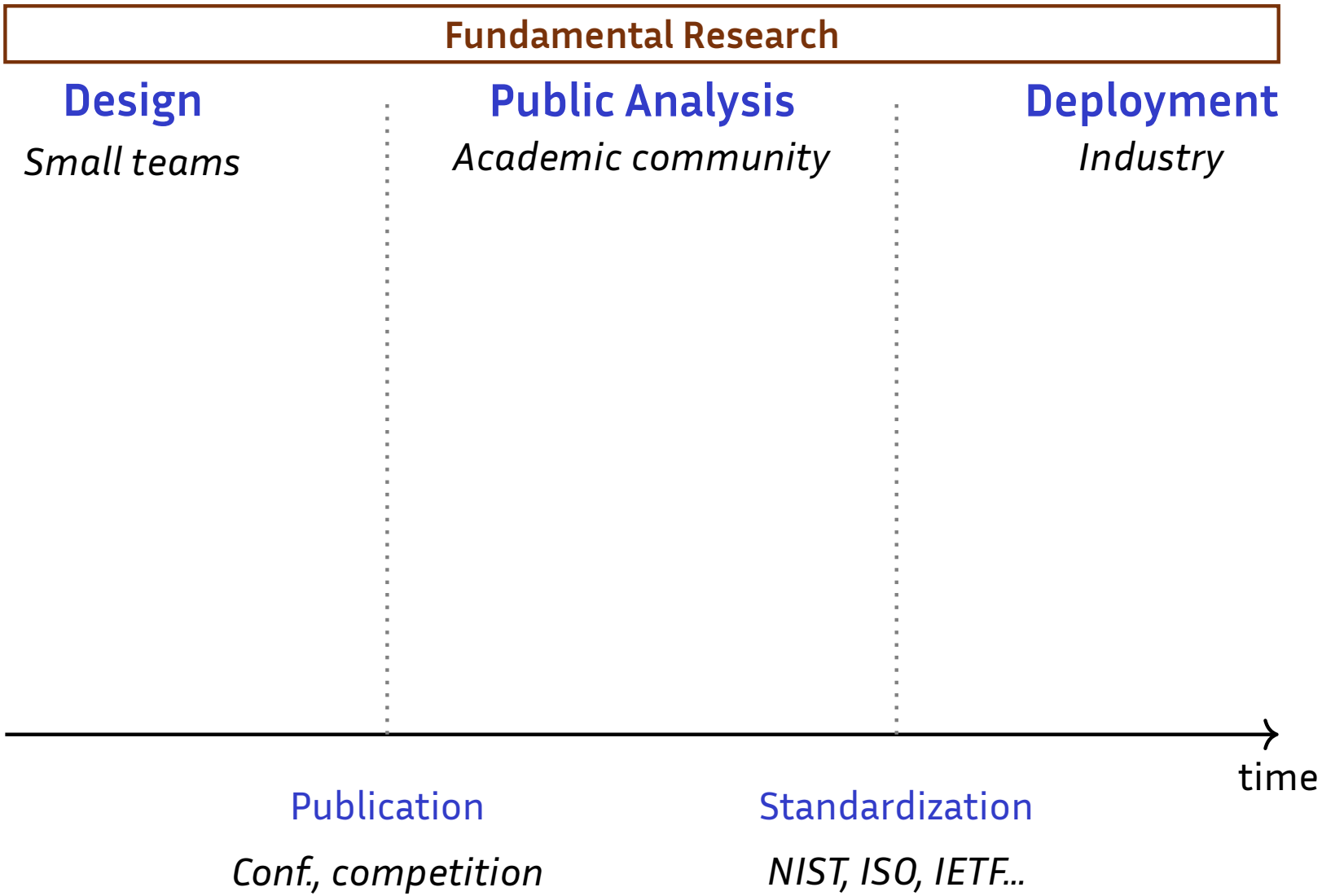

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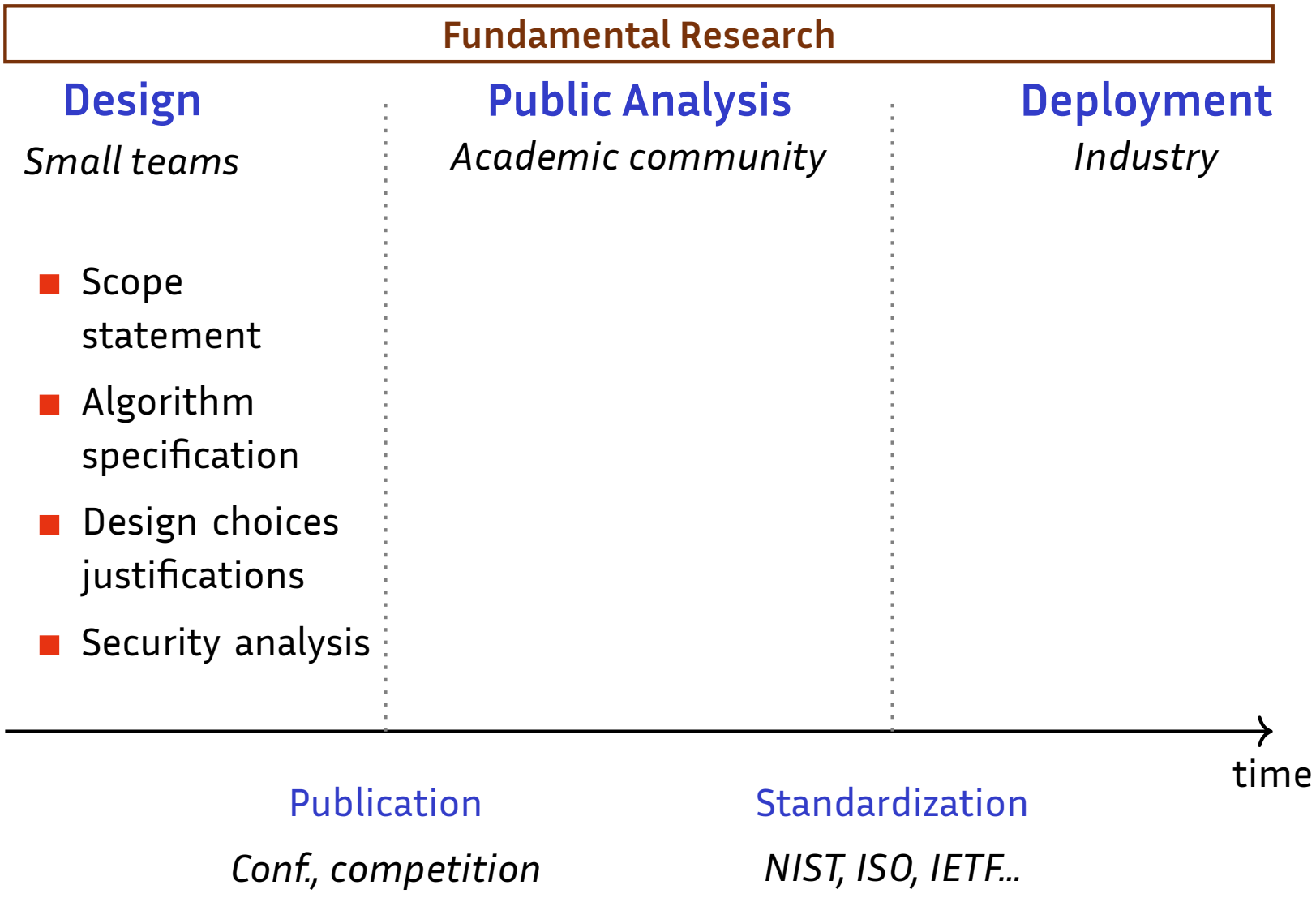

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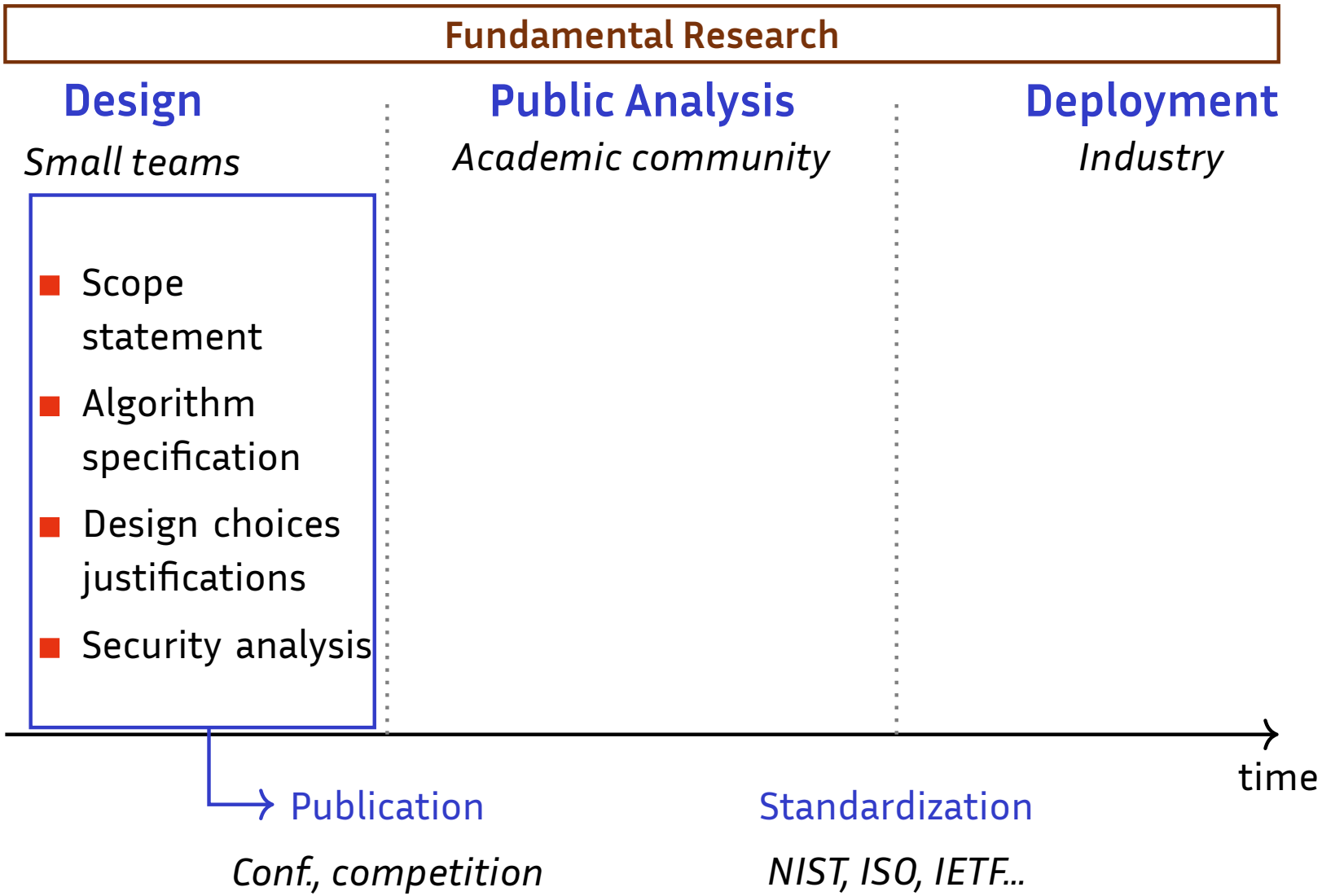

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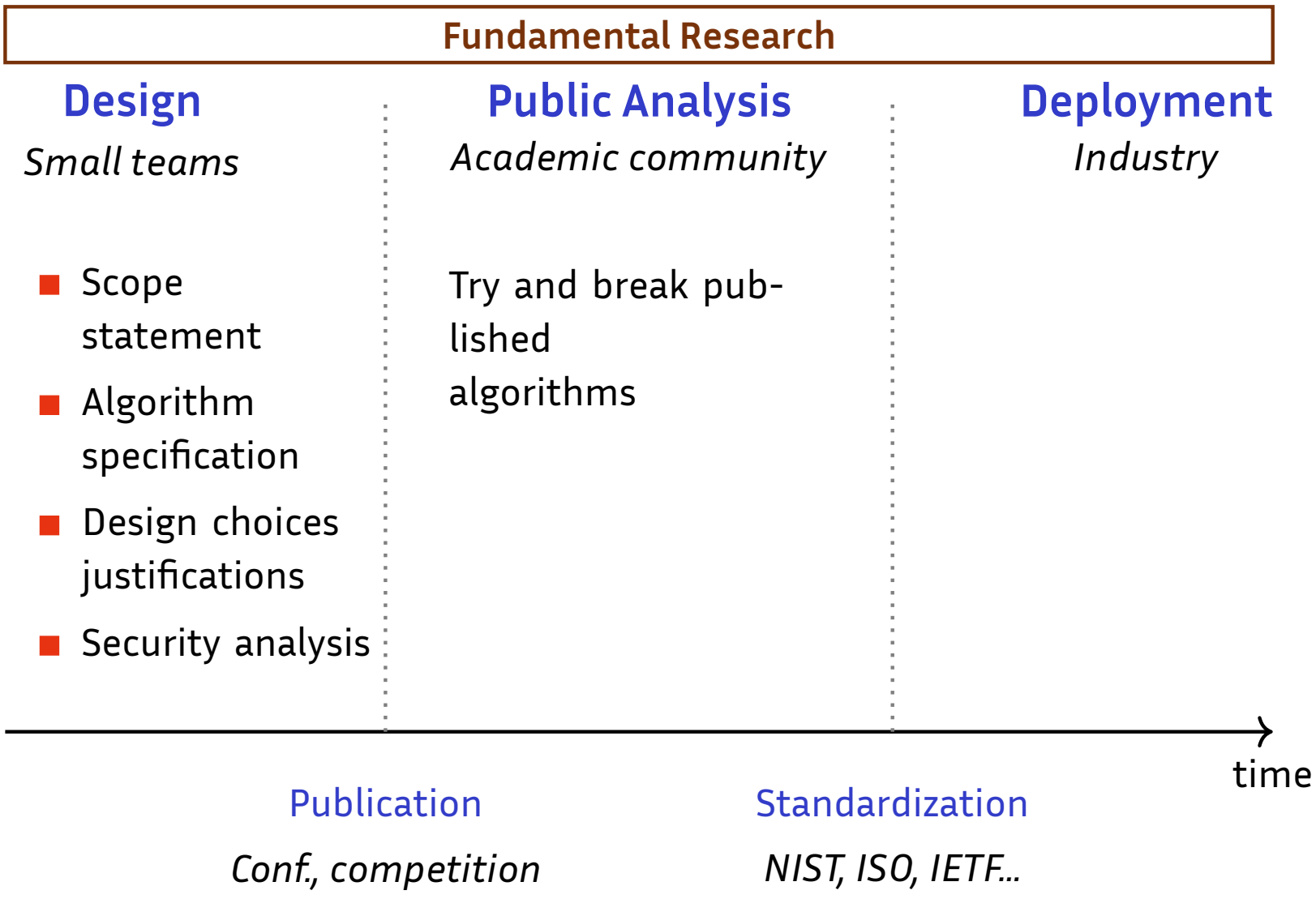

Life Cycle of a Cryptographic Primitive

Fundamental Research

Design

Small teams

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

Public Analysis

Academic community

Try and break published algorithms

Deployment

Industry

time

Publication

Conf., competition

Standardization

NIST, ISO, IETF...

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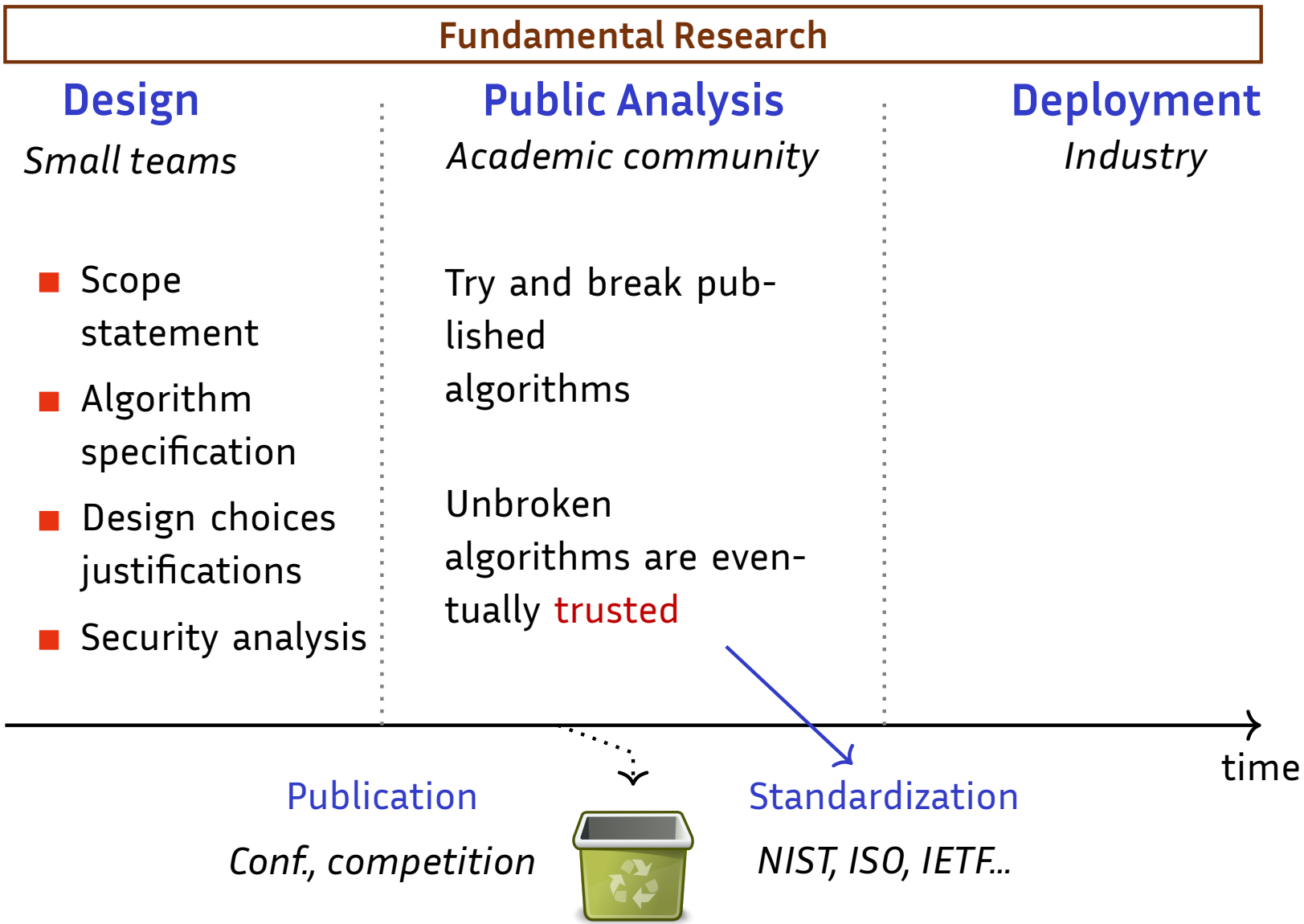

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Unbroken algorithms are eventually trusted

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Industry

Implements algorithms in actual products...

...unless a new attack is found

time

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Some Examples

- **A**dvanced **E**ncryption **S**tandard competition $\longrightarrow$ AES block cipher
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not much cryptanalysis...

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February 2023	NIST chose ASCON

The best approach is the one used in practice!

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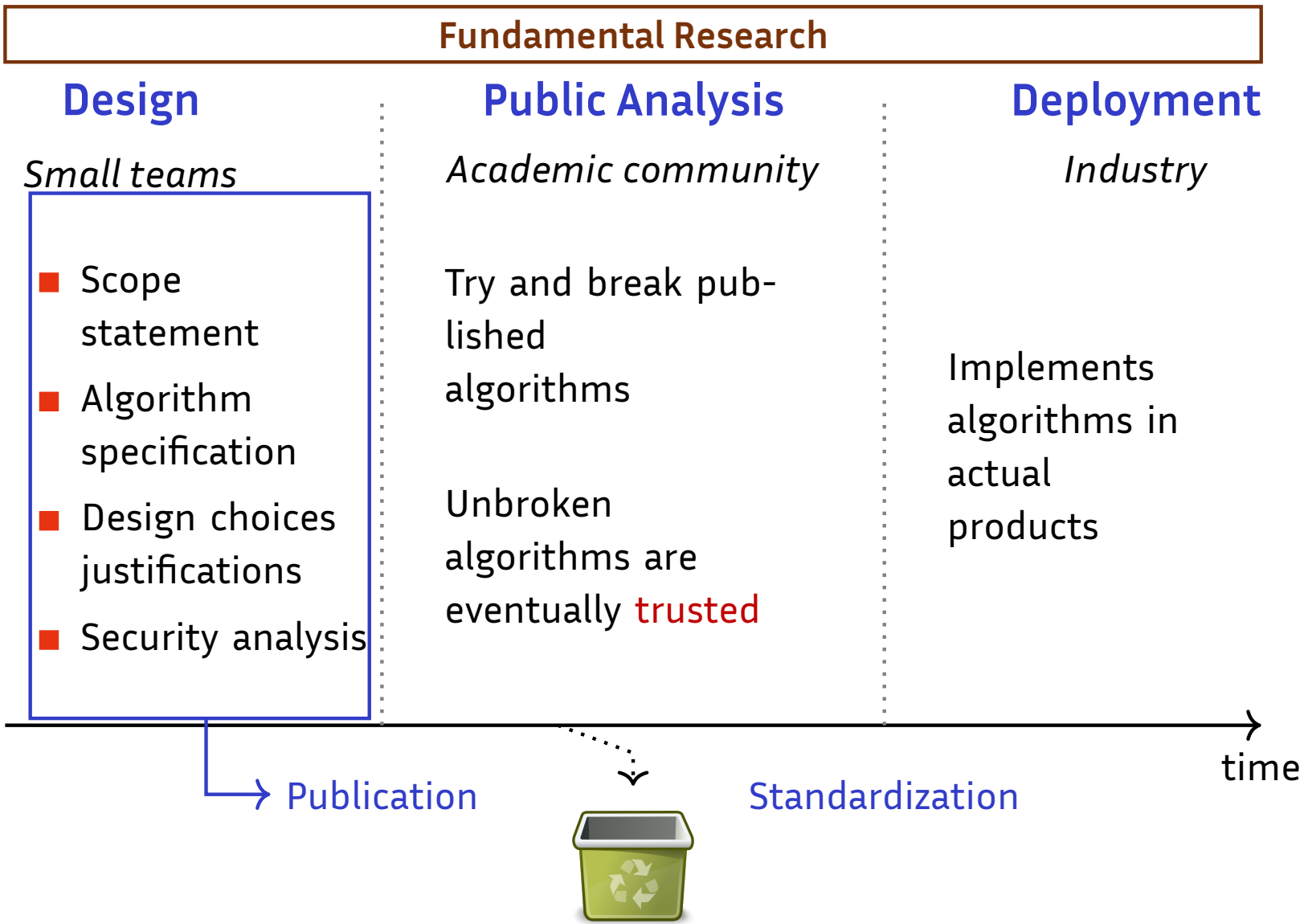
All is well?

The best approach is the one used in practice!

All is well?

... no.

Breaking the Pipeline



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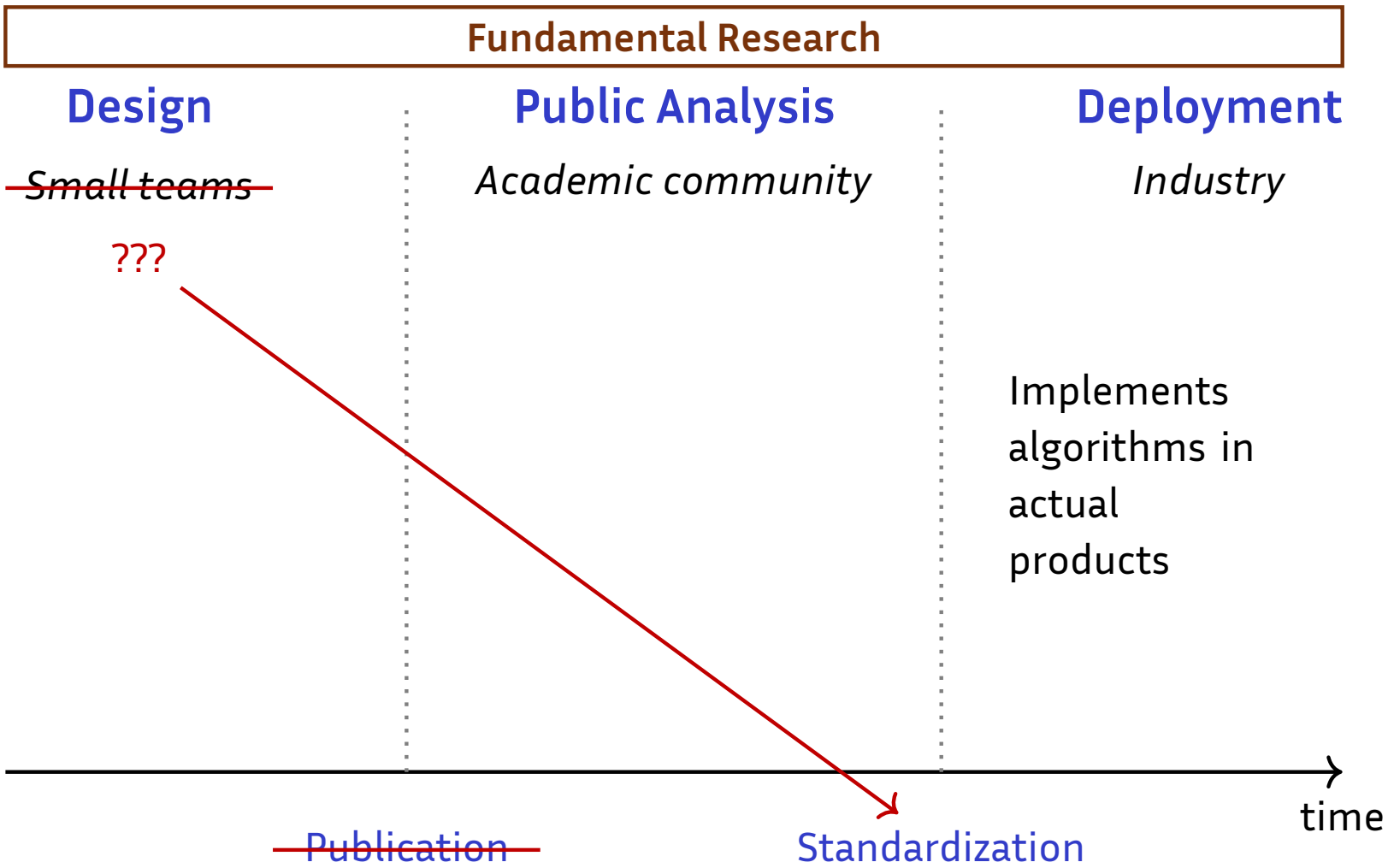

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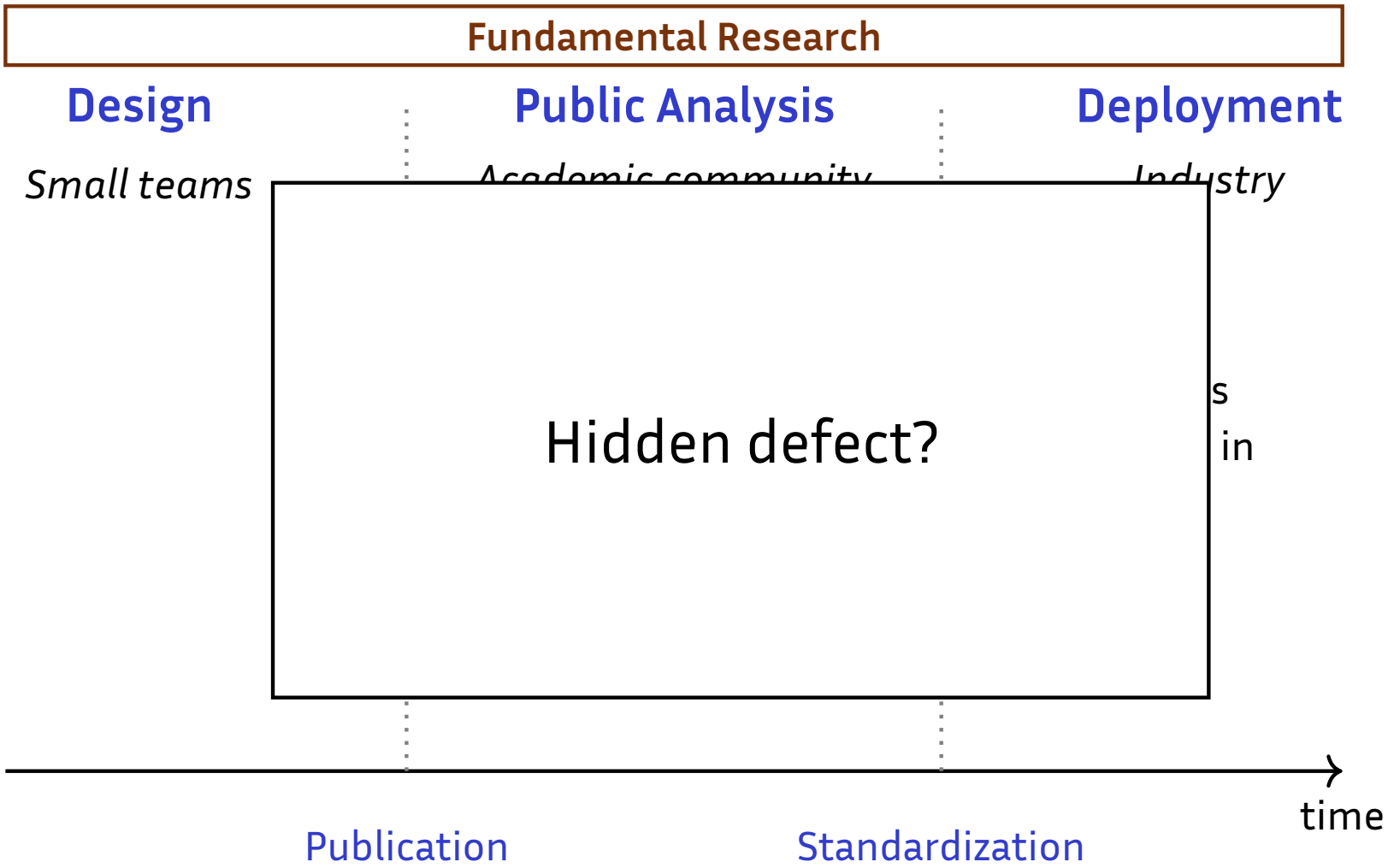

Some (Counter-)Examples

`https://eprint.iacr.org/<year>/<number>`

A5/2

- stream cipher
- 1980's
- used in 2G
- designer: ??
- `wikipedia`

DUAL EC

- PRNG
- 2000's
- general standard
- designer: NSA
- 2015/767 (2016/376)

GEA-1

- 1990's
- stream cipher
- used in EDGE
- designer: ??
- 2021/819

Outline

Plan of this Section

Kuznyechik/Stribog

Stribog

Type Hash function

Publication 2012

Kuznyechik

Type Block cipher

Publication 2015

Kuznyechik/Stribog

Stribog

Type Hash function

Publication 2012

Kuznyechik

Type Block cipher

Publication 2015

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.

π

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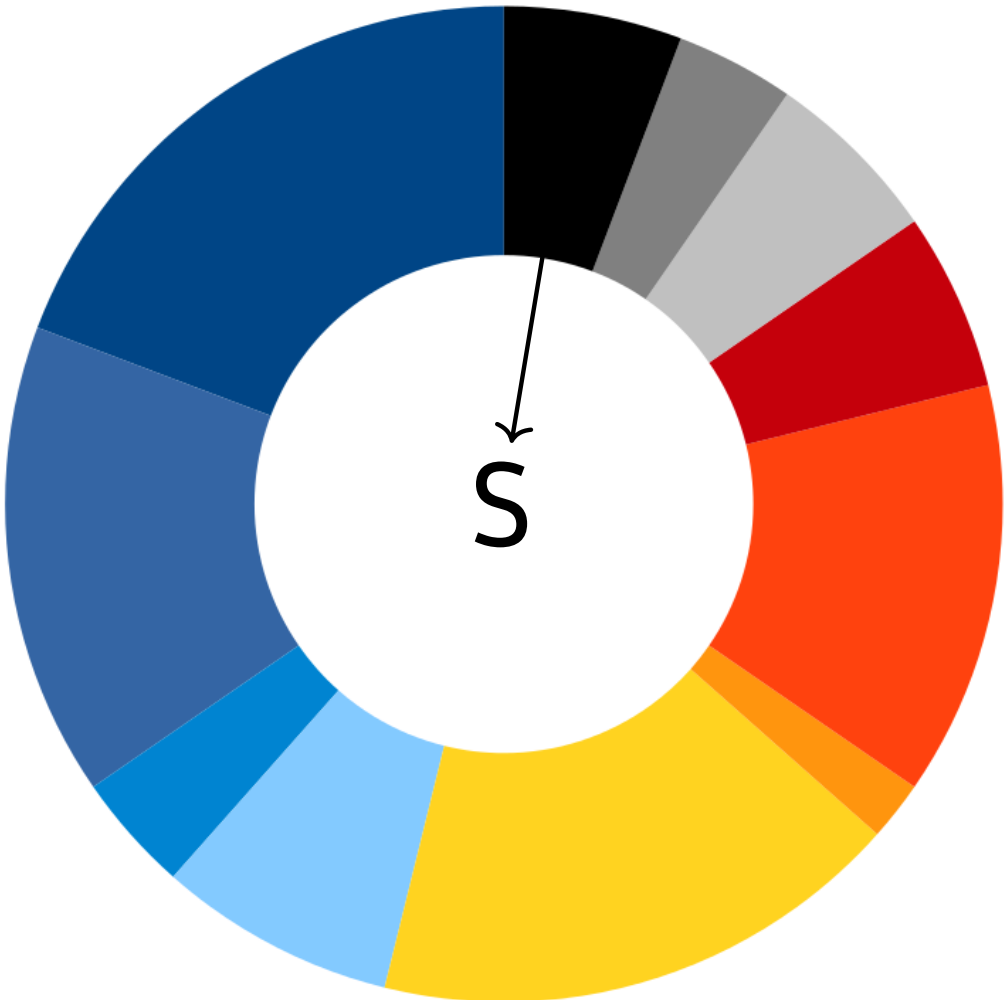
S-Box Reverse-Engineering

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



S-Box Reverse-Engineering

- AES S-Box
- Inverse (other)
- Exponential
- Math (other)
- SPN
- Misty
- Feistel
- Lai-Massey
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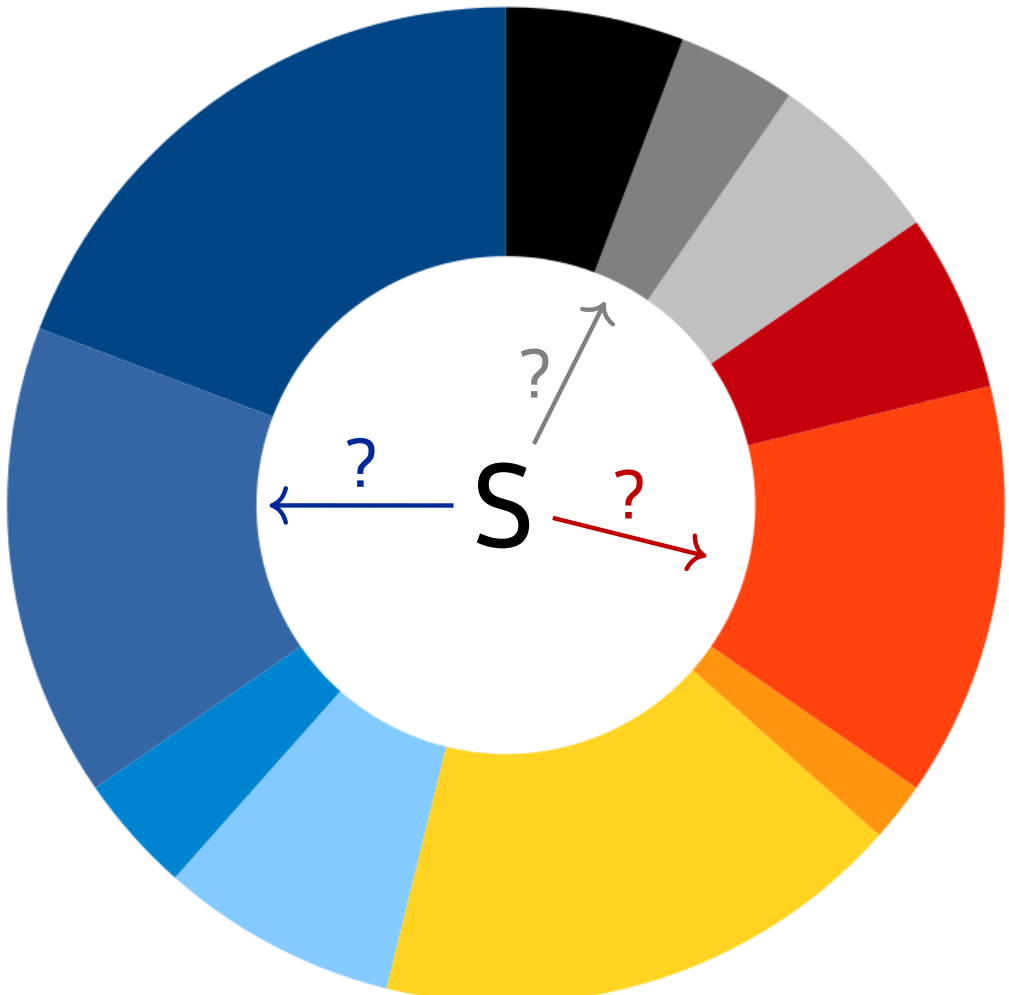

The Two Tables

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

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

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!

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

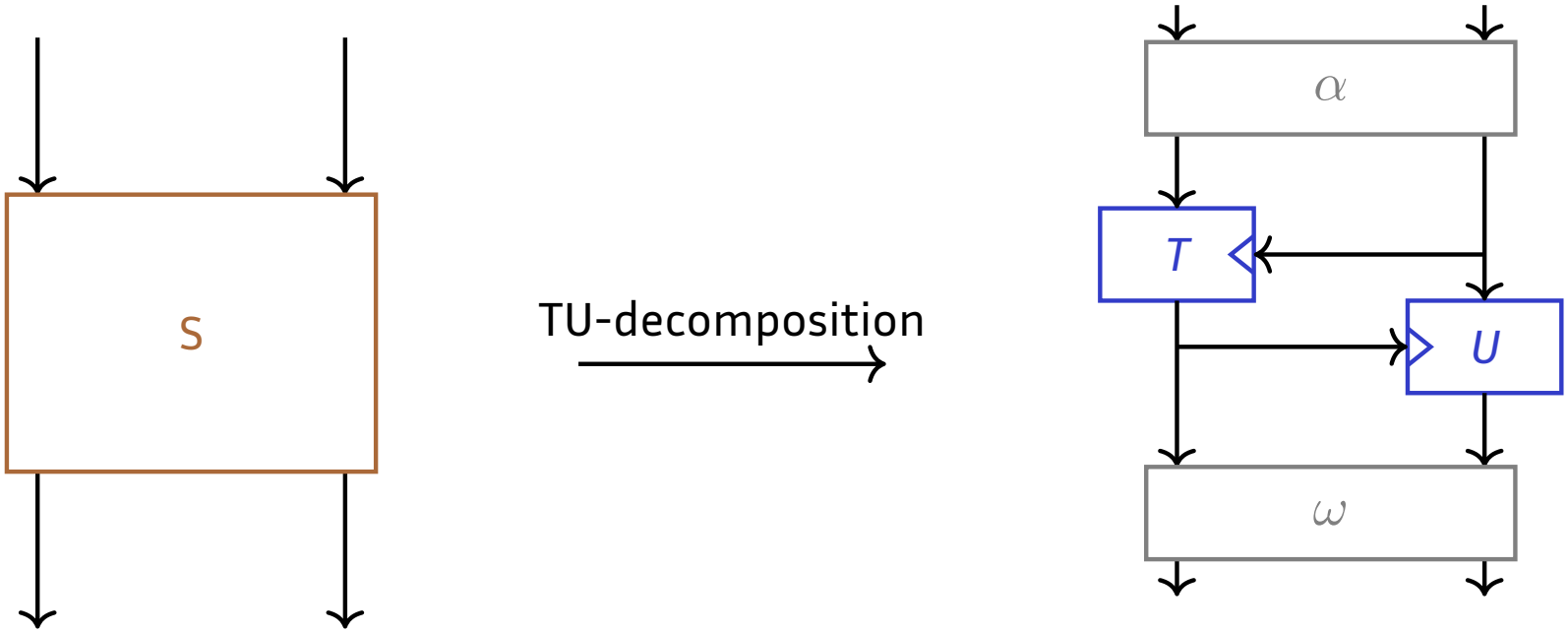
Coding Time! (Kuznyechik)

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

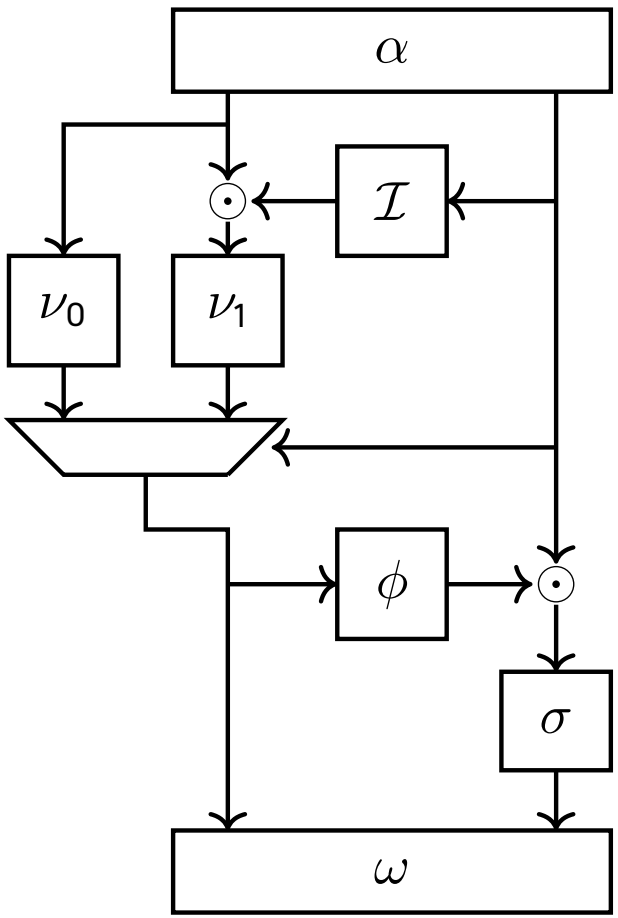
Definition

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

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

Timeline

July 2012	GOST standardization of Streebog
Aug. 2013	RFC for Streebog (RFC6986)
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[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:

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

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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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Everything is wrong except for the green part.

The Russian S-box is too simple

```
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;}
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- 165 ASCII characters that fit on 7 bits: this program is 1155-bit long
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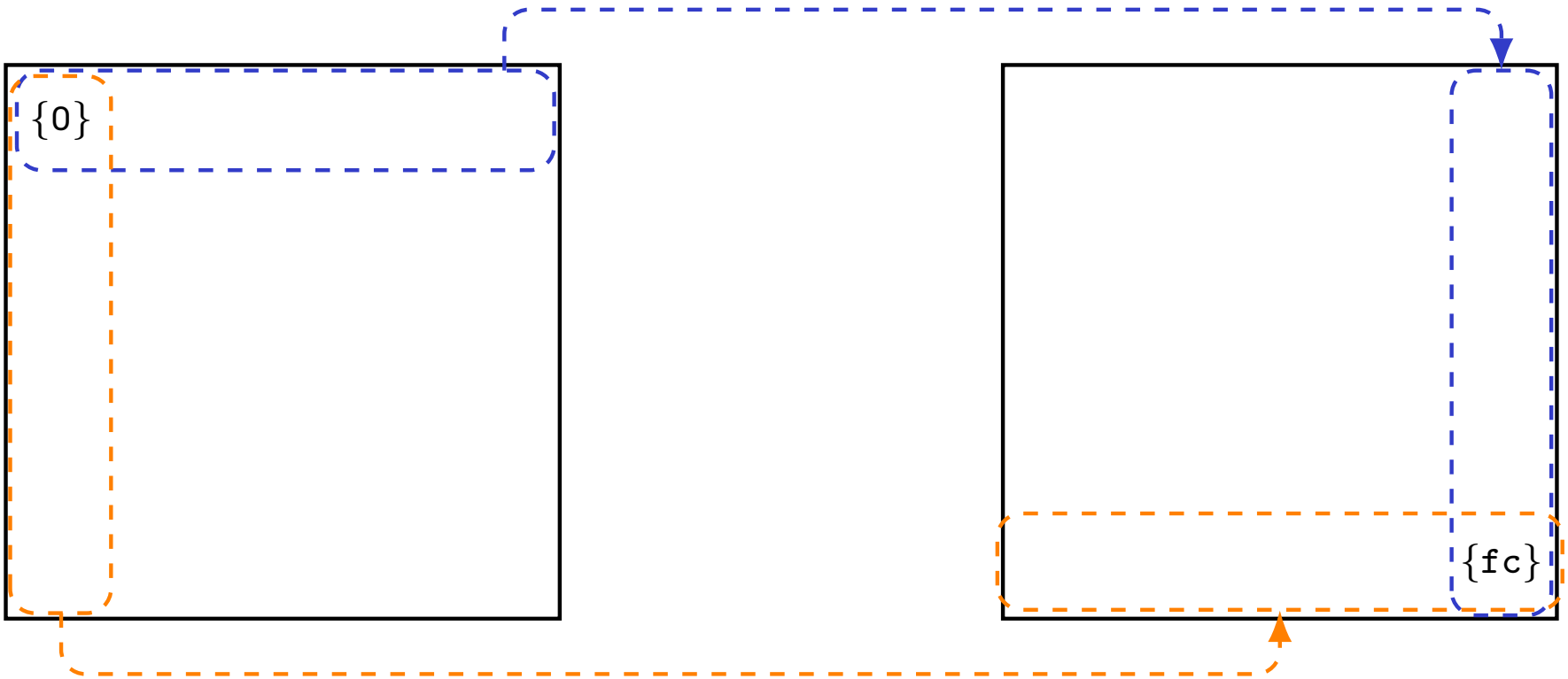
`https://codegolf.stackexchange.com/questions/186498/proving-that-a-russian-cryptographic-standard-is-too-structured`

Cosets to Cosets

$\mathbb{F}_{2^8}$

$\pi(\mathbb{F}_{2^8}) = \mathbb{F}_{2^8}$



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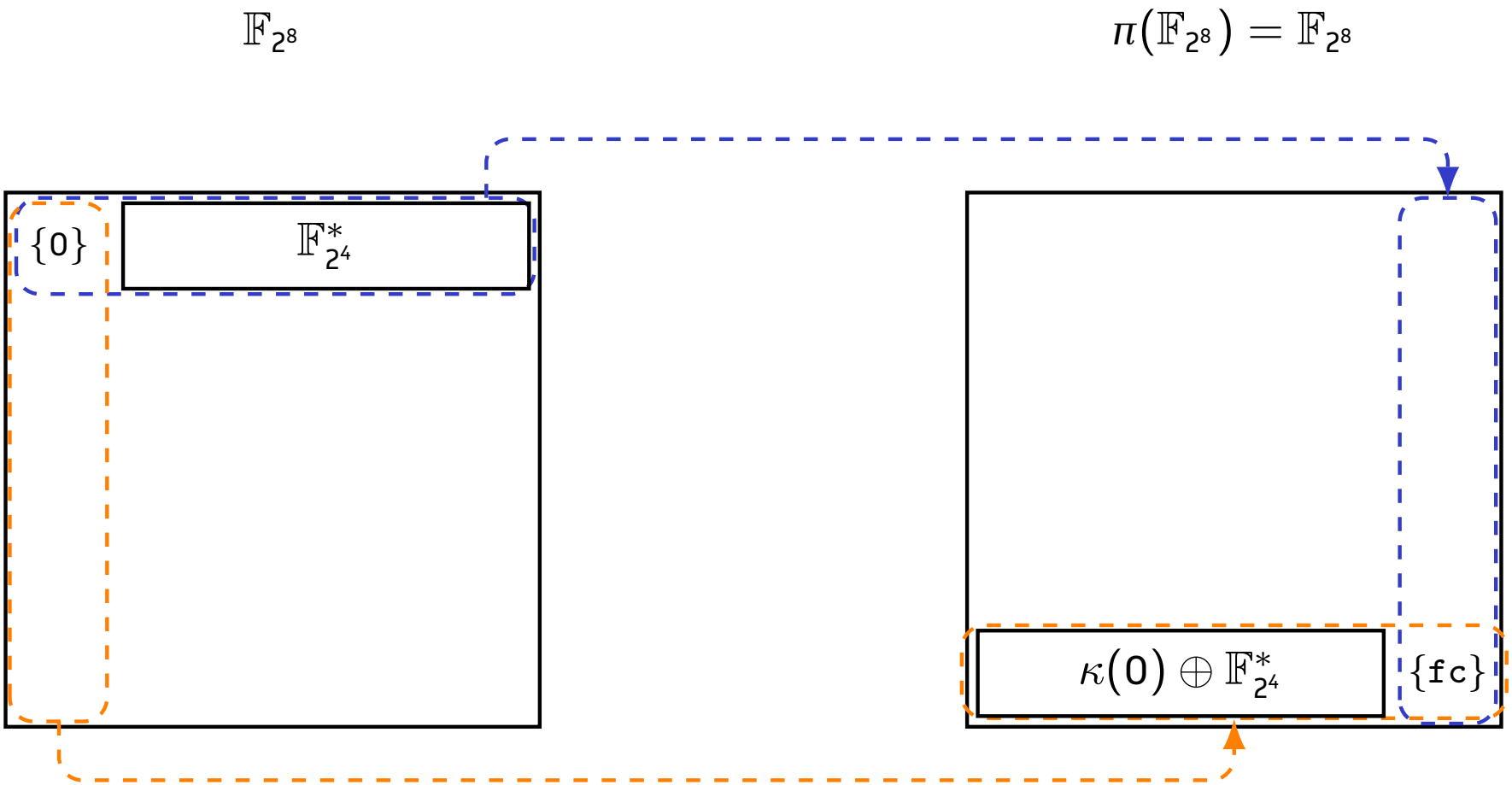

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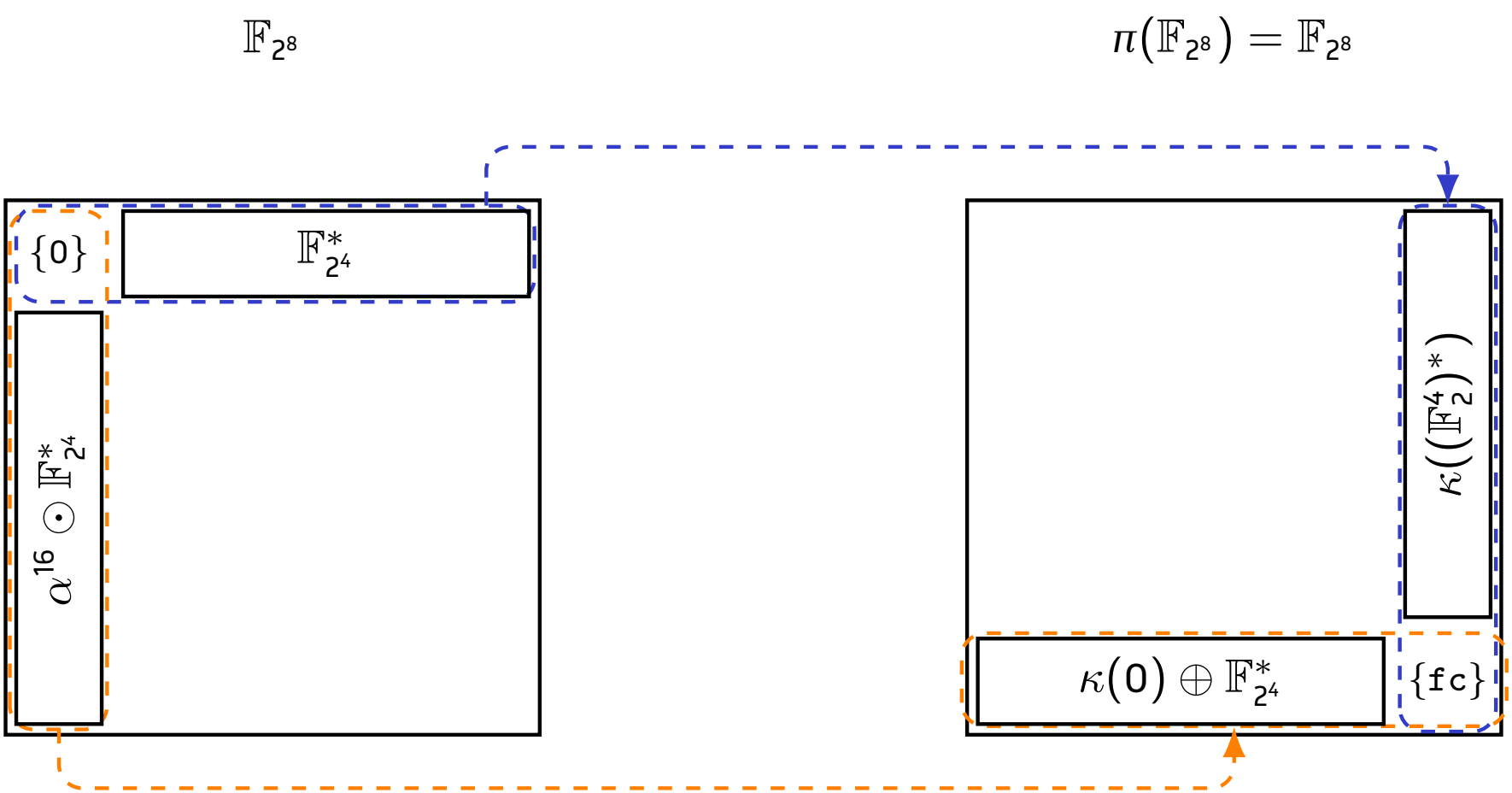

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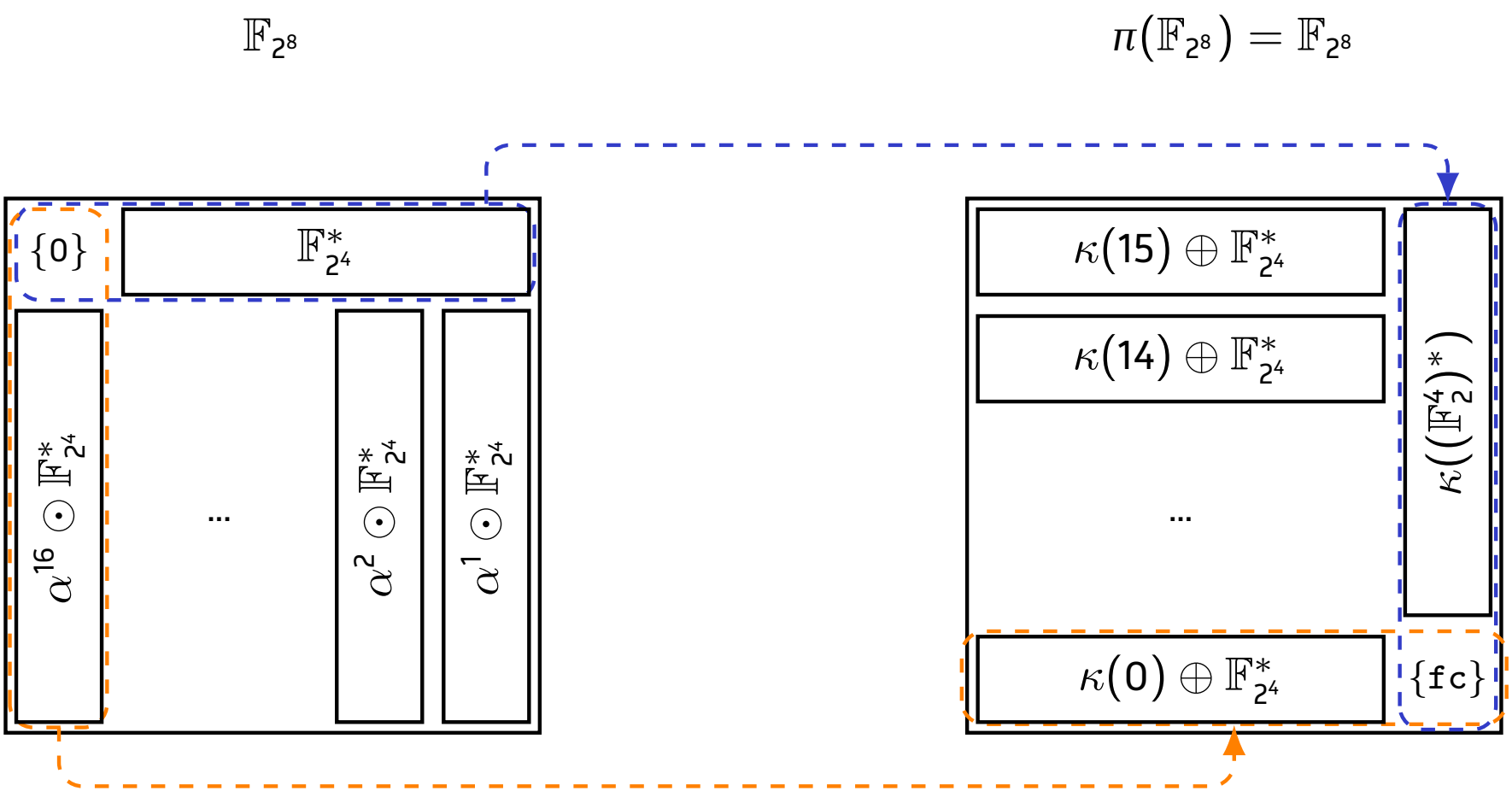

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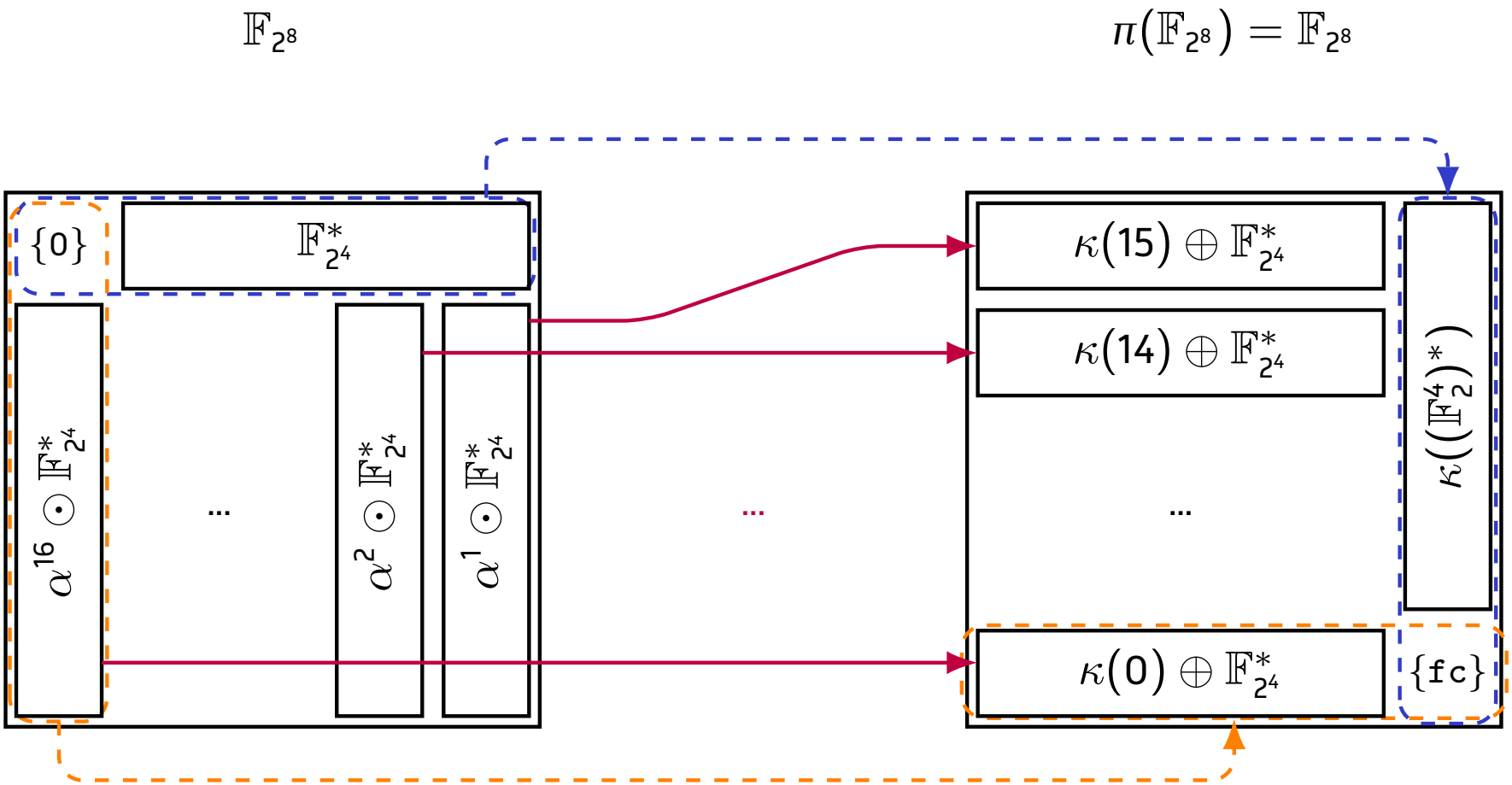
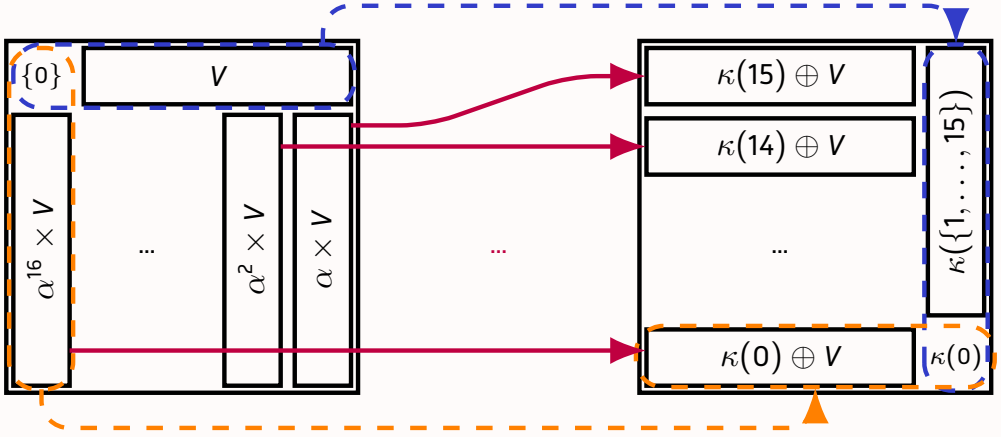
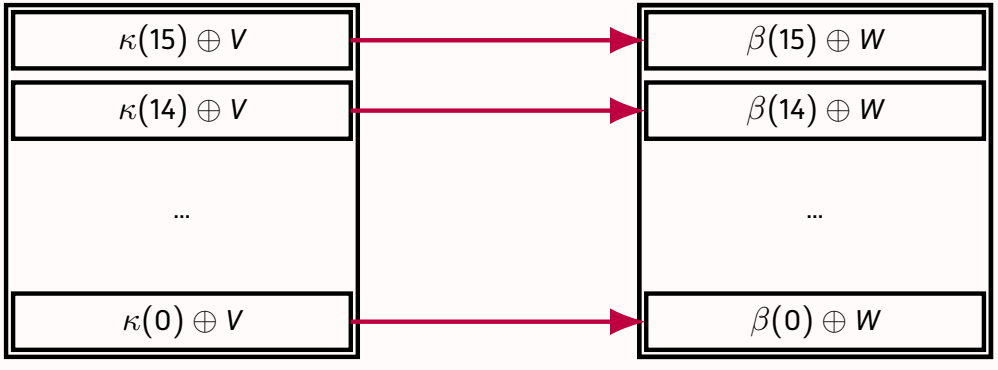


Why it is Worrying

Russia's π



Backdoored S-box



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Sep. 2019	Kuznyechik at ISO: **thanks, but no thanks**

The Russian delegation failed to convince the experts that they were honest: the standardizatoin of Kuznyechik was **refused**

Outline

Plan of this Section

Conclusion

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Conclusion

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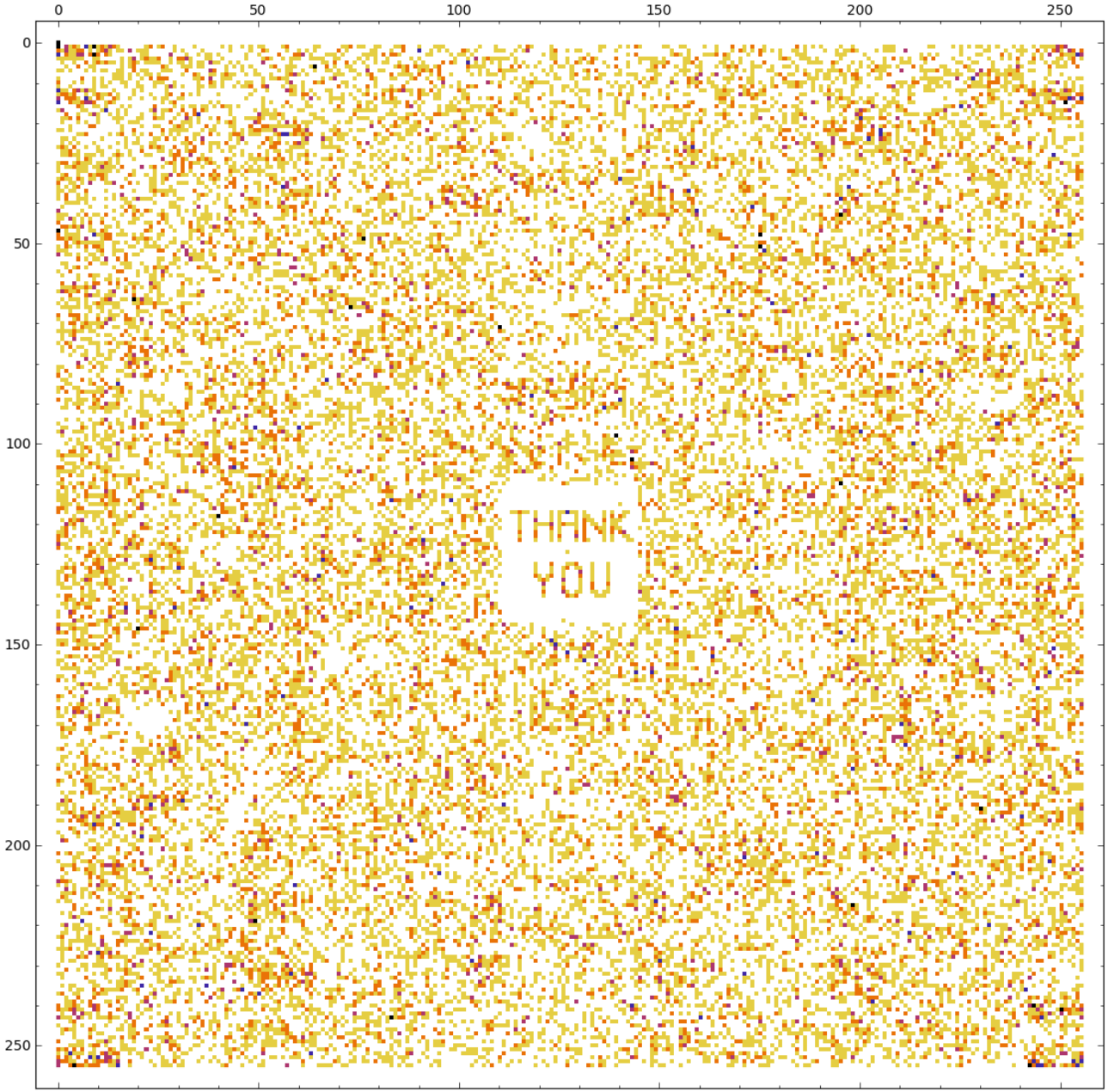
2. If you design a cipher, justify every step of your design.
3. If you choose a cipher, demand a full design explanation.
4. When in doubt, don't trust! (at least as far as crypto is concerned)

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
50
100
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THANK
YOU