Solver-aided programming: going pro

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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 language via direct symbolic evaluation or language embedding.

How to build your own solver-aided language

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

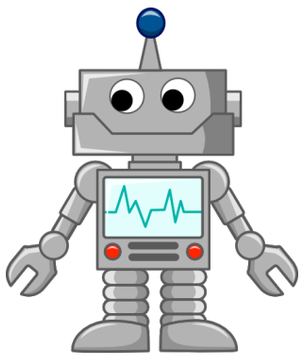
SDSL

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

SVM

SMT

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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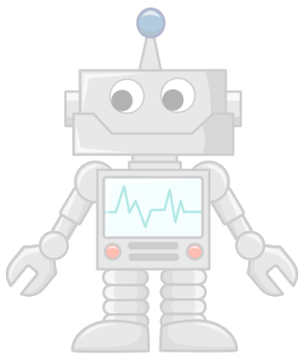

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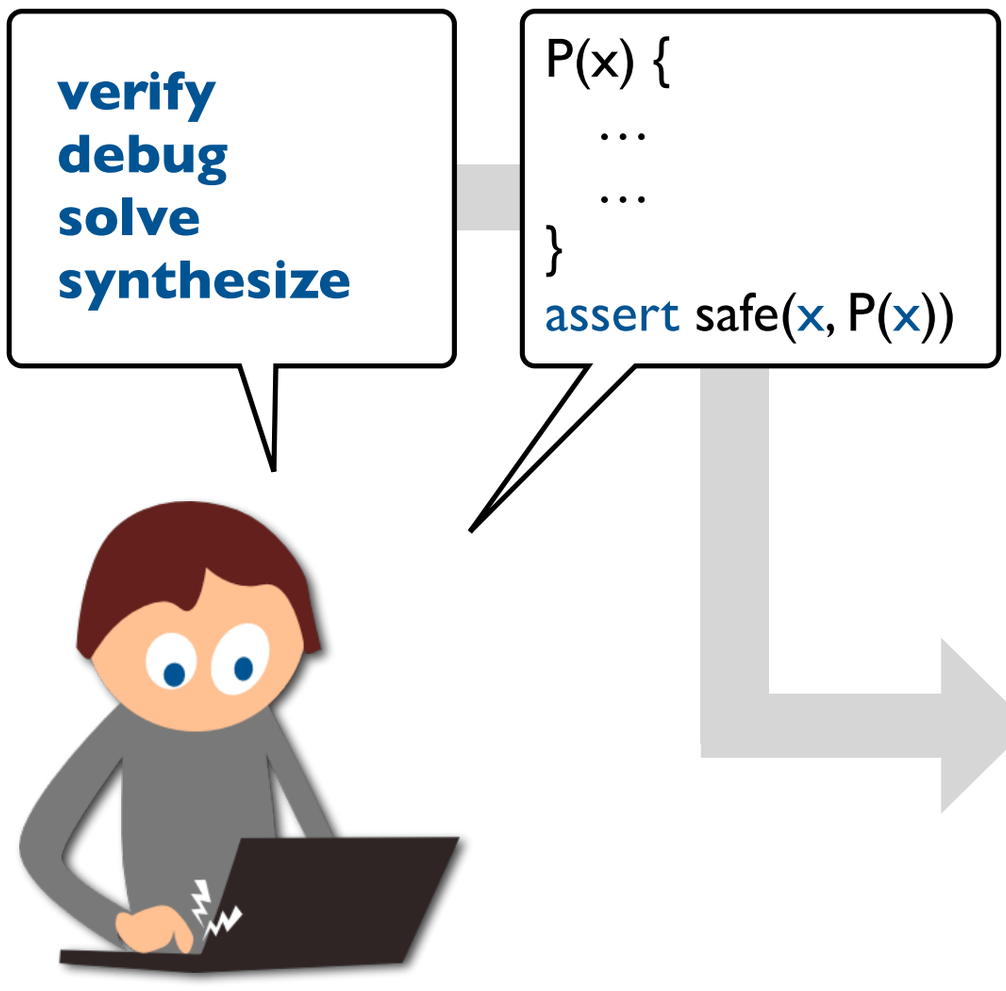

Recall the solver-aided programming tool chain: the tool reduces a query about program behavior to an SMT problem.

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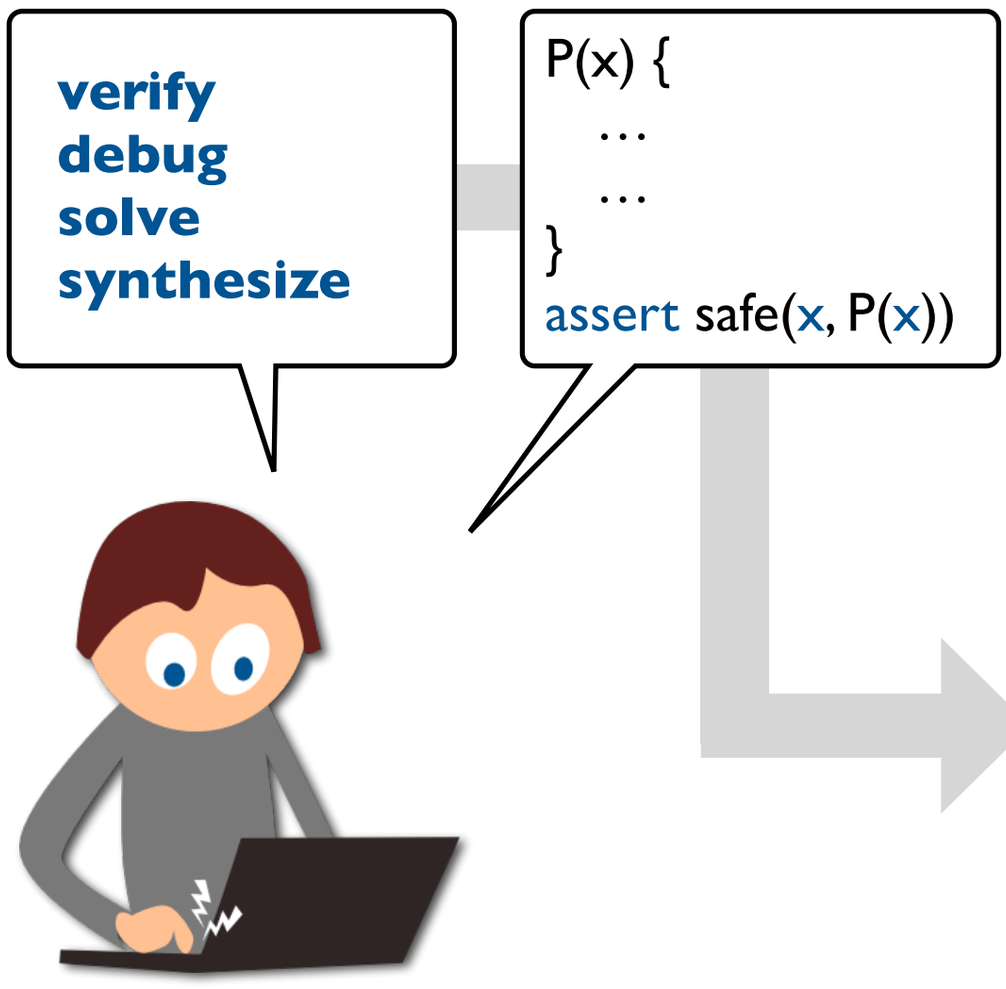

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What all queries have in common: they need to translate programs to constraints!

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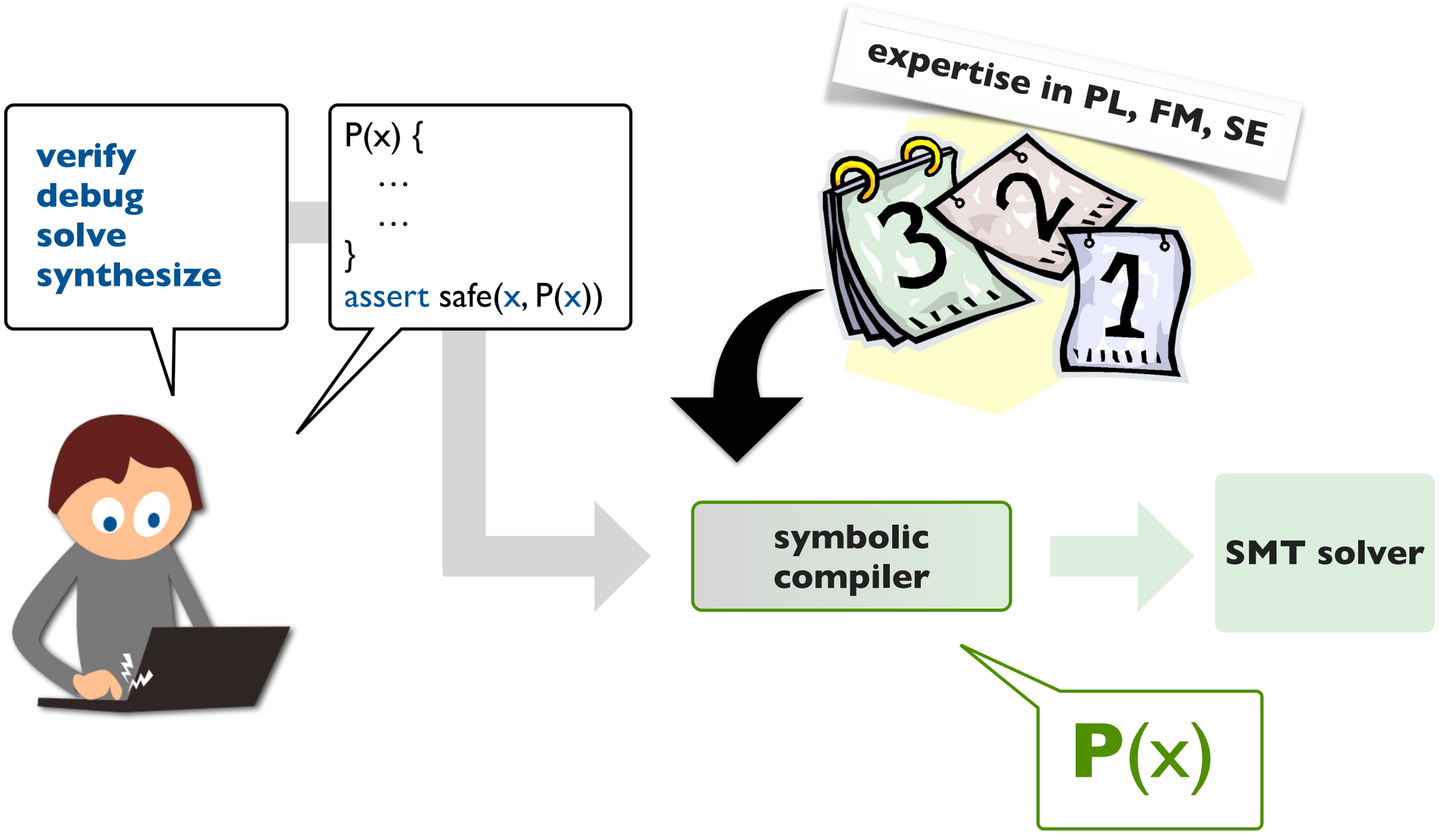

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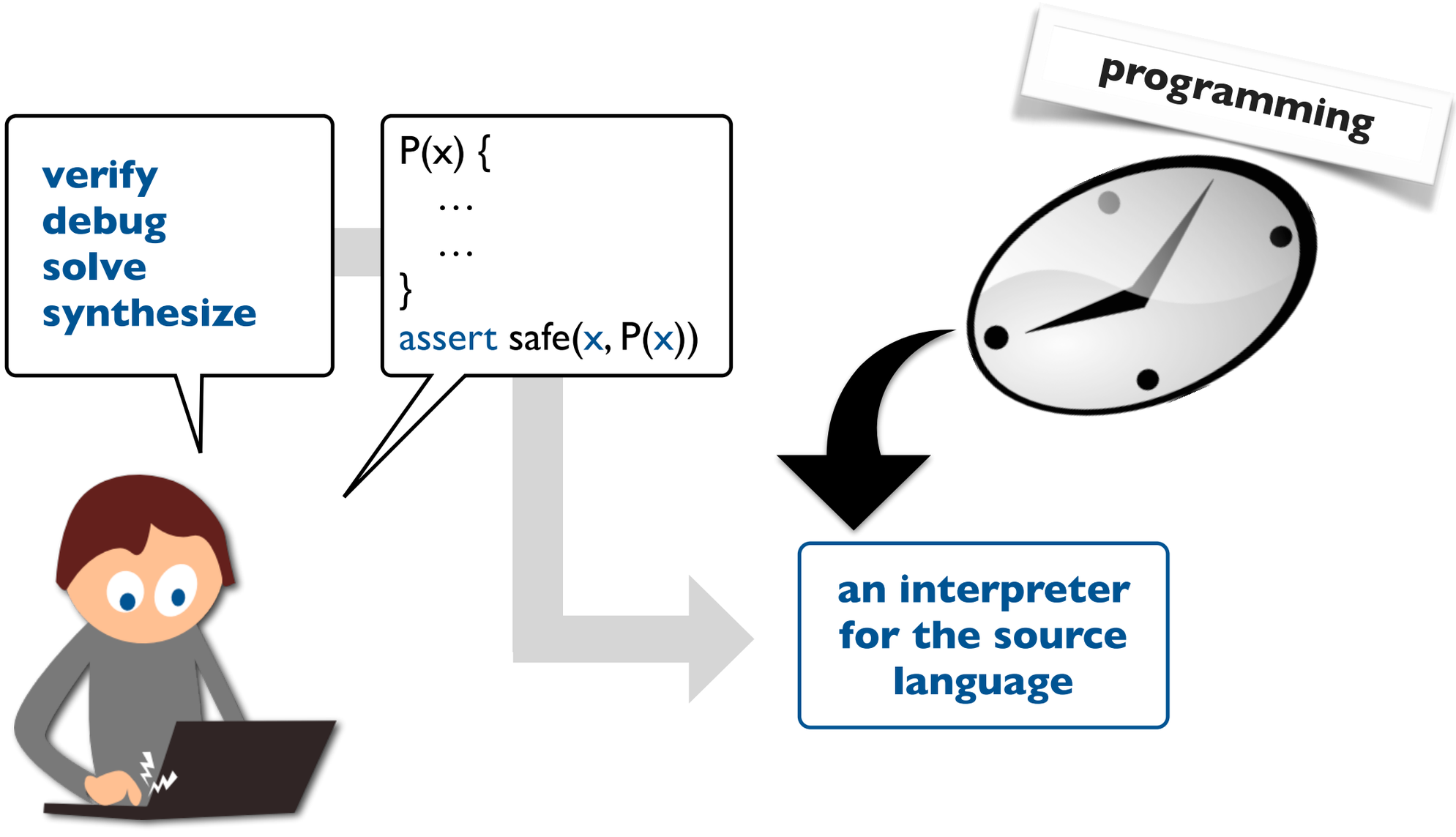

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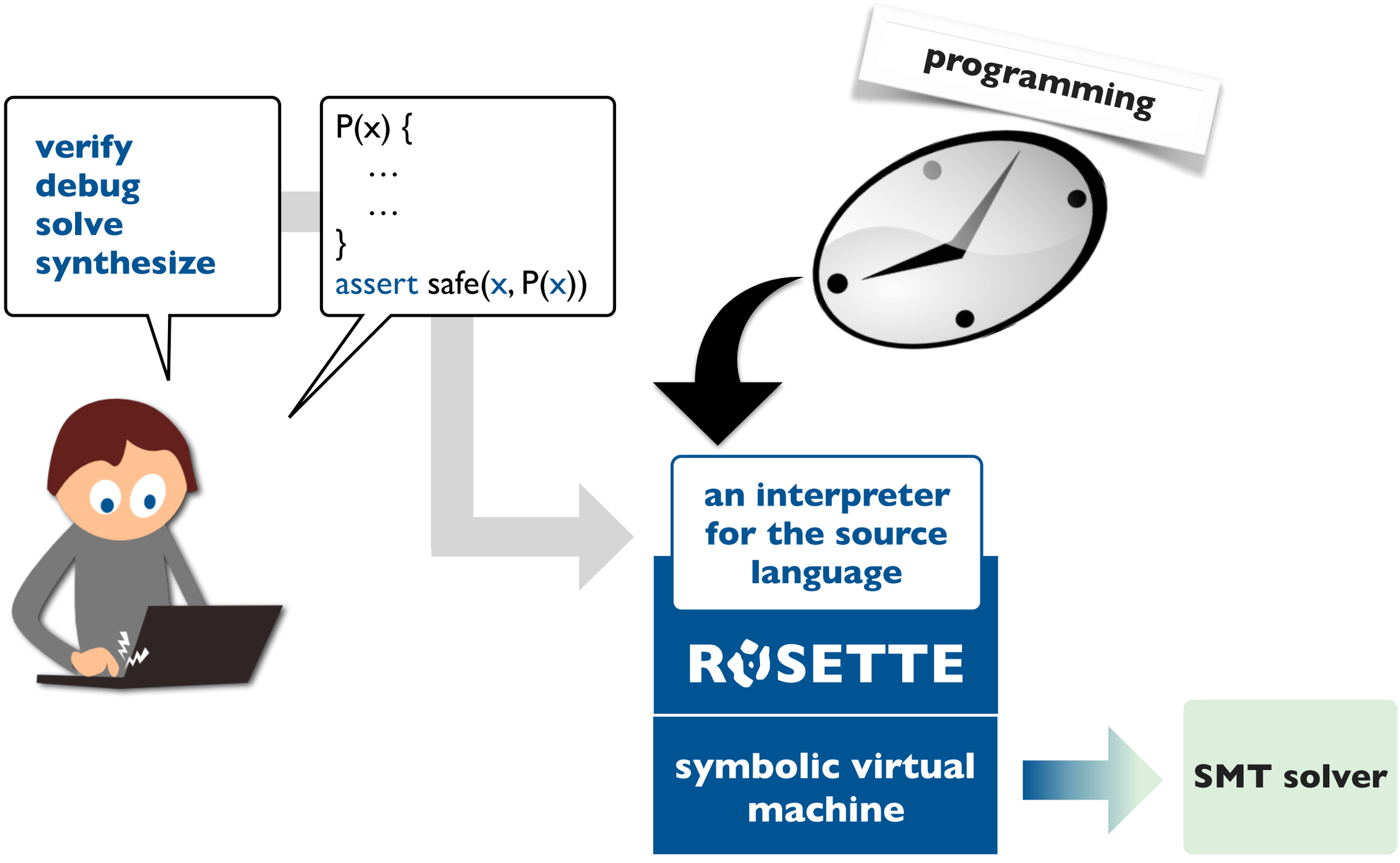

Wanted: an easier way to build tools

verify
debug
solve
synthesize

```
P(x) {
   …
   …
}
assert safe(x, P(x))
```

an interpreter for the source language

ROSETTE

symbolic virtual machine

SMT solver

Technical challenge: how to efficiently translate a program *and* its interpreter?

[Torlak & Bodik, **PLDI'14**]

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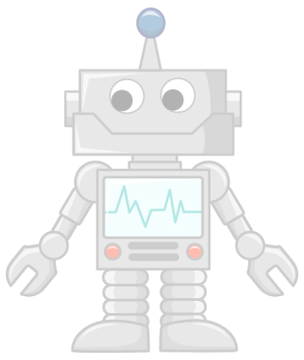

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Layers of classic languages: DSLs and hosts

domain-specific language (DSL)

A formal language that is specialized to a particular application domain and often limited in capability.

host language

A high-level language for implementing DSLs, usually with meta-programming features.

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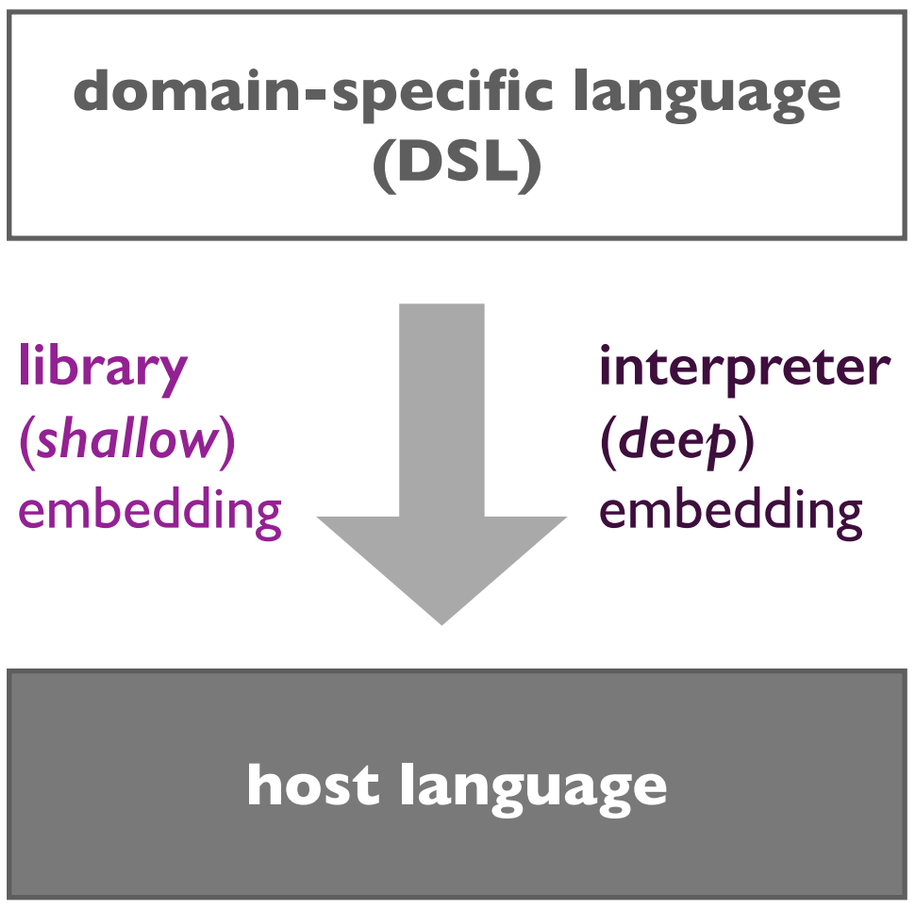

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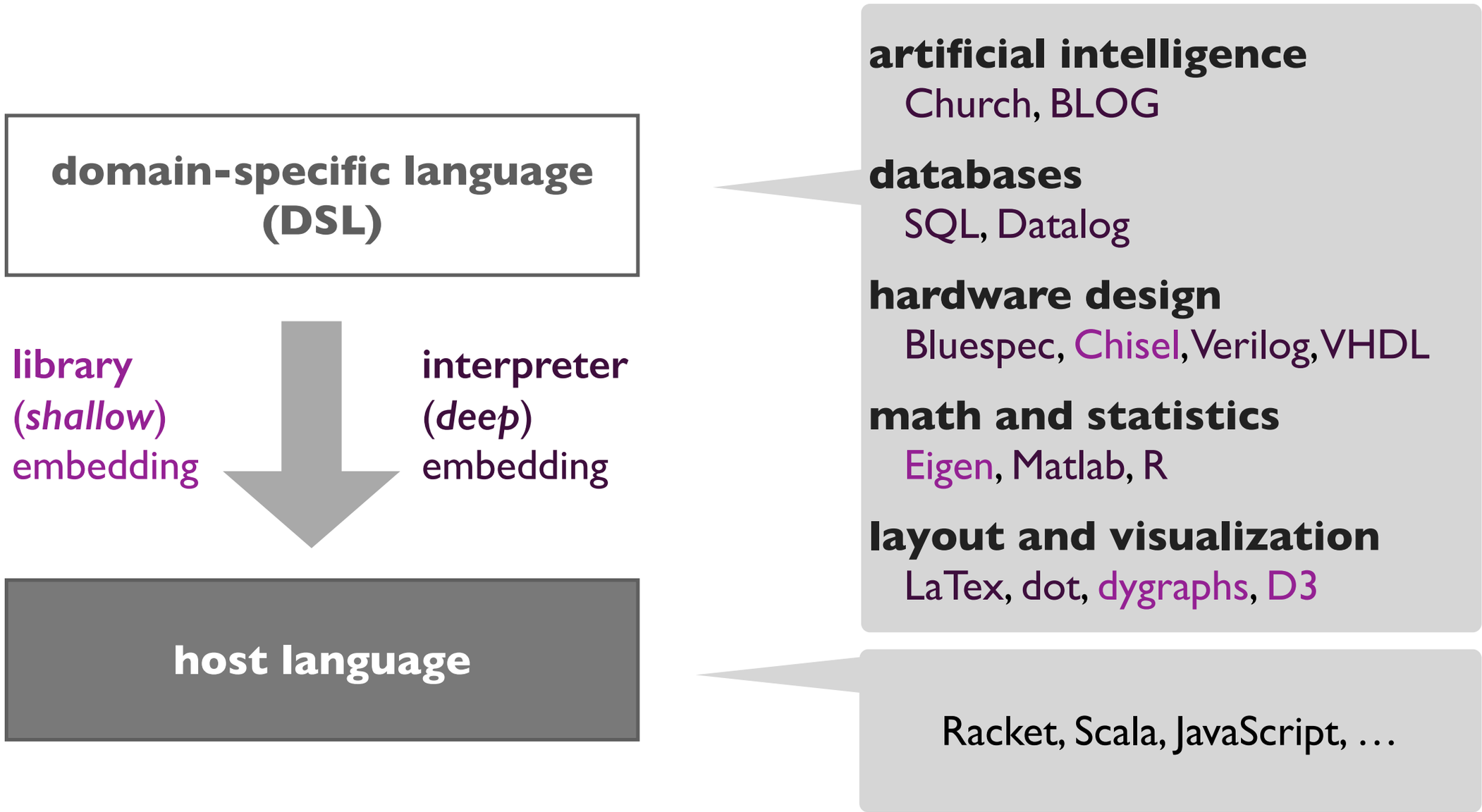
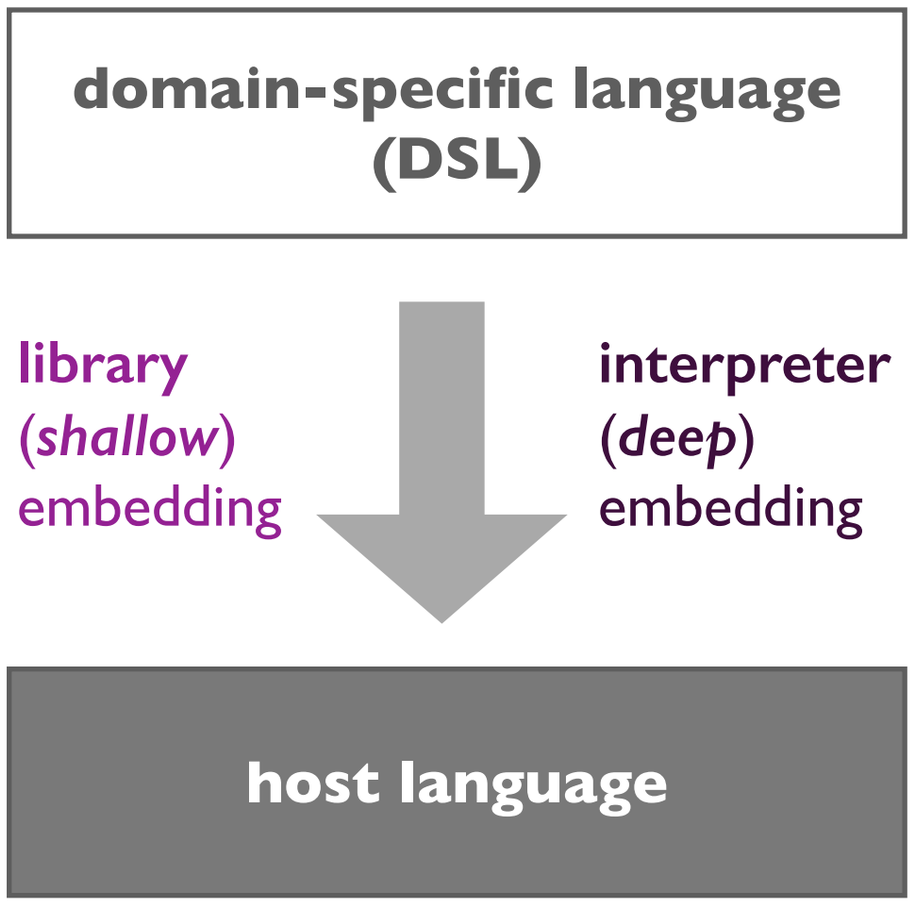
Layers of classic languages: many DSLs and hosts



Layers of classic languages: why DSLs?



Eigen / Matlab

```
C = A * B
```

C / Java

```
for (i = 0; i < n; i++)
 for (j = 0; j < m; j++)
  for (k = 0; k < p; k++)
   C[i][k] += A[i][j] * B[j][k]
```

Layers of classic languages: why DSLs?

domain-specific language (DSL)

library (*shallow*) embedding

interpreter (*deep*) embedding

host language

Easier for people to read, write, and get right.

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[associativity]

Easier for tools to analyze.

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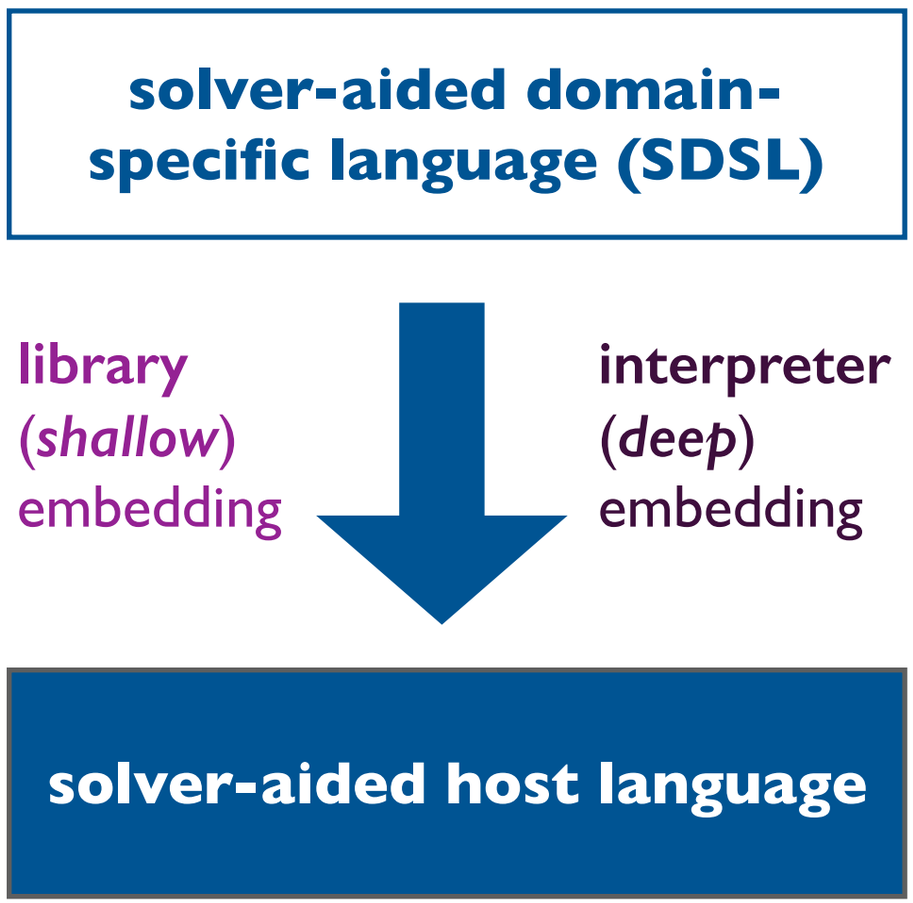
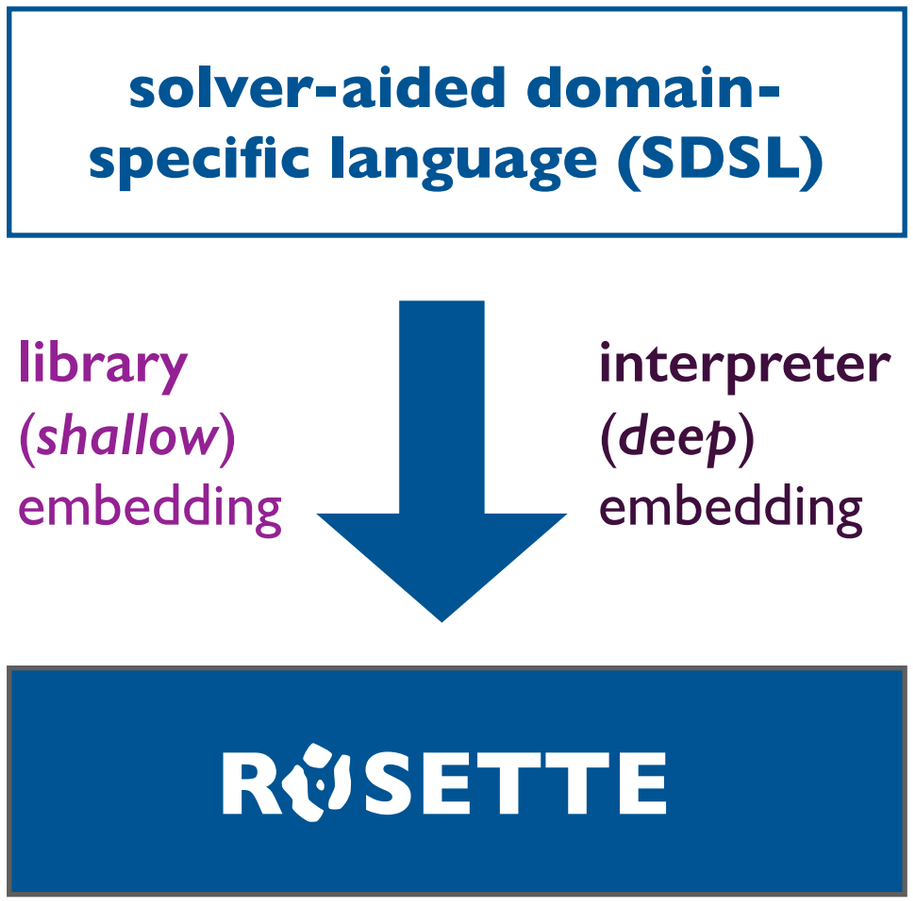
Layers of solver-aided languages



Layers of solver-aided languages: tools as SDSLs



education and games
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synthesis-aided compilation
LinkiTools, Chlorophyll (PLDI'14), GreenThumb (ASPLOS'16)

type system soundness
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databases
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radiation therapy control
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... and more

Layers of solver-aided languages: tools as SDSLs

solver-aided domain-specific language (SDSL)

library (*shallow*) embedding

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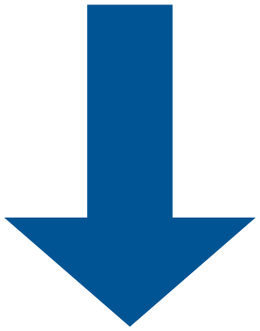

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A tiny example SDSL

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

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

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

1. interpreter [10 LOC]
2. verifier [free]
3. debugger [free]
4. synthesizer [free]

A tiny example SDSL

ROSETTE

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> bvmax(-2, -1)
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`(out opcode in ...)`

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ROSETTE

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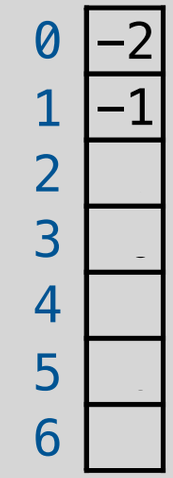


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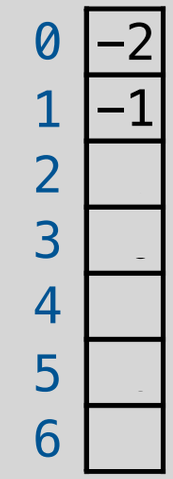


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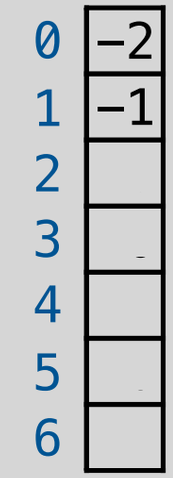


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- pattern matching
- dynamic evaluation
- first-class & higher-order procedures
- side effects

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  r5 = bvand(r3, r4)
  r6 = bvxor(r1, r5)
  return r6

> verify(bvmax, max)
```

query

RⓄSETTE

```
(define-symbolic* in (bitvector 32) [2])
(verify
  (assert (equal? (interpret bvmax in)
                  (interpret max in))))
```

A tiny example SDSL

```
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

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

query

RUSETTE

```
(define-symbolic* in (bitvector 32) [2])
(verify
  (assert (equal? (interpret bvmax in)
                  (interpret max in))))
```

A tiny example SDSL

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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

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

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

query

RⓄSETTE

```
(define-symbolic* in (bitvector 32) [2])
(verify
  (assert (equal? (interpret bvmax in)
                  (interpret max in))))
```

A tiny example SDSL

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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
```

```
> debug(bvmax, max,‘(0, -2))
```

query

```
(define in (list 0 -2))
(debug [integer?]
  (assert (equal? (interpret bvmax in)
                  (interpret max in))))
```

ROSETTE

A tiny example SDSL

ROSETTE

```
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

> debug(bvmax, max,‘(0, -2))
```

query

```
(define in (list 0 -2))
(debug [integer?]
  (assert (equal? (interpret bvmax in)
                  (interpret max in))))
```

A tiny example SDSL

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

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

query

ROSETTE

```
(define-symbolic* in (bitvector 32) [2])
(synthesize
  #:forall in
  #:guarantee
  (assert (equal? (interpret bvmax in)
                  (interpret max in)))))
```

A tiny example SDSL

```
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

RⓄSETTE

```
(define-symbolic* in (bitvector 32) [2])
(synthesize
  #:forall in
  #:guarantee
  (assert (equal? (interpret bvmax in)
                  (interpret max in)))))
```

How to build your own solver-aided language

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

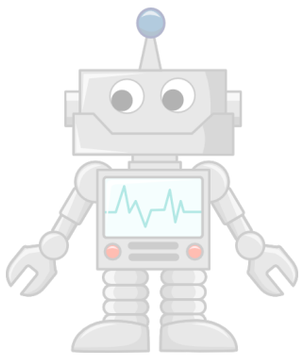
SDSL

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

SVM

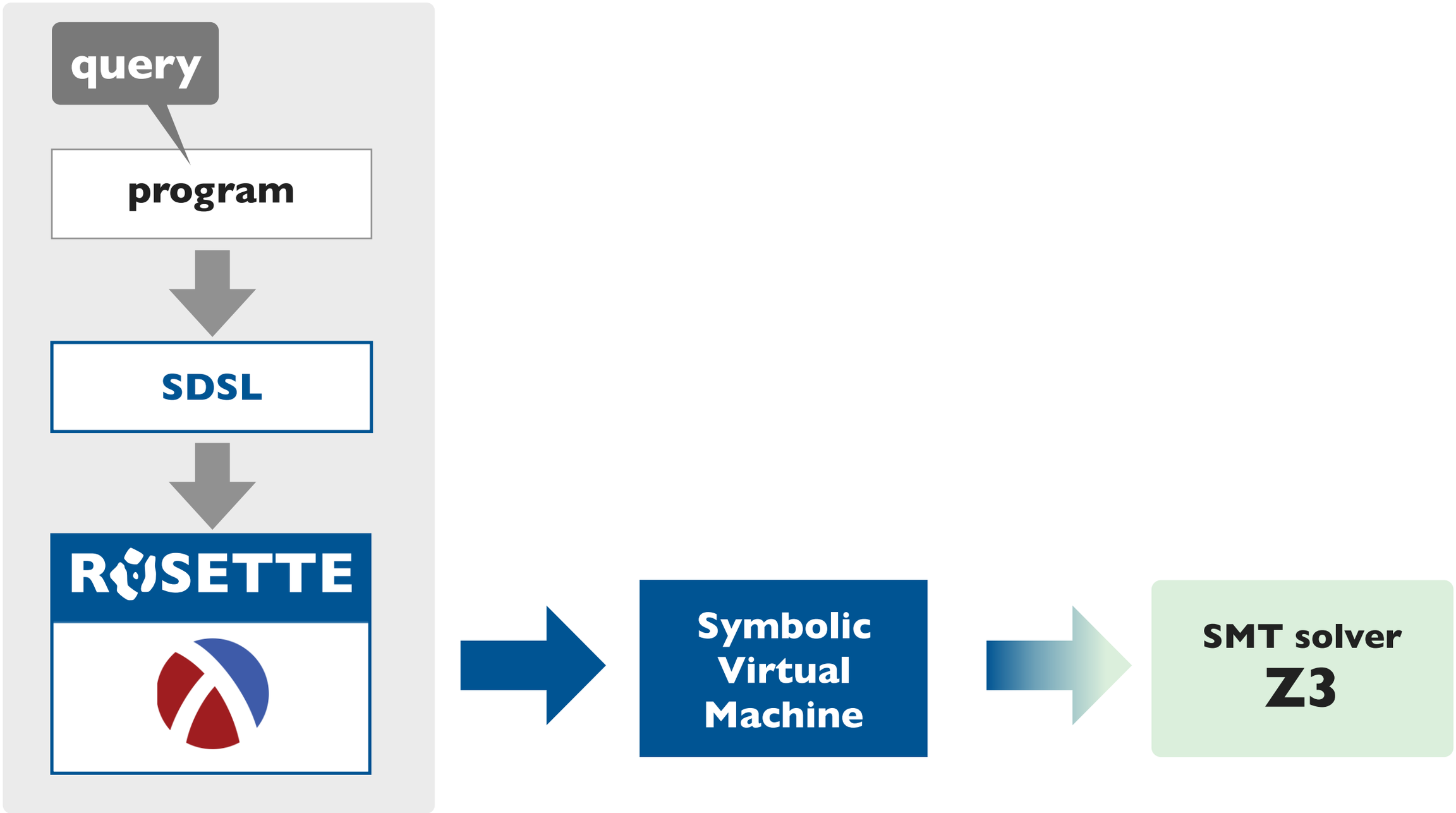
SMT

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

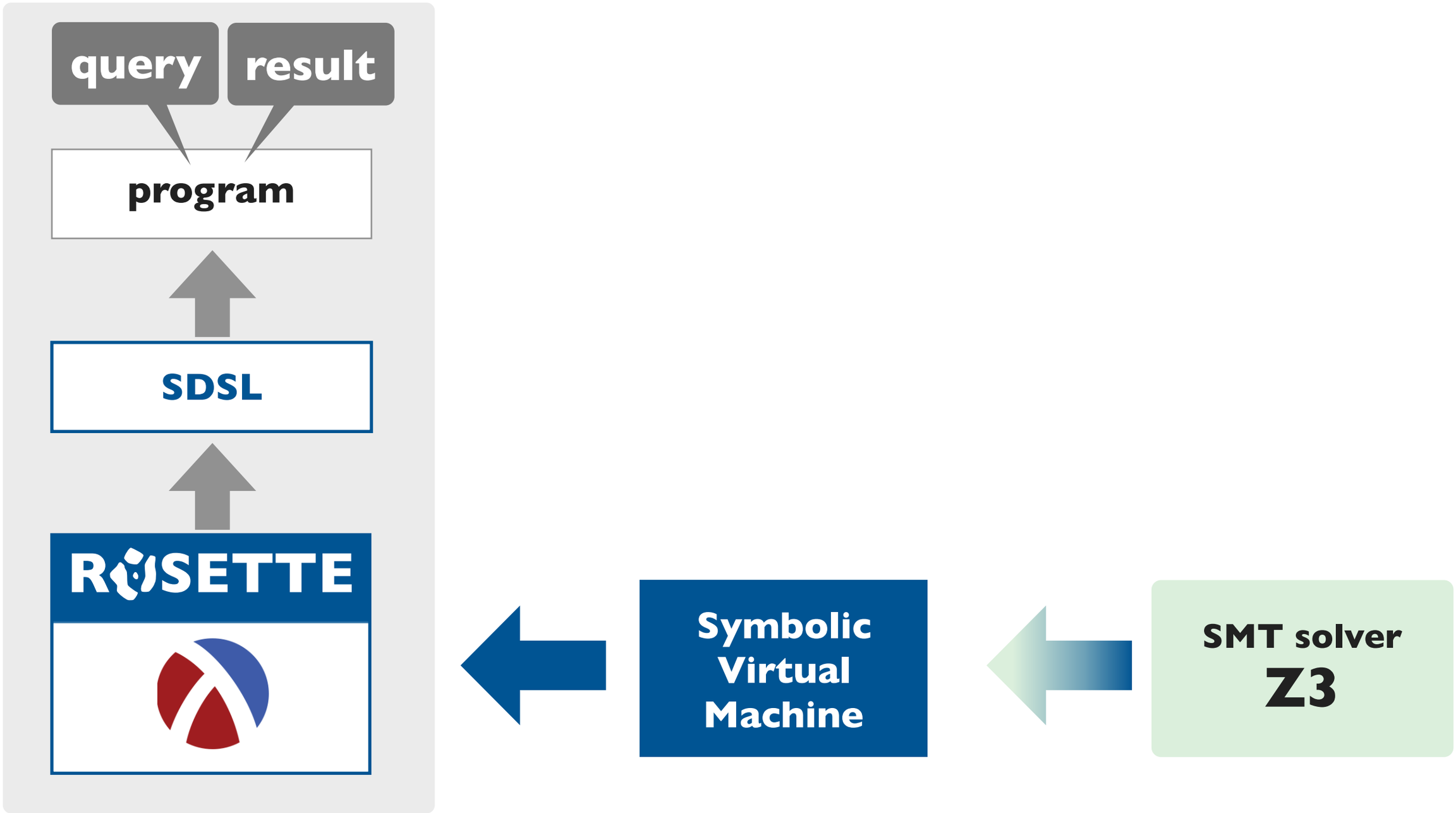


A last look: a few recent applications
Cool tools built with Rosette!

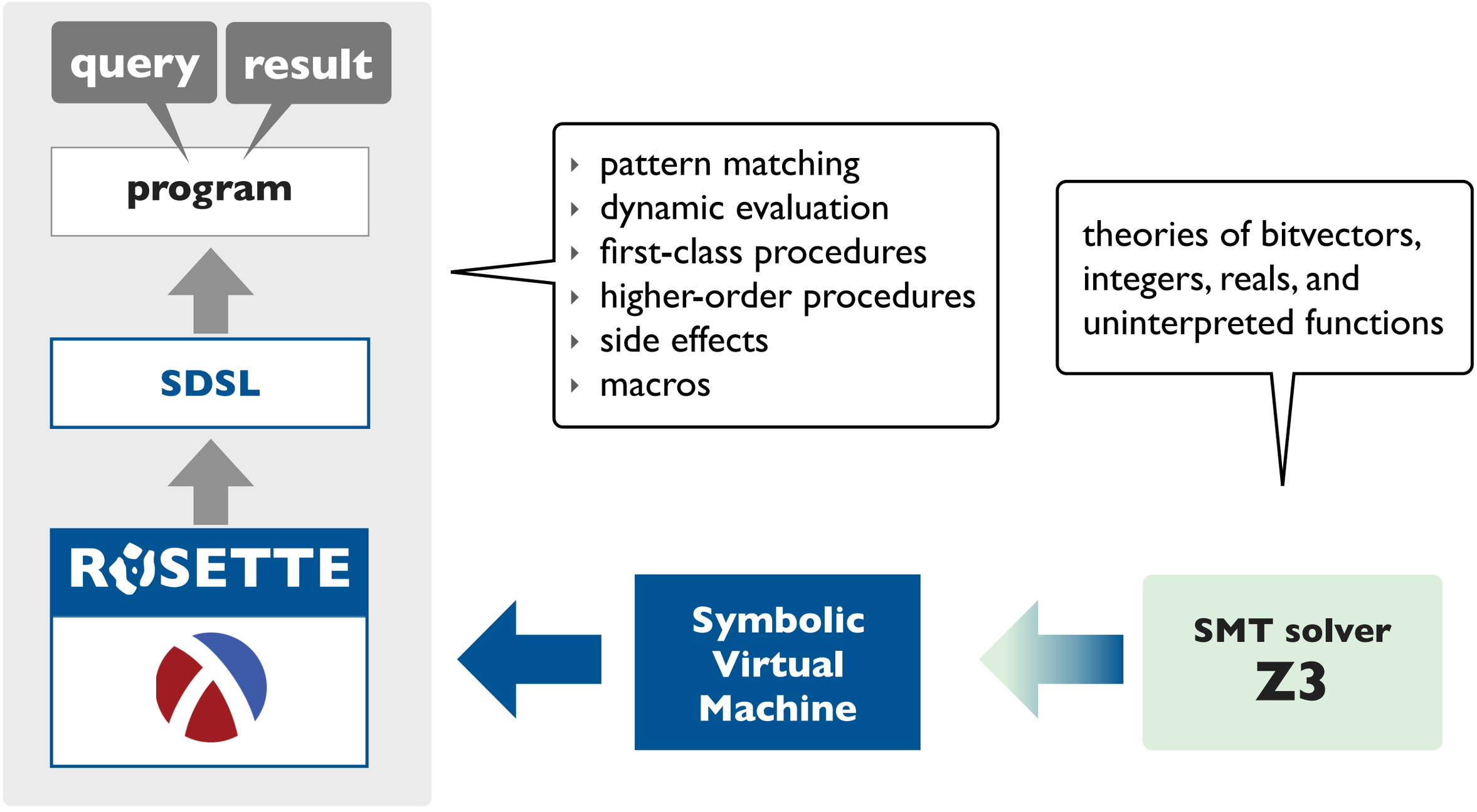
How it all works: a big picture view



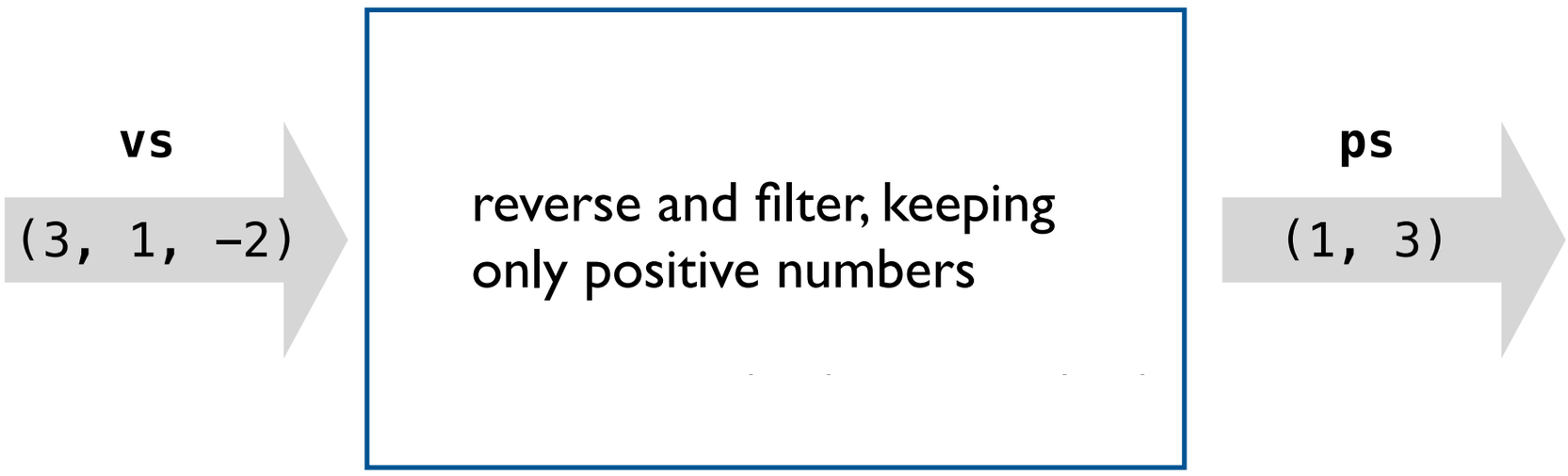
How it all works: a big picture view



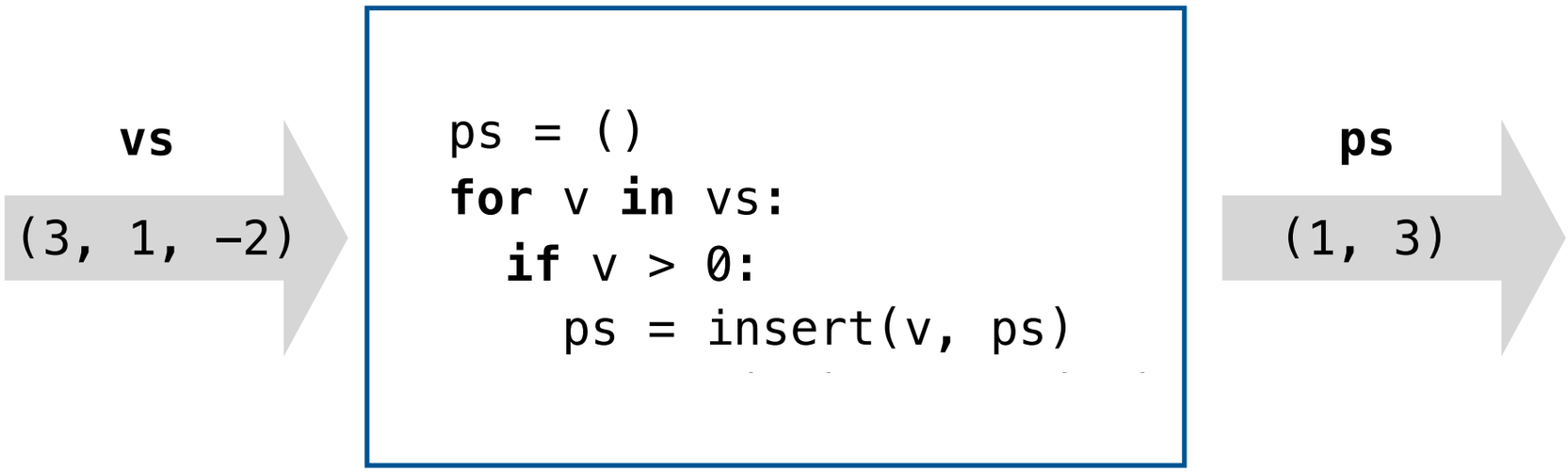
How it all works: a big picture view



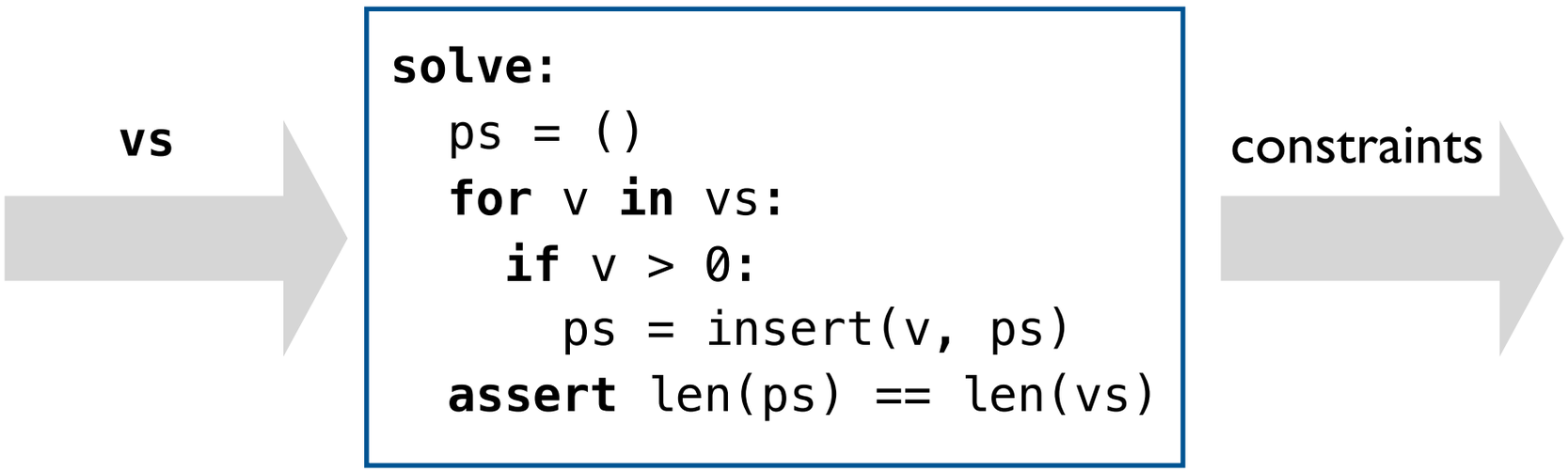
Translation to constraints by example



Translation to constraints by example



Translation to constraints by example



Translation to constraints by example

vs

```
(a, b)
```

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

constraints

Translation to constraints by example

vs

(a, b)

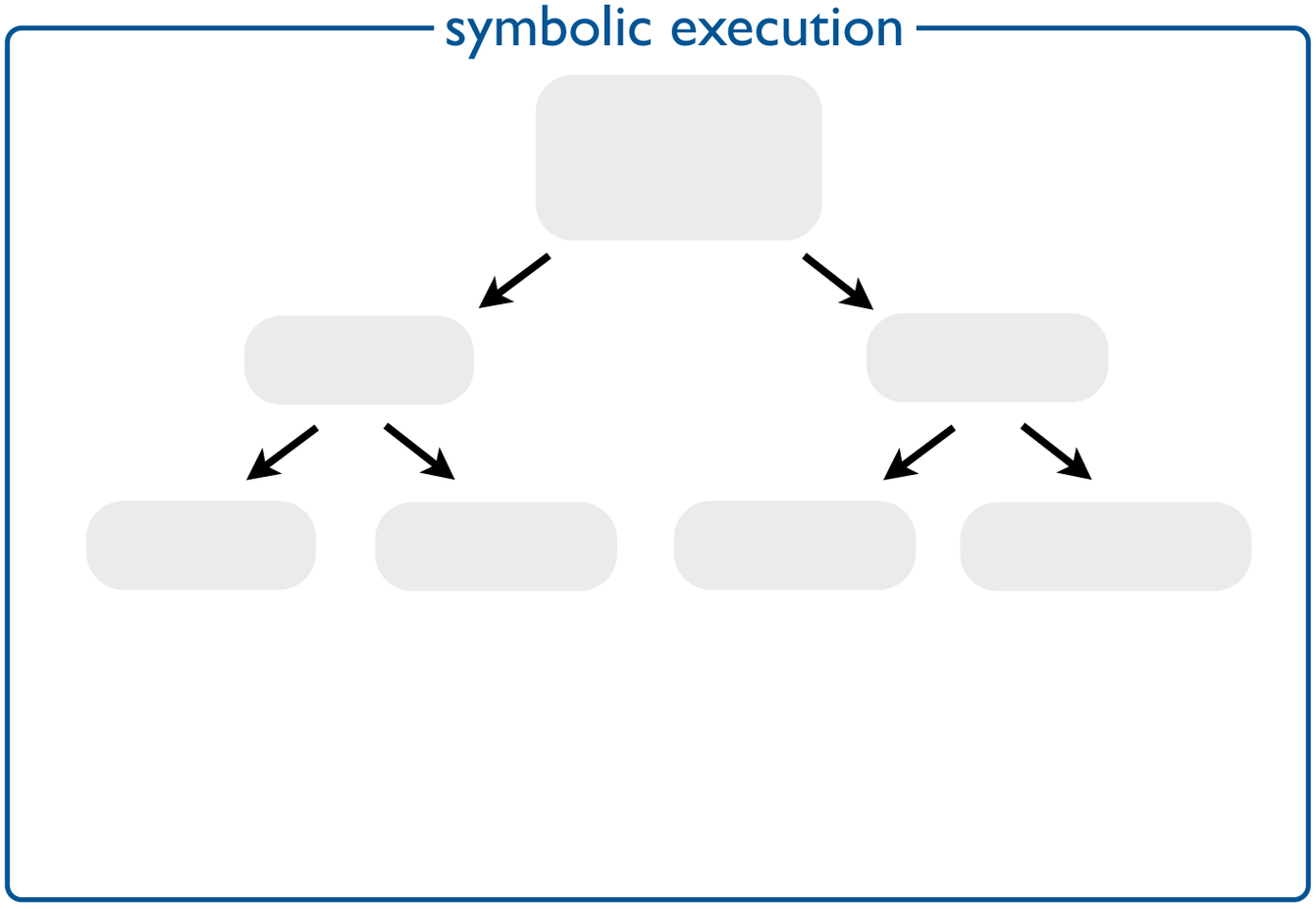
```
solve:
  ps = ()
  for v in vs:
    if v > 0:
      ps = insert(v, ps)
  assert len(ps) == len(vs)
```

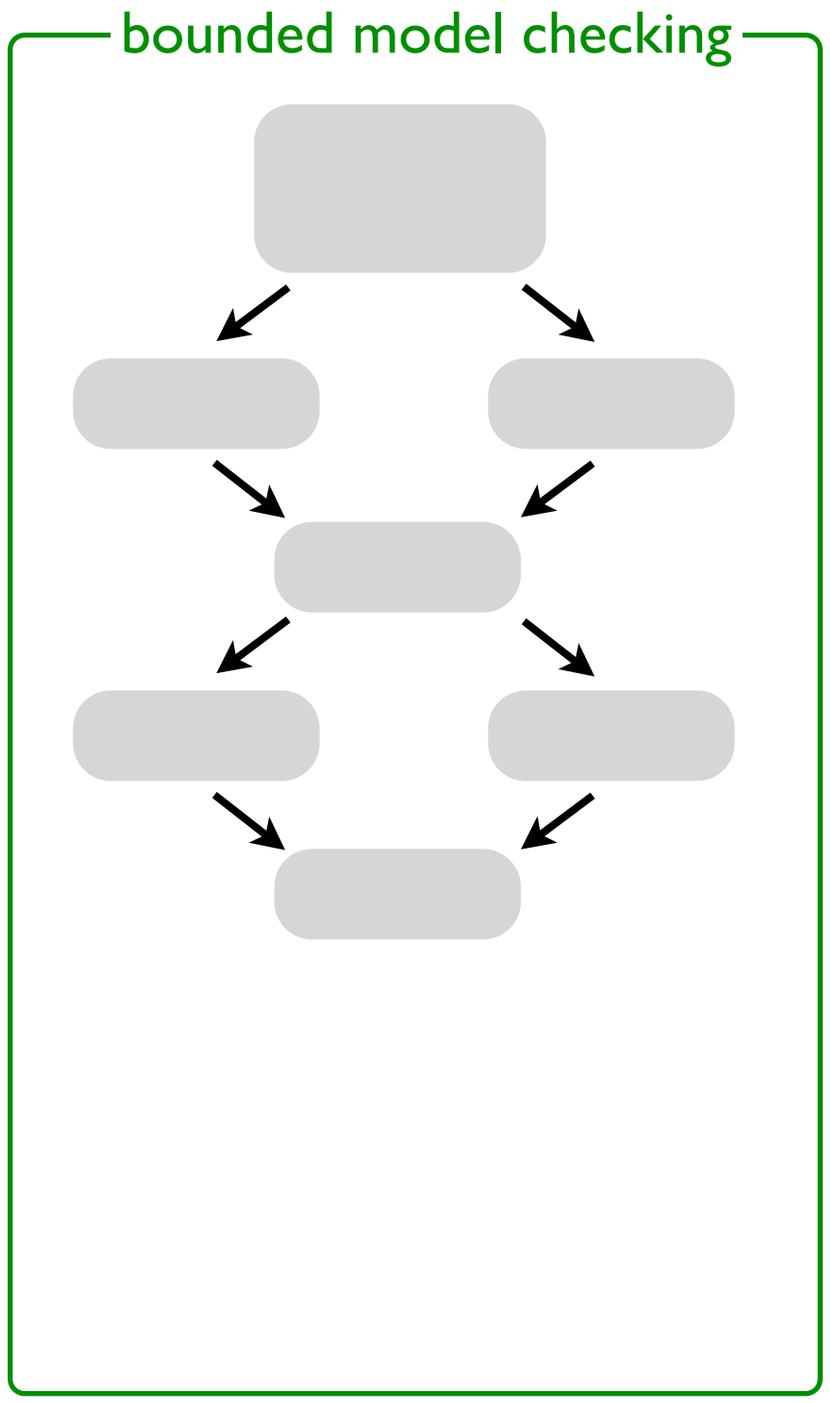
constraints

a>0 ∧ b>0

Design space of precise symbolic encodings

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





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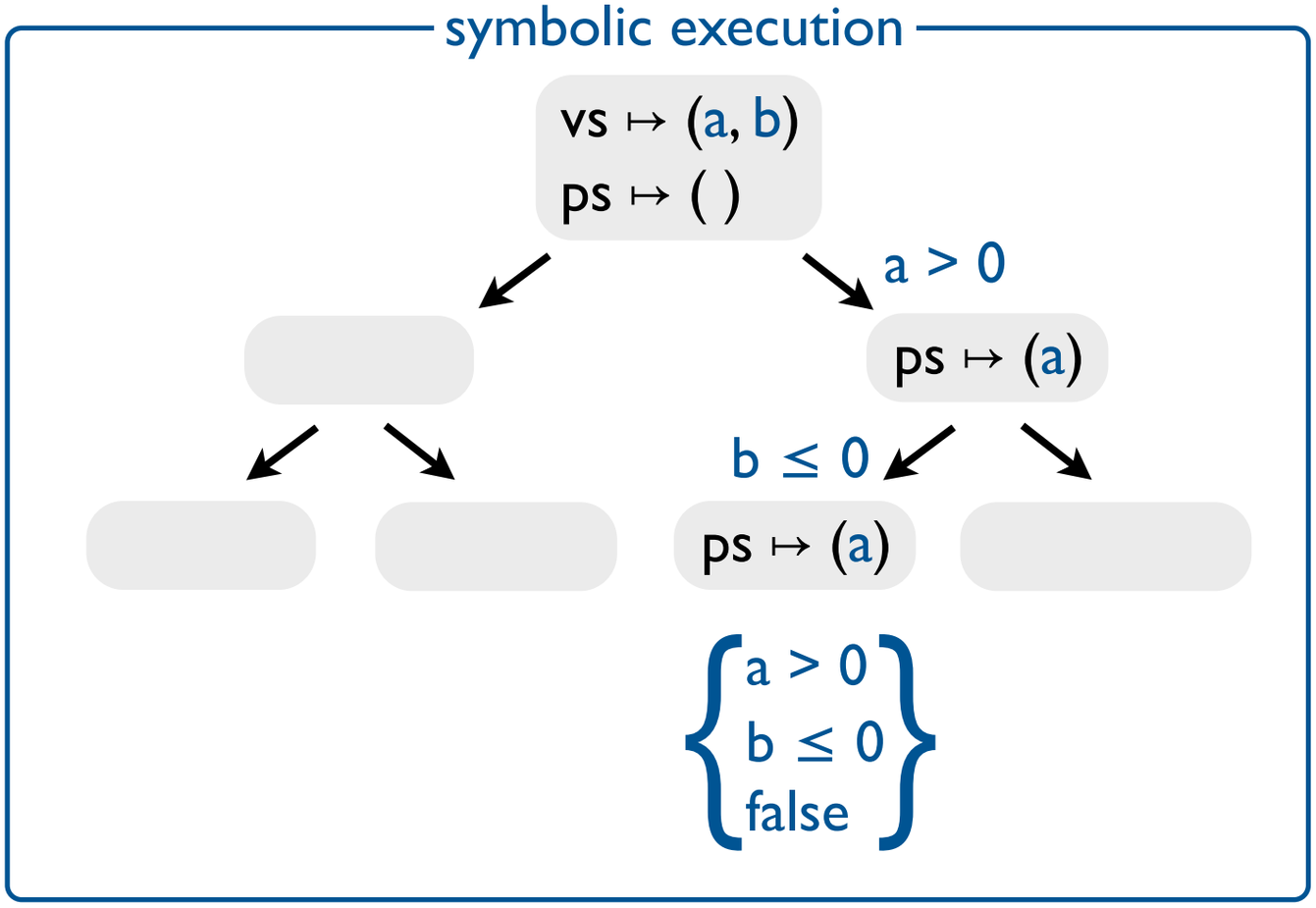

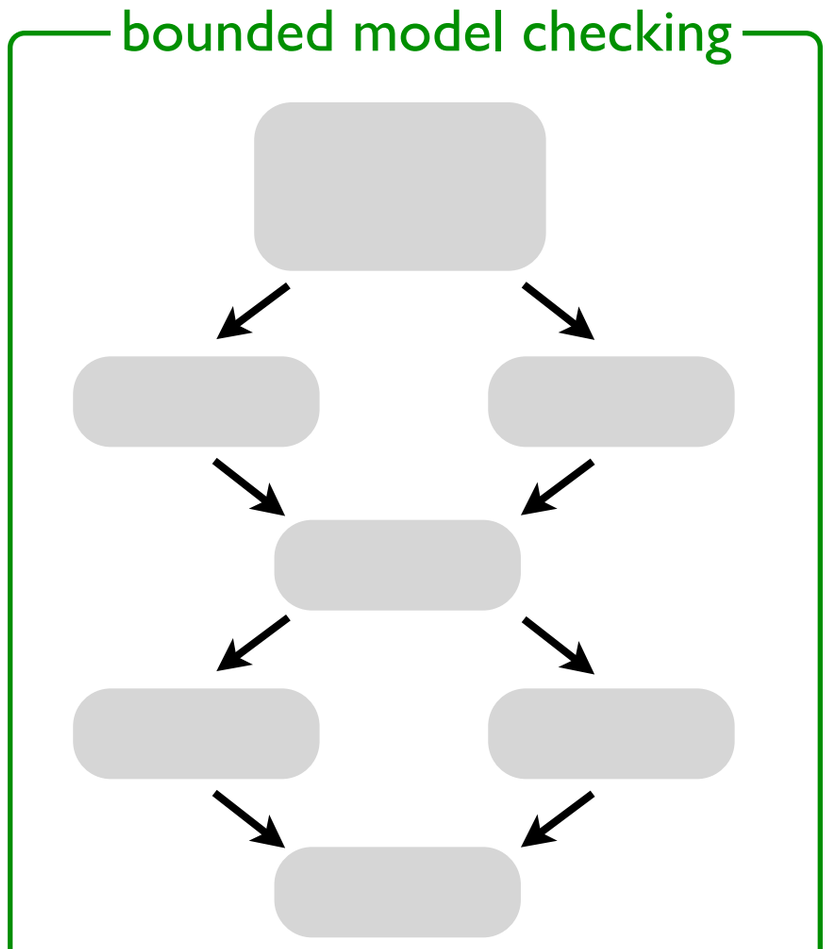

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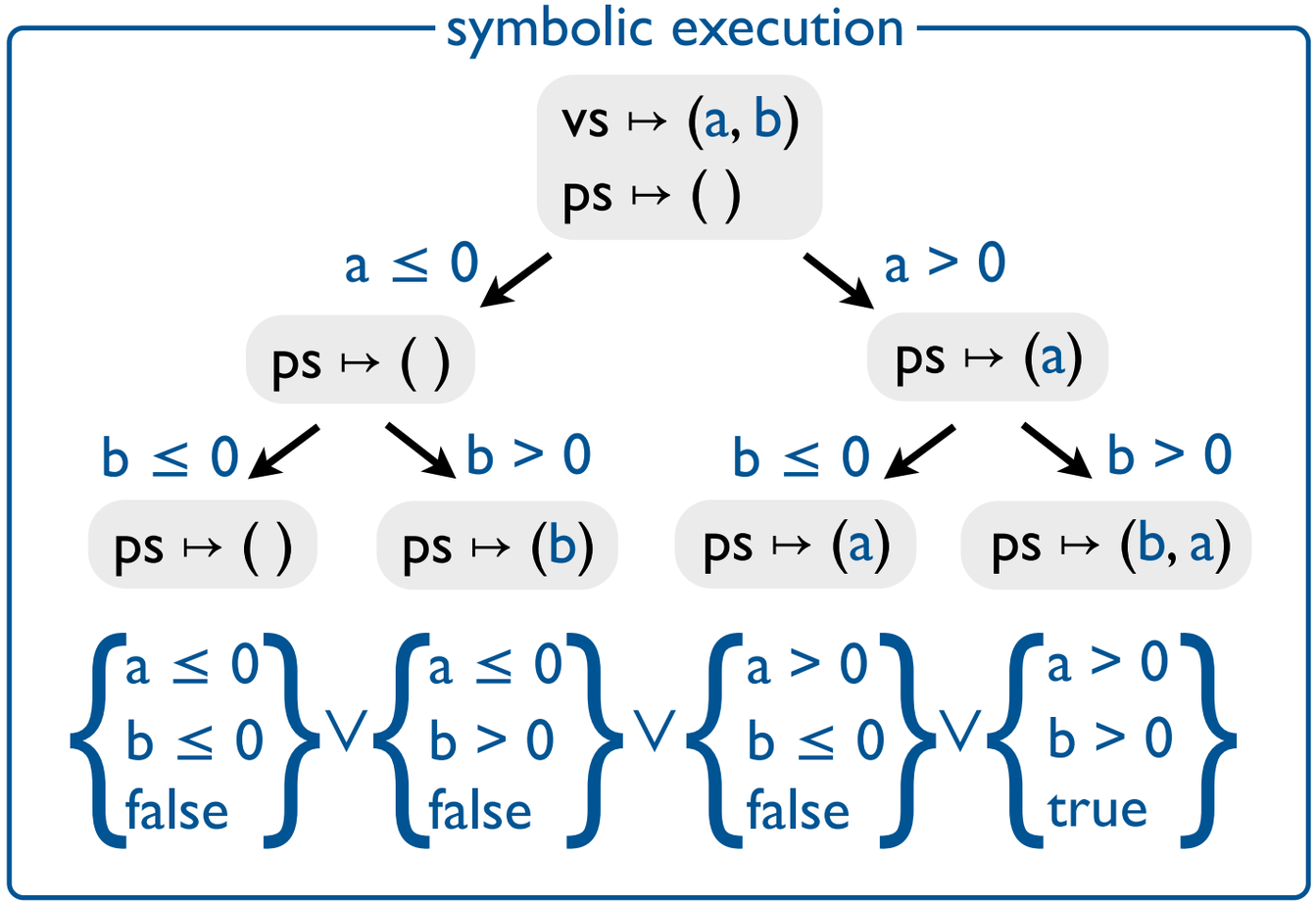

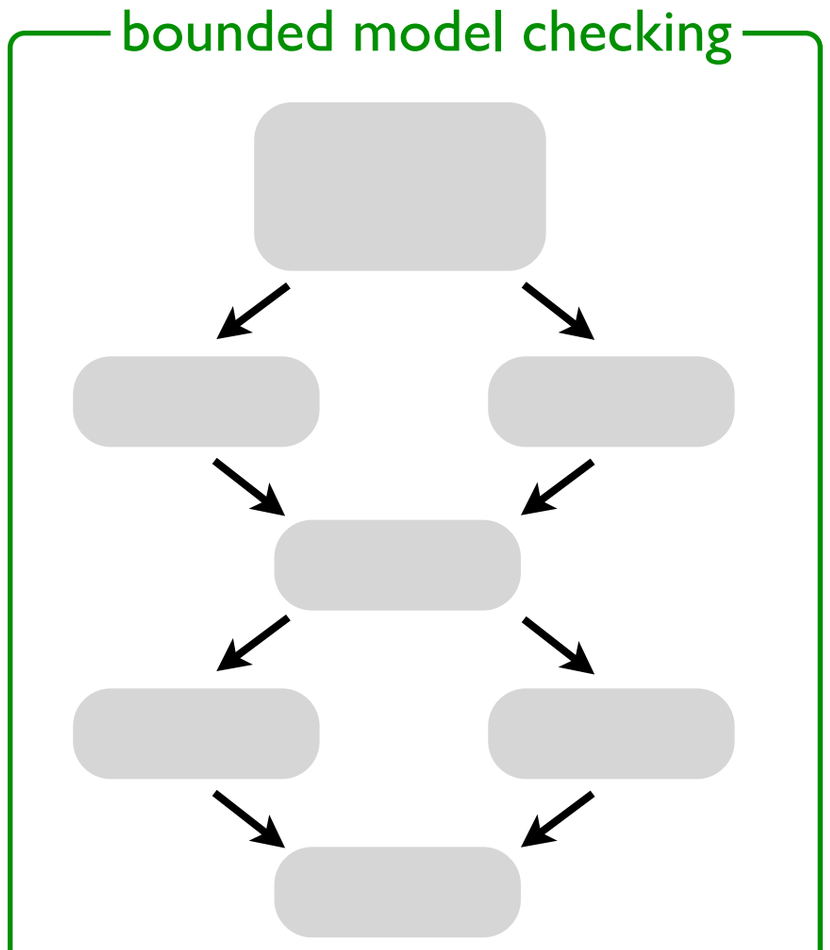

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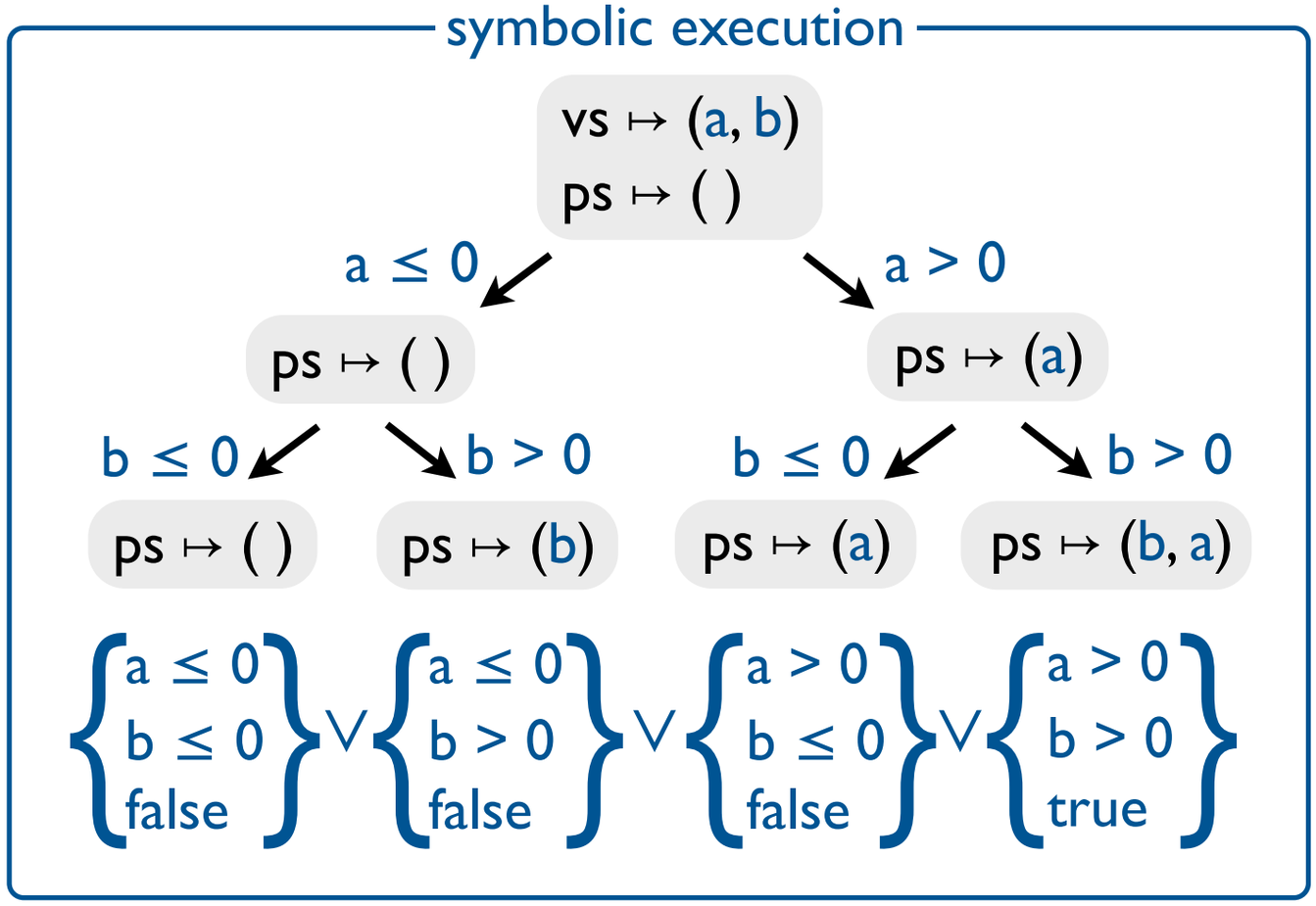

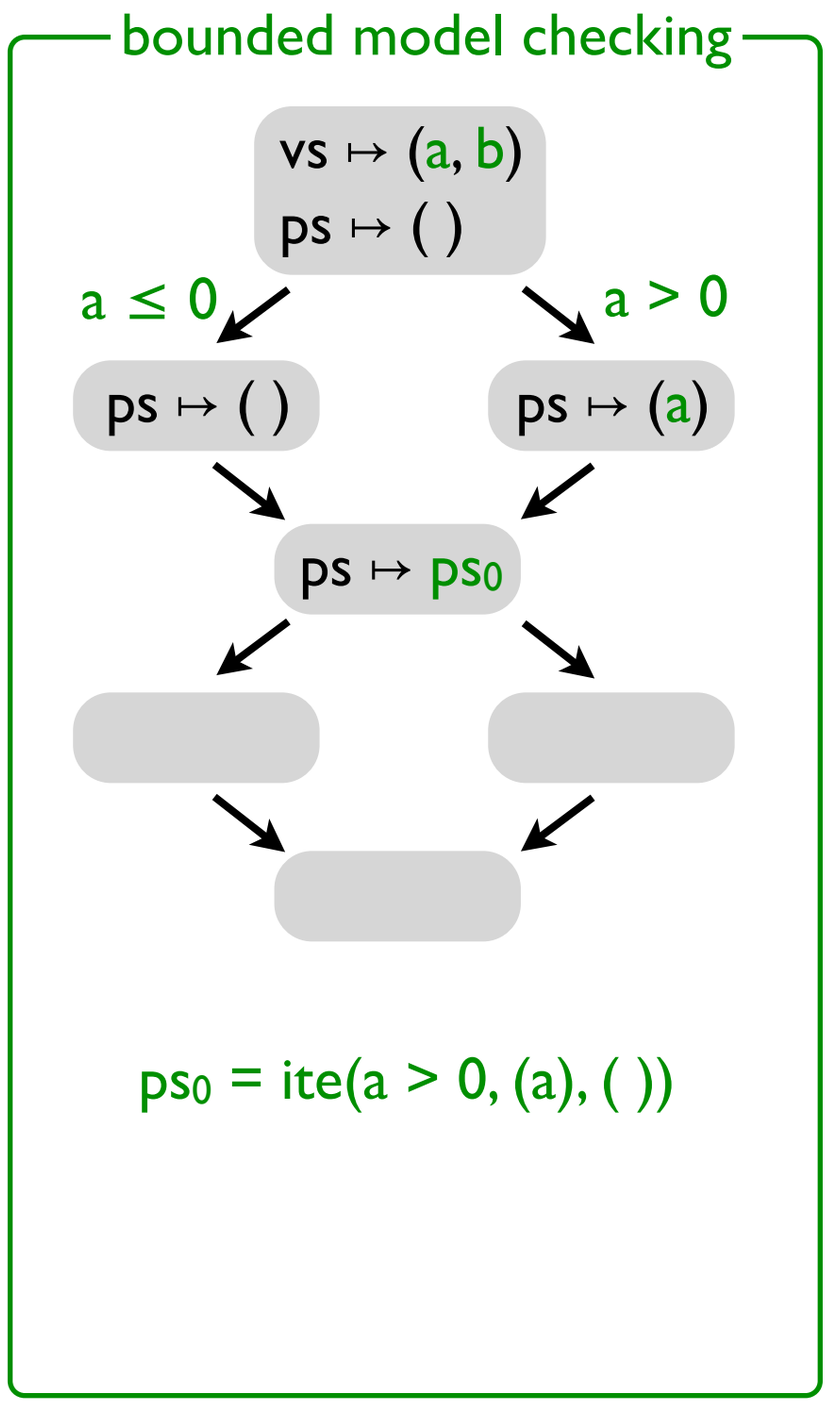

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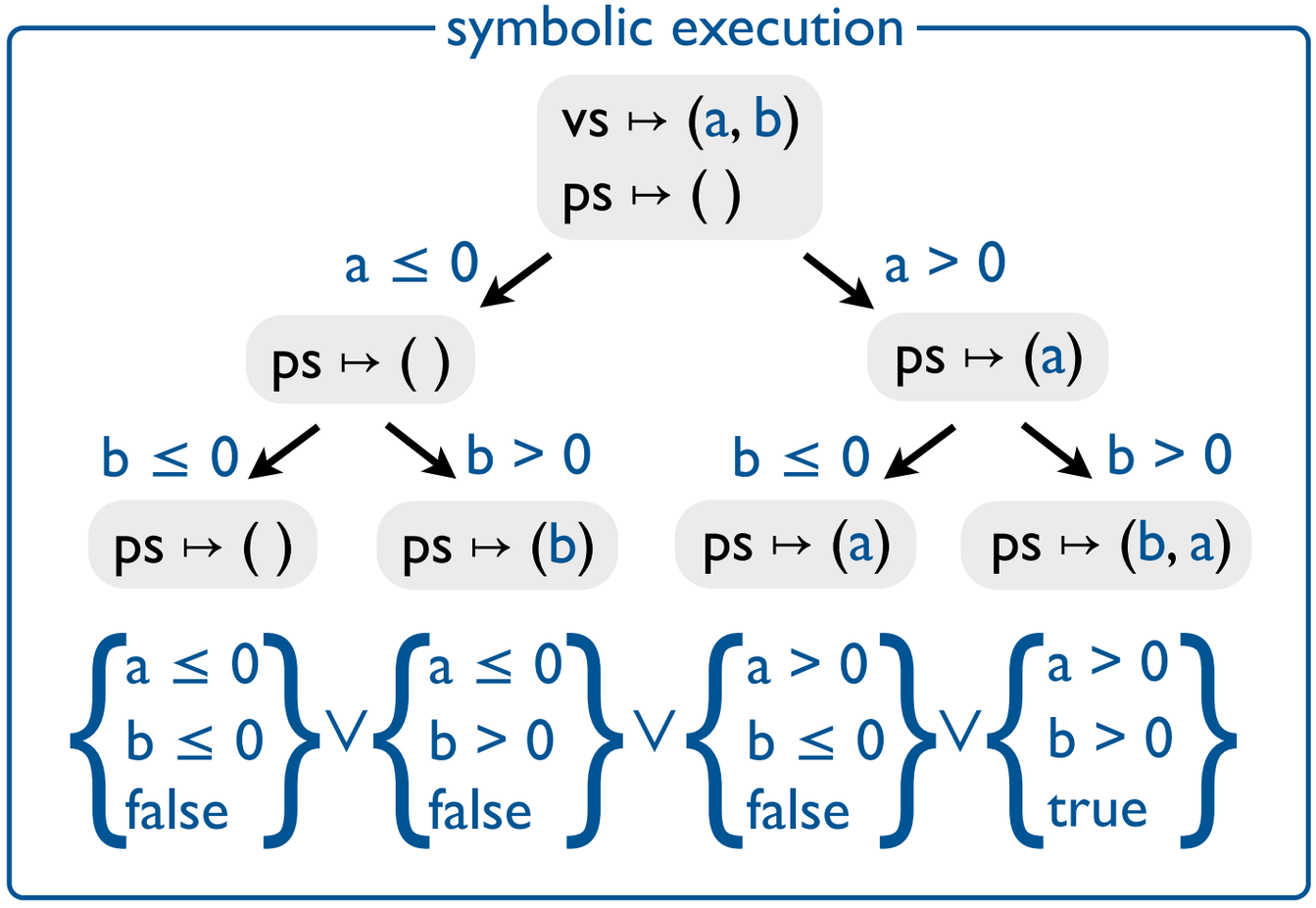

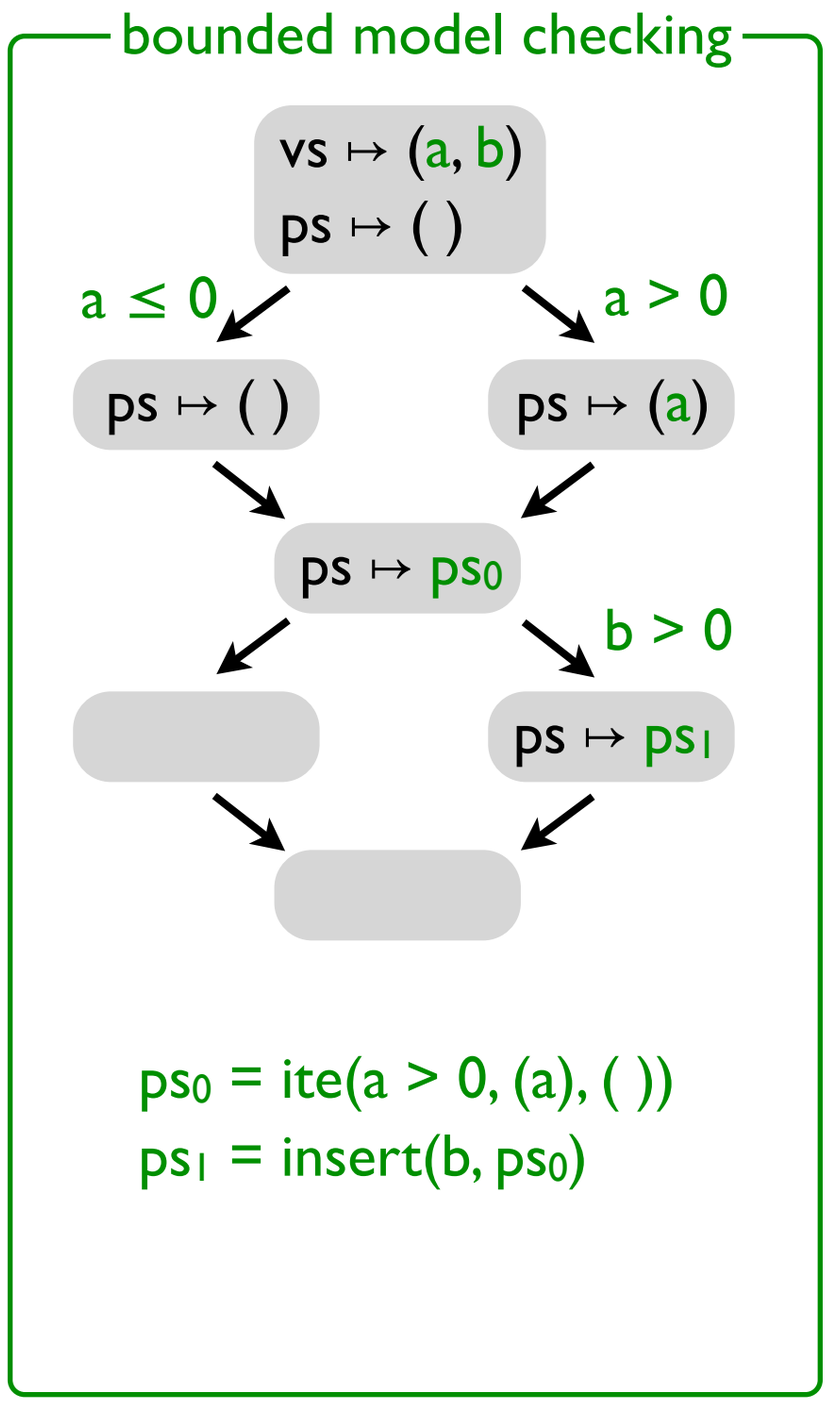

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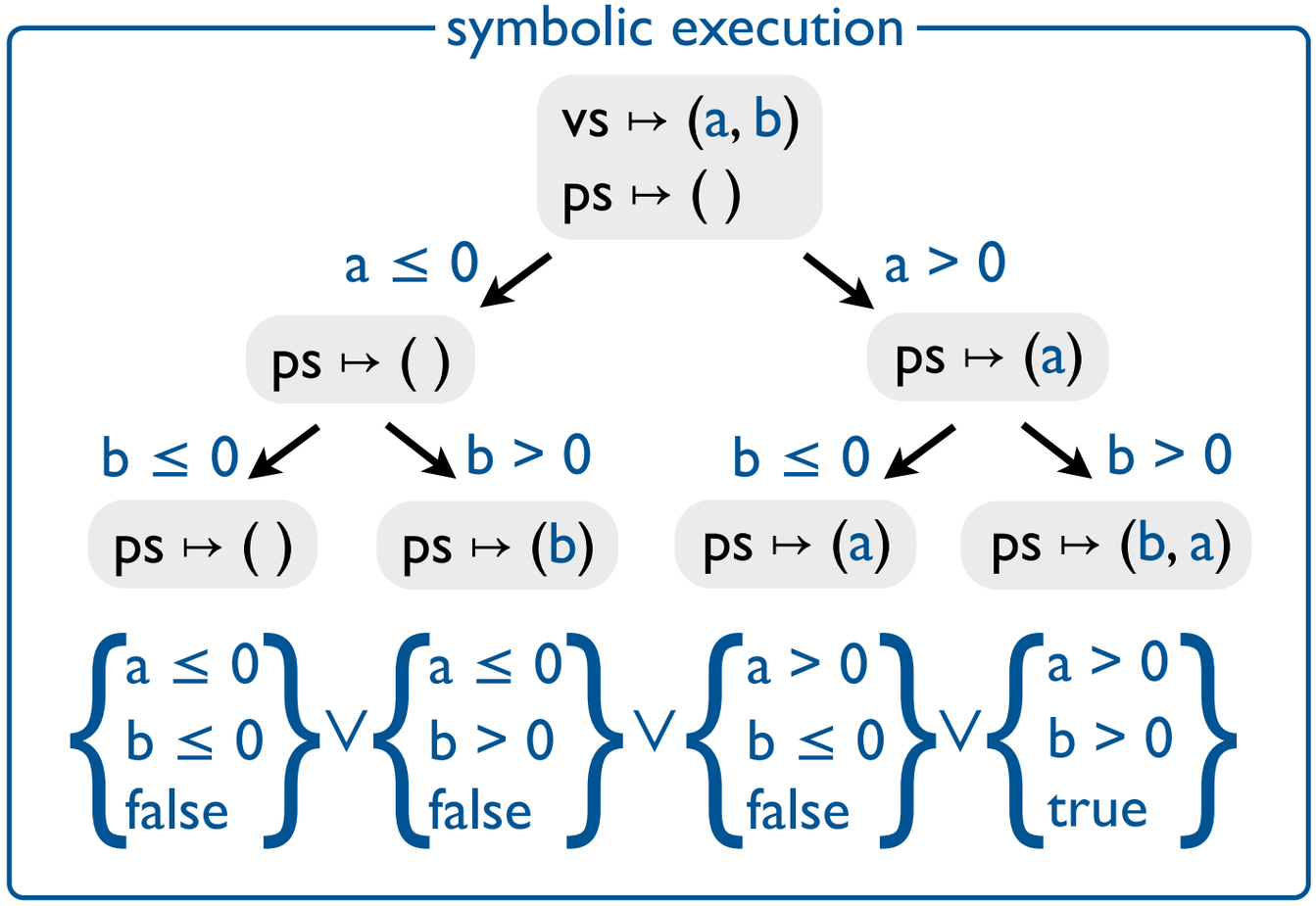

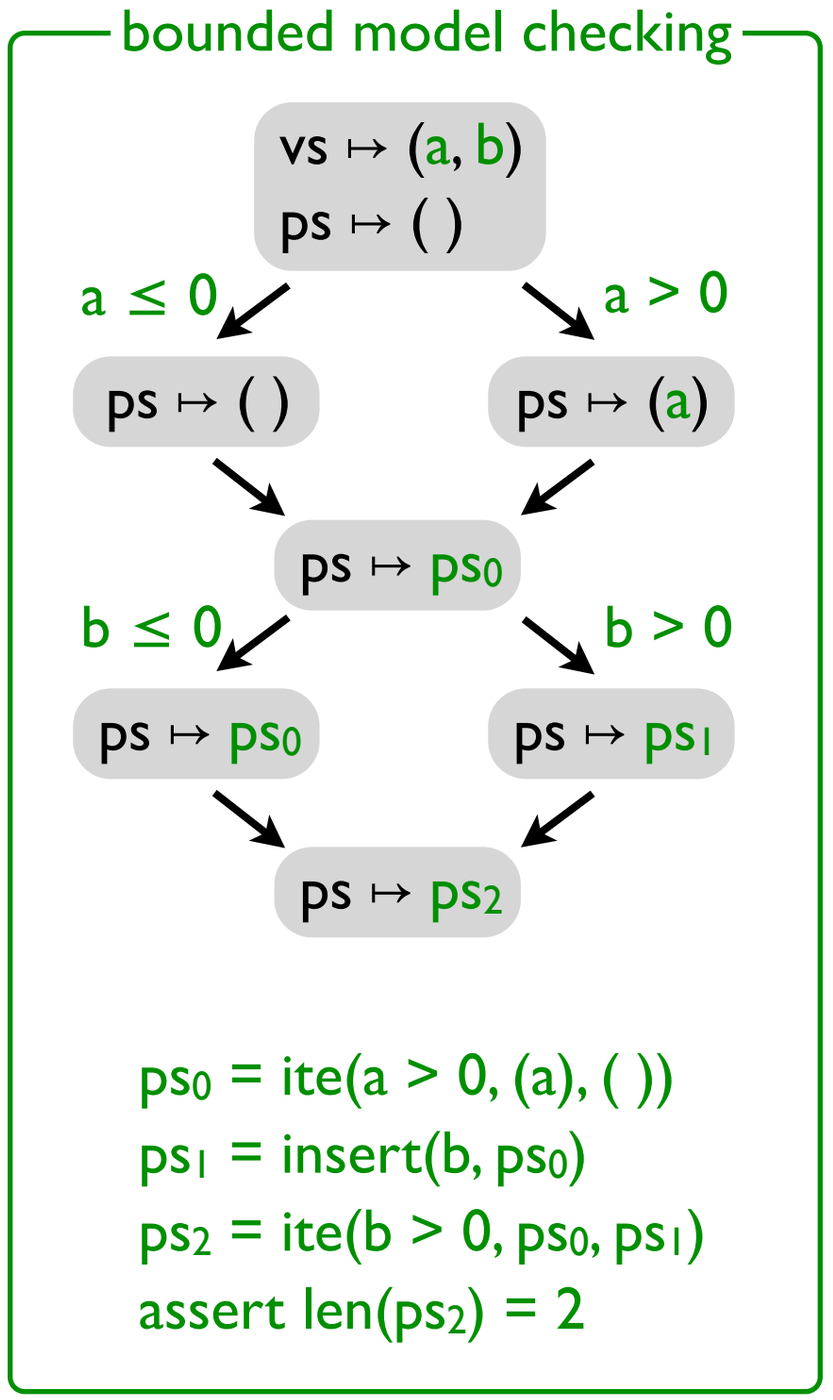

A new design: type-driven state merging

```
solve:
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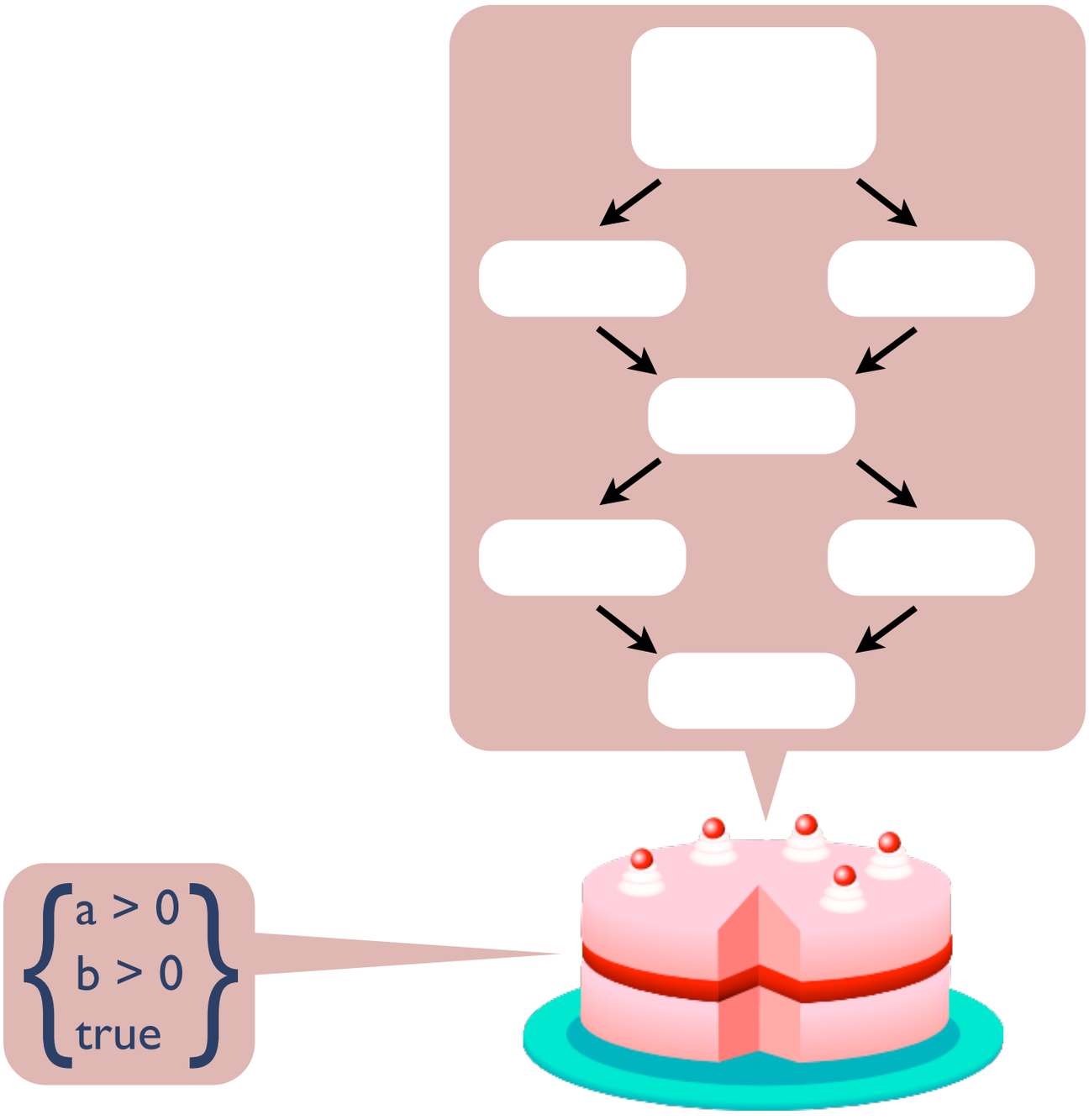

A new design: type-driven state merging

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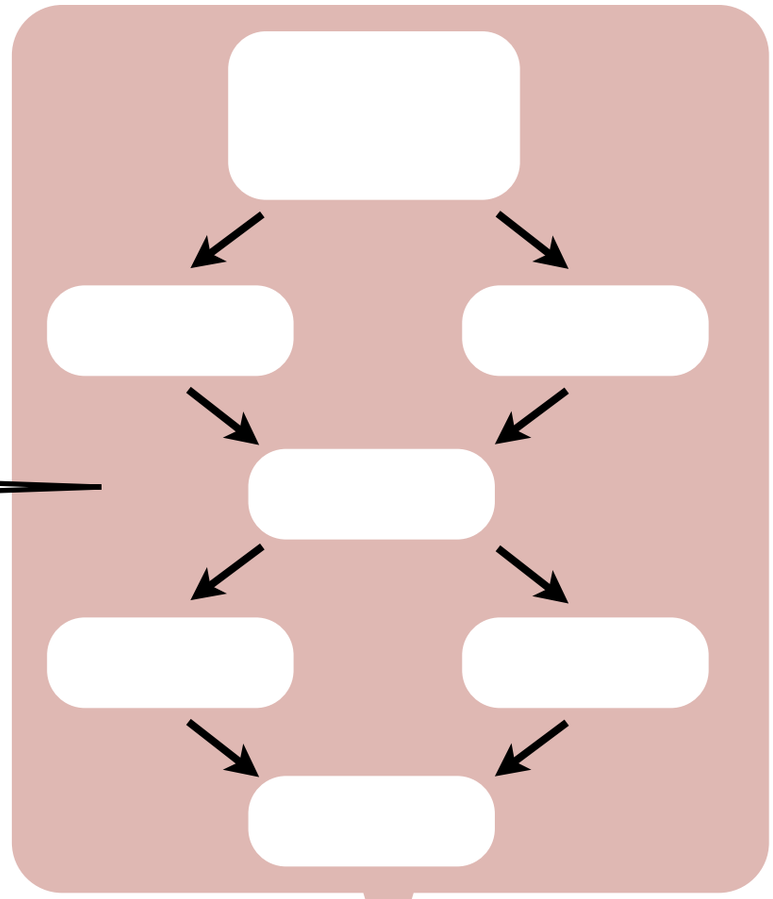
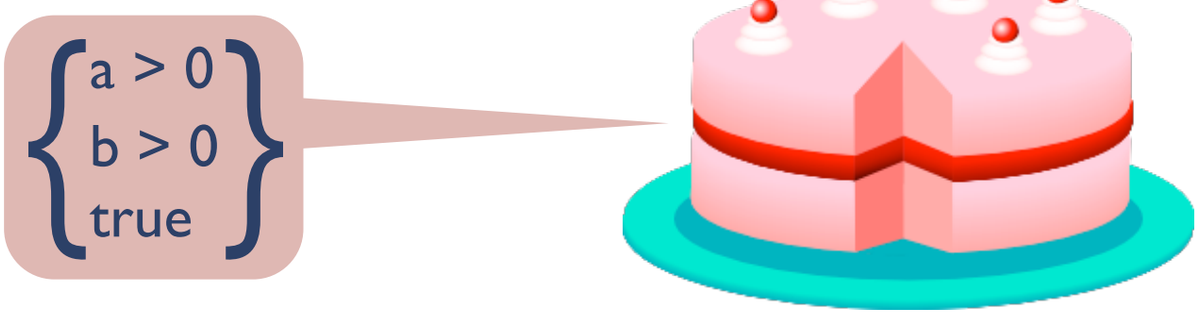
```

Merge values of

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





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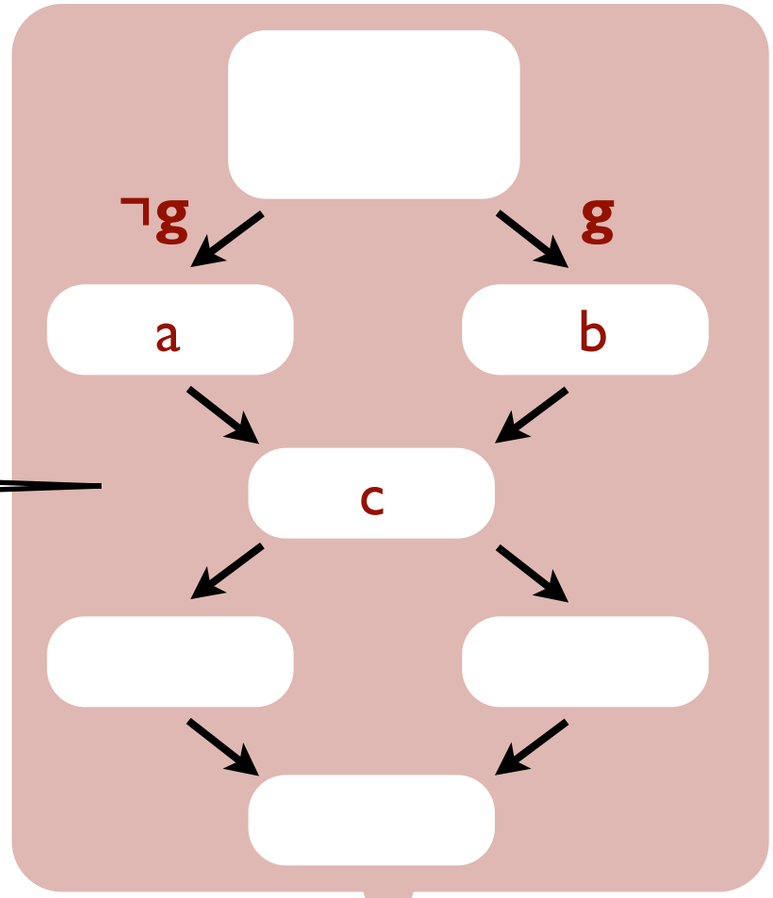

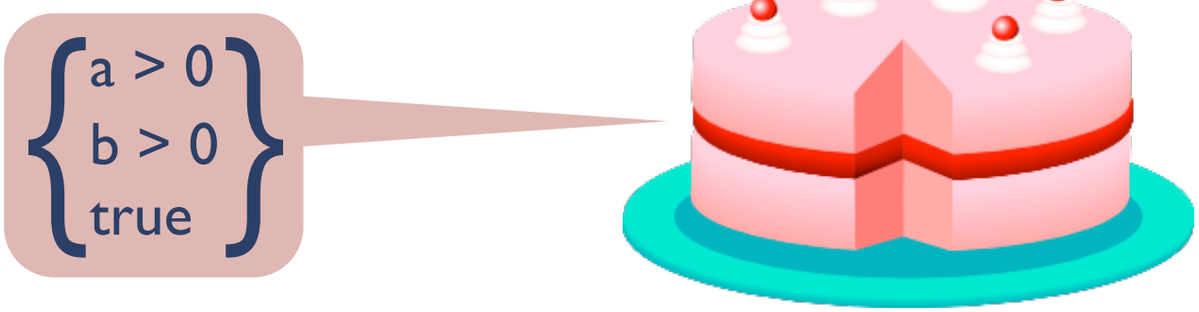

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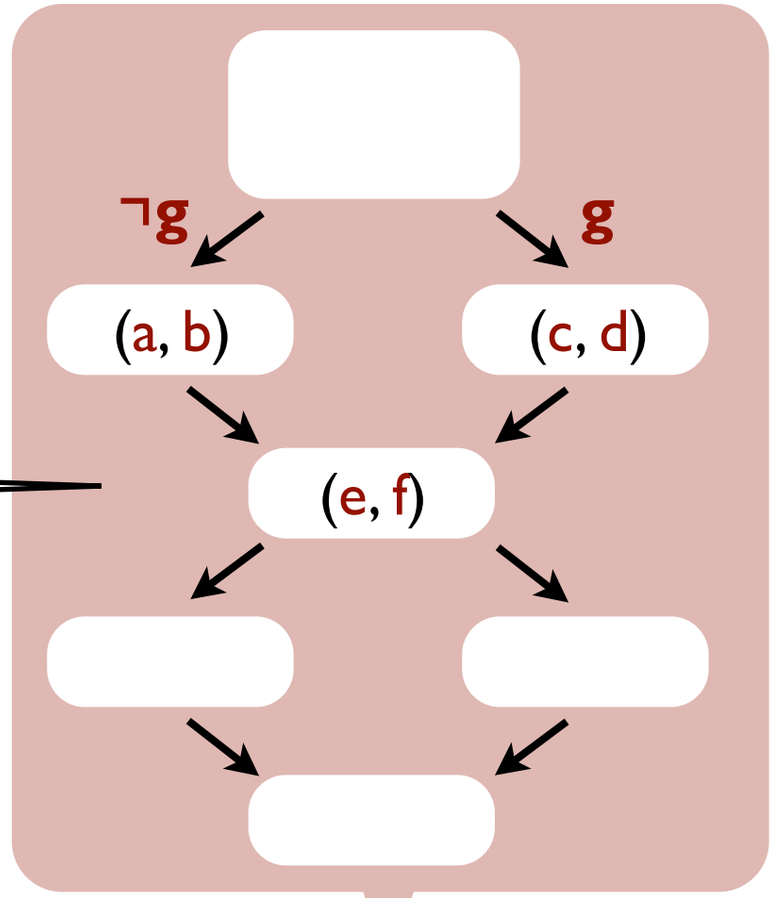

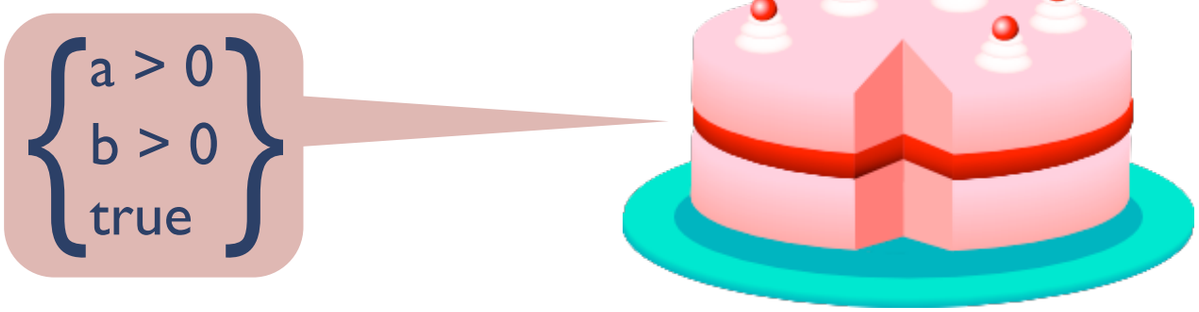

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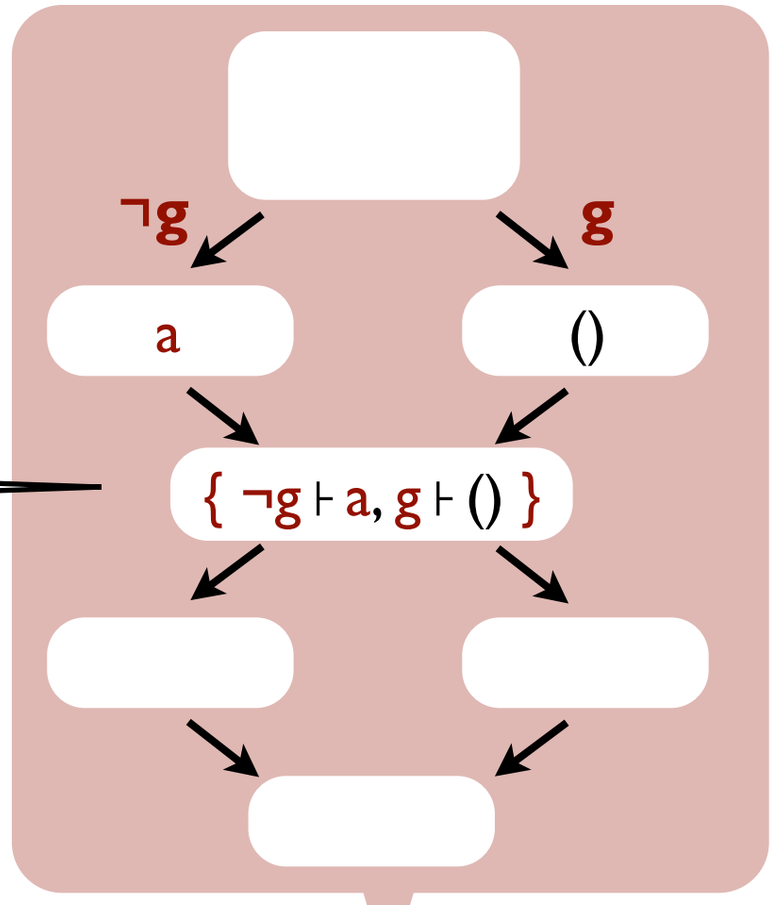

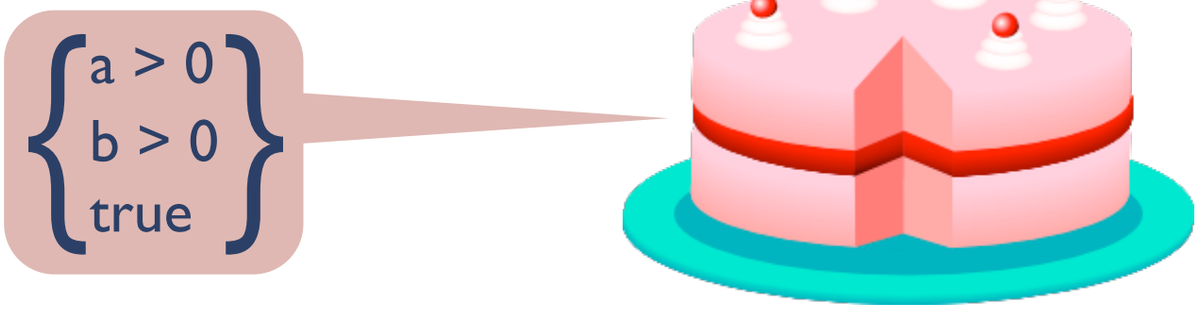

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  for v in vs:
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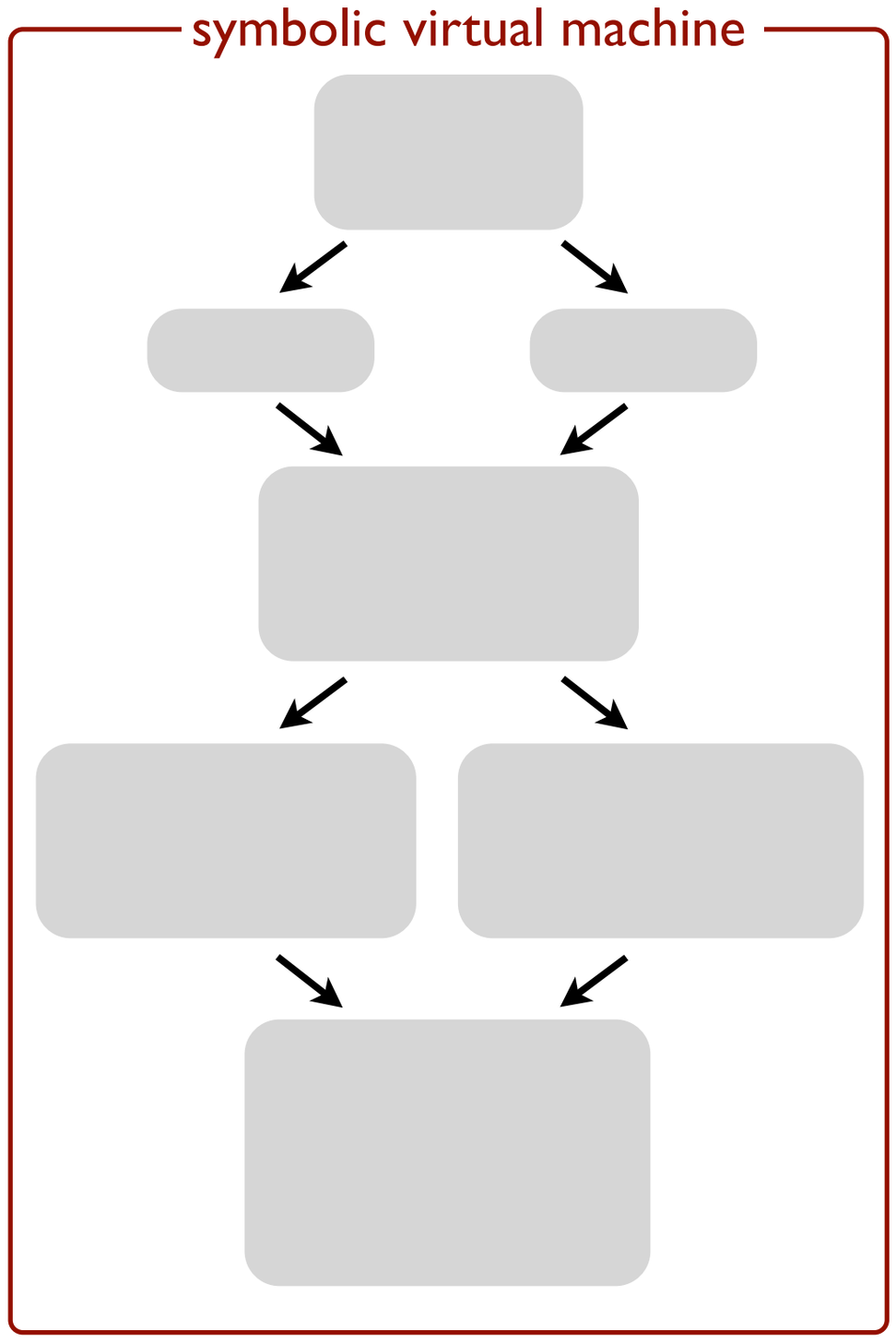

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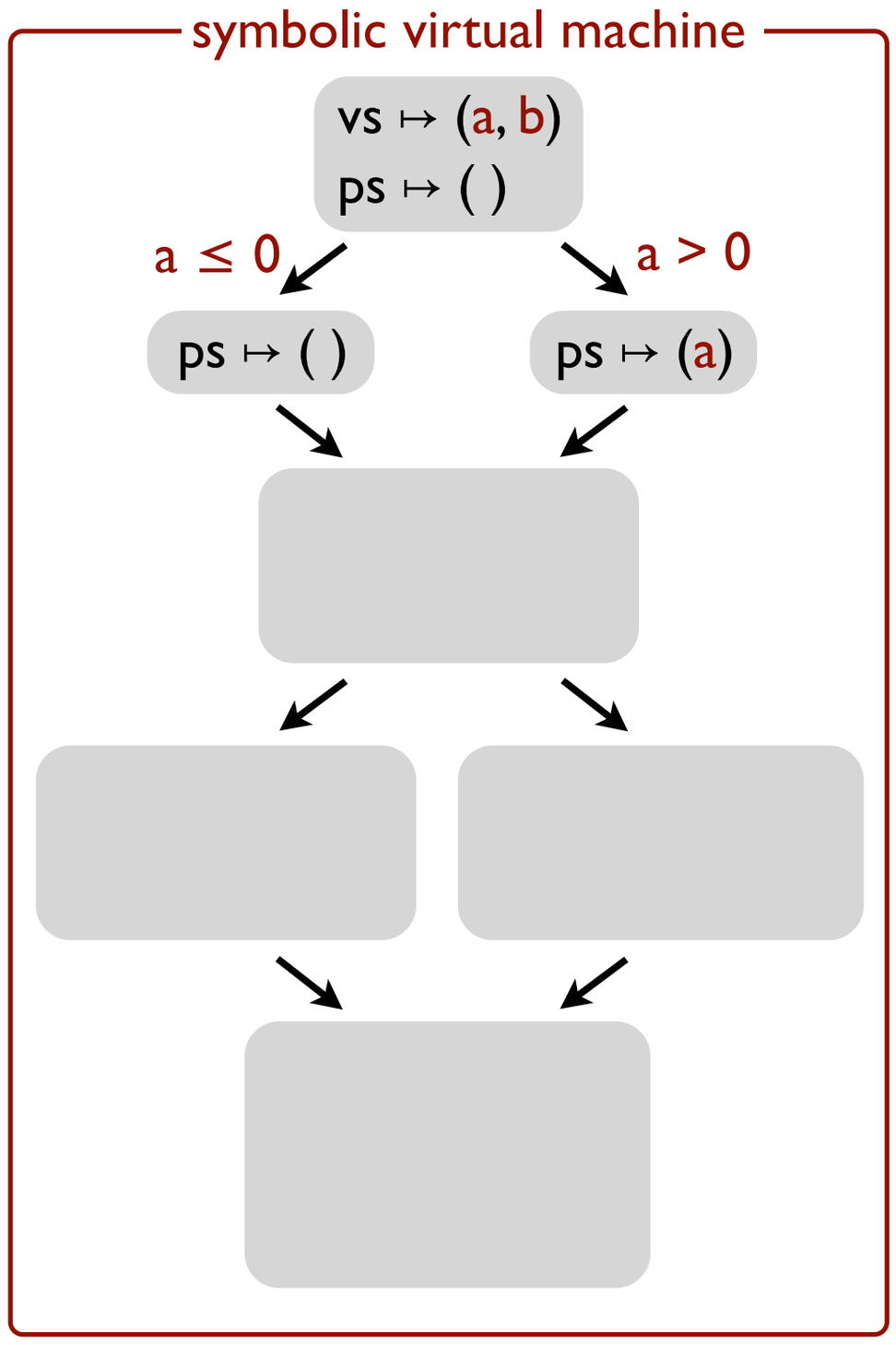
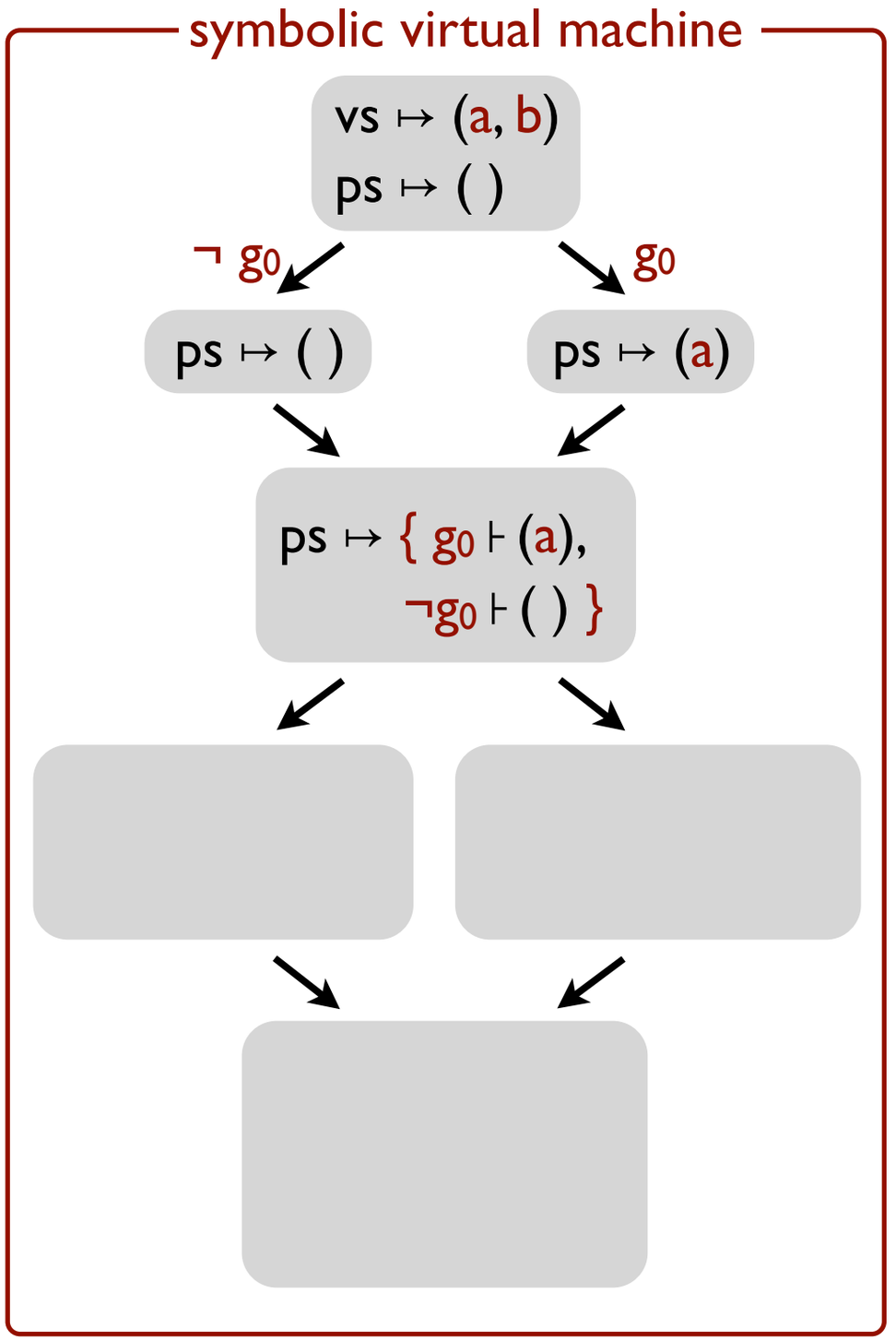


A new design: type-driven state merging

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

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

$g_0 = a > 0$



A new design: type-driven state merging

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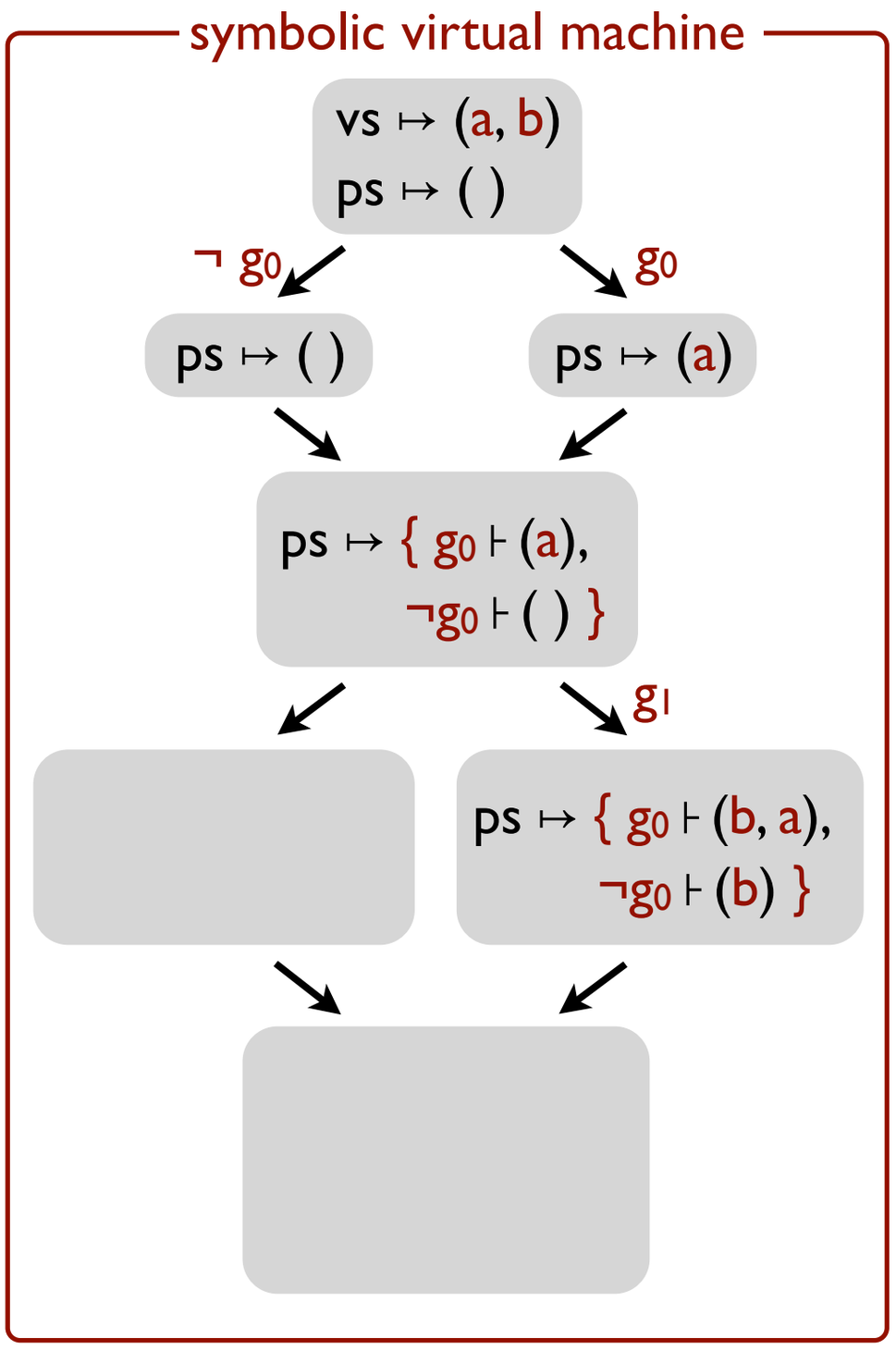
      ps = insert(v, ps)
  assert len(ps) == len(vs)
```

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



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

A new design: type-driven state merging

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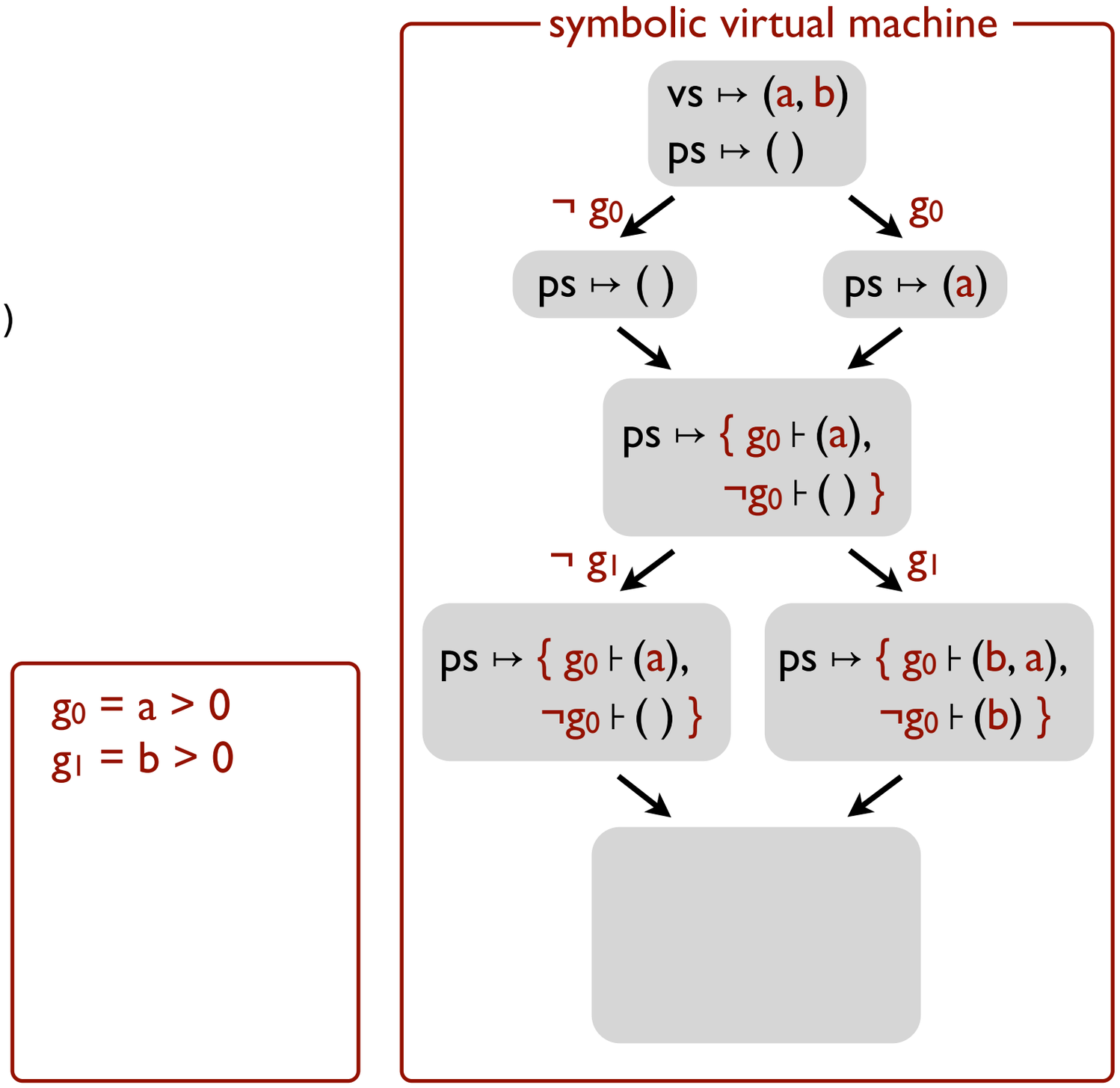

A new design: type-driven state merging

```
solve:
  ps = ()
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    if v > 0:
      ps = insert(v, ps)
  assert len(ps) == len(vs)
```
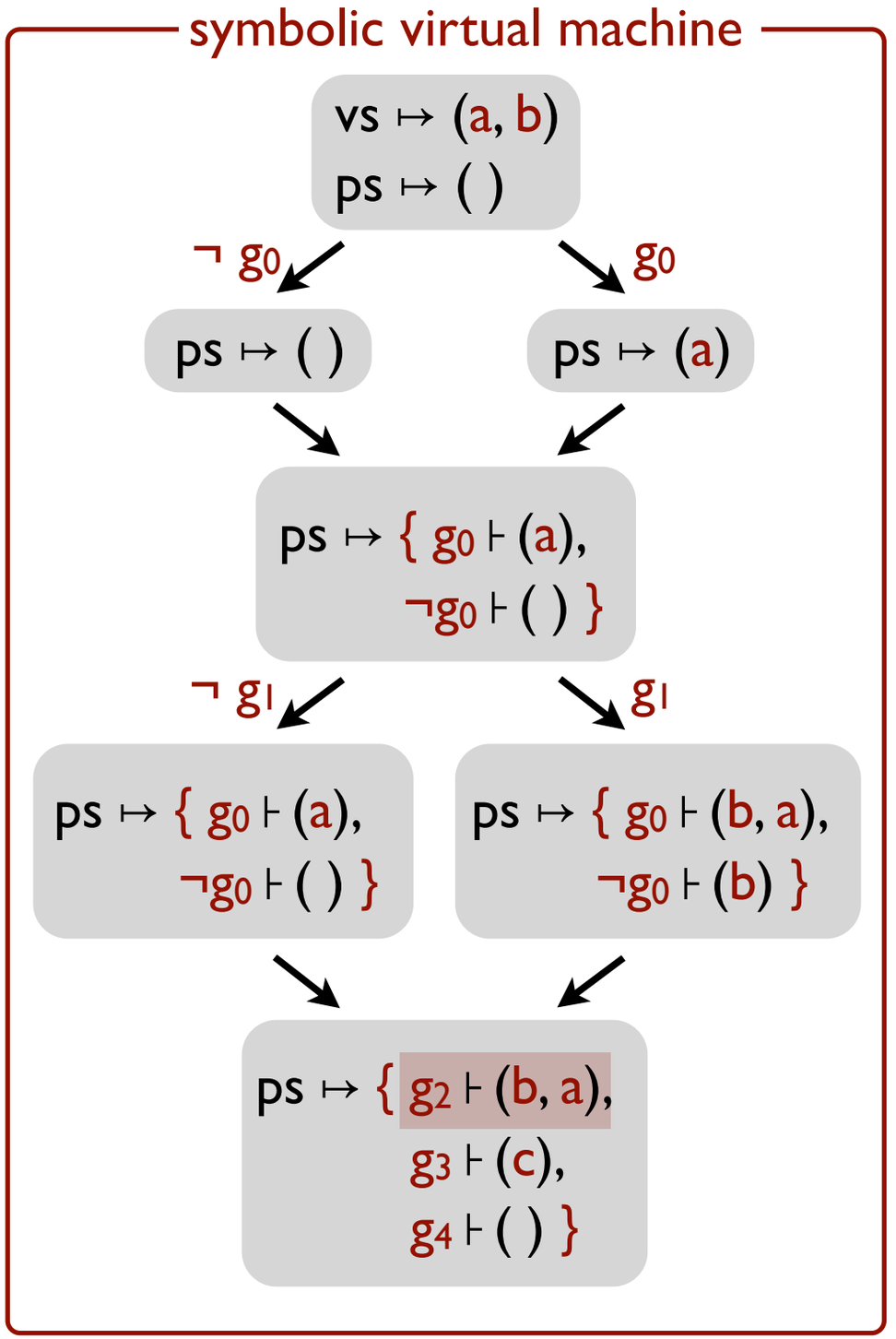

Evaluate `len` concretely on all lists in the union; assertion true only on the list guarded by g_2.

$g_0 = a > 0$
$g_1 = b > 0$
$g_2= g_0 \wedge g_1$
$g_3 = \neg(g_0 \Leftrightarrow g_1)$
$g_4 = \neg g_0 \wedge \neg g_1$
$c = \text{ite}(g_1, b, a)$
assert g_2



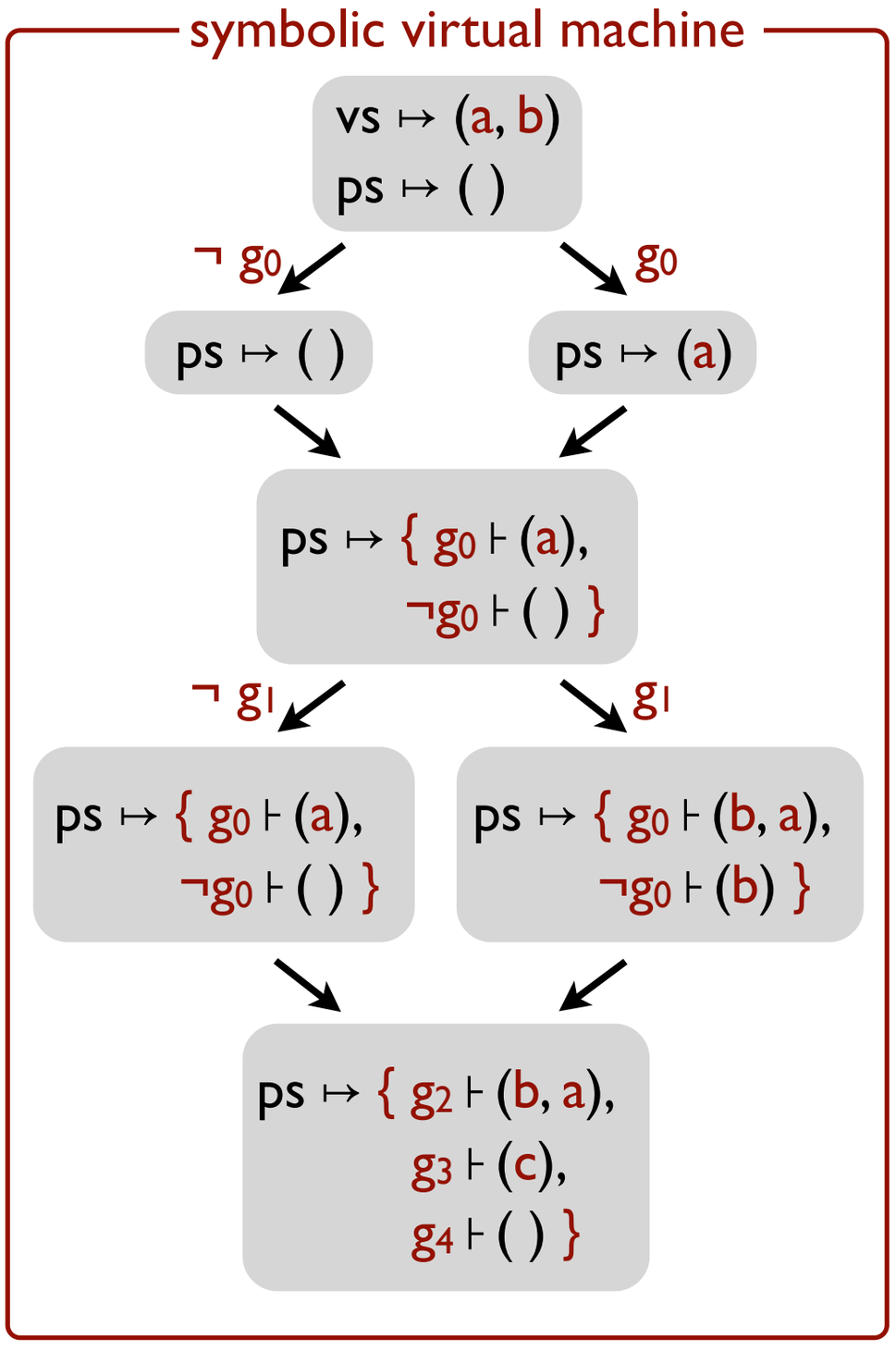
A new design: type-driven state merging

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

polynomial encoding

concrete evaluation

$g_0 = a > 0$
$g_1 = b > 0$
$g_2 = g_0 \wedge g_1$
$g_3 = \neg(g_0 \Leftrightarrow g_1)$
$g_4 = \neg g_0 \wedge \neg g_1$
$c = \text{ite}(g_1, b, a)$
assert g_2



How to build your own solver-aided language

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

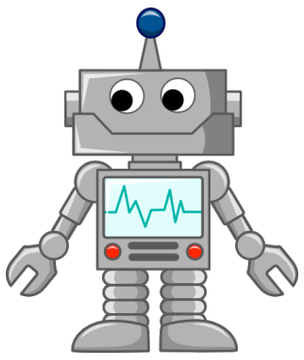
SDSL

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

SVM

SMT

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!

Chlorophyll: ultra low-power computing

Instructions/Second vs Power

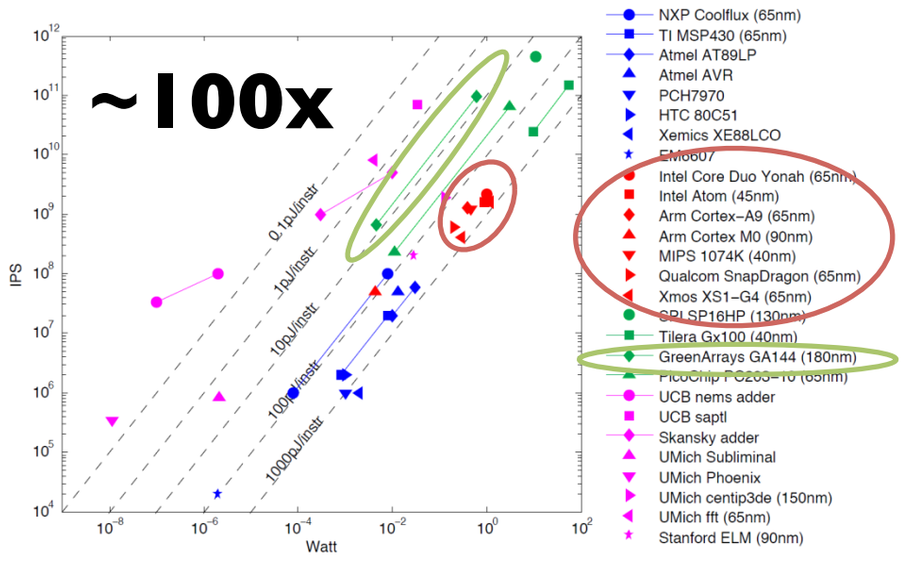
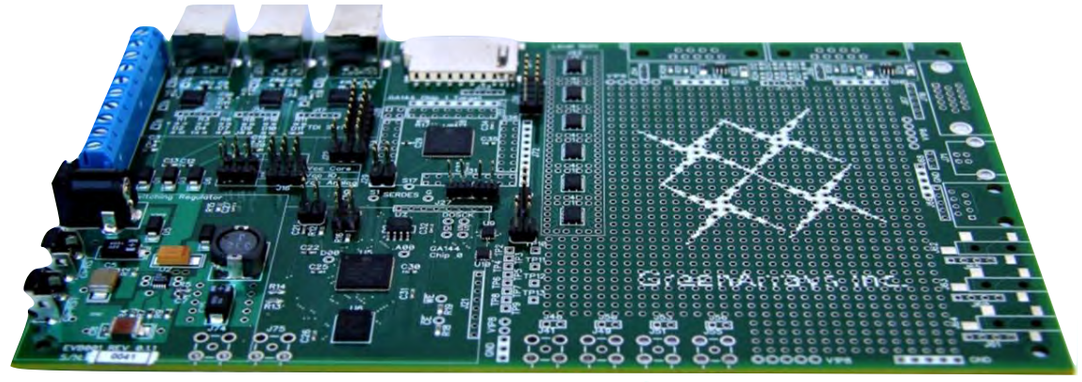


Figure by Per Ljung

GreenArrays GA144 Processor



Chlorophyll: ultra low-power computing

GreenArrays GA144 Processor

- Stack-based 18-bit architecture
- 32 instructions
- 8 x 18 array of asynchronous cores
- No shared resources (cache, memory)
- Limited communication, neighbors only
- < 300 byte memory per core

Manual program partitioning: break programs up into a pipeline with a few operations per core.

Drawing by Mangpo Phothilimthana

Chlorophyll: ultra low-power computing

GreenArrays GA144 Processor

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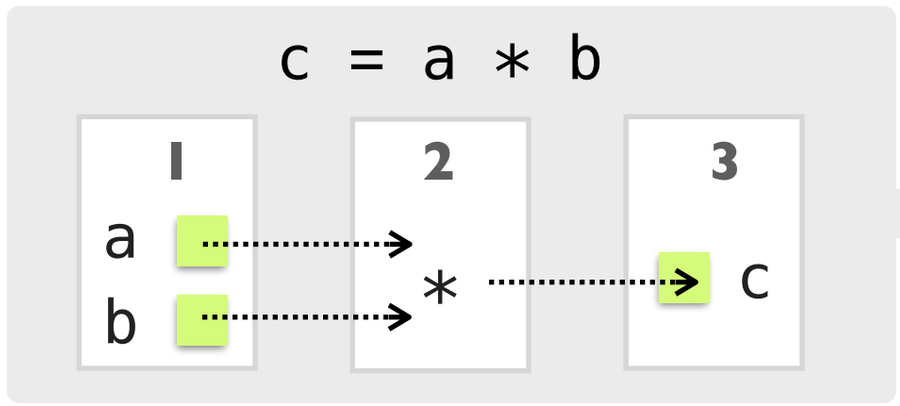
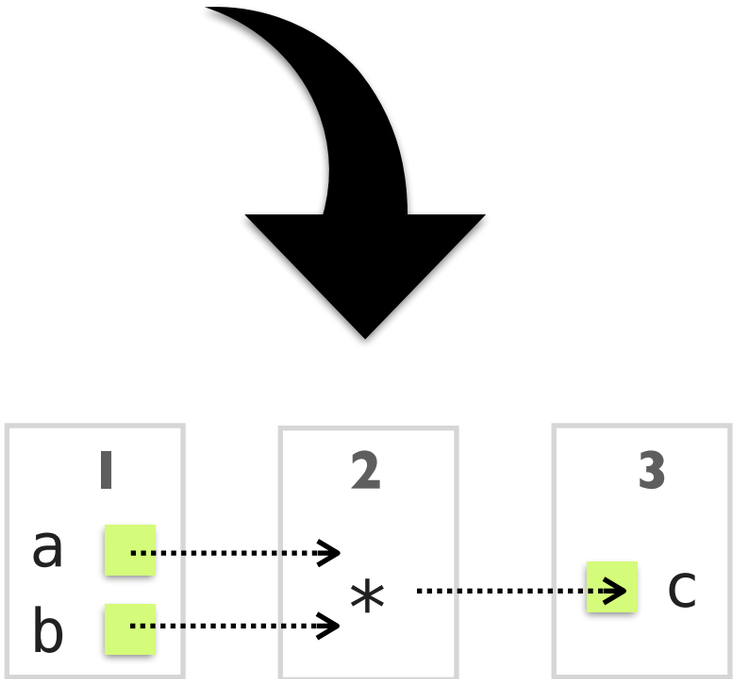


Drawing by Mangpo Phothilimthana

Chlorophyll: ultra low-power computing

```
int a, b;
int c = a * b;
```

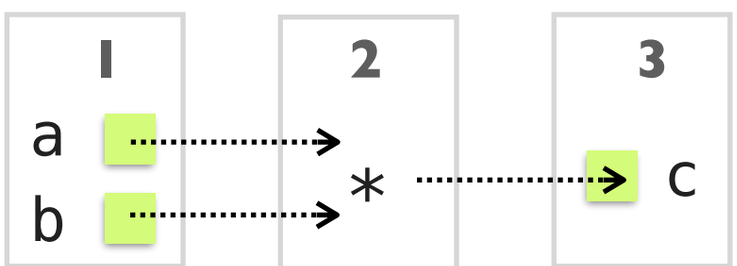


Synthesizes placement of code and data onto cores, by type-checking a program sketch in a C-like DSL.

Chlorophyll: ultra low-power computing

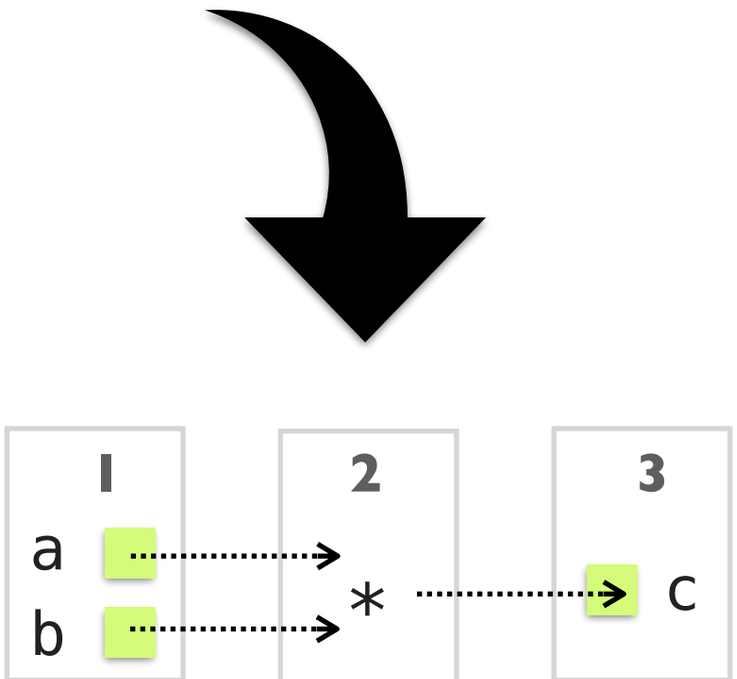
```
int@1 a, b;
int@3 c = a *@2 b;
```

Synthesizes placement of code and data onto cores, by **type-checking a program** sketch in a C-like DSL.



Chlorophyll: ultra low-power computing

```
int@?? a, b;
int@?? c = a *@?? b;
```



Synthesizes placement of code and data onto cores, by type-checking a program sketch in a C-like DSL.

Chlorophyll: ultra low-power computing

```
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```

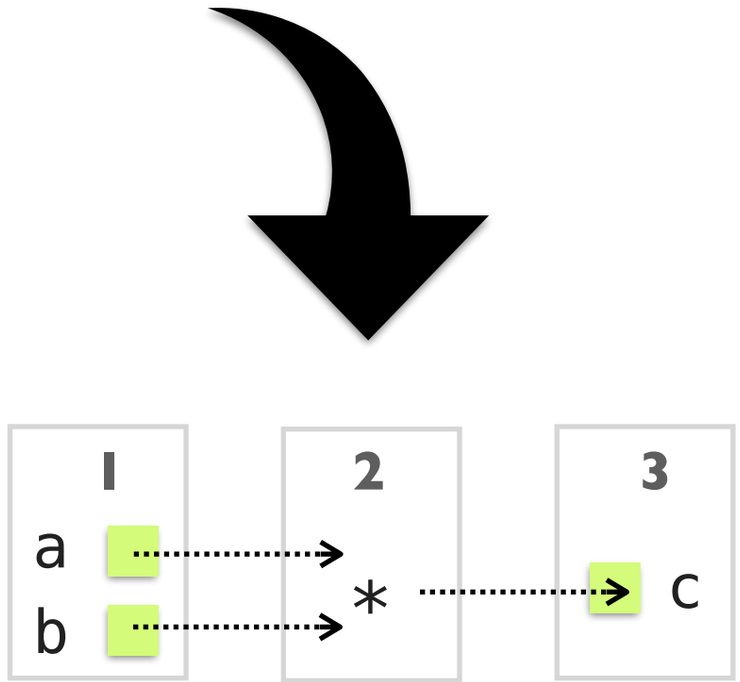

Built by a first-year grad in a few weeks

Phitchaya Mangpo Phothilimthana

Chlorophyll: ultra low-power computing

```
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int@?? c = a *@?? b;
```
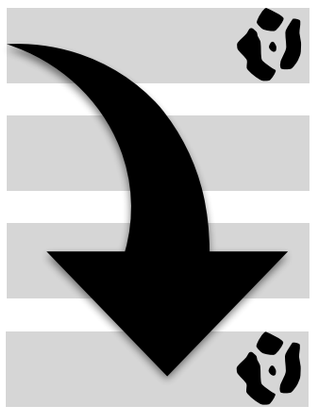
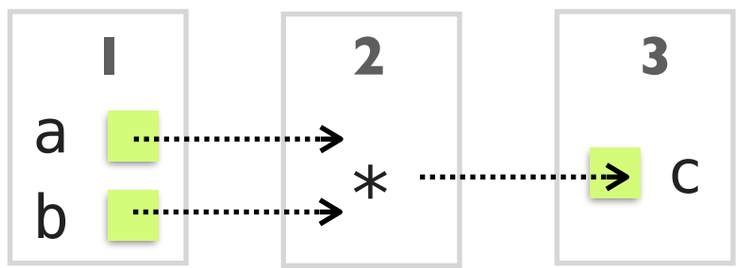





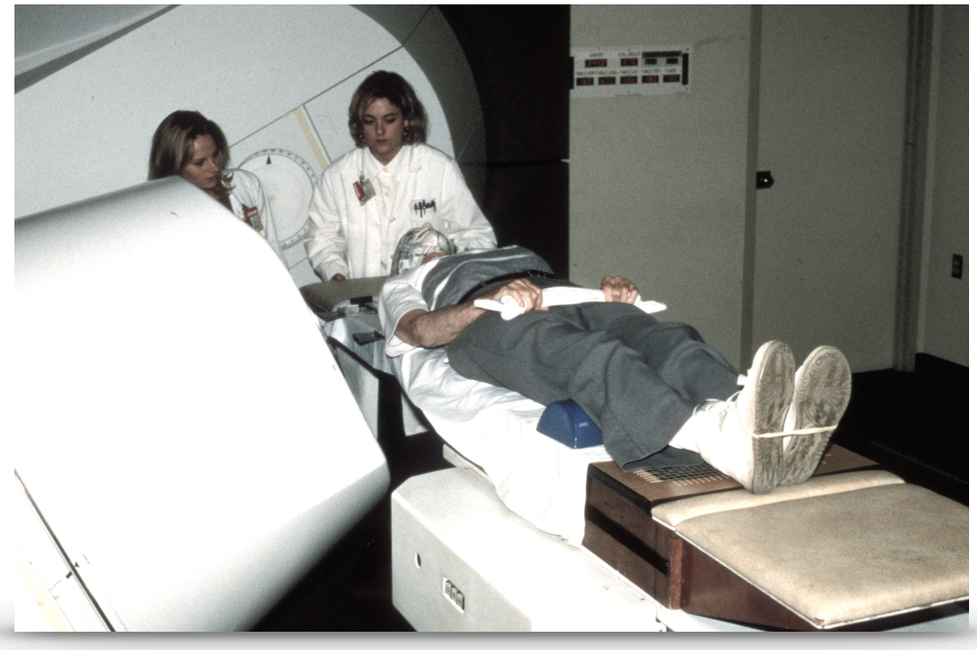
With Chlorophyll, it took one afternoon to build a set of apps that took 3 months to build manually.

[Phothilimthana et al., **PLDI'14**]

Neutrons: verifying a radiotherapy system

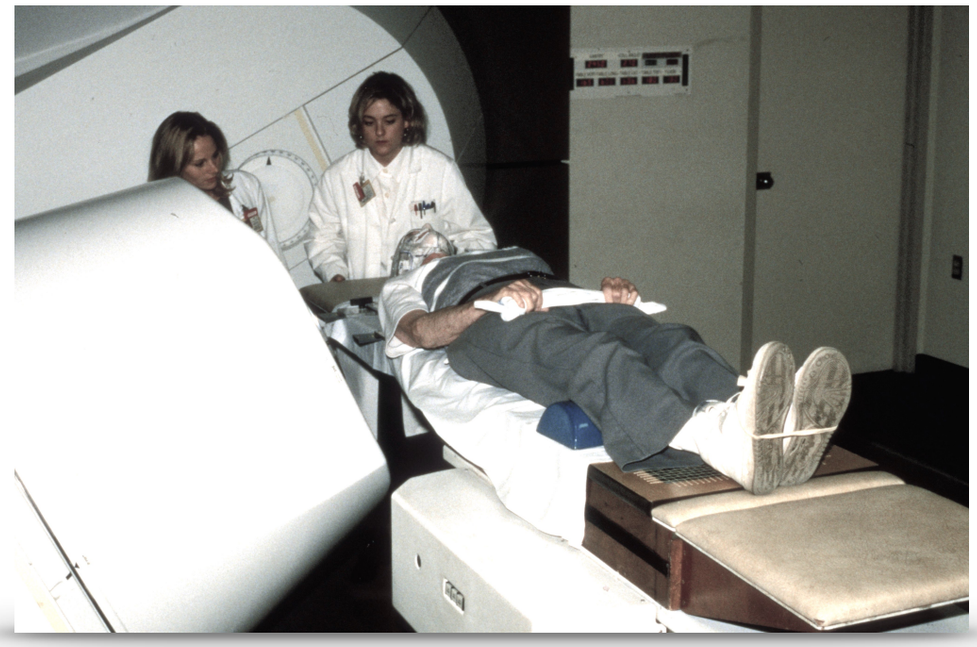
Clinical Neutron Therapy System (CNTS) at UW

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



Neutrons: verifying a radiotherapy system

Clinical Neutron Therapy System (CNTS) at UW



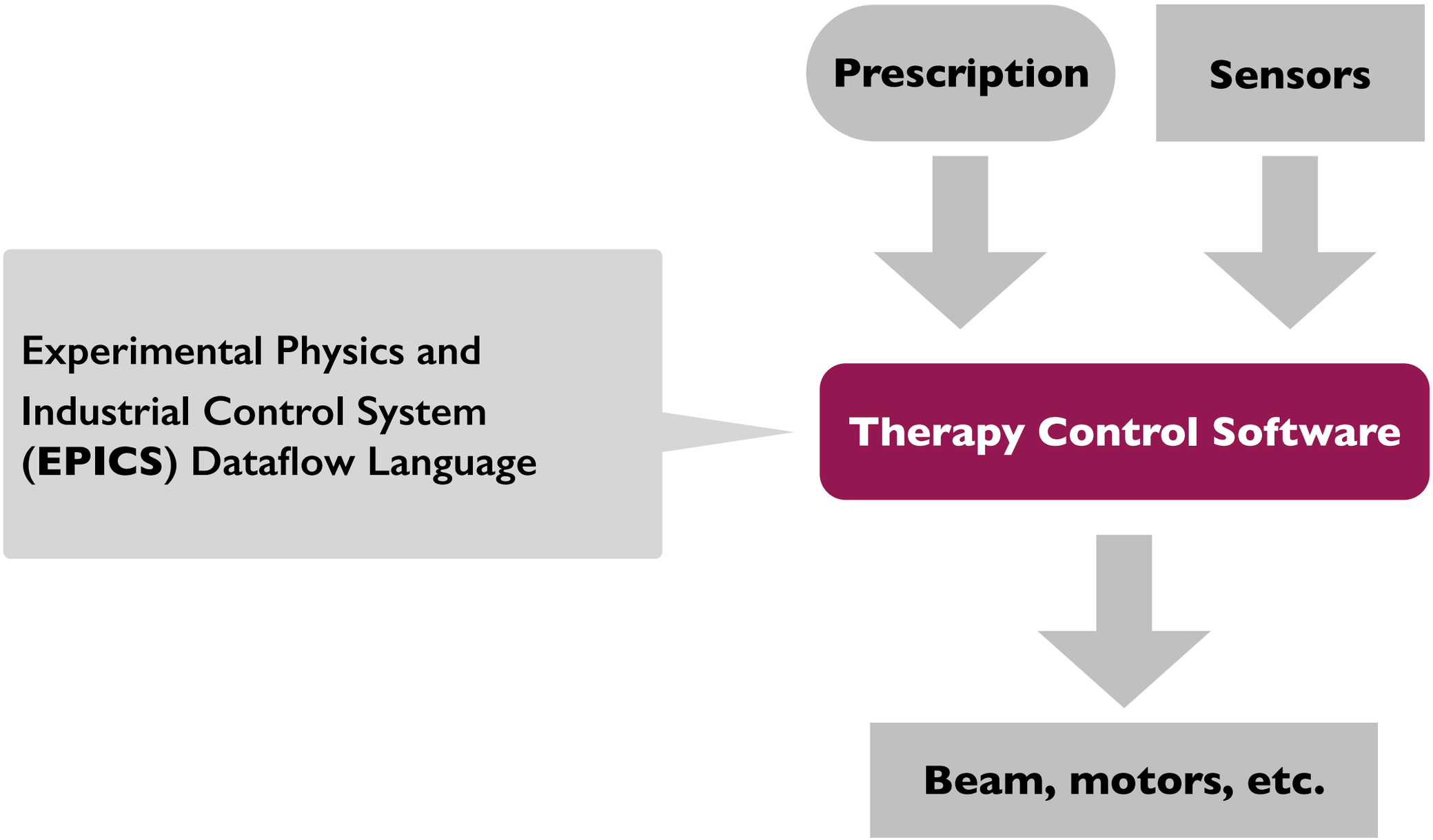
Prescription

Sensors

Therapy Control Software

Beam, motors, etc.

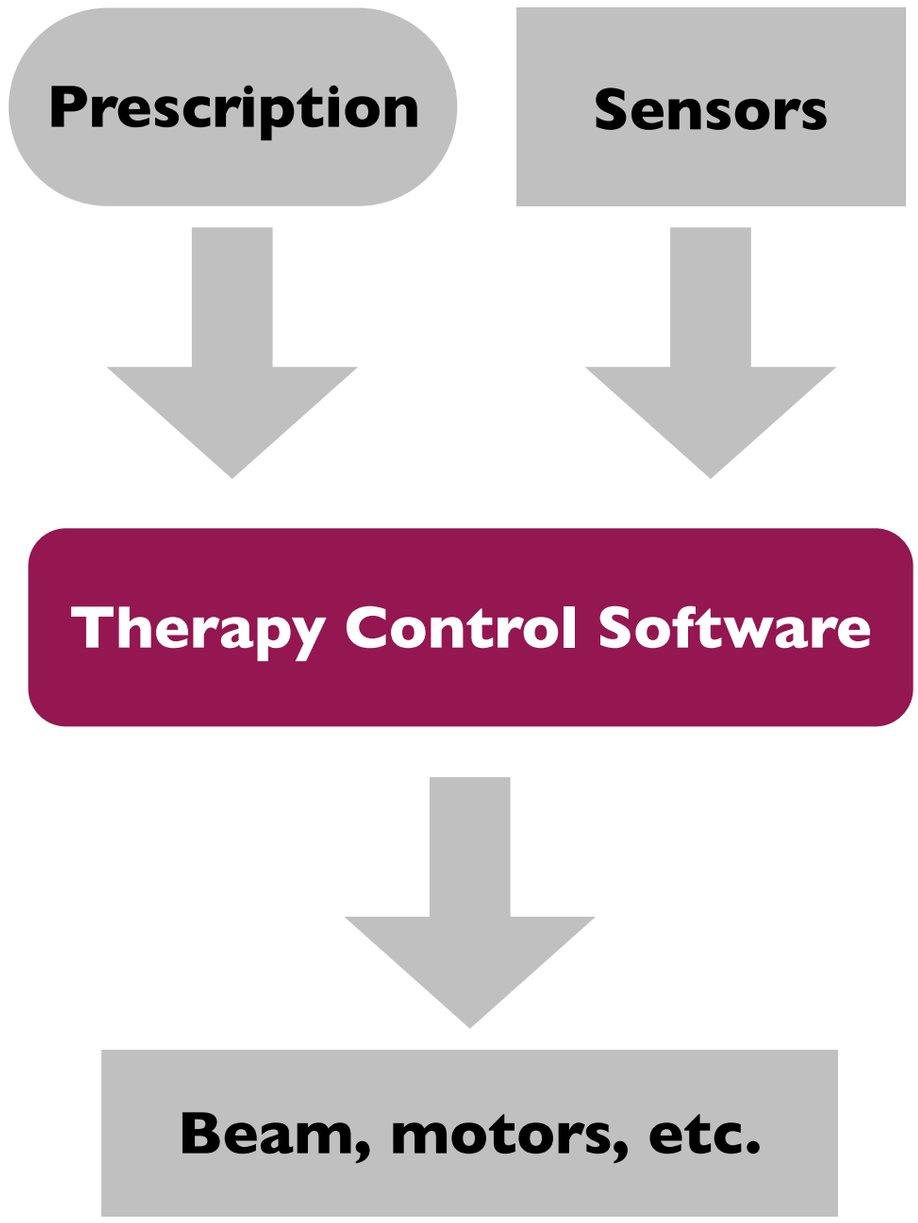
Neutrons: verifying a radiotherapy system



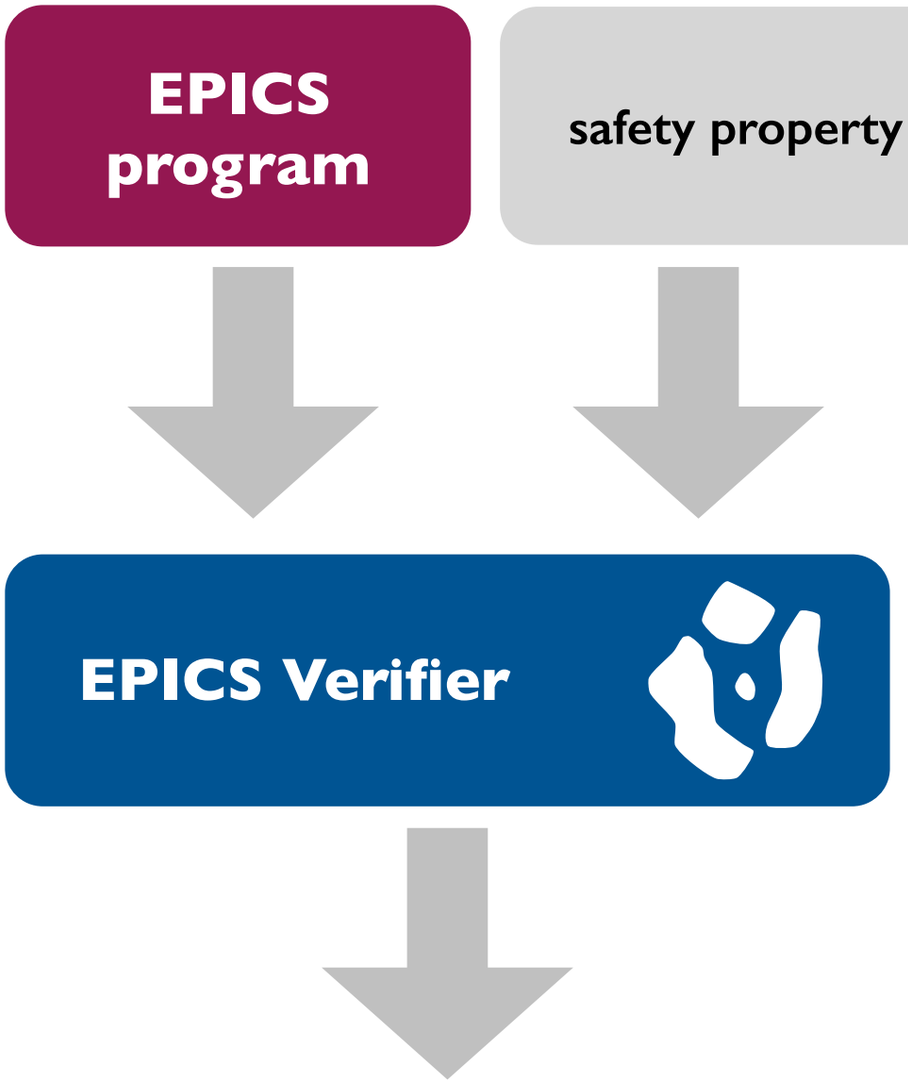
Neutrons: verifying a radiotherapy system

EPICS documentation / semantics

The Maximize Severity attribute is one of NMS (Non-Maximize Severity), MS (Maximize Severity), MSS (Maximize Status and Severity) or MSI (Maximize Severity if Invalid). It determines whether alarm severity is propagated across links. If the attribute is MSI only a severity of INVALID_ALARM is propagated; settings of MS or MSS propagate all alarms that are more severe than the record's current severity. For input links the alarm severity of the record referred to by the link is propagated to the record containing the link. For output links the alarm severity of the record containing the link is propagated to the record referred to by the link. If the severity is changed the associated alarm status is set to LINK_ALARM, except if the attribute is MSS when the alarm status will be copied along with the severity.



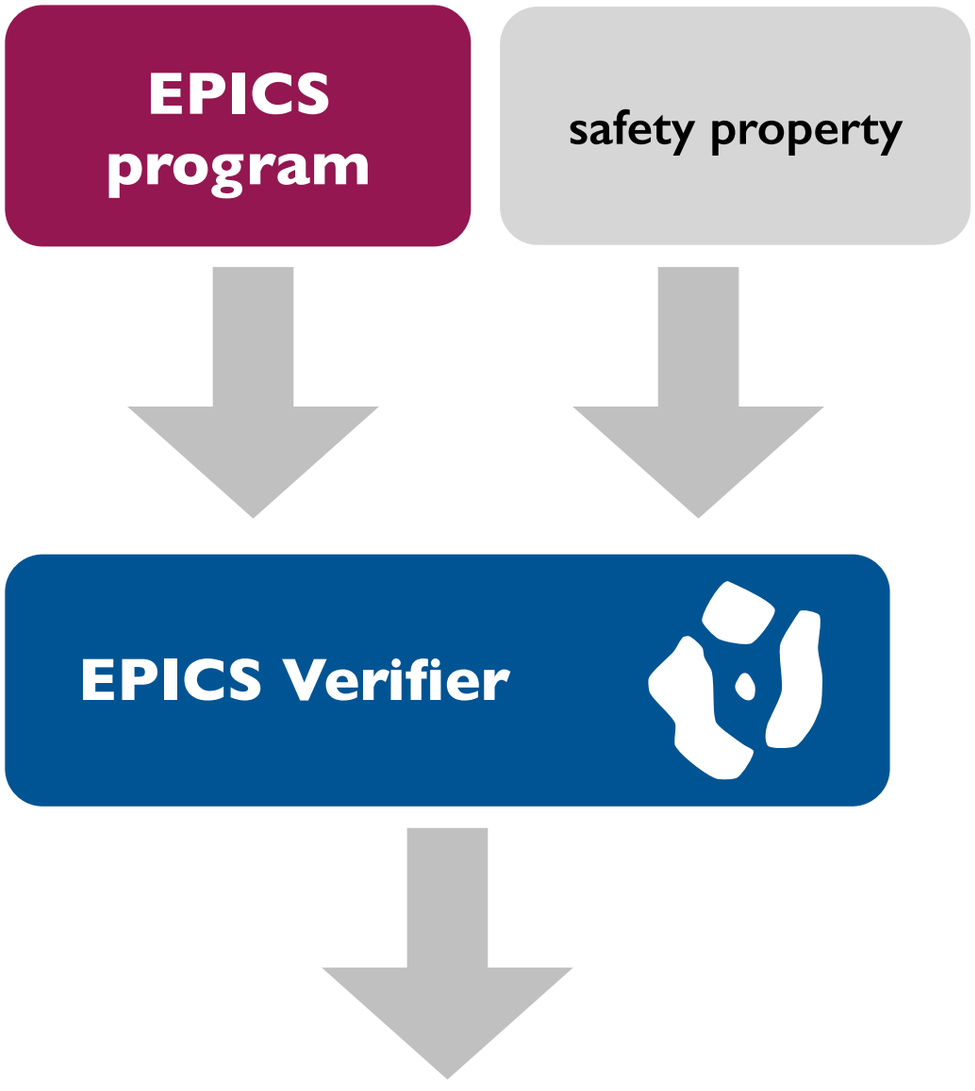
Neutrons: verifying a radiotherapy system



Built by a 2nd year grad in a few days

Calvin Loncaric

Neutrons: verifying a radiotherapy system



[Pernsteiner et al., CAV'16]

Found a bug in the EPICS runtime! Therapy Control depended on this bug for correct operation.

MemSynth: synthesizing memory models

Memory consistency models define memory reordering behaviors on multiprocessors.

x = y = 0	
a = x	b = y
y = 1	x = 1

a ≡ b ≡ 1

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Forbidden by sequential consistency.

Allowed by x86 and other hardware memory models.

MemSynth: synthesizing memory models

Memory consistency models define memory reordering behaviors on multiprocessors.

Formalizing memory models is hard: e.g., PowerPC formalized over 7 publications in 2009-2015.

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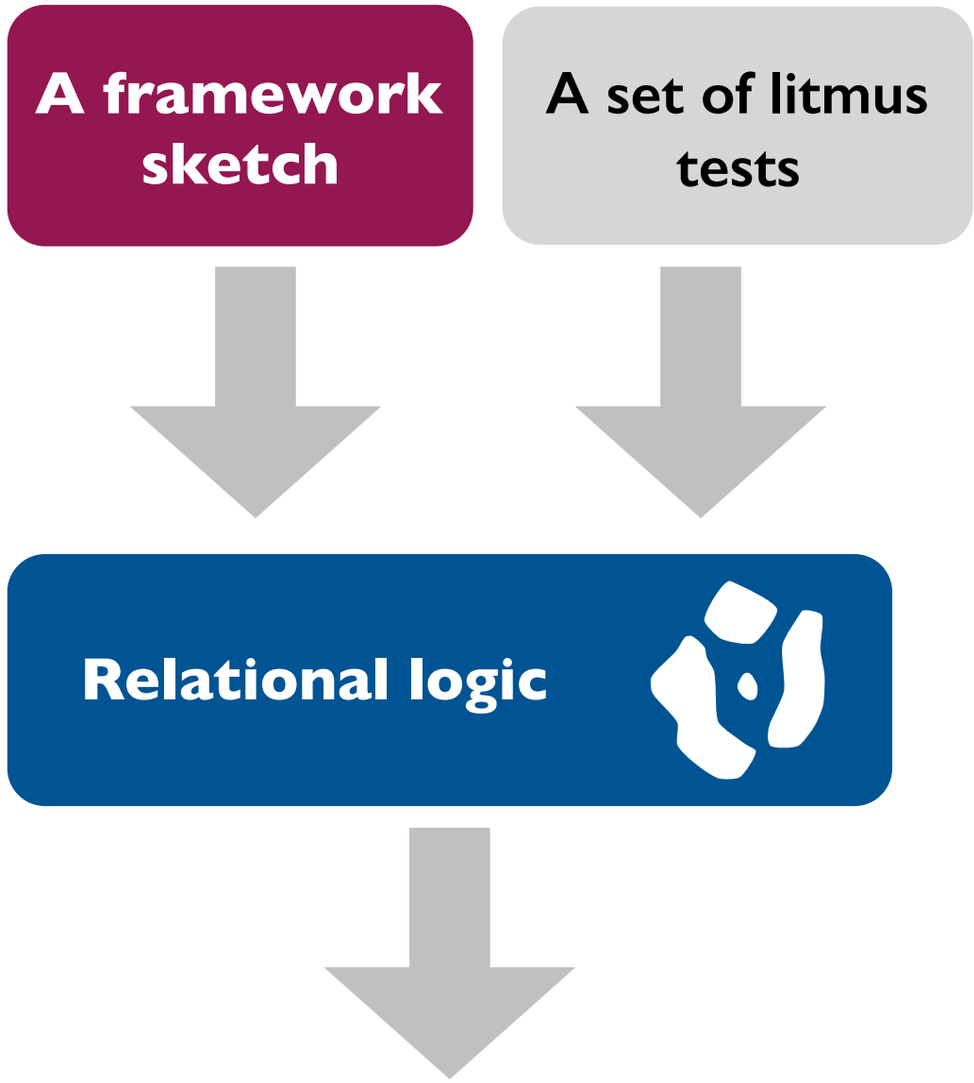


MemSynth: synthesizing memory models

A framework sketch

A set of litmus tests

Relational logic

Memory model specification

Built by a 2nd year grad in a few weeks

James Bornholt

MemSynth: synthesizing memory models

A framework sketch

A set of litmus tests

[Bornholt and Torlak, **PLDI'17**]

Relational logic

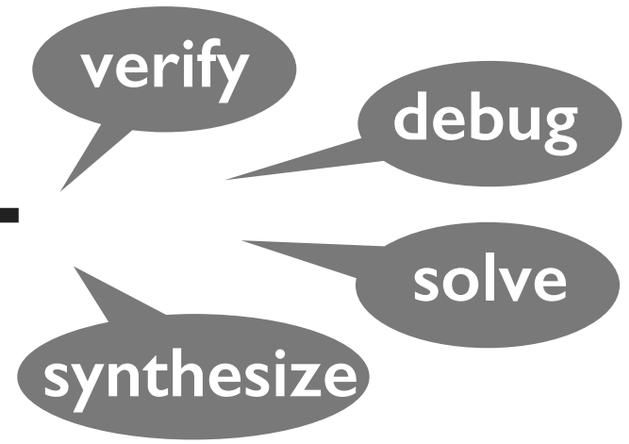
Memory model specification

Synthesized PowerPC in 12 seconds from 768 previously published tests.

Synthesized x86 in 2 seconds from Intel's litmus tests. Discovered 4 tests are missing from the Intel manual.

thanks

your SDSL



ROSETTE

symbolic virtual machine