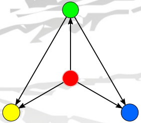

SCIENCE
PASSION
TECHNOLOGY

Autoguess

A Tool for Finding Guess-and-Determine Attacks and Key Bridges

Hosein Hadipour and Maria Eichlseder

ACNS 2022 - Rome, Italy

Outline

Guess-and-Determine

Guess-and-Determine (GD)

Guess-and-Determine

Given a set of variables and a set of relations between them, find the smallest subset of variables guessing the value of which uniquely determines the value of the remaining variables.

Guess-and-Determine (GD)

Guess-and-Determine

Given a set of variables and a set of relations between them, find the smallest subset of variables guessing the value of which uniquely determines the value of the remaining variables.

Example

- $u, \ldots, z \in \mathbb{F}_2^{32}$
- F, G, H: bijective functions
- $c_1, \ldots, c_5$: constants

$$\begin{cases} F(u+v) \oplus G(x) \oplus y \oplus (z \lll 7) & = c_1 \\ G(u \oplus w) + (y \lll 3) + z & = c_2 \\ F(w \oplus x) + y \oplus z & = c_3 \\ F(u) \oplus G(w+z) & = c_4 \\ (F(u) \times G(w \lll 7)) + H(z \oplus v) & = c_5 \end{cases}$$

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Guess-and-Determine (GD)

Guess-and-Determine

Given a set of variables and a set of relations between them, find the smallest subset of variables guessing the value of which uniquely determines the value of the remaining variables.

Example

- Guess w, z
- Determine u (4), y (2)
- Determine x (3), v (5)

$$\begin{cases} F(u+v) \oplus G(x) \oplus y \oplus (z \lll 7) & = c_1 \\ G(u \oplus w) + (y \lll 3) + z & = c_2 \\ F(w \oplus x) + y \oplus z & = c_3 \\ F(u) \oplus G(w+z) & = c_4 \\ (F(u) \times G(w \lll 7)) + H(z \oplus v) & = c_5 \end{cases}$$

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Symmetric and Implication Relations

Assumption: Relations are symmetric or implication

- **Implication relations:**

$$x_1, \ldots, x_n \Rightarrow y$$

- **Symmetric relations:**

$$[x_1, \ldots, x_n]$$

Example

Assume that $x, y, z, k \in \mathbb{F}_2^{32}$, and $F : \mathbb{F}_2^{32} \to \mathbb{F}_2^{32}$ is bijective:

$$z = x \times y \qquad\qquad z = F(x + k) \oplus y$$

$$x, y \Rightarrow z \qquad\qquad [x, y, z, k]$$

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System of Equations

$$E: \begin{cases} e_1 : F(u+v) \oplus G(x) \oplus y \oplus (z \lll 7) & = c_1 \\ e_2 : G(u \oplus w) + (y \lll 3) + z & = c_2 \\ e_3 : F(w \oplus x) + y \oplus z & = c_3 \\ e_4 : F(u) \oplus G(w+z) & = c_4 \\ e_5 : (F(u) \times G(w \lll 7)) + H(z \oplus v) & = c_5 \end{cases}$$

$$X = \{u, v, w, x, y, z\},\ E = \{e_1, \ldots, e_5\}$$

System of Equations $\Rightarrow$ System of Relations

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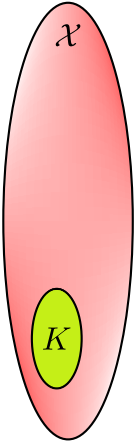
$$X = \{u, v, w, x, y, z\},\ E = \{e_1, \ldots, e_5\}$$

$$\mathcal{R} : \begin{cases} r_1 : [u, v, x, y, z], & r_2 : [u, w, y, z] \\ r_3 : [w, x, y, z], & r_4 : [u, w, z] \\ r_5 : u, w \Rightarrow t, & r_6 : [t, z, v] \end{cases}$$

$$\mathcal{X} = \{u, v, w, x, y, z, t\},\ \mathcal{R} = \{r_1, \ldots, r_6\}$$

Knowledge Propagation

$(\mathcal{X}, \mathcal{R})$: System of relations, $K \subseteq \mathcal{X}$



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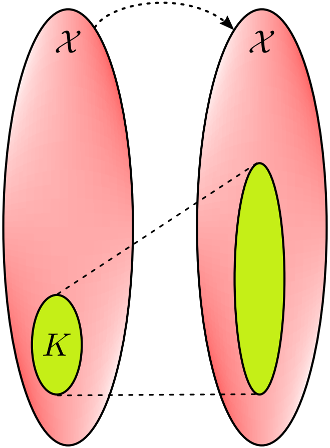

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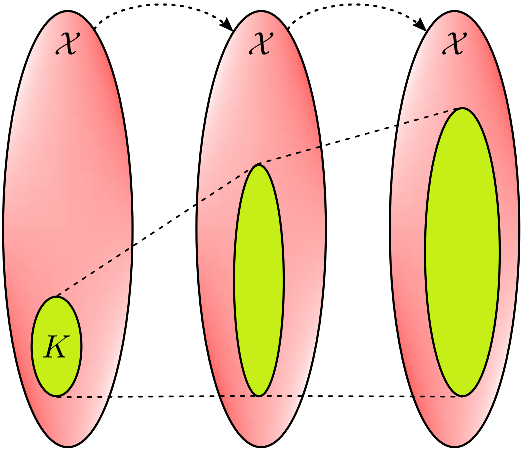

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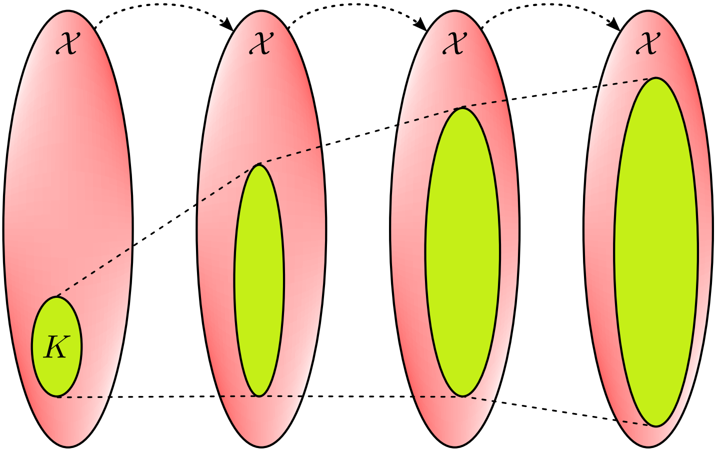

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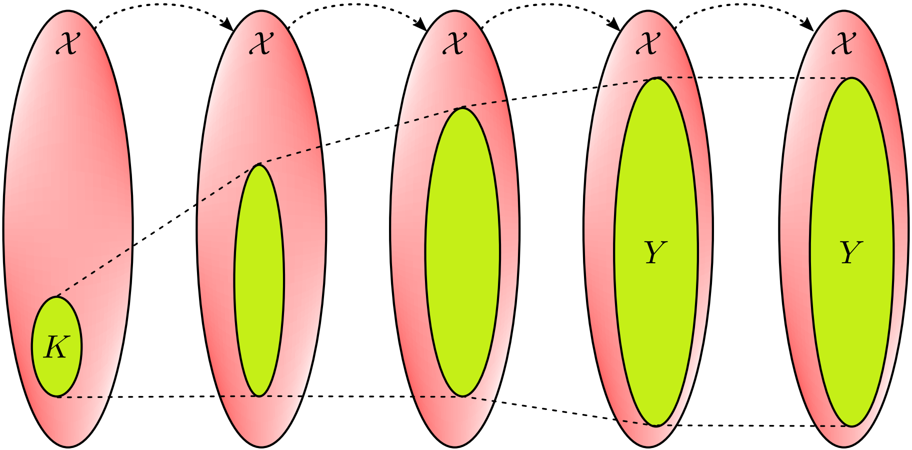
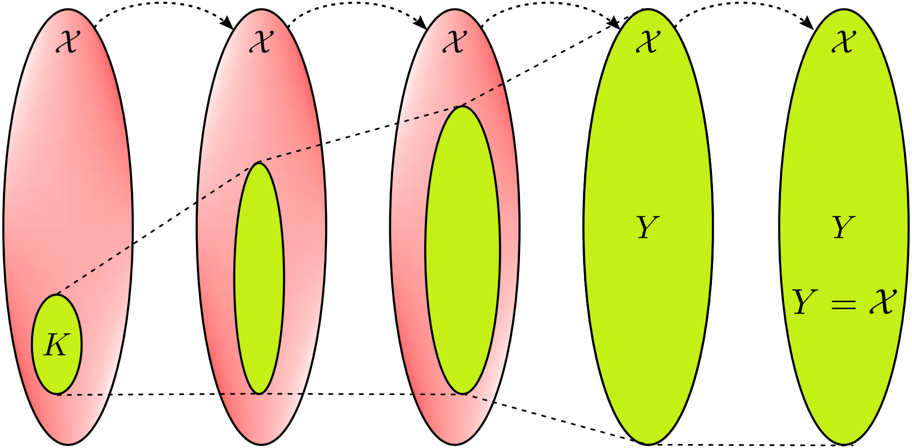


$Y = \texttt{Propagate}(K)$

Knowledge Propagation

$(\mathcal{X}, \mathcal{R})$: System of relations, $K \subseteq \mathcal{X}$



If $\mathcal{X} = \texttt{Propagate}(K)$, then we say K is a *Guess Basis*

Naive Approach for GD

Given a system of relations $(\mathcal{X}, \mathcal{R})$, where $|\mathcal{X}| = n$, is there any guess basis of size $\leq m$?

Brute-force

- For $k = 1 \rightarrow m$
  - For each subset $K \subseteq \mathcal{X}$, where $|K| = k$:
    - If $\texttt{Propagate(K)} = \mathcal{X}$ then return K

- Time complexity $\approx \sum_{k=1}^{m} \binom{n}{k}$
- Exponential with respect to both n and m

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Naive Approach for GD

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Previous Works

- Heuristic Approaches:
  - Dynamic programming: [AE09]
  - Dedicated algorithm for GD attaks on AES: [BDF11]
- Using off-the-shelf solvers:
  - MILP: [Cen+20]
  - Gröbner basis: [DK20]

We borrowed the idea introduced in [Cen+20] to convert the GD problem to the CP/SAT problem.

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We borrowed the idea introduced in [Cen+20] to convert the GD problem to the CP/SAT problem.

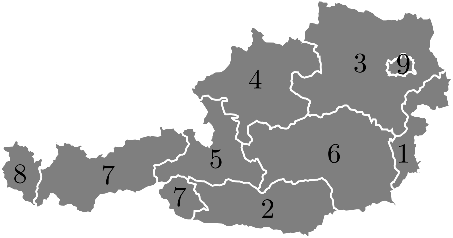
Constraint Programming Model for GD

Constraint Programming (CP)

In CP we specify the properties of the solution to be found:

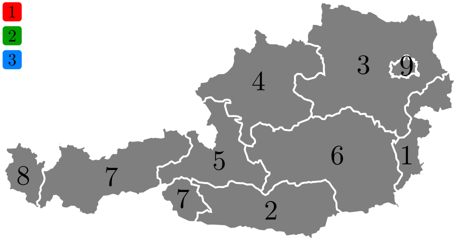
- We define a set of variables: $\mathcal{X}$
- We specify the domain of each variable: $\mathbb{F}_2, \mathbb{Z}, \mathbb{R}, \ldots$
- We define a set of constraints: $\mathcal{C}$
- We define an objective function (if it is required)

CP Problem - Example




```
int: nc = 3;
array[1..9] of var 1..nc: r;
constraint r[1] != r[3]; constraint r[1] != r[6];
constraint r[2] != r[5]; constraint r[2] != r[6]; constraint r[2] != r[7];
constraint r[3] != r[9]; constraint r[3] != r[6]; constraint r[3] != r[4];
constraint r[4] != r[6]; constraint r[4] != r[5];
constraint r[5] != r[6]; constraint r[5] != r[7];
constraint r[7] != r[8];
solve satisfy;
r = [3, 3, 2, 3, 2, 1, 1, 2, 1];
```

CP Problem - Example

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constraint r[4] != r[6]; constraint r[4] != r[5];
constraint r[5] != r[6]; constraint r[5] != r[7];
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solve satisfy;
r = [3, 3, 2, 3, 2, 1, 1, 2, 1];
```


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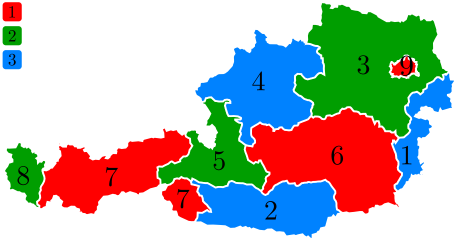
CP Problem - Example

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solve satisfy;
```

```
r = [3, 3, 2, 3, 2, 1, 1, 2, 1];
```

Main Steps of Our Approach

Our method inspired from [Cen+20] has three main phases:

- Convert the system of equations to a system of (implication and symmetric) relations
- Convert the problem of finding a minimal guess basis for the system of relations to a CP problem or a sequence of SAT problems
- Employ the off-the-shelf SAT/CP solvers to solve the problem

Convert GD to a CP Problem

$$r_0 : [x, y, z]$$
$$r_1 : [z, w, y]$$
$$r_2 : [w, x, u]$$

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Convert GD to a CP Problem

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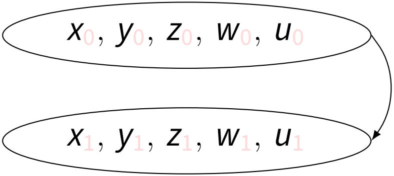

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Convert GD to a CP Problem

$$r_0 : [x, y, z]$$
$$r_1 : [z, w, y]$$
$$r_2 : [w, x, u]$$

$$x_0,\ y_0,\ z_0,\ w_0,\ u_0$$
$$x_1,\ y_1,\ z_1,\ w_1,\ u_1$$
$$x_2,\ y_2,\ z_2,\ w_2,\ u_2$$

- Fix the number of steps in knowledge propagation (e.g. 2 here)
- $X = \{x_i, y_i, z_i, w_i, u_i : 0 \leq i \leq 2\}$
- $x_i = 1$ iff x is known after the ith step of knowledge propagation, otherwise $x_i = 0$
- $\mathcal{C} \leftarrow \emptyset$

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Convert GD to a CP Problem

$r_0 : [x, y, z]$

$r_1 : [z, w, y]$

$r_2 : [w, x, u]$

$$x_0,\ y_0,\ z_0,\ w_0,\ u_0$$

$$x_1,\ y_1,\ z_1,\ w_1,\ u_1$$

$$X \leftarrow X \cup \{x_{0,0}, x_{0,1}\}$$

$$\mathcal{C} \leftarrow \mathcal{C} \cup \{x_{0,0} = y_0 \wedge z_0\}$$

$$\mathcal{C} \leftarrow \mathcal{C} \cup \{x_{0,1} = w_0 \wedge u_0\}$$

$$\mathcal{C} \leftarrow \mathcal{C} \cup \{x_1 = x_{0,0} \vee x_{0,1}\}$$

Convert GD to a CP Problem

$r_0 : [x, y, z]$

$r_1 : [z, w, y]$

$r_2 : [w, x, u]$

$x_0,\ y_0,\ z_0,\ w_0,\ u_0$

$x_1,\ y_1,\ z_1,\ w_1,\ u_1$

$$\mathcal{X} \leftarrow \mathcal{X} \cup \{y_{0,0}, y_{0,1}\}$$

$$\mathcal{C} \leftarrow \mathcal{C} \cup \{y_{0,0} = x_0 \wedge z_0\}$$

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Convert GD to a CP Problem

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$r_1 : [z, w, y]$
$r_2 : [w, x, u]$

$$x_0,\ y_0,\ z_0,\ w_0,\ u_0$$

$$x_1,\ y_1,\ z_1,\ w_1,\ u_1$$

Do it for z, w, u as well

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Convert GD to a CP Problem

$r_0 : [x, y, z]$

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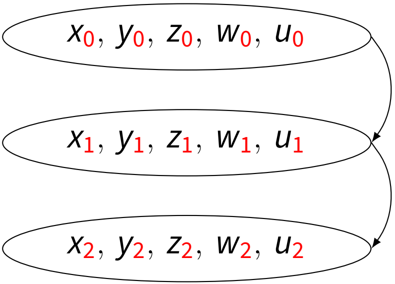

Do it for each transition in knowledge propagation

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Convert GD to a CP Problem

$r_0 : [x, y, z]$

$r_1 : [z, w, y]$

$r_2 : [w, x, u]$

$$\begin{tikzcd} x_0,\ y_0,\ z_0,\ w_0,\ u_0 \arrow[d] \\ x_1,\ y_1,\ z_1,\ w_1,\ u_1 \arrow[d] \\ x_2,\ y_2,\ z_2,\ w_2,\ u_2 \end{tikzcd}$$

All variables should be known at the last step:

$$\mathcal{C} \leftarrow \mathcal{C} \cup \{x_2 \wedge y_2 \wedge z_2 \wedge w_2 \wedge u_2 = 1\}$$

Convert GD to a CP Problem

$r_0 : [x, y, z]$

$r_1 : [z, w, y]$

$r_2 : [w, x, u]$

$$x_0,\ y_0,\ z_0,\ w_0,\ u_0$$

$$x_1,\ y_1,\ z_1,\ w_1,\ u_1$$

$$x_2,\ y_2,\ z_2,\ w_2,\ u_2$$

$$\min x_0 + y_0 + z_0 + w_0 + u_0$$

$s.t.$ all constraints in $\mathcal{C}$ are satisfied

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Convert GD to a CP Problem

$r_0 : [x, y, z]$

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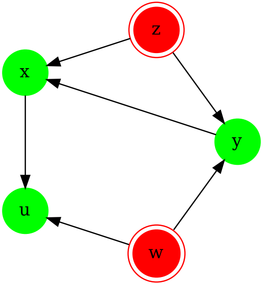
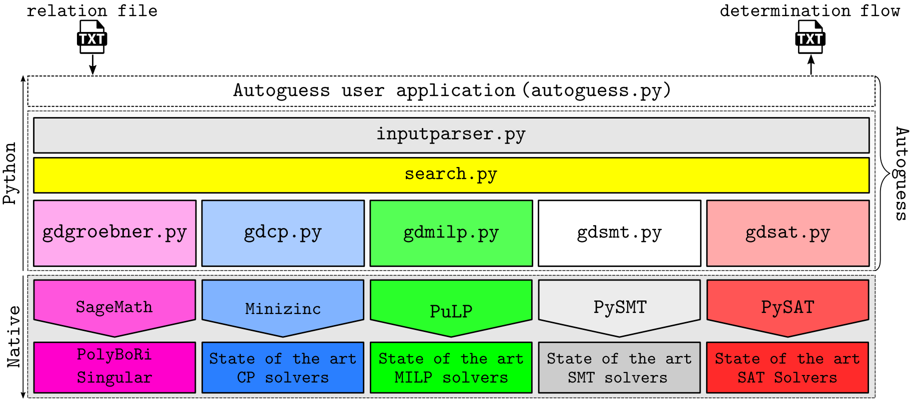


$$\min x_0 + y_0 + z_0 + w_0 + u_0$$

$$s.t. \text{ all constraints in } \mathcal{C} \text{ are satisfied}$$

Autoguess

Autoguess


relation file
determination flow
TXT
TXT
Autoguess user application (autoguess.py)
inputparser.py
search.py
gdgroebner.py
gdcp.py
gdmilp.py
gdsmt.py
gdsat.py
SageMath
Minizinc
PuLP
PySMT
PySAT
PolyBoRi
Singular
State of the art
CP solvers
State of the art
MILP solvers
State of the art
SMT solvers
State of the art
SAT Solvers
Python
Native
Autoguess

Autoguess - Simple User Interface

$$
\begin{cases}
F(u + v) \oplus G(x) \oplus y \oplus (z \lll 7) & = c_1 \\
G(u \oplus w) + (y \lll 3) + z & = c_2 \\
F(w \oplus x) + y \oplus z & = c_3 \\
F(u) \oplus G(w + z) & = c_4 \\
(F(u) \times G(w \lll 7)) + H(z \oplus v) & = c_5
\end{cases}
$$

Autoguess - Simple User Interface

Input file (`relations.txt`):

```
# Comments
connection relations
u, v, x, y, z
u, w, y, z
w, x, y, z
u, w, z
u, w => t
t, z, v
end
```

Run Autoguess:

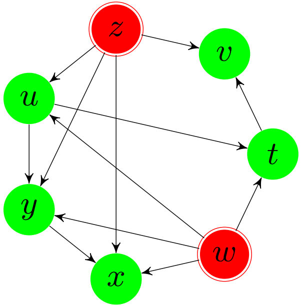
```
python3 autoguess.py -i relations.txt -maxsteps 5 -solver cp
```

Autoguess - Simple User Interface

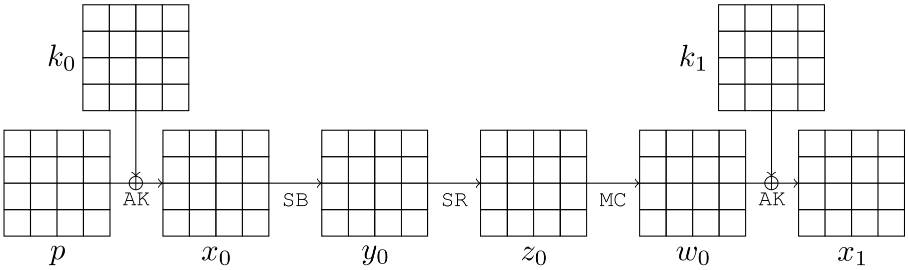
Input file (`relations.txt`):

```
# Comments
connection relations
u, v, x, y, z
u, w, y, z
w, x, y, z
u, w, z
u, w => t
t, z, v
end
```

Output:



GD Attack on Block Ciphers (1 round of AES)



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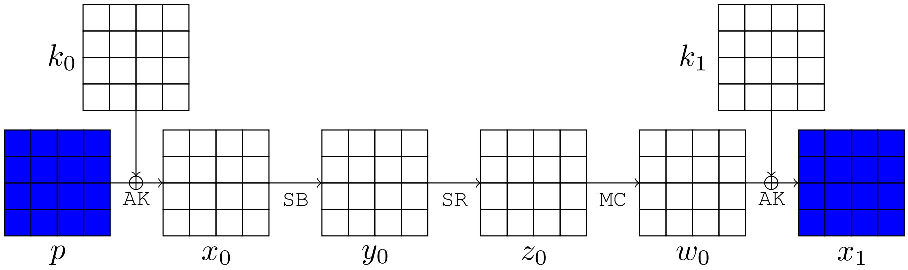

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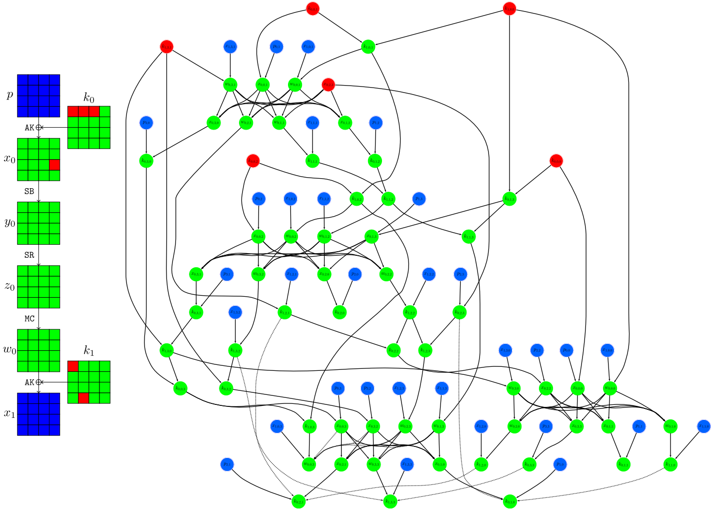

Found in 0.02 seconds on a `2.8 GHz i7-1165G7 CPU`

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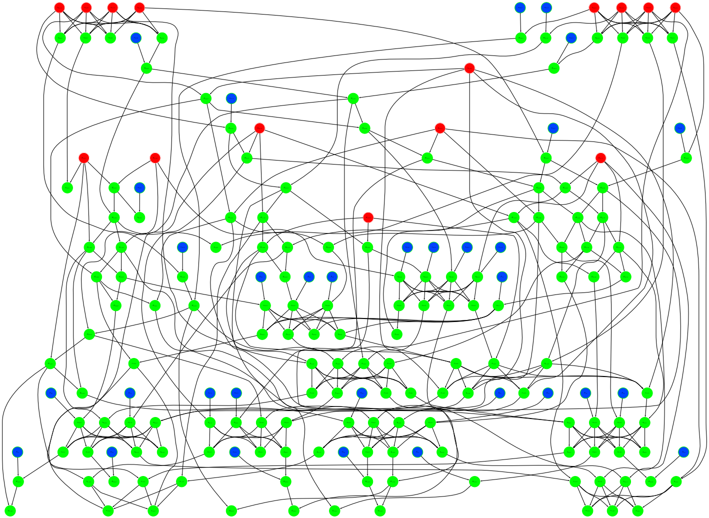
ACNS 2022 - Rome, Italy

GD Attack on Block Ciphers (3 Rounds of AES)



Found in 34.51 seconds on a `2.8 GHz i7-1165G7 CPU`

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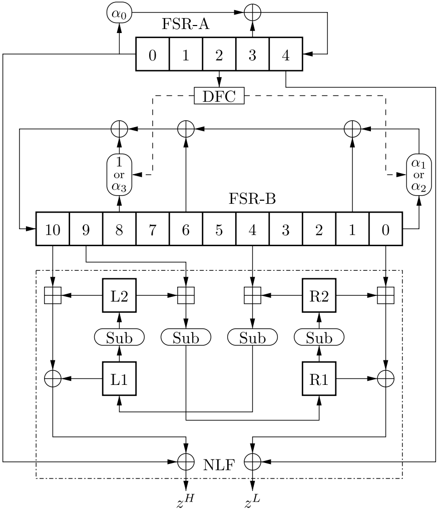
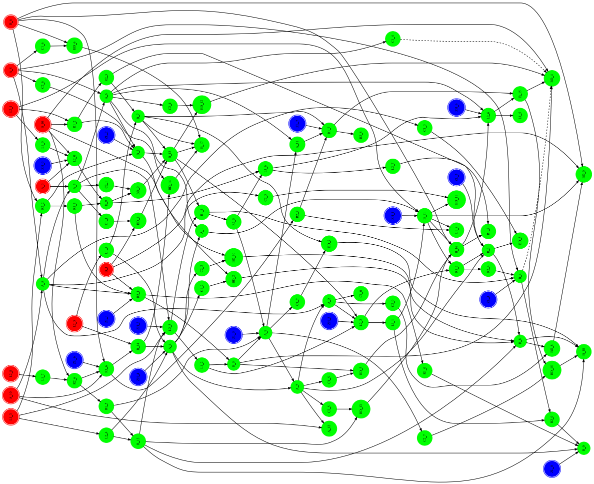
GD Attack on Stream Ciphers (KCipher-2)



ISO/IEC 18033-4

GD Attack on Stream Ciphers (KCipher-2)



Found in 7 seconds on a `2.8 GHz i7-1165G7 CPU`

Key-Bridging (KB)

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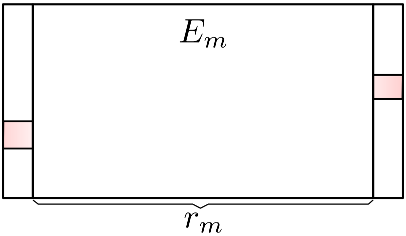

- We want to determine a subset of sub-key bits: $B \cup F$
- Key schedule implies some relations between the sub-key bits in $B \cup F$

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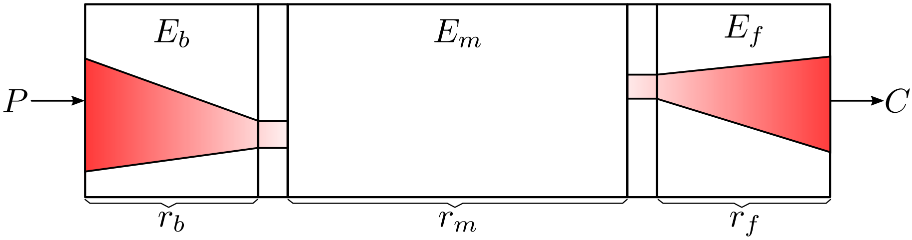

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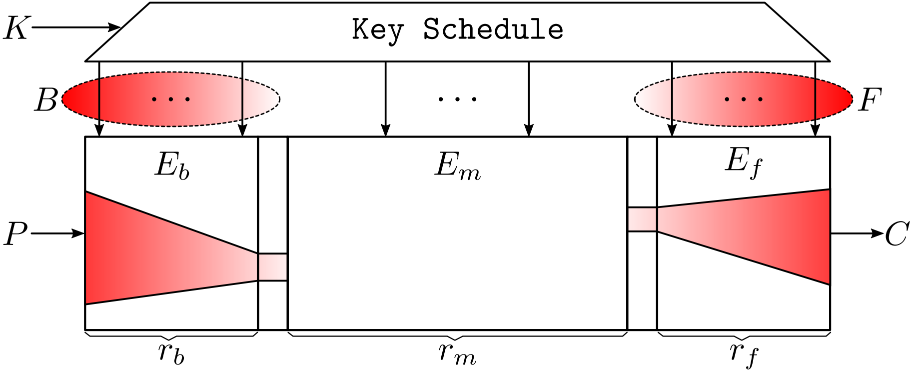

- We want to determine a subset of sub-key bits: $B \cup F$
- Key schedule implies some relations between the sub-key bits in $B \cup F$
- Find a minimal guess basis for $B \cup F$ (not for the entire set of variables)

$\mathcal{DS}$-MITM Attacks On SKINNY and TWINE

- We combined our CP-based method for KB with CP-based method to search for distinguishers
- We applied our method to optimize $\mathcal{DS}$-MITM attack on SKINNY [Bei+16] and TWINE [Suz+11]

Cipher	#Rounds	Data	Memory	Time	Attack	Setting	Reference
SKINNY-128-256	19	2^{96} CP	$2^{210.99}$	$2^{238.26}$	$\mathcal{DS}$-MITM	ST	This paper
SKINNY-64-192	21	2^{60} CP	$2^{133.99}$	$2^{186.63}$	$\mathcal{DS}$-MITM	ST	This paper
SKINNY-64-128	18	2^{32} CP	$2^{61.91}$	$2^{126.32}$	$\mathcal{DS}$-MITM	ST	This paper
TWINE-80	20	2^{32} CP	$\mathbf{2^{62.91}}$	$2^{76.92}$	$\mathcal{DS}$-MITM	-	This paper
TWINE-80	20	2^{32} CP	$2^{82.91}$	$2^{77.44}$	$\mathcal{DS}$-MITM	-	[Shi+18]

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Conclusion

Our Contributions - I

- We introduced two new encoding methods for GD technique (CP & SAT)
- We provided the open-source tool Autoguess integrating our new methods as well as almost all of the previous methods for GD technique
- We applied our tool on a wide variety of symmetric primitives:
  - Improving the GD attack on ZUC [ETS11; Tea18]
  - Rediscovering the GD attack on 3 rounds of AES in less than a minute
- We applied Autoguess to find key-bridges in key recovery attacks on block ciphers

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Our Contributions - II

- We combined our CP-based approach for key-bridging with the CP-based methods to search for distinguishers, and introduced a unified method to find key-recovery friendly distinguishers:

Thanks for your attention!

: https://github.com/hadipourh/autoguess

: https://ia.cr/2021/1529

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