Cryptanalysis of symmetric cipher using generic solvers

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CAPSULE IRISA

Cryptography

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- Confidentiality
- Integrity
- Authentication
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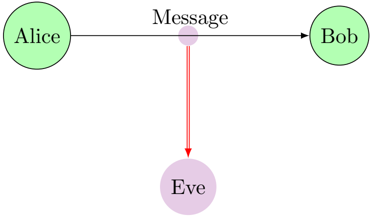

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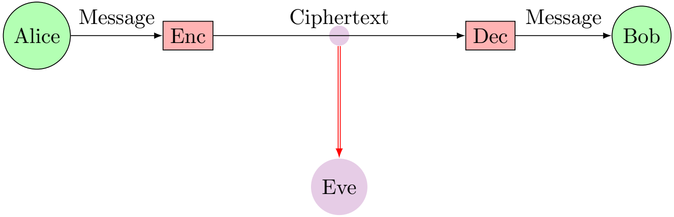

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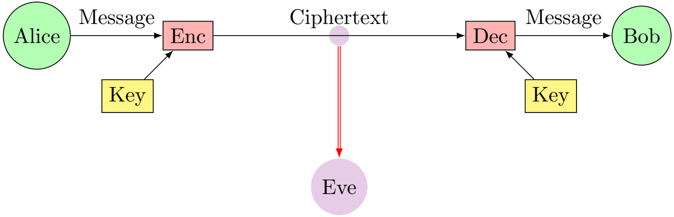


Symmetric ciphers

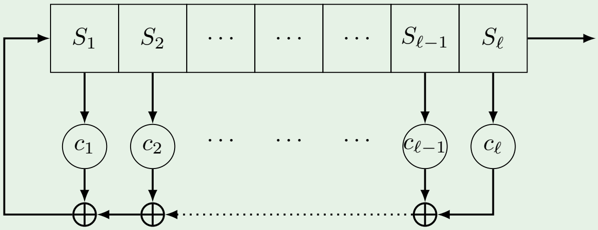
An invertible function E:

$$E : key \times message \to ciphertext$$

An iterated round function f:

$$E = f(f(\dots f(f(key, message))\dots))$$

Stream cipher example: Linear Feedback Shift Register (LFSR)



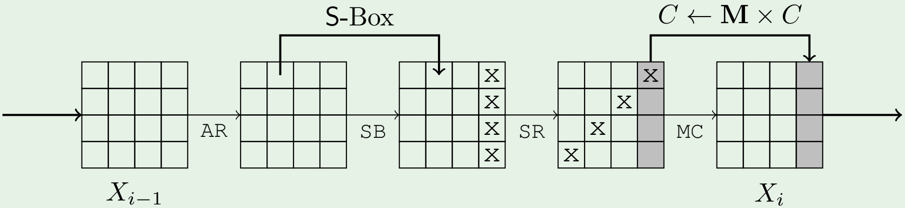
Some stream ciphers: A5/1 (GSM 1987), RC4 (Wifi 1987), E0 (Bluetooth 1999), **Trivium** (2004),...

Symmetric ciphers

Properties of a resistant cipher:

- Diffusion (permutation, XOR,. . .)
- Confusion (Substitution Box)

Block cipher example: Advanced Encryption Standard (AES)



Some block ciphers families: **Feistel networks**, Substitution permutation networks, ARX,. . .

Distinguishers

Distinguish a cipher from a random message

- Various types of distinguishers
- An analysis of each distinguisher on each cipher

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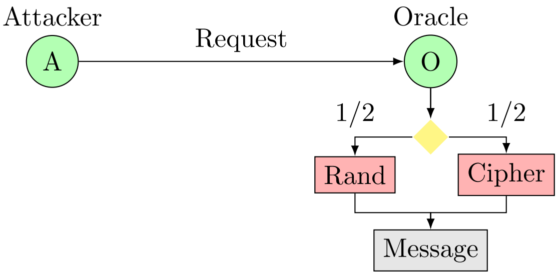

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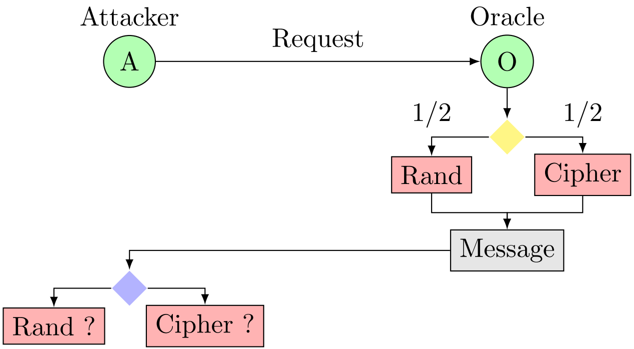
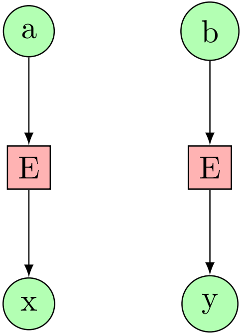


Differentials [BS93, BS90]

Differential characteristics

- Difference: $a \oplus b = \delta$
- Probability: $P(E(x) = E(x \oplus \delta_{in}) \oplus \delta_{out})$



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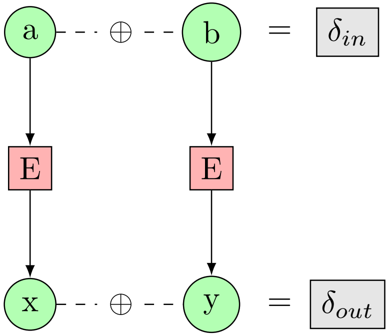

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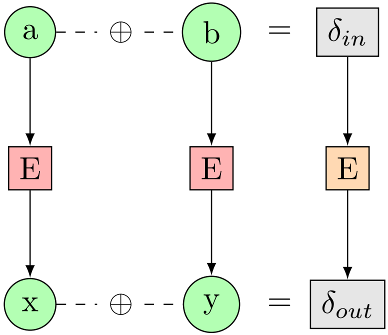

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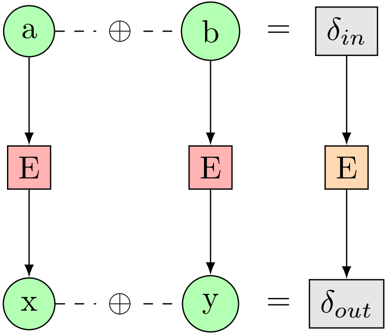
$$\Delta x_i = \begin{cases} 0 & \text{if} \quad \delta x_i = 0 \\ 1 & \text{if} \quad \delta x_i \in [\![1, 2^n - 1]\!] \end{cases}$$



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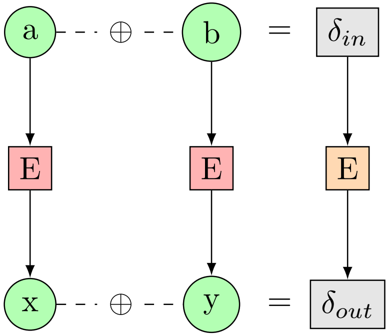
Two steps method [BN10, FJP13, GLMS20]

Solving methods

Branch and bound, dynamic programming, generic solvers, ...



Generic solvers

1. Model the problem

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Linear Programming MILP

- **Constraints**: Linear
- **Variables**: Integer or/and real
- **Optimize** a linear objective

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Solving CP model

- Branch and bound
- Filtering algorithms

↪ Choco

Subject of the thesis

Cryptography problems

- **Design** with good properties
- **Analysis** with all distinguishers

Goal: Find new CP models for the design and analysis of symmetric ciphers

Contributions

Superpoly recovery on Trivium

- **Problem**: Cube attack, algebraic attack
- **Target**: Trivium
- **Method**: Graph representation, MILP model

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Explanation generation for CP solvers

- **Problem**: Deduce new constraint explanations
- **Target**: Improve CDCL-CP solvers
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Superpoly recovery on Trivium

- **Problem**: Cube attack, algebraic attack
- **Target**: Trivium
- **Method**: Graph representation, MILP model

Optimal permutation for diffusion in GFN

- **Problem**: Optimal full diffusion
- **Target**: Generalized Feistel Networks
- **Method**: Graph representation, ad hoc algorithm

Explanation generation for CP solvers

- **Problem**: Deduce new constraint explanations
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Automated tool for differentials

- **Problem**: Differential characteristics
- **Target**: All word-oriented cipher
- **Method**: Graph representation, CP model

Table of Contents

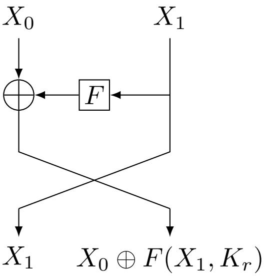
Feistel

Feistel Networks

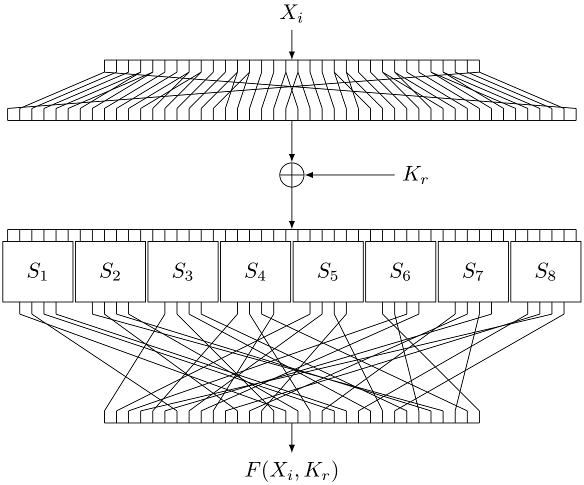
- Horst Feistel [Smi71, Fei73]
- Data Encryption Standard (DES) 1977-1999 (-2017)

Properties

- Two blocks X_0, X_1
- If F is a "pseudorandom" function, the cipher is perfect after 4 rounds



Examples of F functions



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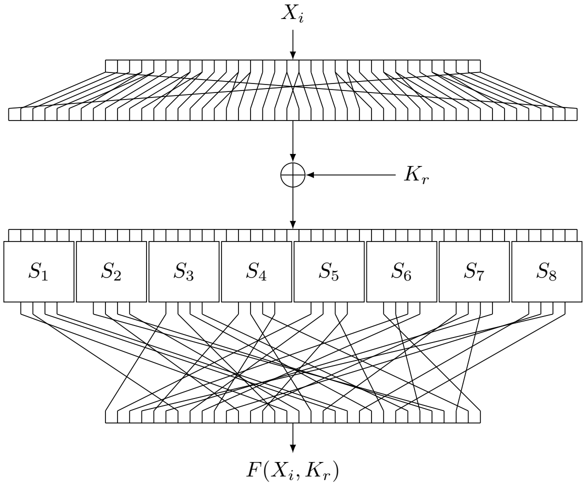

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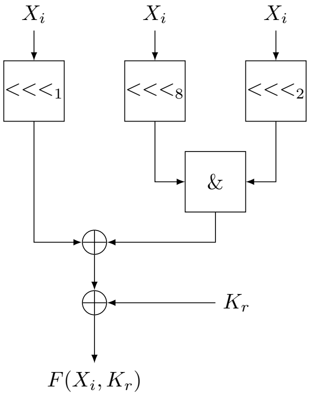
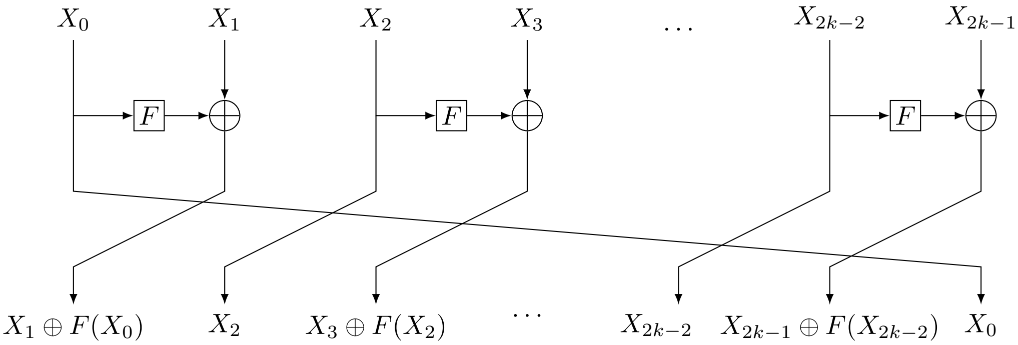


SIMON

Generalizations of Feistel Networks [ZMI89]



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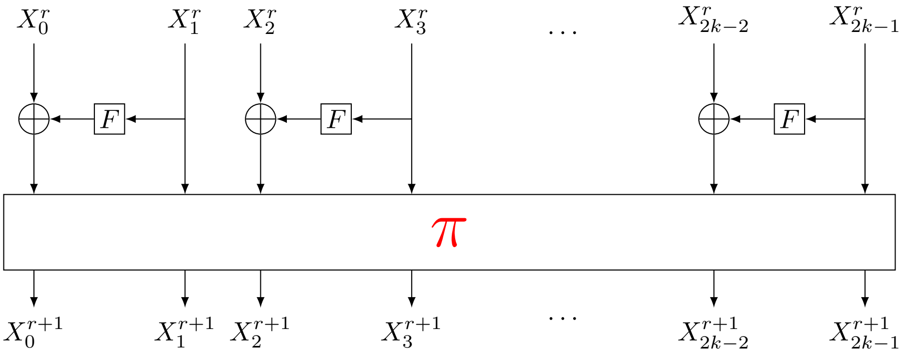
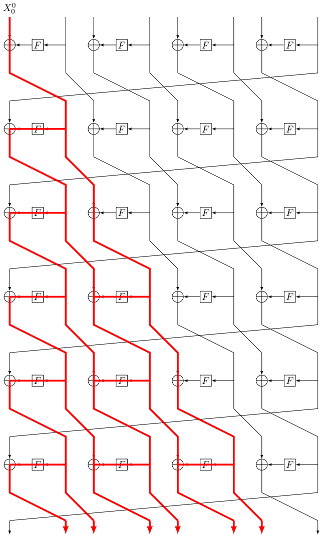


Diffusion in GFN



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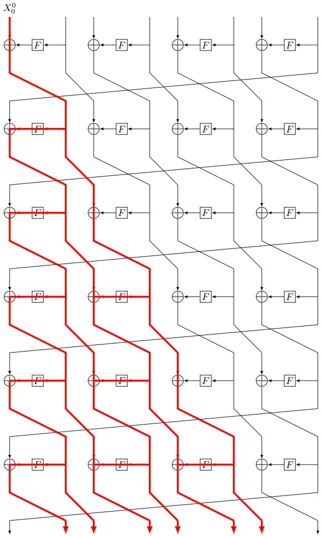

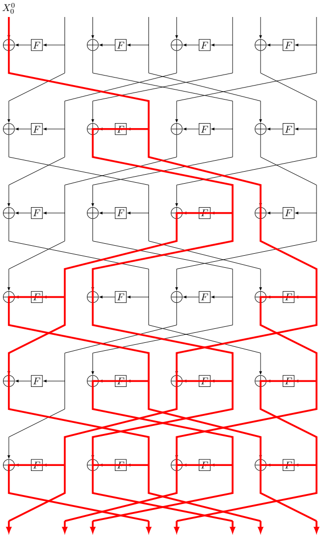

Best permutations

Definition (Diffusion Round)

$DR_i(\pi)$ is the minimum number of rounds r such that X_i^0 are diffused to all X_i^r.

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Previous methods

- [SM10] Enumerate all π and test diffusion
- [CGT19] Use equivalence classes
- [DFLM19] Focus on even-odd π

GOAL: Find the best π in the general case

$2k$	even-odd			non-even-odd	
	LB	DR	Ref	DR	Ref
6	5	5	[SM10]	6	[SM10]
8	6	6		6	
10	6	7		7	
12	7	8		8	
14	7	8		8	
16	7	8		8	
18	8	8	[CGT19]	9	[CGT19]
20	8	9		9	
22	8	8		?	
24	8	9			
26	8	9	[DFLM19]		
28	9	9			
30	9	9			
32	9	9			
34	9	10			
36	9	9			

CP model with Set variables

Integer variables P_i (with $i \in [\![0, 2k-1]\!]$) represents π:

$$\mathit{AllDifferent}(P)$$

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Set variables $S_{i,r}$ (with $i \in [\![0, 2k-1]\!], r \in [\![1, R]\!]$) represents the diffusion from block i after r rounds:

$$\begin{cases} S_{2i,1} = \{P_{2i}\} \\ S_{2i+1,1} = \{P_{2i}, P_{2i+1}\} \end{cases} \quad \forall i \in [\![0, k-1]\!]$$

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$$S_{i,r} = \bigcup_{j \in S_{i,r-1}} S_{j,1} \quad \forall i \in [\![0, 2k-1]\!]\ \forall r \in [\![2, R]\!]$$

Optimizations:

- Symmetry constraints

Early models conclusions

Other models:

- Adjacency matrices
- Graph variable
- Table constraints

Early models conclusions

Other models:

- Adjacency matrices
- Graph variable
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Conclusion:

- **2 New lines:** the set model can find the best π for up to 24 blocks.
- **Not efficient enough:** still a lot of symmetric solutions.

$2k$	even-odd			non-even-odd	
	bound	DR	Ref	DR	Ref
6	5	5	[SM10]	6	[SM10]
8	6	6		6	
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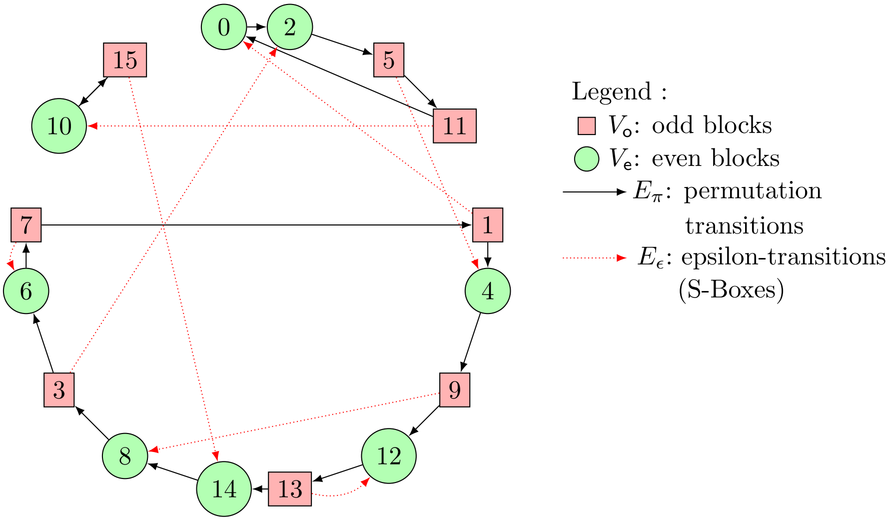
16	7	8		8	
18	8	8	[CGT19]	9	[CGT19]
20	8	9		9	
22	8	8		9	**New**
24	8	9		≥ 9	
26	8	9	[DFLM19]	**?**	
28	9	9			
30	9	9			
32	9	9			
34	9	10			
36	9	9			

Graph representation of GFN permutations

i	0	1	2	...
$\pi(i)$	2	4	5	...



Properties

Diffusion round $DR(\pi) = R$

All pairs of nodes have a path of R edges in E_π

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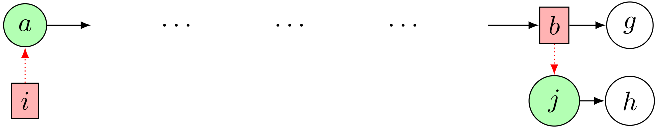

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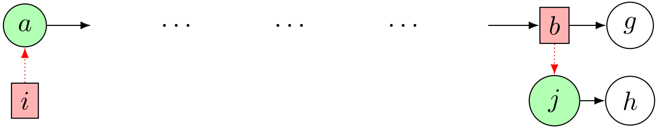


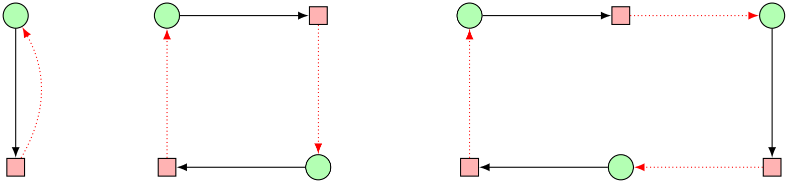
Diffusion round (even-odd) $DR(\pi) = R$

All pair of nodes in (V_o, V_e) have a path of $R - 3$ edges in E_π

Properties for symmetries

Definition (ϵ-cycle)

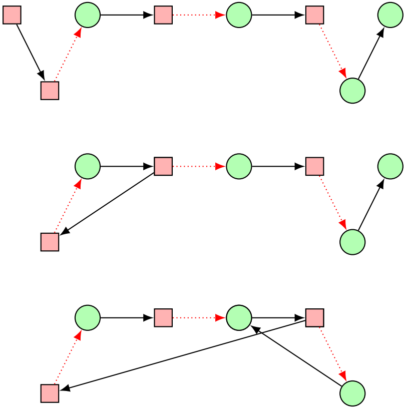
An ϵ-cycle is a path $c = (e_1, \ldots, e_{2l})$ in which the first and last nodes are equal, and edges alternate between E_π and E_ϵ one by one.



Properties for symmetries

Definition (ϵ-chain)

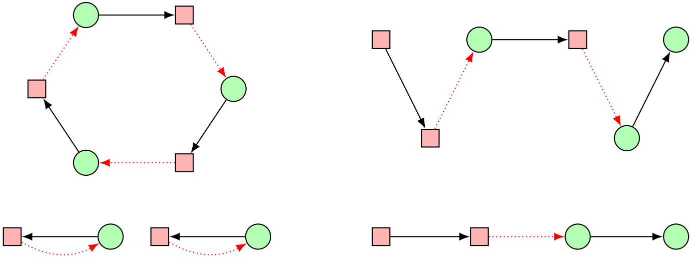
An ϵ-chain is a path $c = (e_1, \ldots, e_{2l+1})$ in which the two first nodes are in V_o, and the two last nodes are in V_e. The edges alternate between E_π and E_ϵ one by one.



Skeleton

Definition (Skeleton)

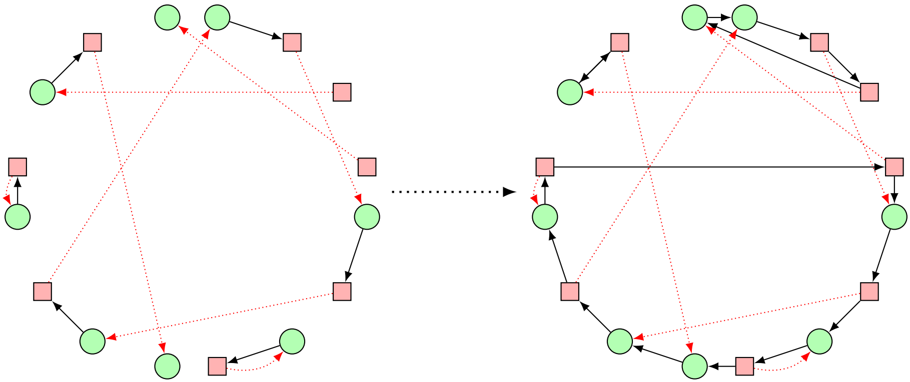
A *skeleton* of size k is a set of ϵ-cycles and ϵ-chains whose sum of sizes is k.



Number of skeletons: $\sum_{i=0}^{k} \mathcal{N}_i \times \mathcal{N}_{k-i}$

- 16 blocks: 163 skeletons (22 even-odd)
- 32 blocks: 5591 skeletons (231 even-odd)

Complete the skeleton



Build the paths: an example with $DR(\pi) = 5$

Paths of length 4:

$0 \rightarrow 3$?

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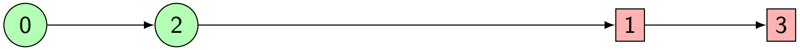

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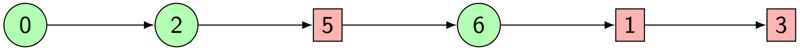

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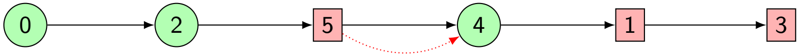

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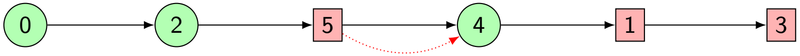

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$2 \to 3$ ✓

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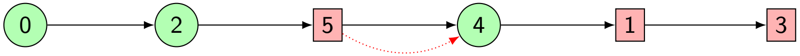

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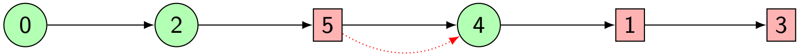

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$2 \to 3$ ✓

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No π with $DR = 5$

Contribution

Implementation:

- Parallel path builder algorithm on each skeleton
- Strategy: start the paths by the smallest ϵ-chains

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Results:

- Non-even-odd permutations are not strictly better for up to 32 blocks and 36 blocks.

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14	7	8		8	
16	7	8		8	
18	8	8	[CGT19]	9	[CGT19]
20	8	9		9	
22	8	8		9	**New**
24	8	9		≥ 9	
26	8	9	[DFLM19]	≥ 9	
28	9	9		≥ 9	
30	9	9		≥ 9	
32	9	9		≥ 9	
34	9	10		≥ 9	
36	9	9		≥ 9	

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Automatic differential cryptanalysis

Problem

- Each cipher must be resistant to differentials

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Automated tools for differentials ?

- YAARX [Leu12] dedicated algorithms (ARX)
- CryptoSMT [Köl] SMT models
- TAGADA [LDLS21] DAG to MiniZinc models
- CASCADA [RR22] SMT models
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A tool for truncated differentials: Tagada

- **Input:** cipher DAG and optional bound
- **Output:** truncated solutions

Generate a MiniZinc model and solve it (Solver: PicatSAT)

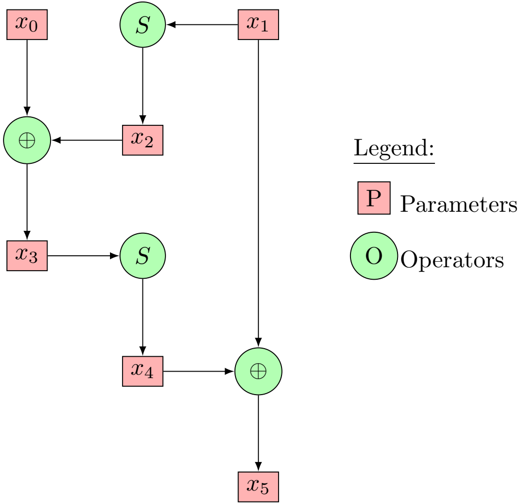
Unified description of ciphers

Directed Acyclic Graph (DAG)

- **Parameters:** variables or constants
- **Operators:** cipher operators

Example (S operator)

- Domain: $[\![0, 256]\!]$
- Co-Domain: $[\![0, 256]\!]$
- Function:
  - type: S-Box
  - lookup table $[170, 22, 3, \ldots]$



Second step with CP (Choco)

Contribution

- **Input:** cipher DAG, truncated solutions and optional bound
- **Output:** differentials of best probability

Generate a CP model and solve it (Solver: Choco)

↪ **How to model all the operators ?** (S-Boxes, XORs, LFSRs, Galois Fields operations,. . .)

S-Box and Differential Distribution Table (DDT)

DDT	0	1	2	3	4	...
0	**64**	0	0	0	0	
1	0	0	0	6	0	
2	0	0	0	8	0	...
3	14	4	2	2	10	
4	0	0	0	6	0	
⋮			⋮			⋱

Computing DDT

$$DDT(\delta_{in}, \delta_{out}) = \#\{X | S(X) \oplus S(X \oplus \delta_{in}) = \delta_{out}\}$$

Modeling DDT with table constraint

- List of tuples: $tuple(\delta_{in}, \delta_{out}, Prob)$
- **Filtering:** efficient data structure to retain always one valid tuple

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⋮			⋮			⋱

$$tuple(0, 0, 1)$$
$$tuple(3, 0, \frac{14}{64})$$
$$tuple(3, 1, \frac{4}{64})$$
$$\dots$$

XOR filtering algorithm

Previous works

- Table constraint
- Dedicated algorithm

Filtering quality

- The set is unlikely to filter values.

↪ Filtering condition: $\#D_a \times \#D_b \leq \#D_c$

Algorithm 1: 3-variable XOR filtering

Input: IntVar a, IntVar b, IntVar c (target)

```
set ← ∅;
// Loop through possible values
for all v1 ∈ D_a do
    for all v2 ∈ D_b do
        set ← set ∪ {v1 ⊕ v2};
D_c ← D_c ∩ set;
```

Other filtering algorithms

Non-linear Operators		
Operator	Name	Constraint
DDT	Differential Distribution Table	Table

Linear Operators		
$\oplus$	N-ary Bitwise XOR	Custom
$\otimes_K$	Galois Field Multiplication with Constant	
LFSR	Linear Feedback Shift Register	
$\ll$ or $\gg$	Left (Right) Shift	
$\lll$ or $\ggg$	Left (Right) Circular Shift	
$\odot_K$	Galois Field Matrix Multiplication with Constant Matrix	Decomposition to $\otimes_K$ and $\oplus$
$=$	Equal	Native
$\&_K$	Bitwise AND with Constant	Table
$\Vert_K$	Bitwise OR with Constant	
$AB \to (A, B)$	Split	
$(A, B) \to AB$	Concat	
T	Linear Lookup Table	

Optimisations

Optimizations

- **Simplification:** Remove inactive S-Boxes
- **Heuristic:** Start search near S-Boxes
- **Solving:** Parallel competitive models
- **Solving:** Two steps together

Algorithm 2: TWOSTEP

$List1 \leftarrow$ STEP1-ENUM(LB) ;
$List2 \leftarrow$ STEP2-PARALLEL$(List1)$;

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Algorithm 5: TwoStep

$S1, UB \leftarrow$ Step1-opt() ;
while $LB < UB$ **do**
  $S2, LB \leftarrow$ Step2($S1, LB$) ;
  if $LB < UB$ **then**
    $S1 \leftarrow$ Step1-next(UB) ;
    if $S1$ *is* `null` **then**
      $S1, UB \leftarrow$ Step1-opt(UB)

Contribution

Tagada two steps results:

- Reproduce all these results within a day

Cipher	Max R	Proba	Ref
Midori-64	16	2^{-16}	[Gér18]
Midori-128	20	2^{-40}	
Warp	41	2^{-40}	[TB22]
Twine-80	18	2^{-64}	[SMS+20]
Twine-128	16	2^{-52}	
Skinny-64-TK1	11	2^{-64}	[DDH+21]
Skinny-128-TK1	11	2^{-74}	
AES-128	5	2^{-105}	[GLMS20]
AES-192	9	2^{-146}	
AES-256	14	2^{-146}	
Rijndael-128-160	7	2^{-120}	[RGMS22]
Rijndael-128-224	12	2^{-212}	
Rijndael-160-128	4	2^{-112}	
Rijndael-160-160	6	2^{-138}	

Cipher	Max R	Proba	Ref
Rijndael-160-192	8	2^{-141}	[RGMS22]
Rijndael-160-224	9	2^{-190}	
Rijndael-160-256	11	2^{-204}	
Rijndael-192-128	3	2^{-54}	
Rijndael-192-160	5	2^{-118}	
Rijndael-192-192	7	2^{-153}	
Rijndael-192-224	8	2^{-205}	
Rijndael-192-256	9	2^{-179}	
Rijndael-224-128	3	2^{-54}	
Rijndael-224-160	4	2^{-122}	
Rijndael-224-192	5	2^{-124}	
Rijndael-224-224	7	2^{-196}	
Rijndael-224-256	8	2^{-182}	
Rijndael-256-128	3	2^{-54}	
Rijndael-256-160	4	2^{-130}	
Rijndael-256-192	5	2^{-148}	
Rijndael-256-224	4	2^{-115}	
Rijndael-256-256	6	2^{-128}	

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  - ↪ Solution proof

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"Unlike Theseus's boat, half of this thesis is still CP in the end"

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