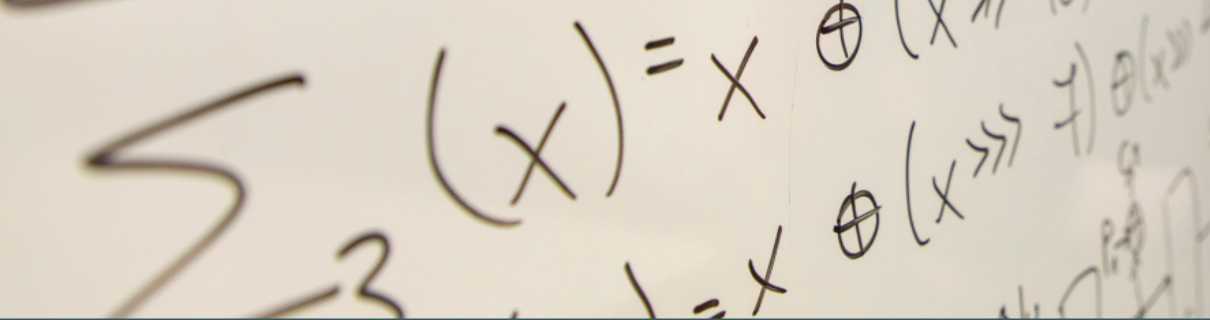


Automating the Search for Cryptanalytic Attacks

Maria Eichlseder

- FSE 2024
- Leuven · 26 Mar 2024

› https://iaik.tugraz.at

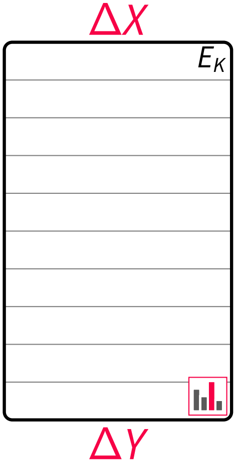
Outline

- Motivation
- Finding Distinguishers with MILP/SAT Solvers
  - Mixed-Integer Linear Programming (MILP)
  - Boolean Satisfiability and Constraint Programming (SAT/SMT, CP)
- Dedicated Algorithms
- Optimized Key Recovery Attacks
- Frameworks

Motivation

Differential Cryptanalysis [BS90]

Method



Attack Goals

collision,
forgery

key recovery

. . .

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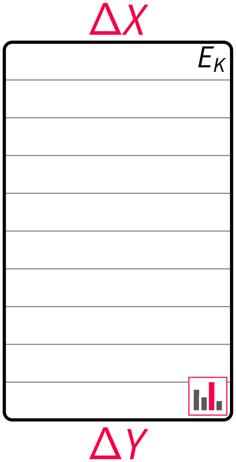

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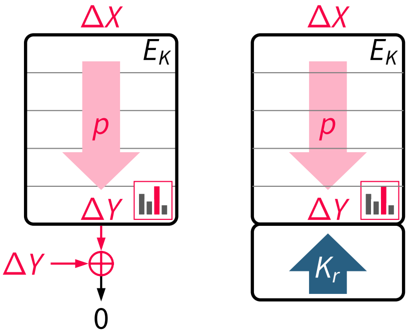

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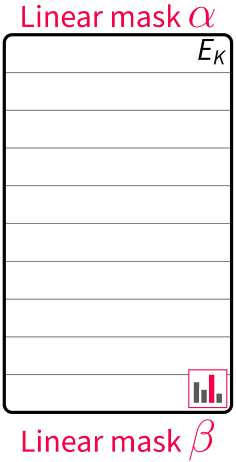

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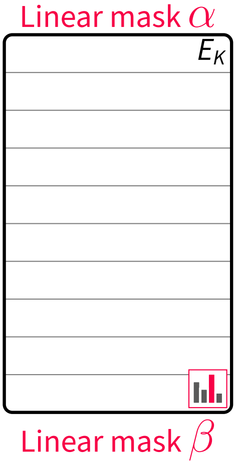

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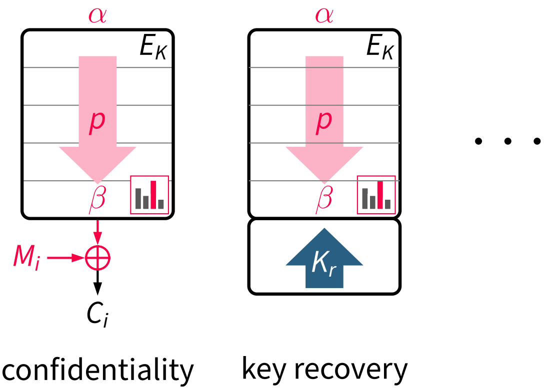

Integral Cryptanalysis [Lai94; Knu94; KW02]

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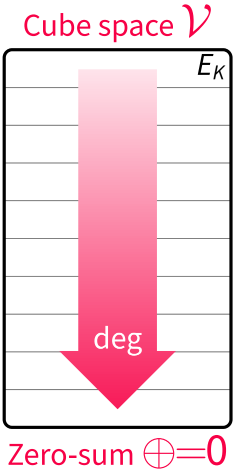

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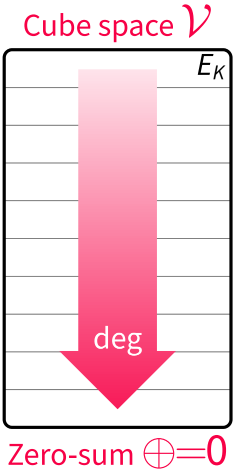

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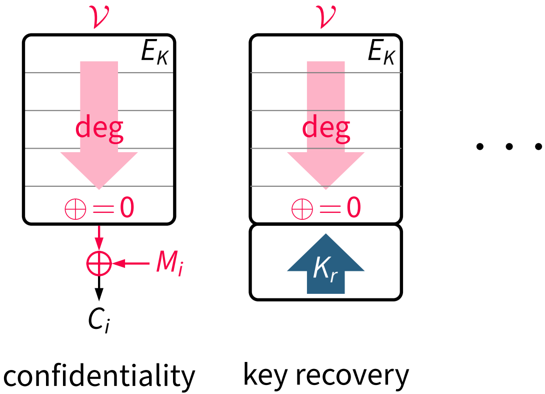

How to Find Distinguishers

- By hand
- Dedicated solvers
- General-purpose solvers:
  - SAT/SMT (Boolean SATisfiability/Sat. Modulo Theories)
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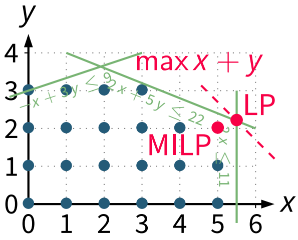

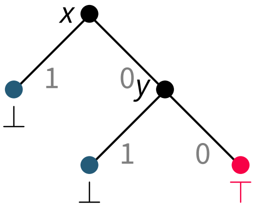

Finding Distinguishers with MILP/SAT Solvers

Basic Approach

- Model constraints that characterize correct characteristics/solutions
  - Coarse-grained: truncated patterns (which S-boxes are active?)
  - Fine-grained: precise differences/masks
- Model cost (if applicable)
- Express the search goal: any one / all / best / good solution(s)?

Mixed-Integer Linear Program (MILP)

Linear Programming (LP) is a method to solve optimization problems

- on the real-valued, positive decision variables $x \in \mathbb{R}^d, x \geq 0$
- with a linear objective function (min or max) $f(x) = c^\top x = \sum_{i=1}^{d} c_i x_i$
- under J linear constraints (s.t.) $Ax \leq b$, i.e., $\sum_{i=1}^{d} a_{ji} x_i \leq b_j$ for $1 \leq j \leq J$:

$$\max_{x \in \mathbb{R}^d} \{c^\top x \mid Ax \leq b \wedge x \geq 0\}$$

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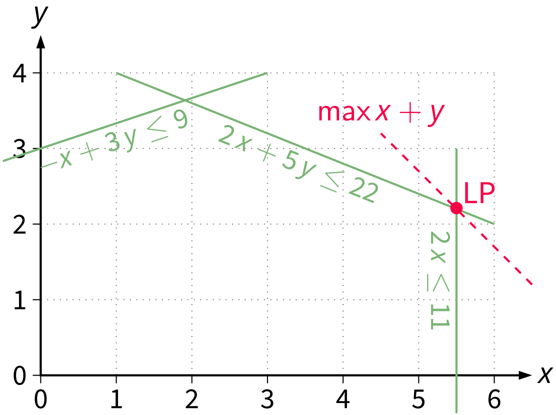

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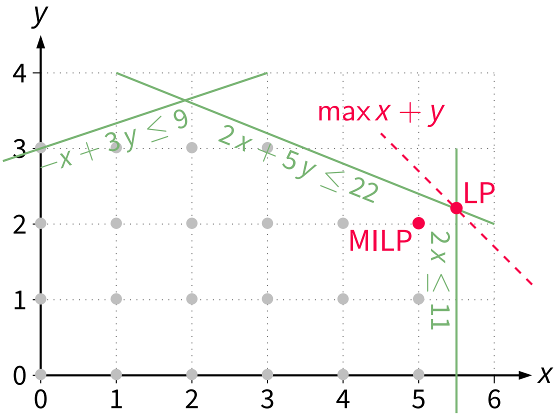
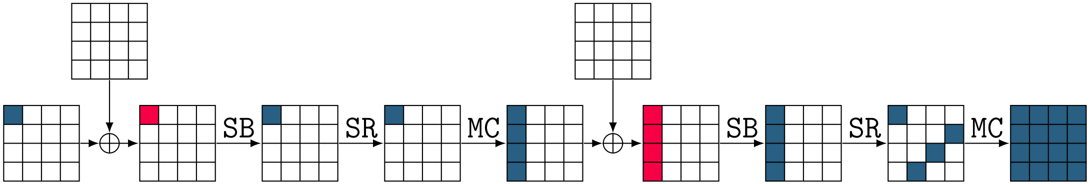


MILP – Example application: AES [MWGP11; WW11]



Variables: 1 binary variable per state byte (active/inactive)

- AddRoundKey: input = output
- SubBytes: input = output, cost = sum(inputs)
- ShiftRows: variable renaming
- MixColumns: for each active column: sum(inputs) + sum(outputs) $\geq$ 5 (= $\mathcal{B}$)

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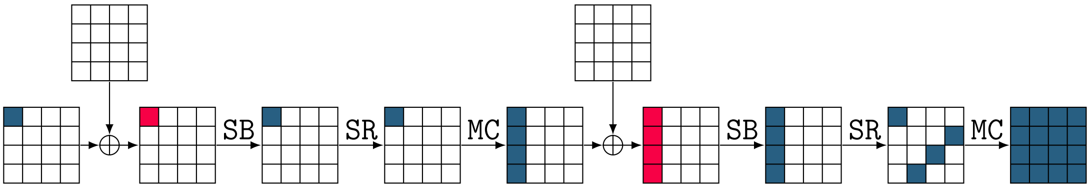

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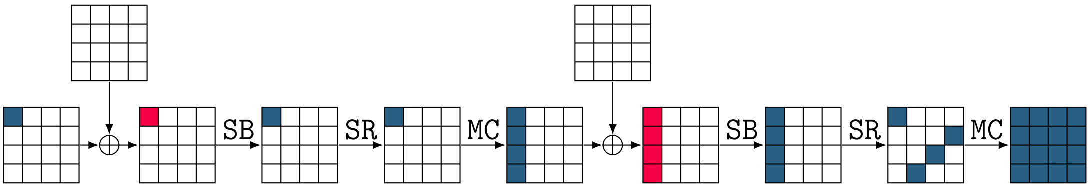

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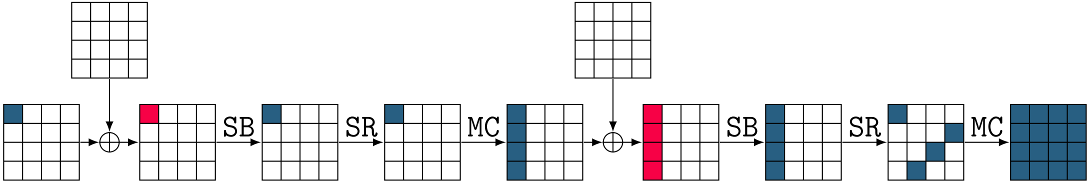

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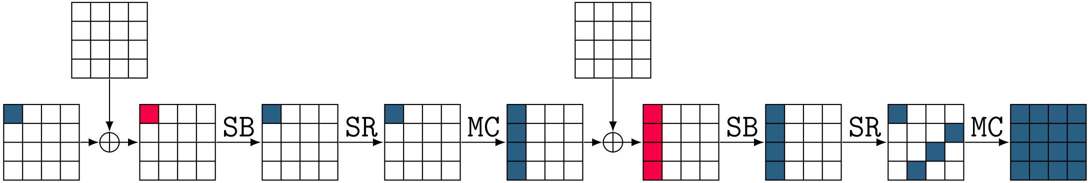

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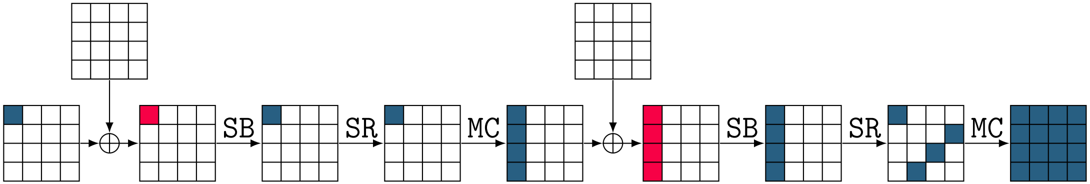

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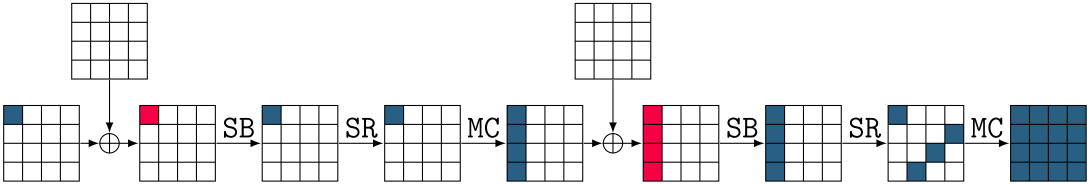

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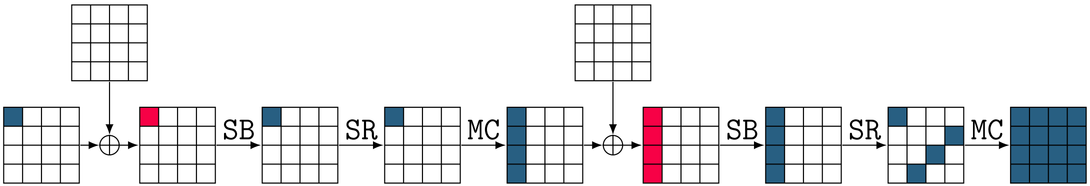

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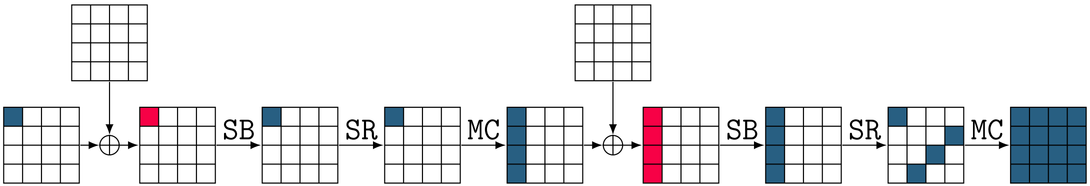

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MILP – Example application: AES [MWGP11]

Variables:

- $S_{r,i,j} \in \{0, 1\}$: Is S-box in row i, column j in round r active?
- $M_{r,j} \in \{0, 1\}$: Is MixColumns j in round r active?

Linear Program:

$$\min \sum_{r,i,j} S_{r,i,j} \qquad \text{(Min \# active S-boxes)}$$

$$\text{s.t.} \quad \mathcal{B} \cdot M_{r,j} \leq \sum_i S_{r,i,(i+j)\%4} + \sum_i S_{r+1,i,j} \leq 8 \cdot M_{r,j} \qquad \text{(For each MixColumns)}$$

$$\sum_{i,j} S_{0,i,j} \geq 1 \qquad \text{(Non-triviality)}$$

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MILP – Example application: AES – Code in sagemath

```
#!/usr/bin/env sage
rounds = range(4)
p = MixedIntegerLinearProgram(maximization=False)
S = p.new_variable(name='sbox', binary=True)
M = p.new_variable(name='mcol', binary=True)

for r in rounds:
    for j in [0..3]:
        activecells = sum(S[r,i,(i+j)%4] for i in [0..3]) \
                    + sum(S[r+1,i,j] for i in [0..3])
        p.add_constraint(5*M[r,j] <= activecells <= 8*M[r,j])
p.add_constraint(sum(S[0,i,j] for i in [0..3] for j in [0..3]) >= 1)

p.set_objective(sum(S[r,i,j] for r in rounds for i in [0..3] \
                                              for j in [0..3]))
p.solve()
print(p.get_objective_value(), p.get_values(S))
```

MILP – Advanced models

- Modeling more complex relations of “allowed transitions” accurately
  - Activity patterns for linear layers: XOR, near-MDS matrices [ABD+23], …
  - DDT/LAT for bitwise S-box models [SHW+14b; SHW+14a], ARX [FWG+16]
- Need to translate **vertex representation** into **half-space representation**

XOR :

- inputs ☐, ☐ → output ☐
- inputs ☐, ■ → output ■
- inputs ■, ☐ → output ■
- inputs ■, ■ → output ☐ or ■

➔

$$\begin{cases} I_1 + I_2 \geq O \\ I_1 + O \geq I_2 \\ I_2 + O \geq I_1 \end{cases}$$

- For large tables, this becomes very heavy (e.g., 8-bit S-boxes [AST+17; SW23])

SAT/SMT/CP – Different Levels of Convenience

1. **SAT (Satisfiability) Solvers**: Find valid solution or prove unsatisfiability of CNF

$$\bigwedge_i \bigvee_j \ell_{i,j} \qquad \text{with literals } \ell_{i,j} \in \{v_{i,j}, \neg v_{i,j}\}$$

   Example solvers: `MiniSAT`, `lingeling`, and a myriad others

2. **SMT (Sat. Modulo Theories) Solvers**: Accept a more general grammar including bitvector operations such as integer addition.

   Example solvers: `STP` ("Simple Theorem Prover"), …

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SAT/SMT/CP for Finding Distinguishers [MP13; Köl14]

- Solves a **constraint satisfaction problem**, may not be optimal
  - “Emulate” optimization: “is there a solution better than $X, X+1, X+2, \ldots$?”
- Useful to find valid solutions under some constraints
  - Finding characteristics that follow a given truncated pattern
  - Finding solutions for other crypto problems (preimage, …)
- Not so efficient for some more complex problems
  - Not so good for modelling a **cost** sum or optimization [EME22]
  - Not perfectly **parallelizable**

Dedicated Algorithms

Dedicated Tools for Hash Functions: Examples

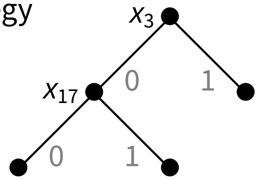
- **SHA-1**: `HashClash`
  https://github.com/cr-marcstevens/hashclash

- **SHA-2**: `nldtool`
  https://github.com/iaikkrypto/nldtool

- **SHA-3**: `KeccakTools`
  https://github.com/KeccakTeam/KeccakTools

Dedicated Guess-and-Determine Search

- Guess-and-Determine Search is a general search strategy
  - Traverse search tree to find a valid solution
  - SAT solvers use it on CNF level
  - This is an example on small (differential) circuits



- `nldtool`: Automated search for characteristics and solutions
  - Hash collision search
  - Application example: SHA-2 [MNS11; MNS13; DEM15]

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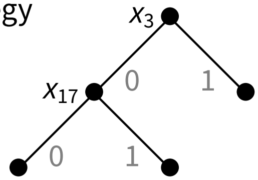

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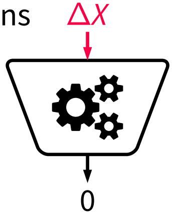


Guess-and-Determine Search Algorithm

while there are undetermined bits **do**

Decision (Guessing)

1. Pick an undetermined bit
2. Constrain this bit

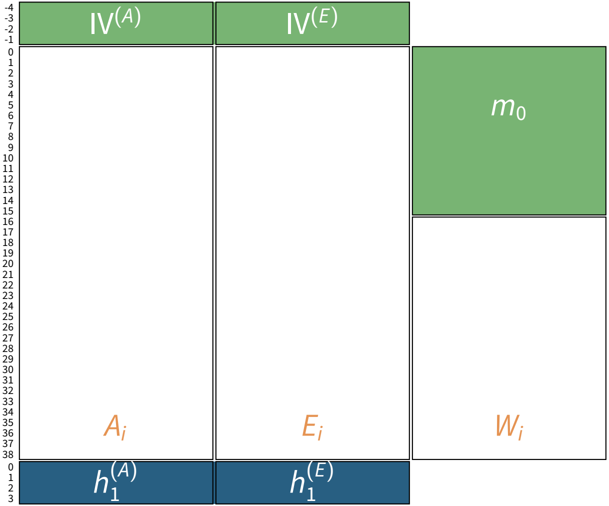
Deduction (Propagating)

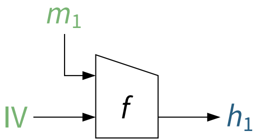
3. Propagate the new information to other variables and equations
4. **if** no inconsistency is detected, goto step 1

Correction (Backtracking)

5. **if** possible, apply a different constraint to this bit, goto step 3
6. **else** undo guesses until this critical bit can be resolved

Example: Semi-Free-Start Collision for 39-step SHA-512





- Shows state words A_i, E_i, W_i
- Inputs IV, m_1
- Output h_1

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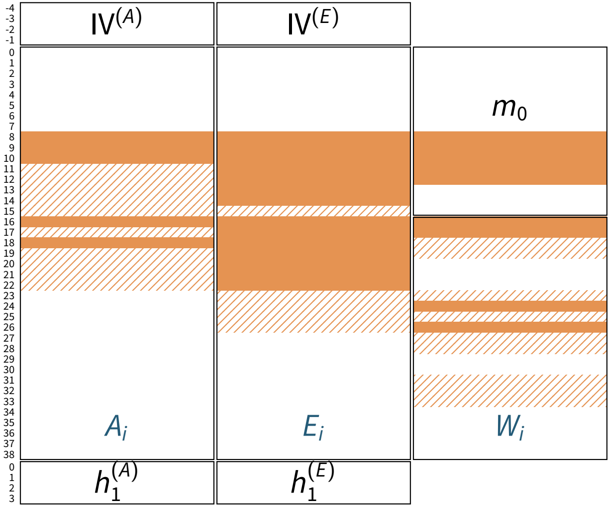

Starting point:

0. "Local Collision" with few active message words

- Active words with differences [?]
- No differences [-] (cancellation required)
- No differences [-]

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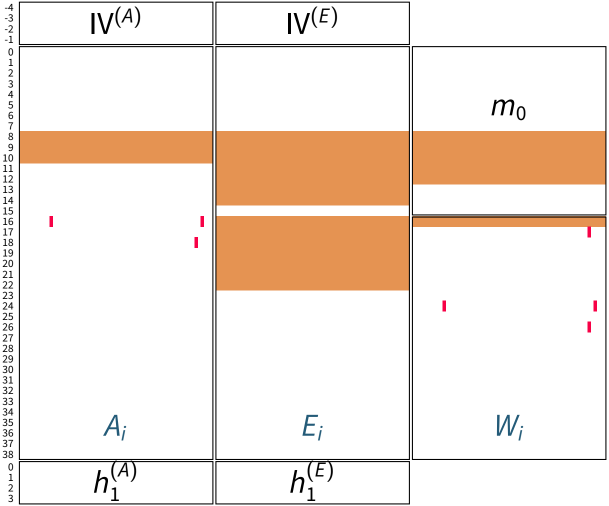

Search strategy:

1. Fix high-probability parts
2. Fix signed differences
3. Find message pair

- Active words with some differences [?]
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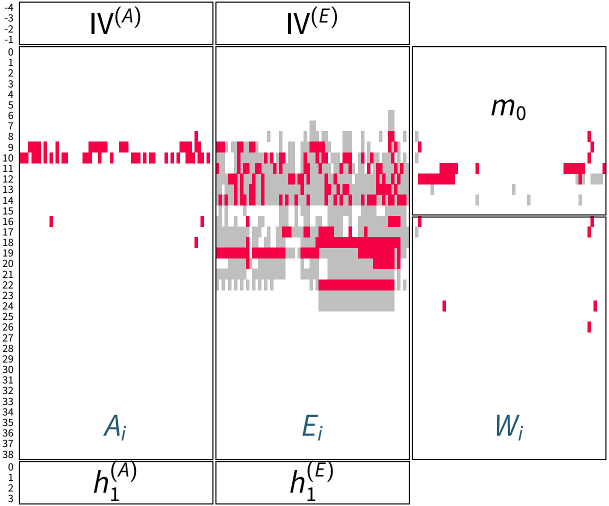

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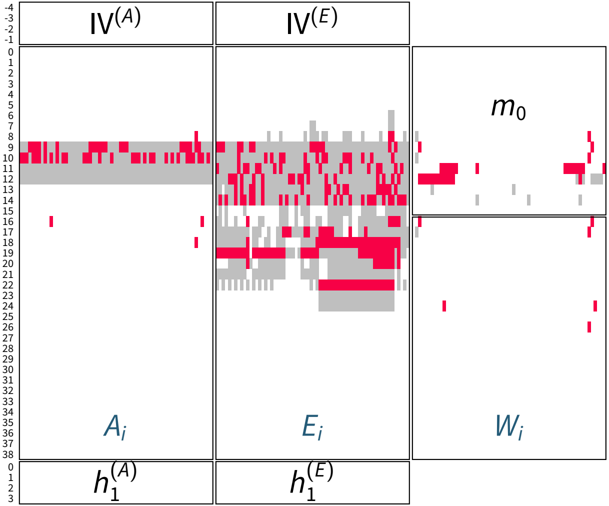

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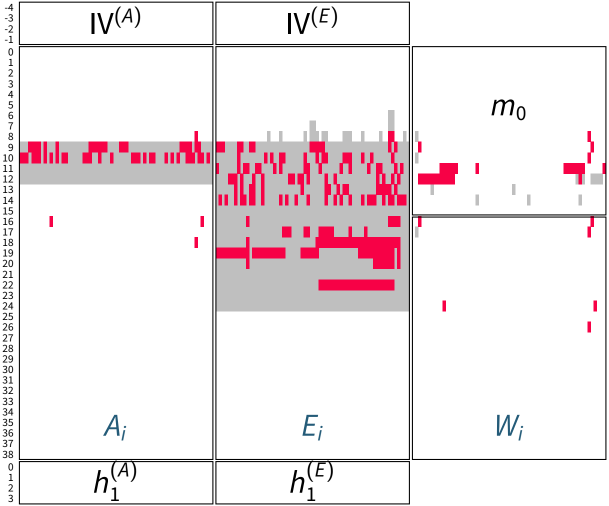

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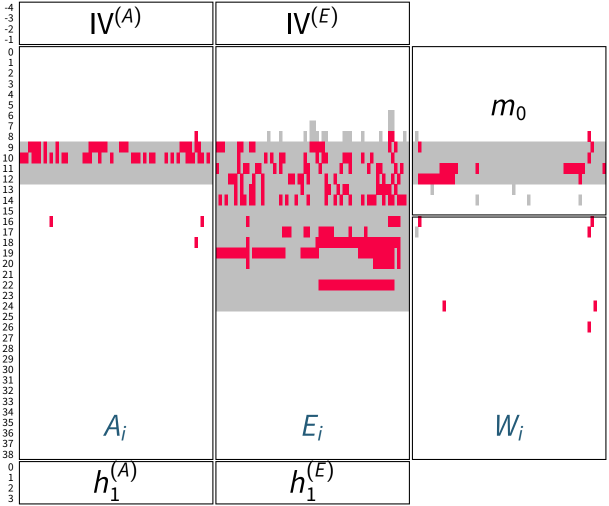

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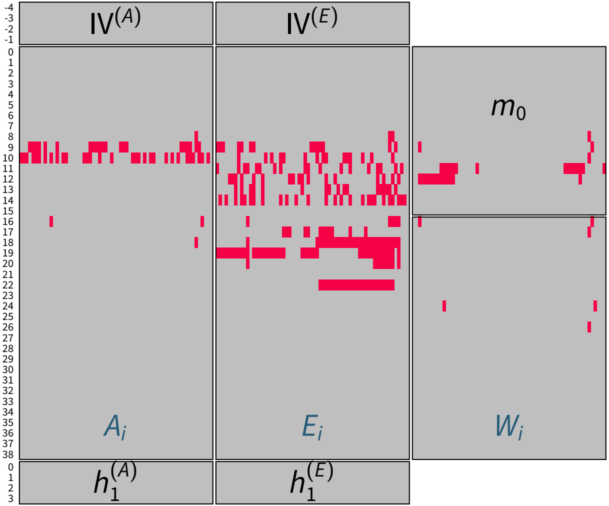

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Optimized Key Recovery Attacks

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- Key recovery has long been ignored
- Fewer choices to make for the attacker

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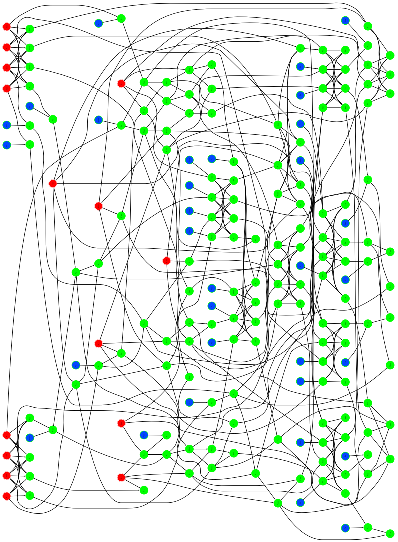

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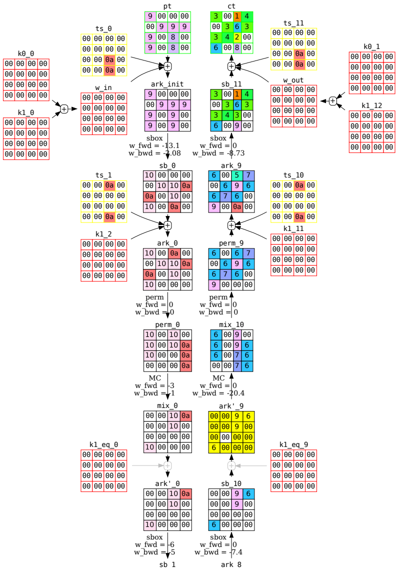

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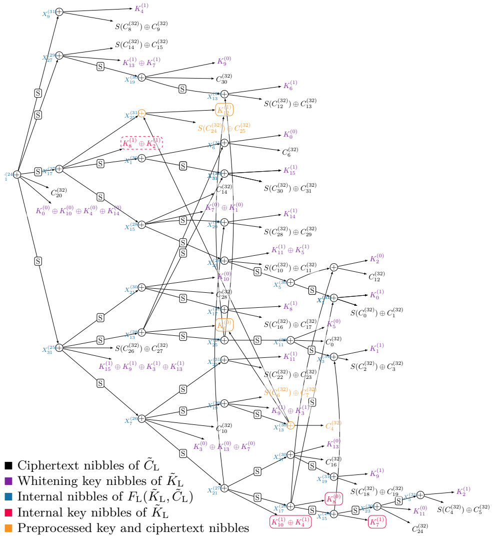

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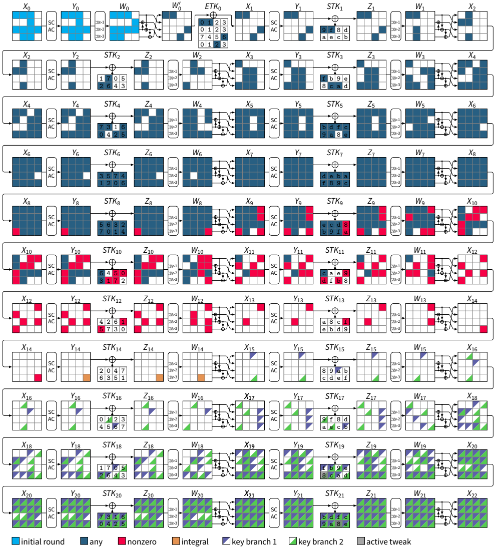

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- Preferably use a **joint model** for distinguisher and key recovery
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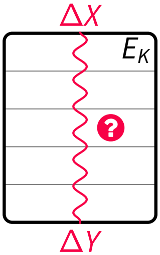

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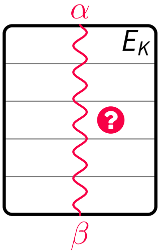

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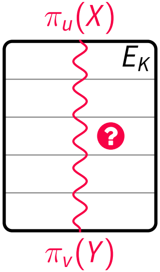

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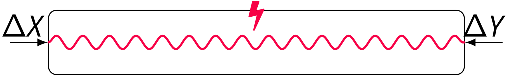

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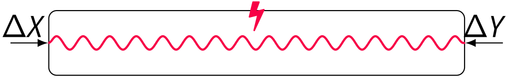

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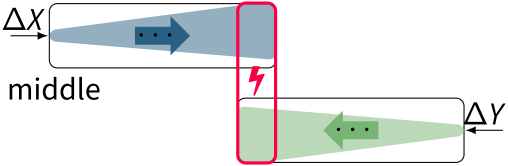

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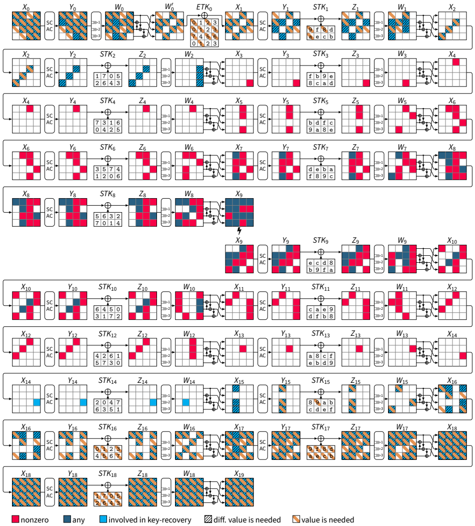

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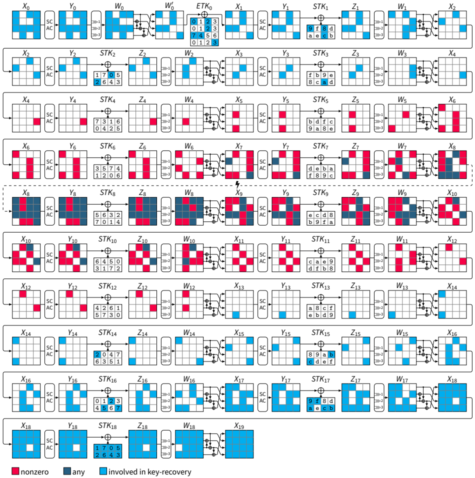

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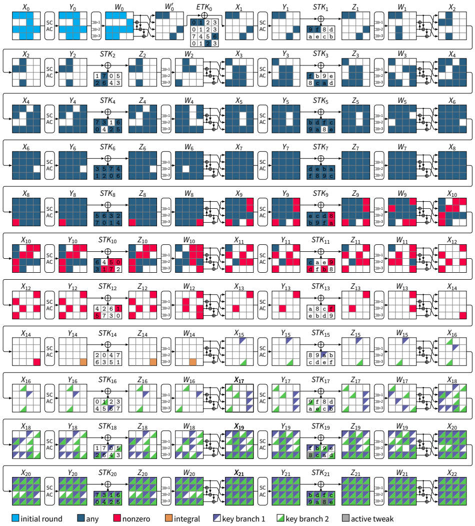

Frameworks

What exactly is a “Framework”?

Judging from paper titles, we have a plethora of frameworks, but …

- ? Generality & Applicability
- ? Reuseability & Extensibility
- ? Maintainability & Verifiability

Frameworks: Examples

- **CryptoSMT** [Köl14; AK18] https://github.com/kste/cryptosmt
  - Differential/linear trails, clustering, key/preimage recovery, ...; based on SMT (STP, Boolector, CryptoMiniSat)
- **CASCADA** [RR22] https://github.com/ranea/CASCADA
  - Differential/linear trails, impossible differentials/zero-correlation, ...; based on SMT
- **CLAASP** [BGG+23] https://github.com/Crypto-TII/claasp
  - All of the above, neural tests; supports many solvers

Frameworks: Challenges

- **Cipher representation**
  - Based on building blocks? As a DAG? Software/hardware code?
- **Efficiency vs. precision**
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Conclusion

- Tools and solvers can help find attacks and derive bounds

- Very active area with many open challenges
  - More efficient and precise models
  - Application to other design paradigms and attack techniques
  - Modeling full attacks (not just the distinguisher)
  - Frameworks and reuseability

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