Combinatorial Optimization Problems in Block Cipher Cryptanalysis

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A Joint work with
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HCP @ Changchun

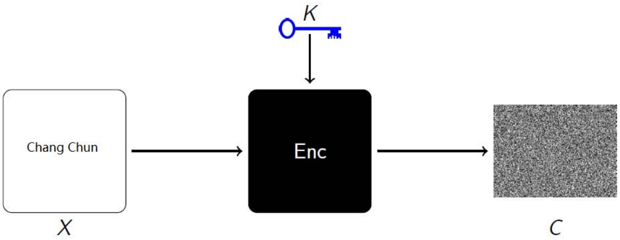
Outline

- Block ciphers
- Cryptanalysis of Block Ciphers
- The essential problems
- Solve the problems with MIP, SAT, SMT, and CP
- Future work
- Resources

Block ciphers

- Ubiquitous systems $\Longrightarrow$ new crypto primitives are needed

Block ciphers

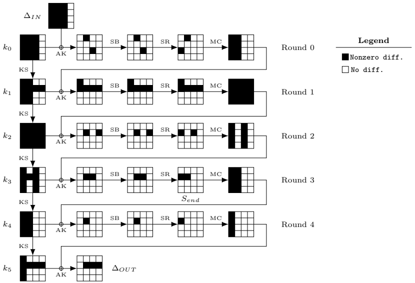


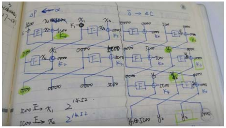
- A function $E : \{0,1\}^n \times \{0,1\}^k \rightarrow \{0,1\}^n$
- Block cipher is the crypto work horse
- DES, AES, SM4 $\cdots$
- Animation of AES

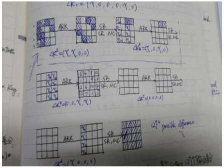
Designing a secure block cipher is difficult

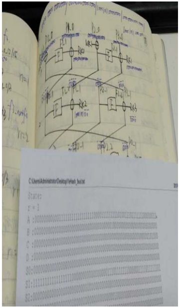
- **Many attacks to consider** : differential attack, impossible differential attack, linear attack, zero-correlation linear attack, relate-key attack, integral attack, invariant subspace attack $\cdots$
- **The resource for crypto is constrained** : RFIDs, battery powered devices, low-end processors, $\cdots$
- **The performance requirement is high** : low latency, high throughput

Cryptanalysis





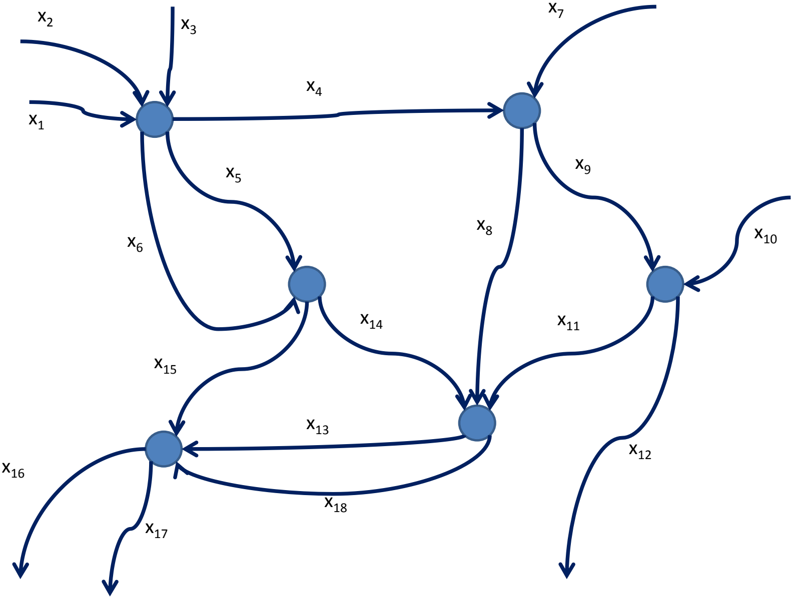




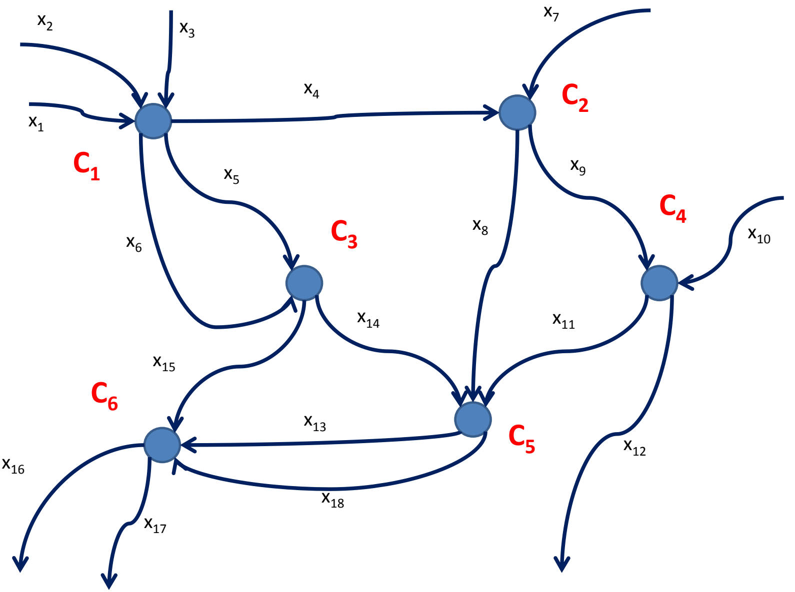
- Tedious, error-prone
- The procedure need to be performed again and again to find the best parameters in the design

Automatic tools are needed !

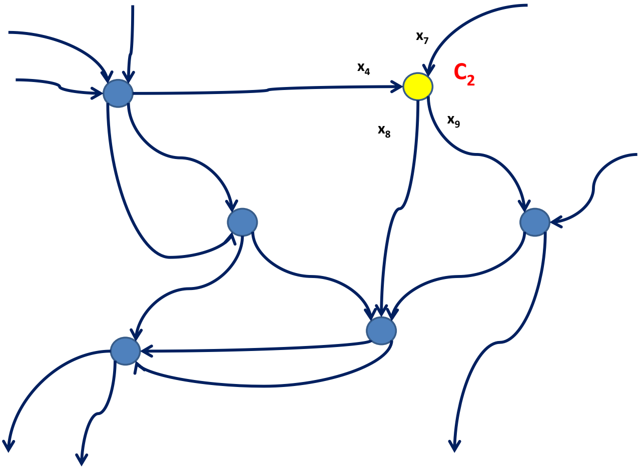
The essential problems



The essential problems

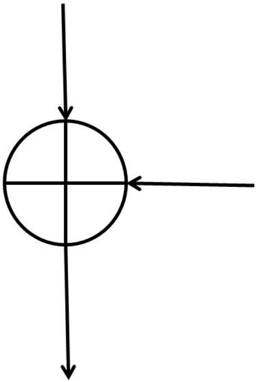


The essential problems

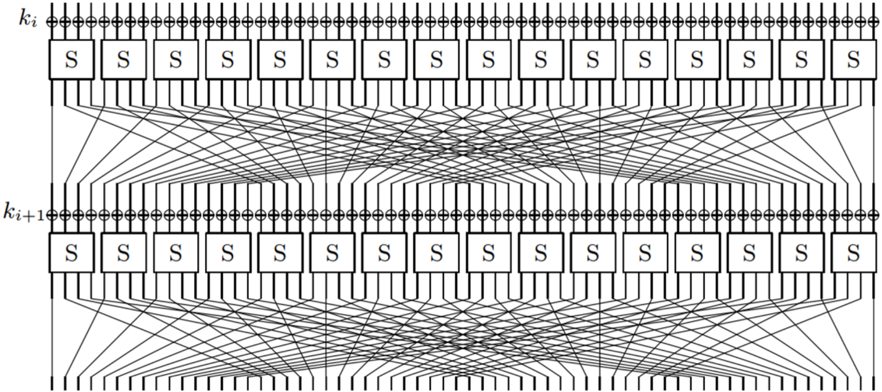


- $(x_4, x_7, x_8, x_9, C_2) \in \{(0,1,0,1,2), (1,1,0,1,0), (1,1,1,1,3)\}$
- Min $\sum C_i$

The essential problems

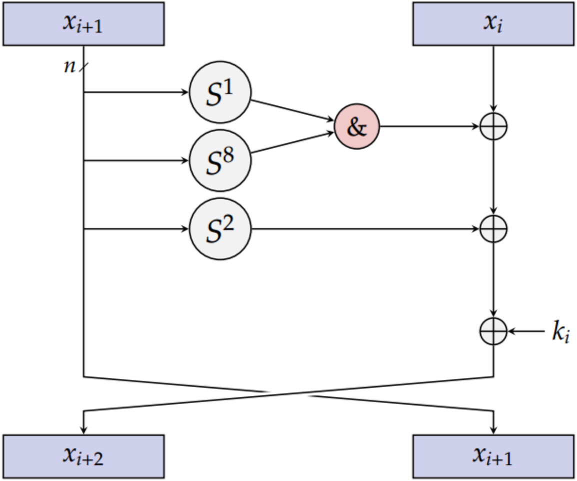


- Differential attack : $(x_1, x_2, x_3, C) \in \{(0,0,0,0),(0,1,1,0),(1,0,1,0),(1,1,0,0)\}$
- Linear attack : $(x_1, x_2, x_3, C) \in \{(0,0,0,0),(1,1,1,0)\}$



x	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
$S[x]$	C	5	6	B	9	0	A	D	3	E	F	8	4	7	1	2

The Block Cipher SIMON : Designed by NSA



Automatic Cryptanalysis of Symmetric-key Algorithms

- Search algorithms implemented from scratch in general-purpose programming languages
- Mixed-integer programming (MILP) based methods
- SAT/SMT based methods
- Constraint programming (CP) based methods

Advantages of the MILP/SAT/SMT/CP approach

- Easy to implement
- Modelling process of CP is much more straightforward : input allowed tuples directly
- directly benefit from the advances in the resolution technique

MILP based methods

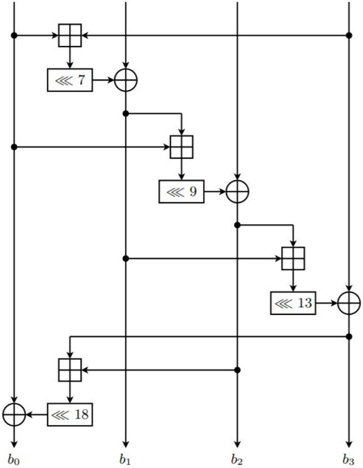
- Convert the constraints into linear inequalities
  - Some operations can be converted into linear inequalities easily :
    $a \oplus b = c \implies a + b + c - 2d = 0$
  - It is more difficult for tuple/table constraints :
    $(x_1, \cdots, x_8) \in \{(0,0,1,0,1,1,0,1), \cdots\} \subseteq \{0,1\}^8$, refer to ASIACRYPT 2014 paper

Limitations

- The method for converting tuple constraints into linear inequalities works only for vectors in $\{0,1\}^n$
- The method for converting tuple constraints into linear inequalities works only for low dim (≤ 8) vectors

Siwei Sun, Lei Hu, Peng Wang, Kexin Qiao, Xiaoshuang Ma, Ling Song (2014)
Automatic Security Evaluation and (Related-key) Differential Characteristic Search : Application to SIMON, PRESENT, LBlock, DES(L) and Other Bit-oriented Block Ciphers
Advances in Cryptology–ASIACRYPT 2014

SAT/SMT based methods



SAT/SMT based methods

Theorem

The input and output words α, β, and γ of the modular addition operation satisfy the following equation

$$\mathrm{eq}(\alpha \lll 1, \beta \lll 1, \gamma \lll 1) \wedge (\alpha \oplus \beta \oplus \gamma \oplus (\beta \lll 1)) = 0$$

where $\mathrm{eq}(x, y, z) := (\neg x \oplus y) \wedge (\neg x \oplus z)$.

- Similar constraints can be easily converted to SAT/SMT formulas.

Nicky Mouha and Bart Preneel (2013)
Towards Finding Optimal Differential Characteristics for ARX : Application to Salsa20
Cryptology ePrint Archive : Report 2013/328

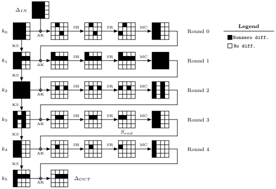
Stefan Kölbl, Gregor Leander, Tyge Tiessen (2015)
Observations on the SIMON block cipher family
Advances in Cryptology–CRYPTO 2014

CP based methods

David Gerault and Marine Minier and Christine Solnon (2016)
Constraint Programming Models for Chosen Key Differential Cryptanalysis
Principles and Practice of Constraint Programming – CP 2016

Siwei Sun, David Gerault, Pascal Lafourcade, Qianqian Yang, Yosuke Todo, Kexin Qiao, Lei Hu (2017)
Analysis of AES, SKINNY, and Others with Constraint Programming
Fast Software Encryption – FSE 2017

Search for related-key differential characteristics of AES-128

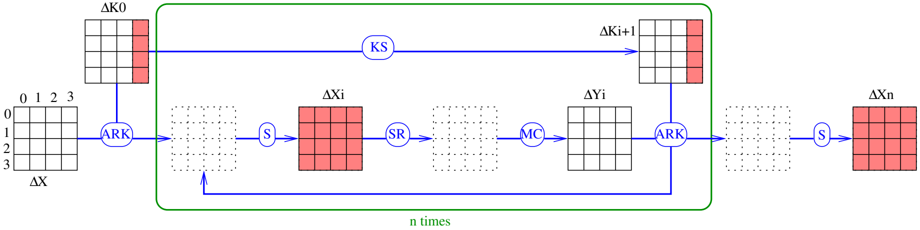


Related work

- [Alex Biryukov and Ivica Nikolić, EUROCRYPT 2010]
- [Pierre-Alain Fouque, Jérémy Jean and Thomas Peyrin, CRYPTO 2013]
- [David Gerault, Marine Minier and Christine Solnon, CP 2016]

- Step 1 : Find truncated differential characteristics with the minimum number of active S-boxes
- Step 2 : Instantiate the truncated differential characteristics with actual differences

CP Model for Step 1 : Variables and Constraints



- 0-1 variables
  - $\Delta X[j][k]$
  - $\Delta X_i[j][k]$
  - $\Delta Y_i[j][k]$
  - $\Delta K_i[j][k]$
- Constraints
  - ARK
  - SR-MC
  - KS
  - XOR

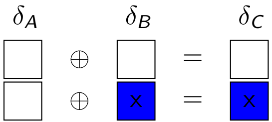
Semantics of the variables

These variables are used to trace the propagation of the truncated differences.

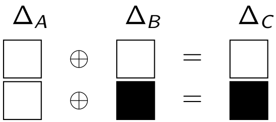
XOR Constraint

(white $= 0$, colored $\neq 0$)

Byte values



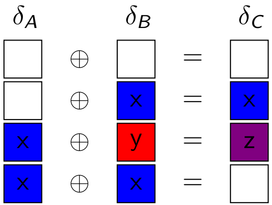
Boolean abstraction



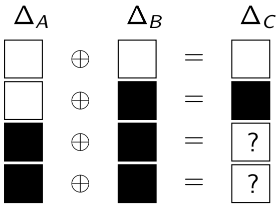
XOR Constraint

(white $= 0$, colored $\neq 0$)

Byte values



Boolean abstraction

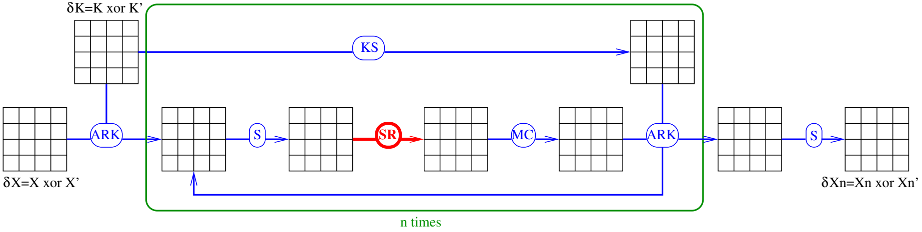


Δ_A	Δ_B	Δ_C
0	0	0
0	1	1
1	0	1
1	1	?

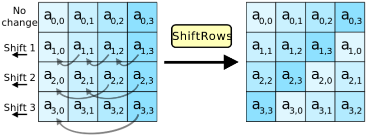
Definition of the XOR constraint

$\Delta_A + \Delta_B + \Delta_C \neq 1$

SR-MC Constraint



At byte level

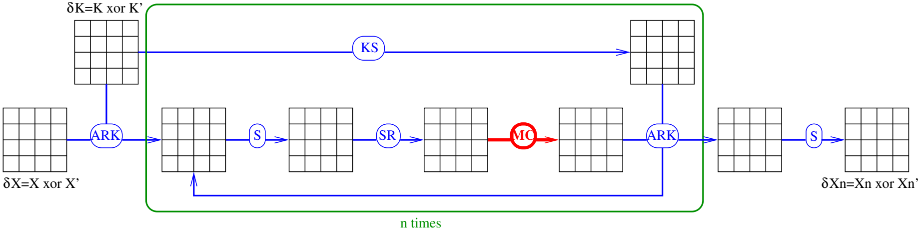


Definition of the SR-MC constraint

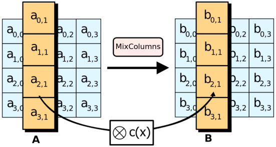
$\forall j \in [0;3]$:

$$\sum_{k=0}^{3} \Delta X_i[(k+j)\%4][k] + \Delta Y_i[j][k] \in \{0,5,6,7,8\}$$

SR-MC Constraint



At byte level



MDS property :
$|A| + |MC(A)| \in \{0, 5, 6, 7, 8\}$
(for diffusion of active cells)

Definition of the SR-MC constraint

$\forall j \in [0; 3]$:
$\sum_{k=0}^{3} \Delta X_i[(k+j)\%4][k] + \Delta Y_i[j][k] \in \{0, 5, 6, 7, 8\}$

CP Model for Step 1

- Impose constraints for all operations having an effect on the the truncated differences
- Impose additional constraints (at least one active byte)
- Set the objective function to minimize the number of active S-boxes

Problem

Too many inconsistent solutions !

CP Model for Step 1

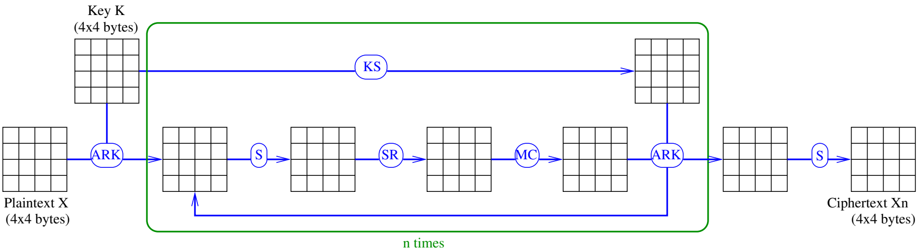
Reduce the number of inconsistency solutions

- Take the equality relationship into consideration : when $A == B$, $A \oplus B == 0$
- Consider the MDS property of two different columns

The Minizinc Code

`http://www.gerault.net/resources/CP_AES.tar.gz`

CP Model for Step 2



- Introduce a variable for every byte, whose domain is $\{0, 255\}$
- Impose the constraints of the differential distribution table, XOR etc. as table constraints
- Impose constraints according to the truncated differential characteristic

The Choco Code

http://www.gerault.net/resources/Step2_AES.tar.gz

Results for AES-128

- We find 19 truncated related-key differential characteristics with 20 active S-boxes in 7 hours, but none of them can be instantiated with an actual differential characteristic.
- We then find 1542 ones with 21 active S-boxes in around 12 hours. Among these, only 20 of them can be instantiated with actual differential characteristics.
- The probability of the optimal characteristic is 2^{-131}.

Round	$\delta X_i = X_i \oplus X_i'$	$\delta K_i = K_i \oplus K_i'$	Pr(States)	Pr(Key)
init.	366d1b80 dc37dbdb 9bc08d5b 00000000			
$i = 0$	00000000 71000000 00004d00 00000000	366d1b80 ad37dbdb 9bc0c05b 00000000	$2^{-6.2}$	–
1	b6f60000 009a0000 009a0000 009a0000	366d1b80 9b5ac05b 009a0000 009a0000	$2^{-7.2} \cdot 2^{-6.3}$	2^{-6}
2	00000000 009a0000 00000000 009a0000	ed6d1b80 7637dbdb 76addbdb 7637dbdb	$2^{-6.2}$	$2^{-6} \cdot 2^{-7.3}$
3	00000000 009a0000 009a0000 00000000	76addbdb 009a0000 7637dbdb 00000000	$2^{-6.2}$	–
4	00000000 009a0000 00000000 00000000	76addbdb 7637dbdb 00000000 00000000	2^{-6}	–
5	00000000 009a0000 009a0000 009a0000	76addbdb 009a0000 009a0000 009a0000	$2^{-6.3}$	2^{-6}
End/6	db000000 db9a0000 db000000 ad37dbdb	adaddbdb ad37dbdb adaddbdb ad37dbdb	–	–

TABLE: The optimal characteristic

TABLE: A comparison between the results obtained by CP and the graph-based search algorithm [Pierre-Alain Fouque, Jérémy Jean and Thomas Peyrin, CRYPTO 2013].

Rounds	Constraint Programming		Graph Search	
	#AS	Prob.	#AS	Prob.
3	5	2^{-31}	5	2^{-31}
4	12	2^{-79}	13	2^{-81}
5	17	2^{-105}	17	2^{-105}
6	21	2^{-131}	-	-

Search for Impossible differential and Zero-correlation Linear Approximation

Related work

- [Yu Sasaki and Yosuke Todo, EUROCRYPT 2017]
- [Cui, Jia, Fu, Chen and Wang, IACR ePrint 2016/689]

- Choose an input-output difference pattern (α, β).
- Construct a CP model $\mathcal{M}_{(\alpha,\beta)}$ whose solution set includes all valid differential characteristics.
- Solve $\mathcal{M}_{(\alpha,\beta)}$. If $\mathcal{M}_{(\alpha,\beta)}$ is infeasible, (α, β) is an impossible differential.
- Choose another (α, β) and repeat.

Search for Integral Distinguishers based on Bit-based Dvision Property

- Division property was proposed by Todo [Todo, EUROCRYPT 2015] which was extended to Bit-based division property [Todo and Morii, FSE 2016].

Bit-based division property

Let $\mathbb{X}$ be a multiset whose elements belong to $\mathbb{F}_2^n$. When the multiset $\mathbb{X}$ has the division property $\mathcal{D}_{\mathbb{K}}^{1^n}$, where $\mathbb{K}$ denotes a set of n-dimensional vectors in $\{0,1\}^n \subseteq \mathbb{Z}^n$, it fulfills the following condition

$$\bigoplus_{\mathbf{x}\in\mathbb{X}} x_0^{u_0} x_1^{u_1} \cdots x_{n-1}^{u_{n-1}} = \begin{cases} \text{unknown} & \text{if there are } \mathbf{k} \in \mathbb{K}, \text{s.t.} \mathbf{u} \succcurlyeq \mathbf{k} \\ 0 & \text{otherwise} \end{cases}$$

where $\mathbf{u} = (u_0, u_1, \cdots, u_{n-1}) \in \{0,1\}^n \subseteq \mathbb{Z}^n$, $\mathbf{x} = (x_0, x_1, \cdots, x_{n-1}) \in \mathbb{F}_2^n$.

Using Division Property

- Construct an input set with division property $\mathcal{D}_{\mathbb{K}}^{1^n}$.
- Propagate it against the target cipher to get the output set with division property $\mathcal{D}_{\mathbb{K}'}^{1^n}$
- Extract some useful integral property from $\mathcal{D}_{\mathbb{K}'}^{1^n}$

The rule of propagation

The propagation of the division property can be described as a set of bit vectors, which in turn can be modeled by the language of CP.

Propagation of Division Property against Vectorial Boolean Functions

Algorithm 1: propagate() Compute the output division property.

Input: A vectorial boolean function $\mathbf{f} : \mathbb{F}_2^m \to \mathbb{F}_2^n$, and an input pattern $\mathbf{u} = (u_0, \cdots, u_{m-1}) \in \mathbb{F}_2^m$, where $f(\mathbf{x}) = (f_0(\mathbf{x}), \cdots, f_{n-1}(\mathbf{x}))$ and $\mathbf{x} = (x_0, \cdots, x_{m-1})$;

Output: $\mathcal{O}$: a set of patterns $\mathbf{v} \in \mathbb{F}_2^n$ describing the division property of the output set;

$\mathcal{O} = \emptyset$;
if $\mathbf{u} = (0, \cdots, 0)$ **then**
  return $\mathcal{O} = \{(0, \cdots, 0)\}$
else
  for $\mathbf{v} \in \mathbb{F}_2^n / (0, \cdots, 0)$ **do**
    Let $F = \prod_{j=0}^{n-1} f_j^{v_j}(x_0, \cdots, x_{n-1})$;
    if $\prod_{j=0}^{m-1} x_j^{u_j} \lessdot F$ **then**
      $\mathcal{O} = \mathcal{O} \cup \{v\}$;
    end
  end
end
return reduced($\mathcal{O}$);

- [Xiang, Zhang, Bao and Lin, ASIACRYPT 2016]
- [Christina Boura and Anne Canteaut, CRYPTO 2016]
- [Ling Sun and Meiqin Wang, IACR ePrint 2016/392]

Example : the PRESENT S-box

Table: Division Trails of PRESENT Sbox

Input $\mathcal{D}_k^{1,4}$	Output $\mathcal{D}_{\mathbb{K}}^{1,4}$
(0,0,0,0)	(0,0,0,0)
(0,0,0,1)	(0,0,0,1) (0,0,1,0) (0,1,0,0) (1,0,0,0)
(0,0,1,0)	(0,0,0,1) (0,0,1,0) (0,1,0,0) (1,0,0,0)
(0,0,1,1)	(0,0,1,0) (0,1,0,0) (1,0,0,0)
(0,1,0,0)	(0,0,0,1) (0,0,1,0) (0,1,0,0) (1,0,0,0)
(0,1,0,1)	(0,0,1,0) (0,1,0,0) (1,0,0,0)
(0,1,1,0)	(0,0,0,1) (0,0,1,0) (1,0,0,0)
(0,1,1,1)	(0,0,1,0) (1,0,0,0)
(1,0,0,0)	(0,0,0,1) (0,0,1,0) (0,1,0,0) (1,0,0,0)
(1,0,0,1)	(0,0,1,0) (0,1,0,0) (1,0,0,0)
(1,0,1,0)	(0,0,1,0) (0,1,0,0) (1,0,0,0)
(1,0,1,1)	(0,0,1,0) (0,1,0,0) (1,0,0,0)
(1,1,0,0)	(0,0,1,0) (0,1,0,0) (1,0,0,0)
(1,1,0,1)	(0,0,1,0) (0,1,0,0) (1,0,0,0)
(1,1,1,0)	(0,1,0,1) (1,0,1,1) (1,1,1,0)
(1,1,1,1)	(1,1,1,1)

```
Tuples integral_path = new Tuples(true);
integral_path.add(0, 0, 0, 0, 0, 0, 0, 0);
integral_path.add(0, 0, 0, 1, 0, 0, 0, 1);
integral_path.add(0, 0, 0, 1, 0, 0, 1, 0);
integral_path.add(0, 0, 0, 1, 0, 1, 0, 0);
integral_path.add(0, 0, 0, 1, 1, 0, 0, 0);
integral_path.add(0, 0, 1, 0, 0, 0, 0, 1);
integral_path.add(0, 0, 1, 0, 0, 0, 1, 0);
integral_path.add(0, 0, 1, 0, 0, 1, 0, 0);
integral_path.add(0, 0, 1, 0, 1, 0, 0, 0);
integral_path.add(0, 0, 1, 1, 0, 0, 1, 0);
integral_path.add(0, 0, 1, 1, 0, 1, 0, 0);
integral_path.add(0, 0, 1, 1, 1, 0, 0, 0);
integral_path.add(0, 1, 0, 0, 0, 0, 0, 1);
integral_path.add(0, 1, 0, 0, 0, 0, 1, 0);
integral_path.add(0, 1, 0, 0, 0, 1, 0, 0);
integral_path.add(0, 1, 0, 0, 1, 0, 0, 0);
integral_path.add(0, 1, 0, 1, 0, 0, 1, 0);
integral_path.add(0, 1, 0, 1, 0, 1, 0, 0);
integral_path.add(0, 1, 0, 1, 1, 0, 0, 0);
integral_path.add(0, 1, 1, 0, 0, 0, 0, 1);
integral_path.add(0, 1, 1, 0, 0, 0, 1, 0);
integral_path.add(0, 1, 1, 0, 1, 0, 0, 0);
integral_path.add(0, 1, 1, 1, 0, 0, 1, 0);
integral_path.add(0, 1, 1, 1, 1, 0, 0, 0);
integral_path.add(1, 0, 0, 0, 0, 0, 0, 1);
integral_path.add(1, 0, 0, 0, 0, 0, 1, 0);
integral_path.add(1, 0, 0, 0, 0, 1, 0, 0);
integral_path.add(1, 0, 0, 0, 1, 0, 0, 0);
integral_path.add(1, 0, 0, 1, 0, 0, 1, 0);
integral_path.add(1, 0, 0, 1, 0, 1, 0, 0);
integral_path.add(1, 0, 0, 1, 1, 0, 0, 0);
integral_path.add(1, 0, 1, 0, 0, 0, 1, 0);
integral_path.add(1, 0, 1, 0, 0, 1, 0, 0);
integral_path.add(1, 0, 1, 0, 1, 0, 0, 0);
integral_path.add(1, 0, 1, 1, 0, 0, 1, 0);
integral_path.add(1, 0, 1, 1, 0, 1, 0, 0);
integral_path.add(1, 0, 1, 1, 1, 0, 0, 0);
```

Propagation of Division Property : Division Trail

- The bit-based division property can be described by the propagation of bit patterns with some special meaning, which leads to the concept of *division trail*.

Division Trail [Xiang, Zhang, Bao and Lin, ASIACRYPT 2016]

Let $\mathcal{F}$ be the round function of an iterated block cipher. Assume that the input multi-set to the block cipher has initial division property $\mathcal{D}^{1^n}_{\mathbb{K}_0}$ with $\mathbb{K}_0 = \{\mathbf{k}\}$. This initial division property propagates through the round function which forms a chain

$$\mathcal{D}^{1^n}_{\mathbb{K}_0} \xrightarrow{\mathcal{F}} \mathcal{D}^{1^n}_{\mathbb{K}_1} \xrightarrow{\mathcal{F}} \mathcal{D}^{1^n}_{\mathbb{K}_2} \xrightarrow{\mathcal{F}} \cdots$$

For any vector $\mathbf{k}_i^* \in \mathbb{K}_i (i \geq 1)$, there must exist a vector $\mathbf{k}_{i-1}^*$ in $\mathbb{K}_{i-1}$ such that $\mathbf{k}_{i-1}^*$ can propagate to $\mathbf{k}_i^*$ according to the rules of division property propagation. Furthermore, for $(\mathbf{k}_0, \mathbf{k}_1, \cdots, \mathbf{k}_r) \in \mathbb{K}_0 \times \mathbb{K}_1 \times \cdots \times \mathbb{K}_r$, if $\mathbf{k}_{i-1}$ can propagate to $\mathbf{k}_i$ for all $i \in \{1, 2, \cdots, r\}$, we call $(\mathbf{k}_0, \mathbf{k}_1, \cdots, \mathbf{k}_r)$ an r-round division trail.

The rule for detecting integral distinguisher based on division property

Set without Integral Property

Let $\mathbb{X}$ be a multiset with division property $\mathcal{D}_{\mathbb{K}}^{1^n}$, then $\mathbb{X}$ does not have integral property if and only if $\mathbb{K}$ contains all the n unit vectors.

- Construct a CP model $\mathcal{M}_{\mathbf{e}_j}$ whose solution set contains all the division trails whose output division property is set to $\mathbf{e}_j$.
- If we can find at least one $\mathcal{M}_{\mathbf{e}_j}$ for $j \in \{0, \cdots, n-1\}$ which is infeasible, then we find an integral distinguisher.

Accelerating the Search

- Ordering heuristic
  - The order in which the variables are assigned has significant impact on the efficiency of the resolution.
  - We choose the generic ordering heuristic called domain over weighted degree [Frédéric Boussemart et al., ECAI 2004]
- Random restart

Results on PRESENT, HIGHT, and SKINNY

- Retrieve the 9-round distinguisher of PRESENT found by MILP method(cost 3.4 minutes) in 36 seconds.
- Rediscover all zero-correlation linear approximations of the 17-round in 1709 seconds (MILP cost 4786).
- SKINNY

Note

During the process of designing new ciphers, the evaluation sometimes needs to be repeated several times. Hence, even though not crucial, a good CPU time is a desirable feature.

Comparing Solvers

- Pick two problems as benchmark
  - Optimization : find the best trail of PRESENT
  - Enumeration : list all solutions in a given linear hull of PRESENT

- Solvers
  - MILP solvers : Gurobi, SCIP
  - CP solvers : Choco, Chuffed, PICAT_SAT

Comparing Solvers

TABLE: Optimization problem, with a time limit of 2 hours.

Rounds	Prob.	Time by Gurobi (sec.)	Time by Choco (sec.)	Time by Chuffed (sec.)	Time by PICAT_SAT (sec.)
3	2^{-8}	2	4.1	0.2	12.8
4	2^{-12}	25	750.8	11.4	22.5
5	2^{-20}	453	-	3404.5	91.4
6	2^{-24}	2184	-	-	486.2
7	2^{-28}	-	-	-	5883.9

Comparing Solvers

TABLE: Enumerating the linear hull of PRESENT

Rounds	Time by SCIP (sec.)	Number of solutions by SCIP	Time by Choco (sec.)	Number of solutions by Choco
4	0.1	3	0.023	3
5	0.28	17	0.031	17
6	37.7	8064	0.359	8064

Future work

- Improve the algorithms for solving cryptanalysis problems
  - Exploit the structure of the problem
  - Large scale parallelism
- Cryptanalysis Automation
  - There are still some cryptanalysis techniques cannot be automated with MILP/SAT/SMT/CP
  - The key-recovery part
- Software for automatic cryptanalysis
  - Domain Specific Language (DSL) for cryptanalysis
  - Tools with graphical user interface

Resources

- **Block cipher cryptanalysis**
  - Book : The block cipher companion
  - Papers : Analysis of PRESENT/AES/SKINNY$\cdots$
- **Cryptanalysis with MILP**
  - Papers : Inscrypt 13, ASIACRYPT 14, FSE 2016, EUROCRYPT 2017
  - Softwares : Gurobi (`http://www.gurobi.com/`)
- **Cryptanalysis with SAT/SMT**
  - Papers : Cryptology ePrint Archive Report 2013/328, CRYPTO 2015
  - Softwares : MiniSAT (`https://www.msoos.org/cryptominisat4/`), Glucose (`http://www.labri.fr/perso/lsimon/glucose/`), Boolector (`http://fmv.jku.at/boolector/`), STP (`https://stp.github.io/`)
- **Cryptanalysis with CP**
  - Papers : CP 2016, FSE 2017
  - Softwares : Minizinc (`http://www.minizinc.org/`), Choco (`http://www.choco-solver.org/`)
  - Open Courses : Modeling Discrete Optimization, Advanced Modeling for Discrete Optimization (`https://www.coursera.org/`)

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Thanks for your attention !