Automatically Proving Memory Safety and Termination of C-Programs

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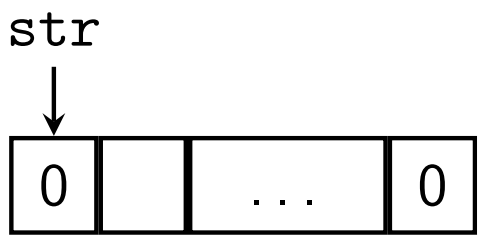
Research Area Computer Science 2
Published: (Termination with Pointer Arithmetic, Ströder et al., 2014)

Feb 23, 2015

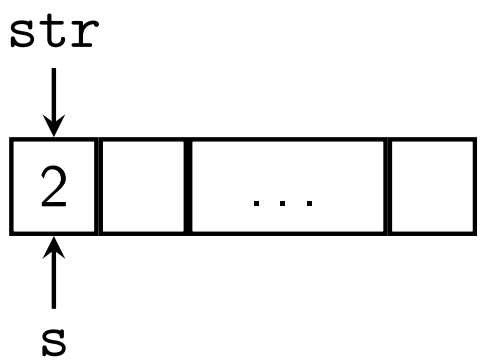
An Example

```
int strlen(char* str) {
    char* s = str;
    while(*(++s));
    return s-str;
}
```



An Example

```
int strlen(char* str) {
    char* s = str;
    while((*s)++);
    return s-str;
}
```



An Example

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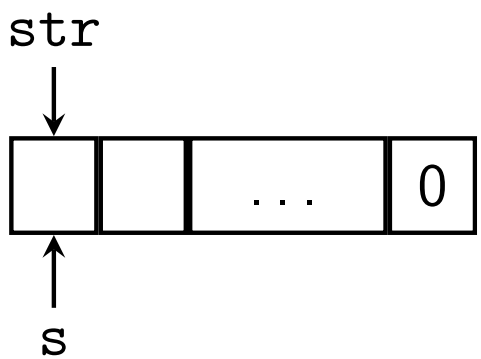

An Example

```
int strlen(char* str) {
    char* s = str;
    while(*s) s++;
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}
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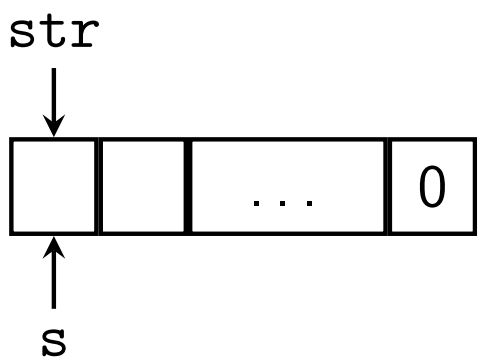

Big Picture

YES/NO/
MAYBE

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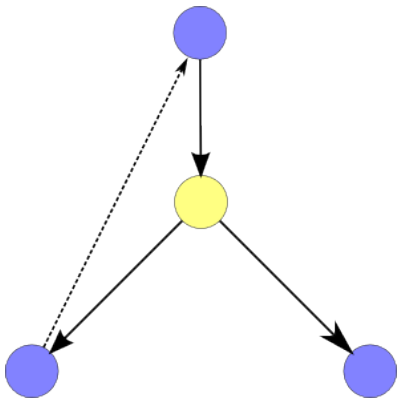
4

2



3

$f(x) \to g(x+1)$
$g(x) \to g(x-1)$

LLVM

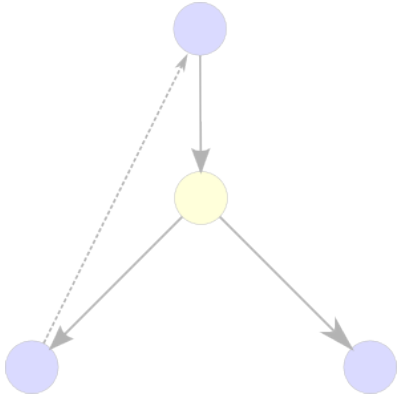
Symbolic Execution Graph

Integer Transition System

C to LLVM

LLVM

?



Symbolic Execution Graph

?

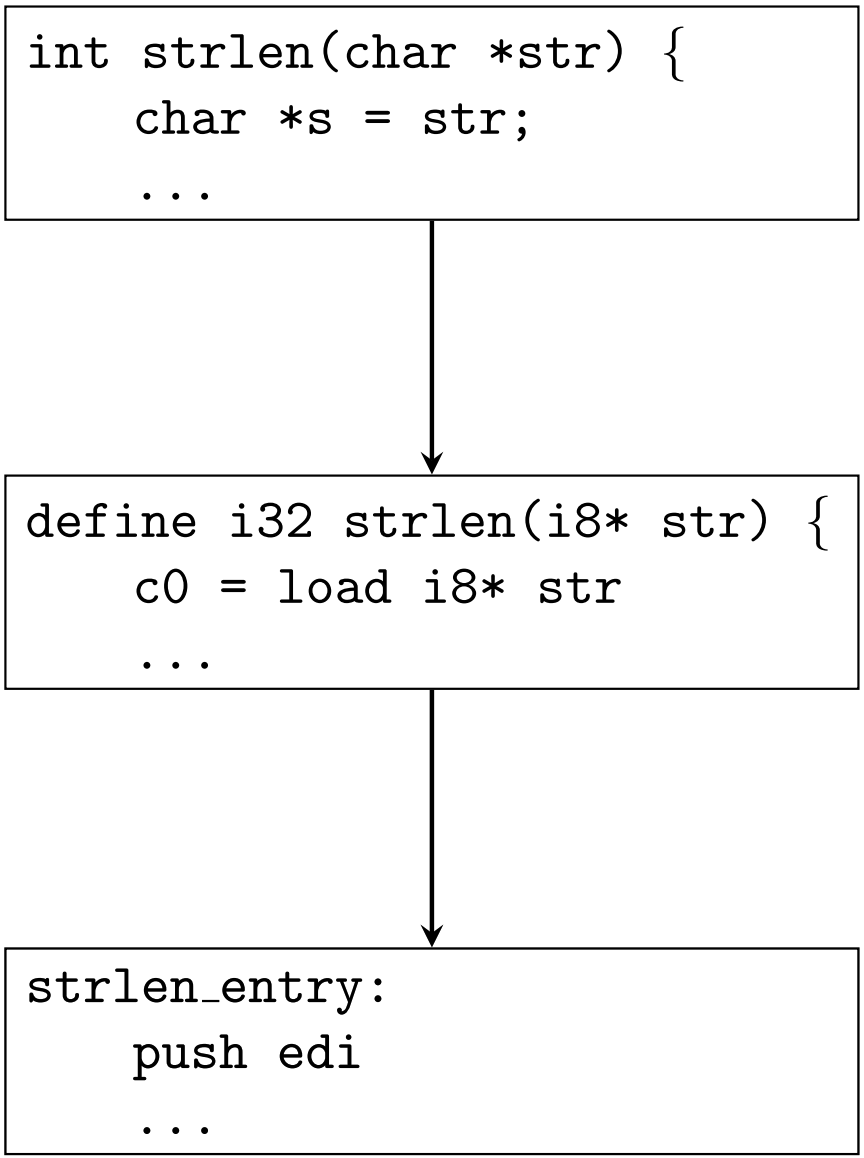
$f(x) \to g(x+1)$
$g(x) \to g(x-1)$

Integer Transition System

?

YES/NO/
MAYBE

LLVM Compiler Infrastructure



C-program

LLVM Internal Representation

Assembler

Some LLVM Instructions

- Control Flow Instructions
  - `ret`, `br`, `call`, ...
- Arithmetic Instructions
  - `add`, `icmp`, ...
- Bitwise Instructions
  - `shl`, `and`, ...
- Memory Instructions
  - `alloca`, `load`, `store`, ...

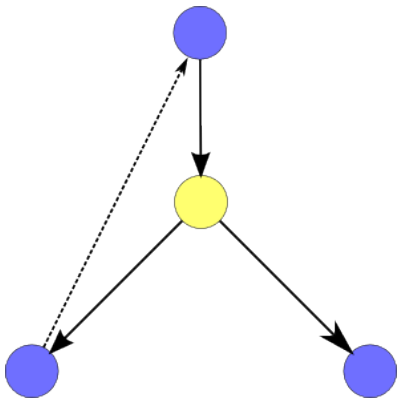
Complete Reference: `http://llvm.org/docs/LangRef.html`

LLVM to Symbolic Execution Graph

✓

LLVM

?



Symbolic Execution Graph

?

YES/NO/
MAYBE

?

$f(x) \to g(x+1)$
$g(x) \to g(x-1)$

Integer Transition System

Problem Definition

Given: LLVM Program, Entry Point

Goal: Description of *at least all possible runs* from the entry point

Idea: Abstract interpretation of program states

Abstract States

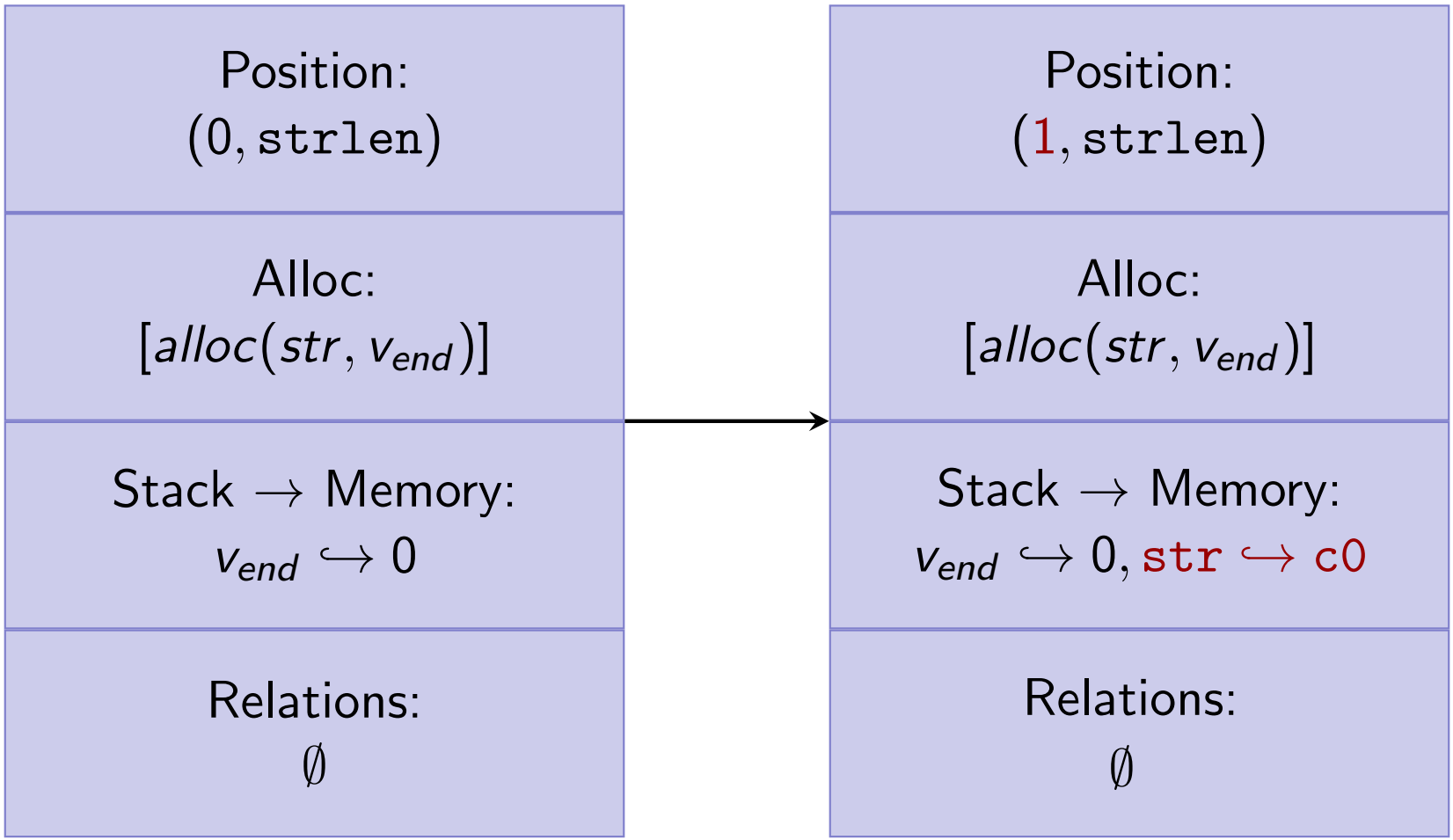
Position:	$(0, \texttt{strlen})$
Alloc:	$[alloc(str, v_{end})]$
Stack $\rightarrow$ Memory:	$v_{end} \hookrightarrow 0$
Relations:	$\emptyset$

Entry Point:

```
define i32 strlen(i8* str) {
    c0 = load i8* str
    ...
```

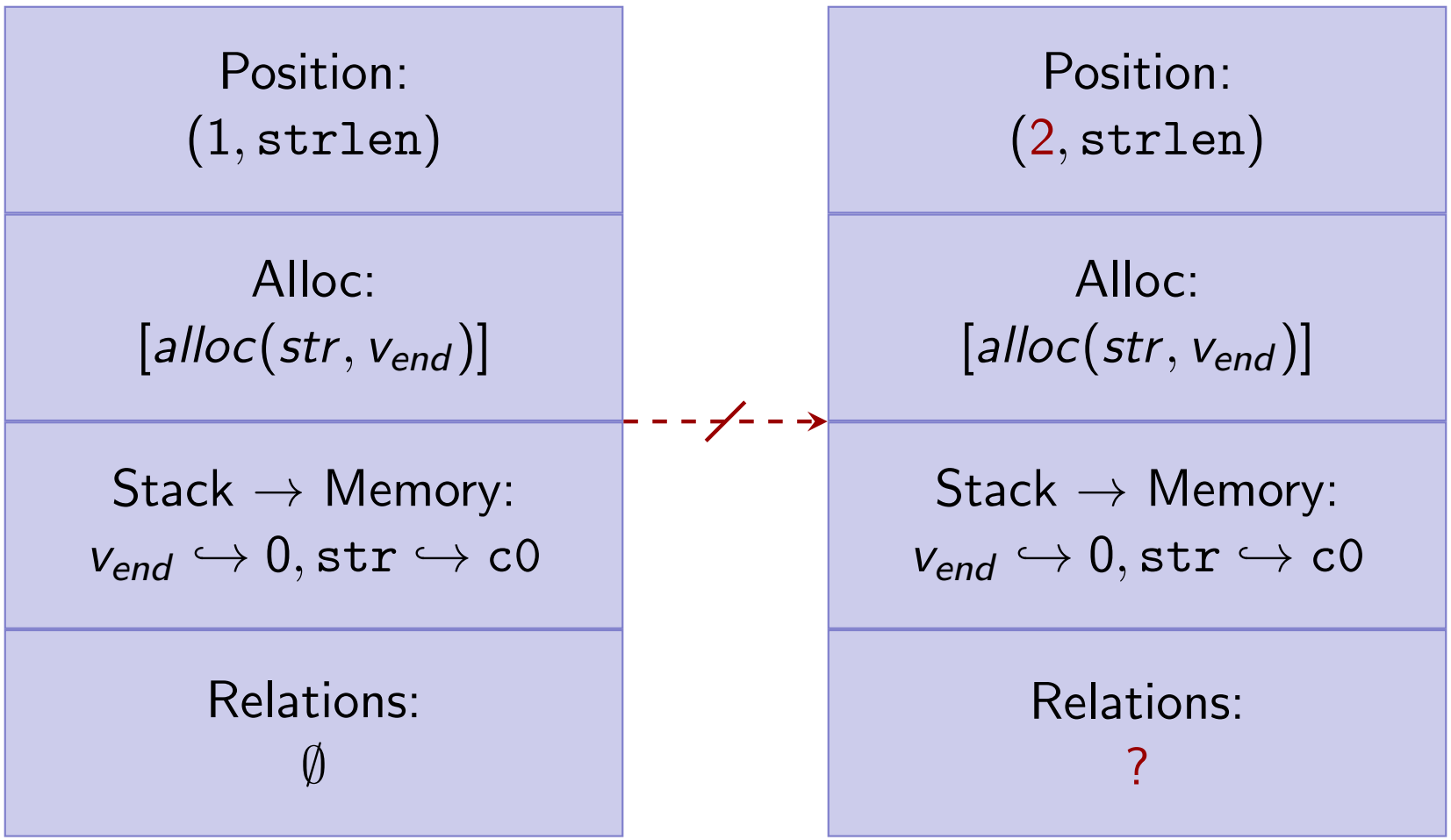
Evaluation of Abstract States

```
c0 = load i8* str
```



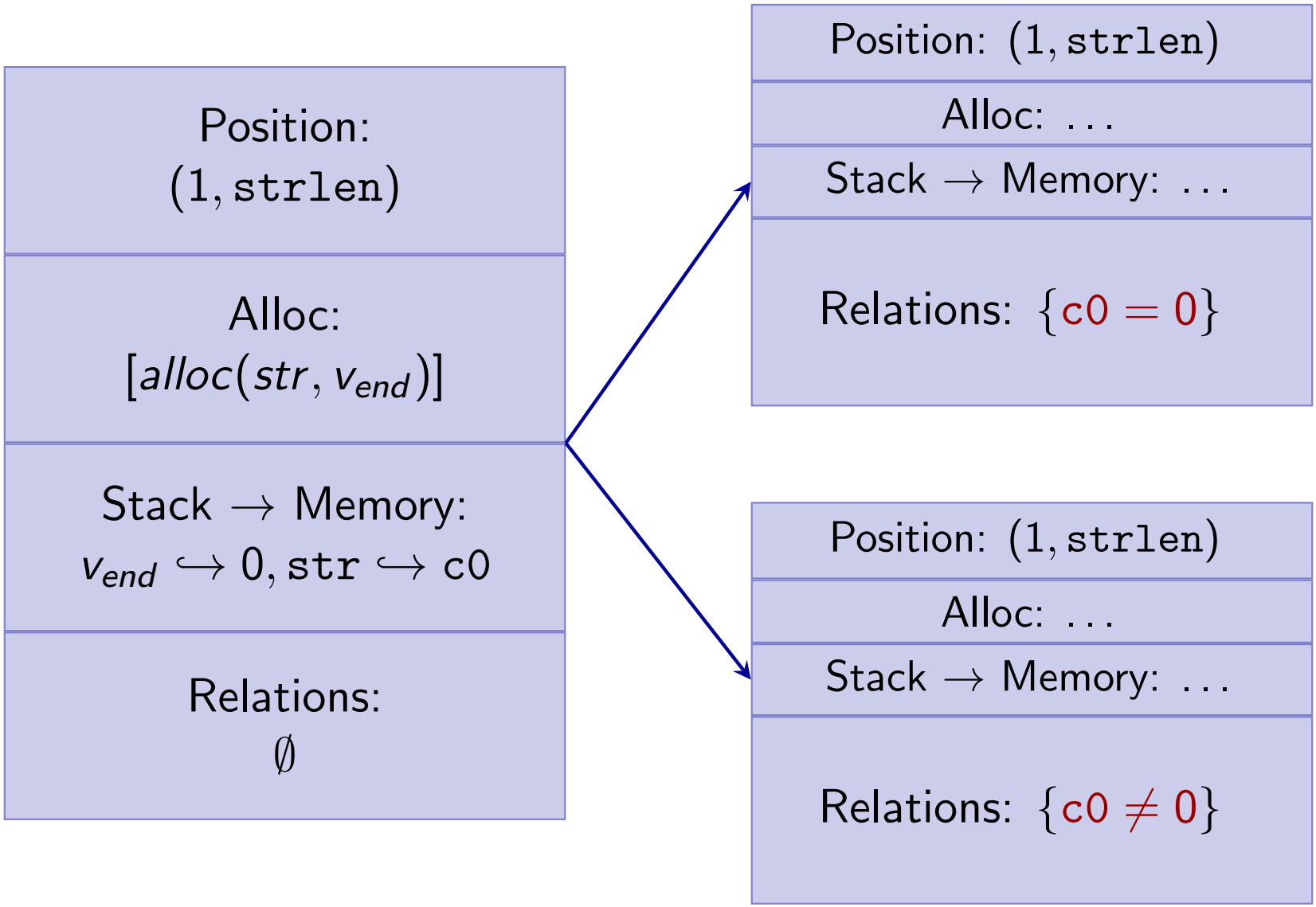
Refinement of Abstract States

$$\texttt{c0zero} = \underbrace{\texttt{icmp eq i8 c0, 0}}_{\texttt{c0==0}}$$



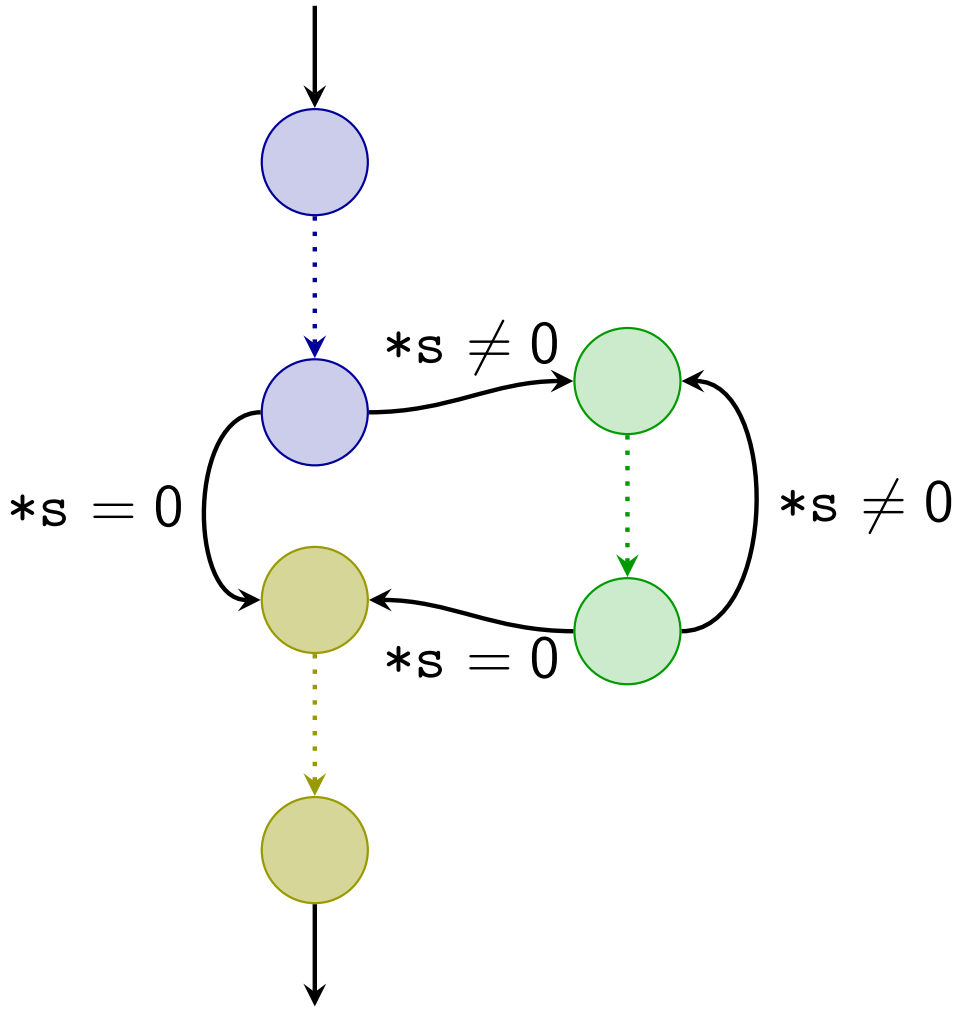
Refinement of Abstract States

```
c0zero = icmp eq i8 c0, 0
```

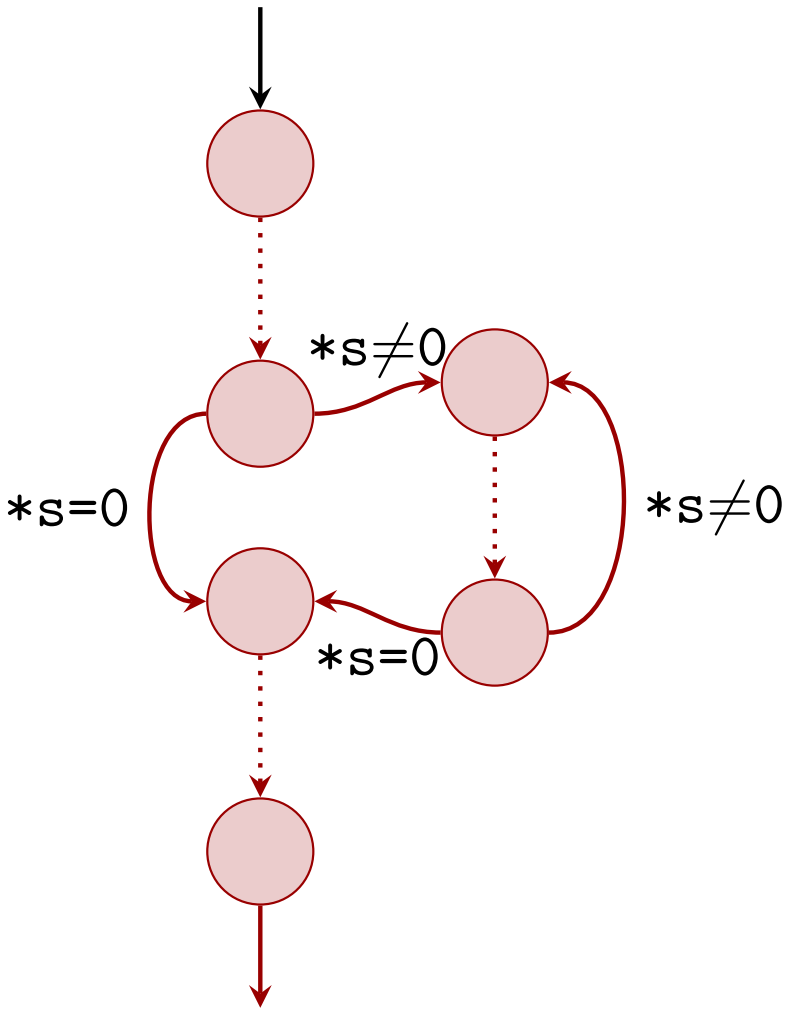


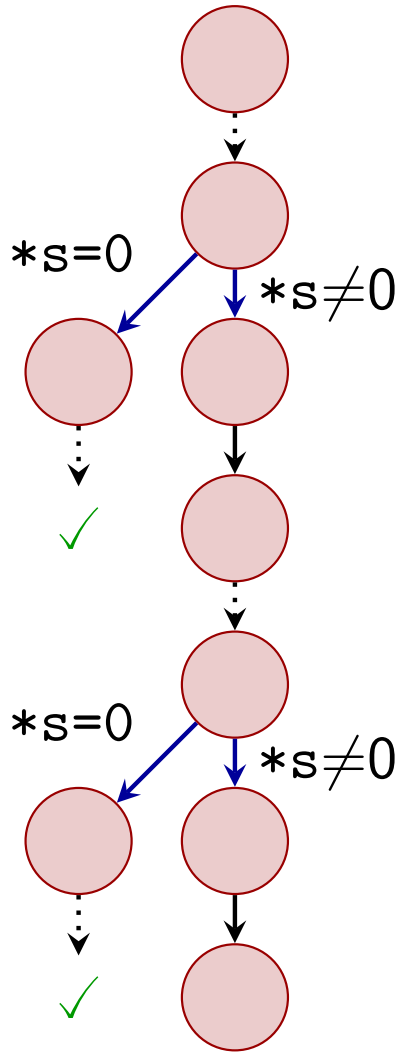
Merging of Abstract States

```
int strlen(char *str) {
    char *s = str;
    while(*s) s++;
    return s-str;
}
```



Merging of Abstract States





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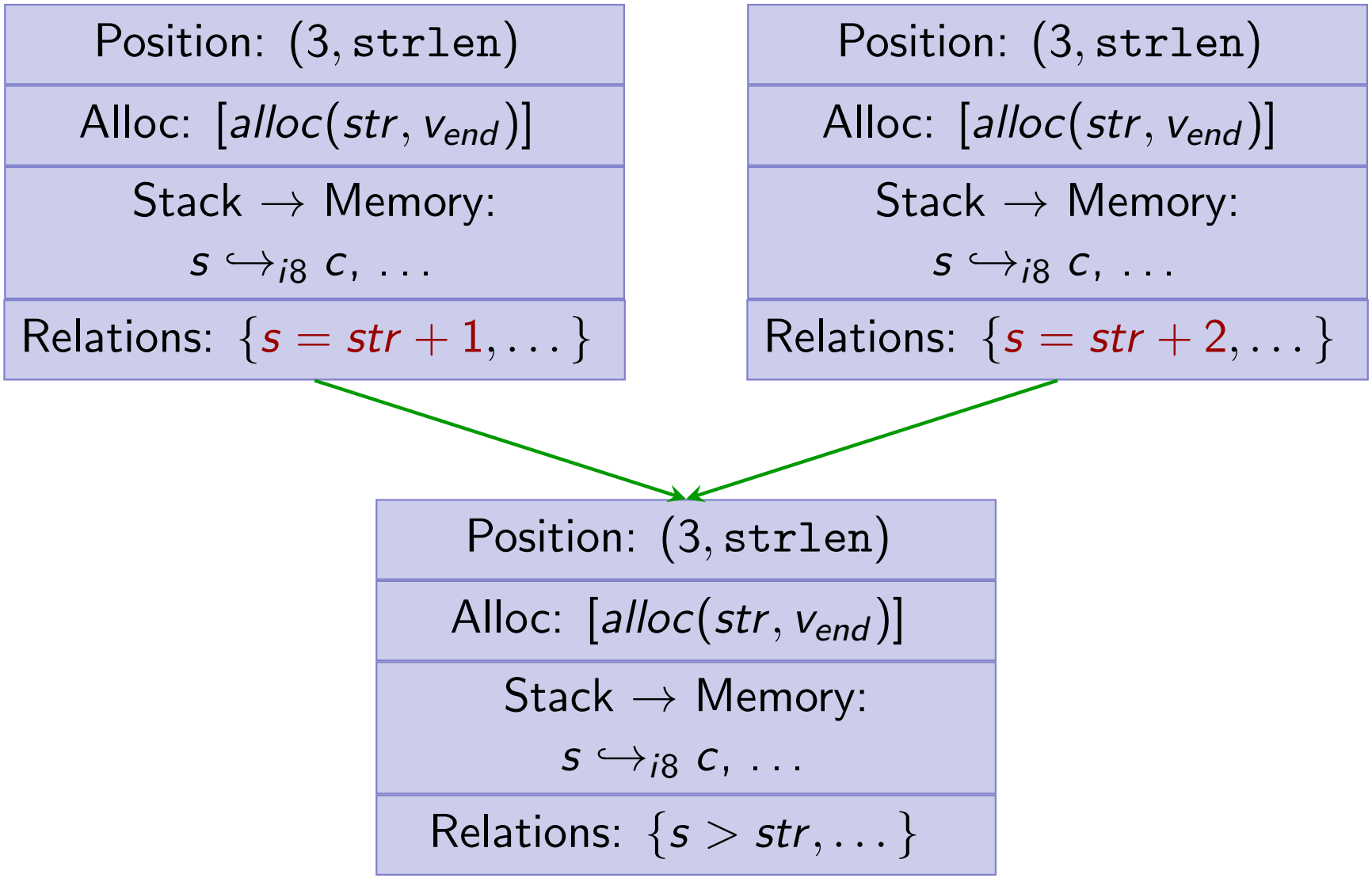
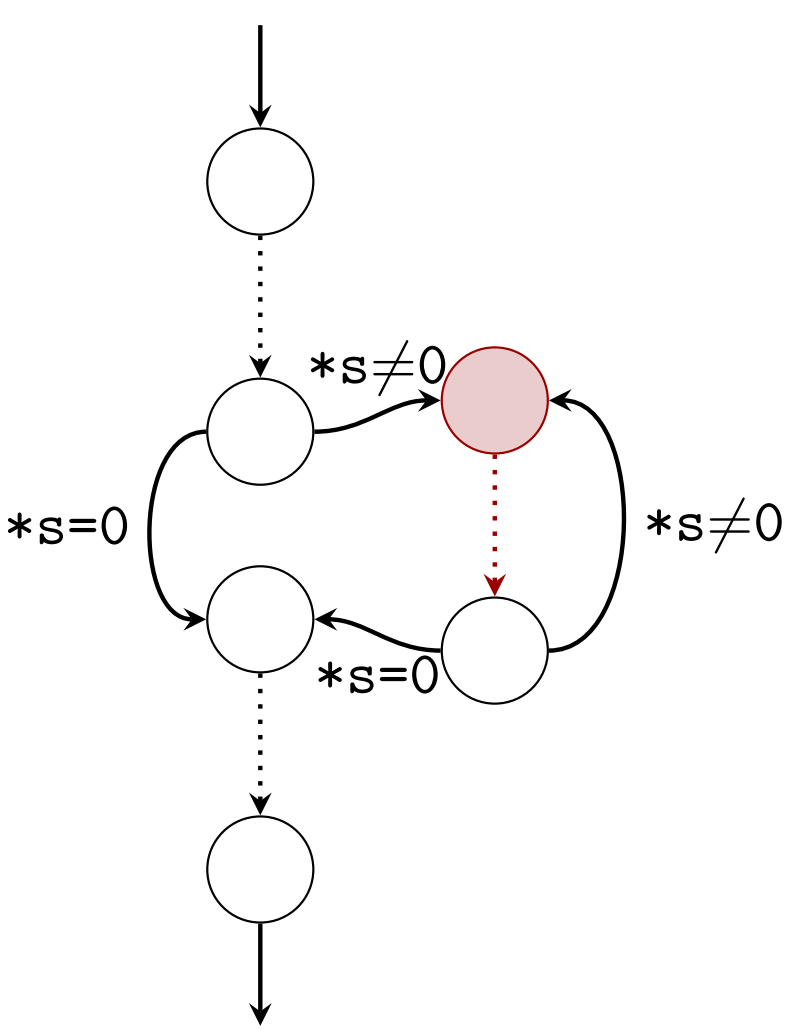
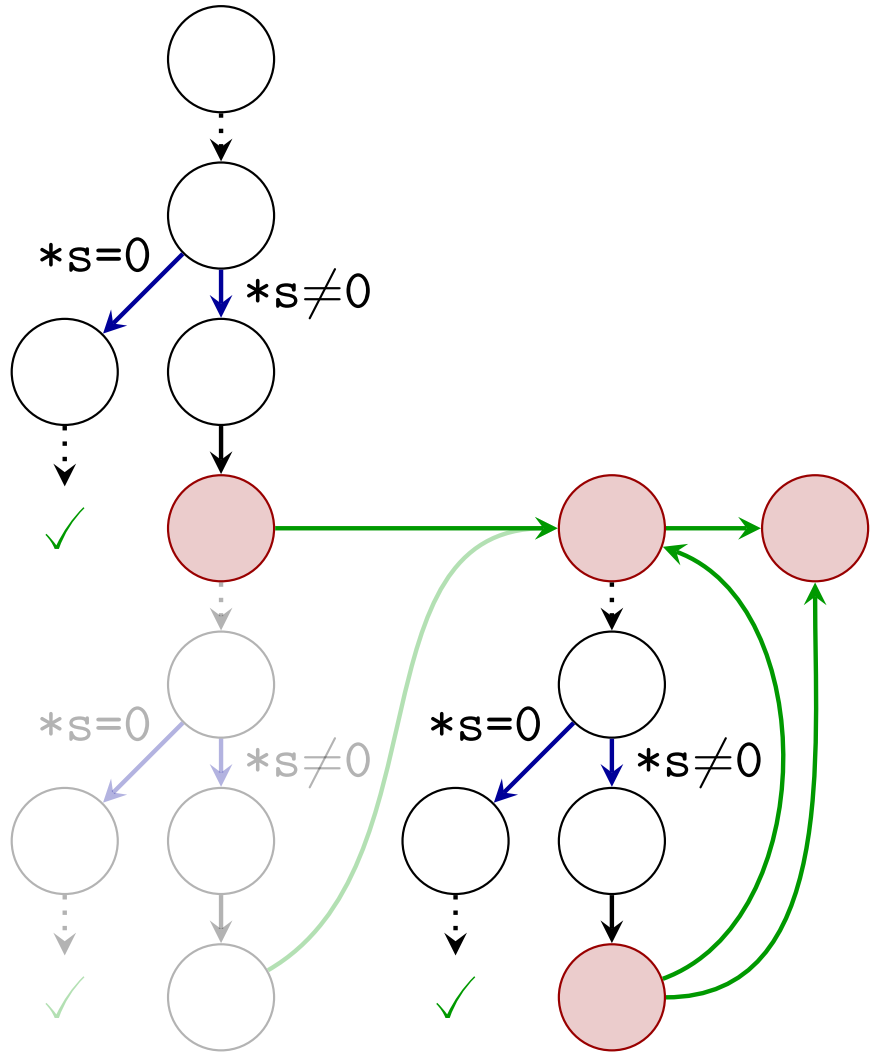
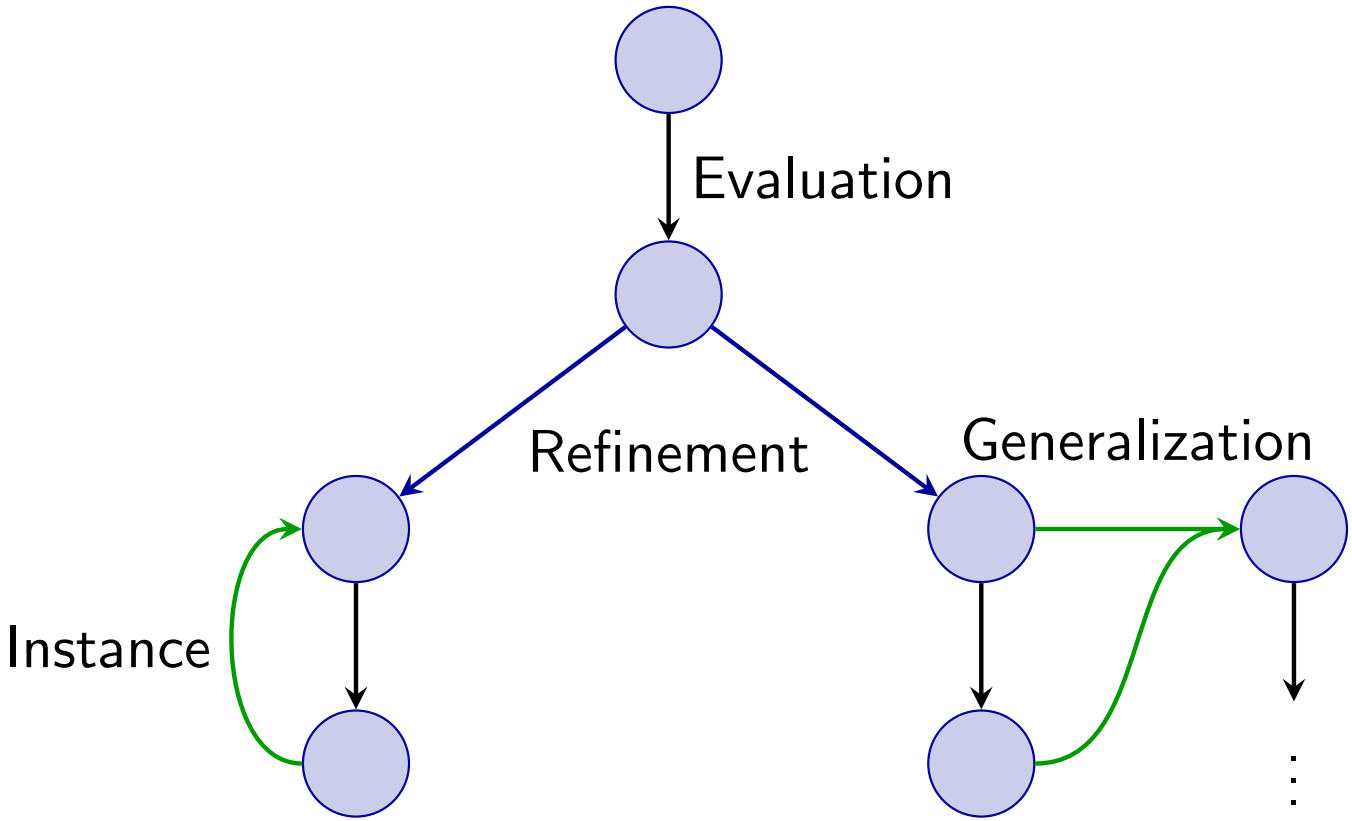


Merging of Abstract States





Summary: Symbolic Execution Graphs

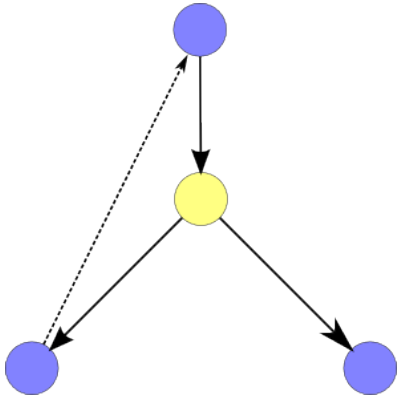


Symbolic Execution Graph to Integer Transition System

✓

LLVM

✓



Symbolic Execution Graph

?

$f(x) \to g(x+1)$
$g(x) \to g(x-1)$

Integer Transition System

?

YES/NO/
MAYBE

Integer Transition Systems

Term Rewriting System:

$$f(x, y) \to g(y, x)$$

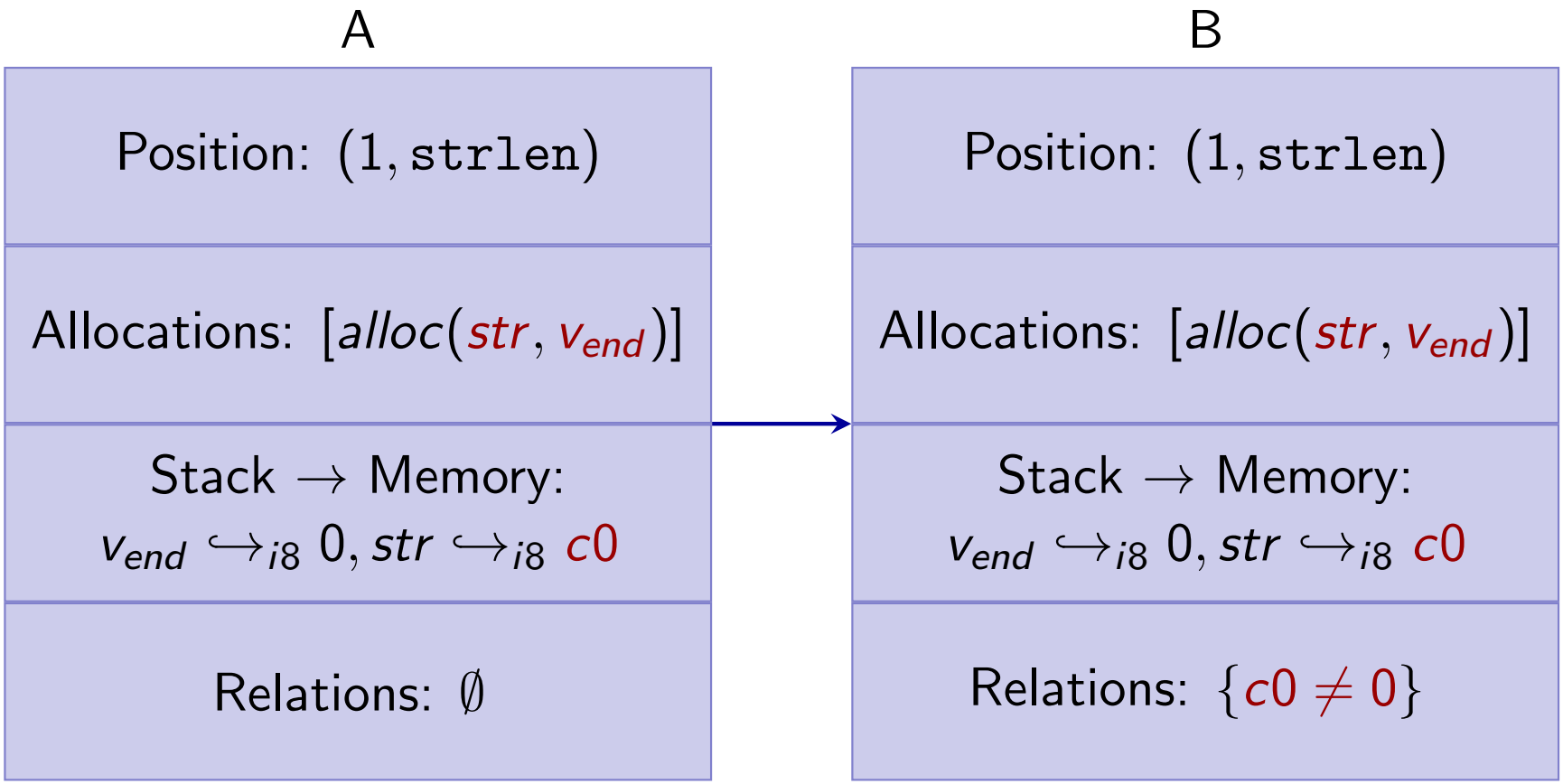
Integer Transition System:

$$f(x, y) \to g(y + 1, x - 2)$$

Integer Transition System:

$$f(x, y) \to g(y + 1, x - 2) \quad | \, x > 0$$

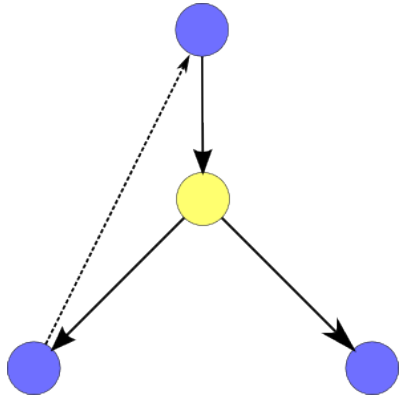
Symbolic Execution Graph to Integer Transition System



$$f_A(str, v_{end}, c0) \rightarrow f_B(str, v_{end}, c0) \mid c0 \neq 0$$

Termination of Integer Transition System

LLVM



Symbolic Execution Graph

YES/NO/
MAYBE

?

$f(x) \to g(x+1)$
$g(x) \to g(x-1)$

Integer Transition System

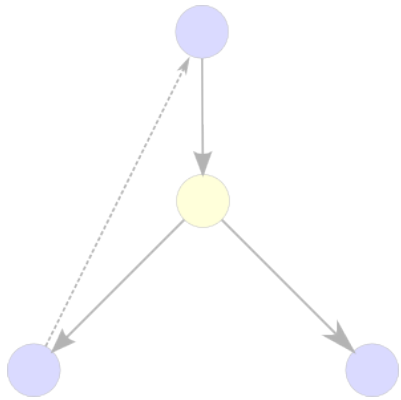
Termination of Integer Transition System

Well-studied problem

Use known techniques to show termination,
e.g. (Termination of Integer Term Rewriting, Fuhs et al., 2009)

Termination of Integer Transition System

LLVM



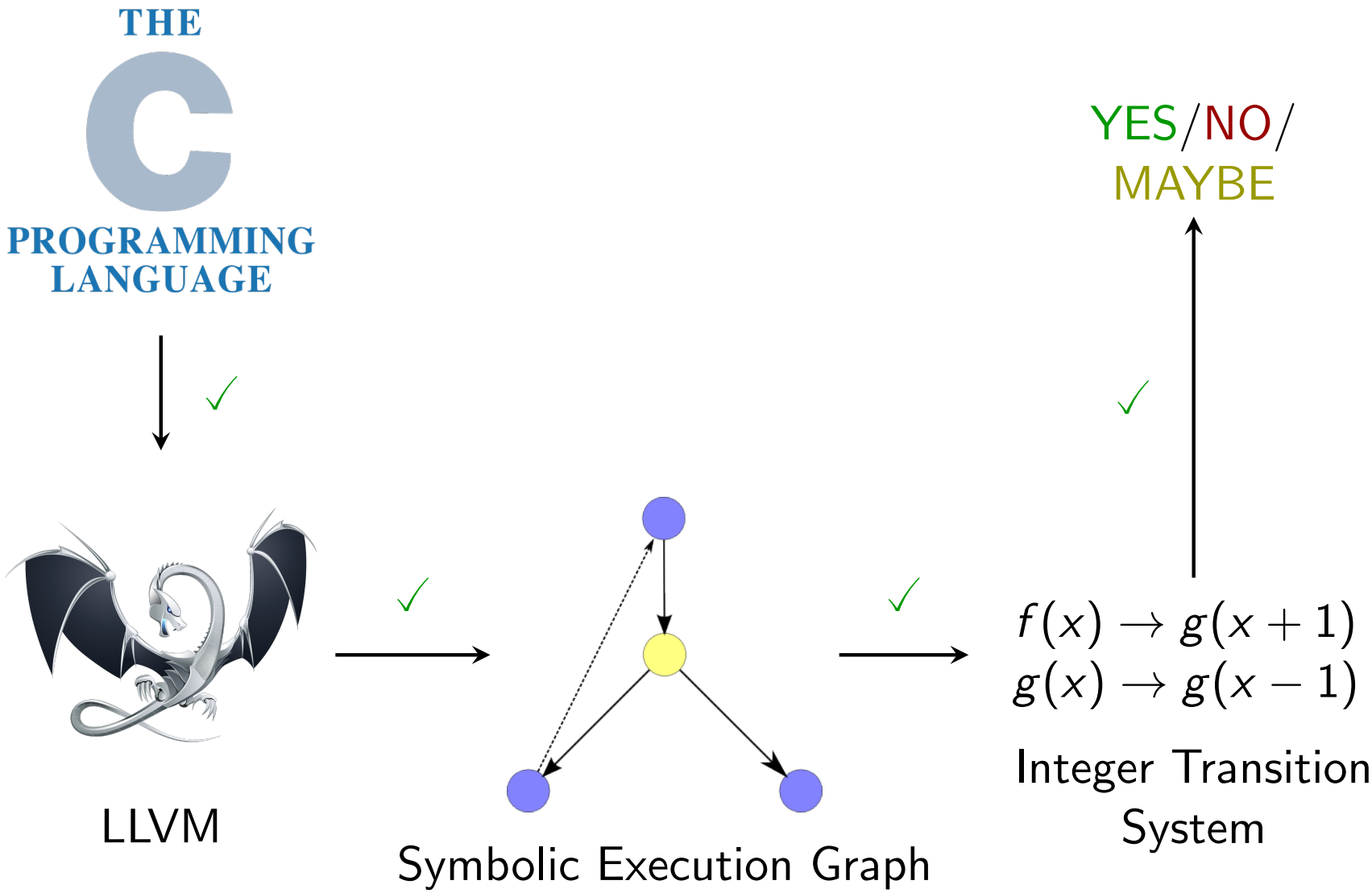
Symbolic Execution Graph

YES/NO/
MAYBE

$f(x) \to g(x+1)$
$g(x) \to g(x-1)$

Integer Transition System

Overview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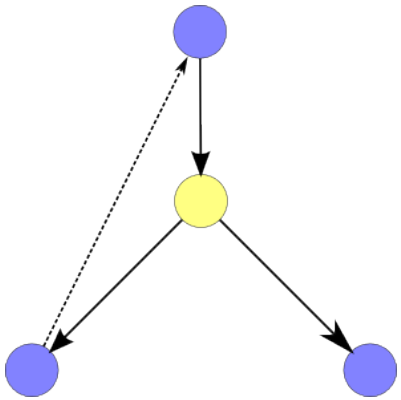
C
PROGRAMMING
LANGUAGE
✓
LLVM
✓
Symbolic Execution Graph
✓
$f(x) \to g(x+1)$
$g(x) \to g(x-1)$
Integer Transition System
✓
YES/NO/
MAYBE

My Contributions

LLVM



Symbolic Execution Graph

$$f(x) \to g(x+1)$$
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Integer Transition System

YES/NO/
MAYBE

My Contributions

Given: Abstract State s, Integer Relation r

Question: Does $s \models r$?

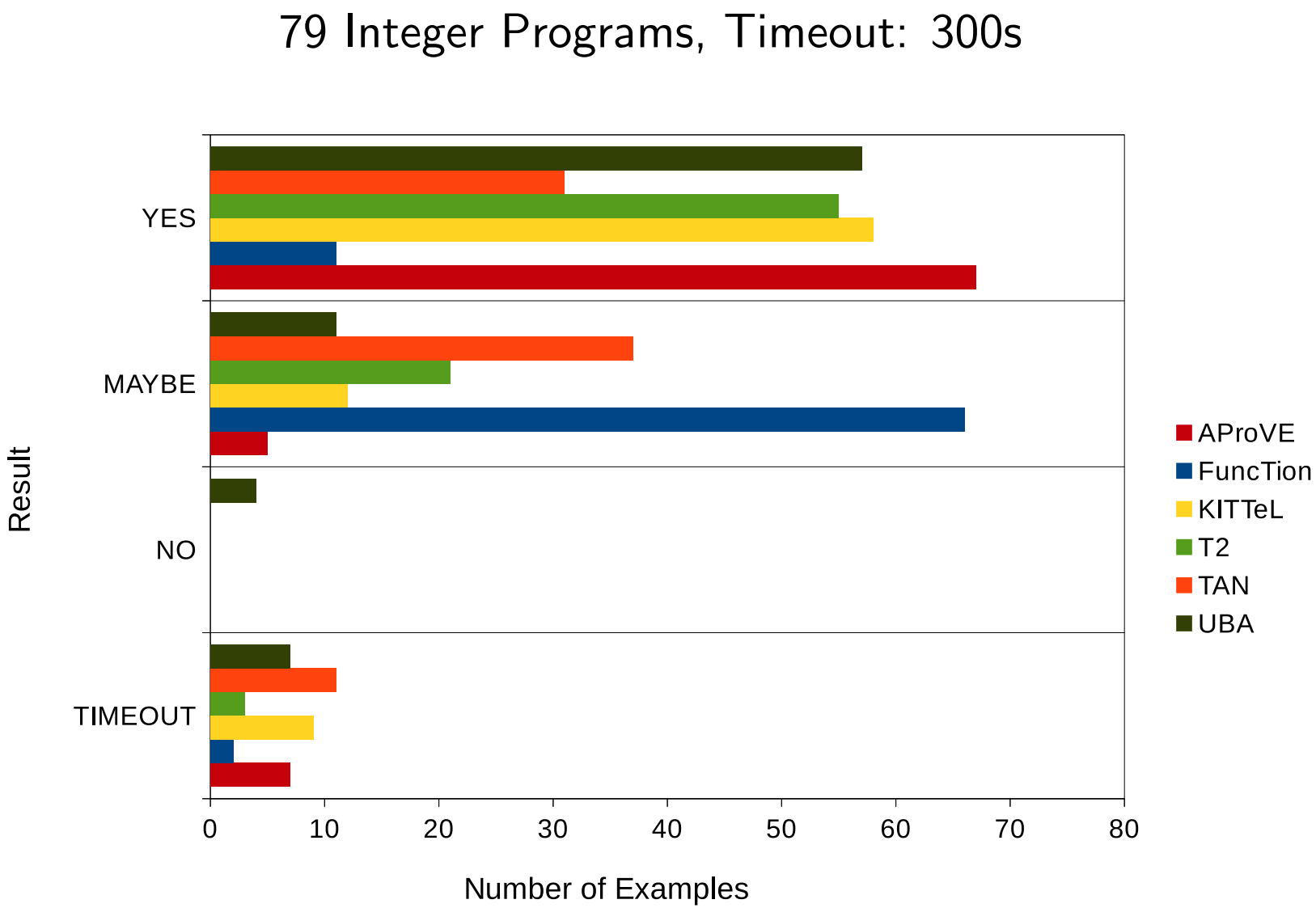
My Contributions

- Reduction from state to set of arithmetic relations
- Inference of knowledge from states
  - Formulation of inference in terms of integer relations
  - New framework for inference
  - Parameterization of framework with abstract arithmetic domain
  - Formulation of existing inference in framework

My Contributions

- Use of Octagon Domain for inference of relations
  - (The Octagon Abstract Domain, Miné, 2006)
- Experimental comparison
  - "Traditional" inference
  - Inference in framework
  - New inference based on Octagons

Evaluation: Empirical Evaluation



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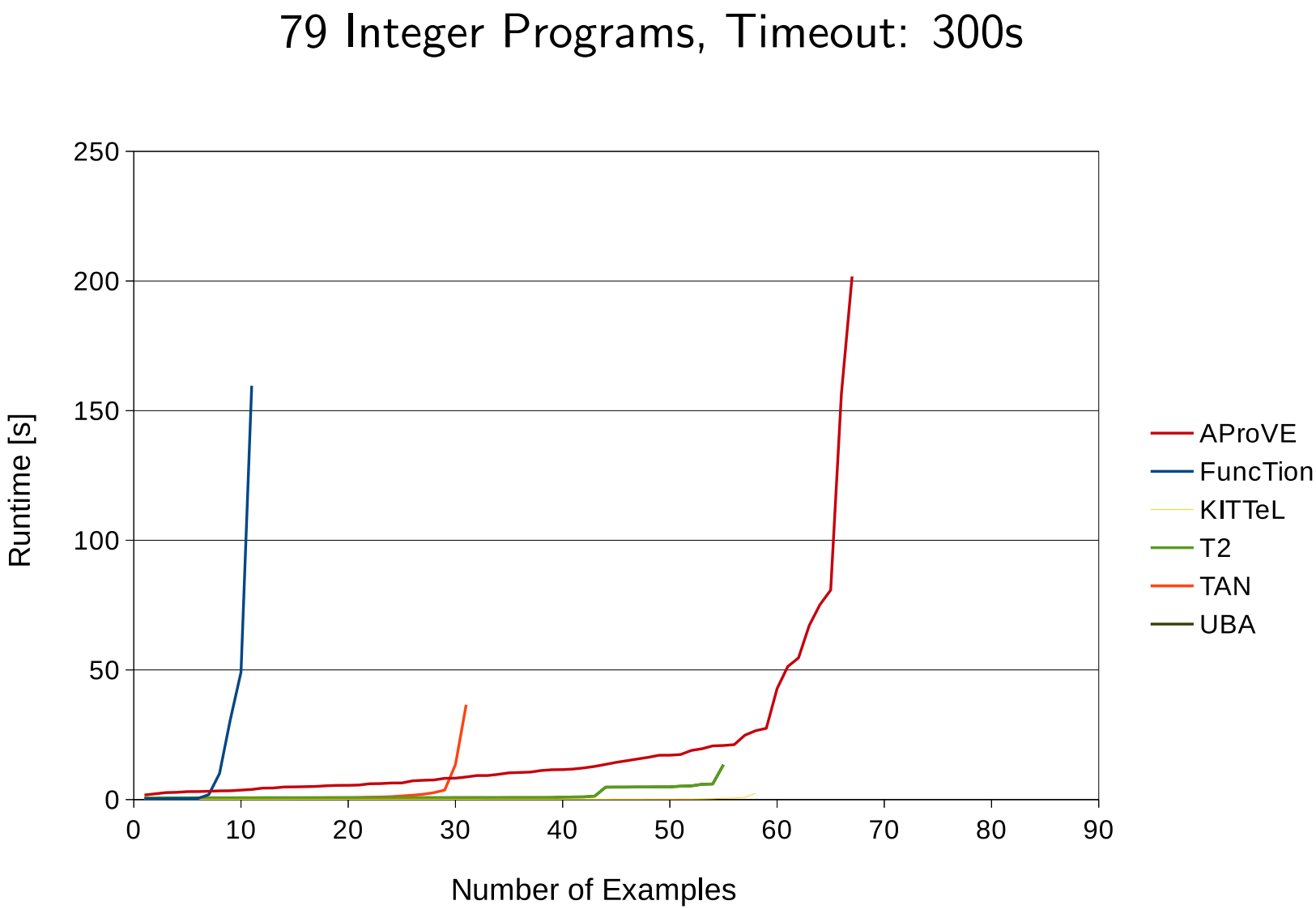

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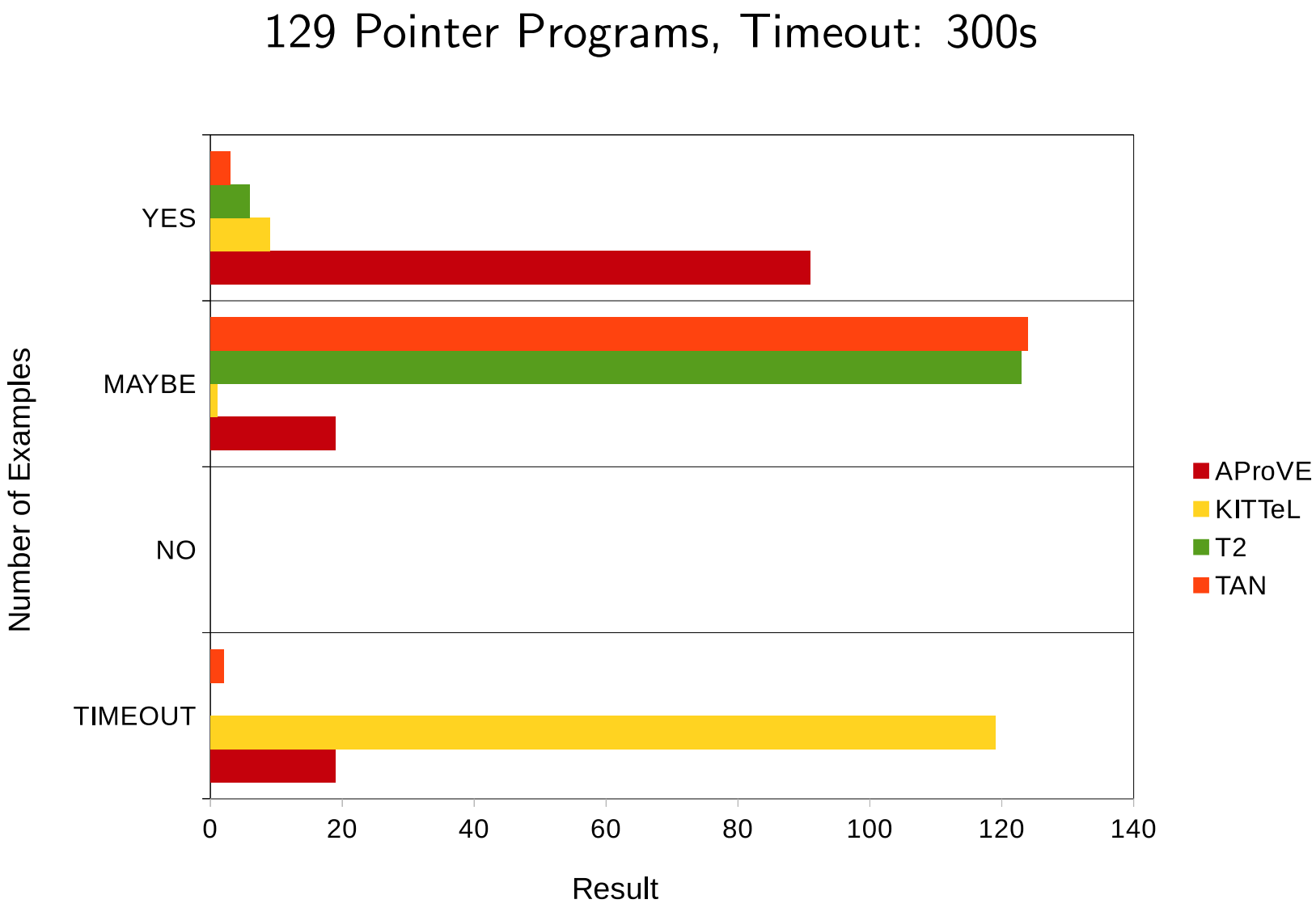

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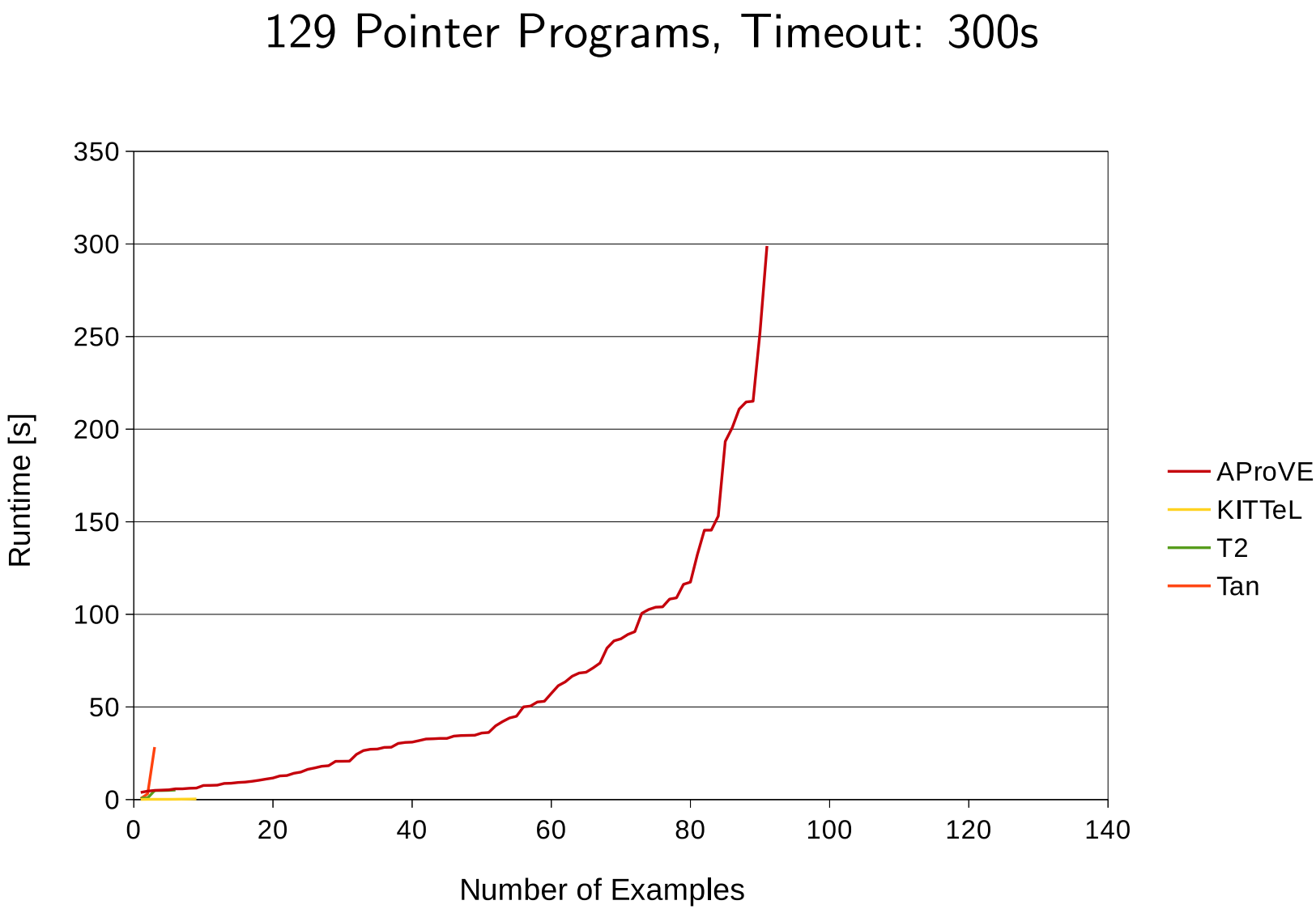

Complete evaluation at

`http://aprove.informatik.rwth-aachen.de/eval/Pointer/`

Thank you for your attention

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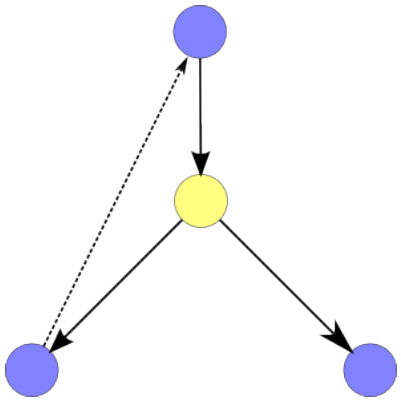
1

LLVM

2



Symbolic Execution Graph

3

$f(x) \to g(x+1)$
$g(x) \to g(x-1)$

Integer Transition System

4

YES/NO/
MAYBE