Computer-Aided Reasoning for Software

CSE507

Solver-Aided Programming II

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Topics

Last lecture

- Getting started with solver-aided programming.

Today

- Going pro with solver-aided programming.

A programming model that integrates solvers into the language, providing constructs for program verification, synthesis, and more.

ROSETTE

Solver-aided programming in two parts: (1) getting started and (2) going pro

How to use a solver-aided language: the workflow, constructs, and gotchas.

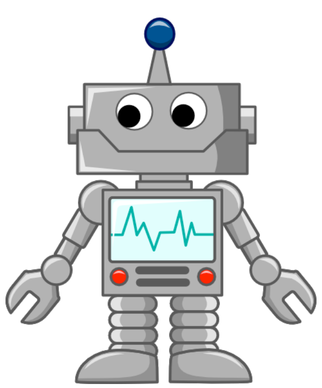
How to build your own solver-aided tool via direct symbolic evaluation or language embedding.

How to build your own solver-aided tool or language

The classic (hard) way to build a tool
What is hard about building a solver-aided tool?

An easier way: tools as languages
How to build tools by stacking layers of languages.

Behind the scenes: symbolic virtual machine
How Rosette works so you don't have to.



A last look: a few recent applications
Cool tools built with Rosette!

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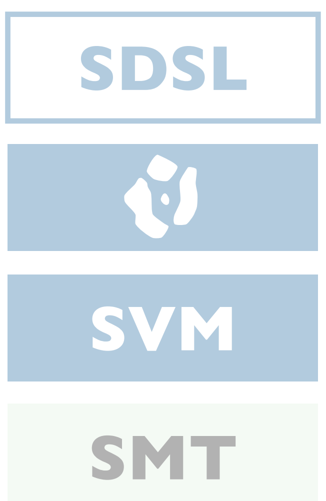

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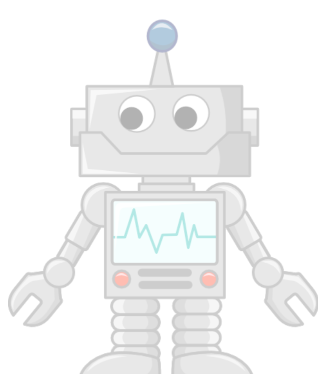

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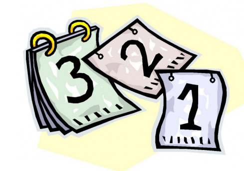
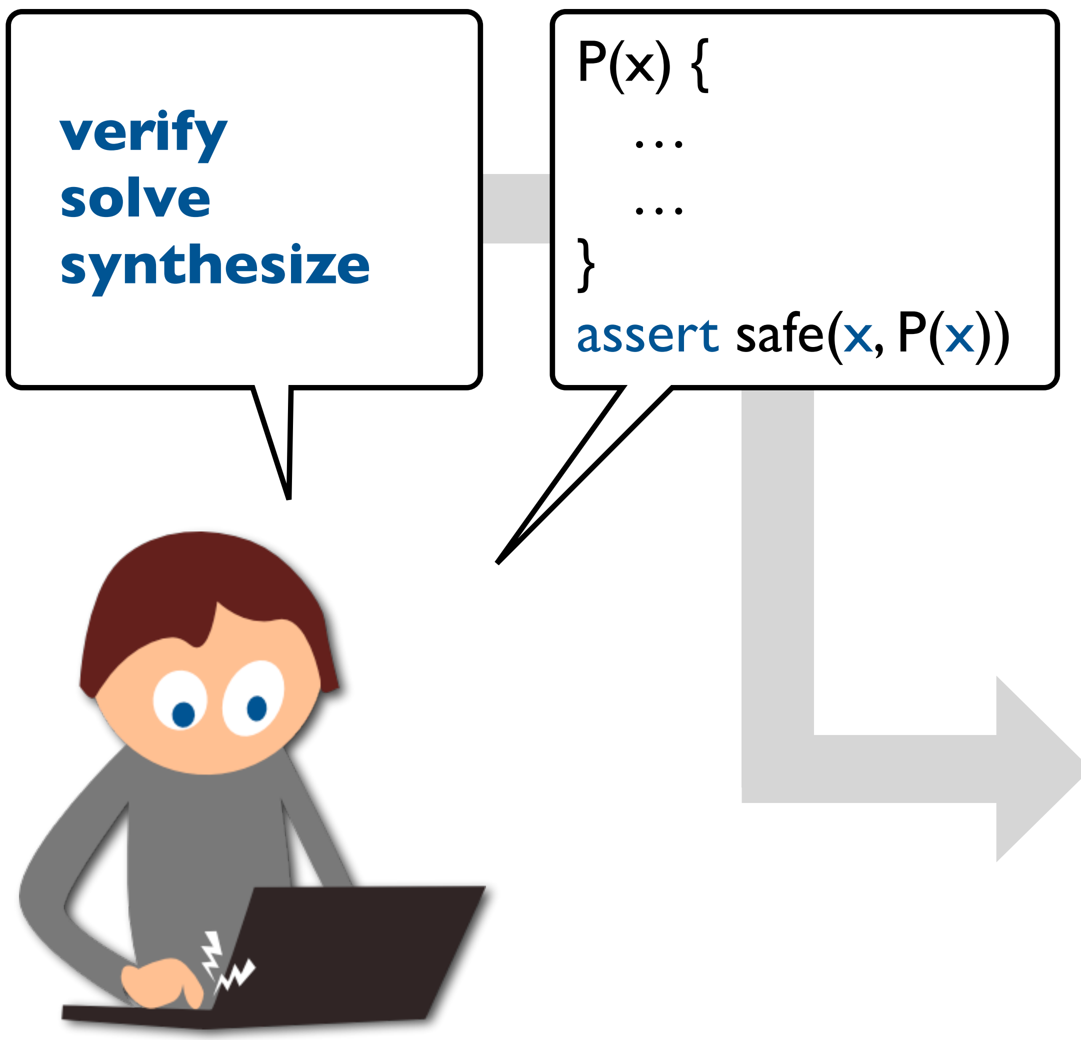
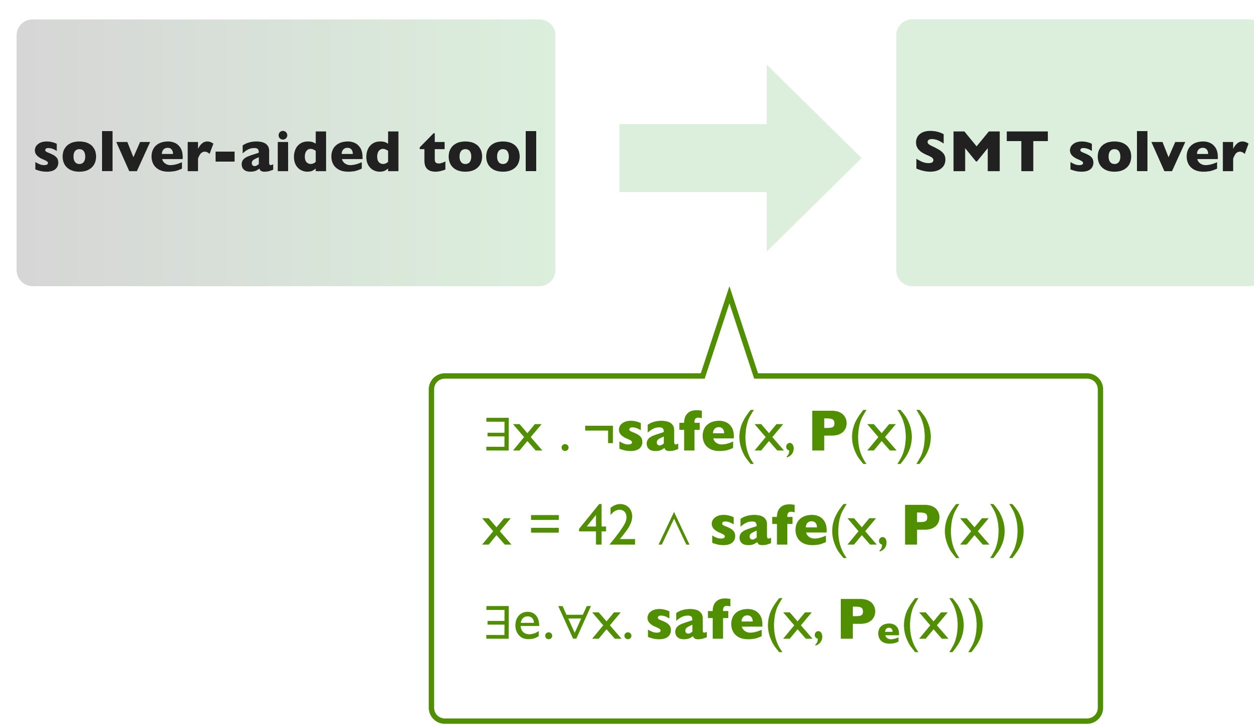
The classic (hard) way to build a tool



Recall the solver-aided programming tool chain: the tool reduces a query about program behavior to an SMT problem.





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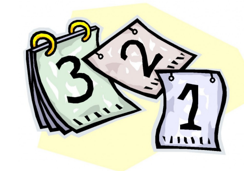
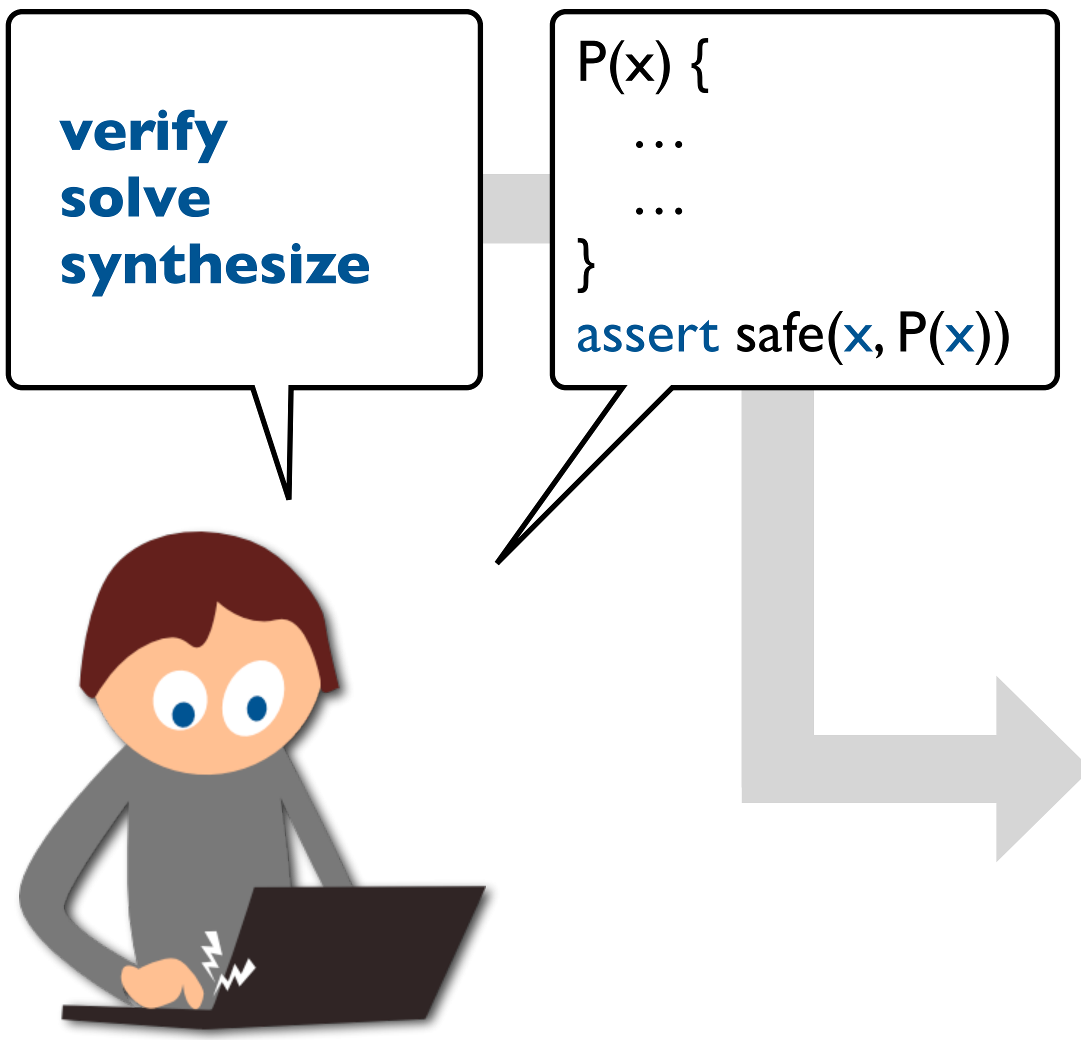
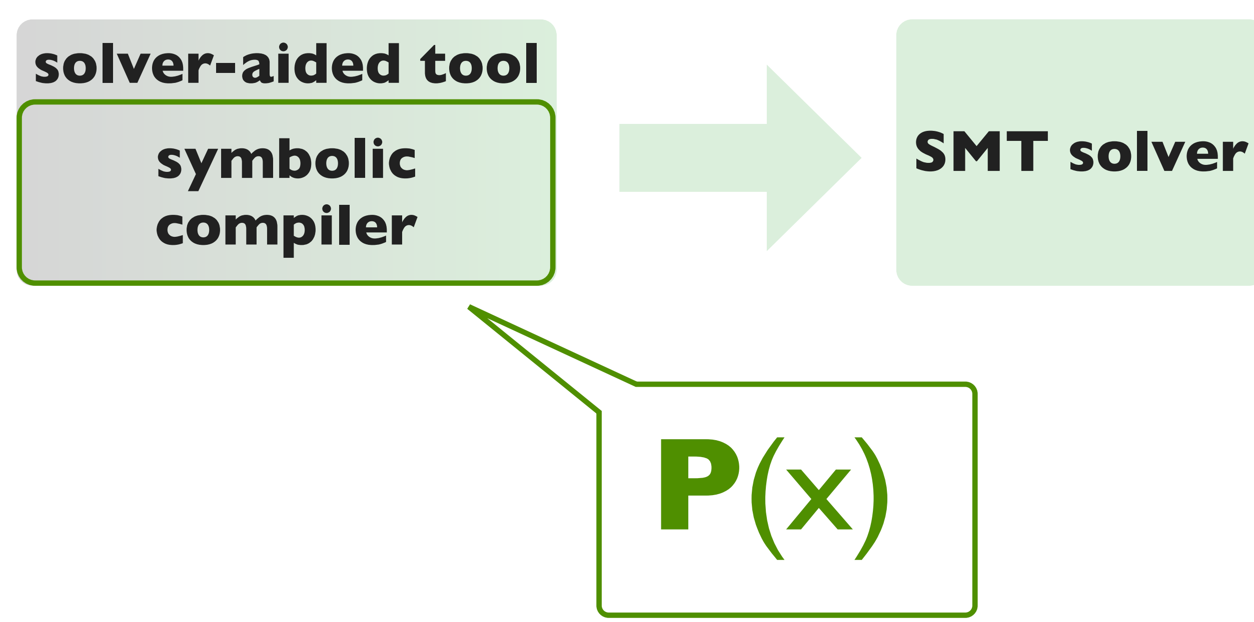




Recall the solver-aided programming tool chain: the tool reduces a query about program behavior to an SMT problem.

What all queries have in common: they need to translate programs to constraints!



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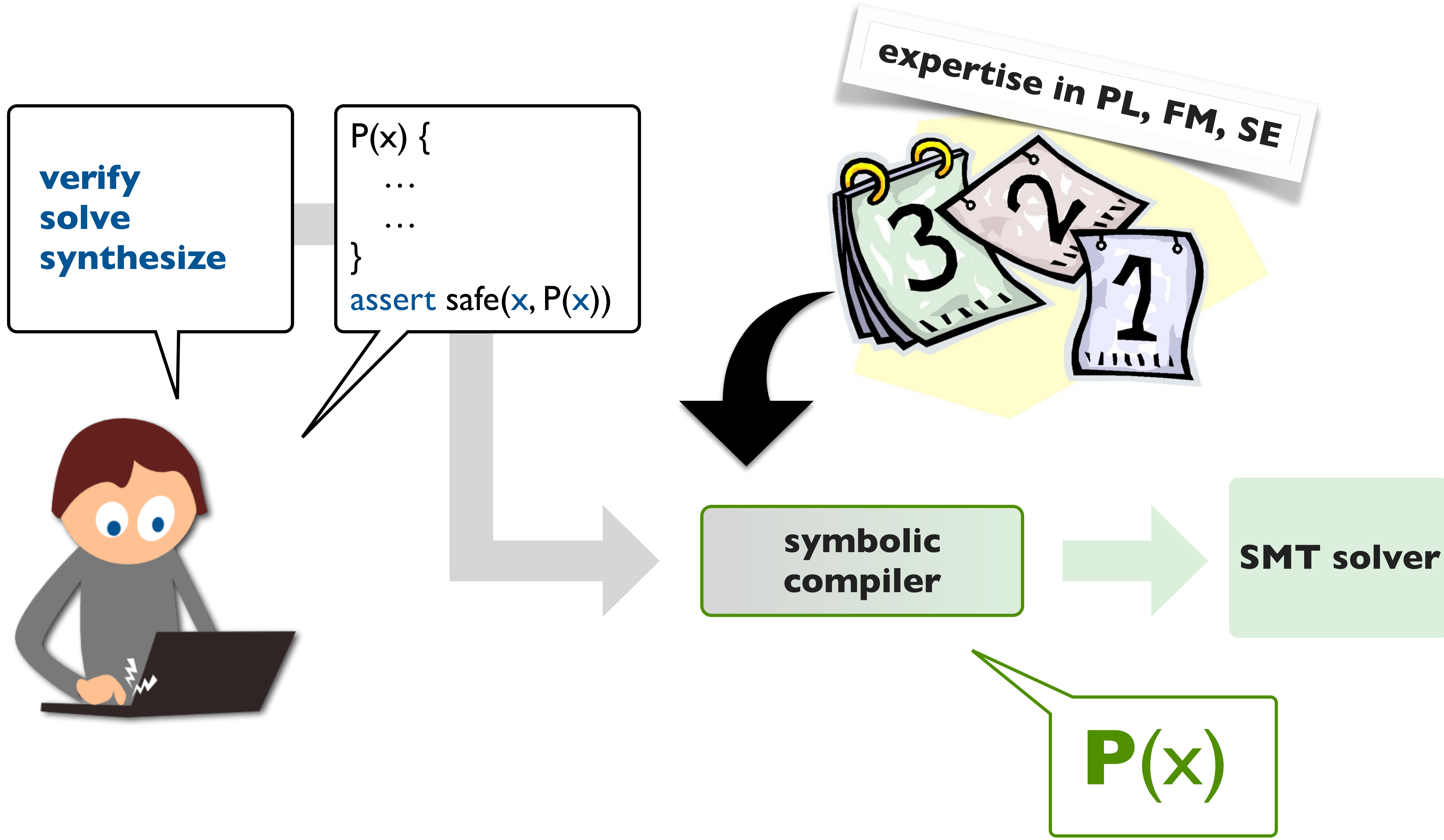
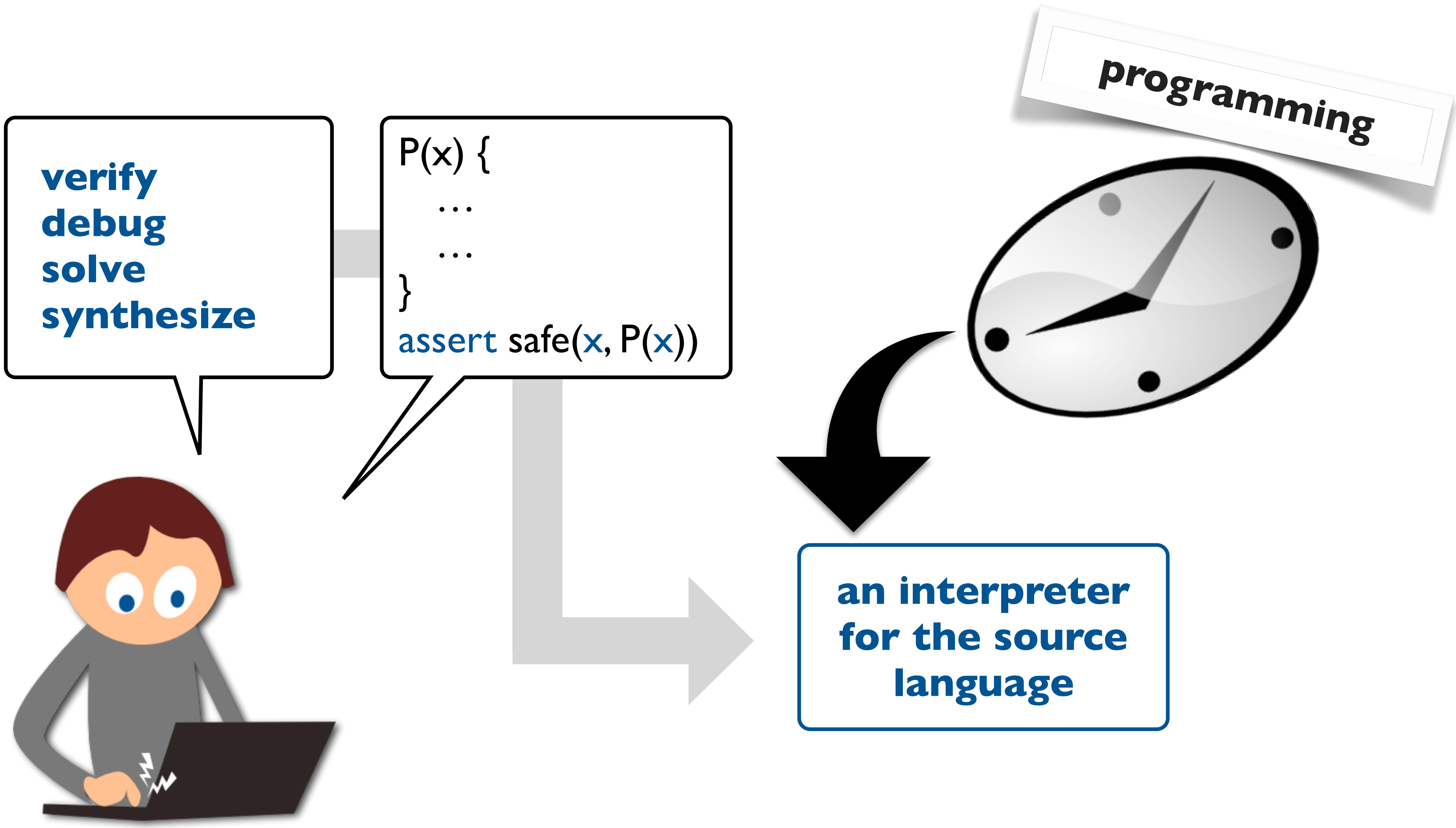


Wanted: an easier way to build tools



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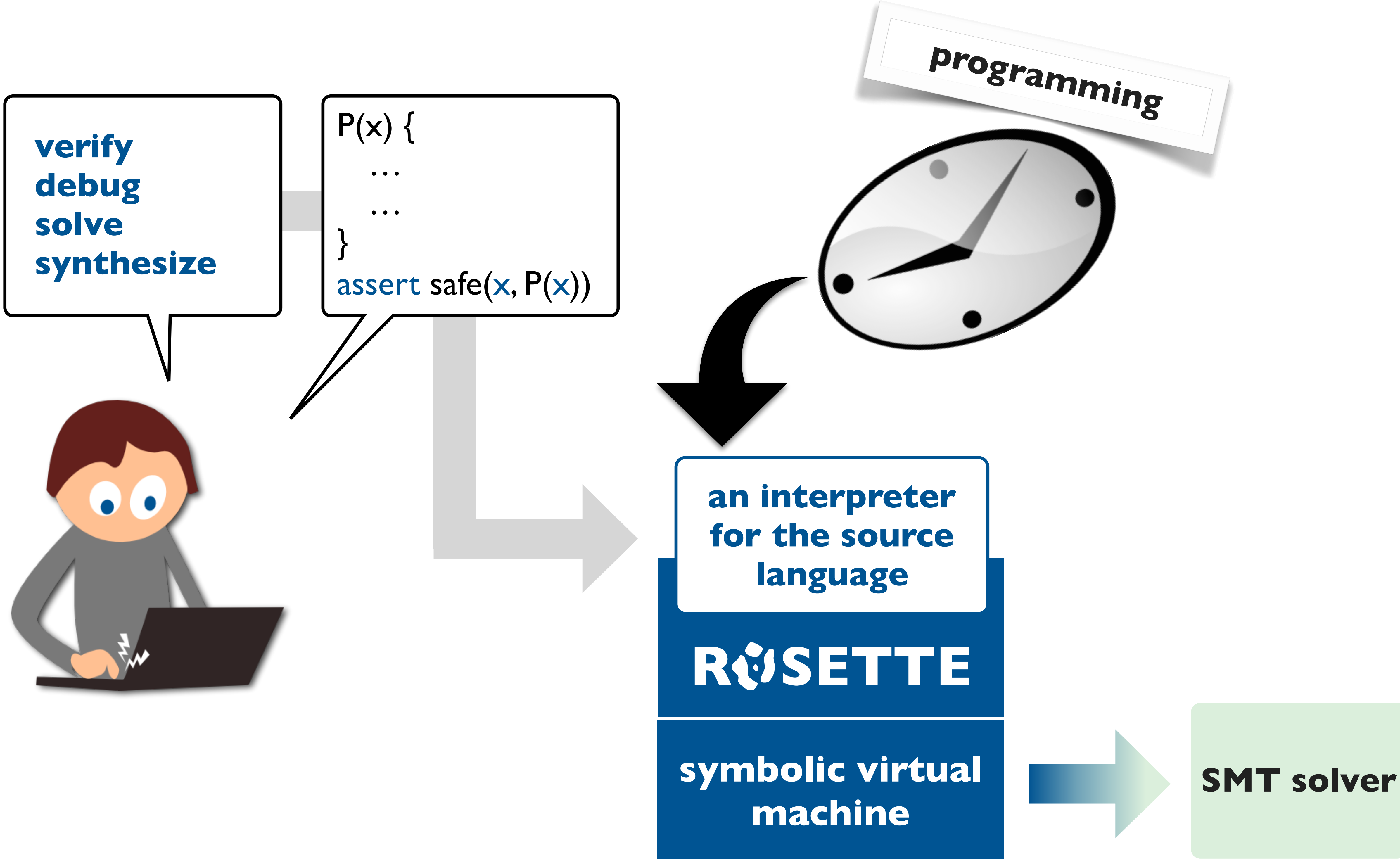

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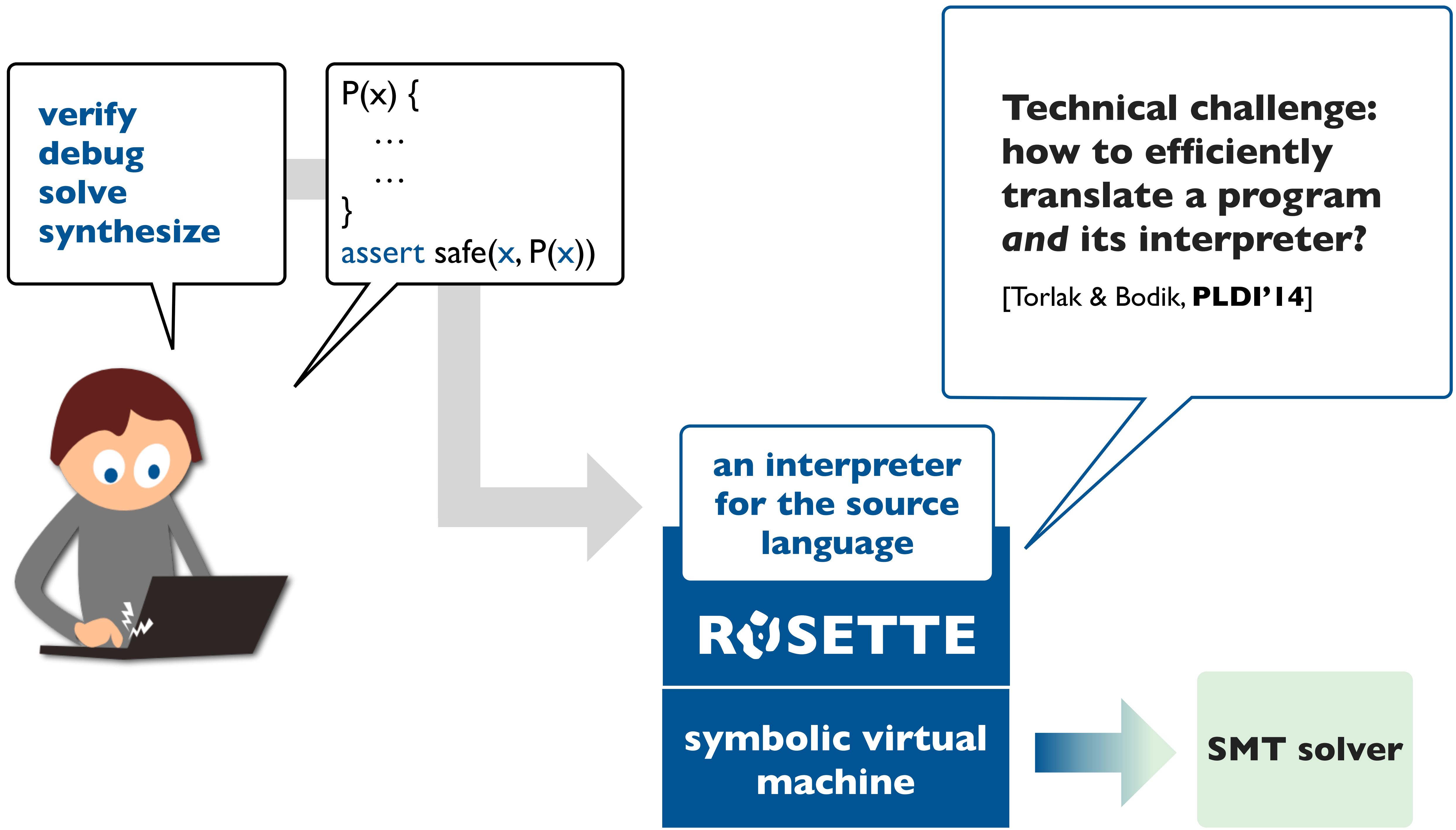

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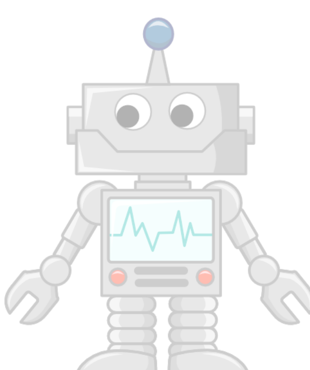

A last look: a few recent applications
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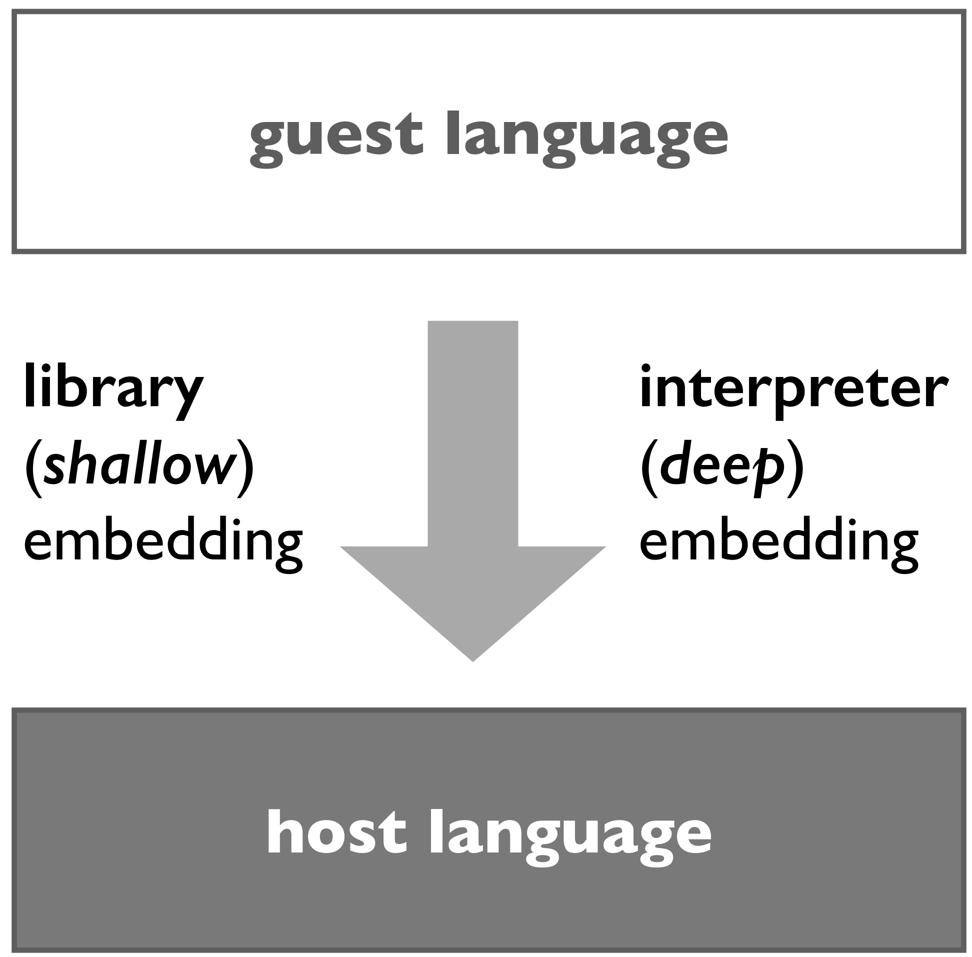
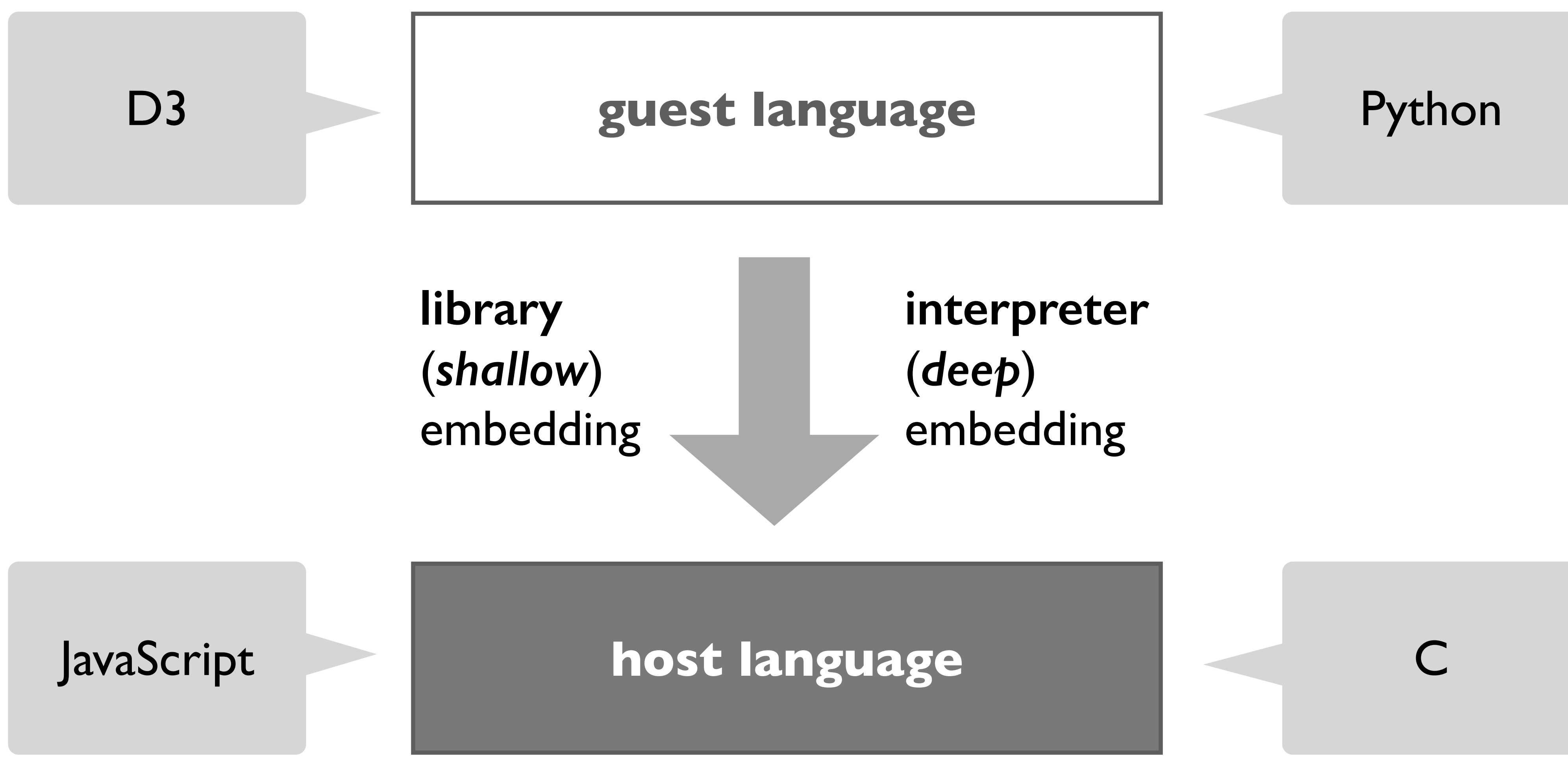
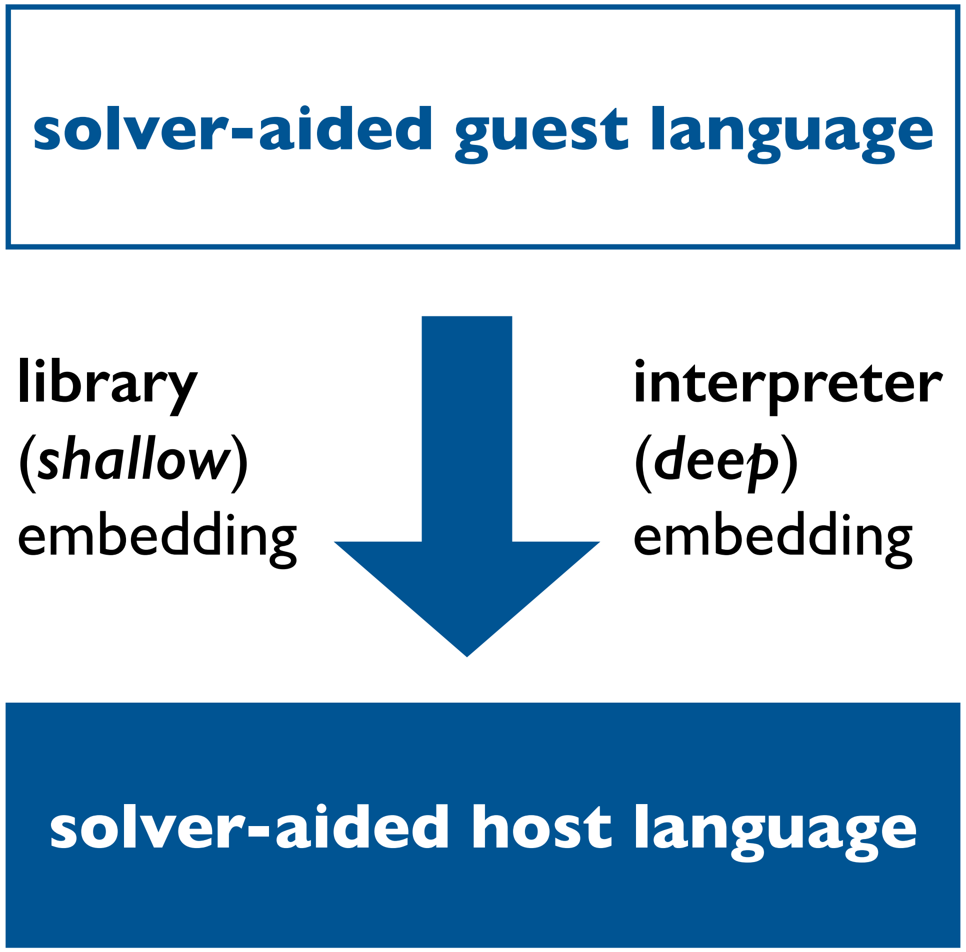
Layers of classic languages: guests and hosts



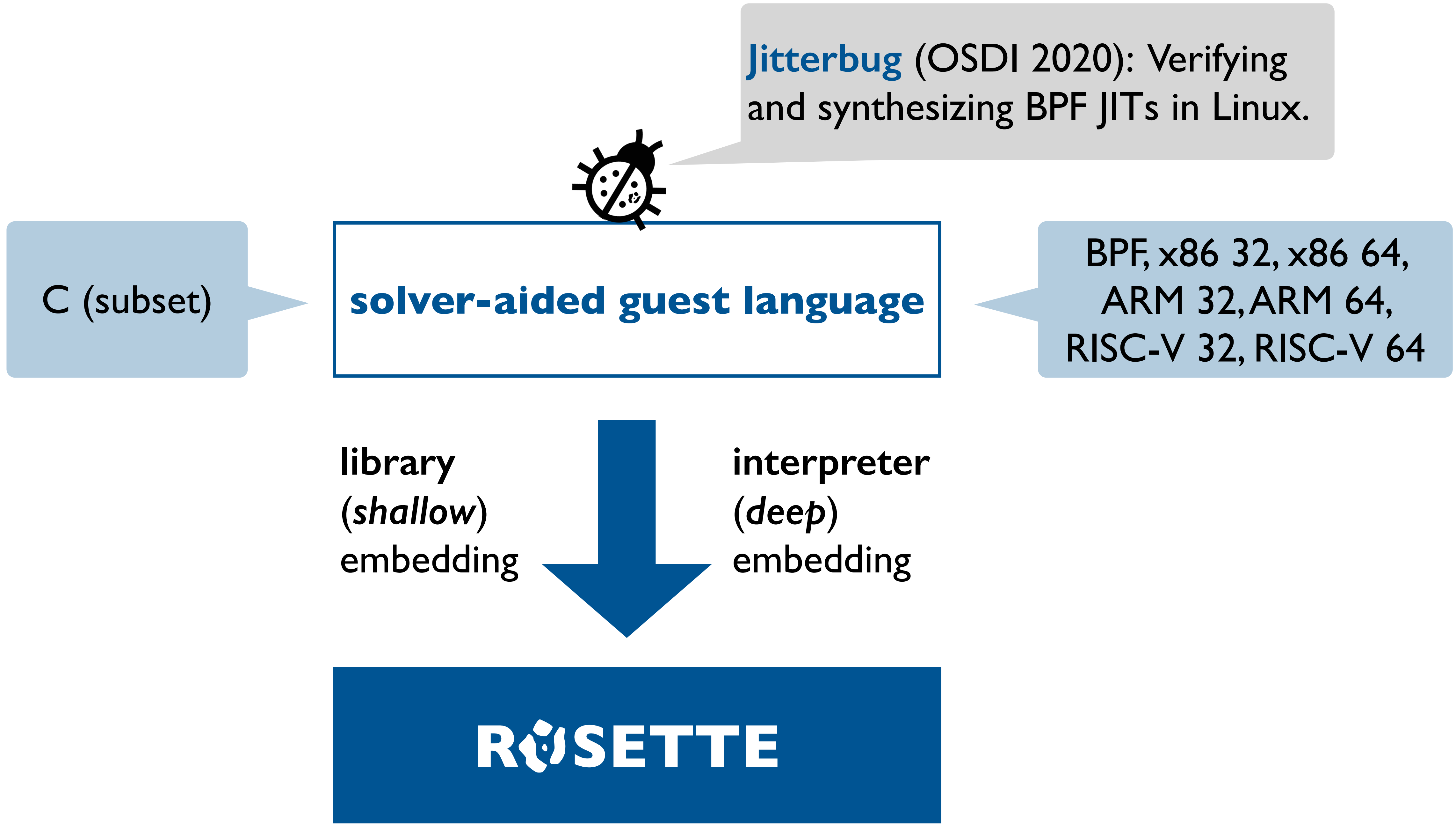
Layers of classic languages: guests and hosts



Layers of solver-aided languages



Layers of solver-aided languages



A tiny example solver-aided guest language

```
def bvmax(r0, r1) :
  r2 = bvsge(r0, r1)
  r3 = bvneg(r2)
  r4 = bvxor(r0, r2)
  r5 = bvand(r3, r4)
  r6 = bvxor(r1, r5)
  return r6
```

BV: A tiny assembly-like language for writing fast, low-level library functions.

A tiny example solver-aided guest language

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def bvmax(r0, r1) :
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```

We want to **test**, **verify**, and **synthesize** programs in the BV SDSL.

BV: A tiny assembly-like language for writing fast, low-level library functions.

A tiny example solver-aided guest language

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```

We want to **test**, **verify**, and **synthesize** programs in the BV SDSL.

BV: A tiny assembly-like language for writing fast, low-level library functions.

1. interpreter [50 LOC]
2. verifier [free]
3. synthesizer [free]

A tiny example language

ROSETTE

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def bvmax(r0, r1) :
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> bvmax(-2, -1)
```

A tiny example language

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parse

```
(define bvmax
 `((2 bvsge 0 1)
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   (6 bvxor 1 5)))
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A tiny example language

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```
(out opcode in ...)
```

A tiny example language

ROSETTE

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> bvmax(-2, -1)
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interpret

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```
`(-2 -1)
```

```
(define (interpret prog inputs)
  (make-registers prog inputs)
  (for ([stmt prog])
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  (load (last)))
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A tiny example language

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6	

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```

```
> bvmax(-2, -1)
-1
```

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- pattern matching
- first-class & higher-order procedures
- side effects

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  r6 = bvxor(r1, r5)
  return r6

> verify(bvmax, max)
```

query

ROSETTE

```
(define-symbolic x y int32?)
(define in (list x y))
(verify
  (assert (equal? (interpret bvmax in)
                  (apply max in))))
```

A tiny example language

ROSETTE

```
def bvmax(r0, r1) :
  r2 = bvsge(r0, r1)
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  r6 = bvxor(r1, r5)
  return r6

> verify(bvmax, max)
```

```
(define (max x y)
 (if (bvsge x y) x y))
```

query

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(define-symbolic x y int32?)
(define in (list x y))
(verify
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```

A tiny example language

ROSETTE

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  return r6

> verify(bvmax, max)
```

query

Creates two fresh symbolic values of type 32-bit integer and binds them to the variables x and y.

```
(define-symbolic x y int32?)
(define in (list x y))
(verify
  (assert (equal? (interpret bvmax in)
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A tiny example language

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def bvmax(r0, r1) :
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```

query

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(define-symbolic x y int32?)
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(verify
  (assert (equal? (interpret bvmax in)
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```

Symbolic values can be used just like concrete values of the same type.

A tiny example language

ROSETTE

```
def bvmax(r0, r1) :
  r2 = bvsge(r0, r1)
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  r5 = bvand(r3, r4)
  r6 = bvxor(r1, r5)
  return r6

> verify(bvmax, max)
```

query

Creates two fresh symbolic values of type 32-bit integer and binds them to the variables x and y.

```
(define-symbolic x y int32?)
(define in (list x y))
(verify
  (assert (equal? (interpret bvmax in)
                  (apply max in))))
```

(**verify** *expr*) searches for a concrete interpretation of symbolic values that causes *expr* to fail.

Symbolic values can be used just like concrete values of the same type.

A tiny example language

ROSETTE

```
def bvmax(r0, r1) :
  r2 = bvsge(r0, r1)
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  r4 = bvxor(r0, r2)
  r5 = bvand(r3, r4)
  r6 = bvxor(r1, r5)
  return r6

> verify(bvmax, max)
[0, -2]
```

query

```
(define-symbolic x y int32?)
(define in (list x y))
(verify
  (assert (equal? (interpret bvmax in)
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```

A tiny example language

ROSETTE

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def bvmax(r0, r1) :
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  r6 = bvxor(r1, r5)
  return r6

> verify(bvmax, max)
[0, -2]

> bvmax(0, -2)
-1
```

query

```
(define-symbolic x y int32?)
(define in (list x y))
(verify
  (assert (equal? (interpret bvmax in)
                  (apply max in))))
```

A tiny example language

ROSETTE

```
def bvmax(r0, r1) :
  r2…r6 = inst??(bvsge, bvneg,
                 bvxor, bvand)
  return r6
```

```
> synthesize(bvmax, max)
```

query

```
(define-symbolic x y int32?)
(define in (list x y))
(synthesize
  #:forall in
  #:guarantee
  (assert (equal? (interpret bvmax in)
                  (apply max in))))
```

A tiny example language

ROSETTE

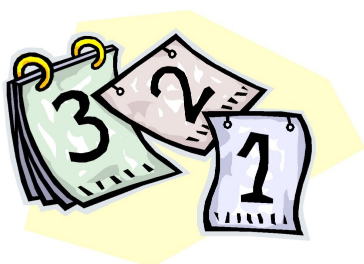
```
def bvmax(r0, r1) :
  r2 = bvsge(r0, r1)
  r3 = bvneg(r2)
  r4 = bvxor(r0, r1)
  r5 = bvand(r3, r4)
  r6 = bvxor(r1, r5)
  return r6

> synthesize(bvmax, max)
```

query

```
(define-symbolic x y int32?)
(define in (list x y))
(synthesize
  #:forall in
  #:guarantee
  (assert (equal? (interpret bvmax in)
                  (apply max in))))
```

How to build your own solver-aided tool or language



The classic (hard) way to build a tool

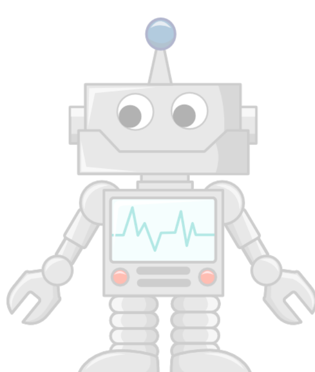
What is hard about building a solver-aided tool?

An easier way: tools as languages

How to build tools by stacking layers of languages.

Behind the scenes: symbolic virtual machine

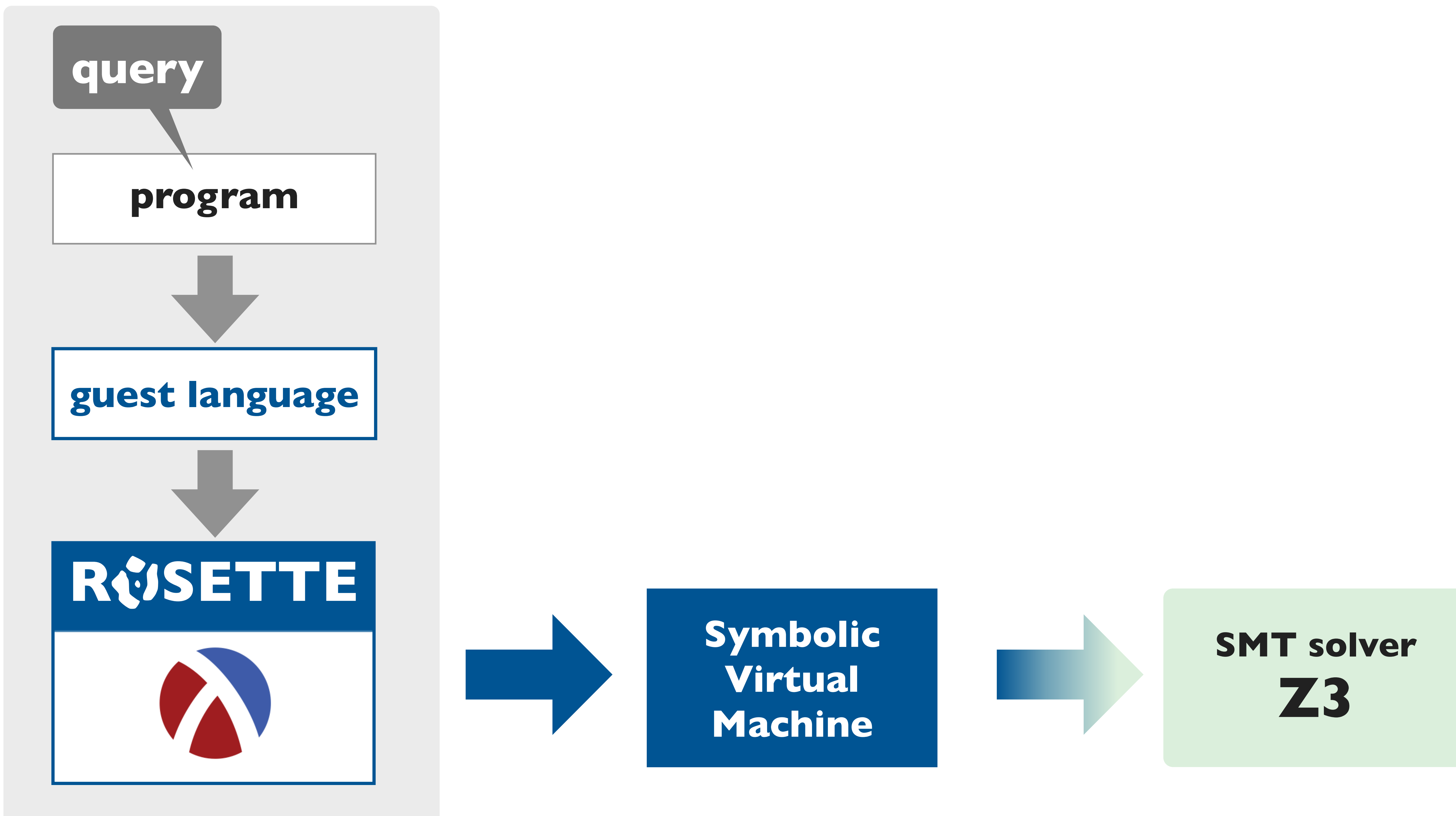
How Rosette works so you don’t have to.



A last look: a few recent applications

Cool tools built with Rosette!

How it all works: a big picture view



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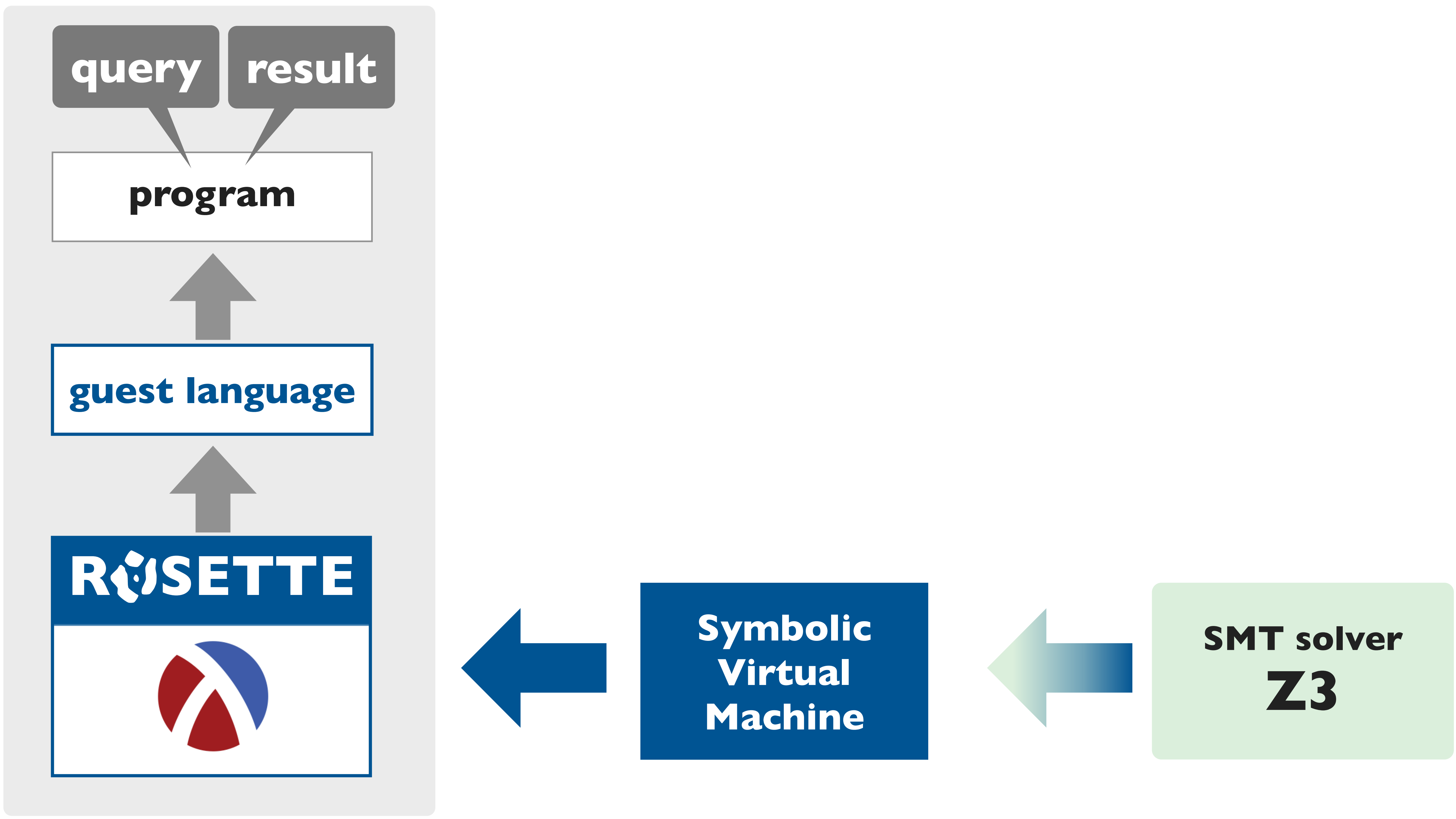

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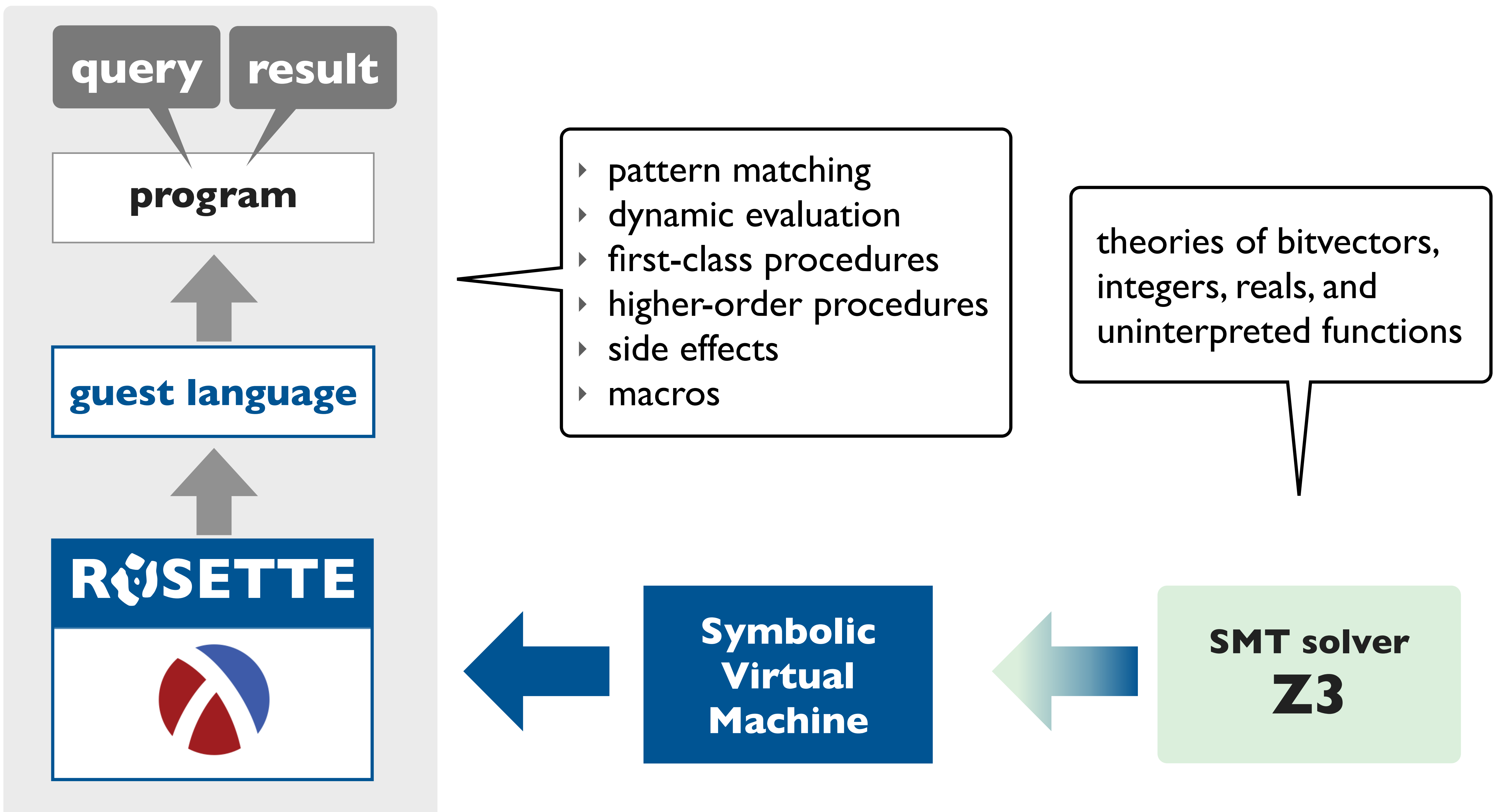
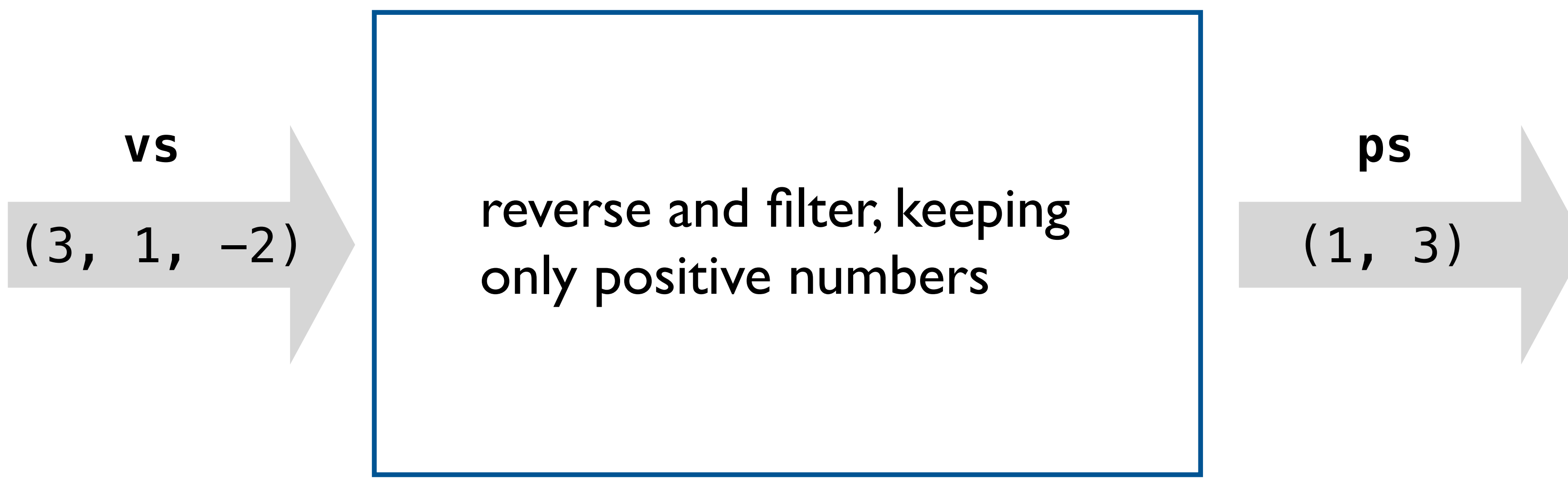


Translation to constraints by example



Translation to constraints by example

vs

(3, 1, −2)

```
ps = ()
for v in vs:
  if v > 0:
    ps = insert(v, ps)
```

ps

(1, 3)

Translation to constraints by example

vs

```
solve:
  ps = ()
  for v in vs:
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      ps = insert(v, ps)
  assert len(ps) == len(vs)
```

constraints

Translation to constraints by example

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(a, b)

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constraints

Translation to constraints by example

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```

constraints

a>0 ∧ b>0

Design space of precise symbolic encodings

```
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  for v in vs:
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  assert len(ps) == len(vs)
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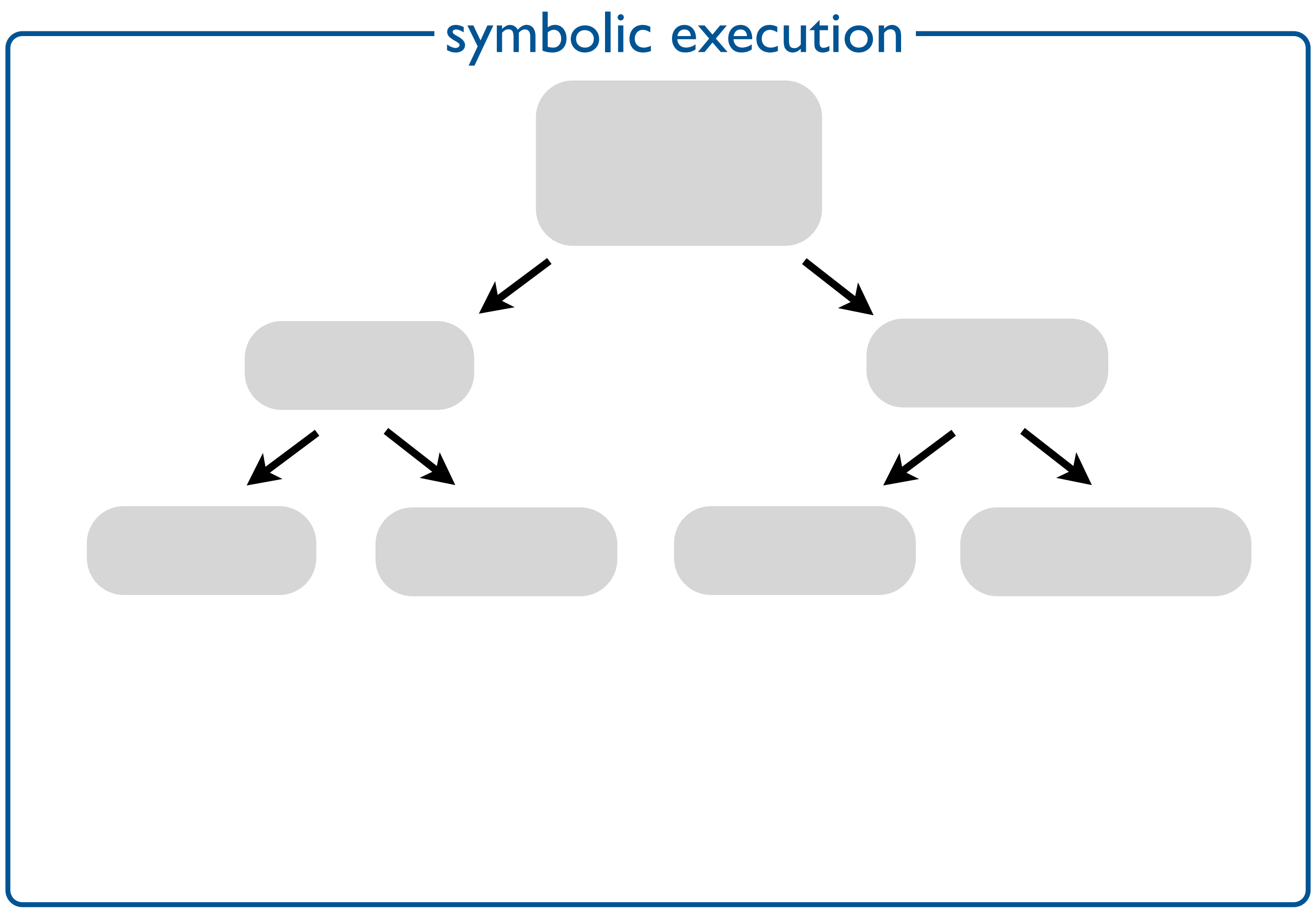

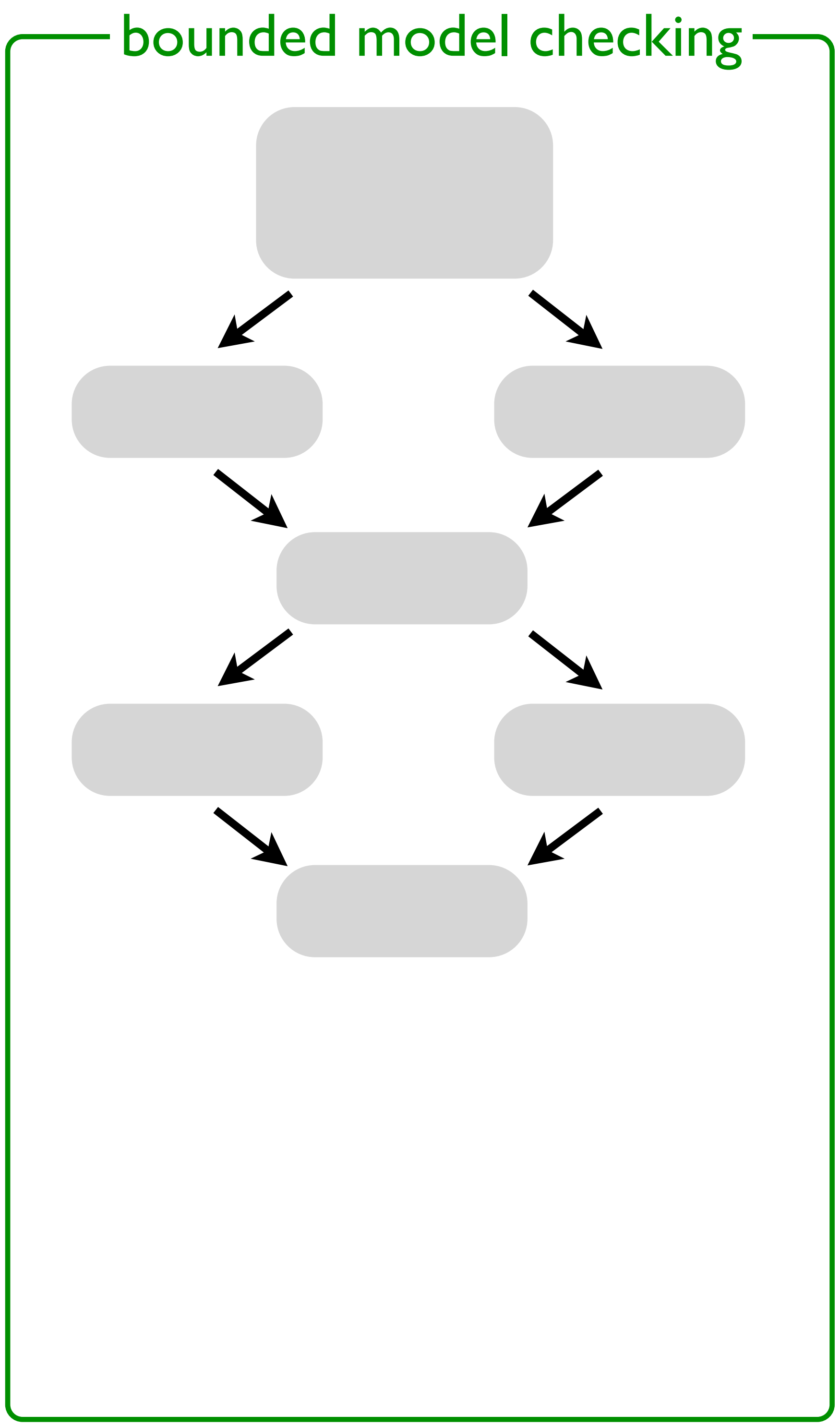

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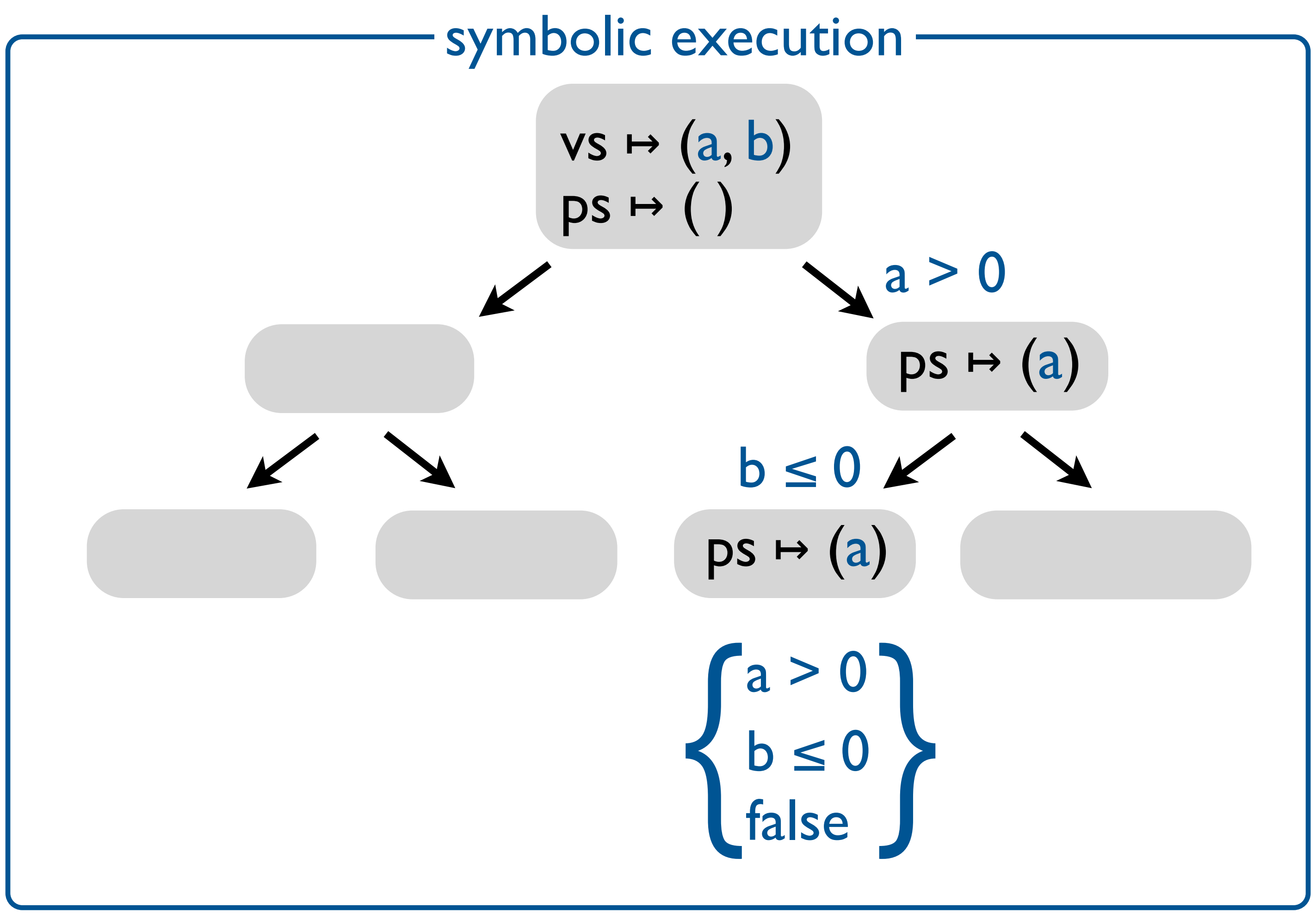

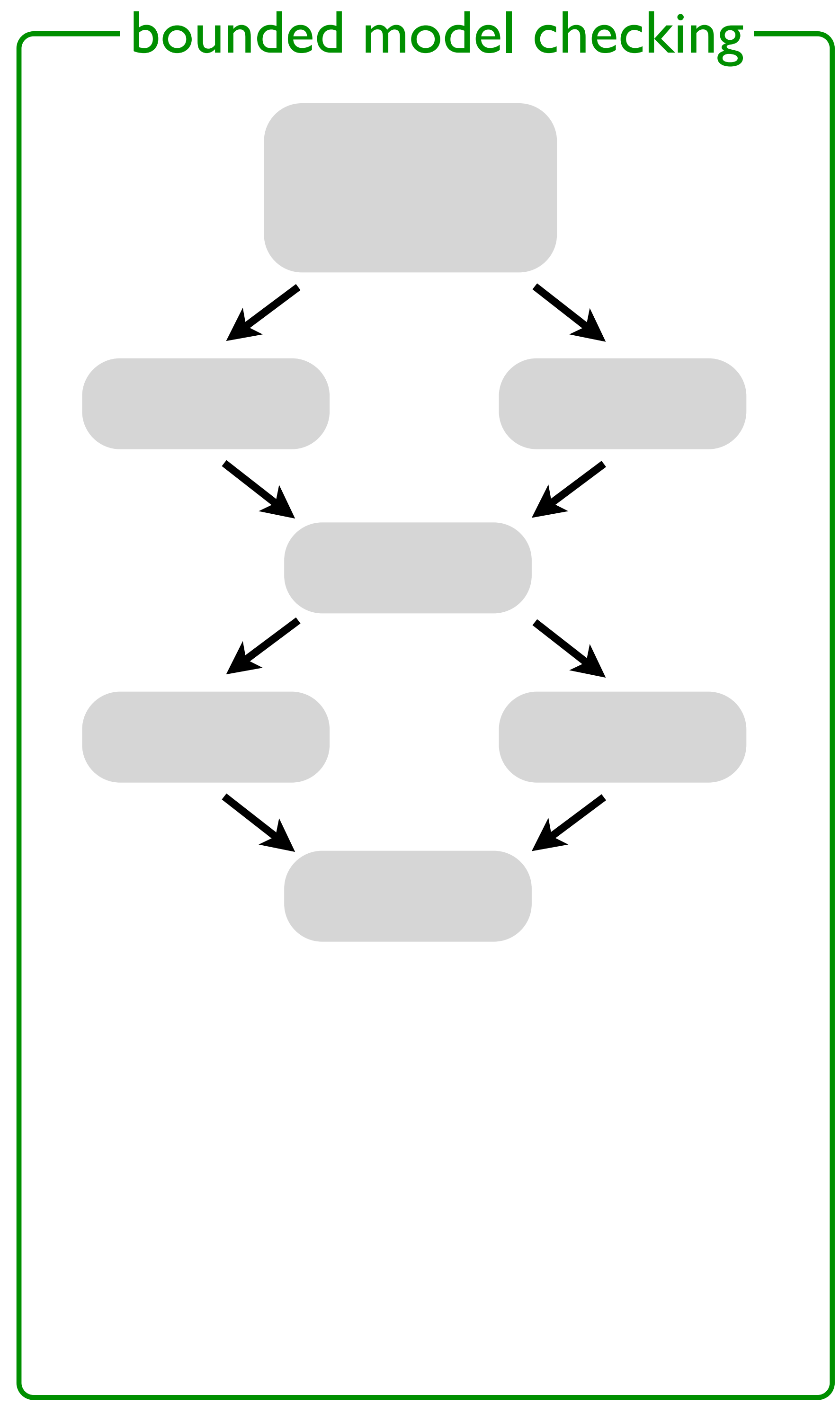

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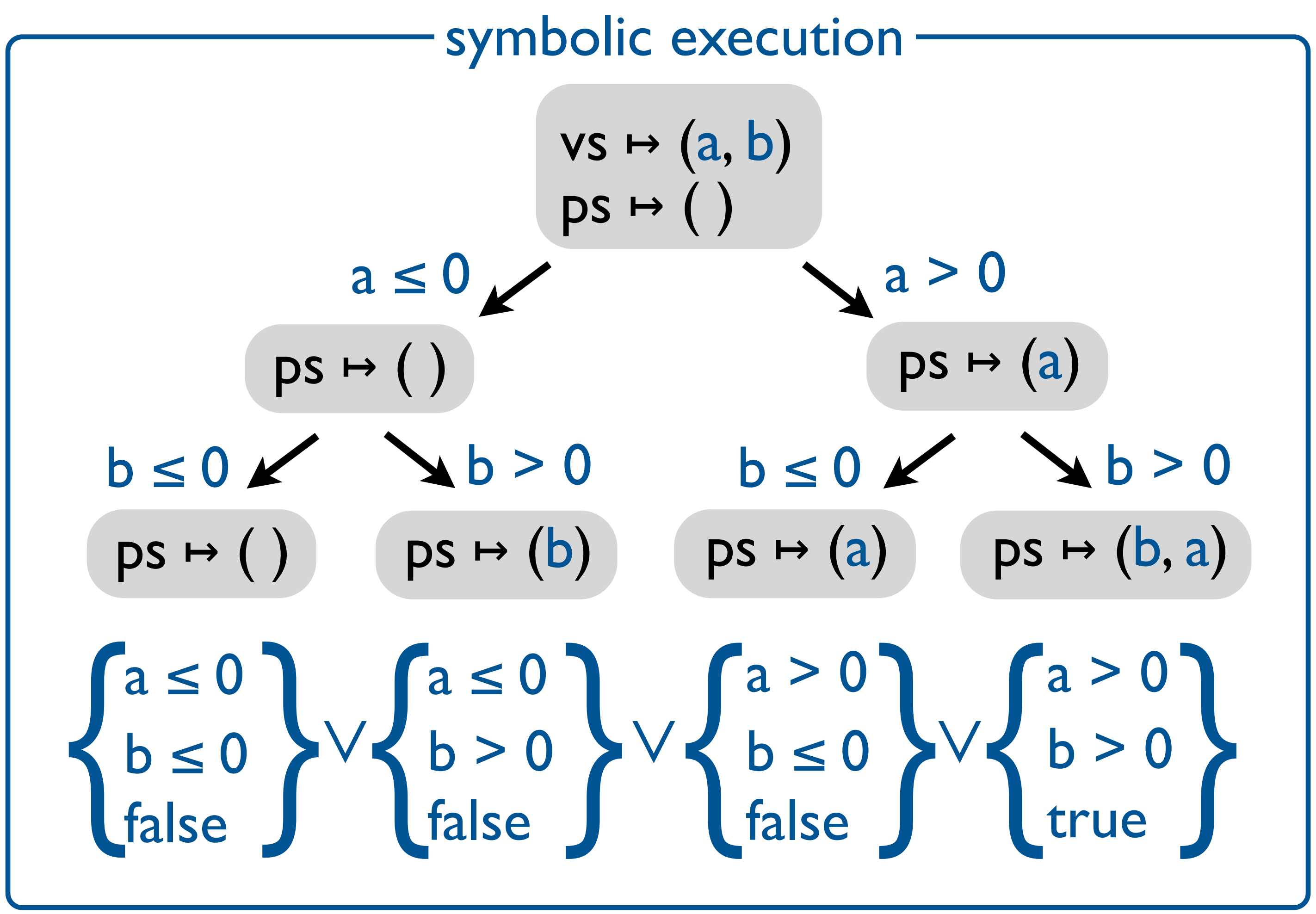

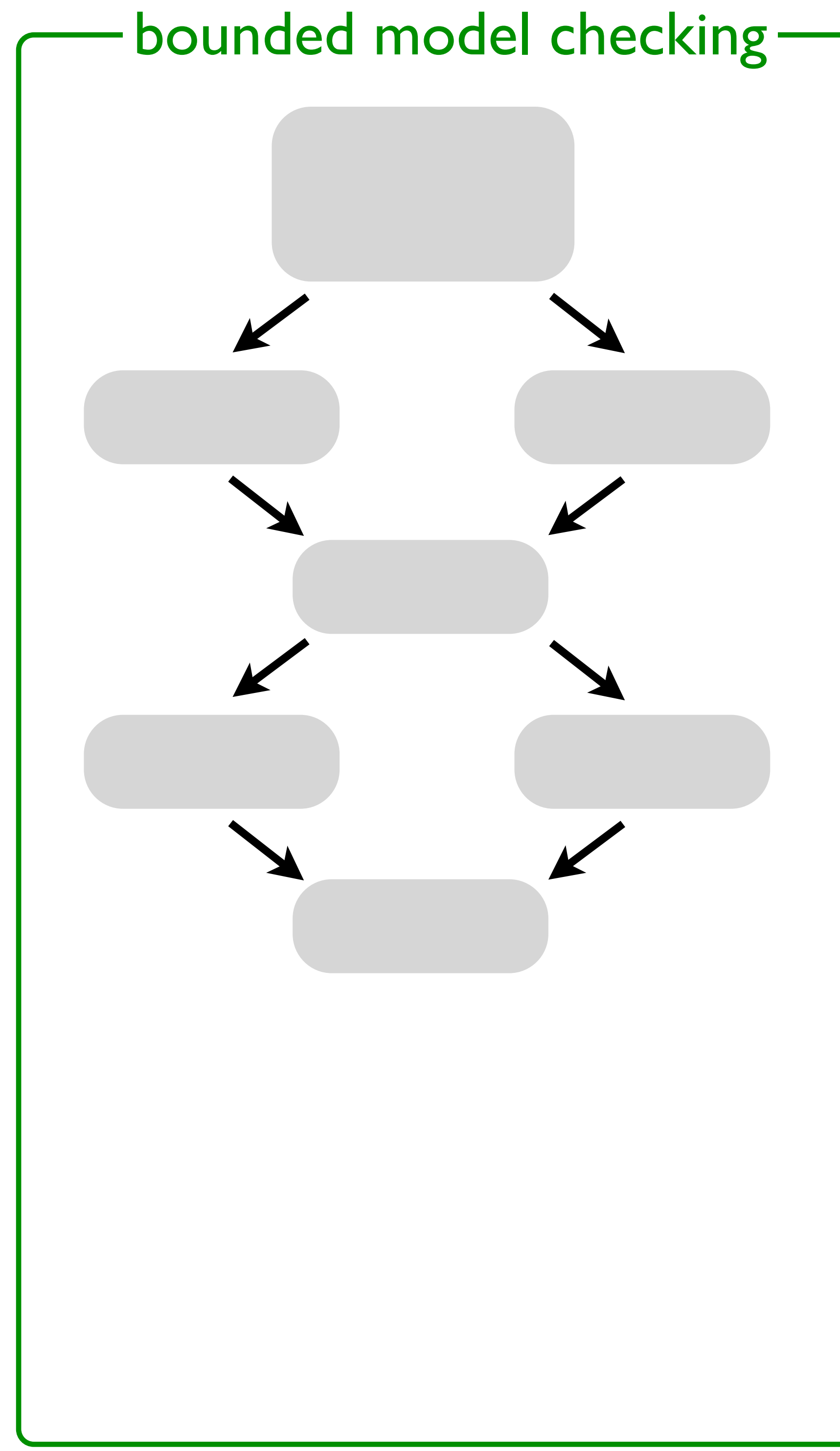

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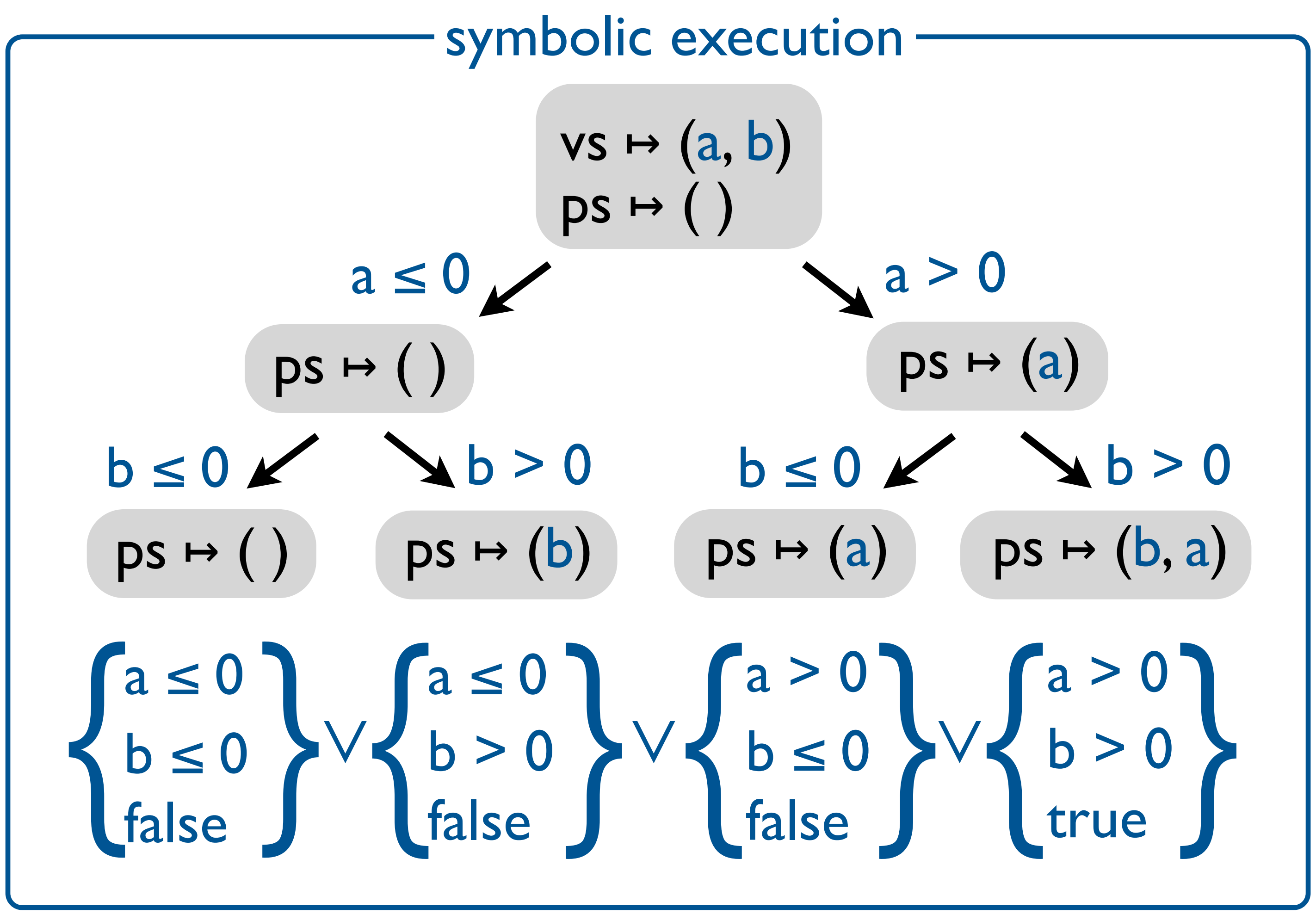

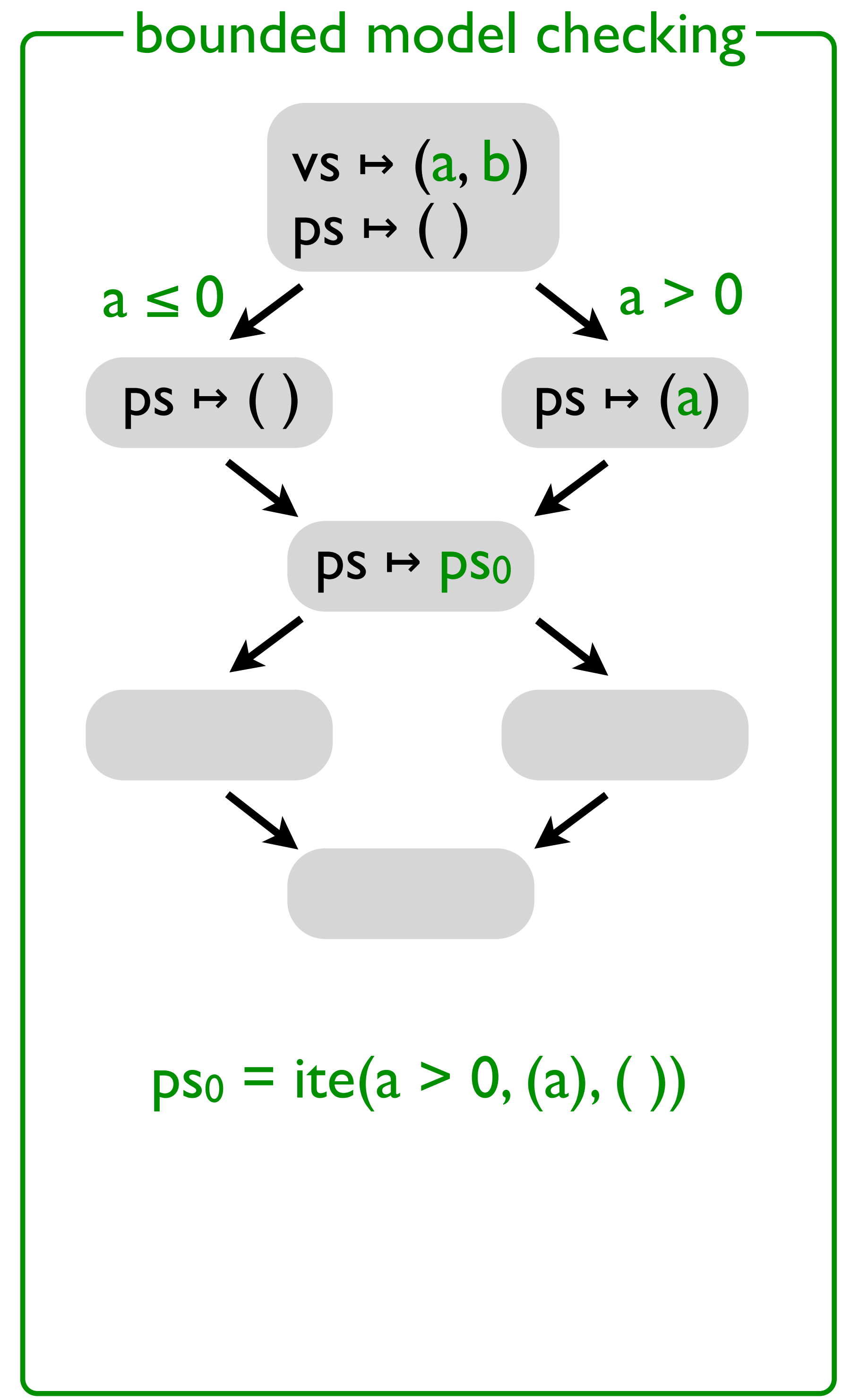

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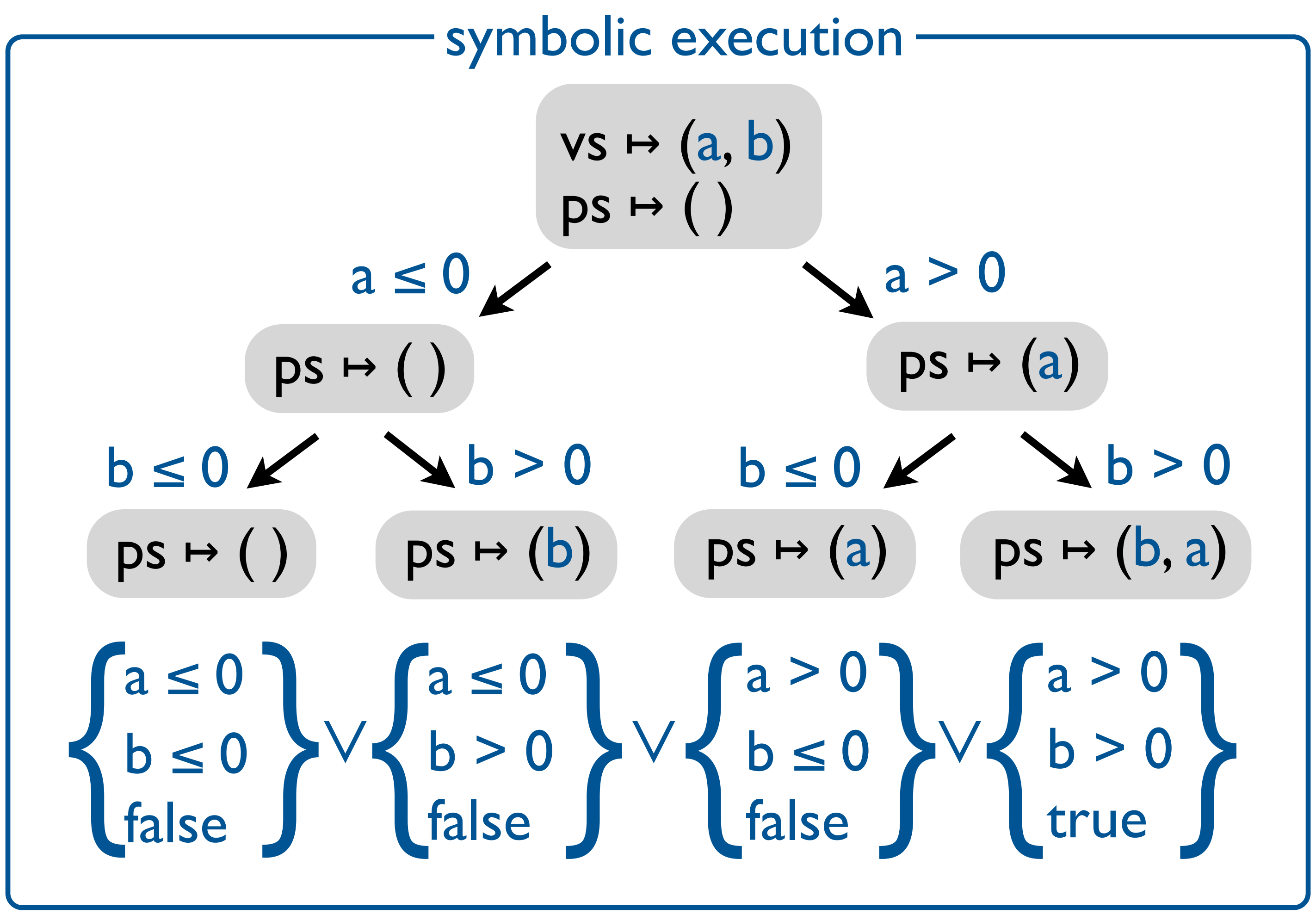

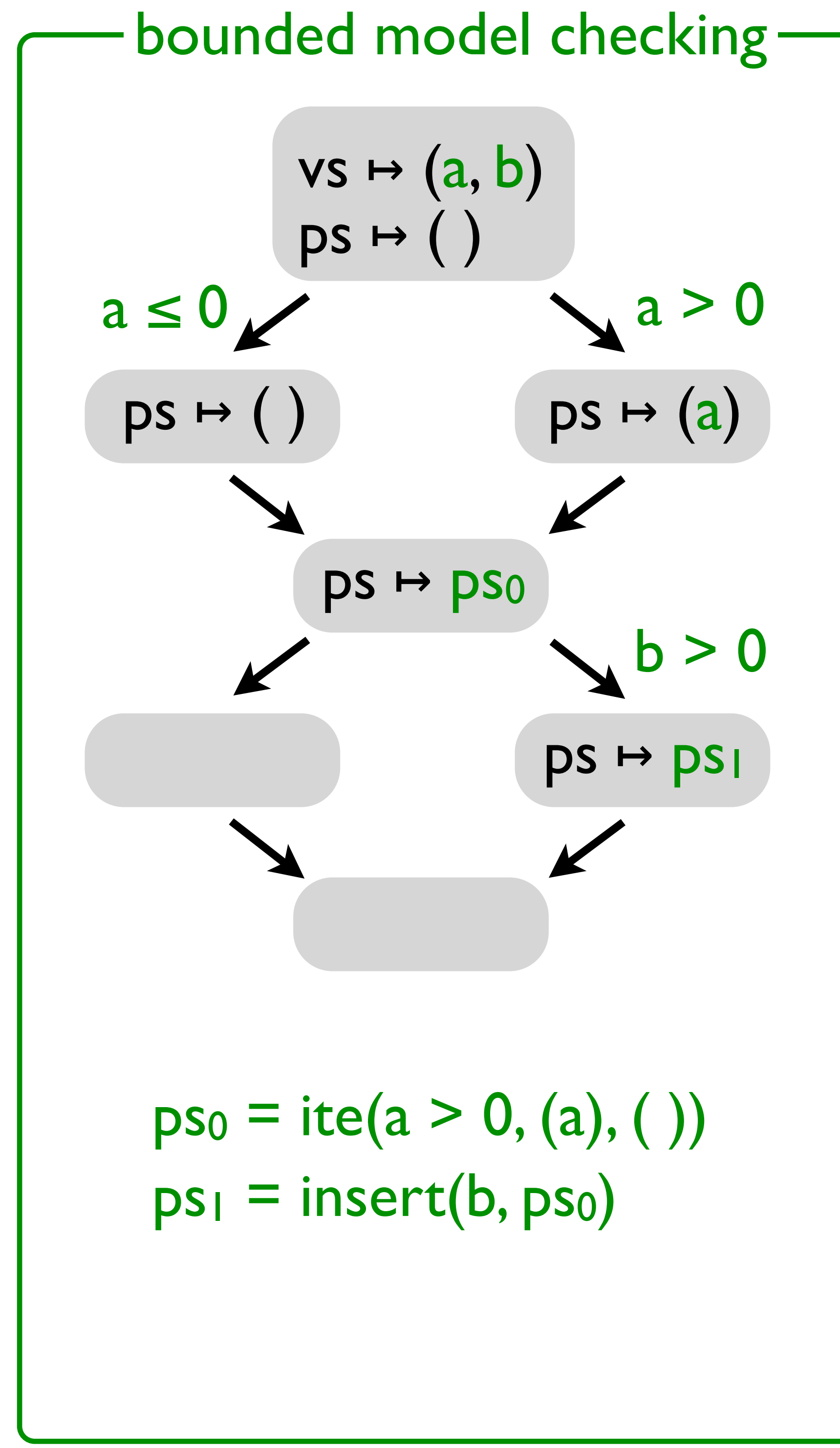

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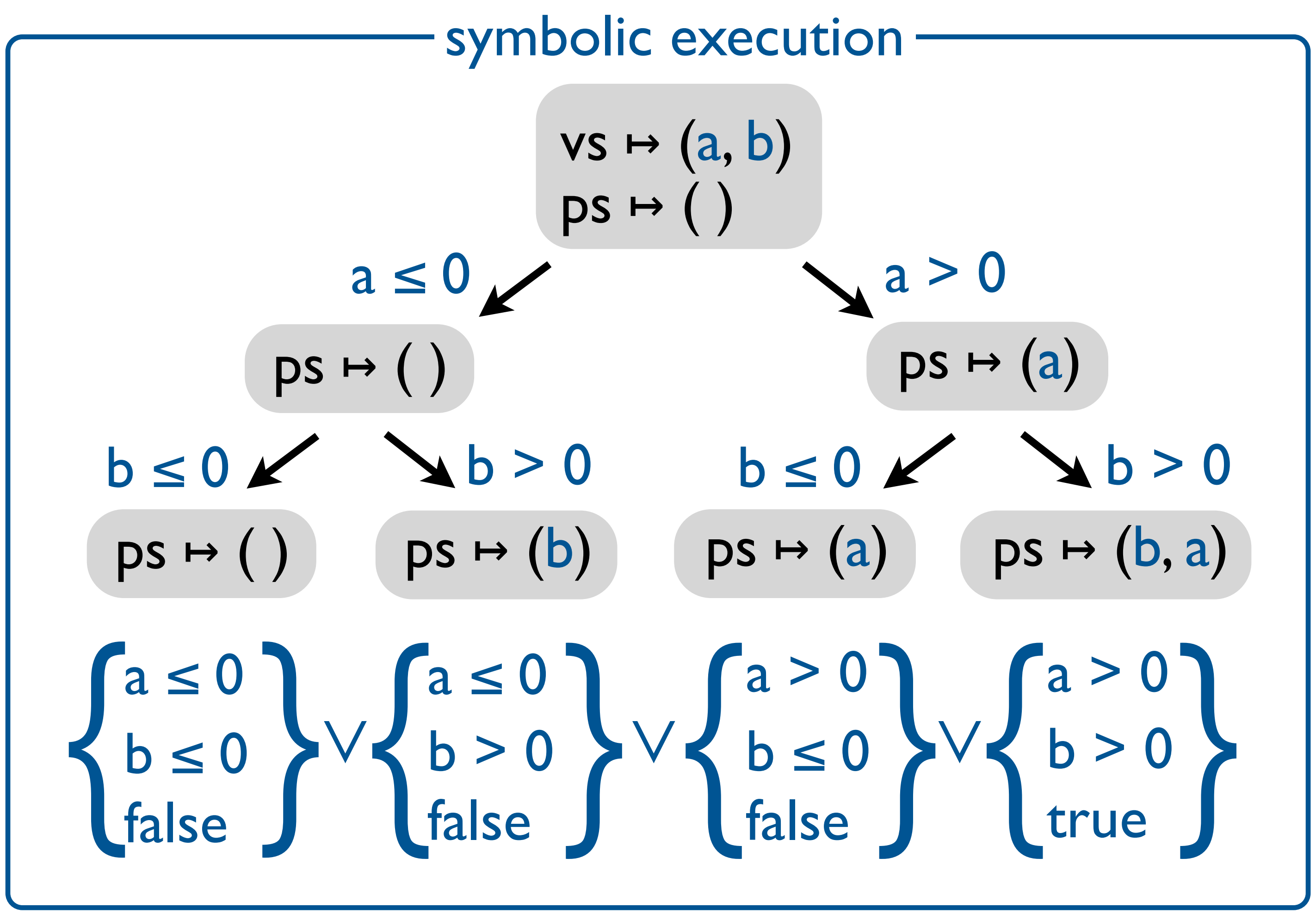
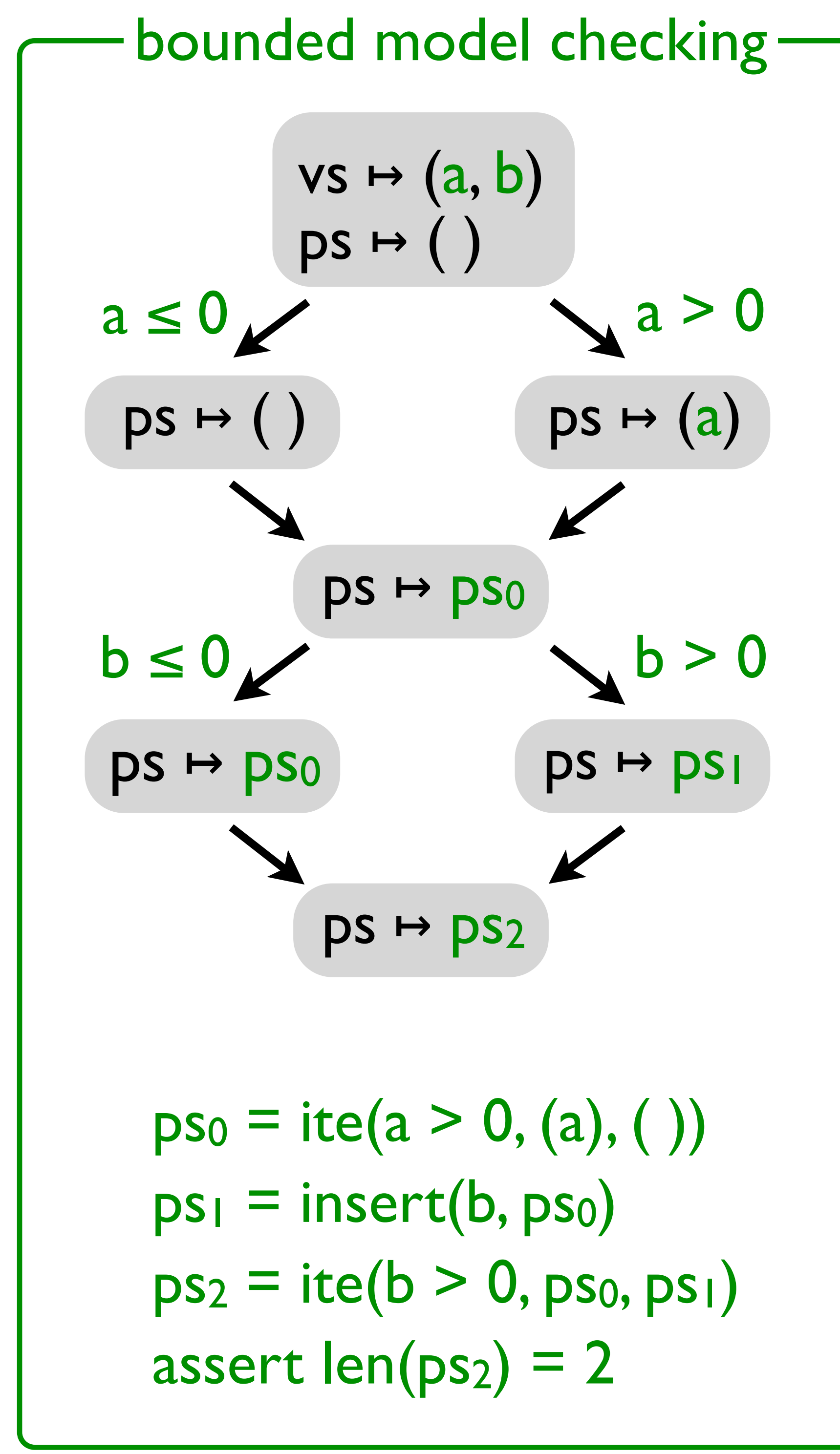
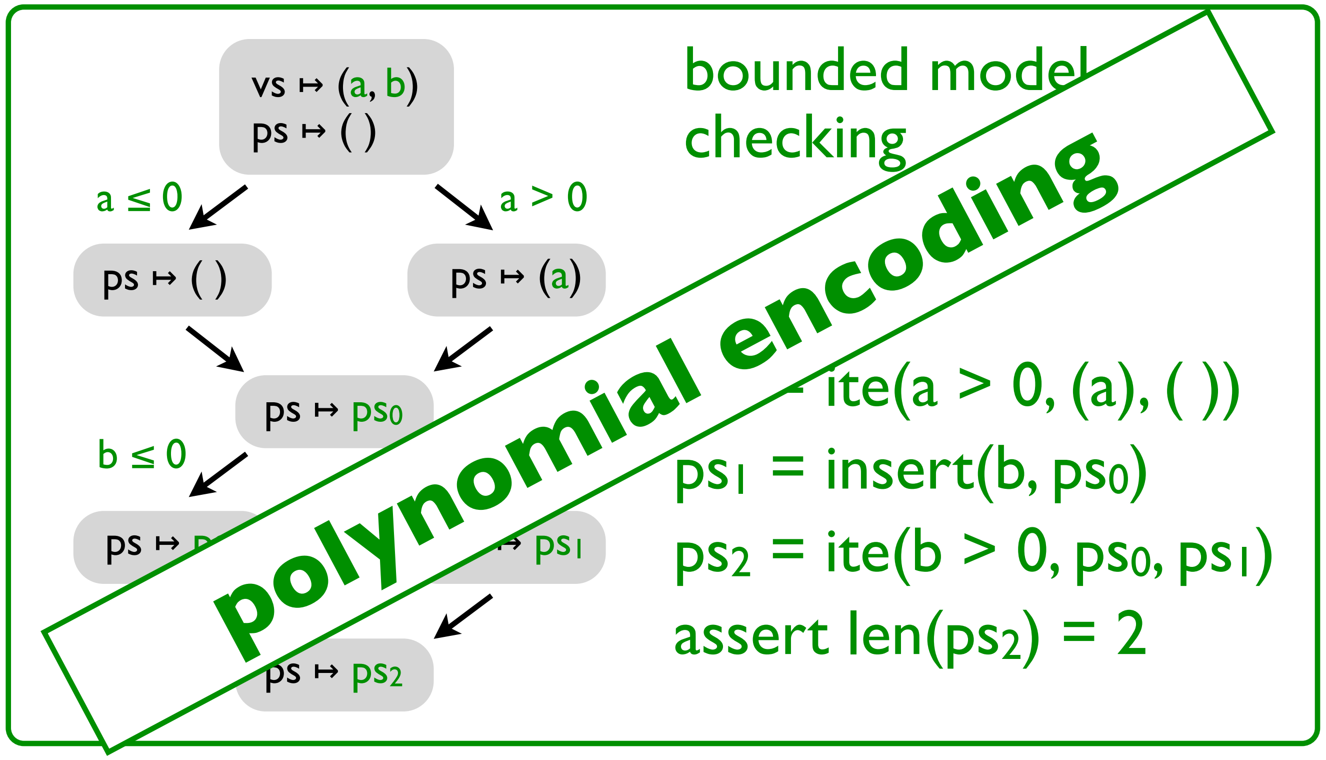
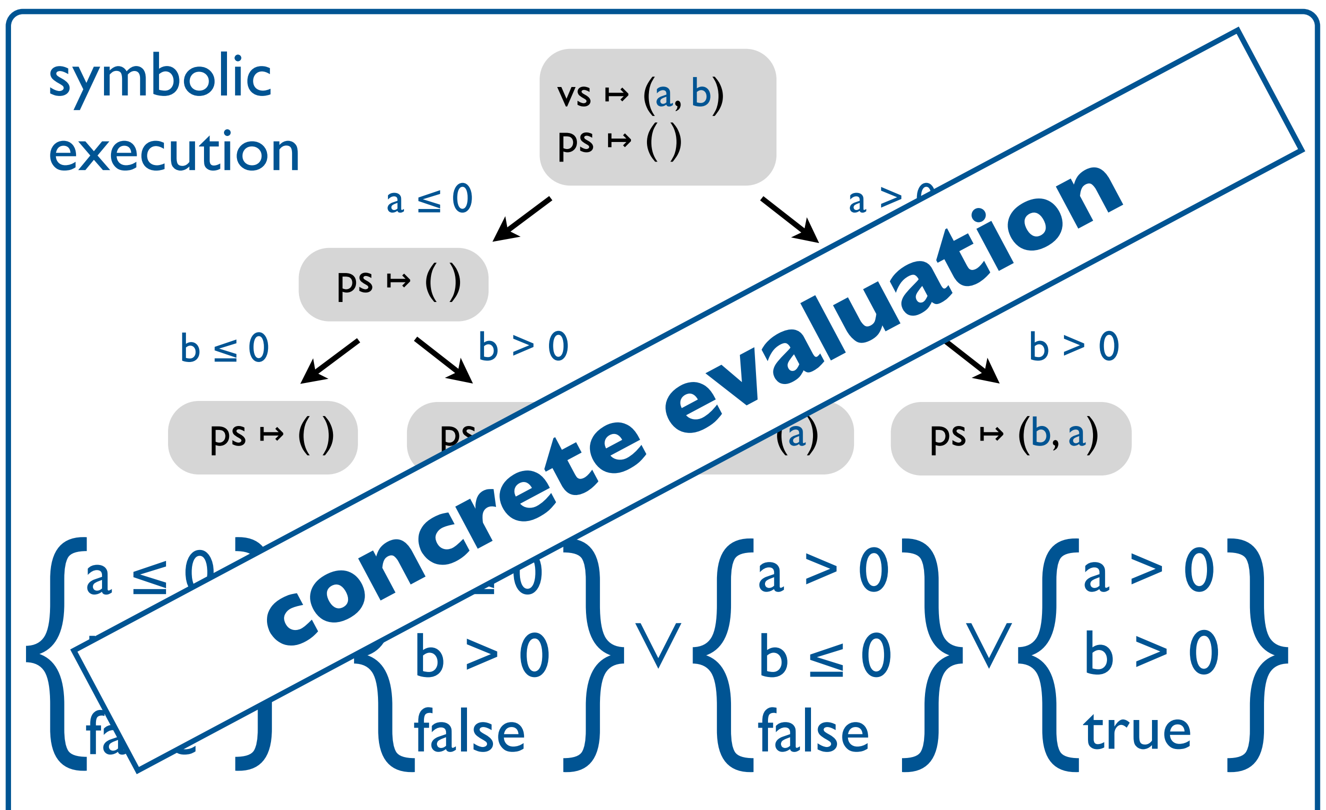




Challenge: simple vs compact encoding (SE and BMC)





Can we have *both* a polynomially sized encoding (like BMC) and concrete evaluation of complex operations (like SE)?

Solution: type-driven state merging

```
solve:
  ps = ()
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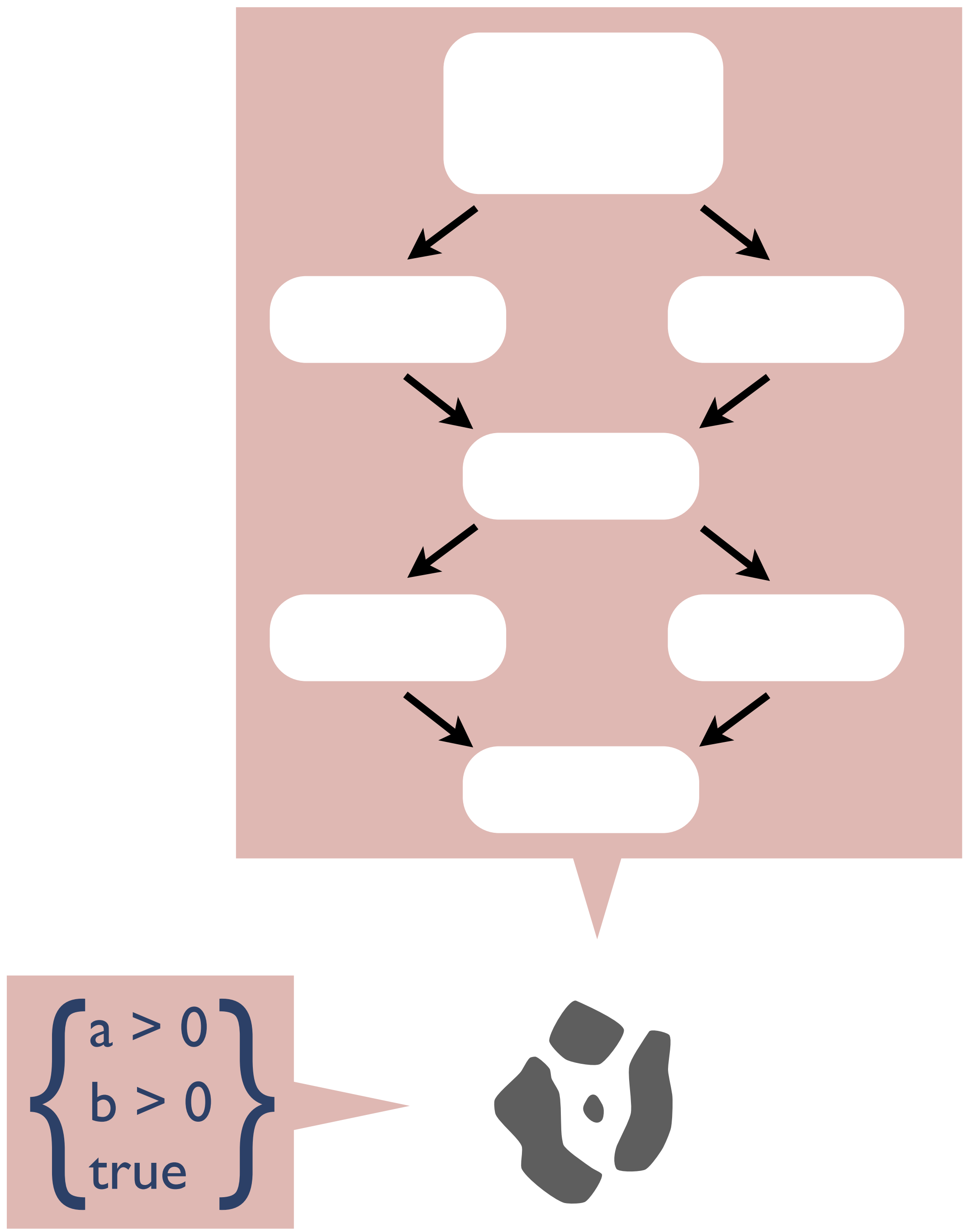

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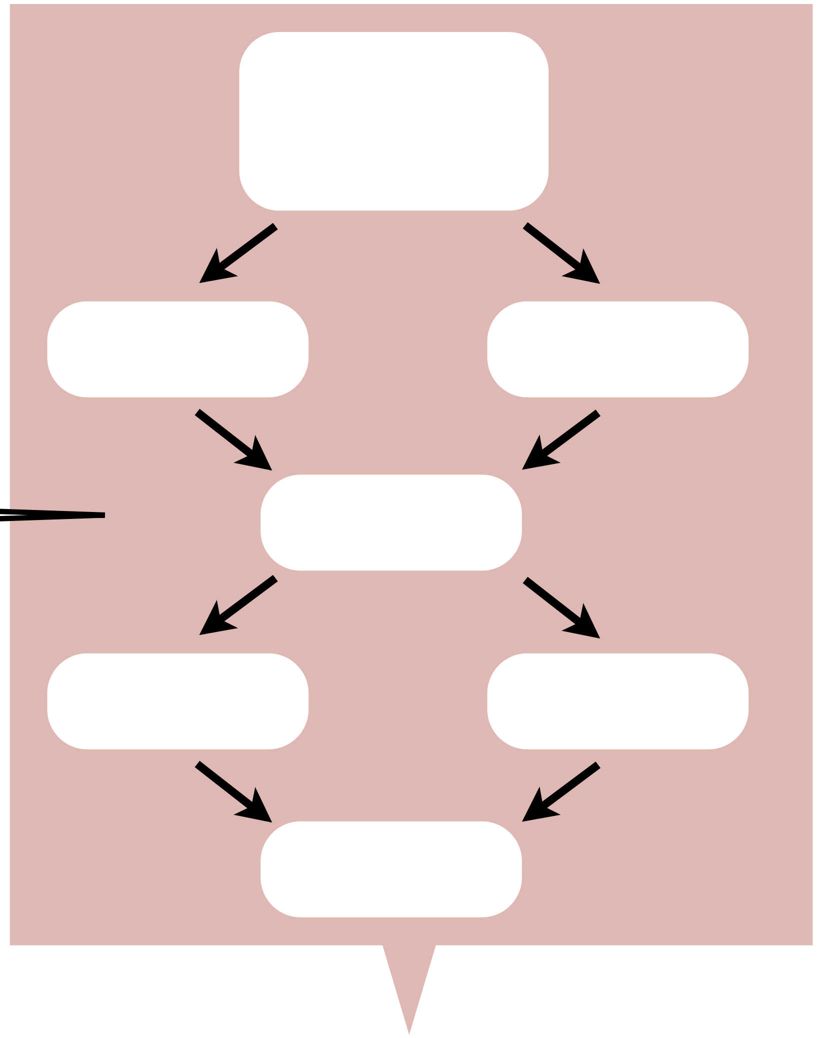
```

Merge instances of

- primitive types: symbolically
- value types: structurally
- all other types: via unions



$$\begin{Bmatrix} a > 0 \\ b > 0 \\ \text{true} \end{Bmatrix}$$

Solution: type-driven state merging

```
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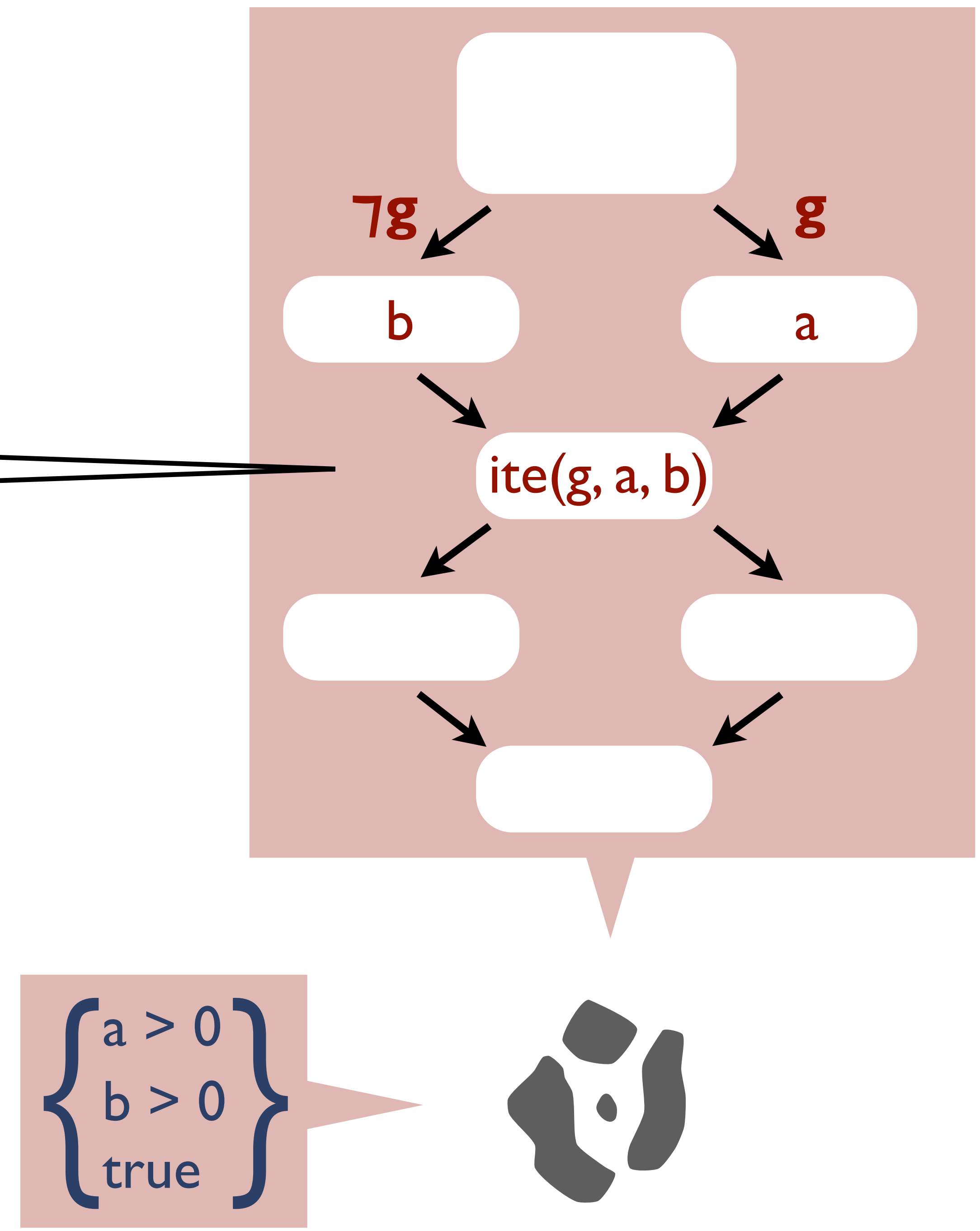

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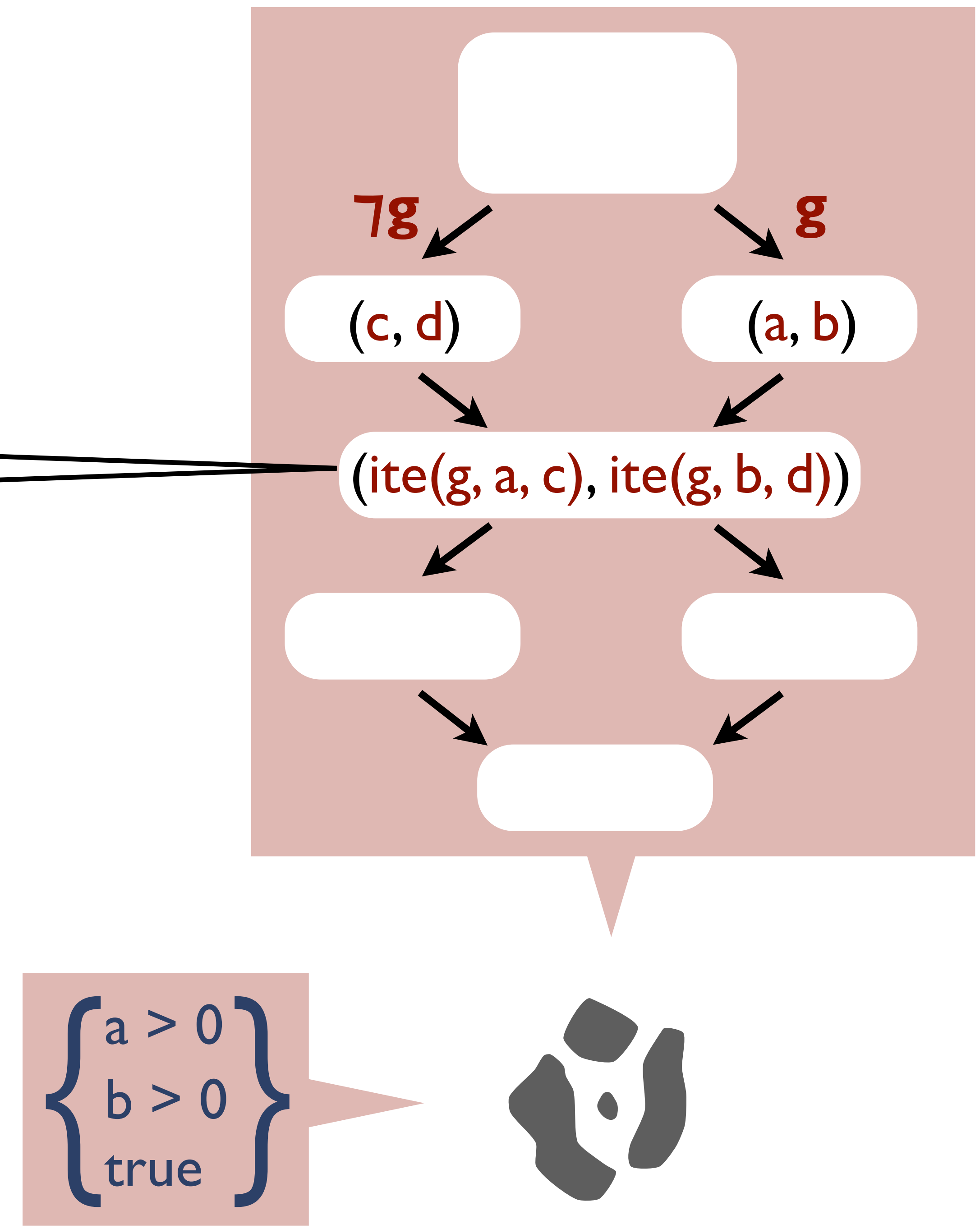

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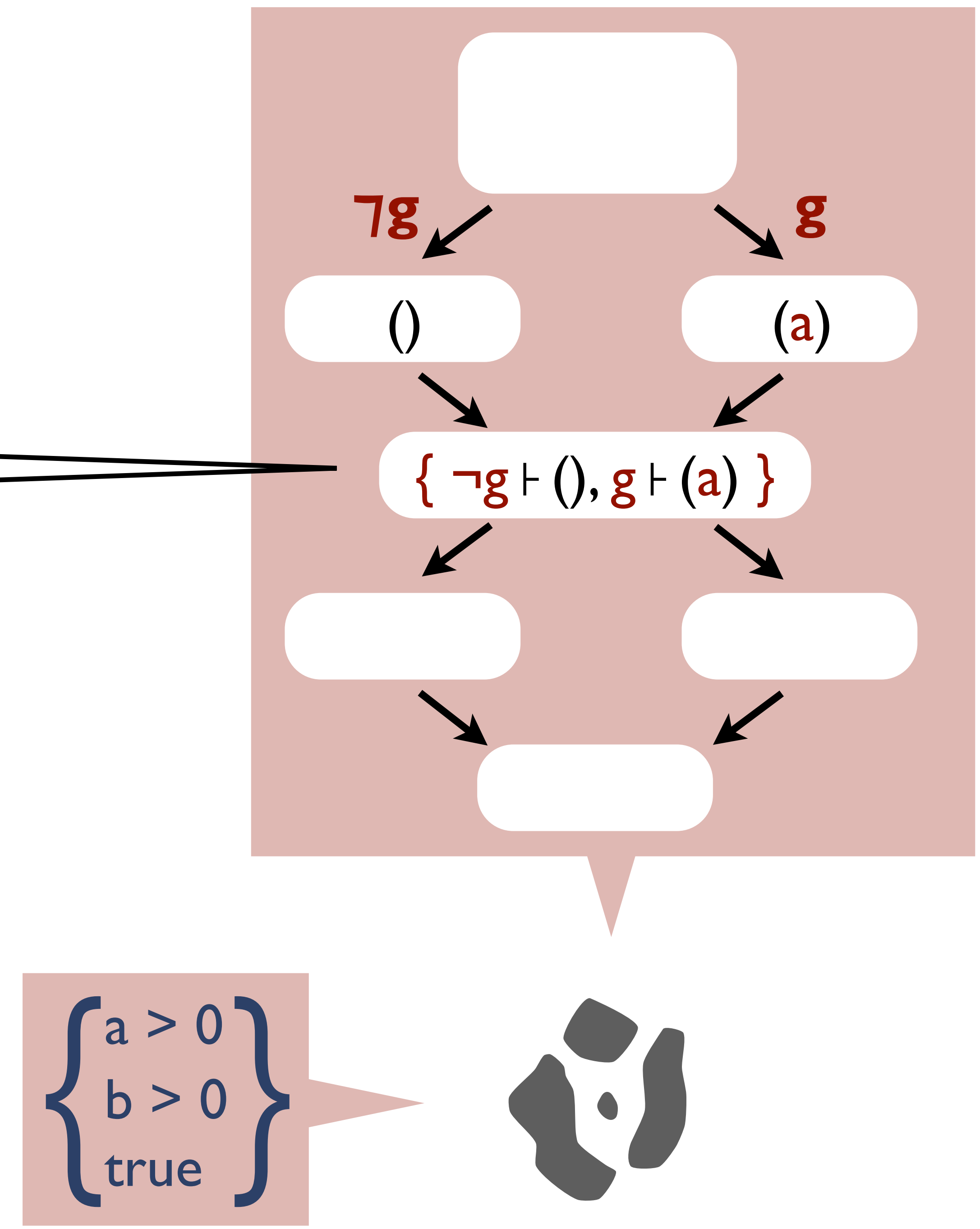

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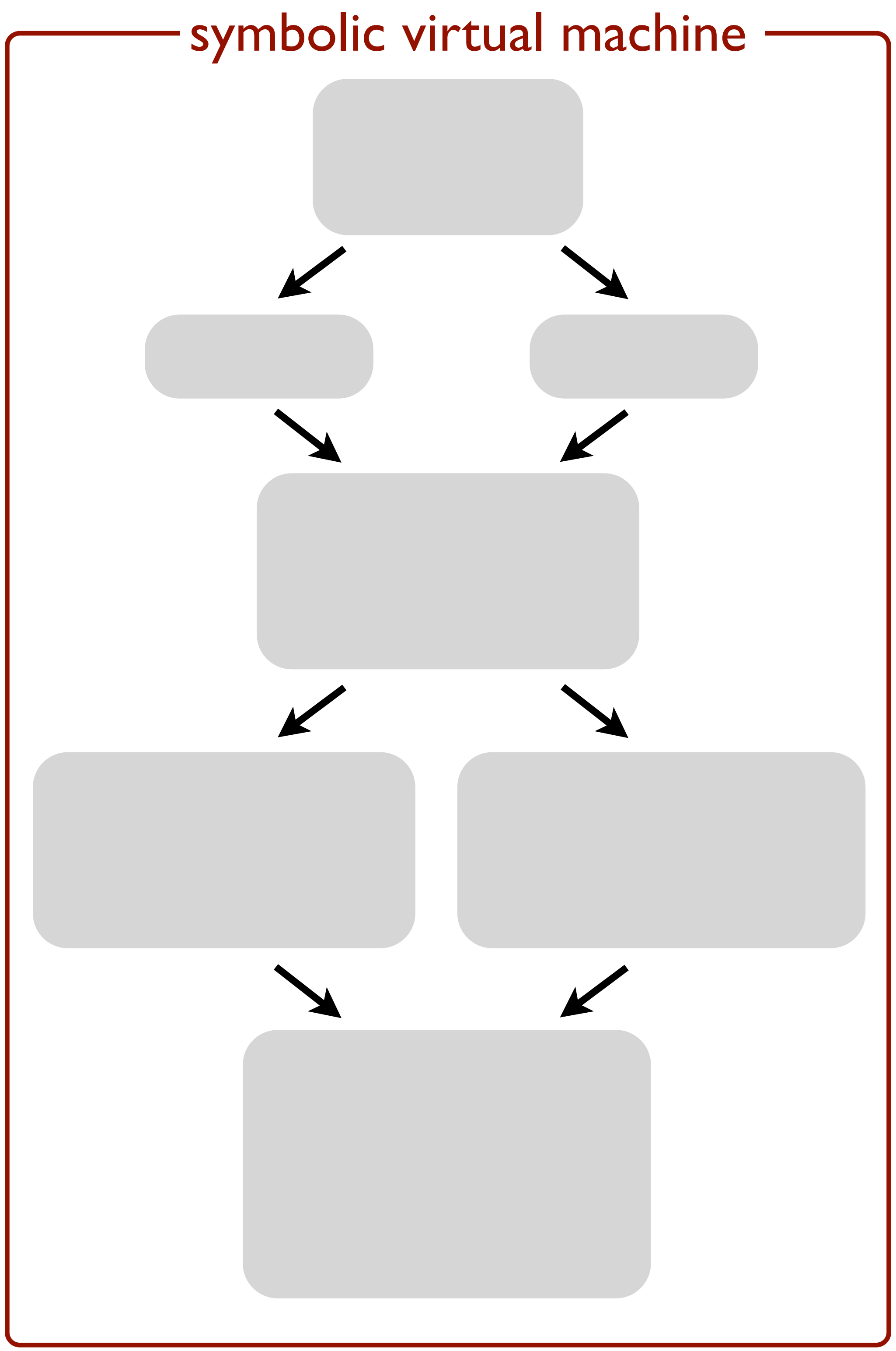

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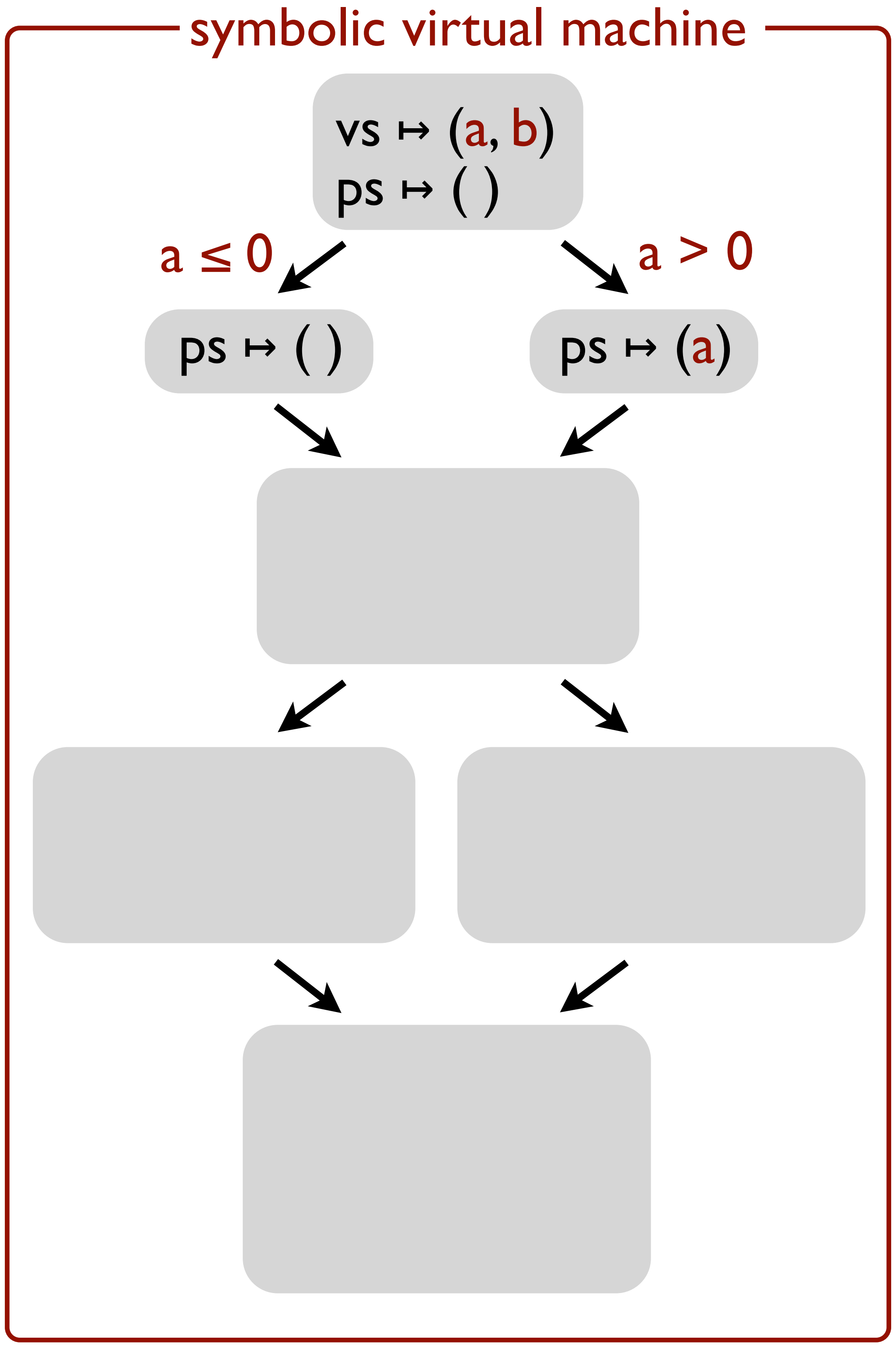

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```
solve:
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  assert len(ps) == len(vs)
```
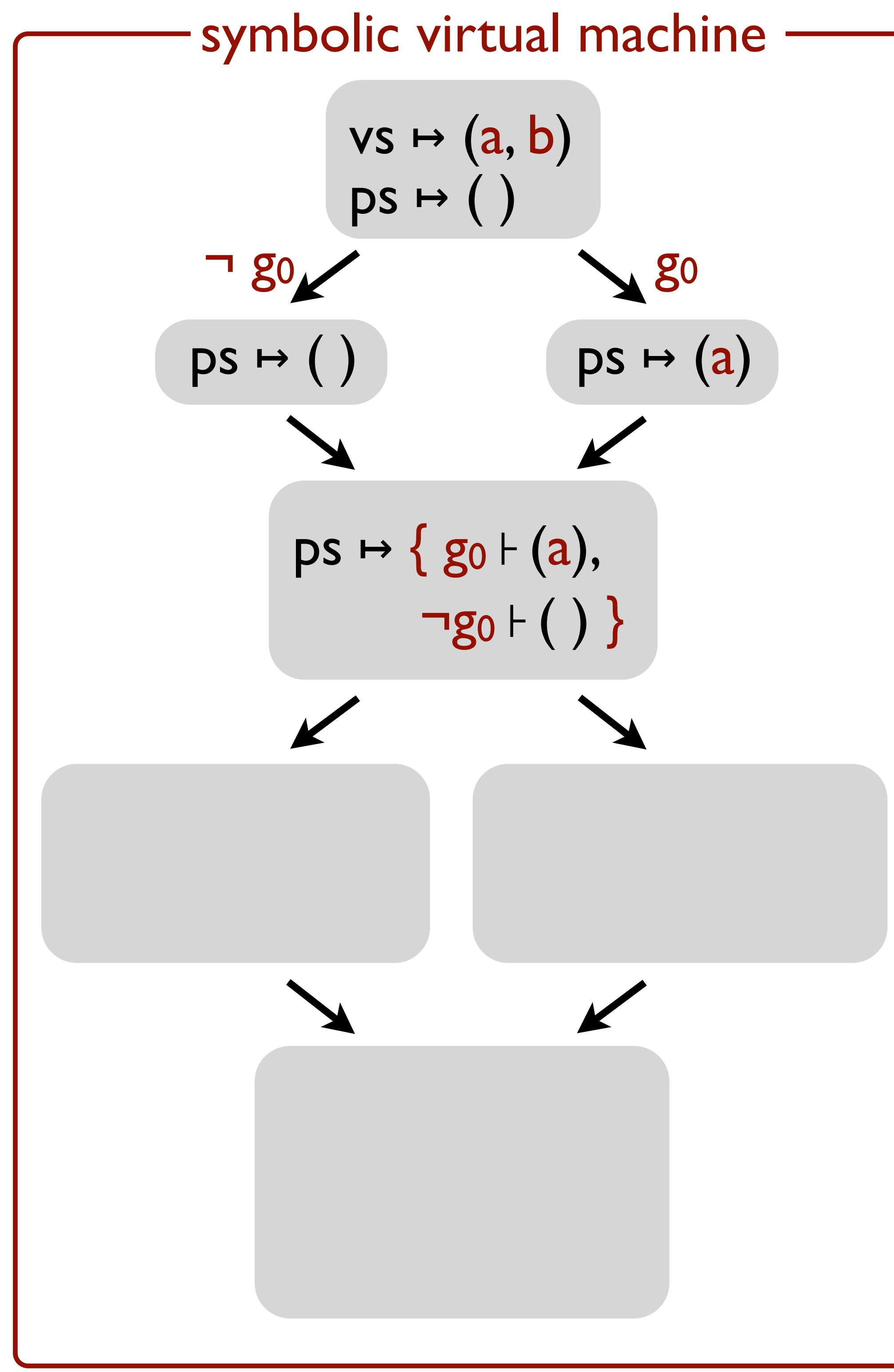

Symbolic union: a set of guarded values, with disjoint guards.

$g_0 = a > 0$



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```
solve:
  ps = ()
  for v in vs:
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      ps = insert(v, ps)
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```
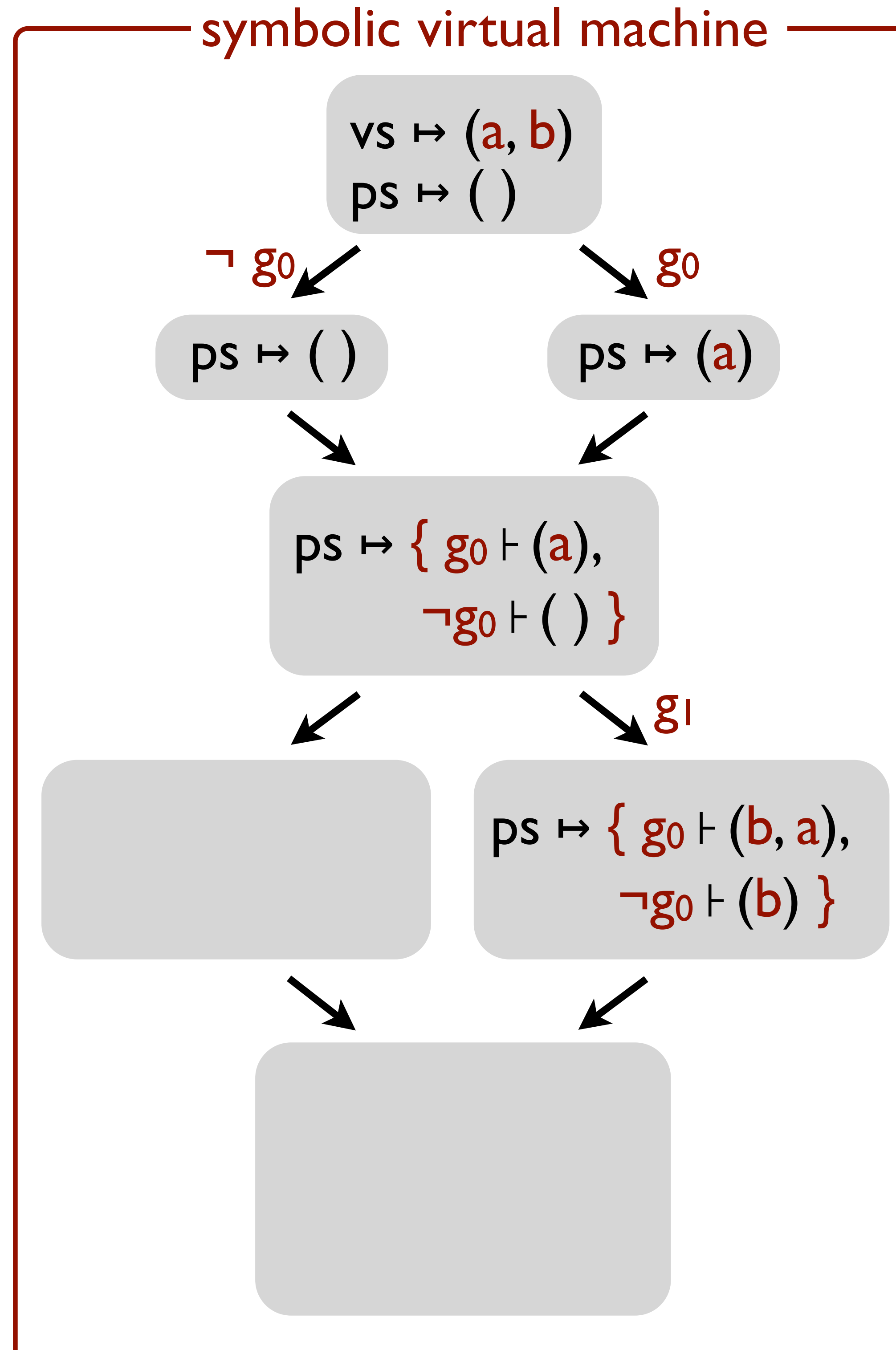

Execute `insert` concretely on all lists in the union.

$g_0 = a > 0$
$g_1 = b > 0$



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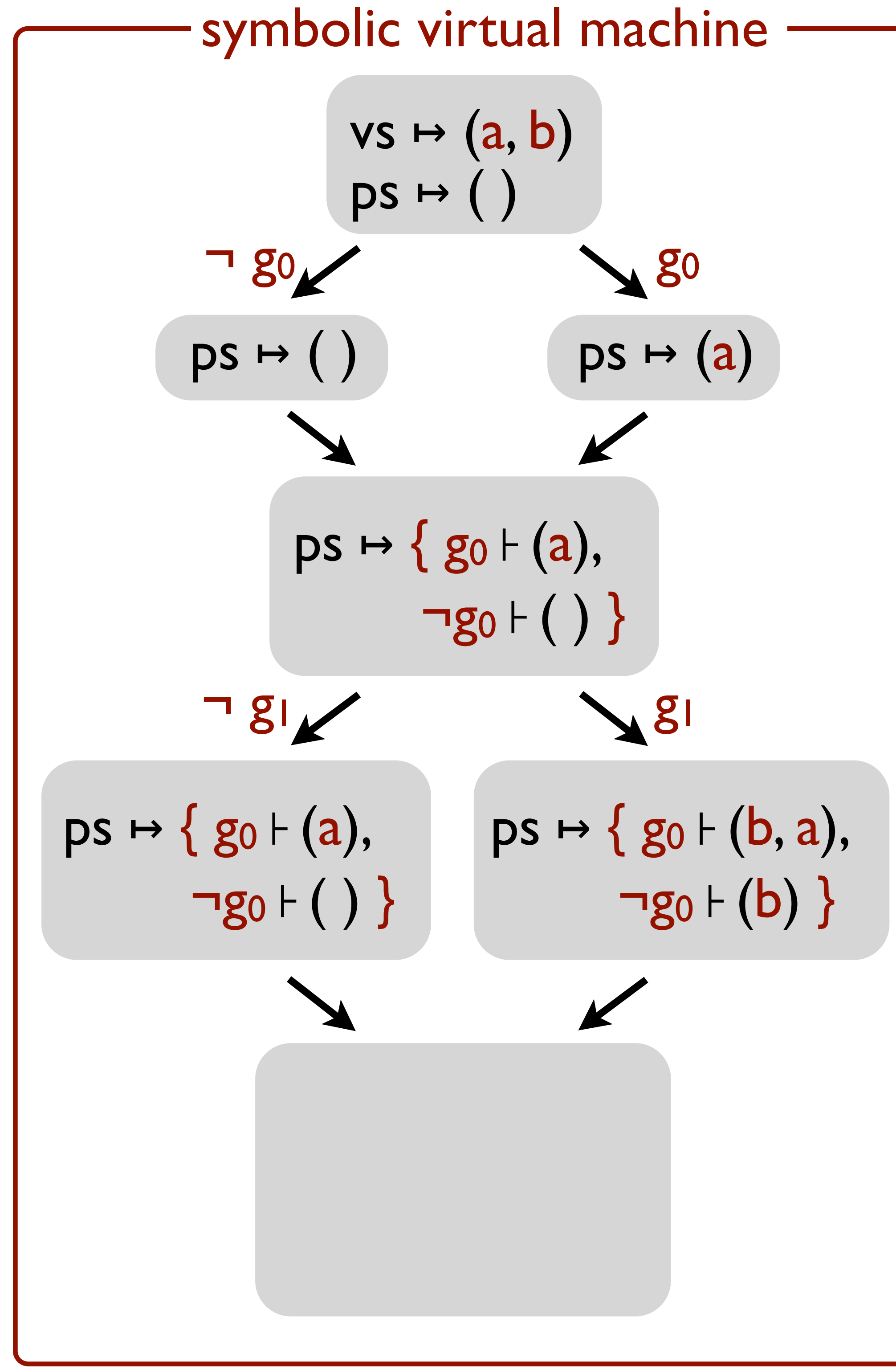

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```
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```

$g_0 = a > 0$

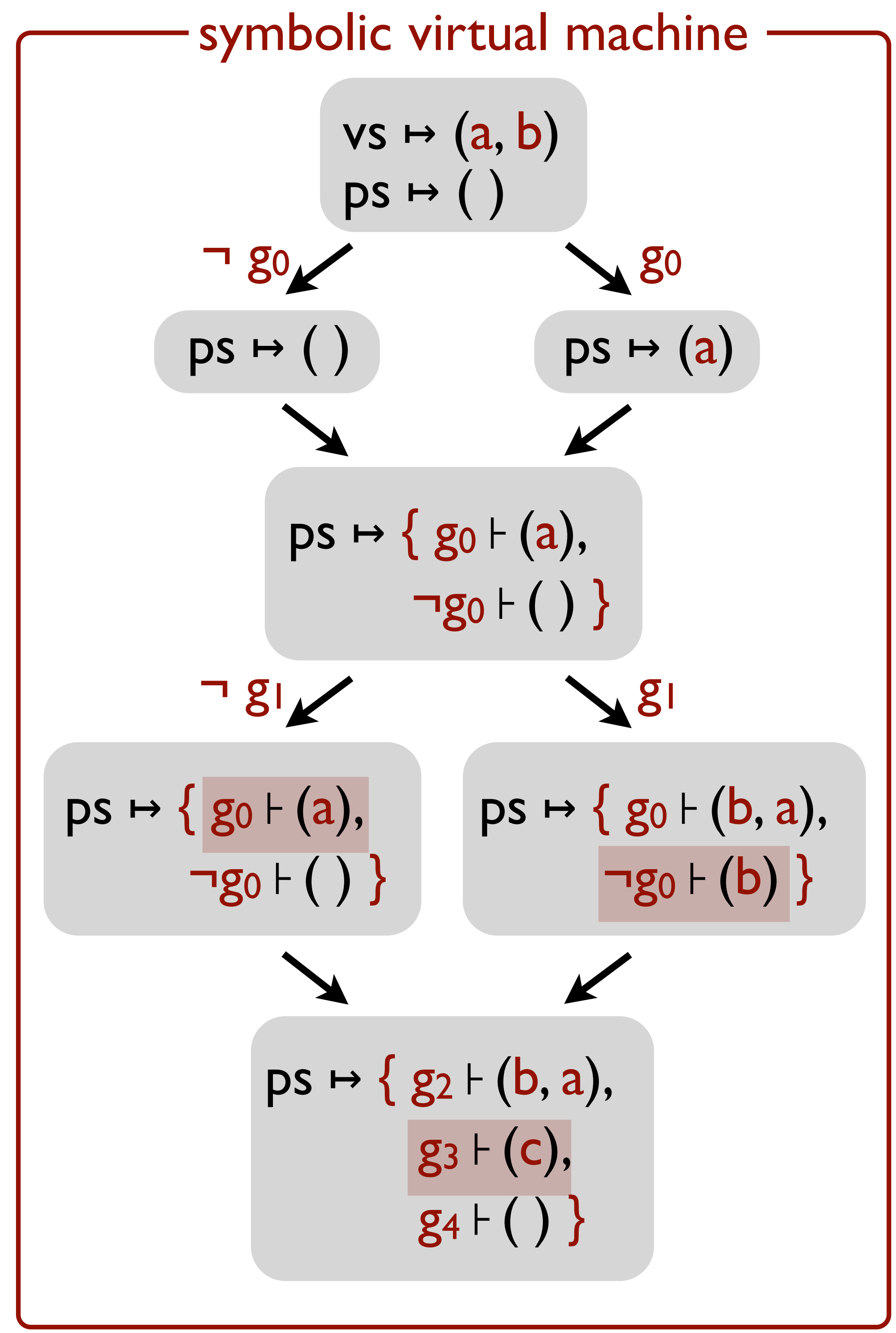
$g_1 = b > 0$

$g_2 = g_0 \wedge g_1$

$g_3 = \neg(g_0 \Leftrightarrow g_1)$

$g_4 = \neg g_0 \wedge \neg g_1$

$c = ite(g_1, b, a)$



Solution: type-driven state merging

```
solve:
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  assert len(ps) == len(vs)
```

Evaluate `len` concretely on all lists in the union; assertion true only on the list guarded by g_2.

$g_0 = a > 0$

$g_1 = b > 0$

$g_2 = g_0 \wedge g_1$

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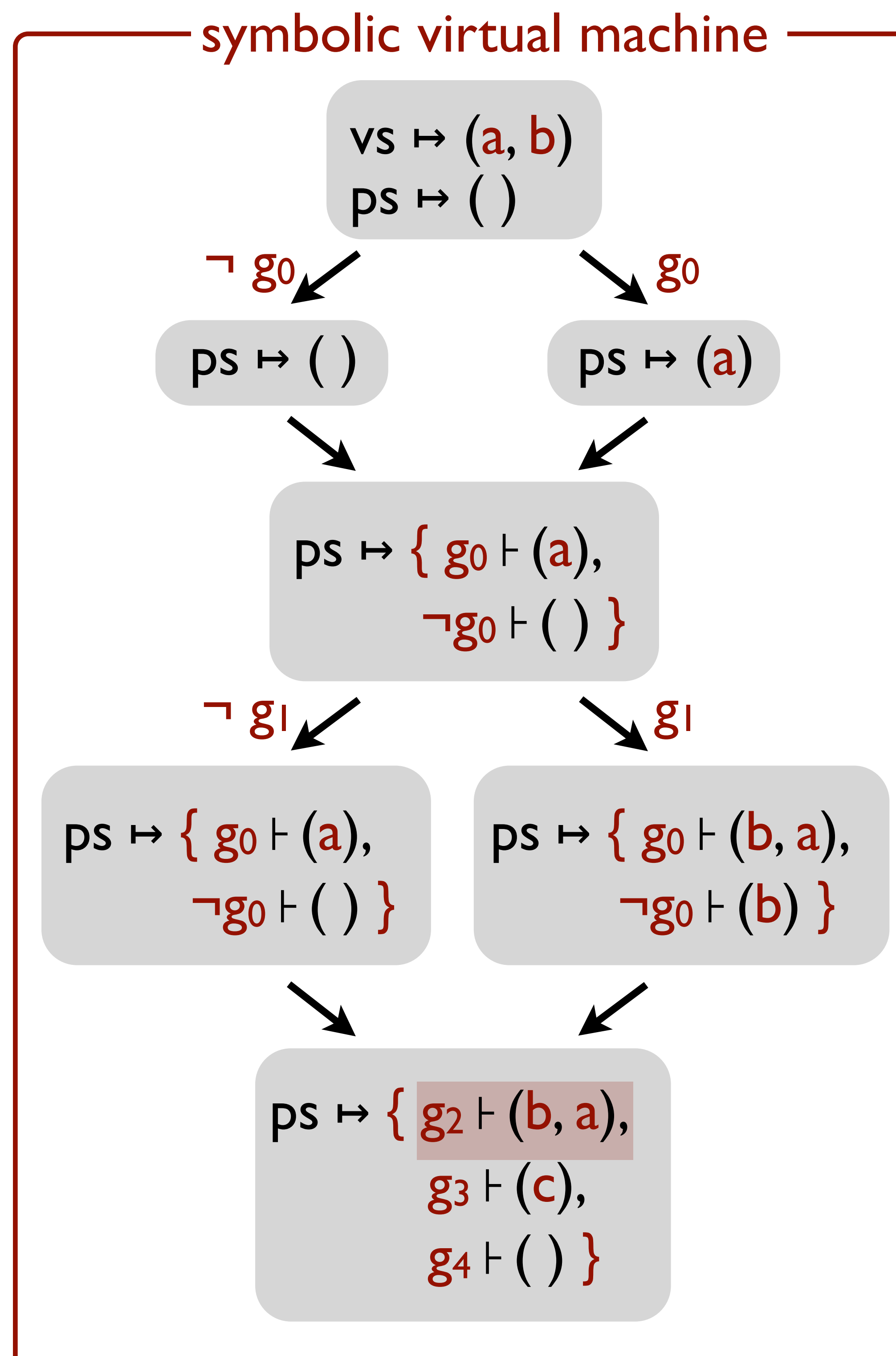
$c = \mathrm{ite}(g_1, b, a)$

assert g_2



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      ps = insert(v, ps)
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```

polynomial encoding

concrete evaluation

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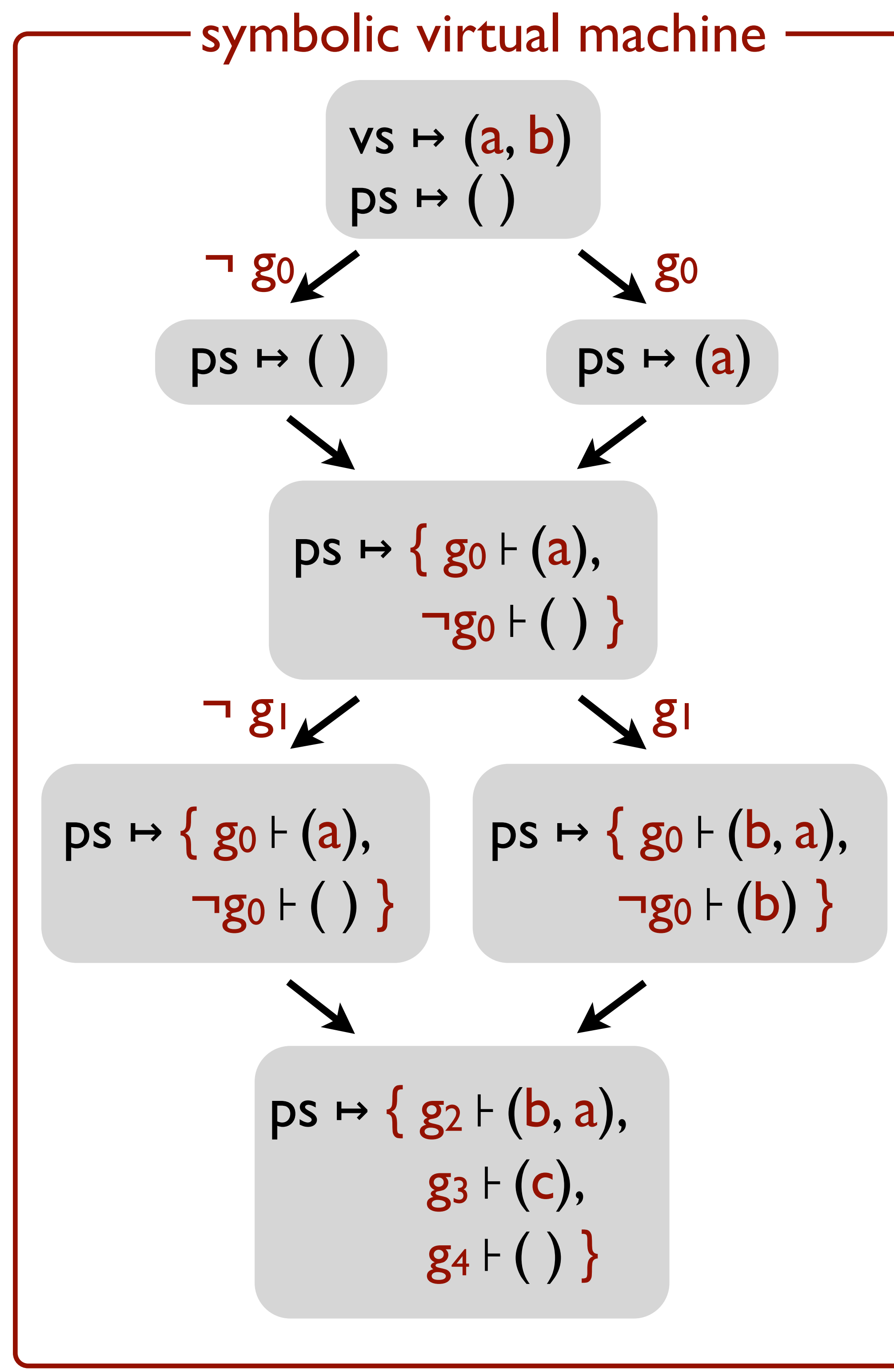

Solution: type-driven state merging

SymPro (OOPSLA'18): use **symbolic profiling** to find performance bottlenecks in solver-aided code.

```
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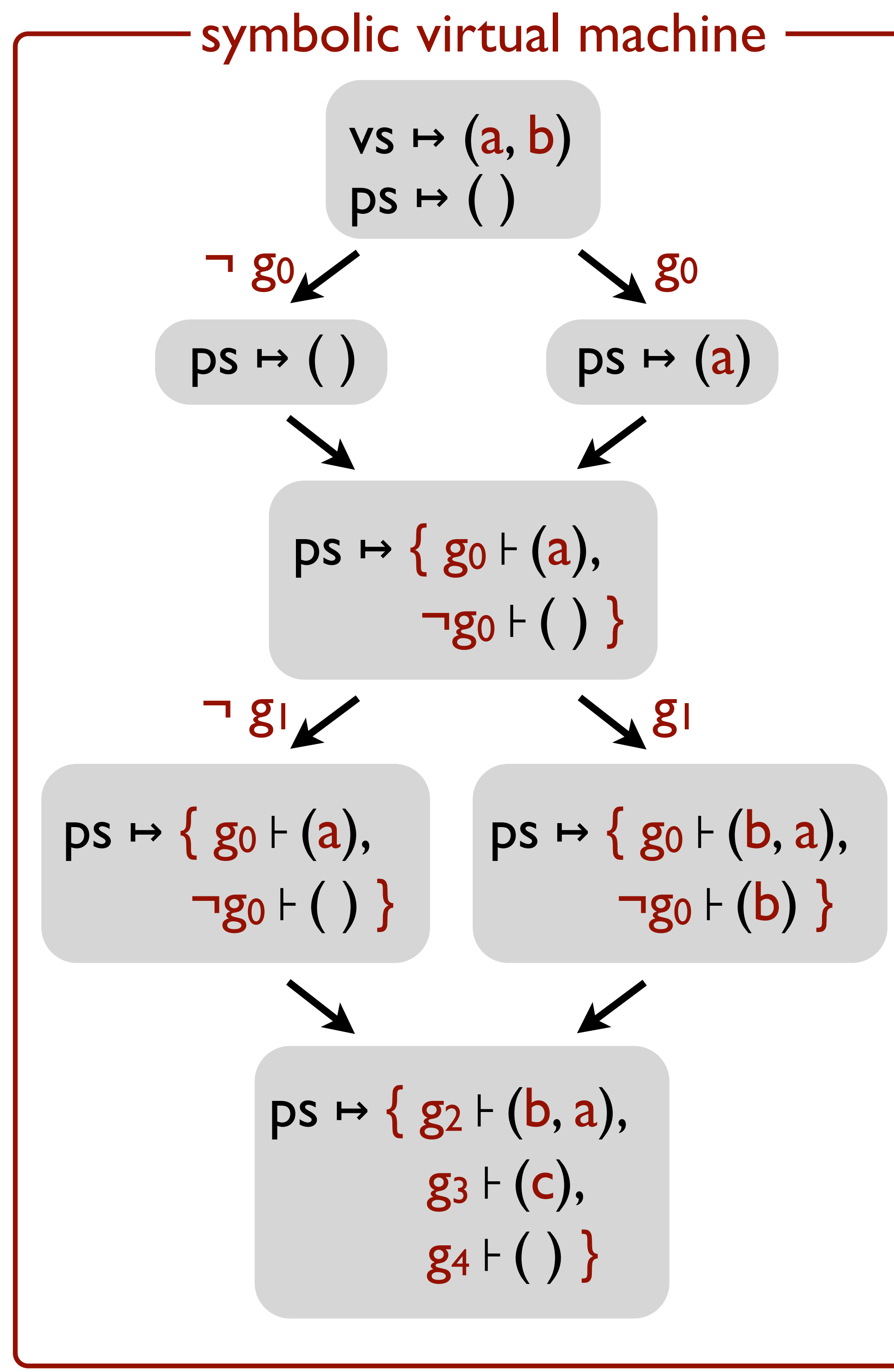

How to build your own solver-aided tool or language

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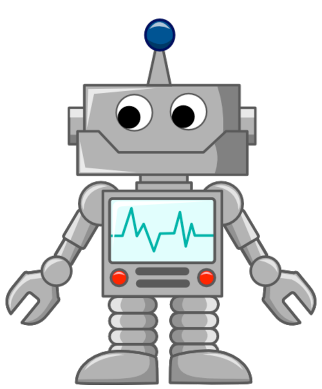
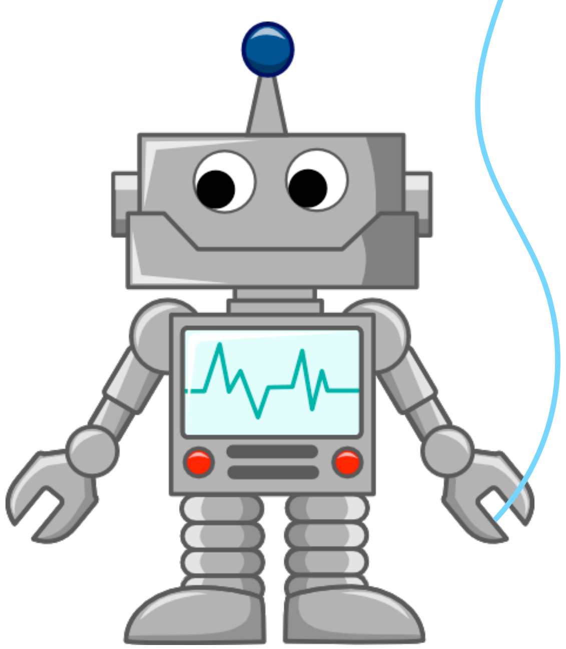


A last look: a few recent applications
Cool tools built with Rosette!

30+ tools

programming languages, software engineering, systems, architecture, networks, security, formal methods, databases, education, games, …



programming languages, formal methods, and software engineering

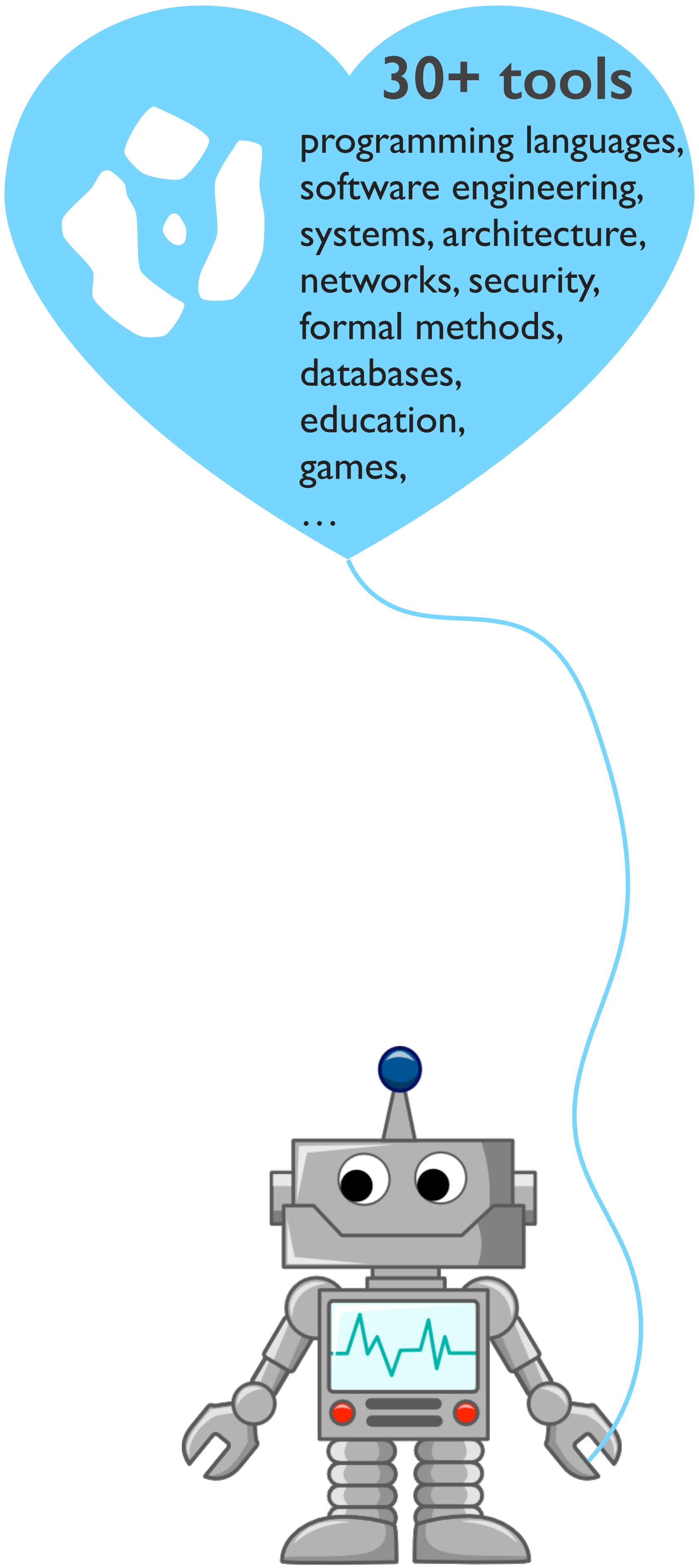
- type systems and programming models
- compilation and parallelization
- safety-critical systems
- test input generation
- software diversification

education and games

- hints and feedback
- problem generation
- problem-solving strategies

systems, architecture, networks, security, and databases

- memory models
- OS components
- data movement for GPUs
- router configuration
- cryptographic protocols



programming languages, formal methods, and software engineering

- type systems and programming models
- compilation and parallelization
- safety-critical systems [CAV'16]
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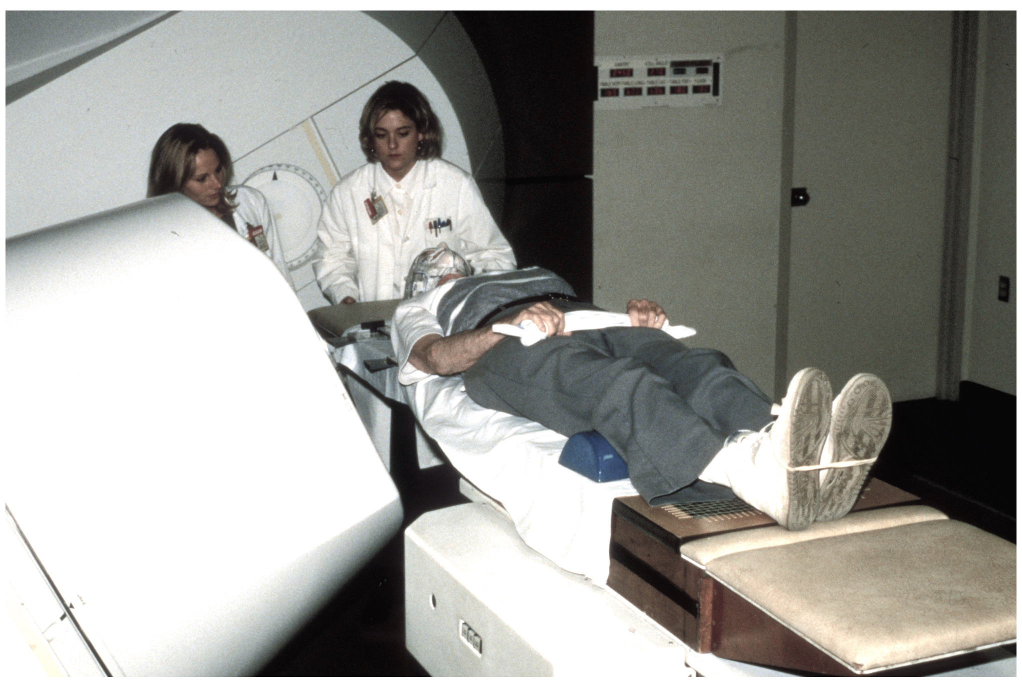
Verifying a radiation therapy system

Clinical Neutron Therapy System (CNTS) at UW



- 30 years of incident-free service.
- Controlled by custom software, built by CNTS engineering staff.
- Third generation of Therapy Control software built recently.

Verifying a radiation therapy system

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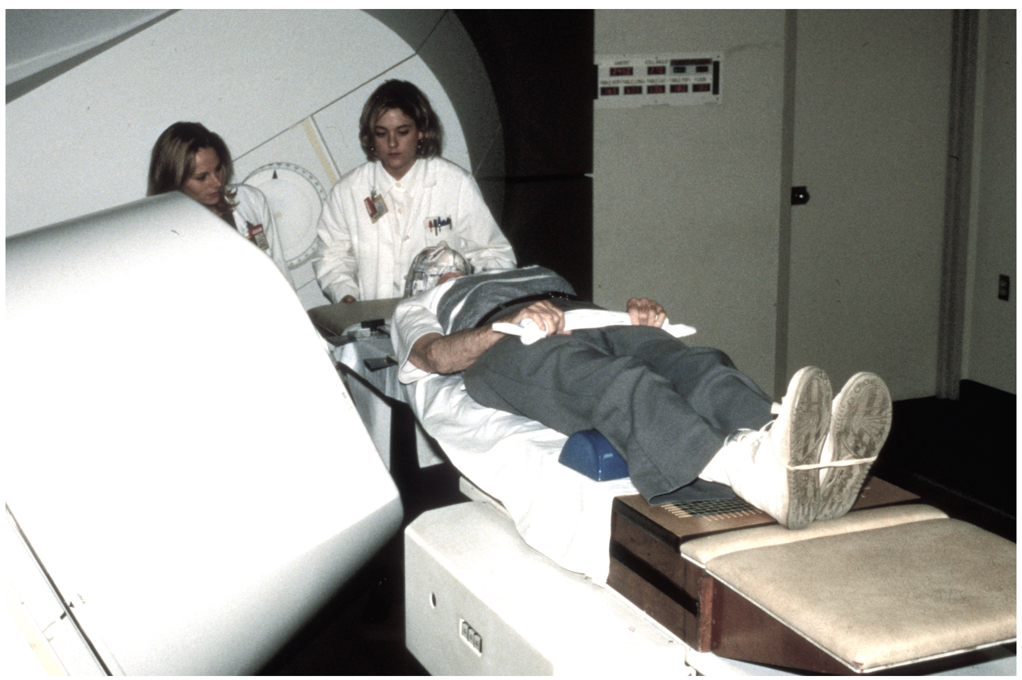

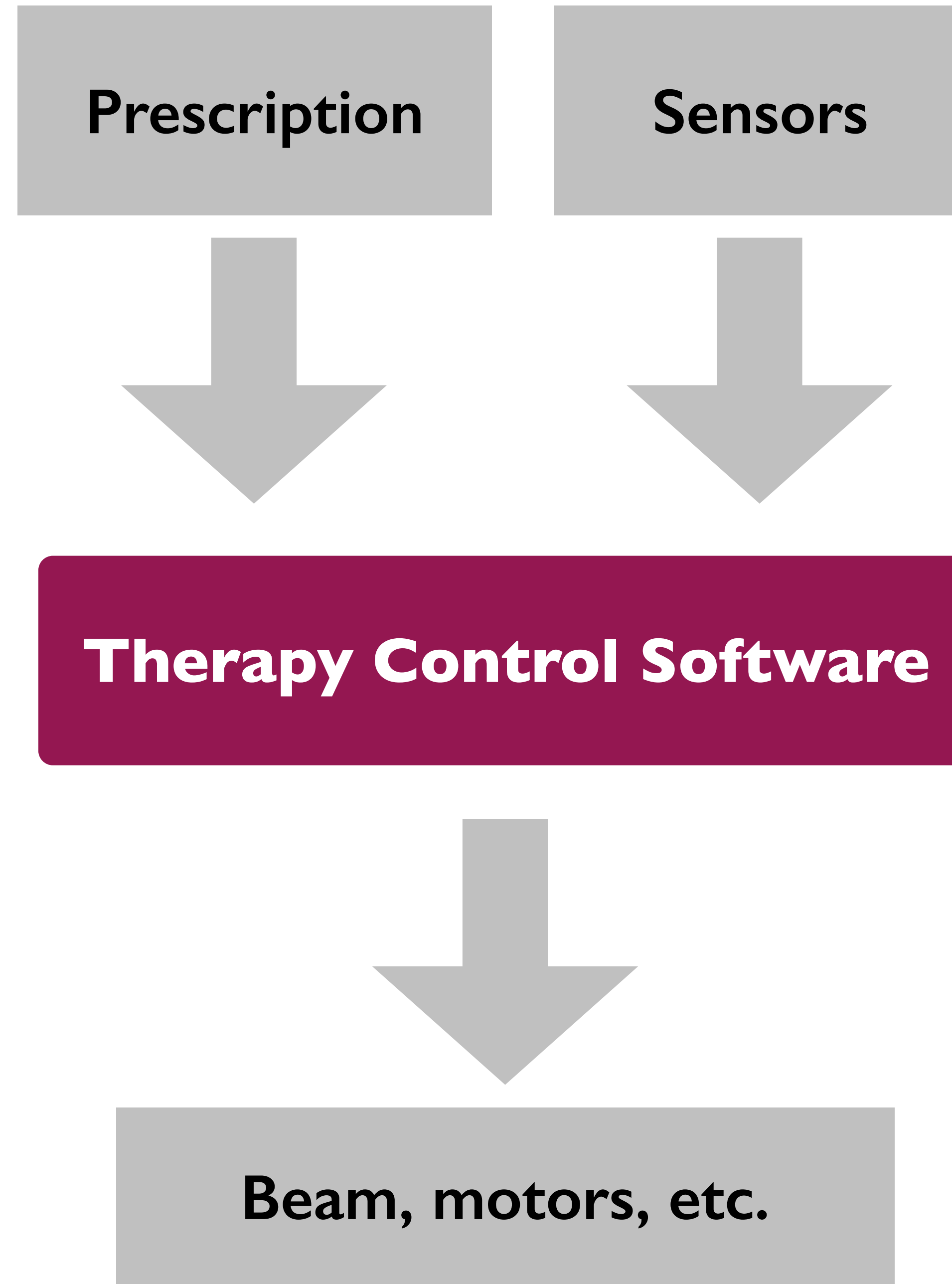

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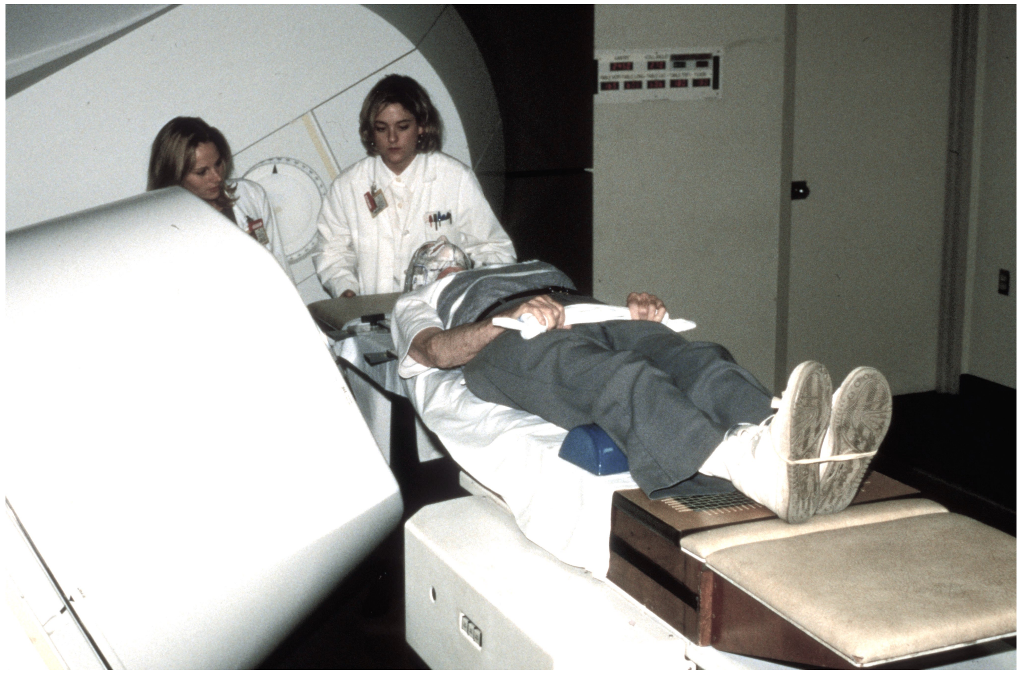

Experimental Physics and Industrial Control System (EPICS) Dataflow Language

Therapy Control Software

Verifying a radiation therapy system

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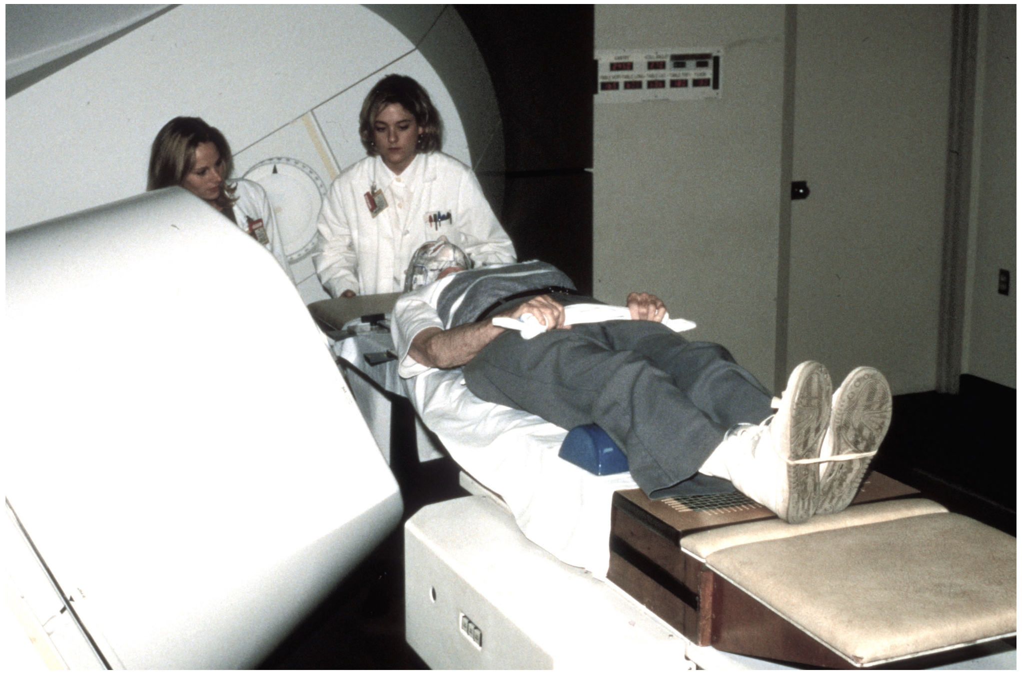

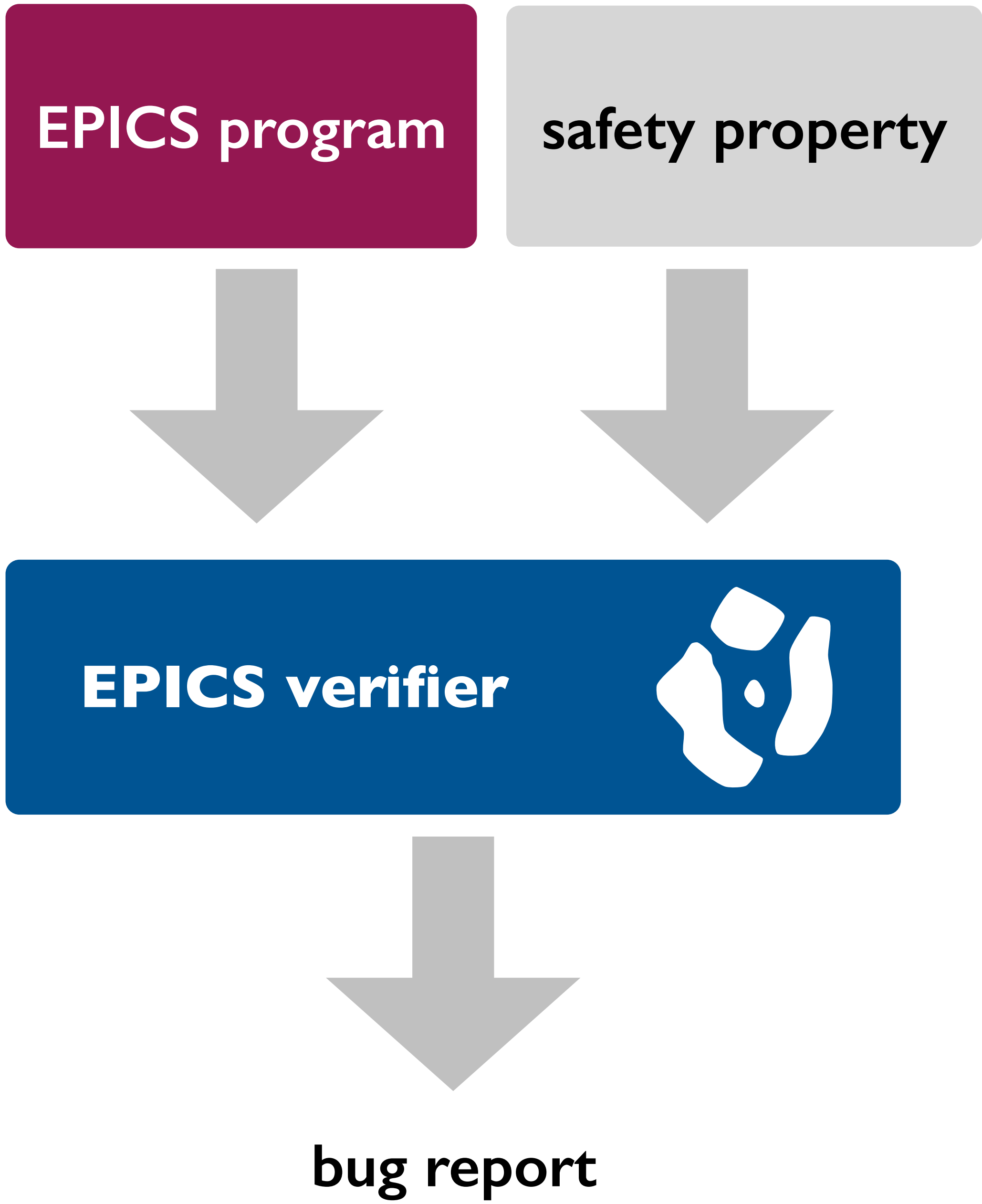

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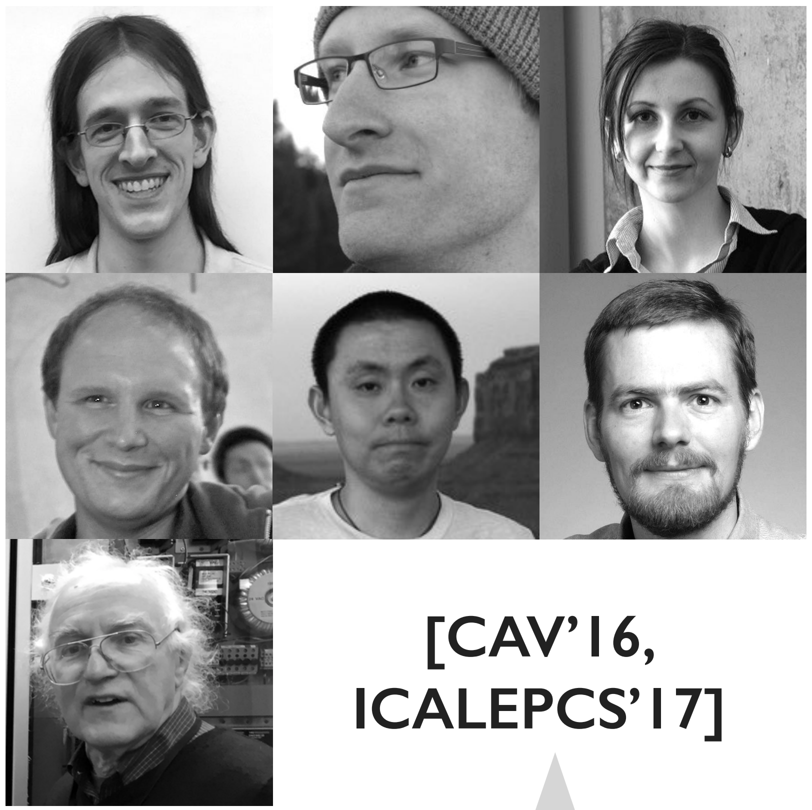
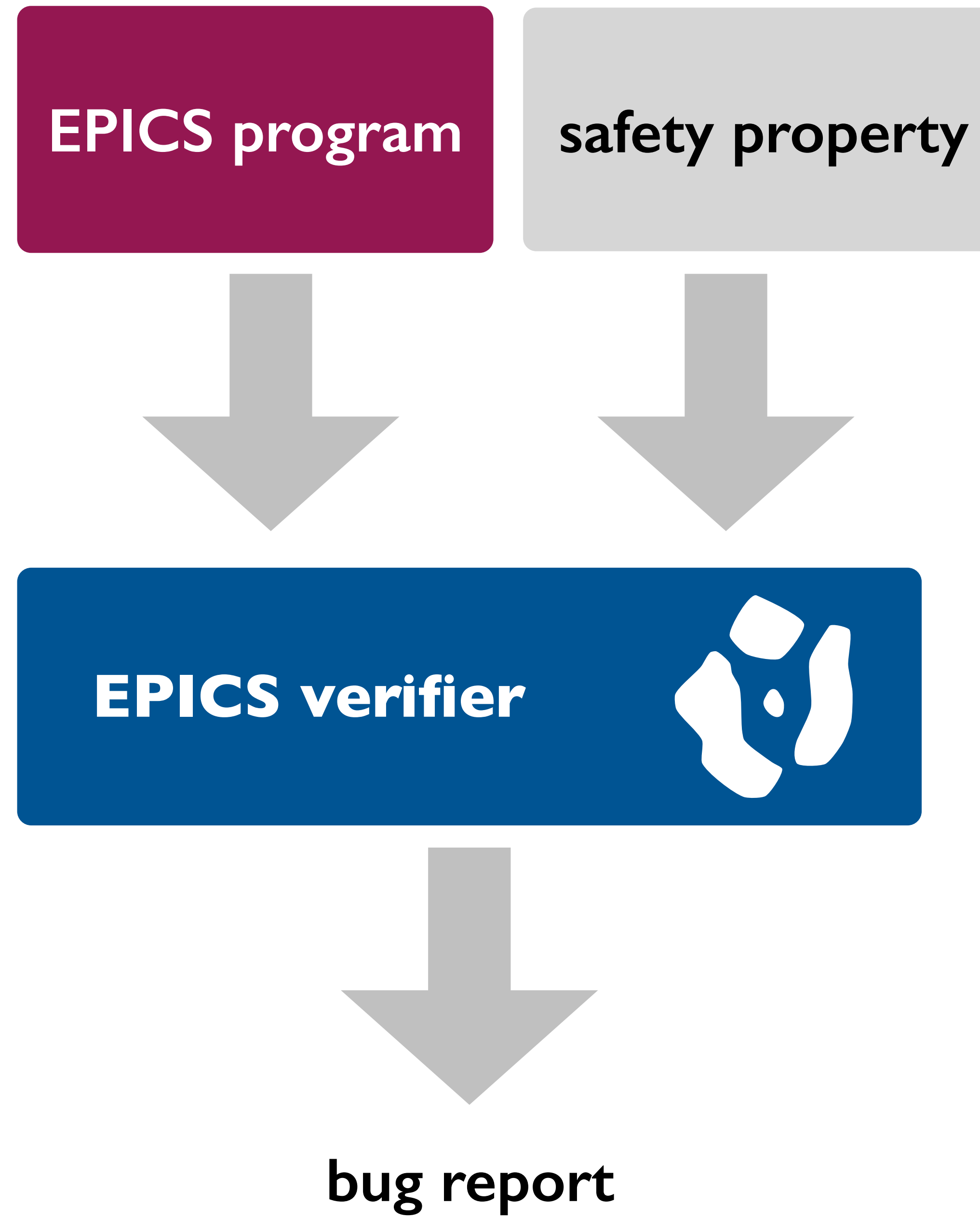


[CAV'16, ICALEPCS'17]

Found safety-critical defects in a pre-release version of the therapy control software.

Used by CNTS staff to verify changes to the controller.



Summary

Today

- Going pro with solver-aided programming.

Next lecture

- Getting started with SAT solving!