# Automatically Proving Memory Safety and Termination of C-Programs

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RWTH Aachen University

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

March 13, 2015

# An Example

```
int strlen(char* str) {
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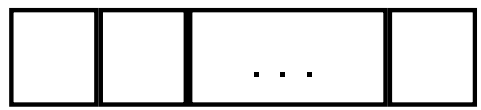

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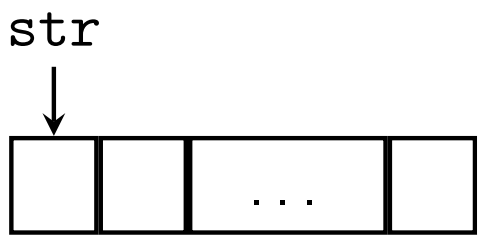

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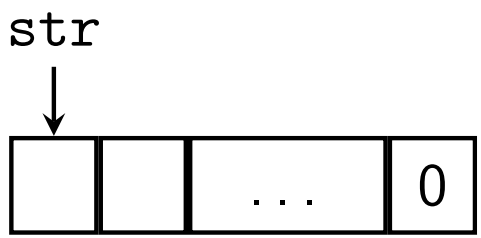

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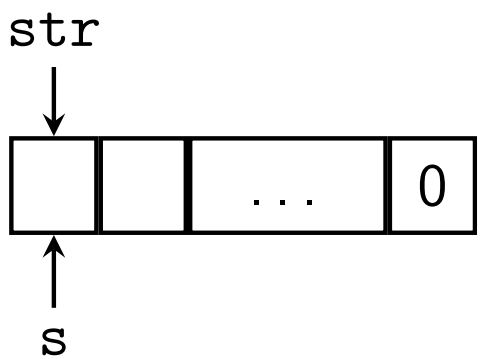

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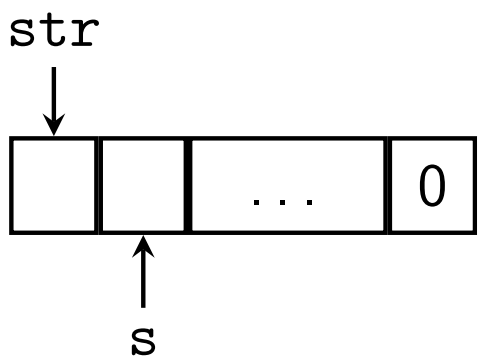

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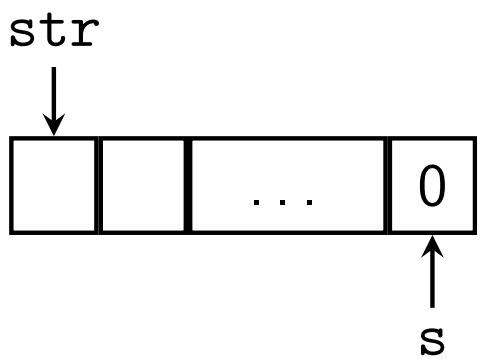

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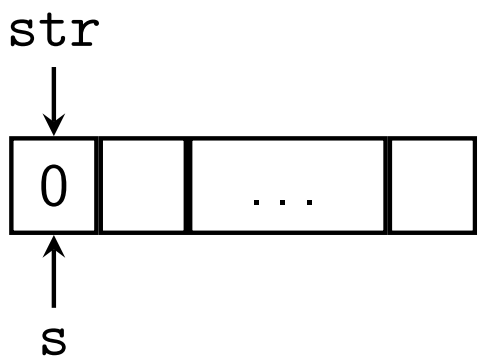

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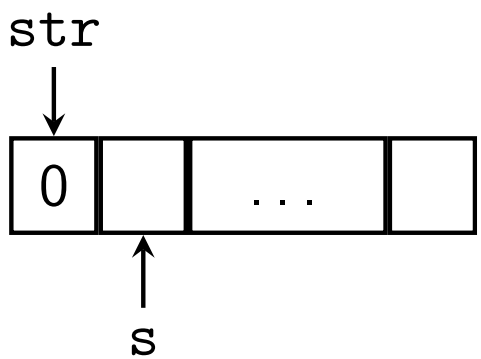

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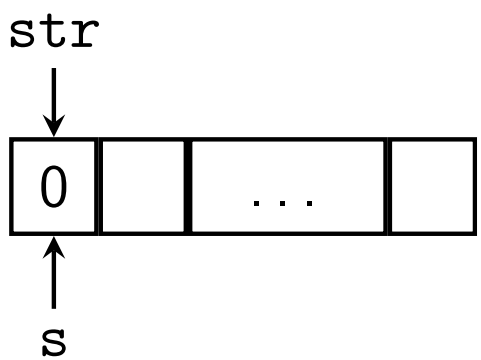

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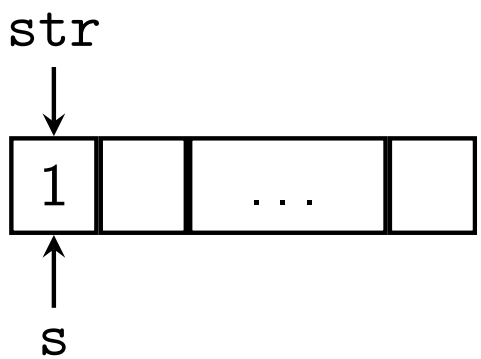

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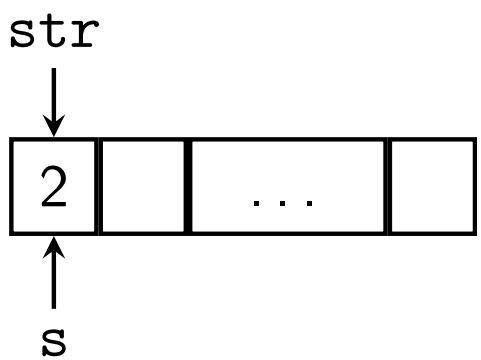

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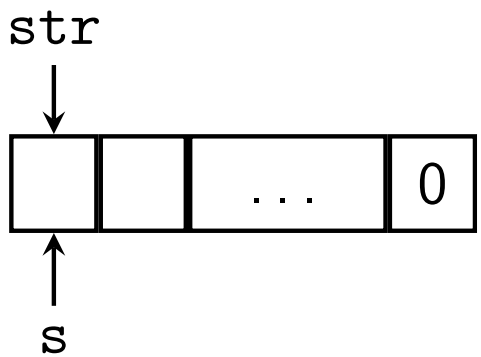

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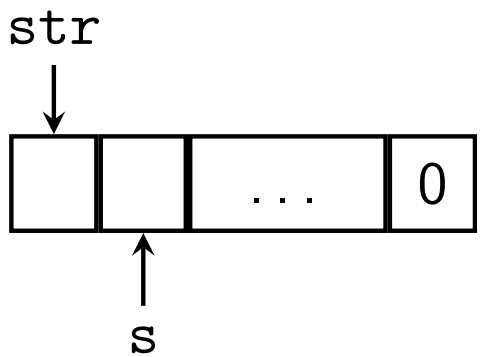

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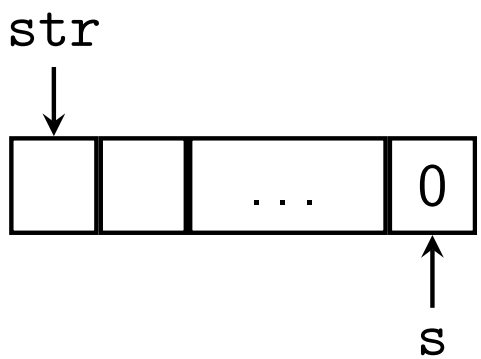

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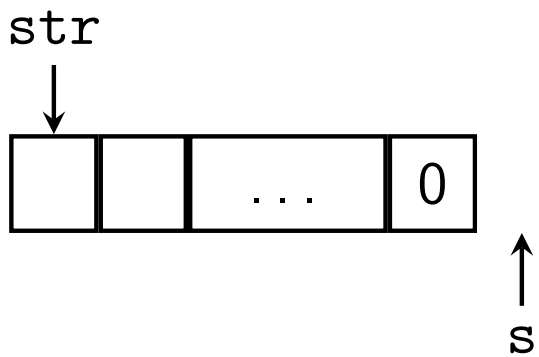

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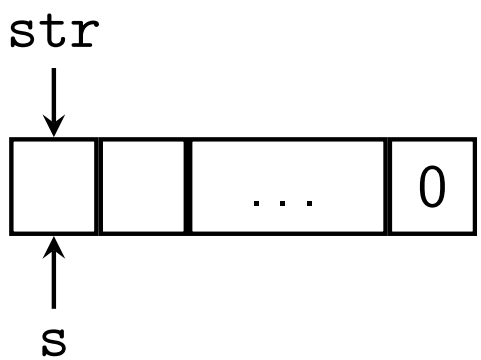

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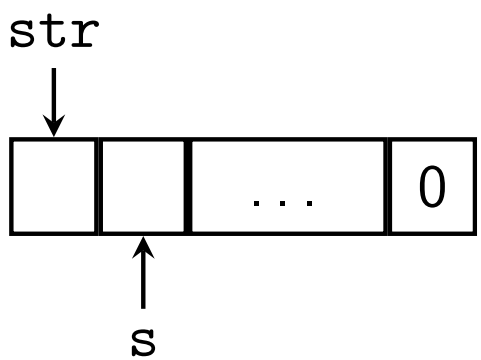

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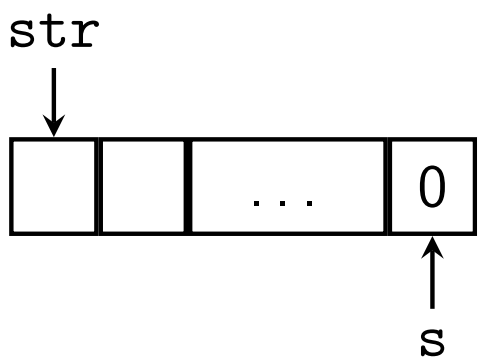

# Big Picture


YES/NO/
MAYBE

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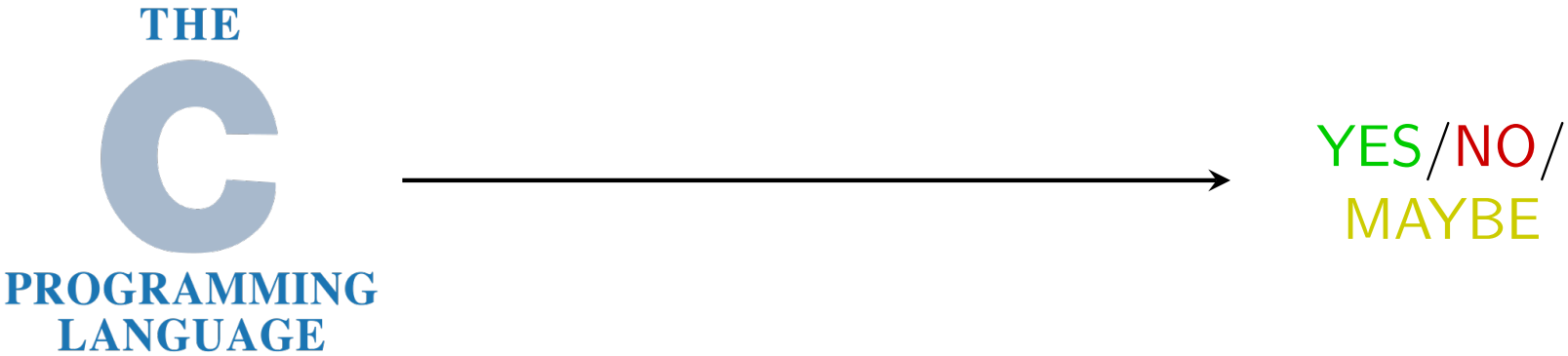

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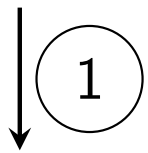


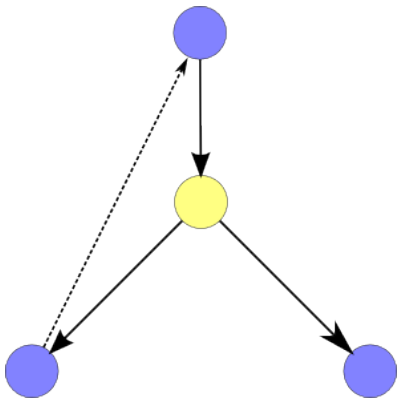

LLVM

# Big Picture


YES/NO/
MAYBE

1

2



LLVM

Symbolic Execution Graph

# Big Picture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LLVM

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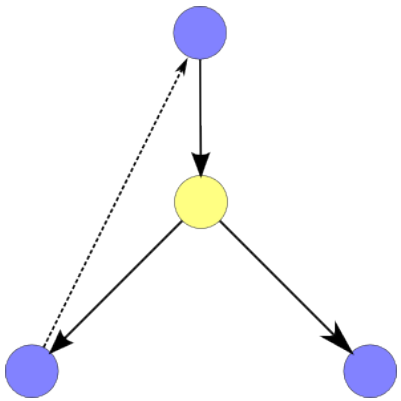

Symbolic Execution Graph

3

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

Integer Transition System

# Big Picture


YES/NO/
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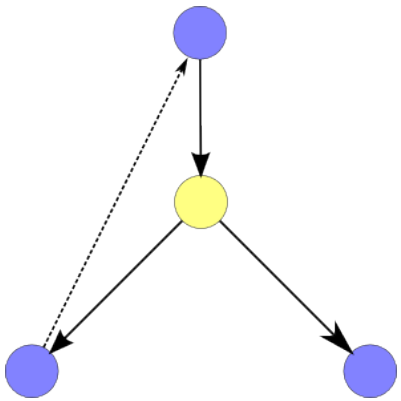
4

2



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LLVM

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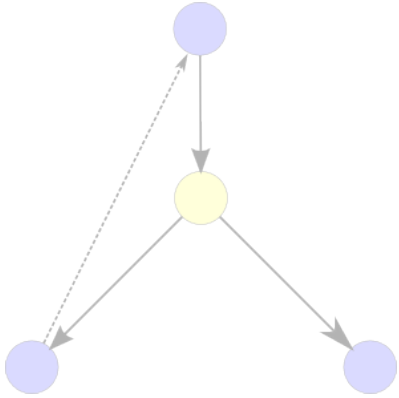
Integer Transition System

# C to LLVM


LLVM

?



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# LLVM Compiler Infrastructure

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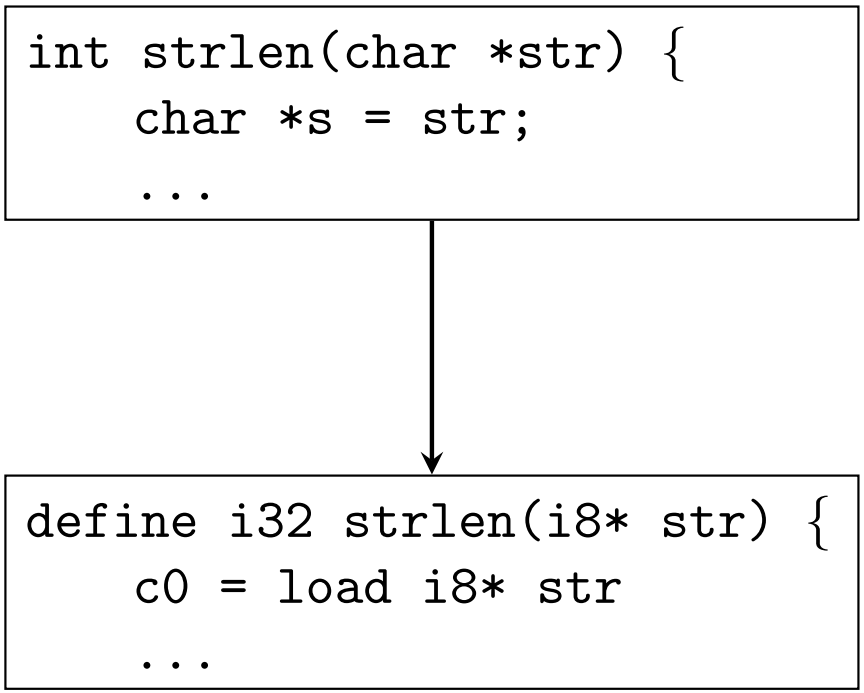
    ...
```

C-program

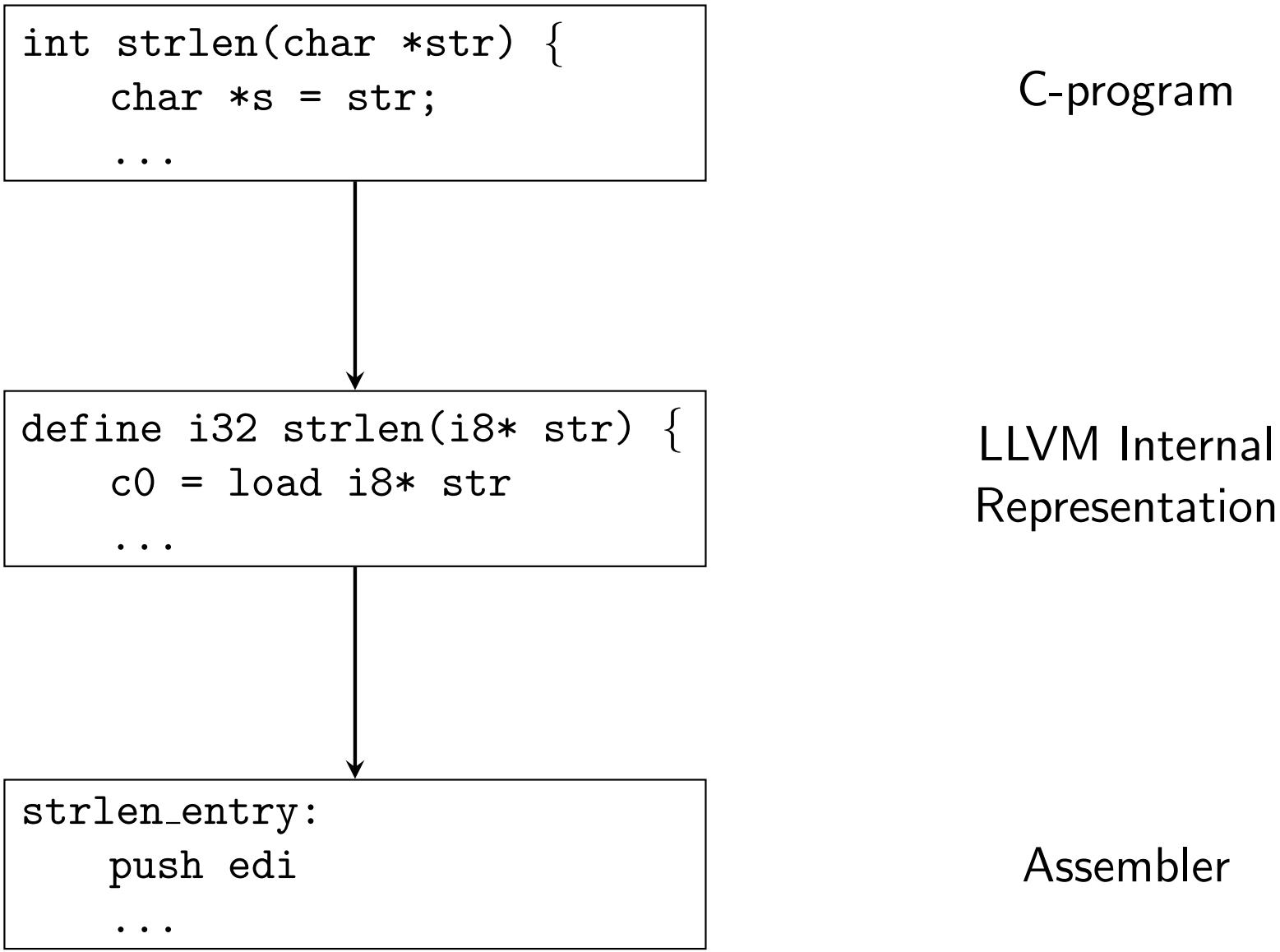
# LLVM Compiler Infrastructure




C-program

LLVM Internal Representation

# LLVM Compiler Infrastructure



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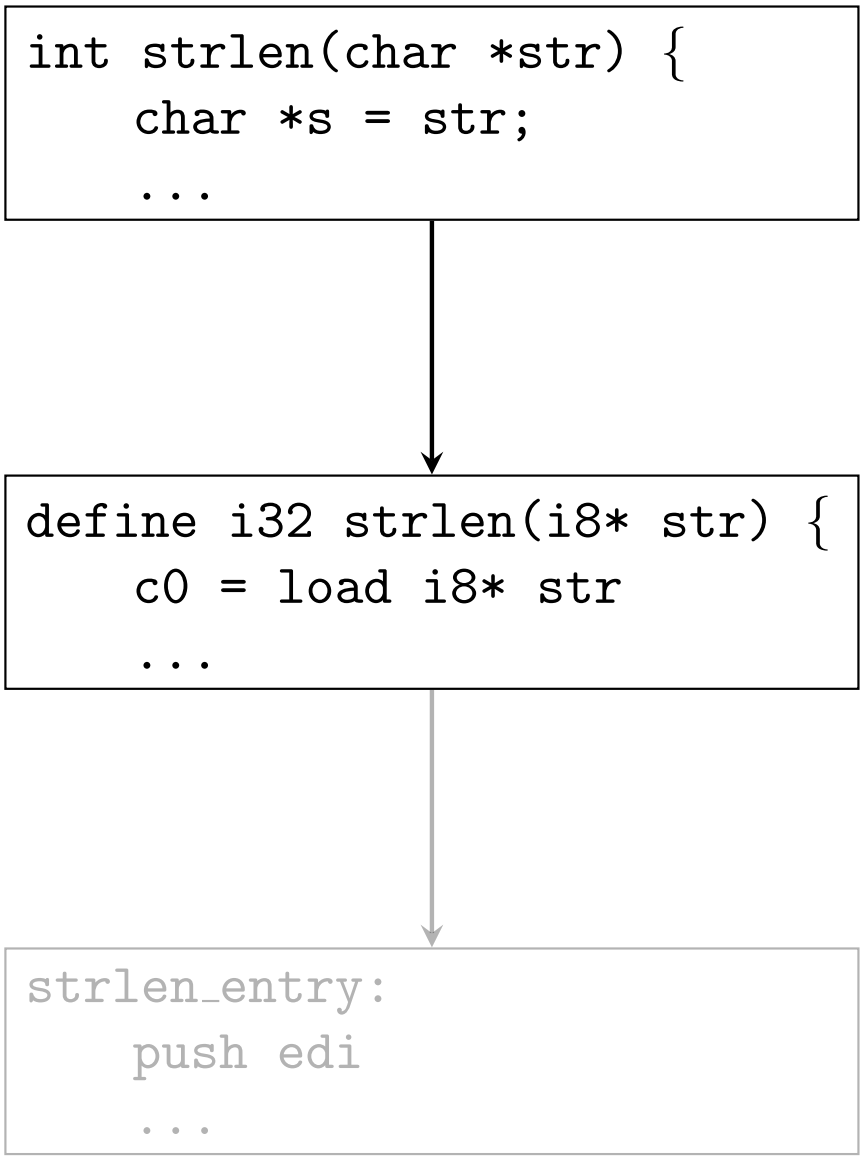


C-program

LLVM Internal Representation

Assembler

# Some LLVM Instructions

- Control Flow Instructions
  - `ret`, `br`, `call`, ...

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

# LLVM to Symbolic Execution Graph


LLVM

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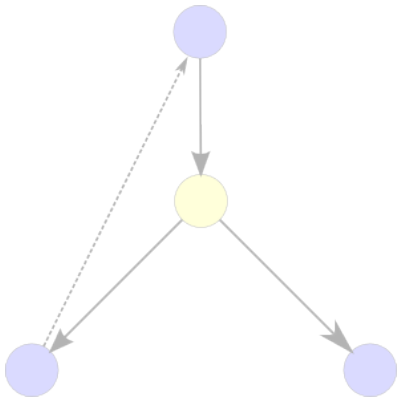

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# LLVM to Symbolic Execution Graph


✓

LLVM

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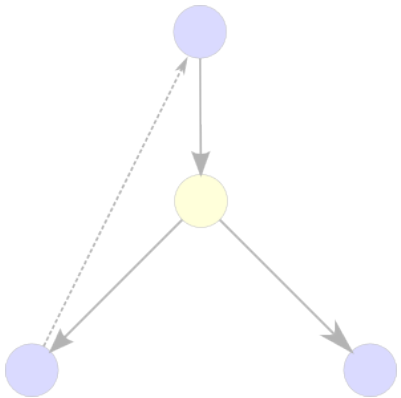

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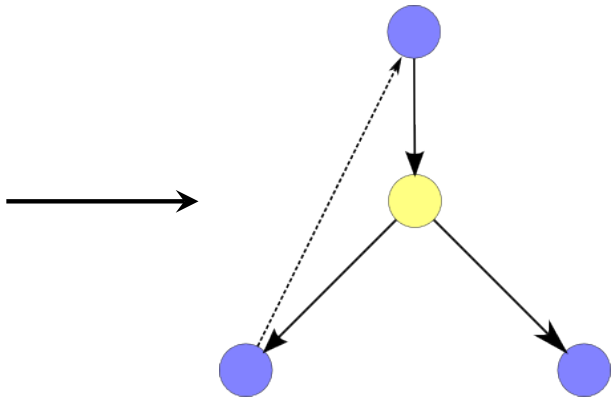
LLVM



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# Problem Definition

Given: LLVM Program, Entry Point

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

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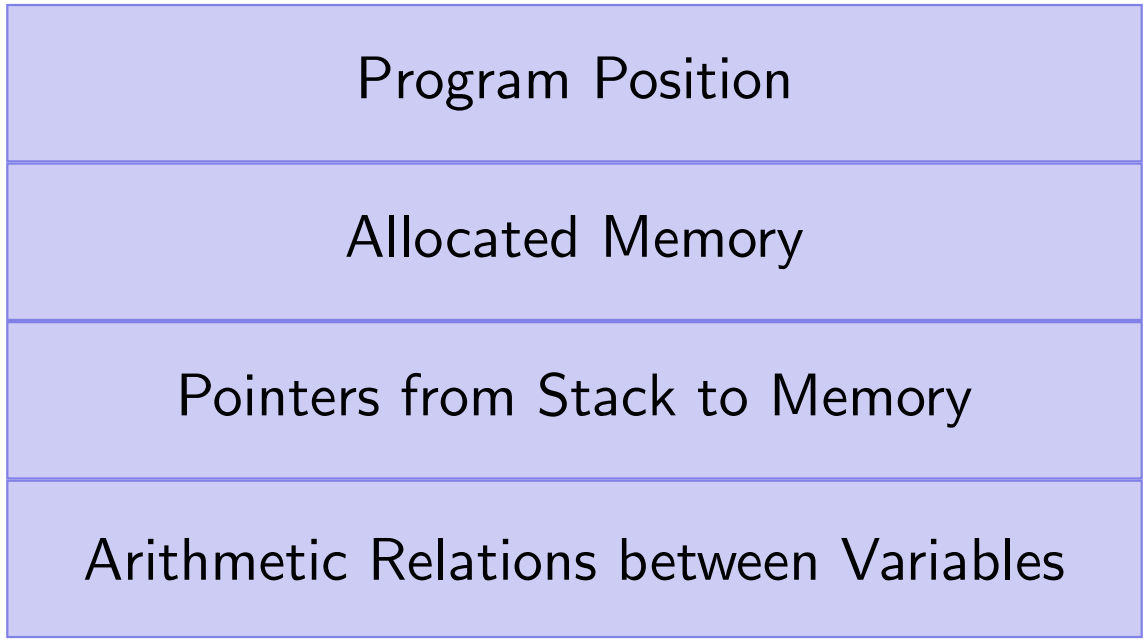
Idea: Abstract interpretation of program states

# Abstract States



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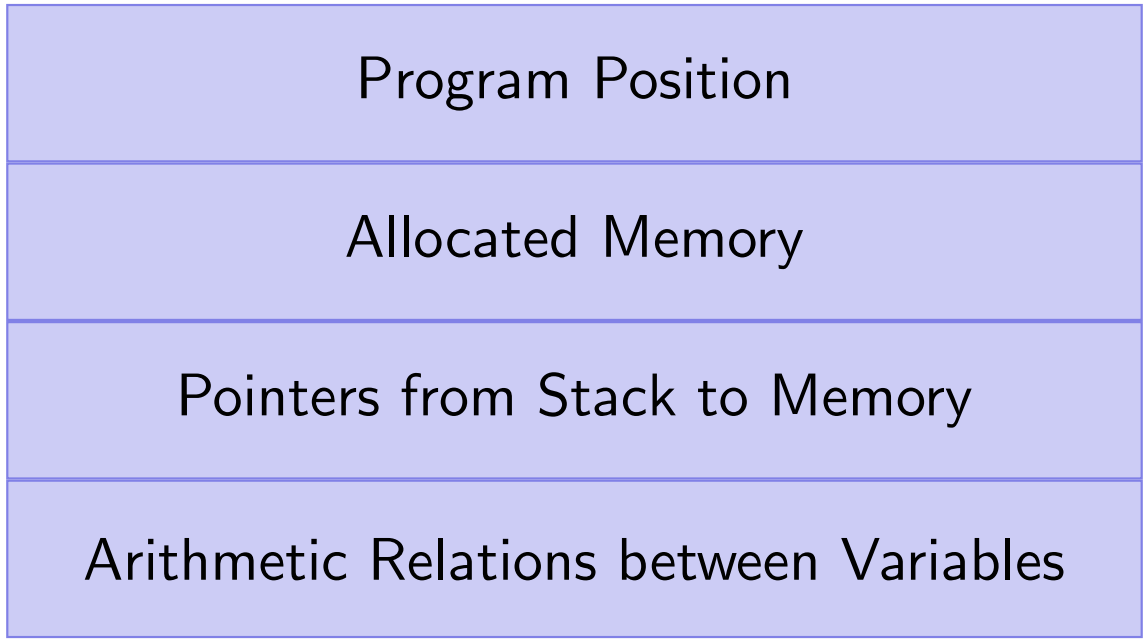


Entry Point:

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

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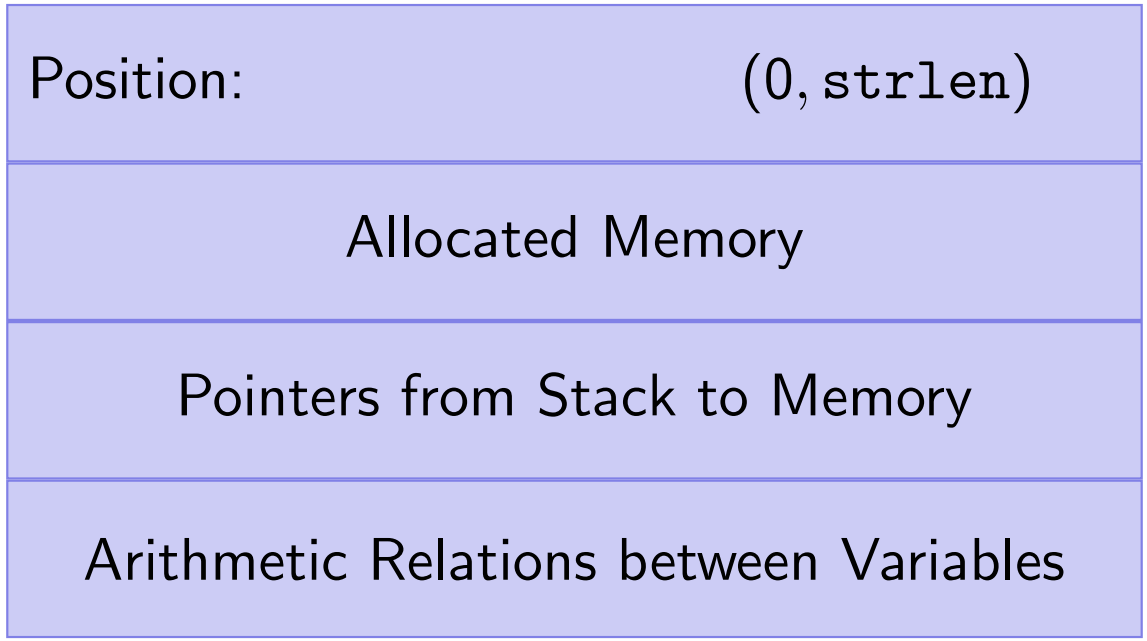


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# Abstract States

| | |
|---|---|
| Position: | $(0, \texttt{strlen})$ |
| Alloc: | $[alloc(str, v_{end})]$ |
| Pointers from Stack to Memory | |
| Arithmetic Relations between Variables | |

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# Evaluation of Abstract States

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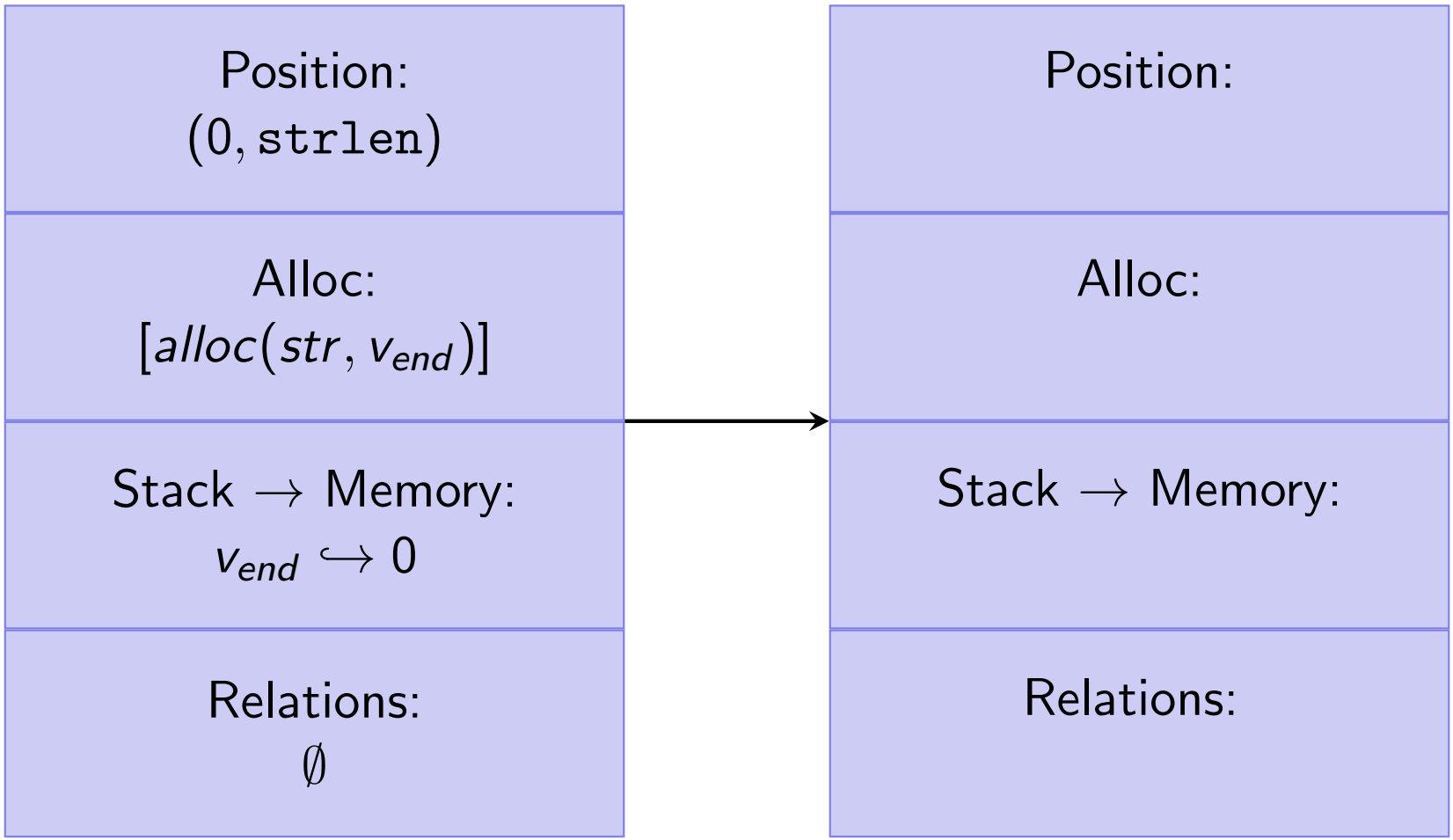

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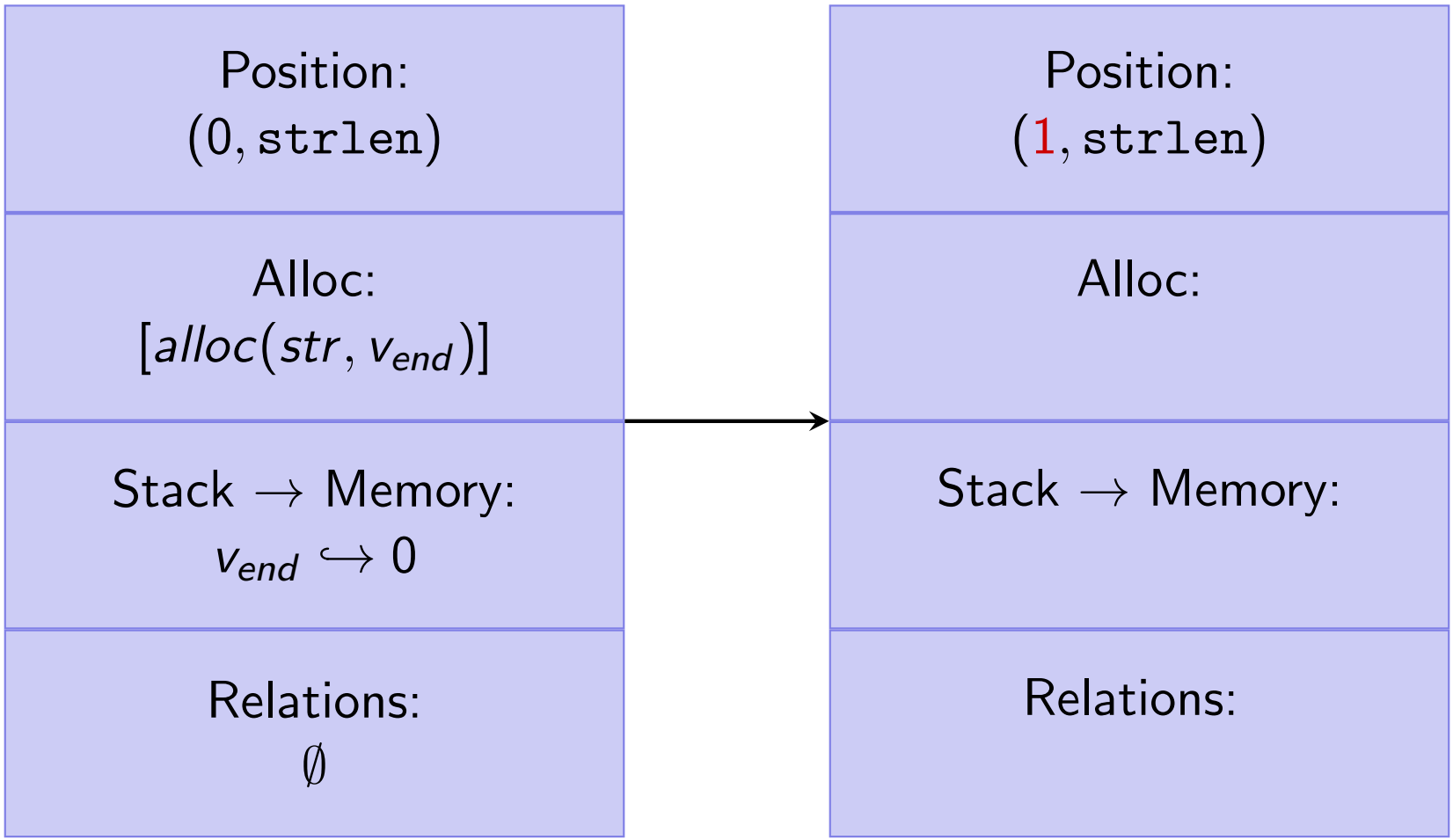

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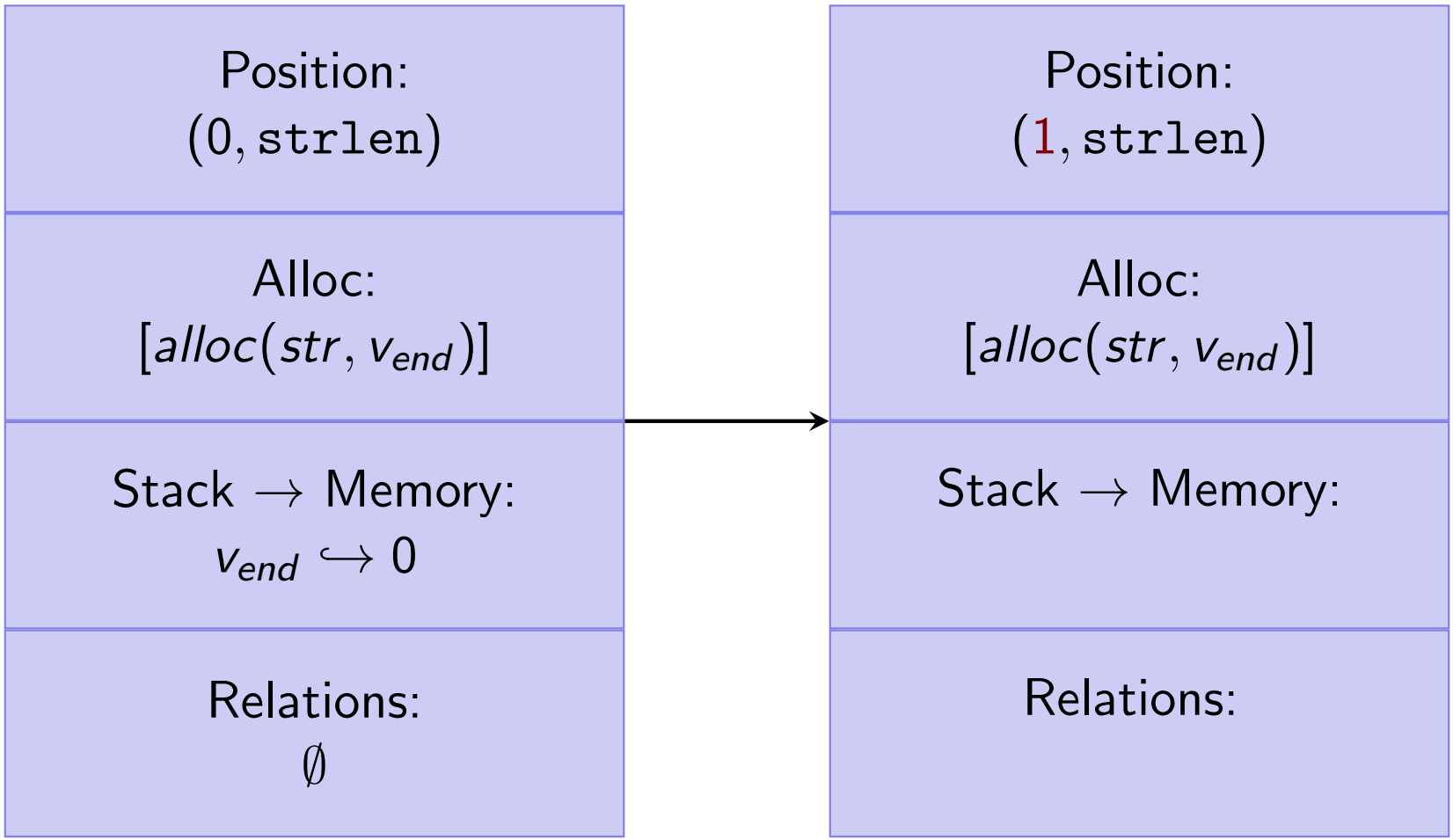

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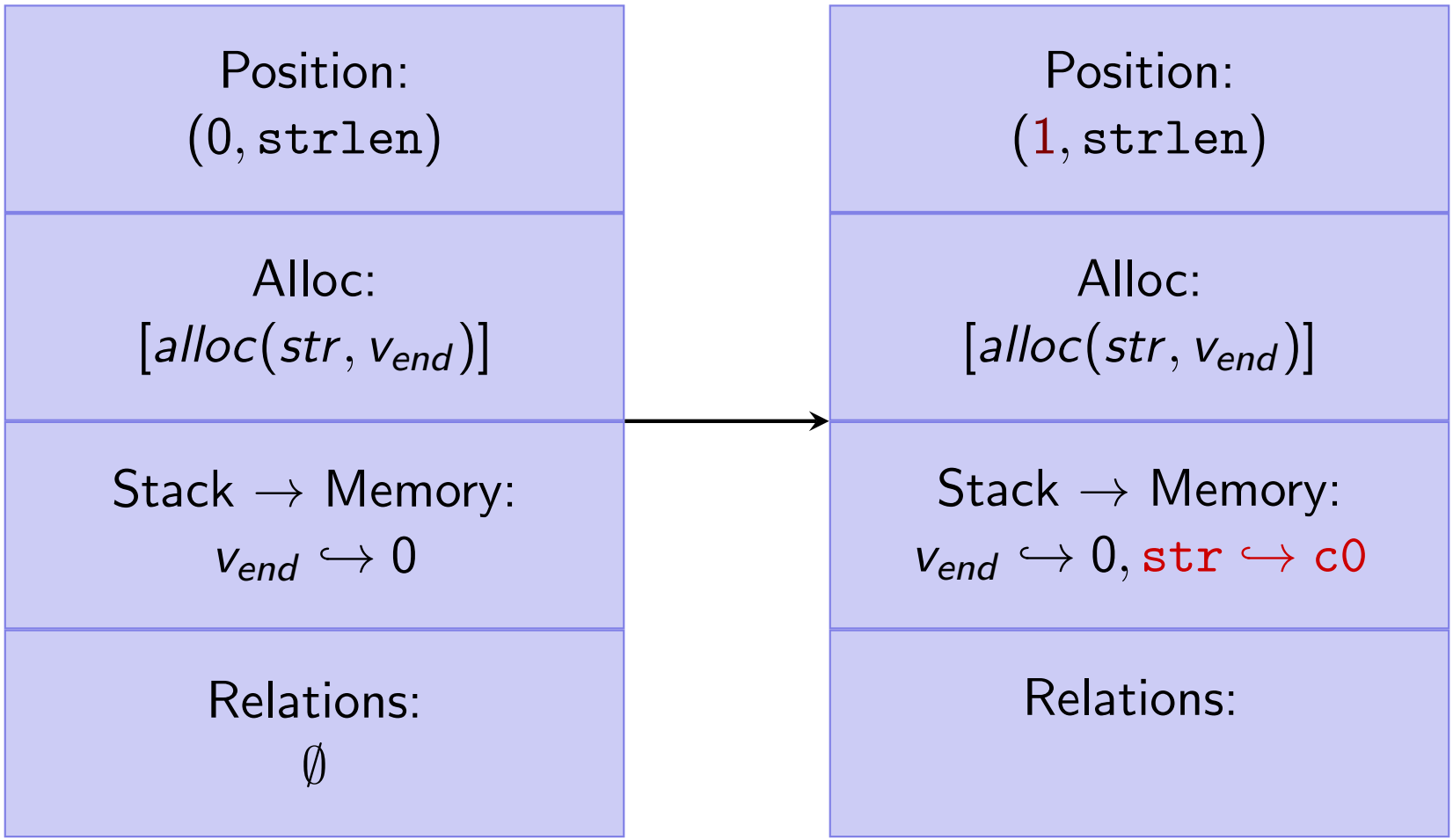

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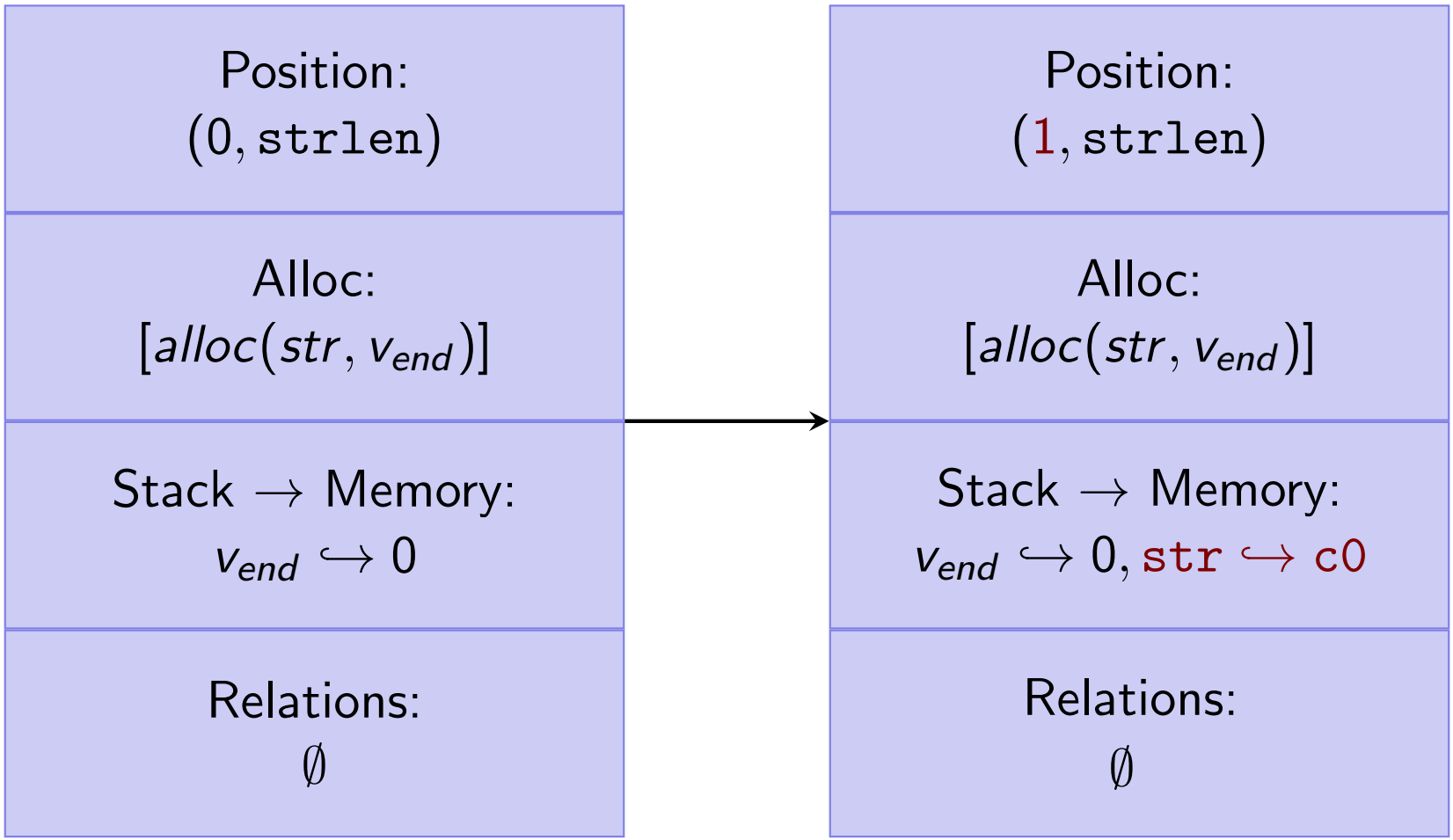

# Refinement of Abstract States

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c0zero = icmp eq i8 c0, 0
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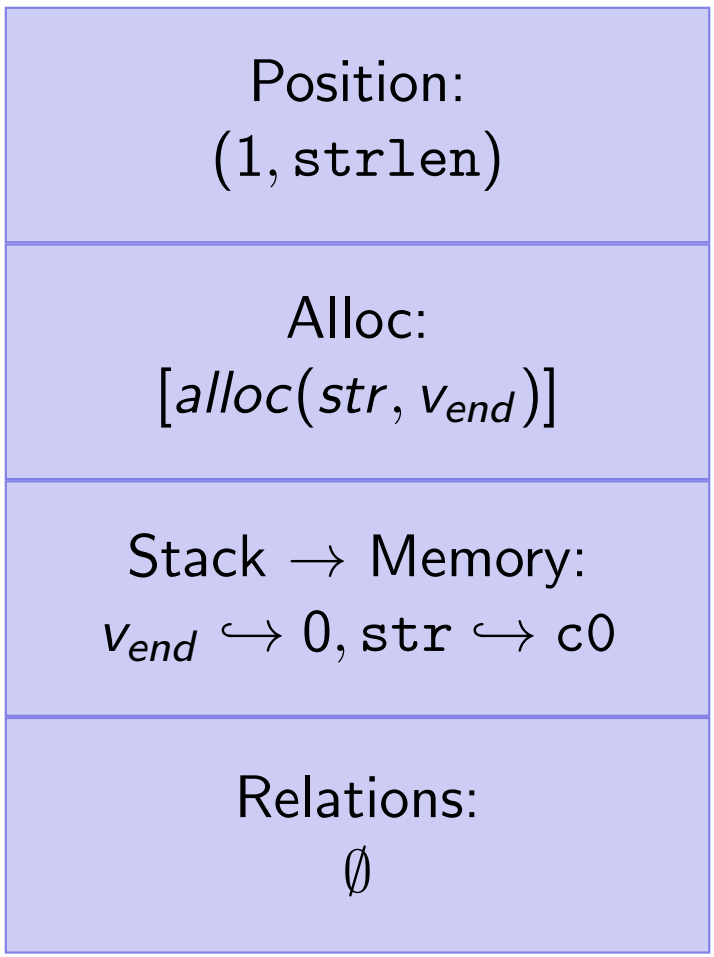


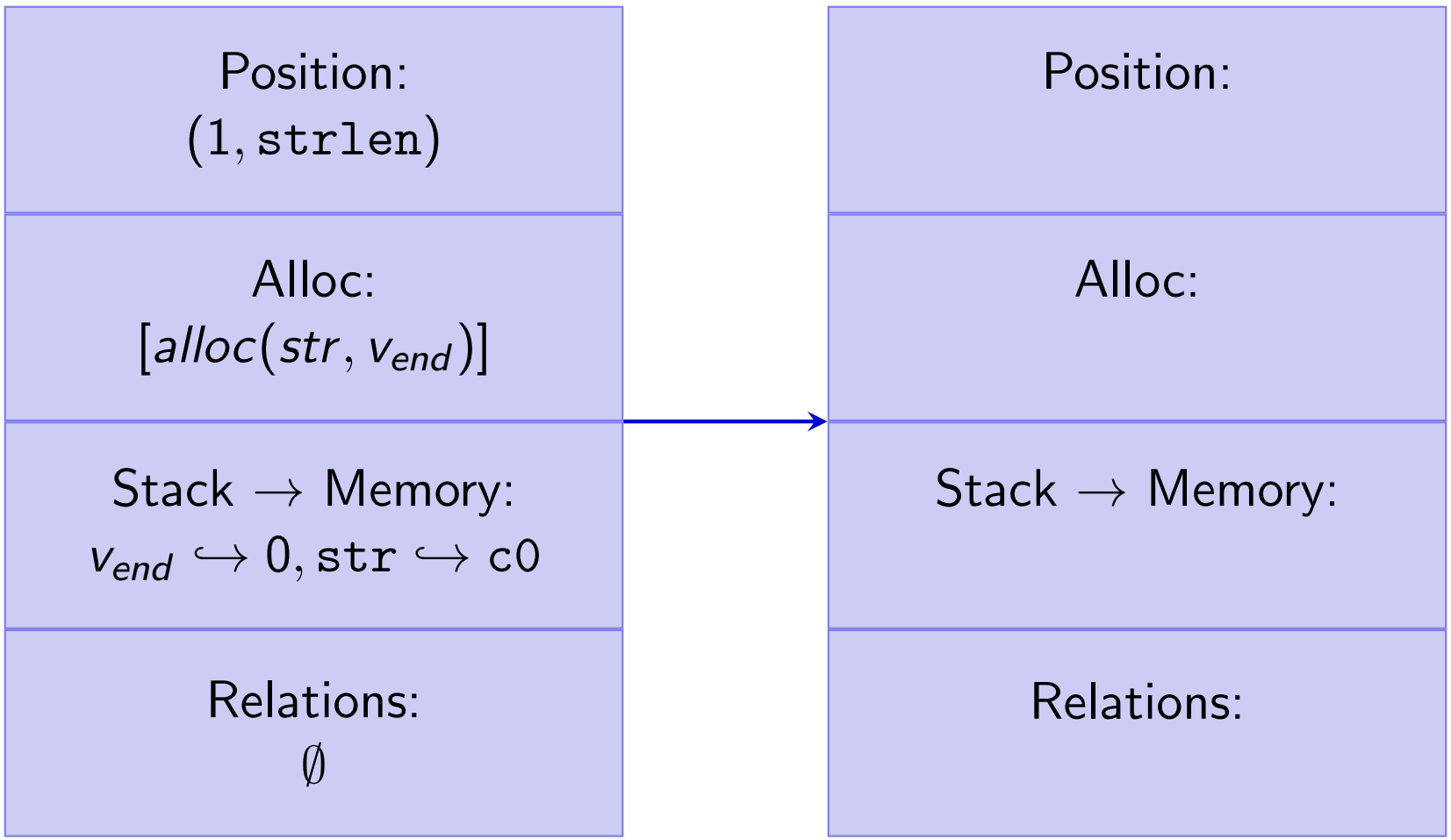
# Refinement of Abstract States

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

| Position: $(1, \texttt{strlen})$ |
| --- |
| Alloc: $[alloc(str, v_{end})]$ |
| Stack $\rightarrow$ Memory: $v_{end} \hookrightarrow 0, \texttt{str} \hookrightarrow \texttt{c0}$ |
| Relations: $\emptyset$ |

# Refinement of Abstract States

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



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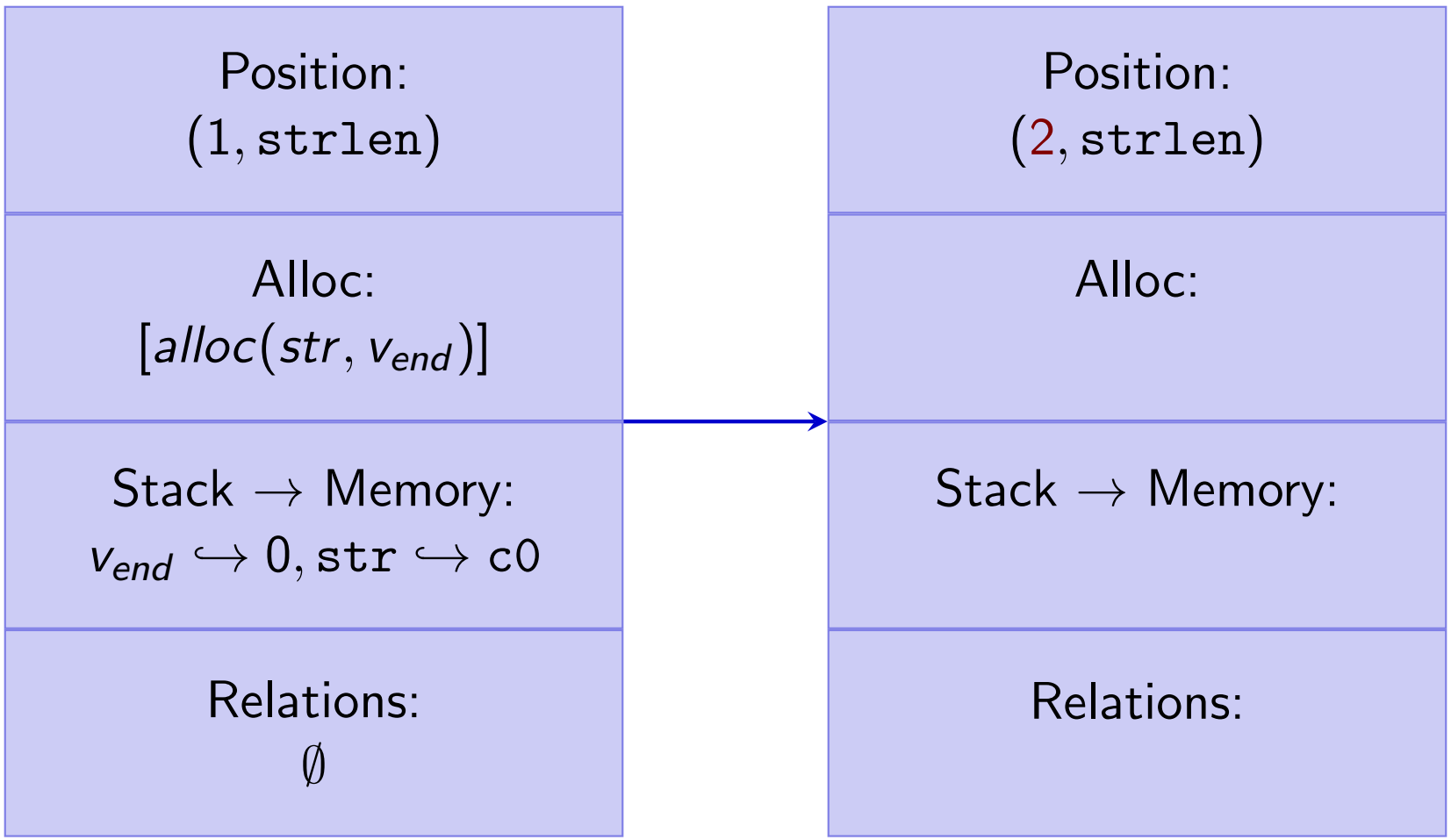

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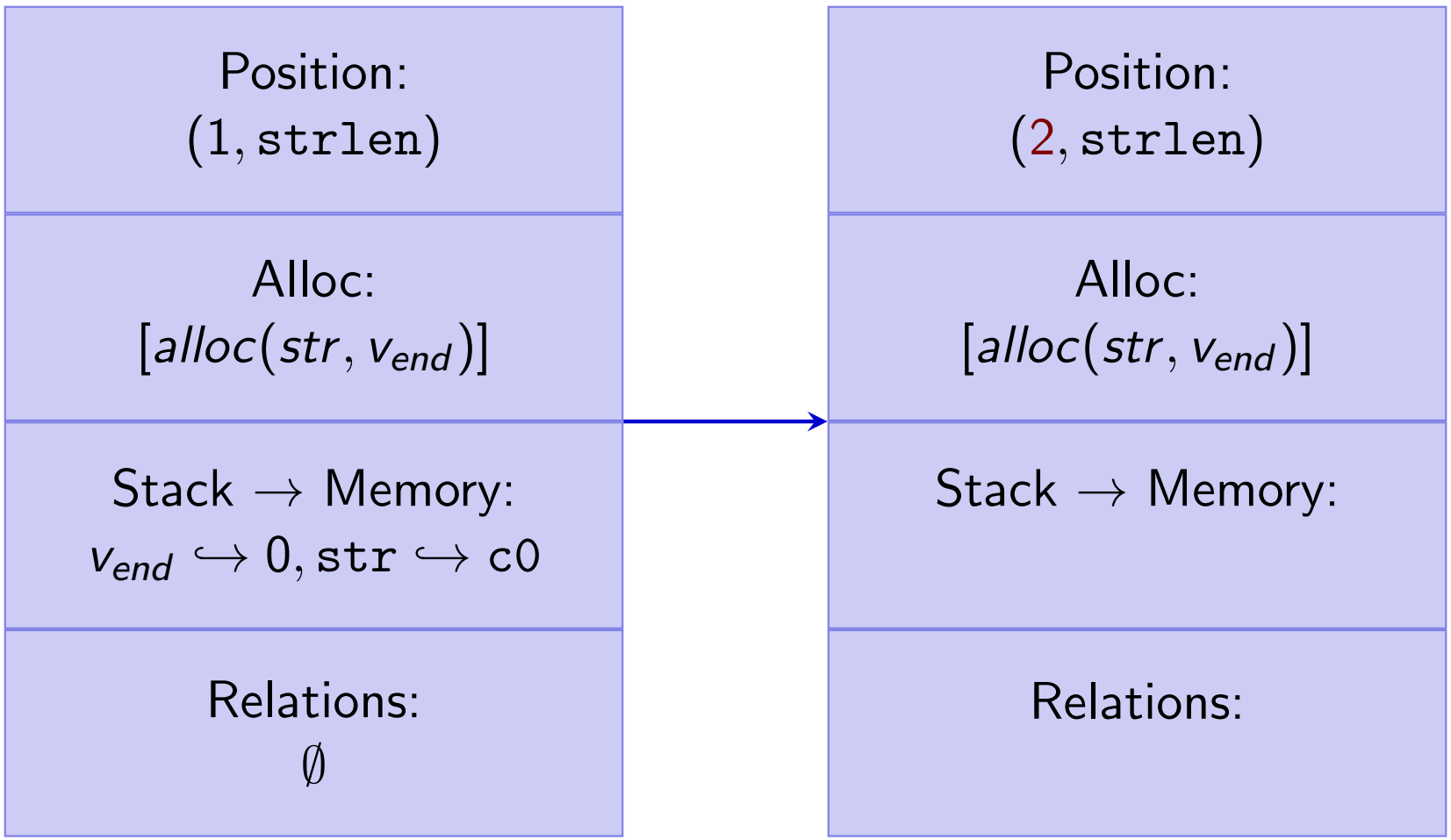

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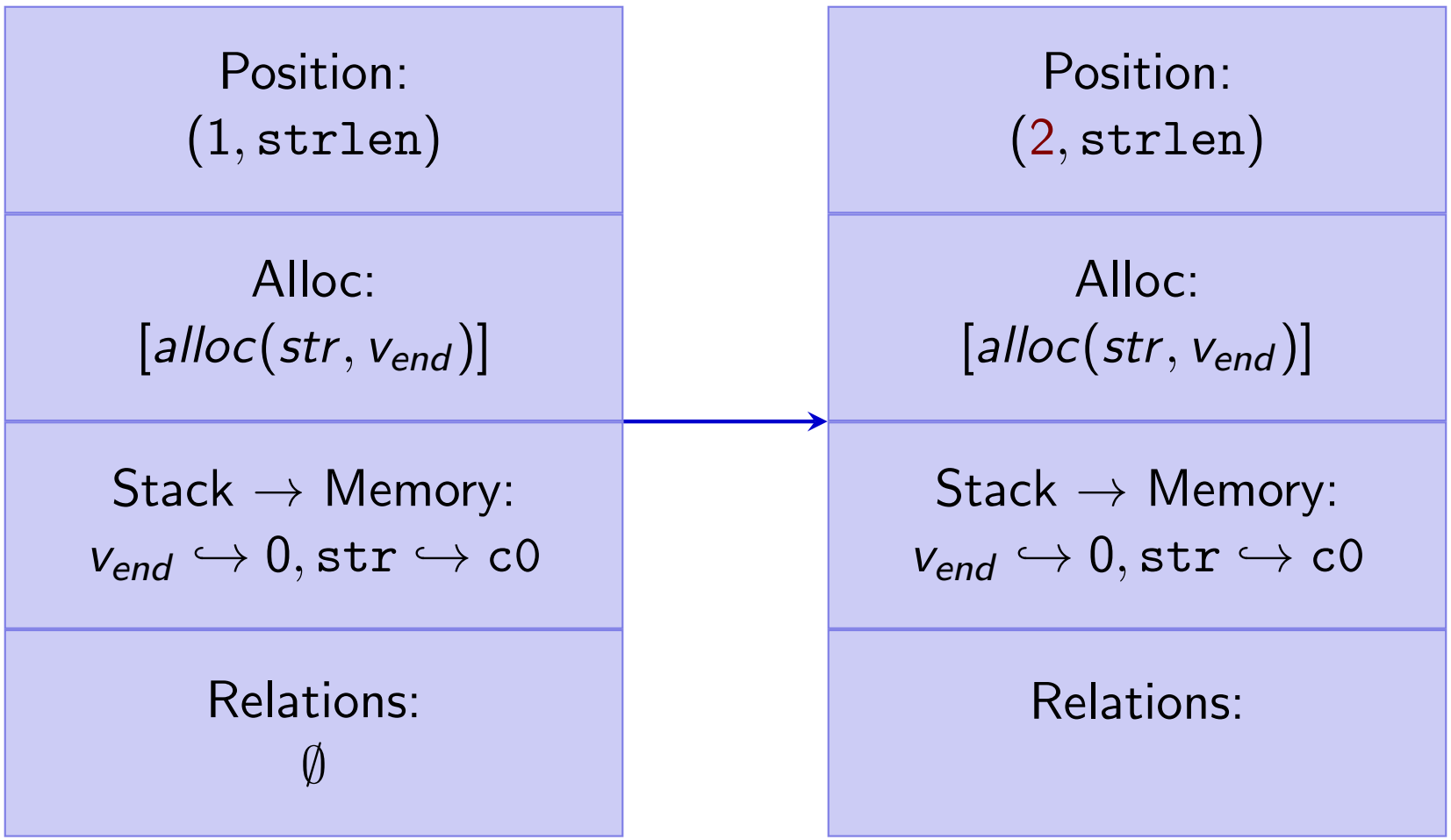

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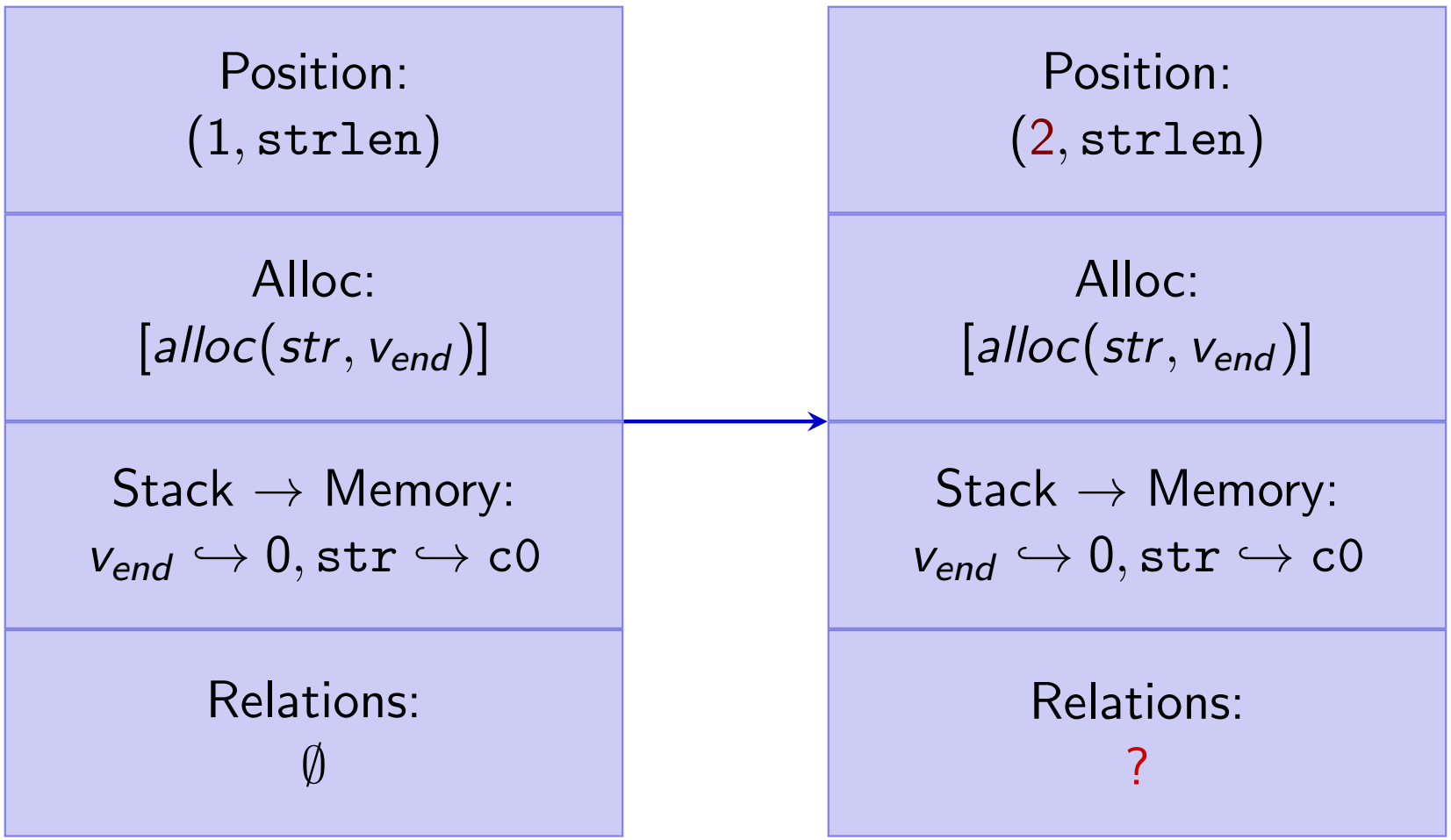

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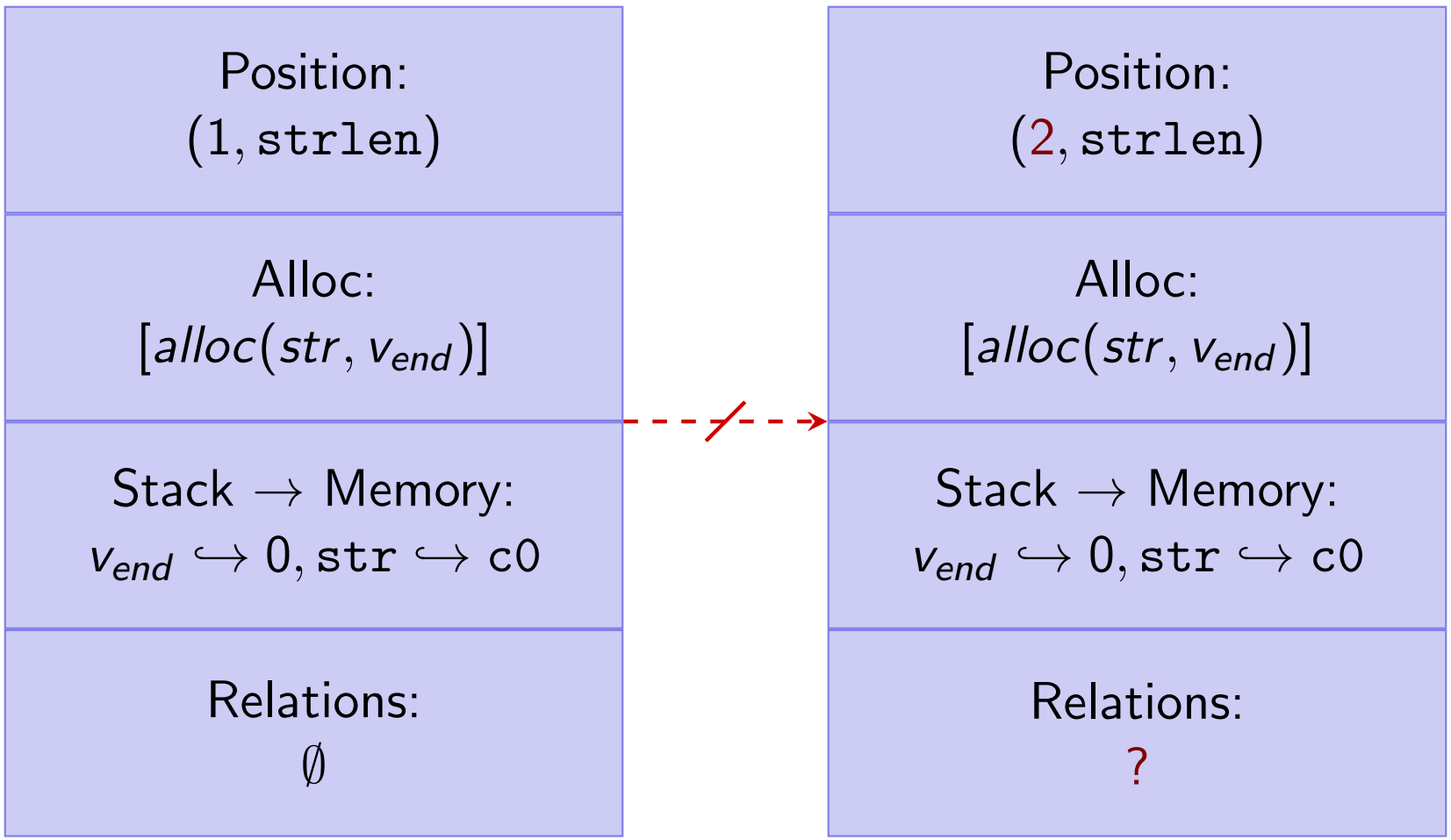

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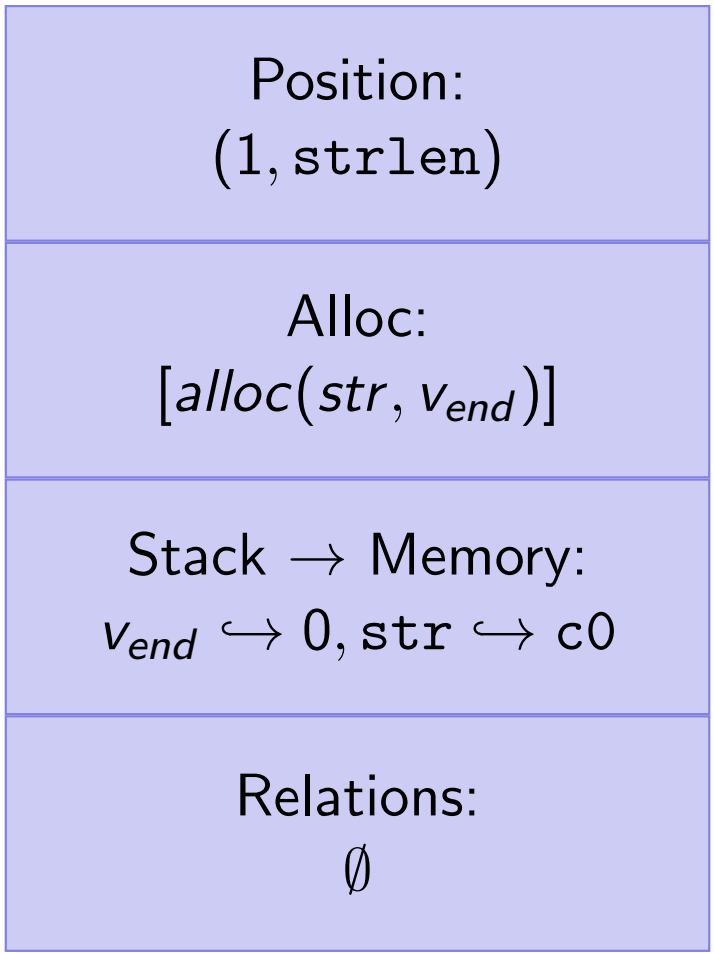

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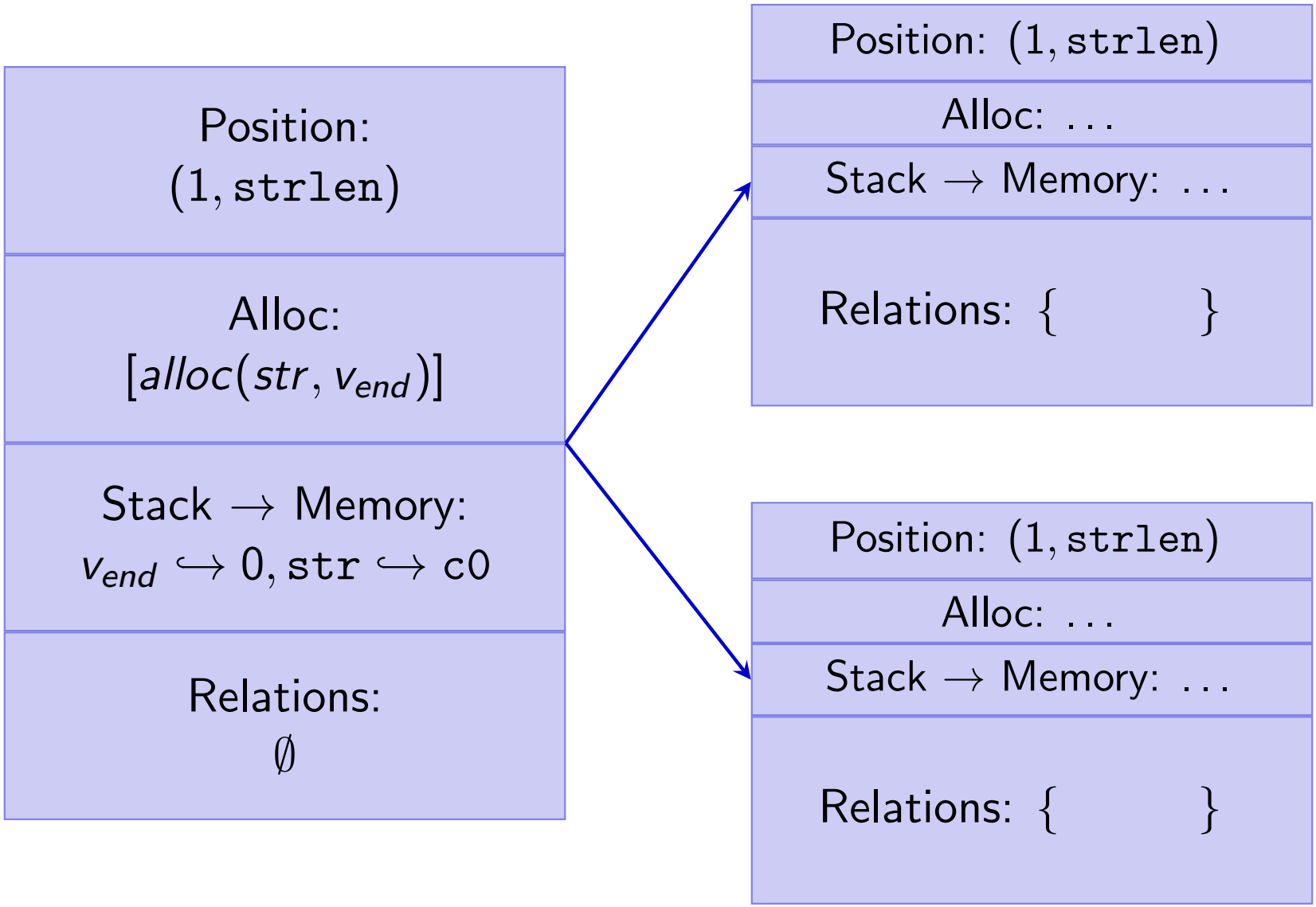

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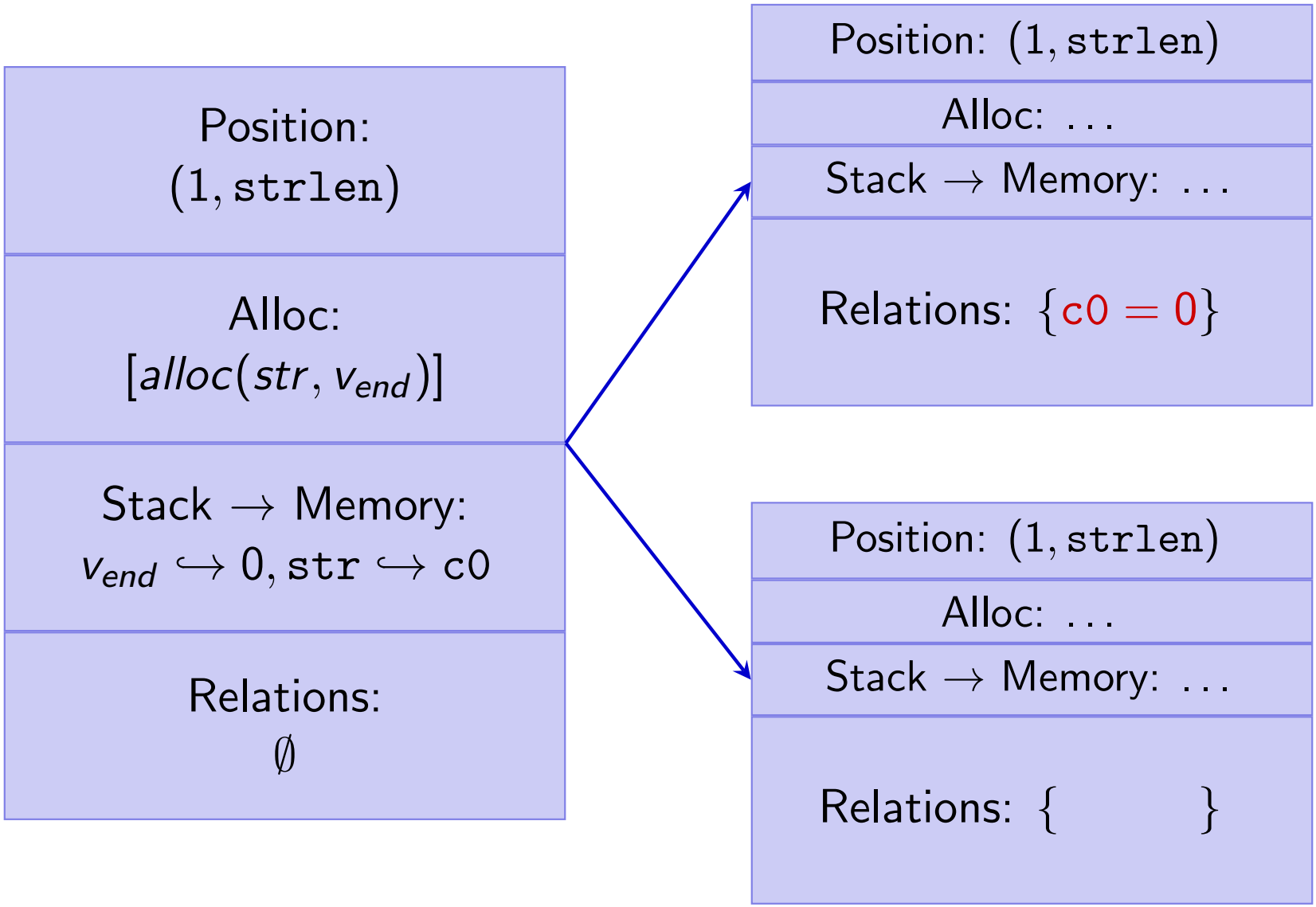

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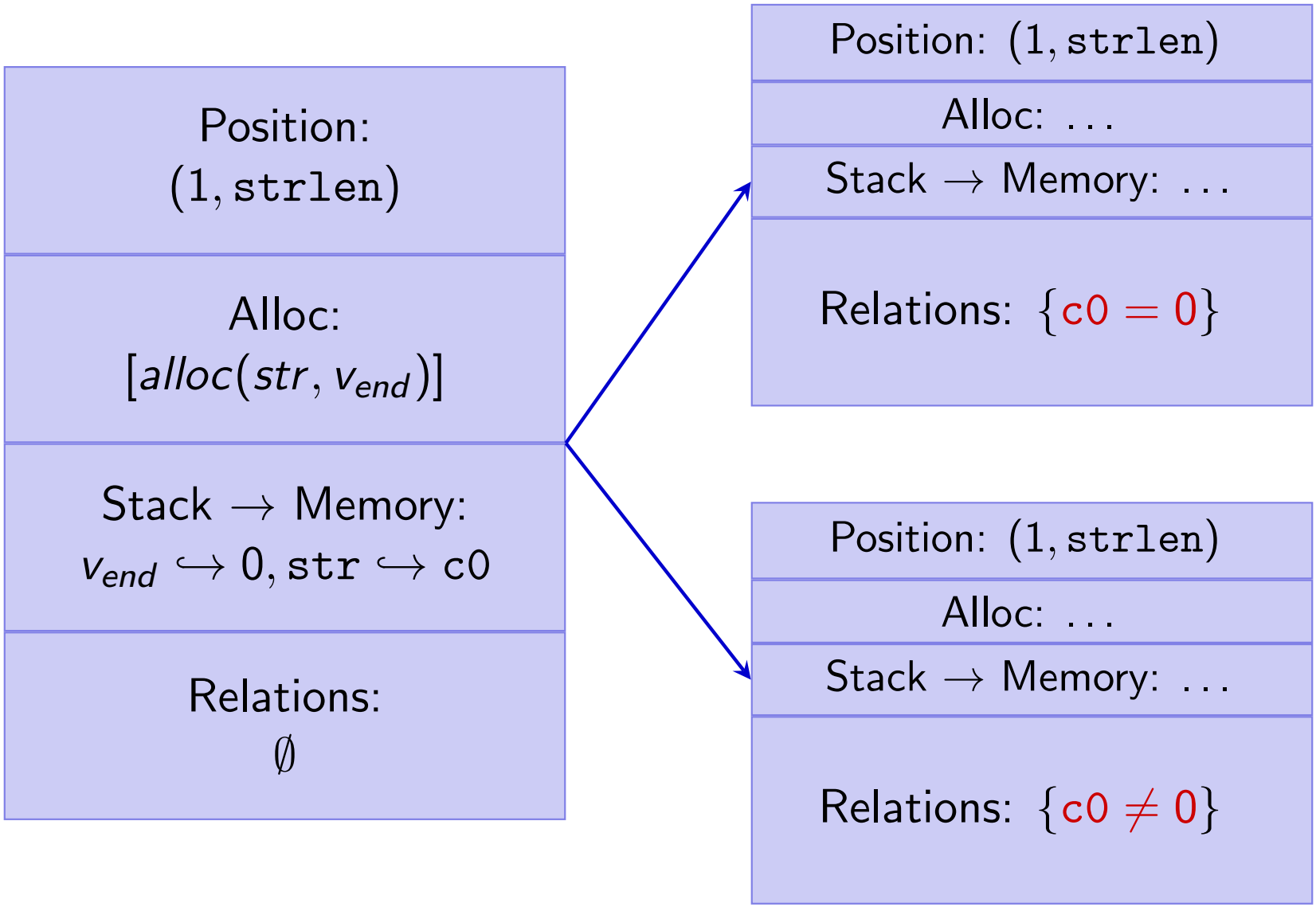

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int strlen(char *str) {
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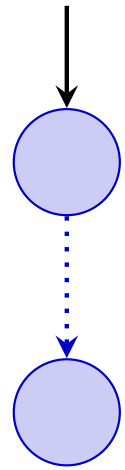

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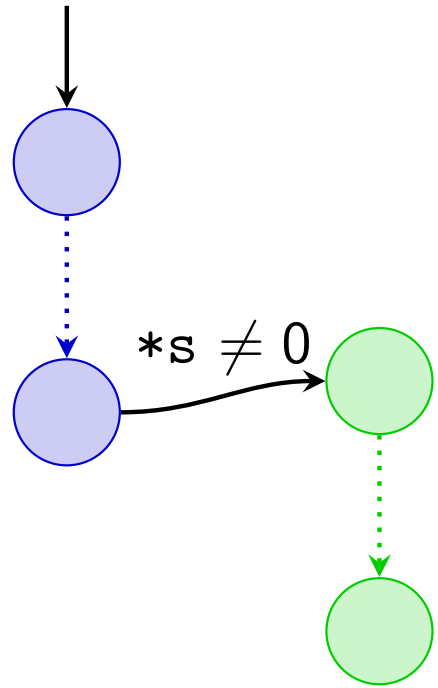

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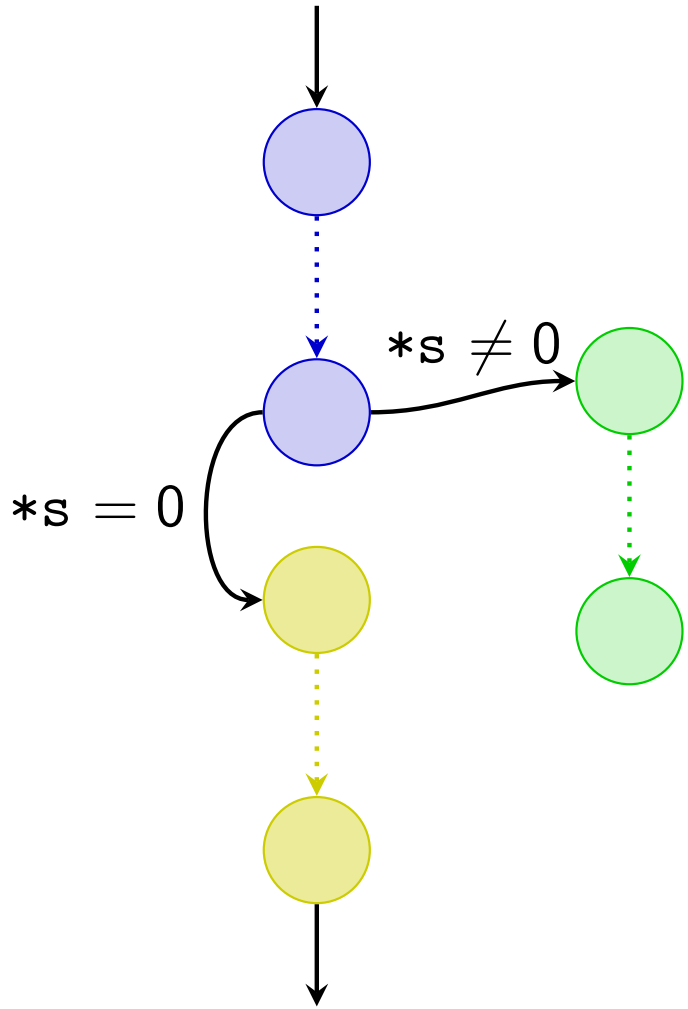

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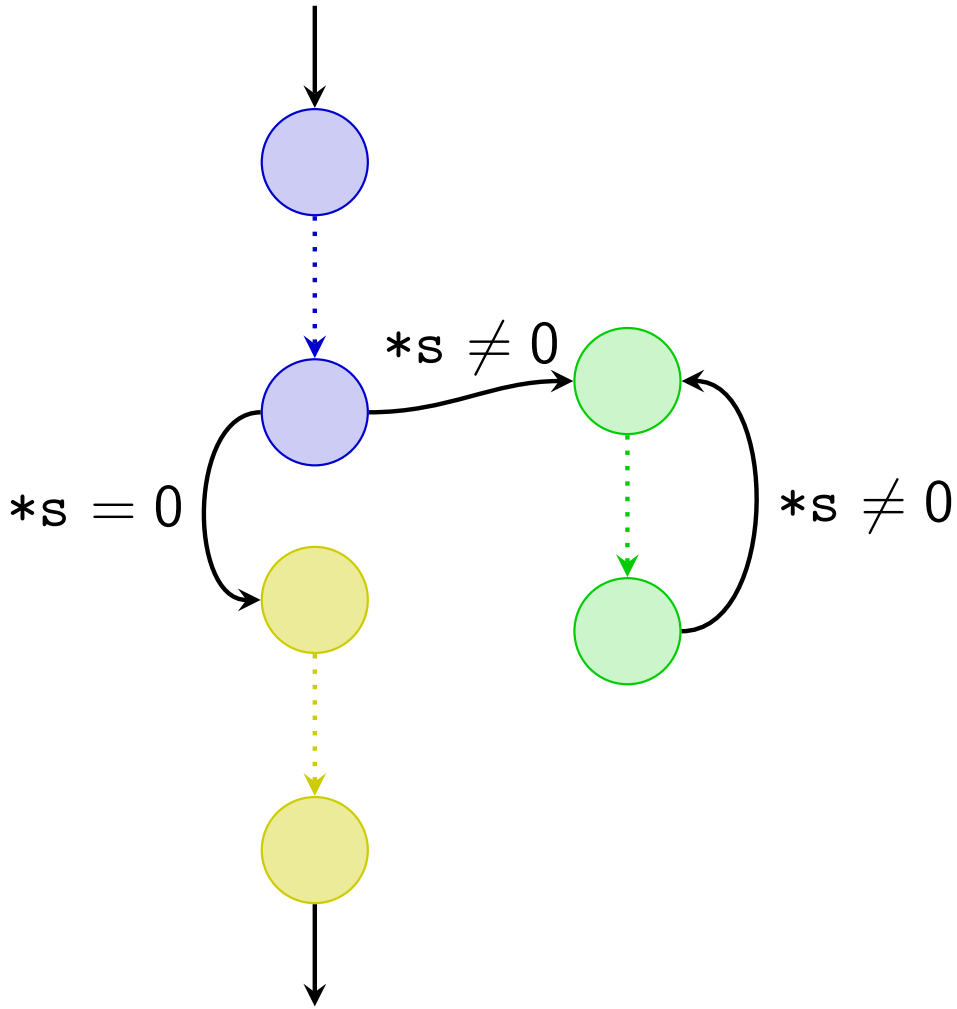

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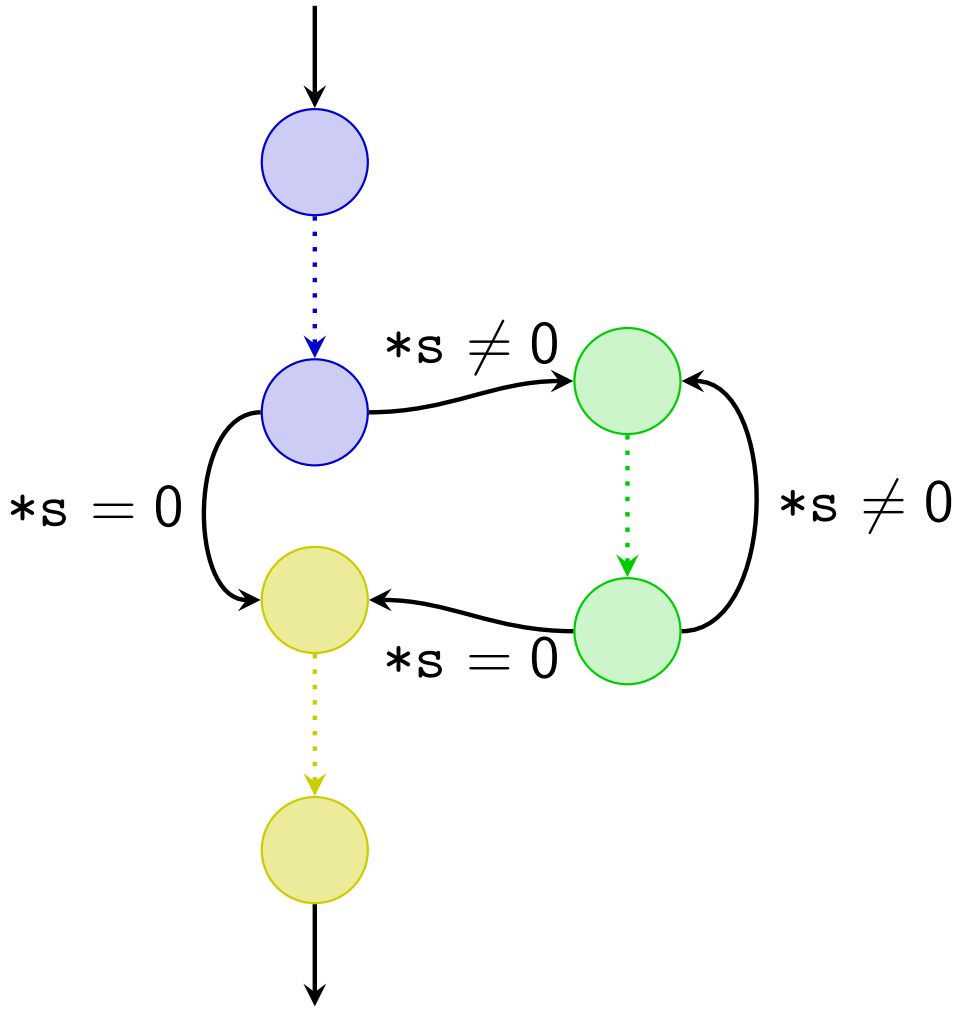

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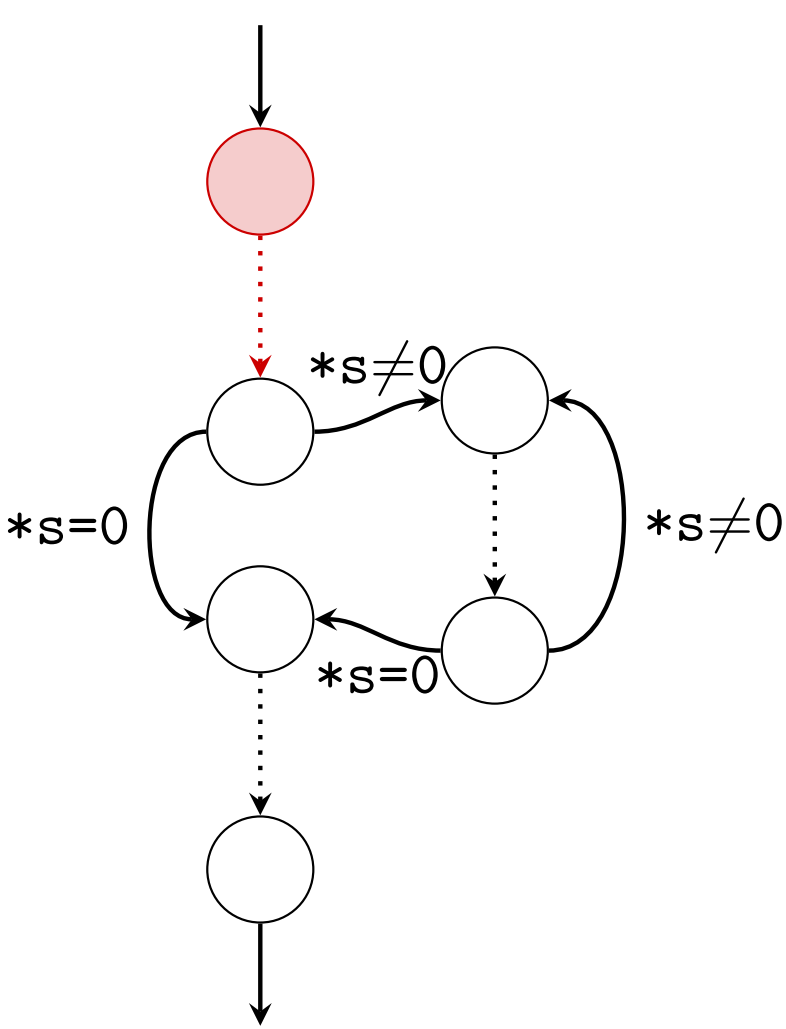


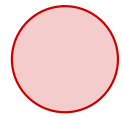

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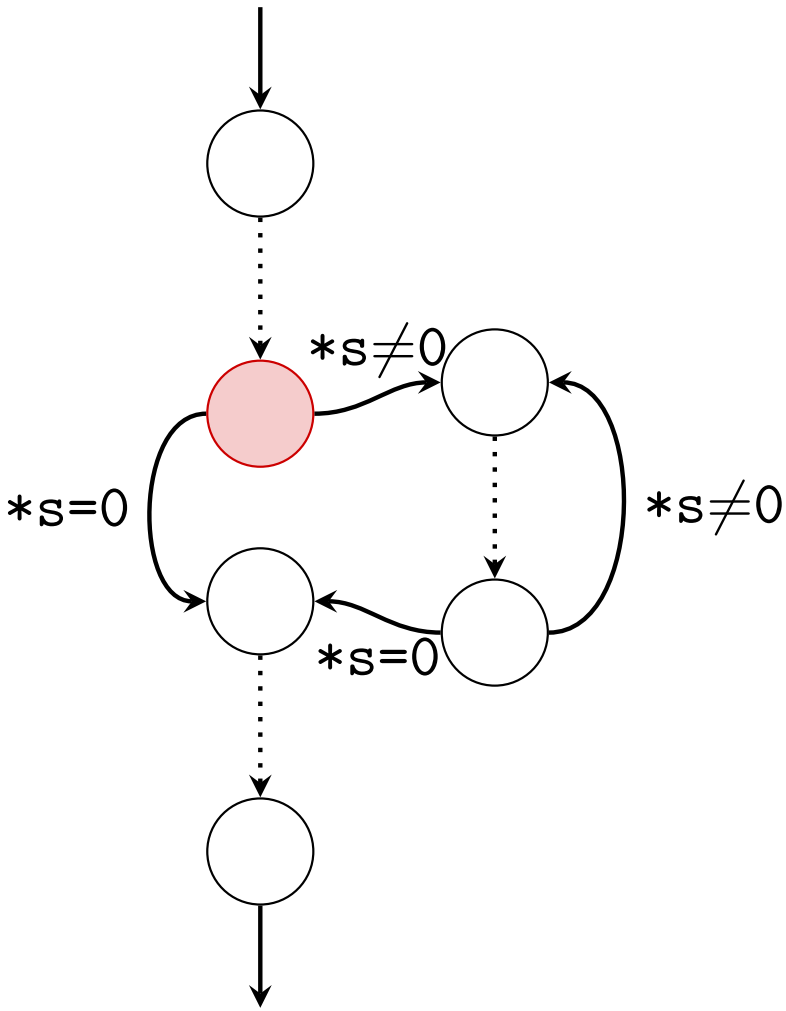


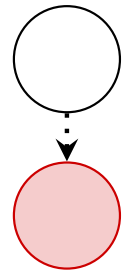

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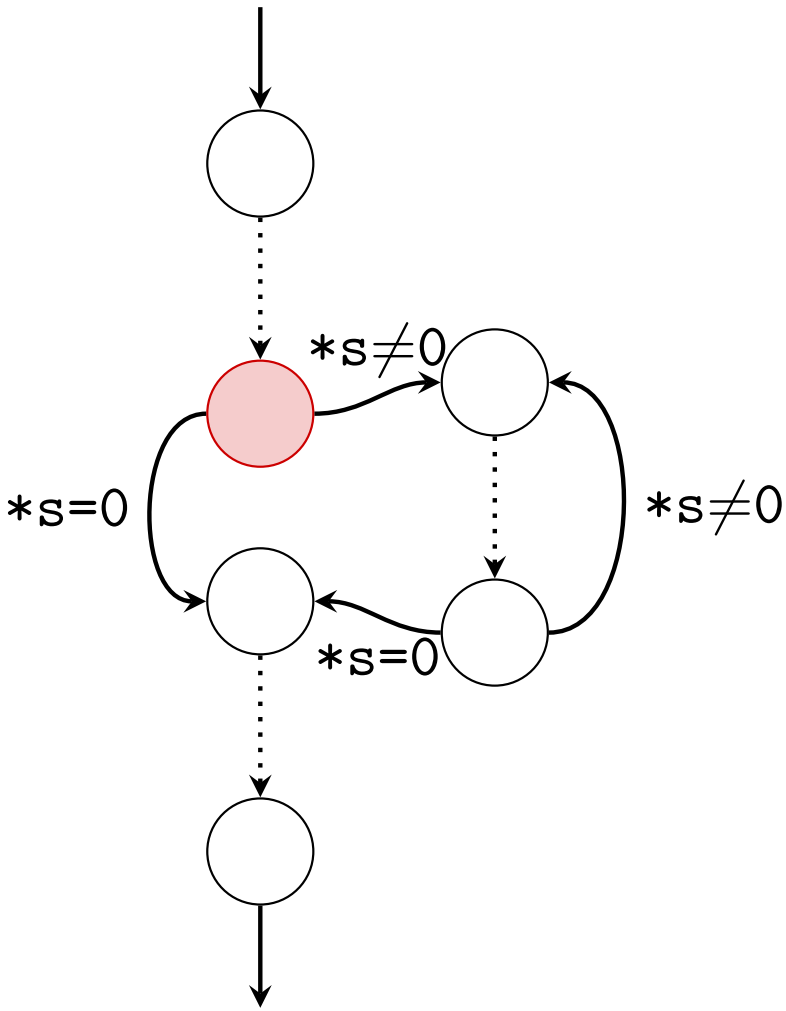


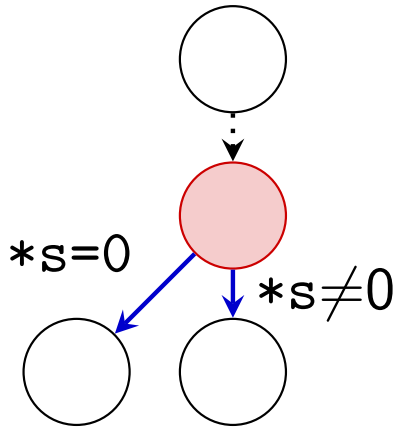

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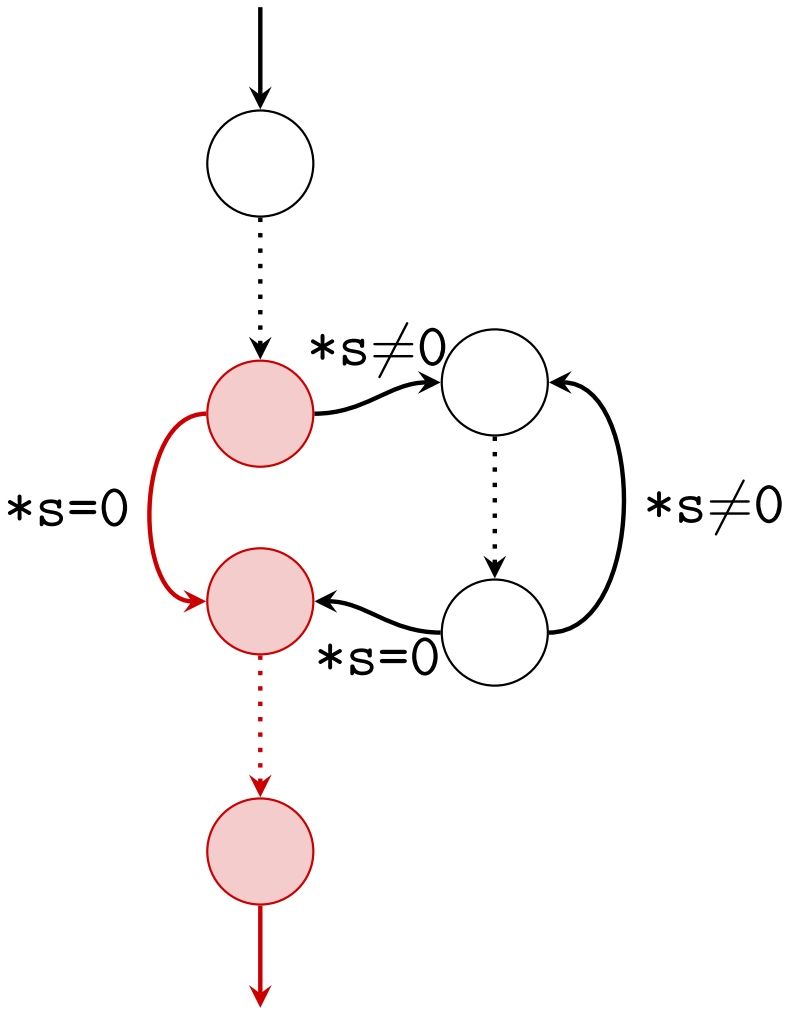


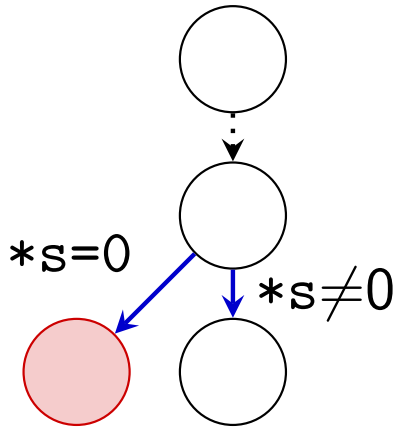

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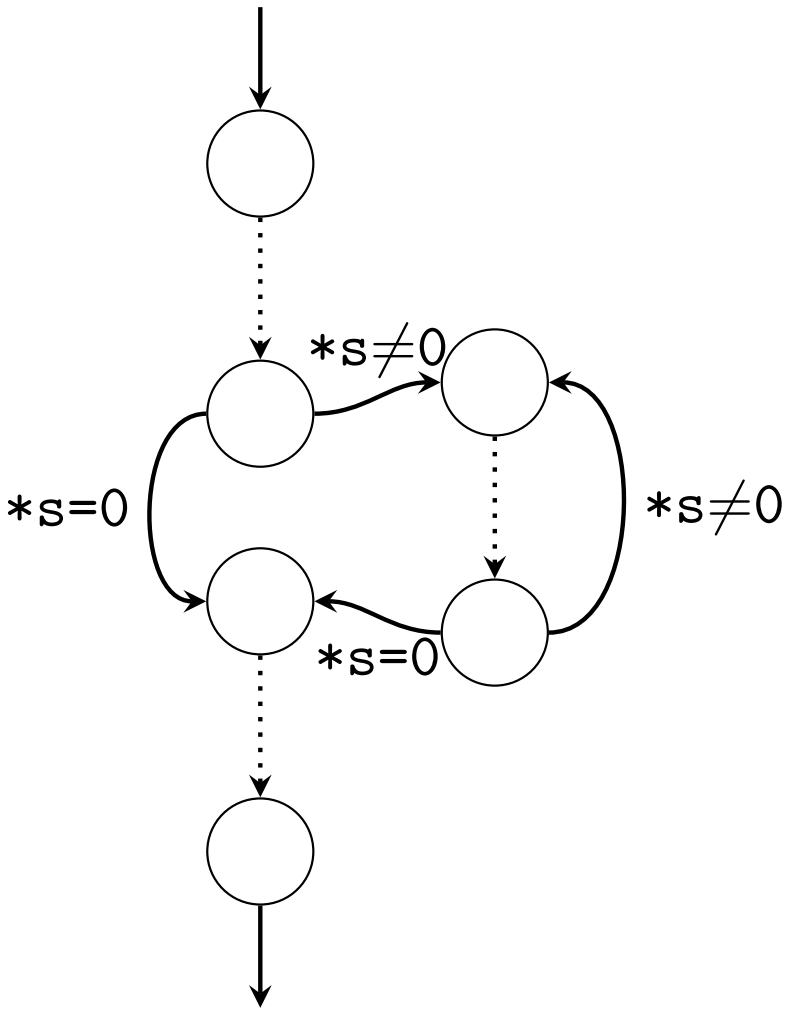


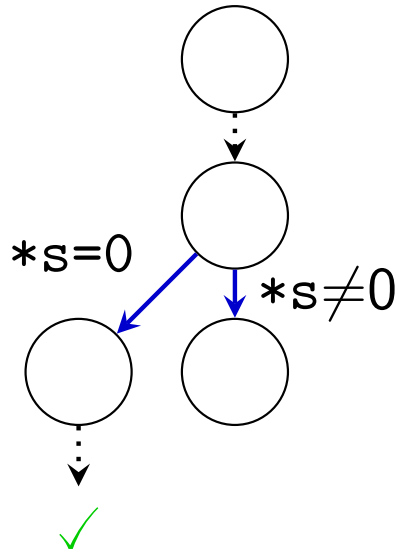

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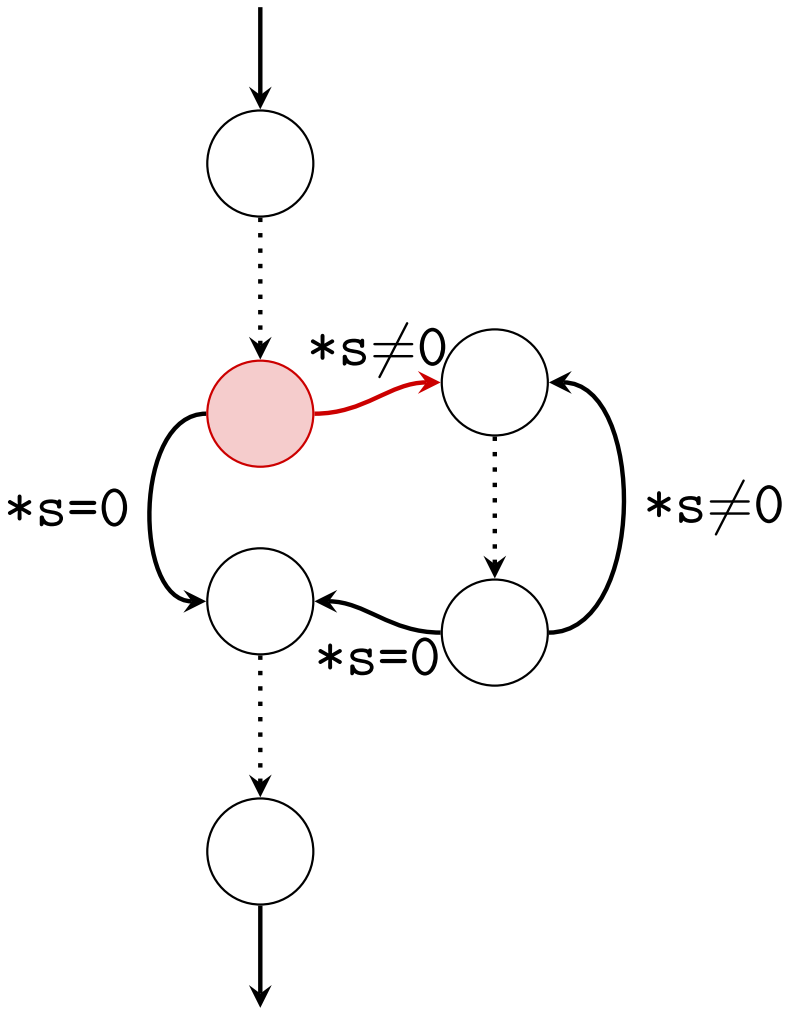


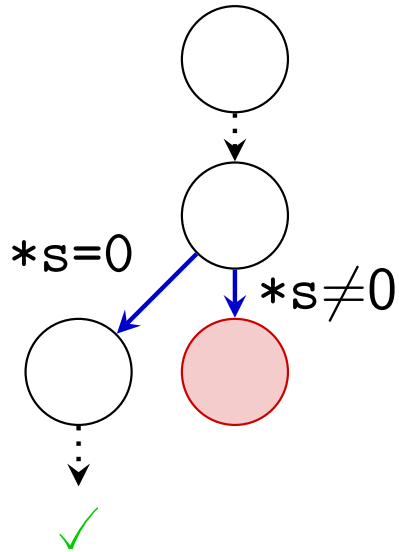

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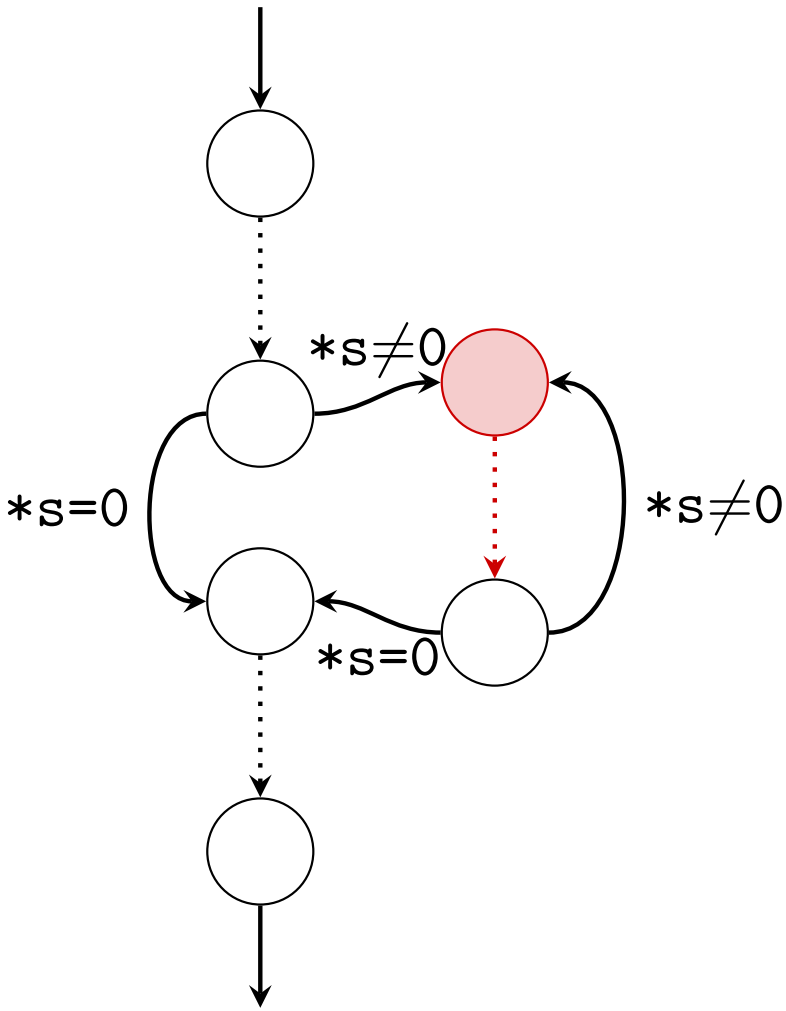


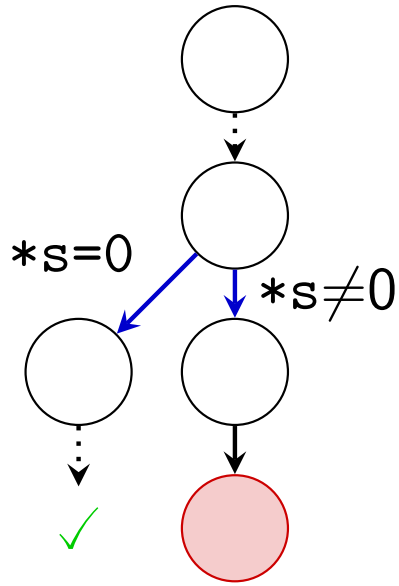

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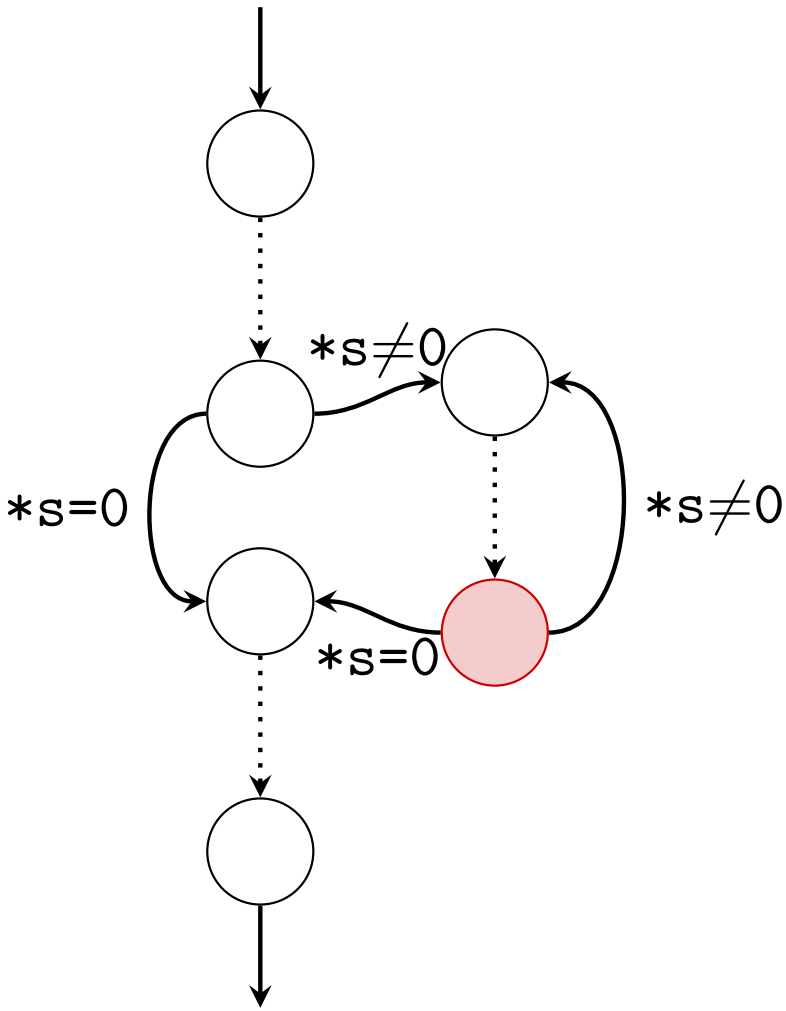


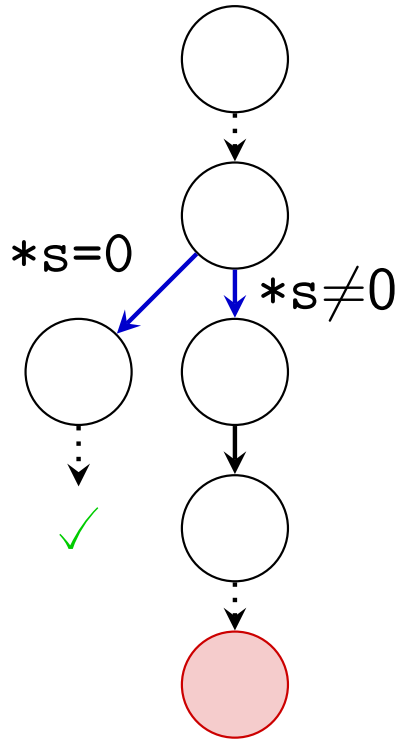

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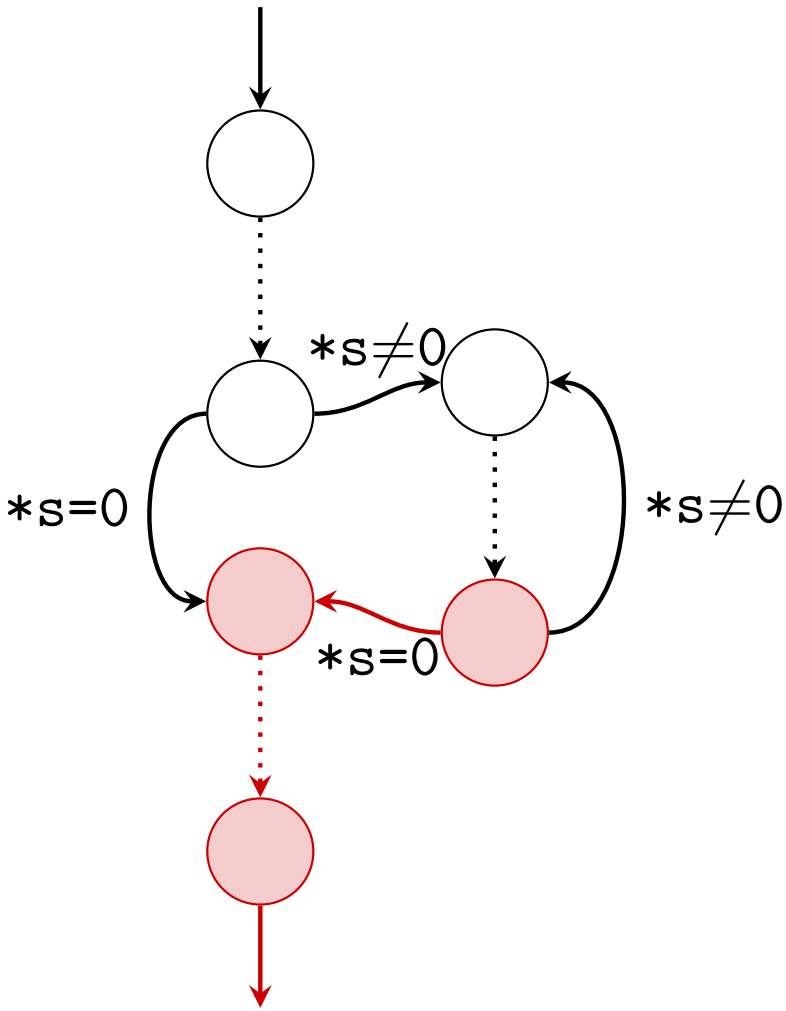


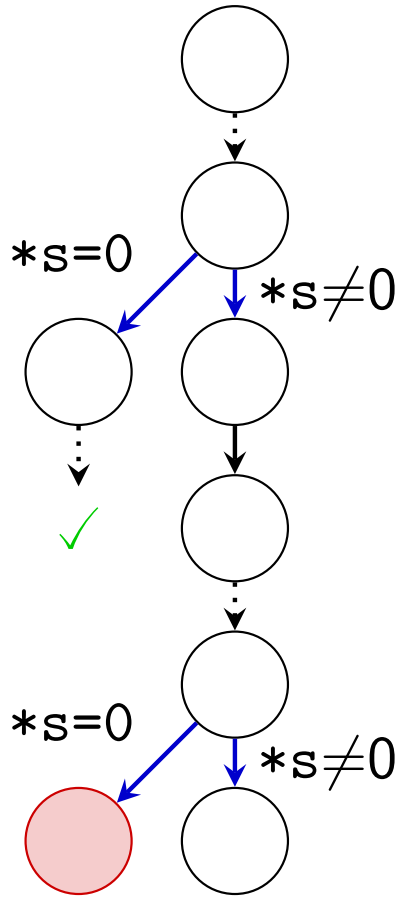

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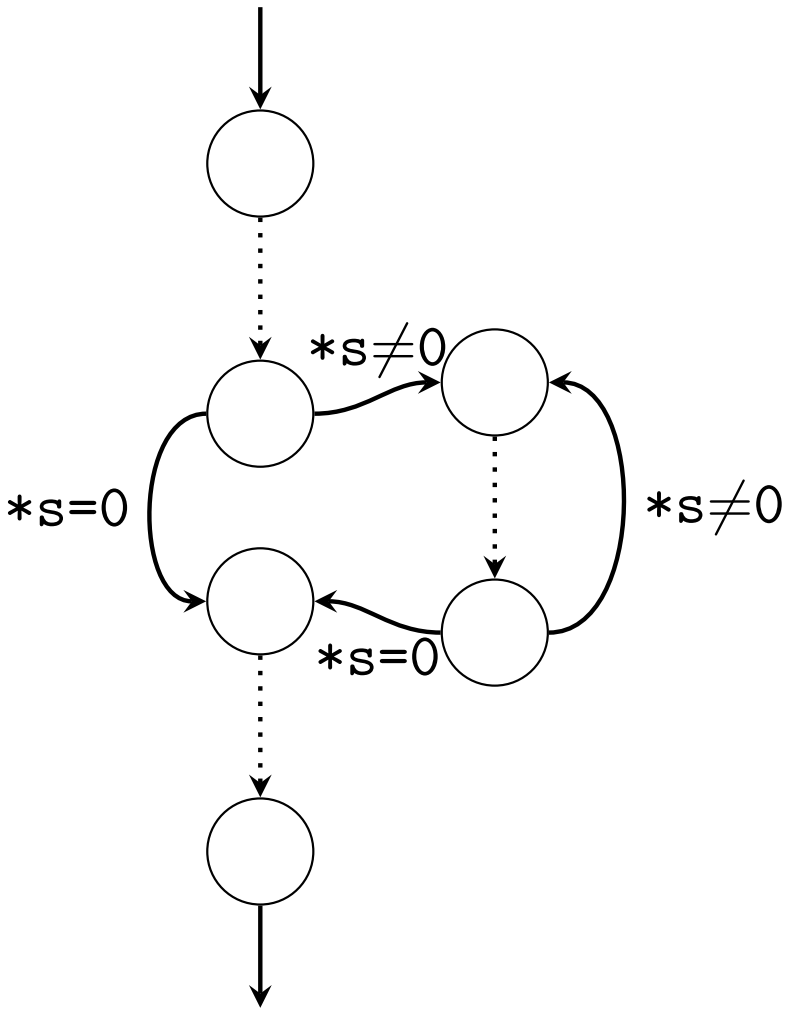


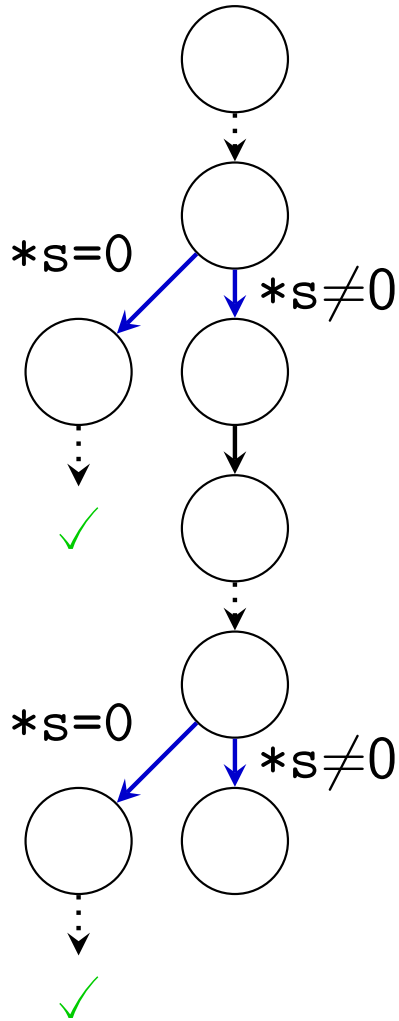

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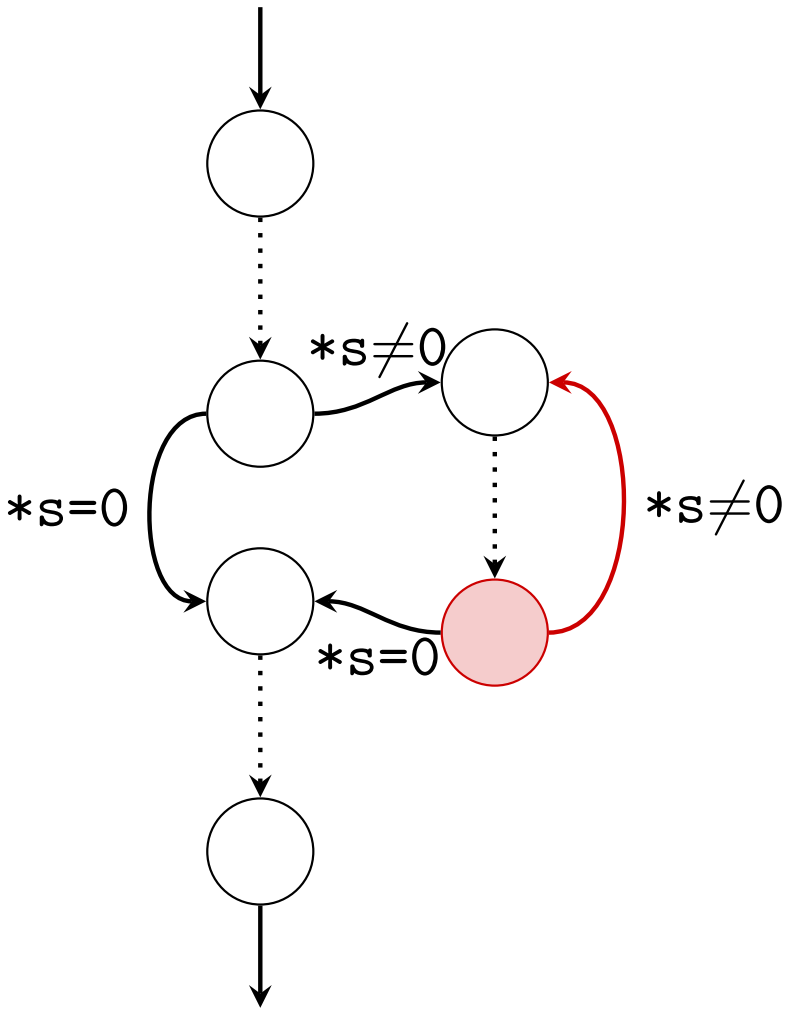


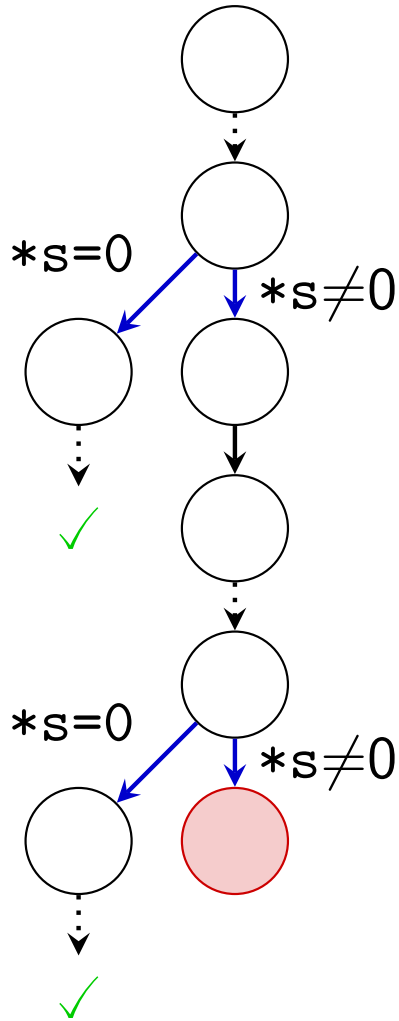

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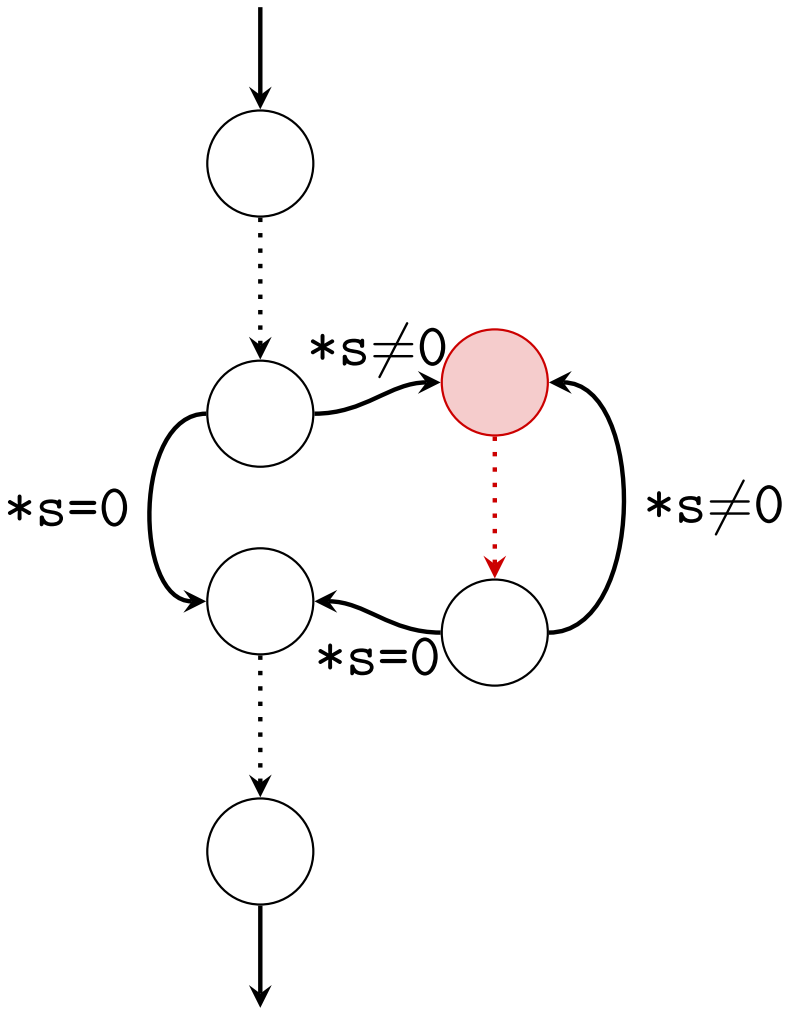


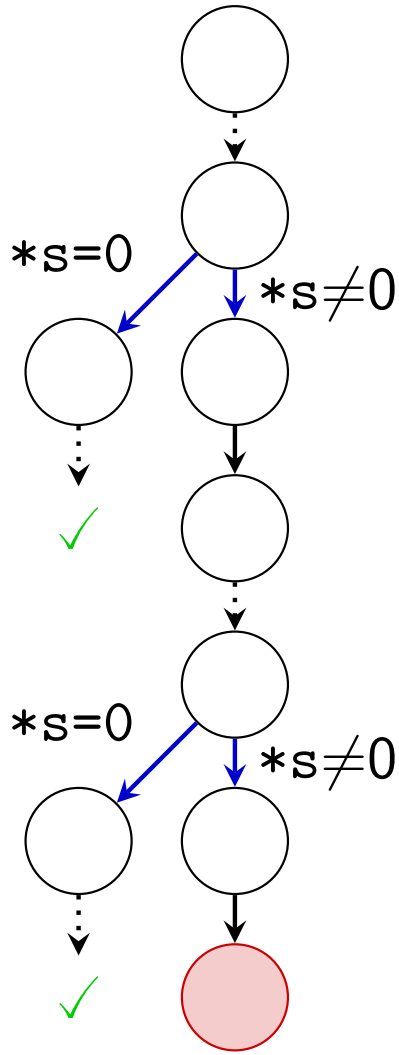

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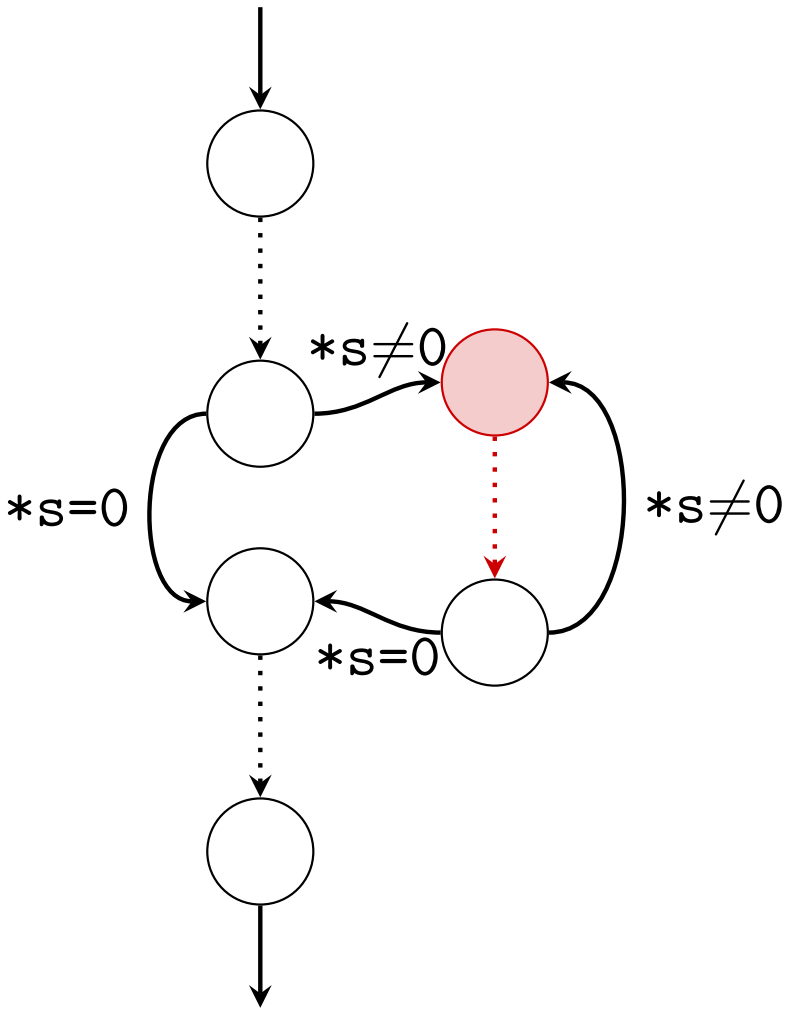


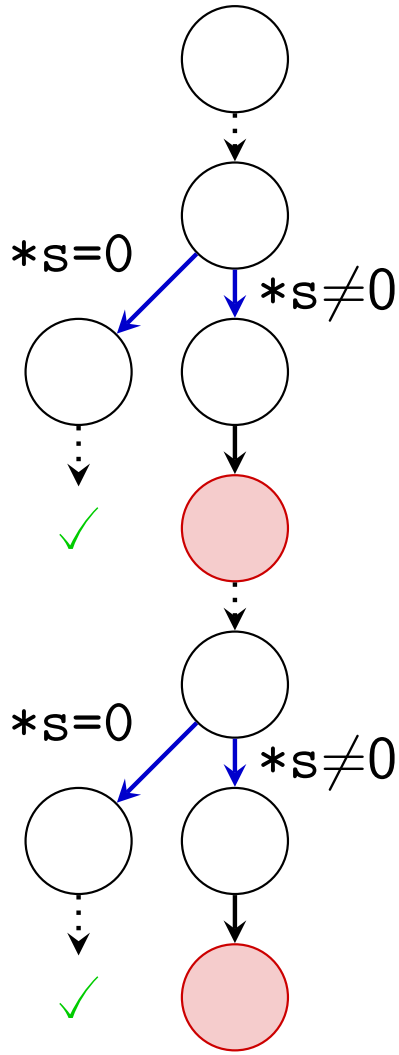

# Merging of Abstract States

| Position: $(3, \texttt{strlen})$ |
| --- |
| Alloc: $[alloc(str, v_{end})]$ |
| Stack $\rightarrow$ Memory: $s \hookrightarrow_{i8} c, \ldots$ |
| Relations: $\{s = str + 1, \ldots\}$ |

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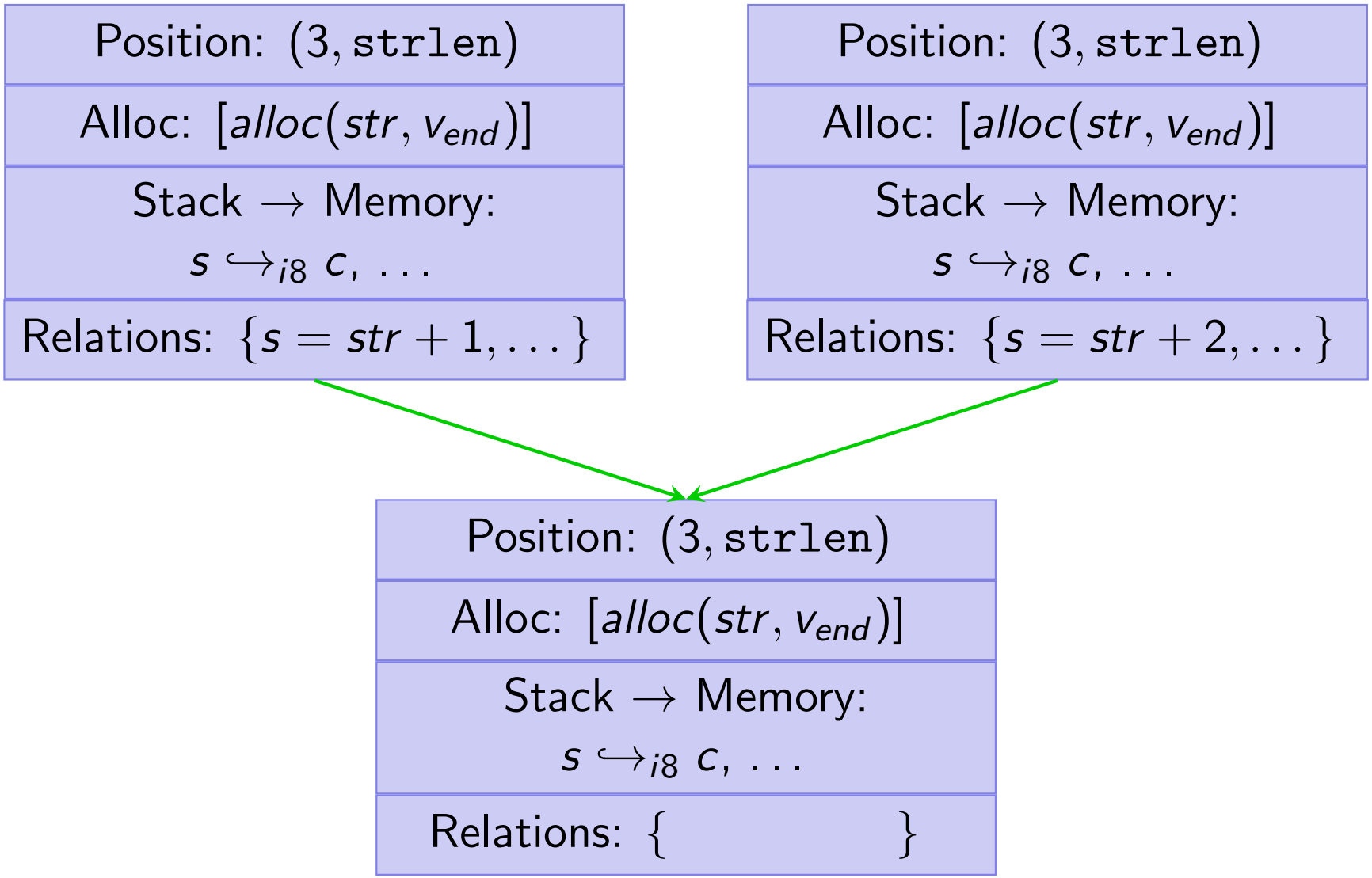

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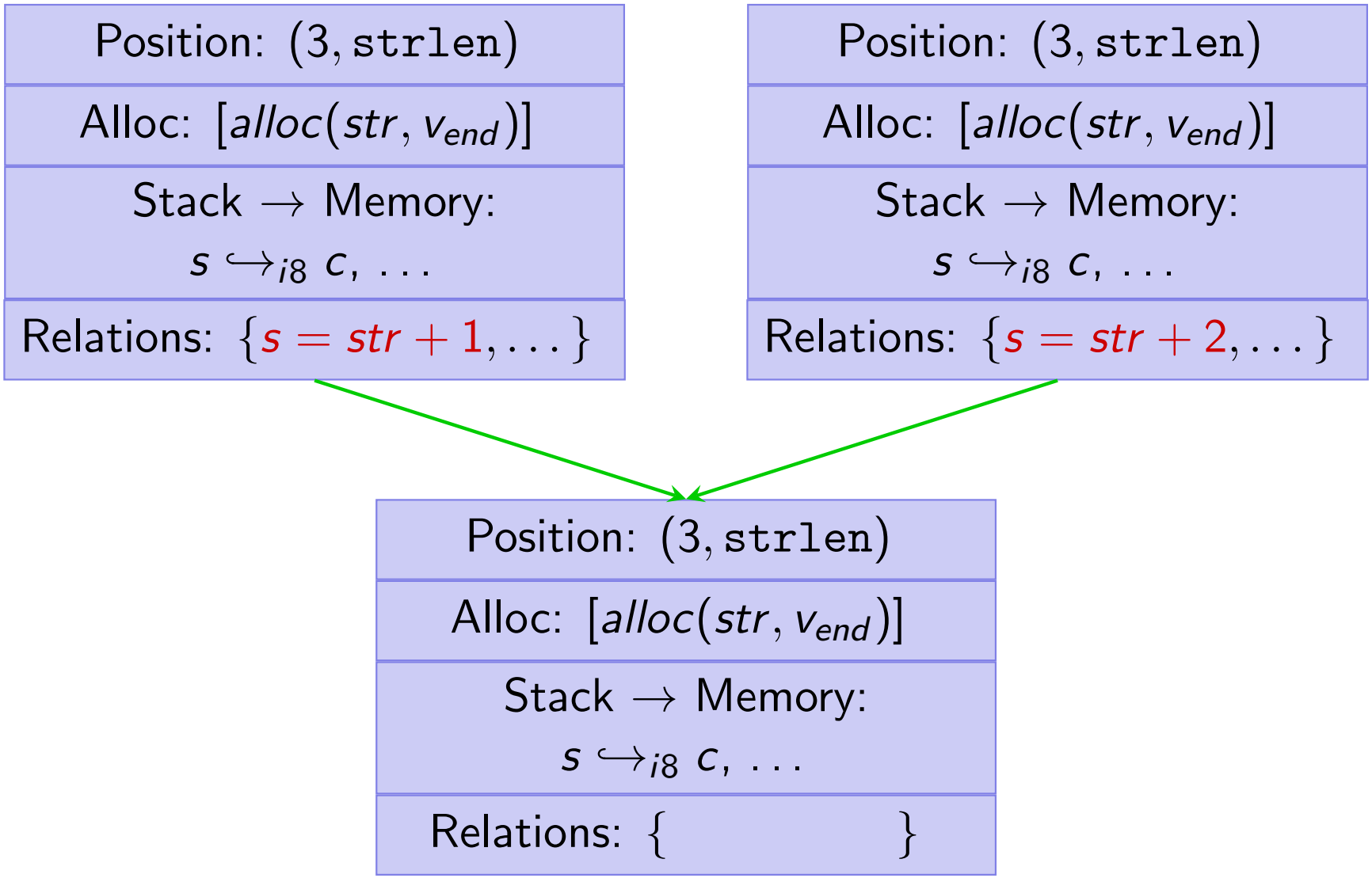

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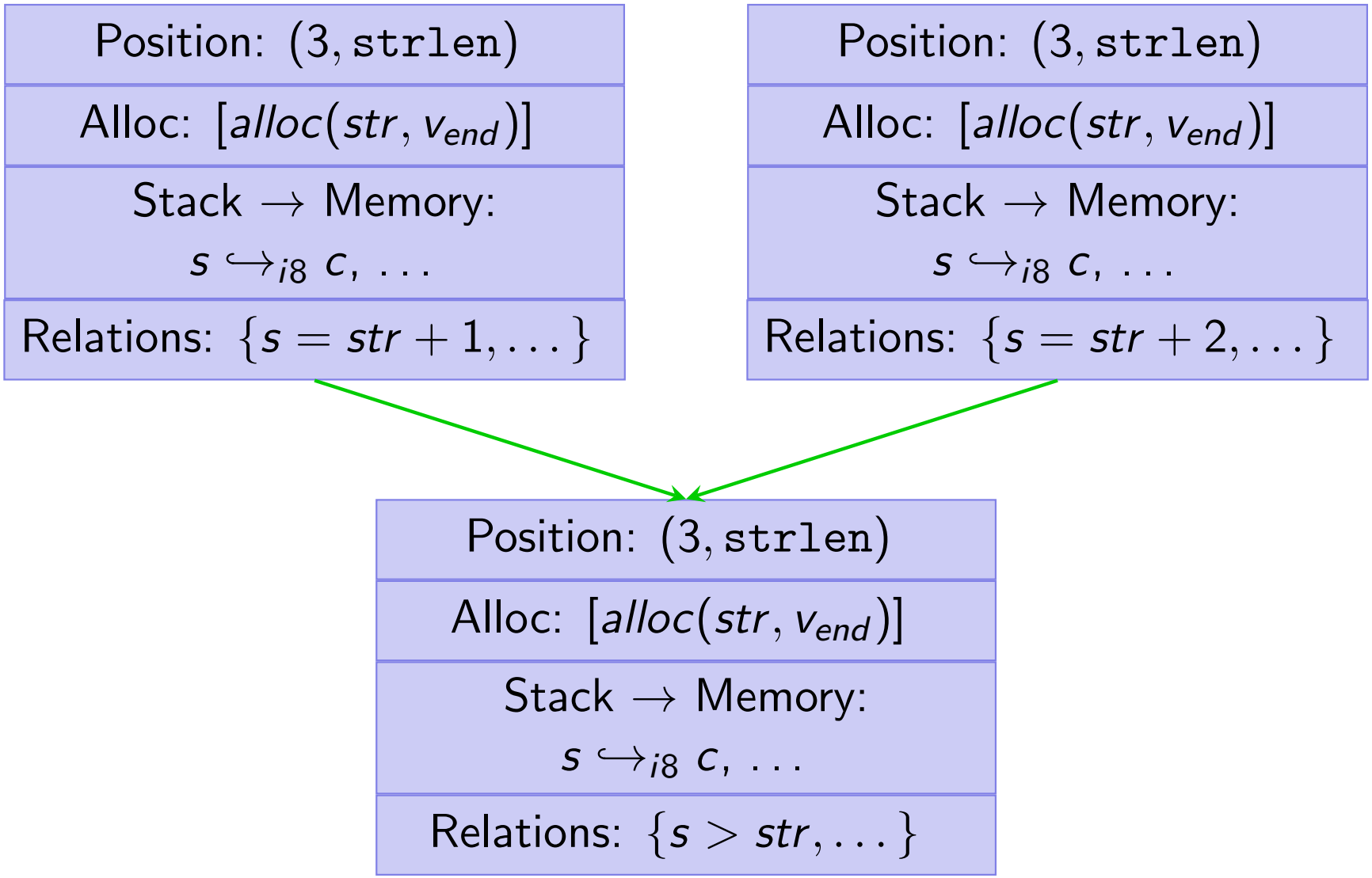

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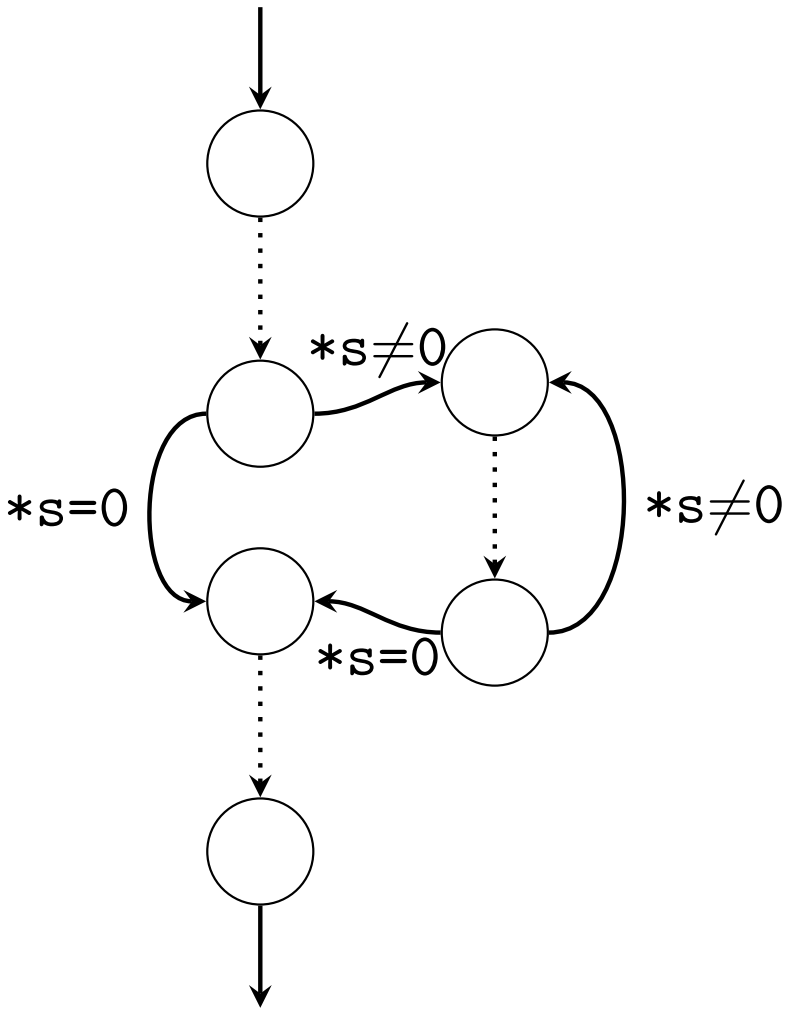


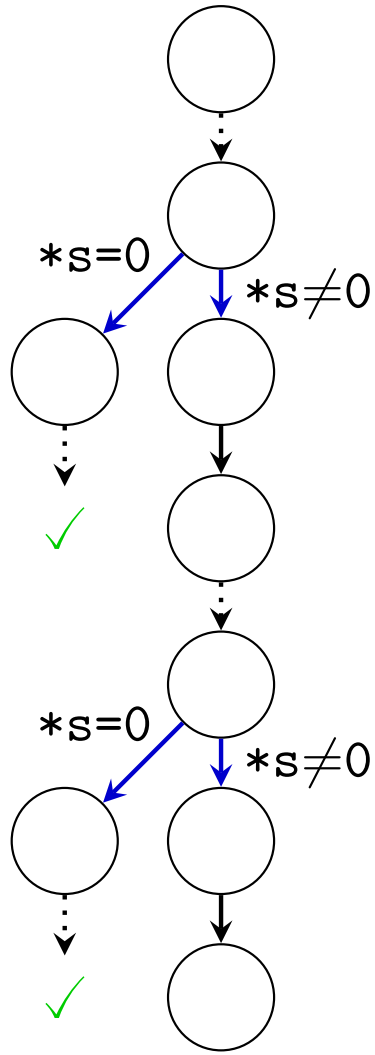

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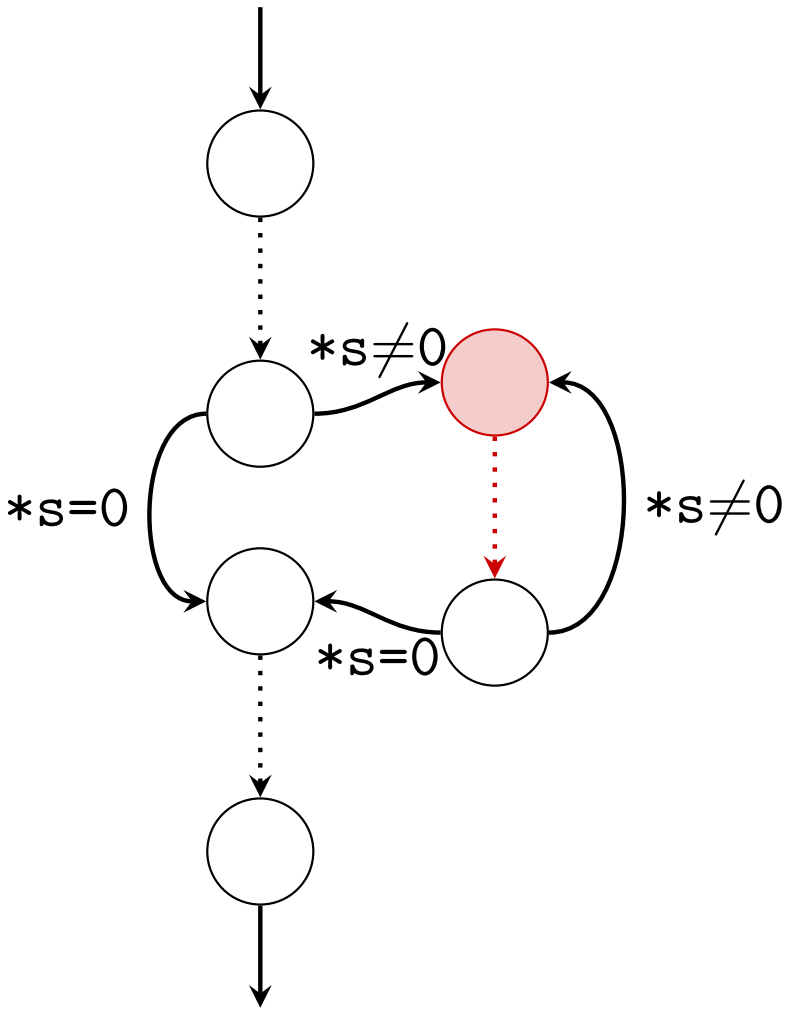


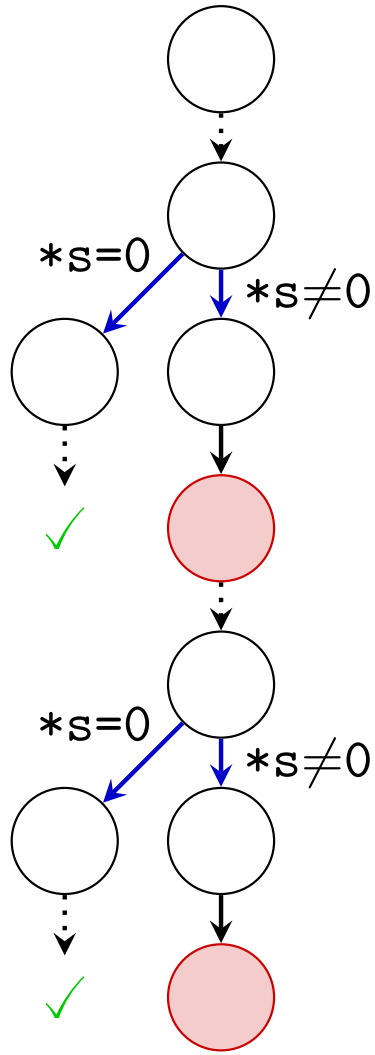

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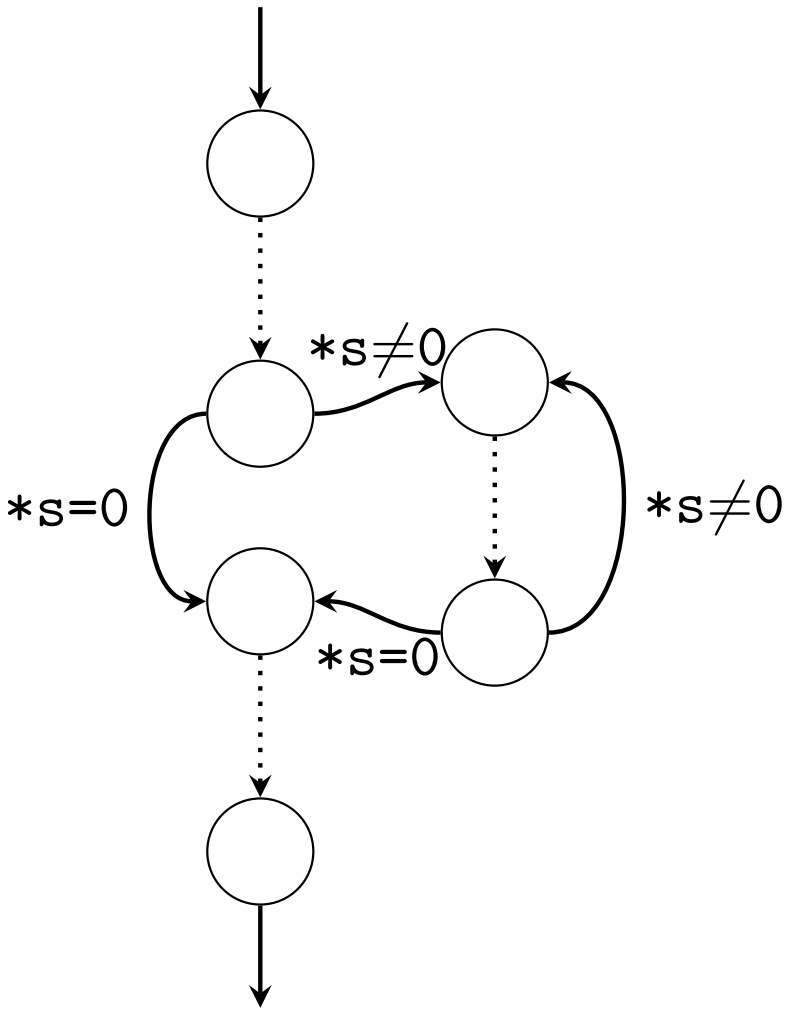


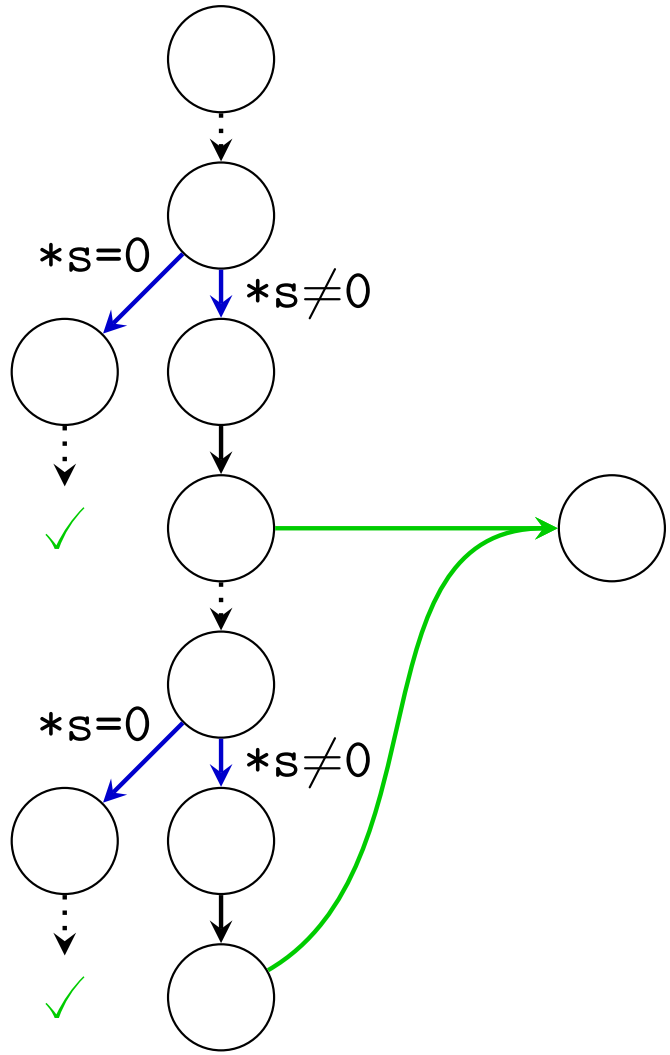

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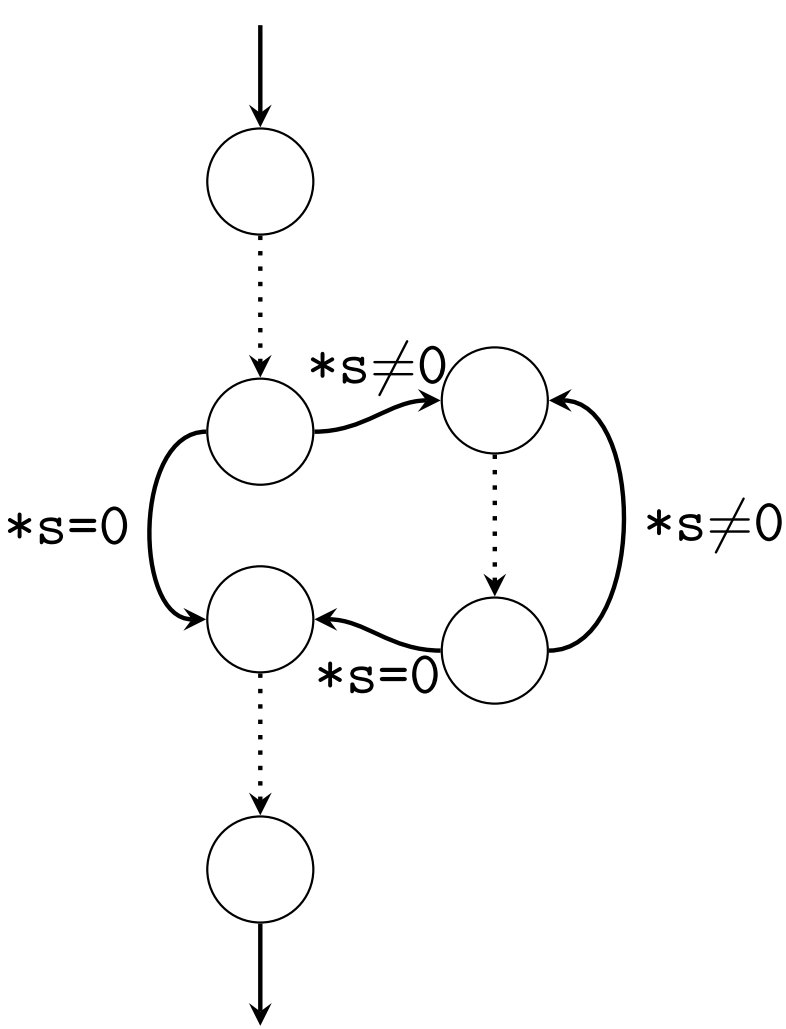


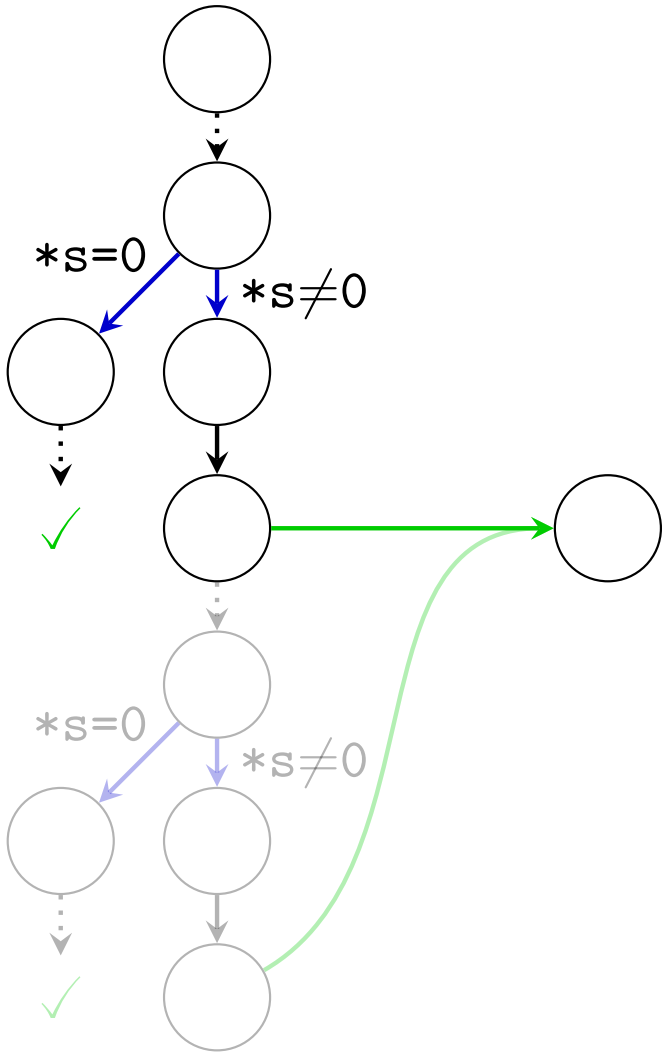

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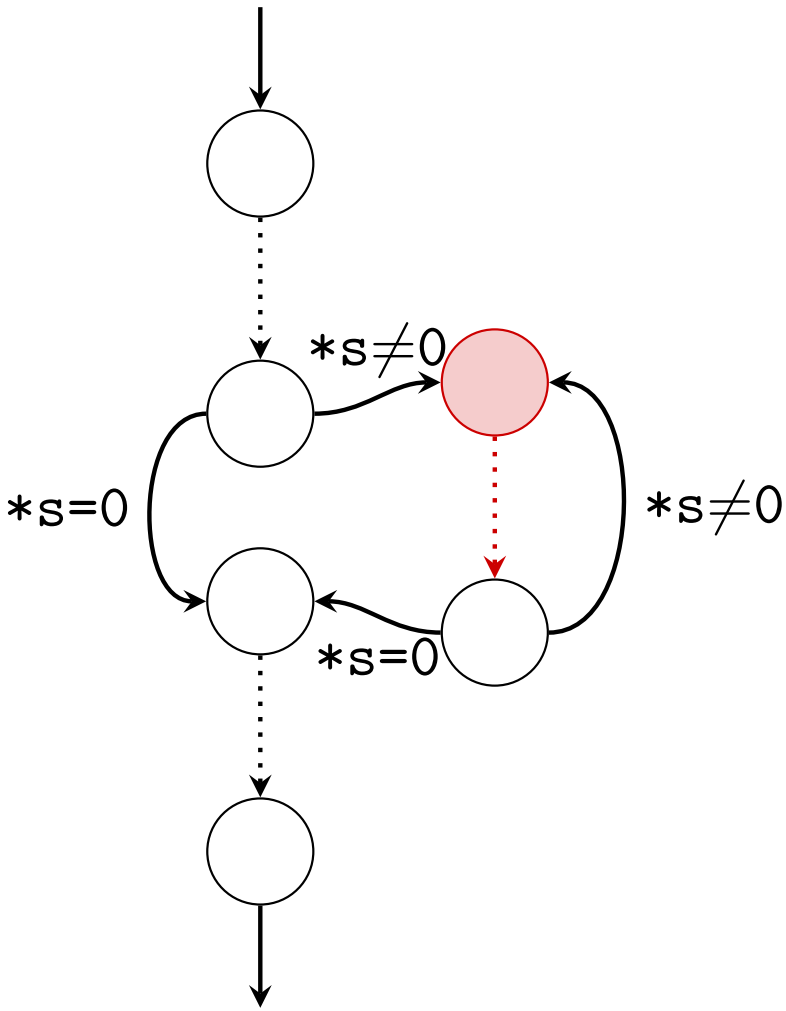
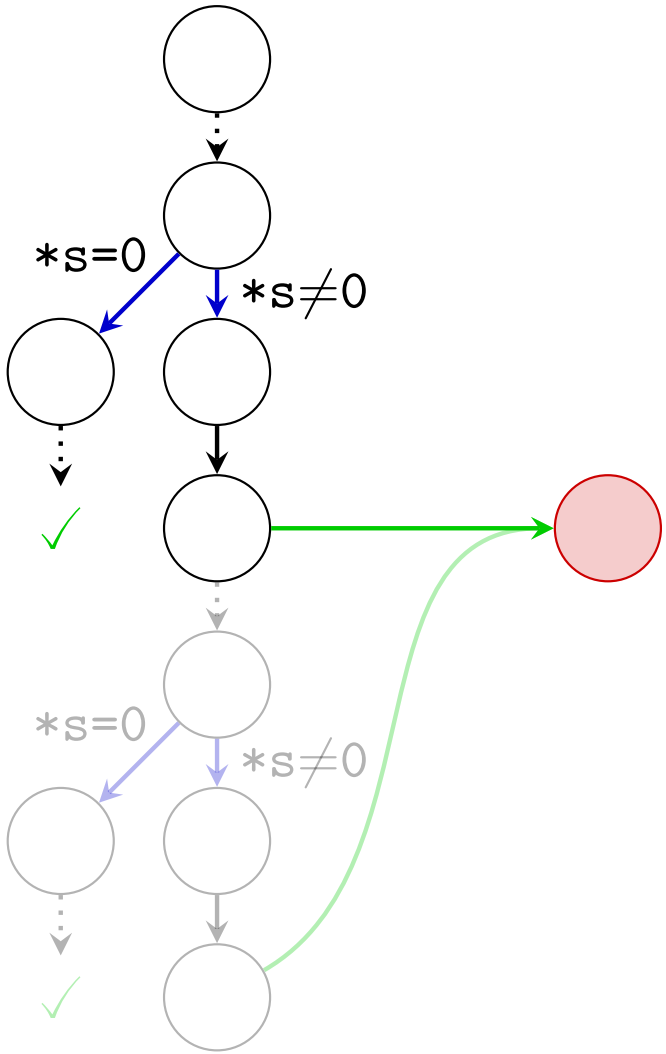
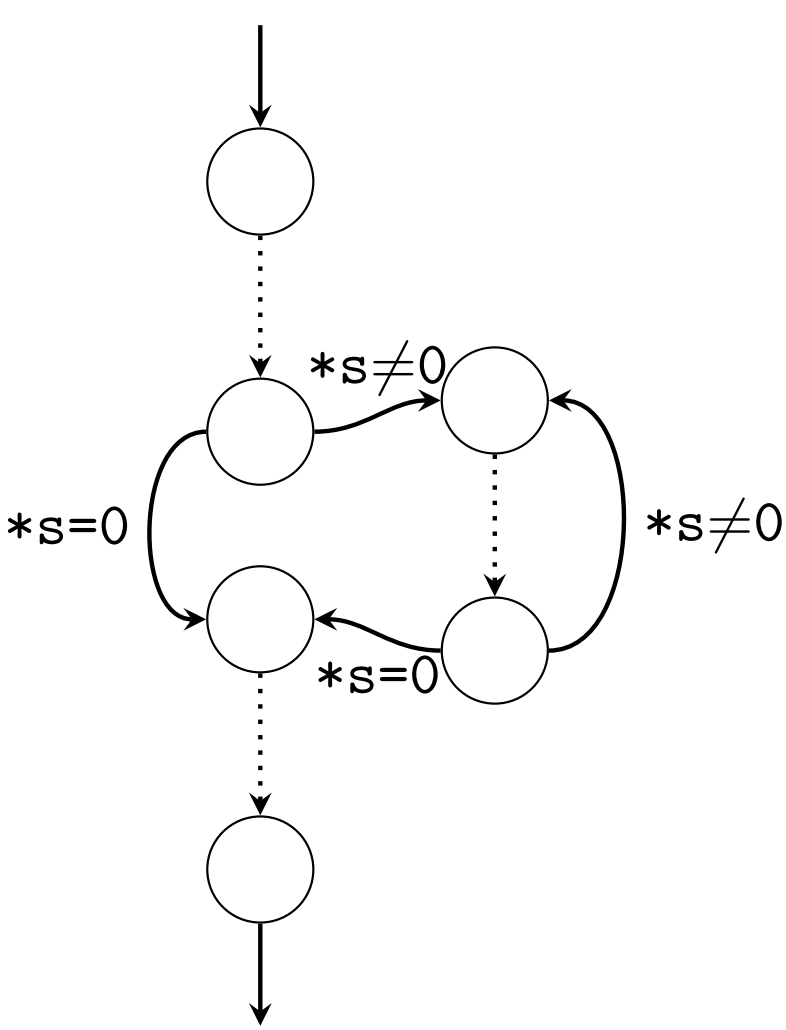
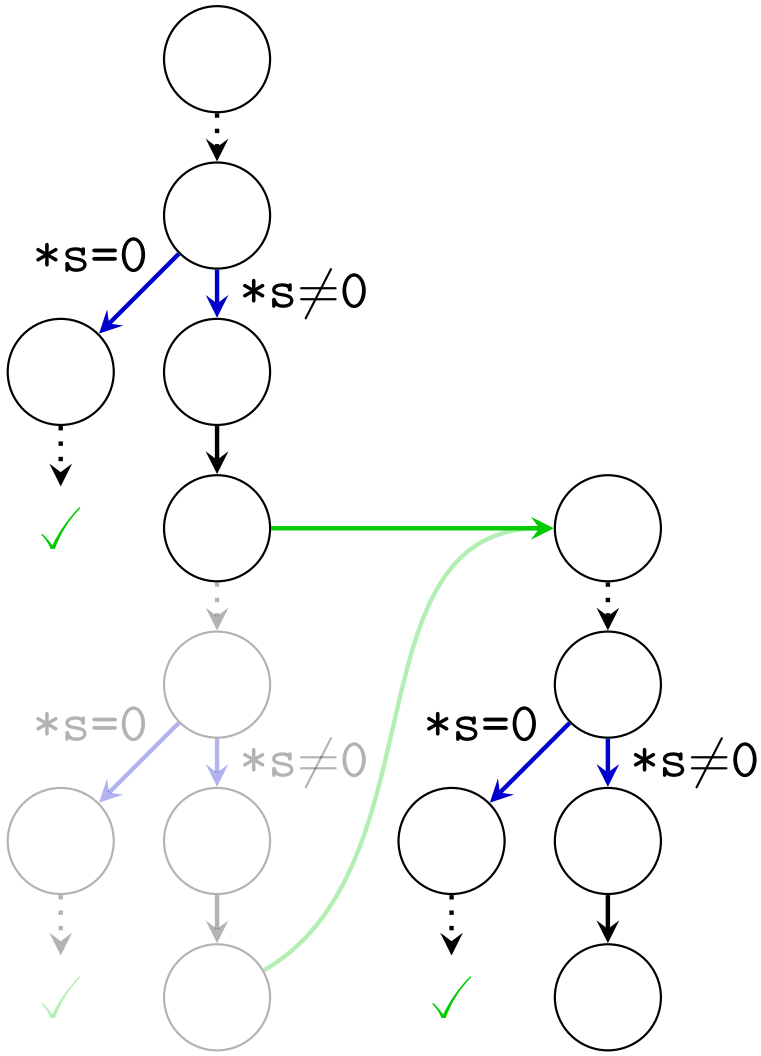


# Merging of Abstract States



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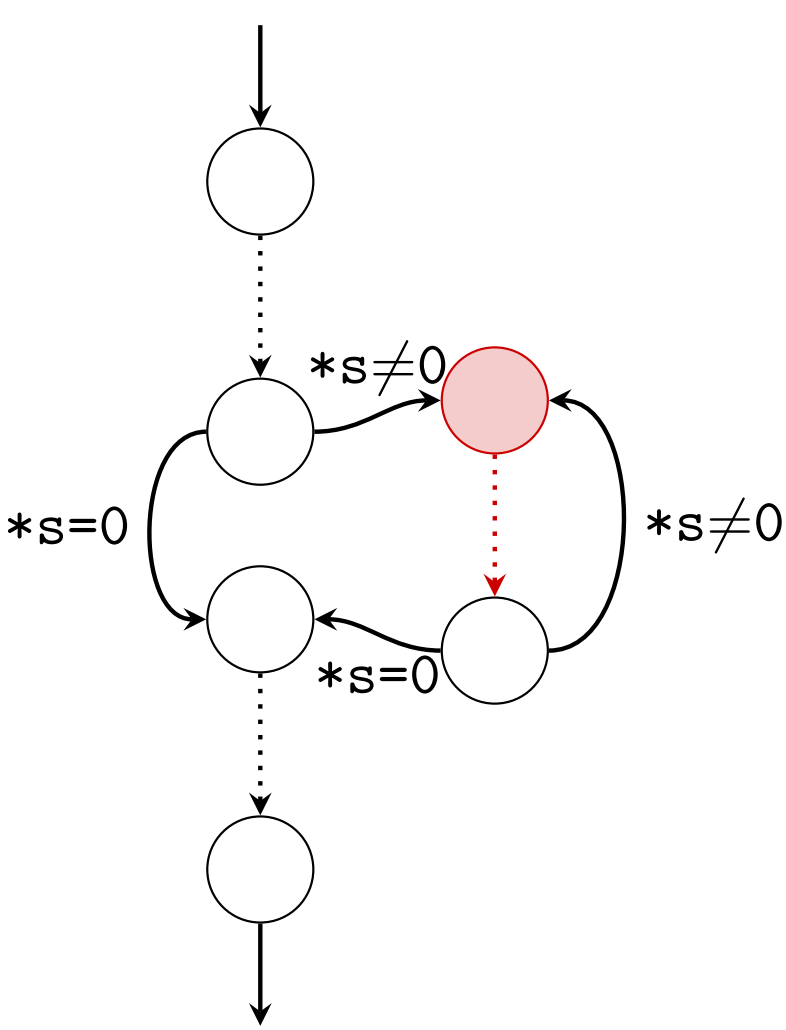


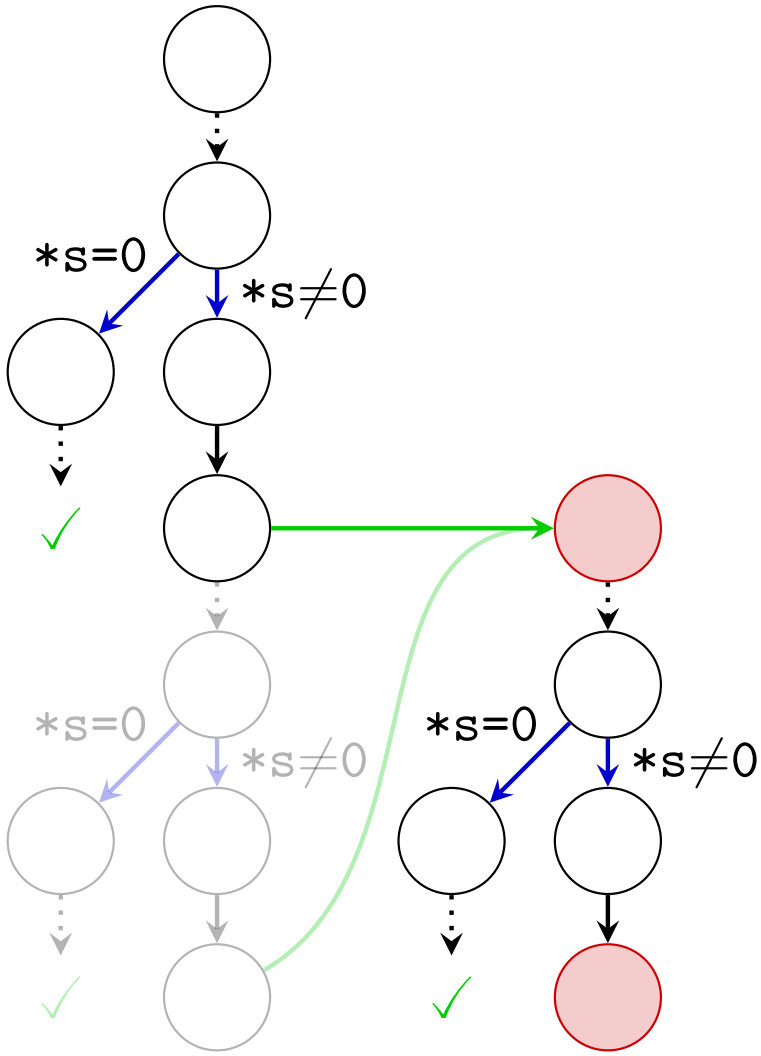

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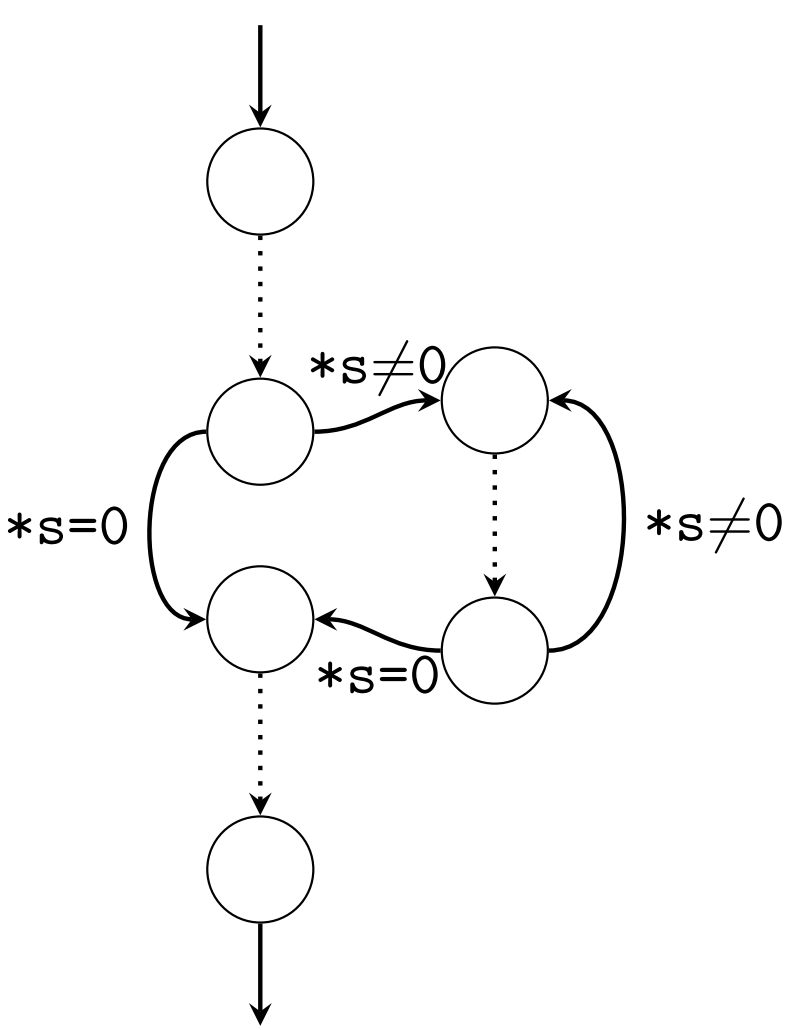
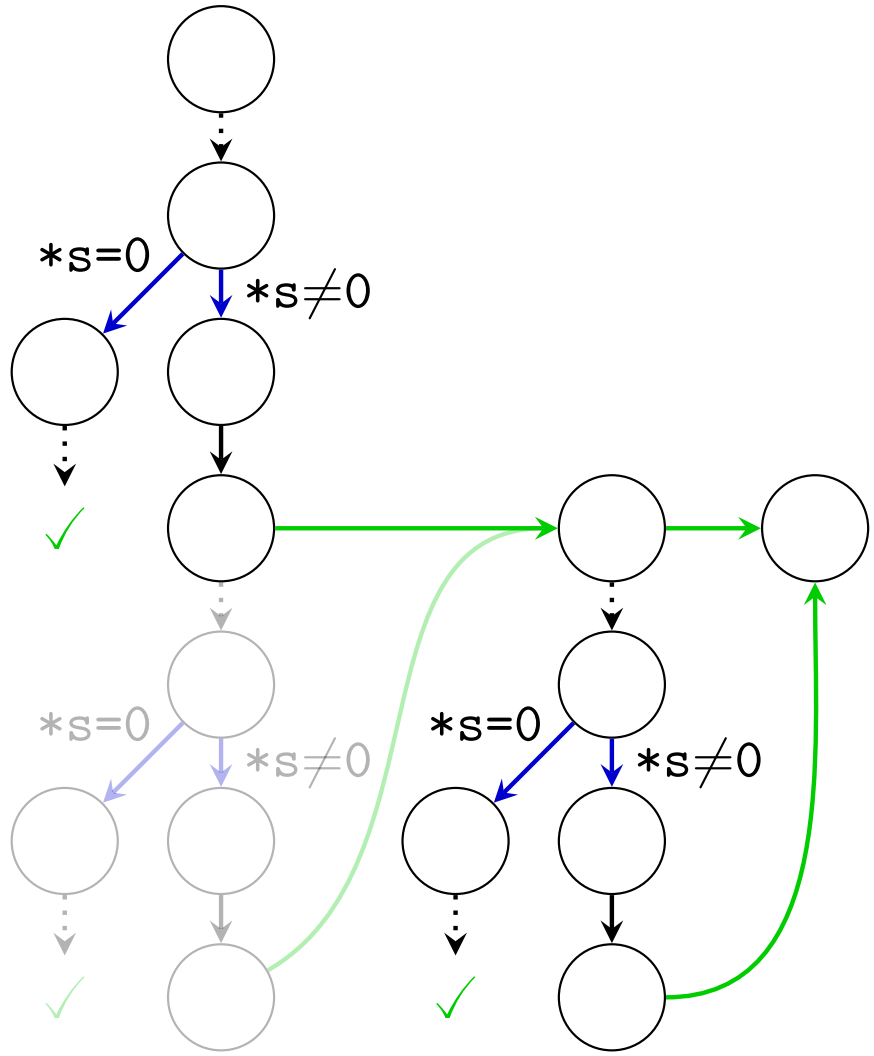
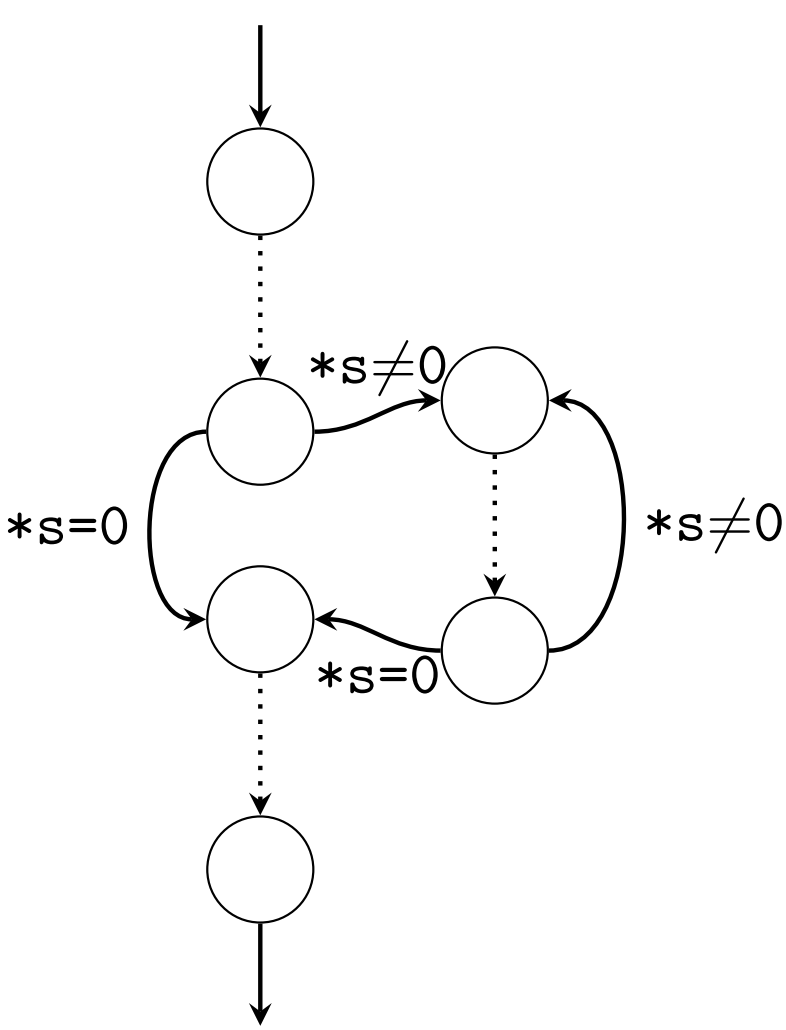
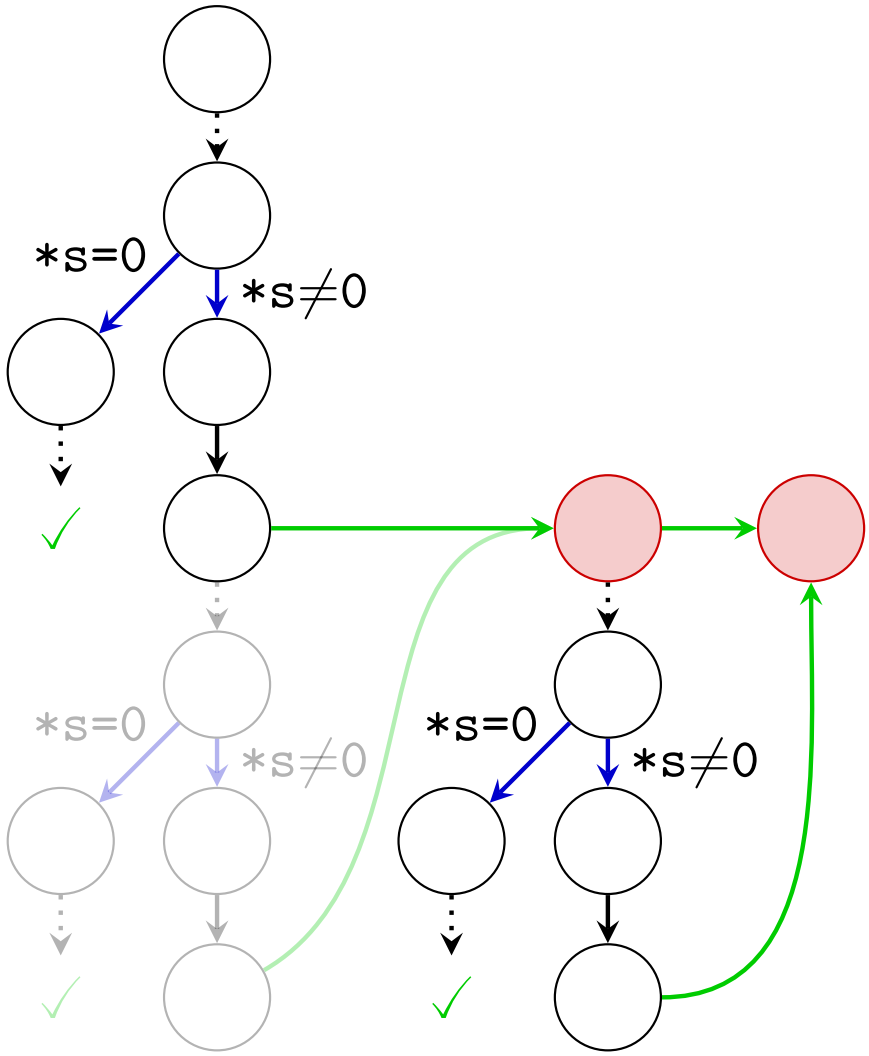


# Merging of Abstract States



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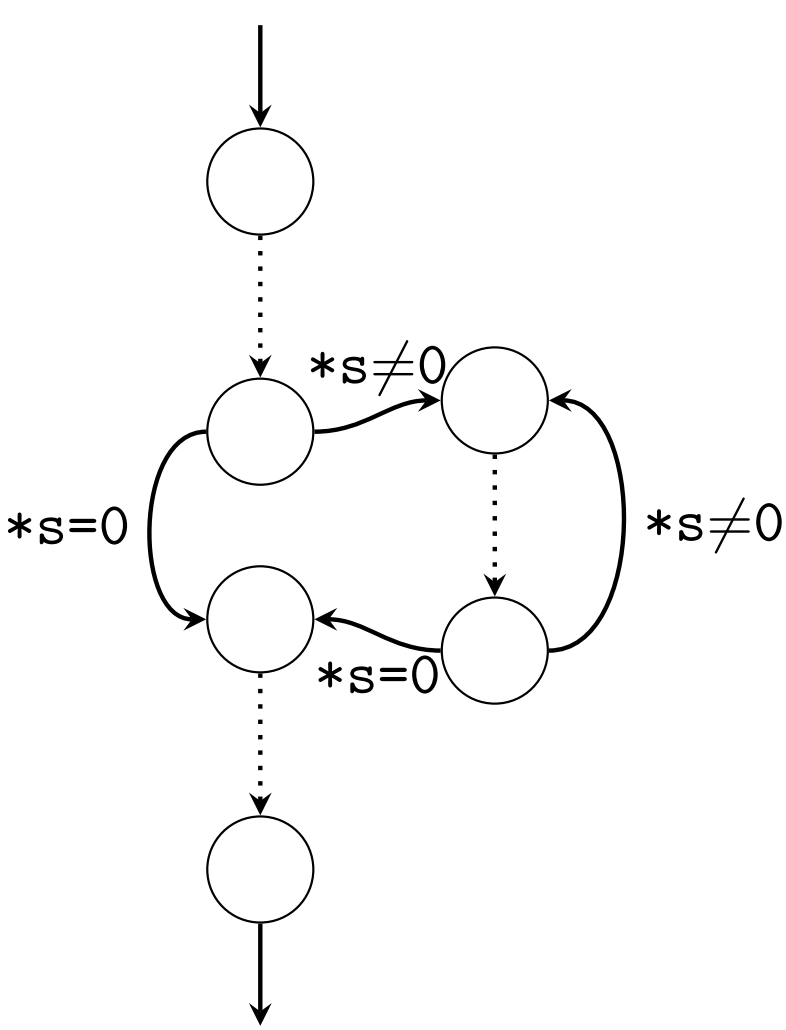
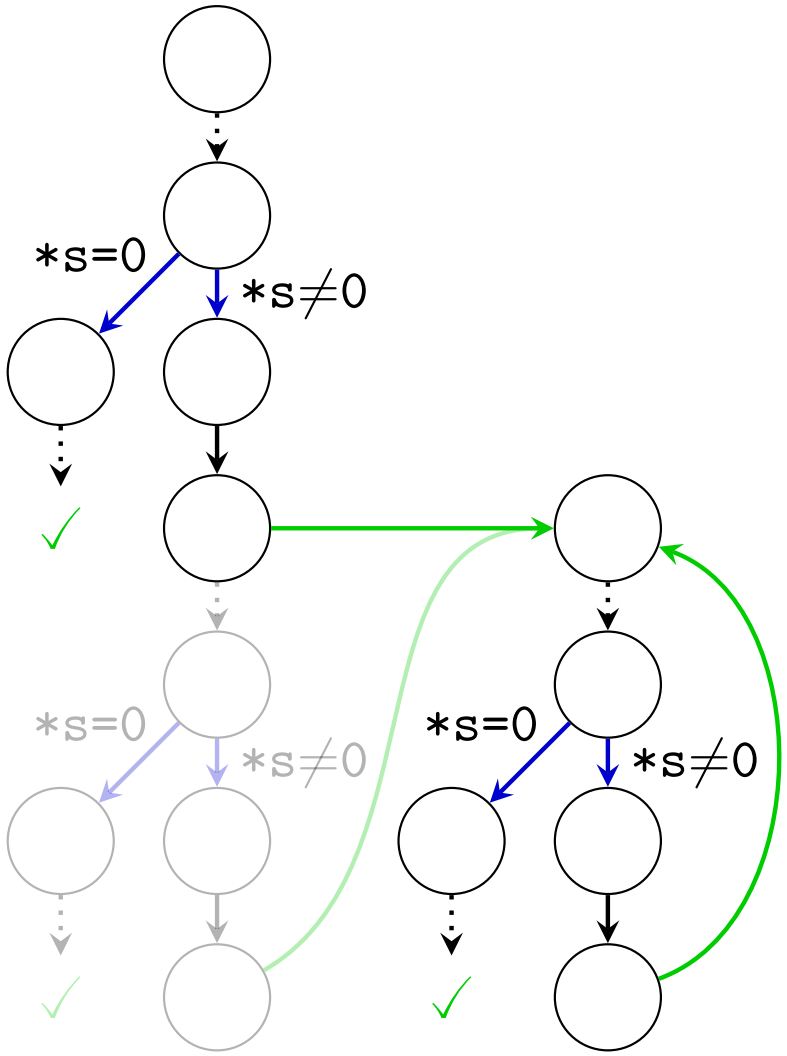
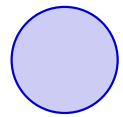


# Summary: Symbolic Execution Graphs



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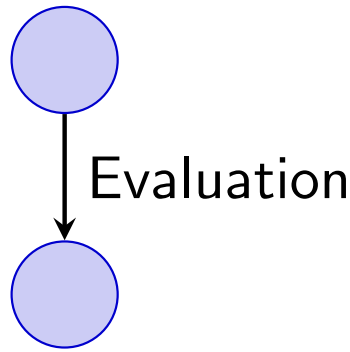
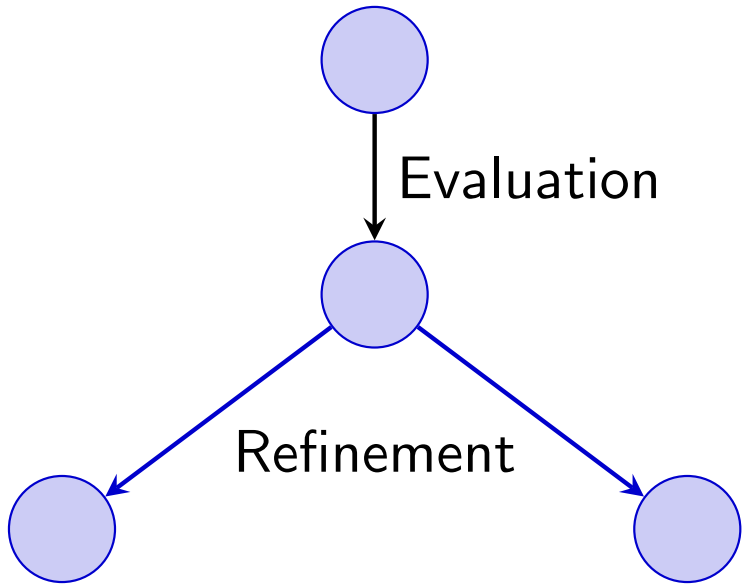
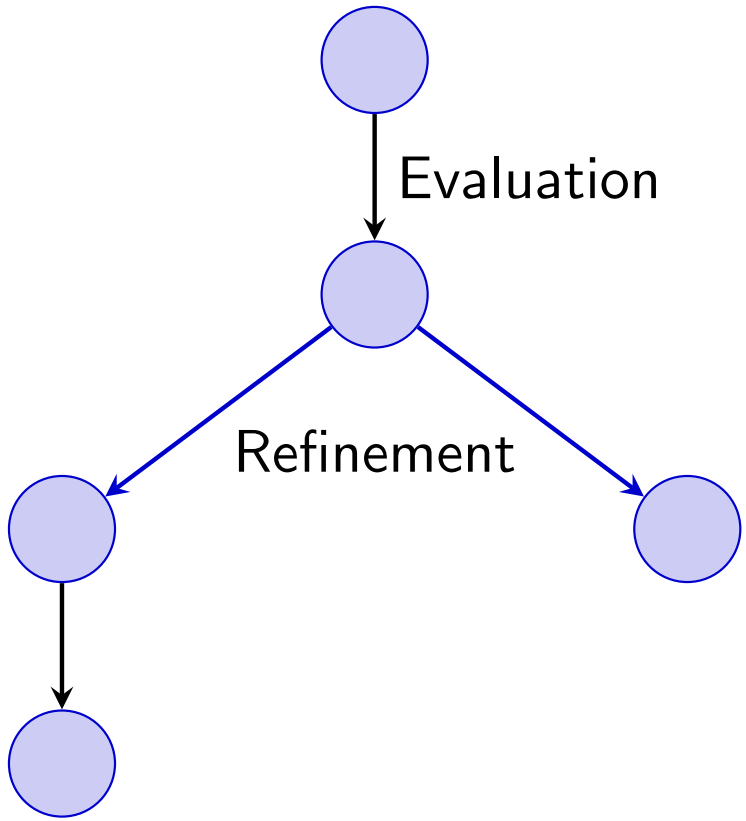


# Summary: Symbolic Execution Graphs



# Summary: Symbolic Execution Graphs



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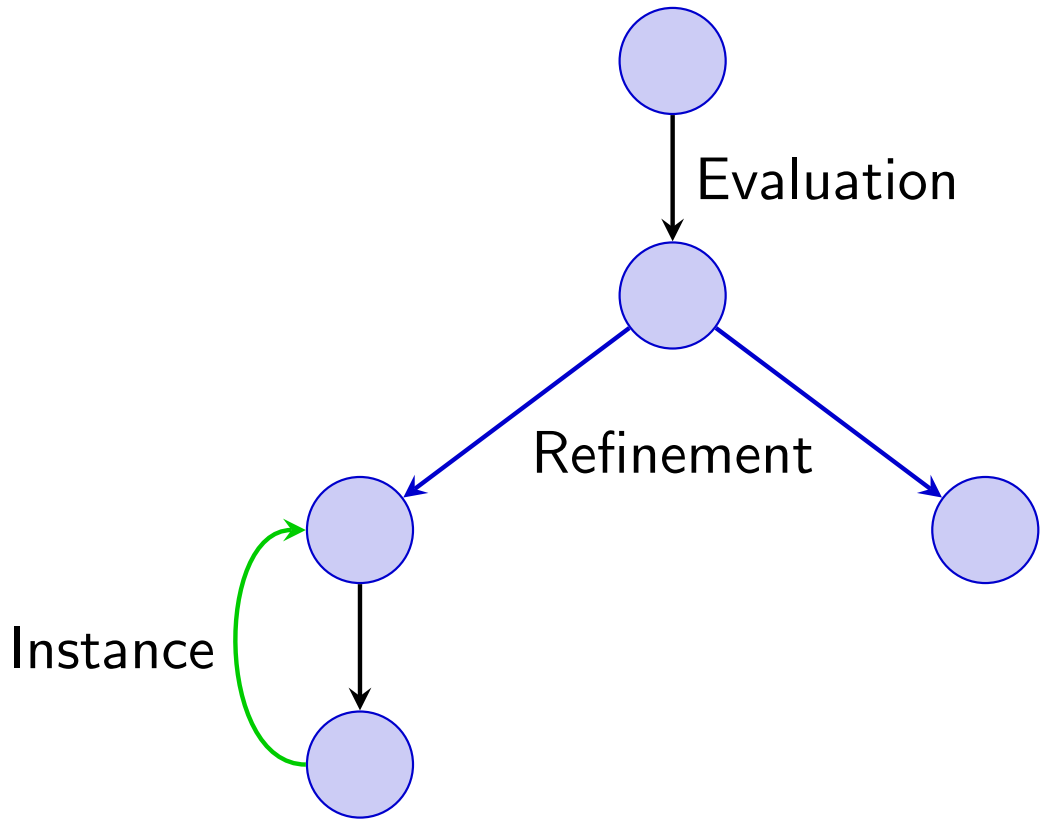

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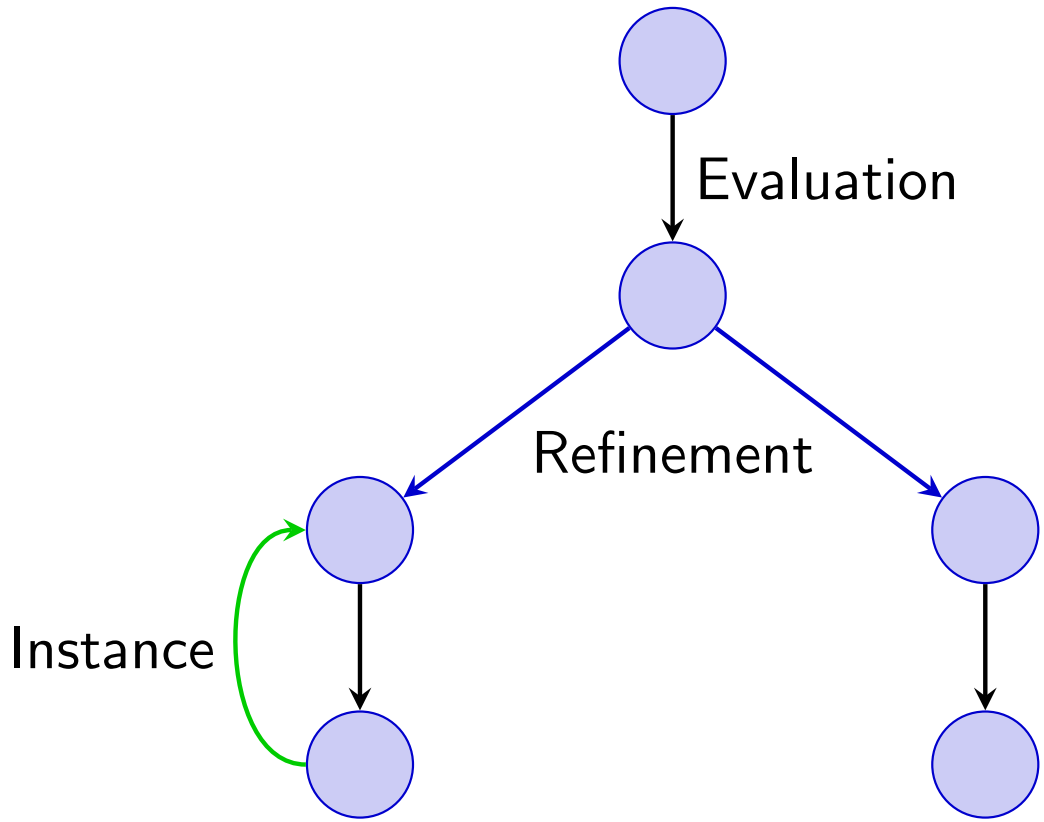

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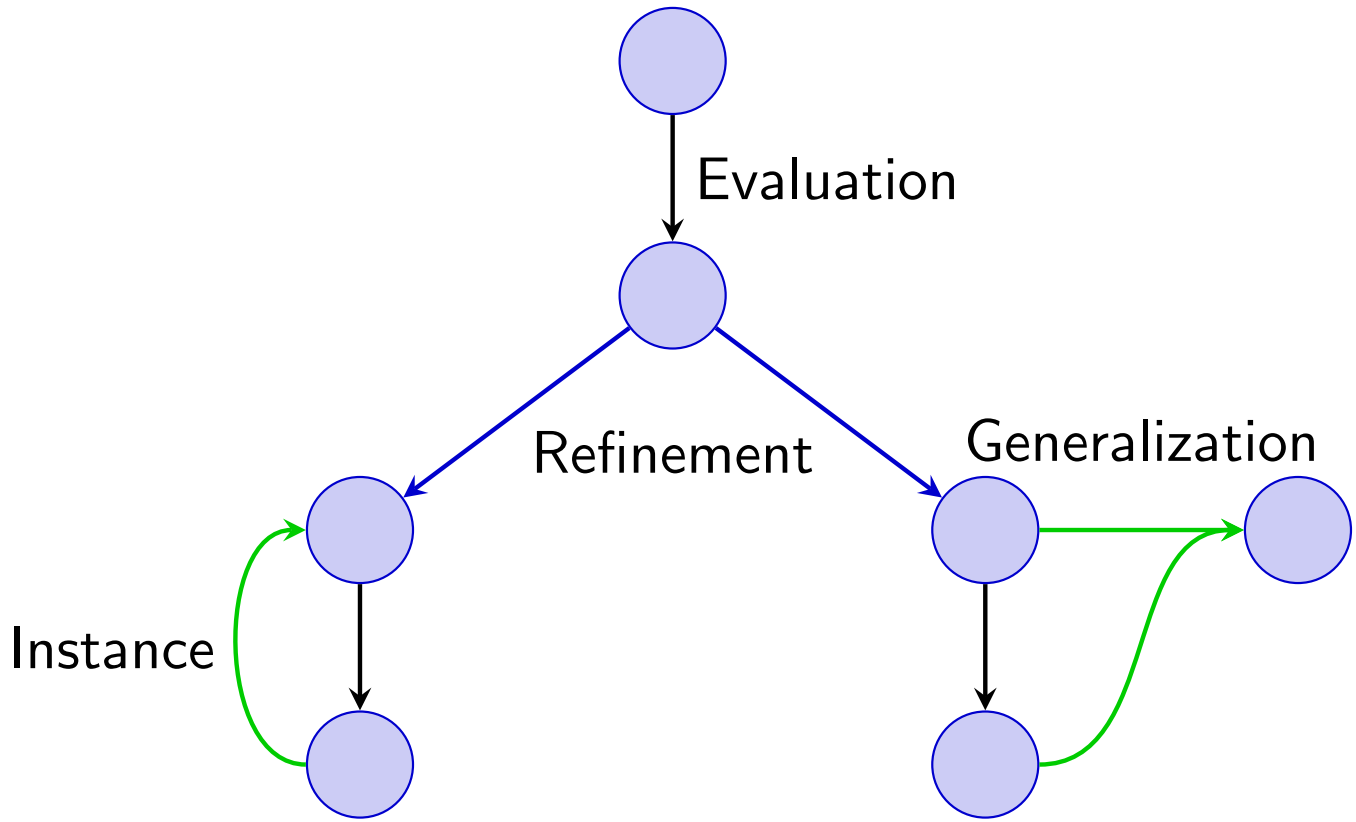
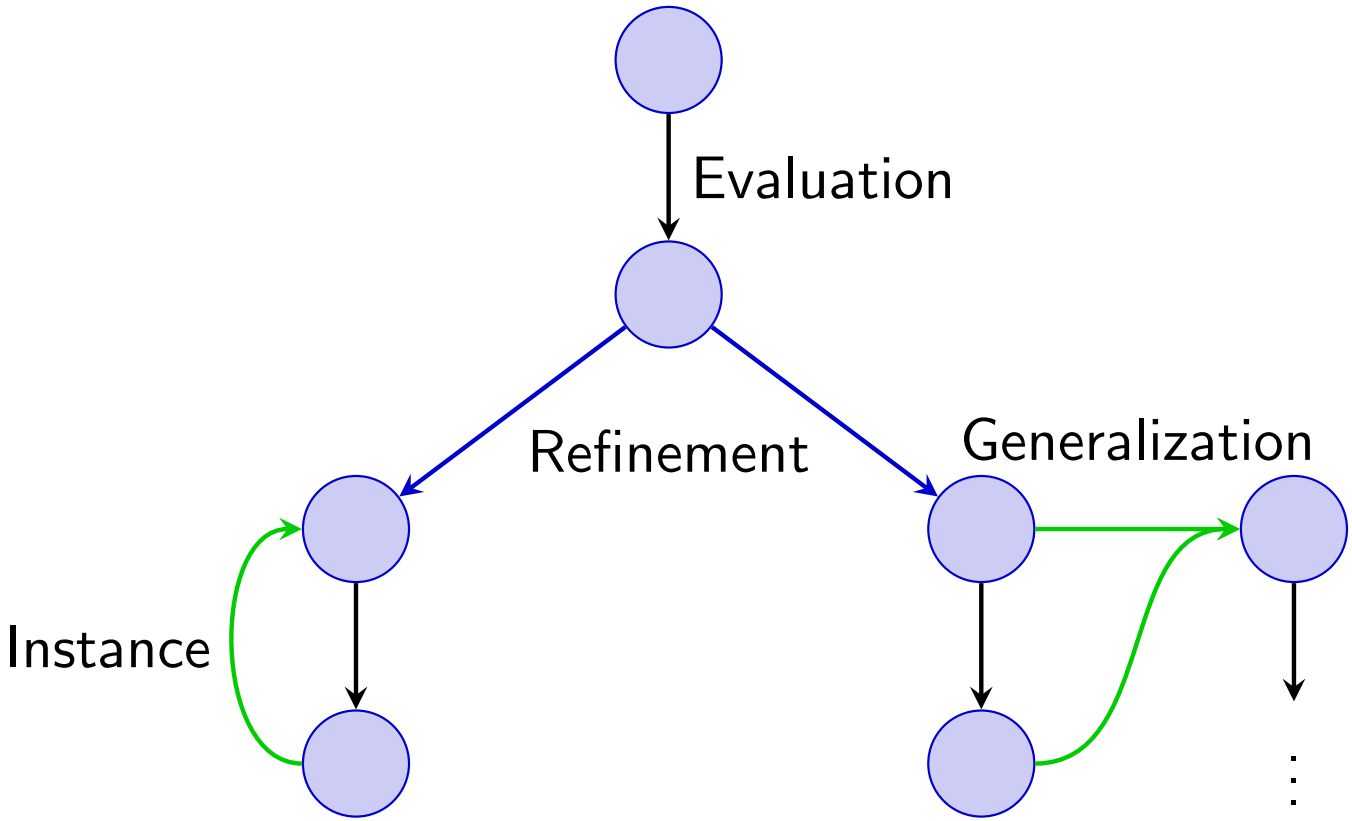
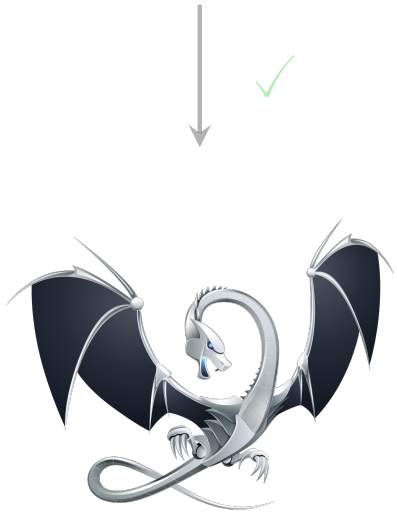


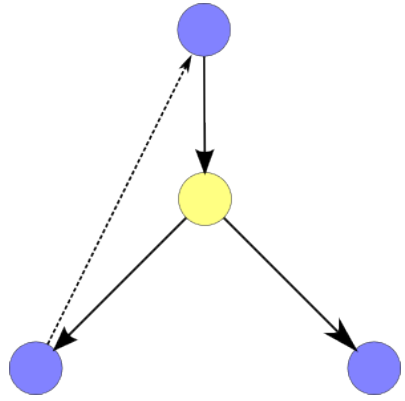
# Summary: Symbolic Execution Graphs



# Symbolic Execution Graph to Integer Transition System

LLVM



Symbolic Execution Graph

?

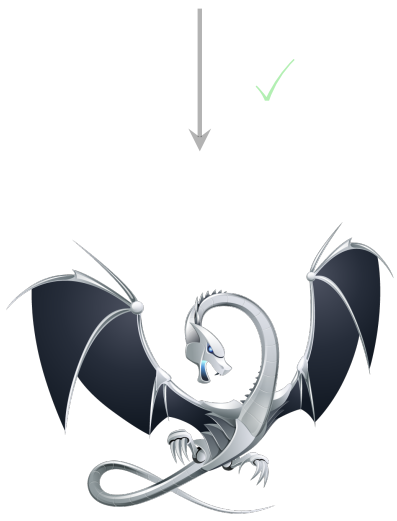
$f(x) \to g(x+1)$
$g(x) \to g(x-1)$

Integer Transition System

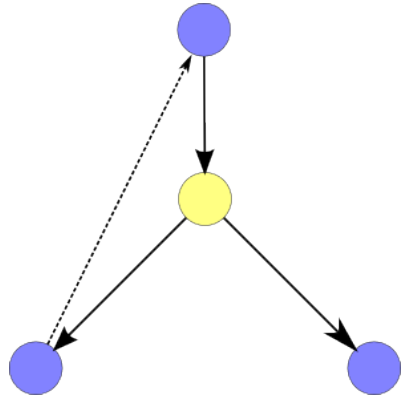
?

YES/NO/
MAYBE

# Symbolic Execution Graph to Integer Transition System

LLVM



Symbolic Execution Graph

YES/NO/
MAYBE

?

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

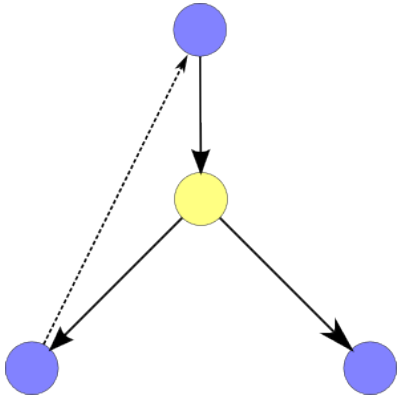
Integer Transition
System

# Symbolic Execution Graph to 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

# Integer Transition Systems

Term Rewriting System:

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

# 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 Systems

Term Rewriting System:

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

Integer Transition System:

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

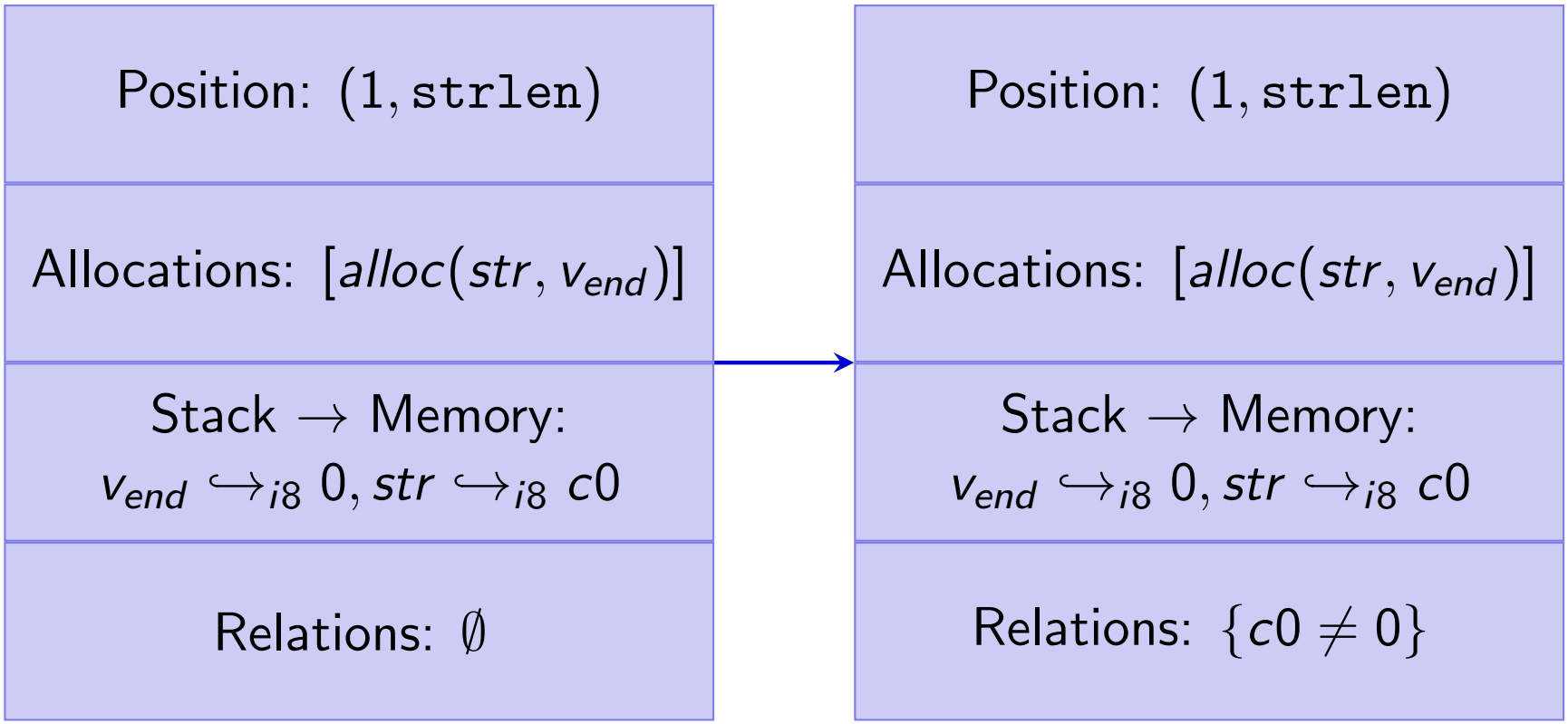
Integer Transition System:

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

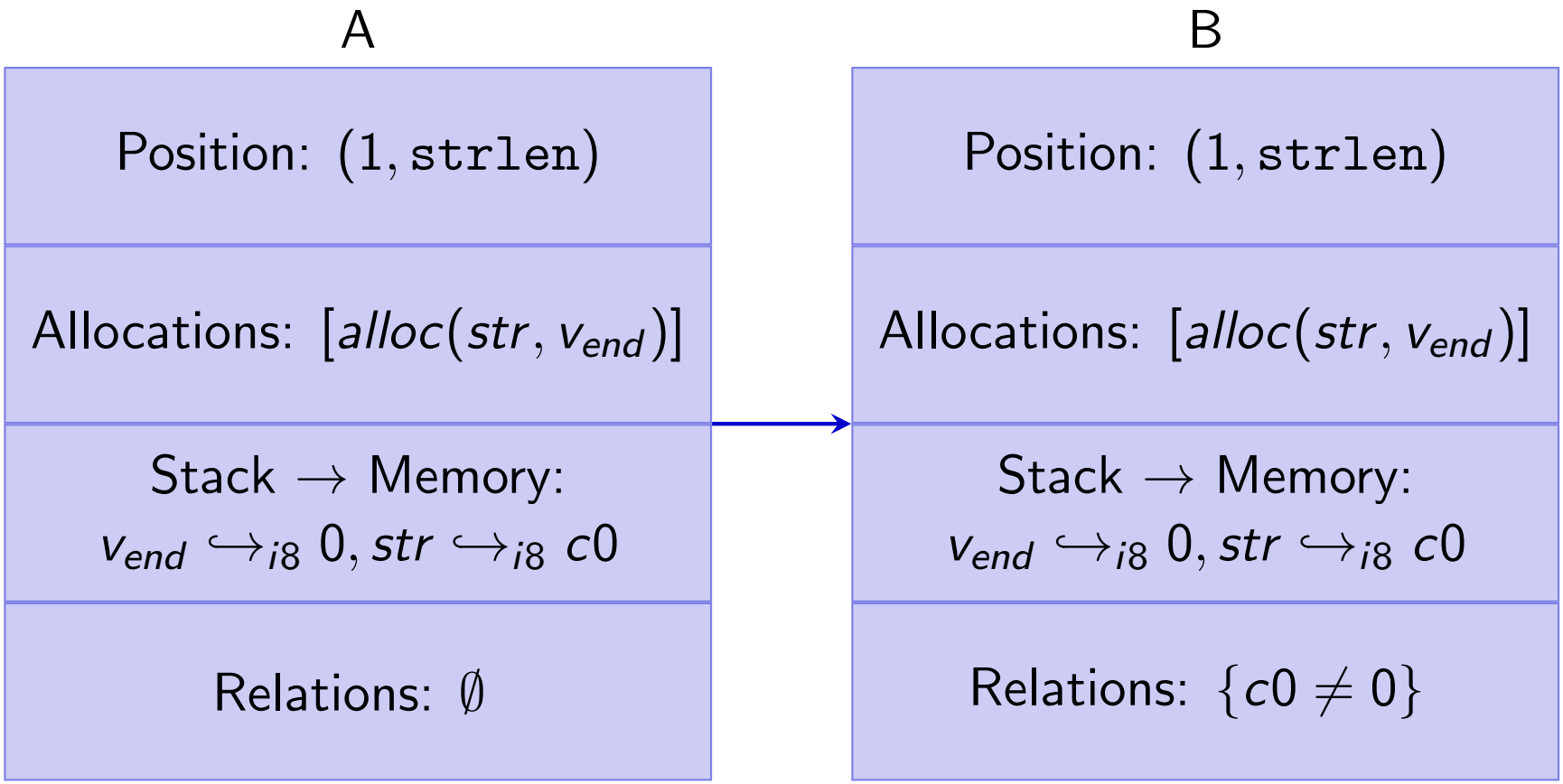
# Symbolic Execution Graph to Integer Transition System

| Position: $(1, \texttt{strlen})$ |
| --- |
| Allocations: $[alloc(str, v_{end})]$ |
| Stack $\rightarrow$ Memory:<br>$v_{end} \hookrightarrow_{i8} 0, str \hookrightarrow_{i8} c0$ |
| Relations: $\emptyset$ |

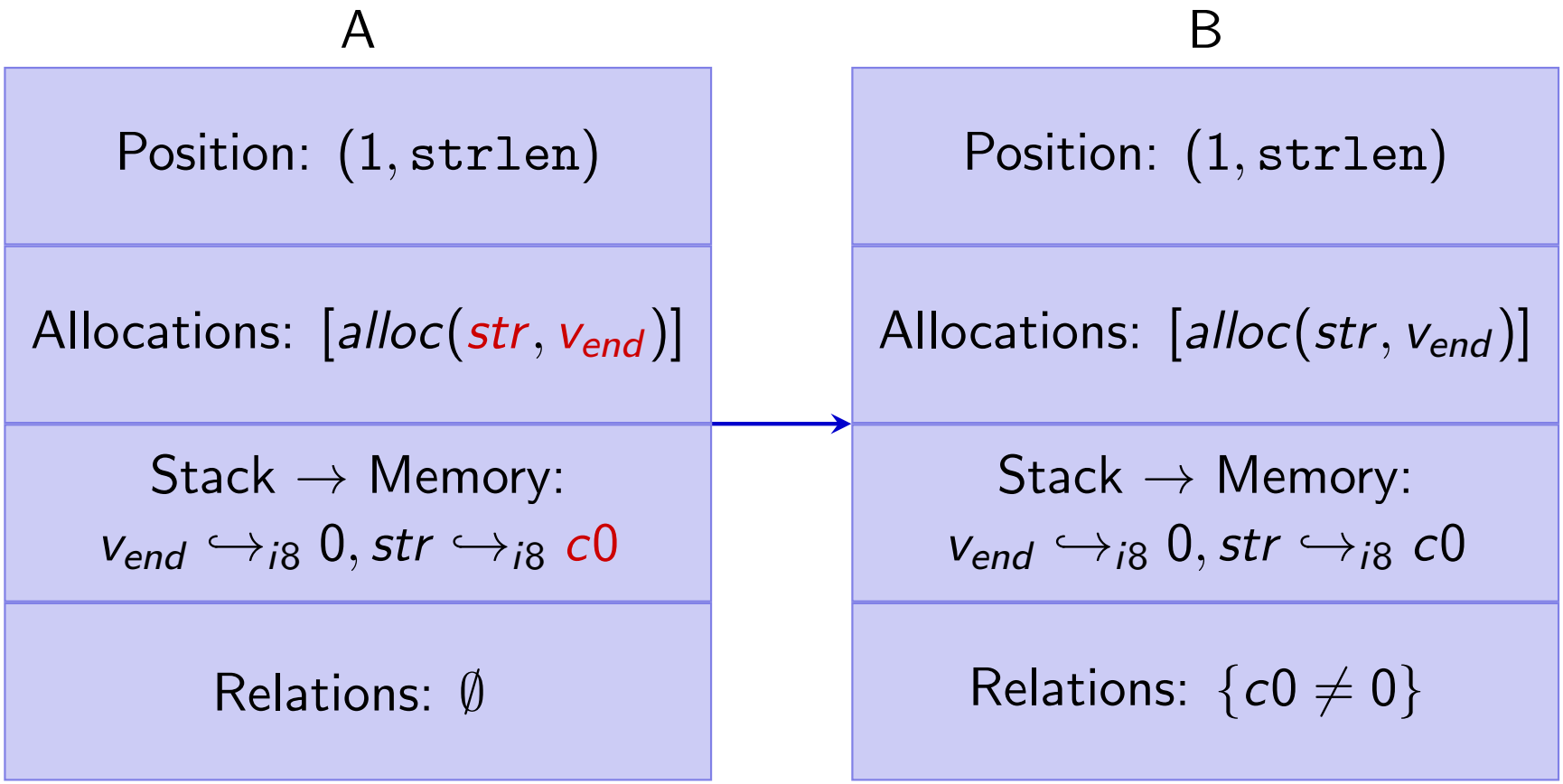
# Symbolic Execution Graph to Integer Transition System



# Symbolic Execution Graph to Integer Transition System

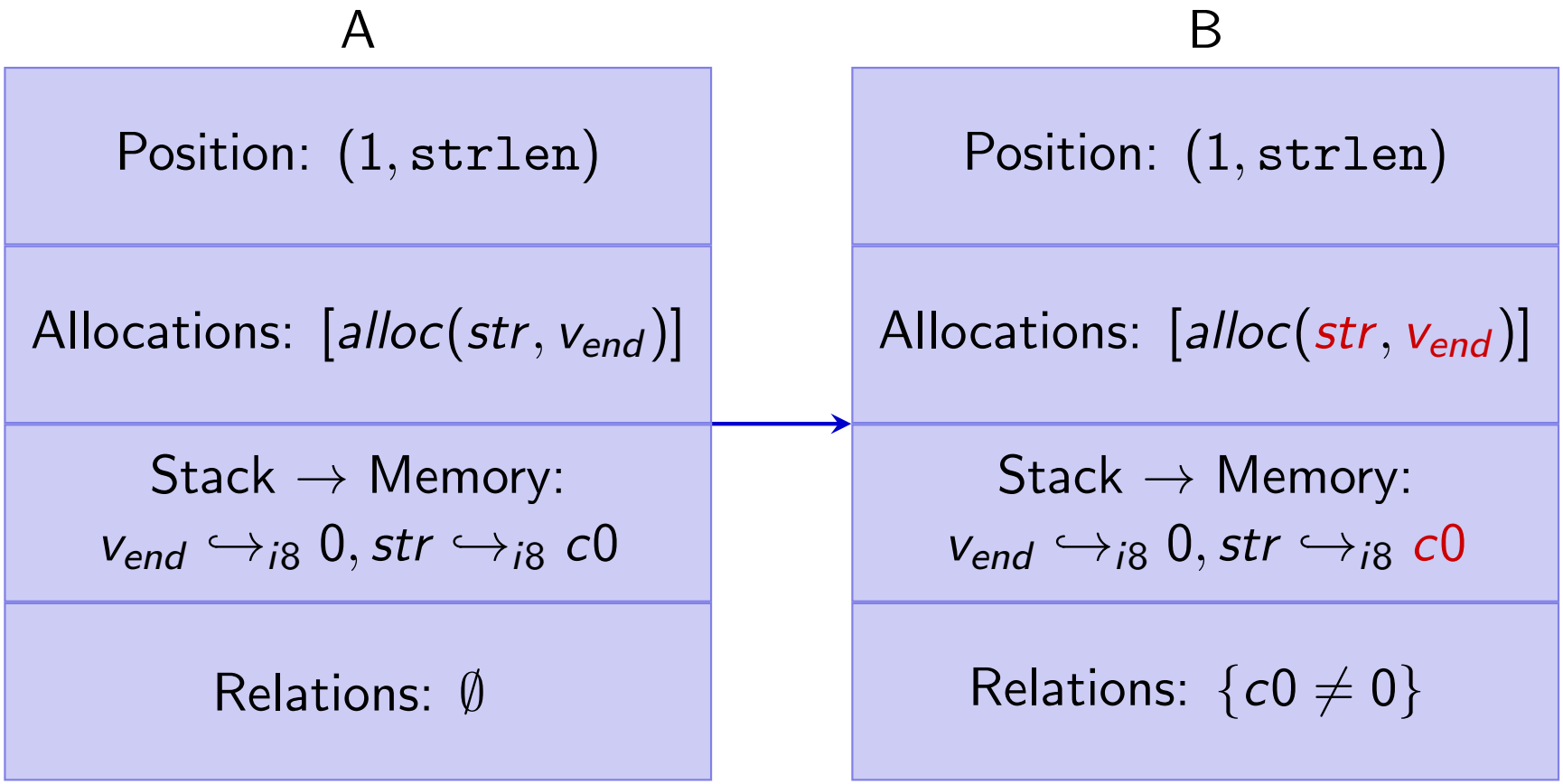


# Symbolic Execution Graph to Integer Transition System



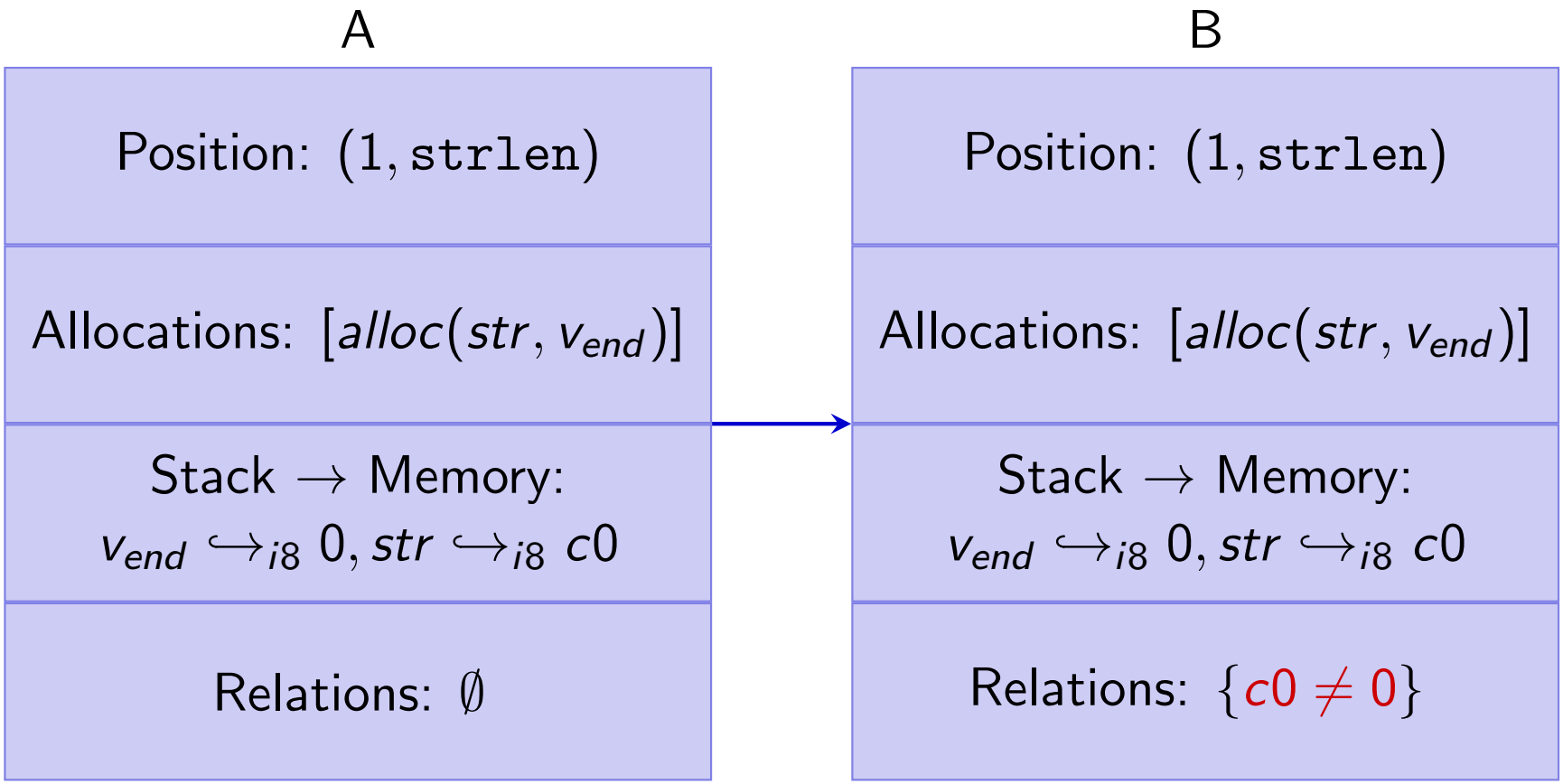

$f_A(str, v_{end}, c0)$

# Symbolic Execution Graph to Integer Transition System




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

# Symbolic Execution Graph to Integer Transition System



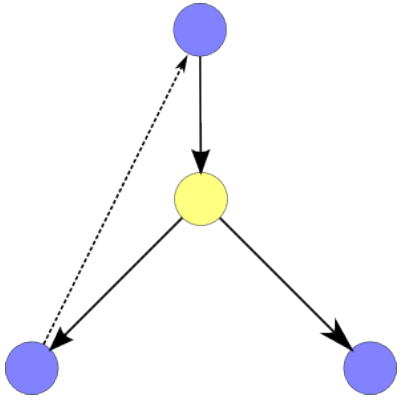

$$f_A(str, v_{end}, c0) \rightarrow f_B(str, v_{end}, c0) \mid c0 \neq 0$$

# Termination of Integer Transition System


✓

LLVM

✓



Symbolic Execution Graph

YES/NO/
MAYBE

?

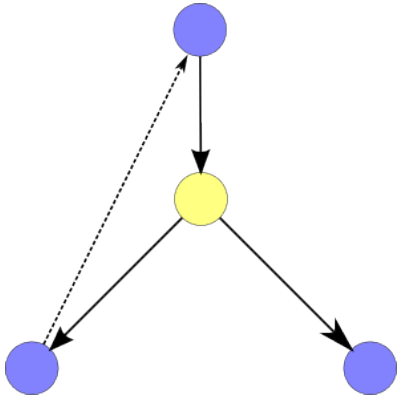
$f(x) \to g(x+1)$
$g(x) \to g(x-1)$

Integer Transition System

# Termination of Integer Transition System




LLVM



Symbolic Execution Graph

YES/NO/
MAYBE

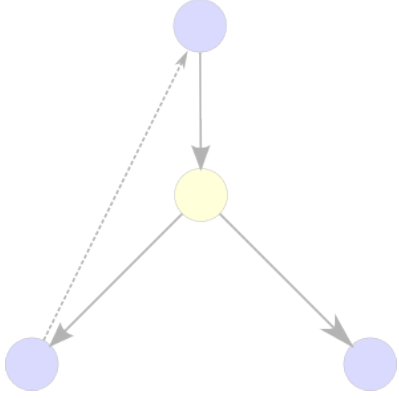
?

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

Integer Transition System

# Termination of Integer Transition System


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

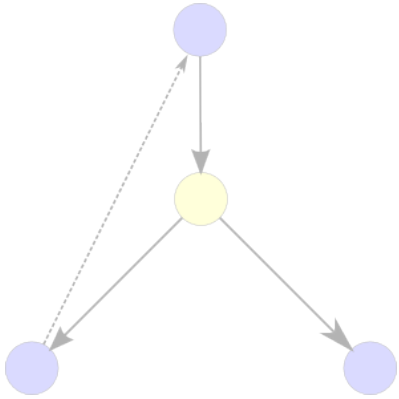
# Termination of Integer Transition System

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

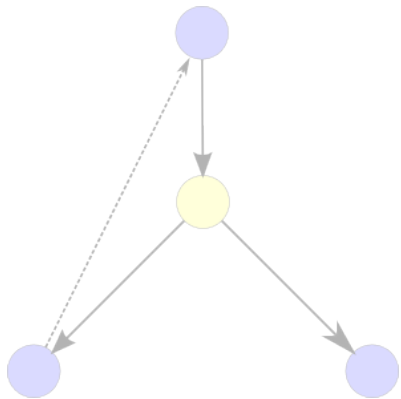
YES/NO/
MAYBE

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

Integer Transition System

# Termination of Integer Transition System


LLVM



Symbolic Execution Graph

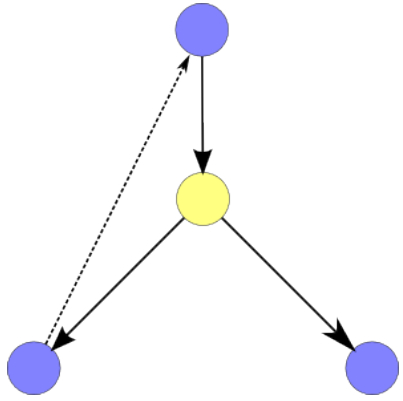
YES/NO/
MAYBE

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

Integer Transition System

# Overview


LLVM



Symbolic Execution Graph

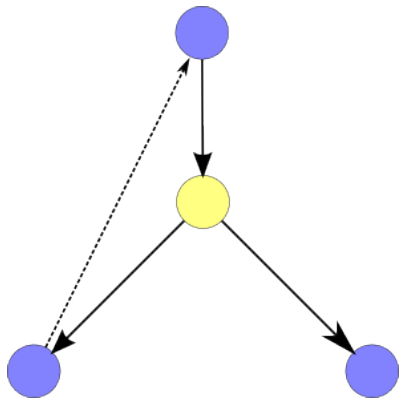
$f(x) \to g(x+1)$
$g(x) \to g(x-1)$

Integer Transition System

YES/NO/
MAYBE

# My Contributions


LLVM



Symbolic Execution Graph

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

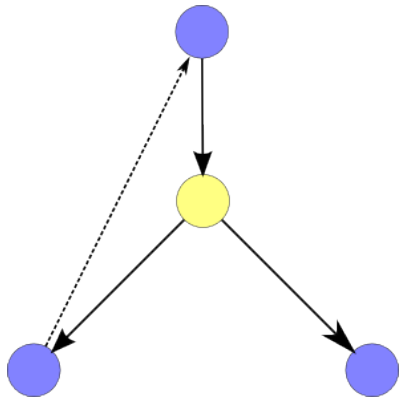
Integer Transition System

YES/NO/
MAYBE

# My Contributions

THE 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

Given: Abstract State $s$, Integer Relation $r$

Question: Does $s \models r$?

# My Contributions

- Reduction from state to set of arithmetic relations

# 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

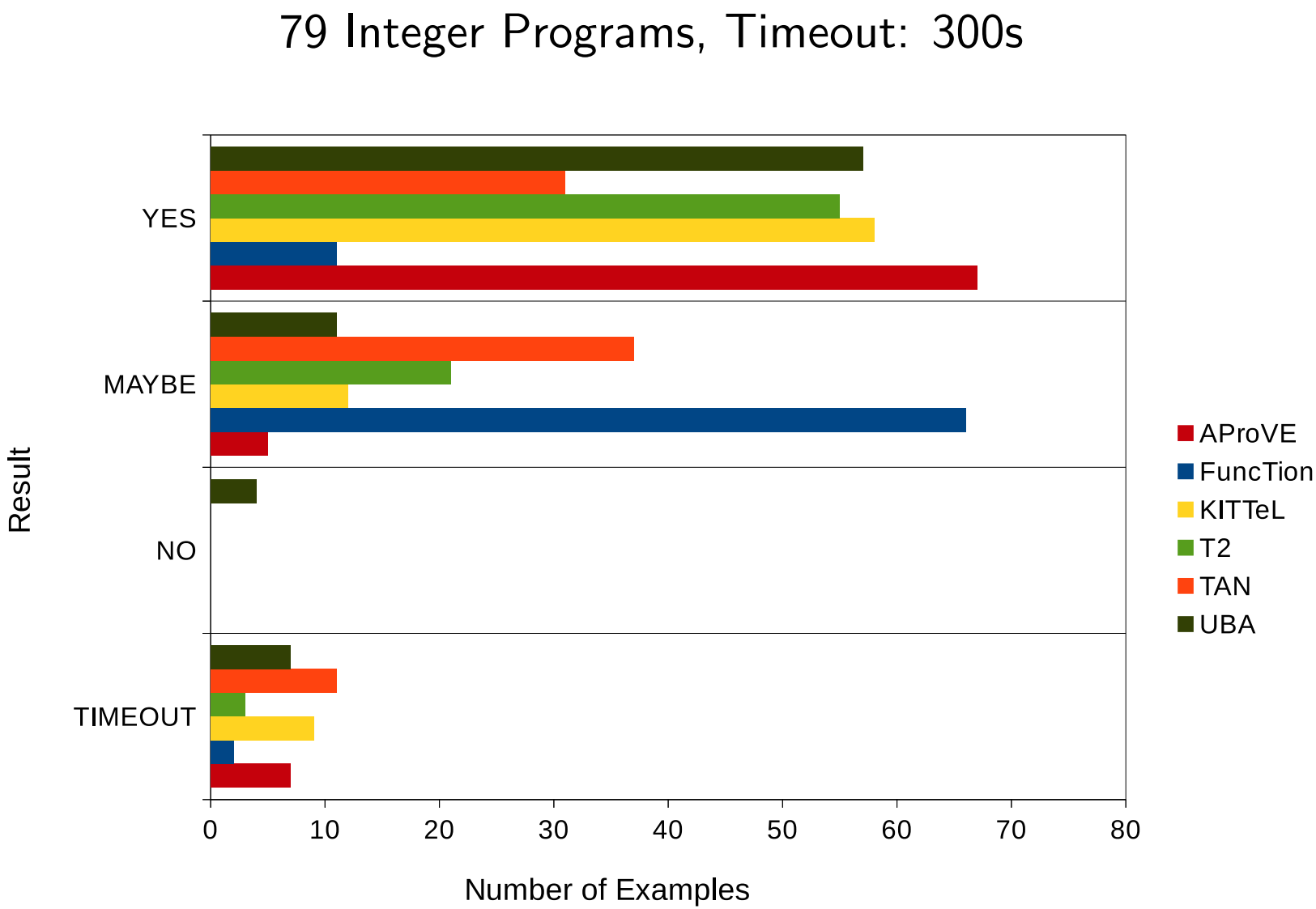
# My Contributions

- Use of Octagon Domain for inference of relations
  - (The Octagon Abstract Domain, Miné, 2006)

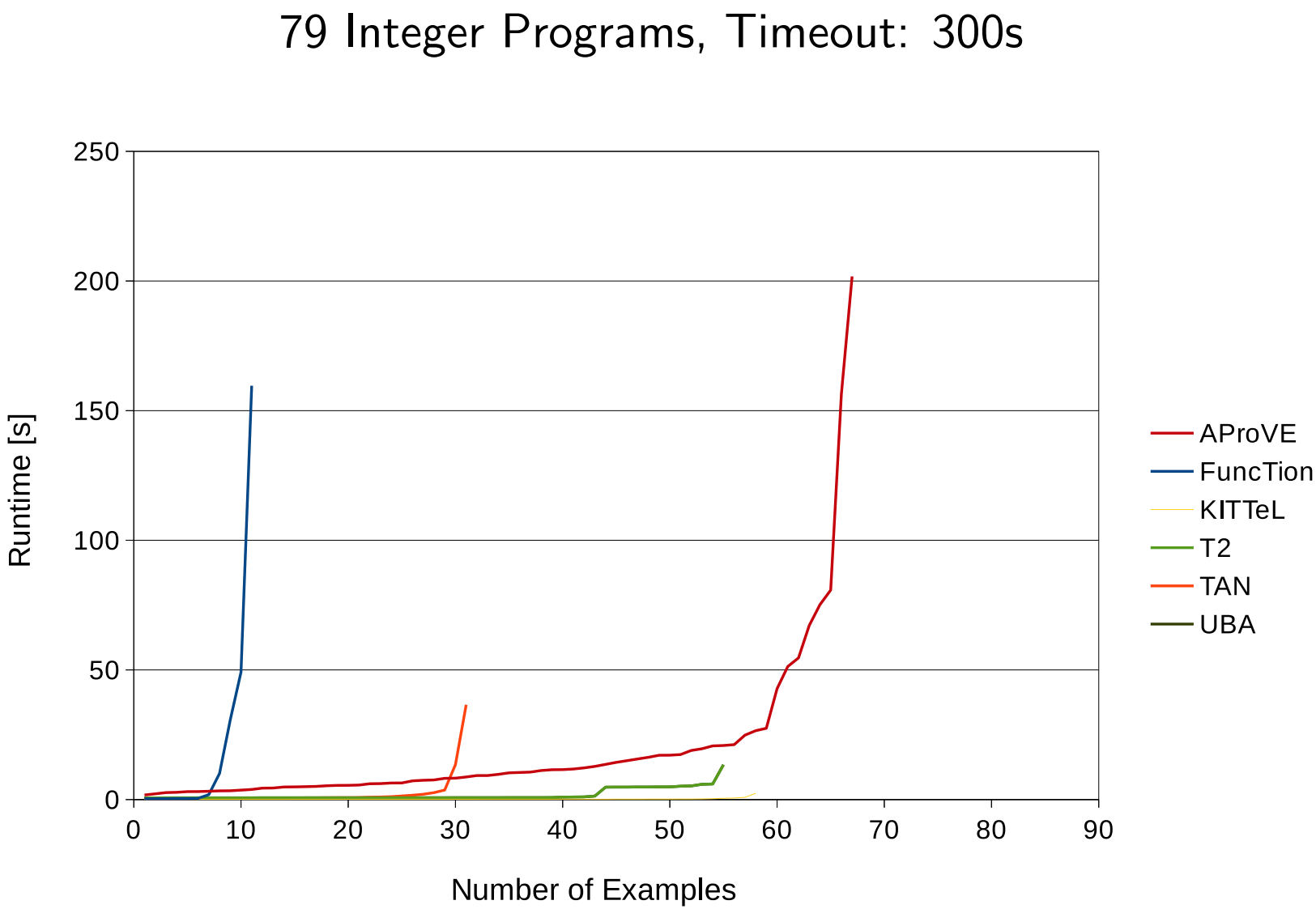
# My Contributions

- 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

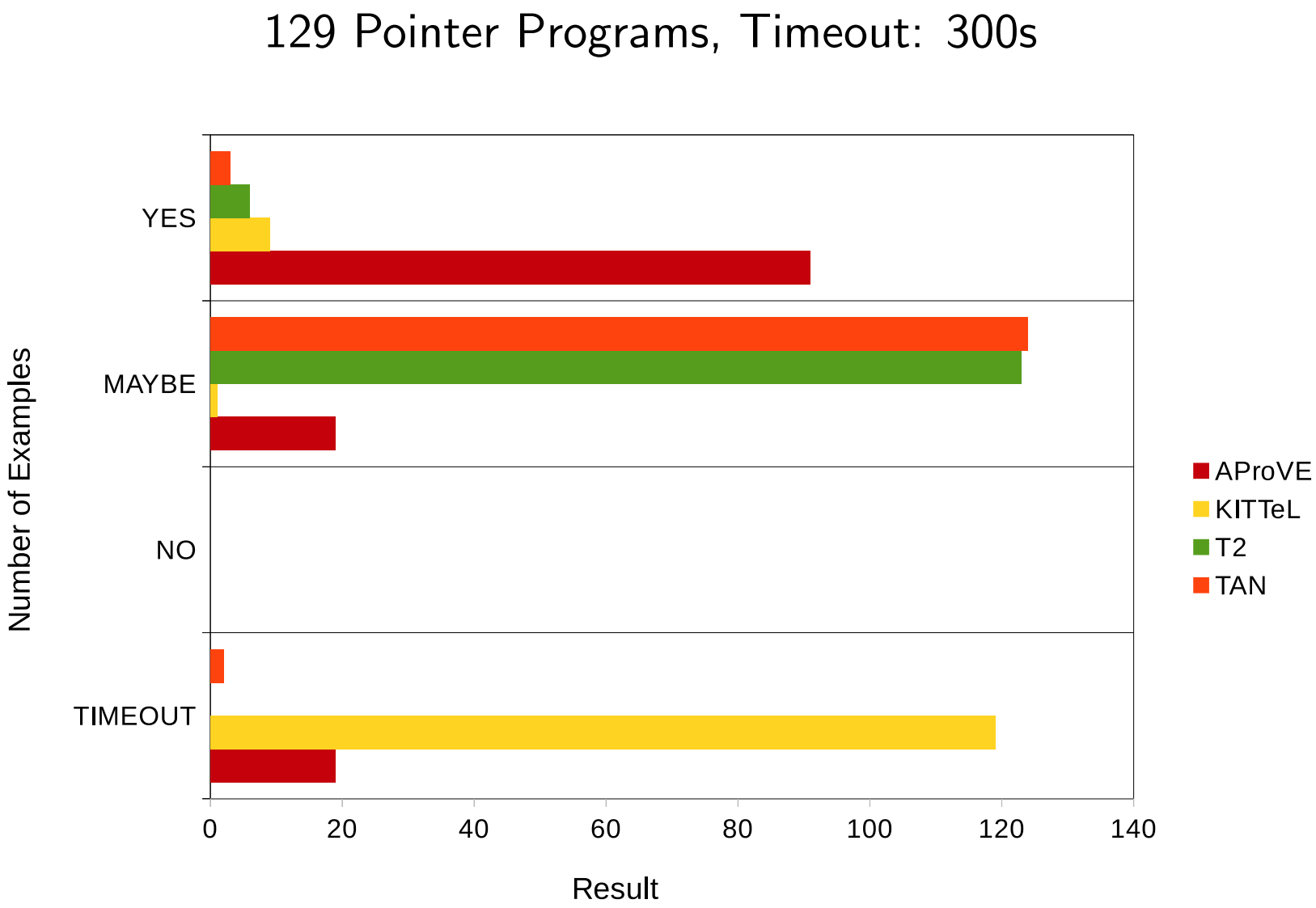
# Evaluation: Empirical Evaluation



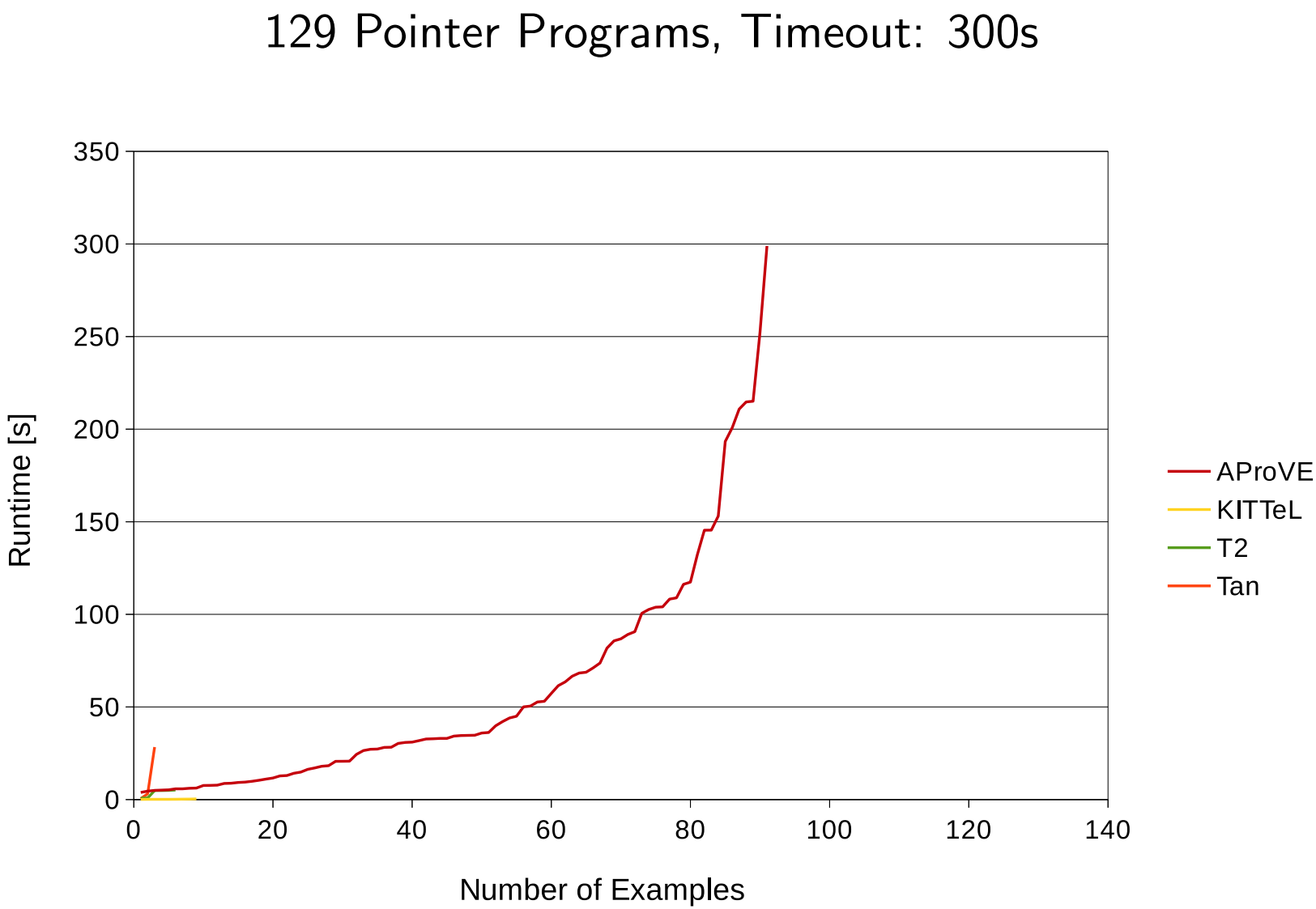
# Evaluation: Empirical Evaluation



# Evaluation: Empirical Evaluation



# Evaluation: Empirical Evaluation



Complete evaluation at

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

# Thank you for your attention

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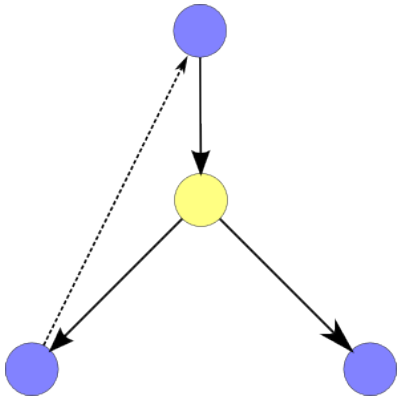
http://alexanderweinert.net/talks
alexander.weinert@rwth-aachen.de


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