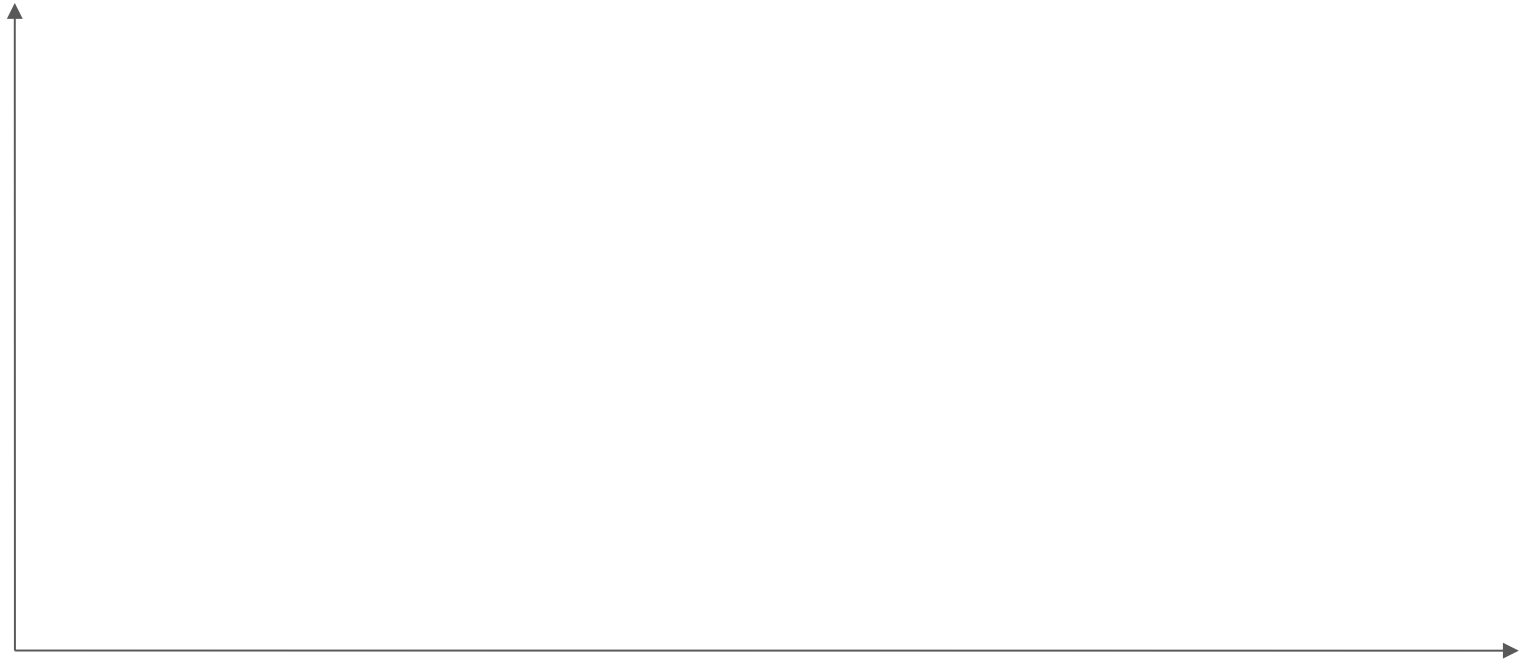
Formal Foundations of the Viper Verification Infrastructure

Thibault Dardinier

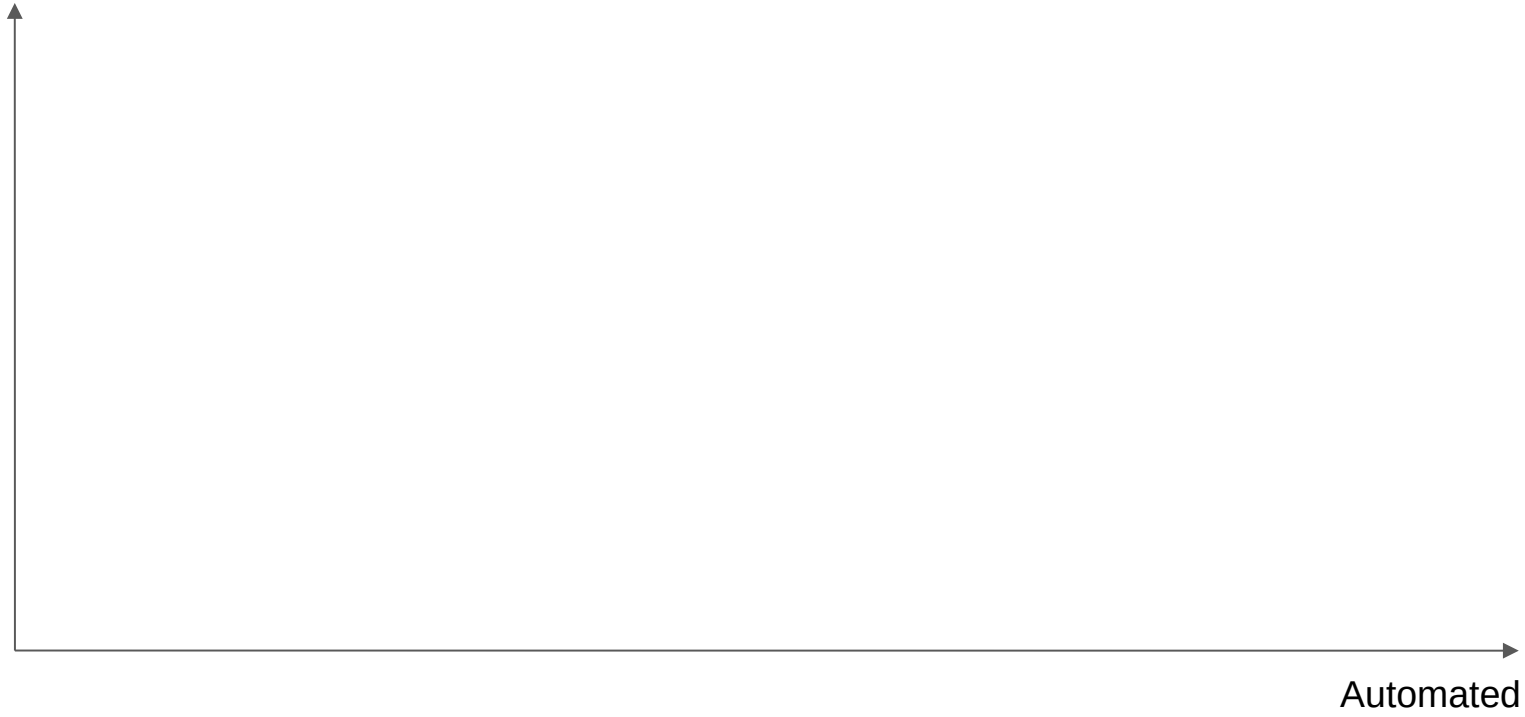
ETH zürich

Joint work with Gaurav Parthasarathy, Alex Summers, Peter Müller

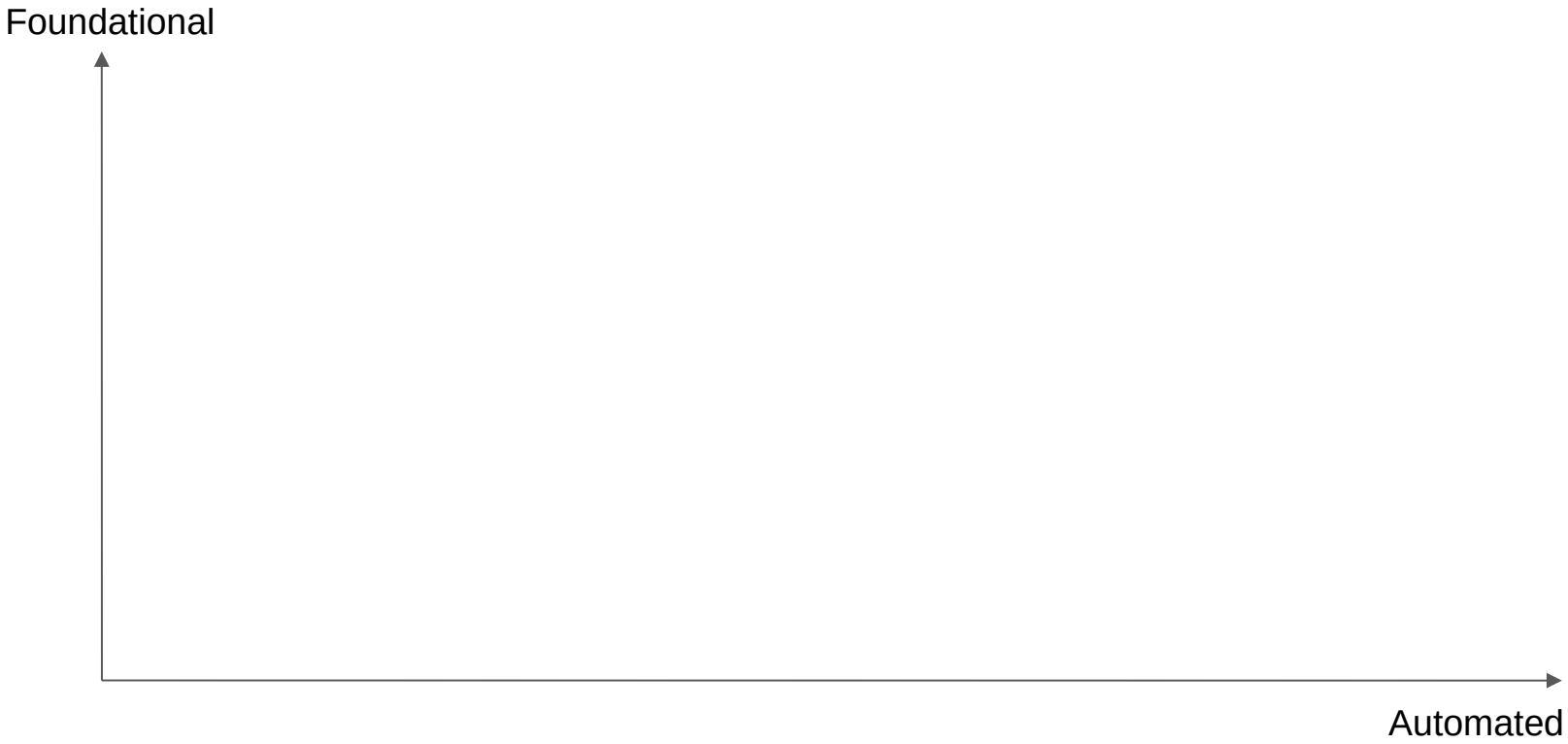
Program Verifiers Based on Separation Logic (SL)



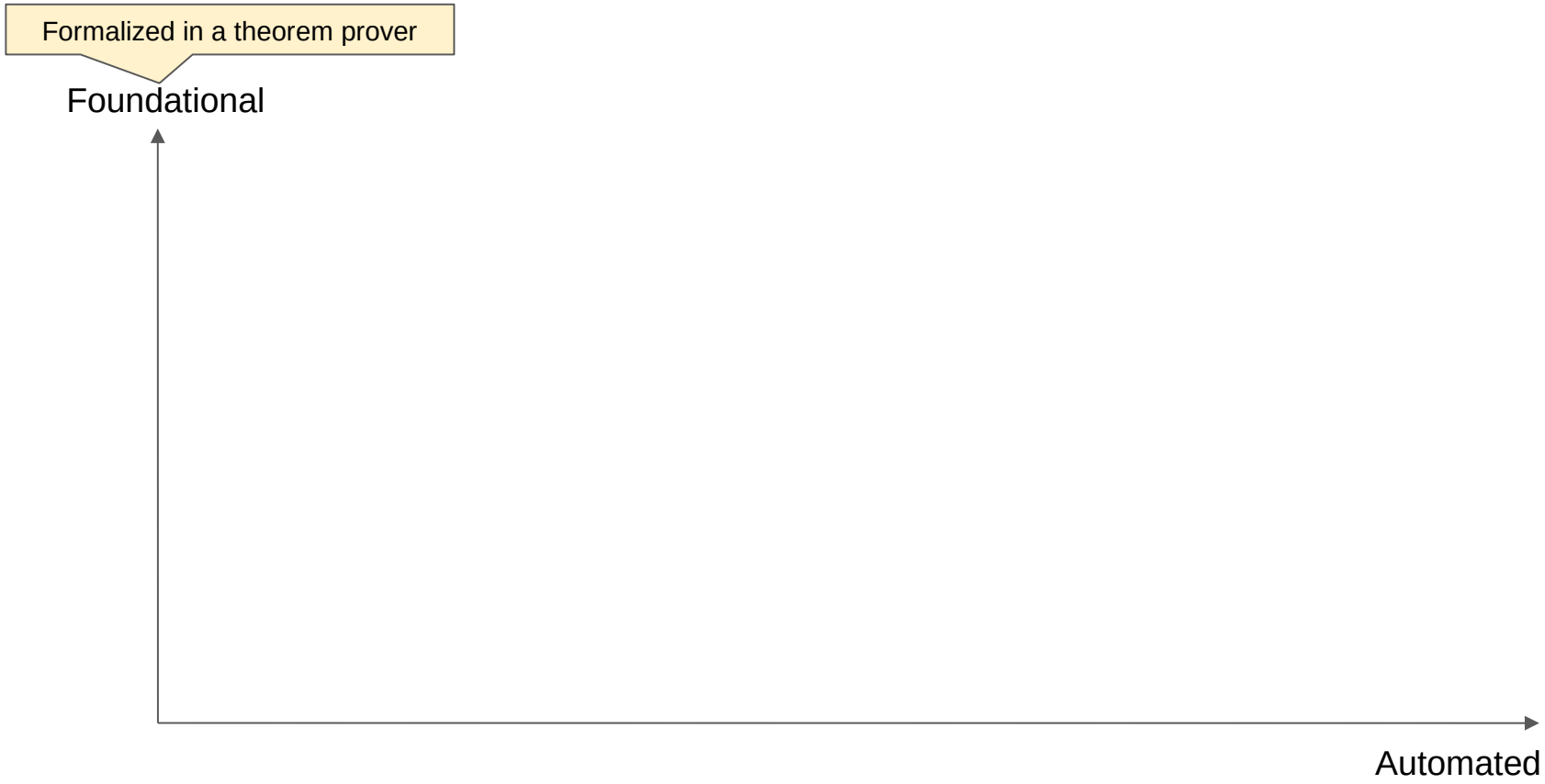
Program Verifiers Based on Separation Logic (SL)



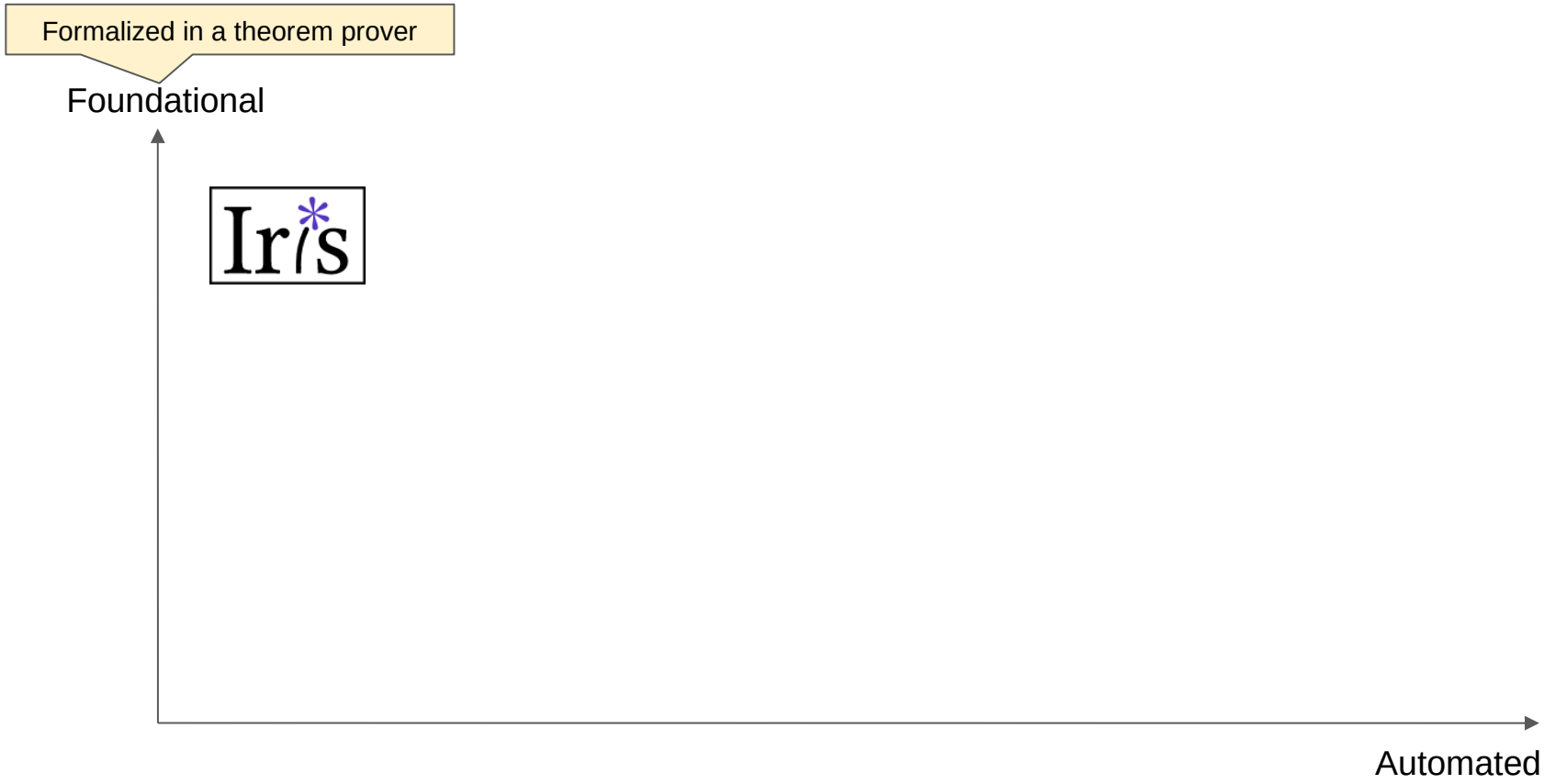
Program Verifiers Based on Separation Logic (SL)



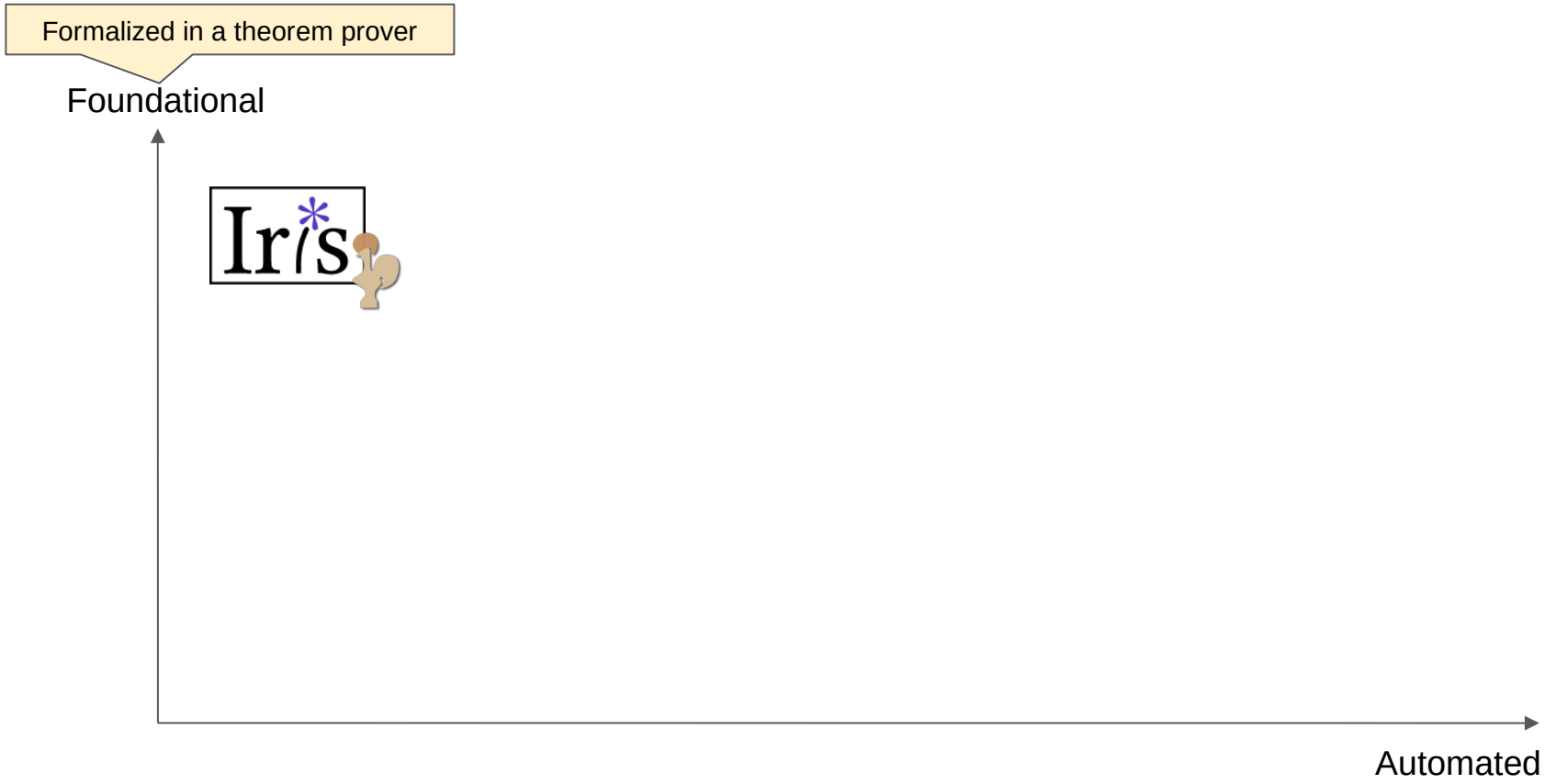
Program Verifiers Based on Separation Logic (SL)



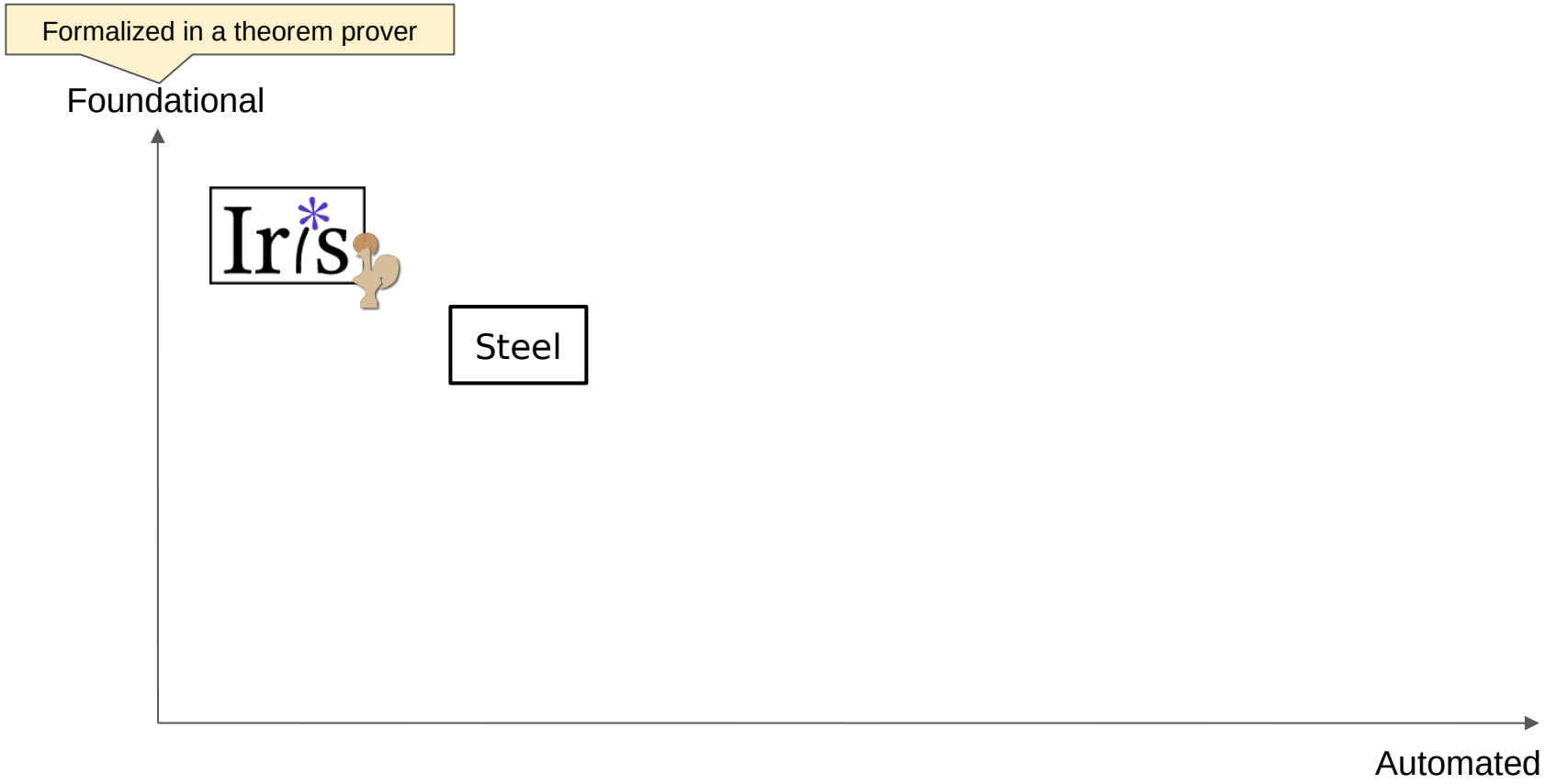
Program Verifiers Based on Separation Logic (SL)



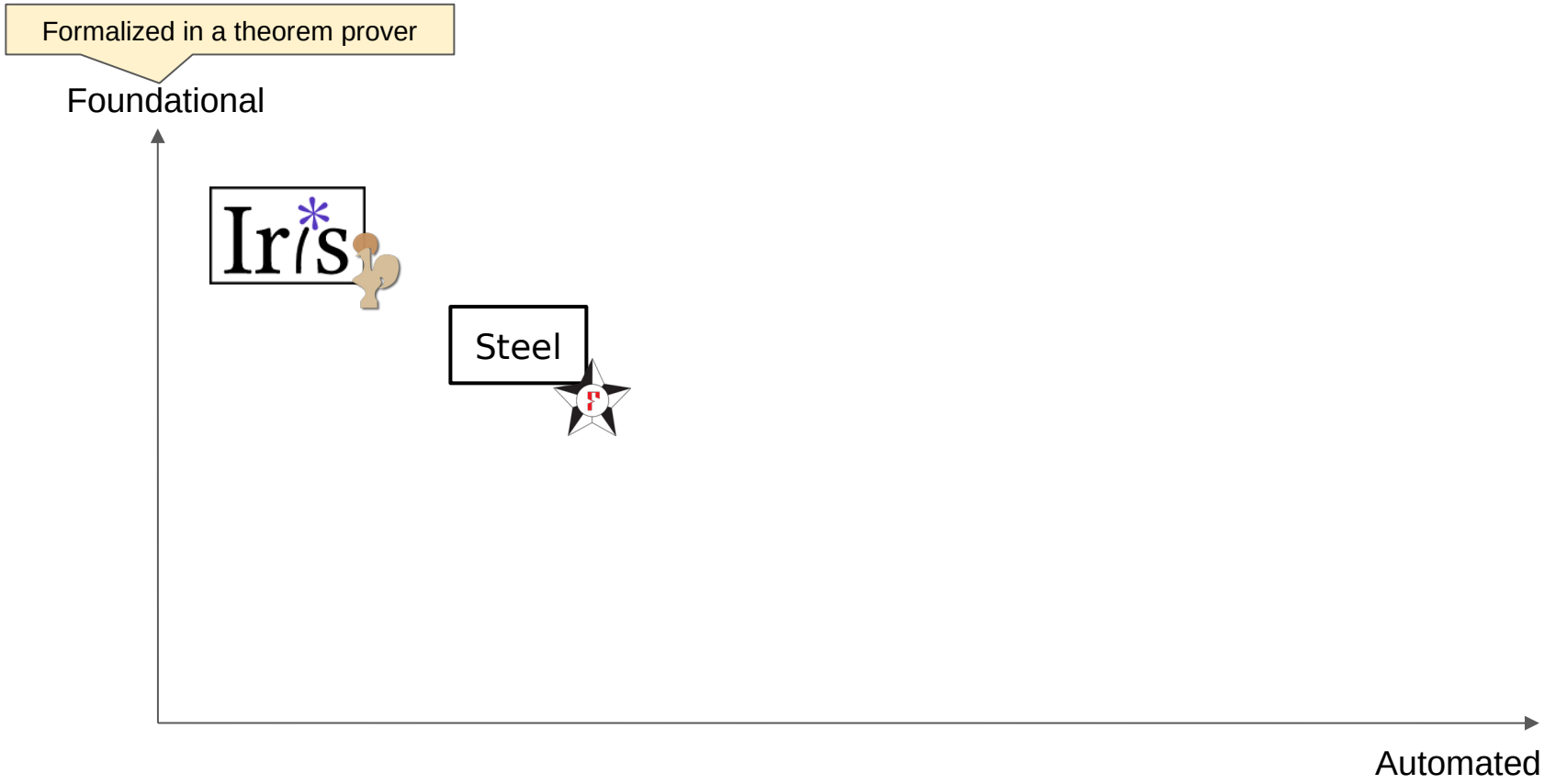
Program Verifiers Based on Separation Logic (SL)



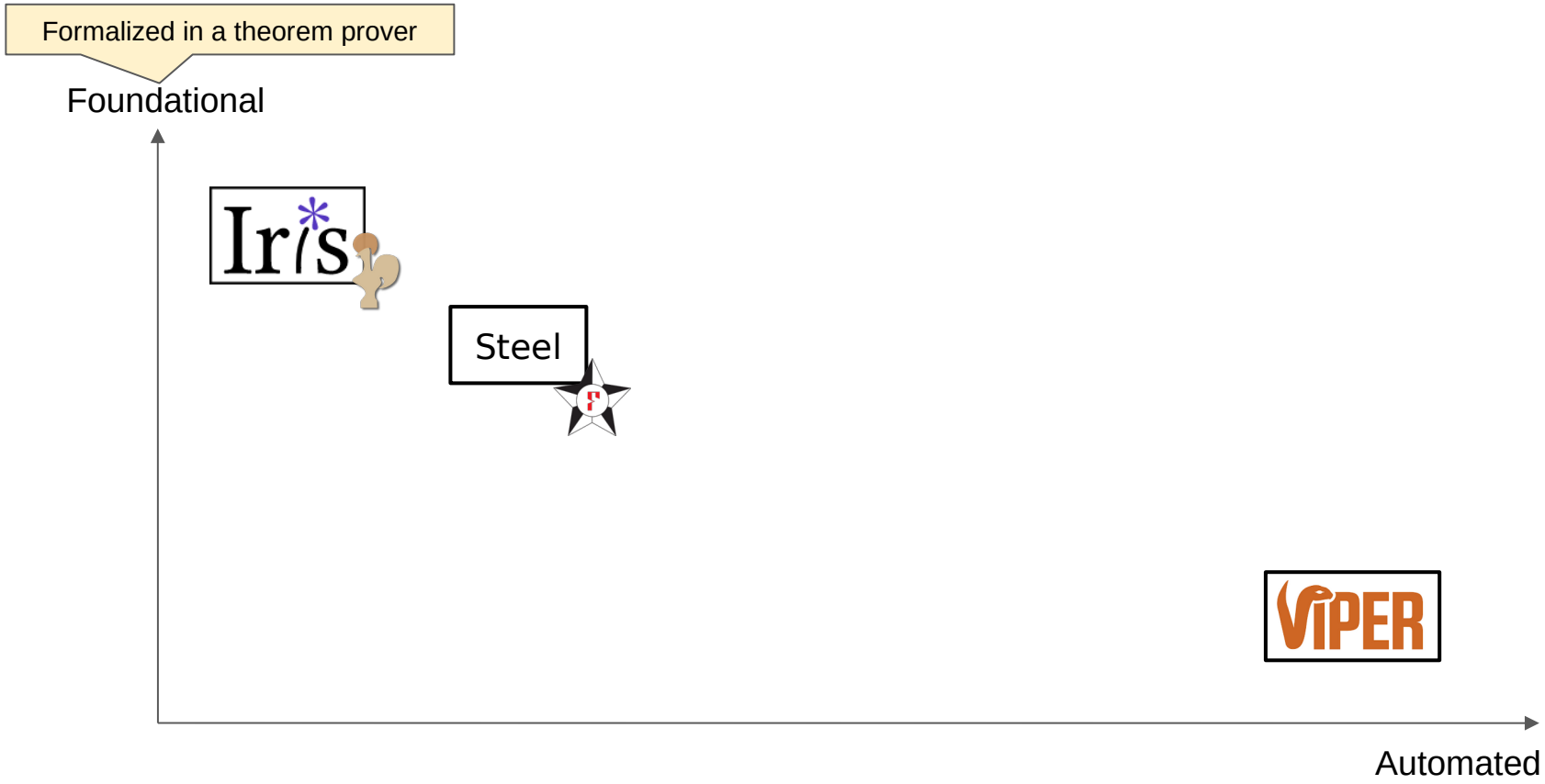
Program Verifiers Based on Separation Logic (SL)



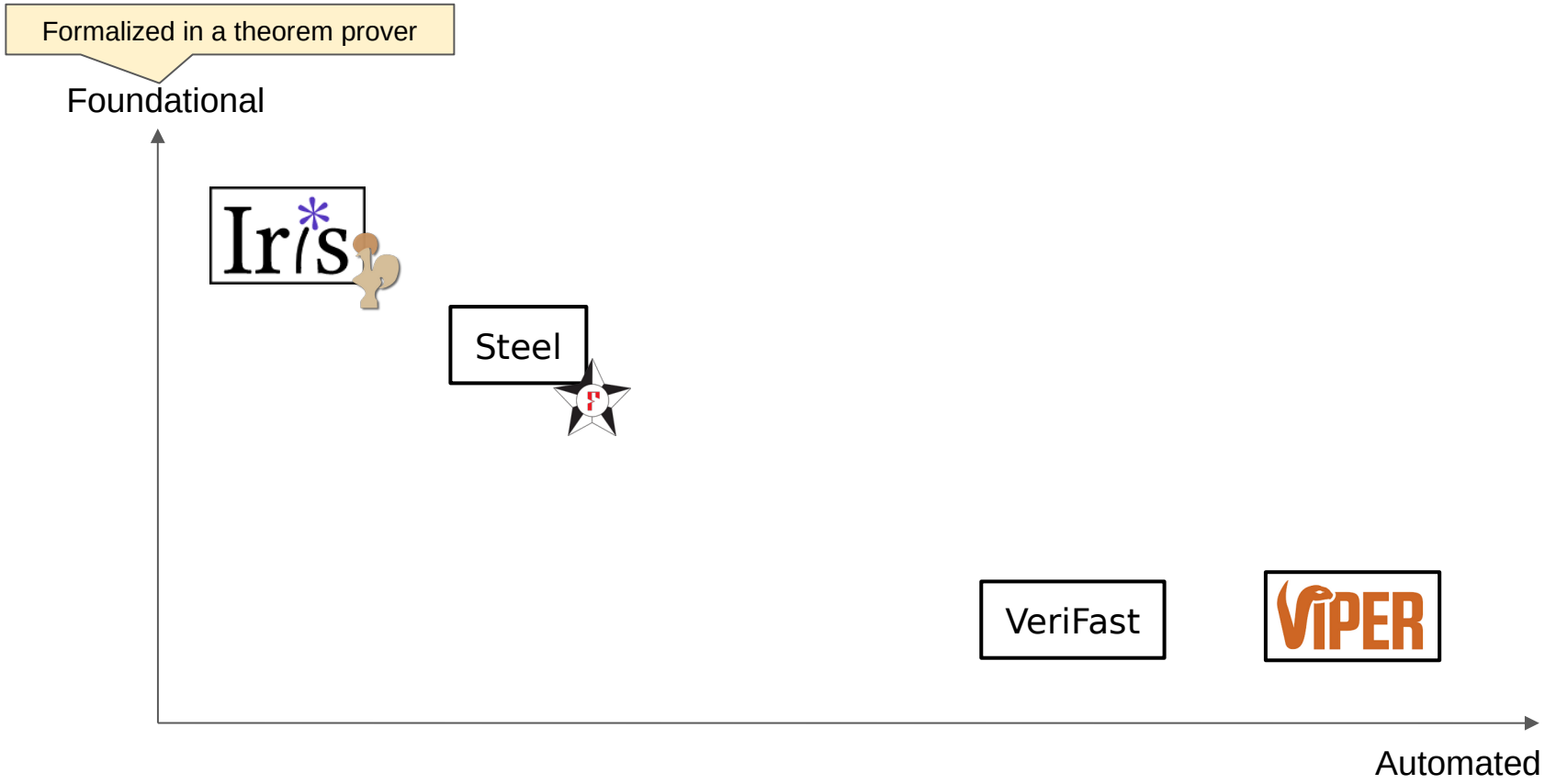
Program Verifiers Based on Separation Logic (SL)



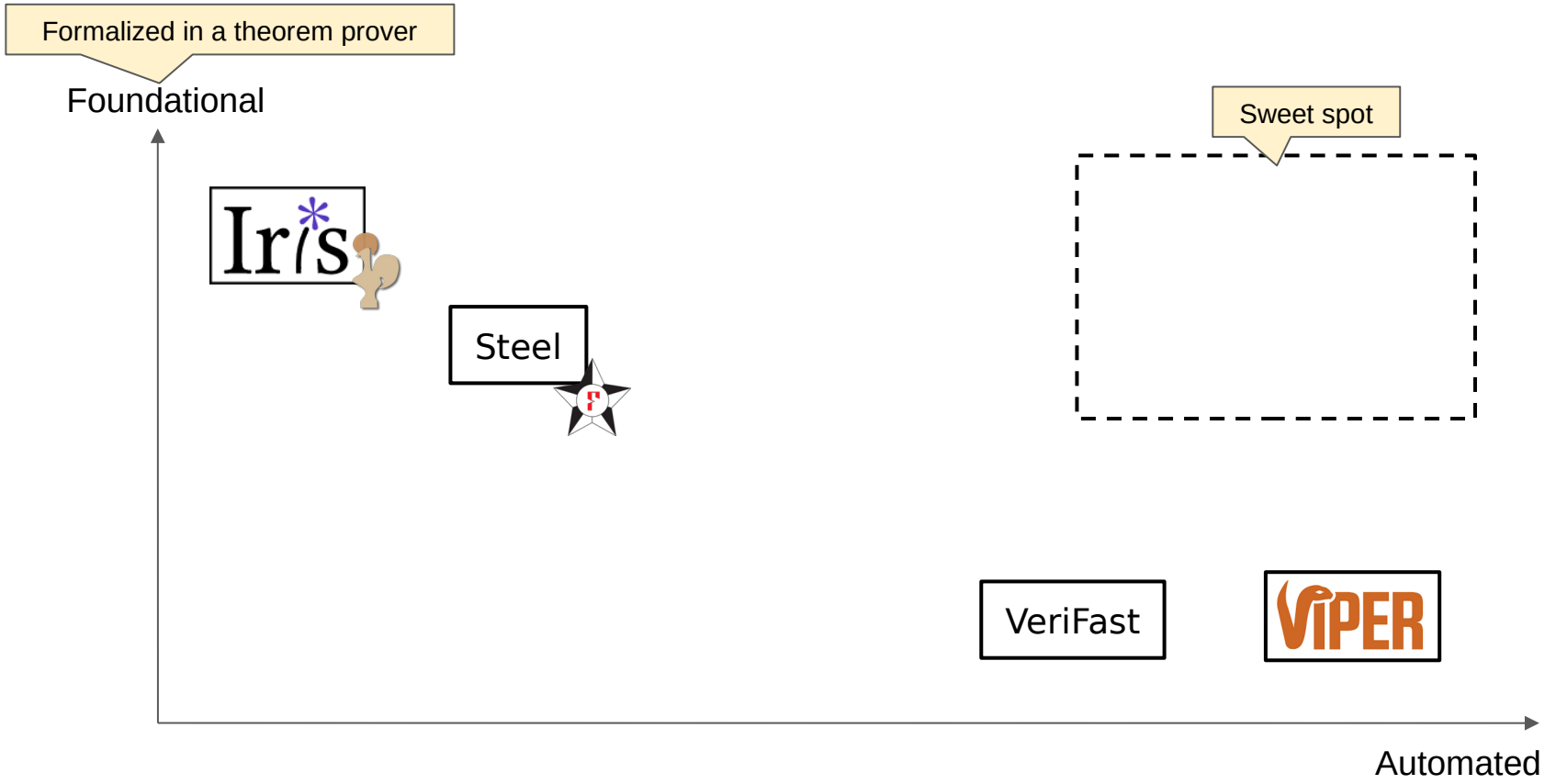
Program Verifiers Based on Separation Logic (SL)



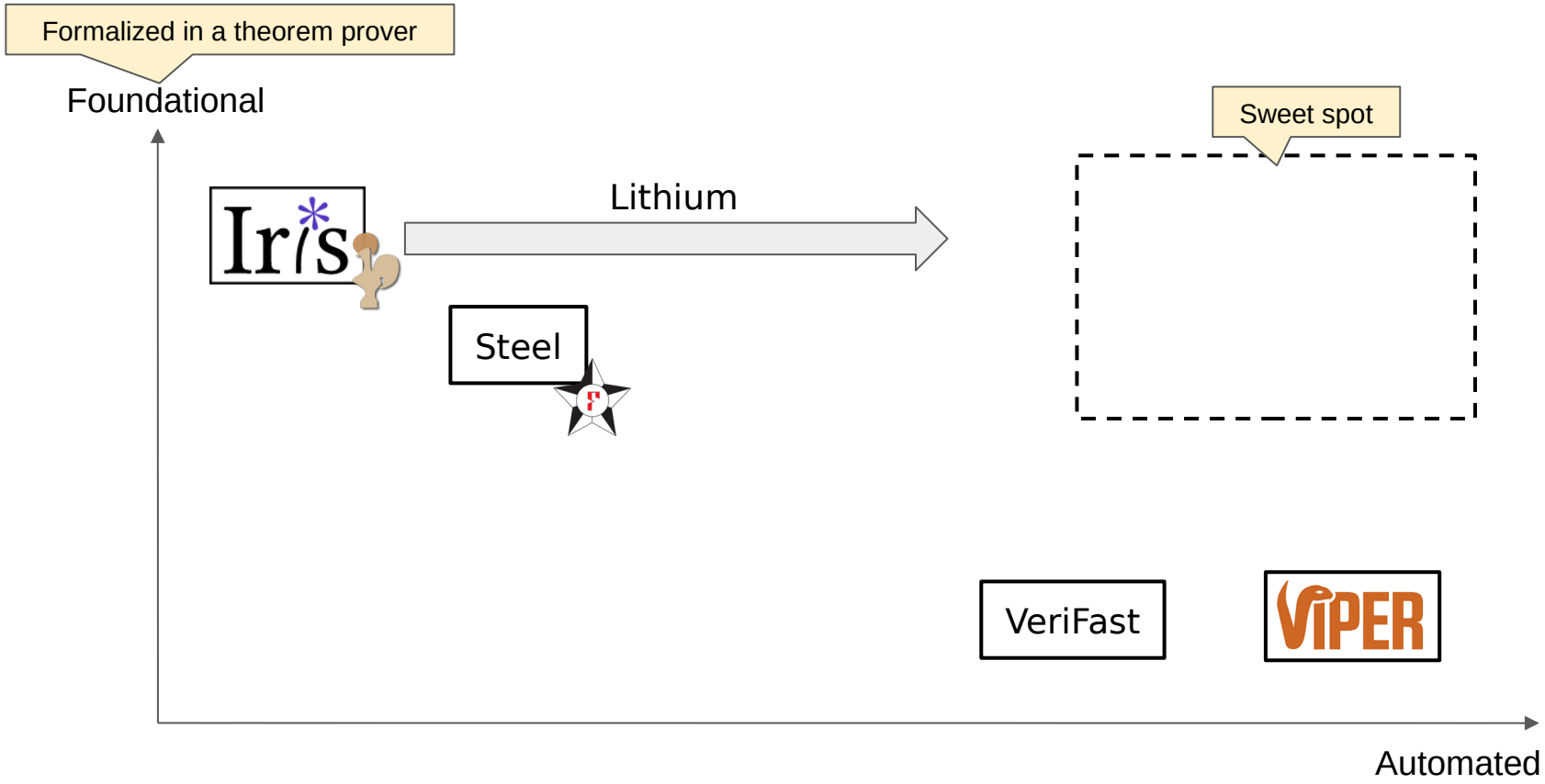
Program Verifiers Based on Separation Logic (SL)



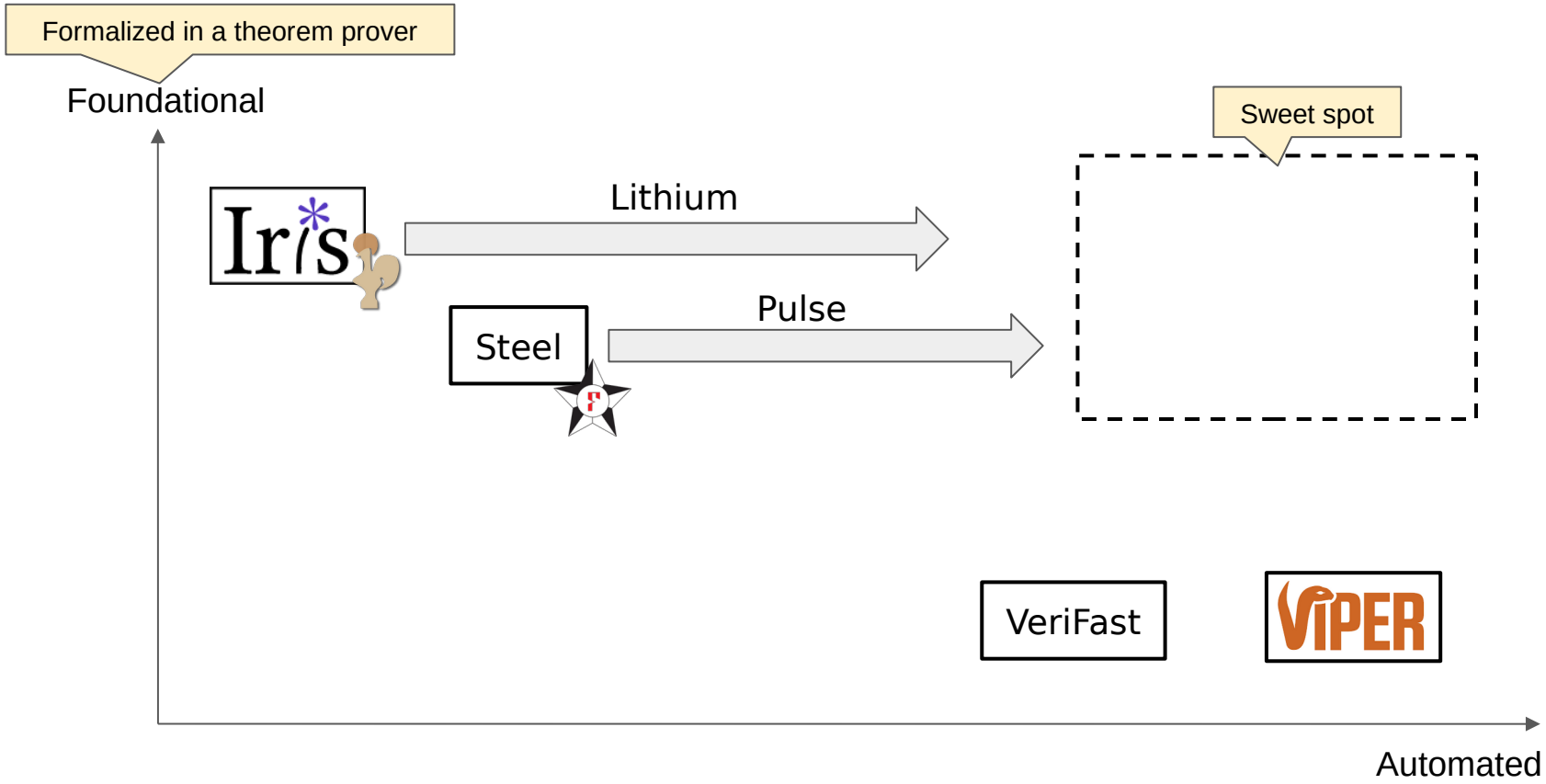
Program Verifiers Based on Separation Logic (SL)



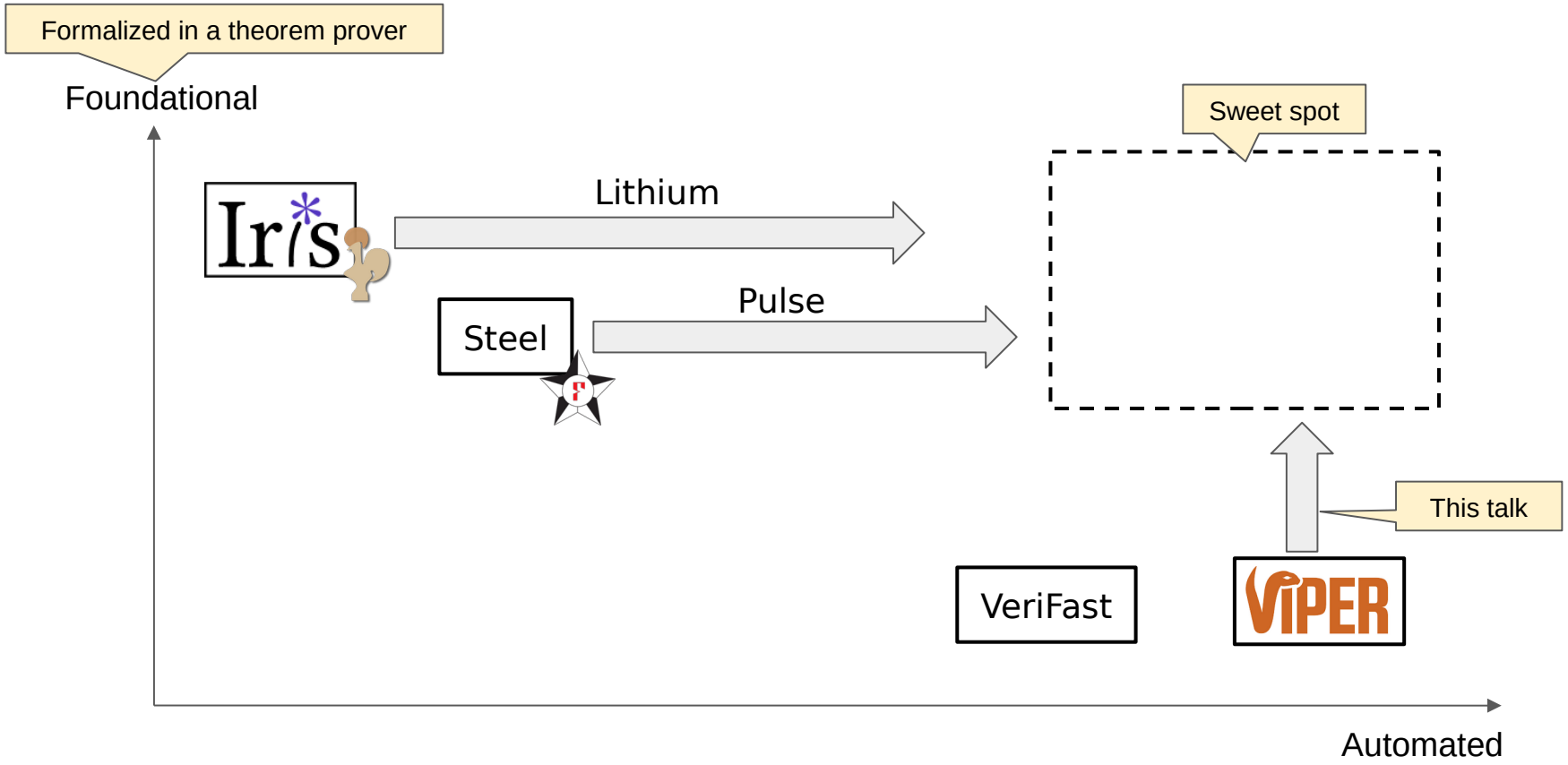
Program Verifiers Based on Separation Logic (SL)



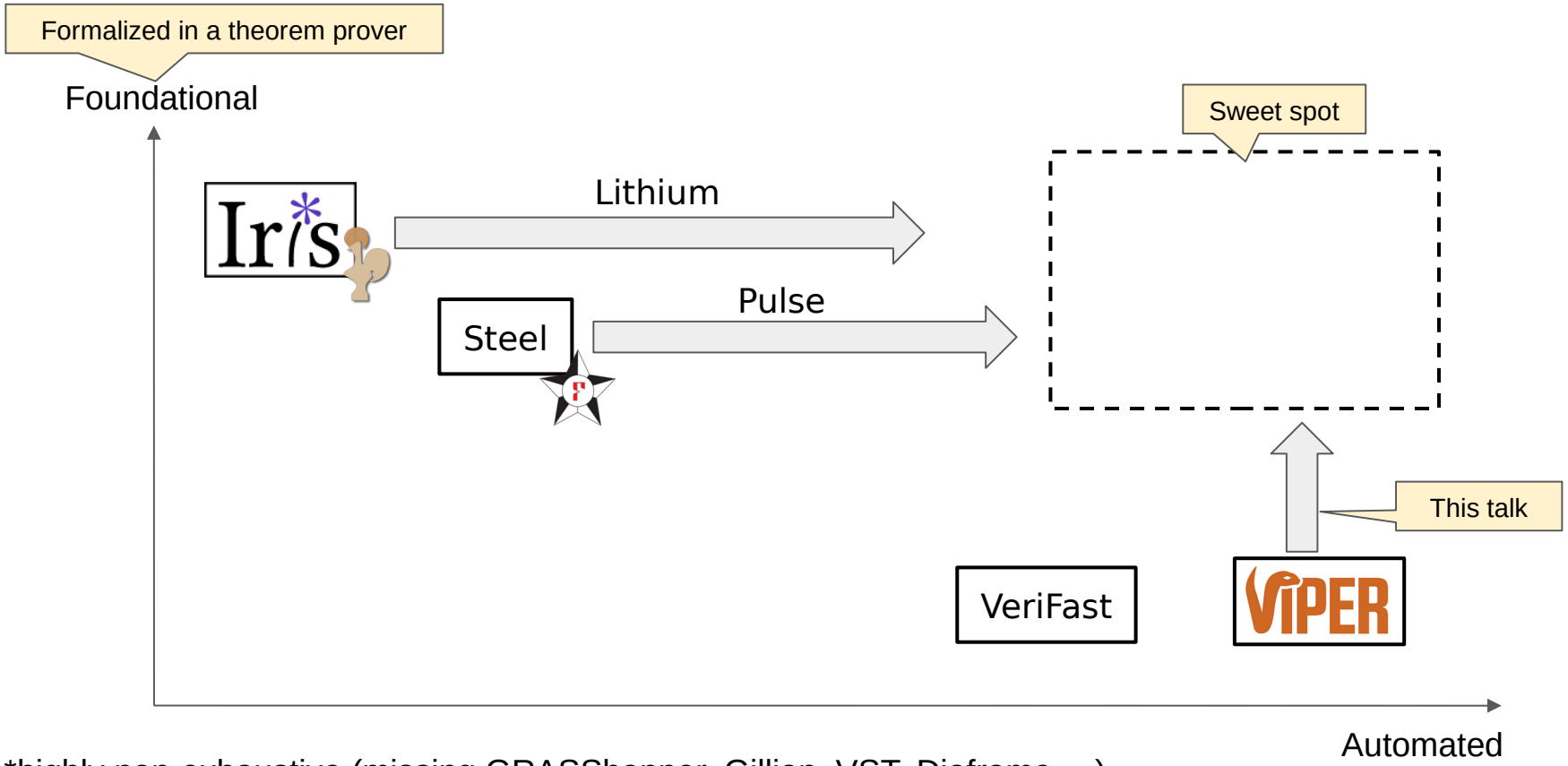
Program Verifiers Based on Separation Logic (SL)



Program Verifiers Based on Separation Logic (SL)



Program Verifiers Based on Separation Logic (SL)



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

Outline of the Talk

Outline of the Talk

1. Overview of Viper

Outline of the Talk

1. Overview of Viper

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

Outline of the Talk

1. Overview of Viper

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

3. Toward a Foundational Viper

Outline of the Talk

1. Overview of Viper

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

3. Toward a Foundational Viper

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 }
```

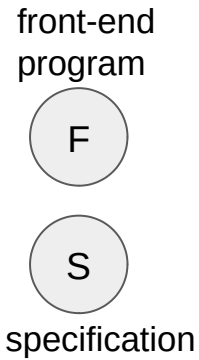
⊗ 1 ⚠ 0 silicon × Verifying demo.vpr failed after 0.5 seconds with 1 error Live Share "demo.vpr" 21L 357C written UTF-8 LF Viper

The Viper Verification Infrastructure

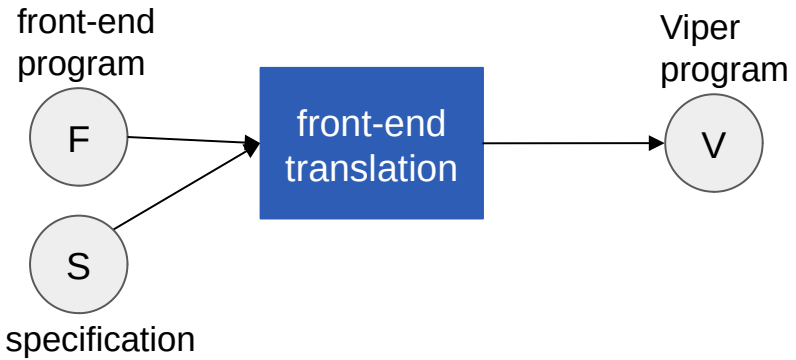
The Viper Verification Infrastructure

front-end
program

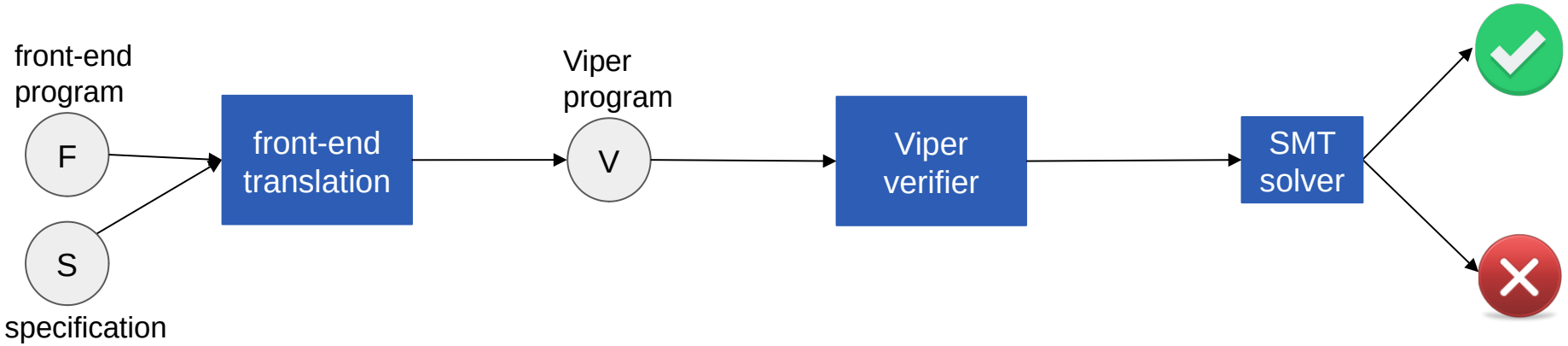
The Viper Verification Infrastructure



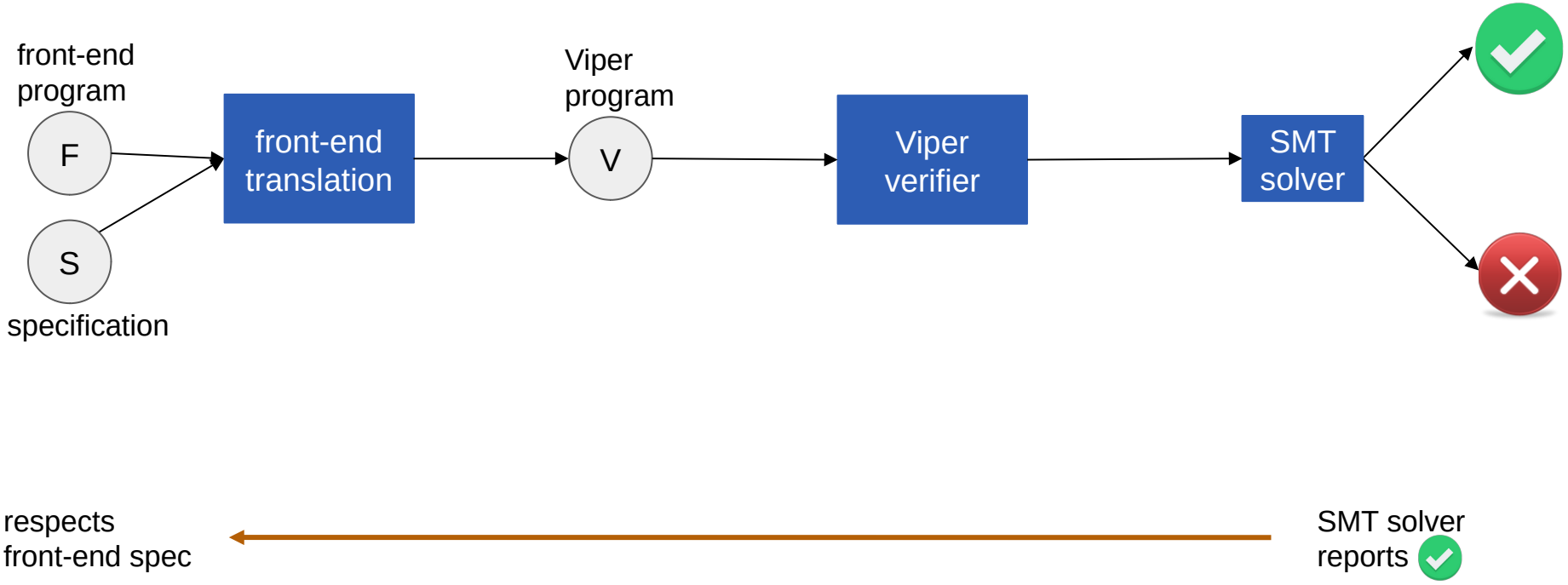
The Viper Verification Infrastructure



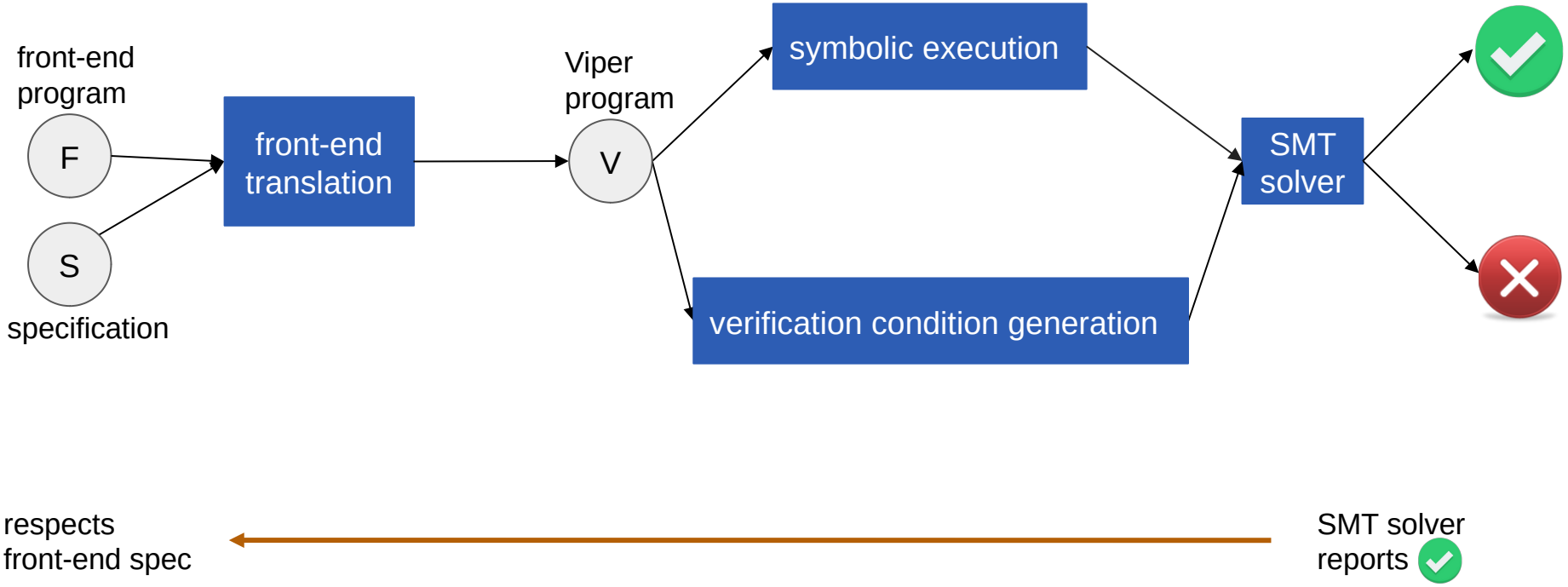
The Viper Verification Infrastructure



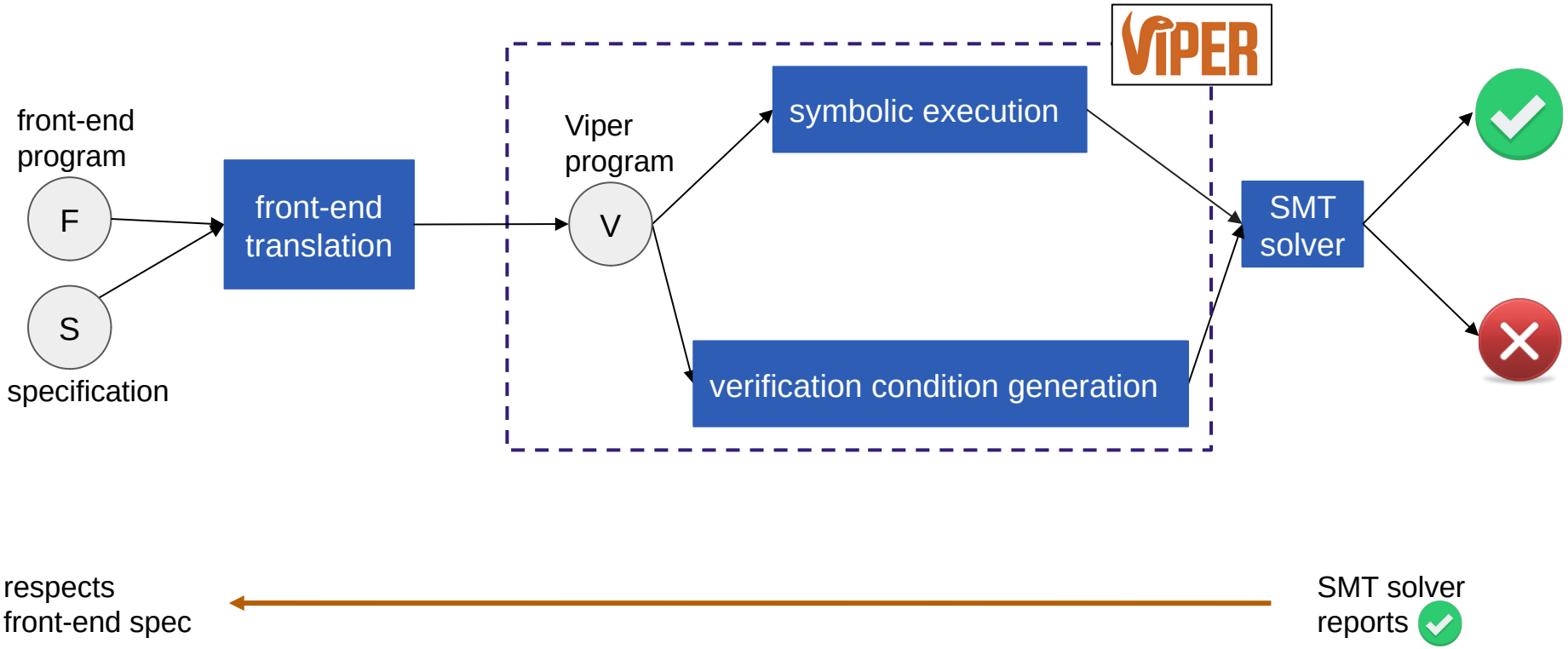
The Viper Verification Infrastructure



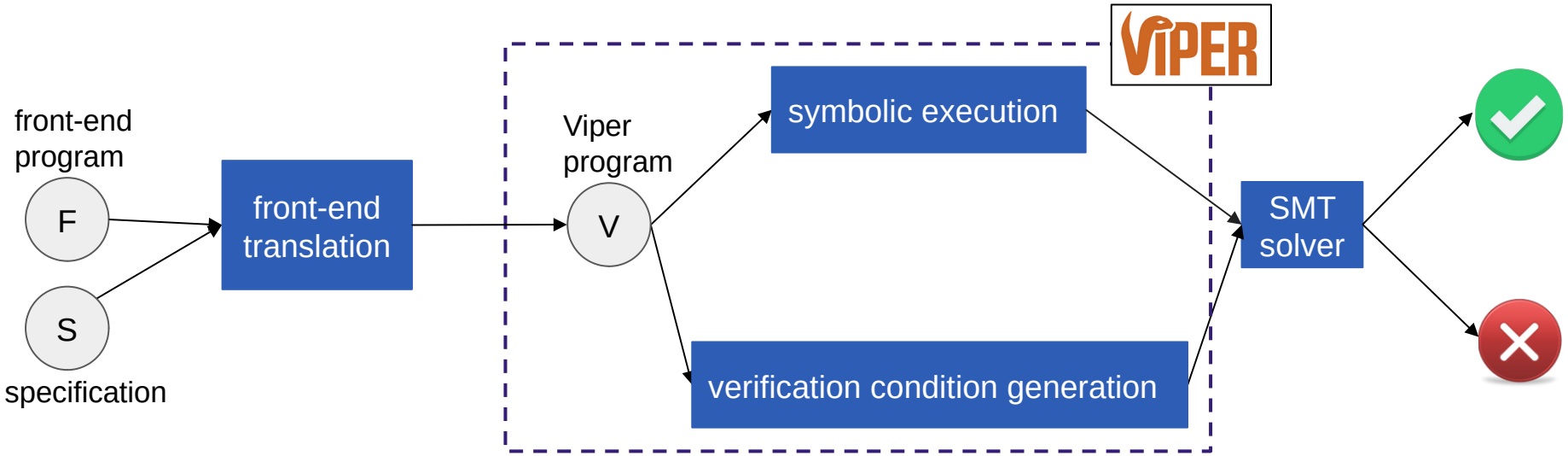
The Viper Verification Infrastructure



The Viper Verification Infrastructure



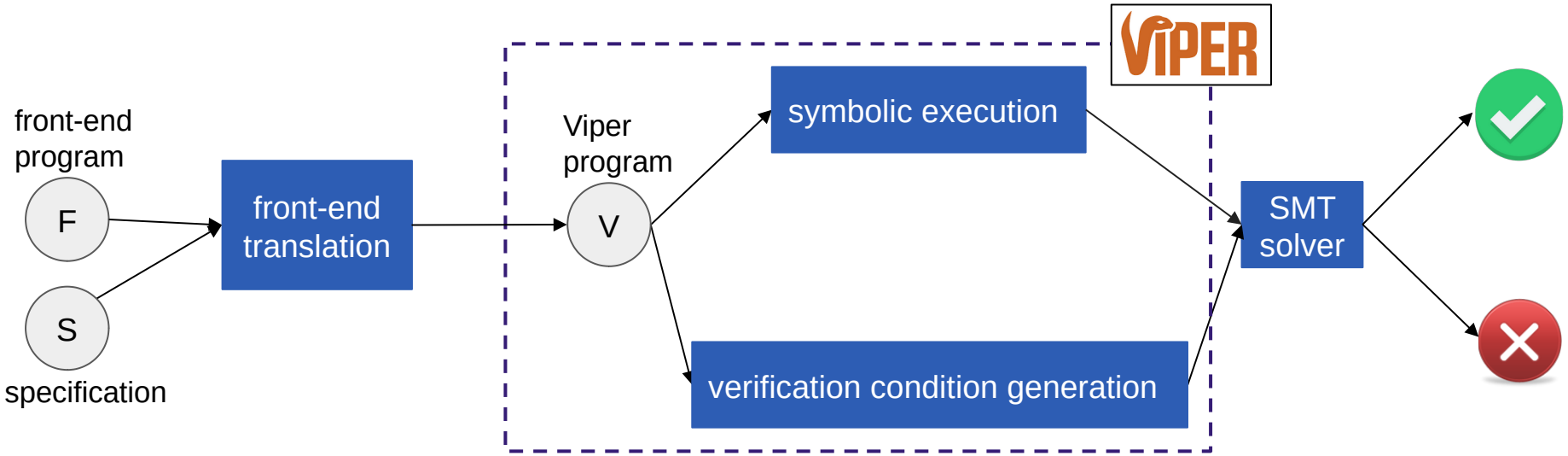
The Viper Verification Infrastructure



Program verifiers built on top of Viper

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

The Viper Verification Infrastructure



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

Program verifiers built on top of Viper

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

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**

Overview of the Viper Language

Program Code

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

Assertion Language

- Fractional permissions

Verification Features

Mathematical Background

Overview of the Viper Language

Program Code

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

Assertion Language

- Fractional permissions
- Inductive predicates

Verification Features

Mathematical Background

Overview of the Viper Language

Program Code

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

Assertion Language

- Fractional permissions
- Inductive predicates
- Iterated separating conjunction

Verification Features

Mathematical Background

Overview of the Viper Language

Program Code

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

Assertion Language

- Fractional permissions
- Inductive predicates
- Iterated separating conjunction
- Magic wands

Verification Features

Mathematical Background

Overview of the Viper Language

Program Code

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

Assertion Language

- Fractional permissions
- Inductive predicates
- Iterated separating conjunction
- Magic wands
- …

Verification Features

Mathematical Background

Overview of the Viper Language

Program Code

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

Assertion Language

- Fractional permissions
- Inductive predicates
- Iterated separating conjunction
- Magic wands
- …

Verification Features

- Standard contract features
- Inhale and exhale
- …

Mathematical Background

Overview of the Viper Language

Program Code

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

Assertion Language

- Fractional permissions
- Inductive predicates
- Iterated separating conjunction
- Magic wands
- …

Verification Features

- Standard contract features
- Inhale and exhale
- …

Mathematical Background

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

Outline of the Talk

1. Overview of Viper

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

3. Toward a Foundational Viper

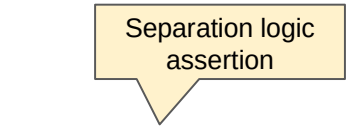
Verification Primitives: Inhale and Exhale

Verification Primitives: Inhale and Exhale

inhale A

exhale A

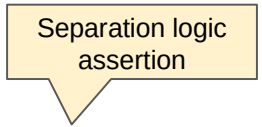
Verification Primitives: Inhale and Exhale



inhale A

exhale A

Verification Primitives: Inhale and Exhale

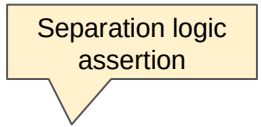


inhale A

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		

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	⊢ **{P}** **inhale** A **{P ∗ A}**	
Operationally		

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	⊢ **{P}** **inhale** A **{P ∗ A}**	
Operationally		

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	⊢ **{P}** **inhale** A **{P ∗ A}** weakestPre(**inhale** A, **Q**) = **A –∗ Q**	
Operationally		

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	⊢ **{P}** **inhale** A **{P ∗ A}** weakestPre(**inhale** A, **Q**) = **A –∗ Q**	⊢ **{P ∗ A}** **exhale** A **{P}**
Operationally		

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	⊢ **{P}** **inhale** A **{P ∗ A}** weakestPre(**inhale** A, **Q**) = **A –∗ Q**	⊢ **{P ∗ A}** **exhale** A **{P}**
Operationally		

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	⊢ **{P}** **inhale** A **{P ∗ A}** weakestPre(**inhale** A, **Q**) = **A –∗ Q**	⊢ **{P ∗ A}** **exhale** A **{P}** weakestPre(**exhale** A, **Q**) = **A ∗ Q**
Operationally		

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	⊢ **{P}** **inhale** A **{P ∗ A}** weakestPre(**inhale** A, **Q**) = **A –∗ Q**	⊢ **{P ∗ A}** **exhale** A **{P}** weakestPre(**exhale** A, **Q**) = **A ∗ Q**
Operationally		

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

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	⊢ **{P}** **inhale** A **{P ∗ A}** weakestPre(**inhale** A, **Q**) = **A –∗ Q**	⊢ **{P ∗ A}** **exhale** A **{P}** weakestPre(**exhale** A, **Q**) = **A ∗ Q**
Operationally	• All logical constraints in A are assumed • All resources required by A are obtained	

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

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	⊢ **{P}** **inhale** A **{P ∗ A}** weakestPre(**inhale** A, **Q**) = **A –∗ Q**	⊢ **{P ∗ A}** **exhale** A **{P}** weakestPre(**exhale** A, **Q**) = **A ∗ Q**
Operationally	• All logical constraints in A are assumed • All resources required by A are obtained	• All logical constraints in A are asserted • All resources required by A are removed

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

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	⊢ **{P}** **inhale** A **{P ∗ A}** weakestPre(**inhale** A, **Q**) = **A –∗ Q**	⊢ **{P ∗ A}** **exhale** A **{P}** weakestPre(**exhale** A, **Q**) = **A ∗ Q**
Operationally	• All logical constraints in A are assumed • All resources required by A are obtained	• All logical constraints in A are asserted • All resources required by A are removed
Separation logic analogue of	**assume** A	**assert** A

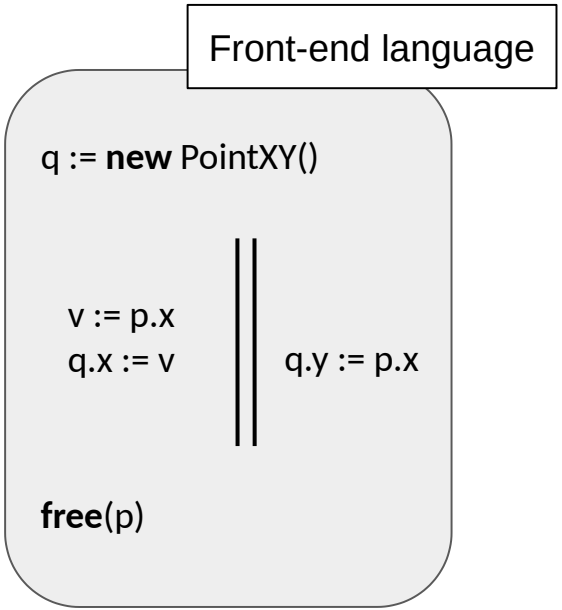
Verification Primitives: Inhale and Exhale

Sometimes called **produce**

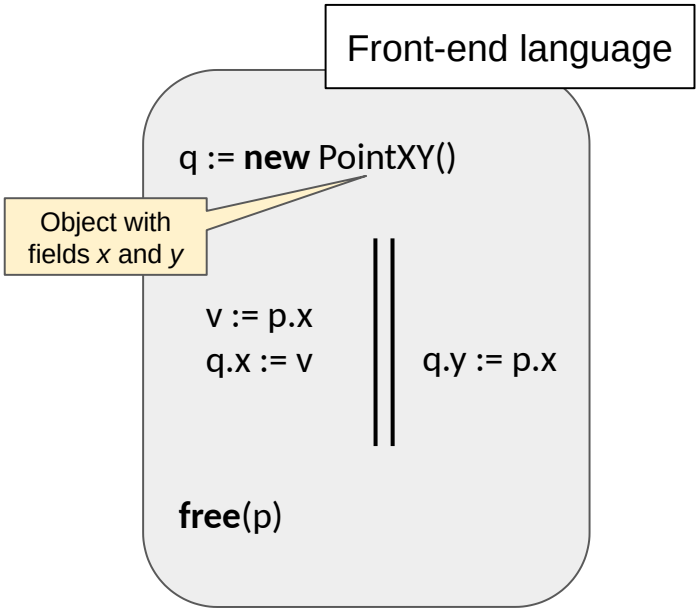
Sometimes called **consume**

	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}** weakestPre(**inhale** A, **Q**) = **A –∗ Q**	⊢ **{P ∗ A}** **exhale** A **{P}** weakestPre(**exhale** A, **Q**) = **A ∗ Q**
Operationally	• All logical constraints in A are assumed • All resources required by A are obtained	• All logical constraints in A are asserted • All resources required by A are removed
Separation logic analogue of	**assume** A	**assert** A

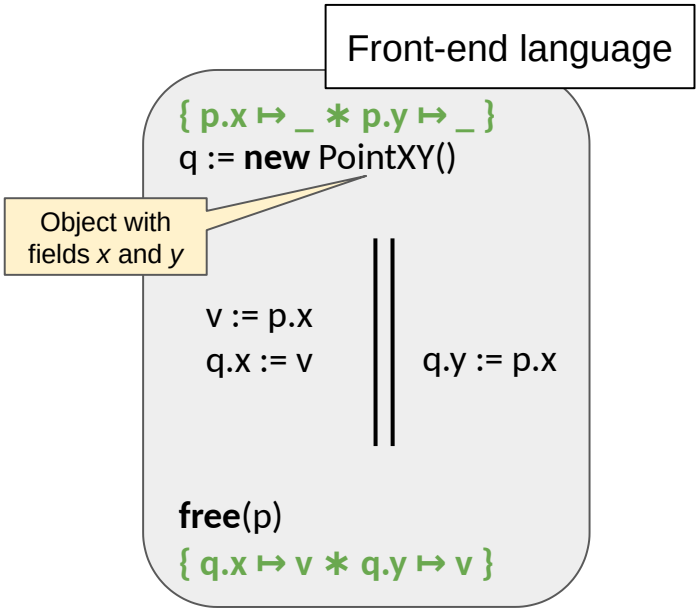
Example: Verifying a Parallel Program (1/2)



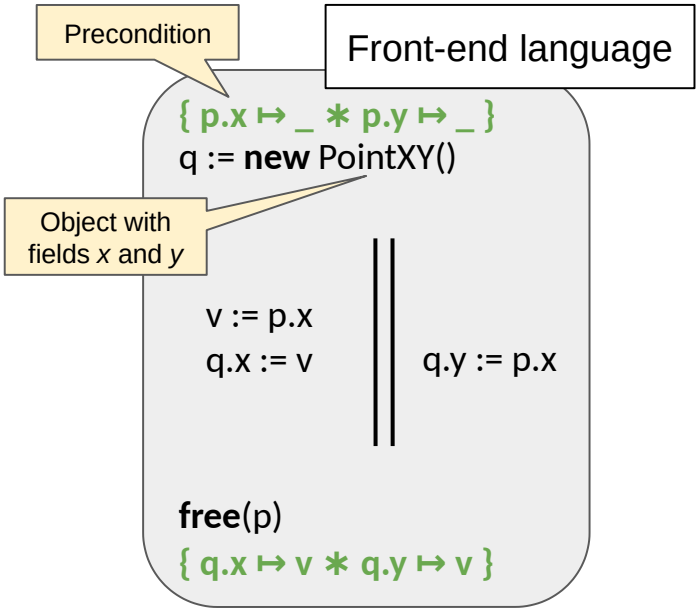
Example: Verifying a Parallel Program (1/2)



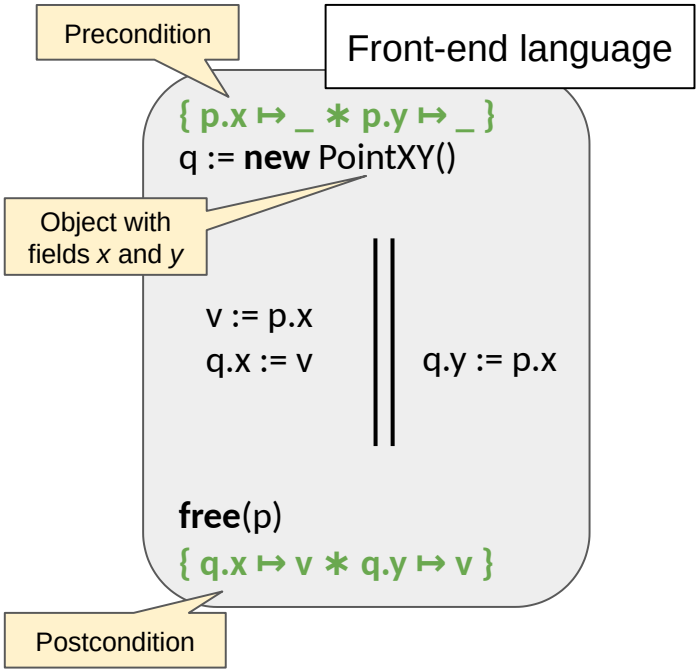
Example: Verifying a Parallel Program (1/2)



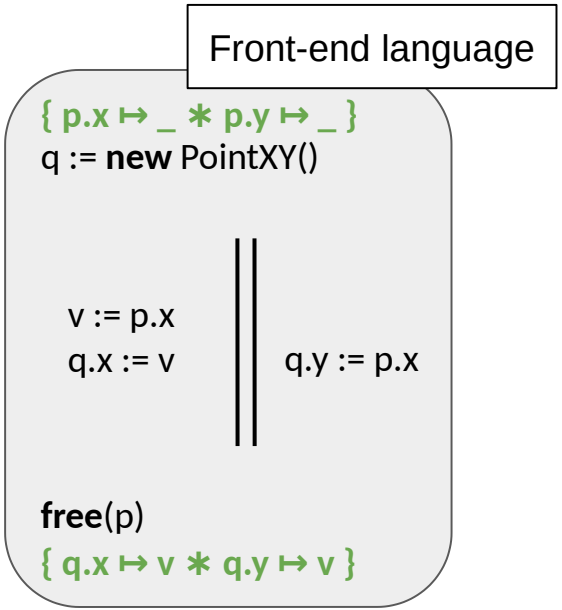
Example: Verifying a Parallel Program (1/2)

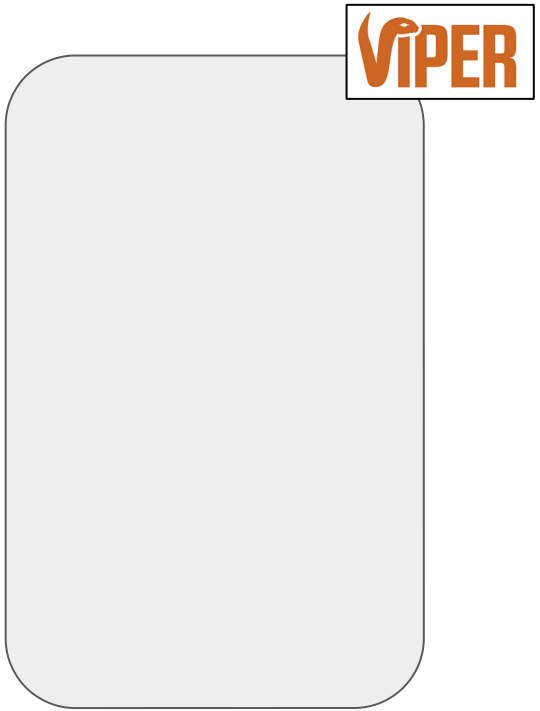


Example: Verifying a Parallel Program (1/2)

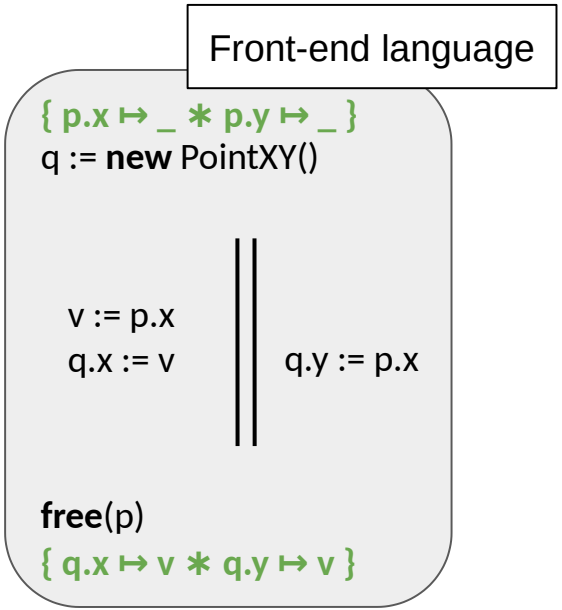


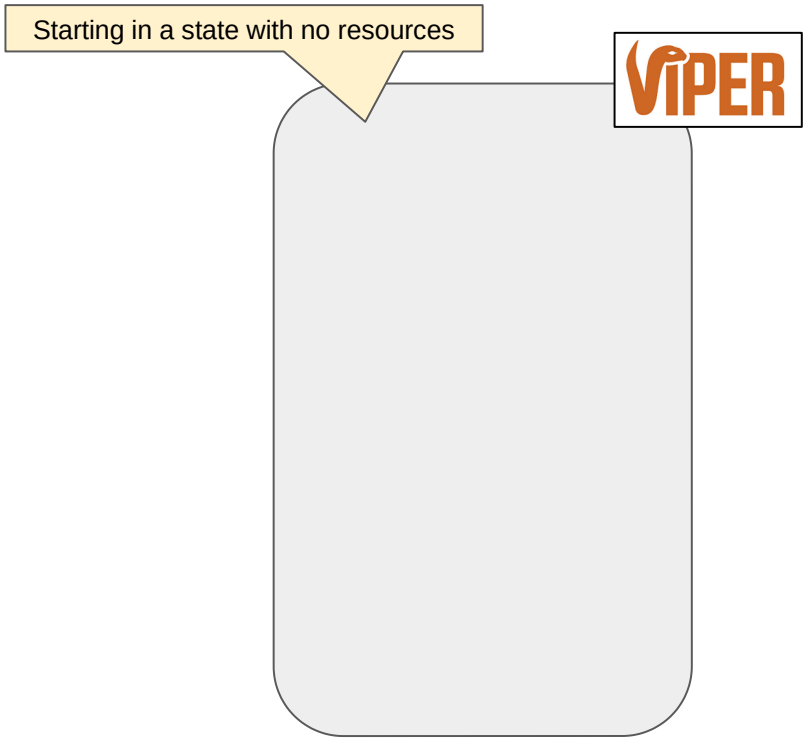
Example: Verifying a Parallel Program (1/2)



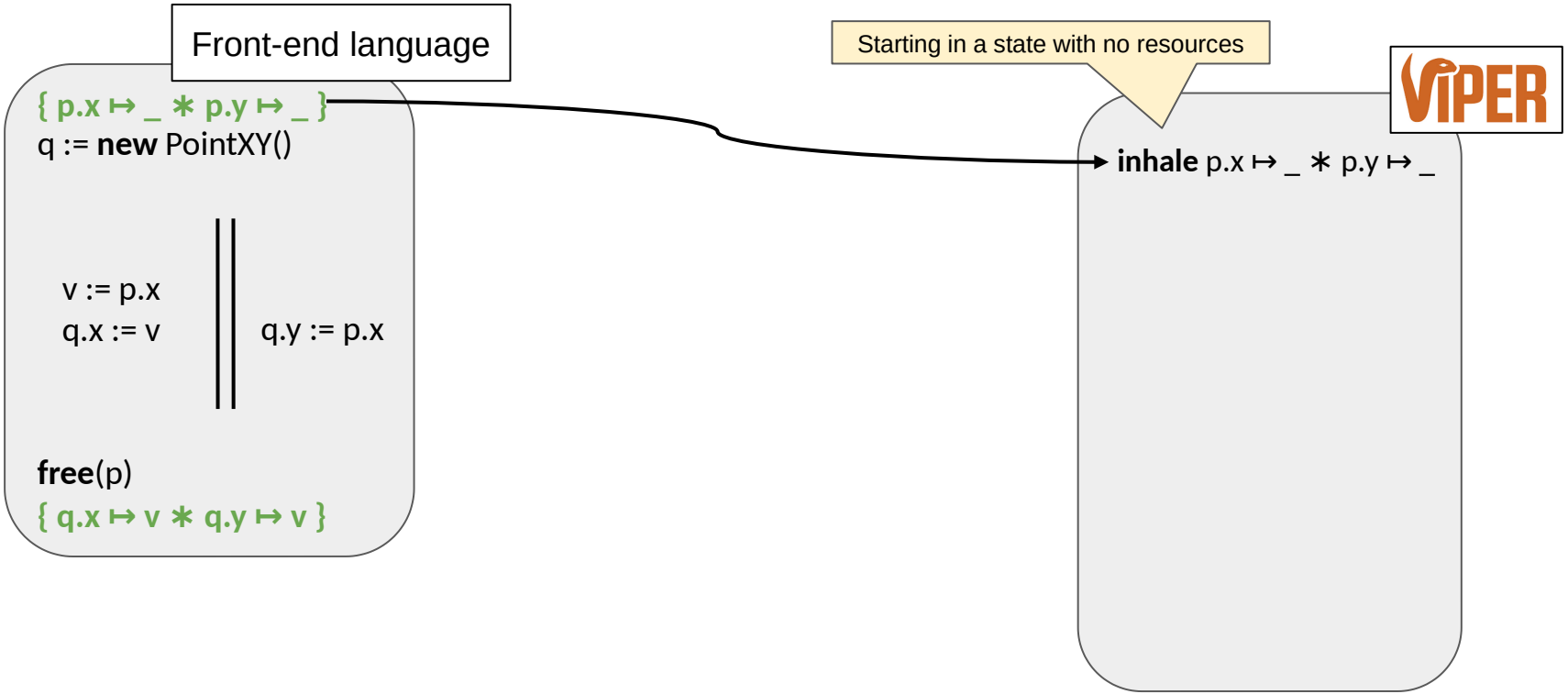


Example: Verifying a Parallel Program (1/2)

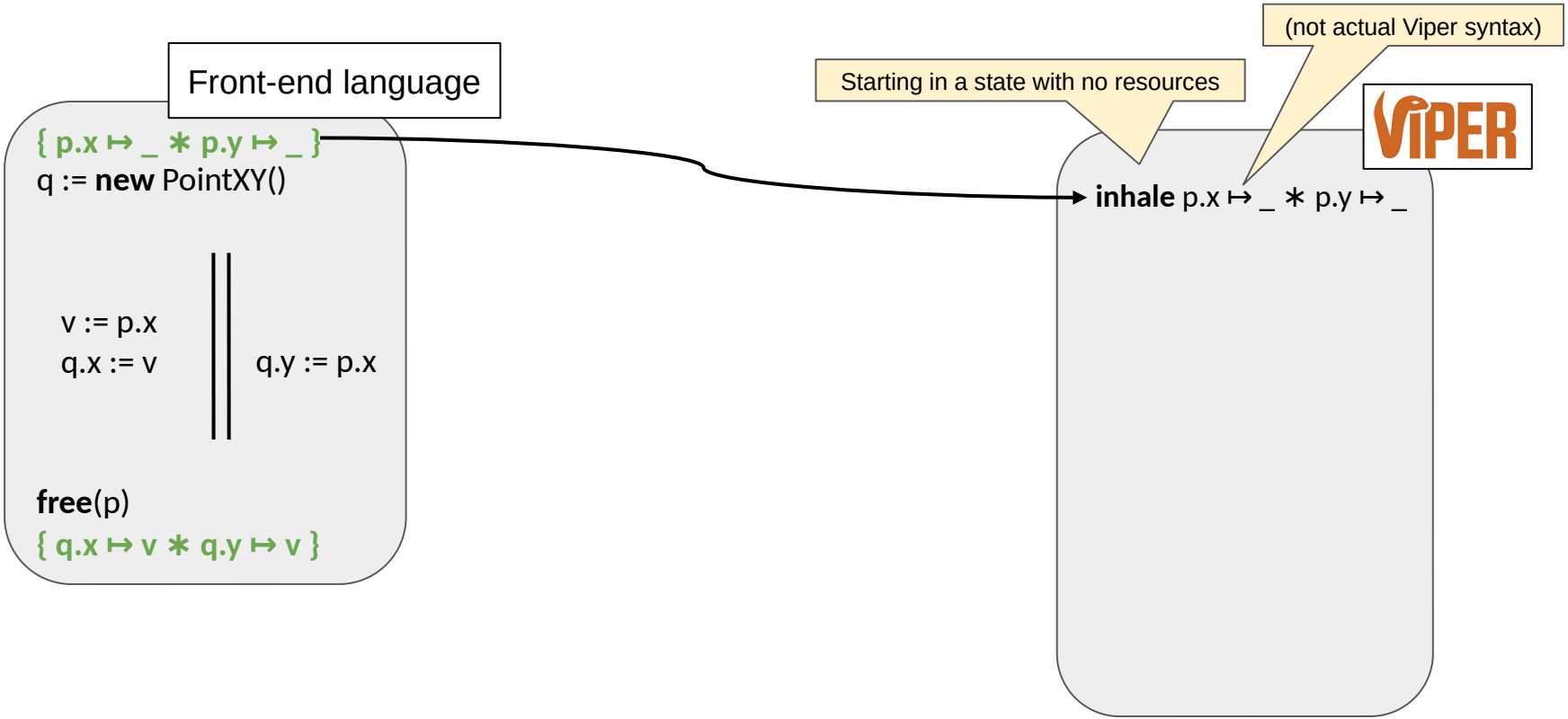




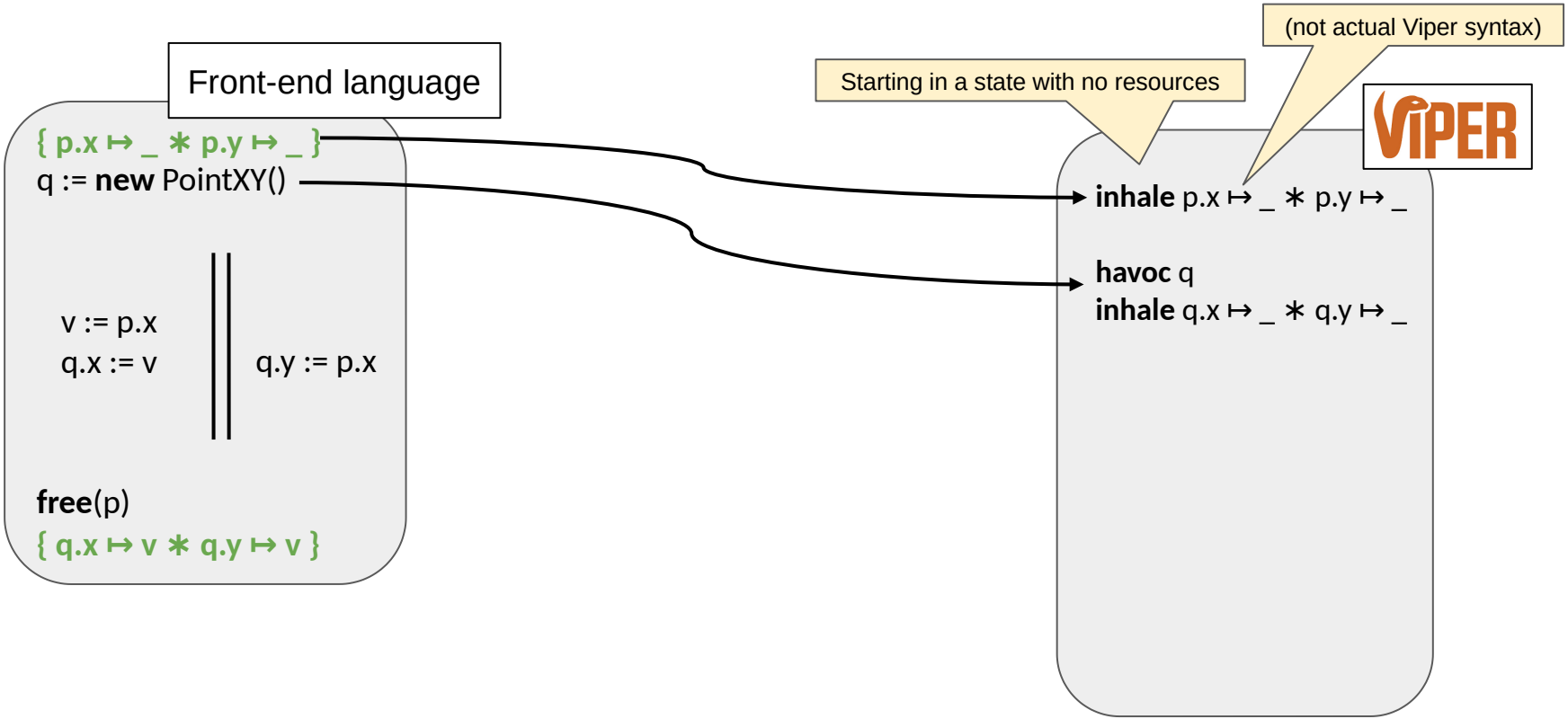
Example: Verifying a Parallel Program (1/2)



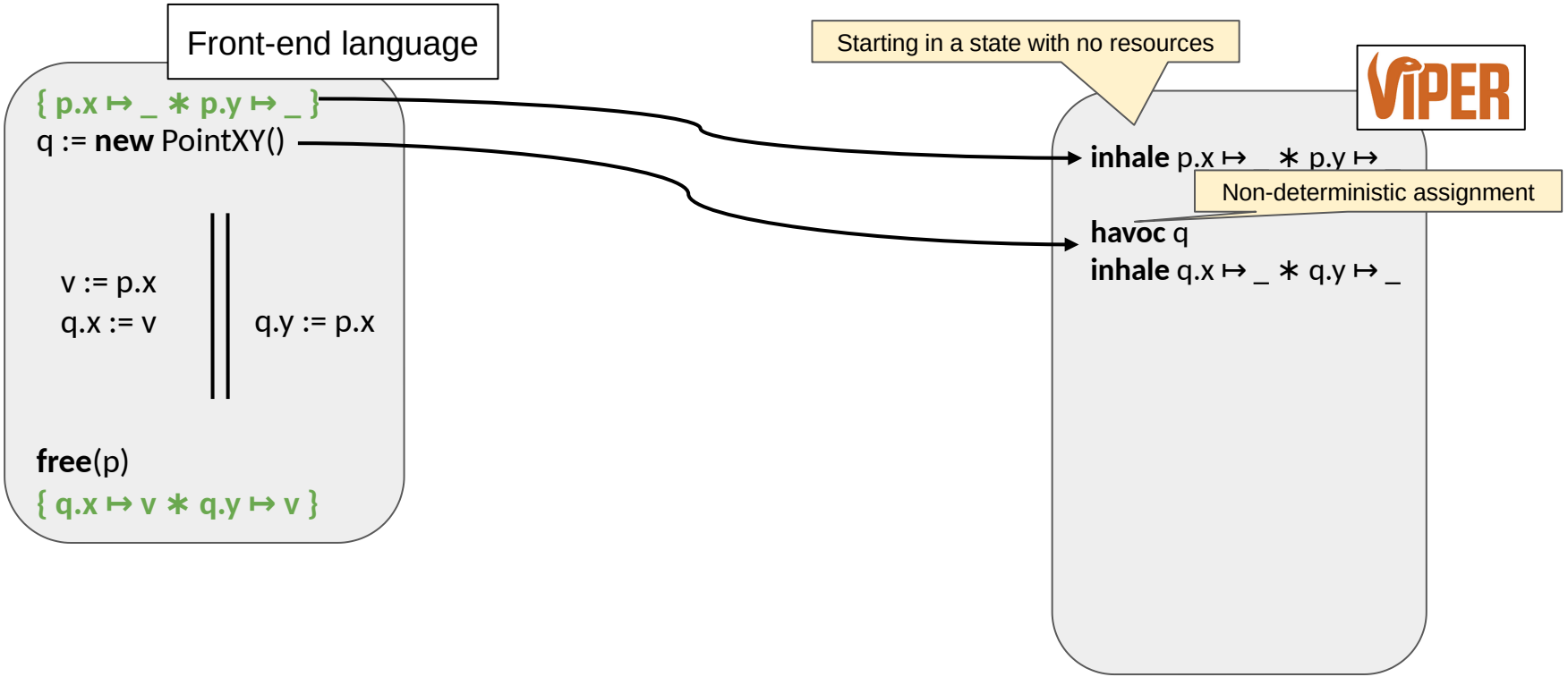
Example: Verifying a Parallel Program (1/2)



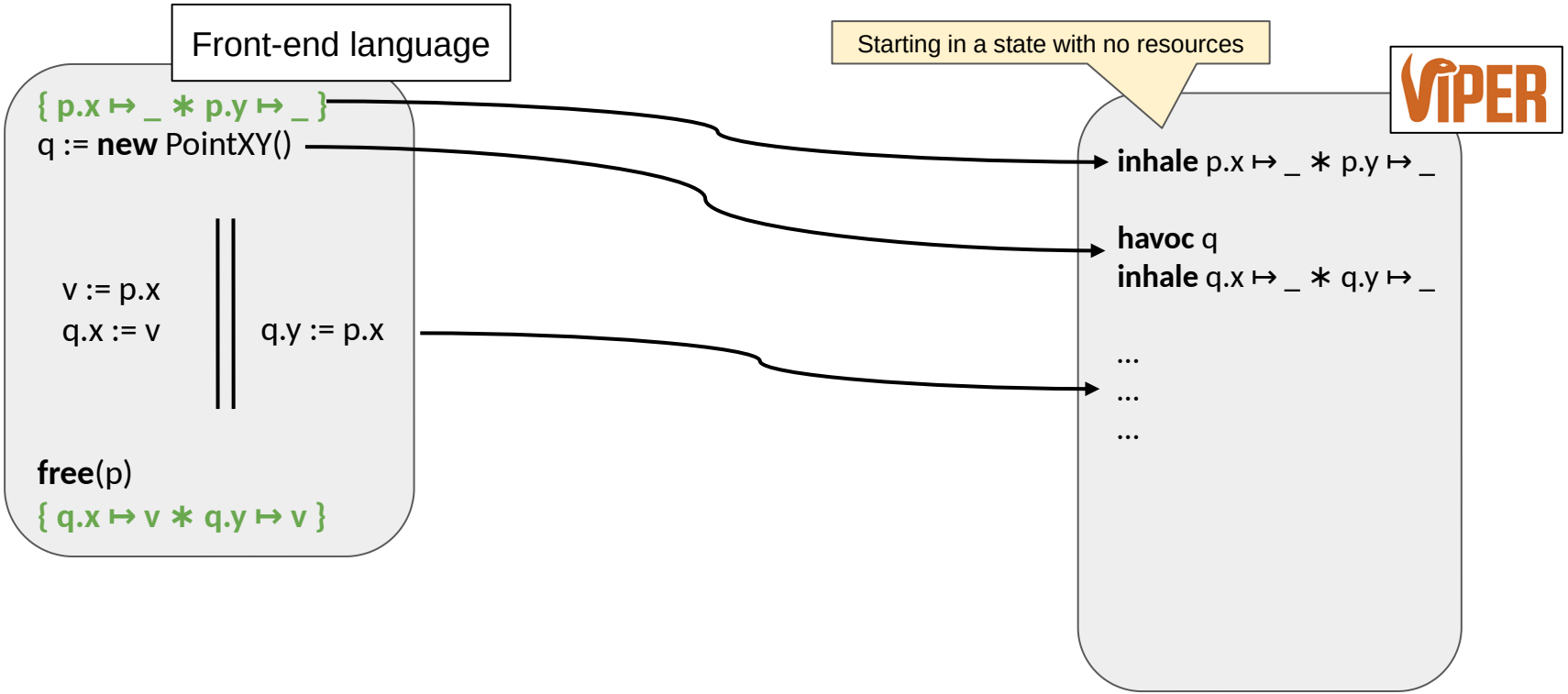
Example: Verifying a Parallel Program (1/2)



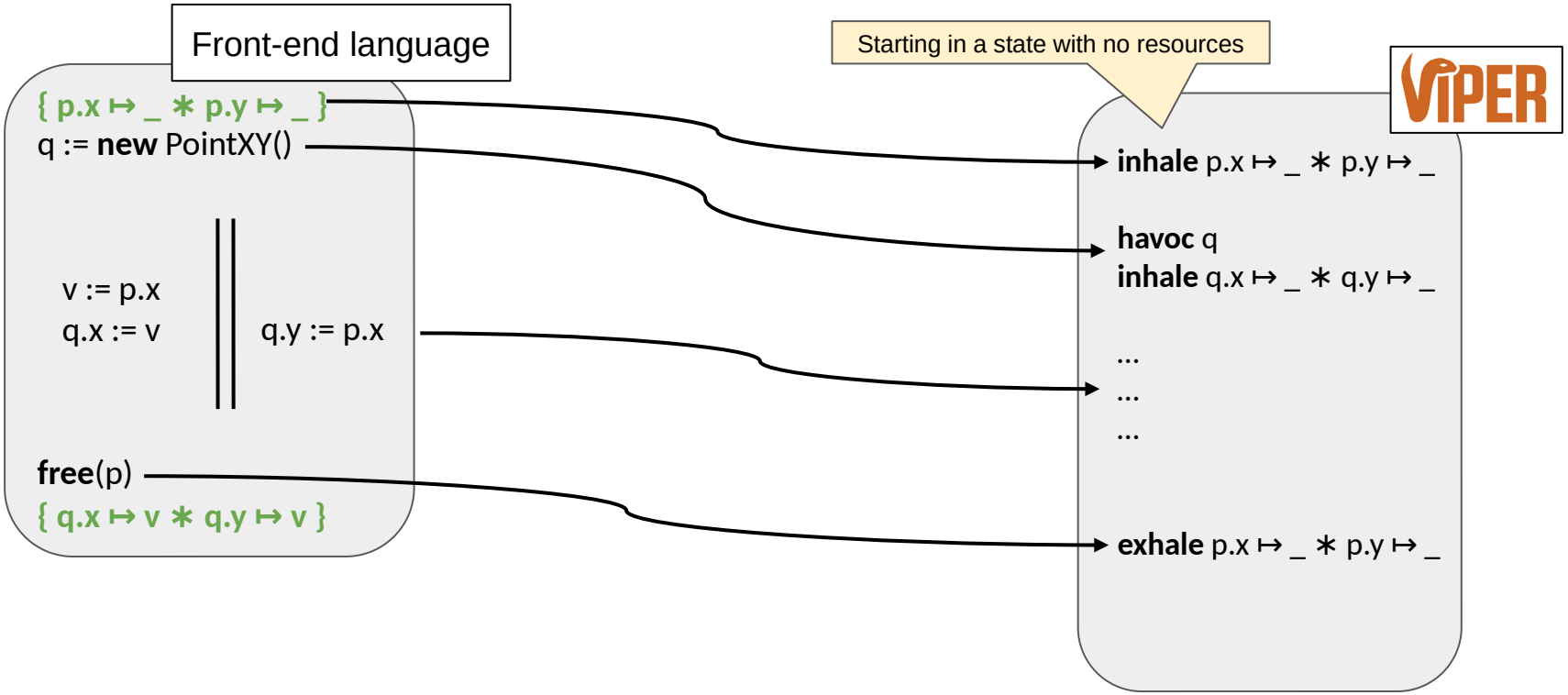
Example: Verifying a Parallel Program (1/2)



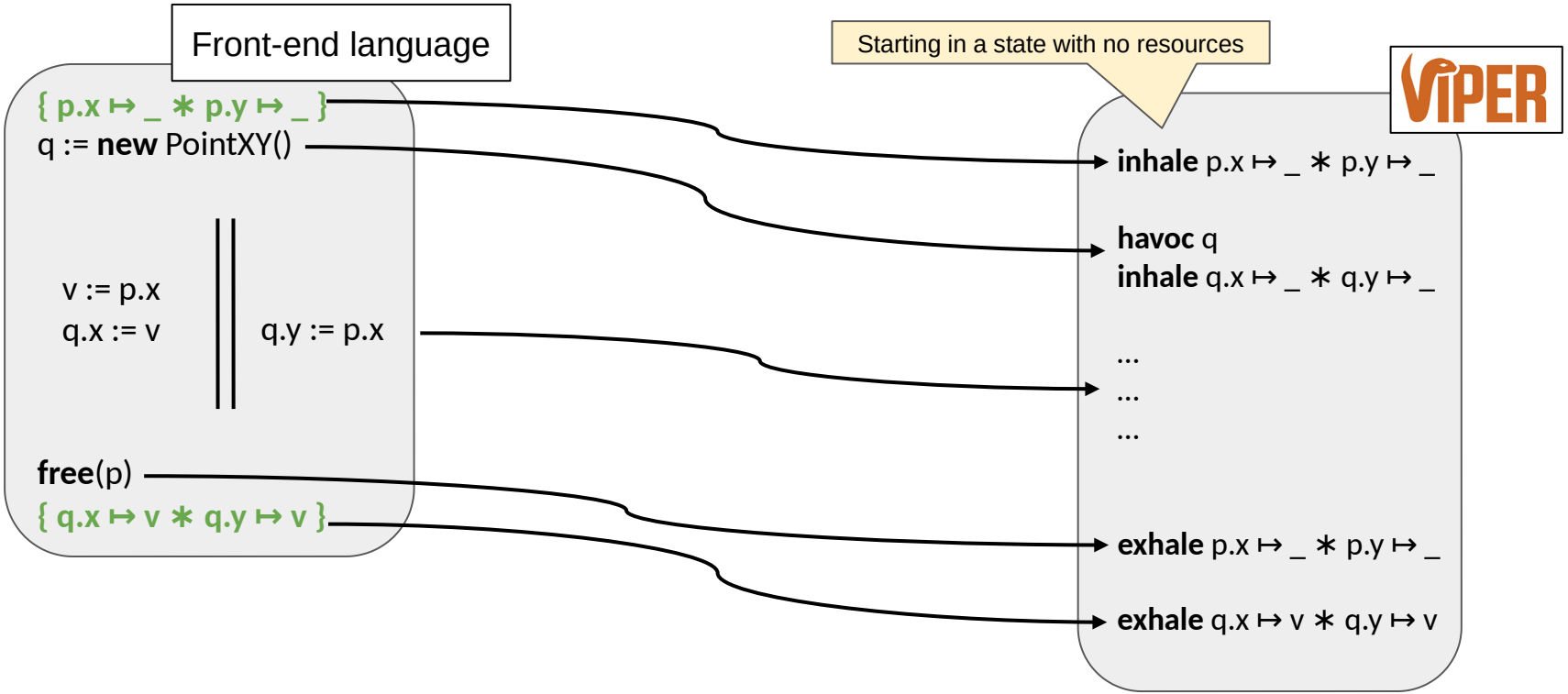
Example: Verifying a Parallel Program (1/2)



Example: Verifying a Parallel Program (1/2)



Example: Verifying a Parallel Program (1/2)



Example: Verifying a Parallel Program (2/2)

Front-end language

```
{ p.x ↦ _ ∗ p.y ↦ _ }
q := new PointXY()

  v := p.x          ||   q.y := p.x
  q.x := v          ||

free(p)
{ q.x ↦ v ∗ q.y ↦ v }
```

VIPER

```
inhale p.x ↦ _ ∗ p.y ↦ _

havoc q
inhale q.x ↦ _ ∗ q.y ↦ _

...
...
...

exhale p.x ↦ _ ∗ p.y ↦ _

exhale q.x ↦ v ∗ q.y ↦ v
```

Example: Verifying a Parallel Program (2/2)

Front-end language

{ p.x ↦ _ ∗ p.y ↦ _ }
q := **new** PointXY()

v := p.x
q.x := v

||

q.y := p.x

free(p)
{ q.x ↦ v ∗ q.y ↦ v }

VIPER

inhale p.x ↦ _ ∗ p.y ↦ _

havoc q
inhale q.x ↦ _ ∗ q.y ↦ _

...
...
...

exhale p.x ↦ _ ∗ p.y ↦ _

exhale q.x ↦ v ∗ q.y ↦ v

Example: Verifying a Parallel Program (2/2)

Parallel rule

$$\frac{\vdash \{P_1\}\ C_1\ \{Q_1\} \quad \vdash \{P_2\}\ C_2\ \{Q_2\} \quad \ldots}{\vdash \{P_1 * P_2\}\ C_1 \,||\, C_2\ \{Q_1 * Q_2\}}$$

Front-end language

```
{ p.x ↦ _ ∗ p.y ↦ _ }
q := new PointXY()

v := p.x          ||          q.y := p.x
q.x := v          ||

free(p)
{ q.x ↦ v ∗ q.y ↦ v }
```

VIPER

```
inhale p.x ↦ _ ∗ p.y ↦ _

havoc q
inhale q.x ↦ _ ∗ q.y ↦ _

...
...
...

exhale p.x ↦ _ ∗ p.y ↦ _

exhale q.x ↦ v ∗ q.y ↦ v
```

Example: Verifying a Parallel Program (2/2)

Parallel rule

$$\frac{\vdash \{P_1\}\ C_1\ \{Q_1\} \quad \vdash \{P_2\}\ C_2\ \{Q_2\} \quad \ldots}{\vdash \{P_1 * P_2\}\ C_1 \,||\, C_2\ \{Q_1 * Q_2\}}$$

Front-end language

```
{ p.x ↦ _ ∗ p.y ↦ _ }
q := new PointXY()

   { P1 }          { P2 }
   v := p.x
   q.x := v        q.y := p.x
   { Q1 }          { Q2 }

free(p)
{ q.x ↦ v ∗ q.y ↦ v }
```

VIPER

```
inhale p.x ↦ _ ∗ p.y ↦ _

havoc q
inhale q.x ↦ _ ∗ q.y ↦ _

...
...
...

exhale p.x ↦ _ ∗ p.y ↦ _

exhale q.x ↦ v ∗ q.y ↦ v
```

Example: Verifying a Parallel Program (2/2)

Parallel rule

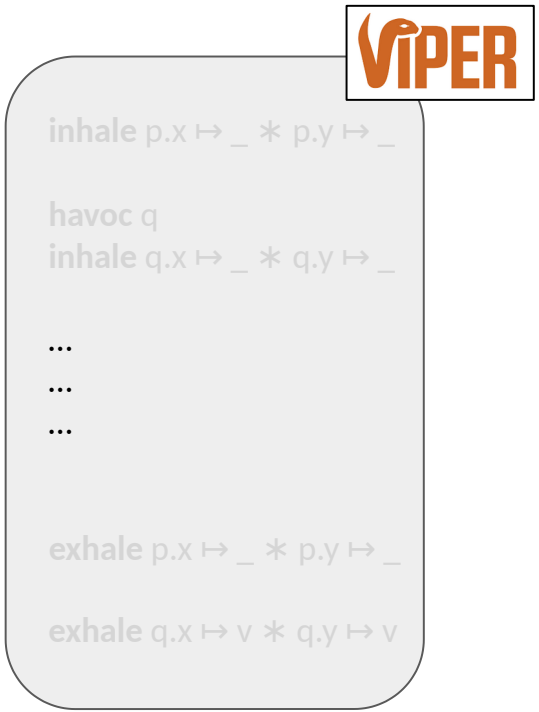
$$\frac{\vdash \{P_1\}\ C_1\ \{Q_1\} \quad \vdash \{P_2\}\ C_2\ \{Q_2\} \quad \ldots}{\vdash \{P_1 * P_2\}\ C_1 \,||\, C_2\ \{Q_1 * Q_2\}}$$

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 Program (2/2)

Parallel rule

$$\frac{\vdash \{P_1\}\ C_1\ \{Q_1\} \quad \vdash \{P_2\}\ C_2\ \{Q_2\} \quad \ldots}{\vdash \{P_1 * P_2\}\ C_1 \,||\, C_2\ \{Q_1 * Q_2\}}$$

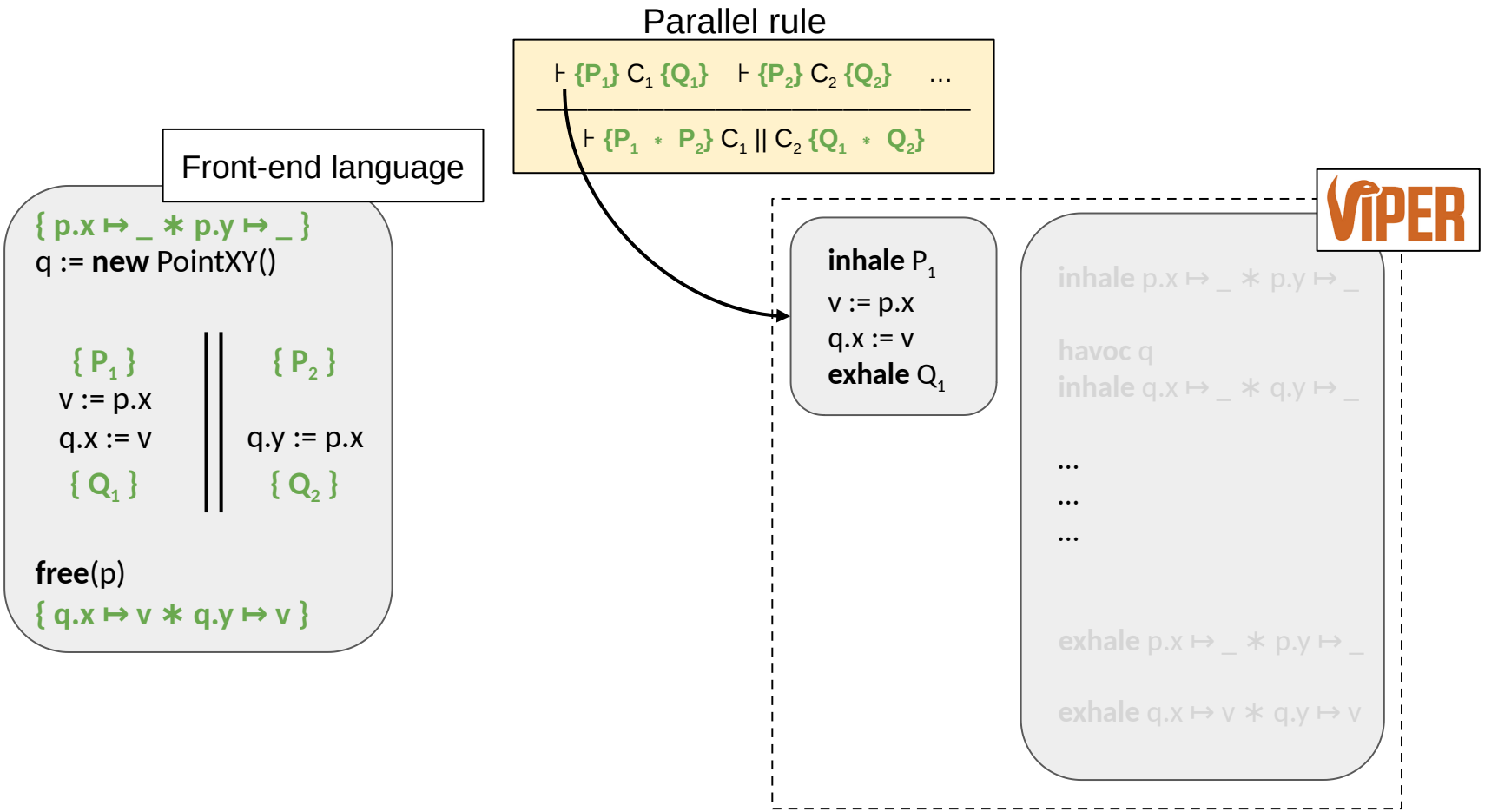
Front-end language

```
{ p.x ↦ _ ∗ p.y ↦ _ }
q := new PointXY()

   { P1 }          { P2 }
   v := p.x
   q.x := v        q.y := p.x
   { Q1 }          { Q2 }

free(p)
{ q.x ↦ v ∗ q.y ↦ v }
```

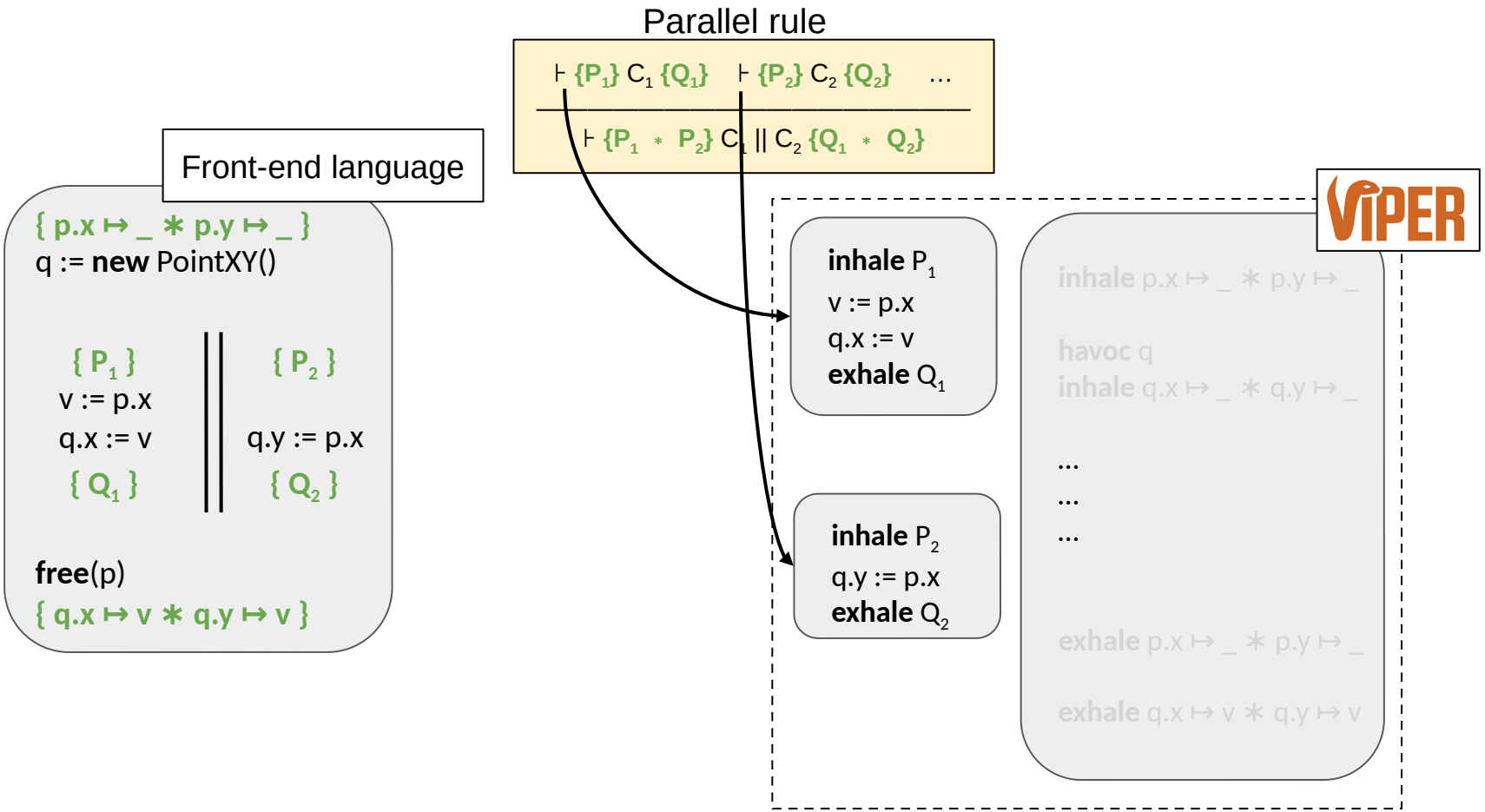
VIPER

```
inhale p.x ↦ _ ∗ p.y ↦ _

havoc q
inhale q.x ↦ _ ∗ q.y ↦ _

...
...
...

exhale p.x ↦ _ ∗ p.y ↦ _

exhale q.x ↦ v ∗ q.y ↦ v
```

Example: Verifying a Parallel Program (2/2)



Example: Verifying a Parallel Program (2/2)



Example: Verifying a Parallel Program (2/2)

Parallel rule

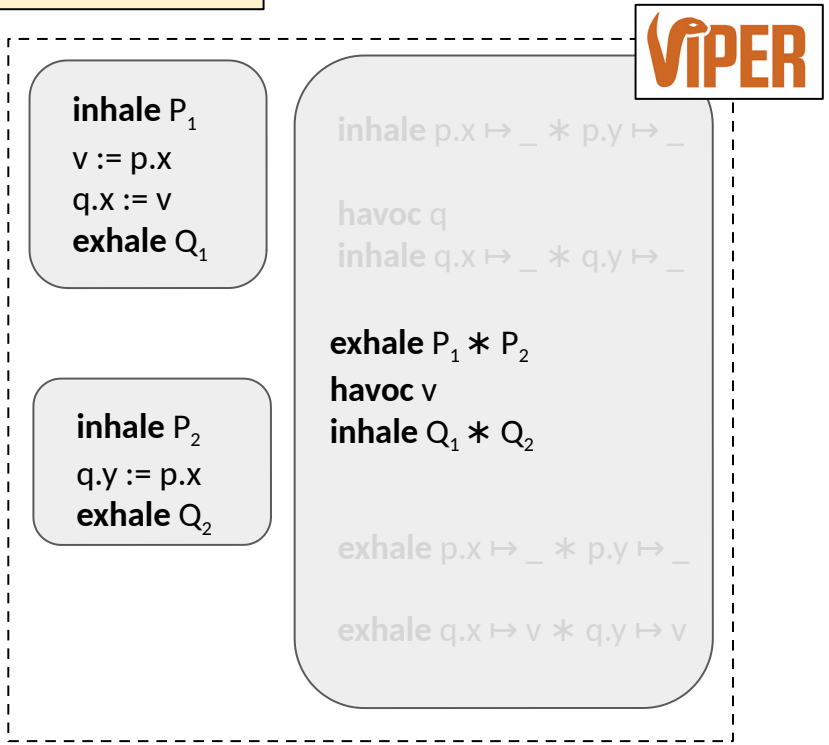
$$\frac{\vdash \{P_1\}\ C_1\ \{Q_1\} \quad \vdash \{P_2\}\ C_2\ \{Q_2\} \quad \ldots}{\vdash \{P_1 * P_2\}\ C_1 \,||\, C_2\ \{Q_1 * Q_2\}}$$

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



Example: Verifying a Parallel Program (2/2)

Parallel rule

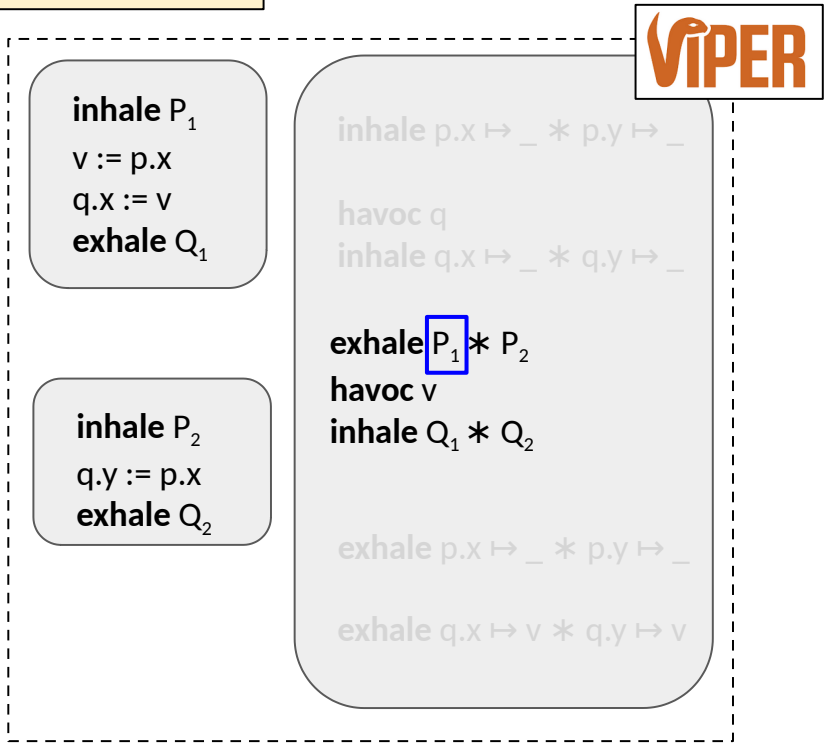
$$\frac{\vdash \{P_1\}\ C_1\ \{Q_1\} \quad \vdash \{P_2\}\ C_2\ \{Q_2\} \quad \ldots}{\vdash \{P_1 * P_2\}\ C_1 \,||\, C_2\ \{Q_1 * Q_2\}}$$

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



Example: Verifying a Parallel Program (2/2)

Parallel rule

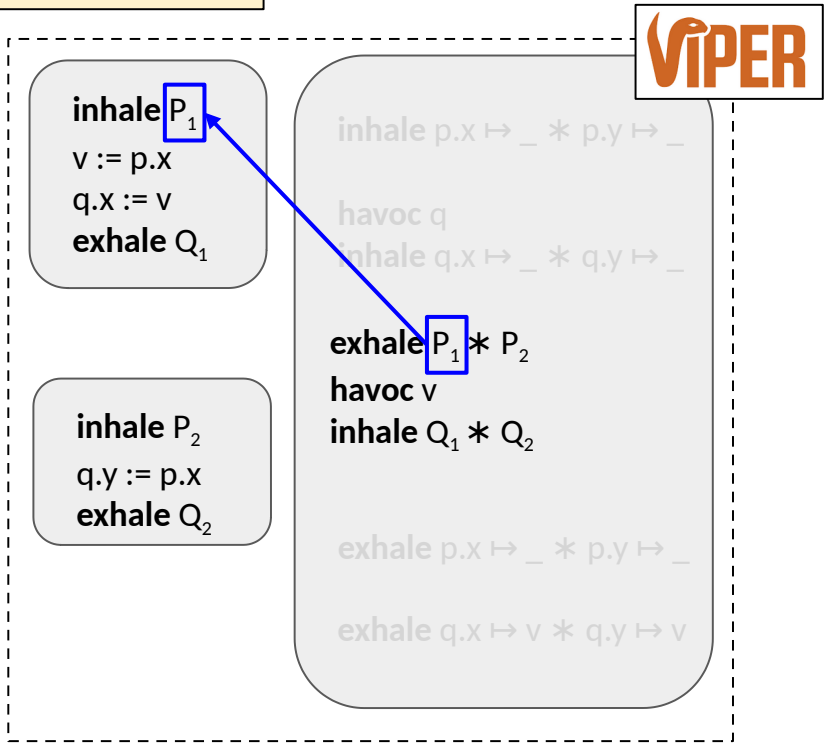
$$\frac{\vdash \{P_1\}\ C_1\ \{Q_1\} \quad \vdash \{P_2\}\ C_2\ \{Q_2\} \quad \ldots}{\vdash \{P_1 * P_2\}\ C_1 \,||\, C_2\ \{Q_1 * Q_2\}}$$

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



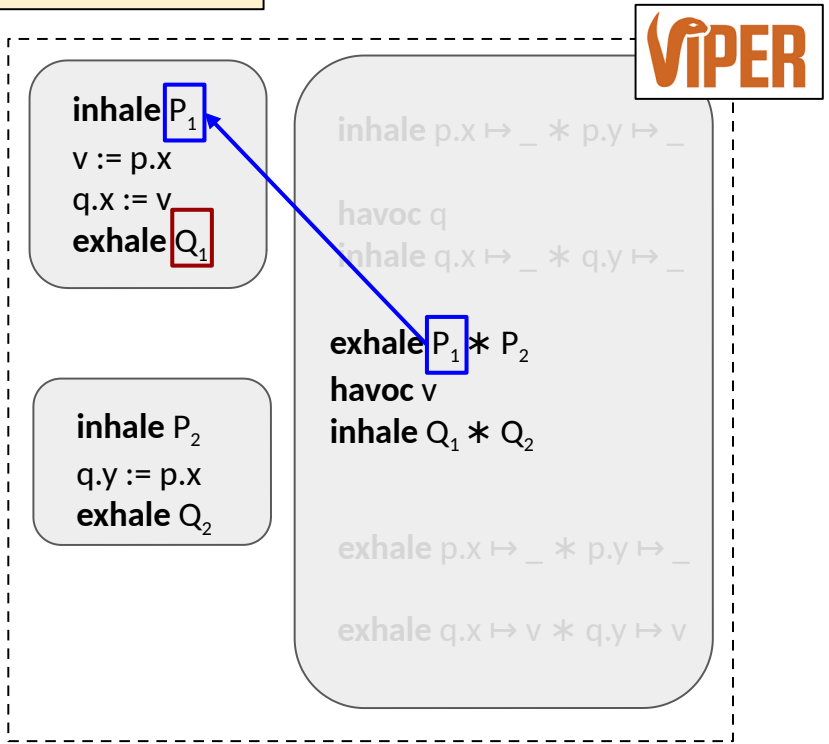
Example: Verifying a Parallel Program (2/2)

Parallel rule

$$\frac{\vdash \{P_1\}\ C_1\ \{Q_1\} \quad \vdash \{P_2\}\ C_2\ \{Q_2\} \quad \ldots}{\vdash \{P_1 * P_2\}\ C_1 \,||\, C_2\ \{Q_1 * Q_2\}}$$

Front-end language

```
{ p.x ↦ _ ∗ p.y ↦ _ }
q := new PointXY()

   { P1 }          { P2 }
   v := p.x
   q.x := v        q.y := p.x
   { Q1 }          { Q2 }

free(p)
{ q.x ↦ v ∗ q.y ↦ v }
```



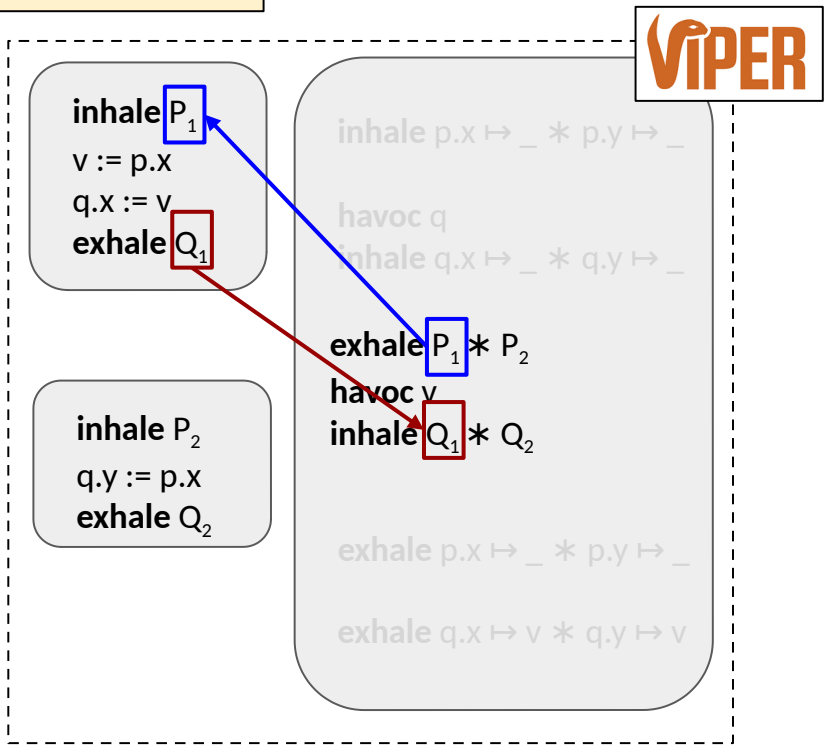
Example: Verifying a Parallel Program (2/2)

Parallel rule

$$\frac{\vdash \{P_1\}\ C_1\ \{Q_1\} \quad \vdash \{P_2\}\ C_2\ \{Q_2\} \quad \ldots}{\vdash \{P_1 * P_2\}\ C_1 \,||\, C_2\ \{Q_1 * Q_2\}}$$

Front-end language

```
{ p.x ↦ _ ∗ p.y ↦ _ }
q := new PointXY()

   { P1 }          { P2 }
   v := p.x
   q.x := v        q.y := p.x
   { Q1 }          { Q2 }

free(p)
{ q.x ↦ v ∗ q.y ↦ v }
```



Example: Verifying a Parallel Program (2/2)

Parallel rule

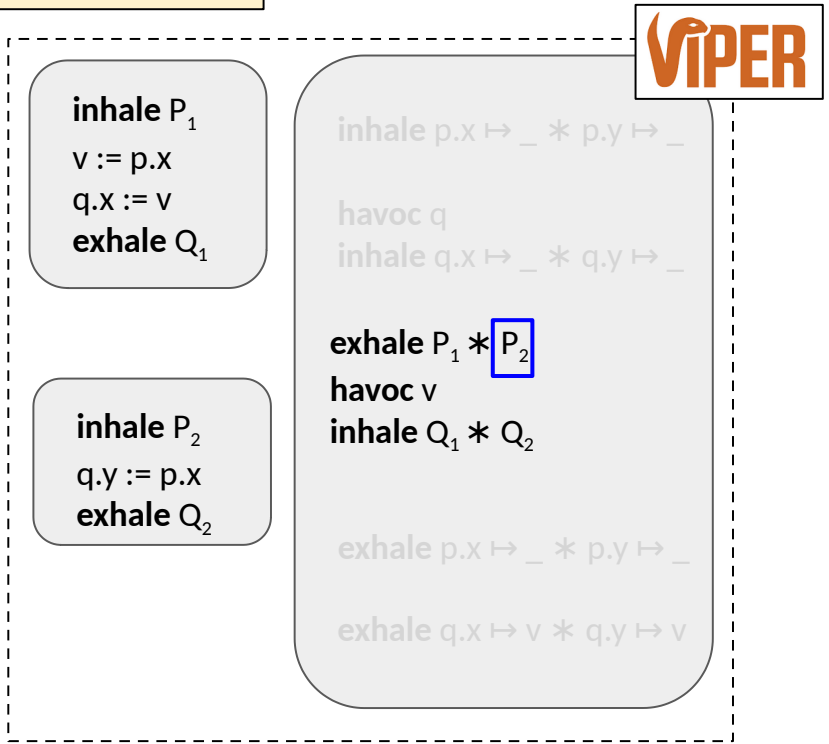
$$\frac{\vdash \{P_1\}\ C_1\ \{Q_1\} \quad \vdash \{P_2\}\ C_2\ \{Q_2\} \quad \ldots}{\vdash \{P_1 * P_2\}\ C_1 \,||\, C_2\ \{Q_1 * Q_2\}}$$

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



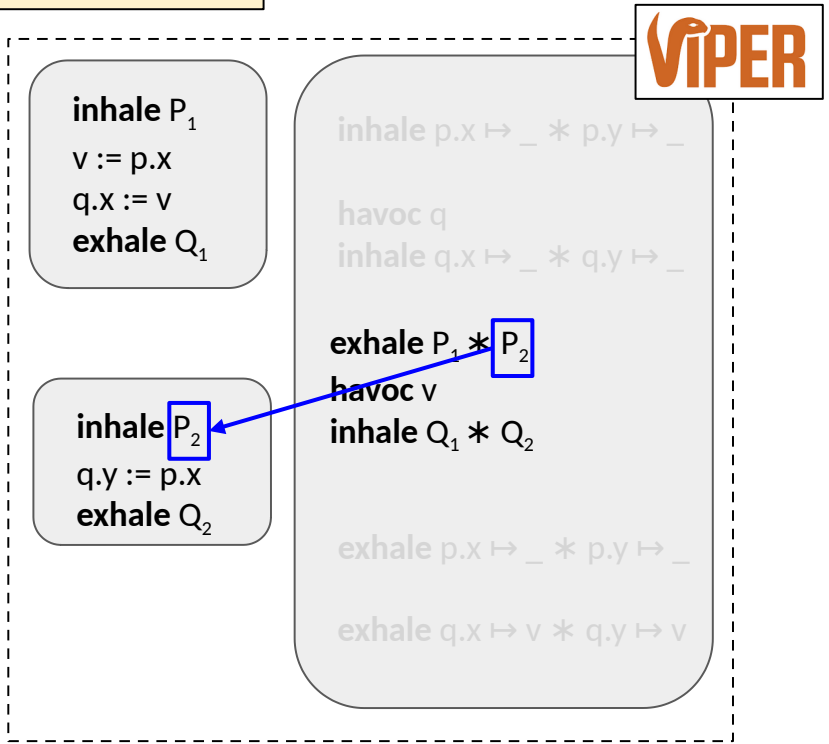
Example: Verifying a Parallel Program (2/2)

Parallel rule

$$\frac{\vdash \{P_1\}\ C_1\ \{Q_1\} \quad \vdash \{P_2\}\ C_2\ \{Q_2\} \quad \ldots}{\vdash \{P_1 * P_2\}\ C_1 \,||\, C_2\ \{Q_1 * Q_2\}}$$

Front-end language

```
{ p.x ↦ _ ∗ p.y ↦ _ }
q := new PointXY()

   { P1 }          { P2 }
   v := p.x
   q.x := v        q.y := p.x
   { Q1 }          { Q2 }

free(p)
{ q.x ↦ v ∗ q.y ↦ v }
```



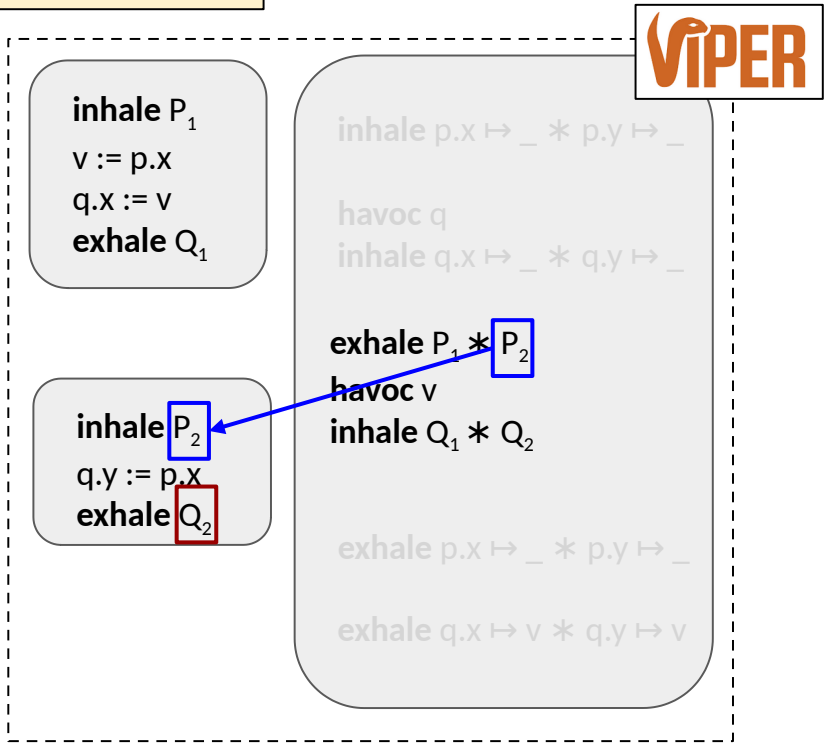
Example: Verifying a Parallel Program (2/2)

Parallel rule

$$\frac{\vdash \{P_1\}\ C_1\ \{Q_1\} \quad \vdash \{P_2\}\ C_2\ \{Q_2\} \quad \ldots}{\vdash \{P_1 * P_2\}\ C_1 \,||\, C_2\ \{Q_1 * Q_2\}}$$

Front-end language

```
{ p.x ↦ _ ∗ p.y ↦ _ }
q := new PointXY()

   { P1 }          { P2 }
   v := p.x
   q.x := v        q.y := p.x
   { Q1 }          { Q2 }

free(p)
{ q.x ↦ v ∗ q.y ↦ v }
```



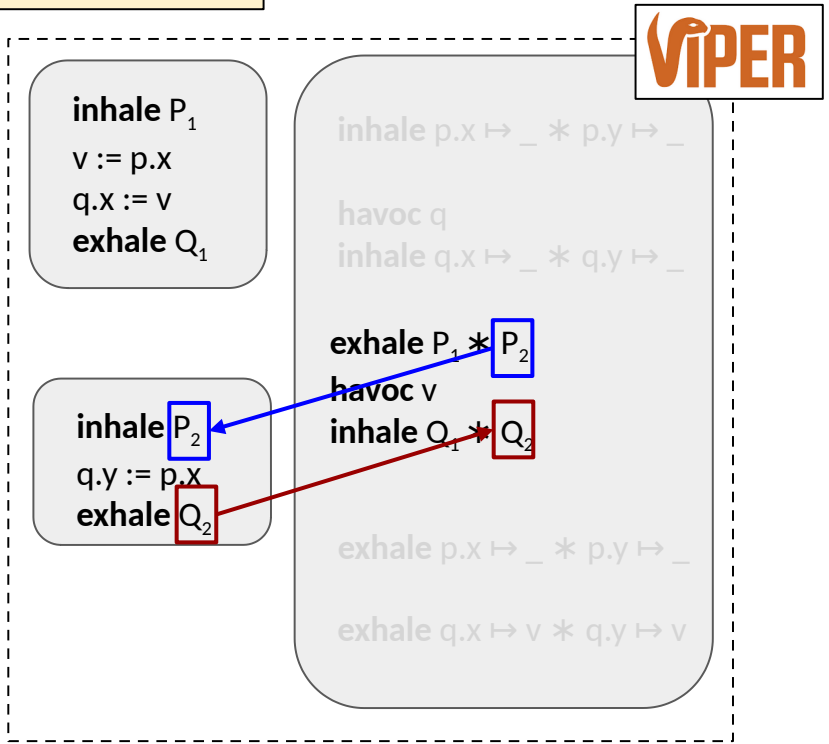
Example: Verifying a Parallel Program (2/2)

Parallel rule

$$\frac{\vdash \{P_1\}\ C_1\ \{Q_1\} \quad \vdash \{P_2\}\ C_2\ \{Q_2\} \quad \ldots}{\vdash \{P_1 * P_2\}\ C_1 \,||\, C_2\ \{Q_1 * Q_2\}}$$

Front-end language

```
{ p.x ↦ _ ∗ p.y ↦ _ }
q := new PointXY()

   { P1 }          { P2 }
   v := p.x
   q.x := v        q.y := p.x
   { Q1 }          { Q2 }

free(p)
{ q.x ↦ v ∗ q.y ↦ v }
```



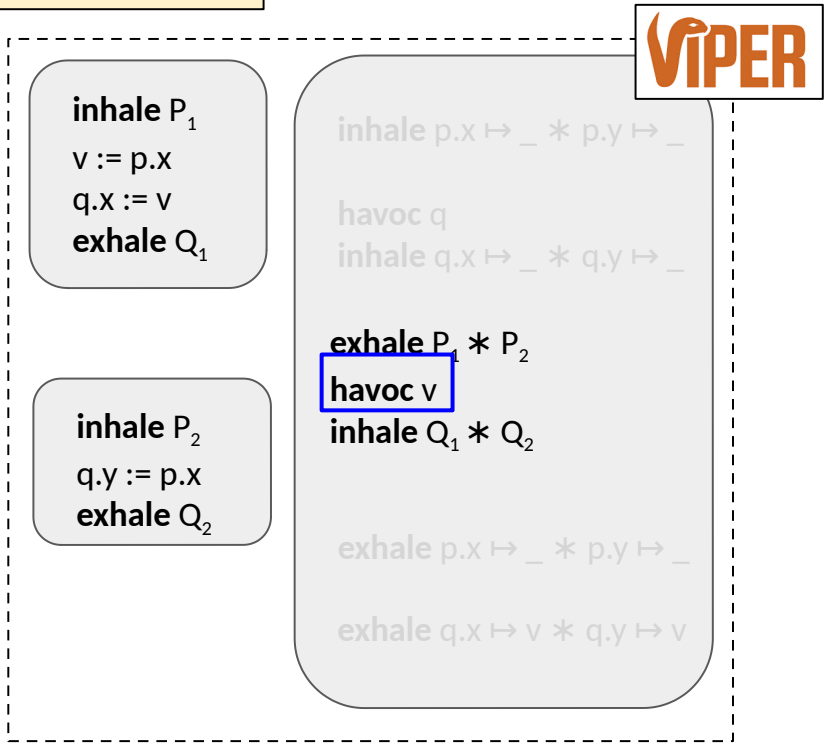
Example: Verifying a Parallel Program (2/2)

Parallel rule

$$\frac{\vdash \{P_1\}\ C_1\ \{Q_1\} \quad \vdash \{P_2\}\ C_2\ \{Q_2\} \quad \ldots}{\vdash \{P_1 * P_2\}\ C_1 \,||\, C_2\ \{Q_1 * Q_2\}}$$

Front-end language

```
{ p.x ↦ _ ∗ p.y ↦ _ }
q := new PointXY()

   { P1 }          { P2 }
   v := p.x
   q.x := v        q.y := p.x
   { Q1 }          { Q2 }

free(p)
{ q.x ↦ v ∗ q.y ↦ v }
```



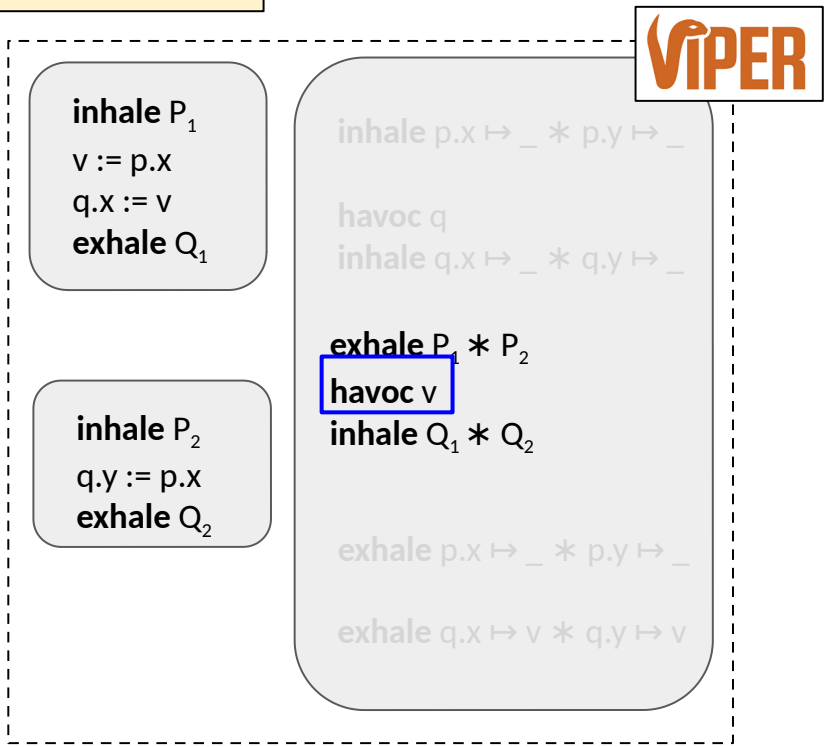
Example: Verifying a Parallel Program (2/2)

Parallel rule

$$\frac{\vdash \{P_1\}\ C_1\ \{Q_1\} \quad \vdash \{P_2\}\ C_2\ \{Q_2\} \quad \ldots}{\vdash \{P_1 * P_2\}\ C_1 \,||\, C_2\ \{Q_1 * Q_2\}}$$

Front-end language

```
{ p.x ↦ _ ∗ p.y ↦ _ }
q := new PointXY()

   { P1 }          { P2 }
   v := p.x
   q.x := v        q.y := p.x
   { Q1 }          { Q2 }

free(p)
{ q.x ↦ v ∗ q.y ↦ v }
```



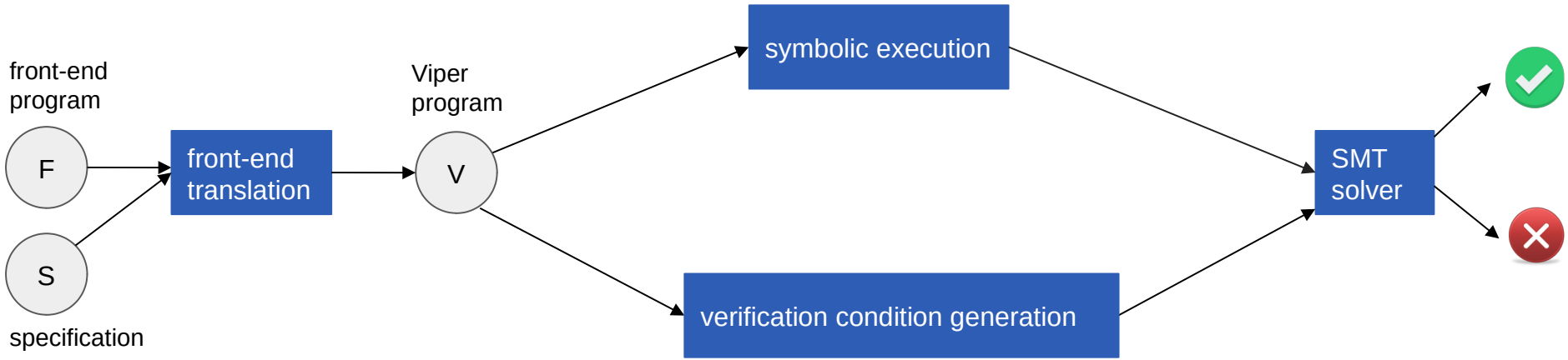
Outline of the Talk

1. Overview of Viper

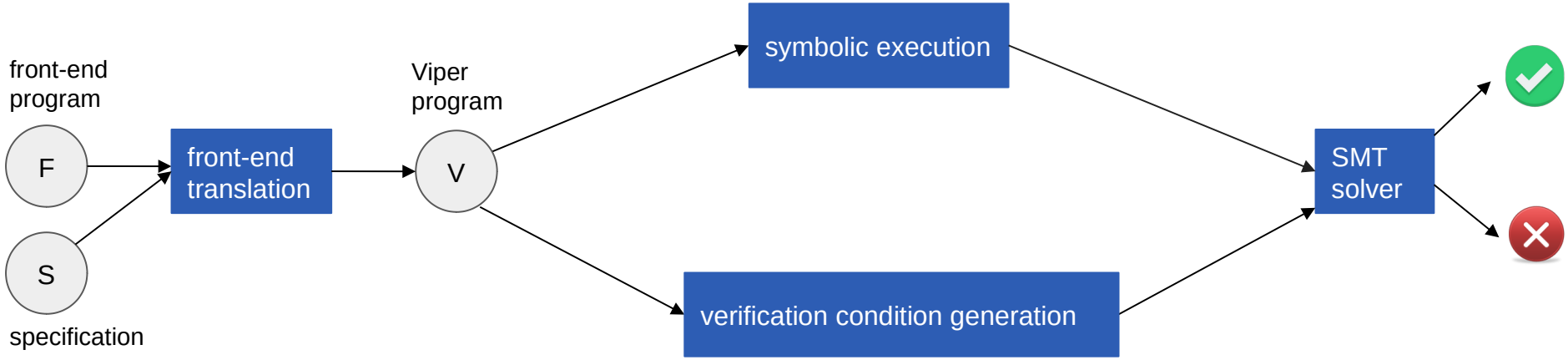
2. Inhale and Exhale: An Operational View of Separation Logic

3. Toward a Foundational Viper

Soundness


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

Soundness

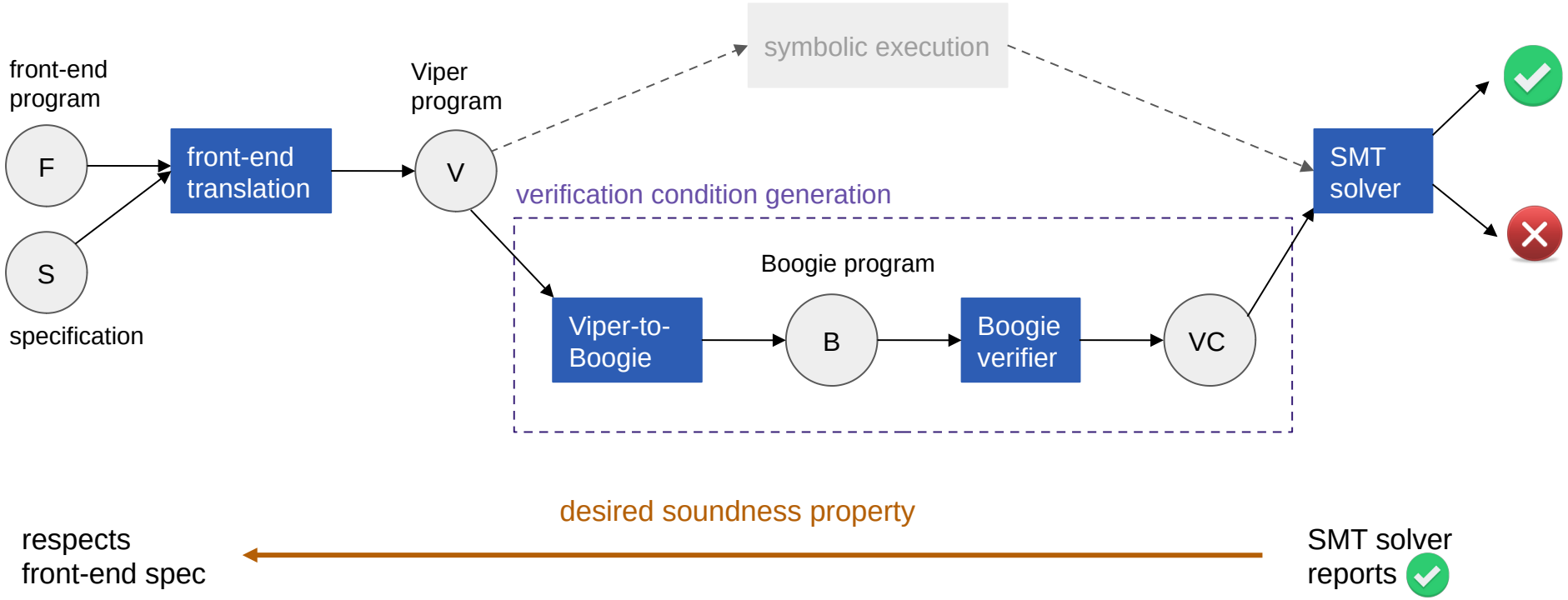


desired soundness property

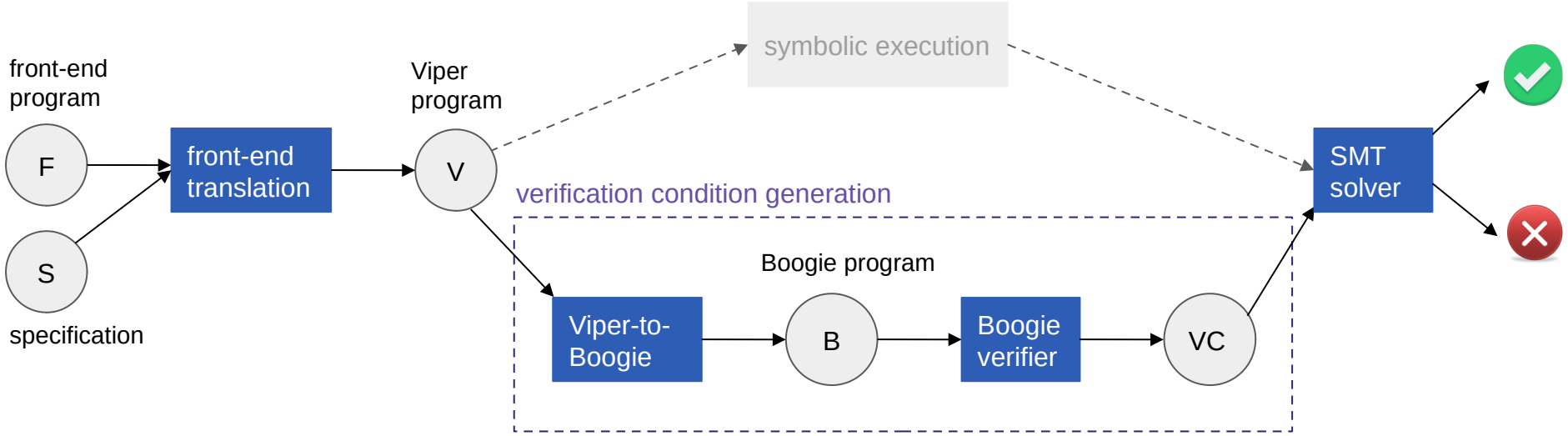
respects
front-end spec

SMT solver
reports

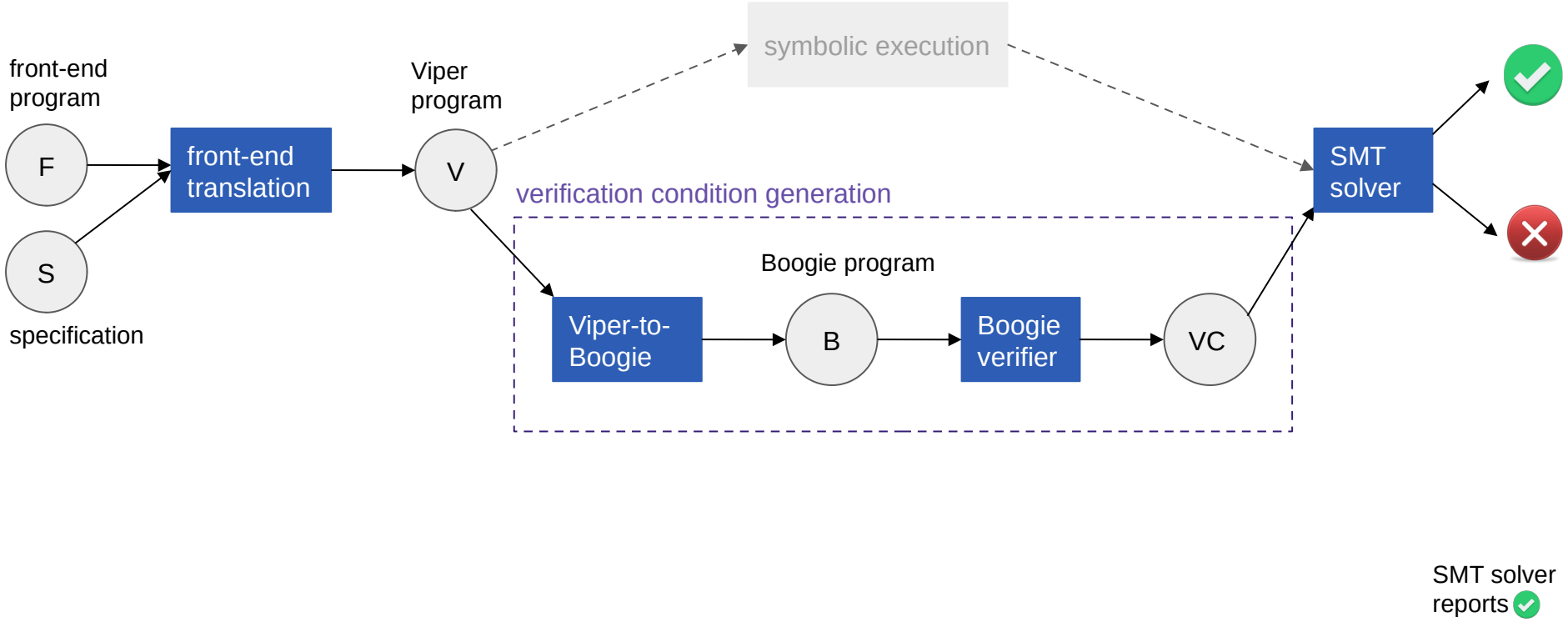
Soundness


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

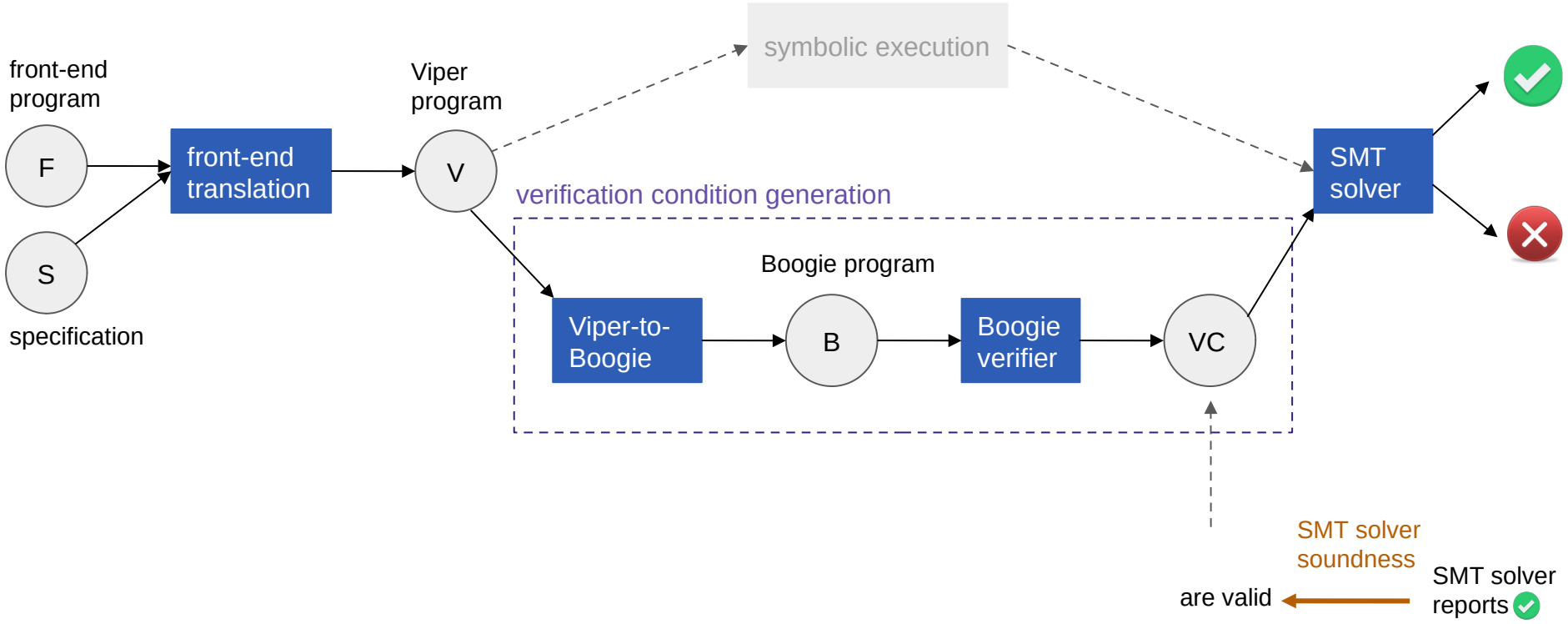
Soundness: Proof Strategy



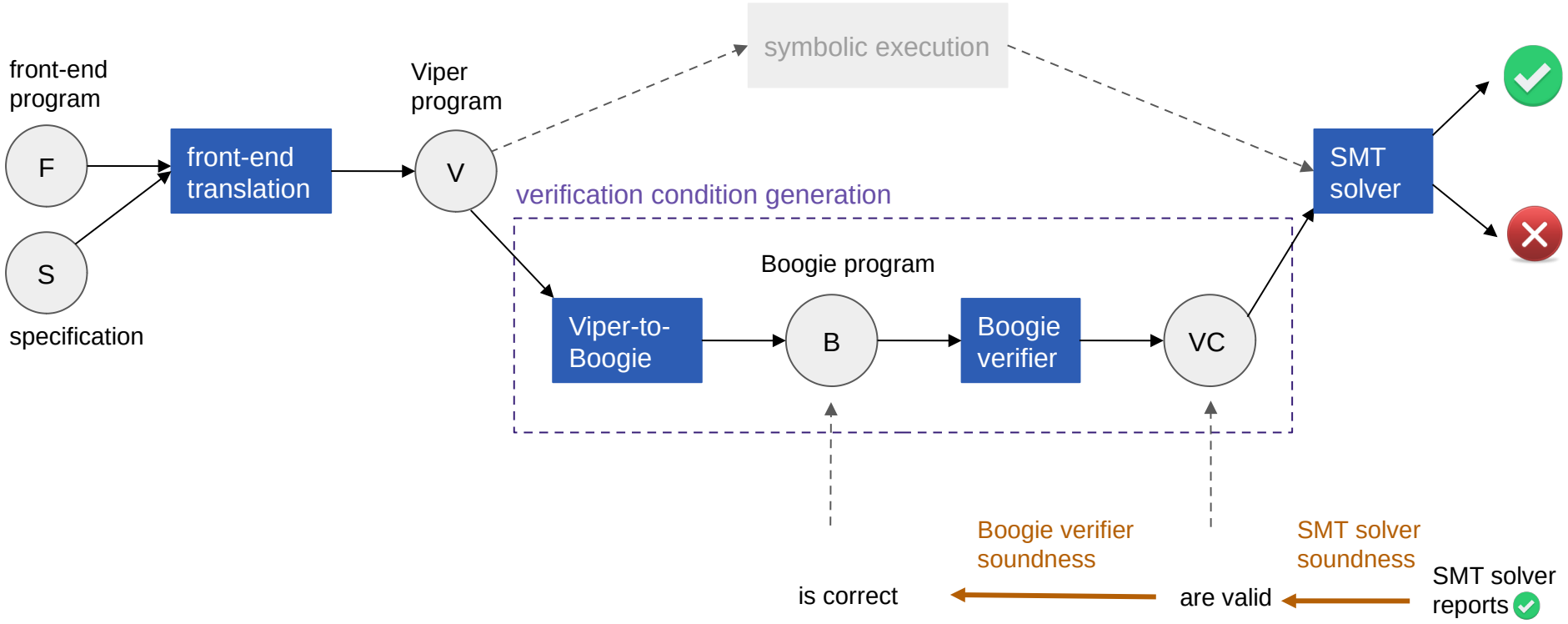
Soundness: Proof Strategy



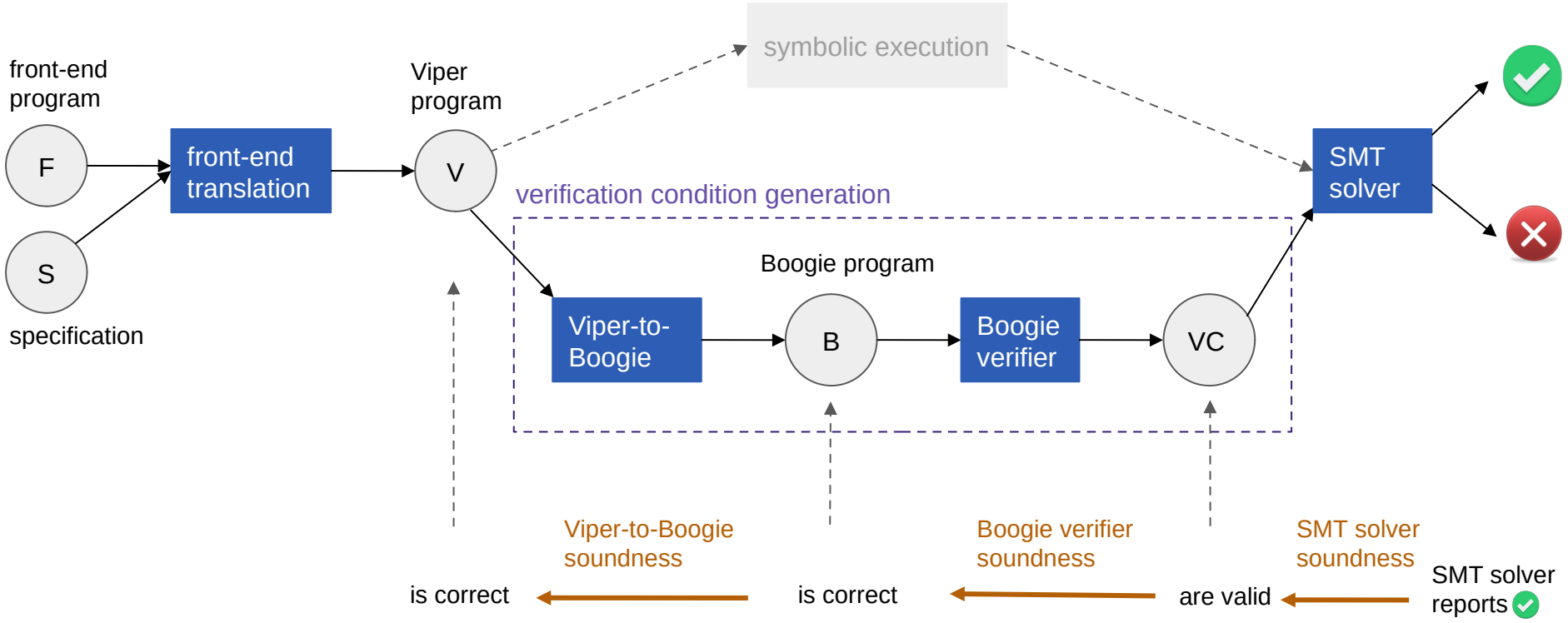
Soundness: Proof Strategy



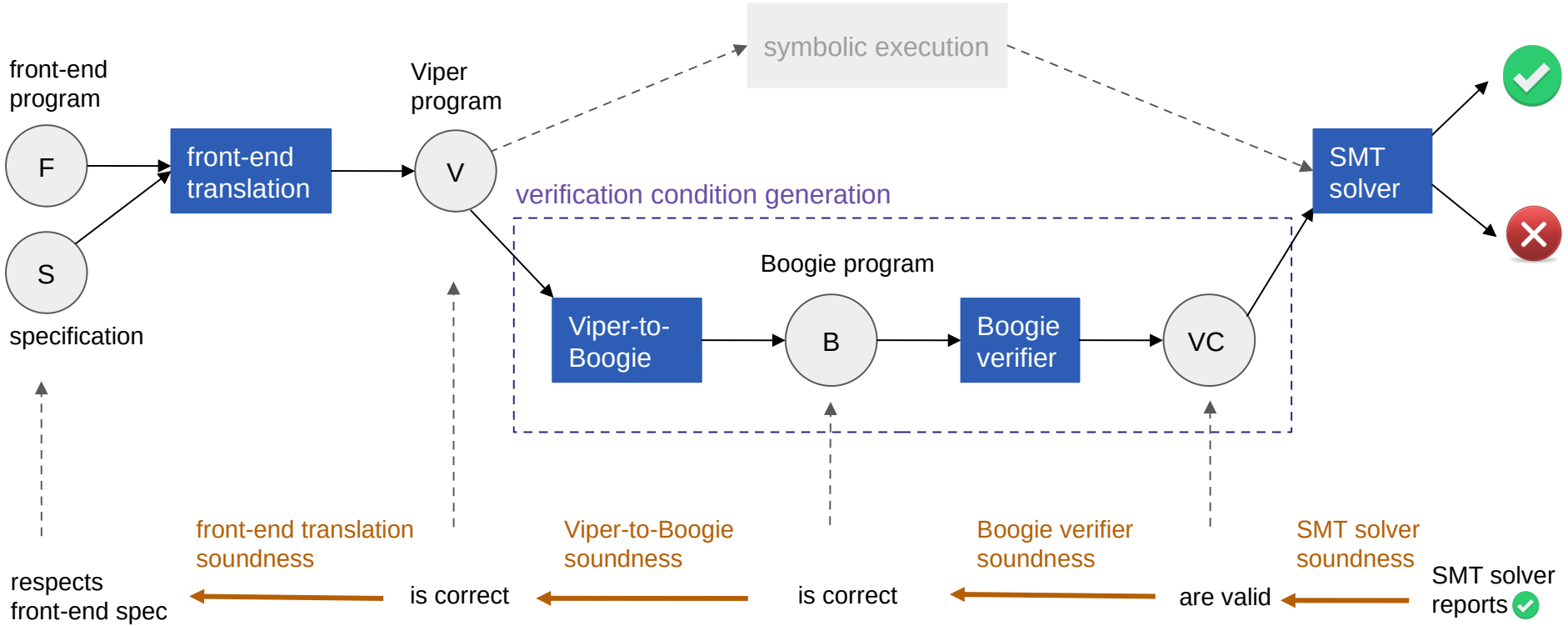
Soundness: Proof Strategy



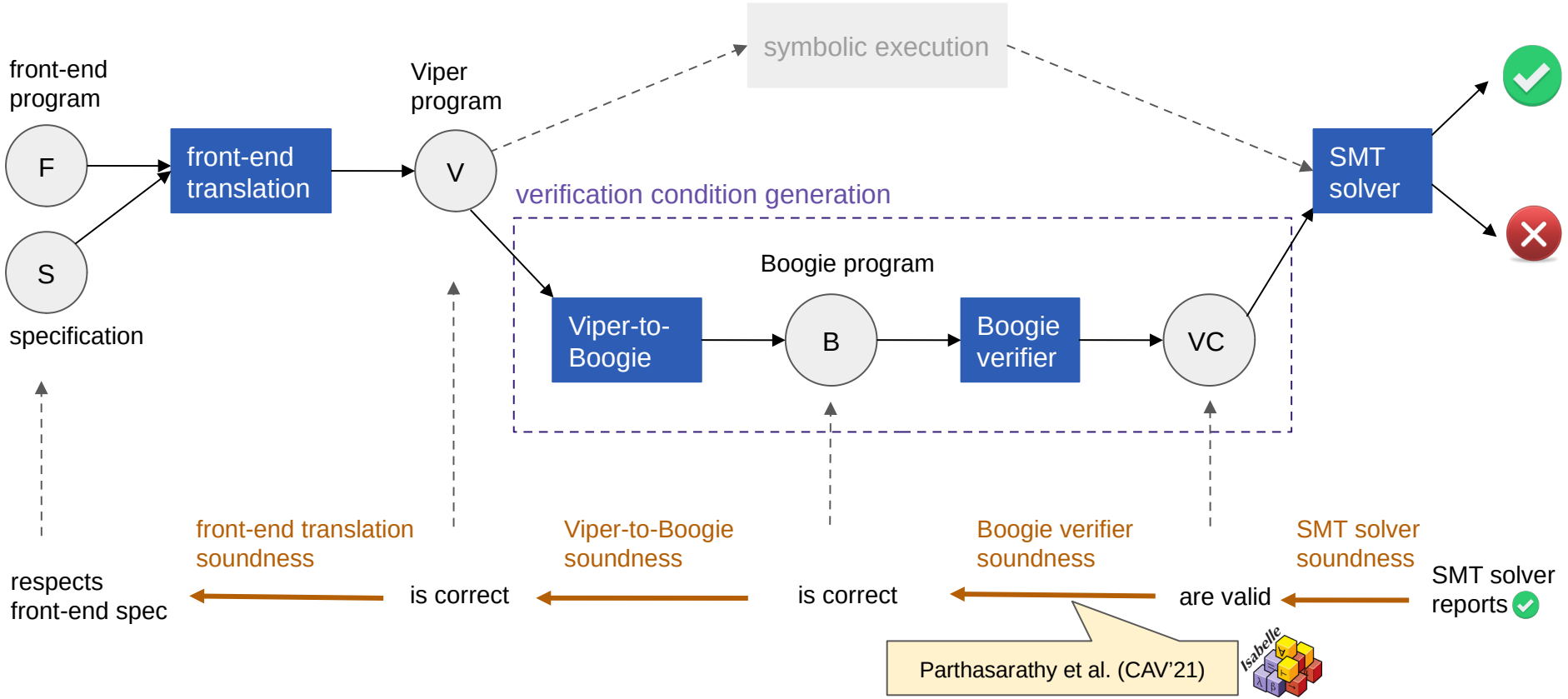
Soundness: Proof Strategy



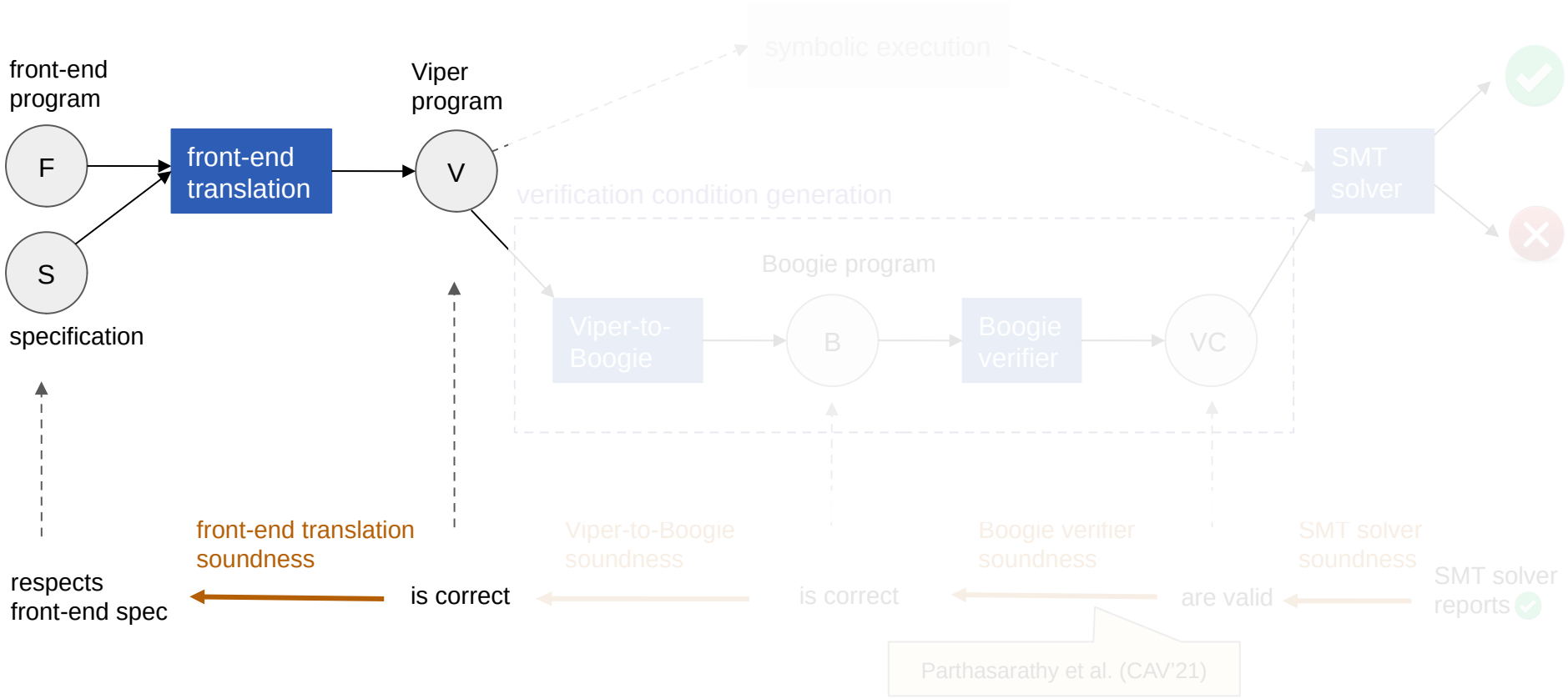
Soundness: Proof Strategy



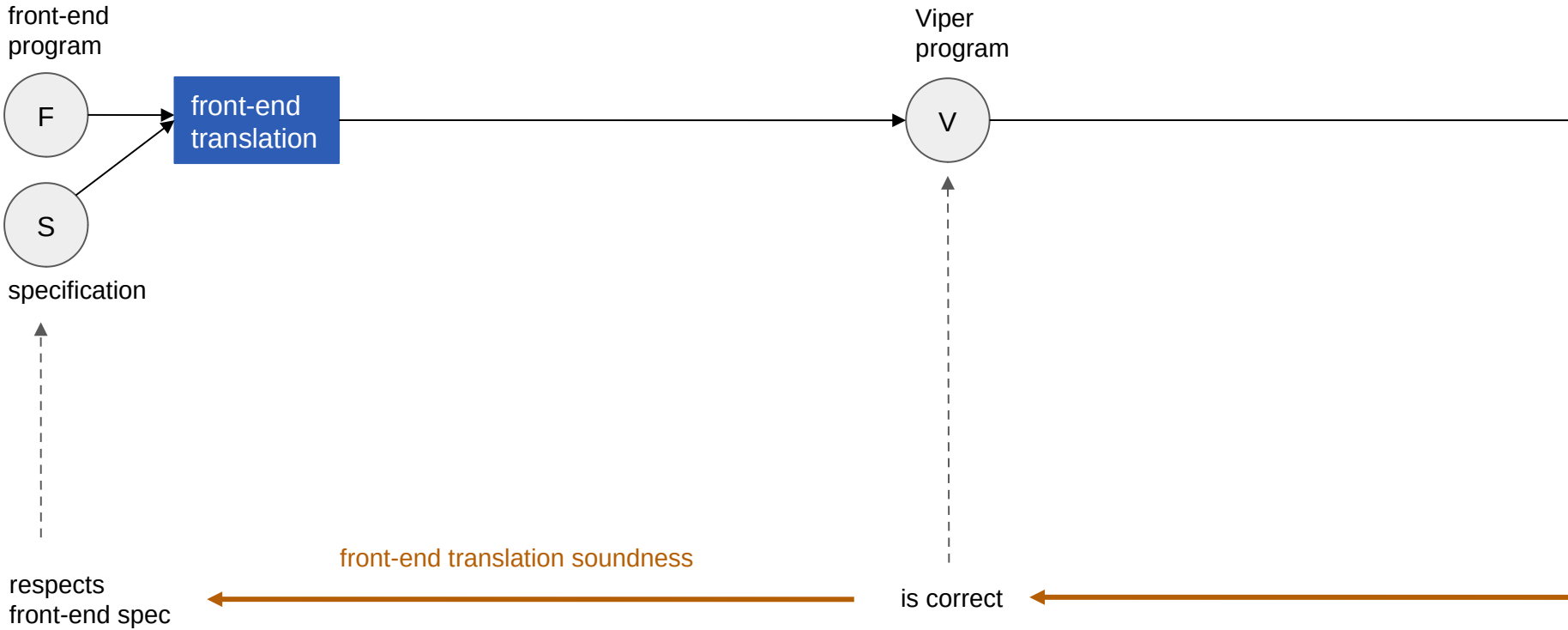
Soundness: Proof Strategy



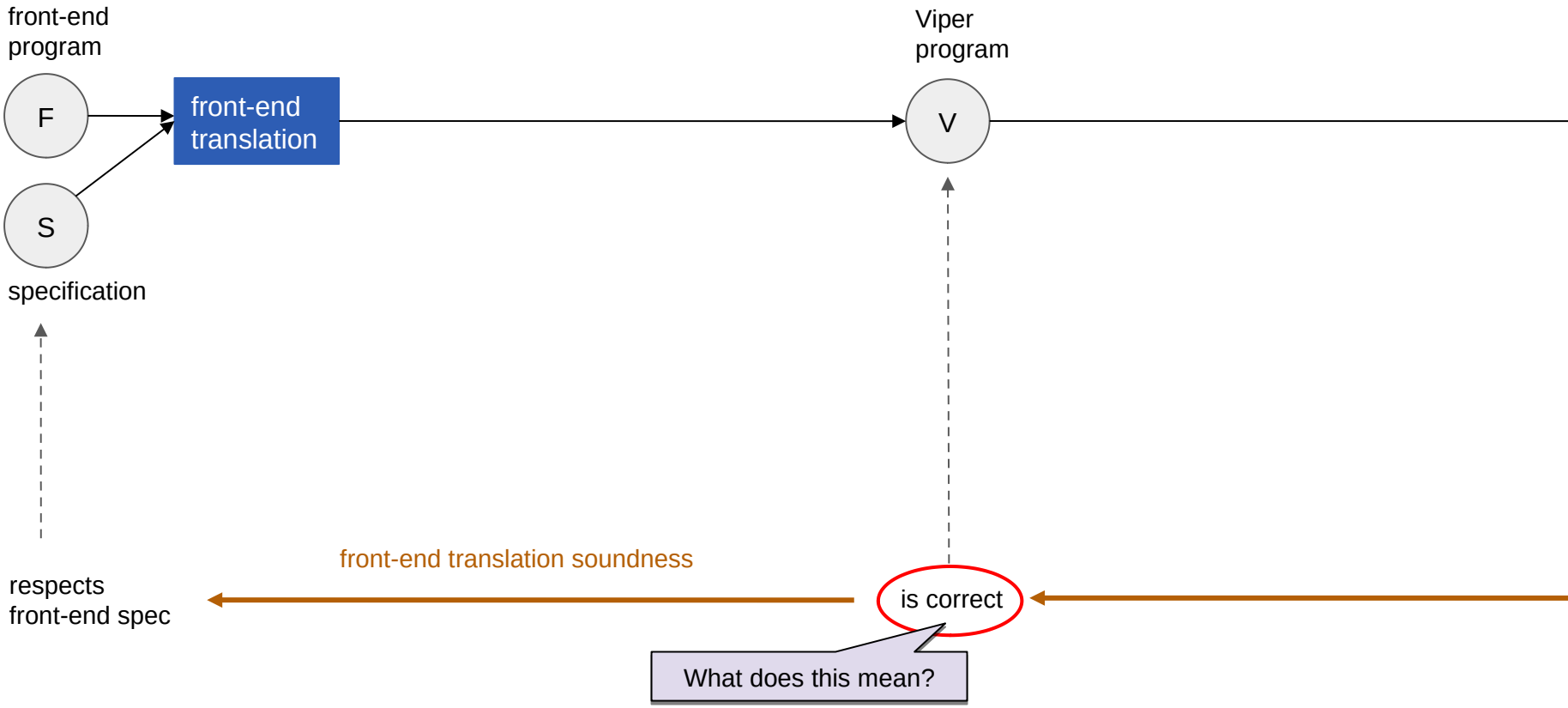
Soundness: Proof Strategy



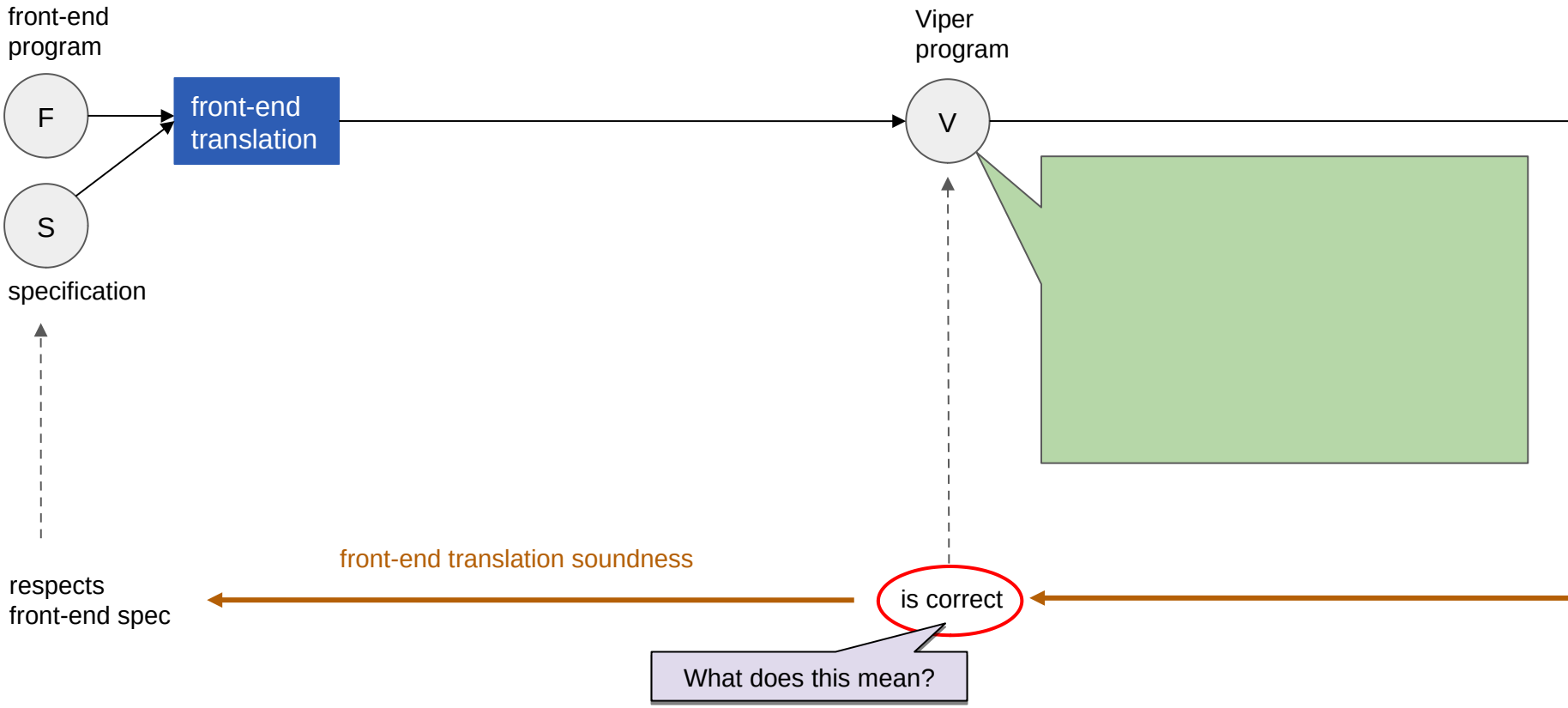
Viper's Formal Foundations



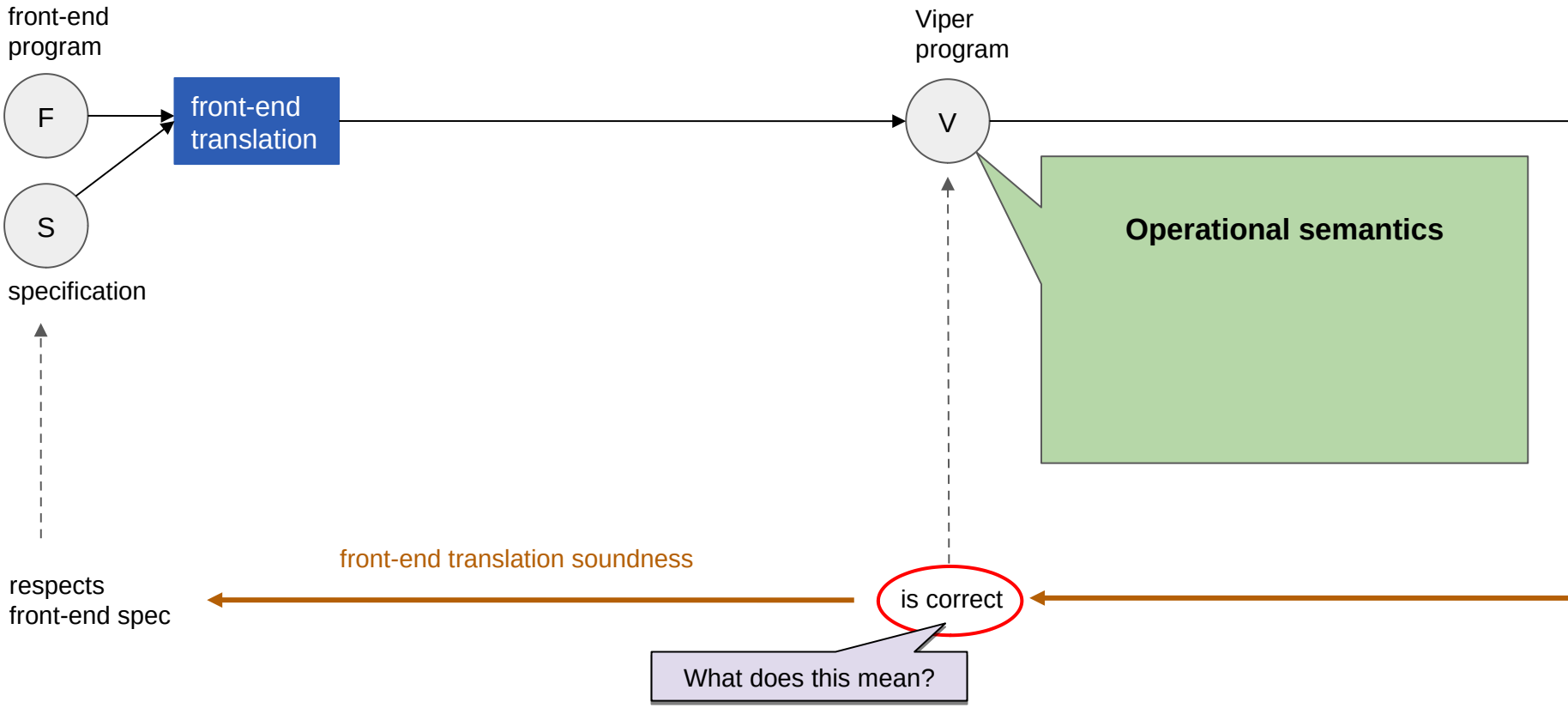
Viper's Formal Foundations



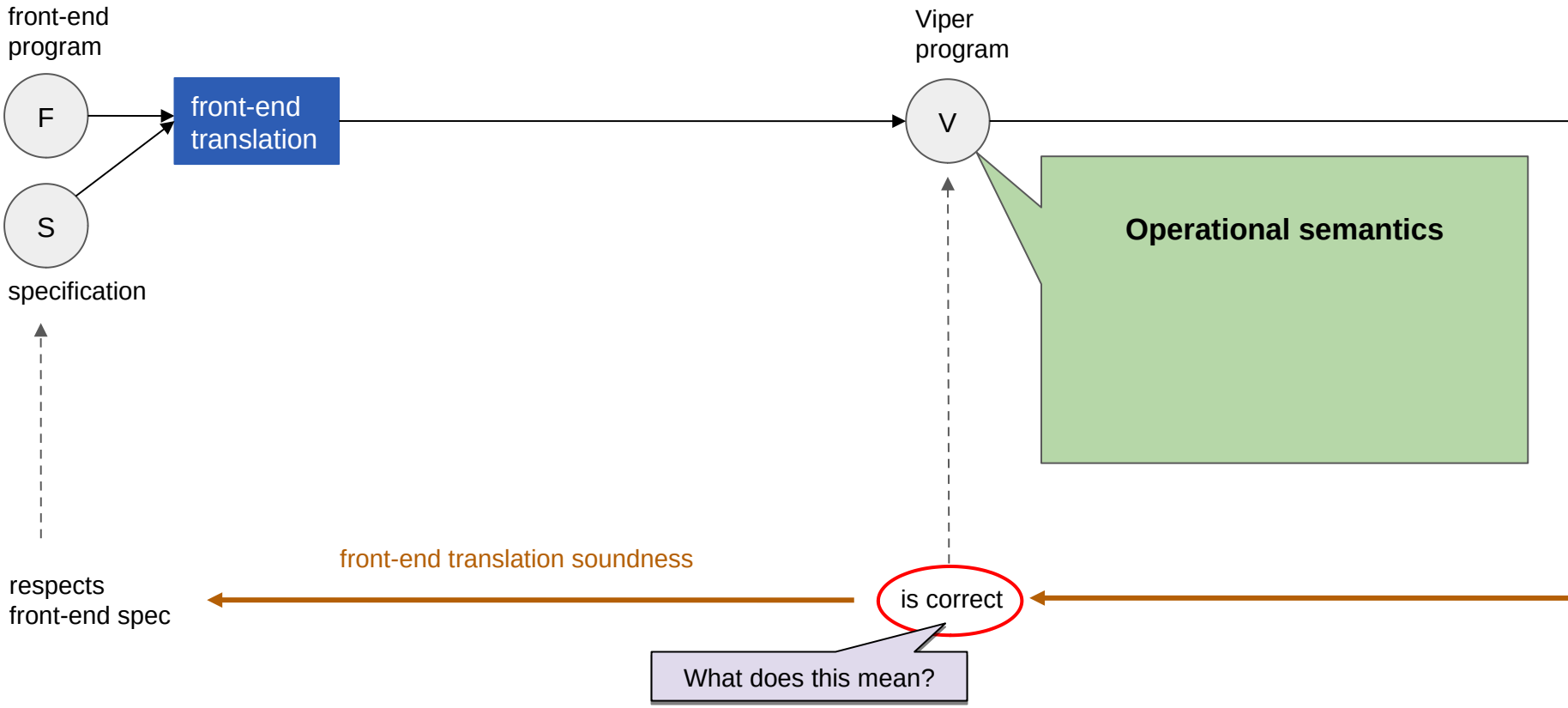
Viper's Formal Foundations



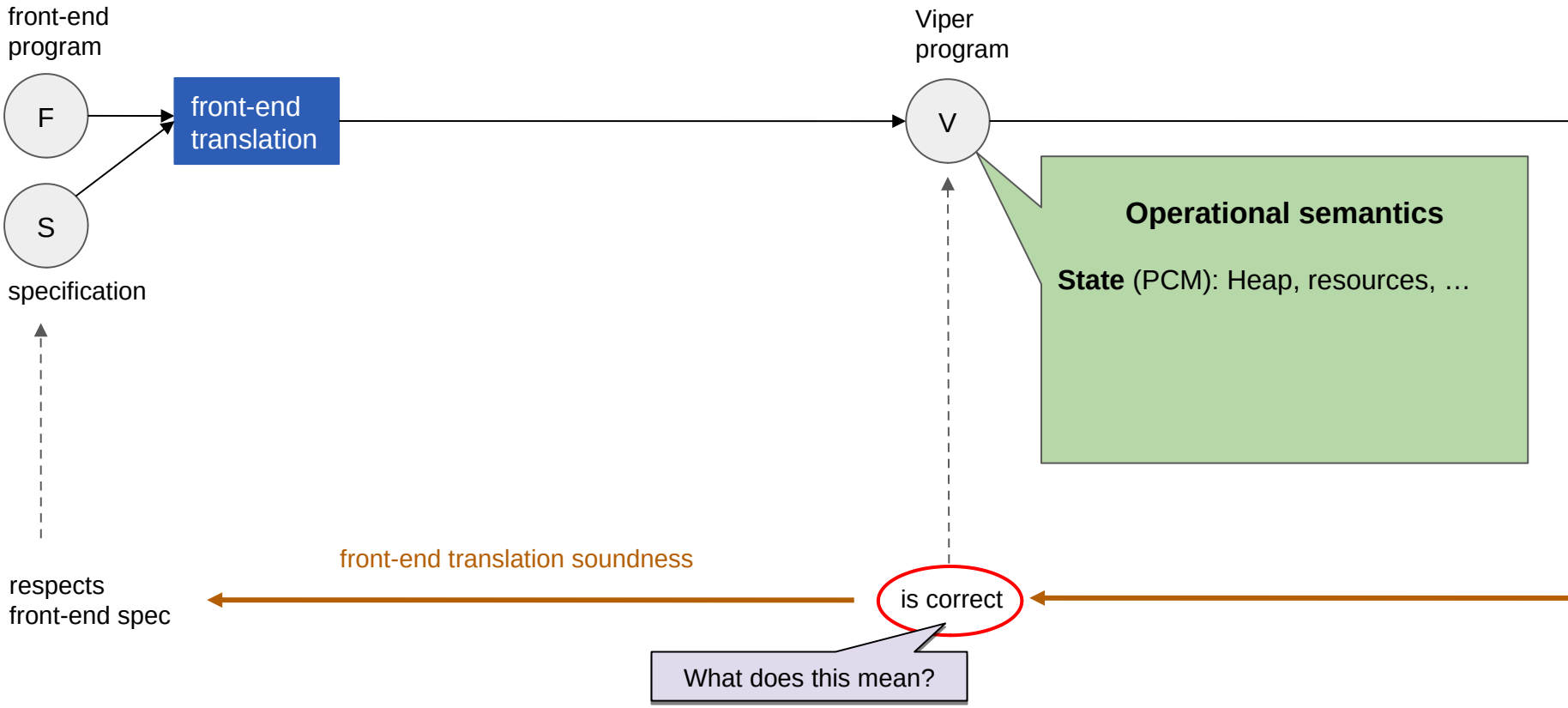
Viper's Formal Foundations



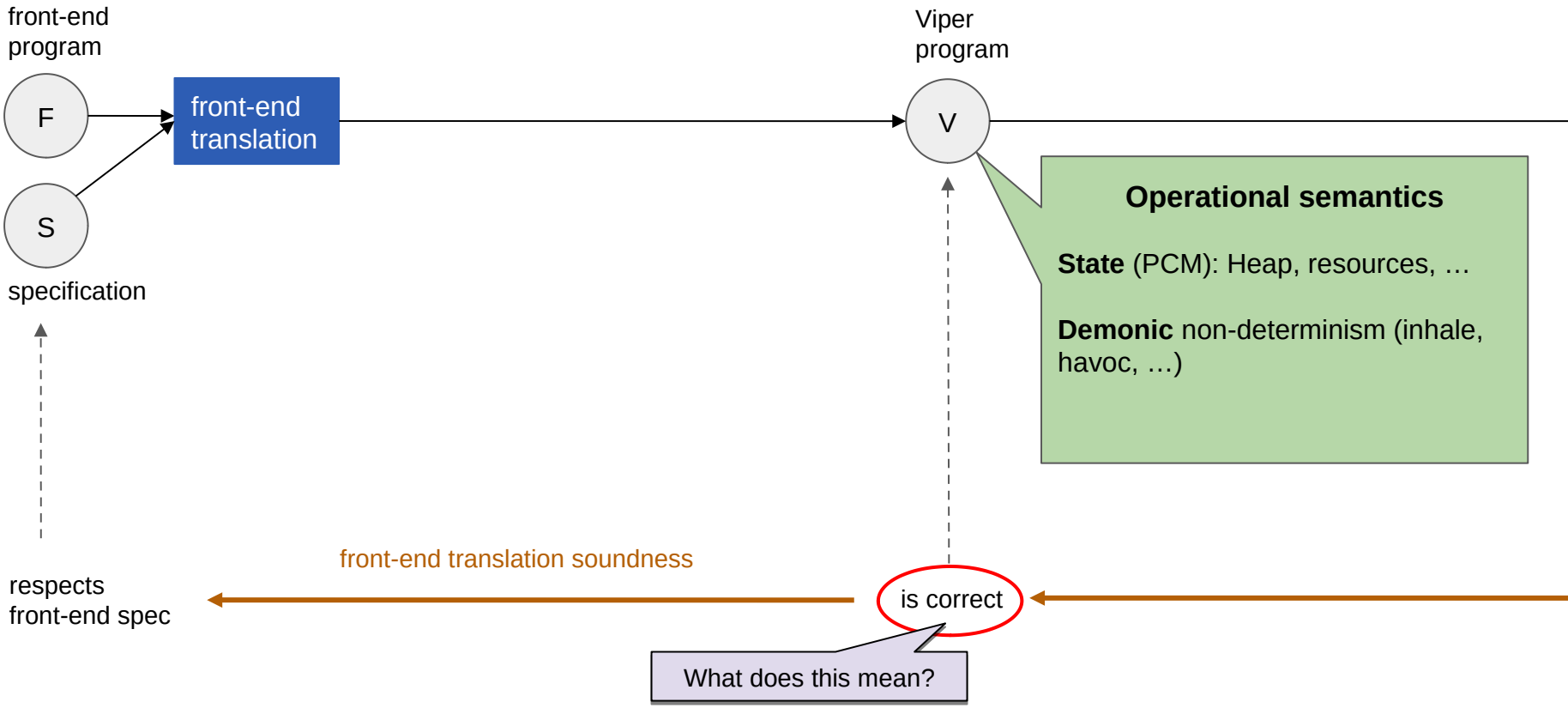
Viper's Formal Foundations



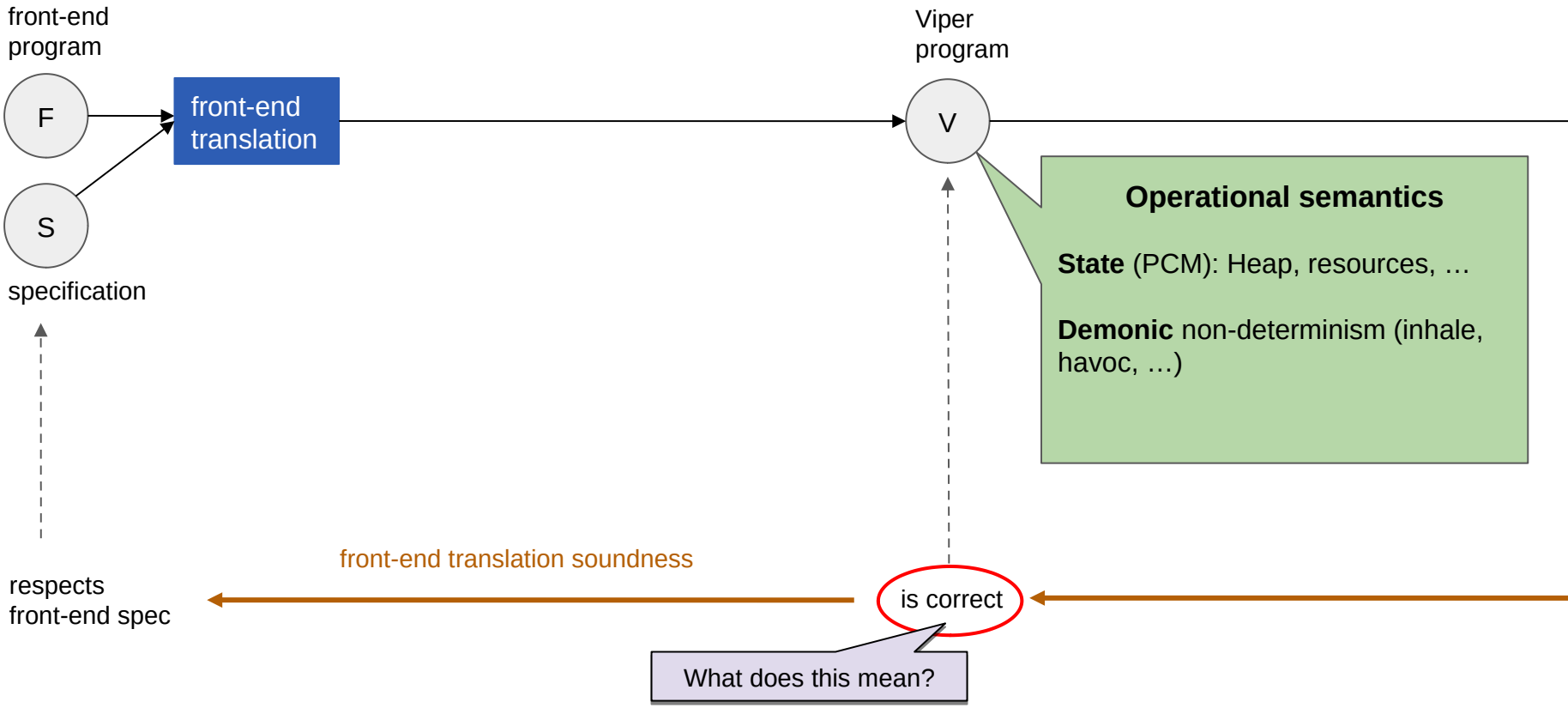
Viper's Formal Foundations



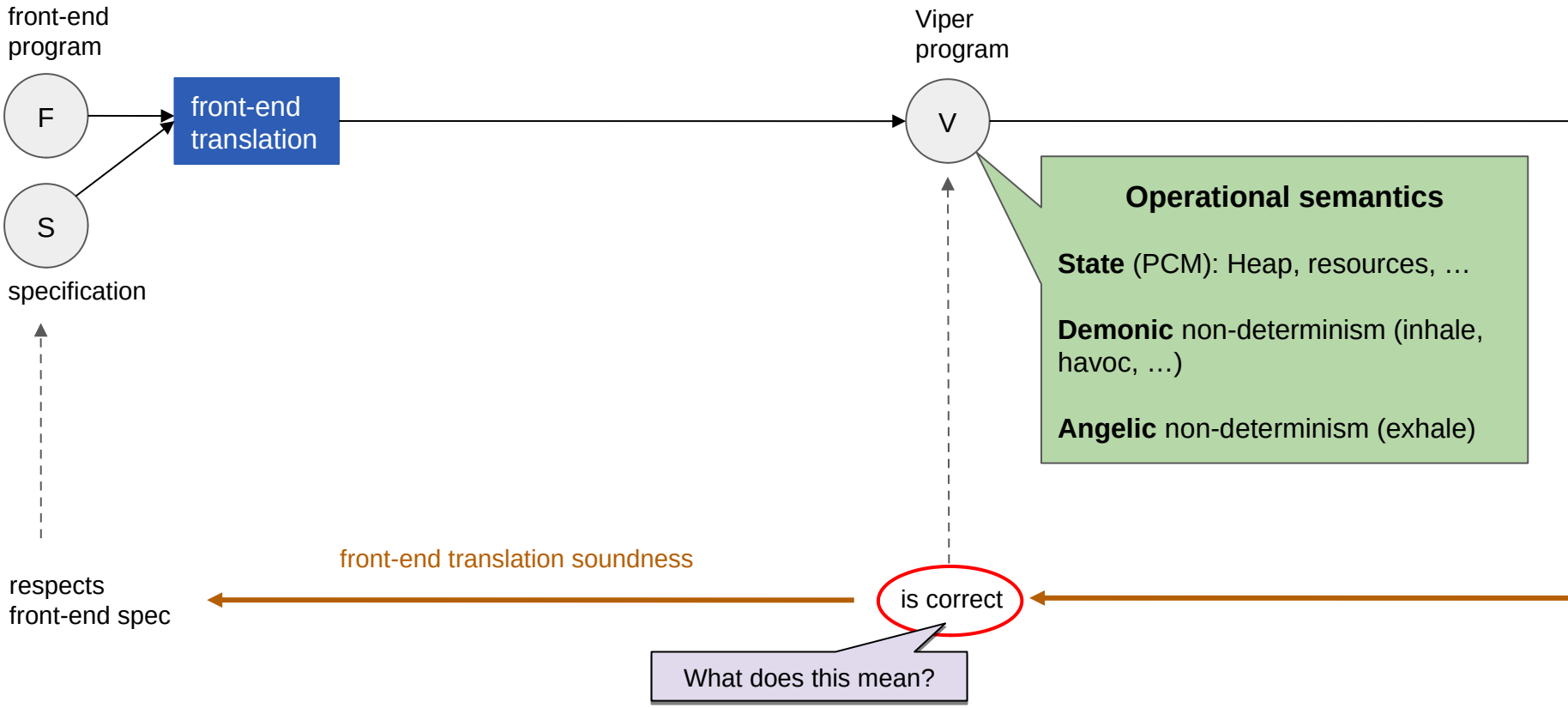
Viper's Formal Foundations



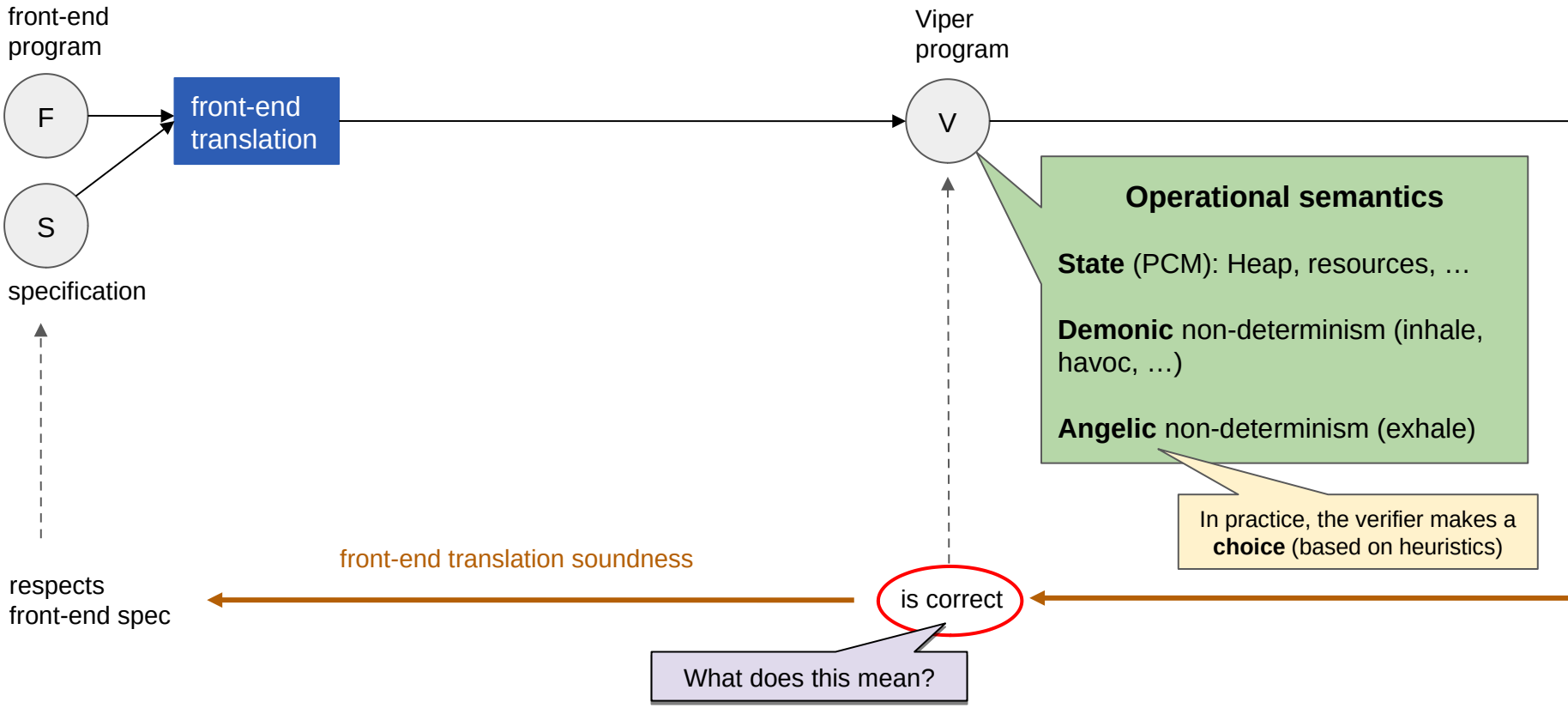
Viper's Formal Foundations



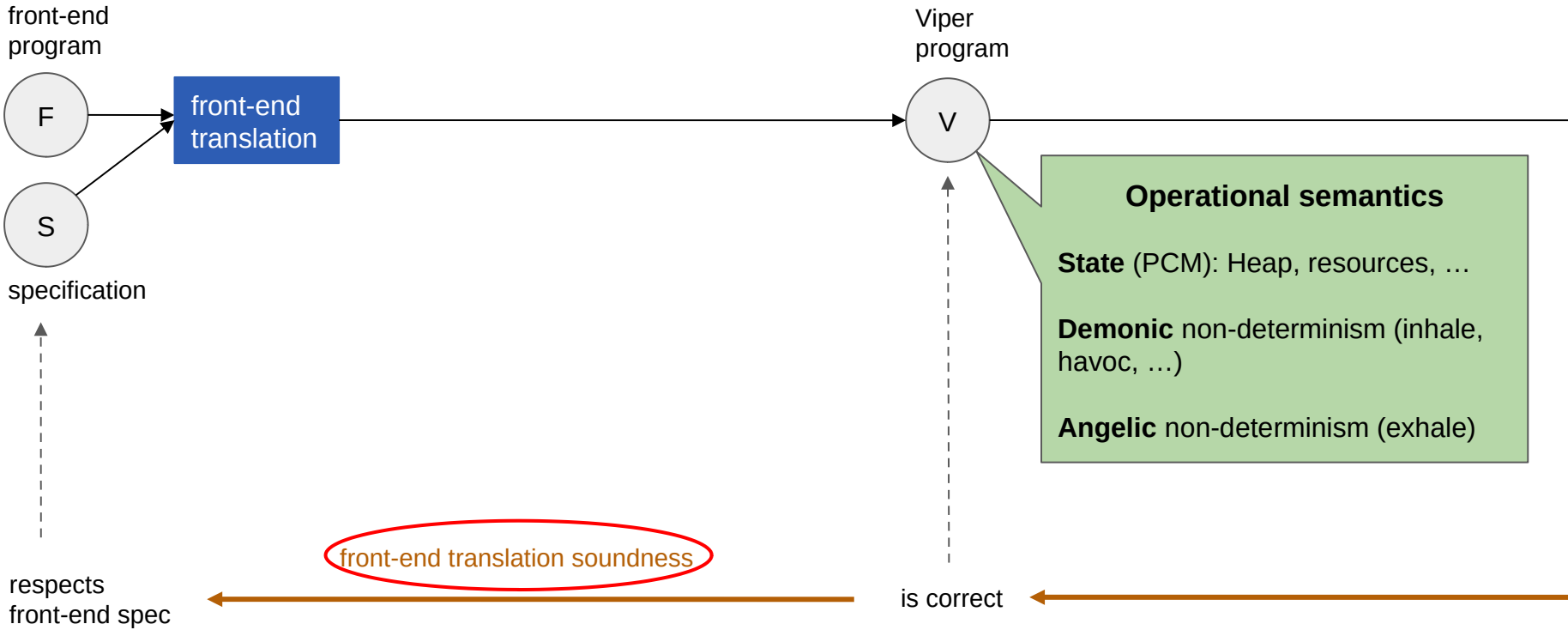
Viper's Formal Foundations



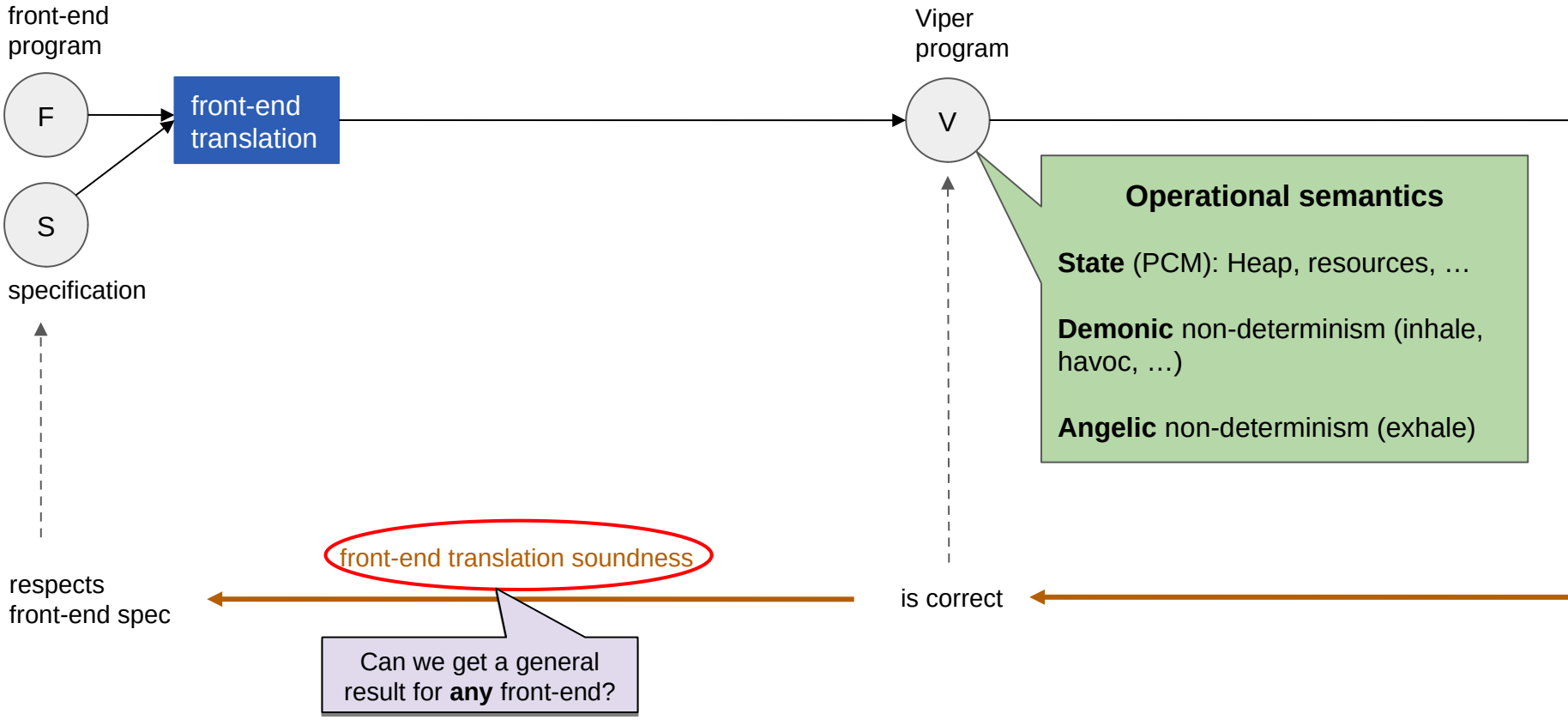
Viper's Formal Foundations



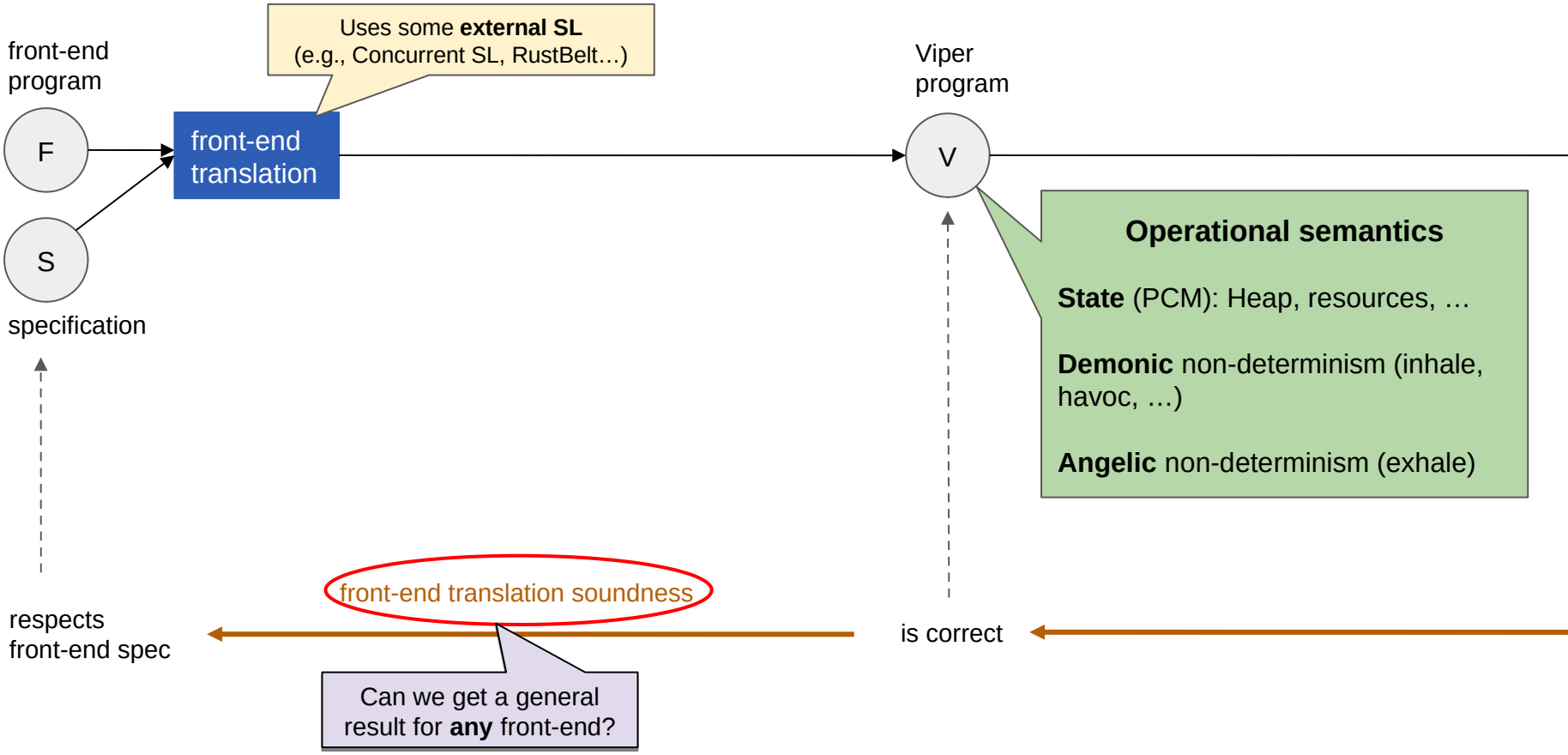
Viper's Formal Foundations



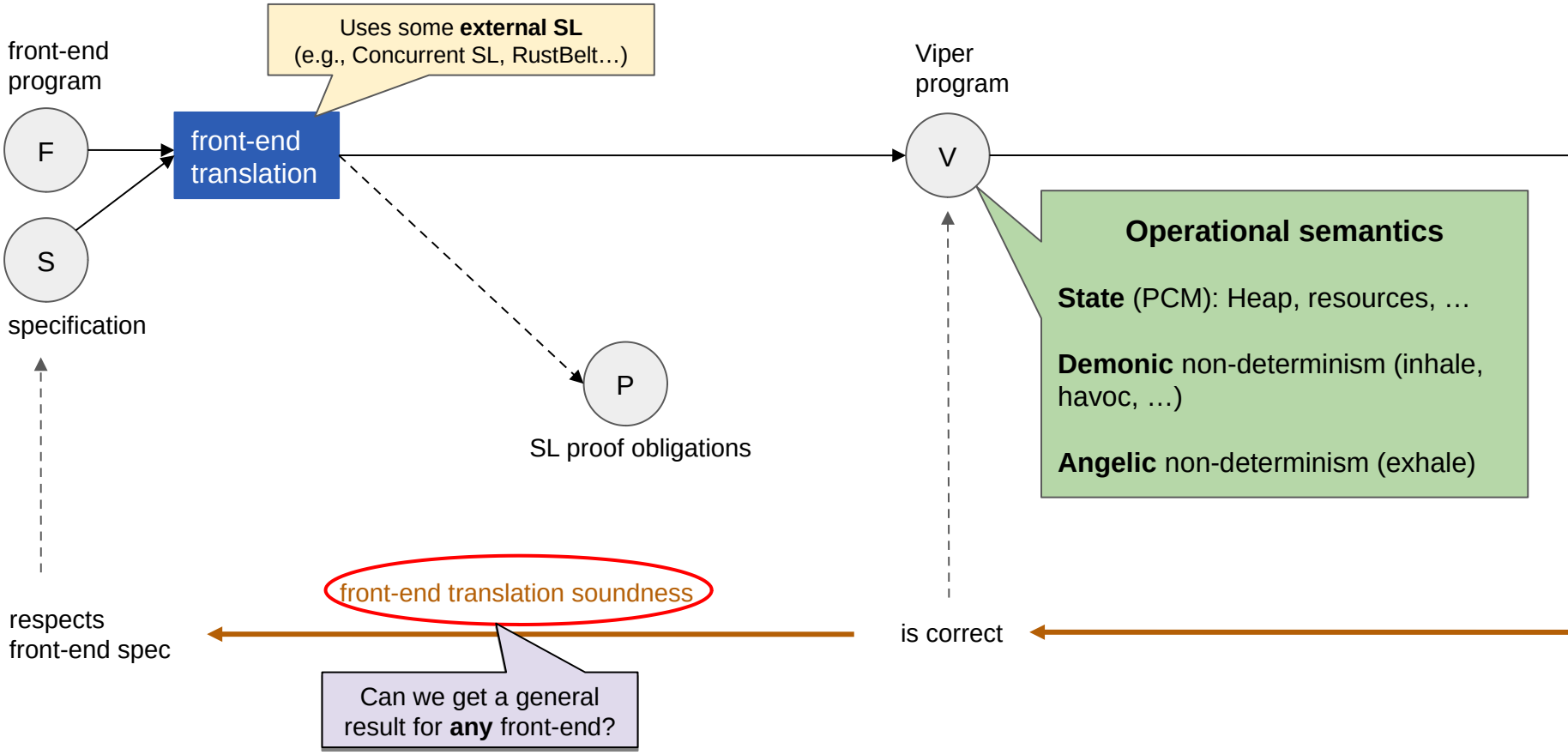
Viper's Formal Foundations



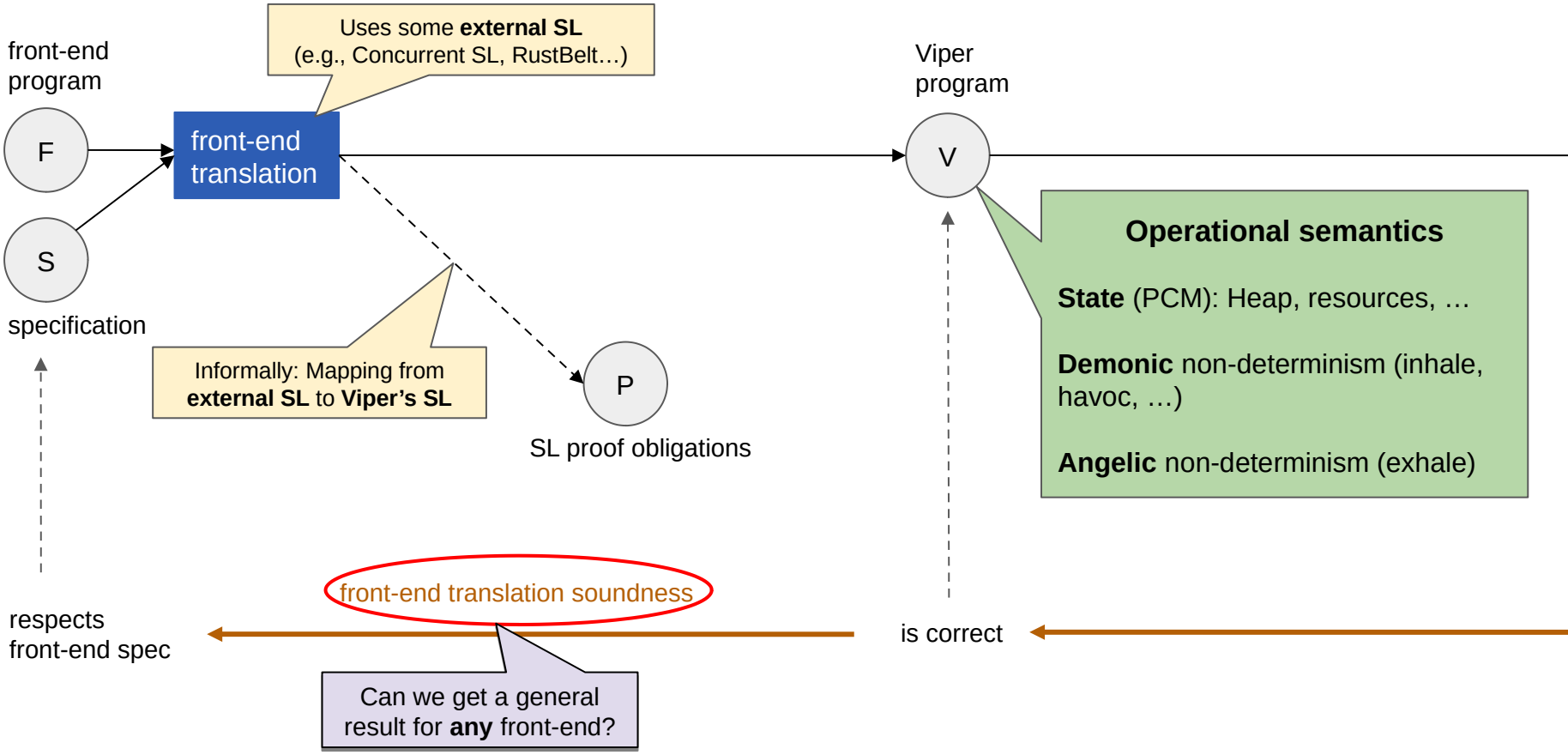
Viper's Formal Foundations



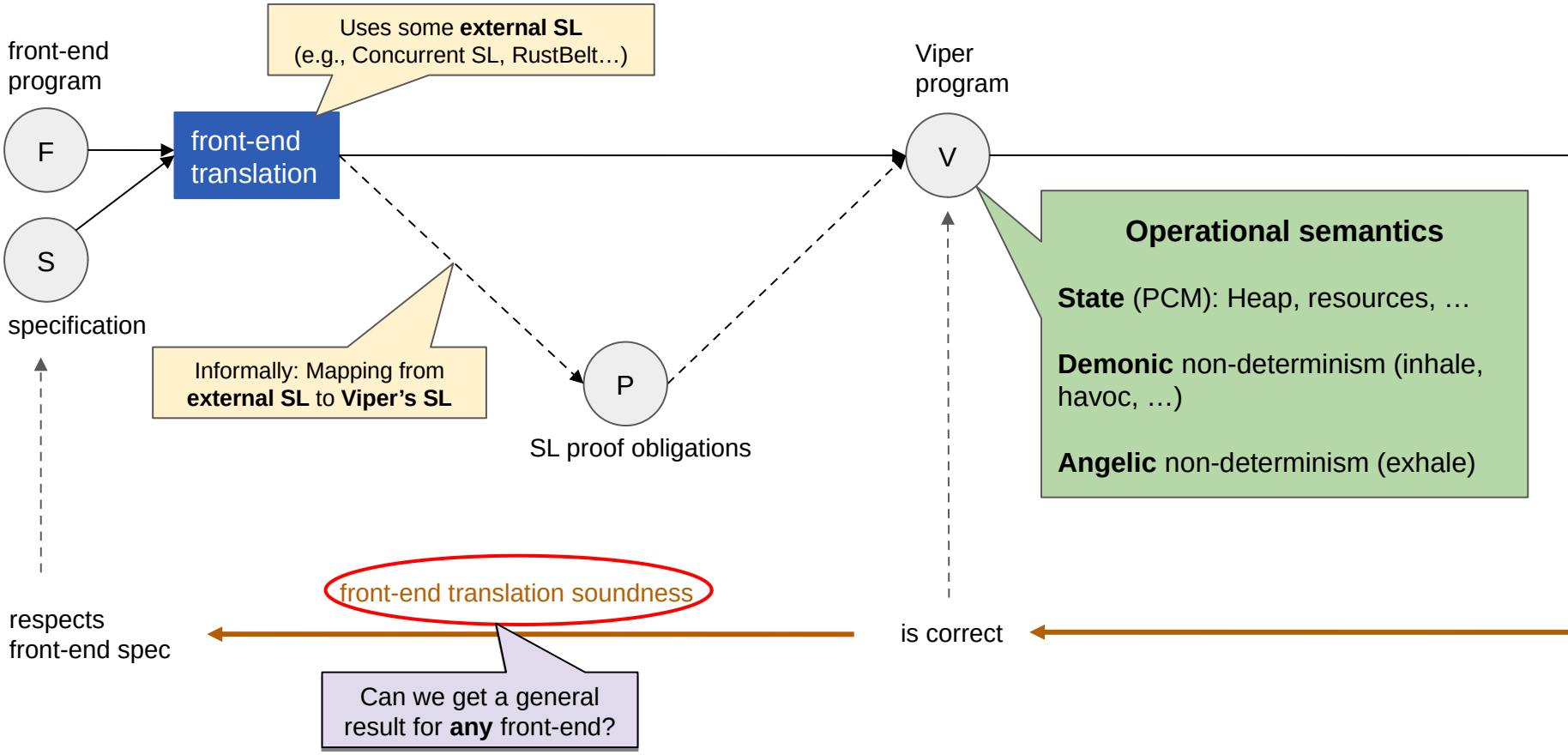
Viper's Formal Foundations



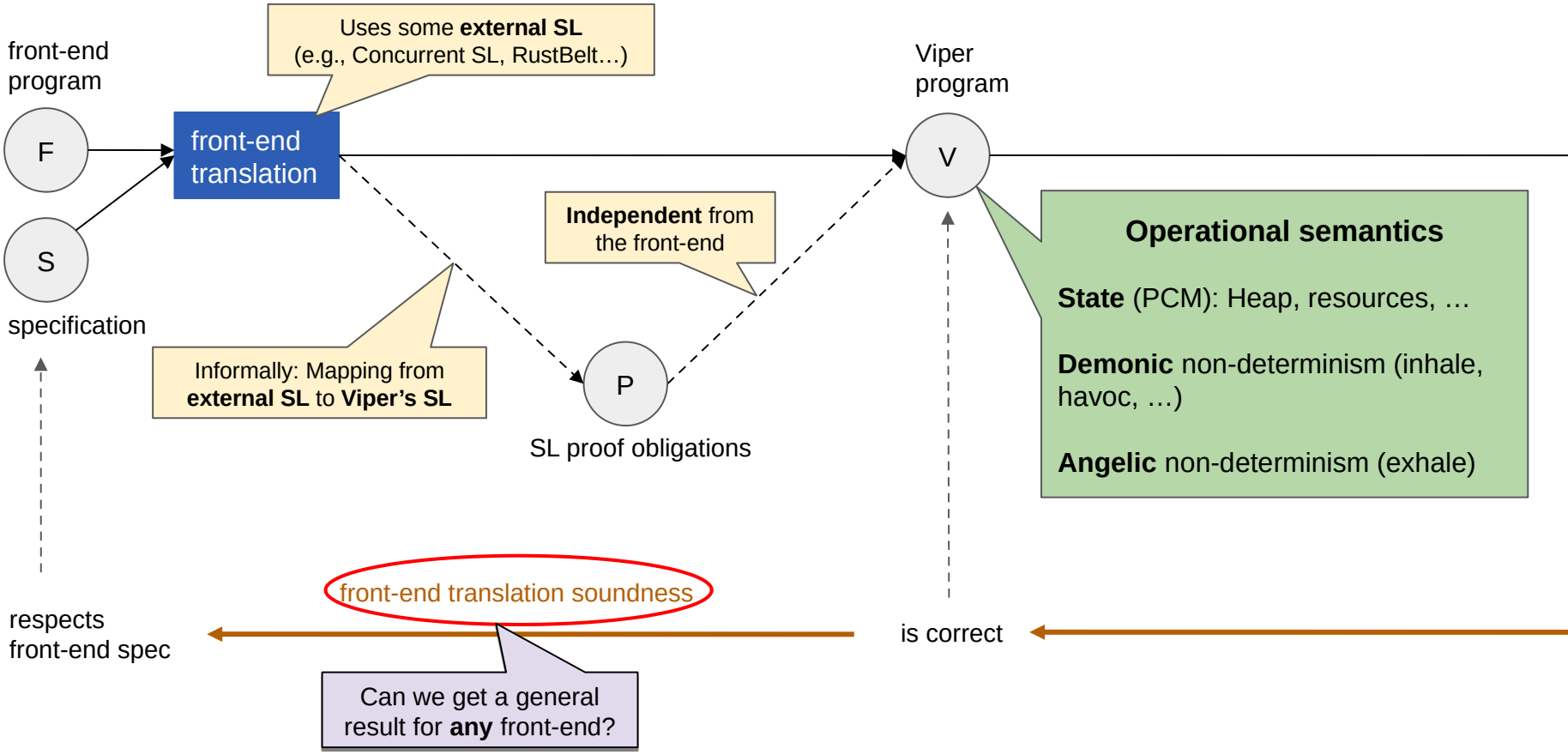
Viper's Formal Foundations



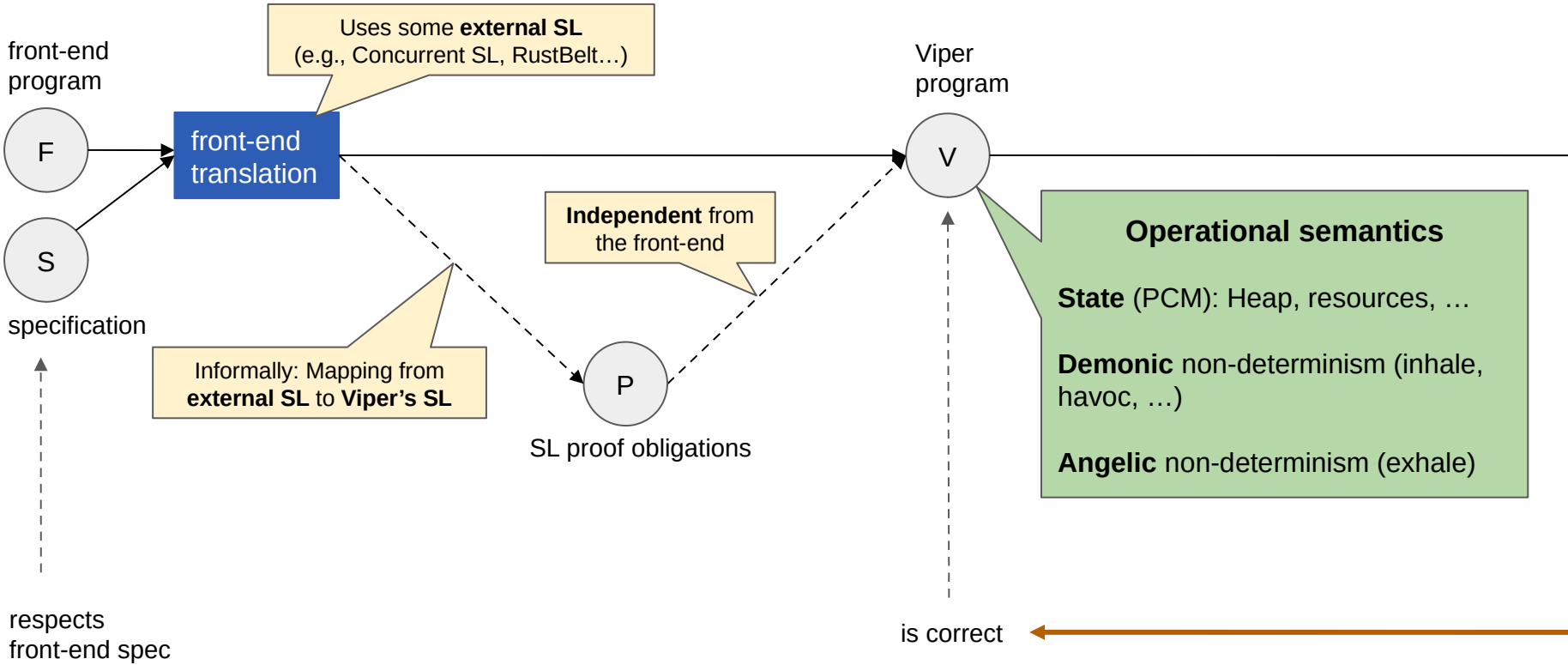
Viper's Formal Foundations



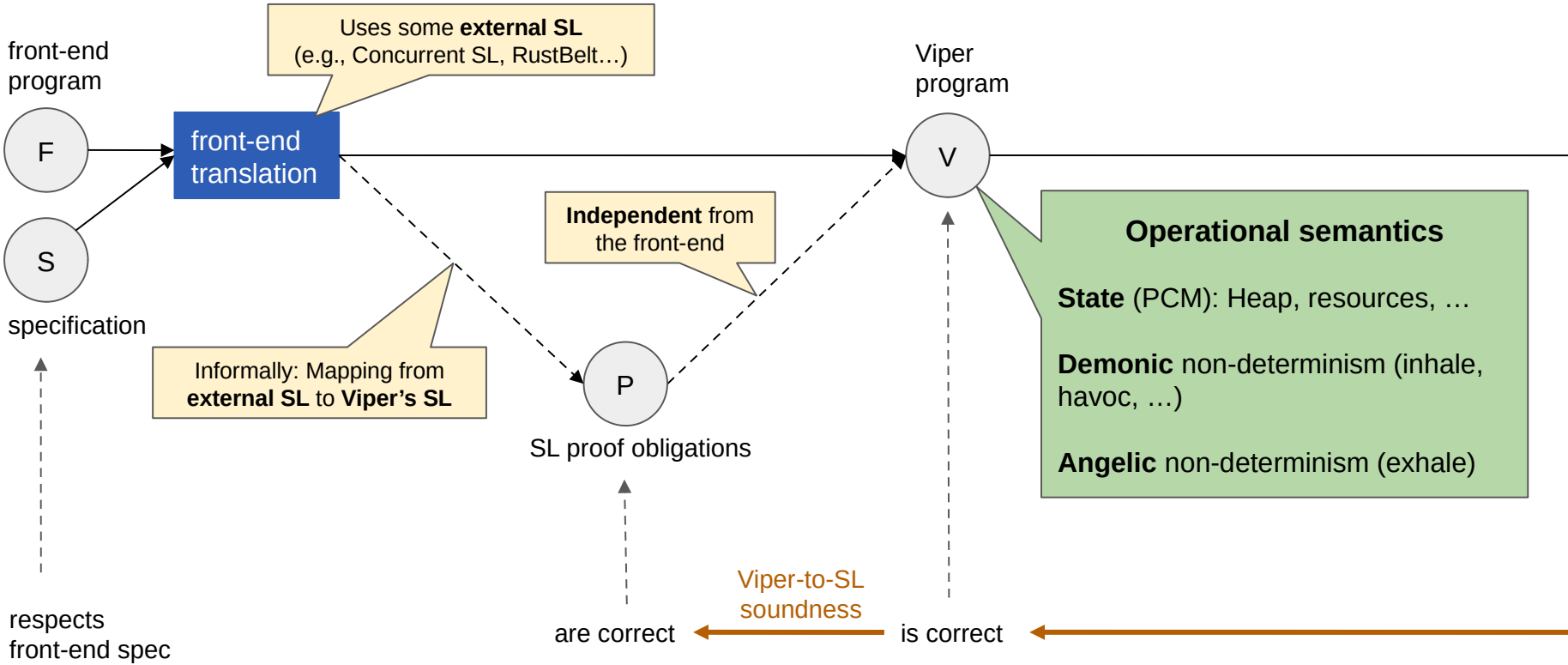
Viper's Formal Foundations



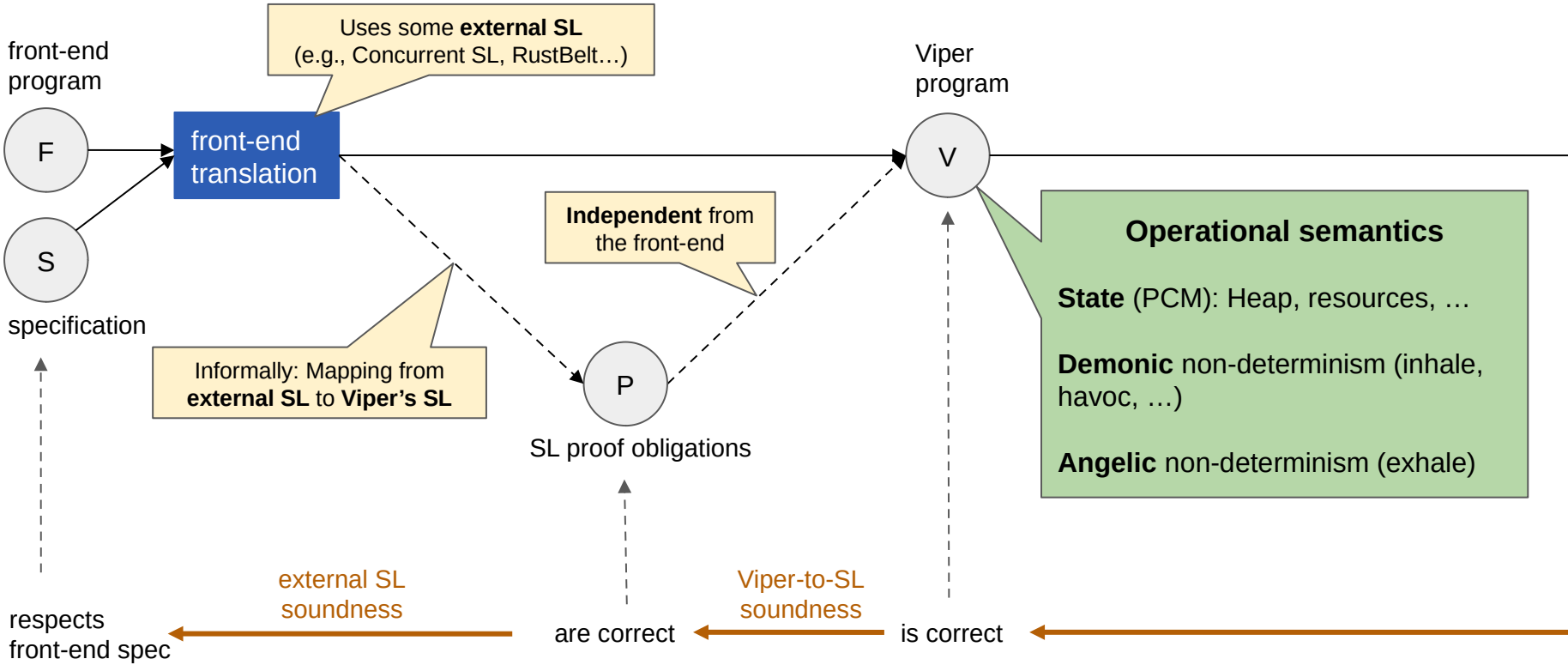
Viper's Formal Foundations



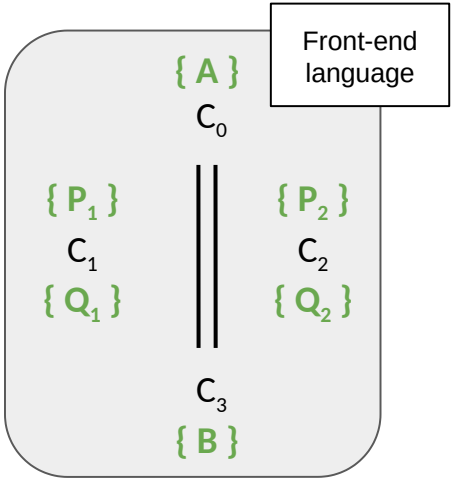
Viper's Formal Foundations



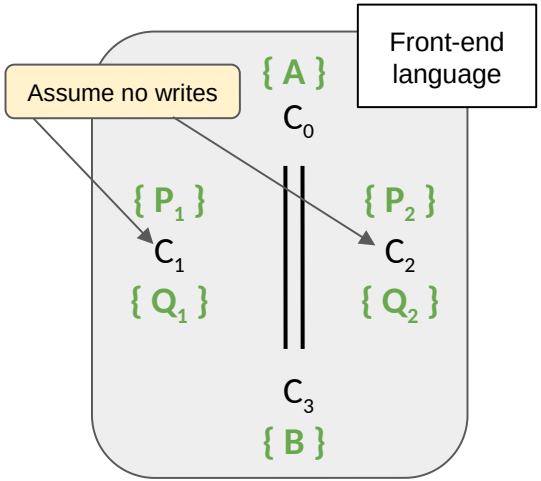
Viper's Formal Foundations



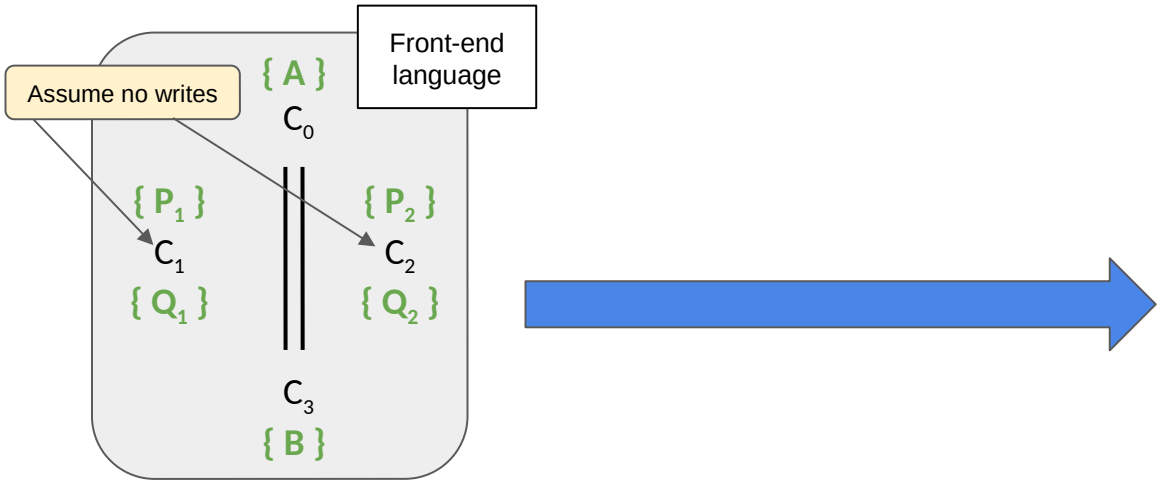
Viper-to-SL: Parallel Program



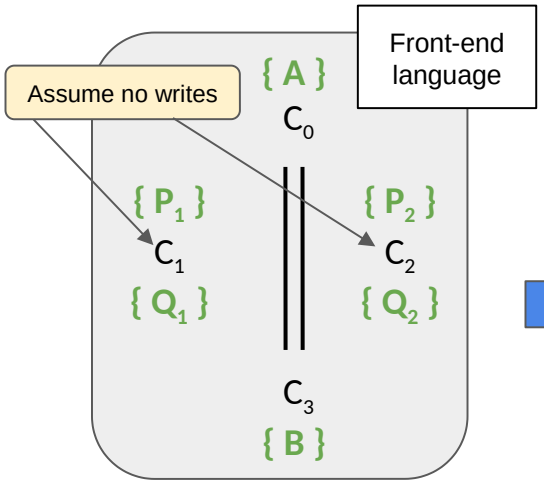
Viper-to-SL: Parallel Program

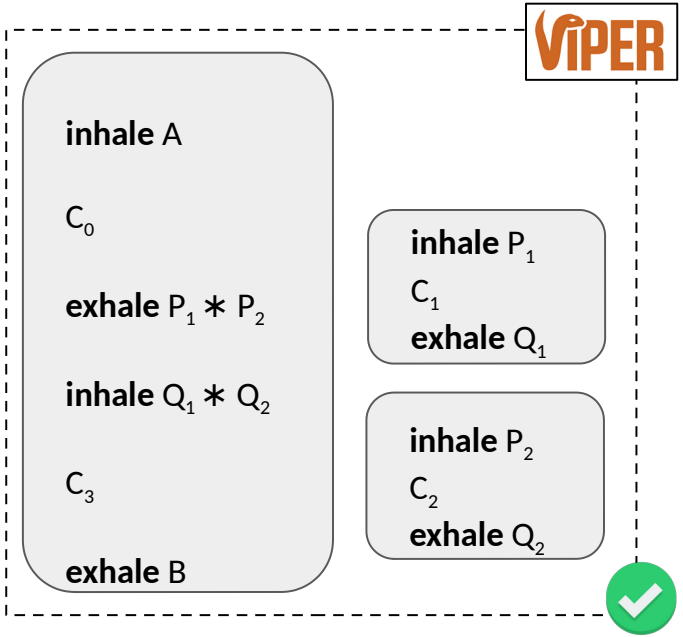


Viper-to-SL: Parallel Program

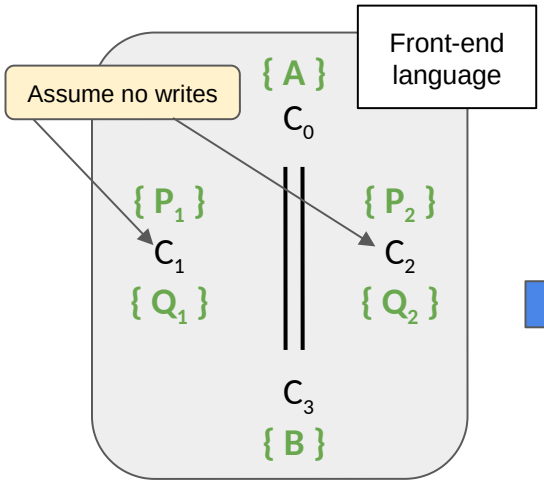


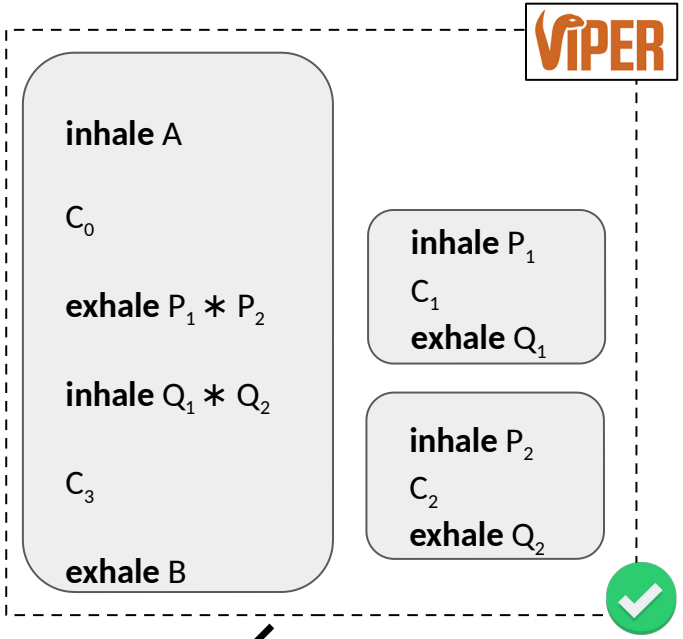
Viper-to-SL: Parallel Program





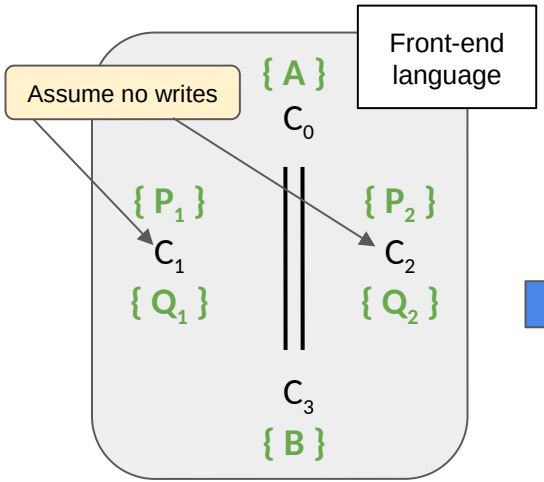
Viper-to-SL: Parallel Program

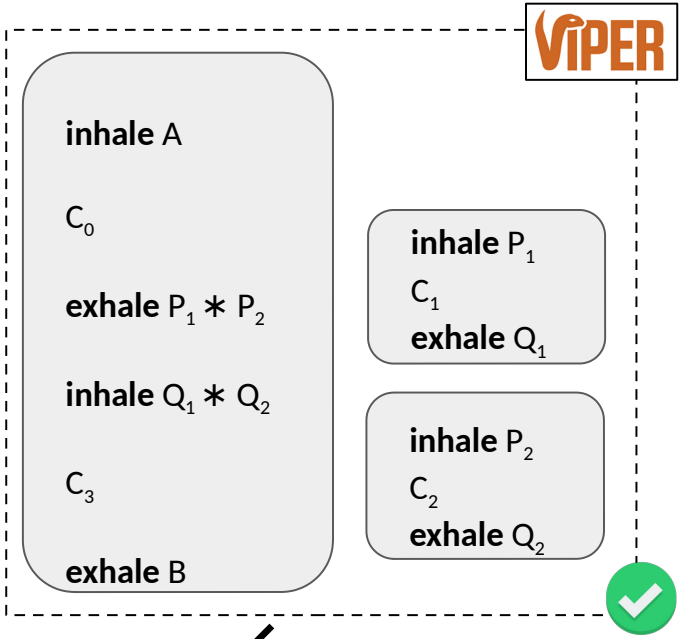




SL proof obligations proven by Viper

Viper-to-SL: Parallel Program

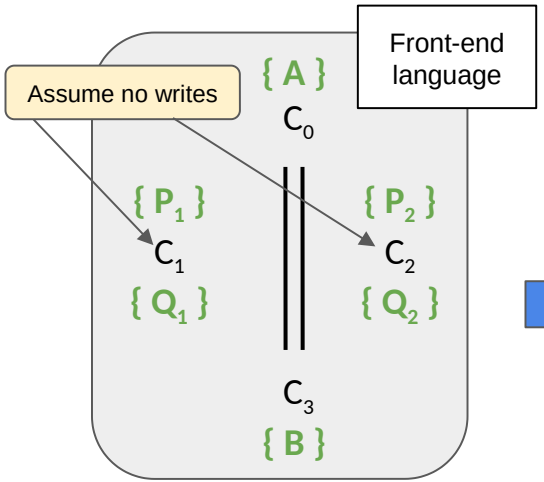


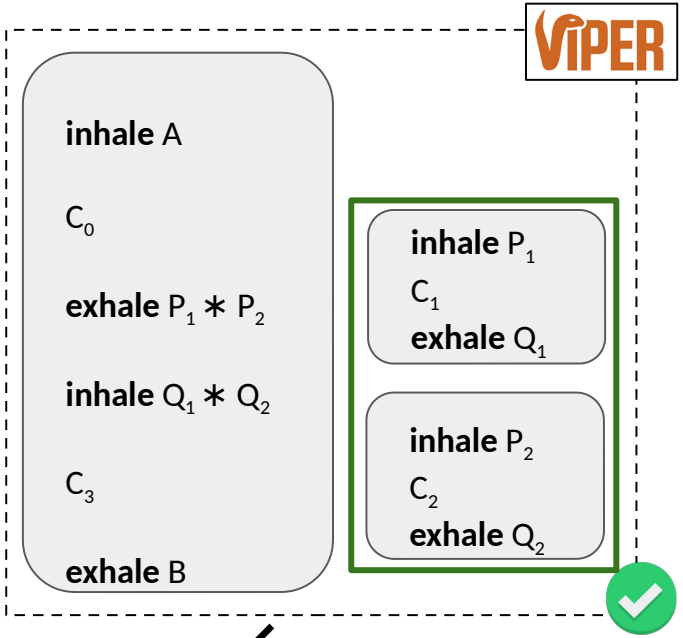


SL proof obligations proven by Viper

Viper-to-SL theorem
(independent from the front-end)

Viper-to-SL: Parallel Program

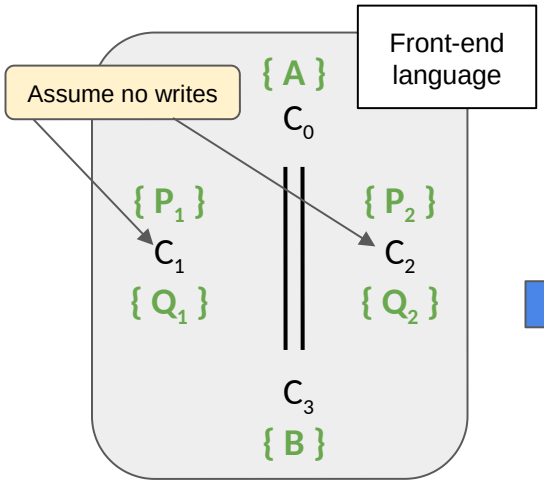


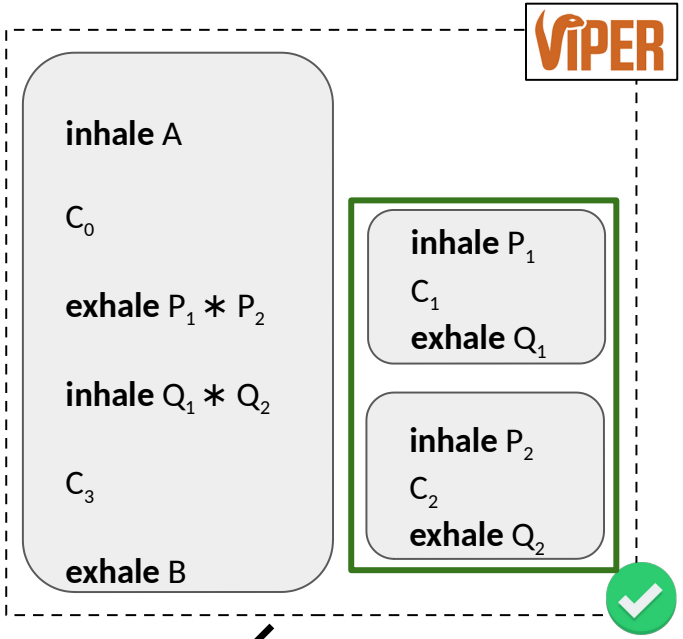


SL proof obligations proven by Viper

Viper-to-SL theorem
(independent from the front-end)

Viper-to-SL: Parallel Program





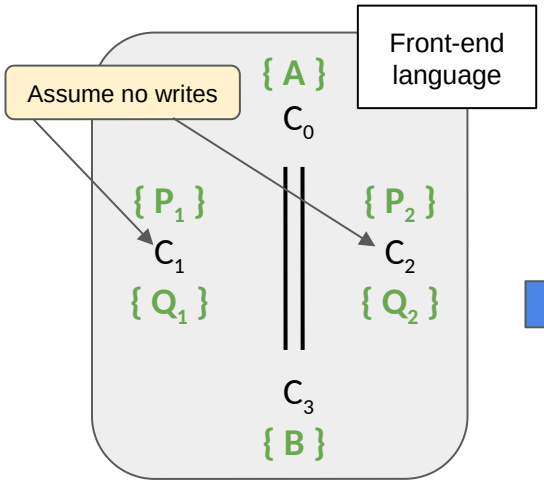
SL proof obligations proven by Viper

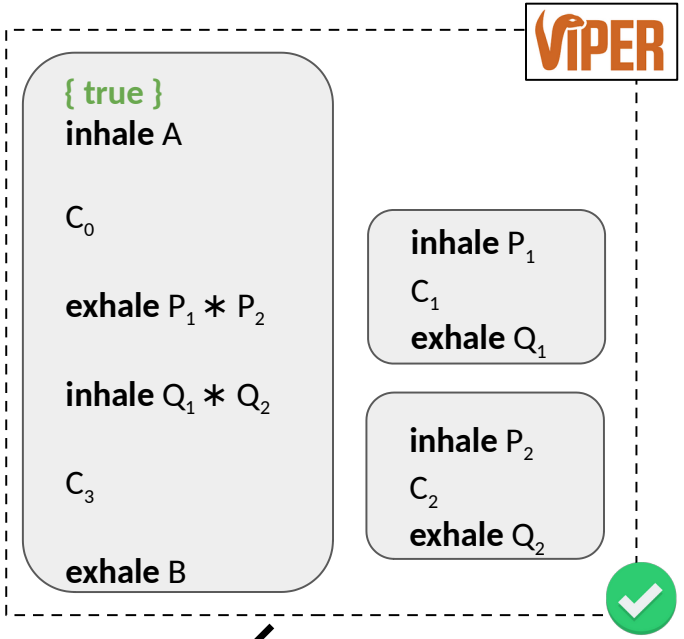
$\vdash \{ P_1 \}\ C_1\ \{ Q_1 \}$

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

Viper-to-SL theorem
(independent from the front-end)

Viper-to-SL: Parallel Program





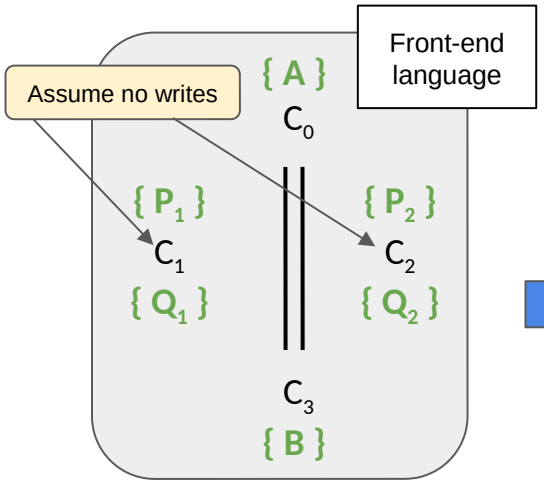
SL proof obligations proven by Viper

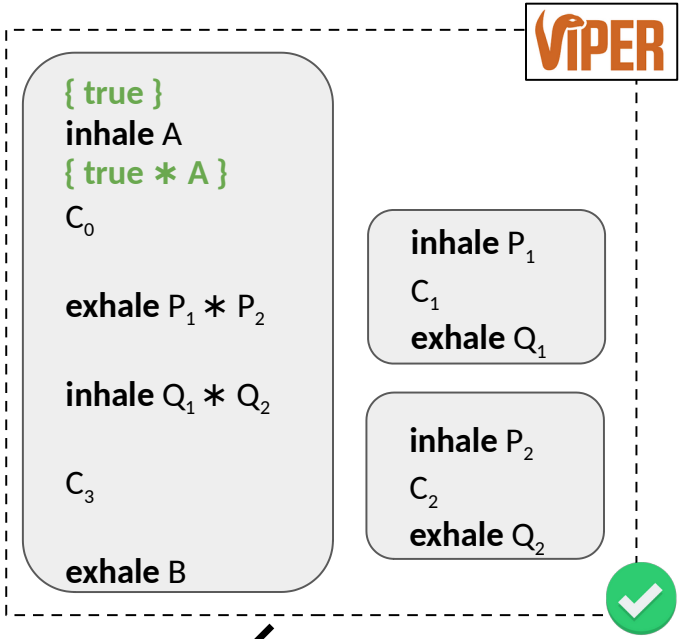
$\vdash \{ P_1 \}\ C_1\ \{ Q_1 \}$

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

Viper-to-SL theorem
(independent from the front-end)

Viper-to-SL: Parallel Program





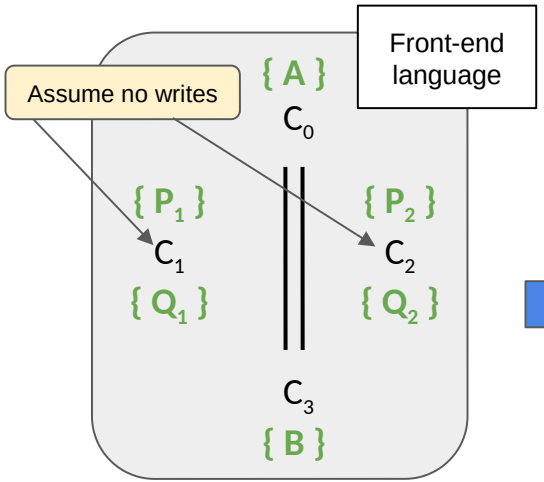
SL proof obligations proven by Viper

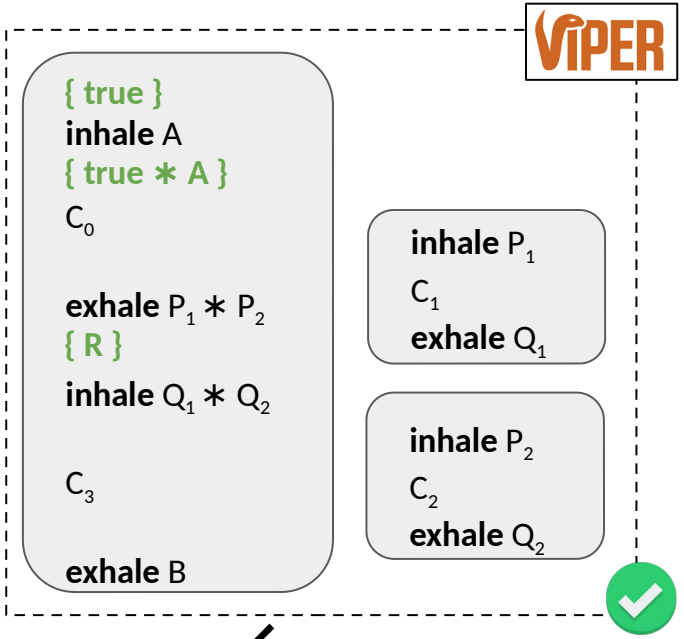
$\vdash \{ P_1 \}\ C_1\ \{ Q_1 \}$

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

Viper-to-SL theorem
(independent from the front-end)

Viper-to-SL: Parallel Program





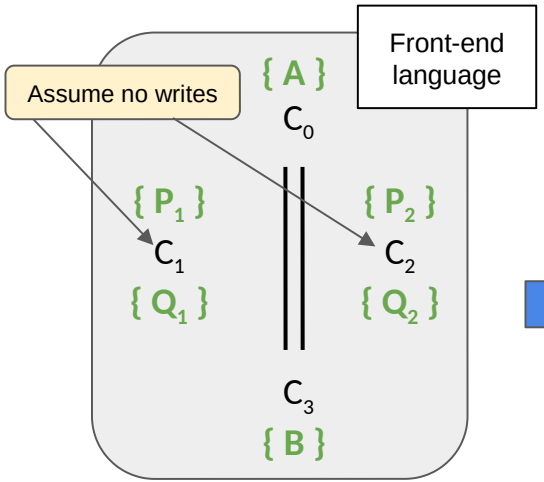
SL proof obligations proven by Viper

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

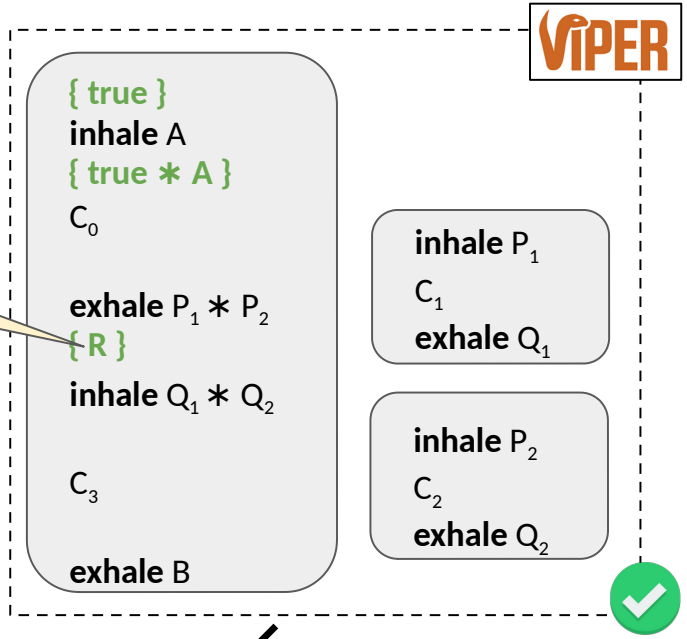
$\vdash \{ P_2 \}\ C_2\ \{ Q_2 \}$

Viper-to-SL theorem
(independent from the front-end)

Viper-to-SL: Parallel Program



Existence given by Viper-to-SL



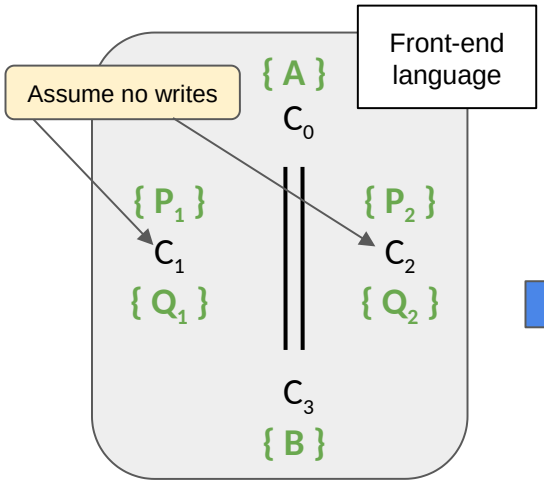
SL proof obligations proven by Viper

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

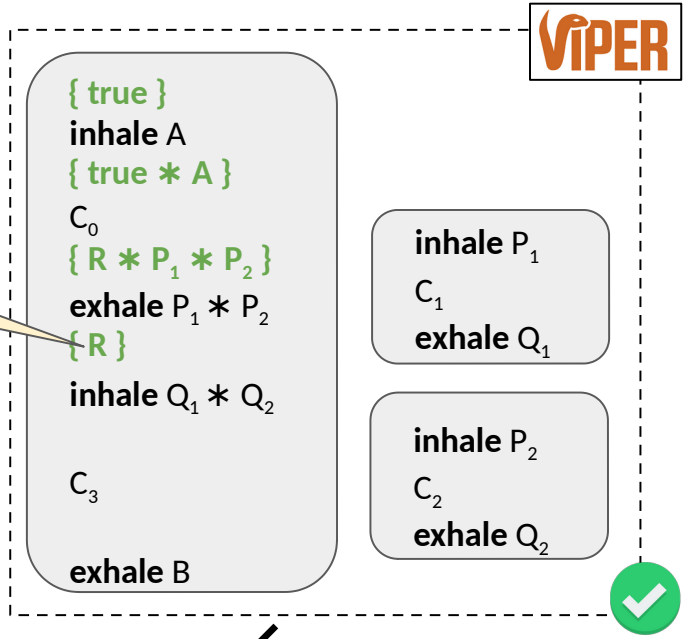
$\vdash \{ P_2 \}\ C_2\ \{ Q_2 \}$

Viper-to-SL theorem
(independent from the front-end)

Viper-to-SL: Parallel Program



Existence given by Viper-to-SL



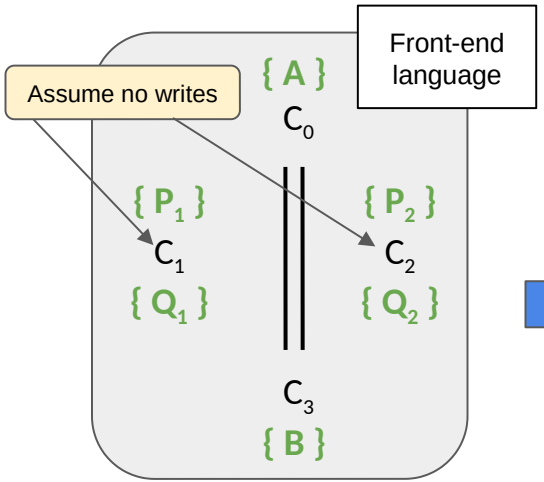
SL proof obligations proven by Viper

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

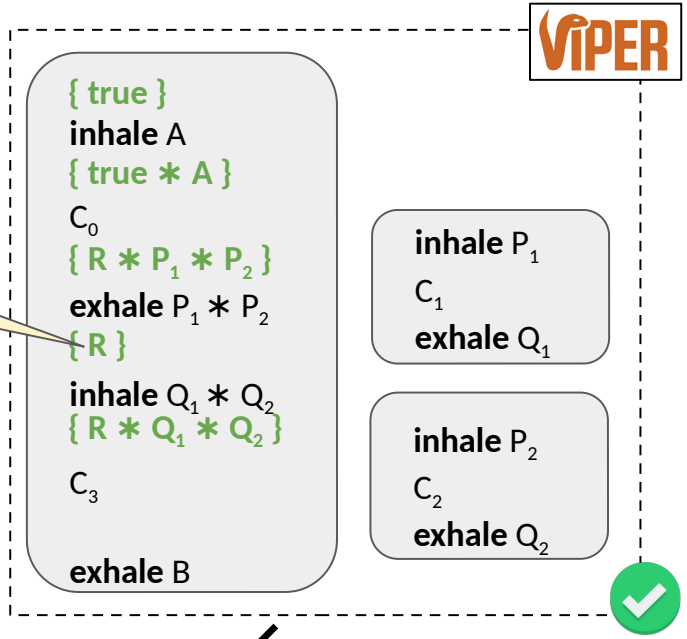
$\vdash \{ P_2 \}\ C_2\ \{ Q_2 \}$

Viper-to-SL theorem
(independent from the front-end)

Viper-to-SL: Parallel Program



Existence given by Viper-to-SL



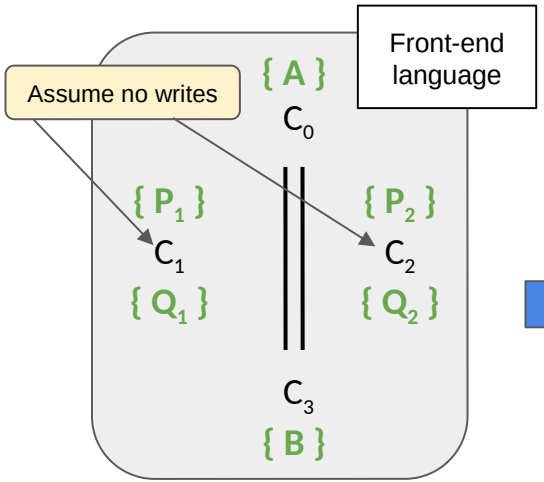
SL proof obligations proven by Viper

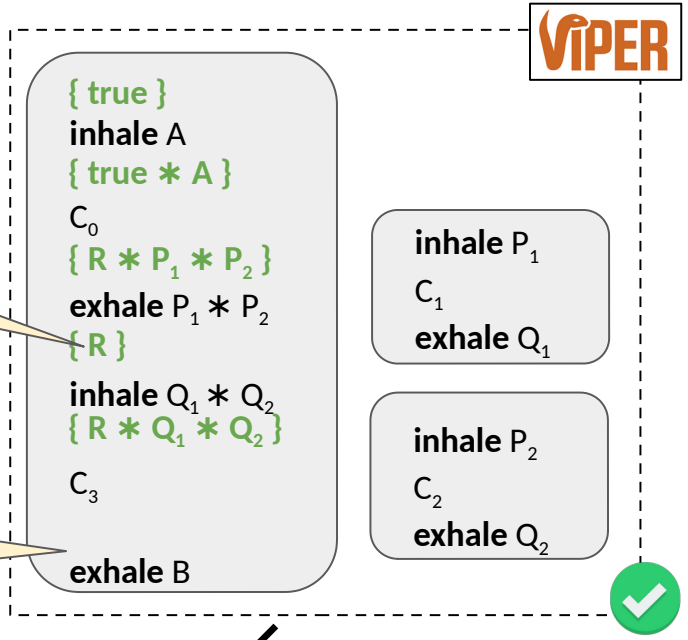
$\vdash \{ P_1 \}\ C_1\ \{ Q_1 \}$

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

Viper-to-SL theorem (independent from the front-end)

Viper-to-SL: Parallel Program





Existence given by Viper-to-SL

Succeeds only if executed in a context satisfying B

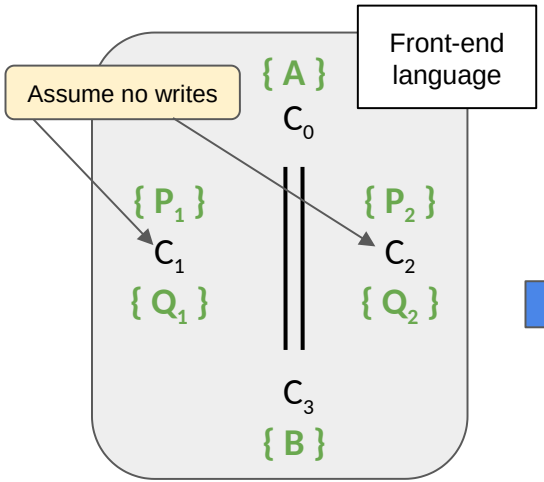
SL proof obligations proven by Viper

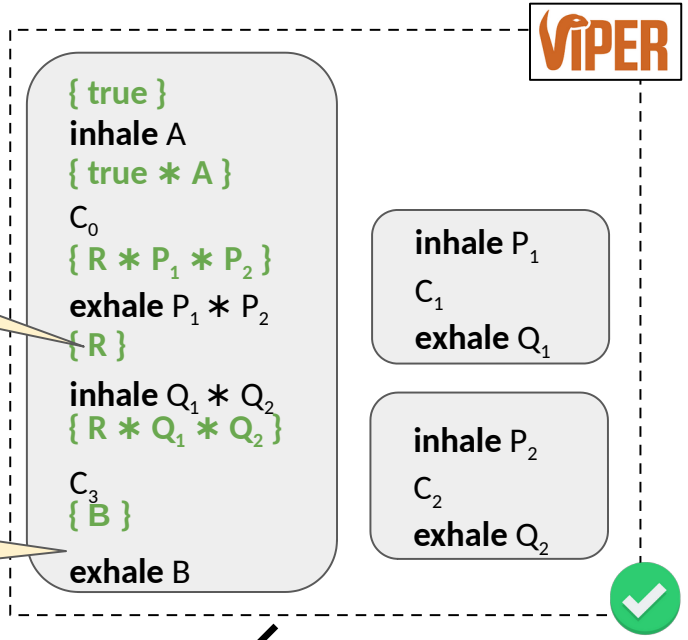
$\vdash \{ P_1 \}\ C_1\ \{ Q_1 \}$

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

Viper-to-SL theorem (independent from the front-end)

Viper-to-SL: Parallel Program





Existence given by Viper-to-SL

Succeeds only if executed in a context satisfying B

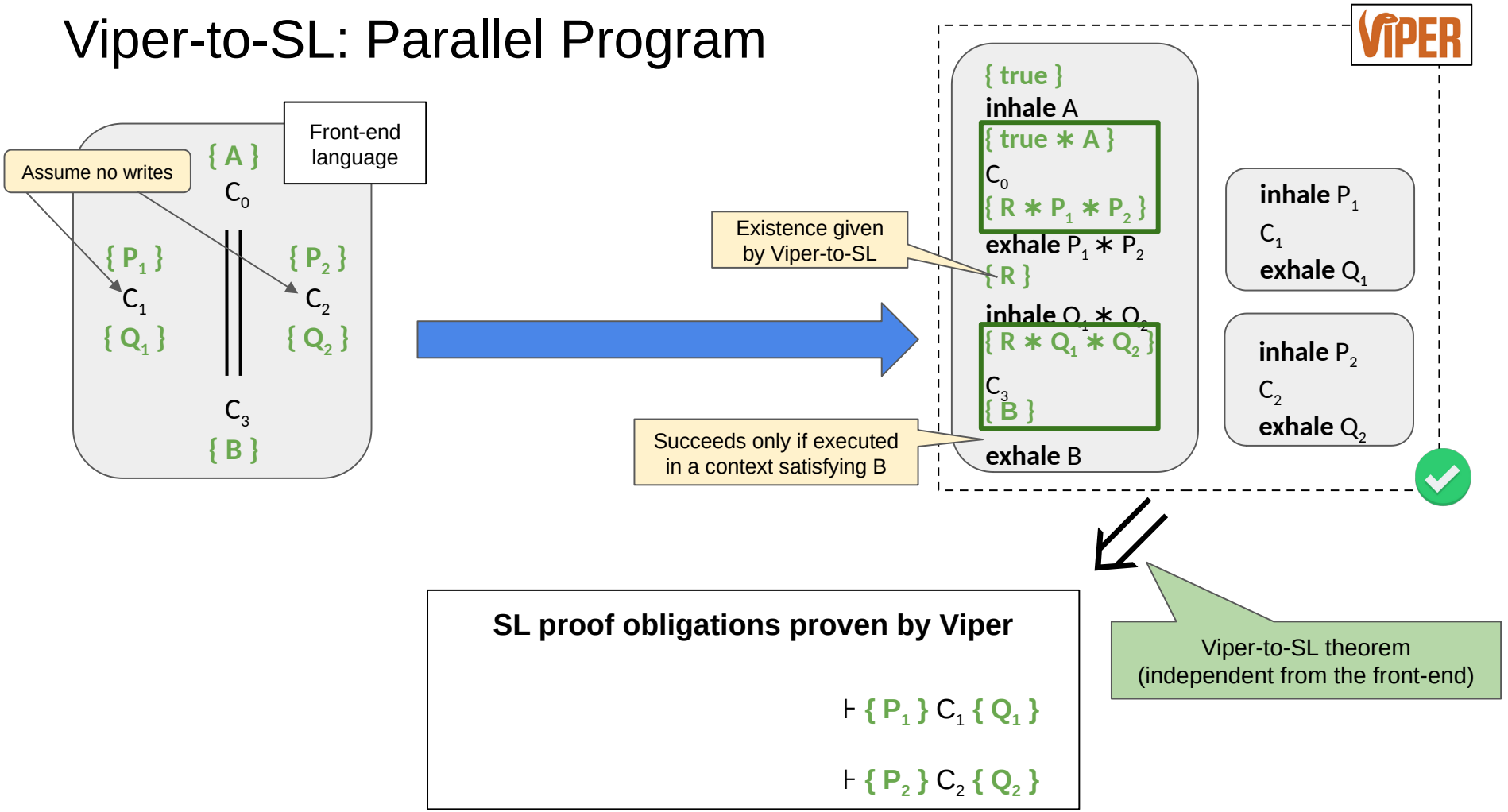
SL proof obligations proven by Viper

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

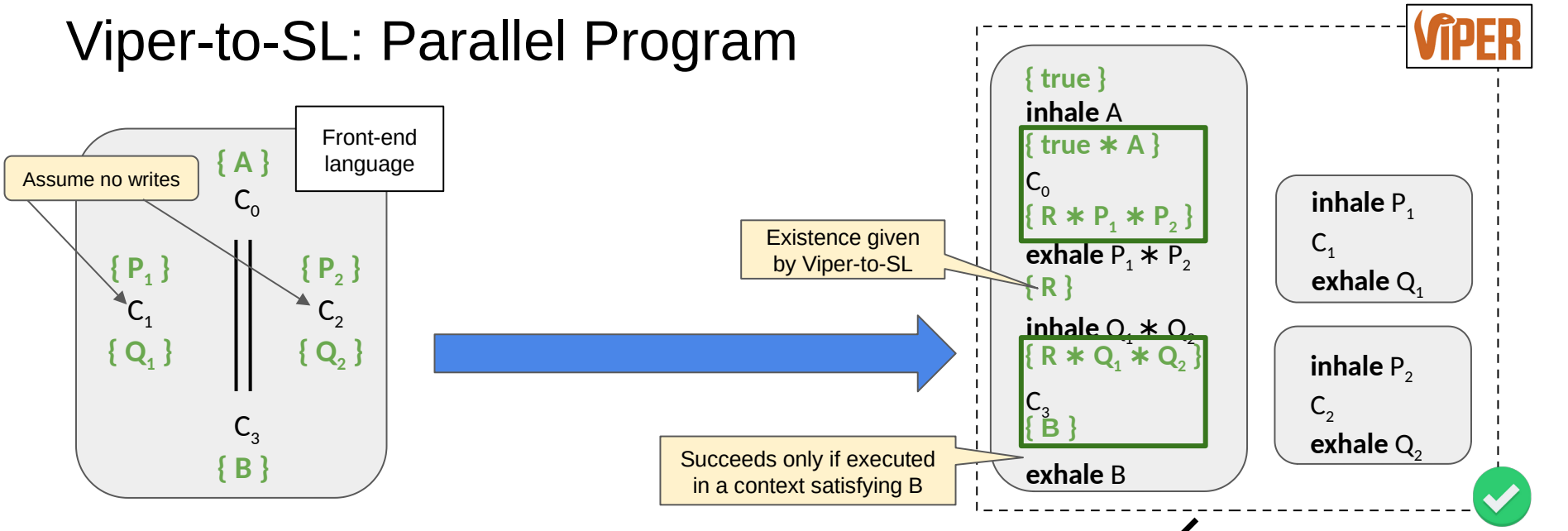
$\vdash \{ P_2 \}\ C_2\ \{ Q_2 \}$

Viper-to-SL theorem (independent from the front-end)

Viper-to-SL: Parallel Program



Viper-to-SL: Parallel Program



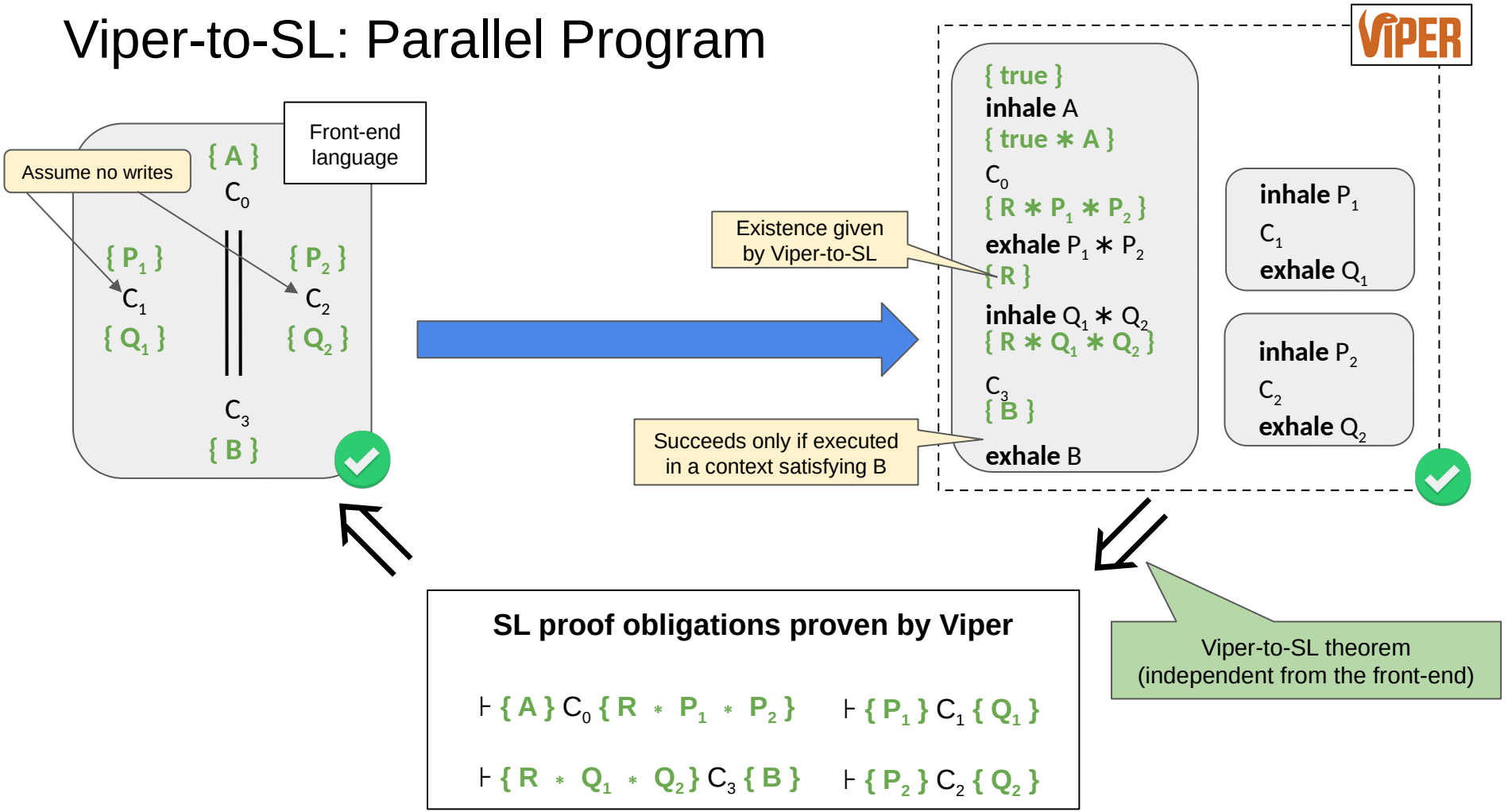
SL proof obligations proven by Viper

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

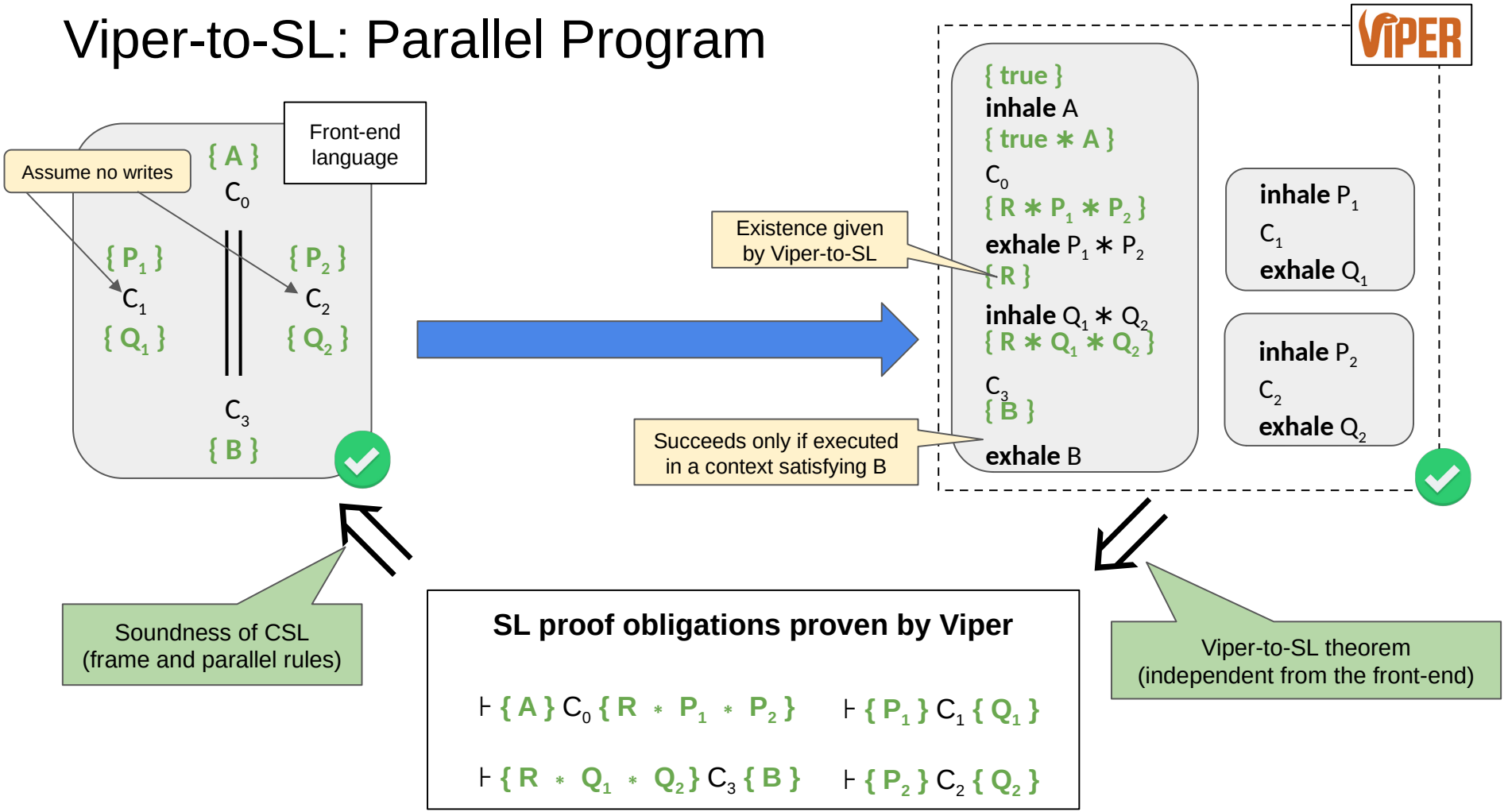
$\vdash \{ R * Q_1 * Q_2 \}\ C_3\ \{ B \}$ $\quad \vdash \{ P_2 \}\ C_2\ \{ Q_2 \}$

Viper-to-SL theorem
(independent from the front-end)

Viper-to-SL: Parallel Program



Viper-to-SL: Parallel Program

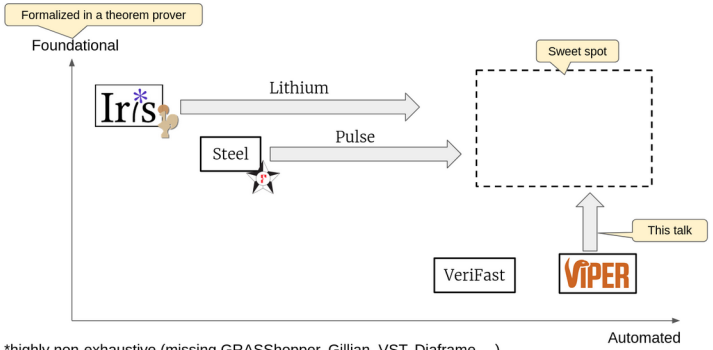


SL proof obligations proven by Viper

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

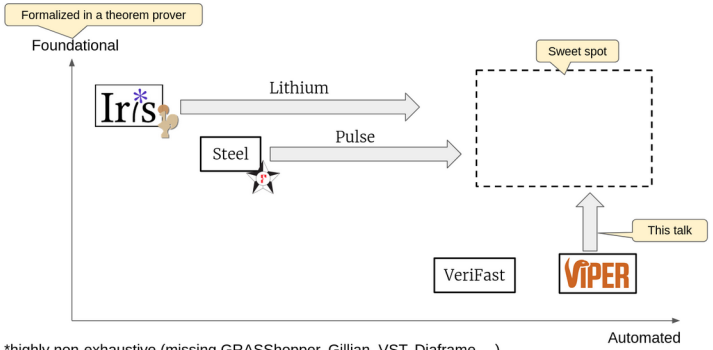
$\vdash \{ R * Q_1 * Q_2 \}\ C_3\ \{ B \}$ $\quad \vdash \{ P_2 \}\ C_2\ \{ Q_2 \}$

Program Verifiers Based on Separation Logic (SL)



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

Program Verifiers Based on Separation Logic (SL)

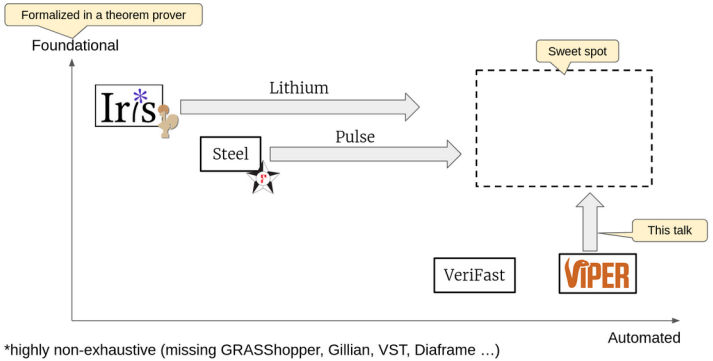


*highly non-exhaustive (missing GRASShopper, Gillian, VST, Diaframe …)

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	⊢ {P} **inhale** A {P ∗ A} weakestPre(**inhale** A, Q) = A −∗ Q	⊢ {P ∗ A} **exhale** A {P} weakestPre(**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
Separation logic analogue of	**assume** A	**assert** A

Program Verifiers Based on Separation Logic (SL)

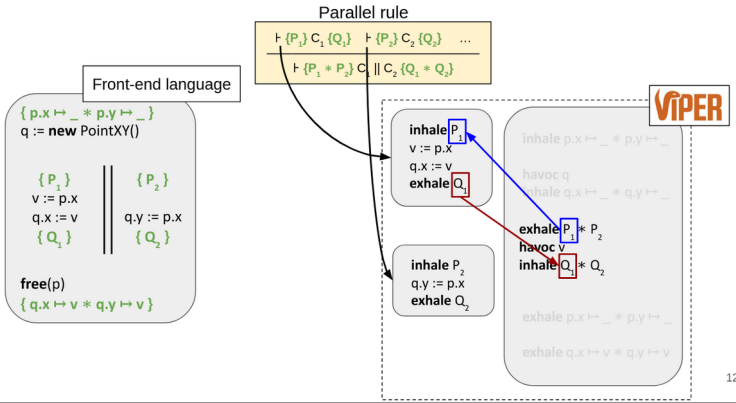


*highly non-exhaustive (missing GRASShopper, Gillian, VST, Diaframe …)

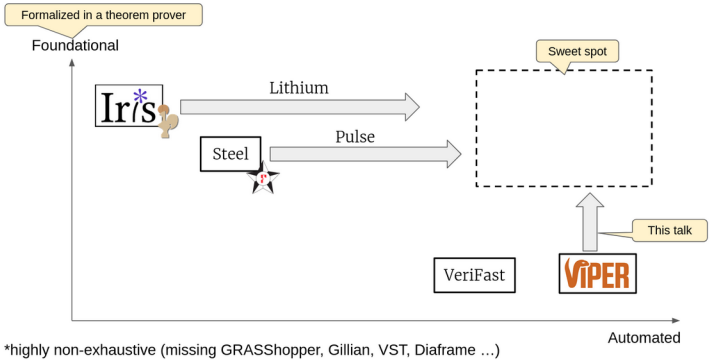
Verification Primitives: Inhale and Exhale

	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	⊢ {P} **inhale** A {P ∗ A} weakestPre(**inhale** A, Q) = A −∗ Q	⊢ {P ∗ A} **exhale** A {P} weakestPre(**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
Separation logic analogue of	**assume** A	**assert** A

Example: Verifying a Parallel Program (2/2)



Program Verifiers Based on Separation Logic (SL)

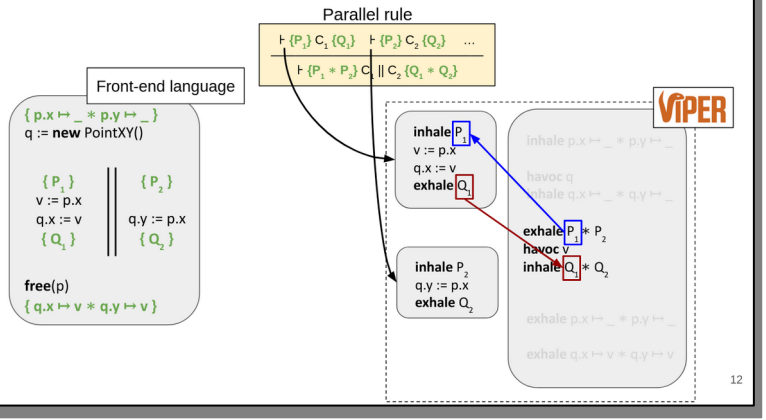


*highly non-exhaustive (missing GRASShopper, Gillian, VST, Diaframe …)

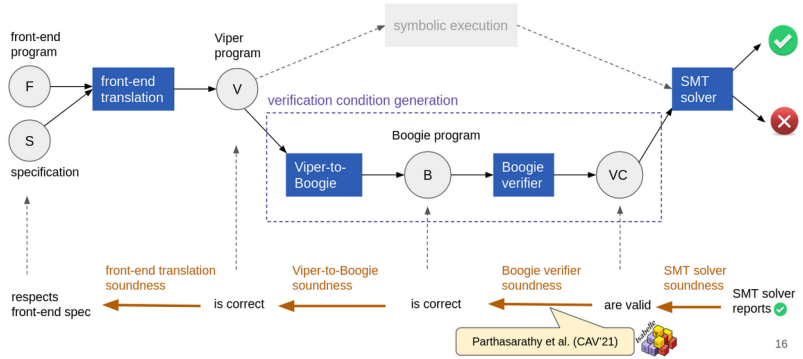
Verification Primitives: Inhale and Exhale

	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	⊢ {P} **inhale** A {P ∗ A} weakestPre(**inhale** A, Q) = A −∗ Q	⊢ {P ∗ A} **exhale** A {P} weakestPre(**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
Separation logic analogue of	**assume** A	**assert** A

Example: Verifying a Parallel Program (2/2)

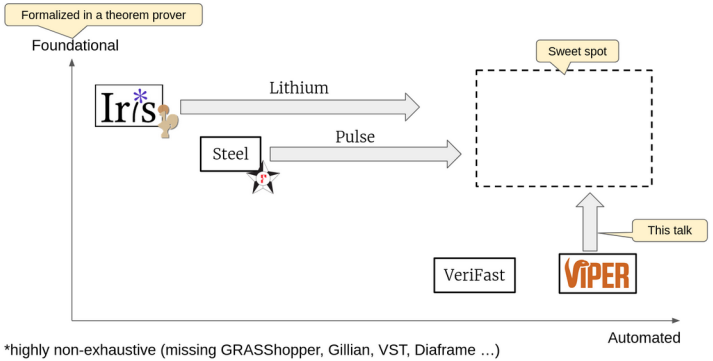


Soundness: Proof Strategy



Thank you for your attention!

Program Verifiers Based on Separation Logic (SL)

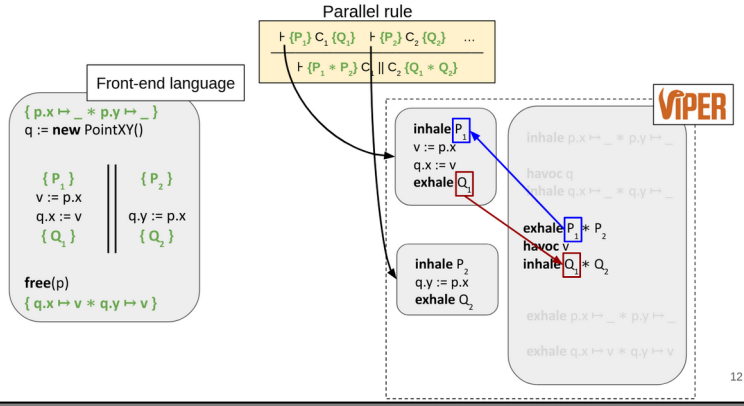


*highly non-exhaustive (missing GRASShopper, Gillian, VST, Diaframe …)

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	⊢ {P} **inhale** A {P ∗ A} weakestPre(**inhale** A, Q) = A −∗ Q	⊢ {P ∗ A} **exhale** A {P} weakestPre(**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
Separation logic analogue of	**assume** A	**assert** A

Example: Verifying a Parallel Program (2/2)



Soundness: Proof Strategy