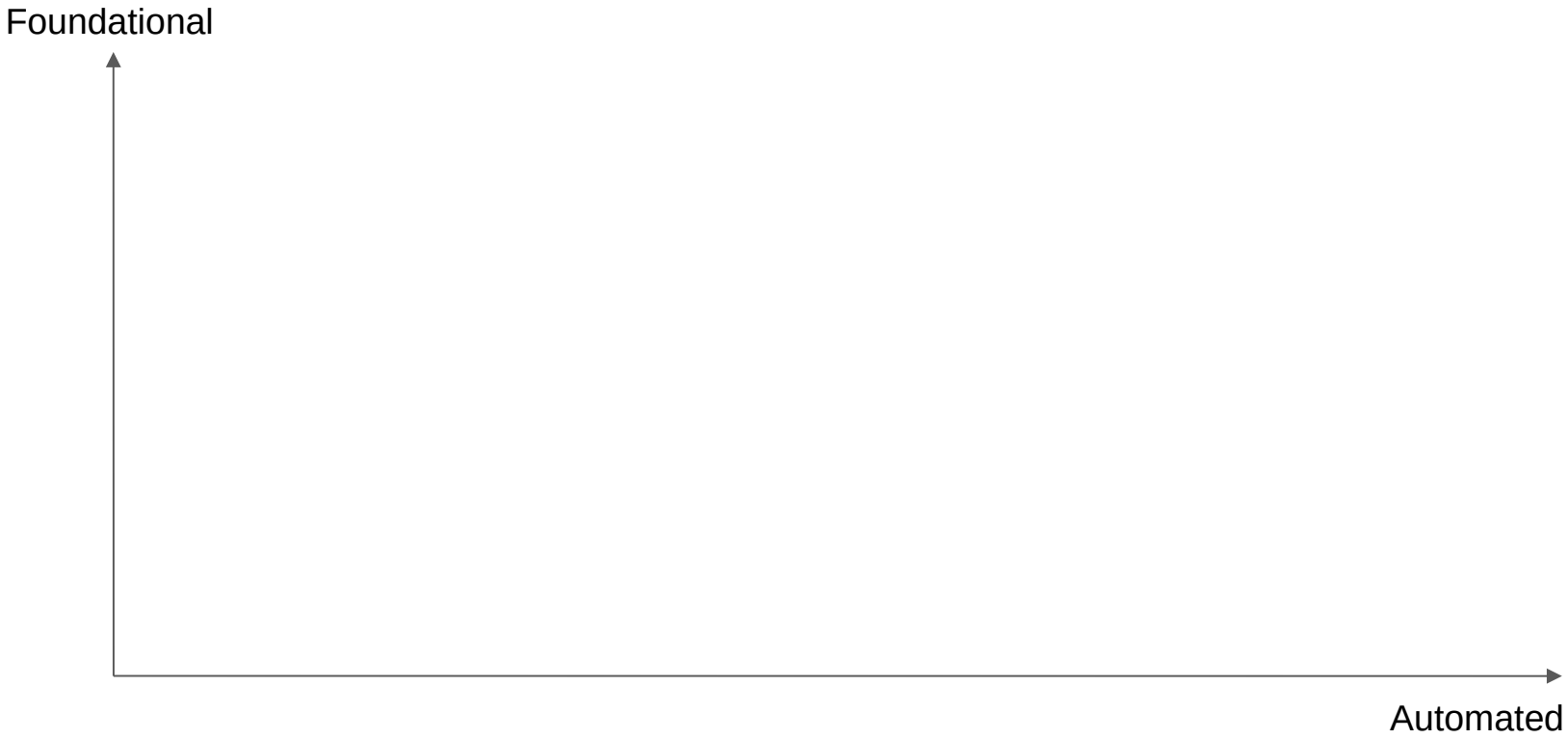
A Verification Framework Designed to Automate Separation Logic

Thibault Dardinier

ETH zürich

Program Verifiers Based on Separation Logic



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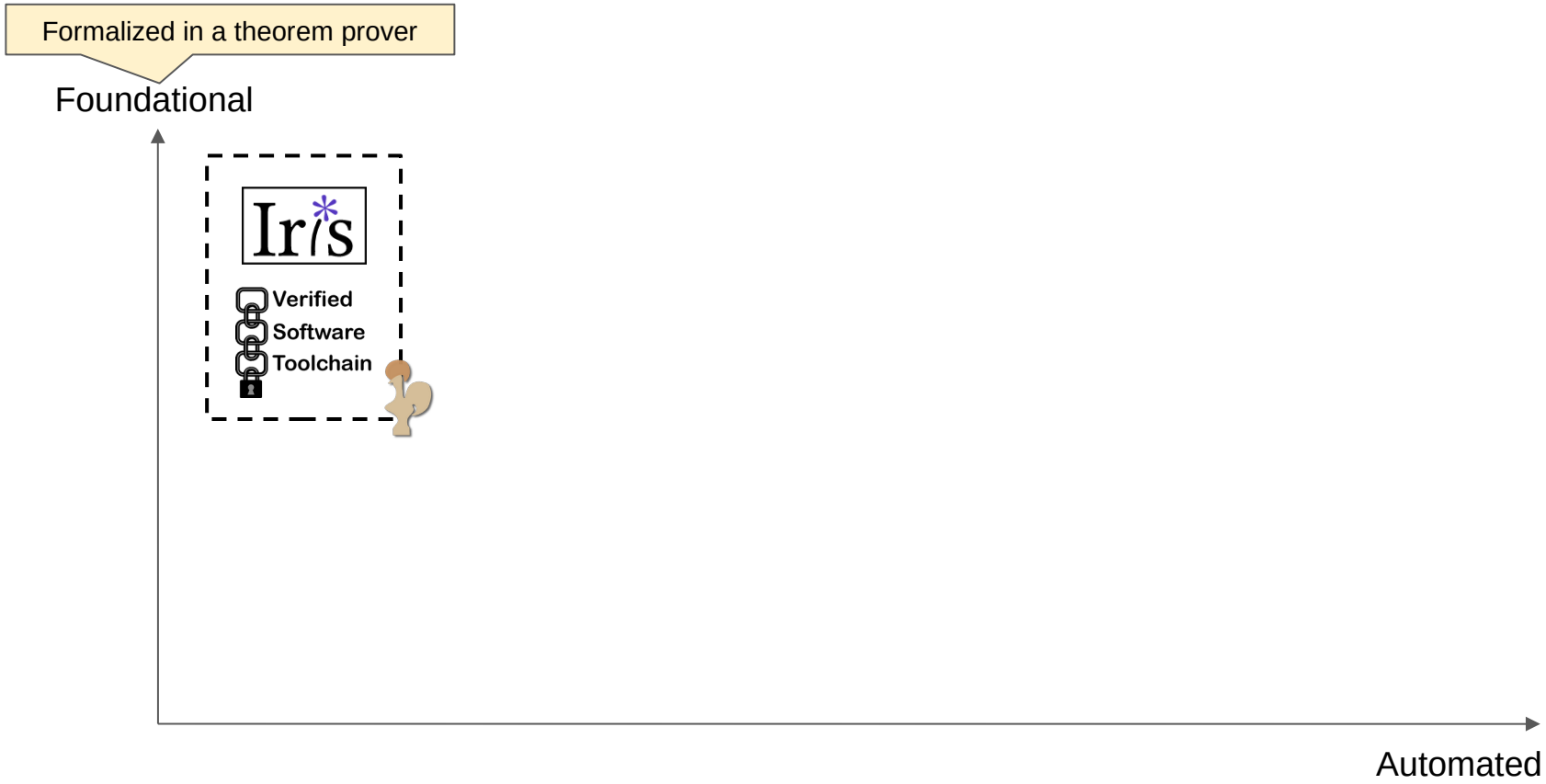

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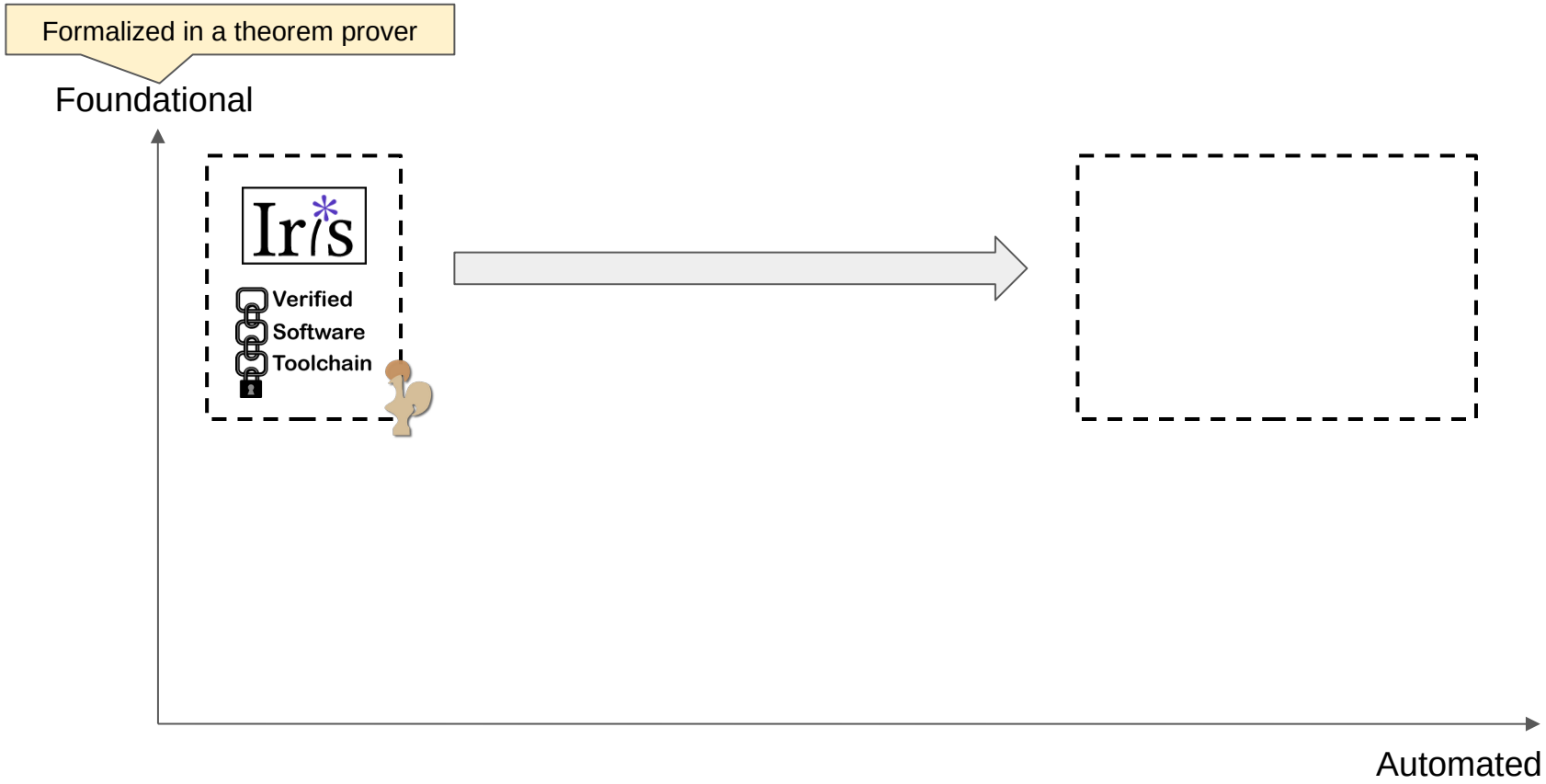

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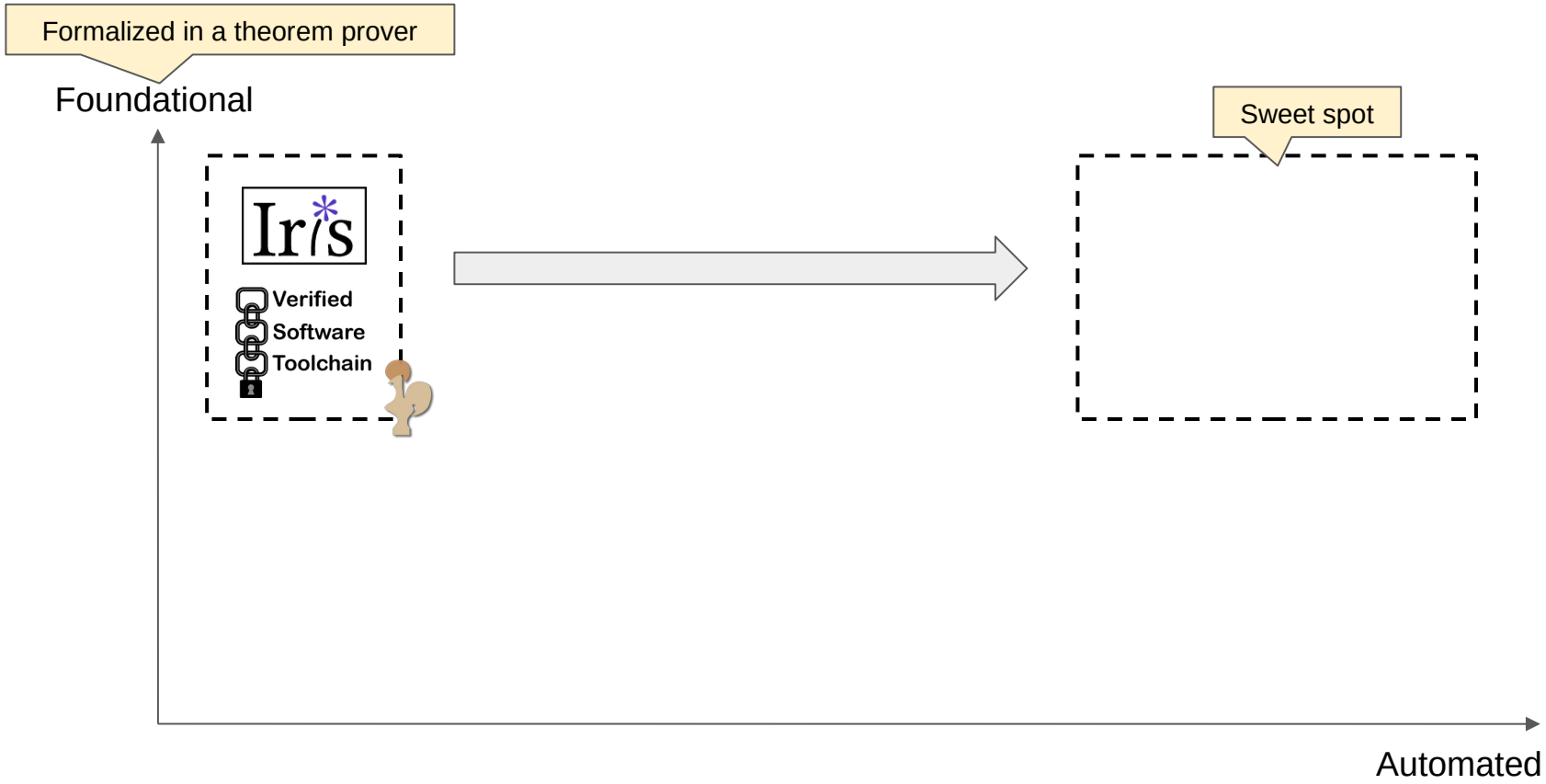

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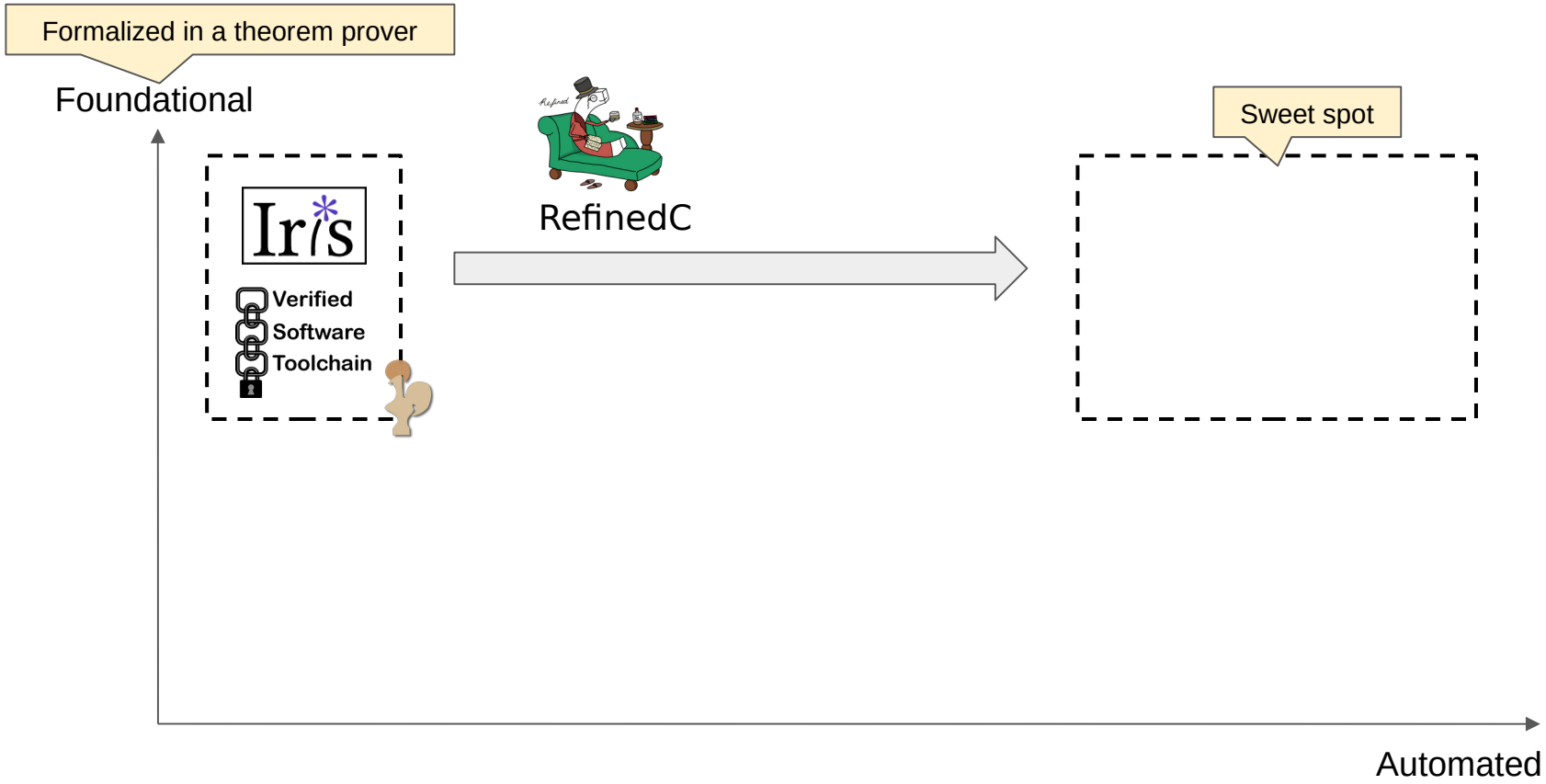

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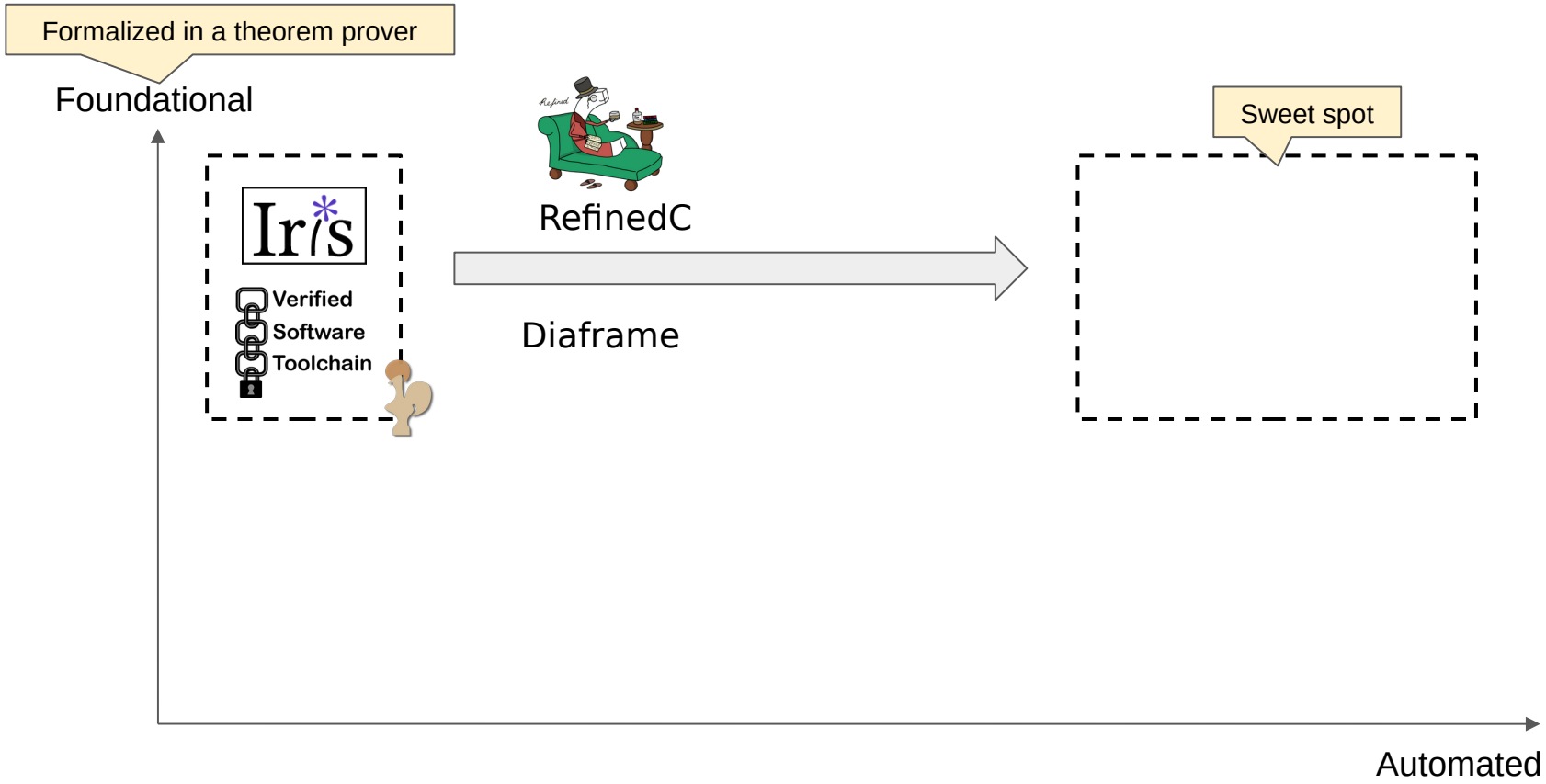

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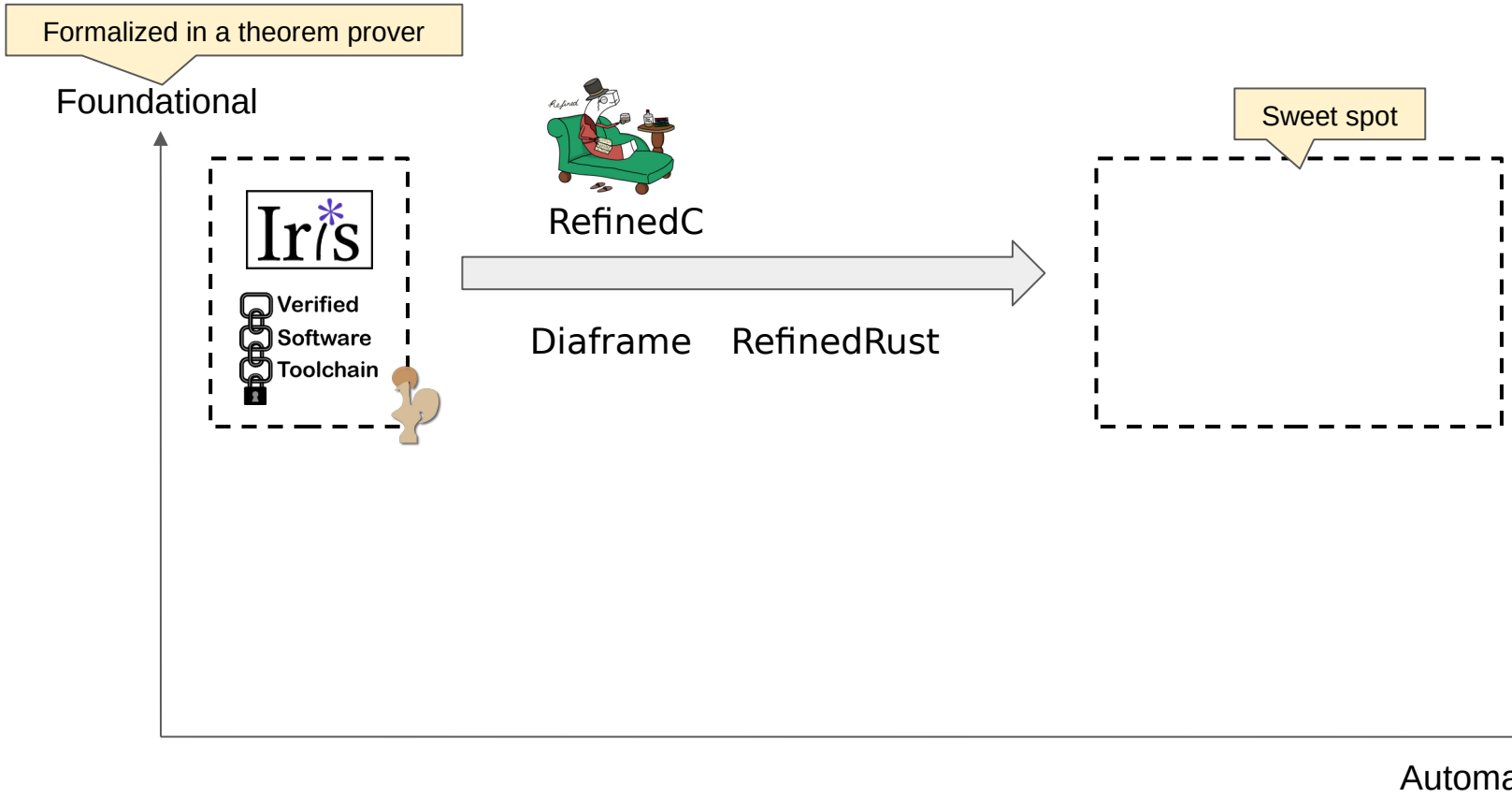

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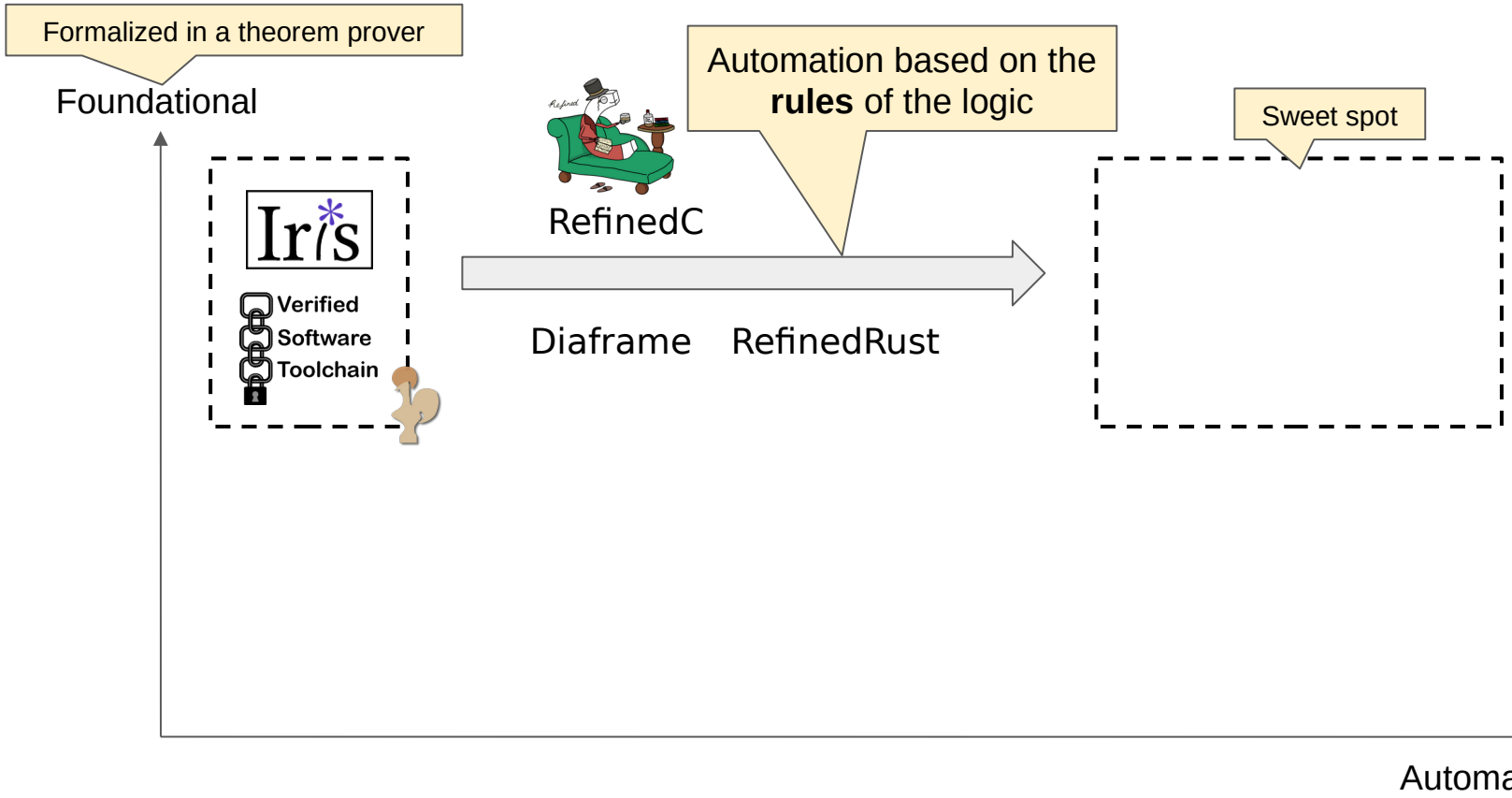

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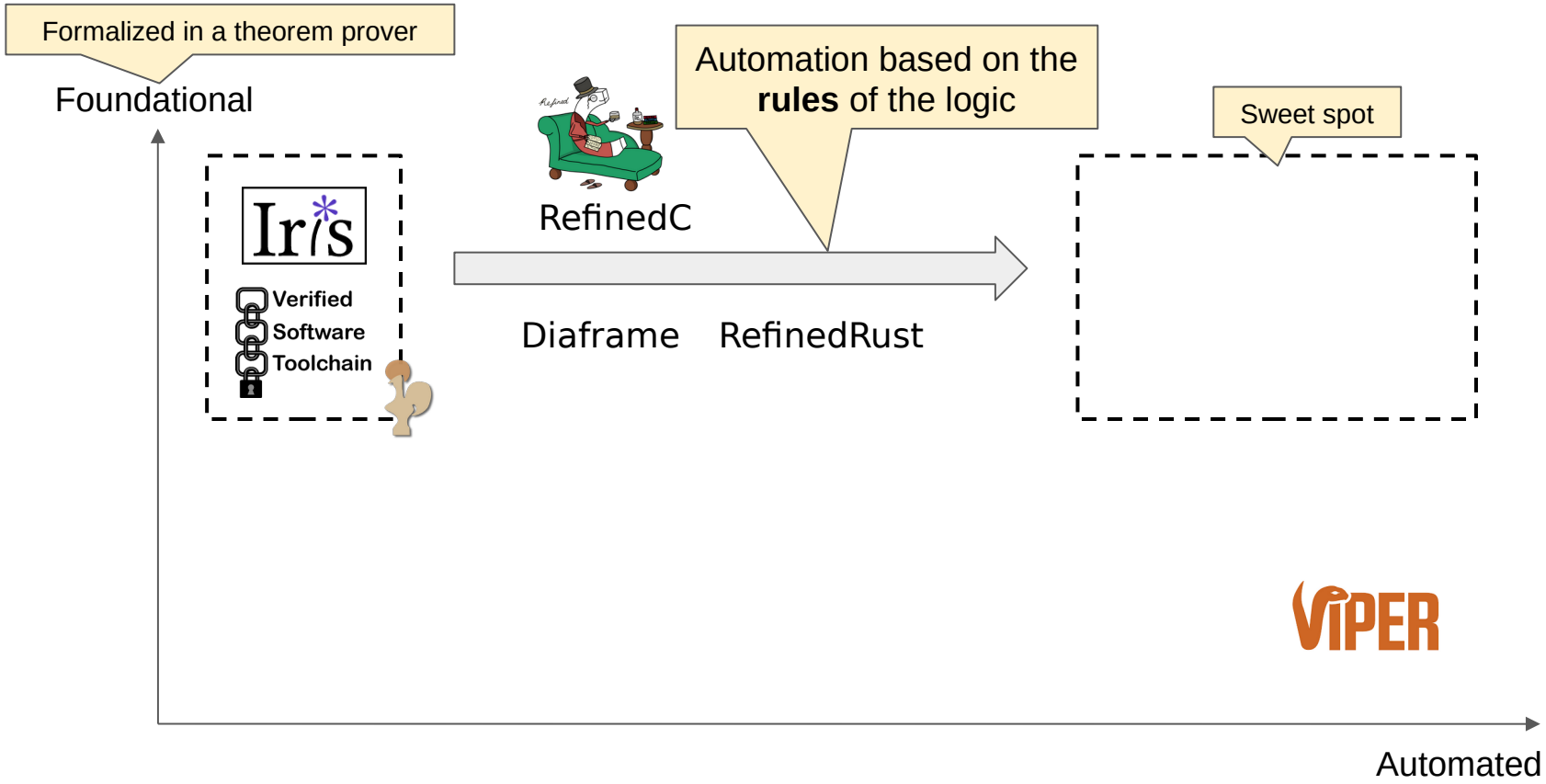

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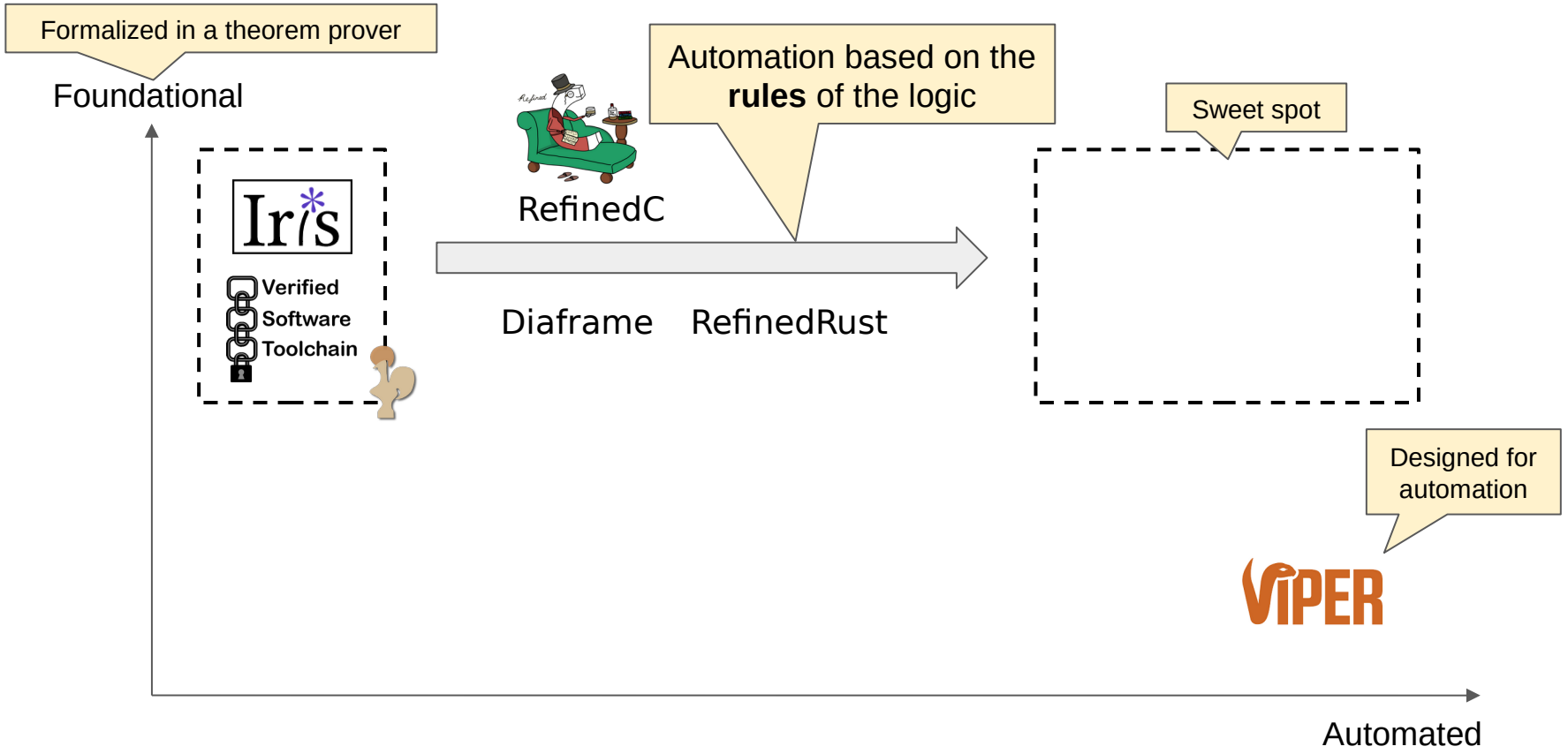

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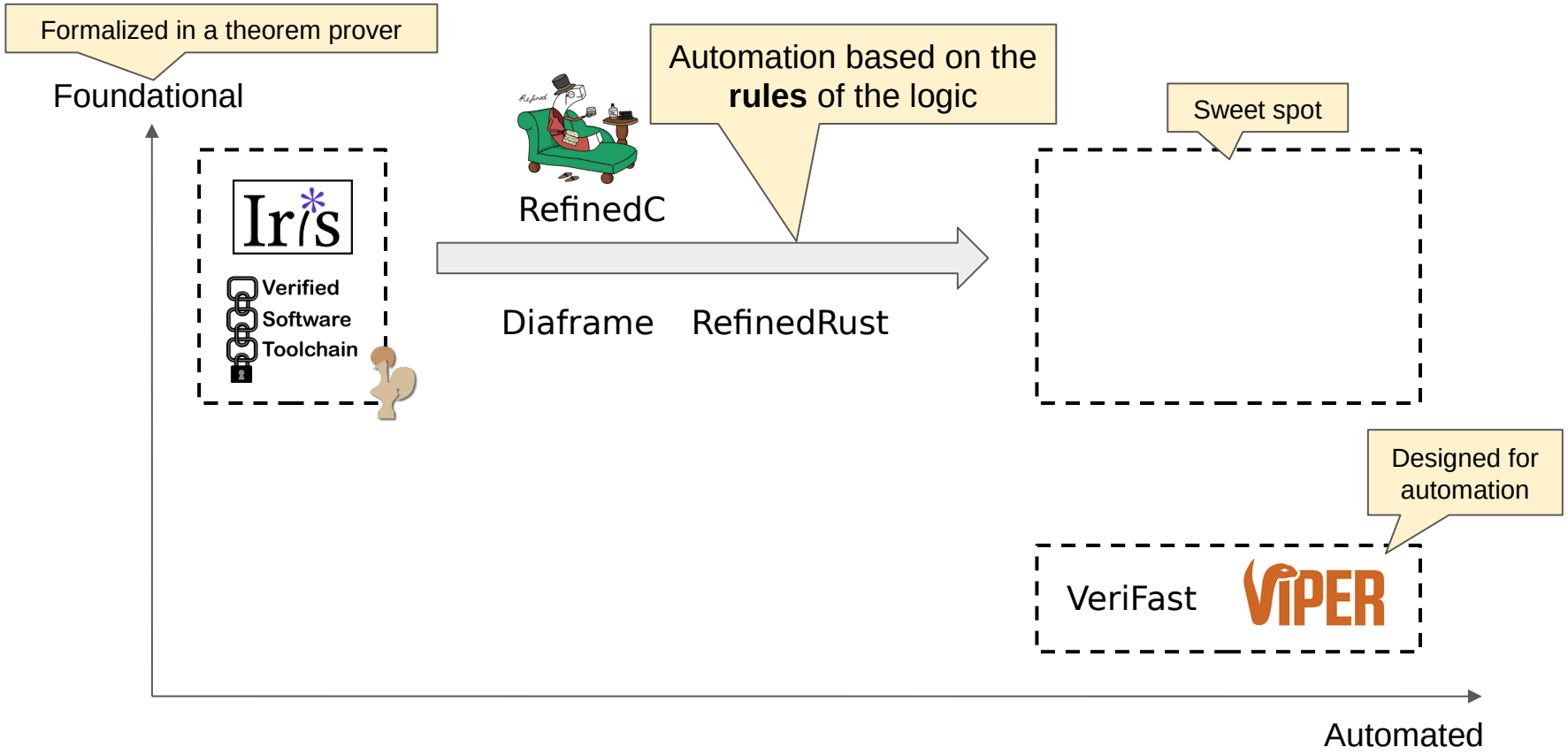

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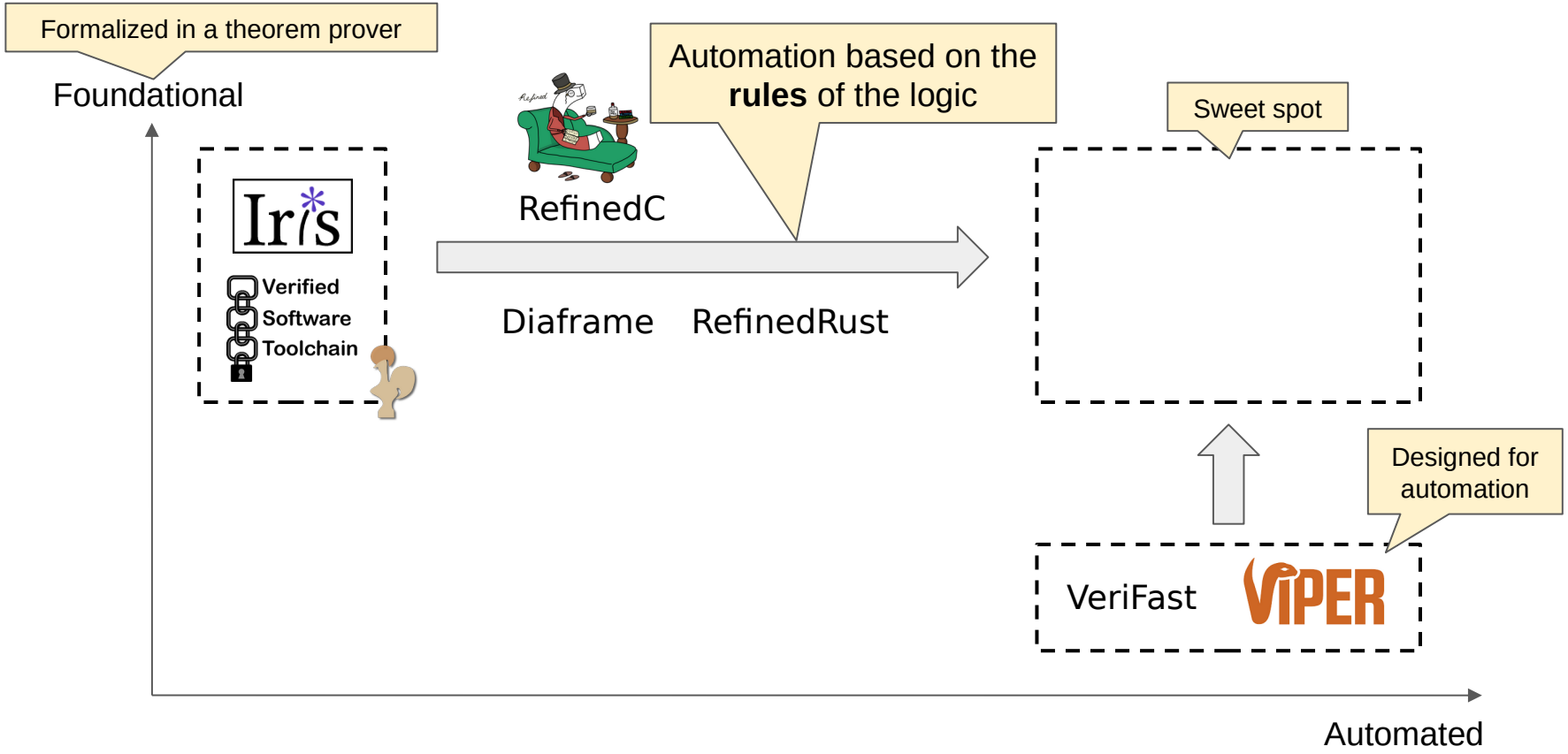

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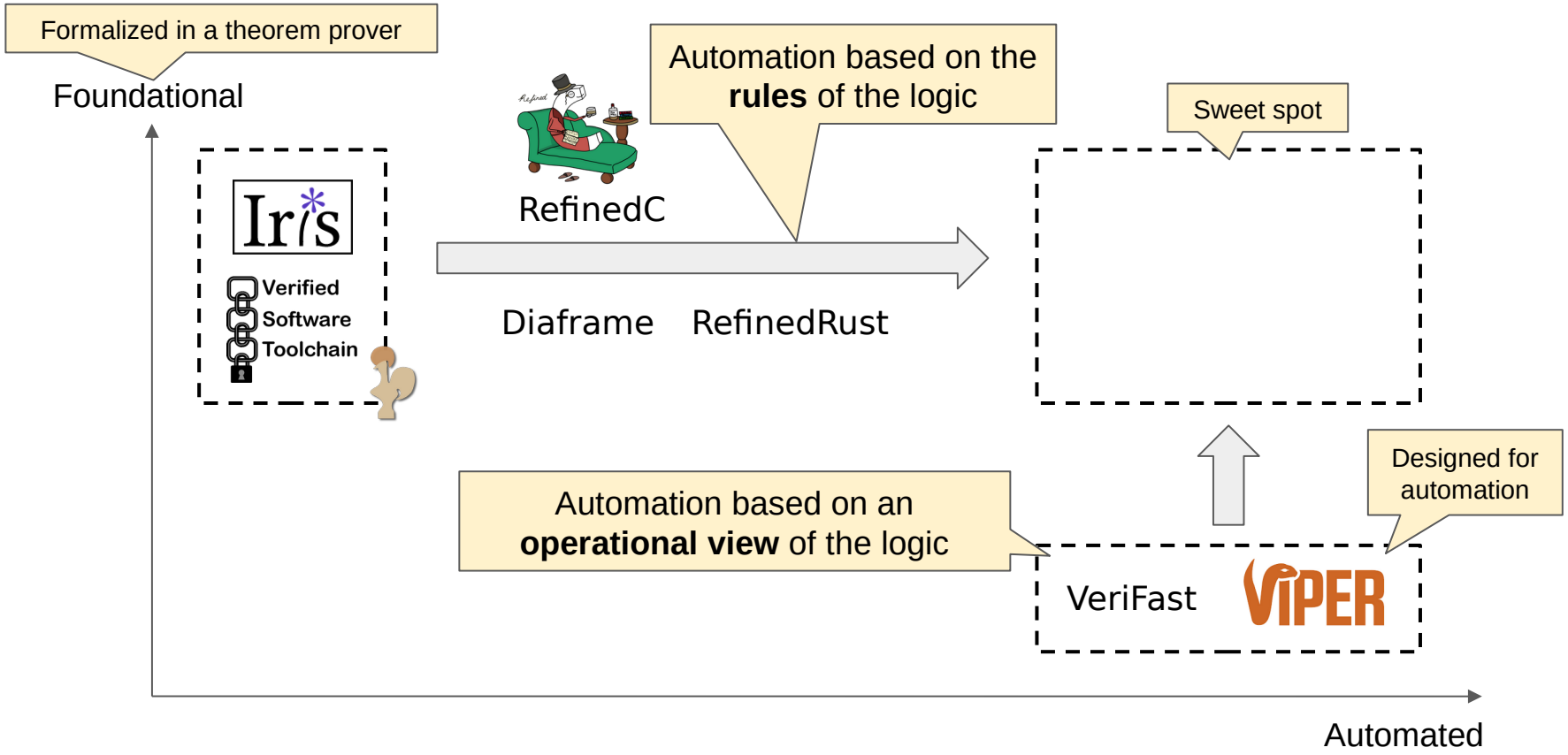

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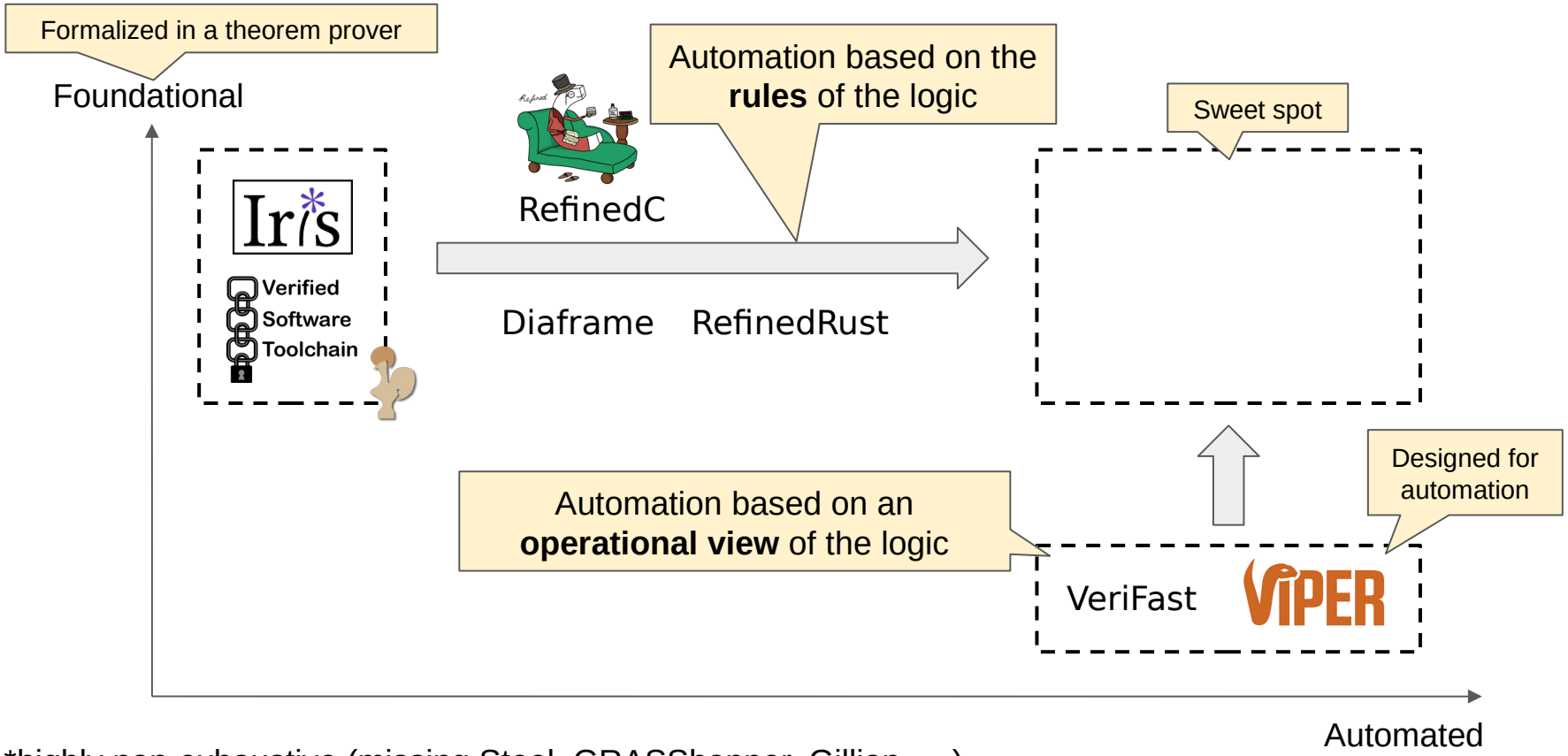

*highly non-exhaustive (missing Steel, GRASShopper, Gillian, …)

Outline of the Talk

Outline of the Talk

1. Overview of Viper

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2. Inhale and Exhale: An Operational View of Separation Logic

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Demo

```
1  field x: Int
2  field y: Int
3
4  method main(point: Ref)
5      requires acc(point.x) && acc(point.y)
6      // point.x |-> _ * point.y |-> _
7  {
8      point.x := 5
9      point.y := 7
10     add(point)
11     assert point.x == 5
12     assert point.y == 12
13 }
14
15 method add(p: Ref)
16     requires acc(p.x, 1/2) && acc(p.y)
17     ensures acc(p.x, 1/2) && acc(p.y)
18     // ensures p.y == old(p.x + p.y)
19 {
20     p.y := p.x + p.y
21 }
```

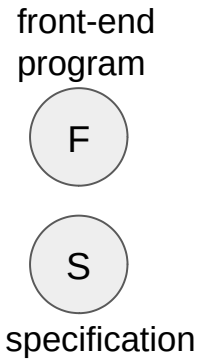
⊗ 1 ⚠ 0 silicon × Verifying demo.vpr failed after 0.5 seconds with 1 error Live Share "demo.vpr" 21L 357C written UTF-8 LF Viper

The Viper Verification Framework

The Viper Verification Framework

front-end
program

The Viper Verification Framework



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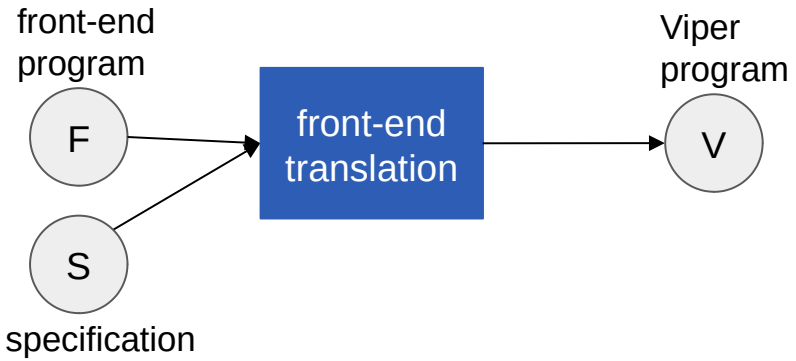

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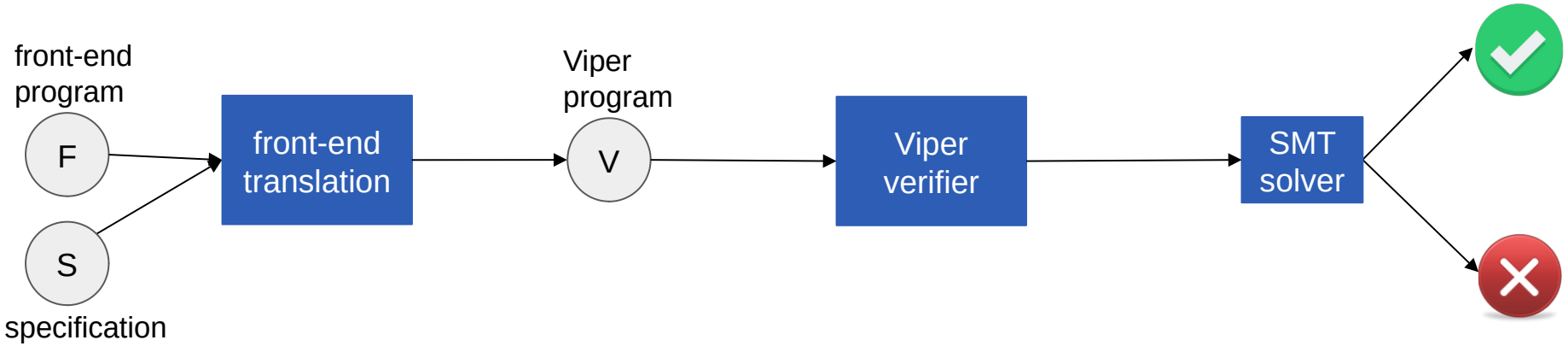

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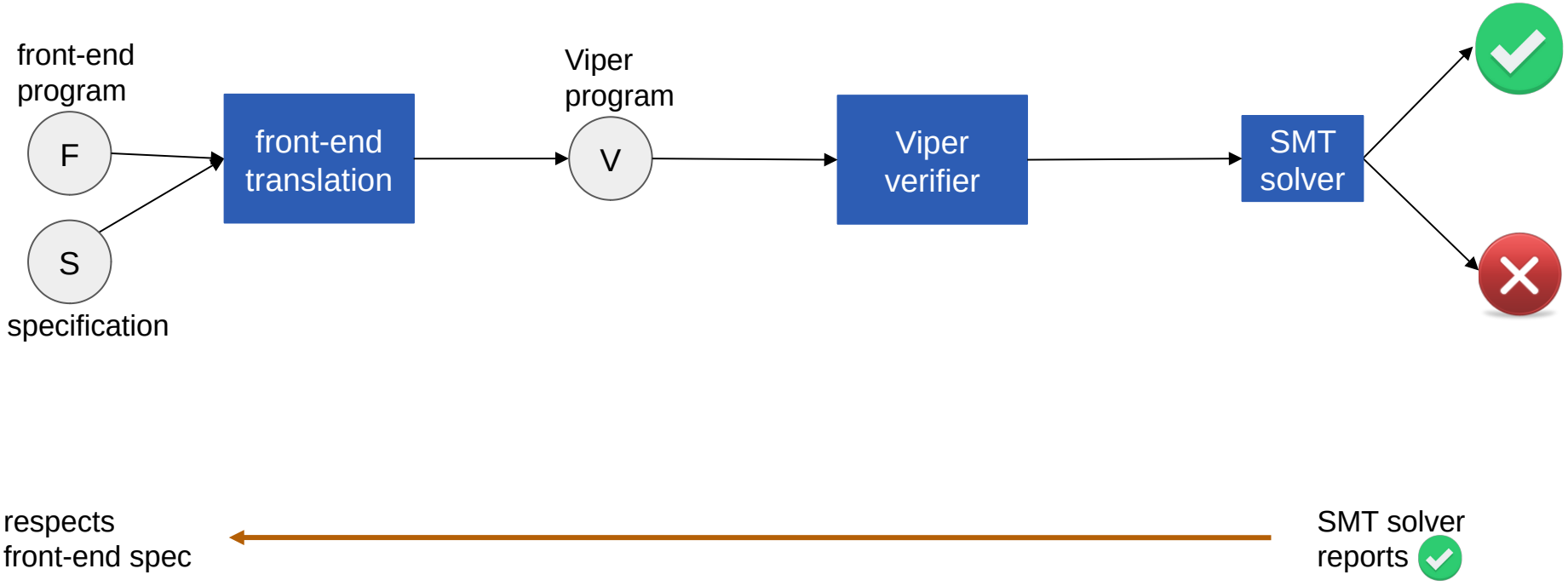

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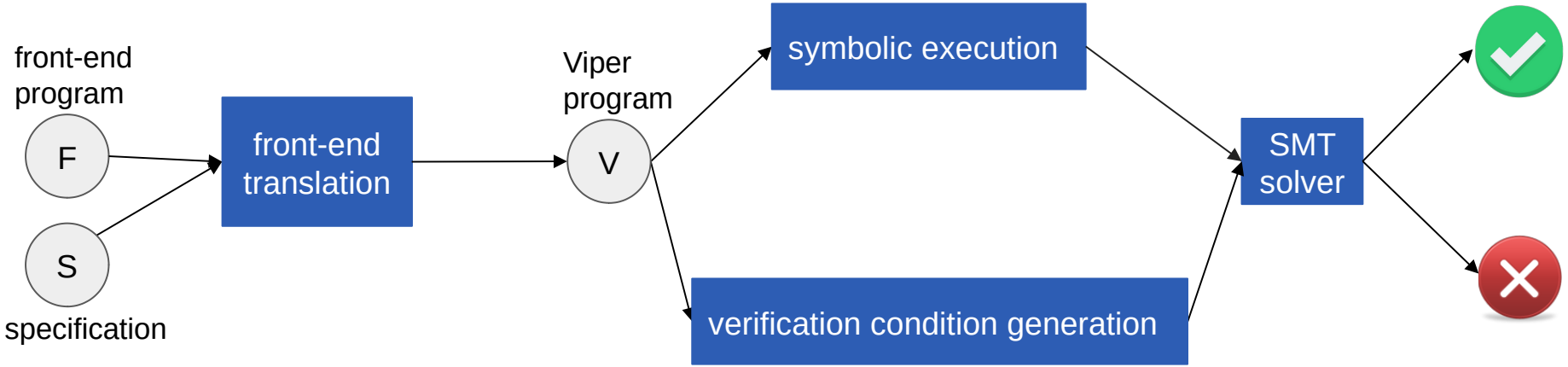
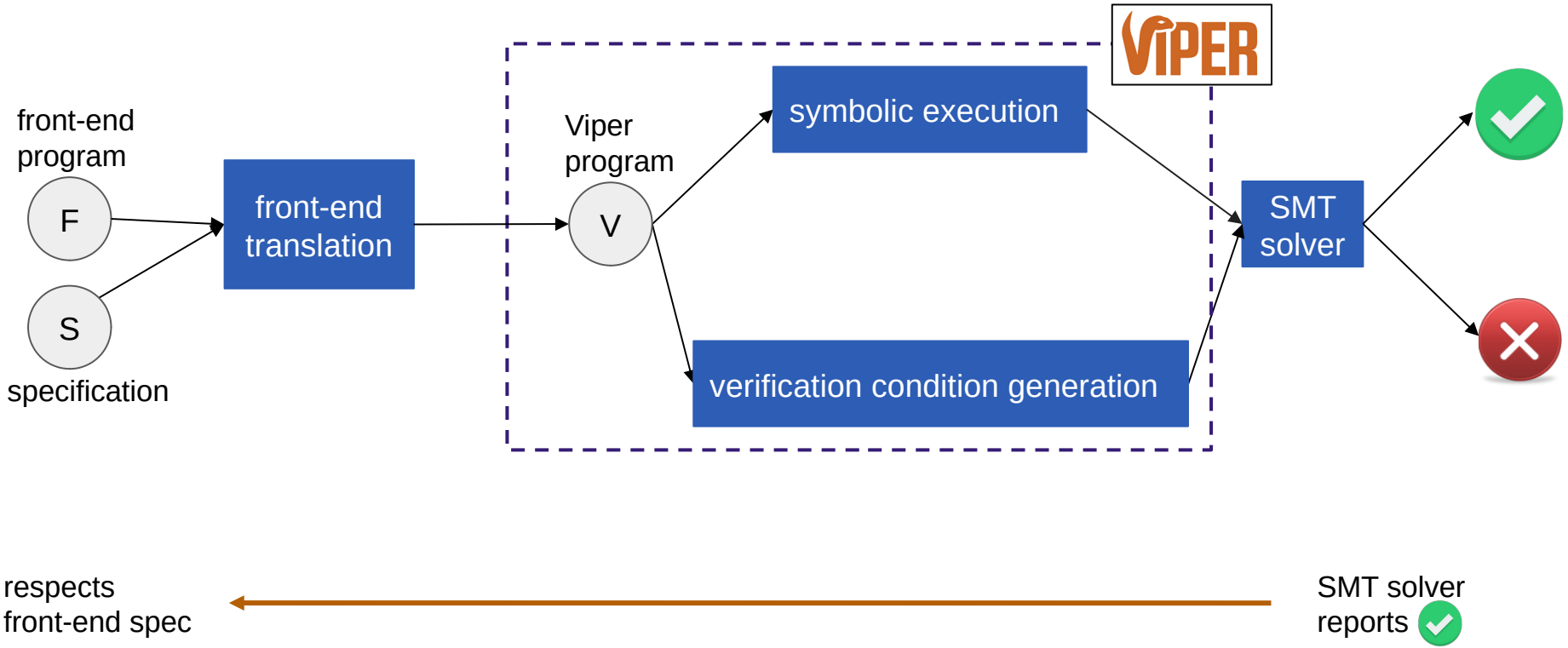


respects front-end spec

SMT solver reports

The Viper Verification Framework



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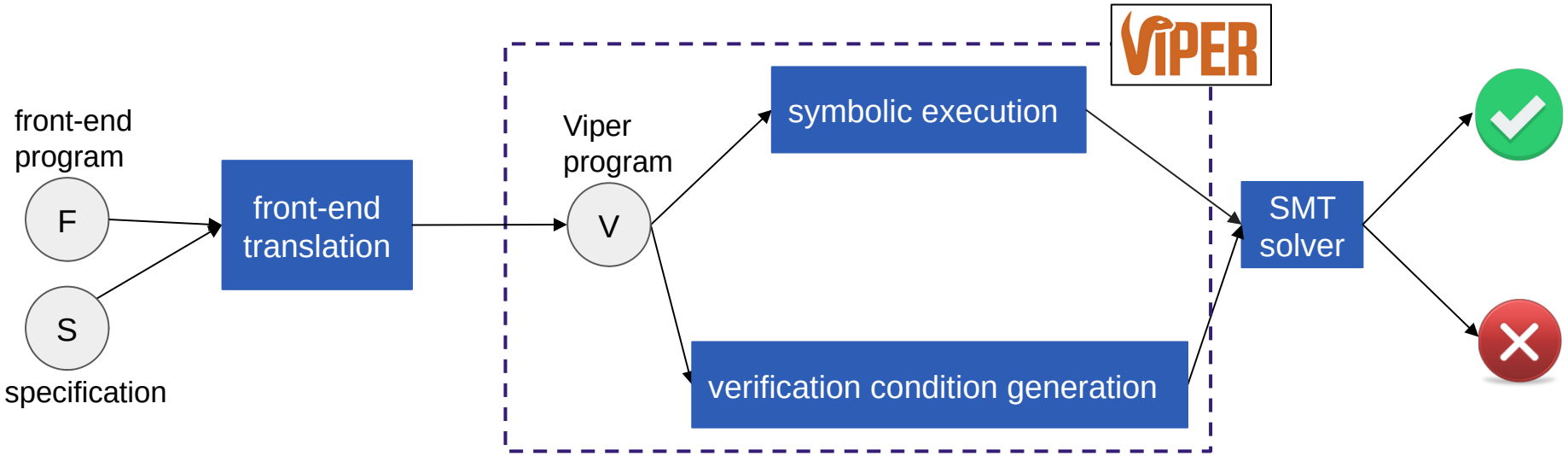

Program verifiers built on top of Viper

Rust (*Prusti*)	Go (*Gobra*)	Python (*Nagini*)
Java, C, OpenCL, OpenMP (*VerCors*)	Smart contracts	RSL, FSL, FSL++
Secure information flow	Gradual verification	…

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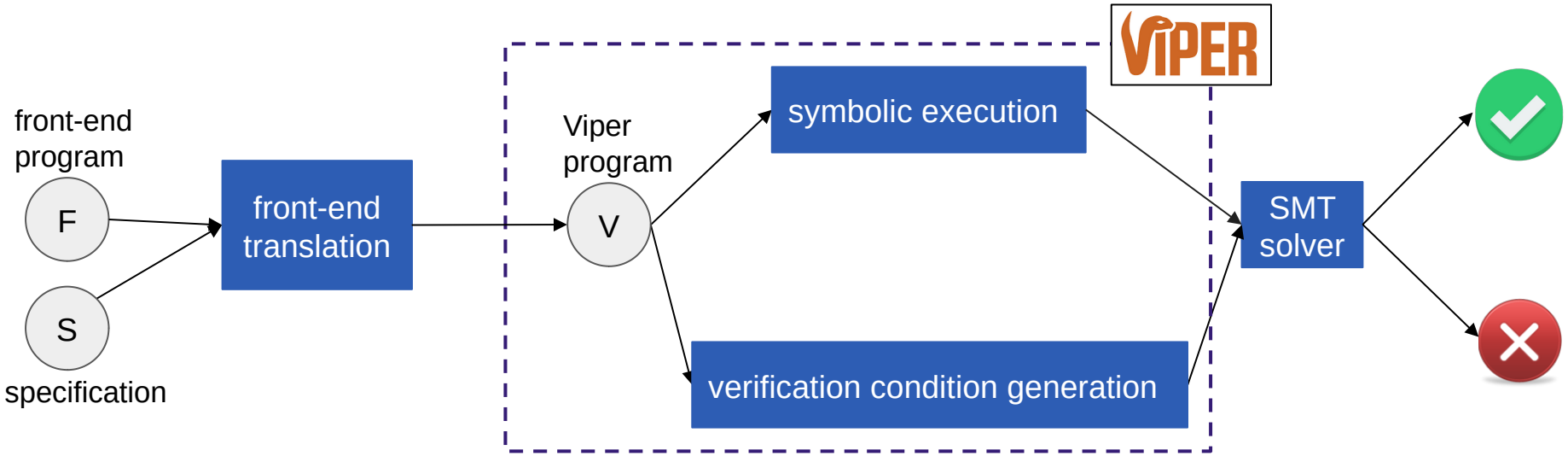

Verification of the SCION Internet architecture (existing router implementation ~5k LOC)

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Overview of the Viper Language

Program Code	Assertion Language
Verification Features	**Mathematical Background**

Overview of the Viper Language

Program Code	Assertion Language
• Sequential, imperative language • Standard control structures • Basic type system • Built-in heap	
Verification Features	**Mathematical Background**

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Program Code

- Sequential, imperative language
- Standard control structures
- Basic type system
- Built-in heap

Assertion Language

- Fractional permissions

Verification Features

Mathematical Background

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Assertion Language

- Fractional permissions
- Inductive predicates

Verification Features

Mathematical Background

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- Inductive predicates
- Iterated separating conjunction

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Verification Features

- Standard contract features
- Inhale and exhale
- …

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Verification Features

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Mathematical Background

- Predefined and user-defined datatypes
- Uninterpreted functions
- Axioms

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Verification Primitives: Inhale and Exhale

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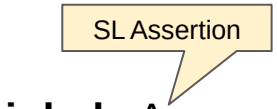
inhale A

exhale A

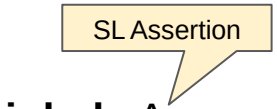
Verification Primitives: Inhale and Exhale



inhale A

exhale A

Verification Primitives: Inhale and Exhale

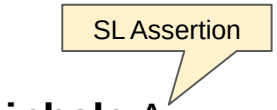


inhale A

exhale A

Adds resources specified by A to the current context

Verification Primitives: Inhale and Exhale



inhale A

Adds resources specified by A to the current context

exhale A

Removes resources specified by A from the current context

Verification Primitives: Inhale and Exhale

	inhale A	**exhale** A
Intuitive meaning	Adds resources specified by A to the current context	Removes resources specified by A from the current context
Logically		
Operationally		

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Operationally		

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Acting on a SL state
(e.g., *Loc* ⇀ *(0, 1]* × *Val*)

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"A Basis for Verifying Multi-Threaded Programs" (Leino and Müller, ESOP 2009)

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Sometimes called **produce**

Sometimes called **consume**

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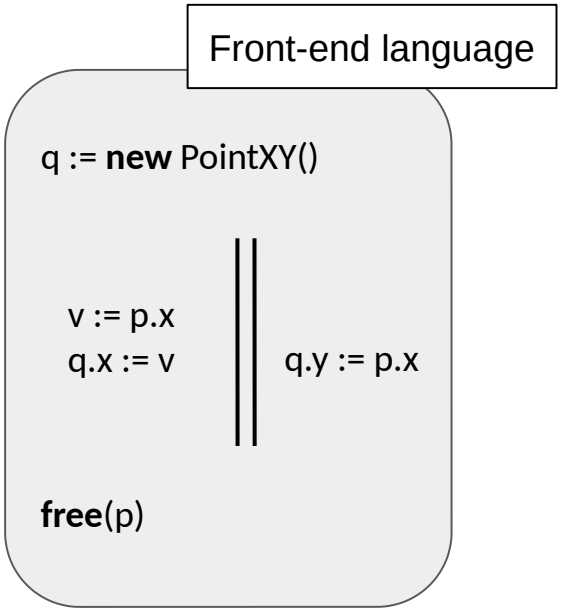
Example: Verifying a Parallel Composition (1/2)



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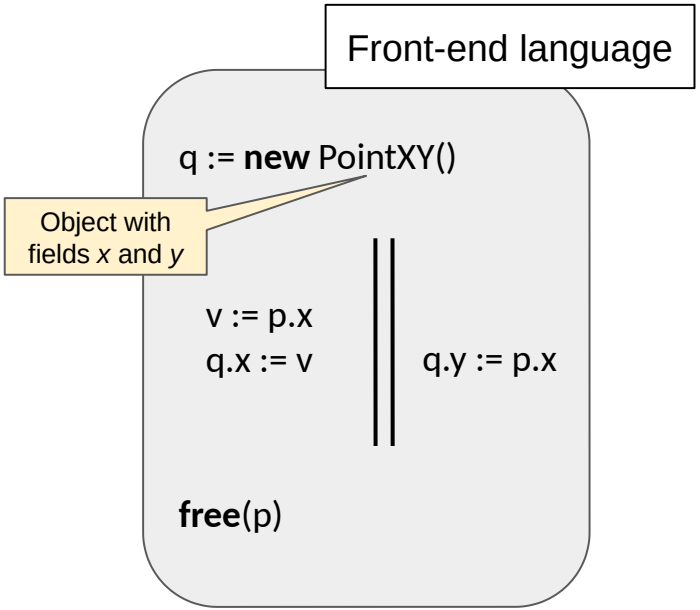

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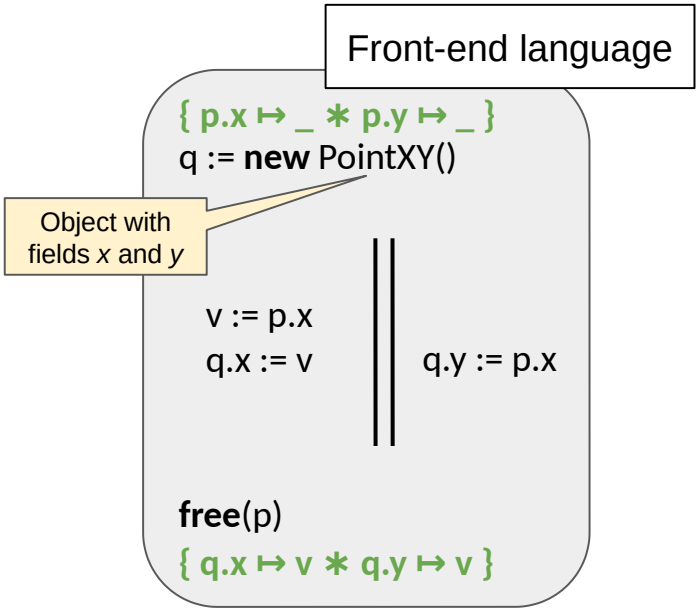

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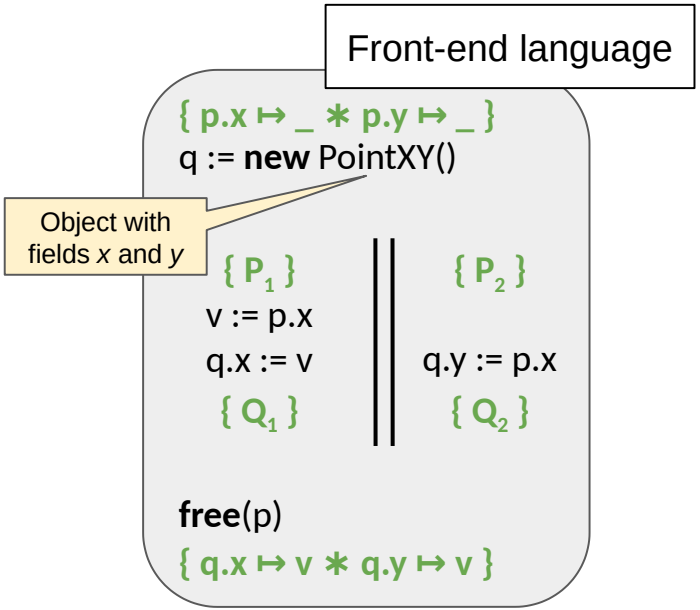

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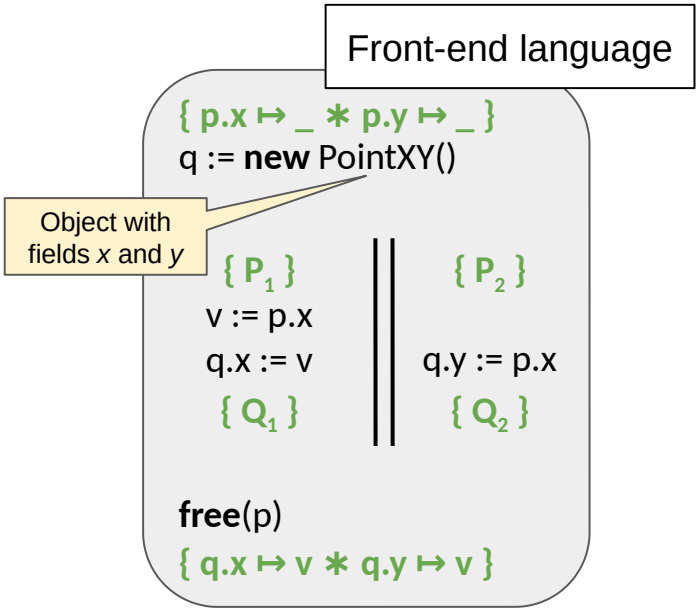

$P_1 \triangleq (q.x \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$ $P_2 \triangleq (q.y \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$

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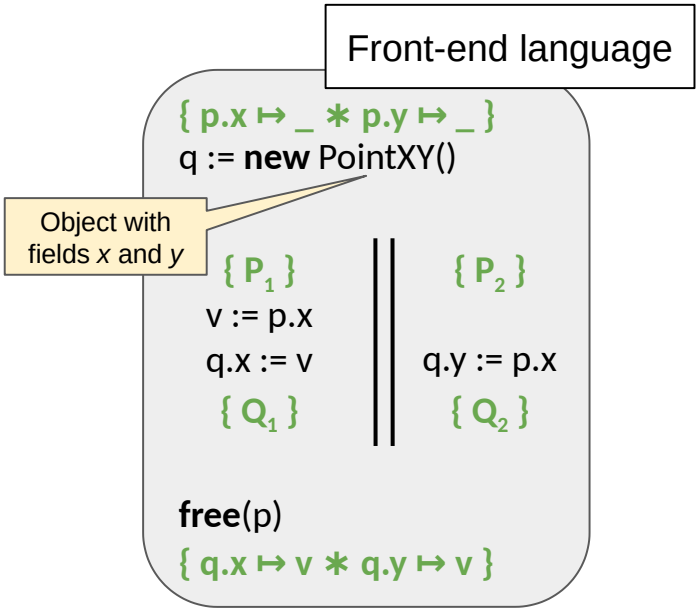

$P_1 \triangleq (q.x \mapsto \_ * p.x \overset{½}{\mapsto} \_)$ $\quad P_2 \triangleq (q.y \mapsto \_ * p.x \overset{½}{\mapsto} \_)$

$Q_1 \triangleq (q.x \mapsto v * p.x \overset{½}{\mapsto} v)$

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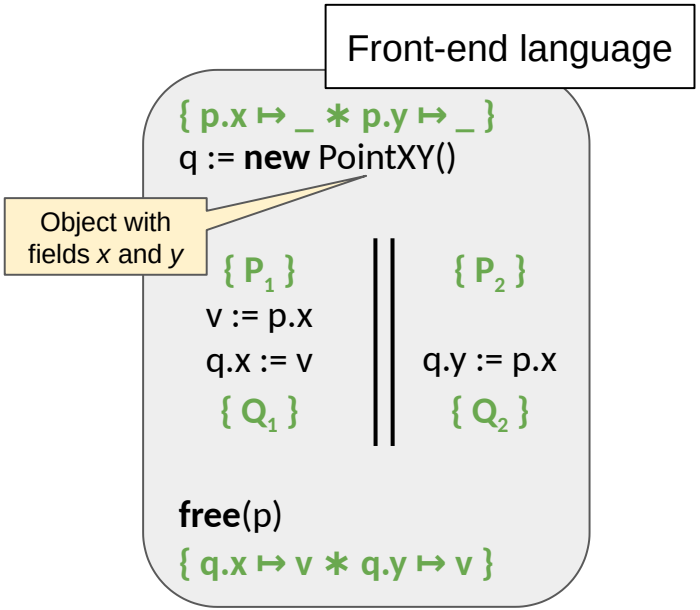


$P_1 \triangleq (q.x \mapsto \_ * p.x \overset{½}{\mapsto} \_)$ $P_2 \triangleq (q.y \mapsto \_ * p.x \overset{½}{\mapsto} \_)$

$Q_1 \triangleq (q.x \mapsto v * p.x \overset{½}{\mapsto} v)$ $Q_2 \triangleq (\exists k.\ q.y \mapsto k * p.x \overset{½}{\mapsto} k)$

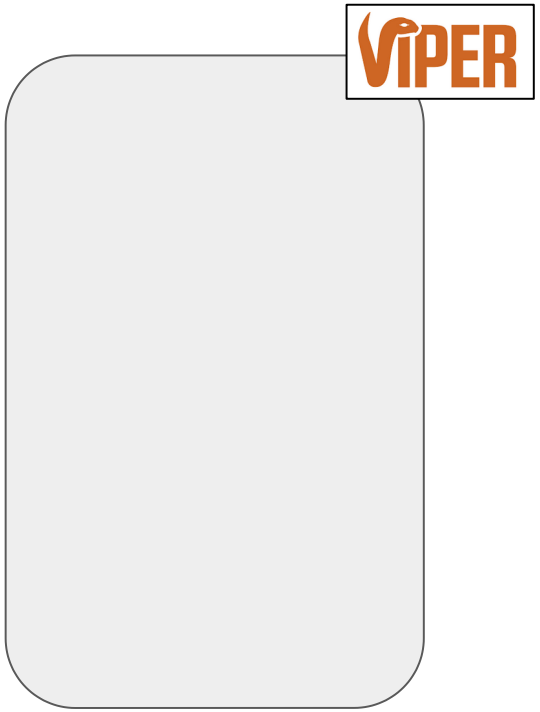
Example: Verifying a Parallel Composition (1/2)

Front-end language

$\{ p.x \mapsto \_ * p.y \mapsto \_ \}$
q := **new** PointXY()

$\{ P_1 \}$		$\{ P_2 \}$
v := p.x	‖	
q.x := v	‖	q.y := p.x
$\{ Q_1 \}$	‖	$\{ Q_2 \}$

free(p)
$\{ q.x \mapsto v * q.y \mapsto v \}$



$P_1 \triangleq (q.x \mapsto \_ * p.x \overset{½}{\mapsto} \_)$ $P_2 \triangleq (q.y \mapsto \_ * p.x \overset{½}{\mapsto} \_)$

$Q_1 \triangleq (q.x \mapsto v * p.x \overset{½}{\mapsto} v)$ $Q_2 \triangleq (\exists k.\ q.y \mapsto k * p.x \overset{½}{\mapsto} k)$

Example: Verifying a Parallel Composition (1/2)

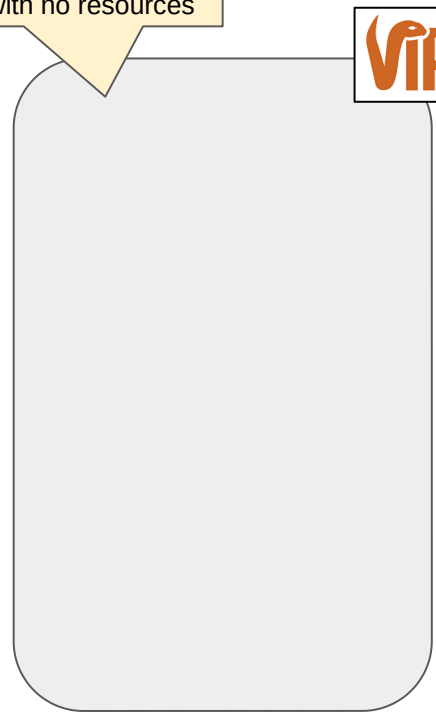
Front-end language

$\{ p.x \mapsto \_ * p.y \mapsto \_ \}$
q := **new** PointXY()

$\{ P_1 \}$	$\{ P_2 \}$
v := p.x	
q.x := v	q.y := p.x
$\{ Q_1 \}$	$\{ Q_2 \}$

free(p)
$\{ q.x \mapsto v * q.y \mapsto v \}$

Starting in a state with no resources



$P_1 \triangleq (q.x \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$ $P_2 \triangleq (q.y \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$

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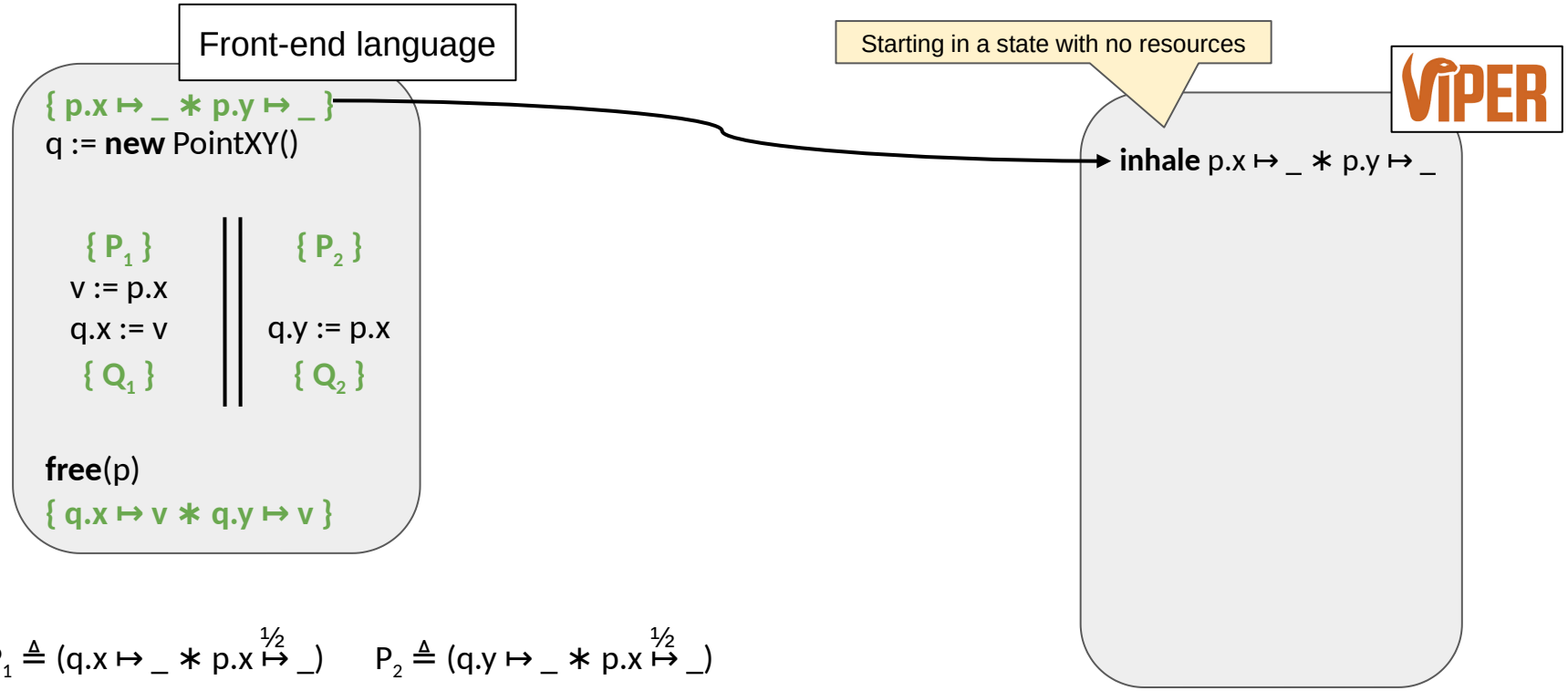
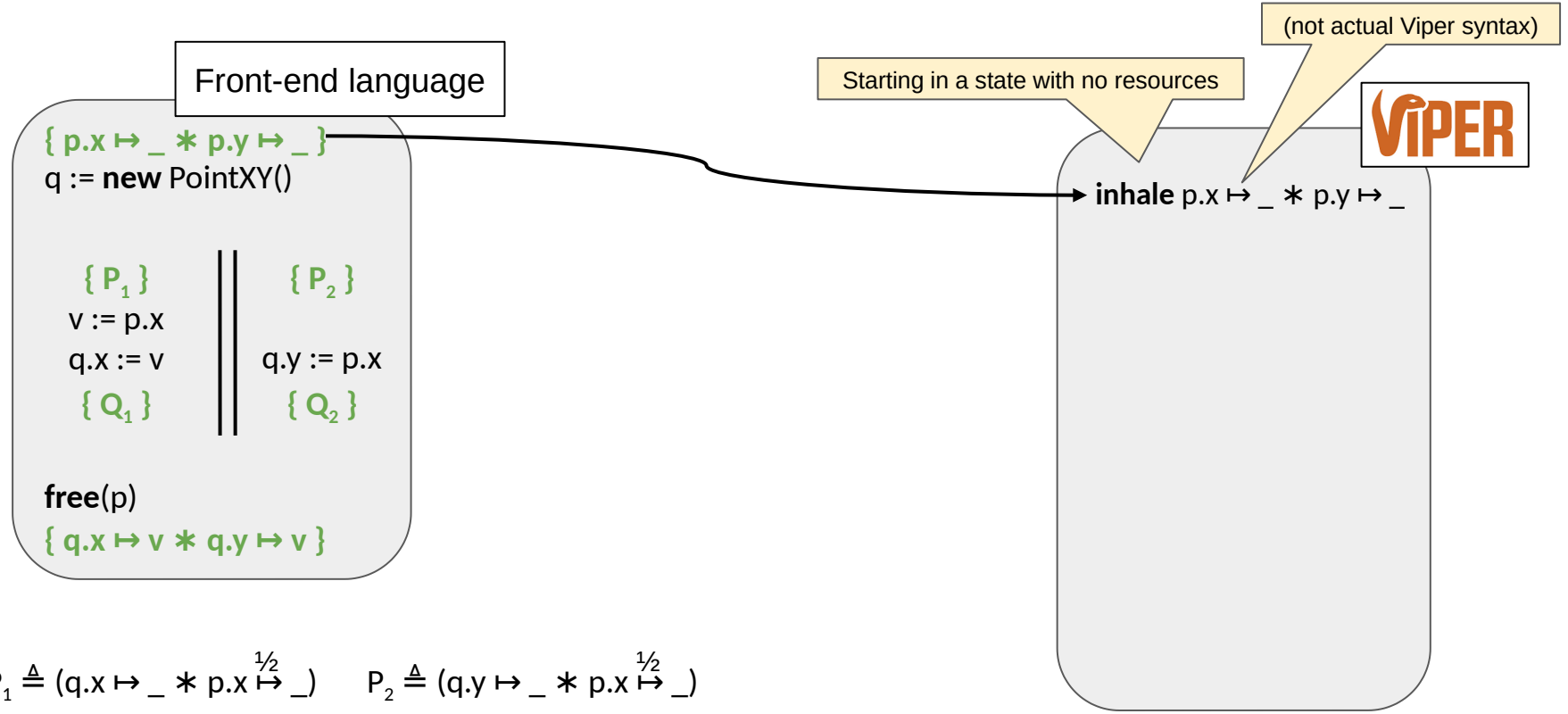
Example: Verifying a Parallel Composition (1/2)



$P_1 \triangleq (q.x \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$ $P_2 \triangleq (q.y \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$

$Q_1 \triangleq (q.x \mapsto v * p.x \overset{1/2}{\mapsto} v)$ $Q_2 \triangleq (\exists k.\ q.y \mapsto k * p.x \overset{1/2}{\mapsto} k)$

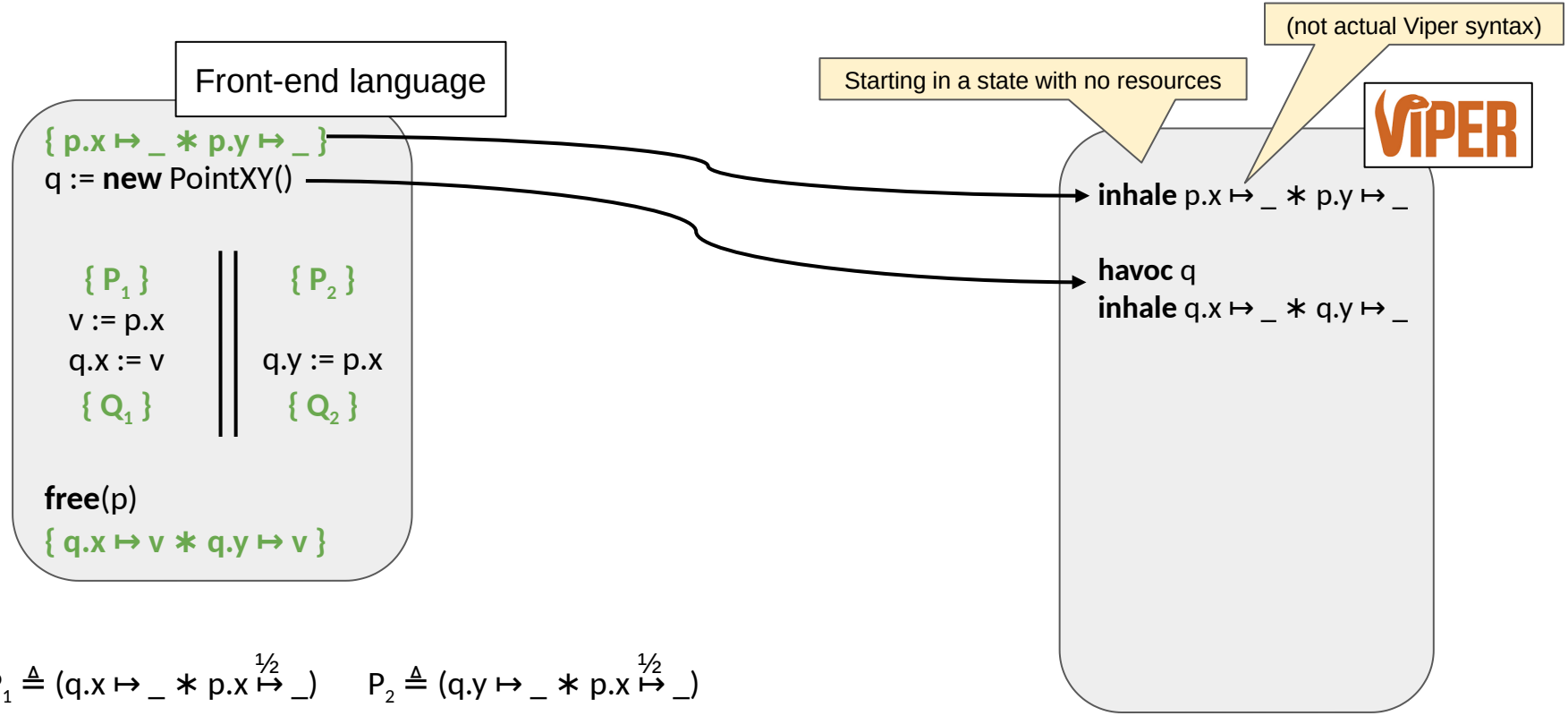
Example: Verifying a Parallel Composition (1/2)



$P_1 \triangleq (q.x \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$ $P_2 \triangleq (q.y \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$

$Q_1 \triangleq (q.x \mapsto v * p.x \overset{1/2}{\mapsto} v)$ $Q_2 \triangleq (\exists k.\ q.y \mapsto k * p.x \overset{1/2}{\mapsto} k)$

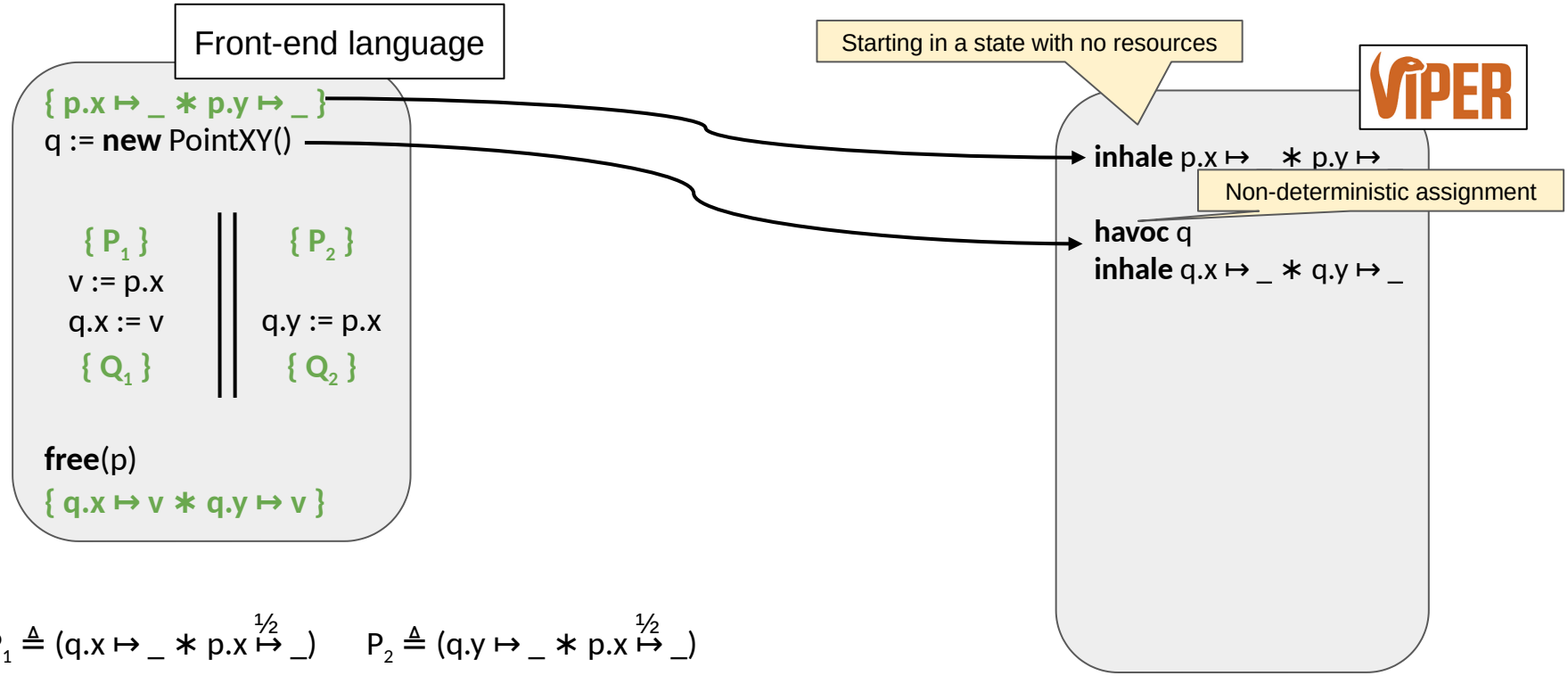
Example: Verifying a Parallel Composition (1/2)



$P_1 \triangleq (q.x \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$ $P_2 \triangleq (q.y \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$

$Q_1 \triangleq (q.x \mapsto v * p.x \overset{1/2}{\mapsto} v)$ $Q_2 \triangleq (\exists k.\ q.y \mapsto k * p.x \overset{1/2}{\mapsto} k)$

Example: Verifying a Parallel Composition (1/2)



$P_1 \triangleq (q.x \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$ $P_2 \triangleq (q.y \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$

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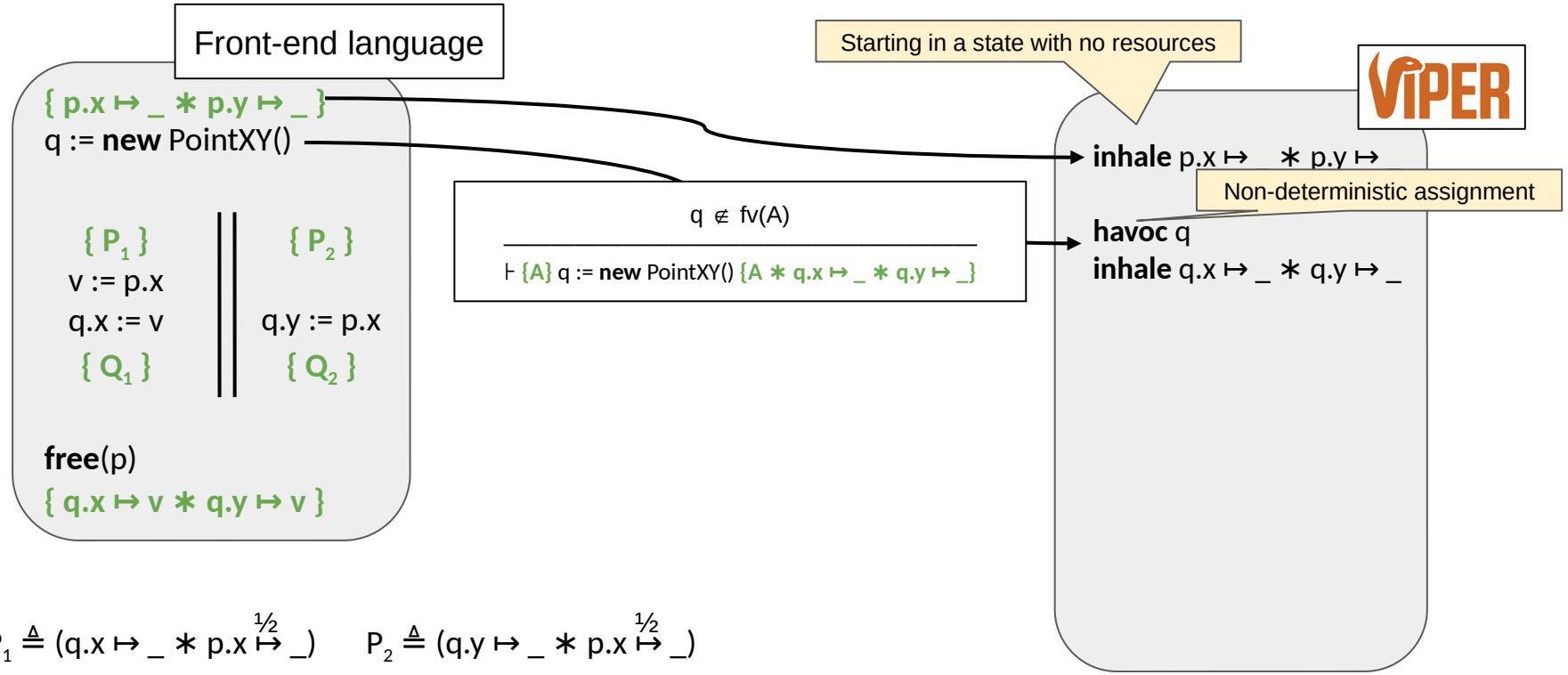
Example: Verifying a Parallel Composition (1/2)



$P_1 \triangleq (q.x \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$ $P_2 \triangleq (q.y \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$

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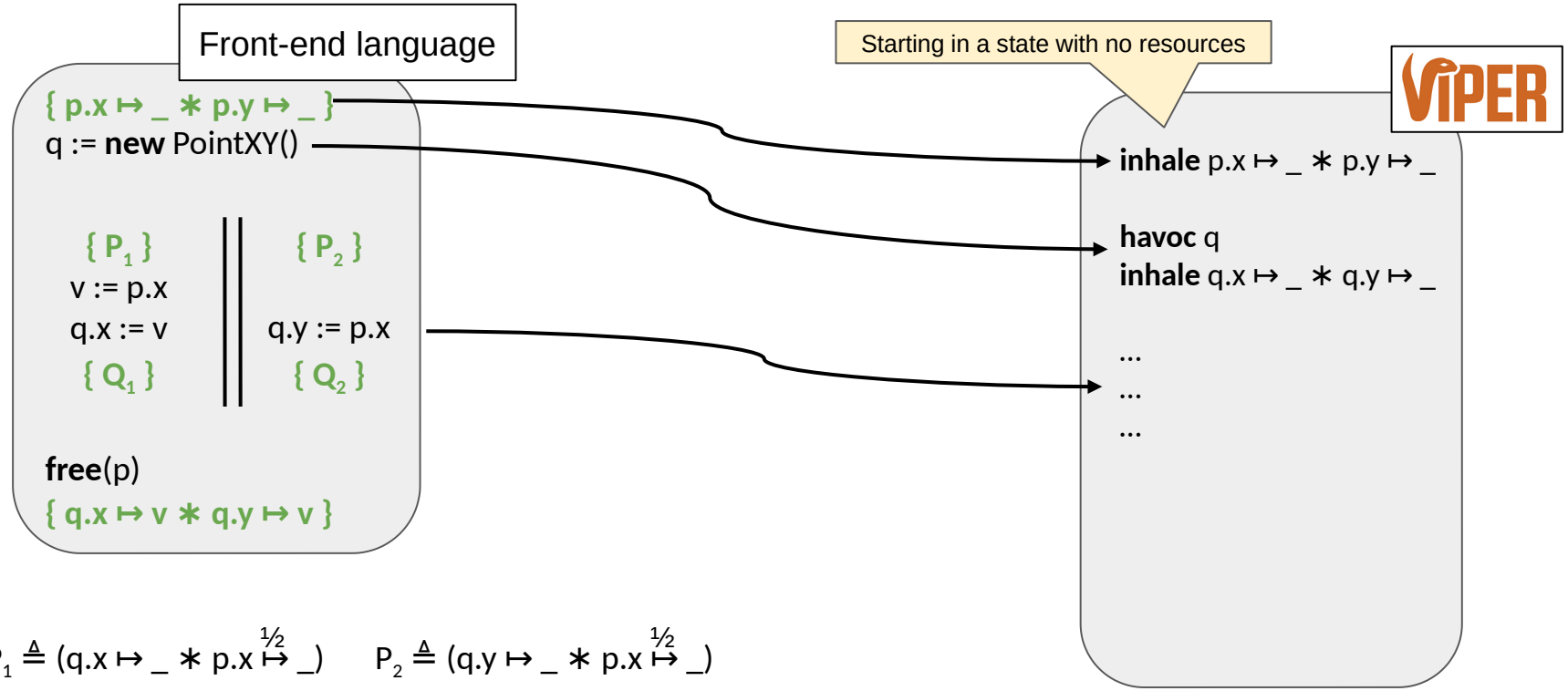
Example: Verifying a Parallel Composition (1/2)



$P_1 \triangleq (q.x \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$ $P_2 \triangleq (q.y \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$

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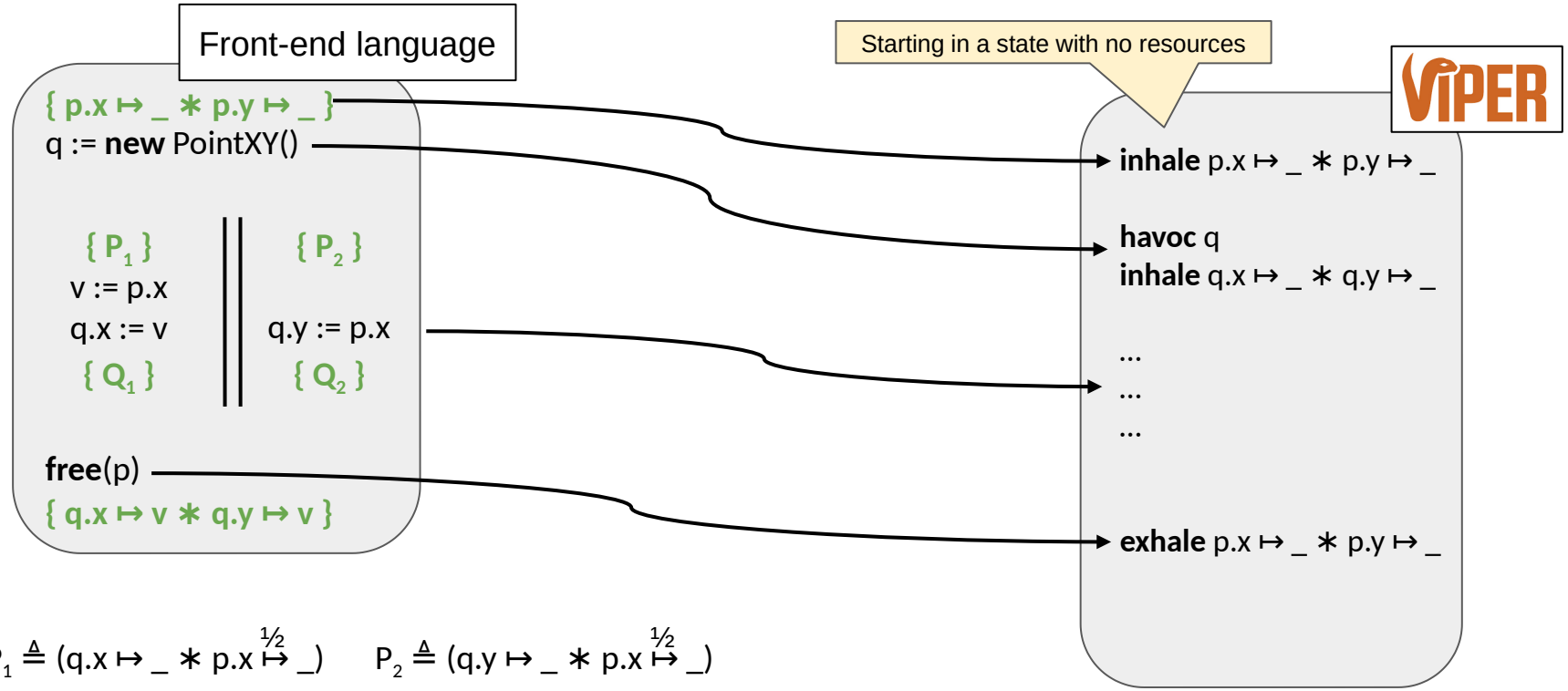

$P_1 \triangleq (q.x \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$ $P_2 \triangleq (q.y \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$

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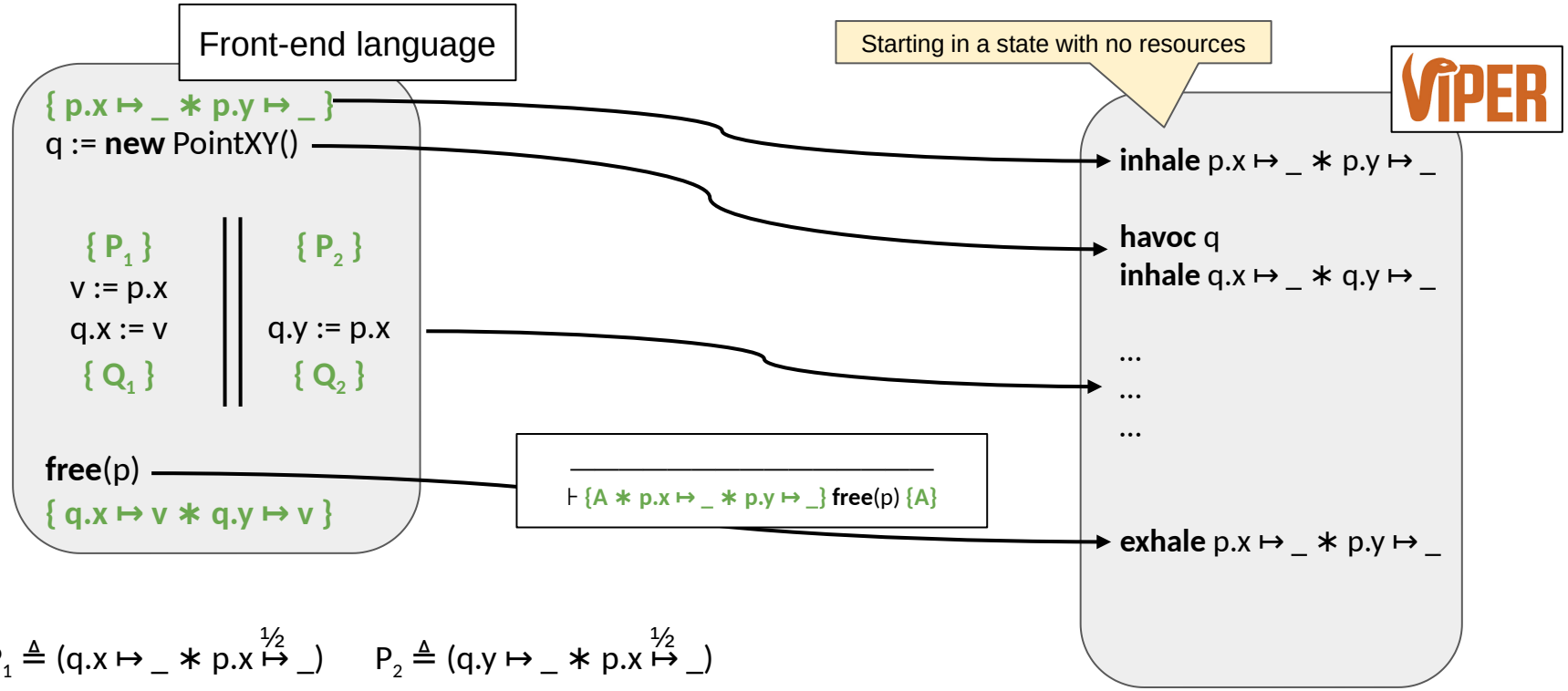
Example: Verifying a Parallel Composition (1/2)



$P_1 \triangleq (q.x \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$ $P_2 \triangleq (q.y \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$

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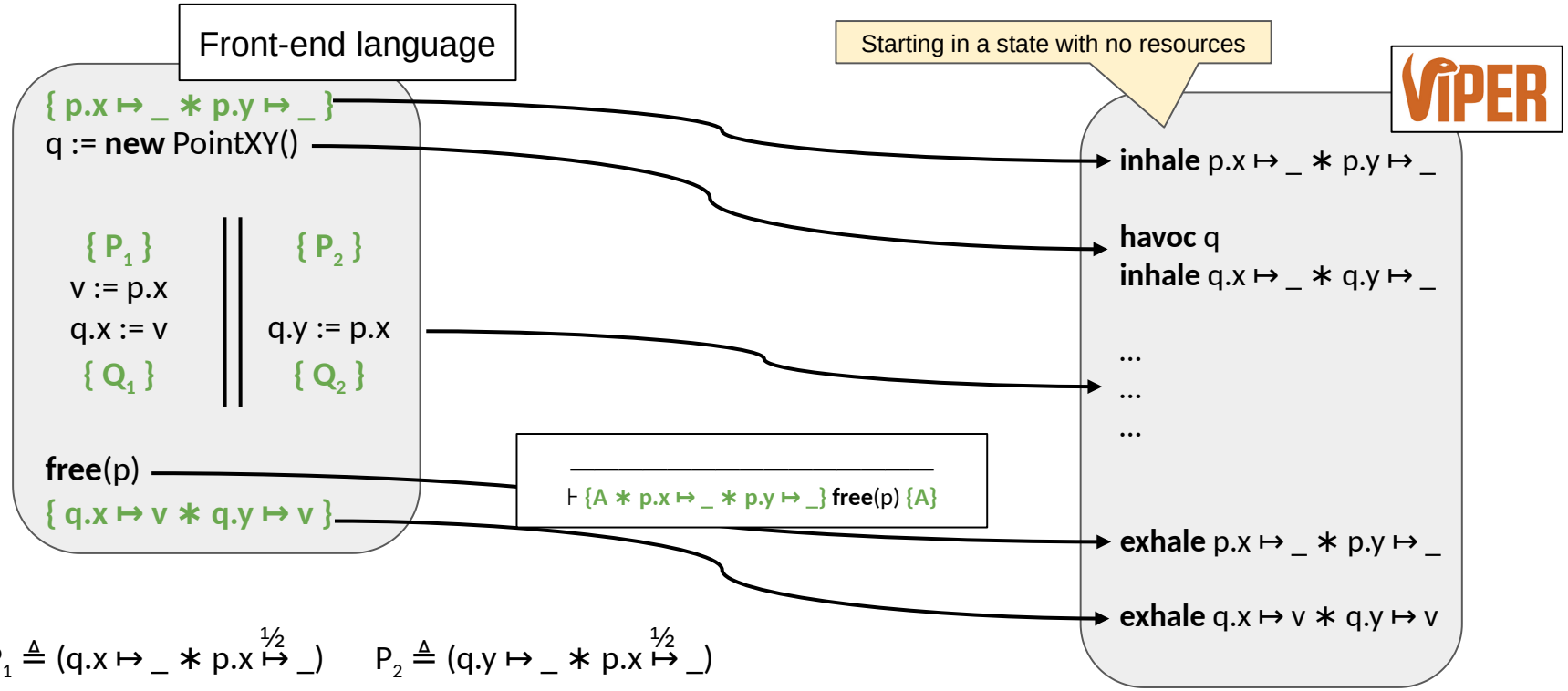
Example: Verifying a Parallel Composition (1/2)



$P_1 \triangleq (q.x \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$ $P_2 \triangleq (q.y \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$

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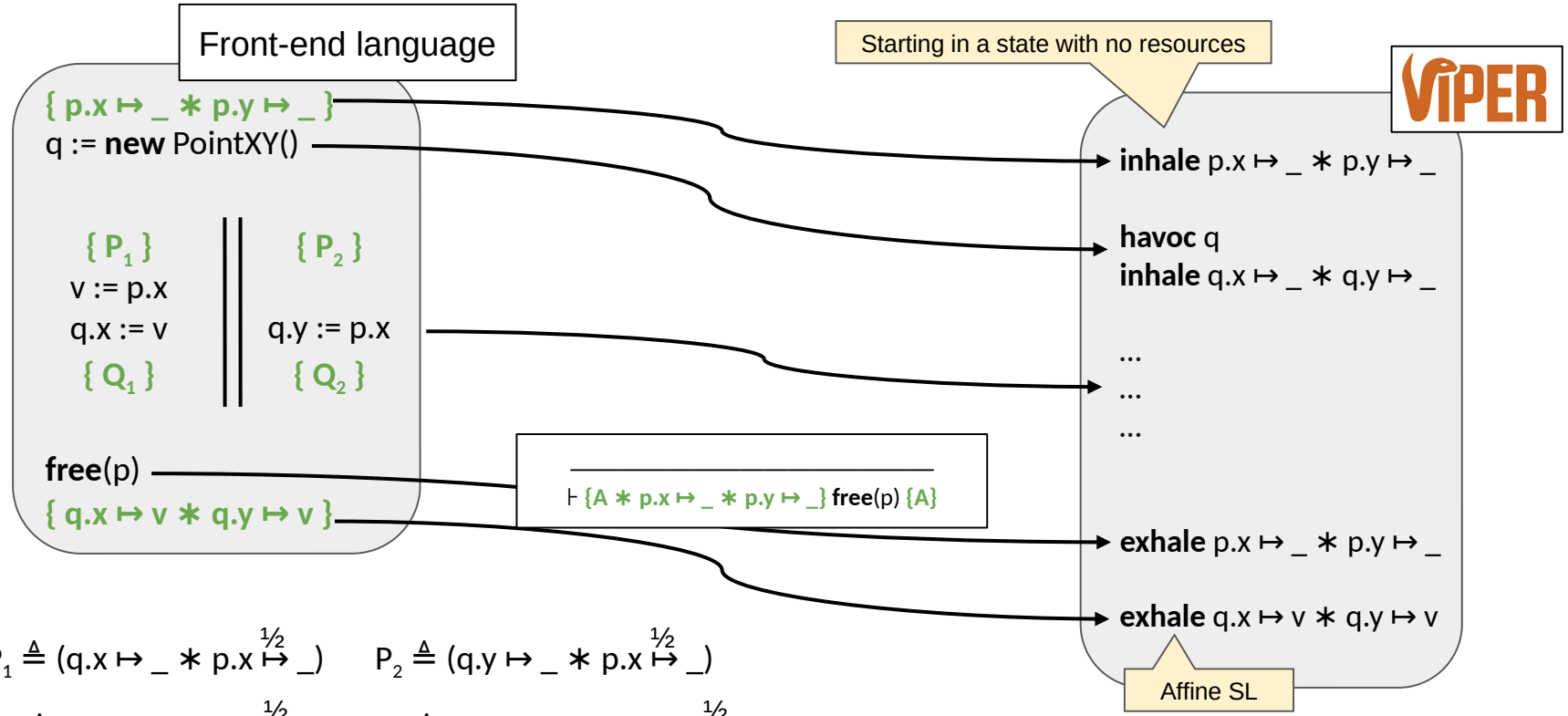

$P_1 \triangleq (q.x \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$ $P_2 \triangleq (q.y \mapsto \_ * p.x \overset{1/2}{\mapsto} \_)$

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Example: Verifying a Parallel Composition (2/2)

Front-end language

$\{ p.x \mapsto \_ * p.y \mapsto \_ \}$
q := **new** PointXY()

$\{ P_1 \}$	$\{ P_2 \}$
v := p.x	
q.x := v	q.y := p.x
$\{ Q_1 \}$	$\{ Q_2 \}$

free(p)

$\{ q.x \mapsto v * q.y \mapsto v \}$

VIPER

inhale $p.x \mapsto \_ * p.y \mapsto \_$

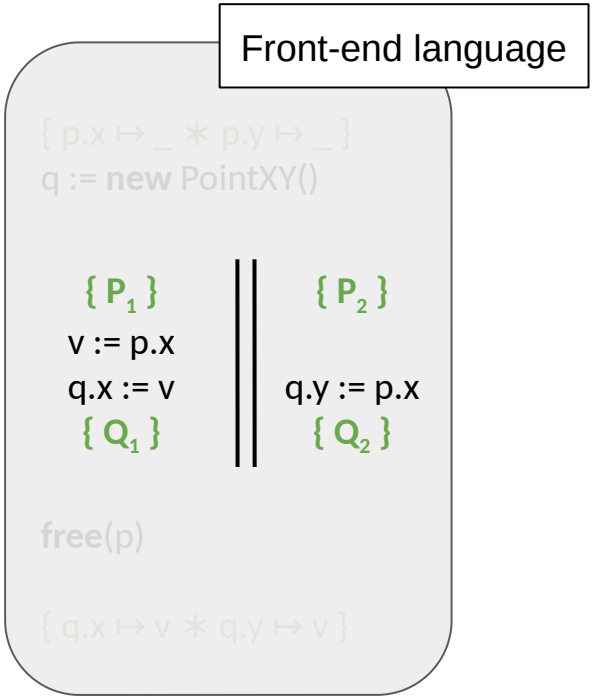
havoc q
inhale $q.x \mapsto \_ * q.y \mapsto \_$

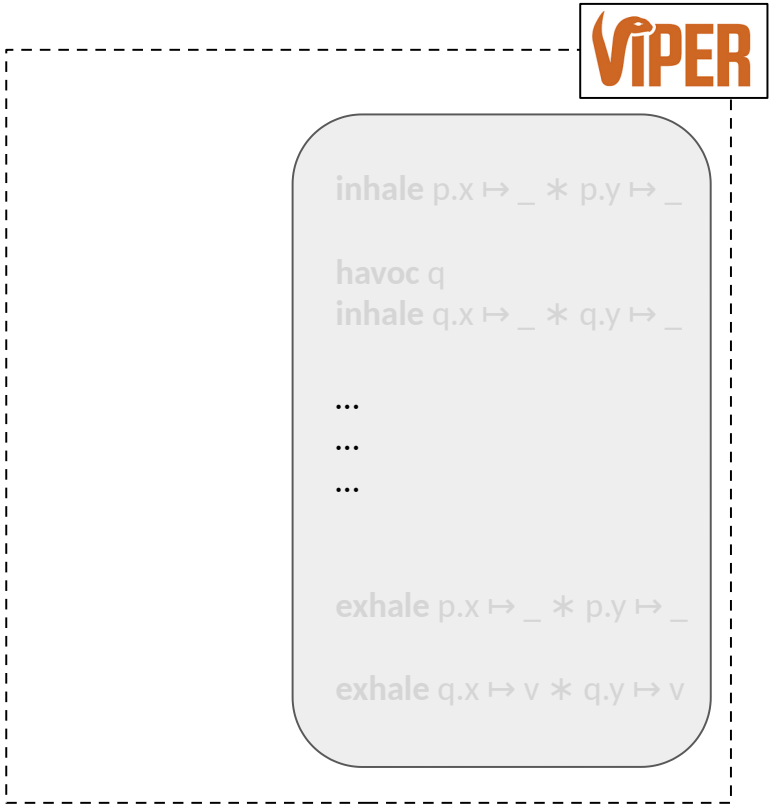
...
...
...

exhale $p.x \mapsto \_ * p.y \mapsto \_$

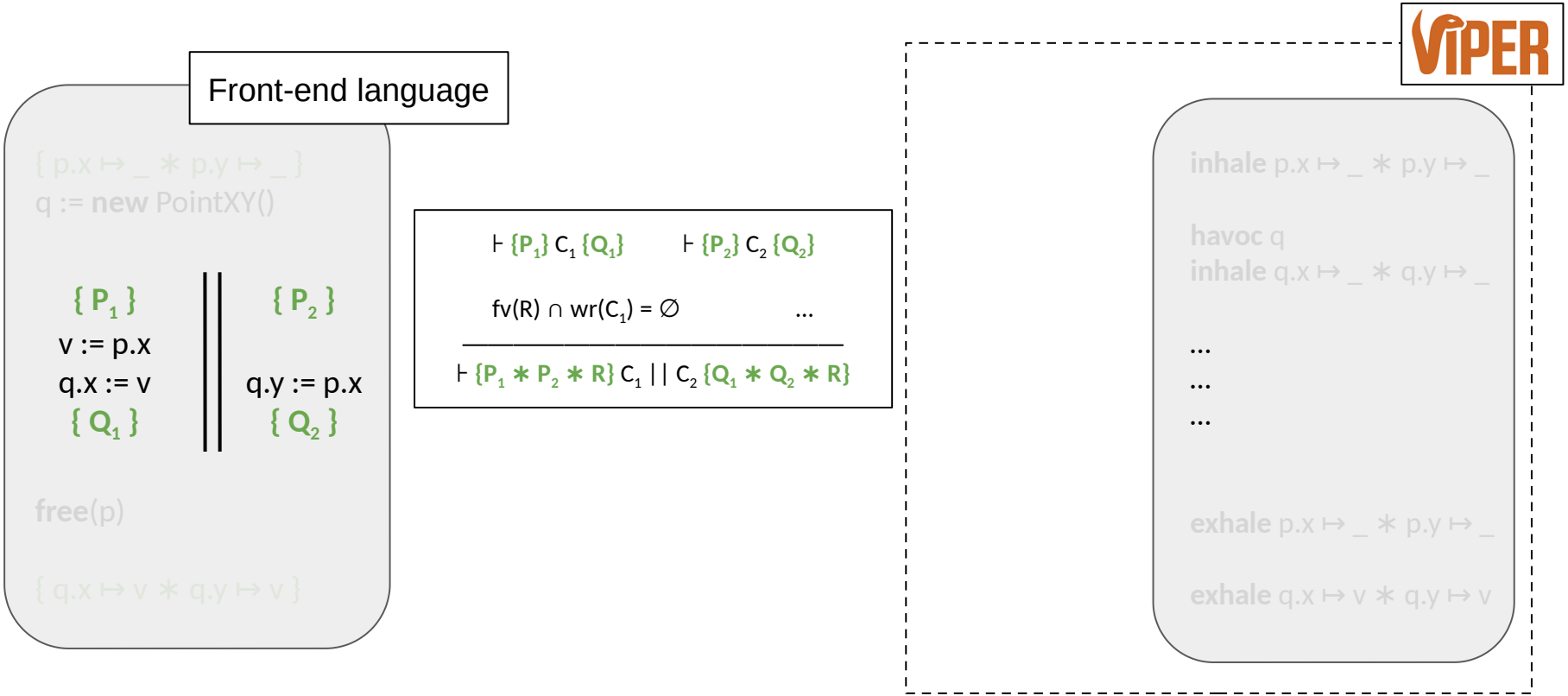
exhale $q.x \mapsto v * q.y \mapsto v$

Example: Verifying a Parallel Composition (2/2)

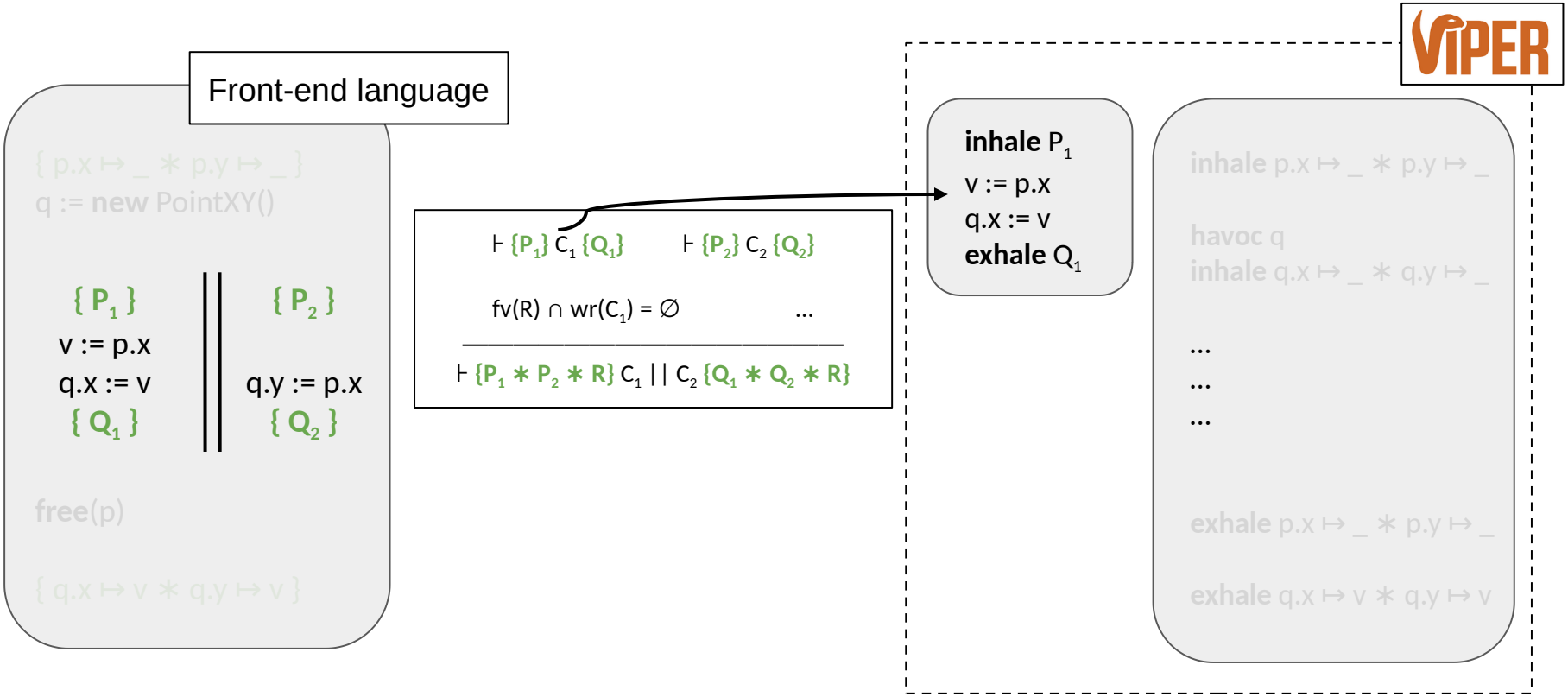




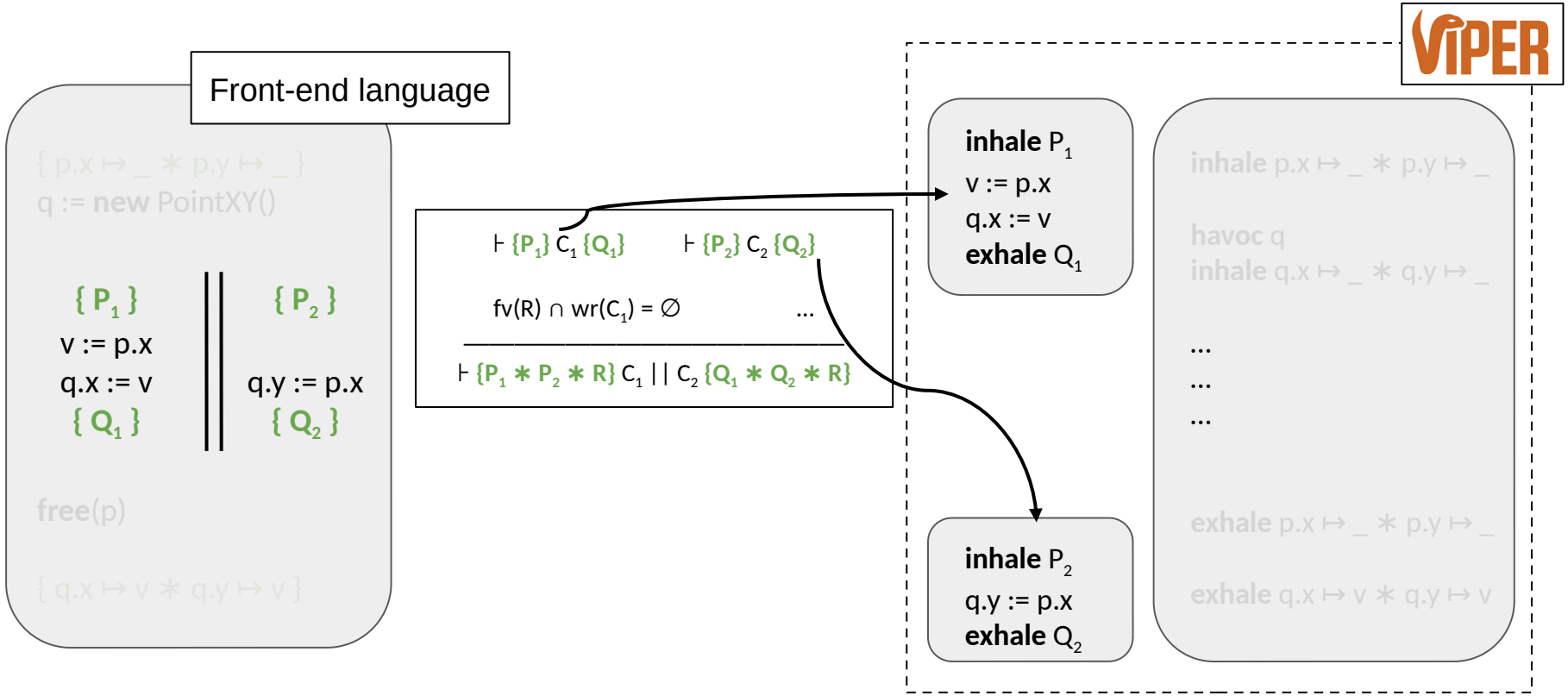
Example: Verifying a Parallel Composition (2/2)



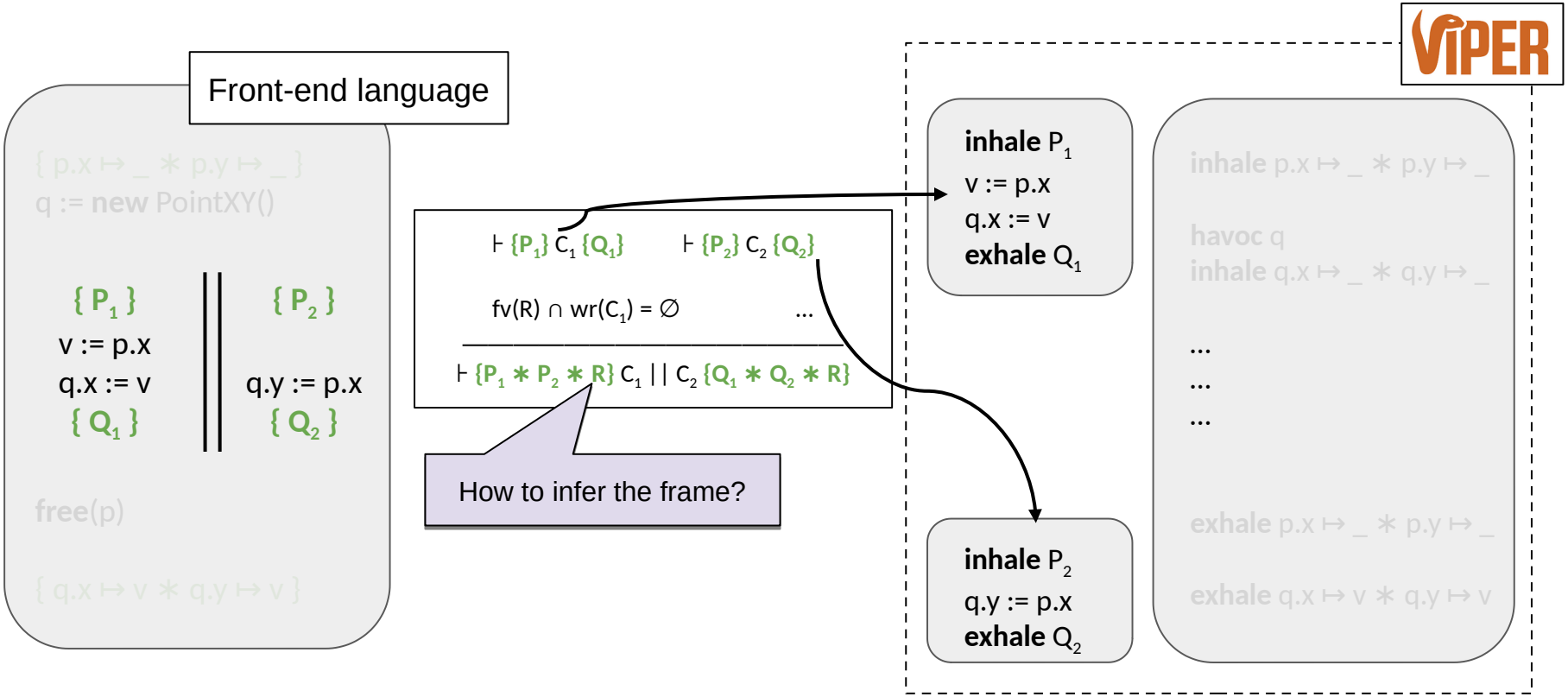
Example: Verifying a Parallel Composition (2/2)



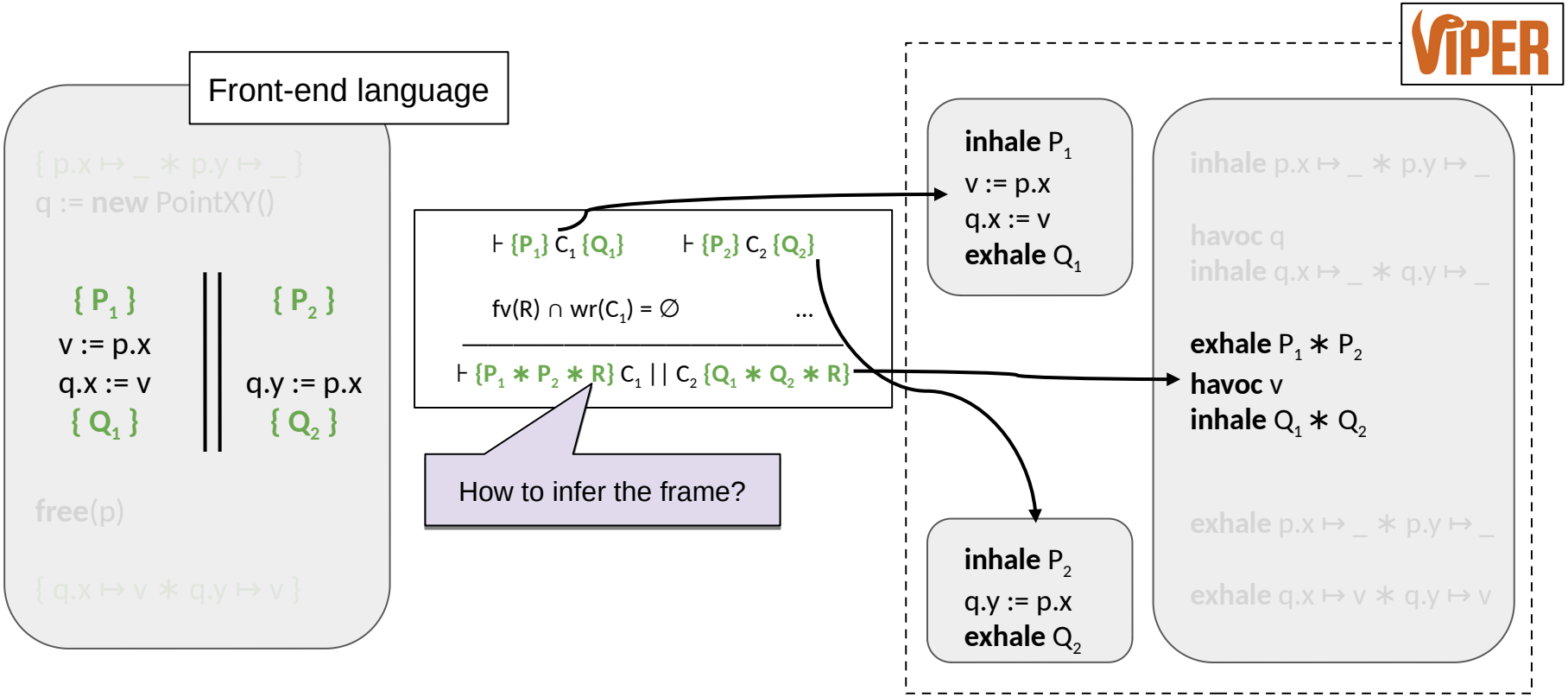
Example: Verifying a Parallel Composition (2/2)



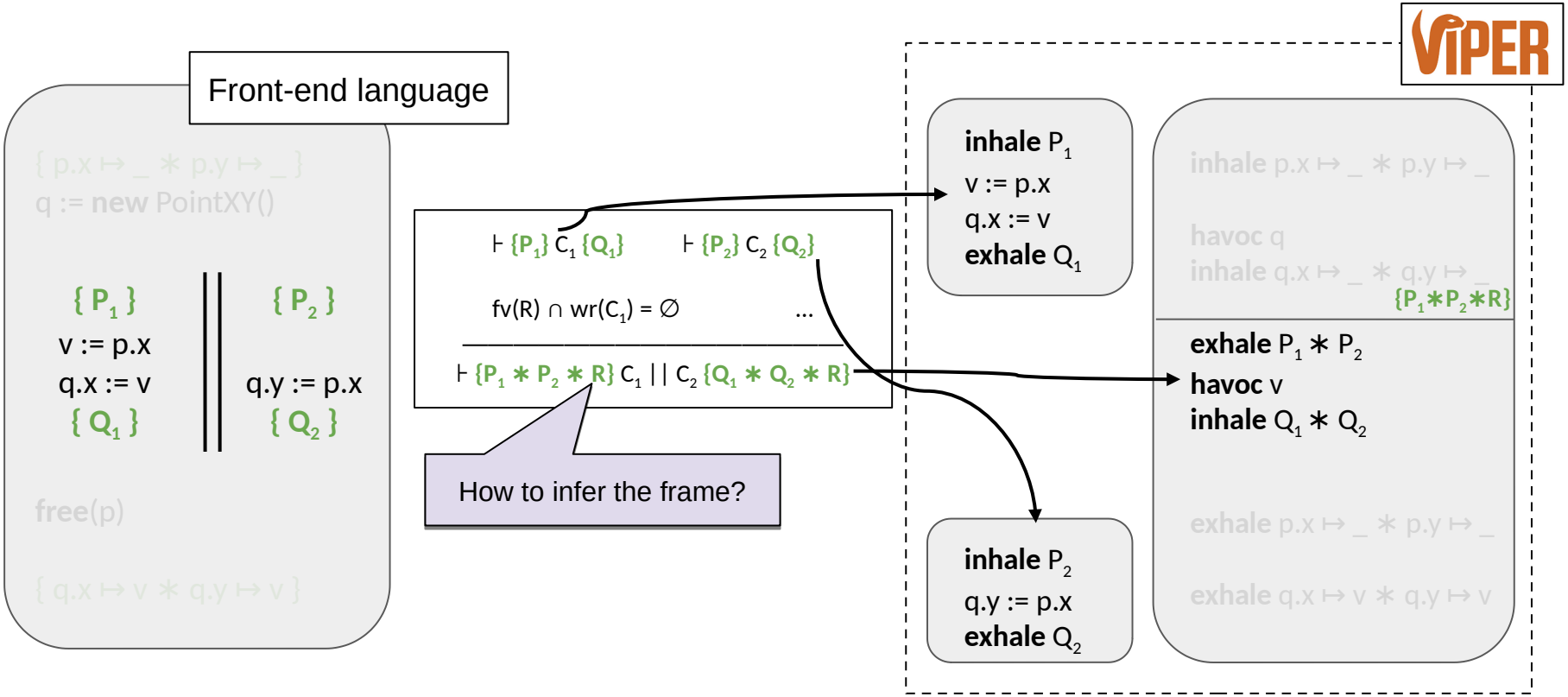
Example: Verifying a Parallel Composition (2/2)



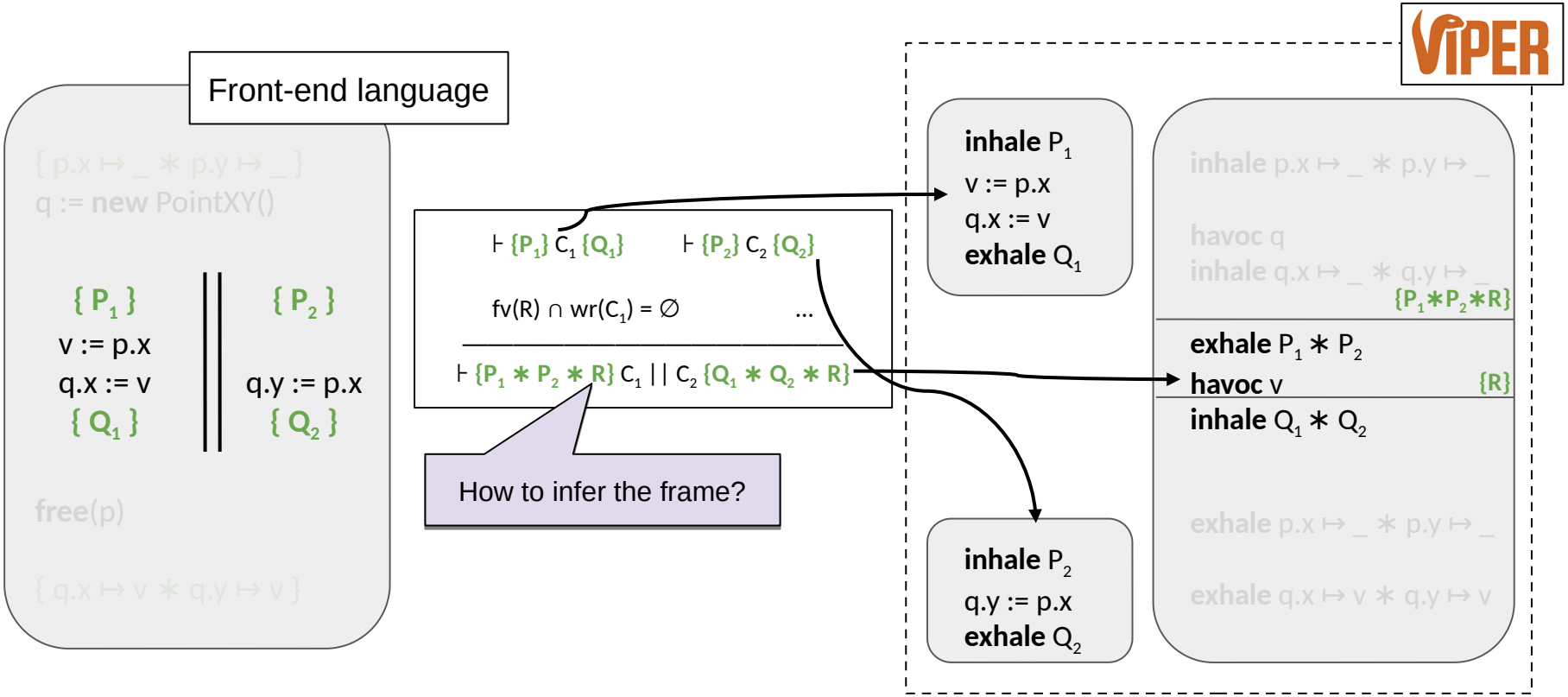
Example: Verifying a Parallel Composition (2/2)



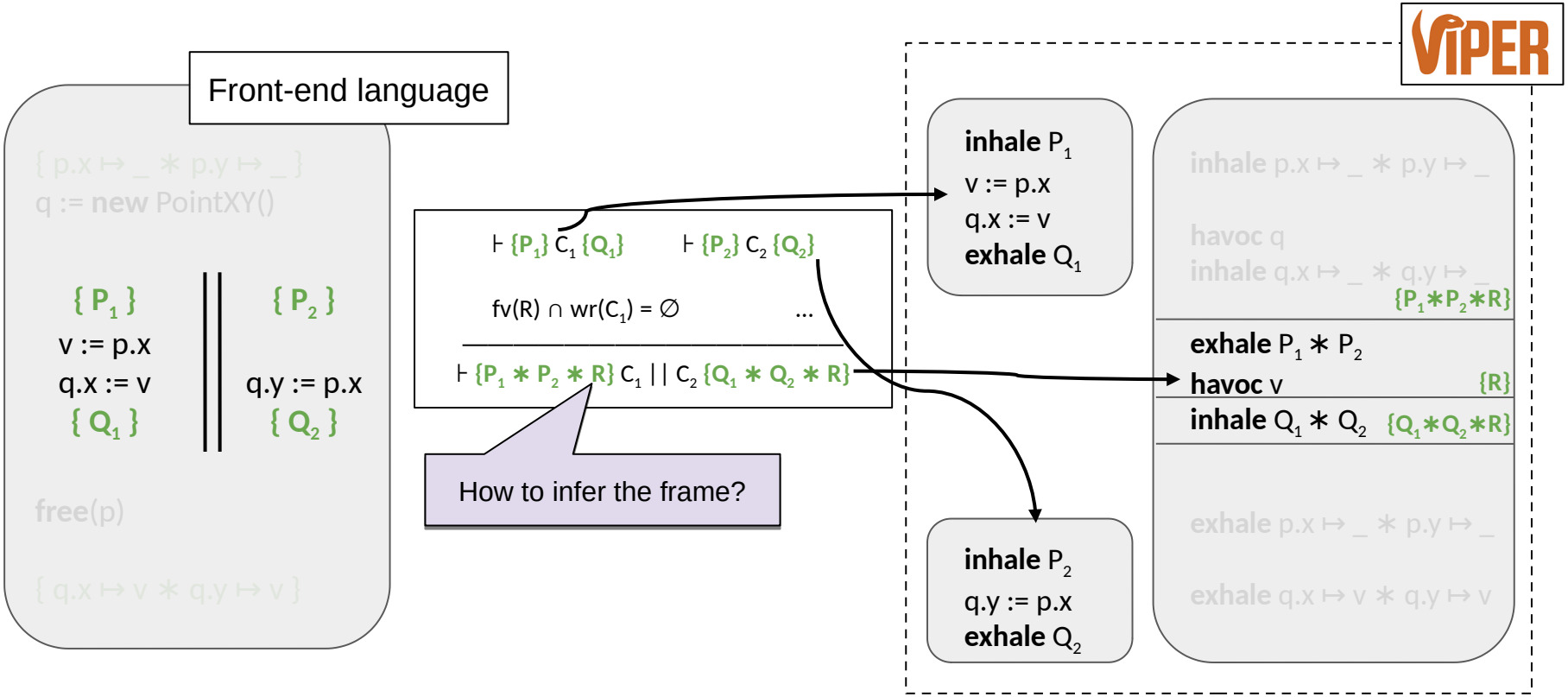
Example: Verifying a Parallel Composition (2/2)



Example: Verifying a Parallel Composition (2/2)



Example: Verifying a Parallel Composition (2/2)



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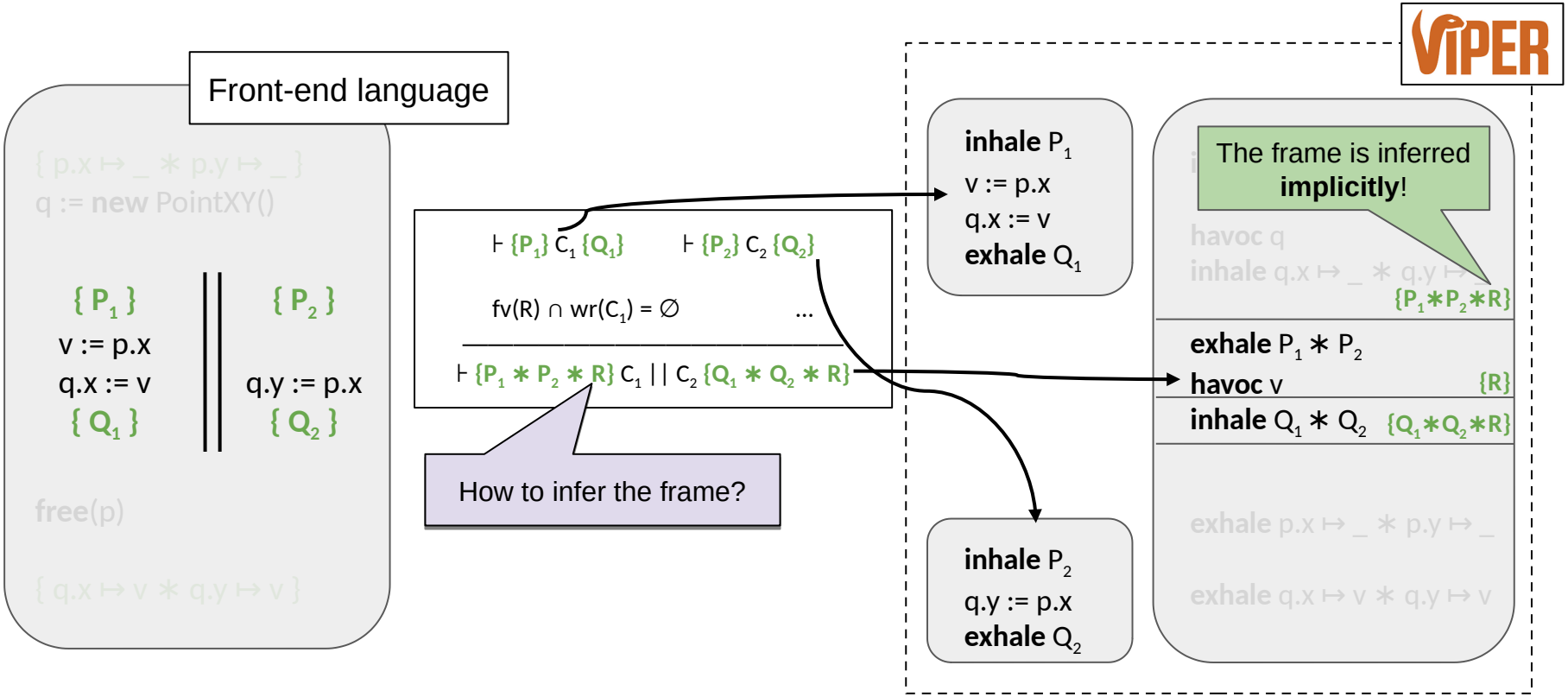

Outline of the Talk

1. Overview of Viper

2. Inhale and Exhale: An Operational View of Separation Logic

3. Designed for Automation

4. Toward a Foundational Viper

Automating Separation Logic: Challenges

Automating Separation Logic: Challenges

Challenge 1

Existentials

Automating Separation Logic: Challenges

Challenge 1

Existentials

Challenge 2

Recursive predicates

Automating Separation Logic: Challenges

Challenge 1

Existentials

Challenge 2

Recursive predicates

Challenge 3

Magic wands

Automating Separation Logic: Challenges

Challenge 1

Existentials

Challenge 2

Recursive predicates

Challenge 3

Magic wands

Which resources to remove when exhaling `A --* B`?

Automating Separation Logic: Challenges

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Existentials

Challenge 2

Recursive predicates

Challenge 3

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Which resources to remove when exhaling `A -∗ B`?

Challenge 4

Iterated separating conjunction

Automating Separation Logic: Challenges

Challenge 1

Existentials

Challenge 2

Recursive predicates

Challenge 3

Magic wands

Which resources to remove when exhaling `A -∗ B`?

Challenge 4

Iterated separating conjunction

…

Automating Separation Logic: Challenges

Challenge 1

Existentials

Challenge 2

Recursive predicates

Challenge 3

Magic wands

Which resources to remove when exhaling A −∗ B?

Challenge 4

Iterated separating conjunction

…

Challenge 1: Existentials

Challenge 1: Existentials

exhale ∃v. (p.x $\overset{½}{\mapsto}$ v ∗ v > 0)

Challenge 1: Existentials

exhale $\exists v.\ (p.x \overset{½}{\mapsto} v * v > 0)$

exhale $\exists s.\ \mathsf{list}(l, s) * |s| > 0$

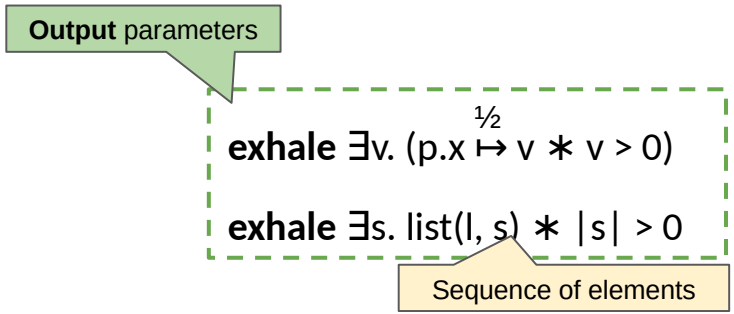
Challenge 1: Existentials

exhale $\exists v.\ (p.x \overset{1/2}{\mapsto} v * v > 0)$

exhale $\exists s.\ \mathrm{list}(l, s) * |s| > 0$

Sequence of elements

Challenge 1: Existentials



Challenge 1: Existentials

Output parameters

exhale $\exists v.\ (p.x \overset{½}{\mapsto} v * v > 0)$

exhale $\exists s.\ list(l, s) * |s| > 0$

exhale $\exists p.\ p.x \mapsto \_ * p.y \mapsto \_$

Challenge 1: Existentials

Output parameters

exhale $\exists v.\ (p.x \overset{½}{\mapsto} v * v > 0)$

exhale $\exists s.\ list(l, s) * |s| > 0$

exhale $\exists p.\ p.x \mapsto \_ * p.y \mapsto \_$

exhale $\exists l.\ list(l, s) * l \neq null$

Challenge 1: Existentials

Output parameters

exhale $\exists v.\ (p.x \overset{½}{\mapsto} v * v > 0)$

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exhale $\exists l.\ list(l, s) * l \neq null$

Challenge 1: Existentials

- ❑ Avoid existentials in the SMT encoding

Output parameters

exhale $\exists v.\ (p.x \overset{½}{\mapsto} v * v > 0)$

exhale $\exists s.\ list(l, s) * |s| > 0$

Input parameters

exhale $\exists p.\ p.x \mapsto \_ * p.y \mapsto \_$

exhale $\exists l.\ list(l, s) * l \neq null$

Challenge 1: Existentials

- ❑ Avoid existentials in the SMT encoding
- ❑ Avoid backtracking

Output parameters

exhale $\exists v.\ (p.x \overset{½}{\mapsto} v * v > 0)$

exhale $\exists s.\ list(l, s) * |s| > 0$

Input parameters

exhale $\exists p.\ p.x \mapsto \_ * p.y \mapsto \_$

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Challenge 1: Existentials

- ❑ Avoid existentials in the SMT encoding
- ❑ Avoid backtracking
- ❑ Predictable automation

Output parameters

exhale $\exists v.\ (p.x \overset{½}{\mapsto} v * v > 0)$

exhale $\exists s.\ list(l, s) * |s| > 0$

Input parameters

exhale $\exists p.\ p.x \mapsto \_ * p.y \mapsto \_$

exhale $\exists l.\ list(l, s) * l \neq null$

Challenge 1: Existentials

- ❑ Avoid existentials in the SMT encoding
- ❑ Avoid backtracking
- ❑ Predictable automation

Output parameters

exhale ∃v. (p.x $\overset{1/2}{\mapsto}$ v ∗ v > 0)

exhale ∃s. list(l, s) ∗ |s| > 0

Input parameters

exhale ∃p. p.x ↦ _ ∗ p.y ↦ _

exhale ∃l. list(l, s) ∗ l ≠ null

Forbidden by Viper's syntax

Challenge 1: Existentials

- ❑ Avoid existentials in the SMT encoding
- ❑ Avoid backtracking
- ❑ Predictable automation

Output parameters

exhale $\exists v.\ (p.x \overset{1/2}{\mapsto} v * v > 0)$

exhale $\exists s.\ list(l, s) * |s| > 0$

Input parameters

exhale $\exists p.\ p.x \mapsto \_ * p.y \mapsto \_$

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Forbidden by Viper's syntax

Viper uses
implicit dynamic frames

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exhale $\exists v.\ (p.x \overset{½}{\mapsto} v * v > 0)$

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Forbidden by Viper's syntax

Viper uses
implicit dynamic frames

≈ SL with **heap-dependent** expressions and functions

Challenge 1: Existentials

- ❑ Avoid existentials in the SMT encoding
- ❑ Avoid backtracking
- ❑ Predictable automation

Output parameters

exhale $\exists v.\ (p.x \overset{1/2}{\mapsto} v * v > 0)$

exhale $\exists s.\ list(l, s) * |s| > 0$

is written as

exhale $acc(p.x, 1/2) * p.x > 0$

Input parameters

exhale $\exists p.\ p.x \mapsto \_ * p.y \mapsto \_$

exhale $\exists l.\ list(l, s) * l \neq null$

Forbidden by Viper's syntax

Viper uses
implicit dynamic frames

≈ SL with **heap-dependent** expressions and functions

Challenge 1: Existentials

- ❑ Avoid existentials in the SMT encoding
- ❑ Avoid backtracking
- ❑ Predictable automation

Output parameters

exhale ∃v. (p.x $\overset{1/2}{\mapsto}$ v ∗ v > 0)

exhale ∃s. list(l, s) ∗ |s| > 0

is written as

Avoids existential

exhale acc(p.x, 1/2) ∗ p.x > 0

Input parameters

exhale ∃p. p.x ↦ _ ∗ p.y ↦ _

exhale ∃l. list(l, s) ∗ l ≠ null

Forbidden by Viper's syntax

Viper uses
implicit dynamic frames

≈ SL with **heap-dependent** expressions and functions

Challenge 1: Existentials

- ❑ Avoid existentials in the SMT encoding
- ❑ Avoid backtracking
- ❑ Predictable automation

Output parameters

exhale ∃v. (p.x $\overset{1/2}{\mapsto}$ v ∗ v > 0)

exhale ∃s. list(l, s) ∗ |s| > 0

is written as

is written as

Avoids existential

exhale acc(p.x, 1/2) ∗ p.x > 0

exhale list(l) ∗ len(l) > 0

Input parameters

exhale ∃p. p.x ↦ _ ∗ p.y ↦ _

exhale ∃l. list(l, s) ∗ l ≠ null

Forbidden by Viper's syntax

Viper uses
implicit dynamic frames

≈ SL with **heap-dependent** expressions and functions

Challenge 1: Existentials

- ❑ Avoid existentials in the SMT encoding
- ❑ Avoid backtracking
- ❑ Predictable automation

Output parameters

exhale ∃v. (p.x ↦[½] v ∗ v > 0)

exhale ∃s. list(l, s) ∗ |s| > 0

is written as

is written as

Avoids existential

exhale acc(p.x, 1/2) ∗ p.x > 0

exhale list(l) ∗ len(l) > 0

Heap-dependent function

Input parameters

exhale ∃p. p.x ↦ _ ∗ p.y ↦ _

exhale ∃l. list(l, s) ∗ l ≠ null

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Avoids existential

is written as

exhale list(l) ∗ len(l) > 0

Heap-dependent function

Input parameters

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exhale ∃l. list(l, s) ∗ l ≠ null

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Allows writing code and specifications in the same language

Challenge 1: Existentials

- ❑ Avoid existentials in the SMT encoding
- ❑ Avoid backtracking
- ❑ Predictable automation

Output parameters

exhale $\exists v.\ (p.x \overset{1/2}{\mapsto} v * v > 0)$ is written as **exhale** acc(p.x, 1/2) ∗ p.x > 0

exhale $\exists s.\ list(l, s) * |s| > 0$ is written as **exhale** list(l) ∗ len(l) > 0

Input parameters

exhale $\exists p.\ p.x \mapsto \_ * p.y \mapsto \_$

exhale $\exists l.\ list(l, s) * l \neq null$

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Allows writing code and specifications in the same language

inhale A ∗ B
exhale A ∗ B

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Implicit existential quantification

inhale A ∗ B
exhale A ∗ B

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Implicit existential quantification

inhale A ∗ B
exhale A ∗ B

operationally equivalent to

inhale A; **inhale** B

Challenge 1: Existentials

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- ❑ Avoid backtracking
- ❑ Predictable automation

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operationally equivalent to

Analogous for **exhale**

inhale A; **inhale** B

Viper’s Expression and Assertion Language

Viper’s Expression and Assertion Language

e ::= e.x | f(e_1, …, e_n) | **old**[l](e) | e_1 + e_2 | e_1 / e_2 | n | v | b ? e_1 : e_2 | …

Viper’s Expression and Assertion Language

Field access

e ::= e.x | f(e_1, ..., e_n) | **old**[l](e) | e_1 + e_2 | e_1 / e_2 | n | v | b ? e_1 : e_2 | ...

Viper’s Expression and Assertion Language

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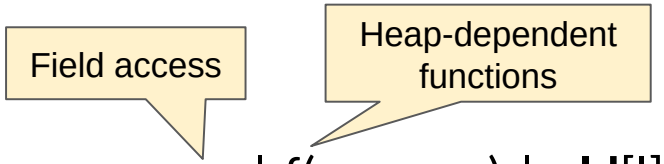
Viper’s Expression and Assertion Language



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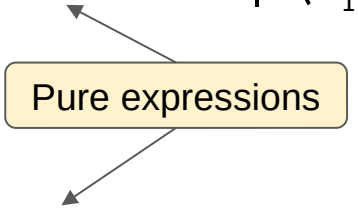

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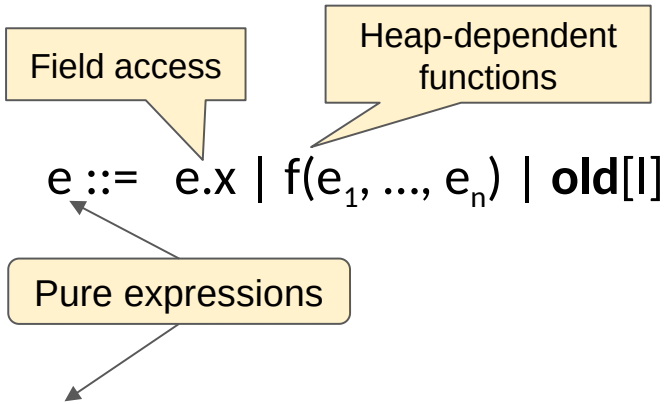

$A ::= b \mid \mathbf{acc}(e_1.x, e_2) \mid \mathbf{acc}(P(e_1, \ldots, e_n), e) \mid A_1 \ast A_2 \mid A_1 -\!\!\ast A_2 \mid \circledast v.\ A \mid b \Rightarrow A \mid \ldots$

Viper's Expression and Assertion Language

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Pure expressions

$b ::= e_1 = e_2 \mid \neg b \mid b_1 \Rightarrow b_2 \mid b_1 \vee b_2 \mid b_1 \wedge b_2 \mid \forall v.\, b \mid \ldots$

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Fractional permissions for heap locations

Viper's Expression and Assertion Language

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Fractional permissions for heap locations

Inductive predicates with fractional permissions

Viper's Expression and Assertion Language

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Fractional permissions for heap locations

Inductive predicates with fractional permissions

Iterated separating conjunction

Viper's Expression and Assertion Language

Design choice

- No impure existential
- No impure disjunction
- No impure implication
- No impure negation
- No impure logical conjunction

Field access

Heap-dependent functions

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Fractional permissions for heap locations

Inductive predicates with fractional permissions

Iterated separating conjunction

Challenge 2: Inductive Predicates

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$$\mathsf{list}(l) \triangleq (l \neq \mathsf{null} \Rightarrow (\mathbf{acc}(l.\mathsf{value}) * \mathbf{acc}(l.\mathsf{next}) * \mathsf{list}(l.\mathsf{next})))$$

Challenge 2: Inductive Predicates

Input parameters only

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1. Existence of a (least) fixed-point?

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2. How to automate **inhale** list(l) and **exhale** list(l)?

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3. How to reason about output parameters?

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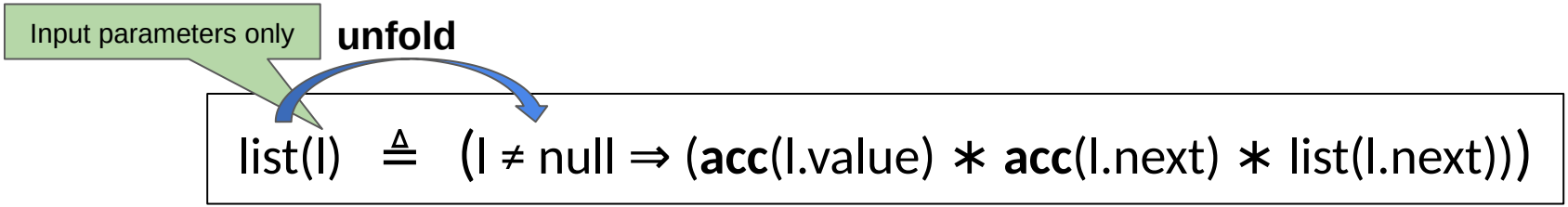
4. How to know when to **unfold** the definition?

Challenge 2: Inductive Predicates



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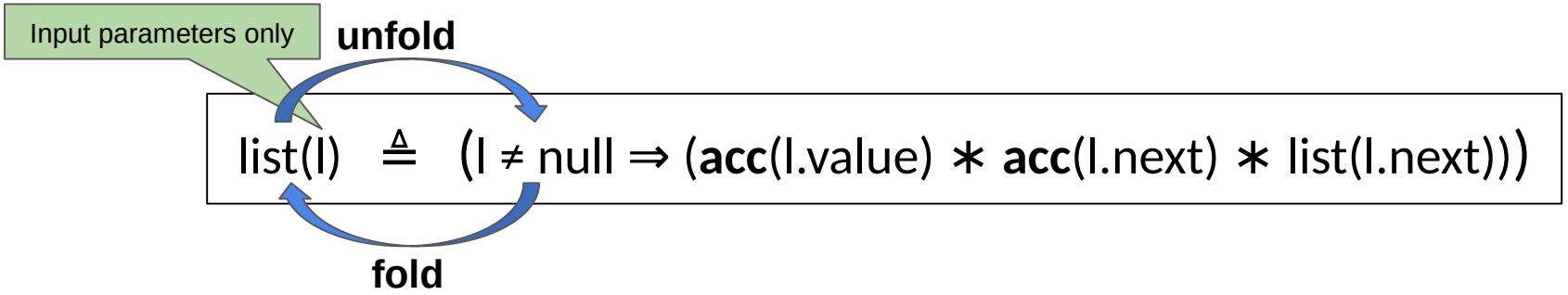

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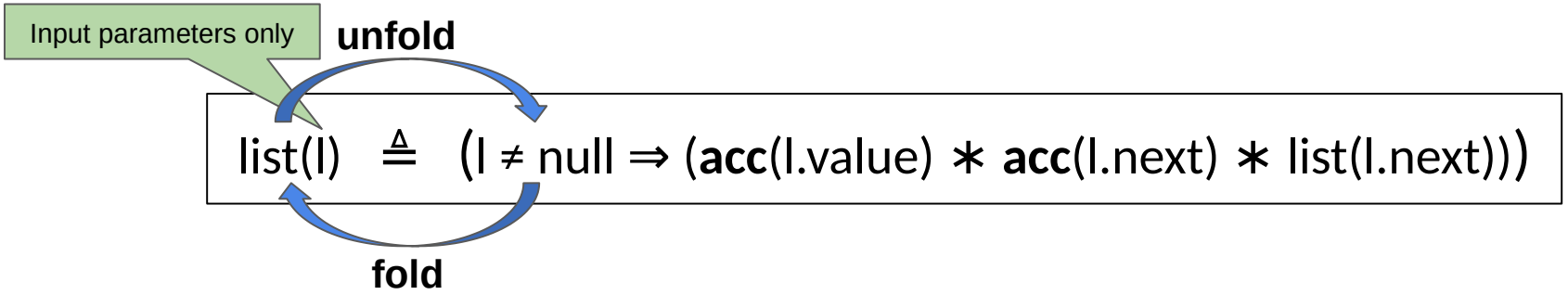

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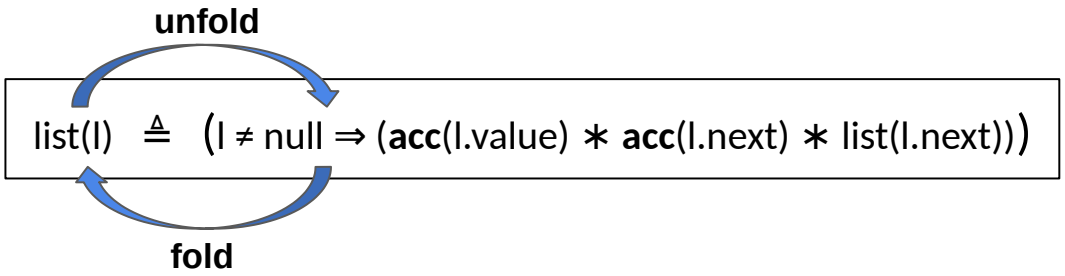
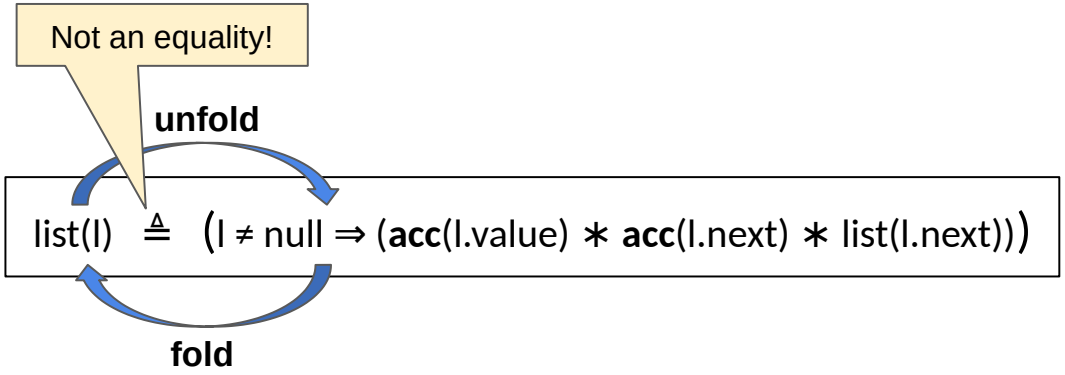
Viper's approach: Treat predicates **isorecursively**

Isorecursive Predicates



Isorecursive Predicates



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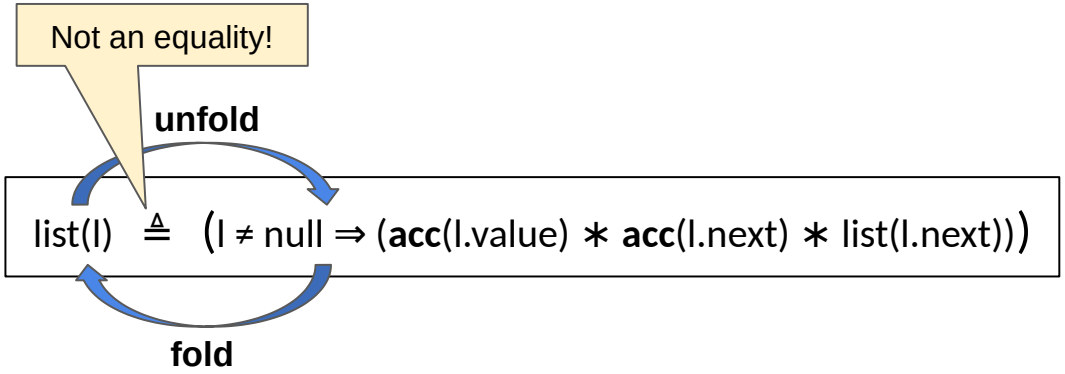
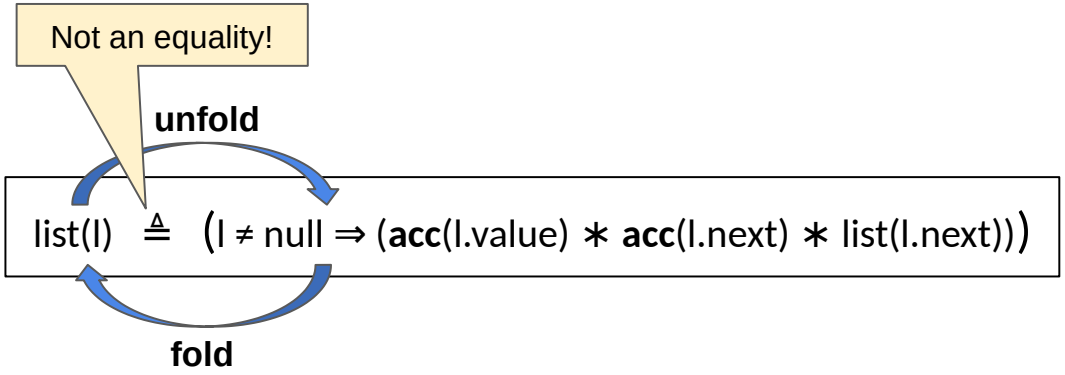


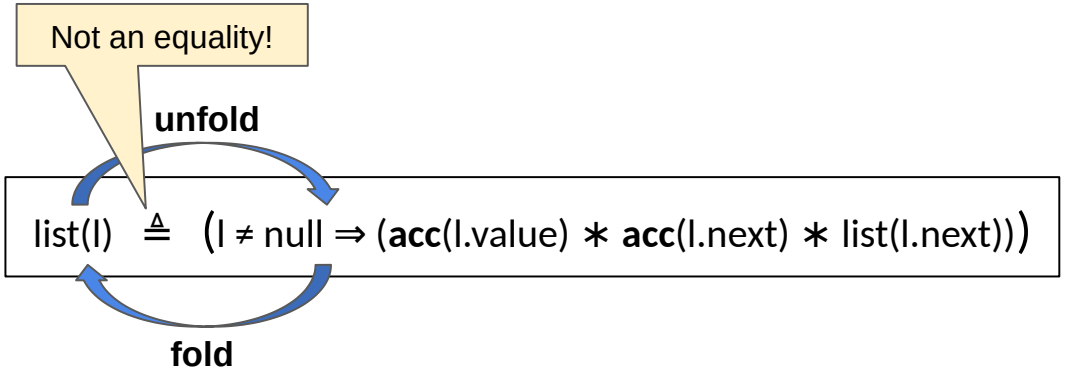
(simplified) Viper's state model: (Loc ⇀ (0, 1] × Val)

Isorecursive Predicates



(simplified) Viper's state model: (Loc ⇀ (0, 1] × Val) × (PredLoc → [0, +∞))

Isorecursive Predicates



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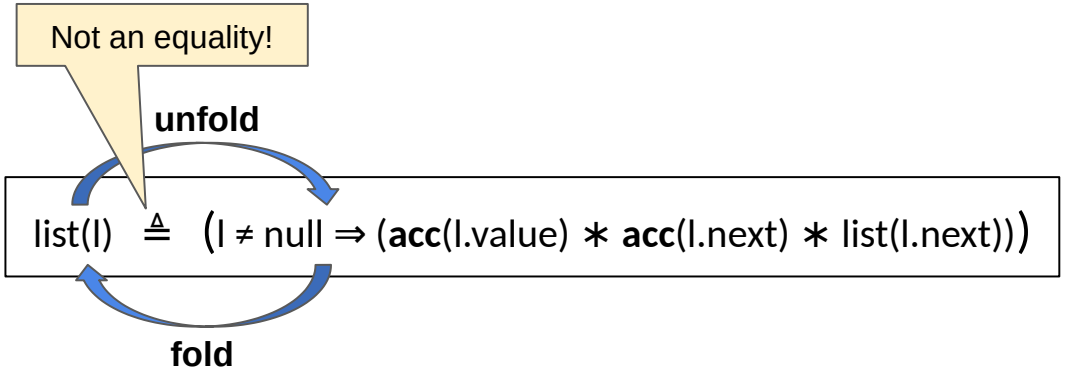
Predicate mask

Isorecursive Predicates



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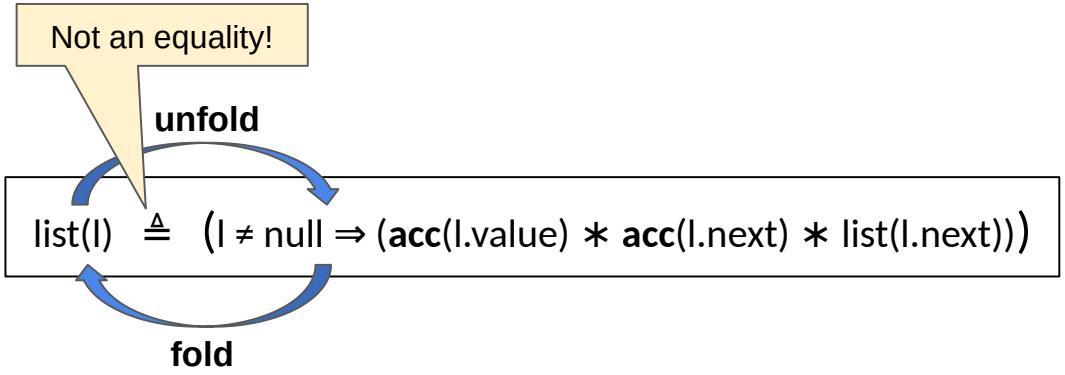

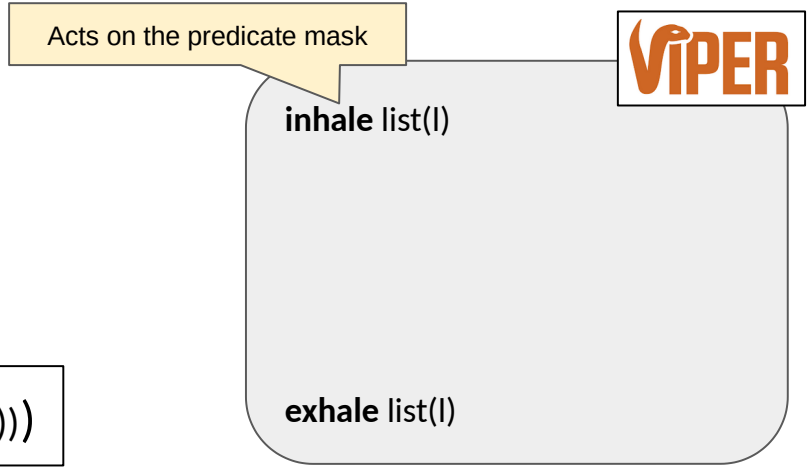

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Predicate mask

Isorecursive Predicates

Acts on the predicate mask

```
inhale list(l)
if (l != null) {

    l.value := l.value + 1


}
exhale list(l)
```

Not an equality!

unfold

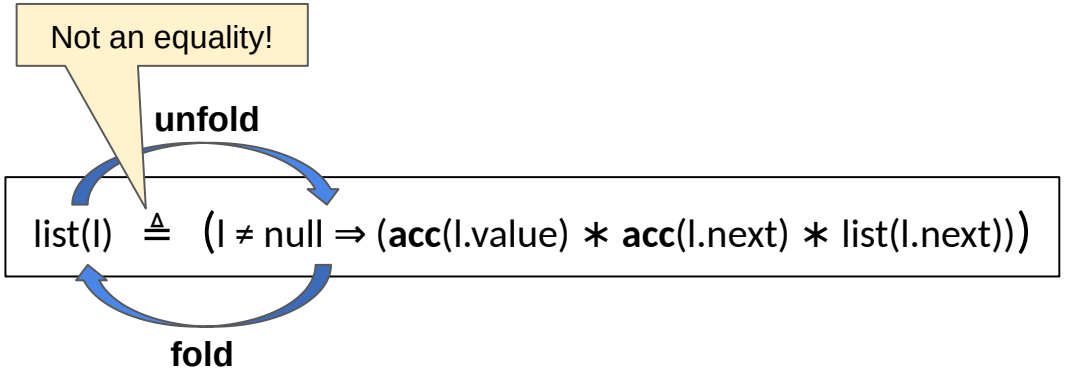
$$\text{list}(l) \triangleq (l \neq \text{null} \Rightarrow (\textbf{acc}(l.\text{value}) * \textbf{acc}(l.\text{next}) * \text{list}(l.\text{next})))$$

fold

(simplified) Viper's state model: $(\text{Loc} \rightharpoonup (0, 1] \times \text{Val}) \times (\text{PredLoc} \rightarrow [0, +\infty))$

Predicate mask

Isorecursive Predicates



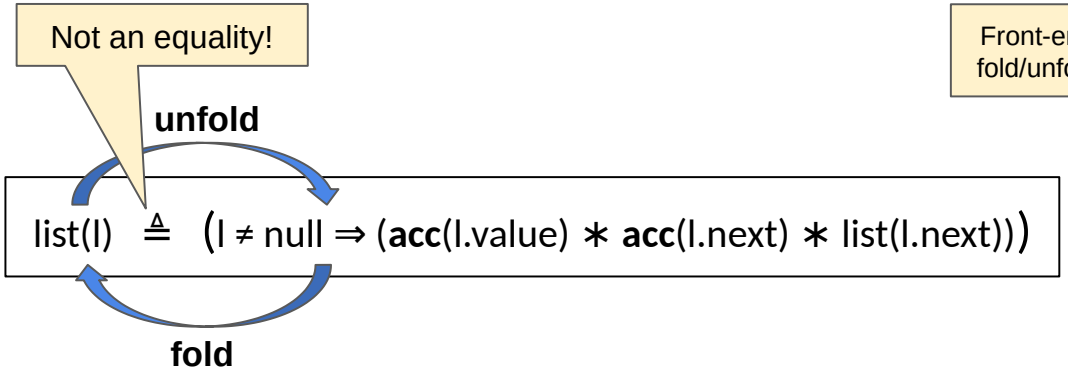
Acts on the predicate mask

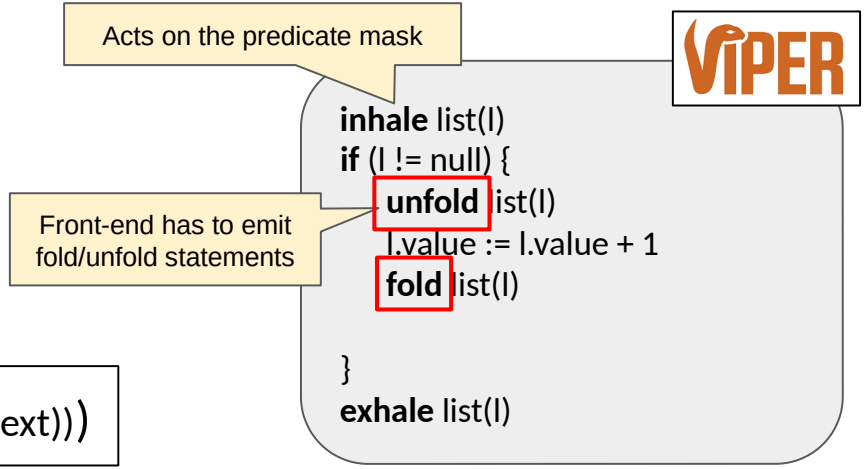
```
inhale list(l)
if (l != null) {
    unfold list(l)
    l.value := l.value + 1
    fold list(l)

}
exhale list(l)
```

(simplified) Viper's state model: $(\mathrm{Loc} \rightharpoonup (0, 1] \times \mathrm{Val}) \times (\mathrm{PredLoc} \rightarrow [0, +\infty))$

Predicate mask

Isorecursive Predicates





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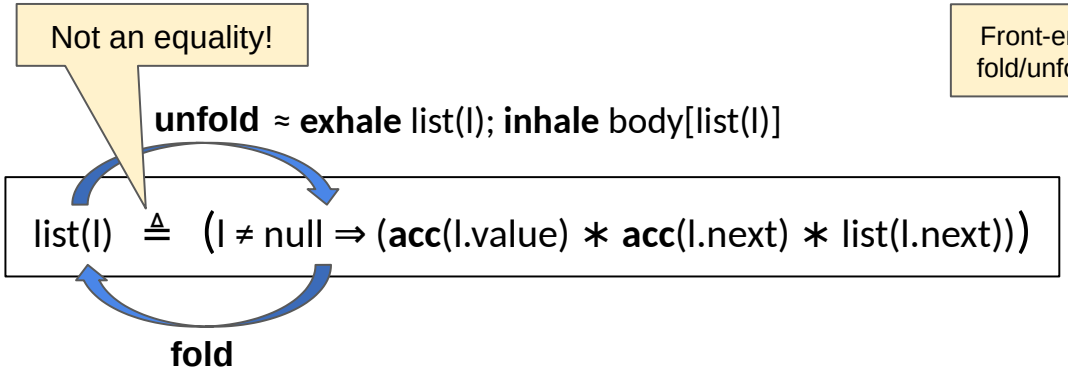

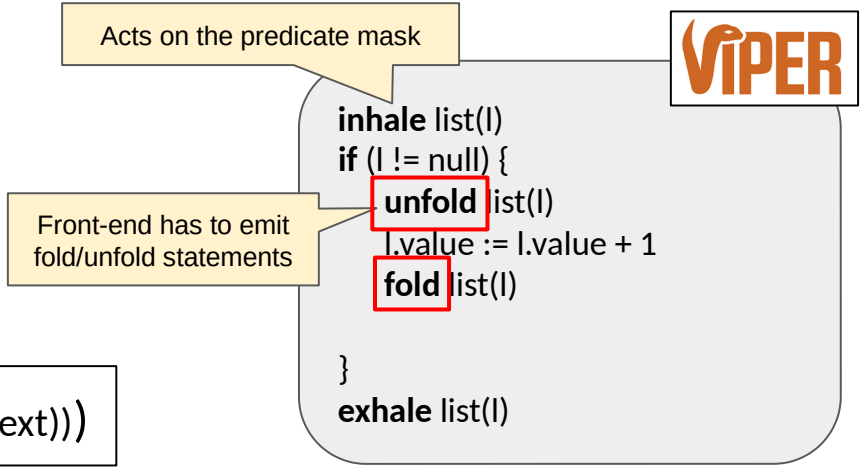

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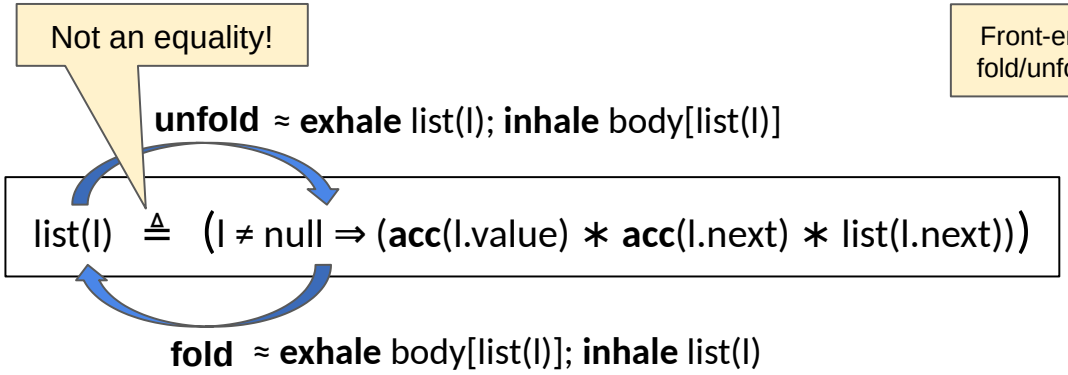

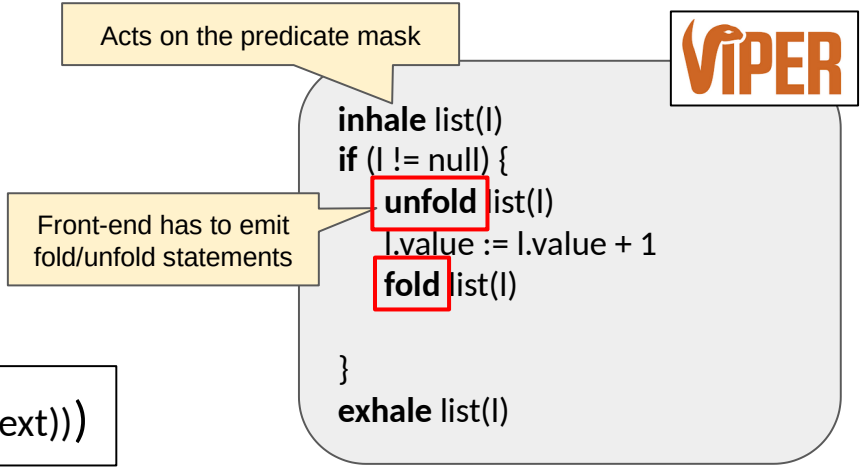

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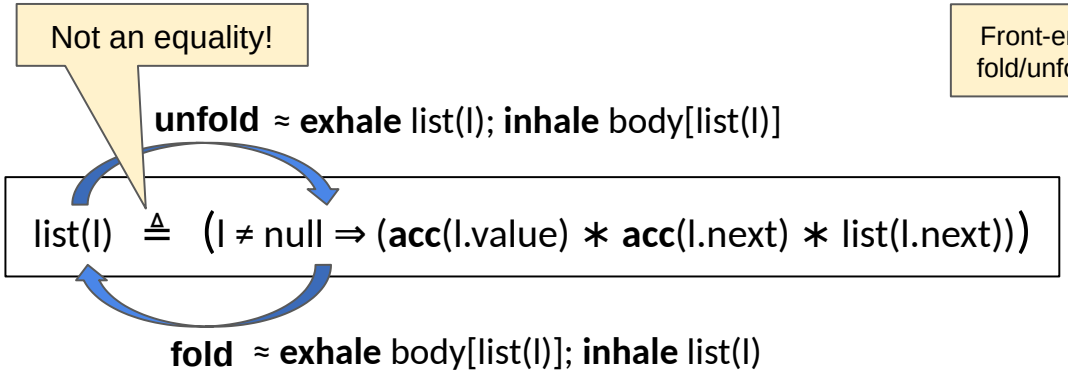
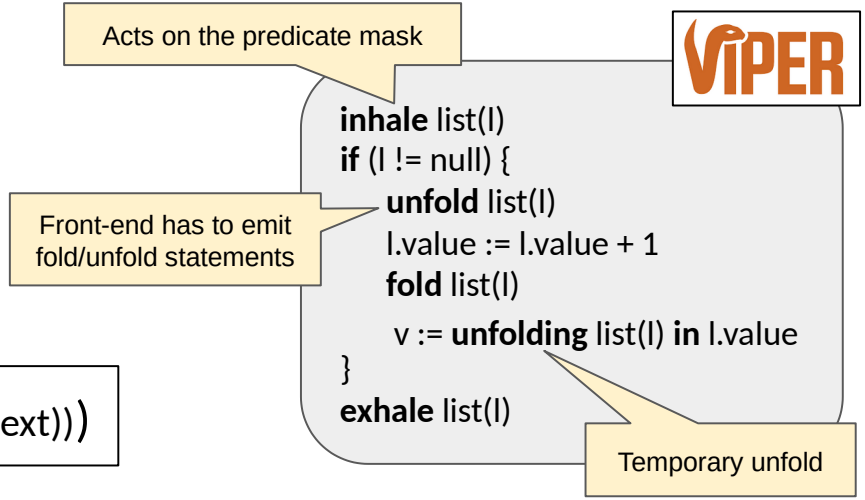
Isorecursive Predicates

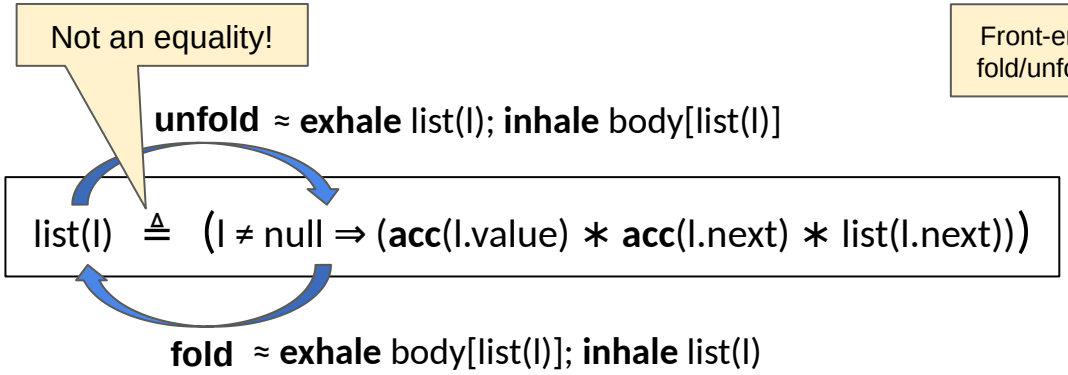


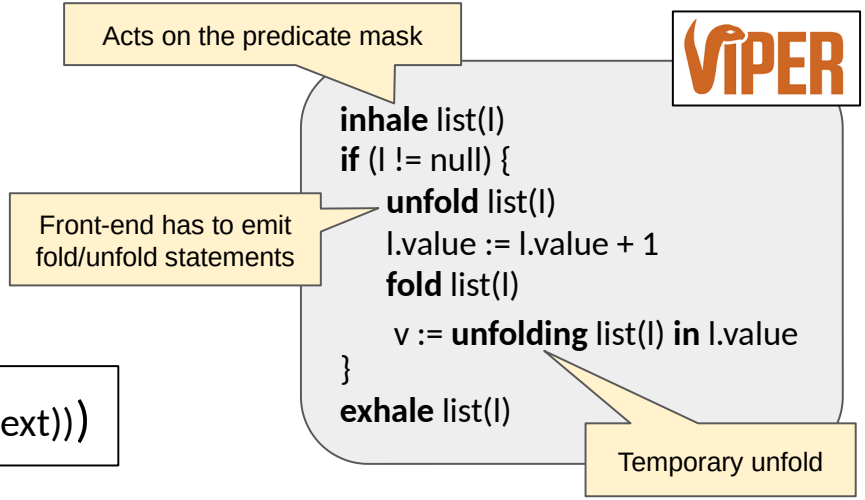


(simplified) Viper's state model: $(\text{Loc} \rightharpoonup (0, 1] \times \text{Val}) \times (\text{PredLoc} \rightarrow [0, +\infty))$

Predicate mask

Isorecursive Predicates

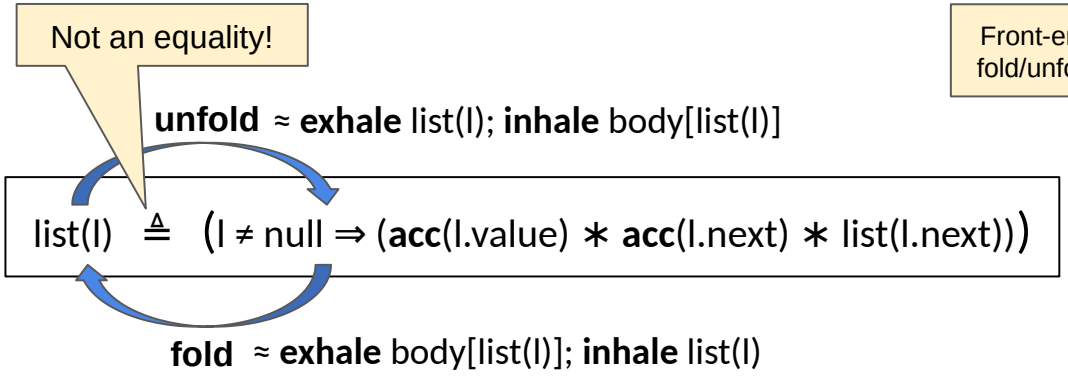


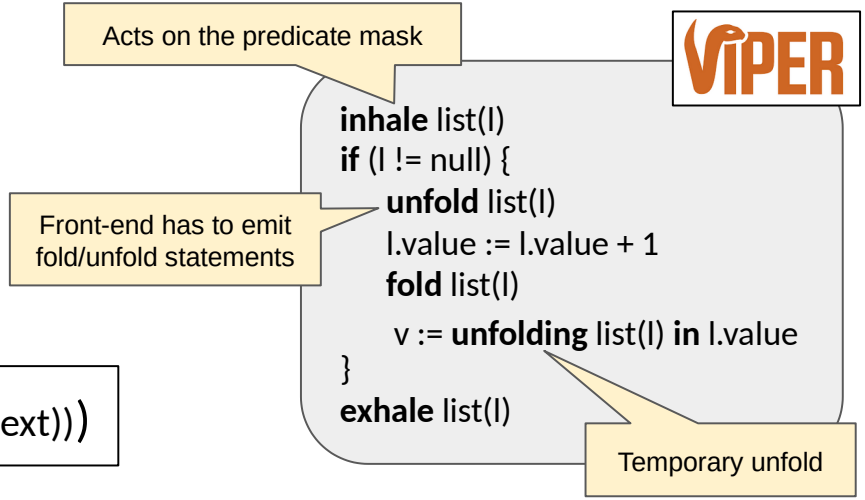


(simplified) Viper's state model: $(\text{Loc} \rightharpoonup (0, 1] \times \text{Val}) \times (\text{PredLoc} \rightarrow [0, +\infty)) \times \ldots \times \ldots \times \ldots$

Predicate mask

Isorecursive Predicates



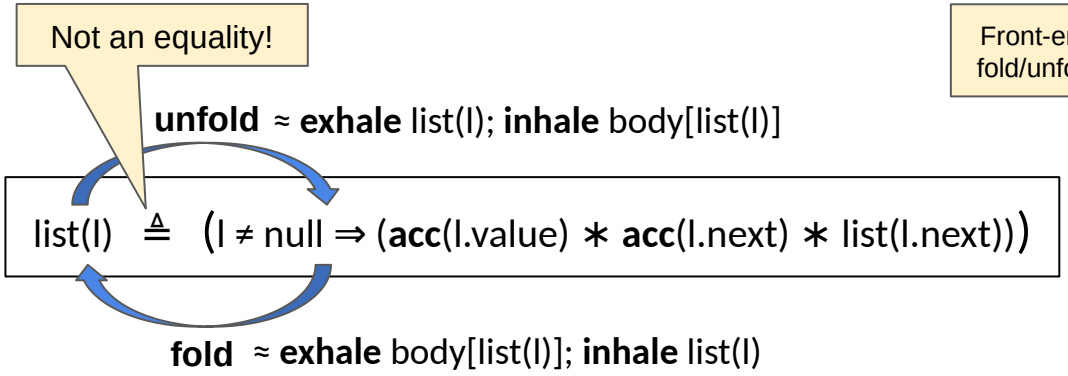


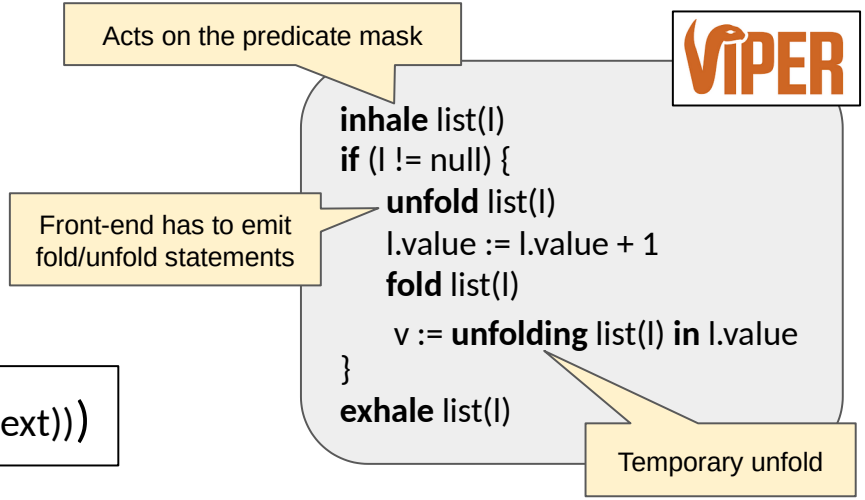
(simplified) Viper's state model: (Loc ⇀ (0, 1] × Val) × (PredLoc → [0, +∞)) × ... × ... × ...

Information about predicates' contents

Predicate mask

Isorecursive Predicates





(simplified) Viper's state model: (Loc ⇀ (0, 1] × Val) × (PredLoc → [0, +∞)) × ... × ... × ...

Information about predicates' contents

Predicate mask

Magic wands

Isorecursive Predicates

Not an equality!

unfold ≈ **exhale** list(l); **inhale** body[list(l)]

$$\text{list}(l) \triangleq (l \neq \text{null} \Rightarrow (\textbf{acc}(l.\text{value}) * \textbf{acc}(l.\text{next}) * \text{list}(l.\text{next})))$$

fold ≈ **exhale** body[list(l)]; **inhale** list(l)

Acts on the predicate mask

Front-end has to emit fold/unfold statements

```
inhale list(l)
if (l != null) {
    unfold list(l)
    l.value := l.value + 1
    fold list(l)
    v := unfolding list(l) in l.value
}
exhale list(l)
```

Temporary unfold

(simplified) Viper's state model: $(\text{Loc} \rightharpoonup (0, 1] \times \text{Val}) \times (\text{PredLoc} \rightarrow [0, +\infty)) \times \ldots \times \ldots \times \ldots$

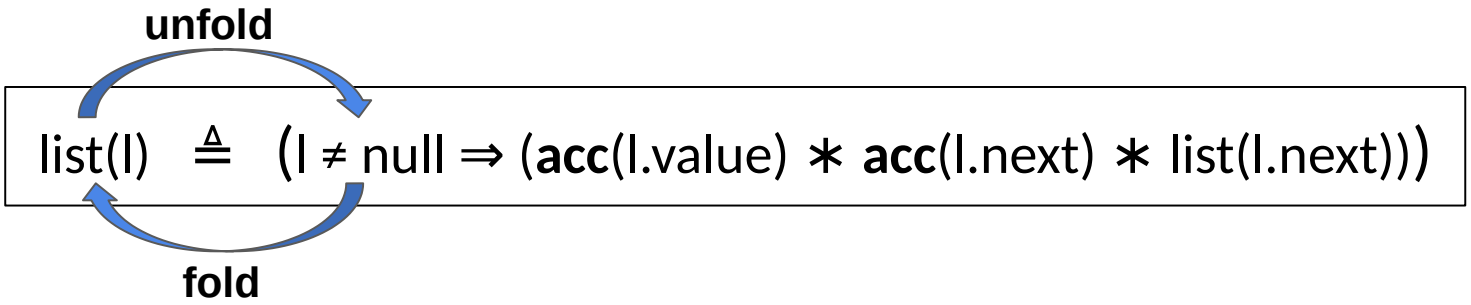
Information about predicates' contents

Information about old states

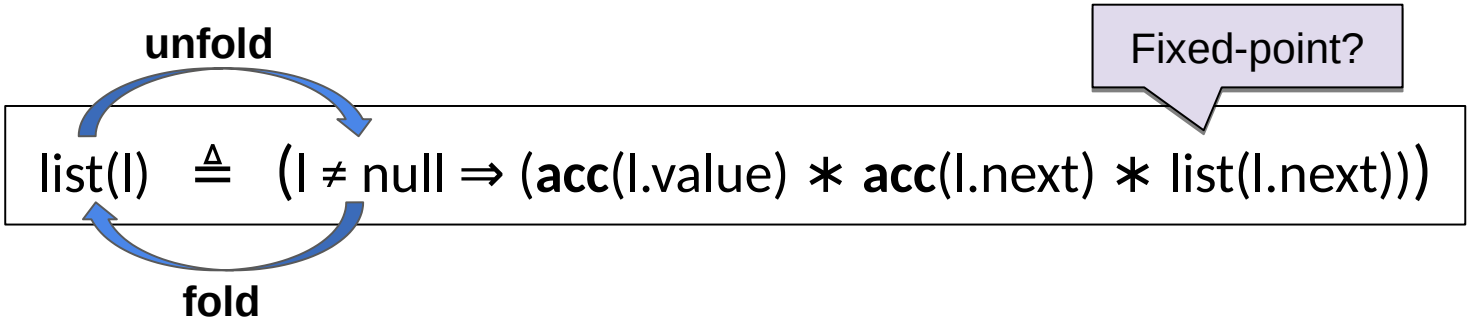
Predicate mask

Magic wands

Existence of a Fixed-Point



Existence of a Fixed-Point



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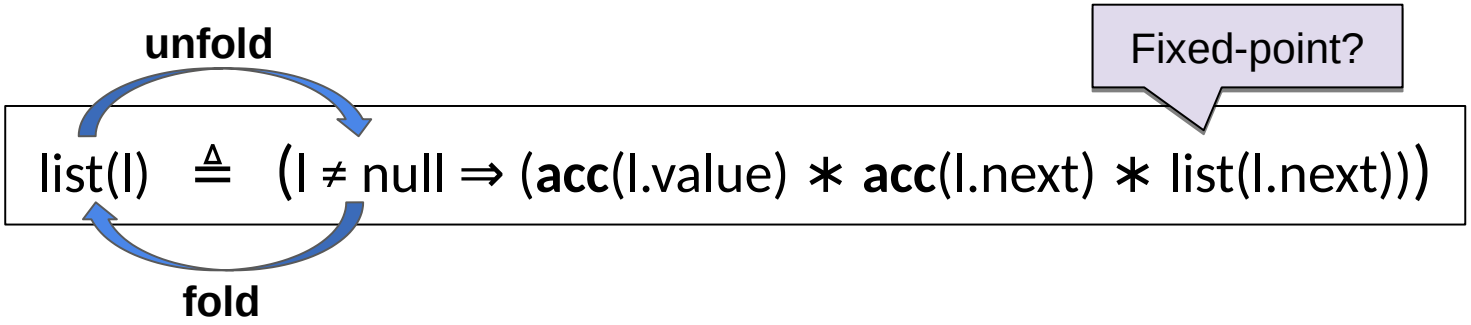
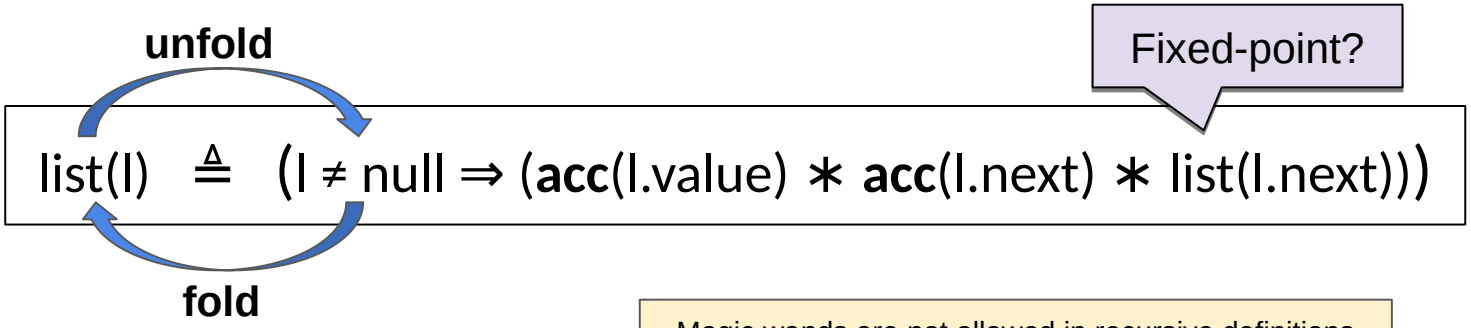


A ::= b | **acc**(e_1.x, e_2) | **acc**(P(e_1, …, e_n), e) | A_1 ∗ A_2 | A_1 −∗ A_2 | ⊛v. A | b ⇒ A | …

Existence of a Fixed-Point



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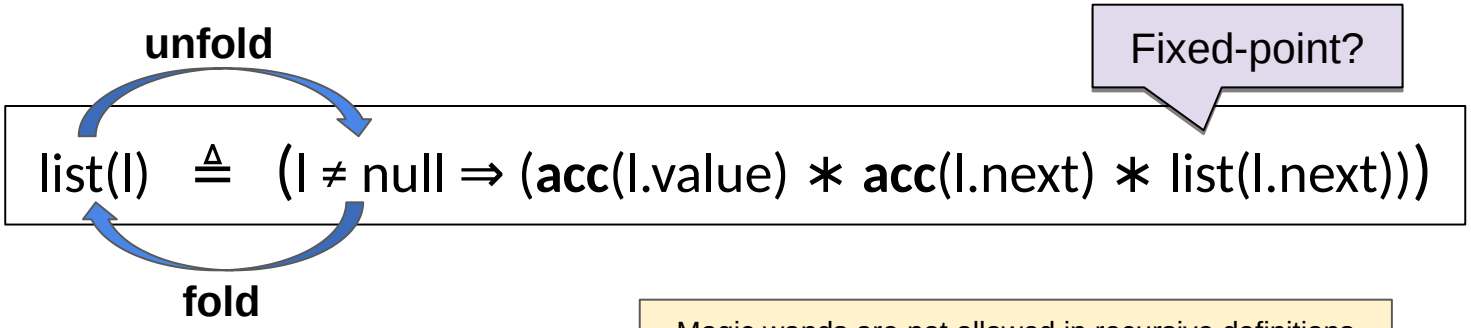
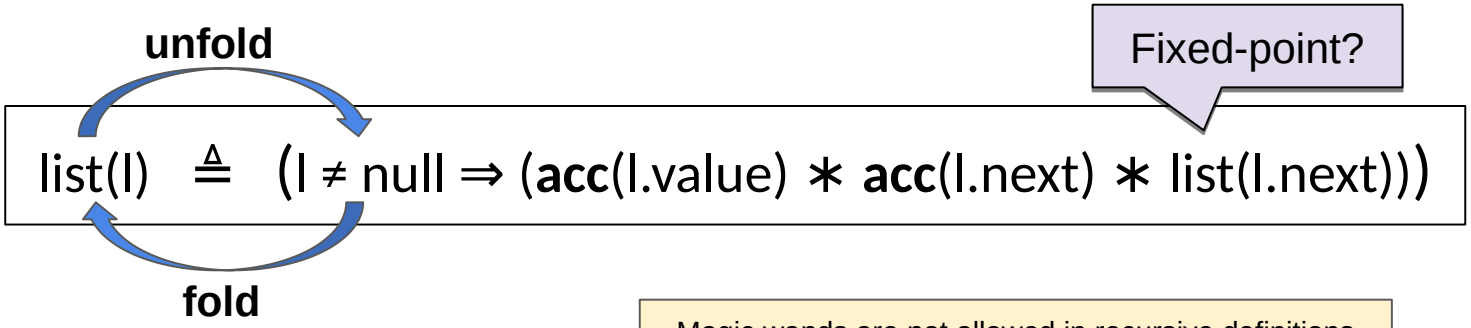


Magic wands are not allowed in recursive definitions

$A ::= b \mid \mathbf{acc}(e_1.x, e_2) \mid \mathbf{acc}(P(e_1, \ldots, e_n), e) \mid A_1 \ast A_2 \mid A_1 -\!\!\ast A_2 \mid \circledast v.\, A \mid b \Rightarrow A \mid \ldots$

Scott-continuity

Existence of a Fixed-Point



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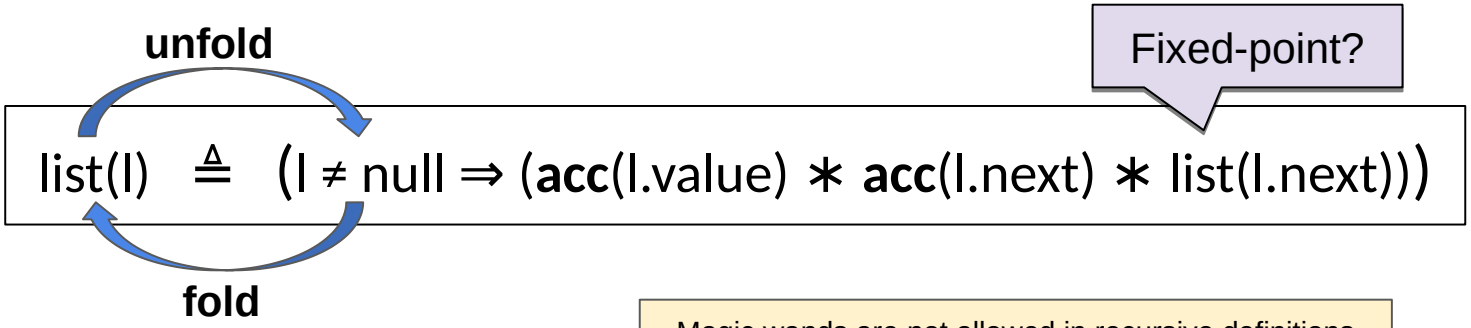
Existence of a least fixed point

Scott-continuity

Existence of a Fixed-Point



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Scott-continuity

- Existence of a least fixed point
- Kleene's theorem → Any given predicate instance has a **finite** number of predicate instances folded within it

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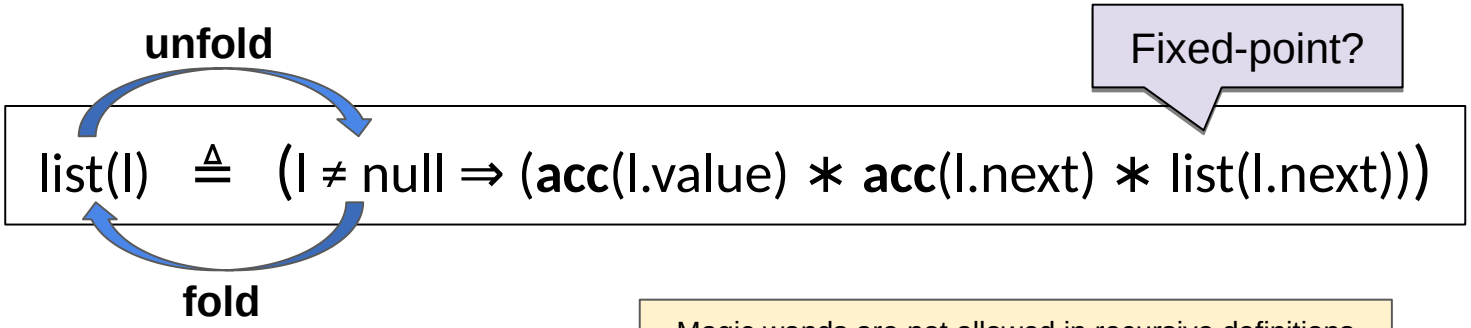

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Scott-continuity

- Existence of a least fixed point
- Kleene's theorem → Any given predicate instance has a **finite** number of predicate instances folded within it

Can be used as a termination measure (e.g., for heap-dependent functions)

Heap-Dependent Functions

$$\text{list}(l) \triangleq (l \neq \text{null} \Rightarrow (\mathbf{acc}(l.\text{value}) * \mathbf{acc}(l.\text{next}) * \text{list}(l.\text{next})))$$

Heap-Dependent Functions

$$\text{list}(l) \triangleq (l \neq \text{null} \Rightarrow (\textbf{acc}(l.\text{value}) * \textbf{acc}(l.\text{next}) * \text{list}(l.\text{next})))$$


```
function len(l): Int
    requires list(l)

{ l == null ? 0 : unfolding list(l) in 1 + len(l.next) }
```

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```
function len(l): Int
    requires list(l)
    ensures result >= 0
{ l == null ? 0 : unfolding list(l) in 1 + len(l.next) }
```

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$$\text{list}(l) \triangleq (l \neq \text{null} \Rightarrow (\textbf{acc}(l.\text{value}) * \textbf{acc}(l.\text{next}) * \text{list}(l.\text{next})))$$

Automatically proven by induction


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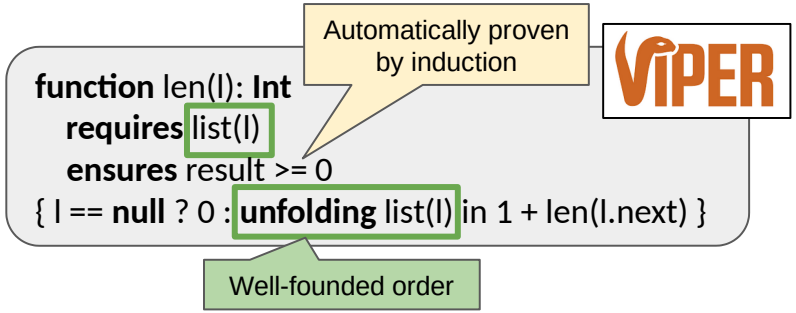

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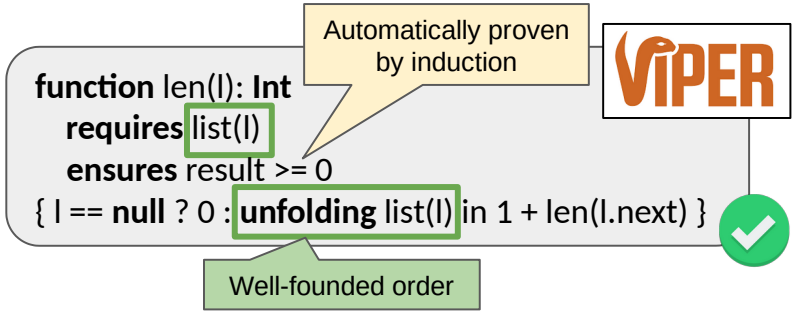

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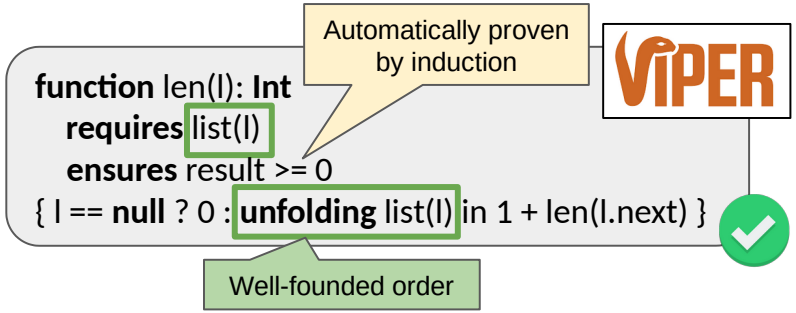

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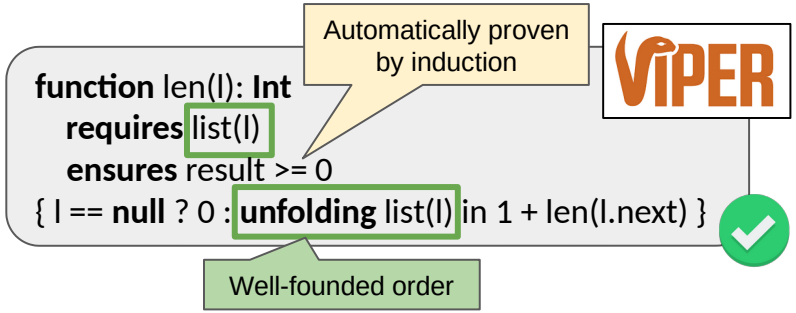

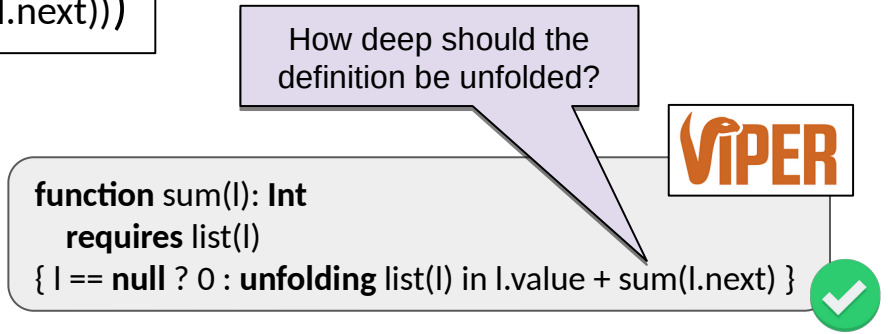

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function len(l): Int
    requires list(l)
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{ l == null ? 0 : unfolding list(l) in 1 + len(l.next) }
```

Well-founded order

How deep should the definition be unfolded?

```
function sum(l): Int
    requires list(l)
{ l == null ? 0 : unfolding list(l) in l.value + sum(l.next) }
```

```
method main(l: Ref)
    requires list(l) * len(l) >= 2
    ensures list(l) * sum(l) == old(sum(l)) + 5
{


    l.next.value := l.next.value + 5


}
```

Heap-Dependent Functions

$$\text{list}(l) \triangleq (l \neq \text{null} \Rightarrow (\textbf{acc}(l.\text{value}) * \textbf{acc}(l.\text{next}) * \text{list}(l.\text{next})))$$

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    ensures list(l) * sum(l) == old(sum(l)) + 5
{
    unfold list(l)
    unfold list(l.next)
    l.next.value := l.next.value + 5
    fold list(l.next)
    fold list(l)
}
```

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{
    unfold list(l)
    unfold list(l.next)
    l.next.value := l.next.value + 5
    fold list(l.next)
    fold list(l)
}
```

sum(l) = l.value + sum(l.next)

Heap-Dependent Functions

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{
    unfold list(l)
    unfold list(l.next)
    l.next.value := l.next.value + 5
    fold list(l.next)
    fold list(l)
}
```

sum(l) = l.value + sum(l.next)

sum(l) = l.value + l.next.value + sum(l.next.next)

Heap-Dependent Functions

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    ensures list(l) * sum(l) == old(sum(l)) + 5
{
    unfold list(l)
    unfold list(l.next)
    l.next.value := l.next.value + 5
    fold list(l.next)
    fold list(l)
}
```

sum(l) = l.value + sum(l.next)

sum(l) = l.value + l.next.value + sum(l.next.next)

Output parameter of list(l.next.next)

Heap-Dependent Functions

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    l.next.value := l.next.value + 5
    fold list(l.next)
    fold list(l)
}
```

sum(l) = l.value + sum(l.next)

sum(l) = l.value + l.next.value + sum(l.next.next)

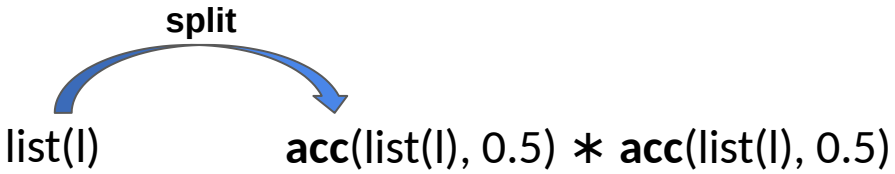
Output parameter of list(l.next.next)

Fractional (Recursive) Predicates

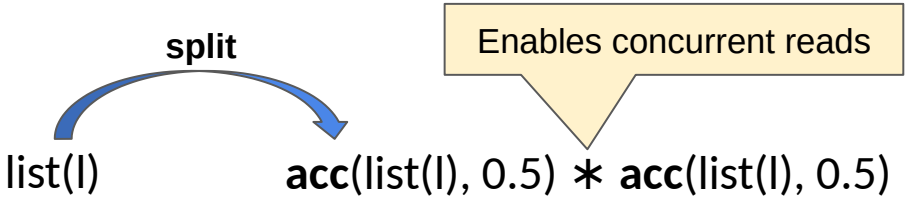
Fractional (Recursive) Predicates

list(l)

Fractional (Recursive) Predicates



Fractional (Recursive) Predicates



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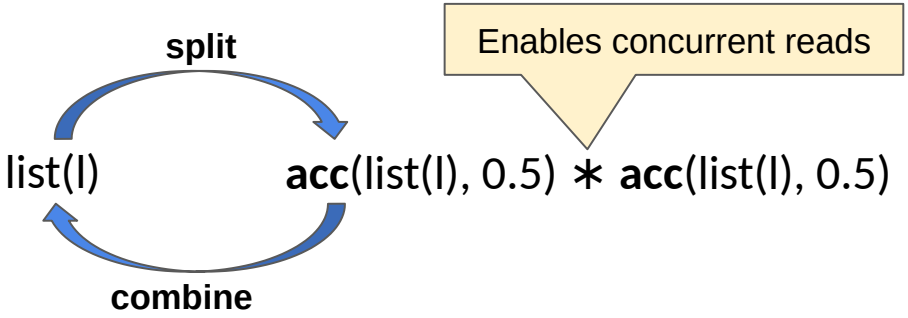
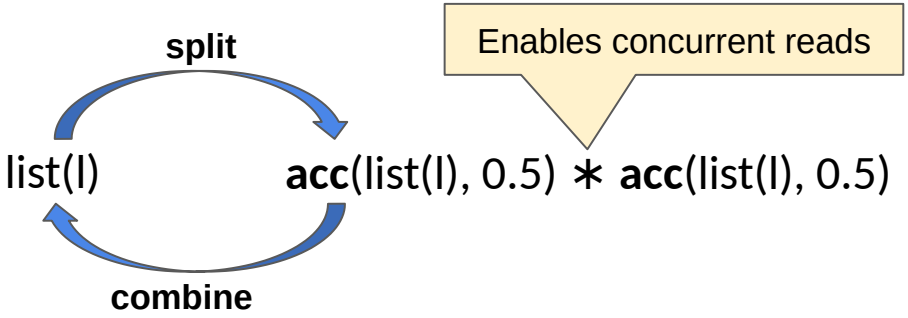
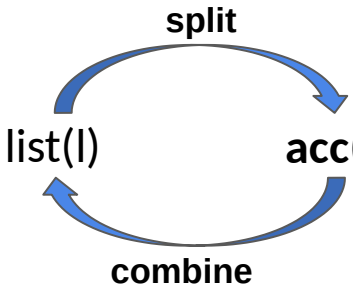


Fractional (Recursive) Predicates



inhale list(l)
…
exhale acc(list(l), 0.5)
…
inhale acc(list(l), 0.5)
…
exhale list(l)

Fractional (Recursive) Predicates



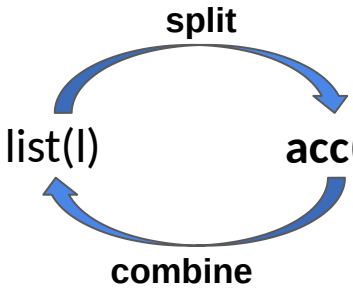
Enables concurrent reads

acc(list(l), 0.5) ∗ **acc**(list(l), 0.5)

Acts on the predicate mask

inhale list(l)
…
exhale acc(list(l), 0.5)
…
inhale acc(list(l), 0.5)
…
exhale list(l)

Fractional (Recursive) Predicates



Enables concurrent reads

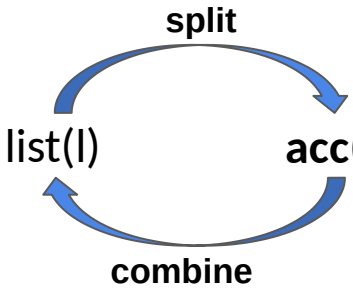
acc(list(l), 0.5) ∗ **acc**(list(l), 0.5)

Acts on the predicate mask

```
inhale list(l)
...
exhale acc(list(l), 0.5)
...
inhale acc(list(l), 0.5)
...
exhale list(l)
```

list(l) ≜ (l ≠ null ⇒ (**acc**(l.value) ∗ **acc**(l.next) ∗ list(l.next)))

Fractional (Recursive) Predicates



Enables concurrent reads

acc(list(l), 0.5) ∗ **acc**(list(l), 0.5)

Acts on the predicate mask

inhale list(l)
...
exhale acc(list(l), 0.5)
...
inhale acc(list(l), 0.5)
...
exhale list(l)

list(l) ≜ (l ≠ null ⇒ (**acc**(l.value) ∗ **acc**(l.next) ∗ list(l.next)))

automatically derived (syntactically)

acc(list(l), 0.5) ≜ (l ≠ null ⇒ (**acc**(l.value, 0.5) ∗ **acc**(l.next, 0.5) ∗ **acc**(list(l.next, 0.5))))

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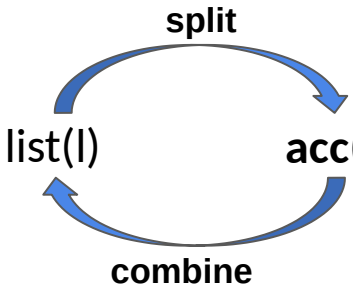

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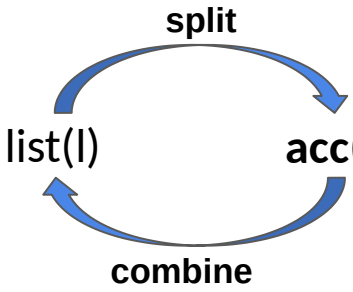

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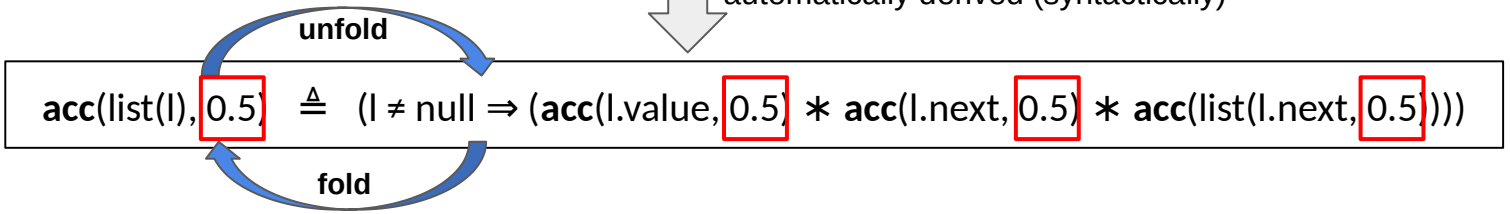
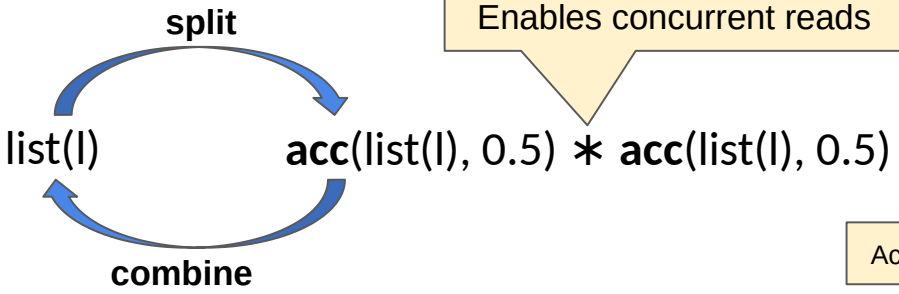
automatically derived (syntactically)



Fractional (Recursive) Predicates



Enables concurrent reads

Acts on the predicate mask

```
inhale list(l)
...
exhale acc(list(l), 0.5)
...
inhale acc(list(l), 0.5)
...
exhale list(l)
```

$$\text{list}(l) \triangleq (l \neq \text{null} \Rightarrow (\textbf{acc}(l.\text{value}) * \textbf{acc}(l.\text{next}) * \text{list}(l.\text{next})))$$

automatically derived (syntactically)

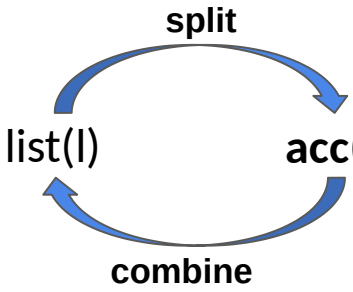
unfold

$$\textbf{acc}(\text{list}(l), 0.5) \triangleq (l \neq \text{null} \Rightarrow (\textbf{acc}(l.\text{value}, 0.5) * \textbf{acc}(l.\text{next}, 0.5) * \textbf{acc}(\text{list}(l.\text{next}, 0.5))))$$

fold

Sound for Viper (recursive) predicate definitions!

Fractional (Recursive) Predicates



$\mathbf{acc}(\text{list}(l), 0.5) * \mathbf{acc}(\text{list}(l), 0.5)$

Enables concurrent reads

Acts on the predicate mask

```
inhale list(l)
...
exhale acc(list(l), 0.5)
...
inhale acc(list(l), 0.5)
...
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```

$$\text{list}(l) \triangleq (l \neq \text{null} \Rightarrow (\mathbf{acc}(l.\text{value}) * \mathbf{acc}(l.\text{next}) * \text{list}(l.\text{next})))$$

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$$\mathbf{acc}(\text{list}(l), 0.5) \triangleq (l \neq \text{null} \Rightarrow (\mathbf{acc}(l.\text{value}, 0.5) * \mathbf{acc}(l.\text{next}, 0.5) * \mathbf{acc}(\text{list}(l.\text{next}, 0.5))))$$

fold

Sound for Viper (recursive) predicate definitions!

Theoretical foundations in our OOPSLA'22 paper
"Fractional Resources in Unbounded Separation Logic"

Outline of the Talk

1. Overview of Viper
2. Inhale and Exhale: An Operational View of Separation Logic
3. Designed for Automation
4. **Toward a Foundational Viper**

Toward a Foundational Viper

Toward a Foundational Viper

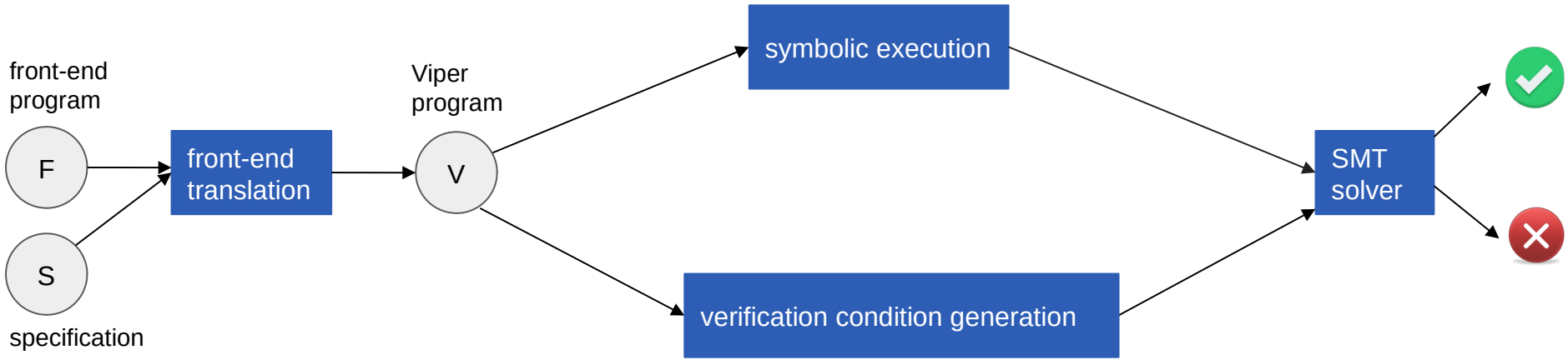
Iris from the ground up: A modular foundation for higher-order concurrent separation logic
Ralf Jung, Robert Krebbers, Jacques-Henri Jourdan, Aleš Bizjak, Lars Birkedal, Derek Dreyer

Toward a Foundational Viper

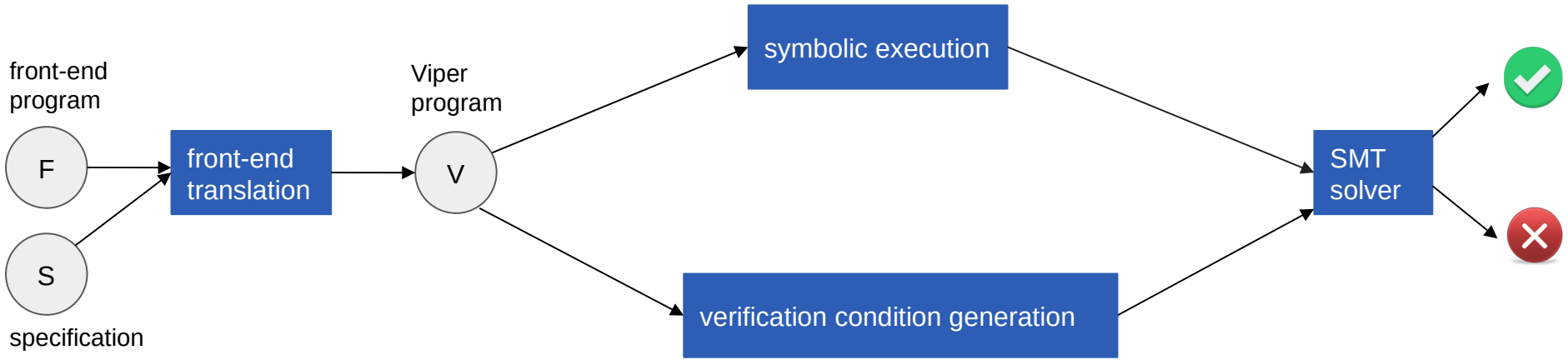
> “This [foundational approach] is in contrast to tools like [...] **Viper**, which have much larger trusted computing bases because they assume the soundness of non-trivial extensions of Hoare logic and do not produce independently checkable proof terms.”

Iris from the ground up: A modular foundation for higher-order concurrent separation logic
Ralf Jung, Robert Krebbers, Jacques-Henri Jourdan, Aleš Bizjak, Lars Birkedal, Derek Dreyer

Soundness


front-end
program
F
S
specification
front-end
translation
Viper
program
V
symbolic execution
verification condition generation
SMT
solver

Soundness

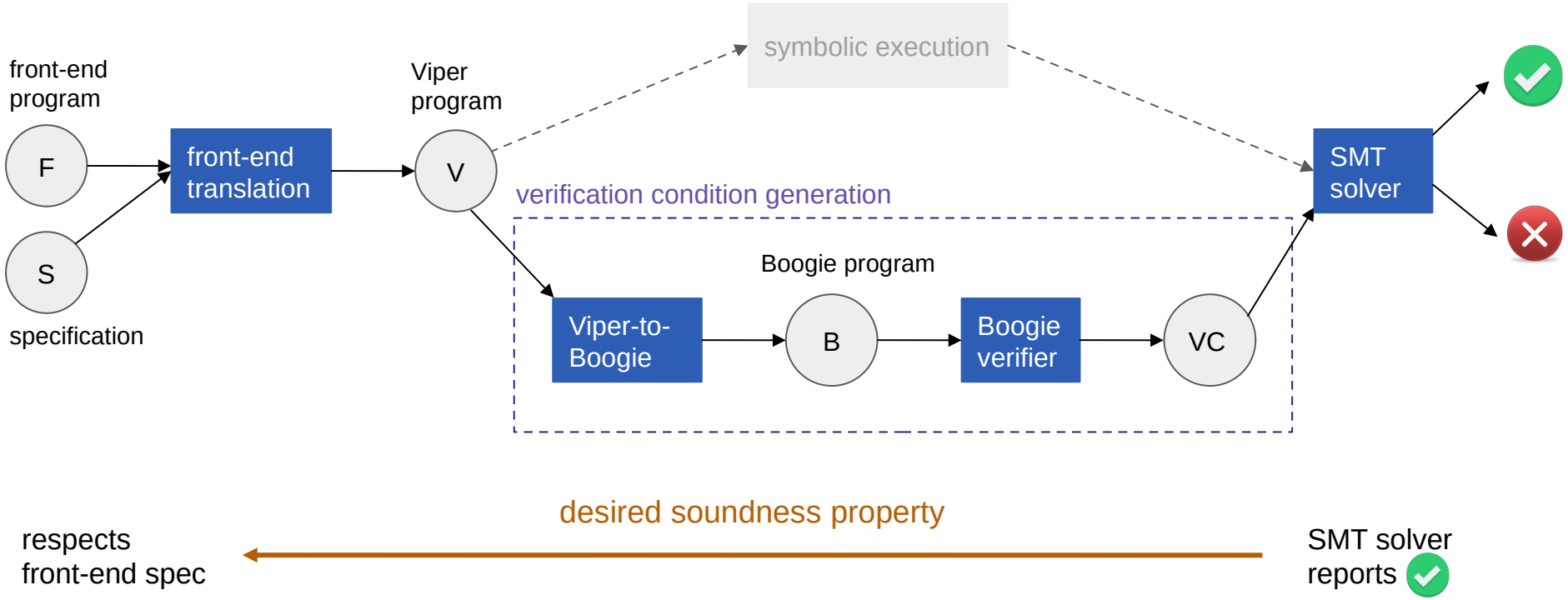


desired soundness property

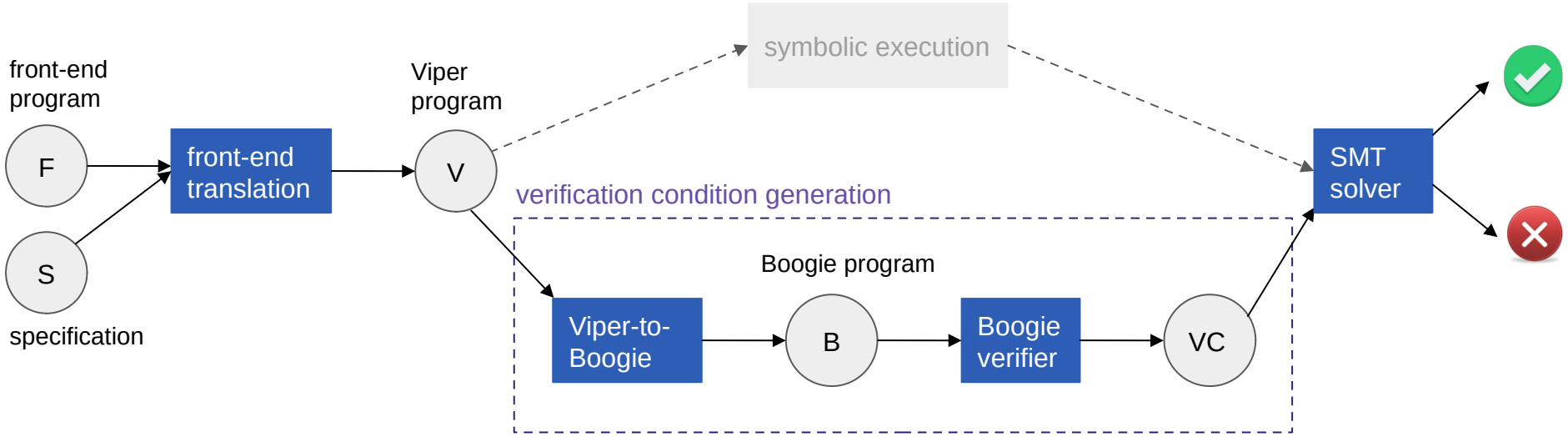
respects
front-end spec

SMT solver
reports

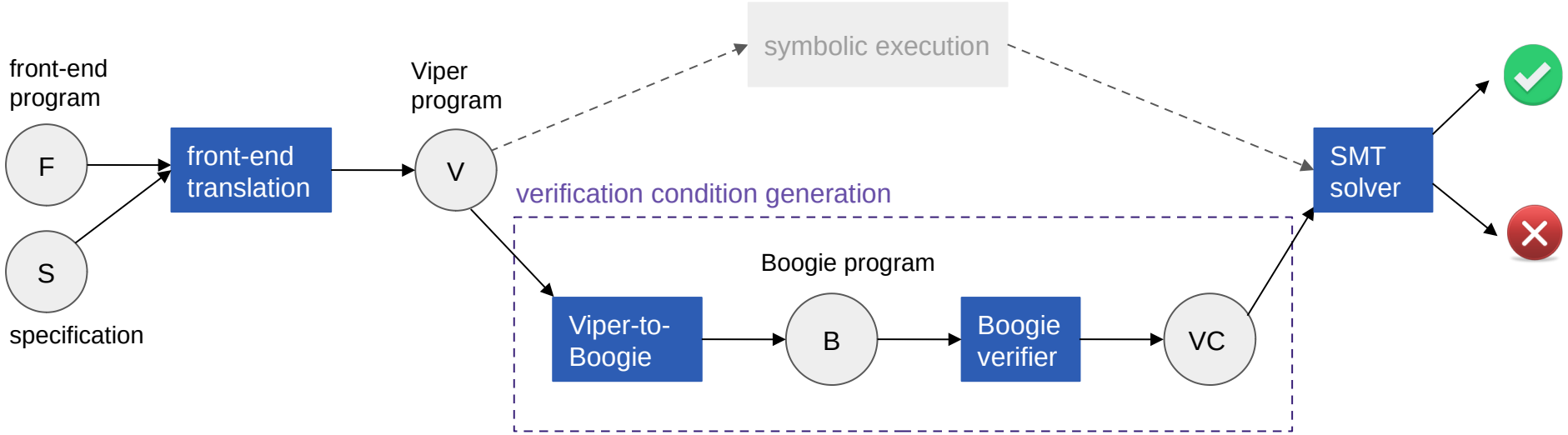
Soundness


front-end program
F
S
specification
front-end translation
Viper program
V
symbolic execution
verification condition generation
Boogie program
Viper-to-Boogie
B
Boogie verifier
VC
SMT solver
desired soundness property
respects front-end spec
SMT solver reports

Soundness: Proof Strategy

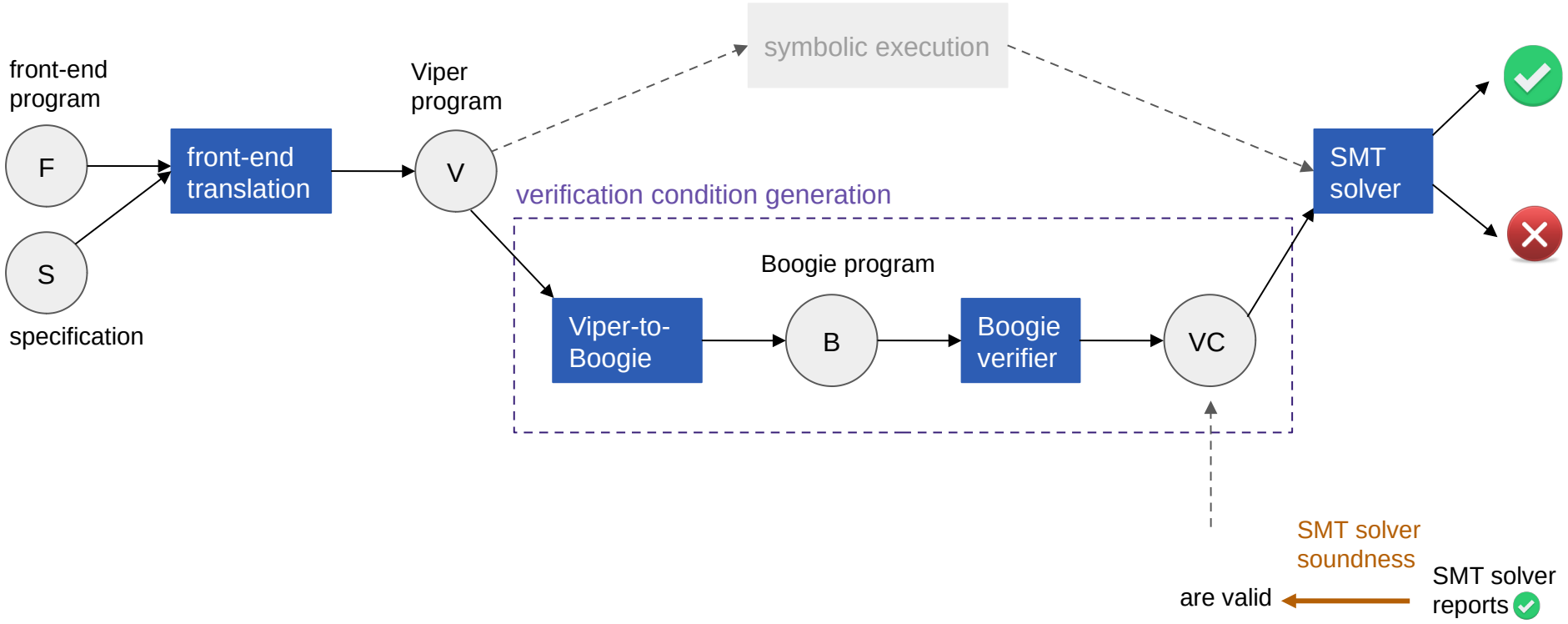


Soundness: Proof Strategy



SMT solver reports

Soundness: Proof Strategy



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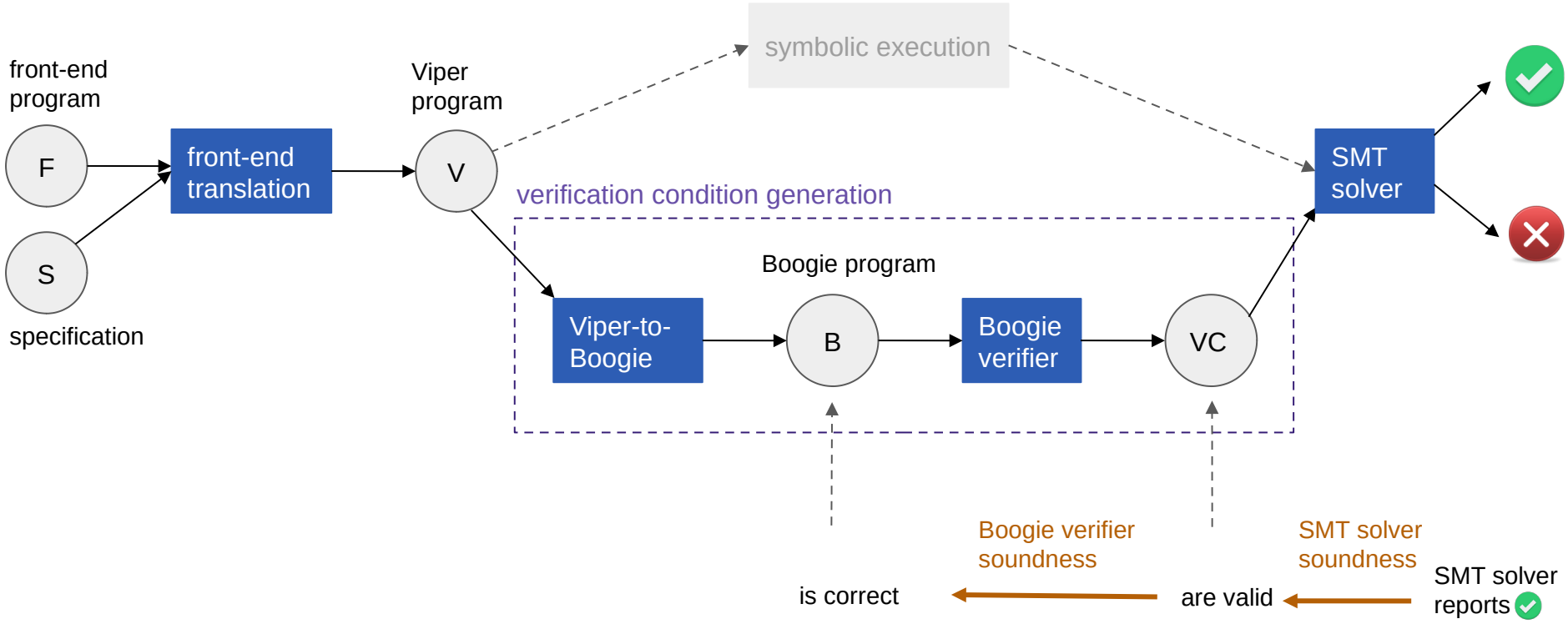
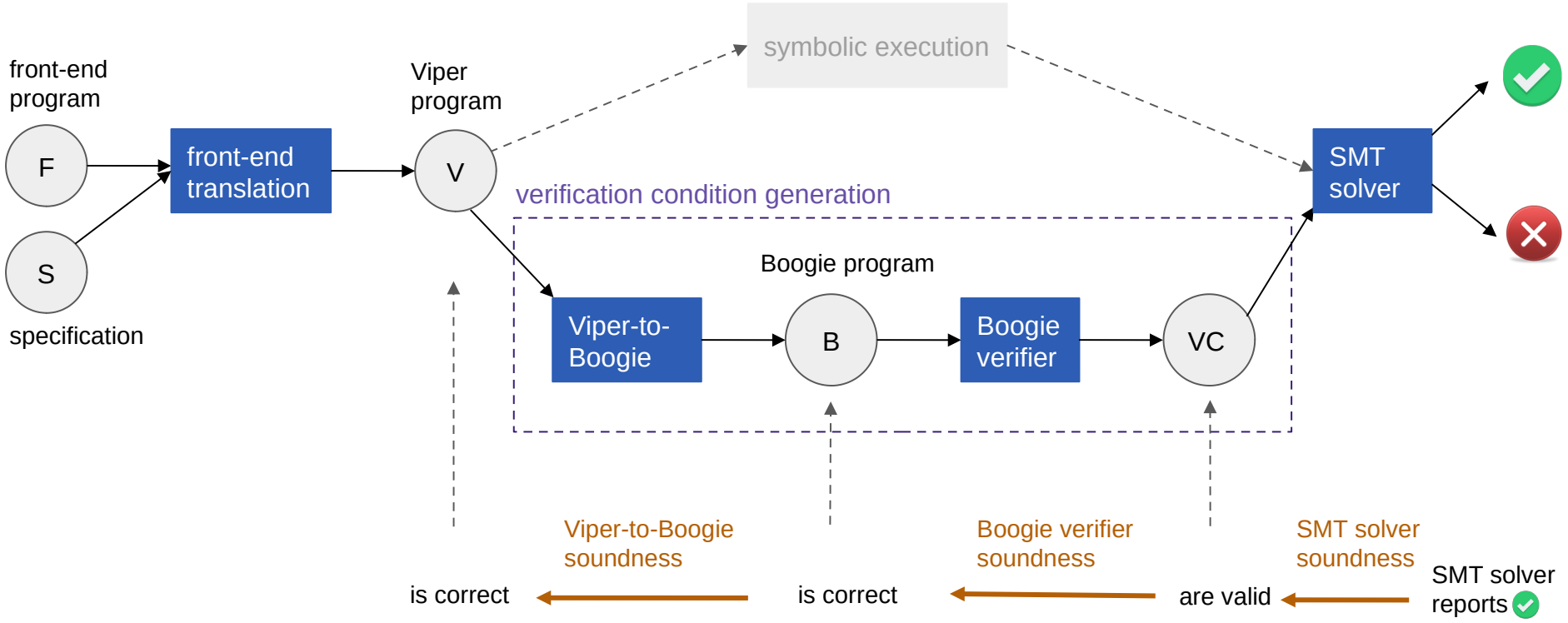


Soundness: Proof Strategy



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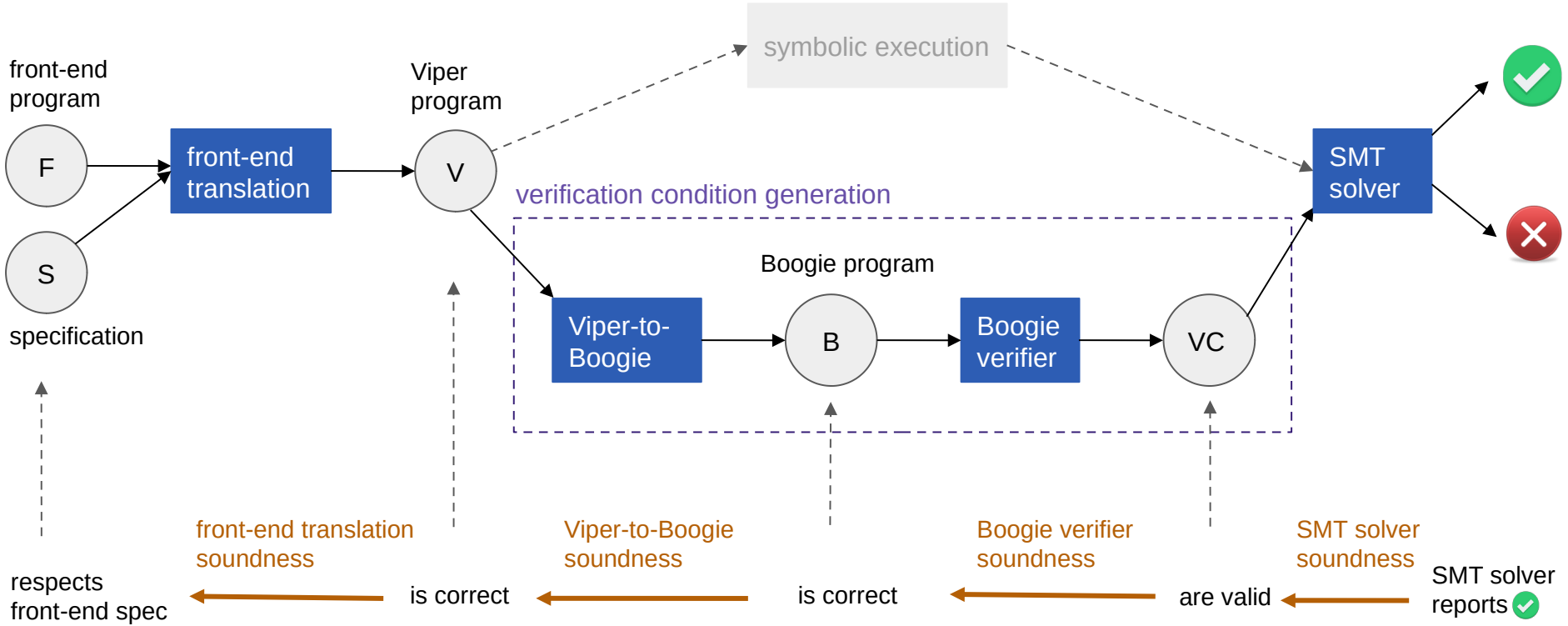

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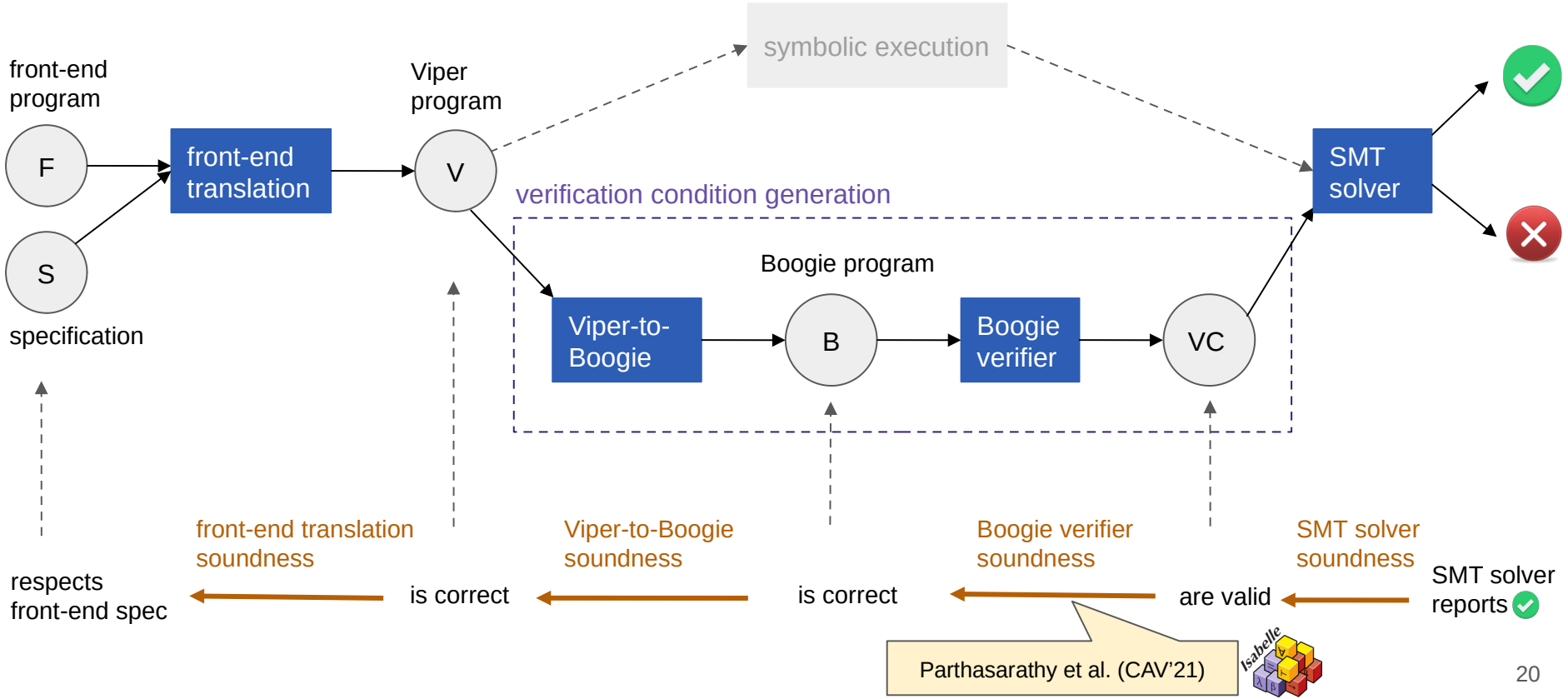

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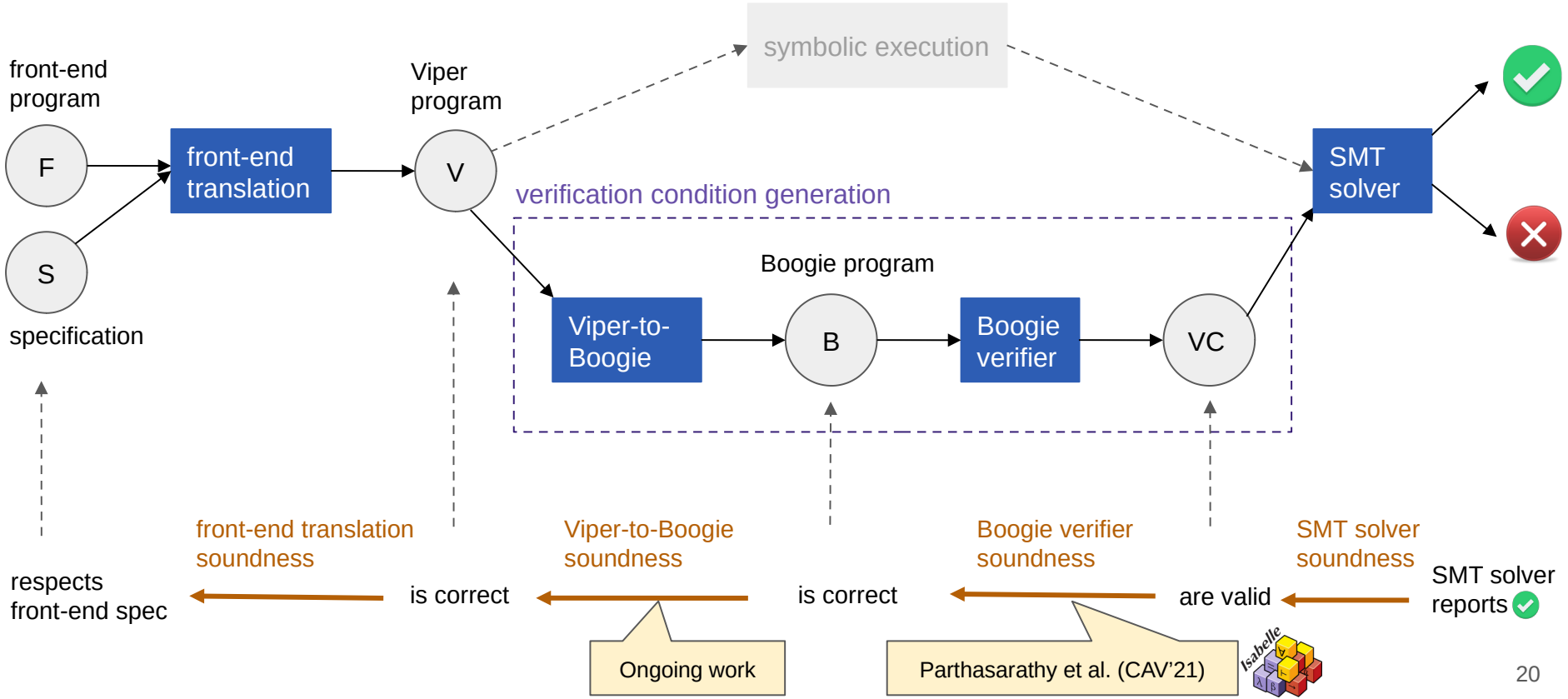

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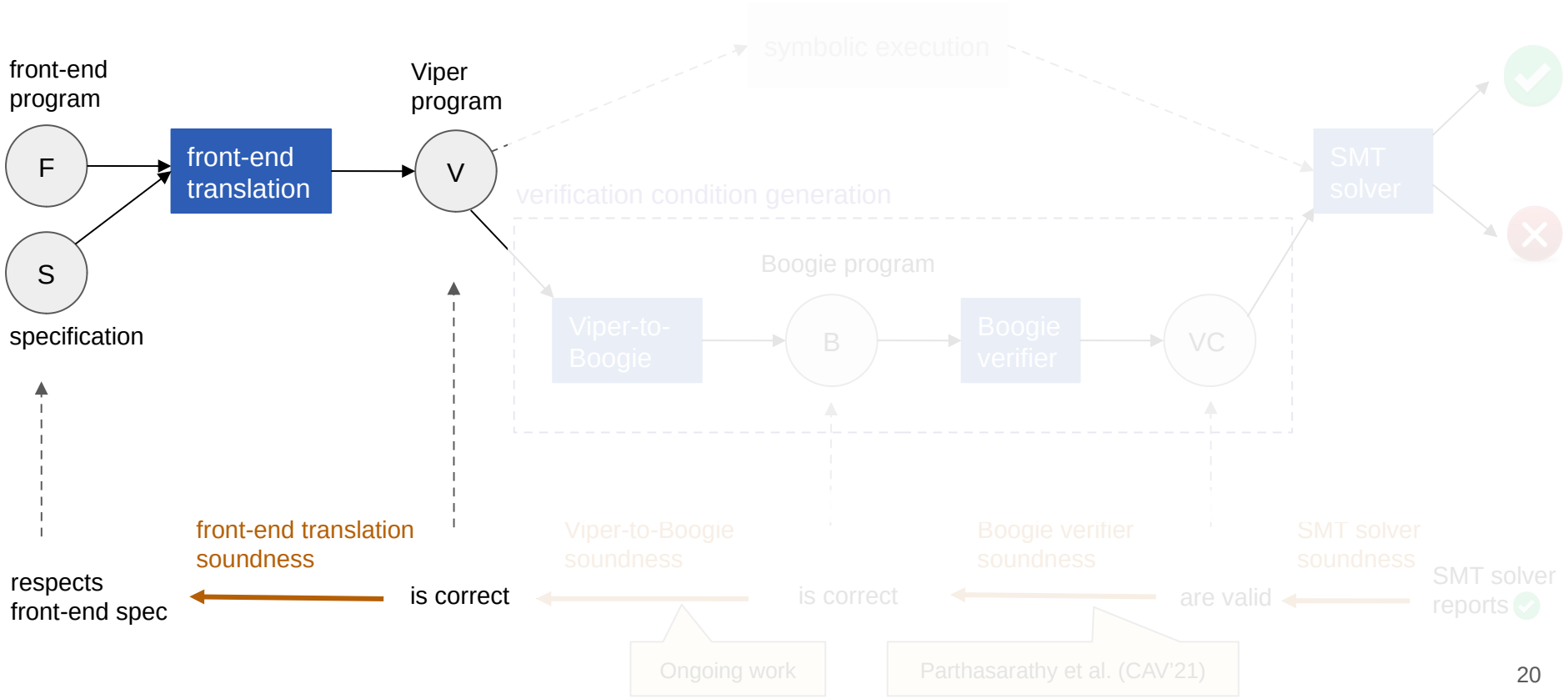
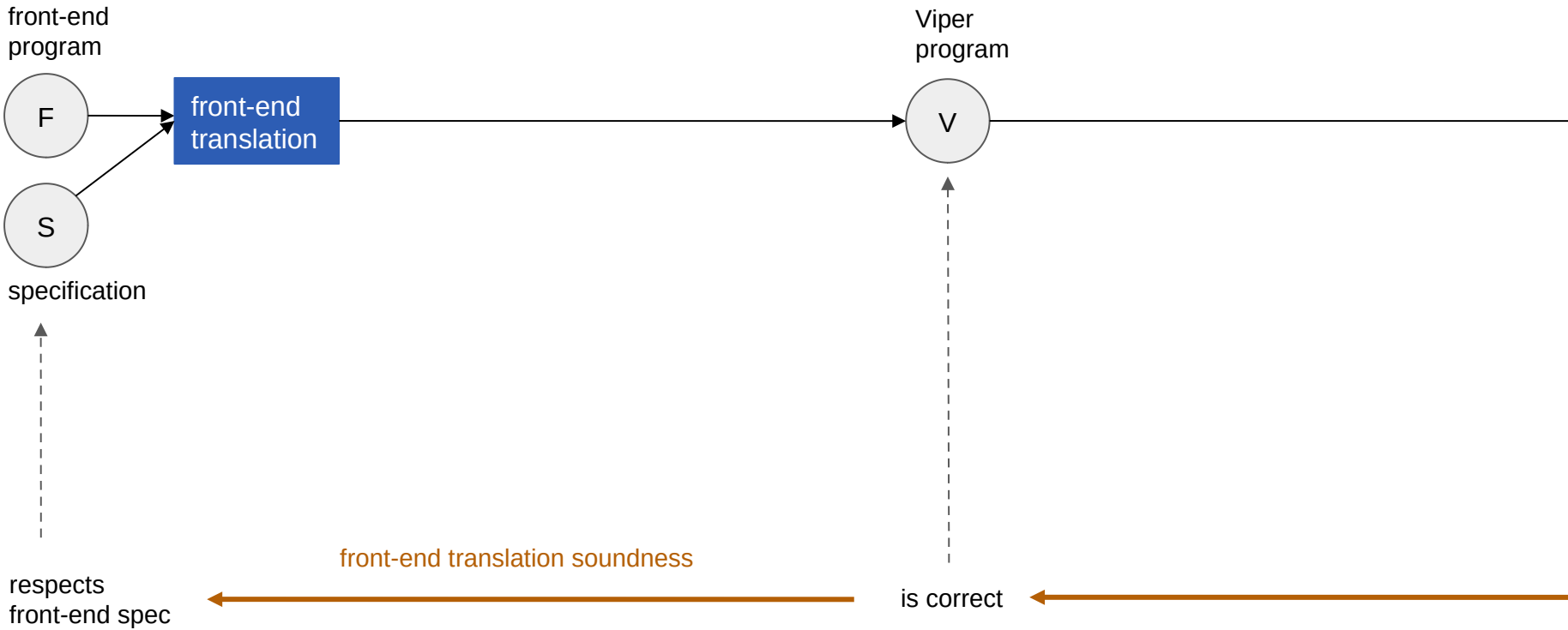


Operational Semantics and Adequacy Theorem



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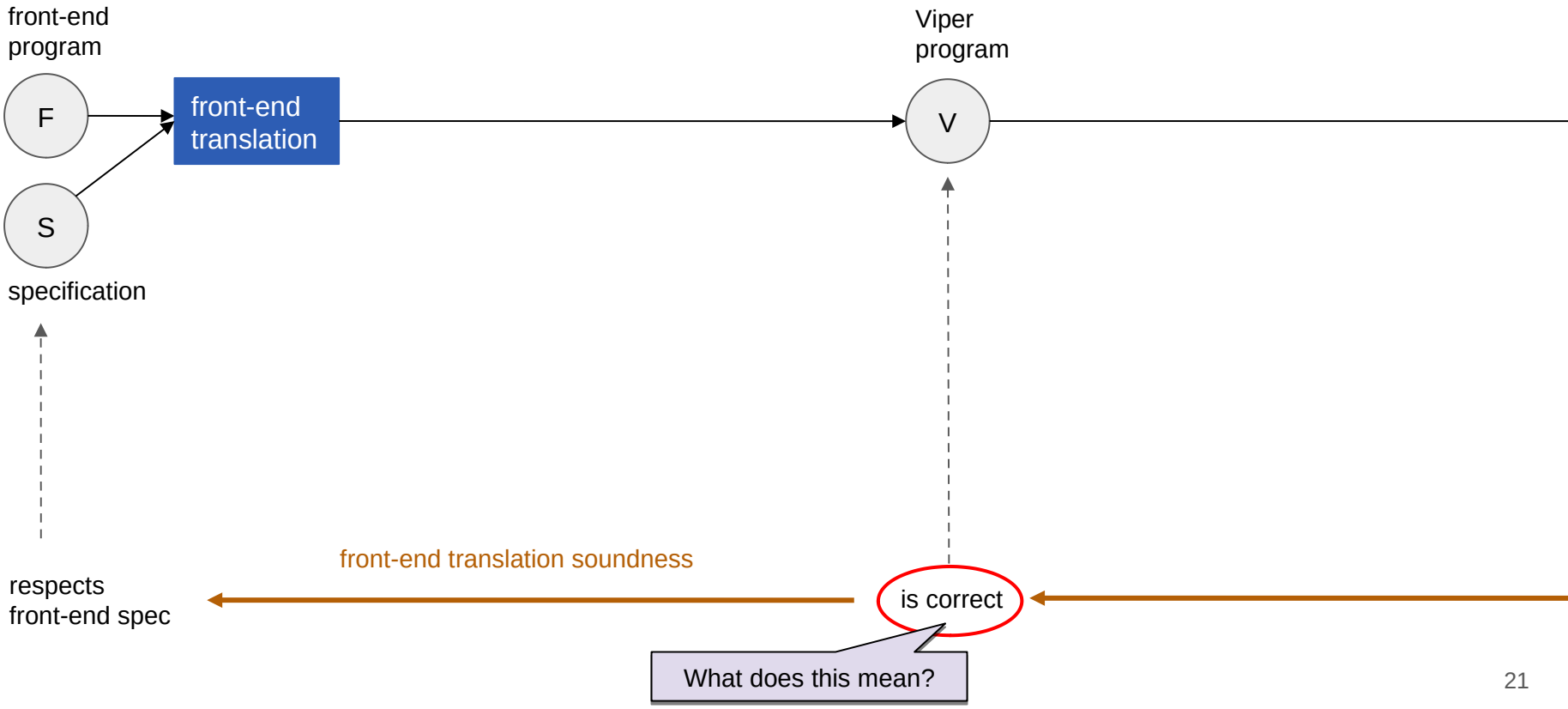

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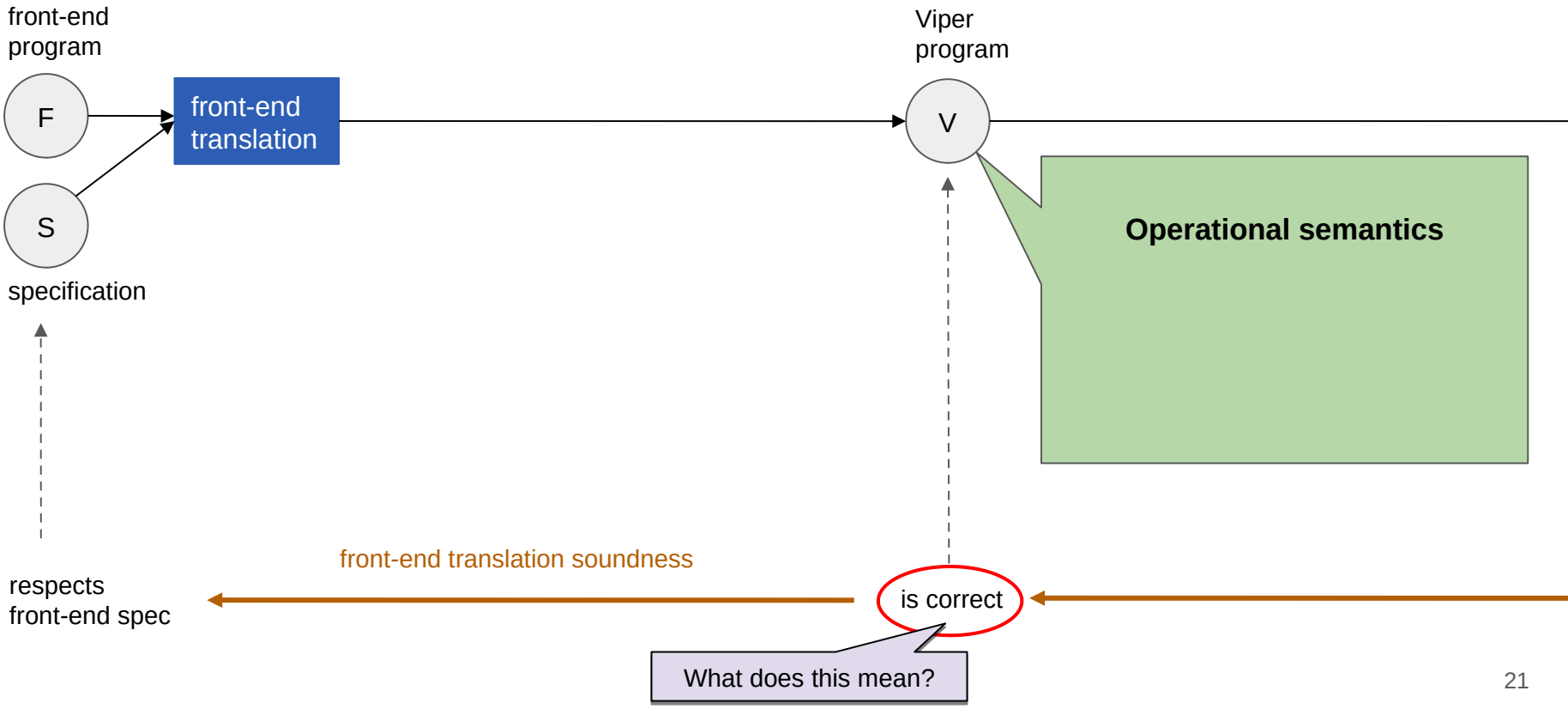

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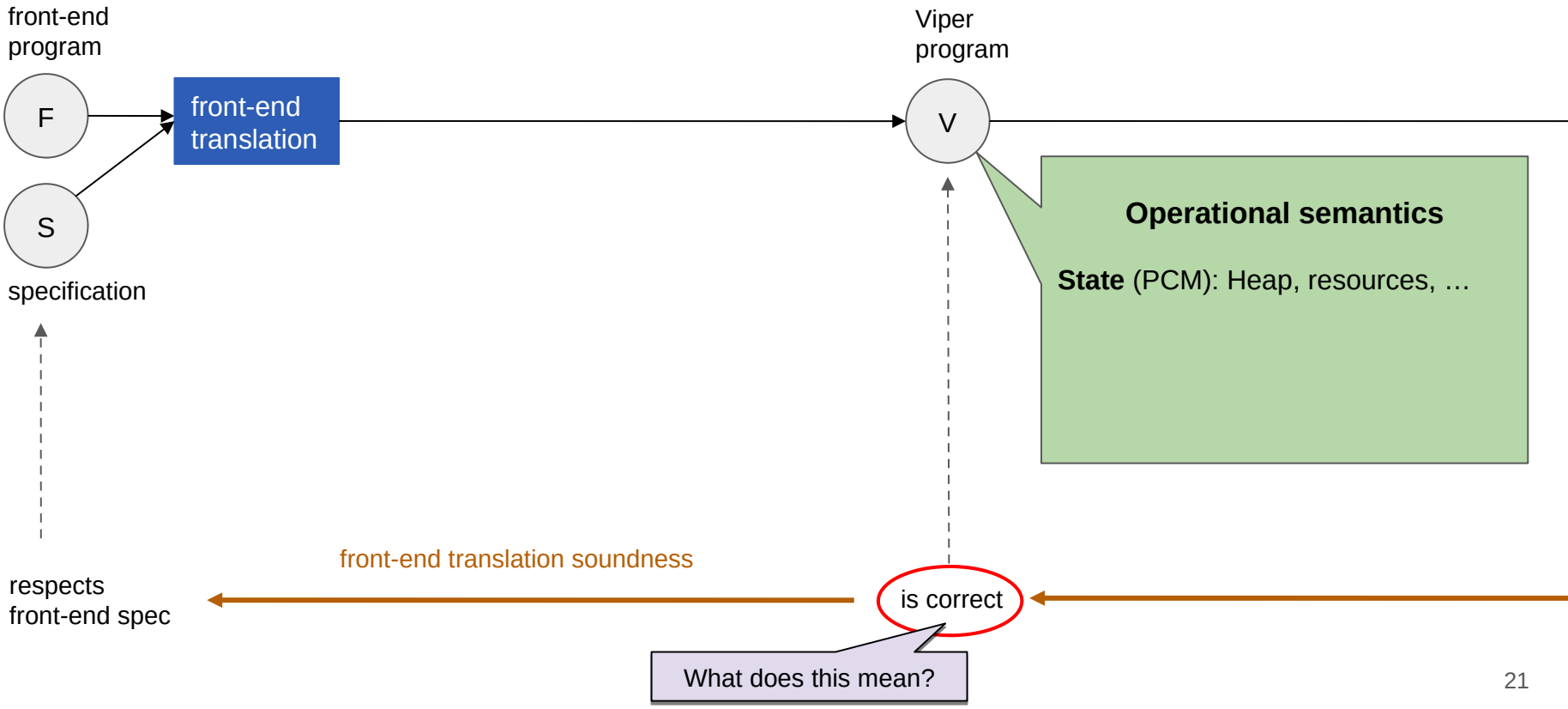

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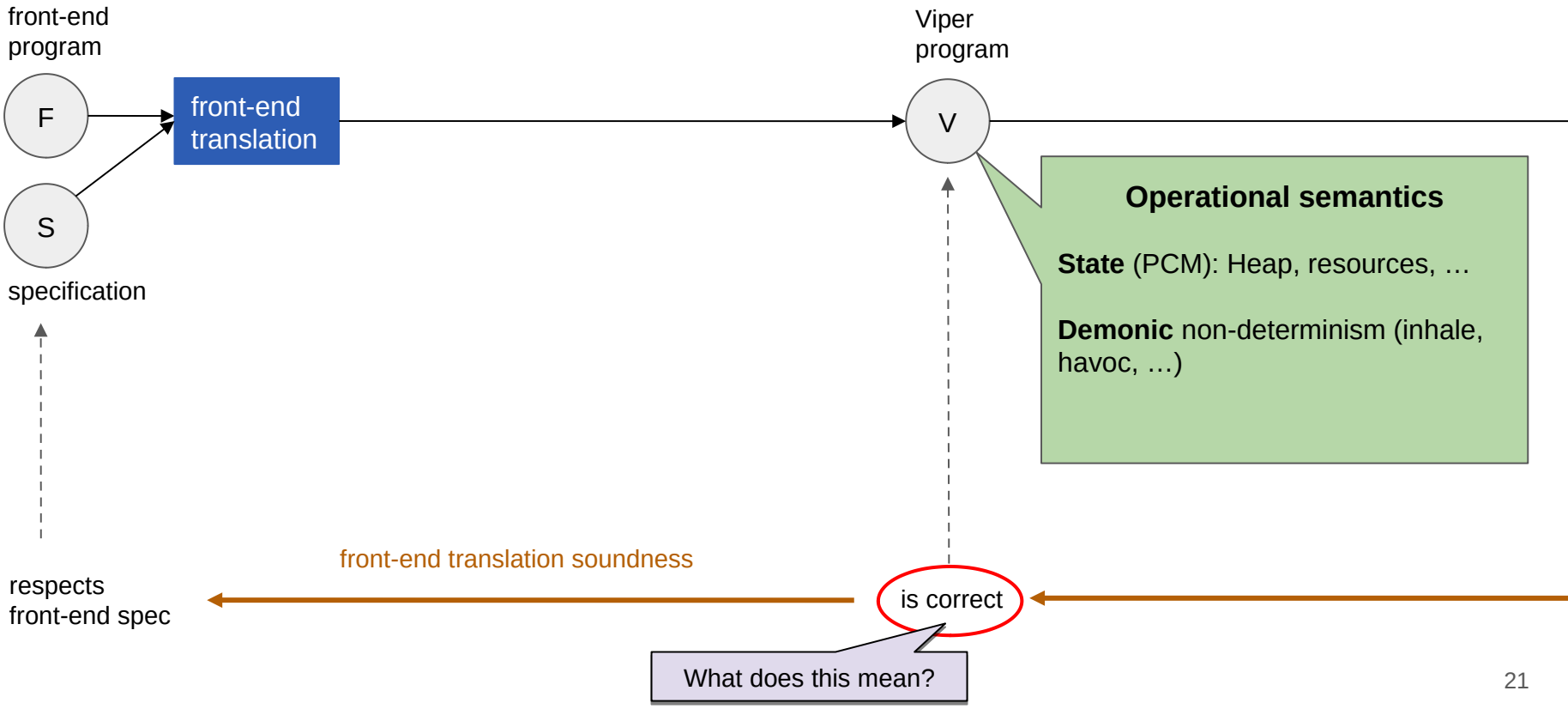

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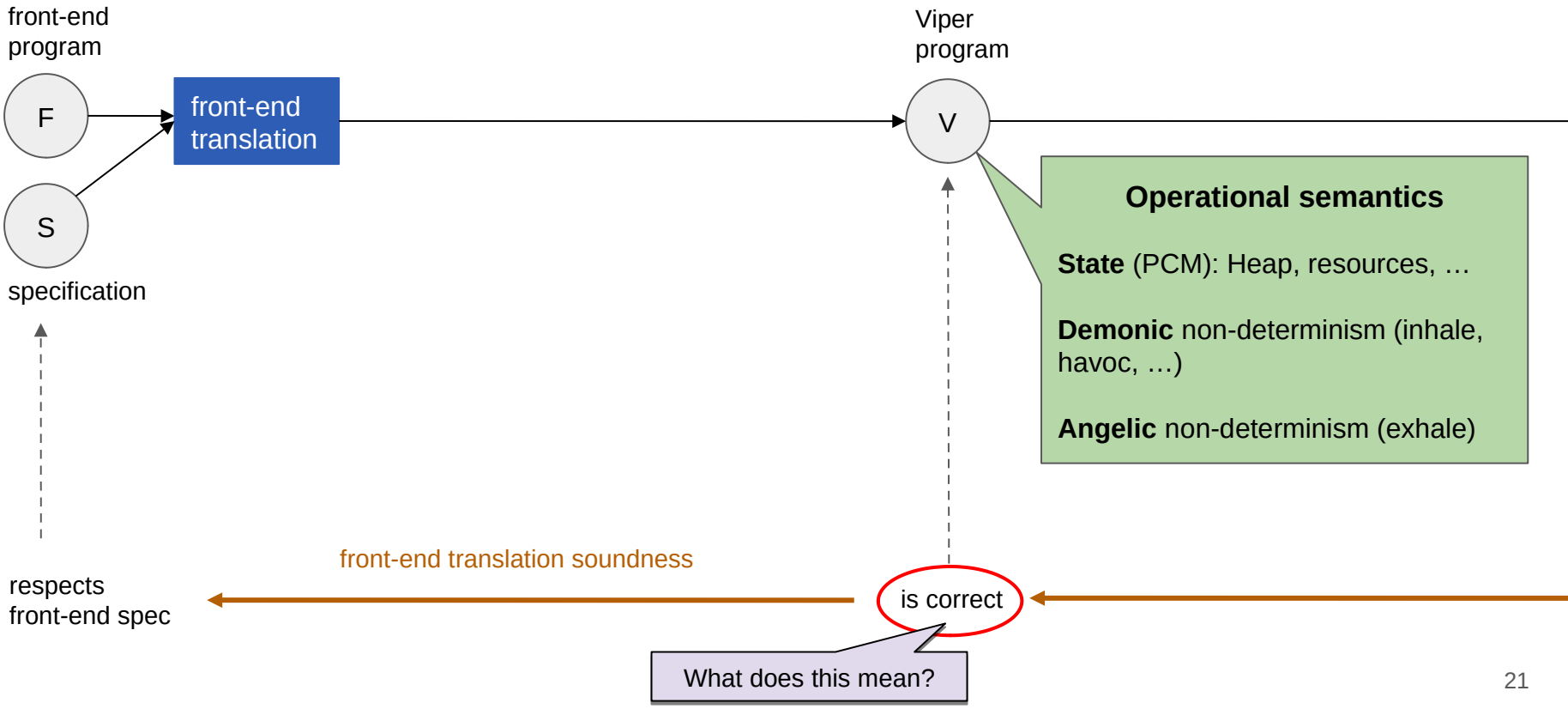

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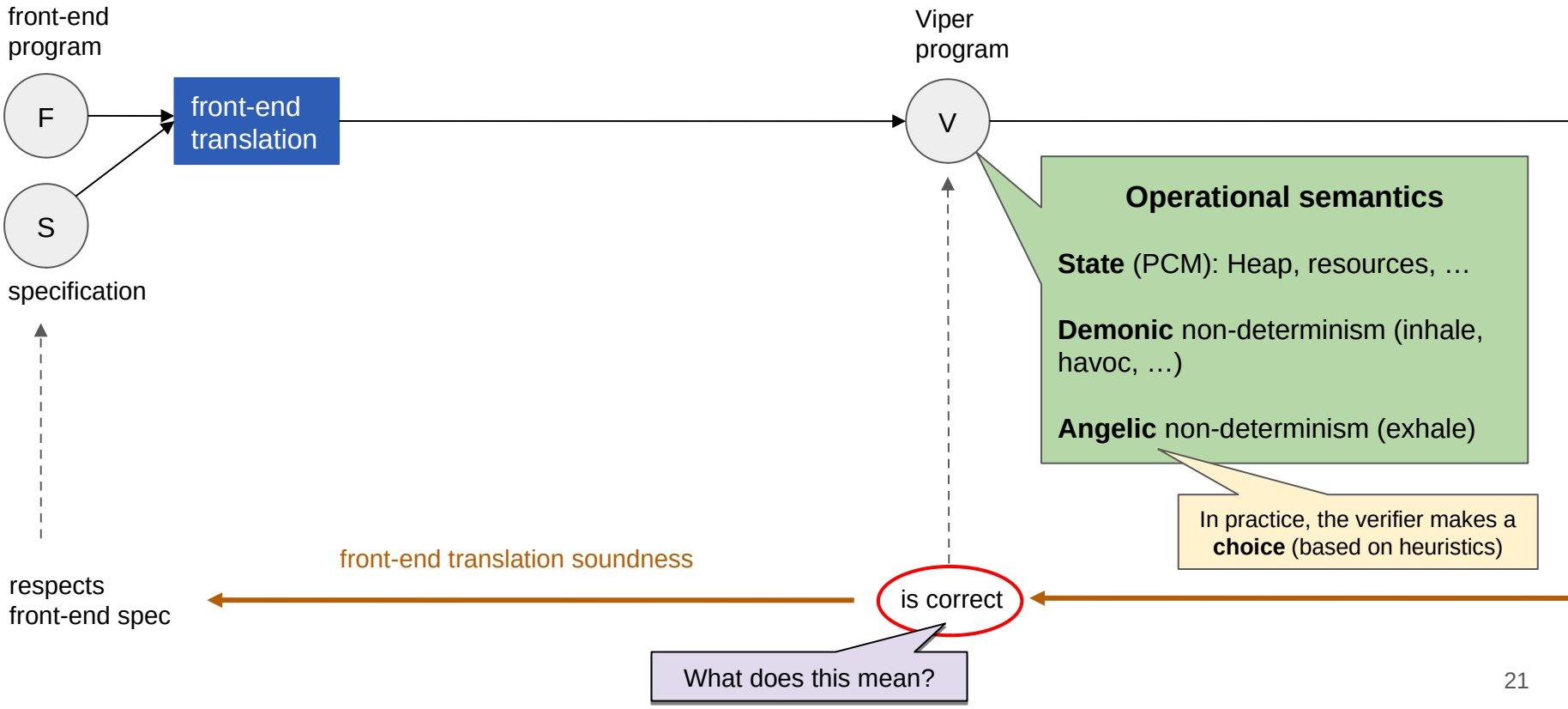

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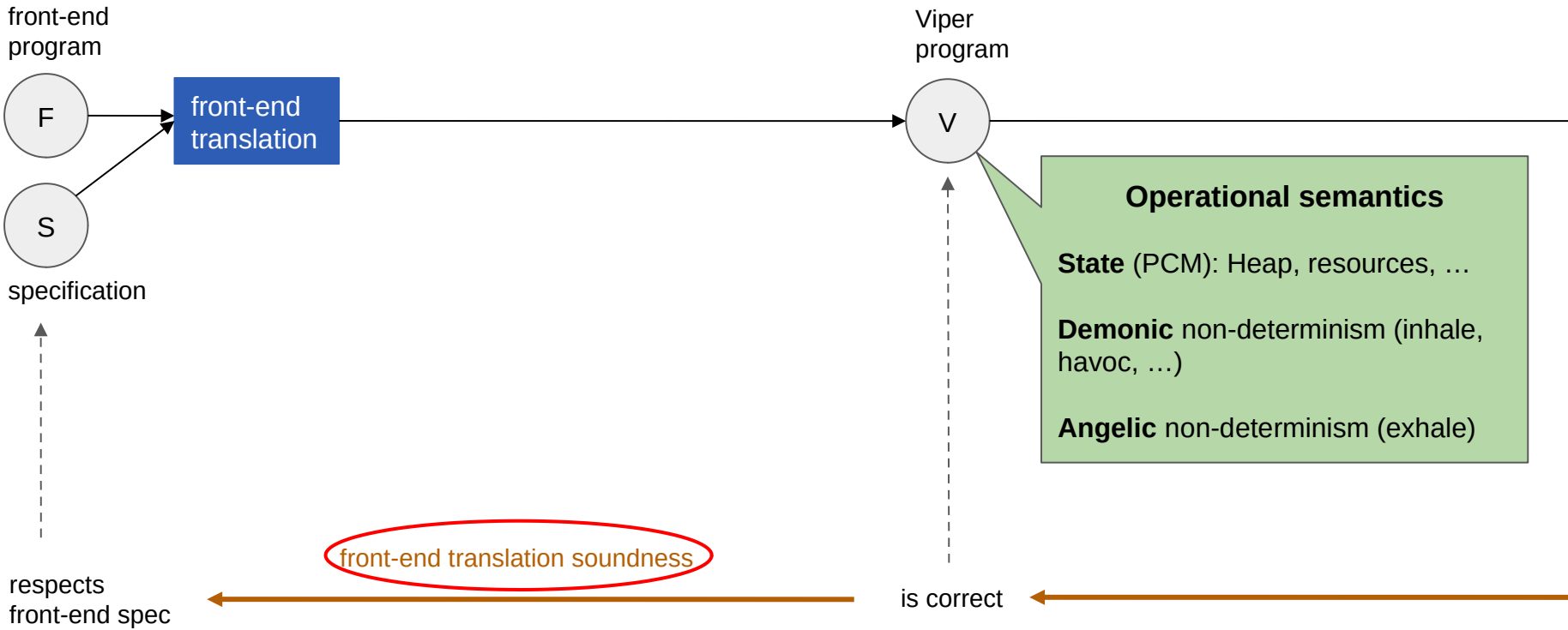

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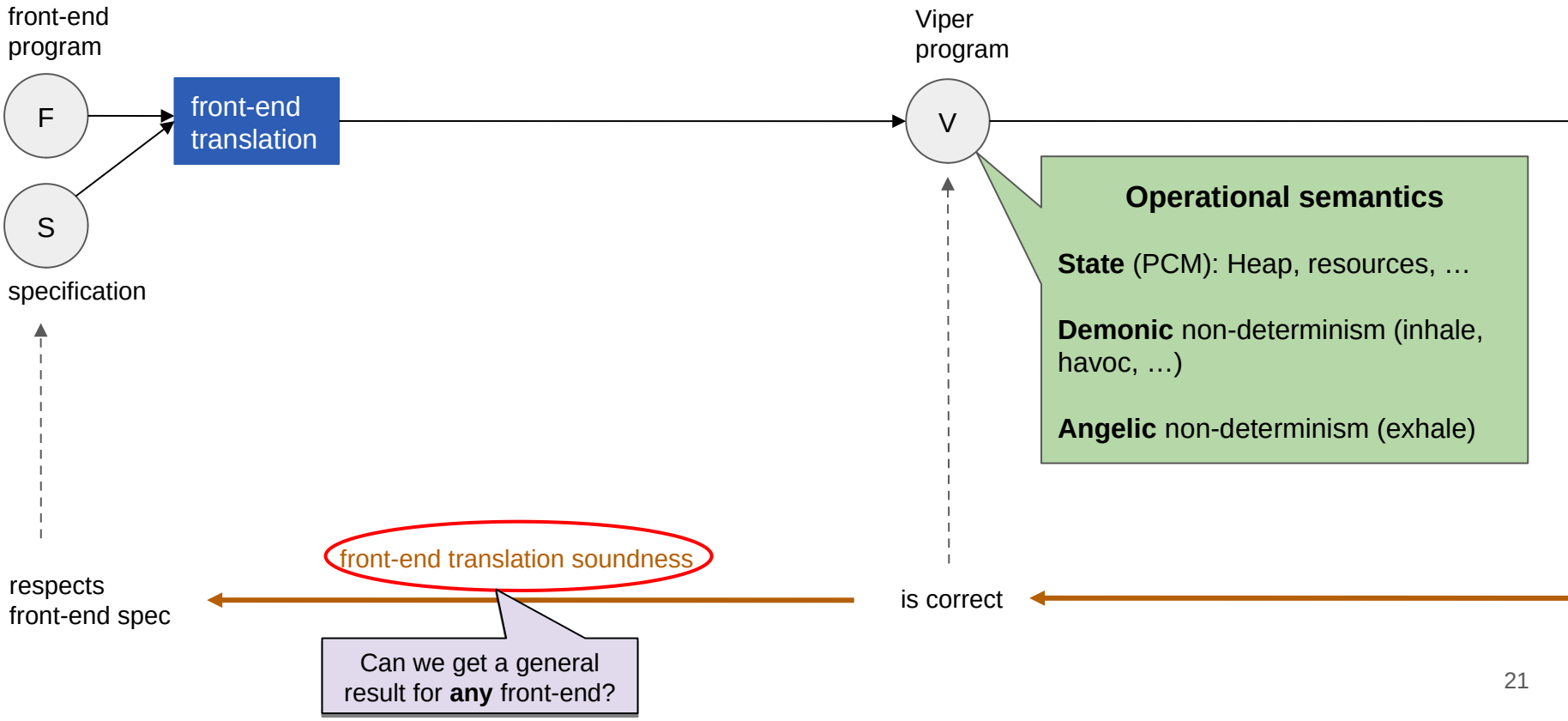

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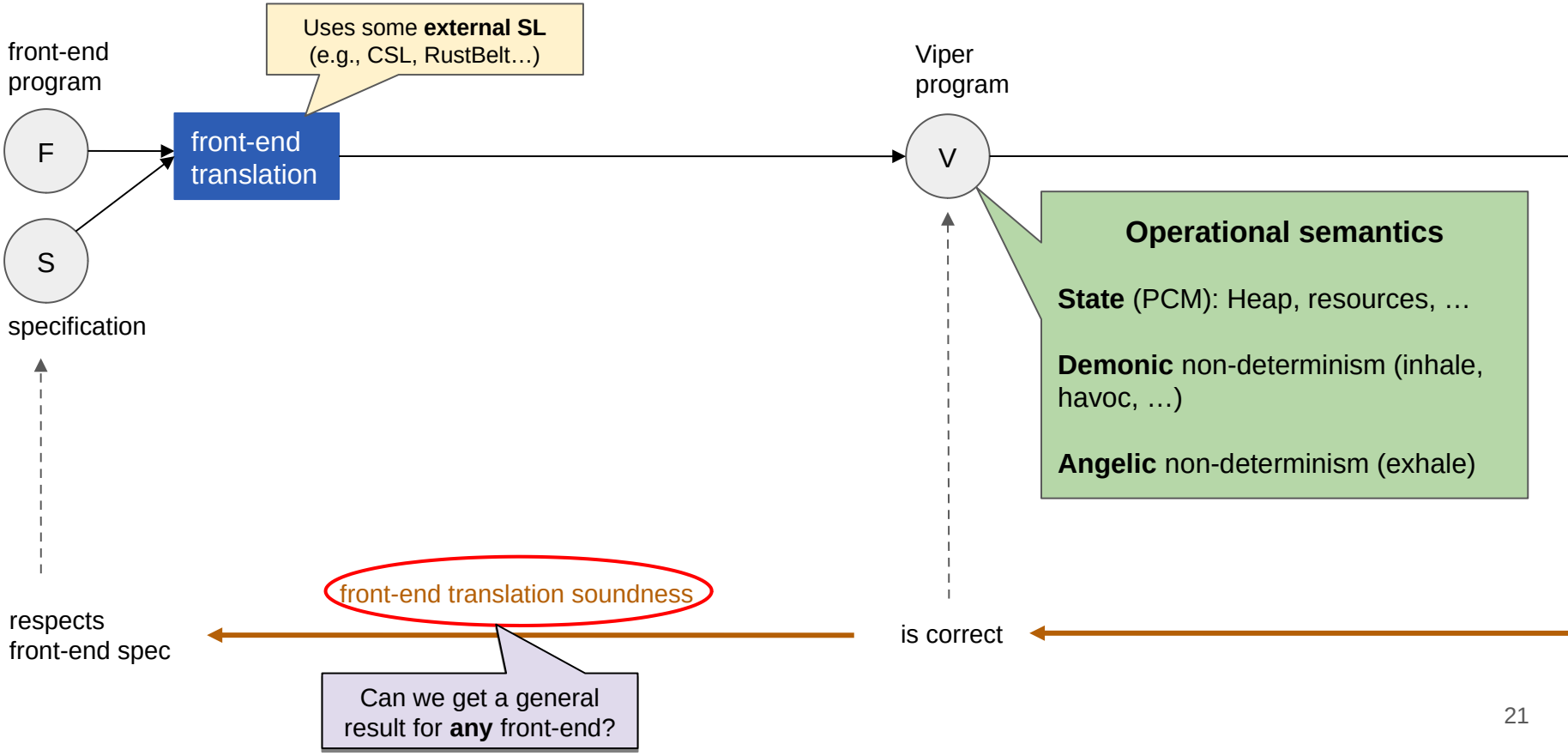

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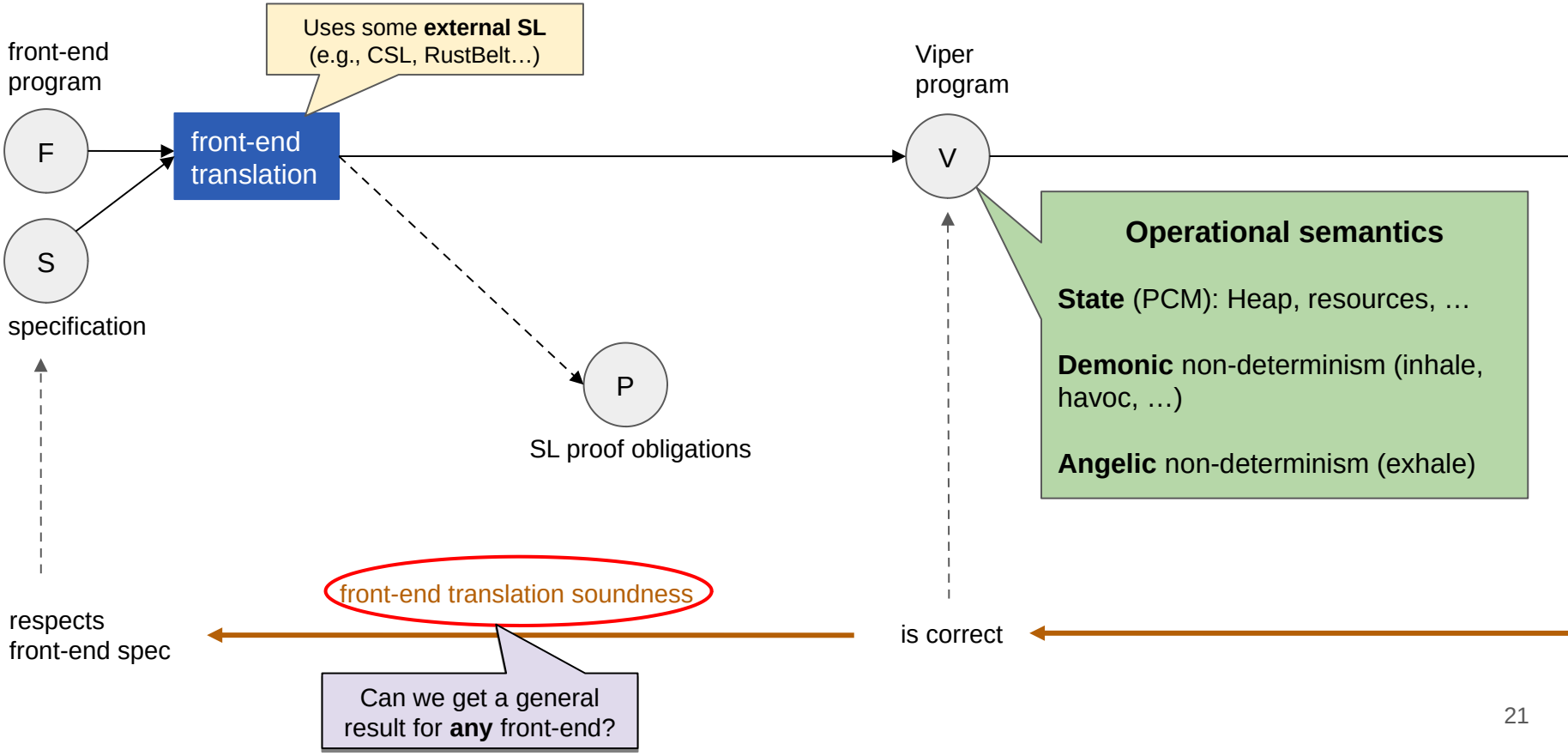

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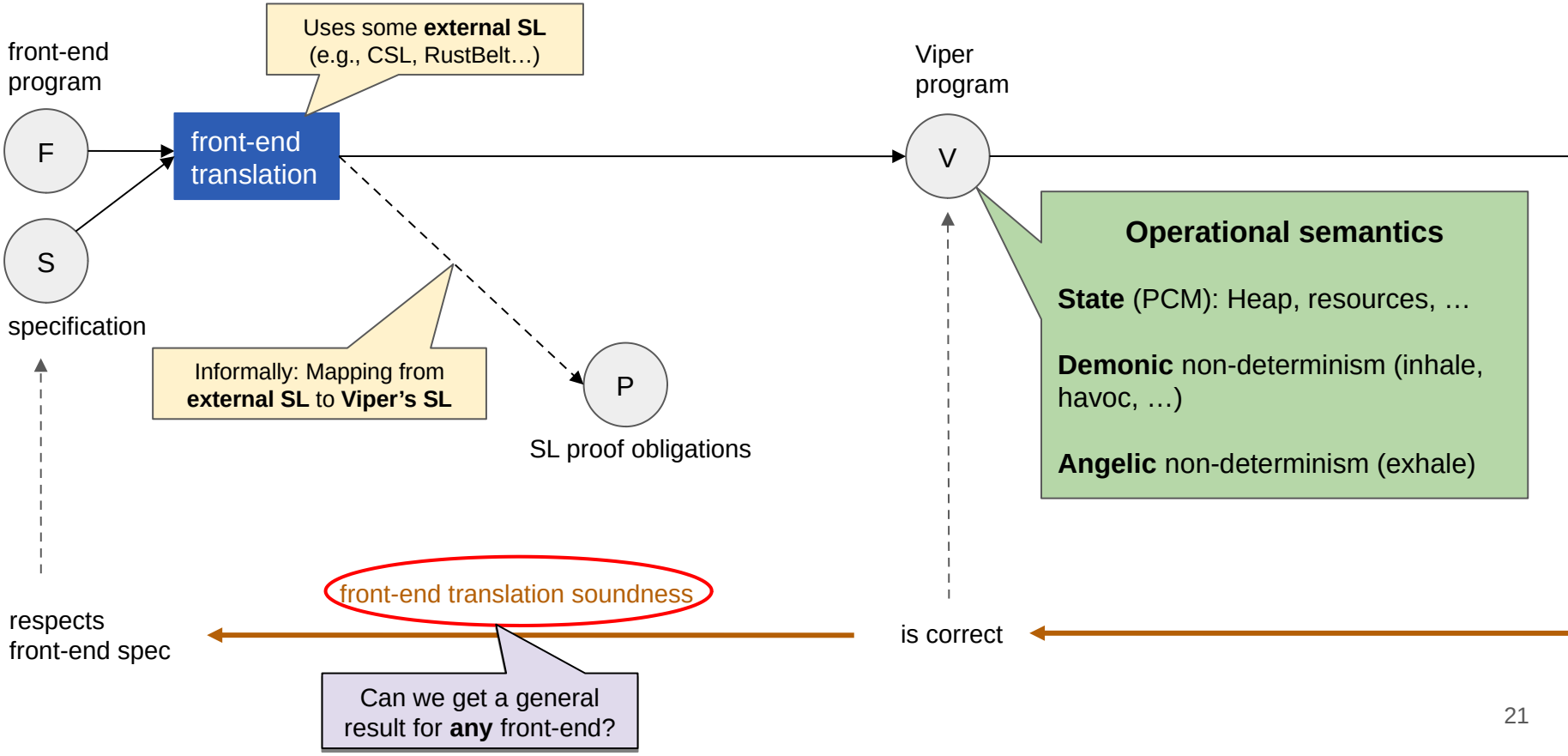

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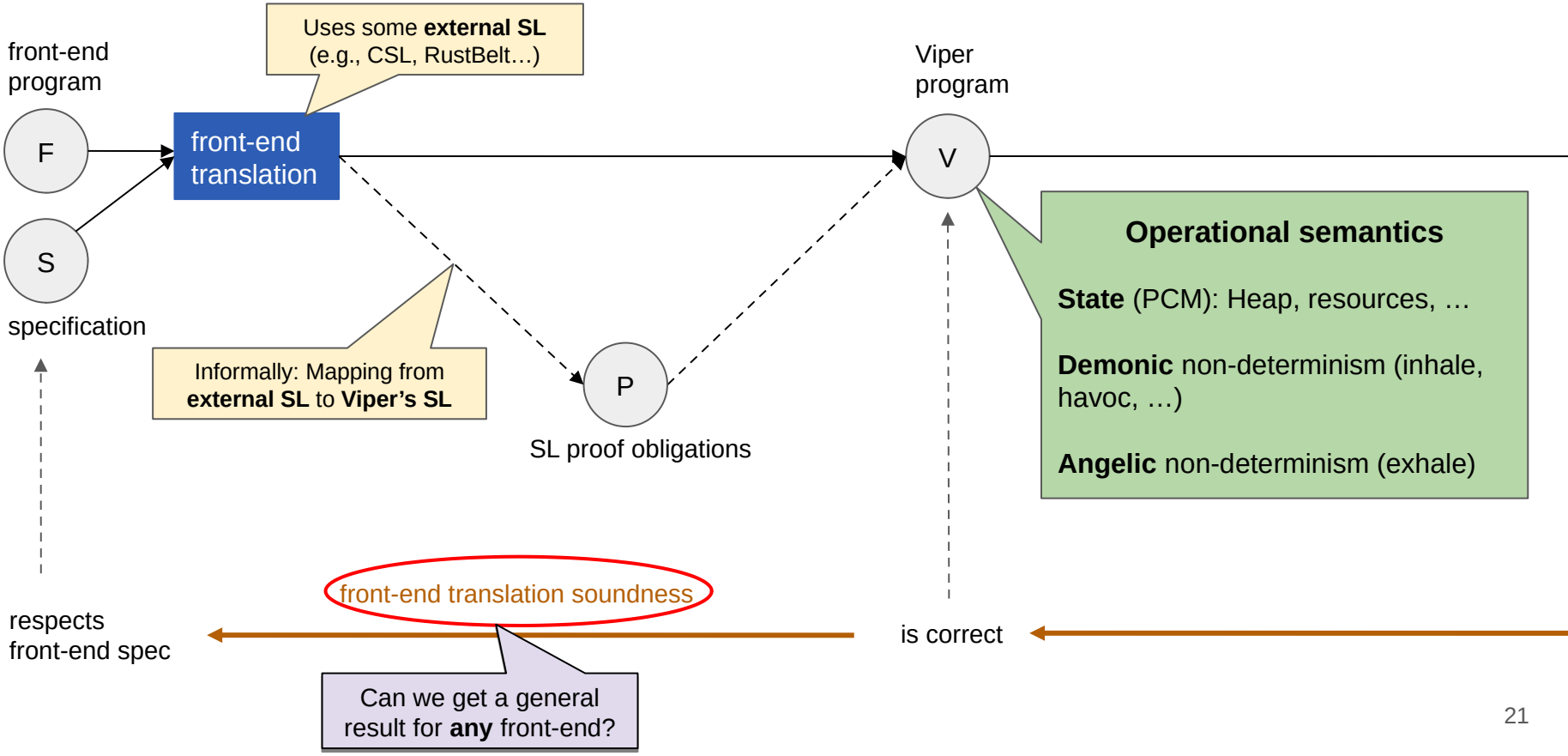

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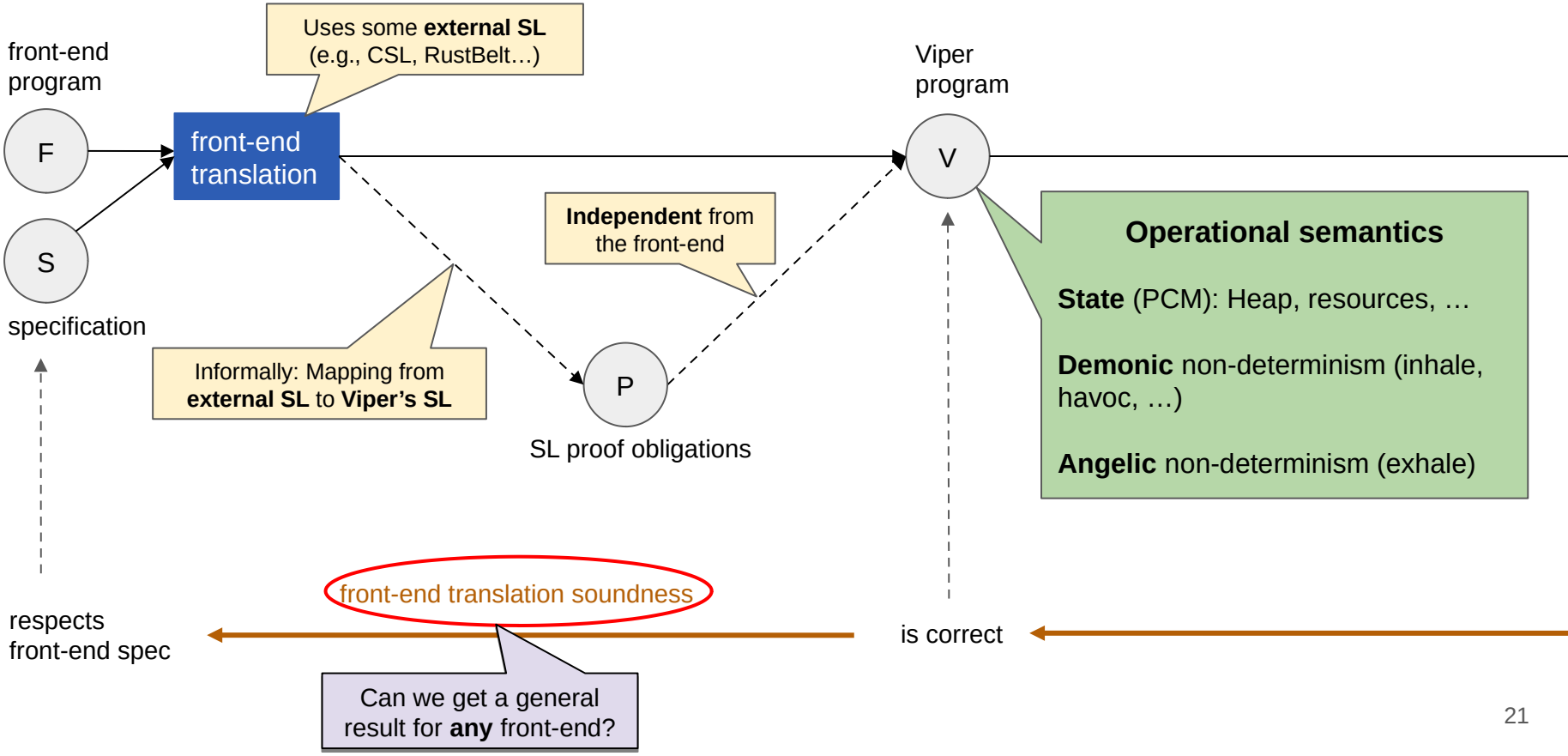

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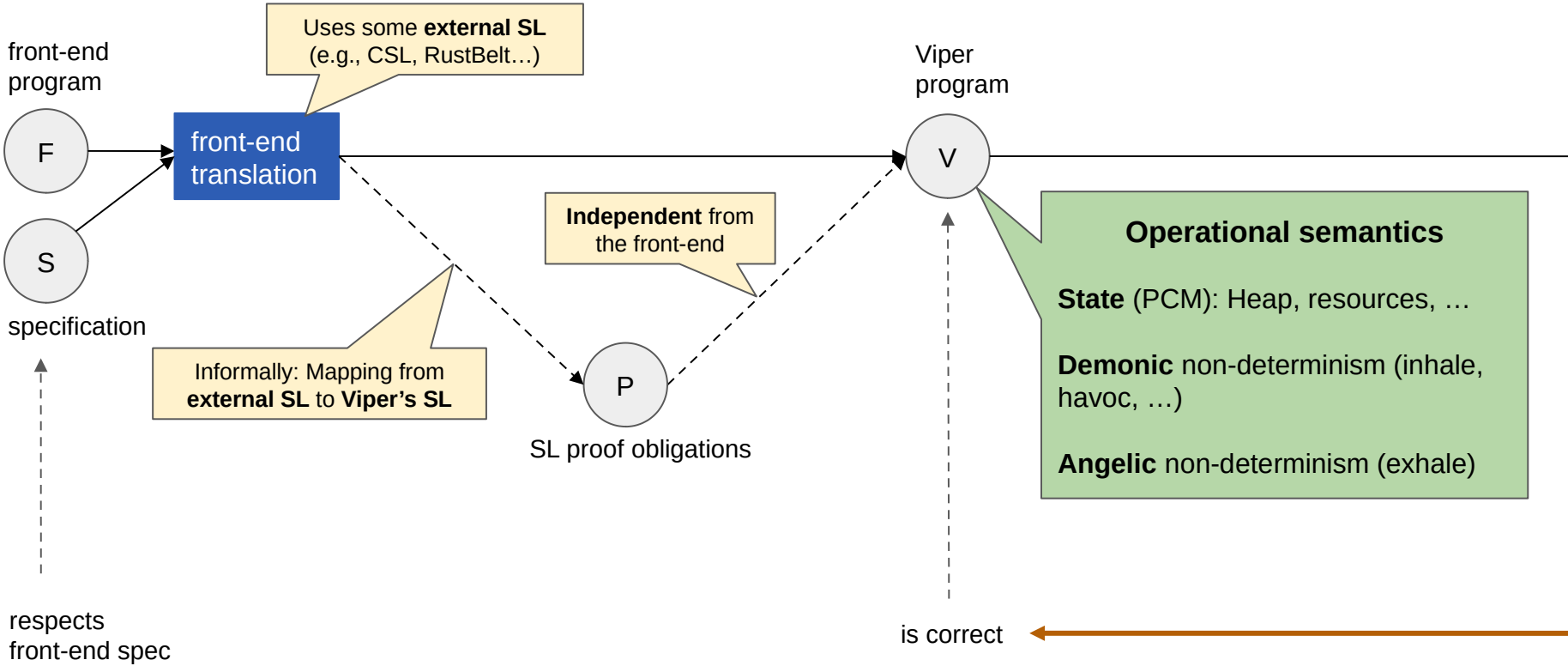

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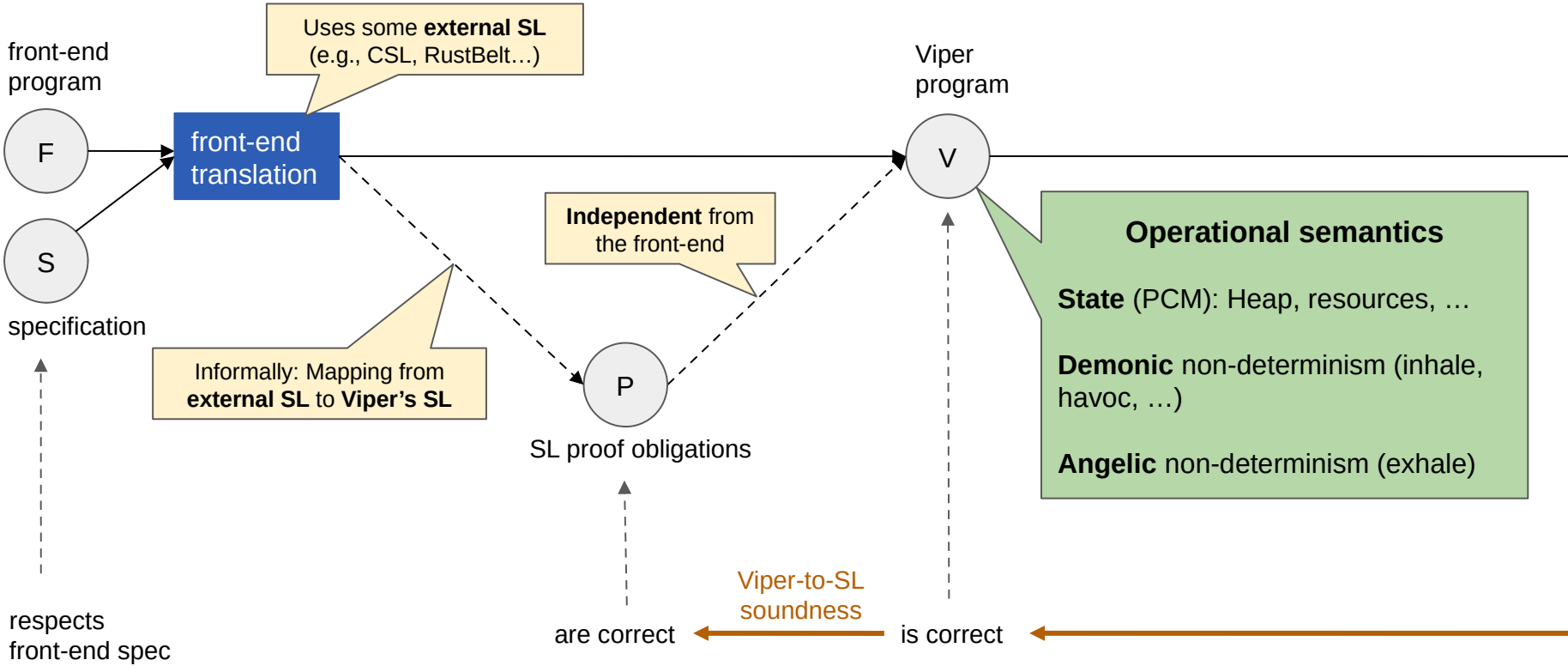

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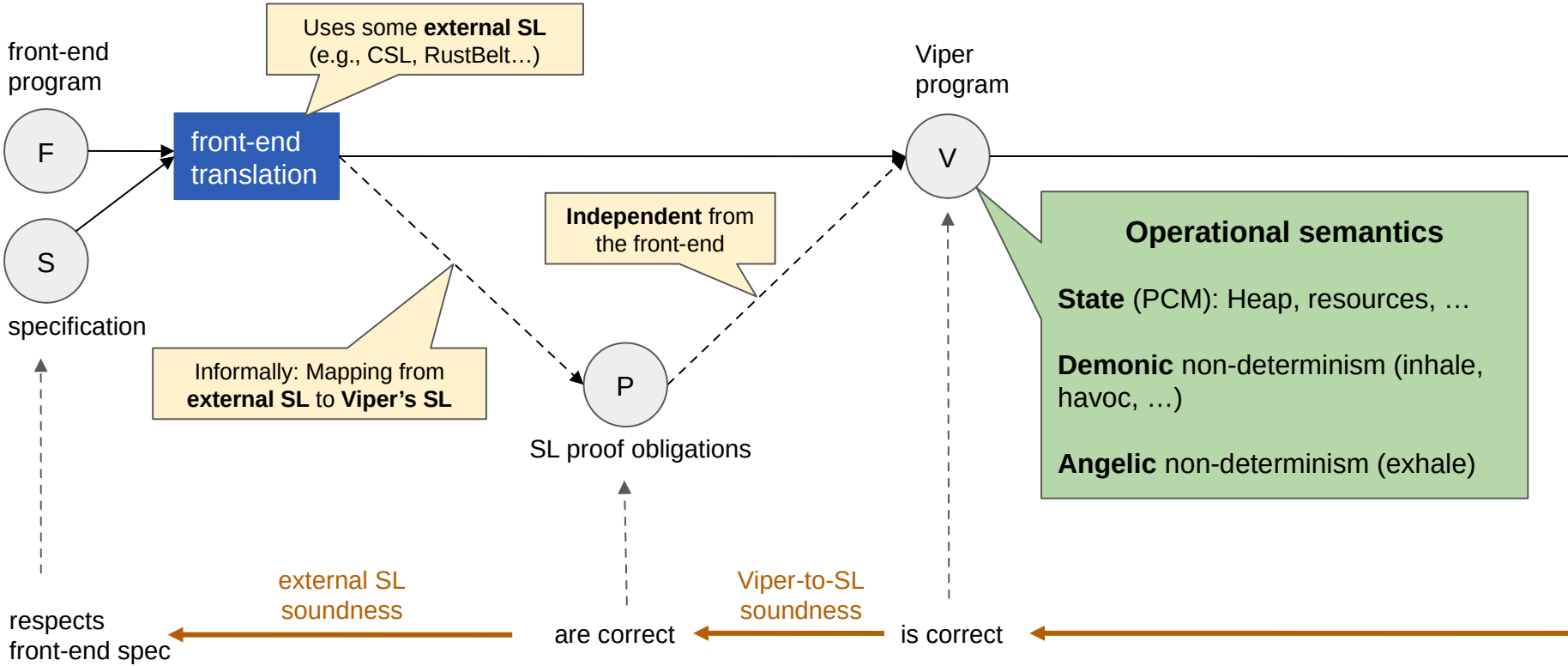
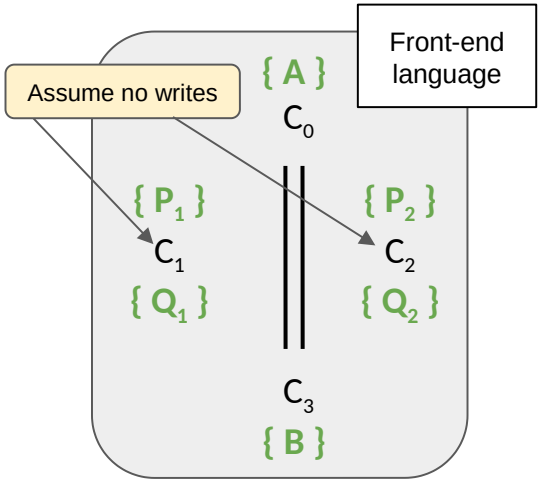


Adequacy Theorem: Viper-to-SL



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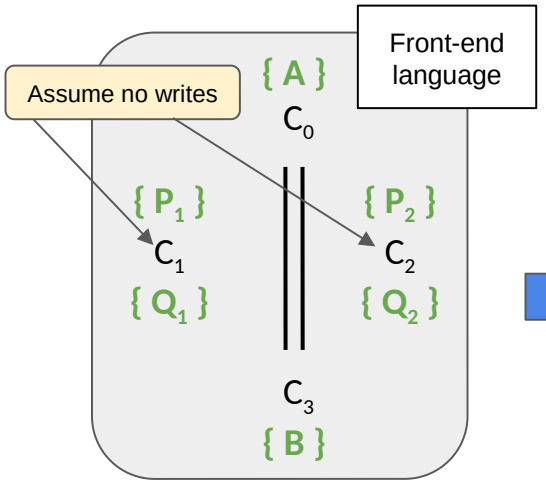

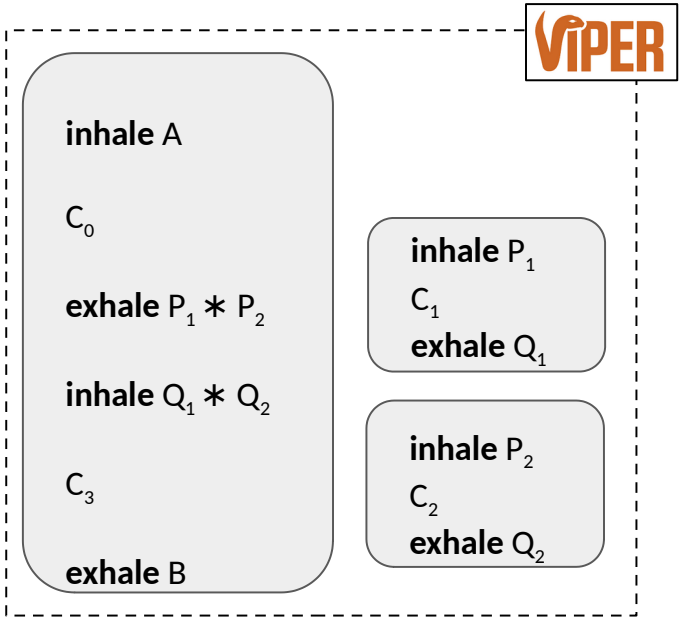

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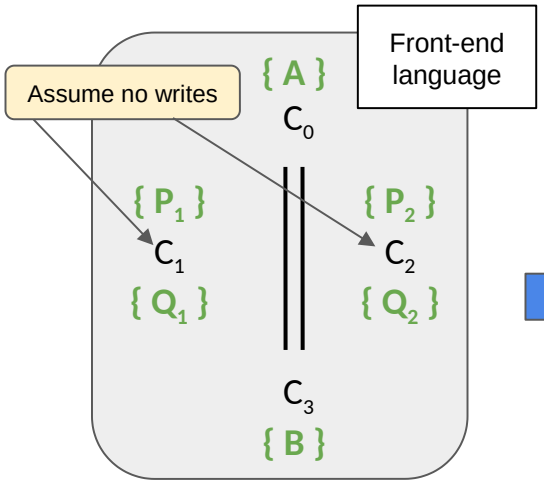

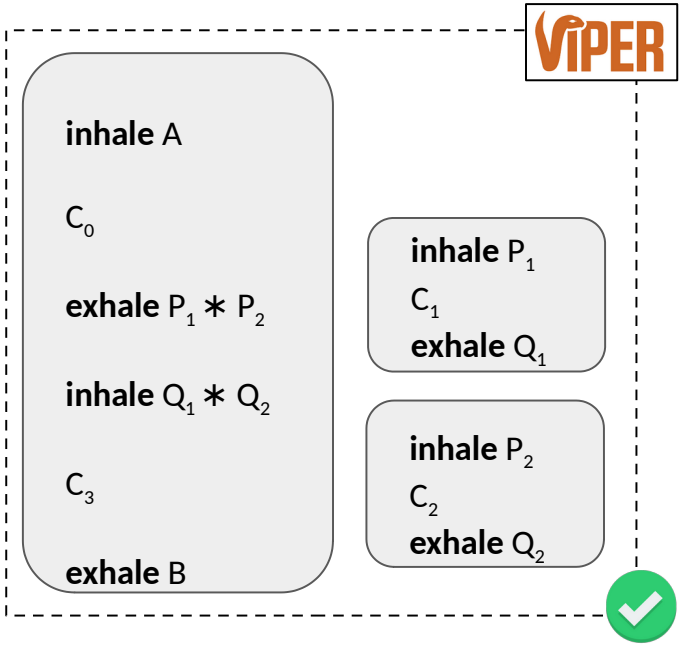

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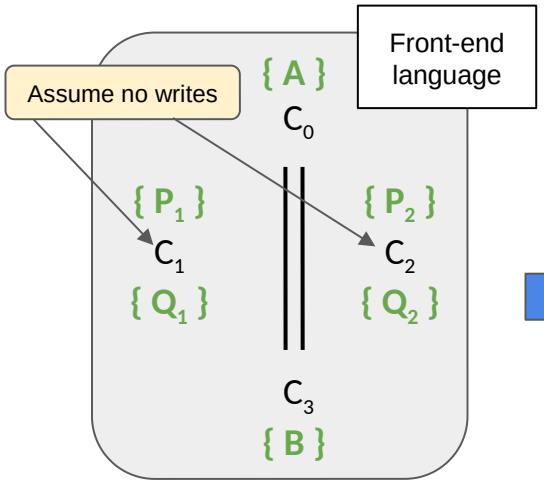
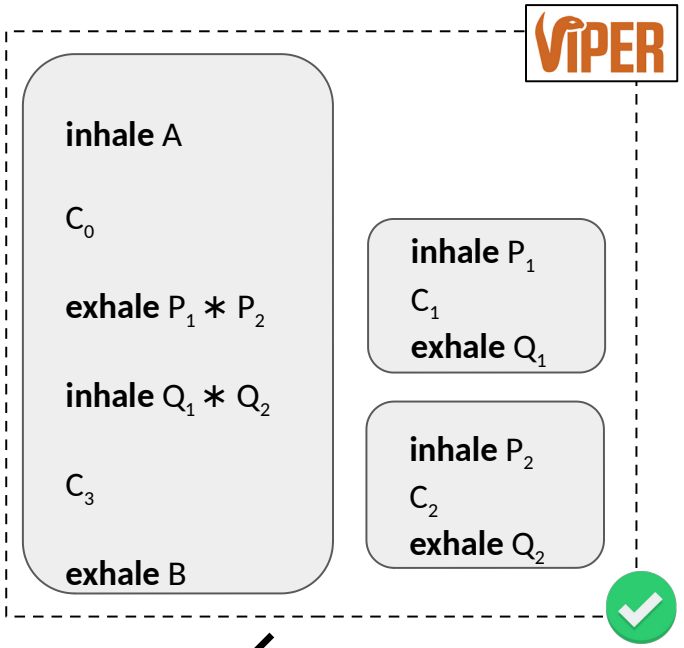
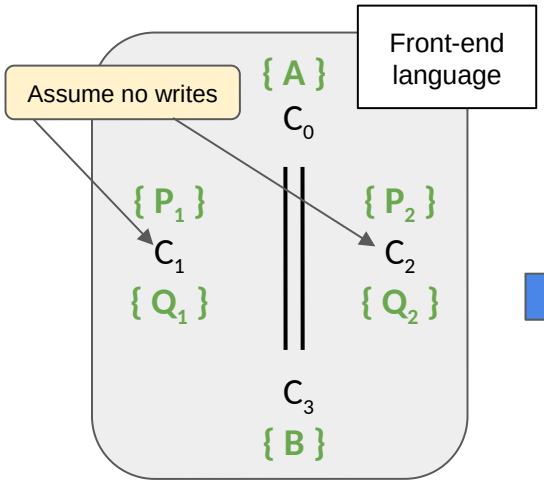
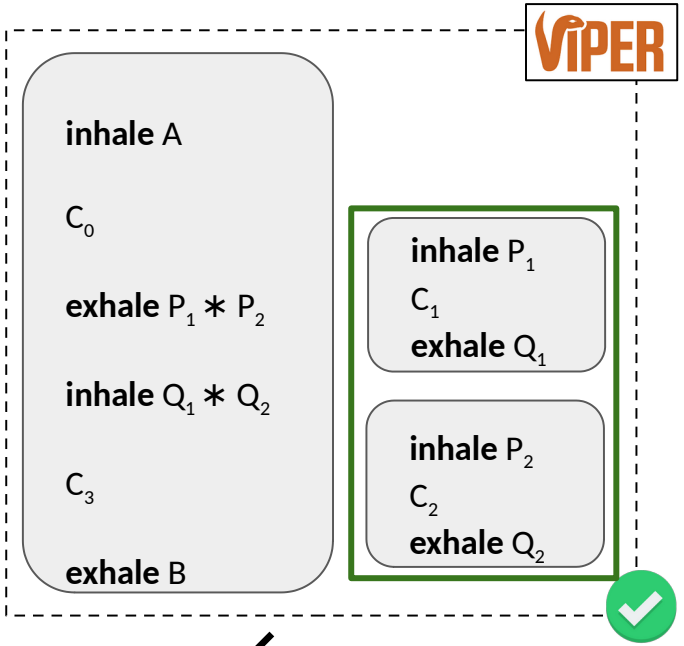




SL proof obligations proven by Viper

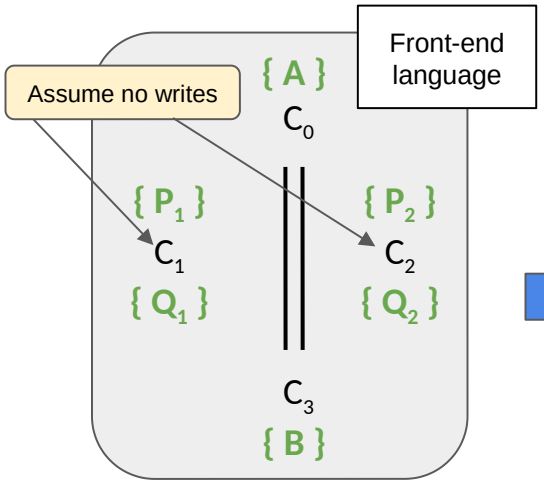
Adequacy Theorem: Viper-to-SL

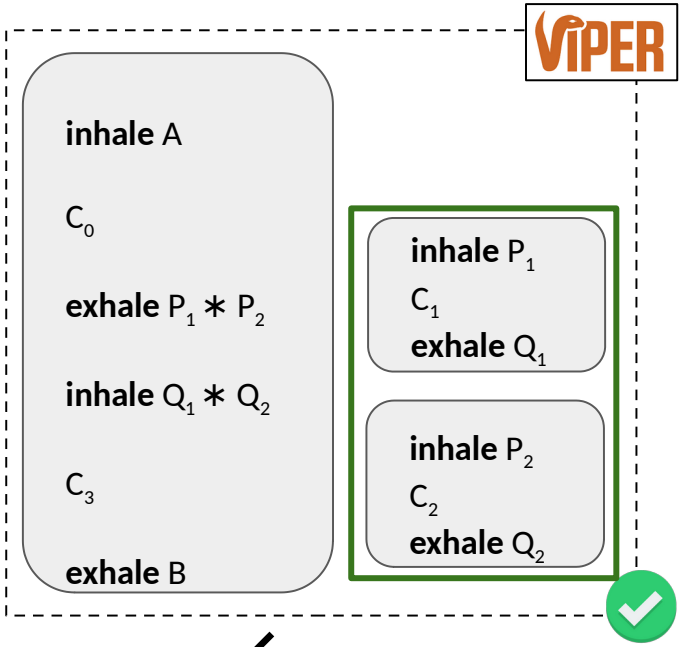




SL proof obligations proven by Viper

Adequacy Theorem: Viper-to-SL



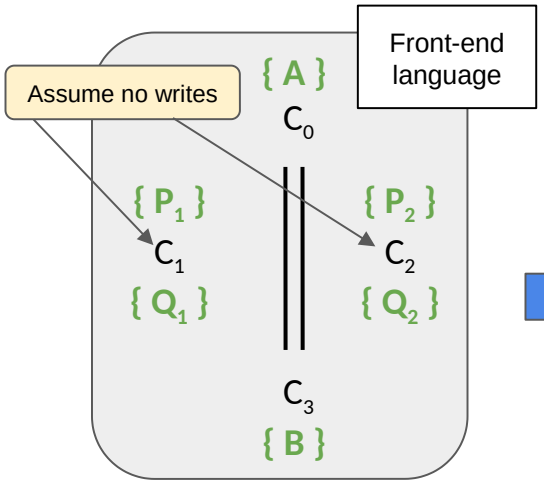


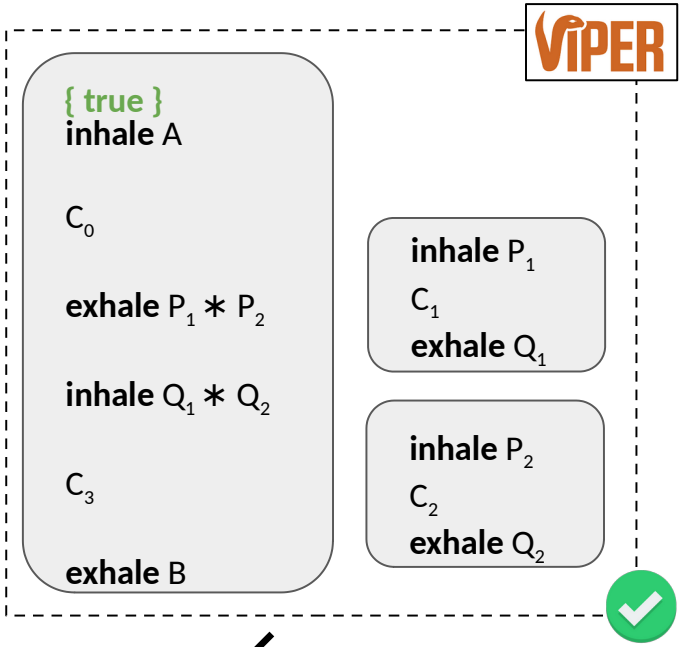
SL proof obligations proven by Viper

$\vdash \{ P_1 \}\, C_1 \,\{ Q_1 \}$

$\vdash \{ P_2 \}\, C_2 \,\{ Q_2 \}$

Adequacy Theorem: Viper-to-SL





SL proof obligations proven by Viper

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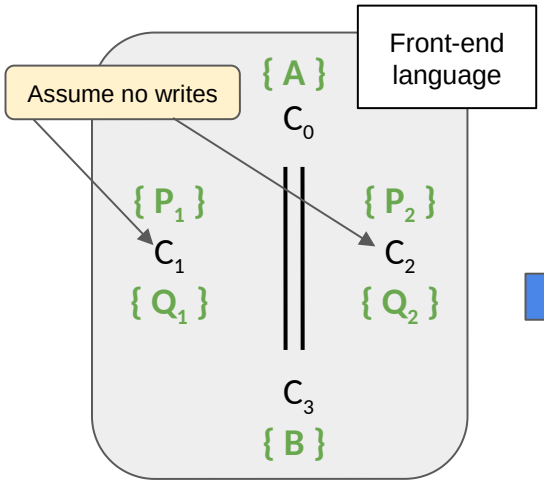

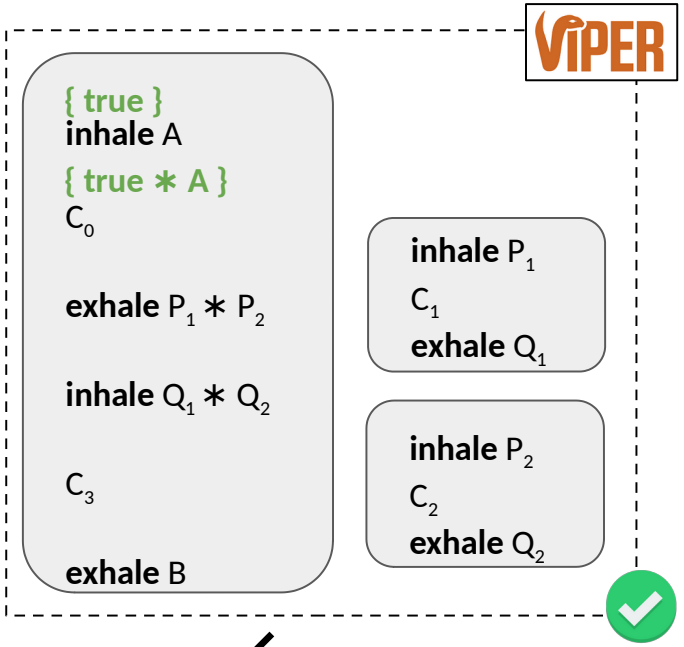

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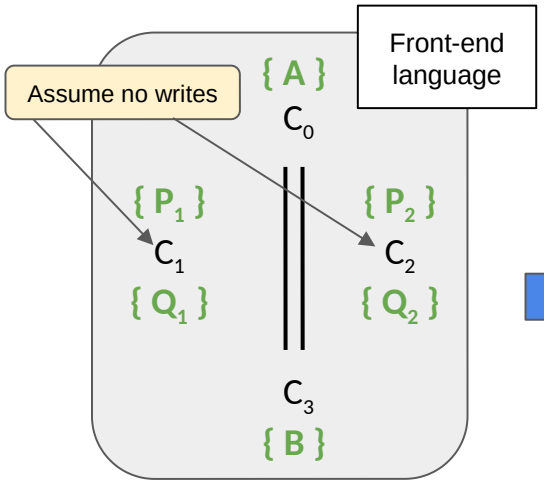

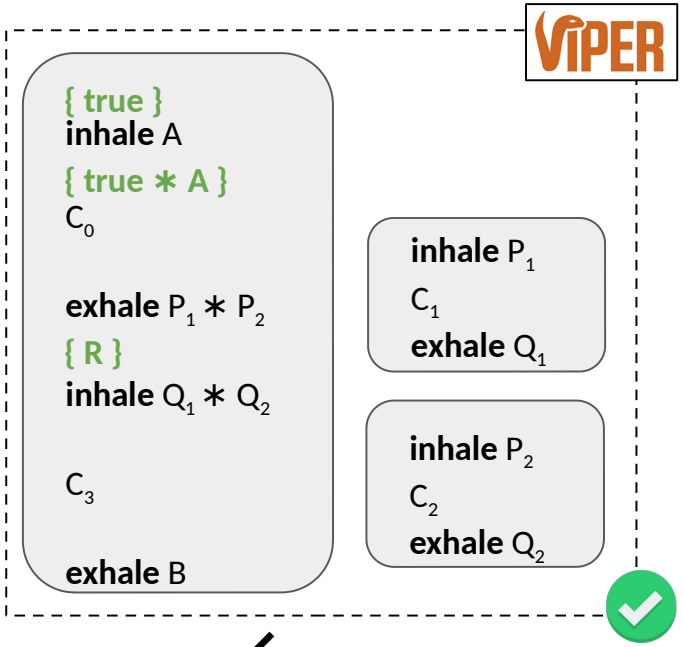

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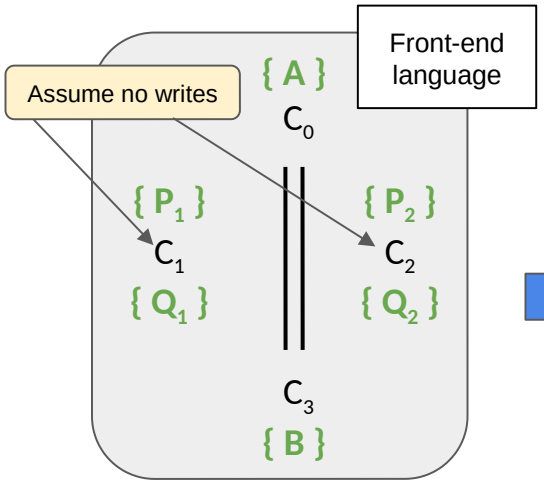

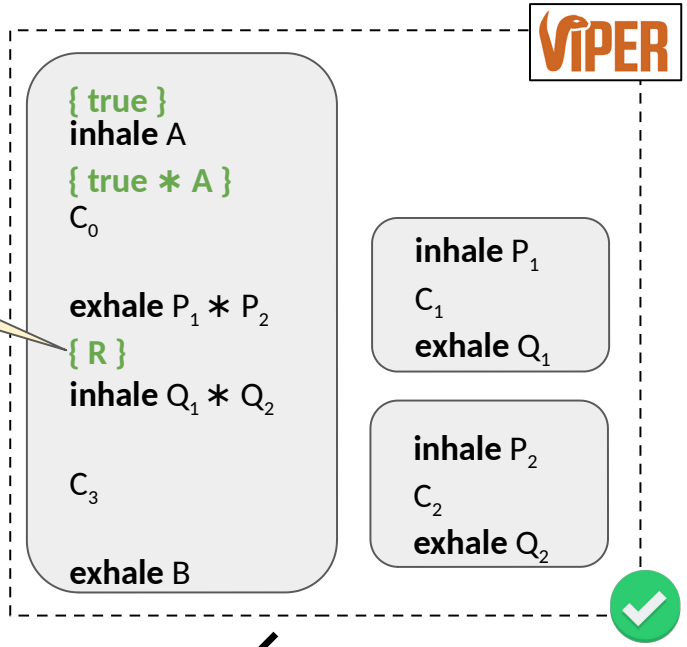

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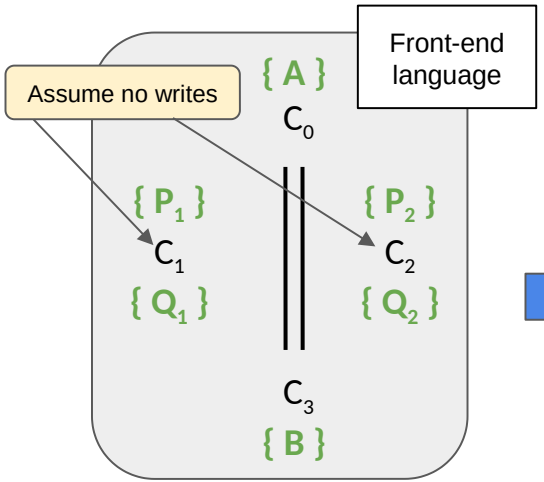
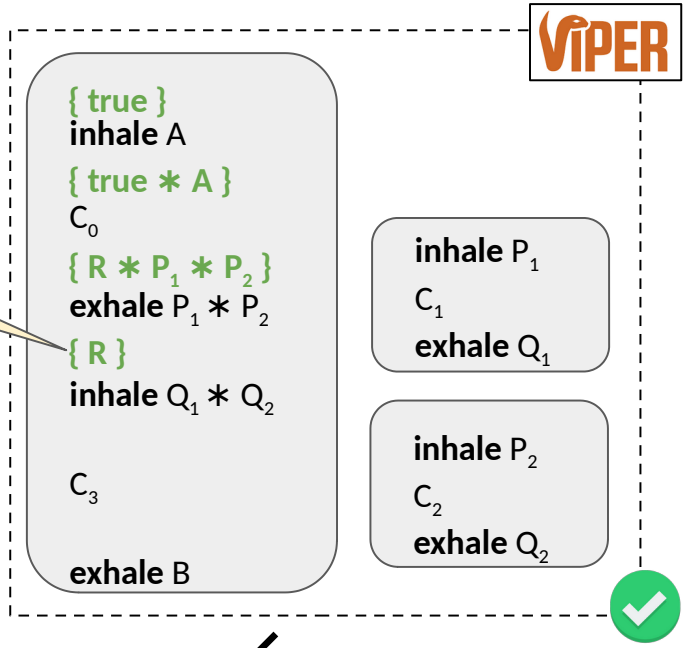


Implicit



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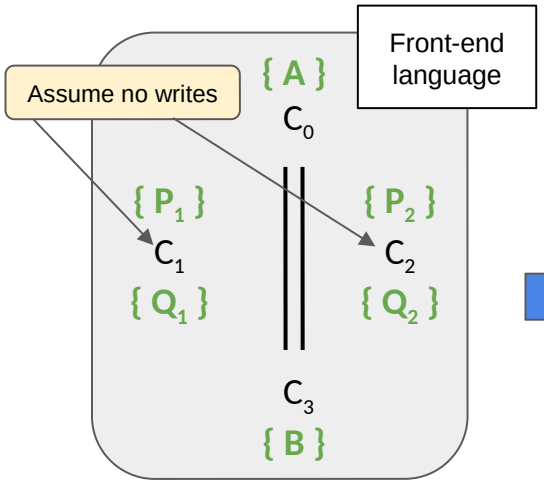

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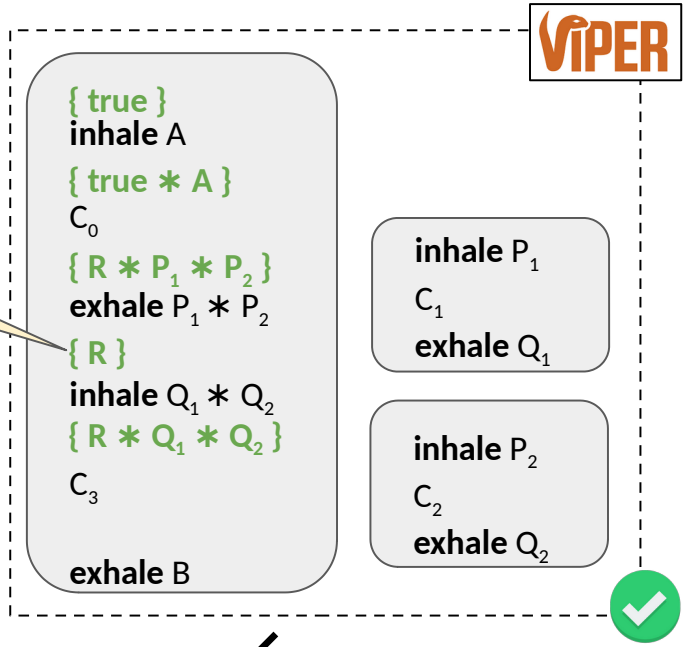

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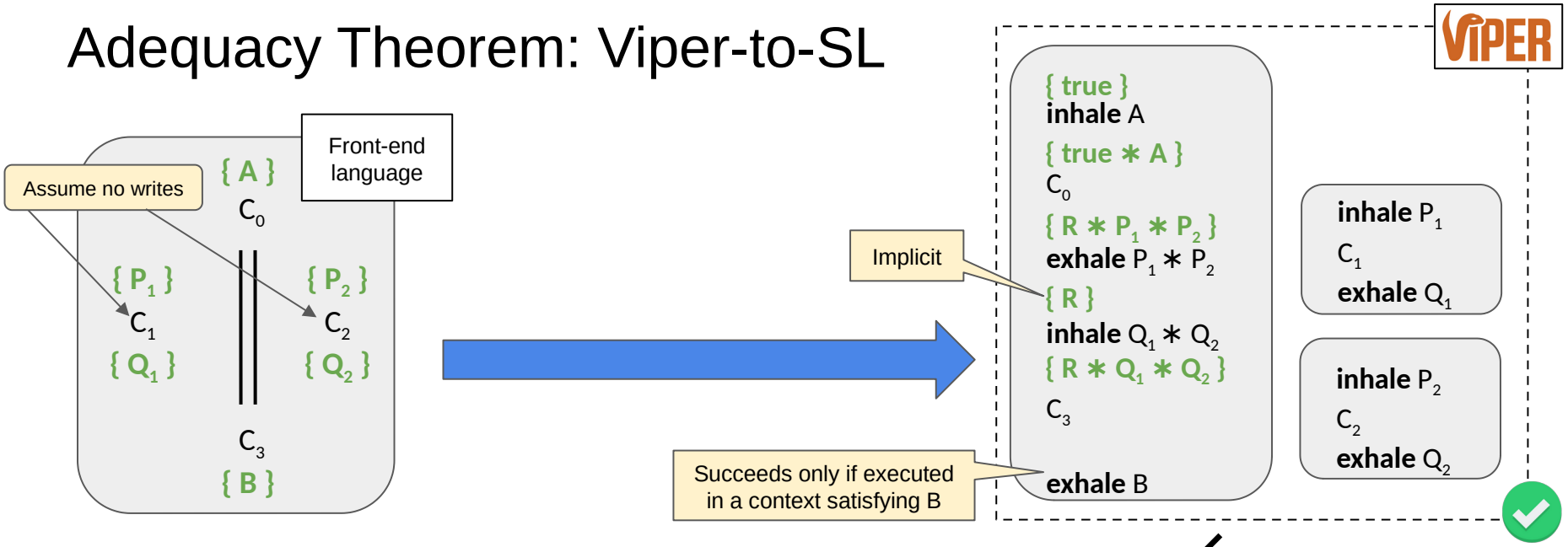

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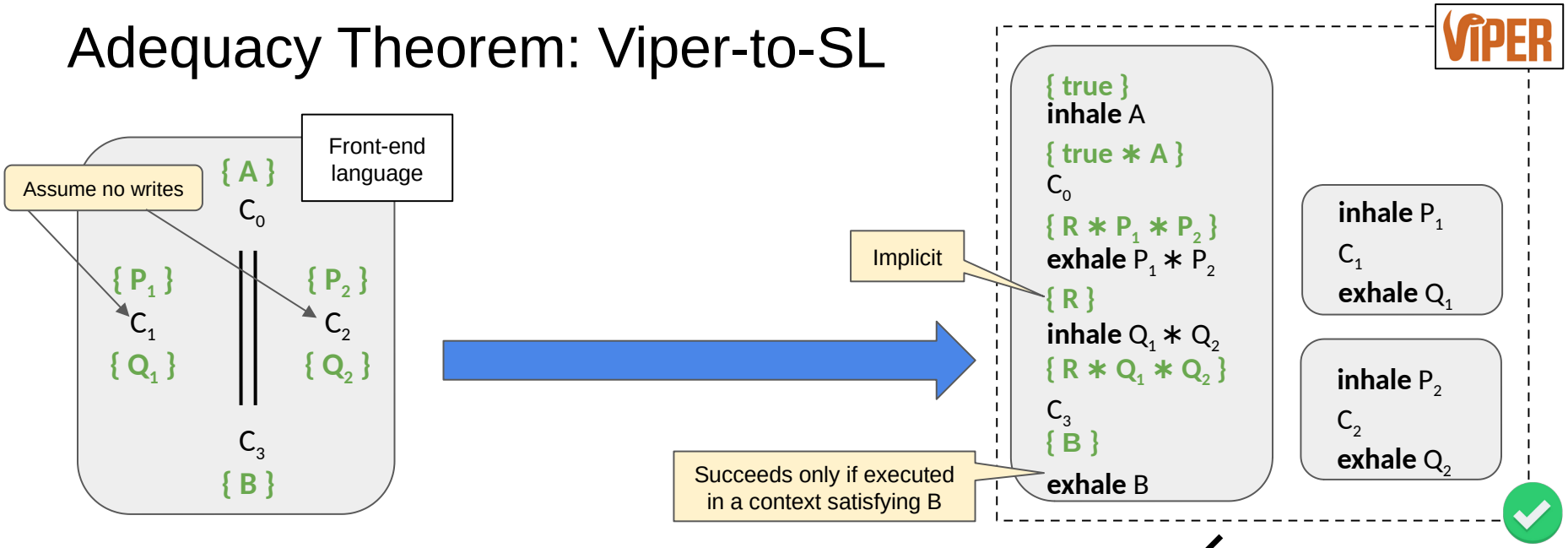

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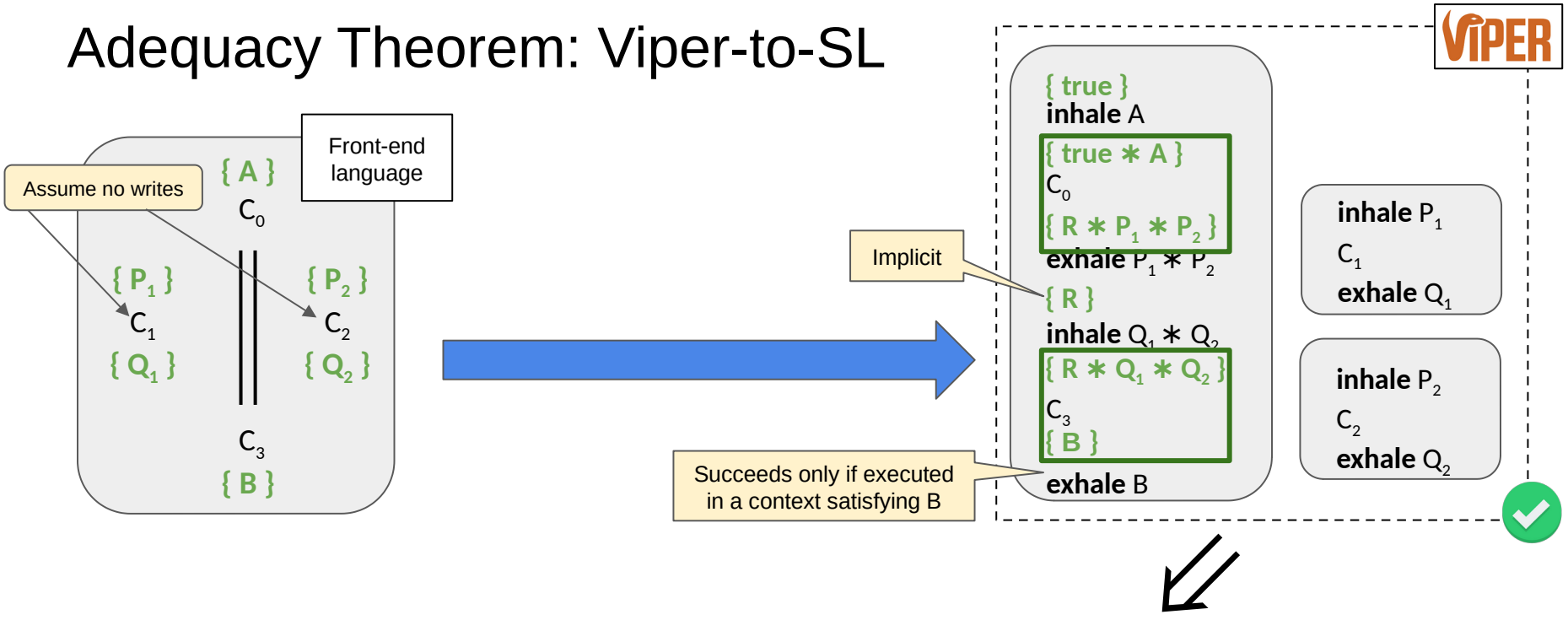

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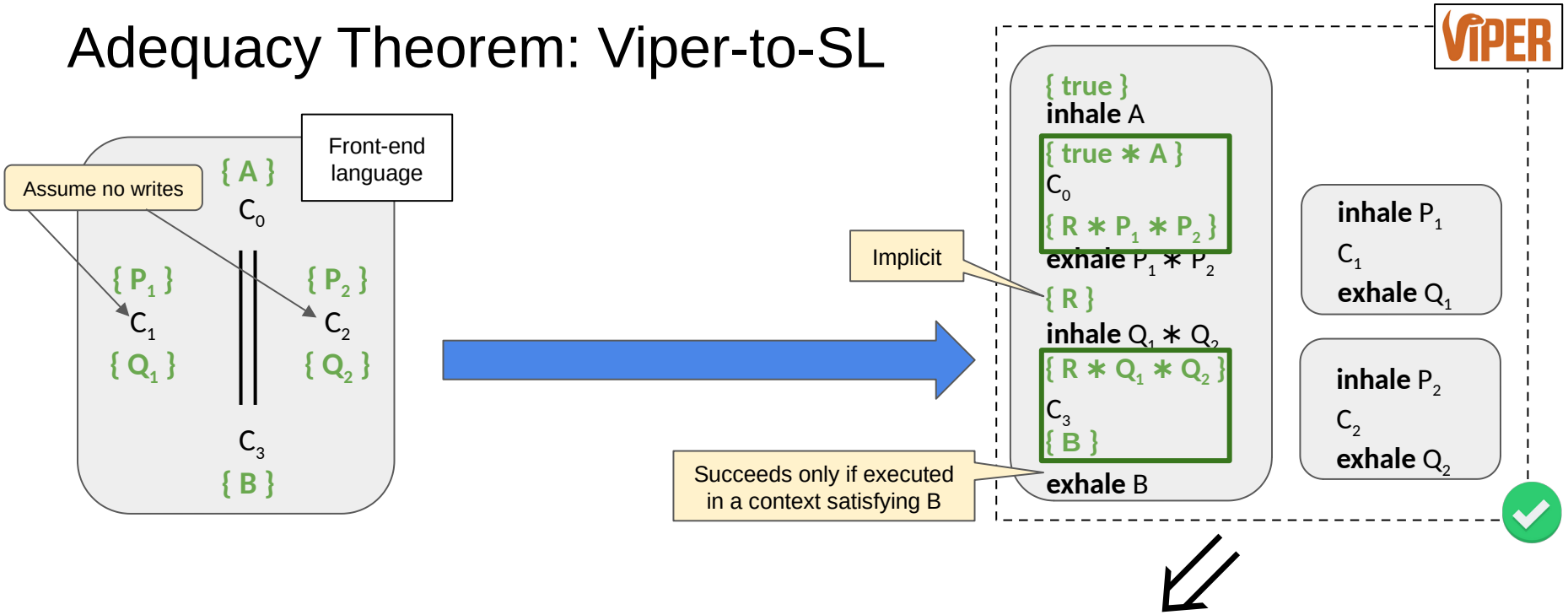
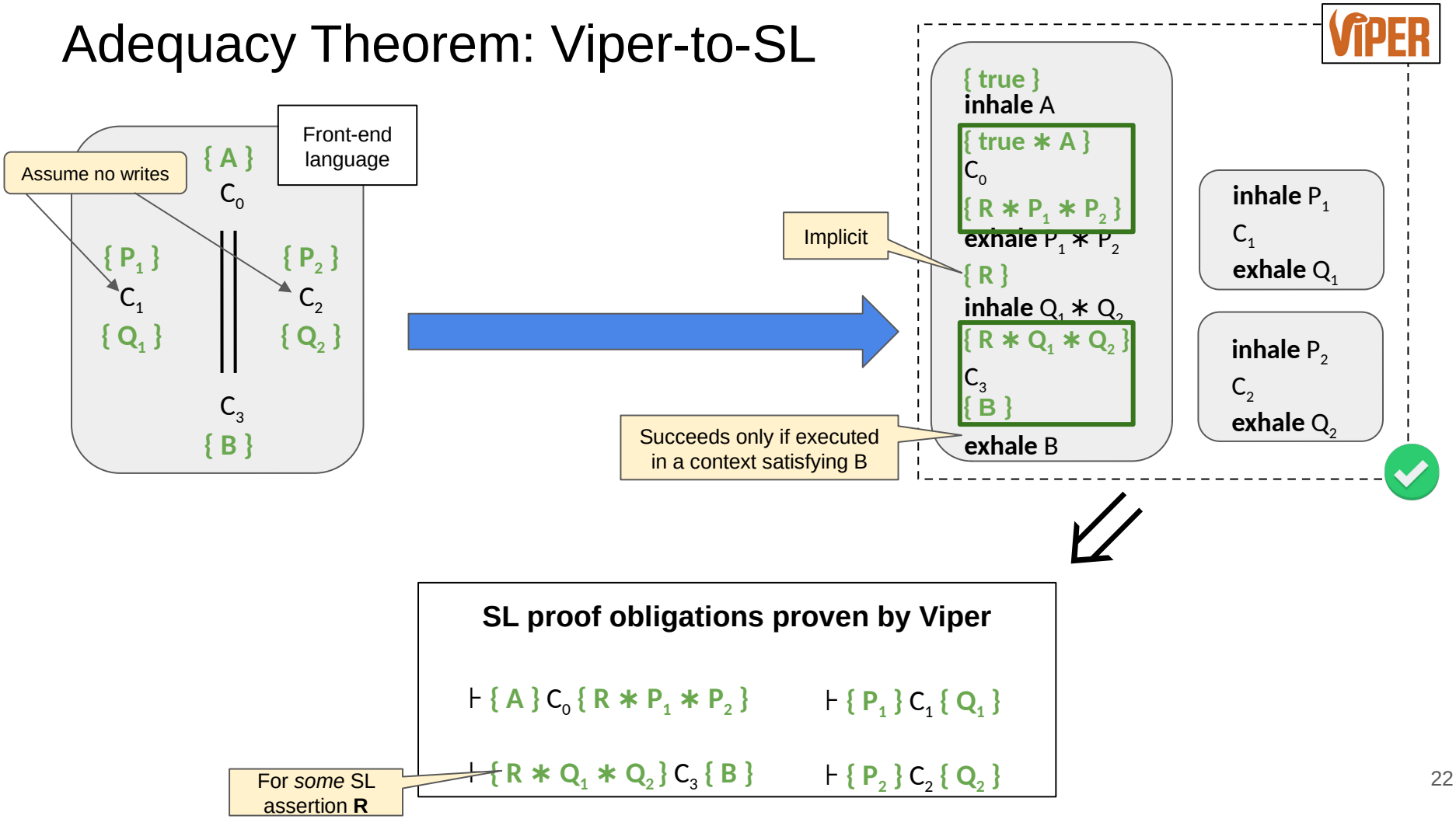


SL proof obligations proven by Viper

$\vdash \{ A \}\, C_0 \,\{ R * P_1 * P_2 \}$ $\quad\quad$ $\vdash \{ P_1 \}\, C_1 \,\{ Q_1 \}$

$\vdash \{ R * Q_1 * Q_2 \}\, C_3 \,\{ B \}$ $\quad\quad$ $\vdash \{ P_2 \}\, C_2 \,\{ Q_2 \}$

Adequacy Theorem: Viper-to-SL



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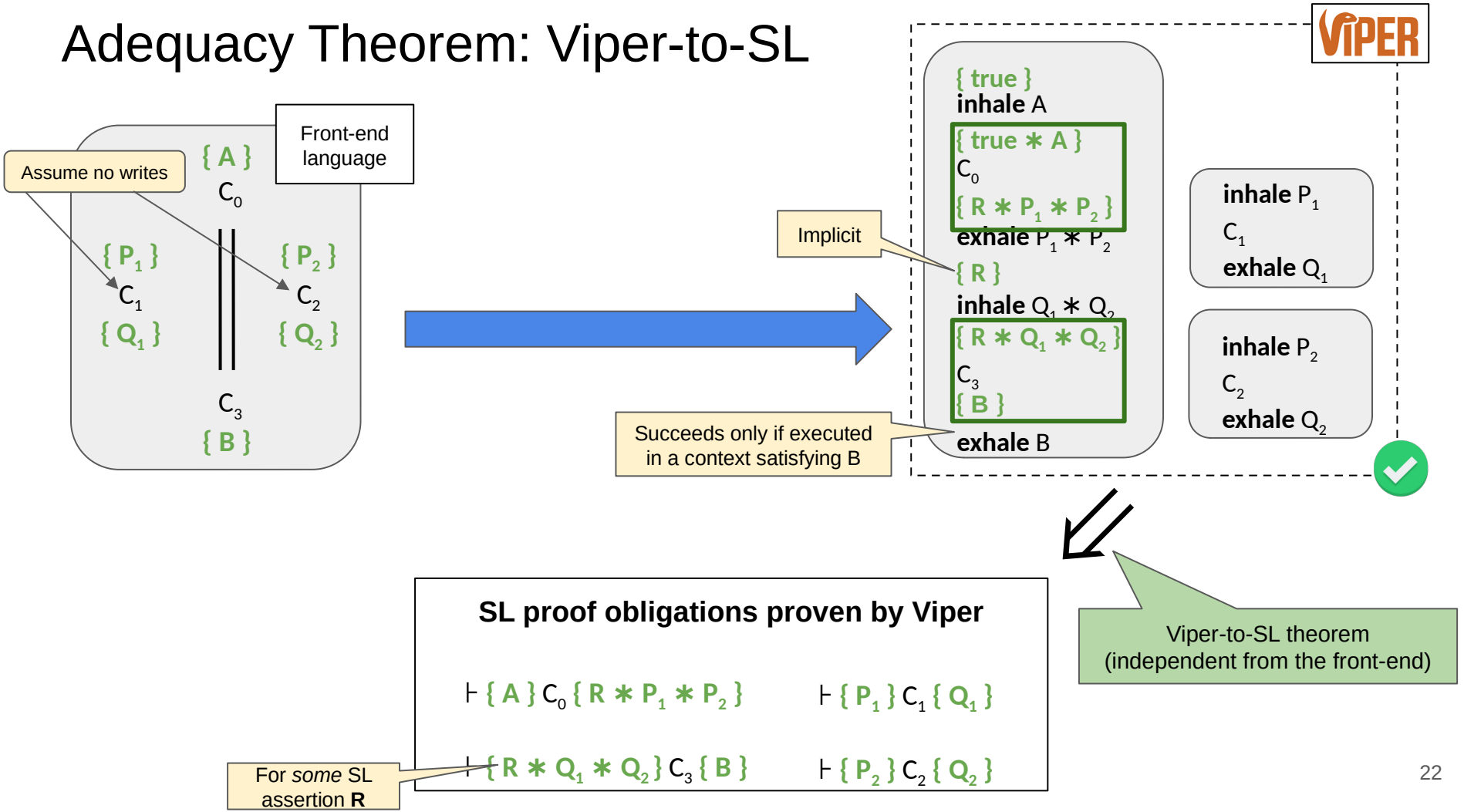

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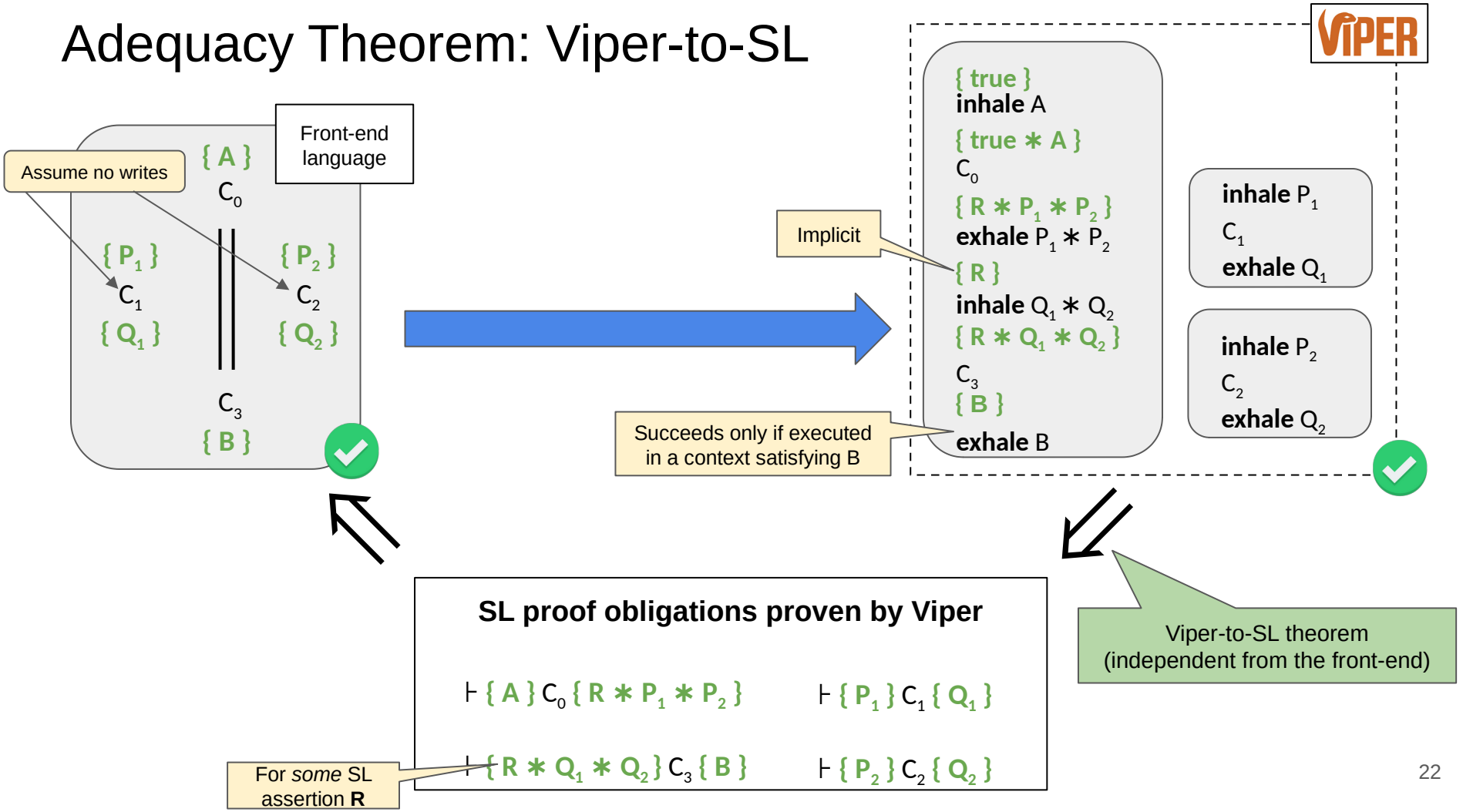

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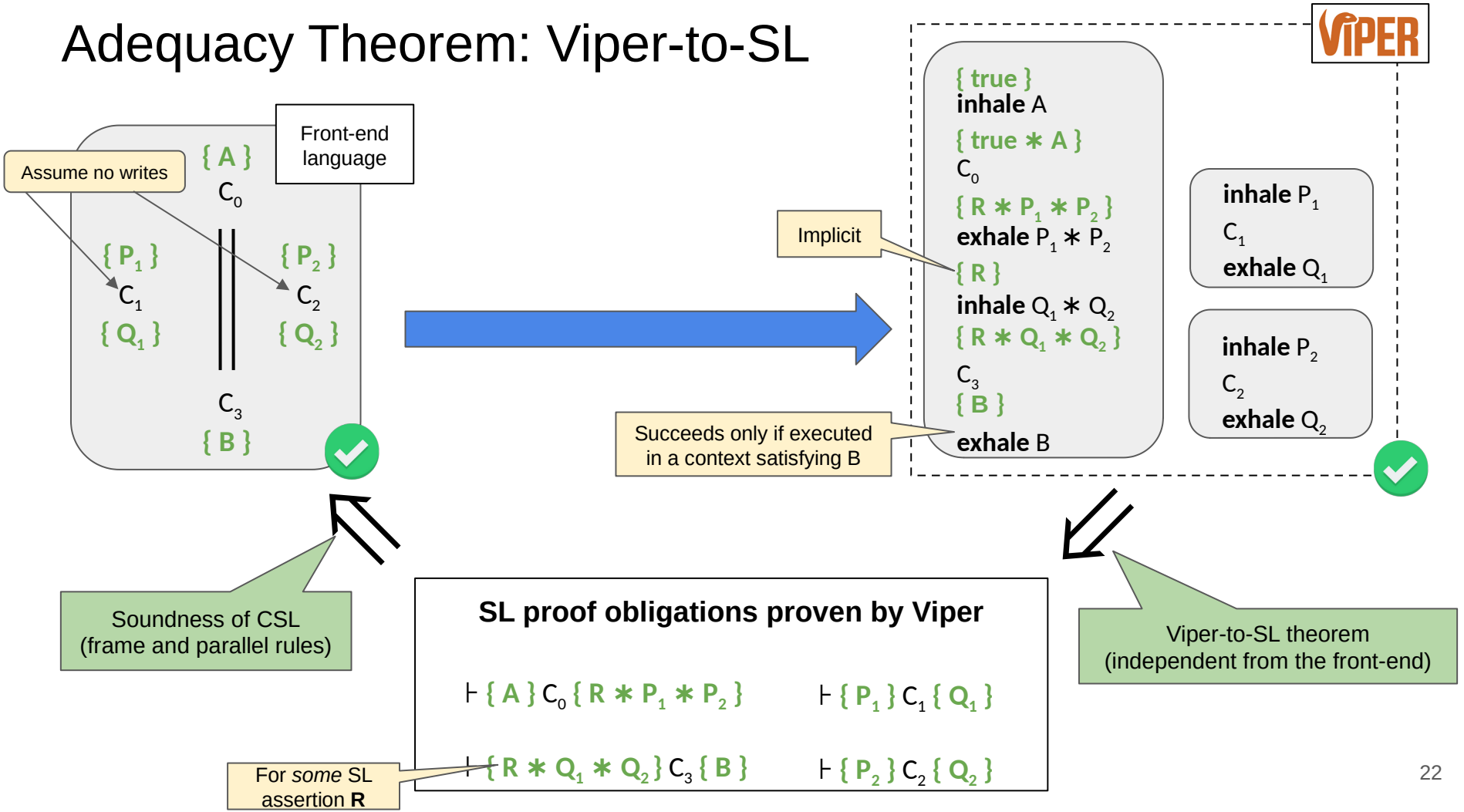
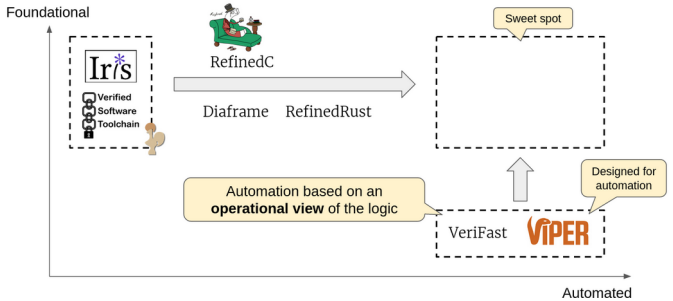


Program Verifiers Based on Separation Logic



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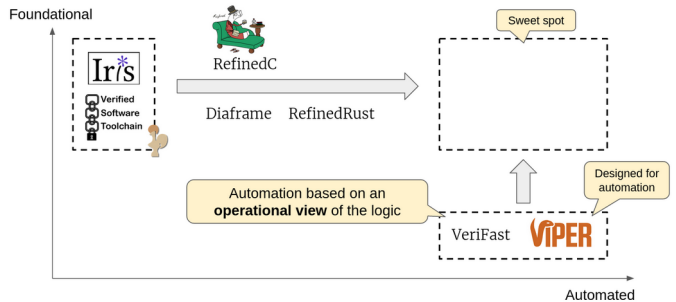
Program Verifiers Based on Separation Logic



3

Verification Primitives: Inhale and Exhale

"A Basis for Verifying Multi-Threaded Programs" (Leino and Müller, ESOP 2009)

	inhale A	**exhale** A
Intuitive meaning	Adds resources specified by A to the current context	Removes resources specified by A from the current context
Logically	⊢ {P} **inhale** A {P ∗ A} wp (**inhale** A) {Q} = A −∗ Q	⊢ {P ∗ A} **exhale** A {P} wp (**exhale** A) {Q} = A ∗ Q
Operationally	• All resources required by A are obtained • All logical constraints are assumed	• All resources required by A are removed • All logical constraints are asserted
SL analogue of	**assume** A	**assert** A

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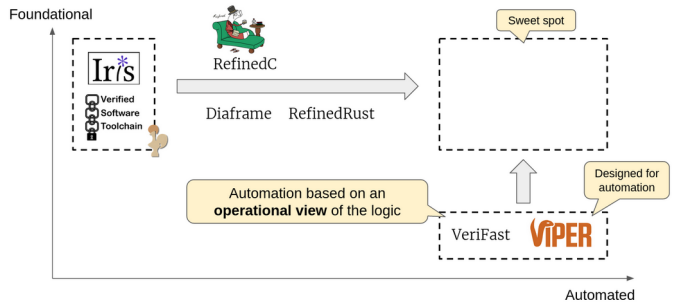

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Viper's Expression and Assertion Language

Design choice
- No impure existential
- No impure disjunction
- No impure implication
- No impure negation
- No impure logical conjunction

Field access

Heap-dependent functions

e ::= e.x | f(e_1, …, e_n) | **old**[l](e) | e_1 + e_2 | e_1 / e_2 | n | v | b ? e_1 : e_2 | …

Pure expressions

b ::= e_1 = e_2 | ¬b | b_1 ⇒ b_2 | b_1 ∨ b_2 | b_1 ∧ b_2 | ∀v. b | …

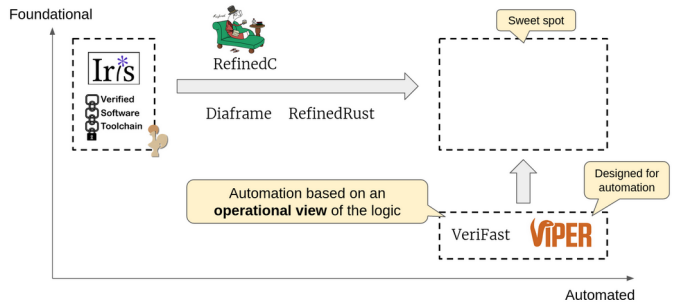
A ::= b | **acc**(e_1.x, e_2) | **acc**(P(e_1, …, e_n), e) | A_1 ∗ A_2 | A_1 −∗ A_2 | ⊛v. A | b ⇒ A | …

Fractional permissions for heap locations

Recursive predicates with fractional permissions

Iterated separating conjunction

Program Verifiers Based on Separation Logic



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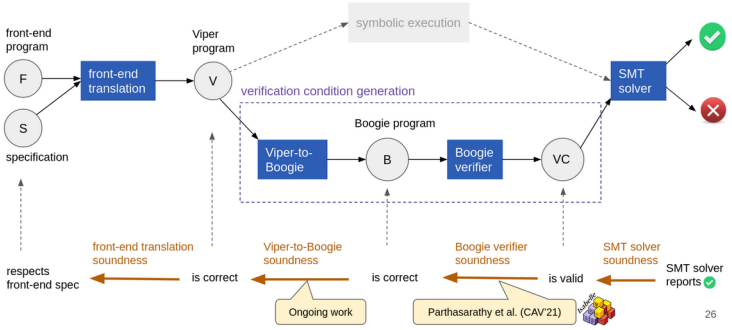
Recursive predicates with fractional permissions

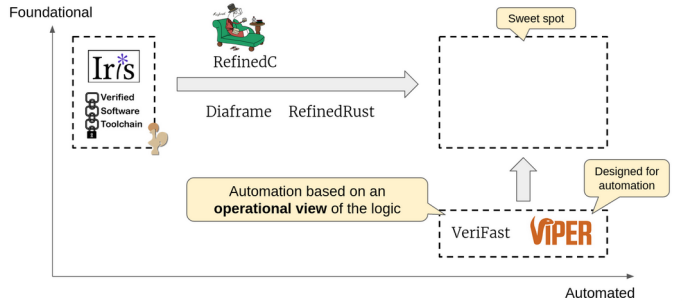
Iterated separating conjunction

Soundness: Proof Strategy



Thank you for your attention!

Program Verifiers Based on Separation Logic



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Pure expressions

$b ::= e_1 = e_2 \mid \neg b \mid b_1 \Rightarrow b_2 \mid b_1 \vee b_2 \mid b_1 \wedge b_2 \mid \forall v.\ b \mid \ldots$

$A ::= b \mid \textbf{acc}(e_1.x, e_2) \mid \textbf{acc}(P(e_1, \ldots, e_n), e) \mid A_1 * A_2 \mid A_1 -\!\!* A_2 \mid \circledast v.\ A \mid b \Rightarrow A \mid \ldots$

Fractional permissions for heap locations

Recursive predicates with fractional permissions

Iterated separating conjunction

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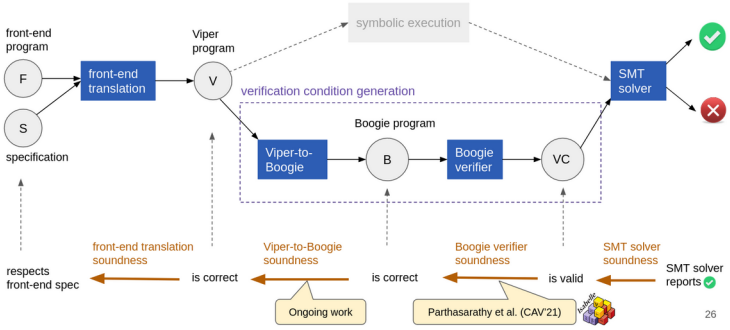
Soundness: Proof Strategy



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