# Inference of Robust Reachability Constraints

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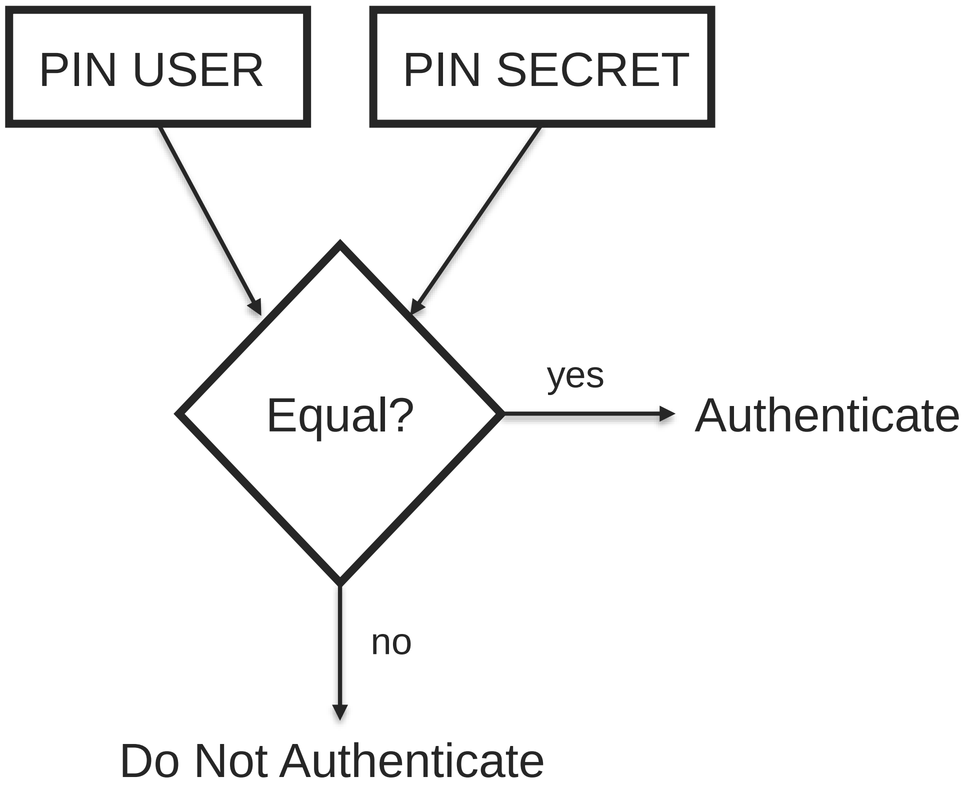
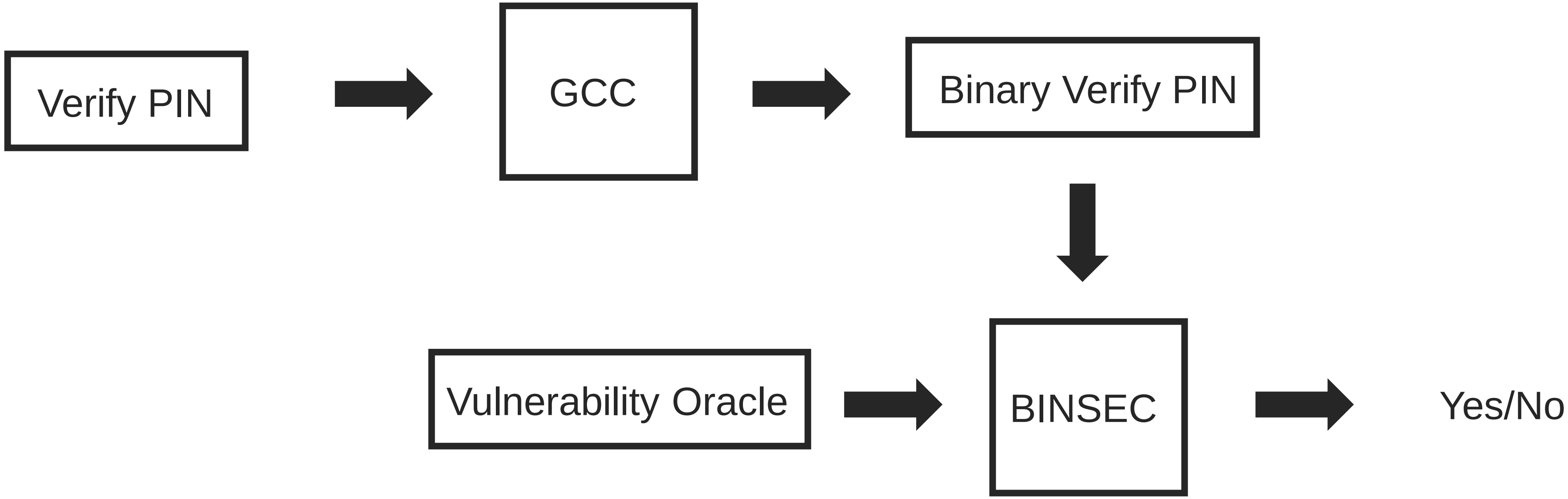
# Example: Verify PIN



- **Compares PINS**
- **Correct when authentication can only happen with correct PIN**
- **Formal Guarantees**

# Example: Verify PIN Formal Verification



Verify PIN

GCC

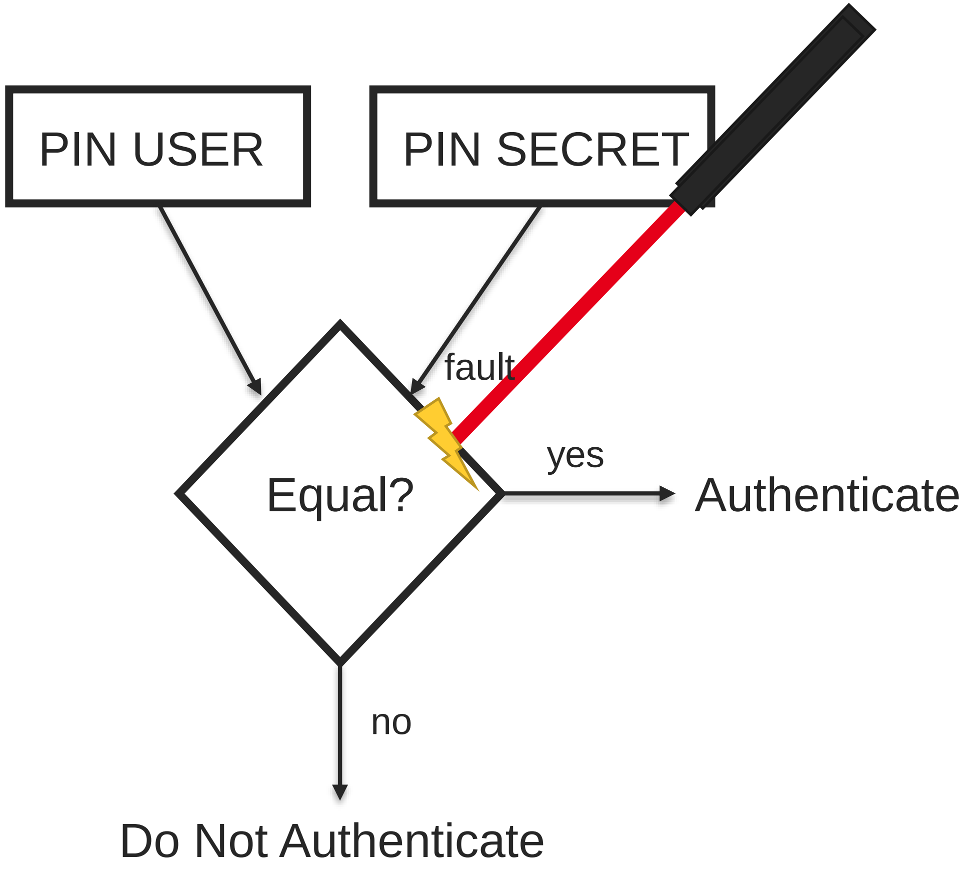
Binary Verify PIN

Vulnerability Oracle

BINSEC

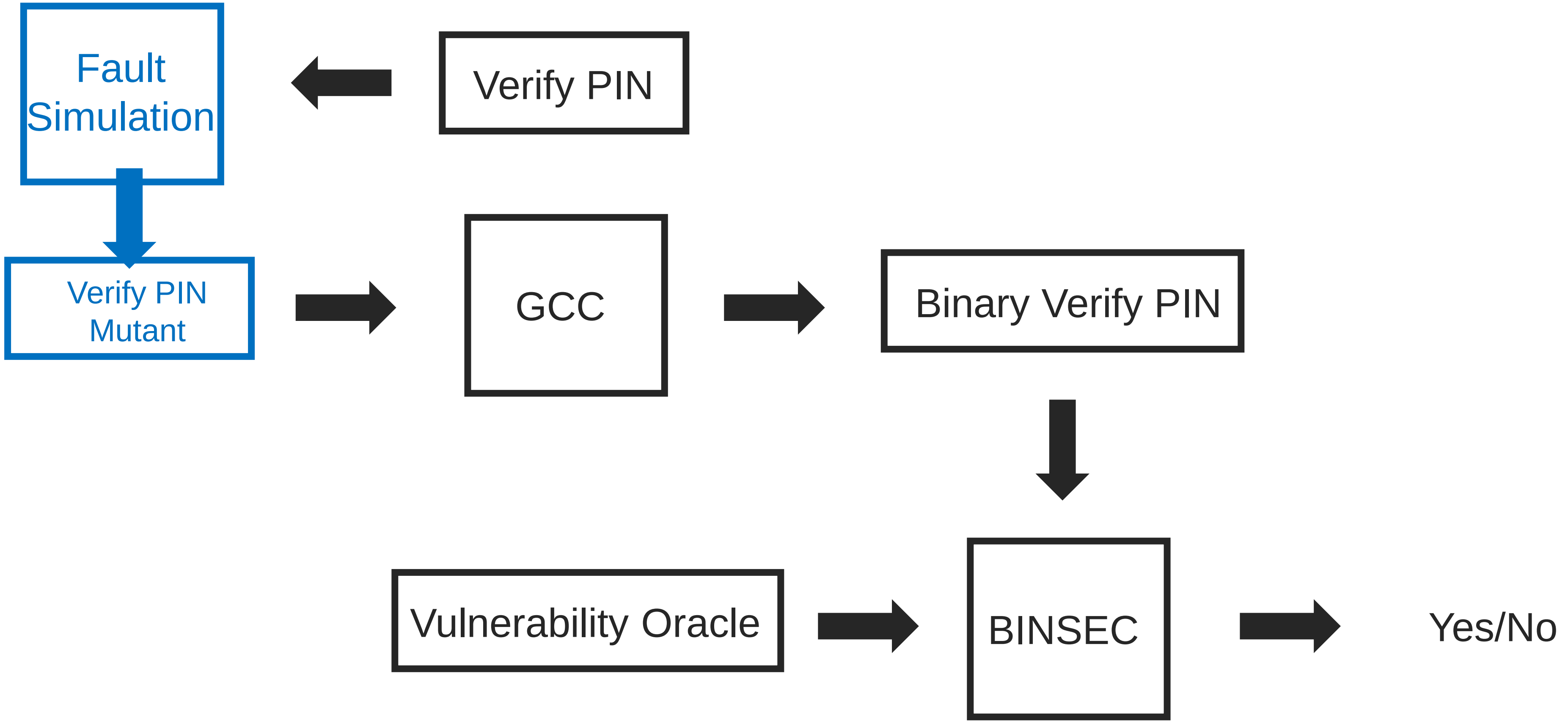
Yes/No

# Example: Verify PIN with Faults



- **Faulted Execution**
- **Alters the behavior of the program**
- **Can we still formally evaluate the feasibility of an unauthorized authentication?**

# Example: Faulted Verify PIN Formal Verification


Fault Simulation

Verify PIN

Verify PIN Mutant

GCC

Binary Verify PIN

Vulnerability Oracle

BINSEC

Yes/No

# Example: Example of Symbolic Execution Result

BINSEC

Yes this VerifyPIN is vulnerable

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Because

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Because

If R2 contains 0xaa

And

R1 is not 0x55

And

R3 is not 0x00

Then you can authenticate with the wrong PIN

# Example: Example of Symbolic Execution Result

BINSEC

Yes this VerifyPIN is vulnerable

Because

If R2 contains 0xaa

And

R1 is not 0x55

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R3 is not 0x00

Then you can authenticate with the wrong PIN

**Great!**

**What do I do with this?**

# Formal Characterization of Fault Injection Attacks Vulnerabilities

- Formal evaluation of the faulted program gives no insight on the severity of the problem

- How to design a formal analysis that provides a more expressive result?

- How to characterize the vulnerabilities we discover?

# Contributions

- **New program-level abduction algorithm for Robust Reachability Constraints Inference**
  - Extends and generalizes Robustness, made more practical
  - Adapts and generalizes theory-agnostic logical abduction algorithm
  - Efficient optimization strategies for solving practical problems

- **Implementation of a restriction to Reachability and Robust Reachability**
  - First evaluation of software verification and security benchmarks
  - Detailed vulnerability characterization analysis in a fault injection security scenario

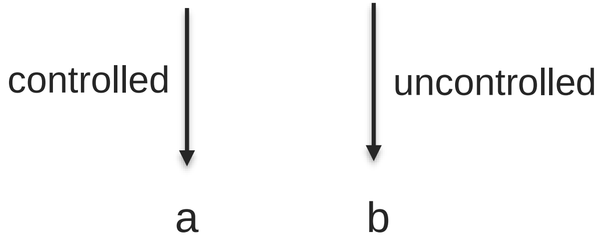
# Robust Reachability

## [Girol, Farinier, Bardin: CAV 2021]

**Idea**

- Partition of the input space
  - What is controlled
  - What is uncontrolled

```
void g() {
    uint a = read();
    uint b; /* uninitialized */
    if (a + b == 0)
        /* bug */
    else
        ...
}
```



controlled

uncontrolled

a

b

# Robust Reachability

## [Girol, Farinier, Bardin: CAV 2021]

**Idea**

- Partition of the input space
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  - What is uncontrolled

**Focus: Reliable Bugs**

- Controlled input that triggers the bug independently of the value of the uncontrolled inputs

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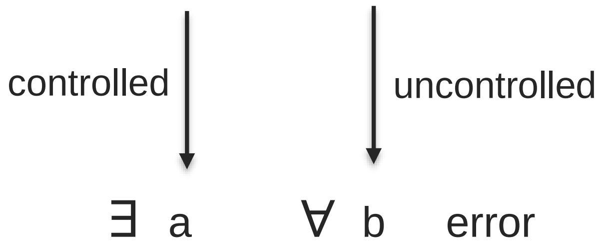

$\exists\ a \quad \forall\ b \quad$ error

# Robust Reachability

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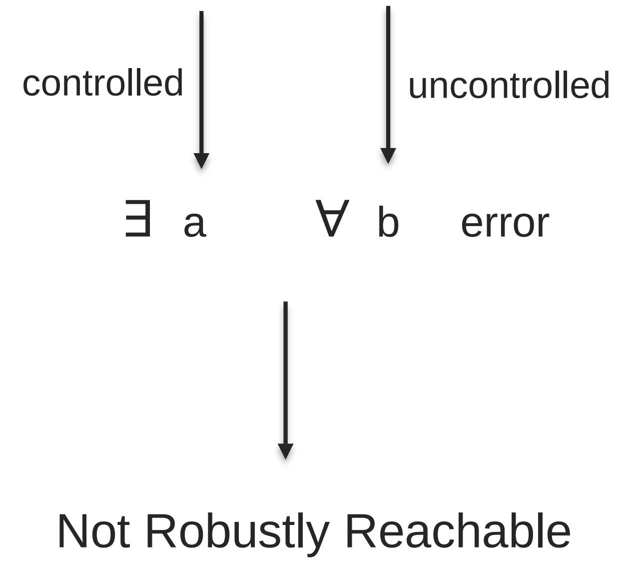


controlled

uncontrolled

$\exists$ a $\forall$ b error

Not Robustly Reachable

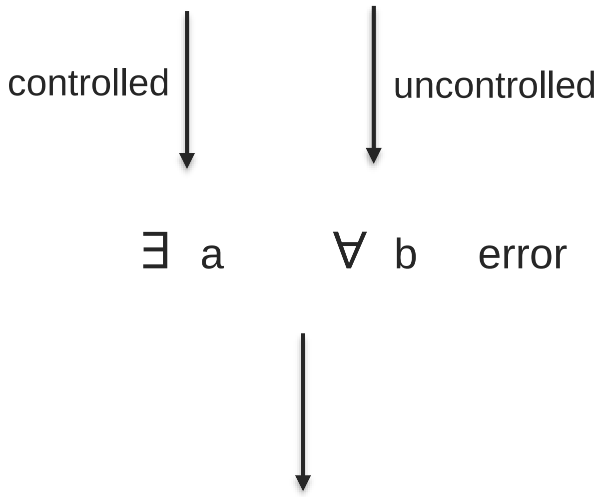
# The Remaining Problem

**Reachability Says: Vulnerable**

**Robust Reachability Says: Not Vulnerable**

**Looks like it can happen**

```
void g() {
    uint a = read();
    uint b; /* uninitialized */
    if ((a + b) % 2 == 0)
        /* bug */
    else
        ...
}
```



controlled

uncontrolled

∃ a ∀ b error

Not Robustly Reachable

# The Remaining Problem

**Reachability Says: Vulnerable**

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**Robust Reachability is Too Strong**

```
void g() {
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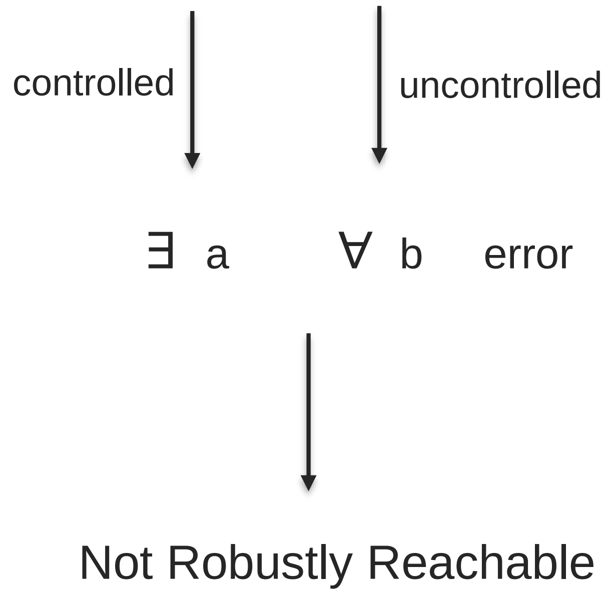

controlled

uncontrolled

$\exists$ a $\forall$ b error

Not Robustly Reachable

# Robust Reachability Constraint

**Definition**

- Predicate on program input sufficient to have Robust Reachability

**Advantages**

- Part of the Robust Reachability framework
- Allows precise characterization

**How to Automatically Generate Such Constraints?**

```
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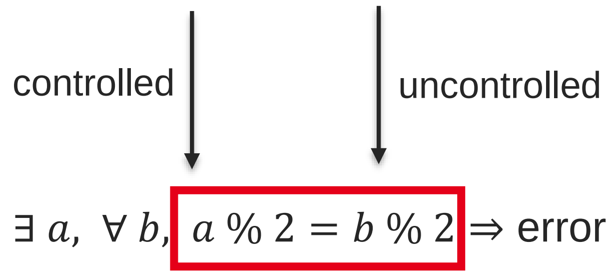
```



$$\exists\, a,\ \forall\, b,\ \boxed{a \,\%\, 2 = b \,\%\, 2} \Rightarrow \text{error}$$

# Abduction of Robust Reachability Constraints

**Abductive Reasoning**

[Josephson and Josephson, 1994]

- Find missing precondition of unexplained goal
- Compute $\phi_M$ in $\phi_H \wedge \phi_M \models \phi_G$

# Abduction of Robust Reachability Constraints

### Abductive Reasoning

[Josephson and Josephson, 1994]

- Find missing precondition of unexplained goal
- Compute $\phi_M$ in $\phi_H \land \phi_M \vDash \phi_G$

### Theory-Specific Abduction

[Bienvenu 2007, Tourret et. al. 2017]

- Handle a single theory

### Specification Synthesis

[Albarghouthi et. al. 2016, Calcagno et. al. 2009,
Zhou et. al. 2021]

- White-box program analysis

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### Theory-Agnostic First-order Abduction

[Echenim et al. 2018, Reynolds et al. 2020]

- Efficient procedures
- Genericity

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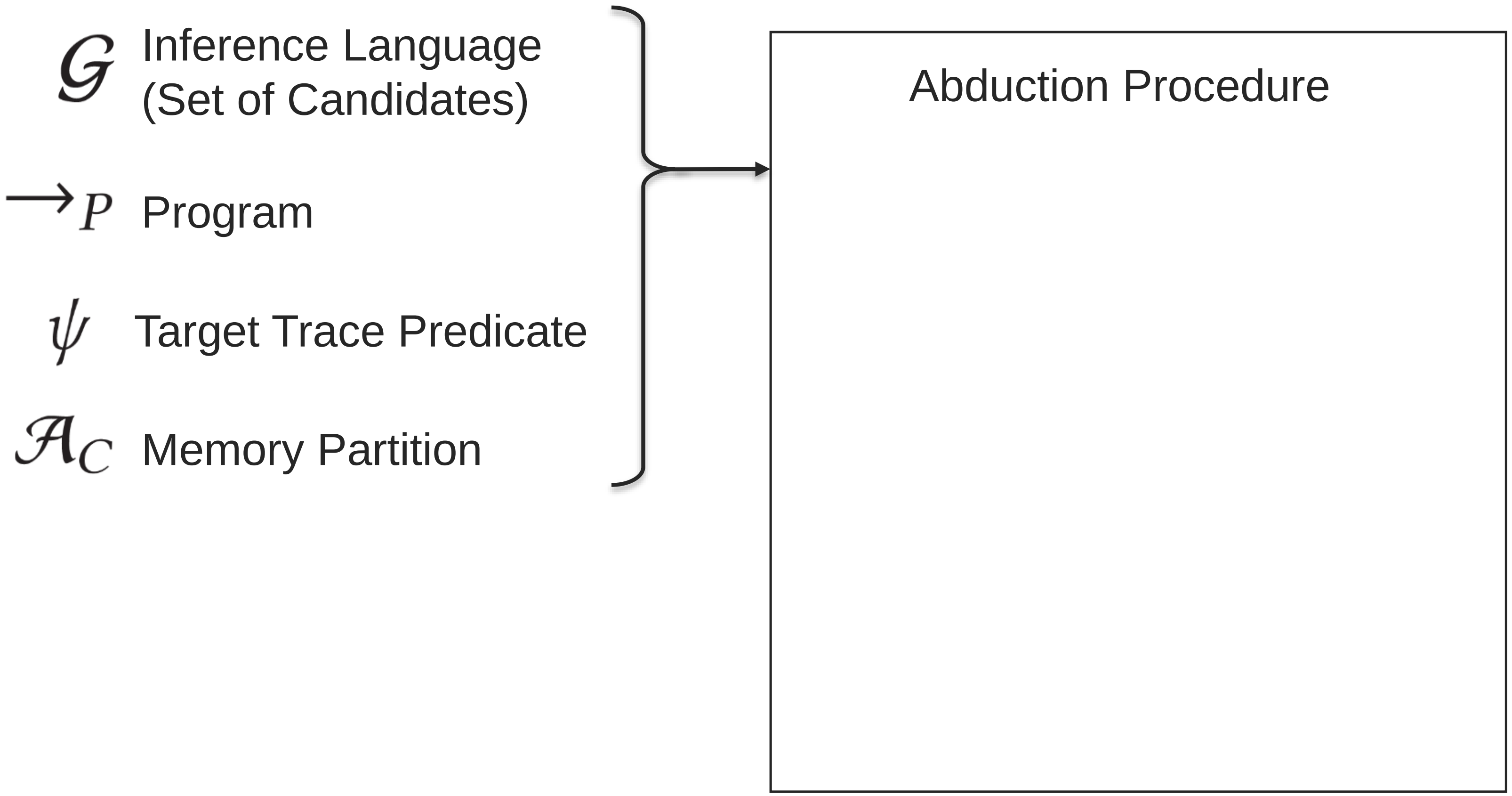
### Our Proposal: Adapt Theory-Agnostic Abduction Algorithm to Compute Program-level Robust Reachability Constraints

- Program-level
- Generic

# Our Solution (Framework)



$\mathcal{G}$ Inference Language (Set of Candidates)

$\longrightarrow P$ Program

$\psi$ Target Trace Predicate

$\mathcal{A}_C$ Memory Partition

Abduction Procedure

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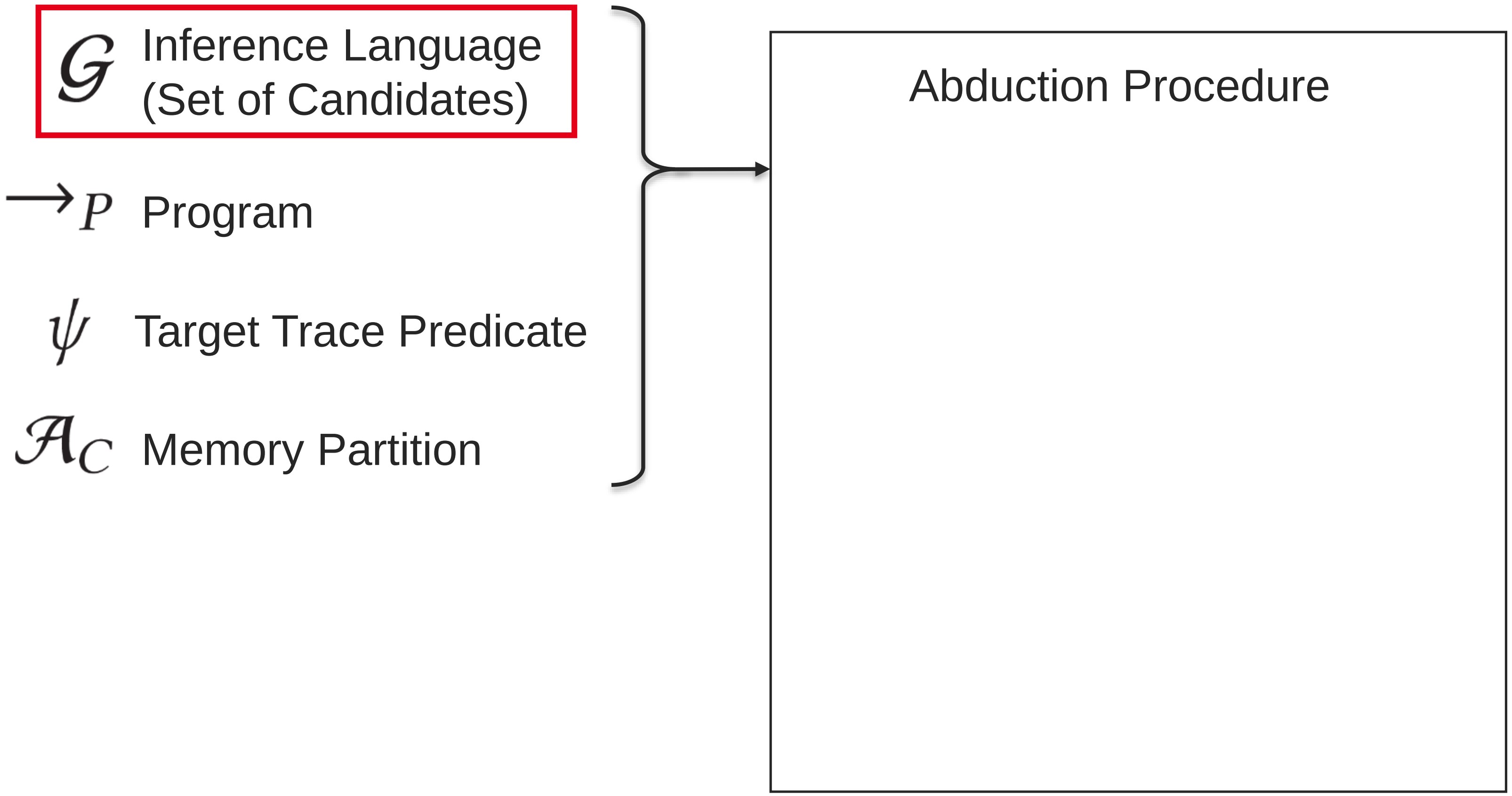

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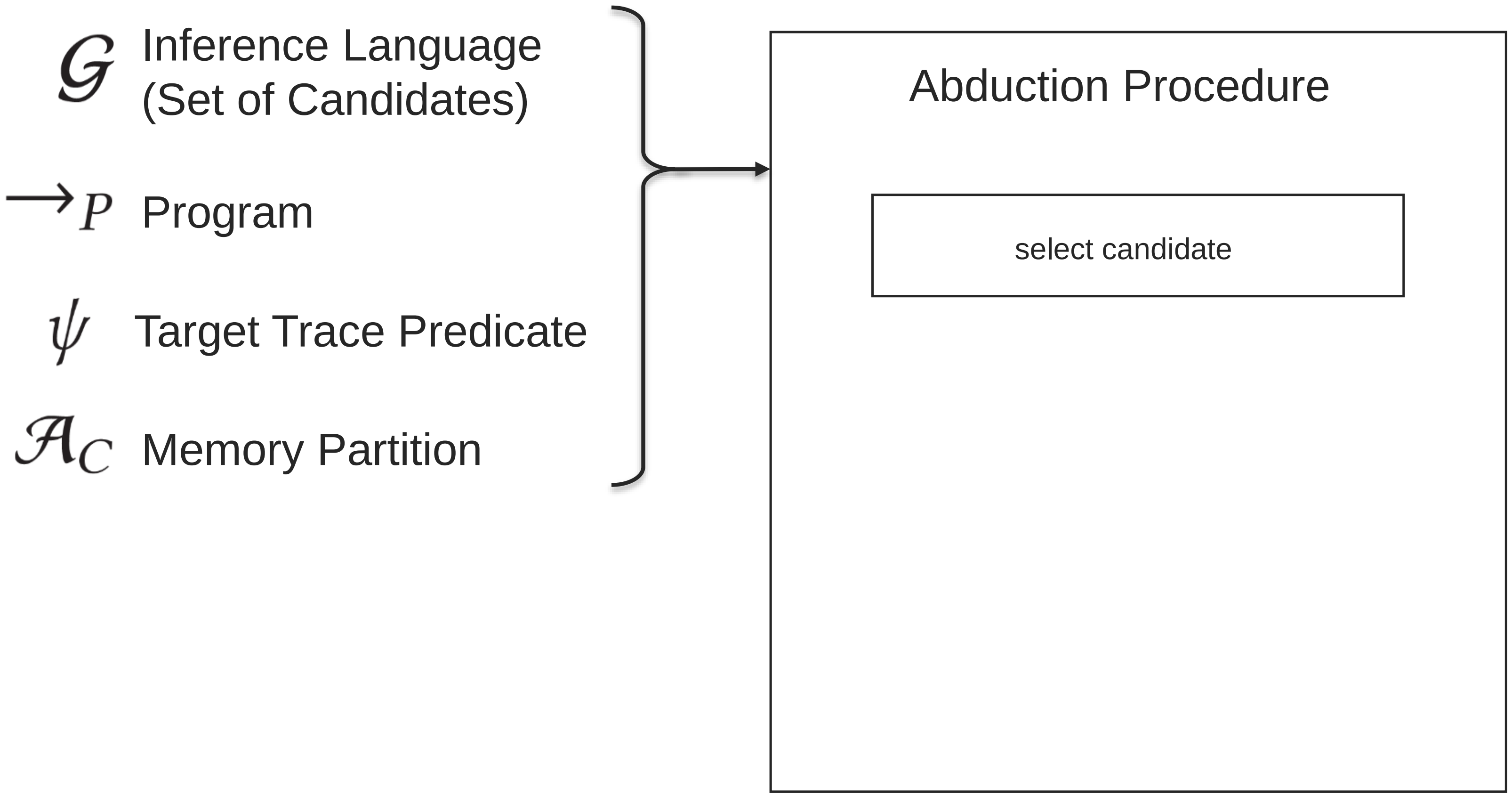

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select candidate

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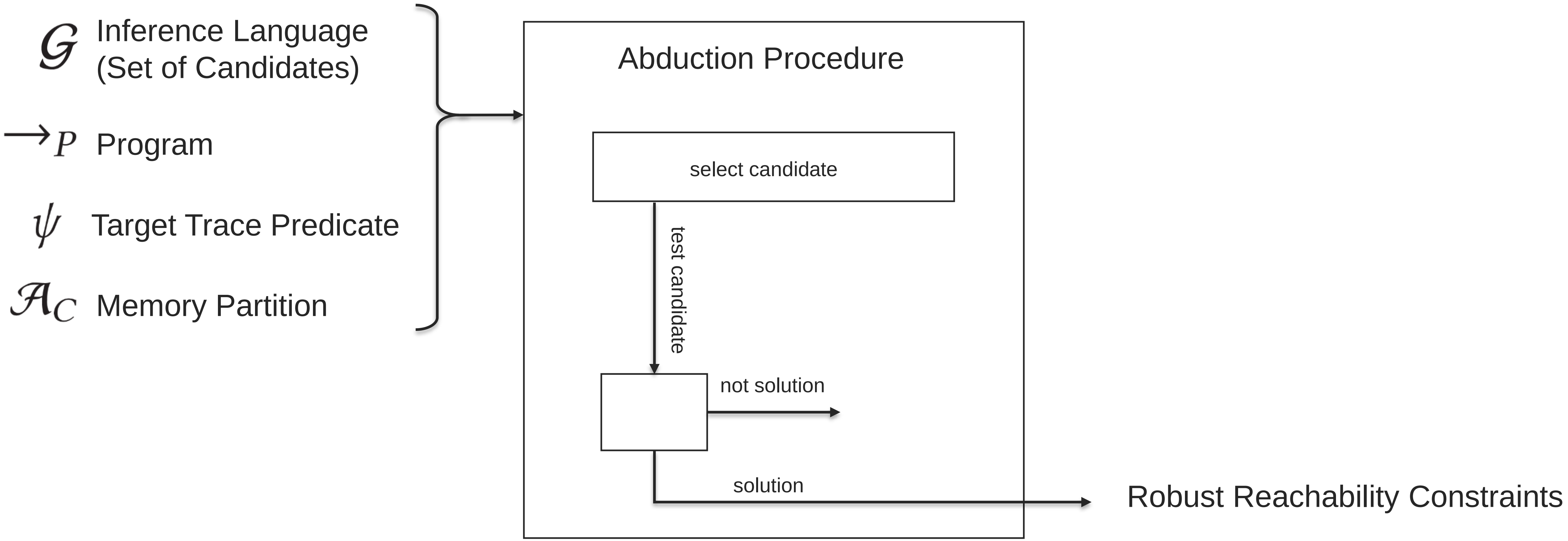

$\mathcal{G}$ Inference Language (Set of Candidates)

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Abduction Procedure

select candidate

test candidate

not solution

solution

Robust Reachability Constraints

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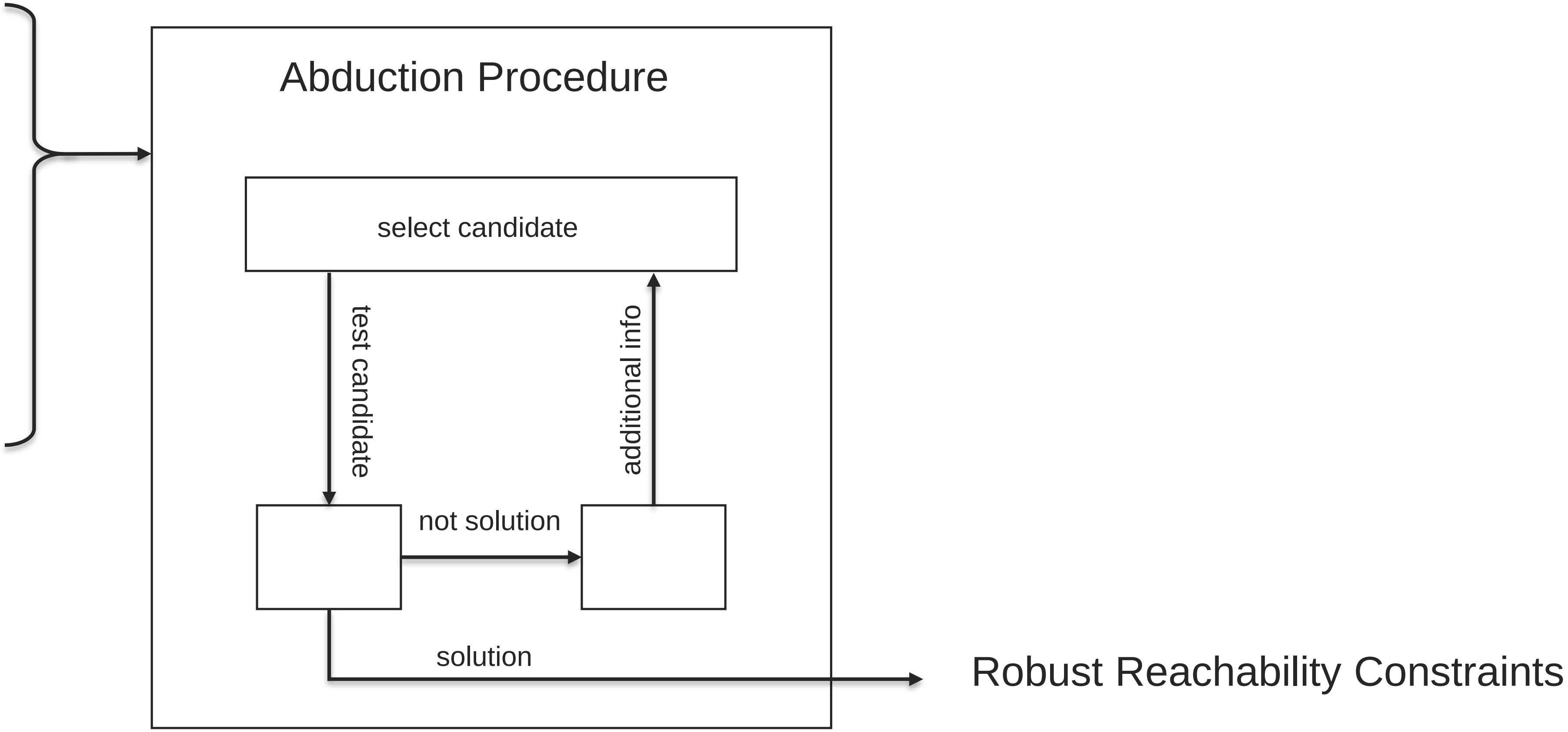

Abduction Procedure

select candidate

test candidate

additional info

not solution

solution

Robust Reachability Constraints

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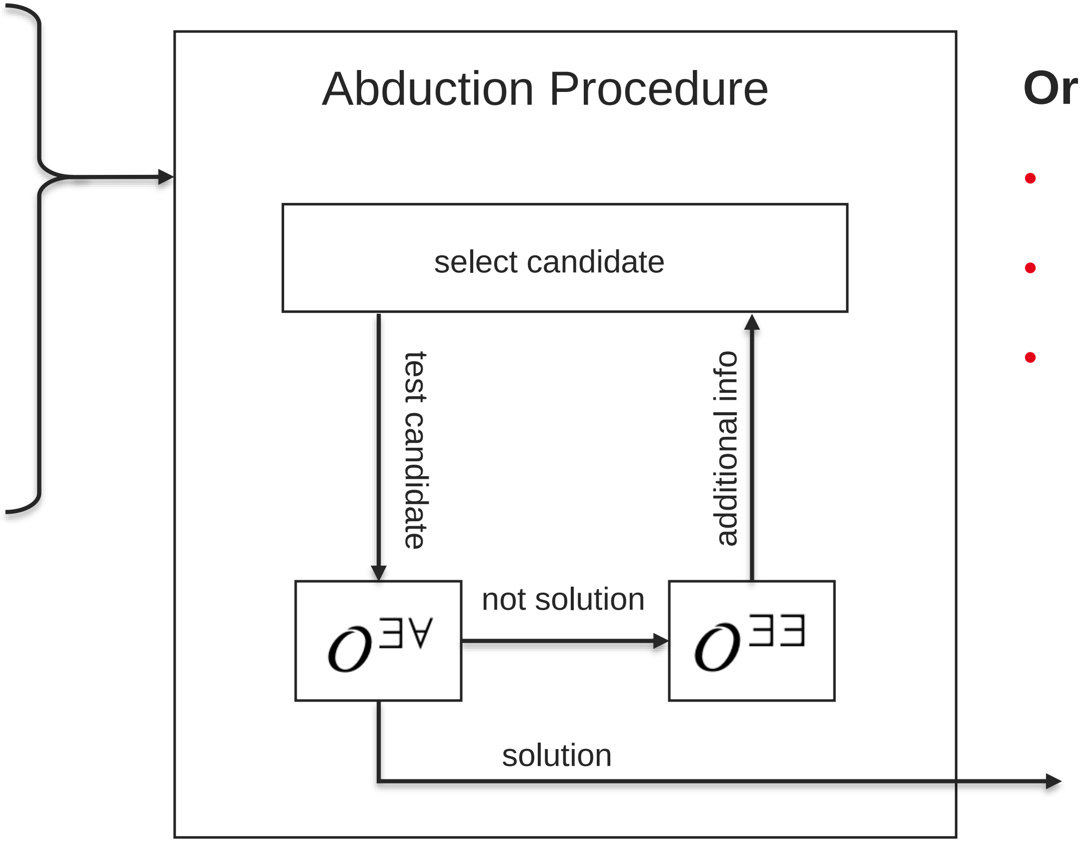

**Oracles on Trace Properties**

- Robust property queries $\mathcal{O}^{\exists\forall}$
- Non-robust property queries $\mathcal{O}^{\exists\exists}$
- Can accomodate various tools (SE, BMC, Incorrectness, …)

Robust Reachability Constraints

# Our Solution (Baseline Algorithm)

```
BaselineRCInfer($\mathcal{G}, \rightarrow_P, \psi, \mathcal{A}_C$)
if $\top, s \leftarrow \mathcal{O}^{\exists\exists}(\rightarrow_P, \psi, \top)$ then
    $R \longleftarrow \{y = s\}$ if $y = s \in \mathcal{G}$ else $\emptyset$;
    for $\phi \in \mathcal{G}$ do
        if $\mathcal{O}^{\exists\forall}(\rightarrow_P, \mathcal{A}_C, \psi, \phi)$ then
            $R \longleftarrow \Delta_{min}(R \cup \{\phi\})$;
            if $\neg\mathcal{O}^{\exists\exists}(\rightarrow_P, \psi, \neg(\bigvee_{\phi' \in R} \phi'))$ then
                return $R$;
    return $R$;
return $\{\bot\}$;
```

**Theorem:**

- **Termination** when the oracles terminate
- **Correction** at any step when the oracles are correct
- **Completeness** w.r.t. the inference language when the oracles are complete

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- Under correction and completeness of the oracles
  - **Minimality** w.r.t. the inference language
  - **Weakest** constraint generation when expressible

# Making it Work

### The Issue

- Exhaustive exploration of the inference language is inefficient

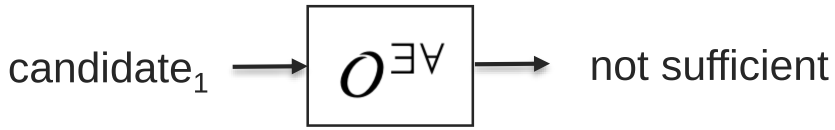
### Key Strategies for Efficient Exploration

- Necessary constraints
- Counter-examples for Robust Reachability
- Ordering candidates

# Making it Work: Necessary Constraints

**The Idea**

- Find and store Necessary Constraints



candidate$_1$ → $\mathcal{O}^{\exists\forall}$ → not sufficient

# Making it Work: Necessary Constraints

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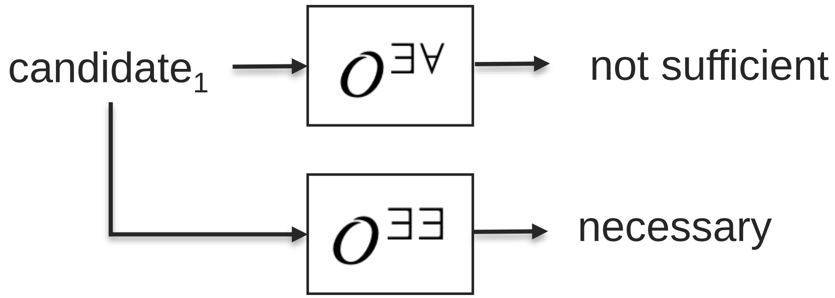


candidate$_1$

$\mathcal{O}^{\exists\forall}$ → not sufficient

$\mathcal{O}^{\exists\exists}$ → necessary

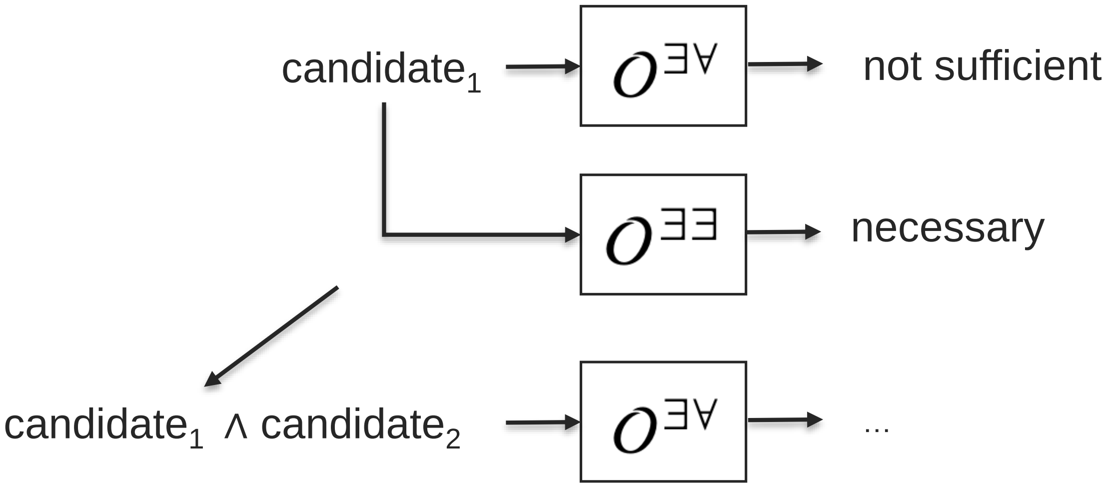
# Making it Work: Necessary Constraints

**The Idea**

- Find and store Necessary Constraints

**Usage**

- Build a candidate solution faster
- Additional information on the bug
- Emulate unsat core usage in the context of oracles



candidate$_1$ → $\mathcal{O}^{\exists\forall}$ → not sufficient

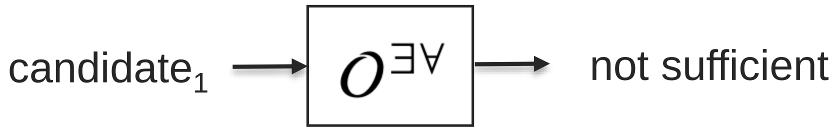
→ $\mathcal{O}^{\exists\exists}$ → necessary

candidate$_1$ ∧ candidate$_2$ → $\mathcal{O}^{\exists\forall}$ → …

# Making it Work: Counter-Examples

**The Idea**

- Reuse information from failed candidate checks



candidate$_1$ → $\mathcal{O}^{\exists\forall}$ → not sufficient

**The Issue**

- Non Robustness (∀∃ quantification) does not give us counter-examples

# Making it Work: Counter-Examples

## The Idea

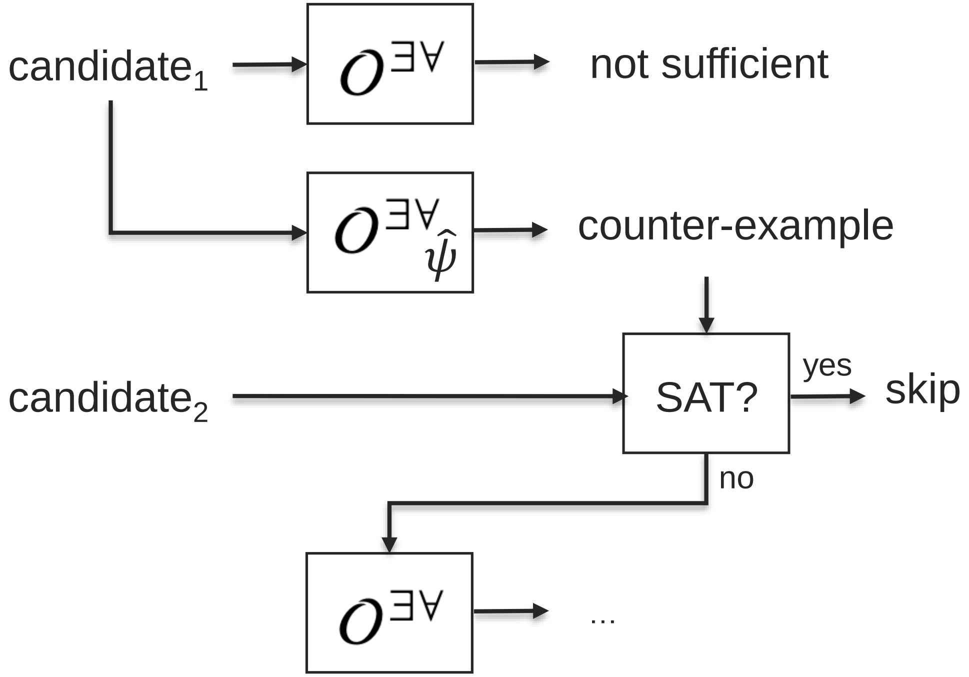
- Reuse information from failed candidate checks

## The Issue

- Non Robustness (∀∃ quantification) does not give us counter-examples

## Proposal

- Use a second trace property that ensures the bug does not arise
- Prune using these counter-examples



candidate$_1$

$\mathcal{O}^{\exists\forall}$

not sufficient

$\mathcal{O}^{\exists\forall}_{\hat{\psi}}$

counter-example

candidate$_2$

SAT?

yes

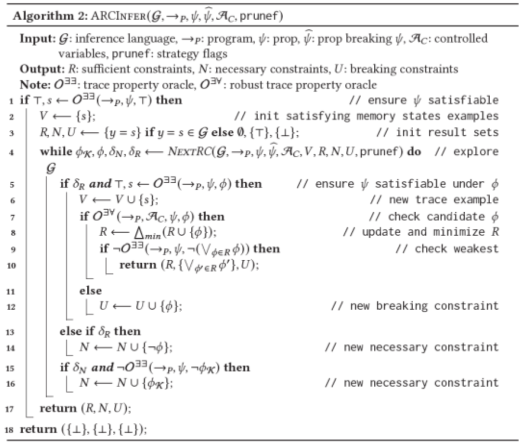
skip

no

$\mathcal{O}^{\exists\forall}$

...

# Final Algorithm



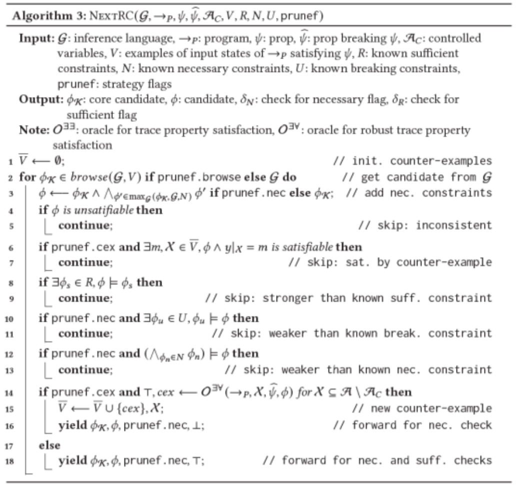
**Algorithm 2:** ARCINFER($\mathcal{G}, \rightarrow_P, \psi, \widehat{\psi}, \mathcal{A}_C$, prunef)

**Input:** $\mathcal{G}$: inference language, $\rightarrow_P$: program, $\psi$: prop, $\widehat{\psi}$: prop breaking $\psi$, $\mathcal{A}_C$: controlled variables, prunef: strategy flags

**Output:** $R$: sufficient constraints, $N$: necessary constraints, $U$: breaking constraints

**Note:** $O^{\exists\exists}$: trace property oracle, $O^{\exists\forall}$: robust trace property oracle

```
if $\top, s \leftarrow O^{\exists\exists}(\rightarrow_P, \psi, \top)$ then                          // ensure $\psi$ satisfiable
    $V \longleftarrow \{s\}$;                                   // init satisfying memory states examples
    $R, N, U \longleftarrow \{y = s\}$ if $y = s \in \mathcal{G}$ else $\emptyset, \{\top\}, \{\bot\}$;          // init result sets
    while $\phi_{\mathcal{K}}, \phi, \delta_N, \delta_R \longleftarrow$ NextRC($\mathcal{G}, \rightarrow_P, \psi, \widehat{\psi}, \mathcal{A}_C, V, R, N, U$, prunef) do   // explore $\mathcal{G}$
        if $\delta_R$ and $\top, s \leftarrow O^{\exists\exists}(\rightarrow_P, \psi, \phi)$ then     // ensure $\psi$ satisfiable under $\phi$
            $V \longleftarrow V \cup \{s\}$;                                         // new trace example
            if $O^{\exists\forall}(\rightarrow_P, \mathcal{A}_C, \psi, \phi)$ then                        // check candidate $\phi$
                $R \longleftarrow \Delta_{min}(R \cup \{\phi\})$;                          // update and minimize $R$
                if $\neg O^{\exists\exists}(\rightarrow_P, \psi, \neg(\bigvee_{\phi \in R} \phi))$ then                 // check weakest
                    return $(R, \{\bigvee_{\phi' \in R} \phi'\}, U)$;
            else
                $U \longleftarrow U \cup \{\phi\}$;                             // new breaking constraint
        else if $\delta_R$ then
            $N \longleftarrow N \cup \{\neg\phi\}$;                            // new necessary constraint
        if $\delta_N$ and $\neg O^{\exists\exists}(\rightarrow_P, \psi, \neg\phi_{\mathcal{K}})$ then
            $N \longleftarrow N \cup \{\phi_{\mathcal{K}}\}$;                           // new necessary constraint
    return $(R, N, U)$;
return $(\{\bot\}, \{\bot\}, \{\bot\})$;
```



**Algorithm 3:** NextRC($\mathcal{G}, \rightarrow_P, \psi, \widehat{\psi}, \mathcal{A}_C, V, R, N, U$, prunef)

**Input:** $\mathcal{G}$: inference language, $\rightarrow_P$: program, $\psi$: prop, $\widehat{\psi}$: prop breaking $\psi$, $\mathcal{A}_C$: controlled variables, $V$: examples of input states of $\rightarrow_P$ satisfying $\psi$, $R$: known sufficient constraints, $N$: known necessary constraints, $U$: known breaking constraints, prunef: strategy flags

**Output:** $\phi_{\mathcal{K}}$: core candidate, $\phi$: candidate, $\delta_N$: check for necessary flag, $\delta_R$: check for sufficient flag

**Note:** $O^{\exists\exists}$: oracle for trace property satisfaction, $O^{\exists\forall}$: oracle for robust trace property satisfaction

```
$\overline{V} \longleftarrow \emptyset$;                                              // init. counter-examples
for $\phi_{\mathcal{K}} \in browse(\mathcal{G}, V)$ if prunef.browse else $\mathcal{G}$ do           // get candidate from $\mathcal{G}$
    $\phi \longleftarrow \phi_{\mathcal{K}} \wedge \bigwedge_{\phi' \in \max_{\mathcal{G}}(\phi_{\mathcal{K}}, \mathcal{G}, N)} \phi'$ if prunef.nec else $\phi_{\mathcal{K}}$;   // add nec. constraints
    if $\phi$ is unsatifiable then
        continue;                                                // skip: inconsistent
    if prunef.cex and $\exists m, \mathcal{X} \in \overline{V}, \phi \wedge y|_{\mathcal{X}} = m$ is satisfiable then
        continue;                                    // skip: sat. by counter-example
    if $\exists \phi_s \in R, \phi \models \phi_s$ then
        continue;                      // skip: stronger than known suff. constraint
    if prunef.nec and $\exists \phi_u \in U, \phi_u \models \phi$ then
        continue;                       // skip: weaker than known break. constraint
    if prunef.nec and $(\bigwedge_{\phi_n \in N} \phi_n) \models \phi$ then
        continue;                         // skip: weaker than known nec. constraint
    if prunef.cex and $\top, cex \longleftarrow O^{\exists\forall}(\rightarrow_P, \mathcal{X}, \widehat{\psi}, \phi)$ for $\mathcal{X} \subseteq \mathcal{A} \setminus \mathcal{A}_C$ then
        $\overline{V} \longleftarrow \overline{V} \cup \{cex\}, \mathcal{X}$;                               // new counter-example
        yield $\phi_{\mathcal{K}}, \phi$, prunef.nec, $\bot$;                        // forward for nec. check
    else
        yield $\phi_{\mathcal{K}}, \phi$, prunef.nec, $\top$;             // forward for nec. and suff. checks
```

## Theorem

- **Termination**, **Correction**, **Completeness** are preserved
- **Correction for necessary constraints** at any step
- **Minimality** is preserved modulo equivalence between formulas
- **Weakest constraints generation** on given return is preserved

## Remarks

- Generic procedure definition with oracle queries abstraction
- The previously described strategies can be activated/deactivated
- Can be applied to a larger range of program properties (reachability, safety, hypersafety)
- If SMT-Solvers are used as oracles, can be used an ∃∀ abduction solver

# Experimental Evaluation

### Implementation

BINSEC

- (Robust) Reachability on binaries
- Tool: **BINSEC** [Djoudi and Bardin 2015]
- Tool: **BINSEC/RSE** [Girol at. al. 2020]

### Prototype

- **PyAbd**, Python implementation of the procedure
- Candidates: Conjunctions of equalities and disequalities on memory bytes

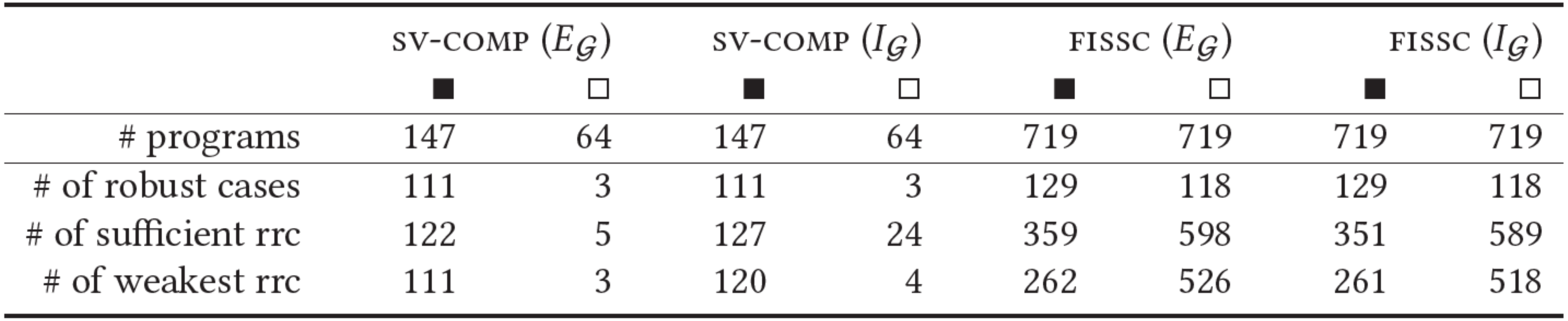
### Research Questions

1) Can we compute non-trivial constraints?
2) Can we compute weakest constraints?
3) What are the algorithmic performances?
4) Are the optimization effective?

### Benchmarks

- Software verification (SVComp extract + compile)
- Security evaluation (FISSC, fault injection)

# Results: Generating Constraints



| | SV-COMP ($E_{\mathcal{G}}$) | | SV-COMP ($I_{\mathcal{G}}$) | | FISSC ($E_{\mathcal{G}}$) | | FISSC ($I_{\mathcal{G}}$) | |
|---|---|---|---|---|---|---|---|---|
| | ■ | □ | ■ | □ | ■ | □ | ■ | □ |
| # programs | 147 | 64 | 147 | 64 | 719 | 719 | 719 | 719 |
| # of robust cases | 111 | 3 | 111 | 3 | 129 | 118 | 129 | 118 |
| # of sufficient rrc | 122 | 5 | 127 | 24 | 359 | 598 | 351 | 589 |
| # of weakest rrc | 111 | 3 | 120 | 4 | 262 | 526 | 261 | 518 |

**Inference languages**

- (dis-)Equality between memory bytes $(E_{\mathcal{G}})$
- + Inequality between memory bytes $(I_{\mathcal{G}})$ → More expressivity but more candidates

# Results: Generating Constraints

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previous
characterization

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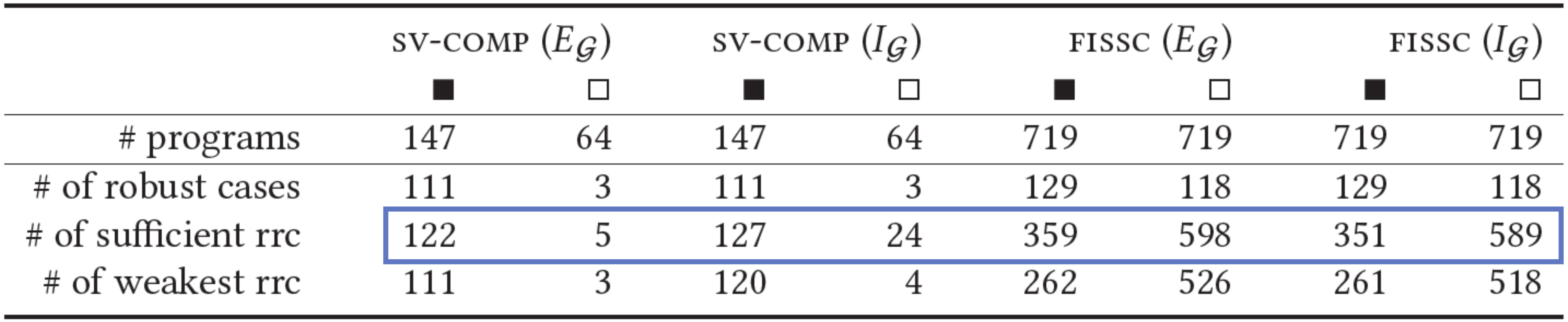

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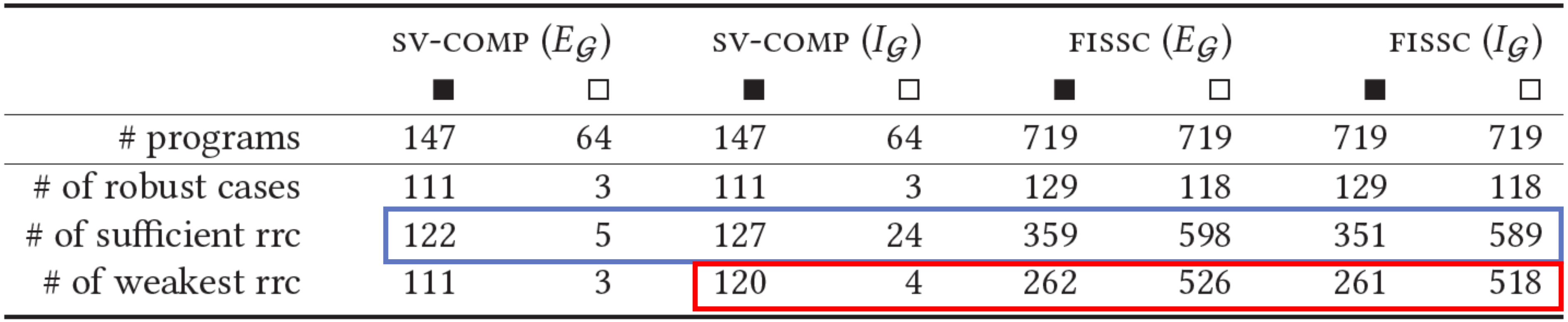

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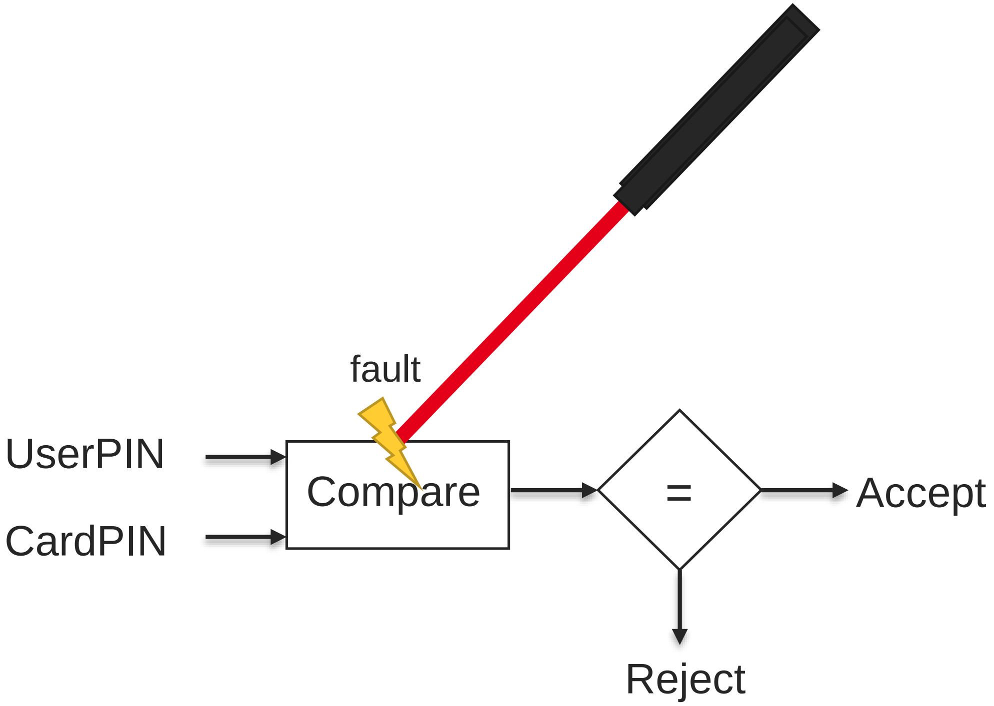
# Benchmark: FISSC

**Fault Injection Attacks**

- Physical perturbation of the system executing the program
- Changes the program behavior
- Introduces new bugs
- How does each method characterize these bugs?

**VerifyPINs**

- 10 protected implementations
- 4800 faulted binary programs



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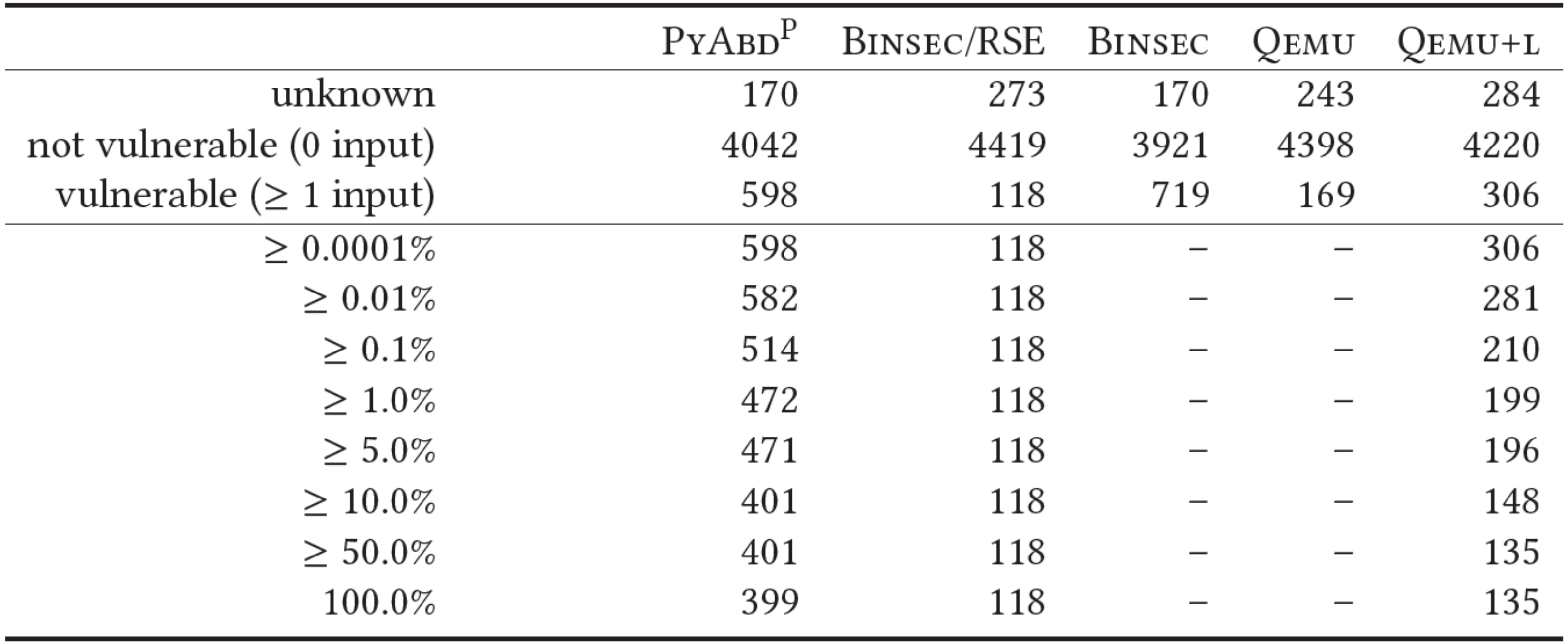

| | PyAbd$^{P}$ | Binsec/RSE | Binsec | Qemu | Qemu+L |
|---:|---:|---:|---:|---:|---:|
| unknown | 170 | 273 | 170 | 243 | 284 |
| not vulnerable (0 input) | 4042 | 4419 | 3921 | 4398 | 4220 |
| vulnerable ($\geq$ 1 input) | 598 | 118 | 719 | 169 | 306 |
| $\geq$ 0.0001% | 598 | 118 | – | – | 306 |
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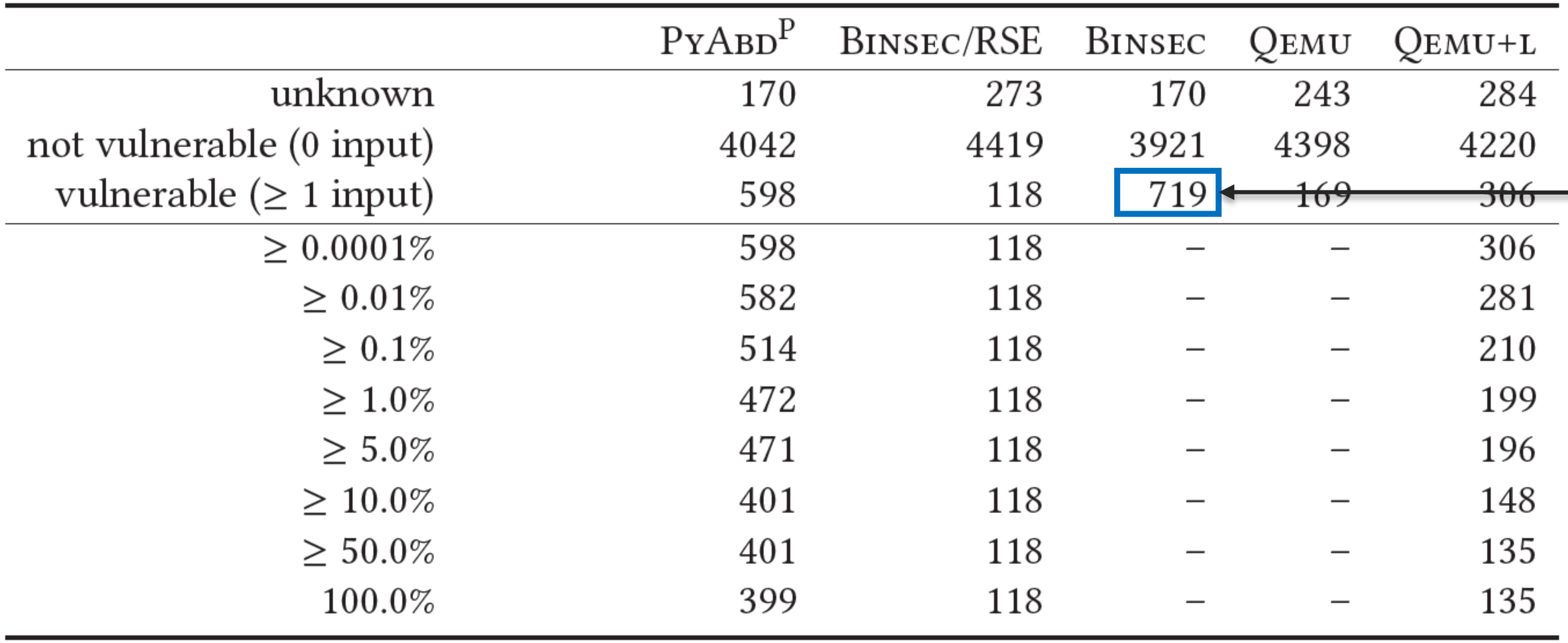

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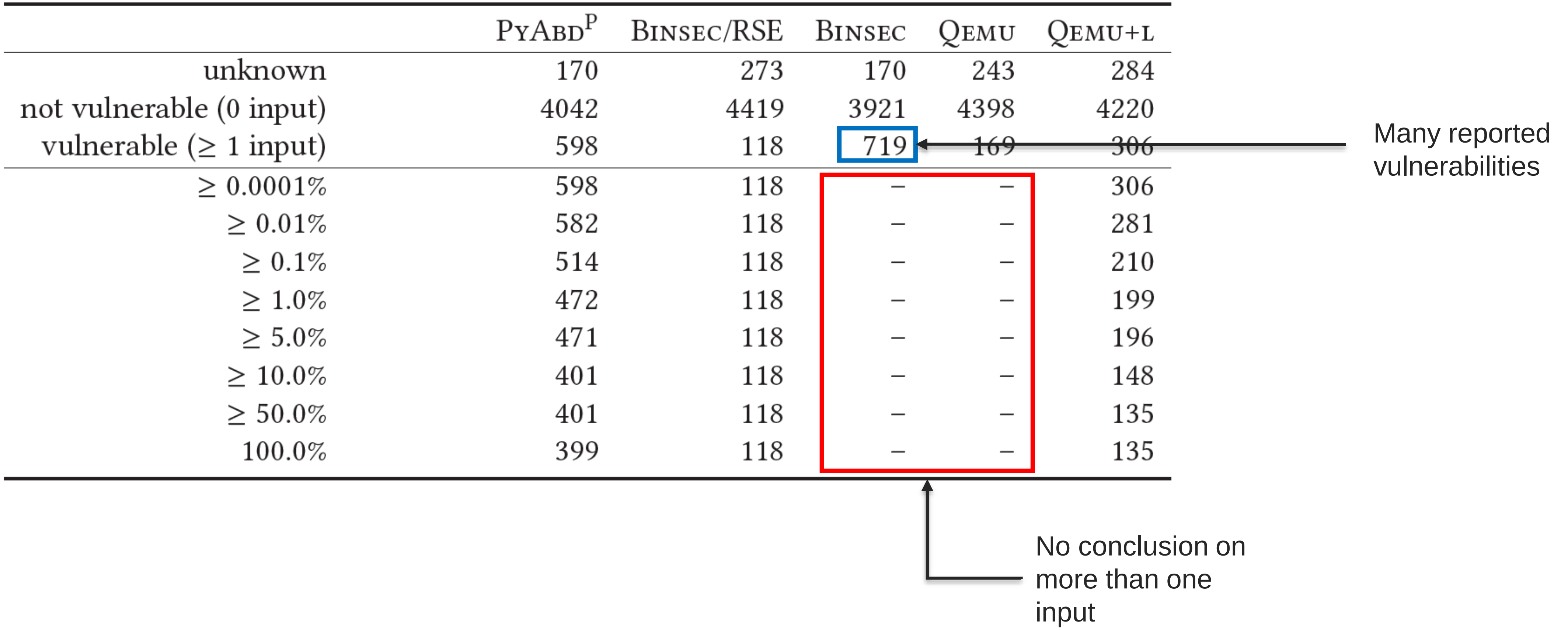

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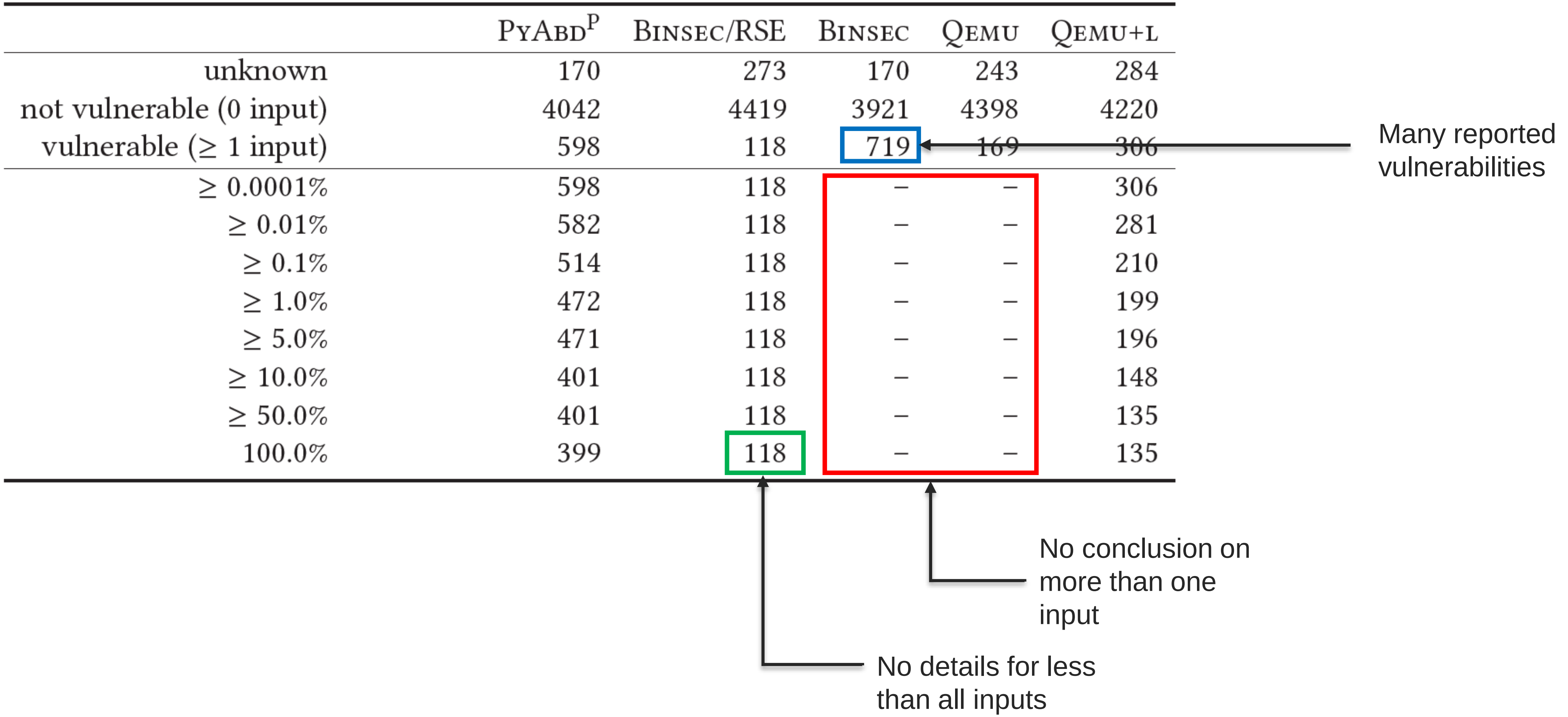

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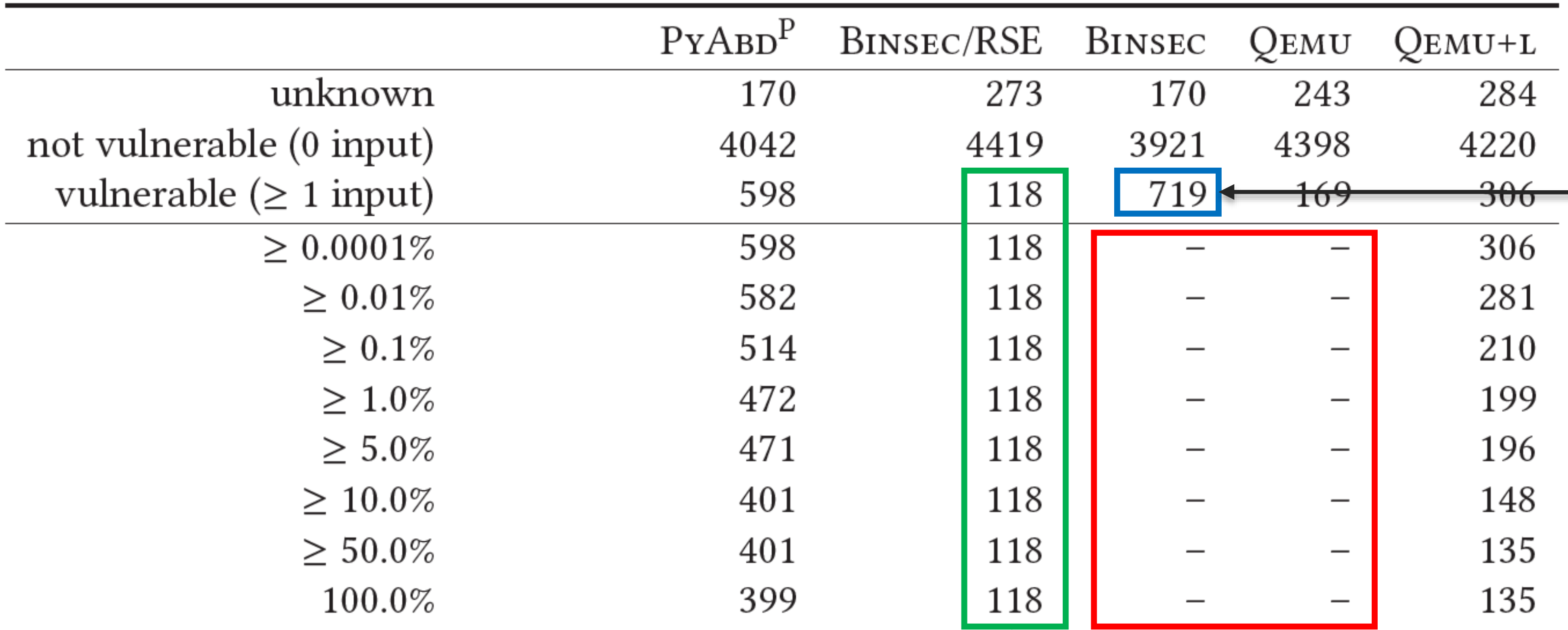

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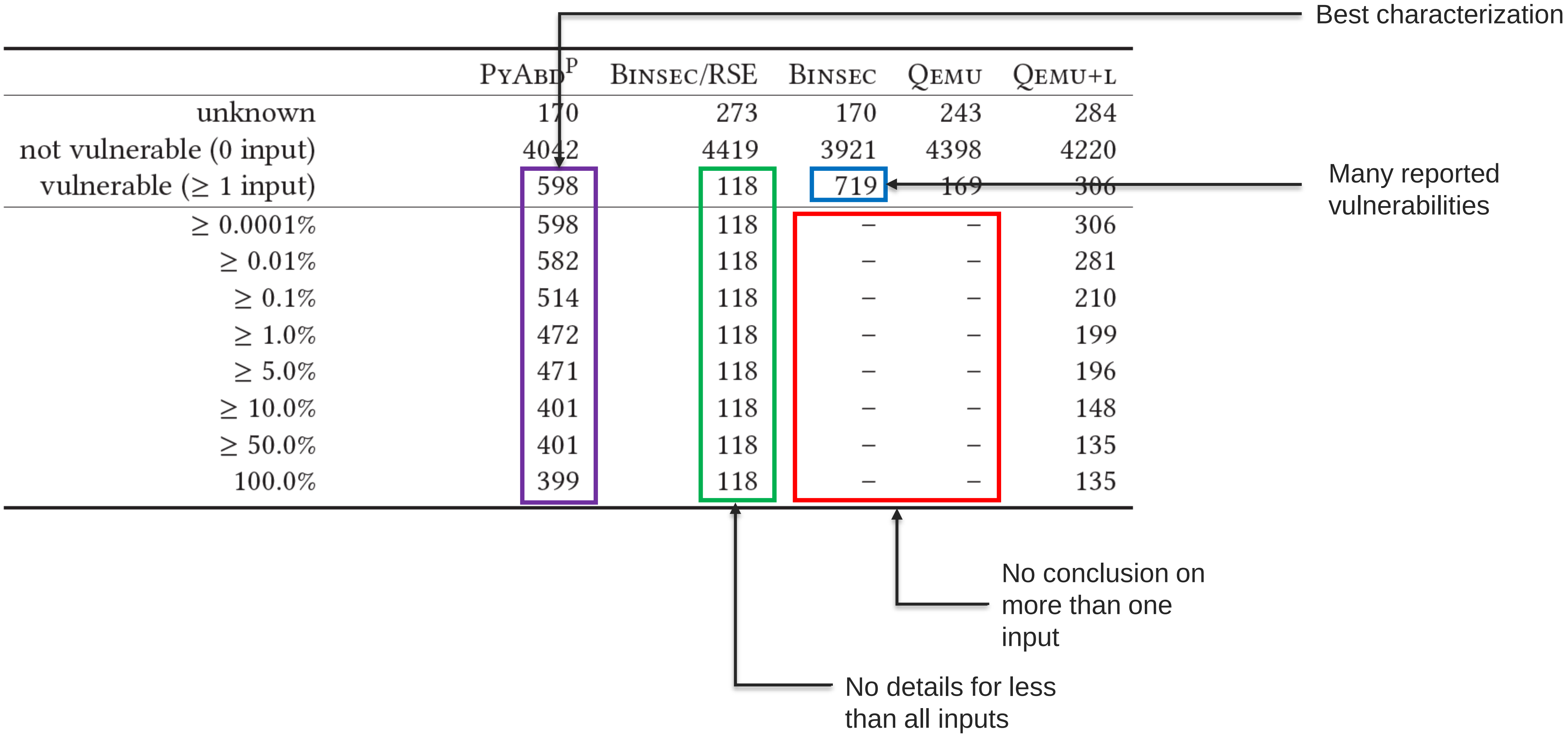

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Best characterization

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# Results: Example of Constraints

- true

  Authentication is always possible

- Card[0] == User[0] && User[0] == 3

  Authentication when first digit is 3

- User[0] == User[1] && User[0] == User[2] && User[0] == User[3] && User[0] != 0

  Authentication when all digits are equal and non zero

- Card[2] != User[2] && Card[3] == User[3] && User[1] == 5

  Authentication when we know the last digit, the 3rd is not correct and the 2$^{nd}$ is 5.

- R0 == User[3] && User[3] == User[2] && User[3] == User[1] && User[3] == User[0]

  Authentication with four time the initial value of R0

- R2 = 0xaa && R1 != 0x55 && R1 != 0

  Authentication if R2=0xaa initially and R1 distinct from both 0x55 and 0x00 initially

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Can be reused for understanding, counting, comparing

Artifacts Available
acm
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BINSEC

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