A Guidance of The Full-Fledged Model

our paper link.

our code link.

Overview

Infrastructure

To run the model, ensure "Minizinc with Or-Tools" is installed on your computing device.

Note that, we run the model on *AMD Ryzen 9 7945HX* with *32* threads, using:

`minizinc --solver CP-SAT -p 32 Modelname.mzn > RESULTs.txt`

Instruction manual

All variables in our model (*solver = CP-SAT*) are integers; when floats arise, try to transform them to a larger integer if it`s possible.

Components

Each part of our model is separated in different *dzn* files, therefore, we have the following components:

- **Main:** "0_Deoxys. mzn" is the center control model. By enabling or disabling the functions in this main model, it`s possible to adjust the searching depth.
- **Pattern (Dis. and Ext.):** "1_differential.dzn" constraints the differential pattern of the whole attack.
  - Returning parameters: active cells r_b, r_f, involved subkeys m_b, m_f, and $probability$.
  - The probabilistic extension is allowed, and m_b, m_f can be smaller when the state test is working in this component.
  - Open `include "1_differential.dzn";` to use this function.
- **Guessing Strategy:** "2_guess_and_determine.dzn" describes the pre-guessing strategy of subkeys.
  - Returning parameters: pre-guessed subkeys m'_b, m'_f, filters r'_b, r'_f.
  - $Gstate$ is also contain in m'_b, m'_f when the state test is working.
  - Open `include "2_guess_and_determine.dzn";` to use this function.
- **Epsilon calculation:** "3-1_epsilon_gandf-ST.dzn" and "3-2_epsilon_table-ST.dzn" give the constraints of step assignment and complexities.

- Returning parameters: processing step of the unguessed subkeys, corresponding filters, time and memory complexity of each step.
- When the state test is working, ST is contained as subkeys, and EGK is eliminated, in some steps.
- Open `include "3-1_epsilon_gandf-ST.dzn";` to use the guess-and-filter approach, and `include "3-2_epsilon_table-ST.dzn";` for the pre-computation hash table approach.

Predicates: "predicates.dzn"

- `include "3-1_epsilon_gandf-ST.dzn";` is set as default.
- Many predicates are included as methods that can be used in other components.

Adjustments in Main

State test

The switch of state test:

```
int: OpenST = 0; % 1 -> Trun on State Test;
constraint if OpenST = 0
          then forall(r in 0..Rb-1, i in 0..15)(uST[r,i] = -1) /\ forall(r in
Rb+Ru+Rm+Rl..Rb+Ru+Rm+Rl+Rf-1, i in 0..15)(lST[r,i] = -1) /\
               forall(r in 0..Rb-1, i in 0..15)(uEGK[r,i] = -1) /\
               forall(r in 0..Rb-1, i in 0..15)(uESB[r,i] = -1) /\
               forall(r in 0..Rb-1, i in 0..15)(uEMC[r,i] = -1) /\
               forall(r in Rb+Ru+Rm+Rl+1..Rb+Ru+Rm+Rl+Rf, i in 0..15)(lEGK[r,i]
= -1) /\
               forall(r in Rb+Ru+Rm+Rl..Rb+Ru+Rm+Rl+Rf-1, i in 0..15)(lESB[r,i]
= -1) /\
               forall(r in Rb+Ru+Rm+Rl..Rb+Ru+Rm+Rl+Rf-2, i in 0..15)(lEMC[r,i]
= -1)
          endif;
```

Key bridging

The following constraints of strong key bridging are applied only when an attack achieves no less than 15 rounds.

3 cases for involvements, guessing strategy, and epsilon calculation....

```
% CASE-1: Strong Key Bridges for involved key
array[0..3] of var int: vRd;
constraint forall(c in 0..3)(vRd[c] = JTable[sum(i in 0..3)
(uVSTK[0,hTable[4*c+i,1]]), sum(i in 0..3)(lVSTK[15,4*c+i])]);
var int: mb  = sum(r in 0..Rb-1, i in 0..15)(uVSTK[r,i] == 1 /\ uEGK[r,i] == -1)
+ sum(r in 0..Rb-1, i in 0..15)(uVstate[r,i]);
var int: mf  = sum(r in Rb+Ru+Rm+Rl+1..Rb+Ru+Rm+Rl+Rf, i in 0..15)(lVSTK[r,i] ==
1 /\ lEGK[r,i] == -1) + sum(r in Rb+Ru+Rm+Rl..Rb+Ru+Rm+Rl+Rf-1, i in 0..15)
(lVstate[r,i]);
var int: mk = 8*(mb + mf) - sum(c in 0..3)(vRd[c]);

% Strong Key Bridges for pre-guessed key
array[0..3] of var int: gRd;
constraint forall(c in 0..3)(
```

```
  if forall(i in 0..3)(uGSTK[0,hTable[4*c+i,1]] = uVSTK[0,hTable[4*c+i,1]] /\
lGSTK[15,4*c+i] = lVSTK[15,4*c+i])
  then gRd[c] = JTable[sum(i in 0..3)(uGSTK[0,hTable[4*c+i,1]]), sum(i in 0..3)
(lGSTK[15,4*c+i])]
  else gRd[c] = 0
  endif);
var int: mb_p = sum(r in 0..Rb-1, i in 0..15)(uGSTK[r,i]) + sum(r in 0..Rb-1, i
in 0..15)(uGstate[r,i]);
var int: mf_p = sum(r in Rb+Ru+Rm+Rl+1..Rb+Ru+Rm+Rl+Rf, i in 0..15)(lGSTK[r,i]) +
sum(r in Rb+Ru+Rm+Rl..Rb+Ru+Rm+Rl+Rf-1, i in 0..15)(lGstate[r,i]);
var int: mk_p = 8*(mb_p + mf_p) - sum(c in 0..3)(gRd[c]);

% Strong Key Bridges for epsilon calculation
array[0..3] of var -1..Step: sBigRd;
array[0..3] of var int: sRd;
constraint forall(c in 0..3)(sBigRd[c] = max(max(i in 0..3)(uSGK[0, hTable[4*c+i,
1]]), max(i in 0..3)(lSGK[15, 4*c+i])));
constraint forall(c in 0..3)(
  if sBigRd[c] >= 1
  then sRd[c] = JTable[sum(i in 0..3)(uSGK[0,hTable[4*c+i,1]] >= 1 /\
uSGK[0,hTable[4*c+i,1]] <= sBigRd[c]),
                       sum(i in 0..3)(lSGK[15,4*c+i] >= 1 /\ lSGK[15,4*c+i] <=
sBigRd[c])]
  else sRd[c] = 0
  endif);
array[1..Step] of var int: sRdS;
constraint forall(s in 1..Step)(if exists(c in 0..3)(sBigRd[c] = s) then sRdS[s]
>= 0 else sRdS[s] = 0 endif);
constraint forall(c in 0..3)(if sBigRd[c] >= 1 then sRdS[sBigRd[c]] = sRd[c]
endif);
```

Since the impact of key bridging is implicit, we give the format output to show the influence of key bridging (redundancy in different processes): easy for verify where the key bridging working in.

```
output[show(mb+mf) ++ " bytes |" ++ show(sum(c in 0..3)(vRd[c])) ++ " bits ------
"]; % involvement
output[show(mb_p+mf_p) ++ " bytes |" ++ show(sum(c in 0..3)(gRd[c])) ++ " bits --
---- "]; % pre-guessing
output[show([sRdS[s] | s in 1..Step])]; % epsilon calculation
```

Objective Functions for Elasticizing

Note that the extra variables for disabling functions exist throughout the entire model, but are constrained out (assigning constants) of solutions when they provide influences.

Main + Pattern

$$\min(a \times PrAtt + b \times (m_b + m_f))$$

Main + Pattern+ Guessing Strategy

$$constraint \;\; Time_\epsilon = 0$$
$$\min(a \times Time + b \times Memory + c \times Date)$$

Whole Model

$$\min(a \times Time + b \times Memory + c \times Memory_{\epsilon} + d \times Data)$$

Due to the long time required to solve the whole model, we provide some constraints as *TEST* for fast verification.

Examples

We give the models and the corresponding results of 2 versions of `Deoxys`, goto:

- **11-round** `Deoxys-BC-256`
- **15-round** `Deoxys-BC-384`

We give the models and the corresponding results of 2 versions of `Deoxys-AE`, goto:

- **10-round** `Deoxys-I-128-128`
- **14-round** `Deoxys-I-256-128`

We give the models and the corresponding results of 2 versions of `Deoxys-multiTK`, goto:

- **16-round** `Deoxys-TBC-512-256`
- **18-round** `Deoxys-TBC-640-256`

Alter-abling specifications for different attacks (example = 11-round rectangle attack on `Deoxys-BC-256`)

```
int: SpecDeoxys = 2; % denotes TK2
int: block_size = 128;
int: key_size = block_size * SpecDeoxys;

int: Rb = 1; % backward extension
int: Ru = 3; % upper differential
int: Rm = 2; % middle
int: Rl = 3; % lower differential
int: Rf = 2; % forward extension
```

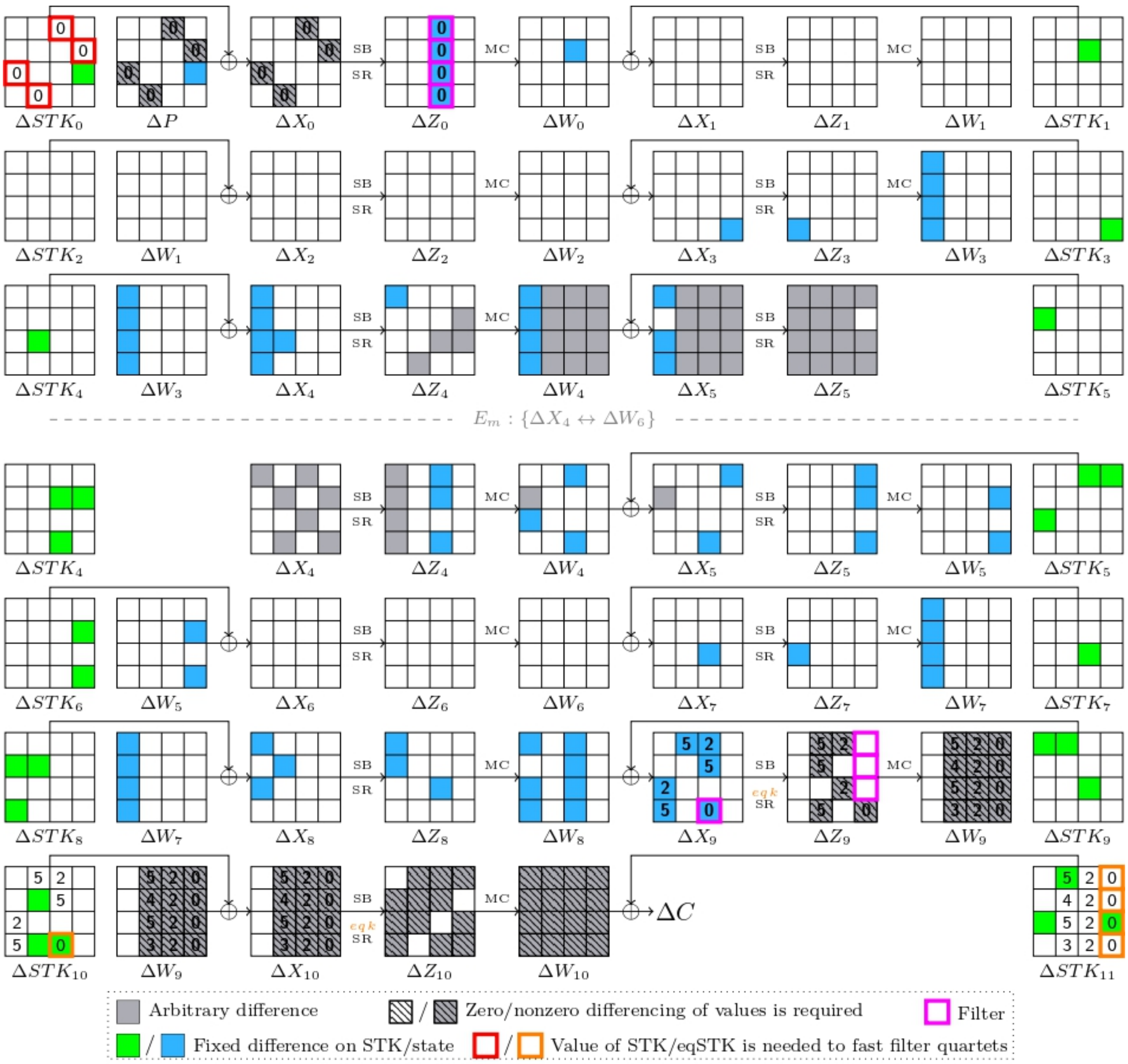
Deoxys-BC-256 (11r)

```
int: SpecDeoxys = 2;
int: block_size = 128;
int: key_size = block_size * SpecDeoxys;

int: Rb = 1;
int: Ru = 3;
int: Rm = 2;
int: Rl = 3;
int: Rf = 2;
```

Result obtained (detail):

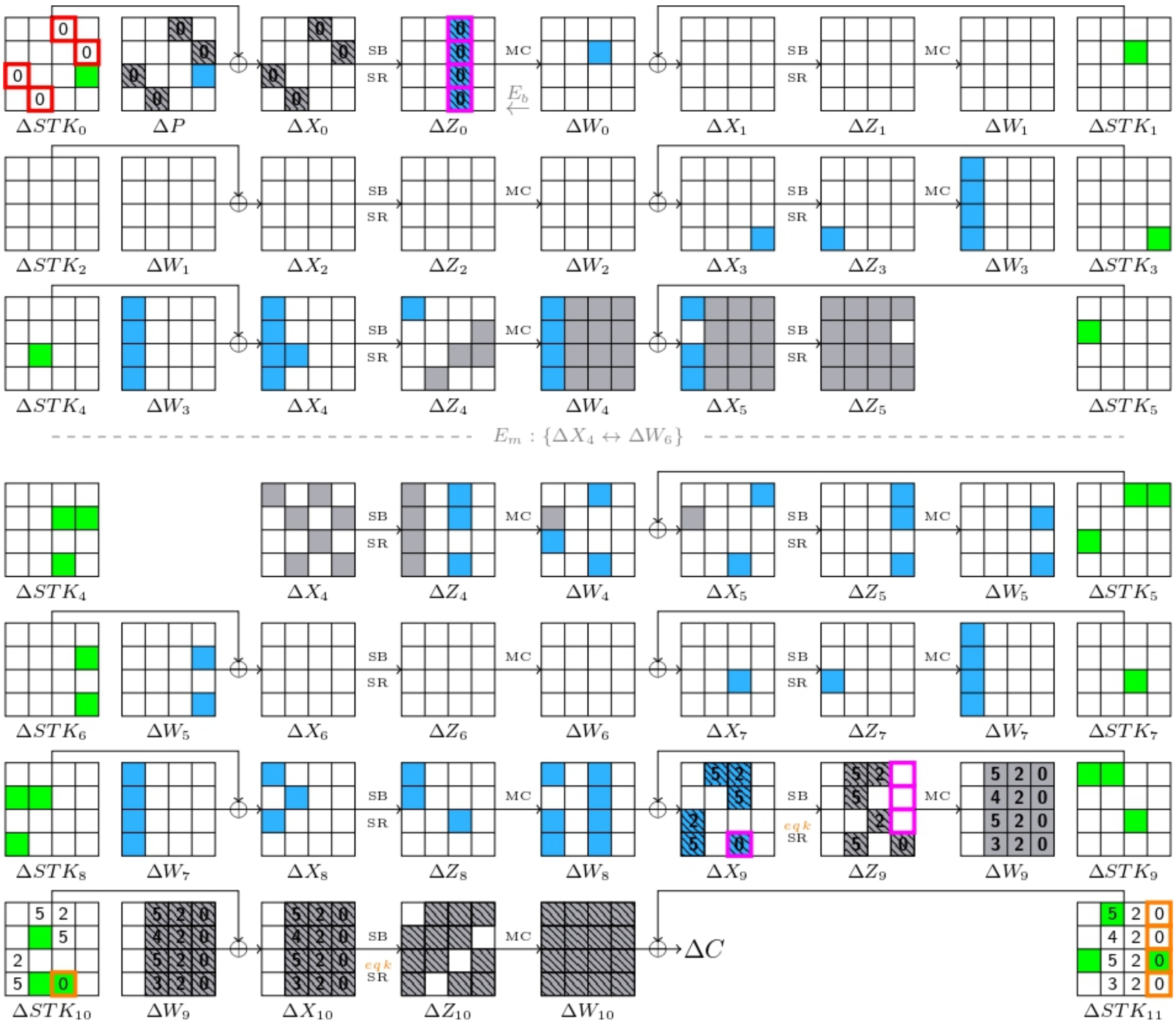
```
Complexity of Rectangle Attack on Deoxys-BC-384:

Parameters:
----------------------
rb= 4 | rb'= 4 | mb= 4 | mb'= 4
rf=12 | rf'= 4 | mf=18 | mf'= 5
----------------------
Prob.  : 112
Data  : 122
MemoryC: 123
TimeC  : 195 [T1=194 | T2u=195, T2l=253 | T3=188 (epsilon=0)]
```

Draw with TikZ latex:



Deoxys-BC-384 (15r)

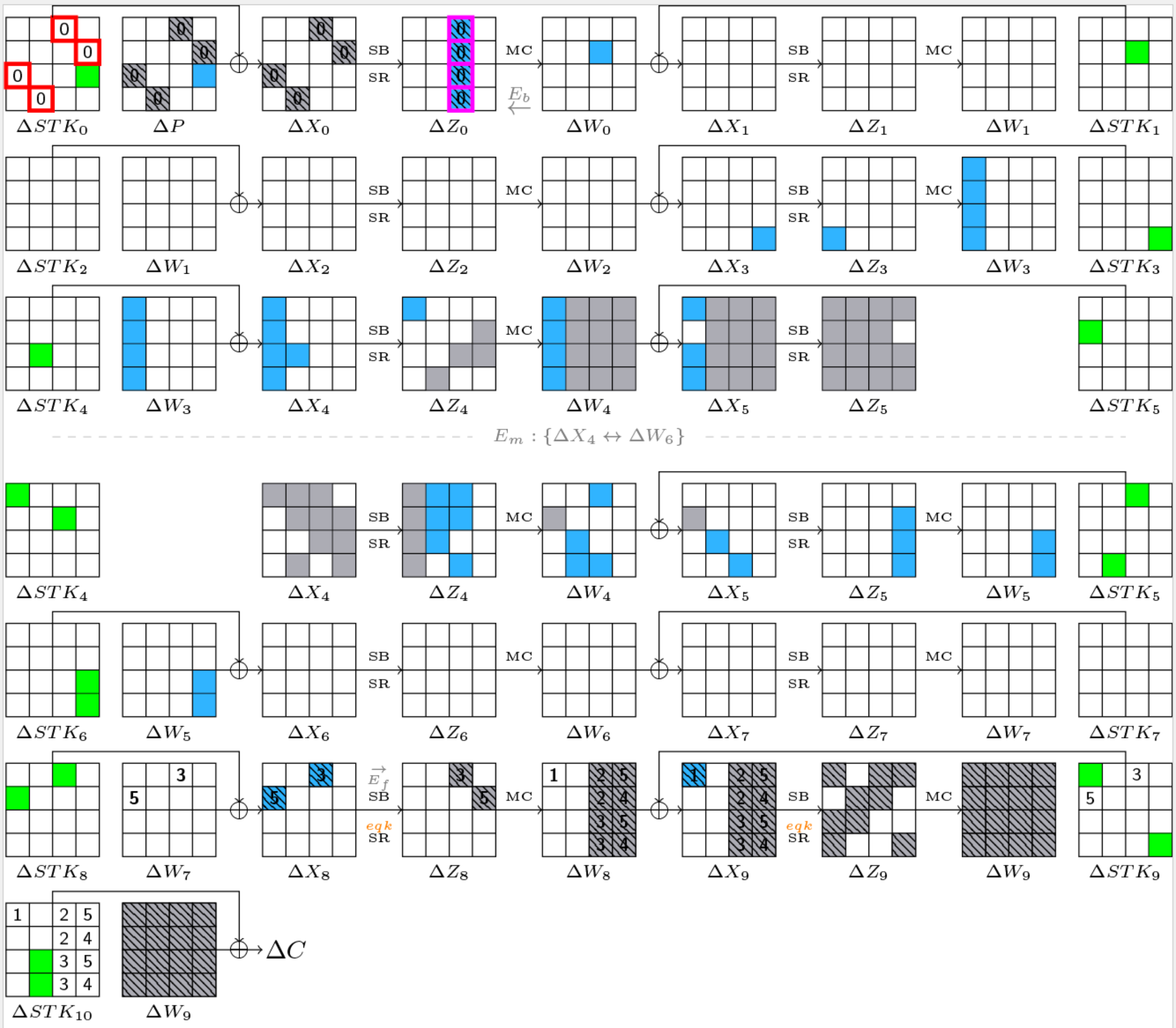
```
int: SpecDeoxys = 3;
int: block_size = 128;
int: key_size = block_size * SpecDeoxys;

int: Rb = 1;
int: Ru = 4;
int: Rm = 2;
int: Rl = 4;
int: Rf = 4;
```



Prob.: 112 (0, 14, 42, 56, 0); $r_b = 4$ $r'_b = 4$ $m_b = 4$ $m'_b = 4$; $r_f = 12$ $r'_f = 4$ $m_f = 18$ $m'_f = 5$

DataC: 122, MemoryC: 123 ($M_\epsilon = 14$), TimeC: 195 [T_1=194, T_{2u}=195 T_{2l}=253, T_3=188 (T_ϵ=0)]

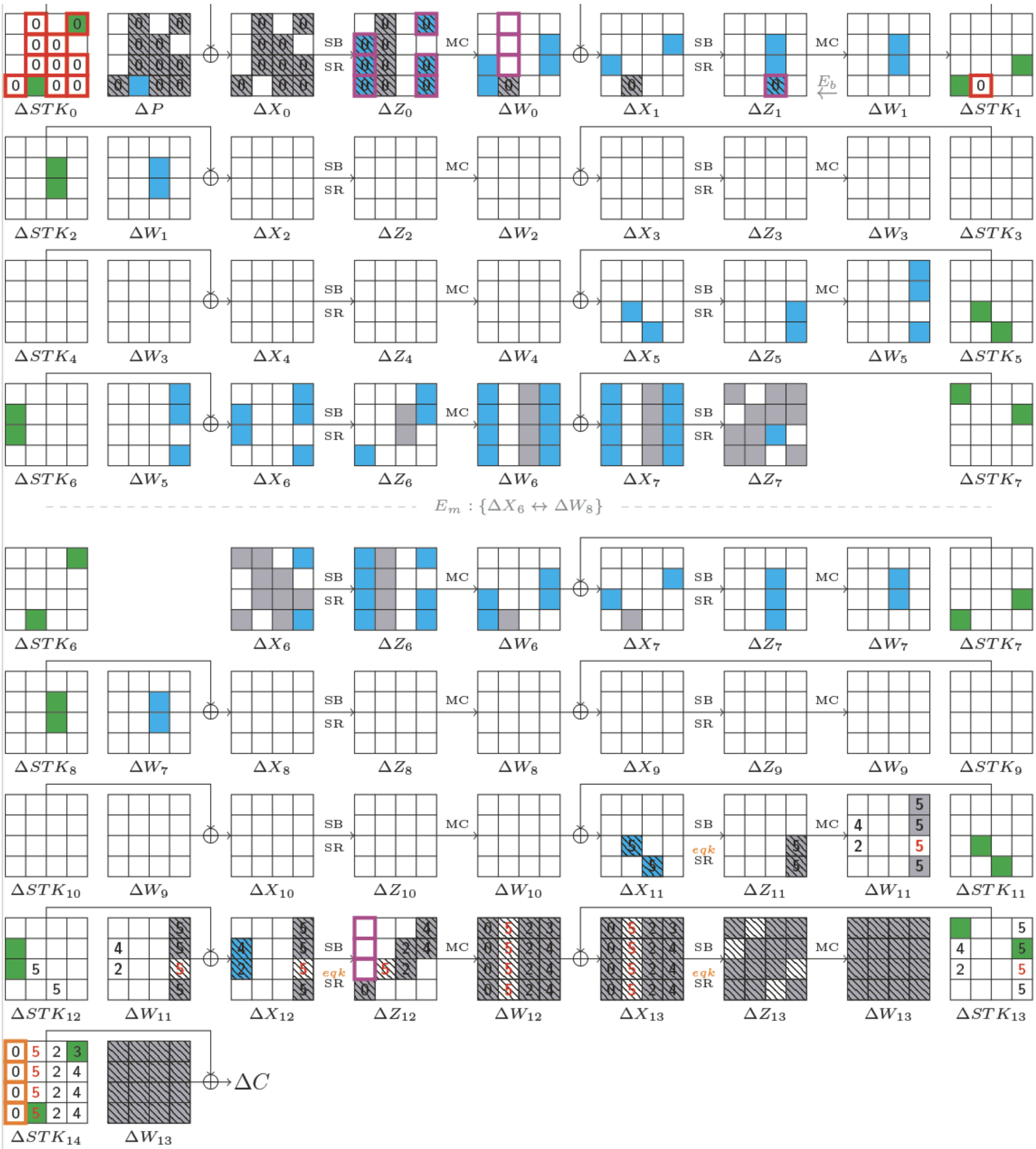
Deoxys-I-128 (10r)



Prob.: 56 (0, 14, 42, 0, 0); $r_b = 4$ $r'_b = 4$ $m_b = 4$ $m'_b = 4$; $r_f = 9$ $r'_f = 0$ $m_f = 11$ $m'_f = 0$

DataC: 94, MemoryC: 95 ($M_\epsilon = 6$), TimeC: 127 [T_1=126, T_{2u}=127 T_{2l}=165, T_3=124 (T_ϵ=2)]

Deoxys-I-256 (14r)



Prob.: 102 (28, 28, 30, 0, 16); $r_b = 10$ $r'_b = 10$ $m_b = 11$ $m'_b = 11$; $r_f = 12$ $r'_f = 3$ $m_f = 19$ $m'_f = 4$
DataC: 117, MemoryC: 120 ($M_\epsilon = 15$), TimeC: 242 [T_1=237, T_{2u}=238, T_3=242 (T_ϵ=0)]

Pretty Output, Drawing Using TikZ

```
include "./format_out/1_format_out_diff.dzn"; % show differential pattern, parameters, and probability
include "./format_out/3-2_format_out_tableST.dzn"; % show step assignment and complexities of epsilon
include "./format_out/0_format_out_Main.dzn"; % show the necessary parameters, complexities of the attack
include "./format_out/drawlatex.dzn"; % draw with tikz
```

Copy the LaTeX code output and paste it into a LaTeX compiler.

For SKINNY

`SKINNY` is a typical example that uses a non-MDS matrix as its linear layer; therefore, in the key recovery phase, differential-determination detection beyond value determination is necessary in the components Guessing Strategy and Epsilon Calculation.

For each differential of state, `X`, sets of variables we used in the key recovery model of `SKINNY-64-192` and `SKINNY-128-384`:

```
vX: value needed
dX: differential needed
gSTK: guessed subkey in Guessing Strategy
detX: value determined
detdiffX: differential determined
sgSTK: guessed subkey in step assignment
saX: value assigned step
sadiffX: differential assigned step
sdvX: value deduced in step assignment
sdSTK: subkey deduced (using the property of Sbox) in step assignment
```

Considering new sets of variables, `detdiffX, sadiffX, sdvX, sdSTK`, allows more delicate relations to be captured in our model. Specifically, in the Epsilon Calculation component, the Sbox property can be used to deduce subkeys that are not guessed in any process.

For Deoxys-TK4/5

Security Claims for `Deoxys-TK4` and `Deoxys-TK5`:

The claimed security margins of these two versions of `Deoxys-BC` are bounded by 2^{256} in single-key-scenario key recovery attacks. The advantage of larger tweakey exhibits at the more frequent subkey cancellations (refers to Benoît Cogliati, Jérémy Jean, Thomas Peyrin, and Yannick Seurin, A Long Tweak Goes a Long Way: High Multi-user Security Authenticated Encryption from Tweakable Block Ciphers. *IACR Communications in Cryptology*, vol. 1, no. 2, Jul 08, 2024, doi: 10.62056/a3qjp2fgx. for details). Notably, the cancellation exists both in the distinguisher and the extension in our models.

Note the tweak update of `Deoxys-TK4` and `Deoxys-TK5` use multiplication in the Finite Field; therefore, the key bridge is excluded in the models for these two block ciphers.