SCIENCE
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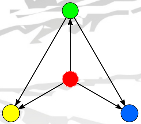

Autoguess

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

Hosein Hadipour and Maria Eichlseder

22 June 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 $F : \mathbb{F}_2^{32} \rightarrow \mathbb{F}_2^{32}$ 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

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

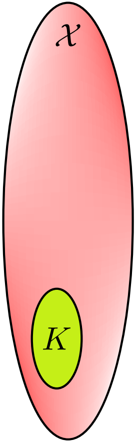
$$X = \{u, v, w, x, y, z\},\ E = \{e_1, \ldots, e_5\}$$

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

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

Knowledge Propagation

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



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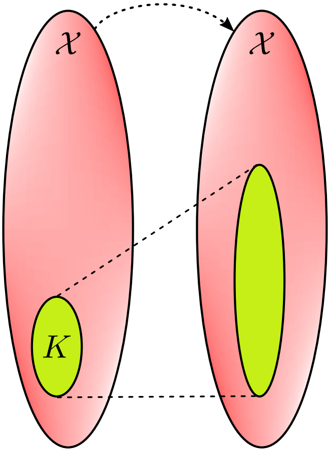

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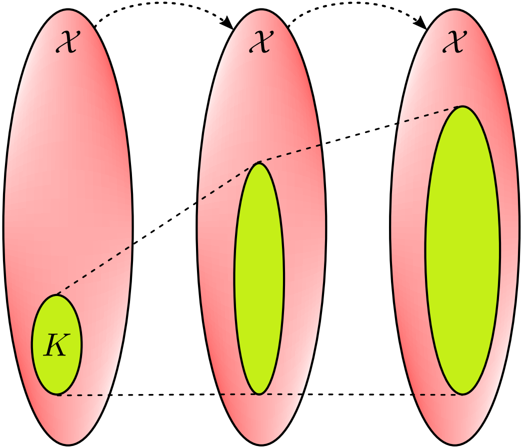

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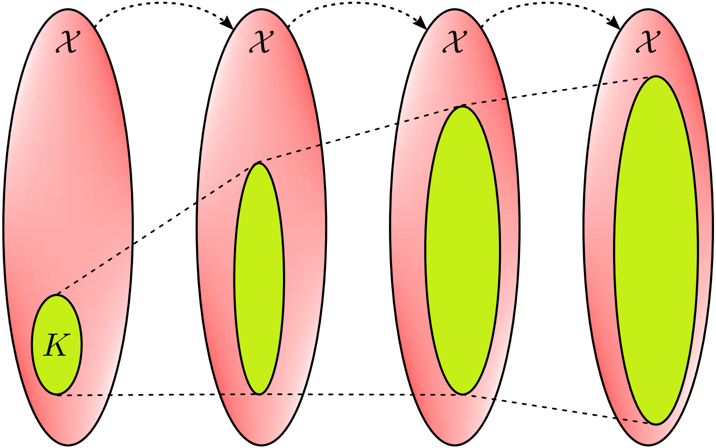

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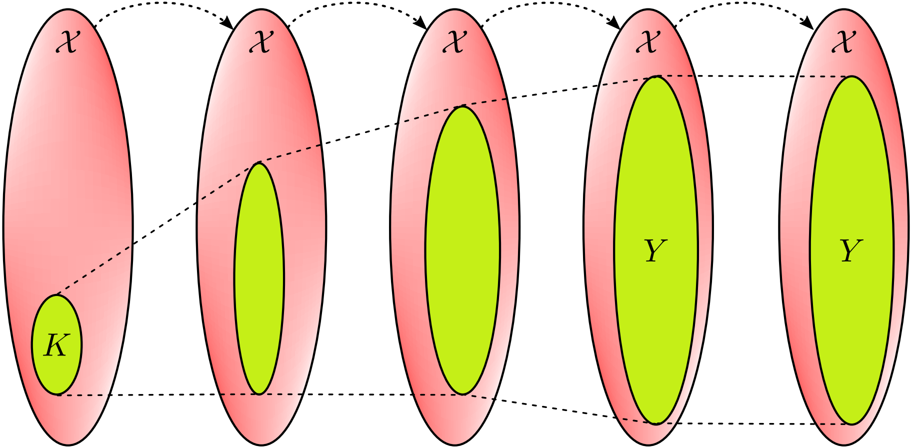
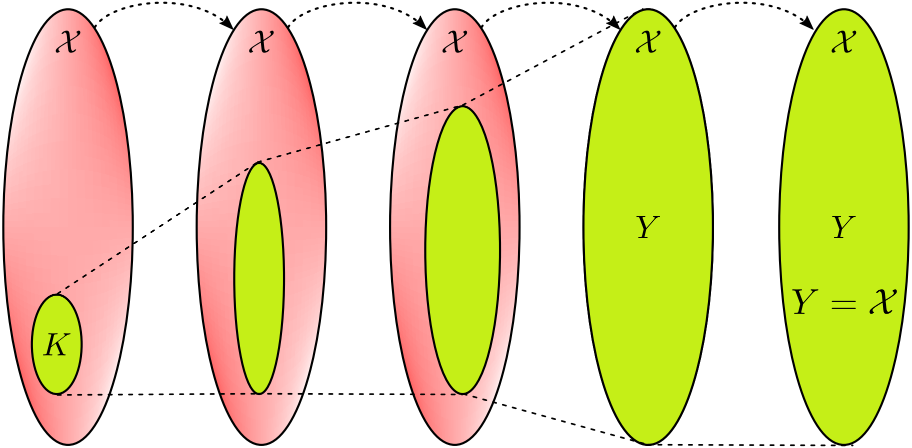


$Y = \texttt{Propagate}(K)$

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 $k = 1 \to m$
  - For each subset $K \subseteq \mathcal{X}$, where $|K| = k$:
    - If `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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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.

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Constraint Programming Model for GD

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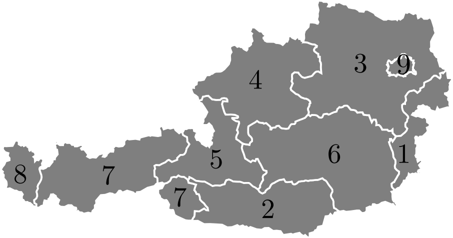
Constraint Programming (CP)

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

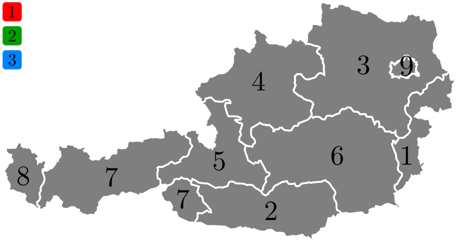
- We define a set of variables: $\mathcal{X}$
- We specify the domain of each variable: $\mathbb{F}_2, \mathbb{Z}, \mathbb{R}, \ldots$
- We define a set of constraints: $\mathcal{C}$
- We deine an objective function (if it is required)

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[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];
```


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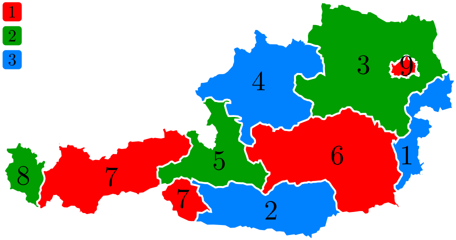
CP Problem - Example

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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];
```

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

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Convert GD to a CP Problem

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

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Convert GD to a CP Problem

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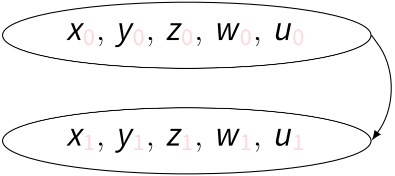

Convert GD to a CP Problem

$r_0 : [x, y, z]$

$r_1 : [z, w, y]$

$r_2 : [w, x, u]$

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

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

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

- 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 $x_i = 0$
- $\mathcal{C} \leftarrow \emptyset$

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

$r_0 : [x, y, z]$

$r_1 : [z, w, y]$

$r_2 : [w, x, u]$

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

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

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

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

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Convert GD to a CP Problem

$r_0 : [x, y, z]$

$r_1 : [z, w, y]$

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

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

Do it for z, w, u as well

Convert GD to a CP Problem

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

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

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

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

Do it for each transition in knowledge propagation

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Convert GD to a CP Problem

$r_0 : [x, y, z]$

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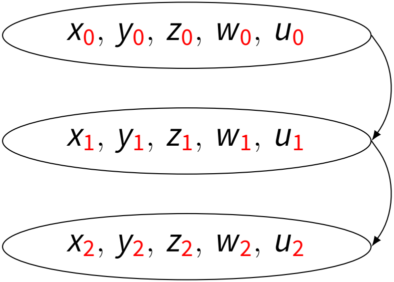

All variables should be known at the last step:

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

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Convert GD to a CP Problem

$r_0 : [x, y, z]$

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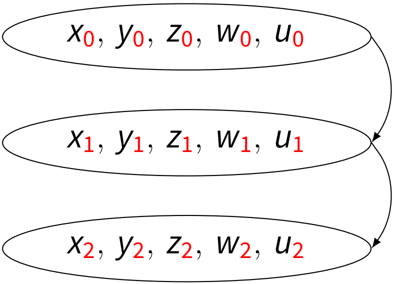

$$\min x_0 + y_0 + z_0 + w_0 + u_0$$
$$s.t. \text{ all constraints in } \mathcal{C} \text{ are satisfied}$$

Convert GD to a CP Problem

$r_0 : [x, y, z]$

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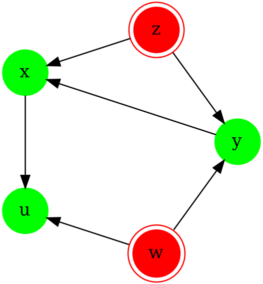

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Autoguess

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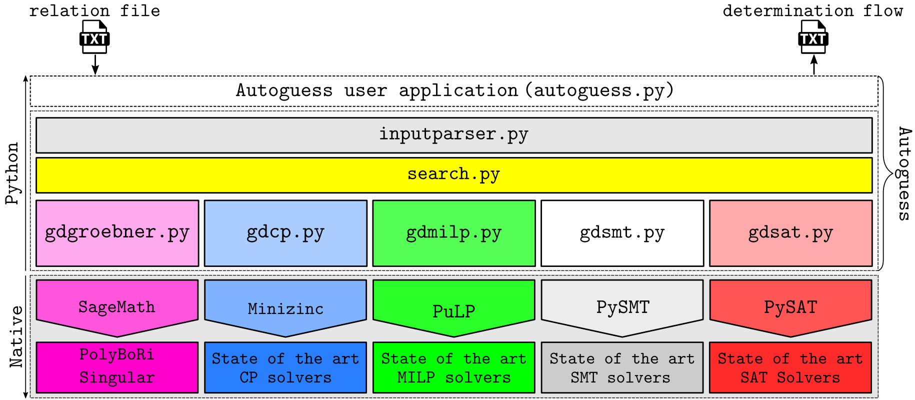

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Autoguess - Simple User Interface

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

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`):

```
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u, v, x, y, z
u, w, y, z
w, x, y, z
u, w, z
u, w => t
t, z, v
end
```
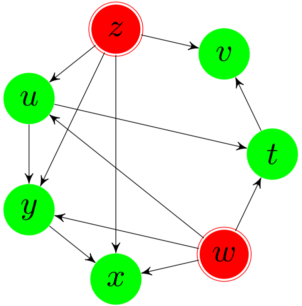
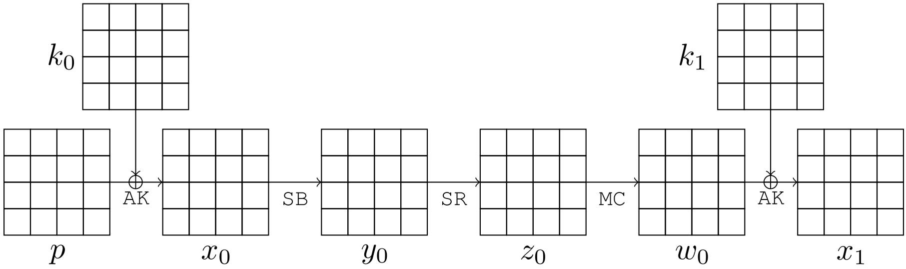

Output:



GD Attack on Block Ciphers (1 round of AES)



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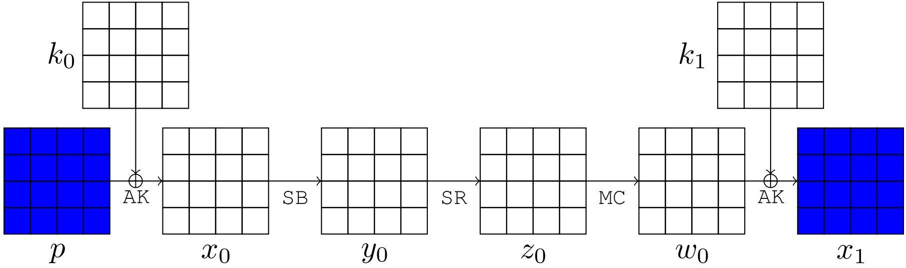

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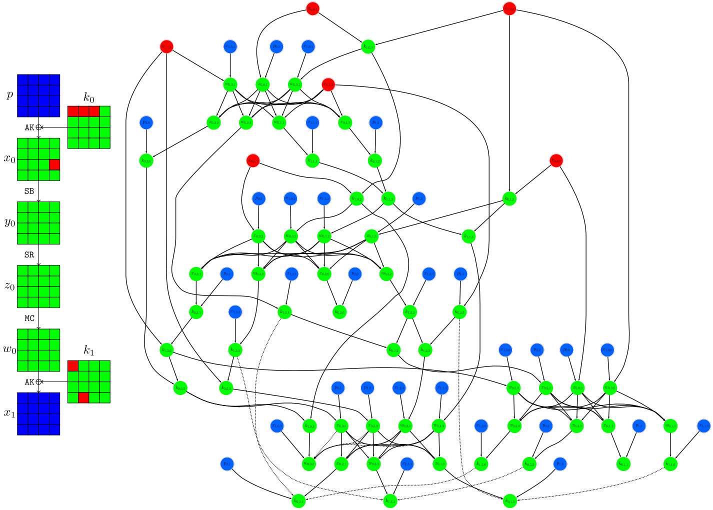

Found in 0.02 seconds on a `2.8 GHz i7-1165G7 CPU`

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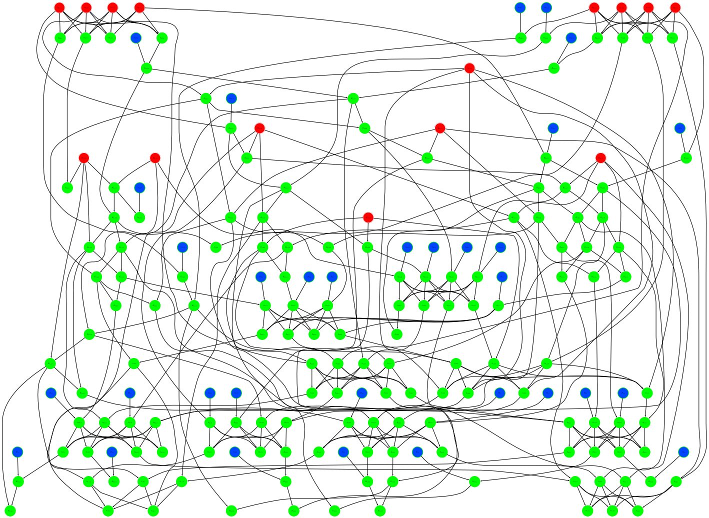
GD Attack on Block Ciphers (3 Rounds of AES)



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

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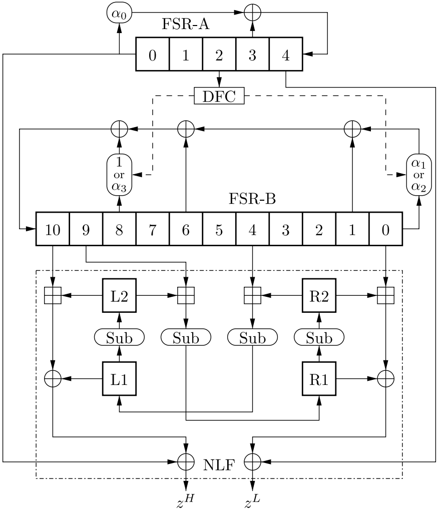
GD Attack on Stream Ciphers (KCipher-2)



ISO/IEC 18033-4

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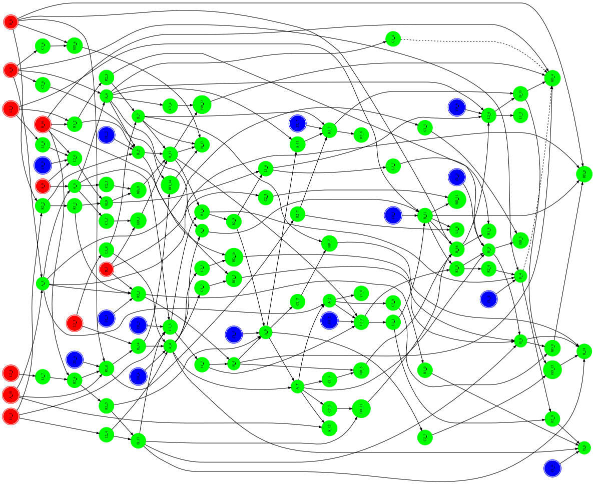

Found in 7 seconds on a `2.8 GHz i7-1165G7 CPU`

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Key-Bridging (KB)

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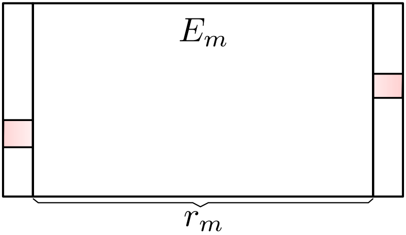

- We want to determine a subset of sub-key bits: $B \cup F$
- Key schedule implies some relations between the sub-key bits in $B \cup F$

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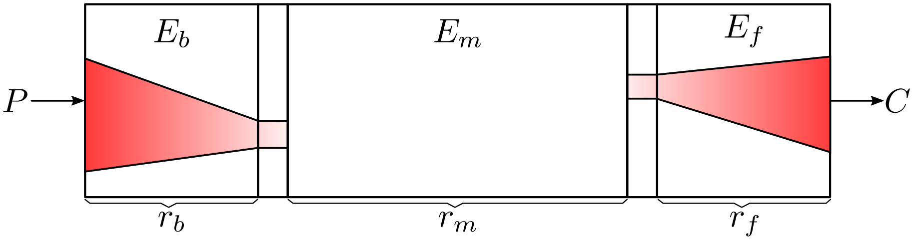

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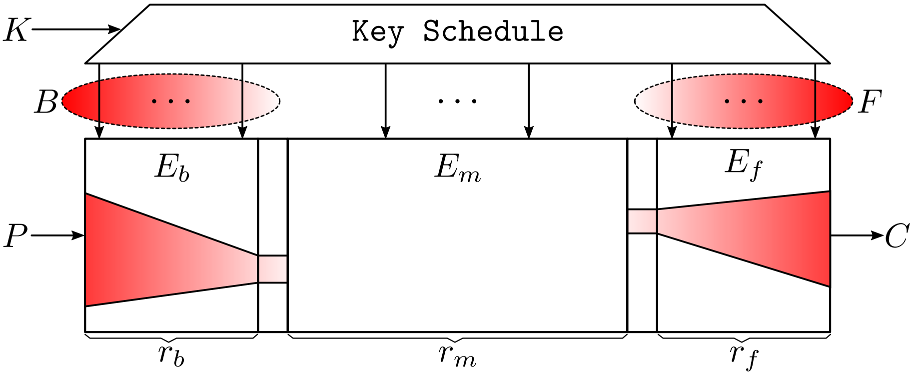

- We want to determine a subset of sub-key bits: $B \cup F$
- Key schedule implies some relations between the sub-key bits in $B \cup F$
- Find a minimal guess basis for $B \cup F$ (not for the entire set of variables)

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$\mathcal{DS}$-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]

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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