Inference of Robust Reachability Constraints

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Automatic Bug Detection

Programs have bugs

Bugs can be exploited → Vulnerabilities

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

We need automated methods to detect bugs

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- Explore the program paths
- Finds program input that exhibits the bug
- Sound: no false positives

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→ a = 0, b = 0

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False Positive in Practice

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- Depends on uncontrolled initial value (b)
- The formal result is not reliably reproducible

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Practical Causes of Unreliable Assignments

- Interaction with the environment
- Stack canaries
- Uninitialized memory/register dependency
- Choice of undefined behaviors

We need to characterize the replicability of bugs

Robust Reachability
[Farinier et. al., CAV 2018; Girol et. al., CAV 2021]

Idea

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

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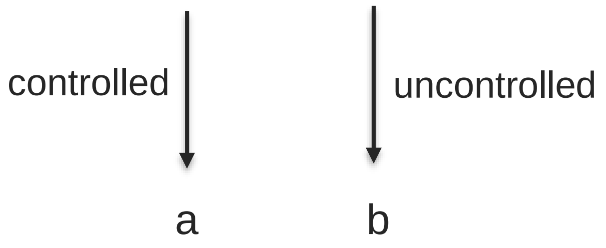

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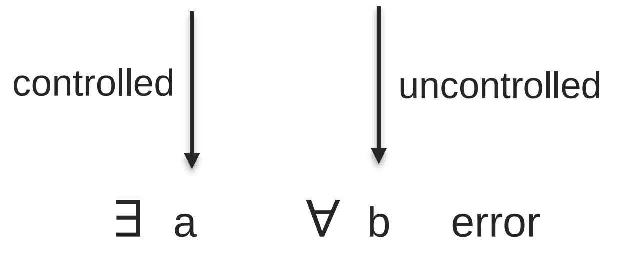

Focus: Reliable Bugs

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

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controlled ↓ uncontrolled ↓

$\exists$ a $\forall$ b error

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Not Robustly Reachable

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Extension of Reachability and Symbolic Execution

```
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uncontrolled

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Not Robustly Reachable

The Remaining Problem

Example 3

- Memcopy with slow and fast path
- Fast path is buggy but slow path is not

```
typedef struct { unsigned char bytes[32]; } uint256_t;

void memcpy(void* dst, const void* src, size_t n) {
    if (((dst | src | n) & 0b11111))
        /* slow path */
        for (size_t i = 0; i < n; i += 1)
            dst[i] = src[i];
    else /* fast path */
        for (size_t i = 0; i <= (n >> 5); i += 1)
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safe → for (size_t i = 0; i < n; i += 1)

buggy → (uint256_t*)dst[i] = (uint256_t*)src[i];

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- Reachability: Vulnerable
- Robust Reachability: Not reliably triggerable
  - Taking the fast path depends on uncontrolled initial values

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$\exists *src, \forall src, dst,$ overflow?

Not Robustly Reachable

The bug is serious but not robustly reachable – The concept is too strong

Robust Reachability Constraints

Definition

- Predicate on program input sufficient to have Robust Reachability

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$$\exists *src,\ \forall src, dst,\ \boxed{src \,\%\, 32 = 0\ \wedge dst \,\%\, 32 = 0} \Rightarrow \text{overflow}$$

(src and dst aligned on 32bits)

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- Allows precise characterization

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How to Automatically Generate Such Constraints?

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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

Target: Computation of ϕ such that $\exists\ \boldsymbol{C}\ \boldsymbol{controlled\ value}, \forall\ \boldsymbol{U}\ \boldsymbol{uncontrolled\ value}, \boldsymbol{\phi}(\boldsymbol{C}, \boldsymbol{U}) \Longrightarrow \boldsymbol{reach}(\boldsymbol{C}, \boldsymbol{U})$

Abduction of Robust Reachability Constraints

Abductive Reasoning

[Josephson and Josephson, 1994]

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

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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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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)

$\vec{P}$ Program

ψ Target Trace Predicate

$\mathcal{A}_C$ Memory Partition

→ Abduction Procedure

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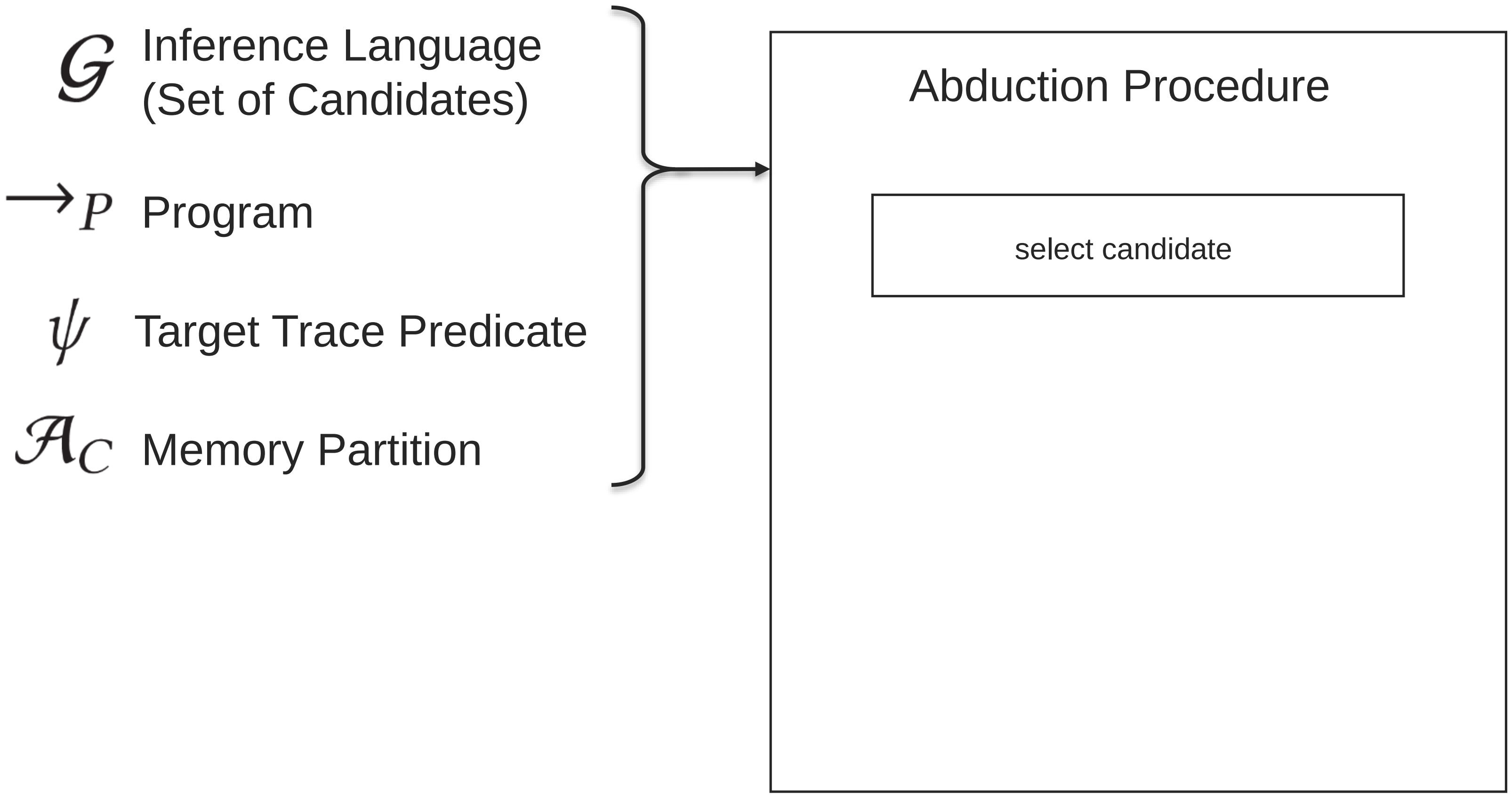

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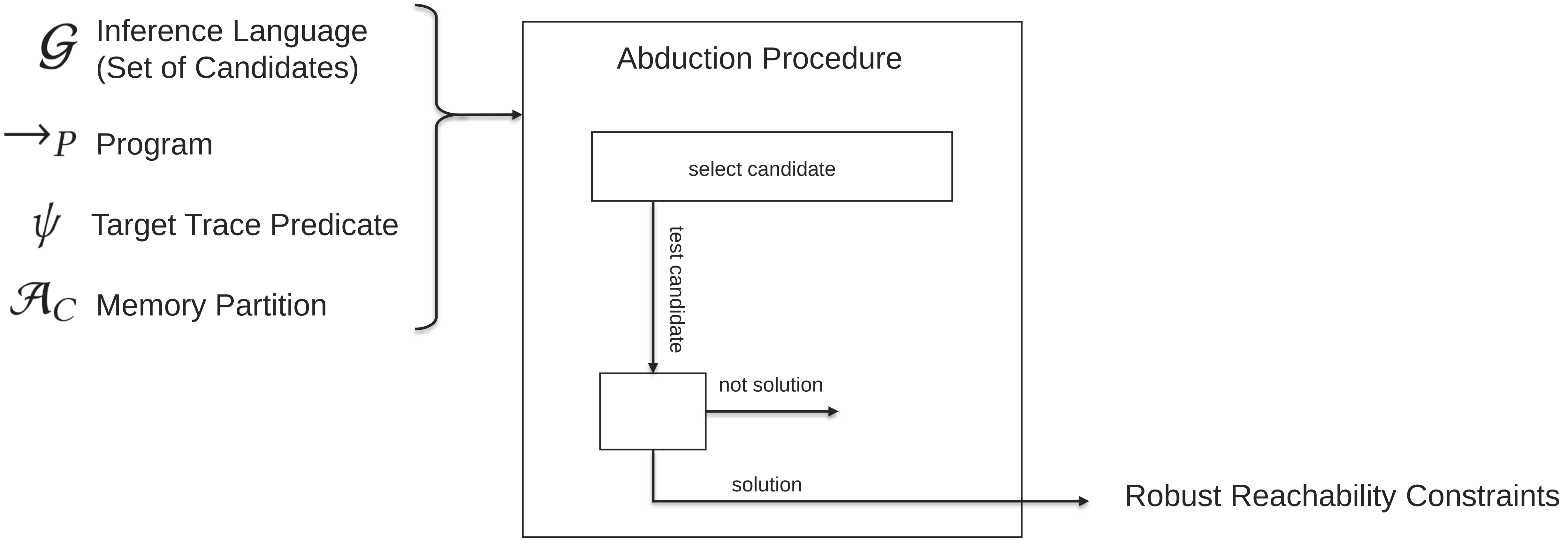

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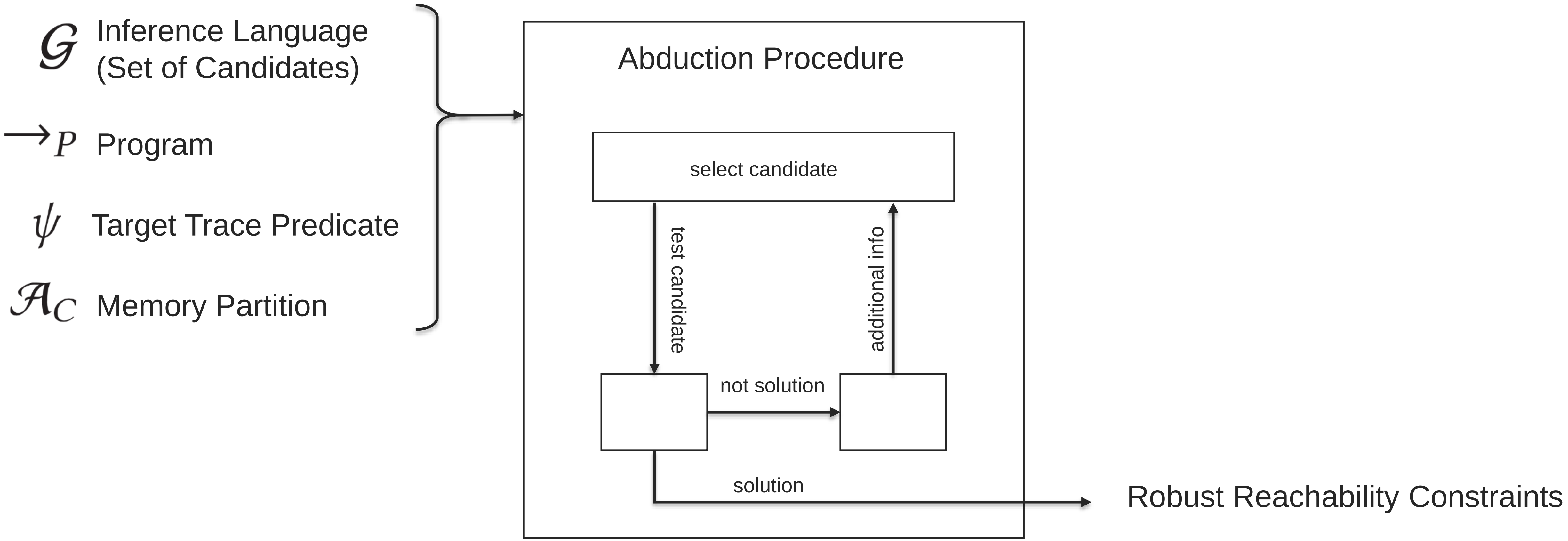

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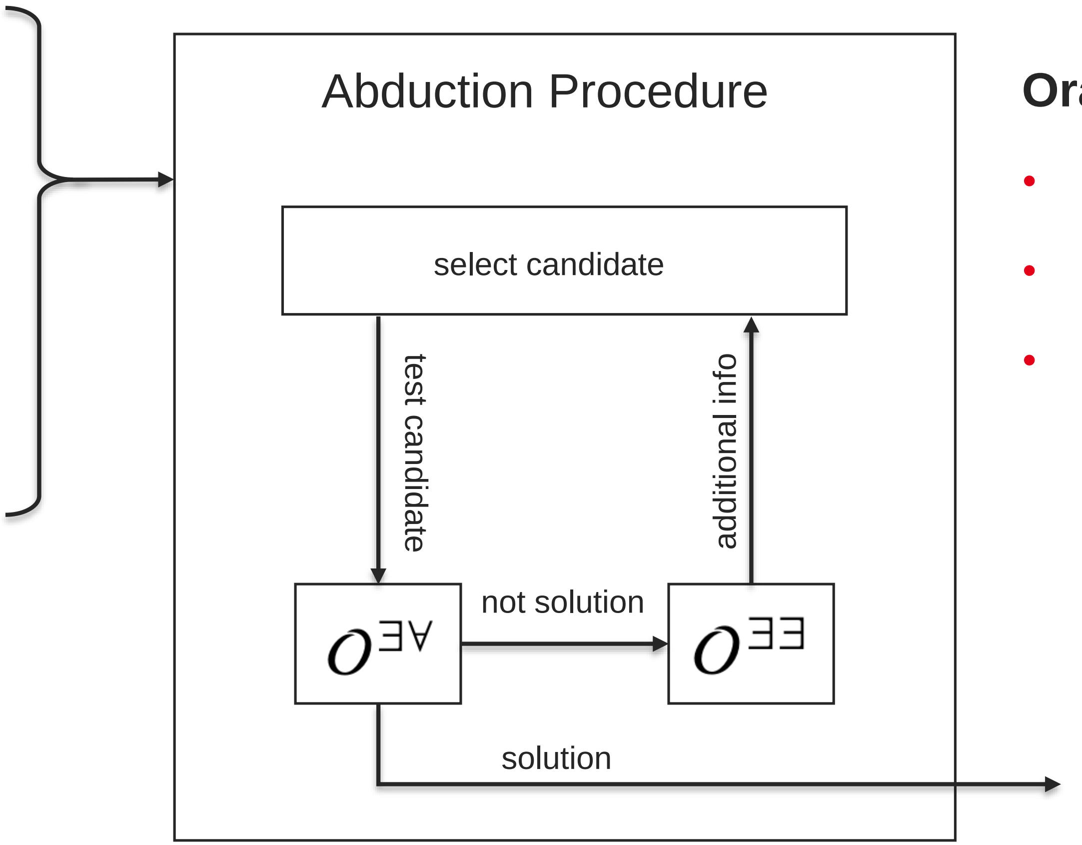

Robust Reachability Constraints

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, …)

Our Solution (Baseline Algorithm)

$\textsc{BaselineRCInfer}(\mathcal{G}, \rightarrow_P, \psi, \mathcal{A}_C)$

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;
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Theorem:

- **Termination** when the oracles terminate
- **Correction** at any step when the oracles are correct
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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

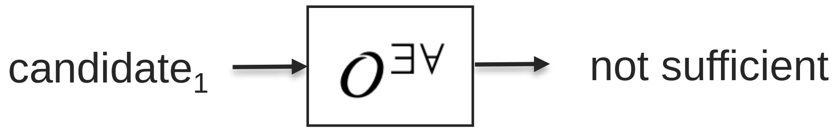
Key Strategies for Efficient Exploration

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

Making it Work: Necessary Constraints

The Idea

- Find and store Necessary Constraints



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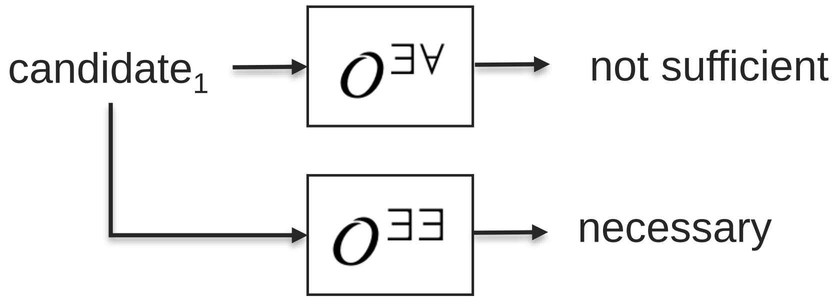

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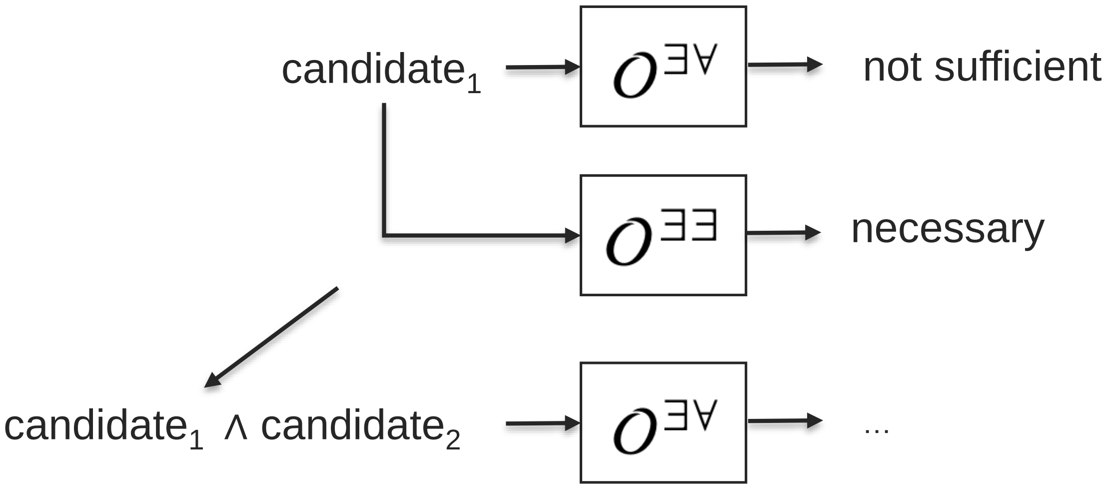
Usage

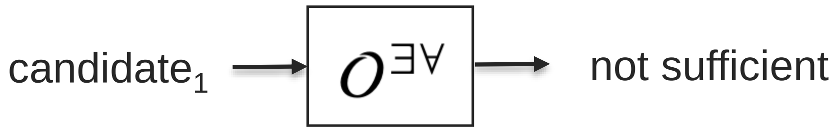
- Build a candidate solution faster
- Additional information on the bug
- Emulate unsat core usage in the context of oracles



Making it Work: Counter-Examples

The Idea

- Reuse information from failed candidate checks



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

Making it Work: Counter-Examples

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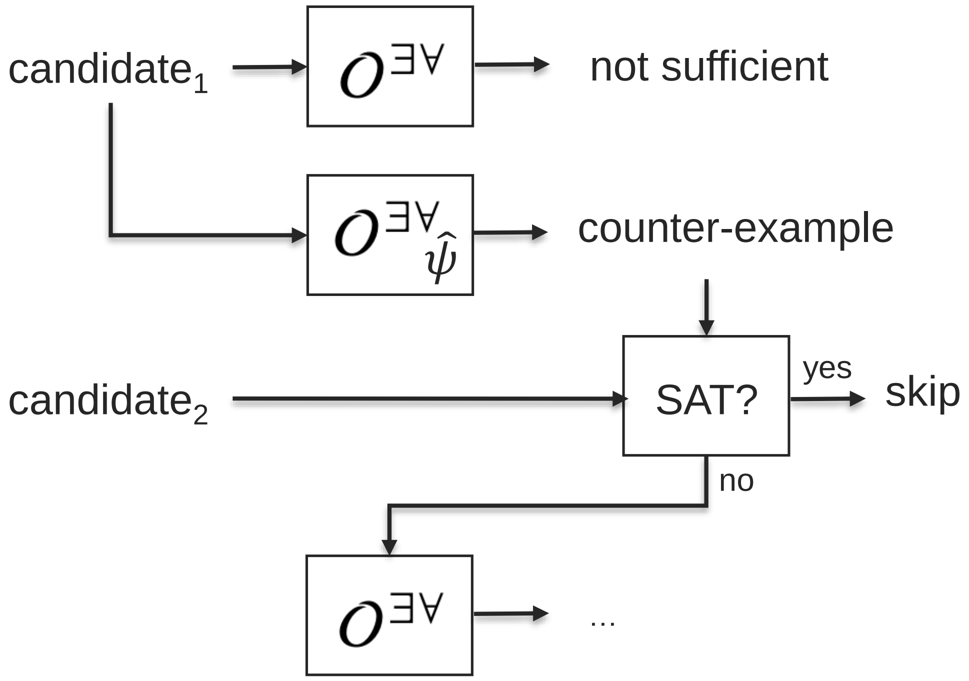
Proposal

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



Experimental Evaluation

Implementation

- (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 $(I_{\mathcal{G}})$ $\rightarrow$ More expressivity but more candidates

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We can find more reliable bugs than Robust Symbolic Execution

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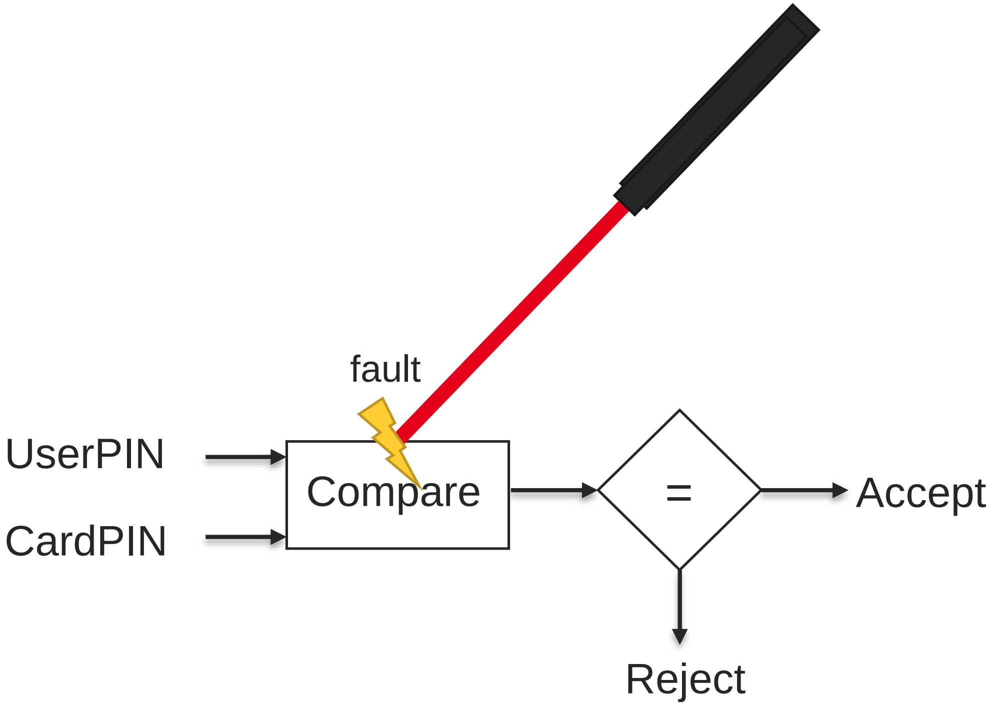
Benchmark: FISSC

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

Number of faulted programs with at least a given proportion of input states triggering the bug

	PyAbd^{P}	Binsec/RSE	Binsec	Qemu	Qemu+L
unknown	170	273	170	243	284
not vulnerable (0 input)	4042	4419	3921	4398	4220
vulnerable (≥ 1 input)	598	118	719	169	306
≥ 0.0001%	598	118	–	–	306
≥ 0.01%	582	118	–	–	281
≥ 0.1%	514	118	–	–	210
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≥ 50.0%	401	118	–	–	135
100.0%	399	118	–	–	135

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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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Preconditions **explain** the vulnerability
Can be reused for understanding, counting, comparing

Artifacts Available acm V1.1

BINSEC

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Questions?

Also, we have open positions

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