Programming for everyone: from solvers to solver-aided languages and beyond

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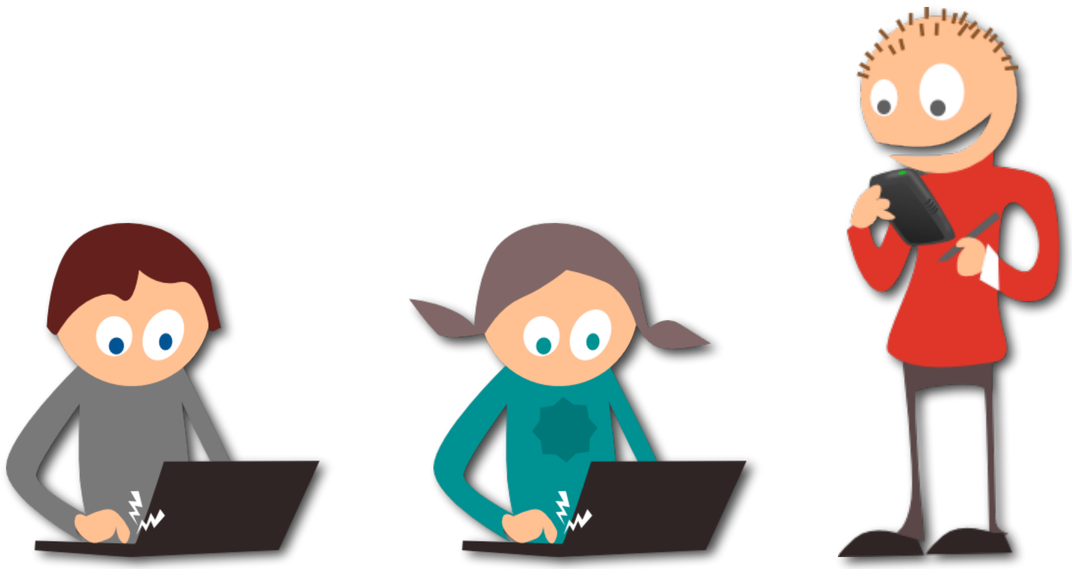
http://people.csail.mit.edu/emina/

vision

a little programming for everyone

A little programming for everyone

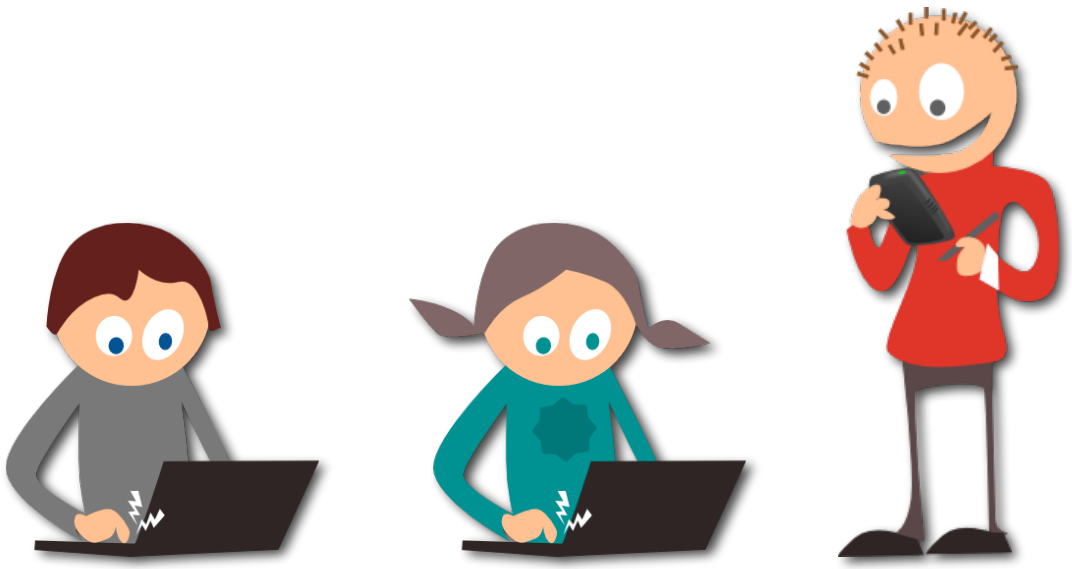
We all want to build programs …



A little programming for everyone

We all want to build programs …

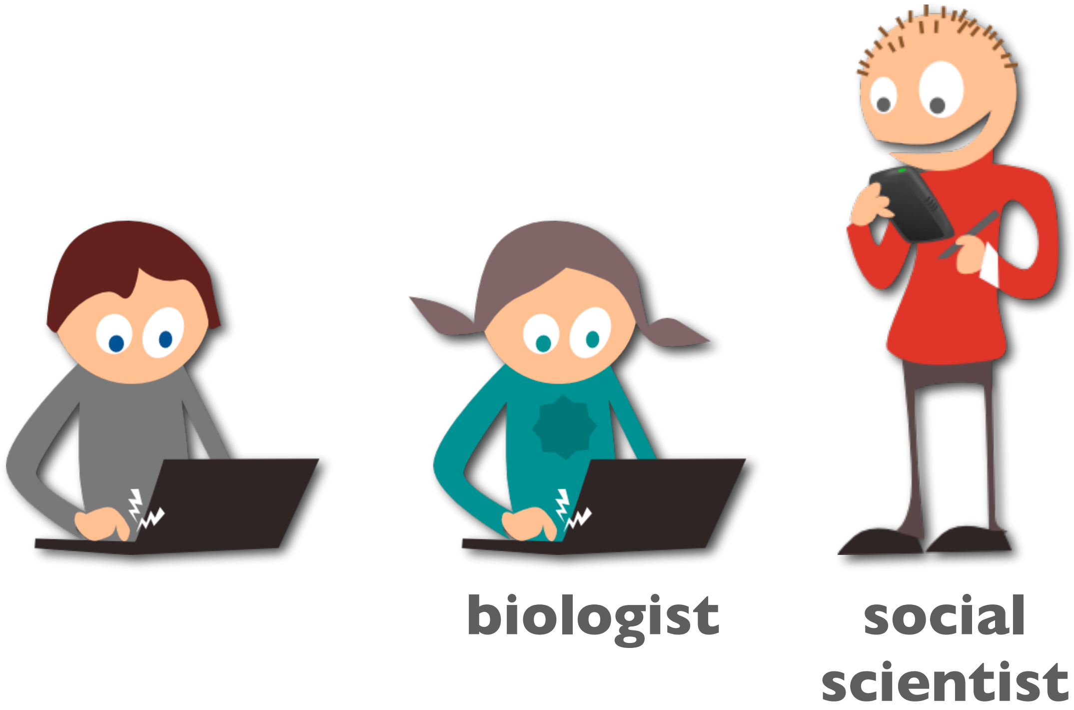
- spreadsheet data manipulation



A little programming for everyone

We all want to build programs …

- spreadsheet data manipulation
- models of cell fates



A little programming for everyone

We all want to build programs …

- spreadsheet data manipulation
- models of cell fates
- cache coherence protocols
- memory models

hardware designer

biologist

social scientist

A little programming for everyone

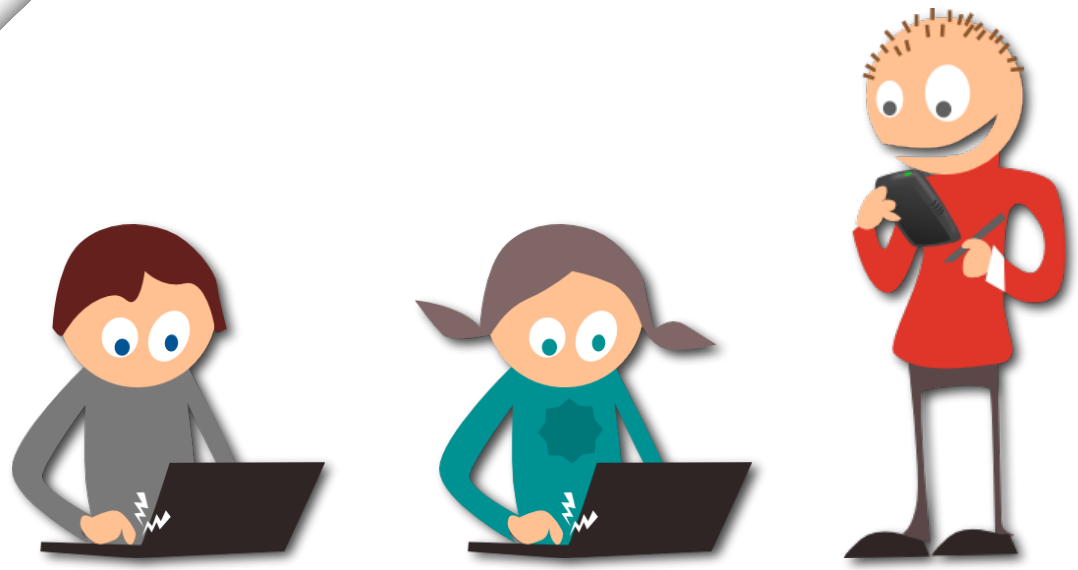
We all want to build programs …

- spreadsheet data manipulation [Flashfill, **POPL’11**]
- models of cell fates [SBL, **POPL’13**]
- cache coherence protocols [Transit, **PLDI’13**]
- memory models [MemSAT, **PLDI’10**]

time

code

effort



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A **little** programming for everyone

We all want to build programs …

- spreadsheet data manipulation
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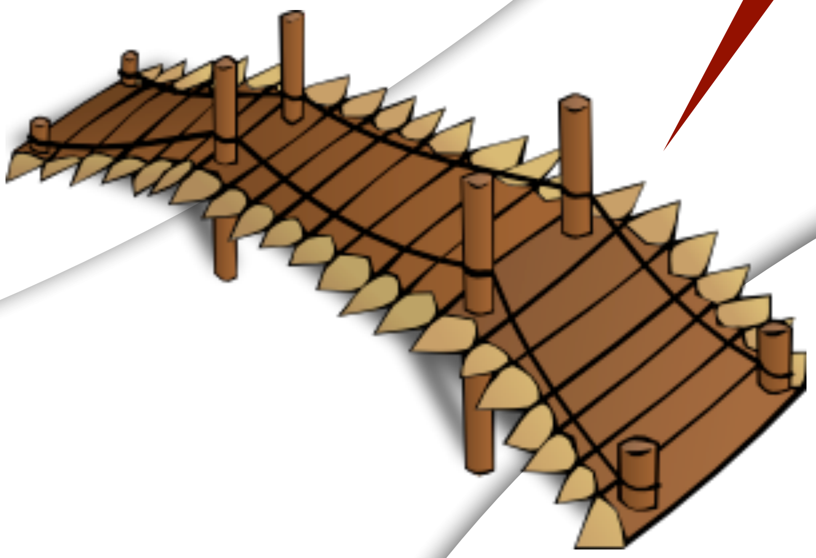
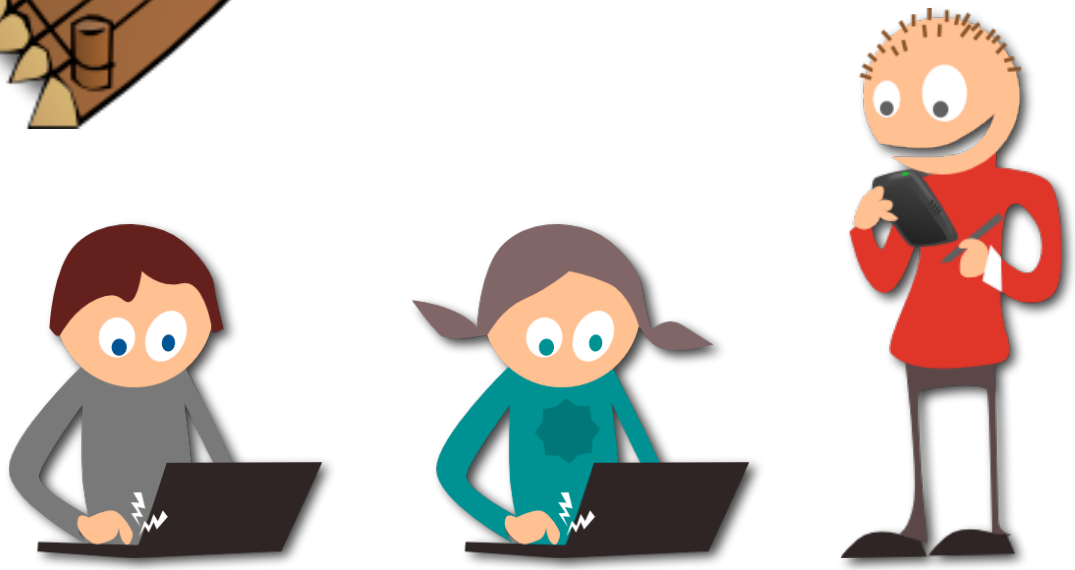
solver-aided languages



less time

less code

less effort



hardware designer

biologist

social scientist

A little history

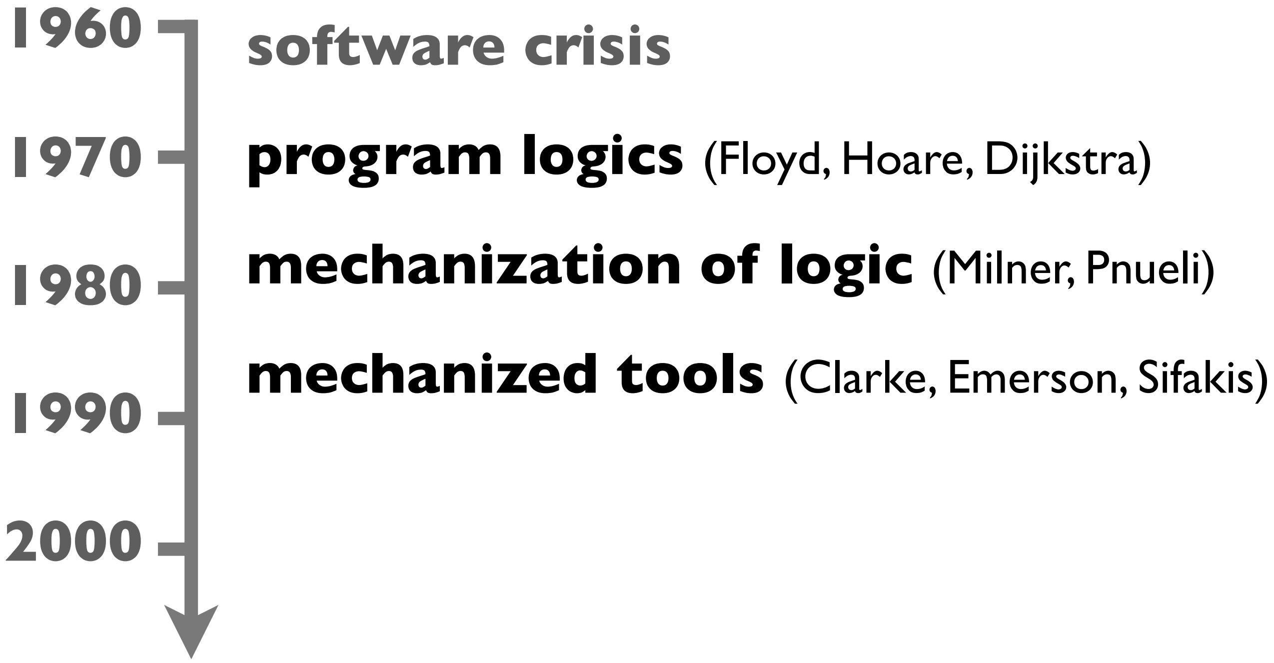
program logics (Floyd, Hoare, Dijkstra)

mechanization of logic (Milner, Pnueli)

mechanized tools (Clarke, Emerson, Sifakis)

better programs

A little history



software crisis

program logics (Floyd, Hoare, Dijkstra)

mechanization of logic (Milner, Pnueli)

mechanized tools (Clarke, Emerson, Sifakis)

better programs

A little history

1960 **software crisis**

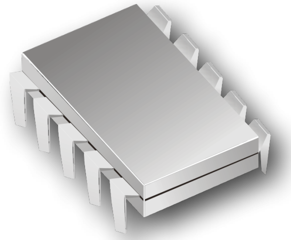
1970 **program logics** (Floyd, Hoare, Dijkstra)

1980 **mechanization of logic** (Milner, Pnueli)

1990 **mechanized tools** (Clarke, Emerson, Sifakis)

2000

better programs



6TH SENSE
[IBM]

ASTRÉE
[AbsInt]

SLAM
[MSR]

A little history

1960
software crisis

1970
program logics (Floyd, Hoare, Dijkstra)

1980
mechanization of logic (Milner, Pnueli)

mechanized tools (Clarke, Emerson, Sifakis)

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software gap

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better programs

A little history

1960
1970
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software crisis

program logics (Floyd, Hoare, Dijkstra)

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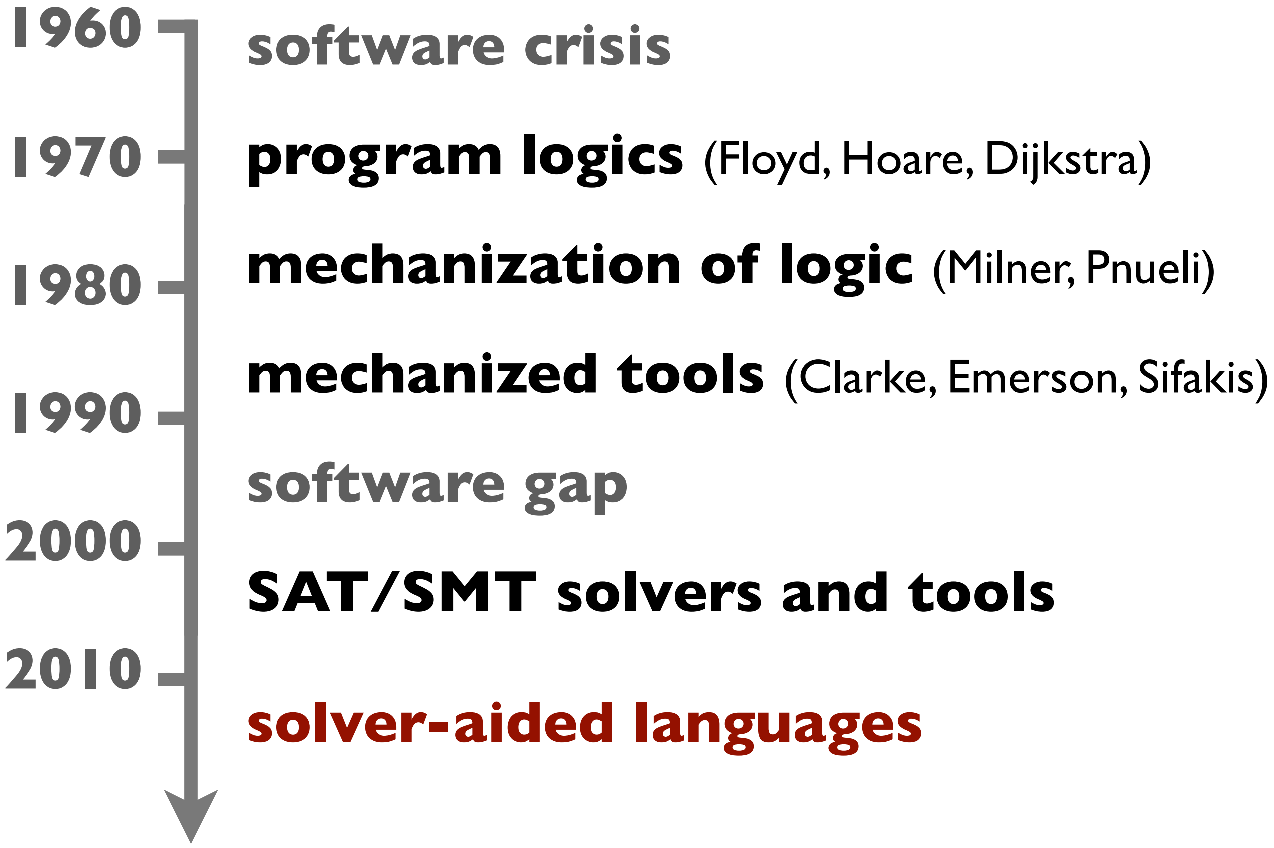
software gap

SAT/SMT solvers and tools

better programs

A little history



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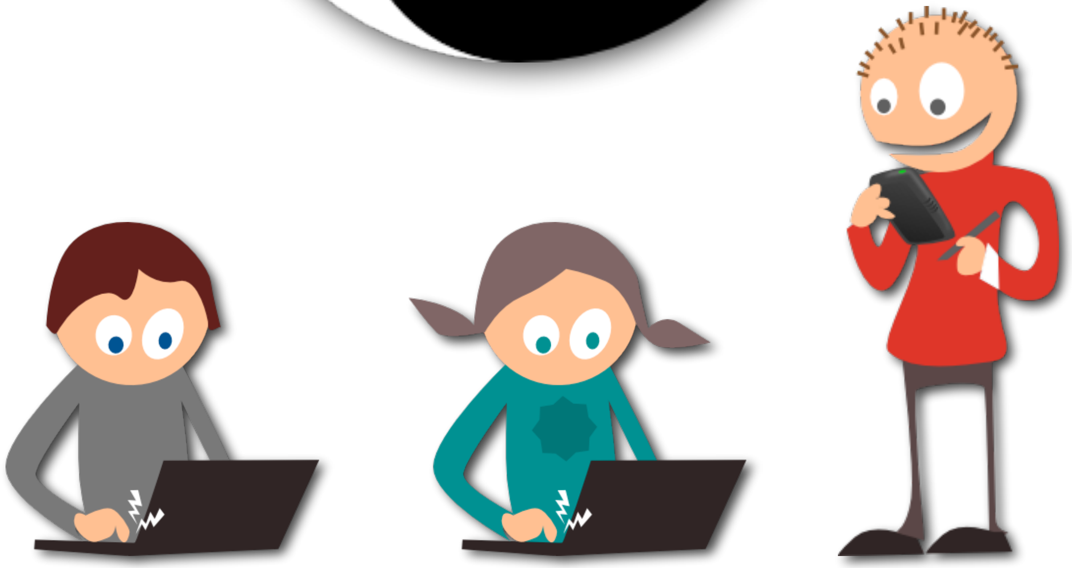
SAT/SMT solvers and tools

2010

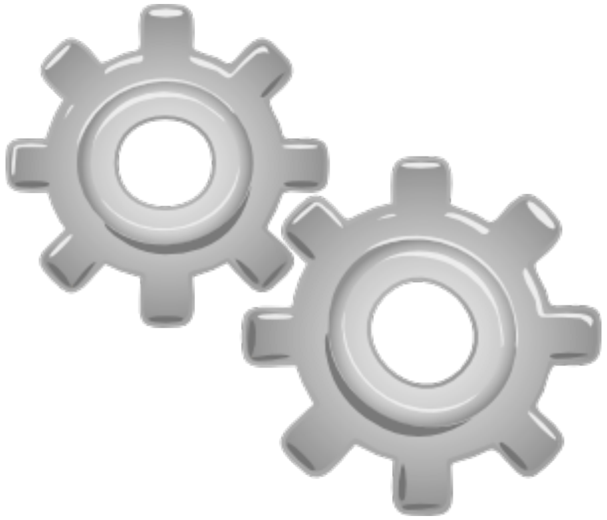
solver-aided languages



outline

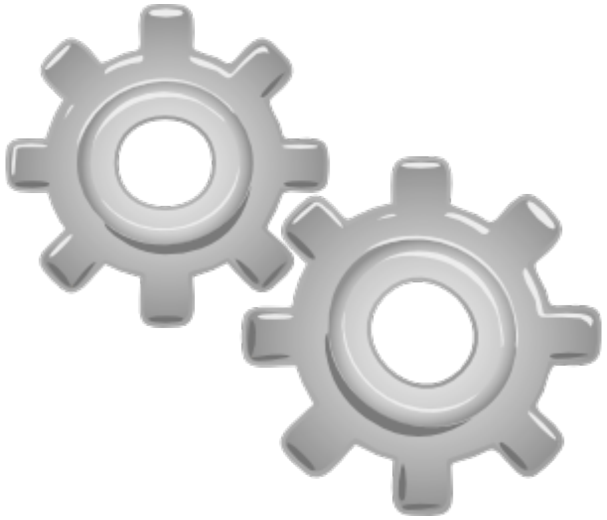
outline

solver-aided tools



outline

solver-aided tools, languages

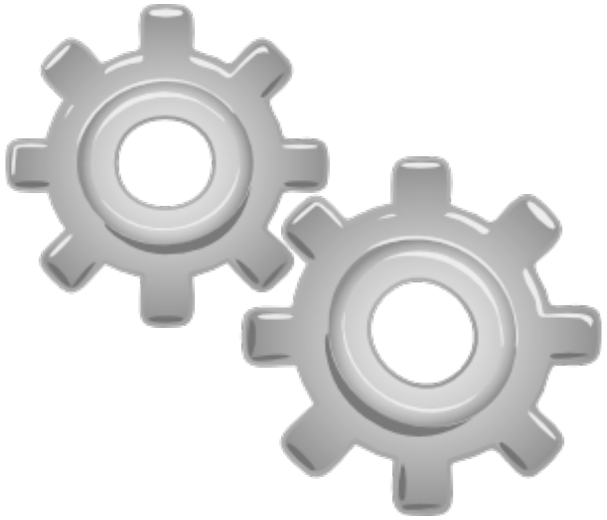


outline

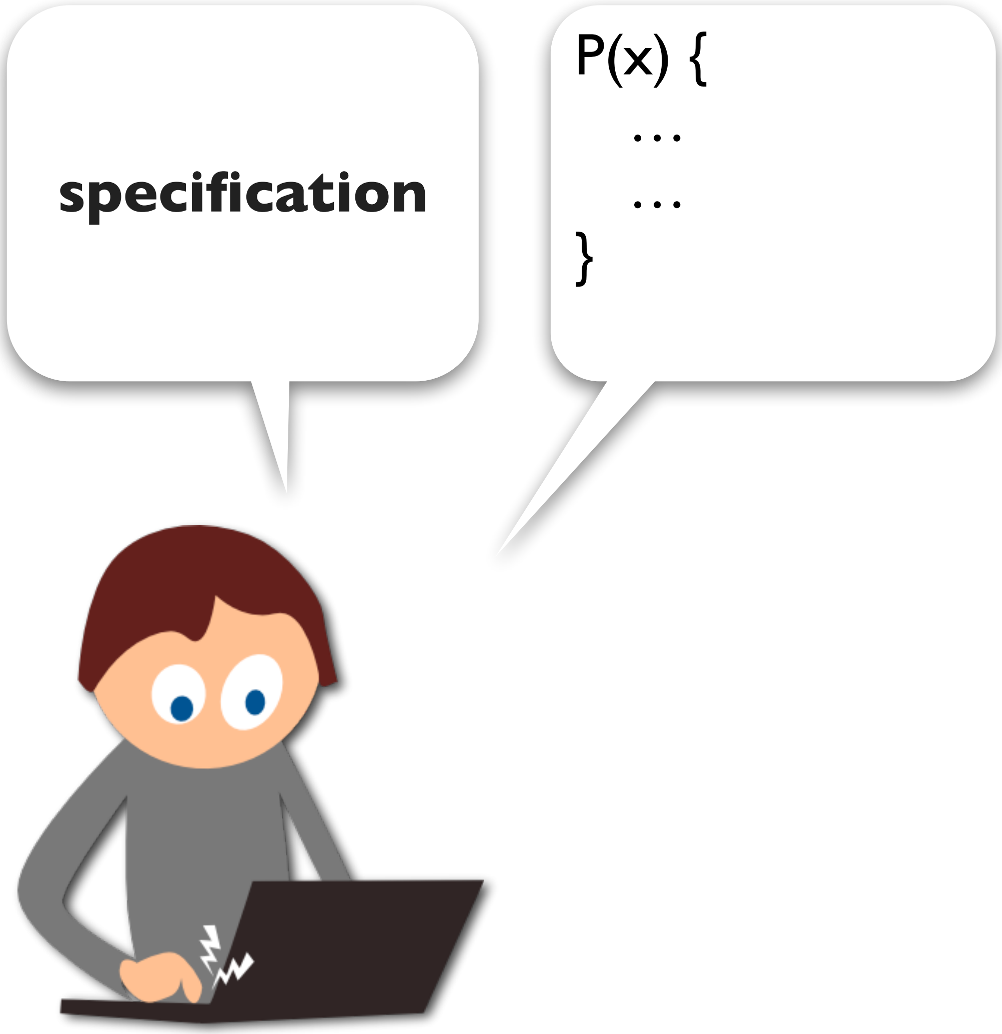
solver-aided tools, languages and demos

story

solver-aided tools



Programming ...



specification

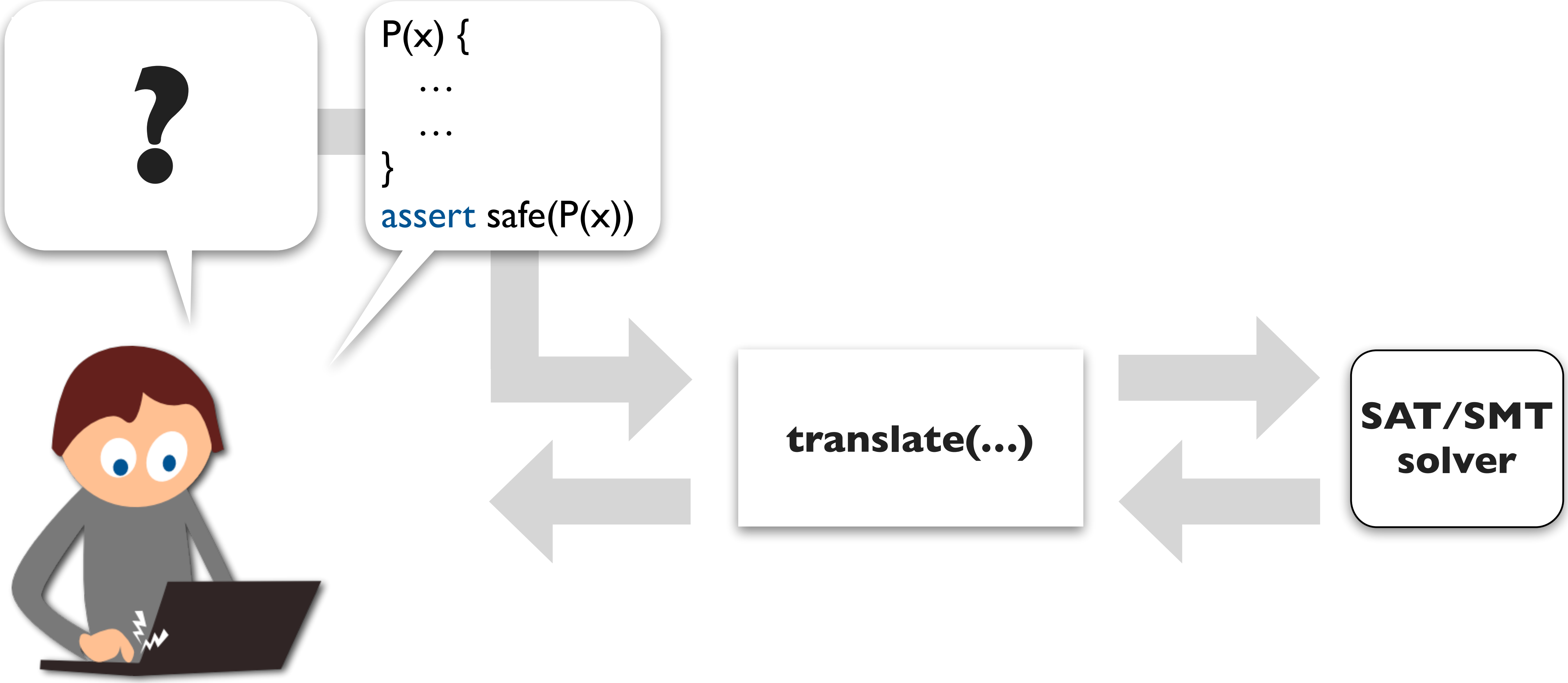
```
P(x) {
   ...
   ...
}
```

Programming ...

test case

```
P(x) {
   …
   …
}
assert safe(P(2))
```

Programming with a solver-aided tool



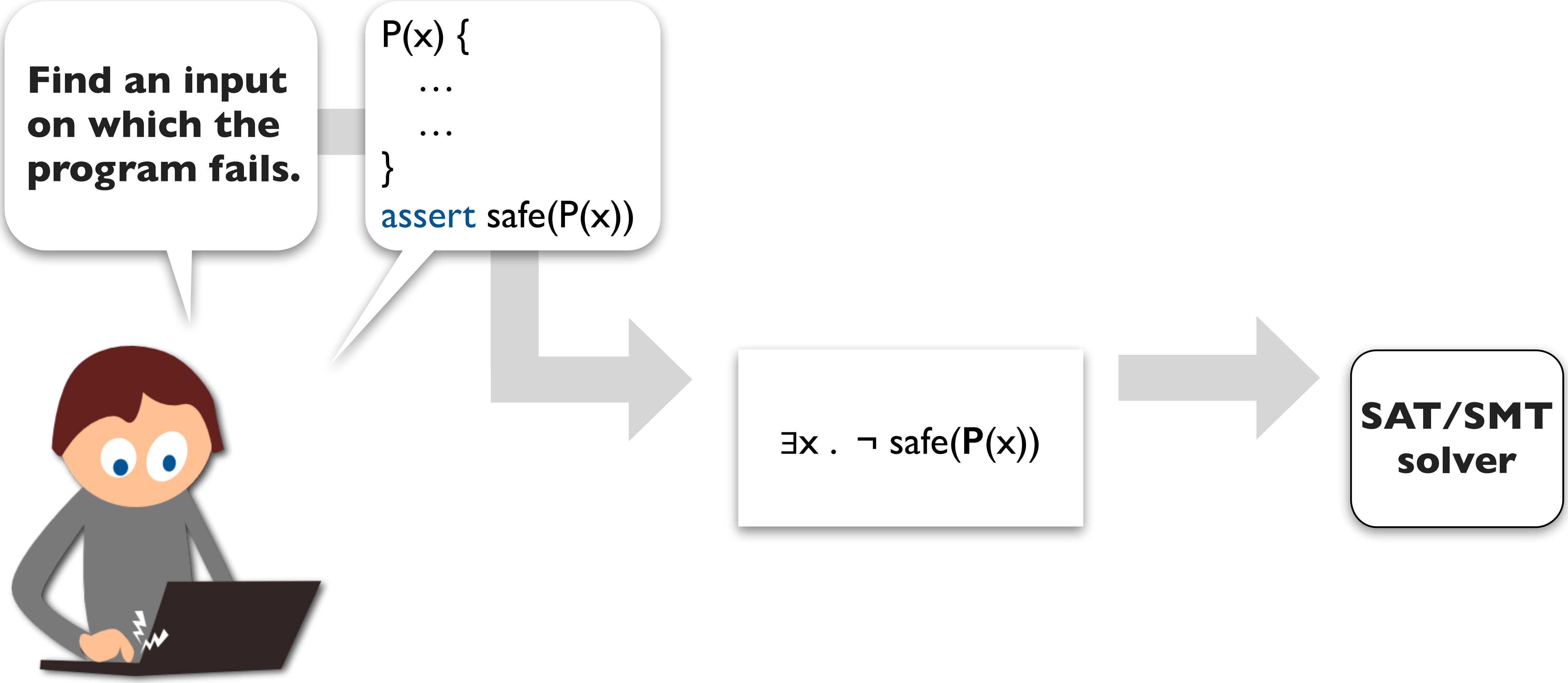
?

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

translate(…)

SAT/SMT solver

Solver-aided tools: verification



Find an input on which the program fails.

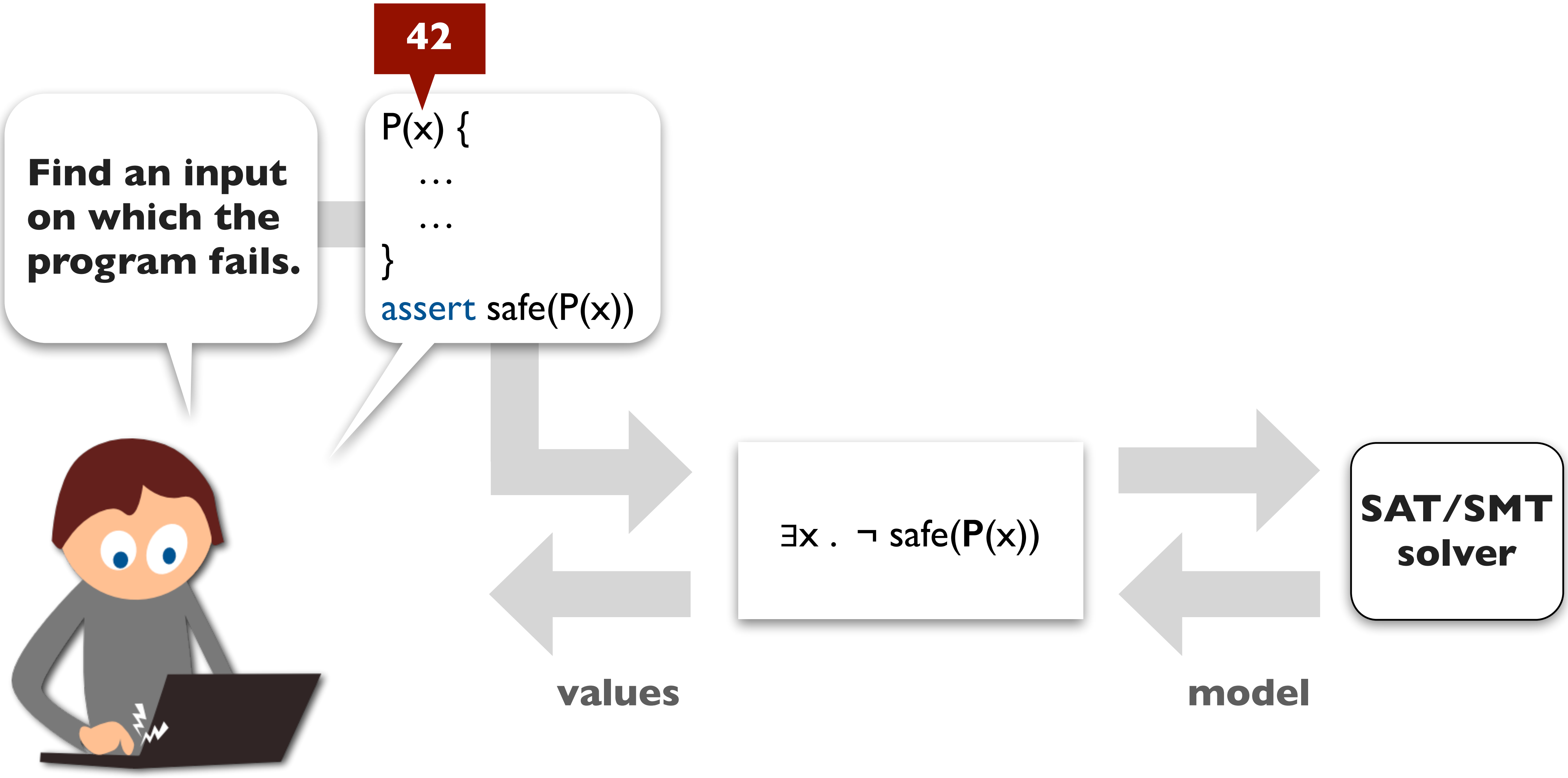
```
P(x) {
   …
   …
}
assert safe(P(x))
```

$\exists x \,.\; \neg\, \text{safe}(\mathbf{P}(x))$

SAT/SMT solver

CBMC [CMU], Dafny [MSR],
Miniatur [IBM], Klee [Stanford], etc.

Solver-aided tools: verification



Find an input on which the program fails.

42

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

$\exists x \,.\, \neg\, \mathrm{safe}(\mathbf{P}(x))$

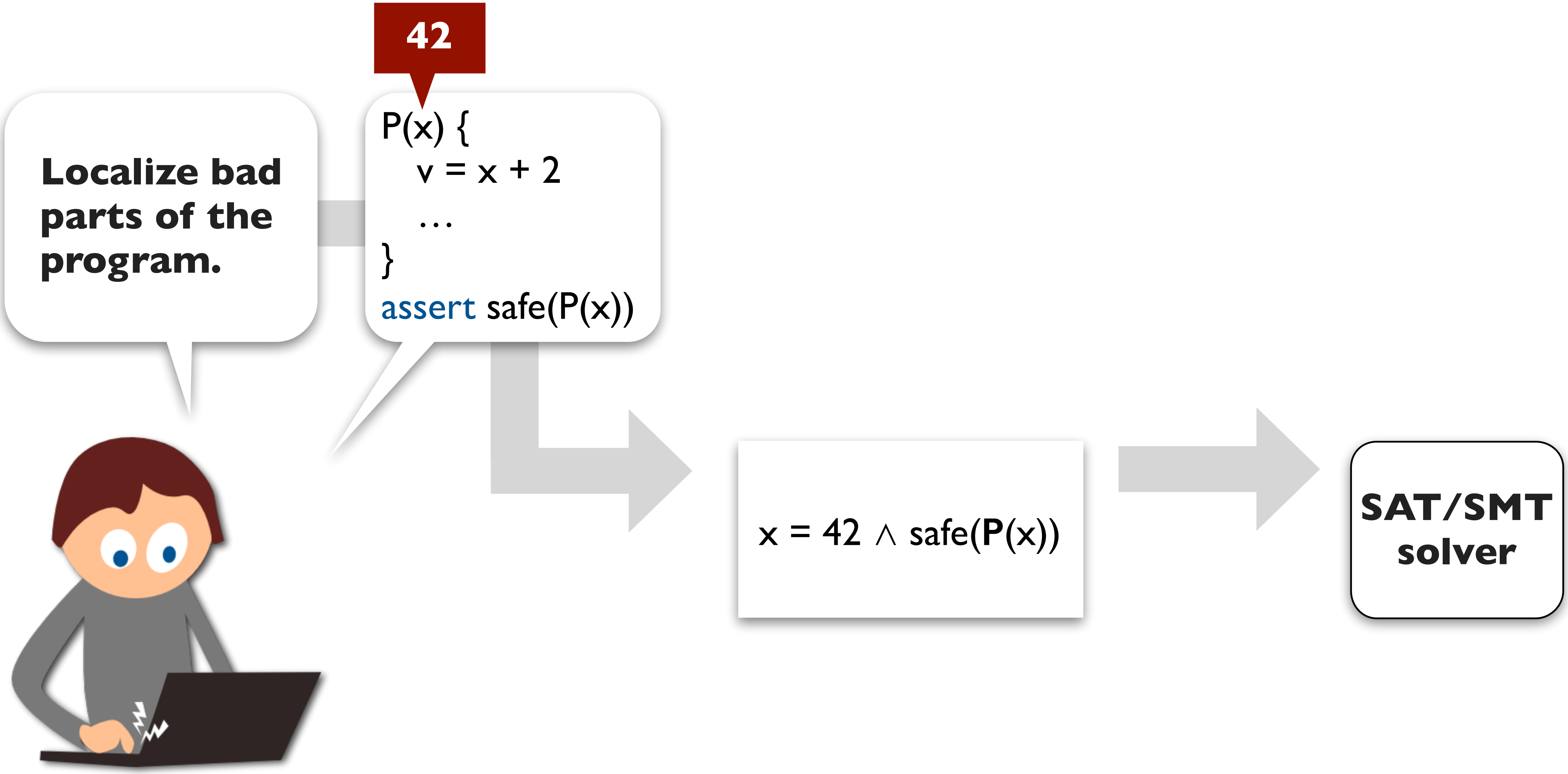
SAT/SMT solver

values

model

CBMC [CMU], Dafny [MSR],
Miniatur [IBM], Klee [Stanford], etc.

Solver-aided tools: debugging



Localize bad parts of the program.

42

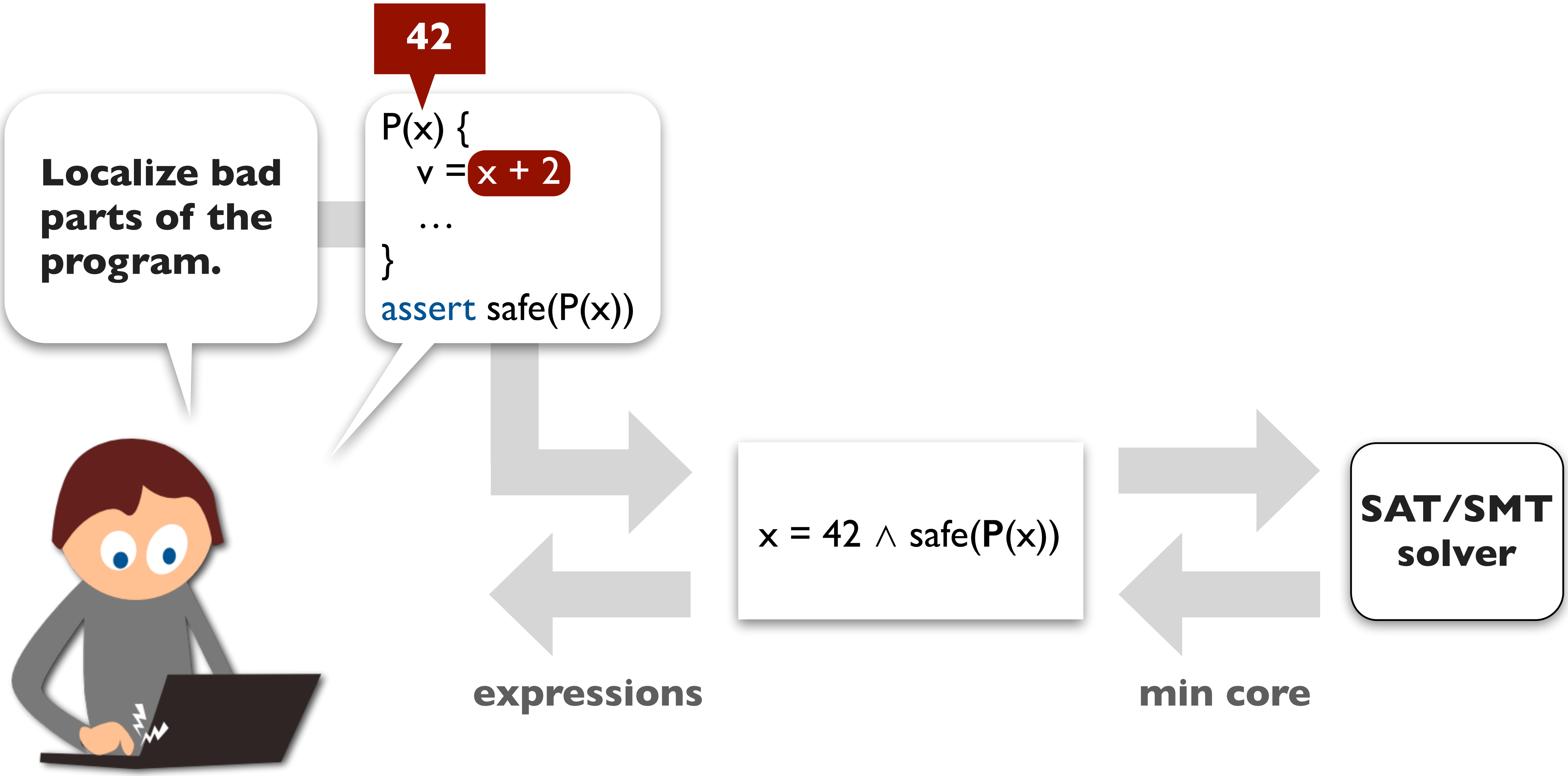
```
P(x) {
  v = x + 2
  …
}
assert safe(P(x))
```

x = 42 ∧ safe(P(x))

SAT/SMT solver

BugAssist [UCLA / MPI-SWS]

Solver-aided tools: debugging



Localize bad parts of the program.

42

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x = 42 ∧ safe(P(x))

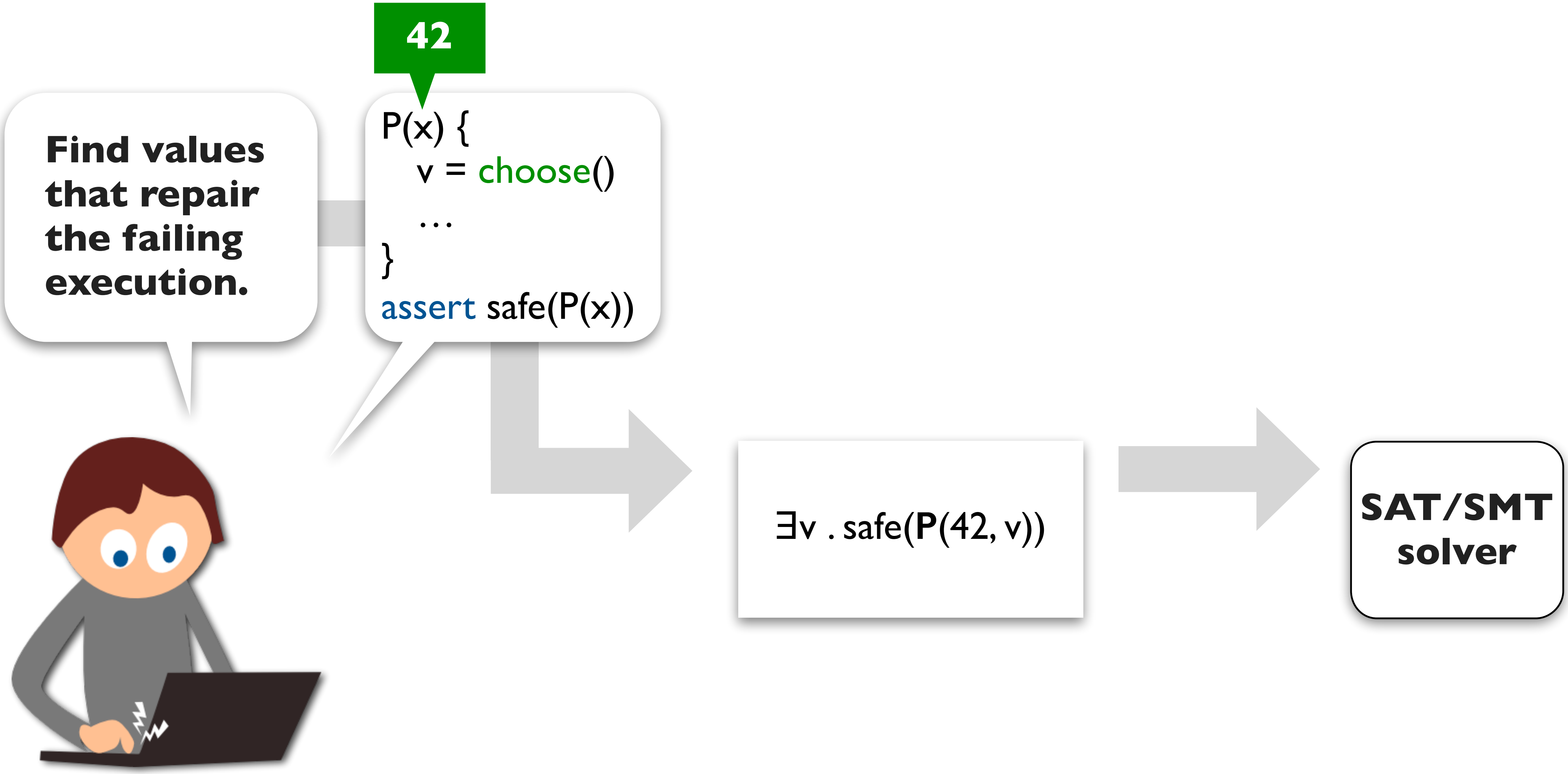
SAT/SMT solver

expressions

min core

BugAssist [UCLA / MPI-SWS]

Solver-aided tools: angelic execution



Find values that repair the failing execution.

42

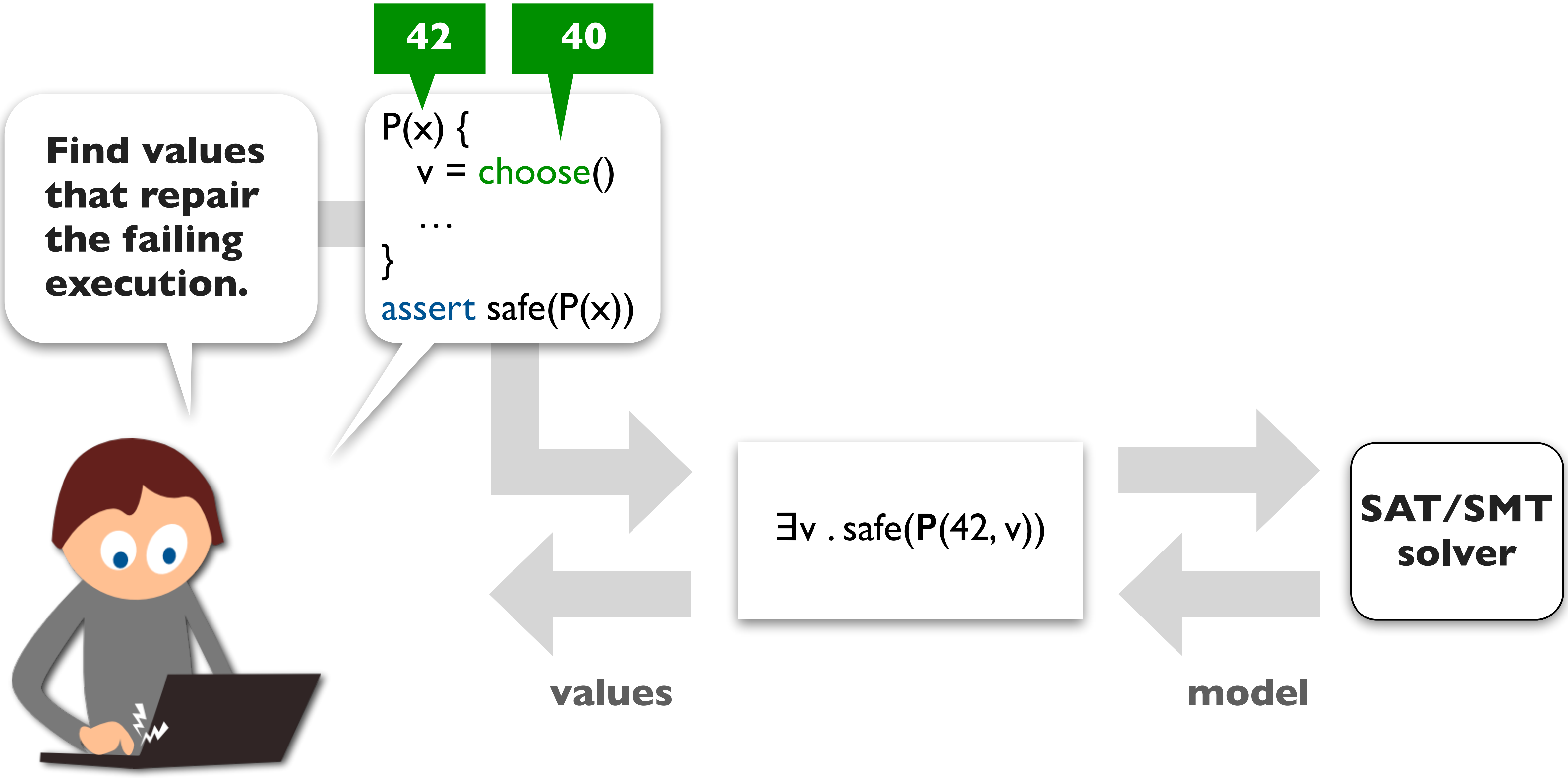
```
P(x) {
   v = choose()
   …
}
assert safe(P(x))
```

$\exists v \,.\, \text{safe}(P(42, v))$

SAT/SMT solver

Kaplan [EPFL], PBnJ [UCLA], Skalch [Berkeley], Squander [MIT], etc.

Solver-aided tools: angelic execution



Find values that repair the failing execution.

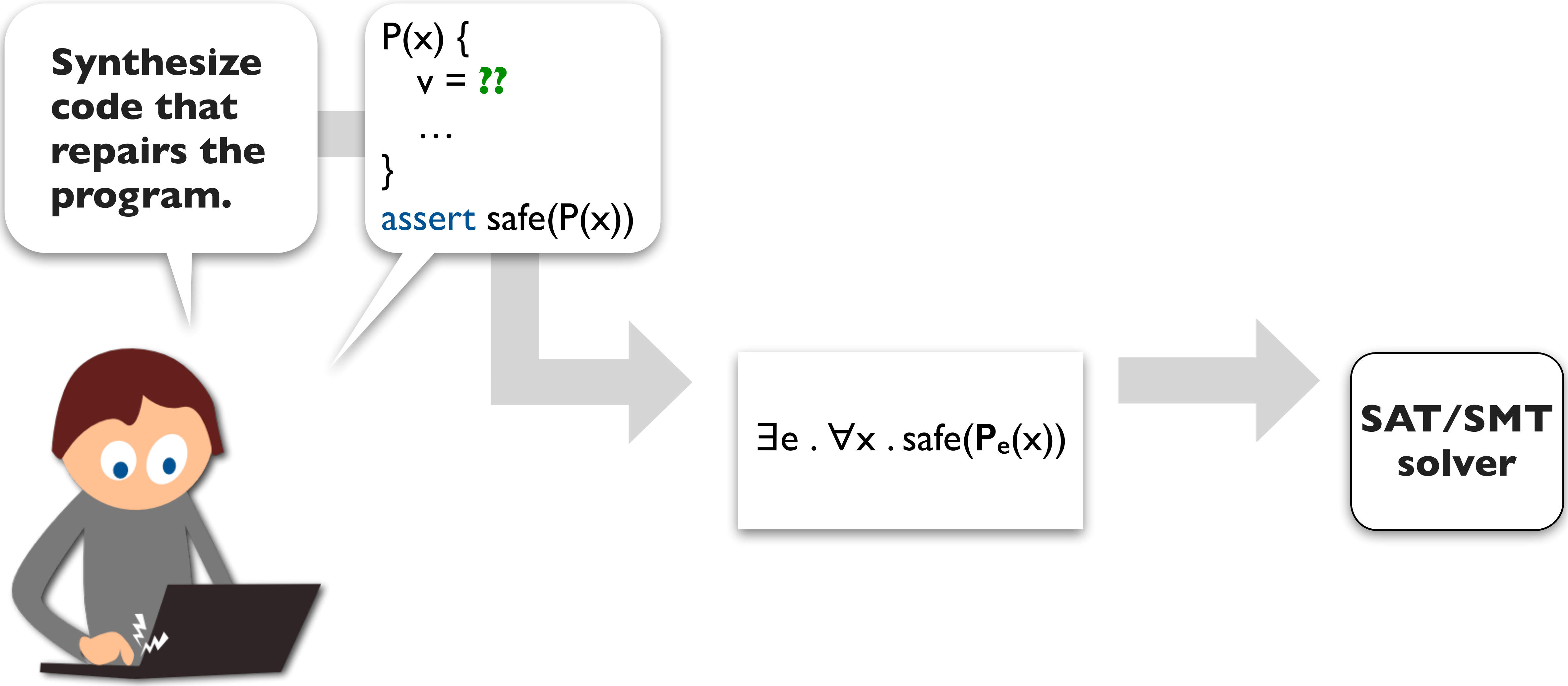
```
P(x) {
   v = choose()
   …
}
assert safe(P(x))
```

$\exists v$. safe(**P**(42, v))

SAT/SMT solver

Kaplan [EPFL], PBnJ [UCLA], Skalch [Berkeley], Squander [MIT], etc.

Solver-aided tools: synthesis



Synthesize code that repairs the program.

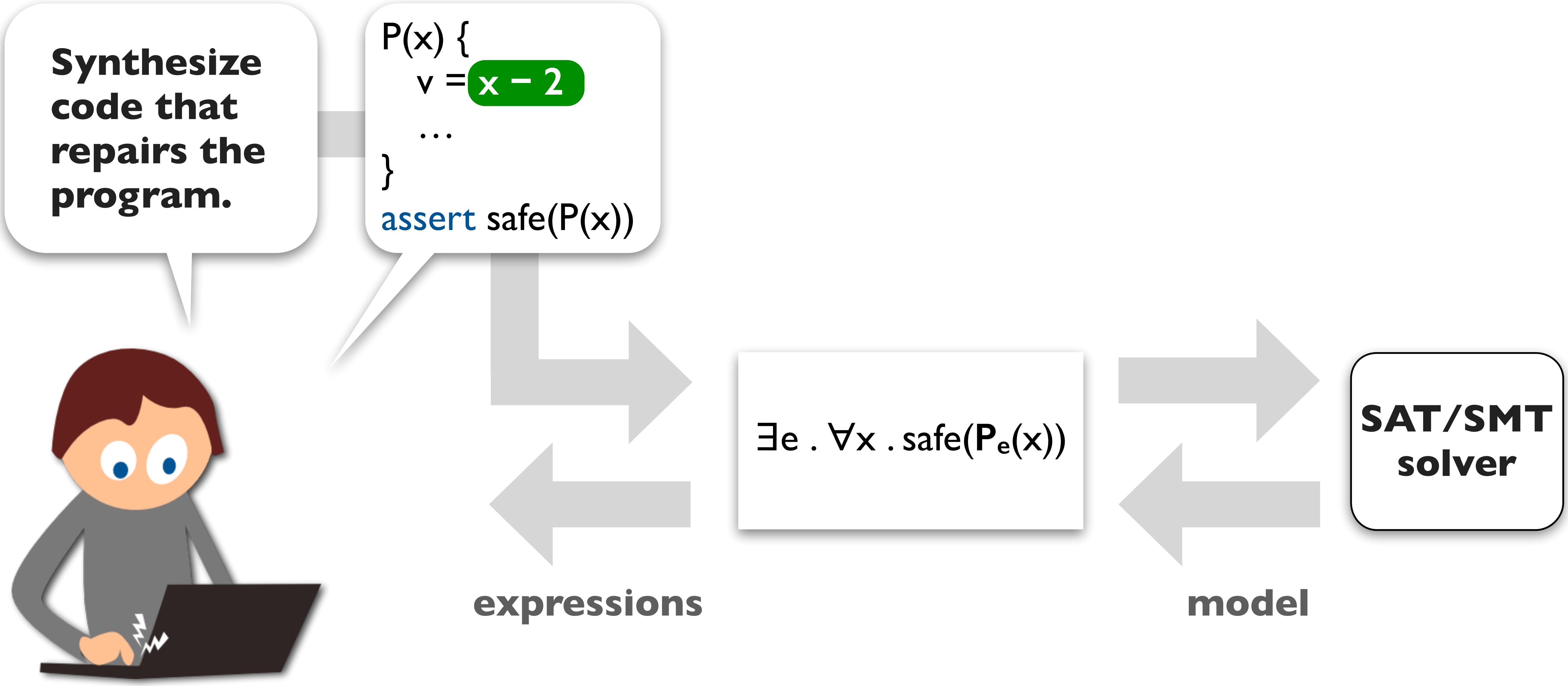
```
P(x) {
   v = ??
   …
}
assert safe(P(x))
```

$\exists e\ .\ \forall x\ .\ \text{safe}(\mathbf{P}_e(x))$

SAT/SMT solver

Comfusy [EPFL], Sketch [Berkeley / MIT]

Solver-aided tools: synthesis



Synthesize code that repairs the program.

```
P(x) {
  v = x − 2
  …
}
assert safe(P(x))
```

$\exists e \,.\, \forall x \,.\, \text{safe}(\mathbf{P}_e(x))$

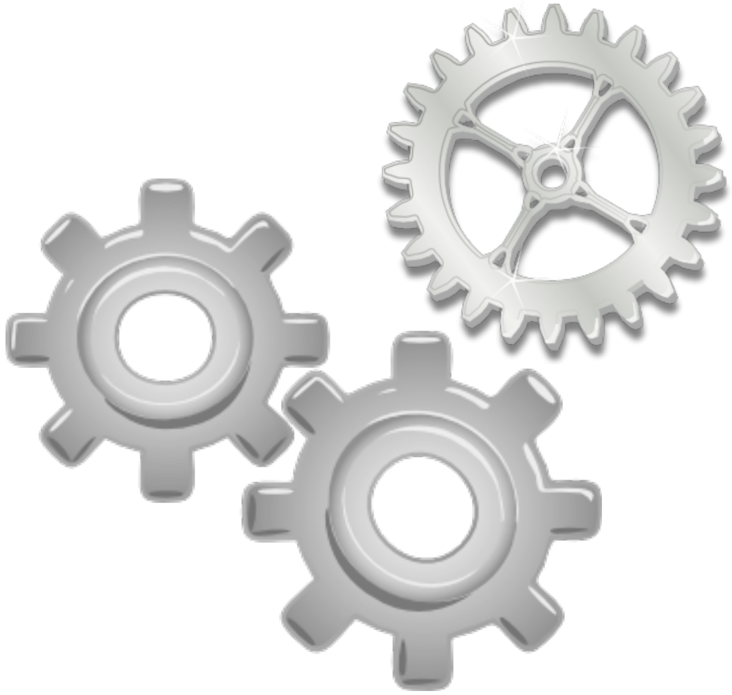
SAT/SMT solver

expressions

model

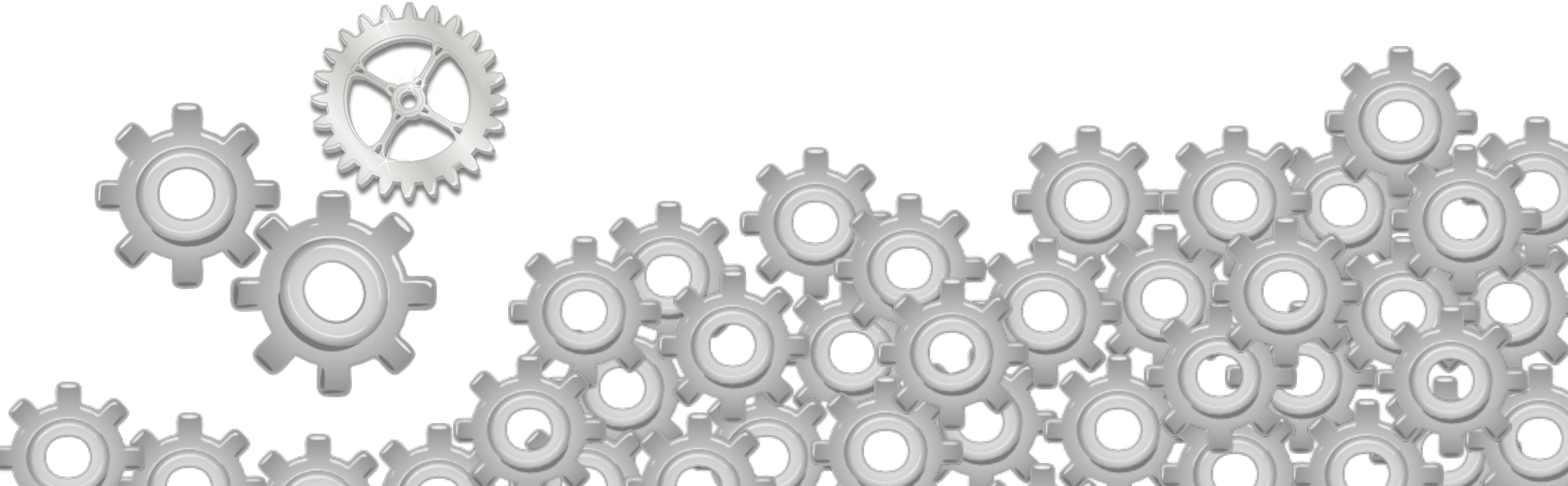
Comfusy [EPFL], Sketch [Berkeley / MIT] wanted

more solver-aided tools …

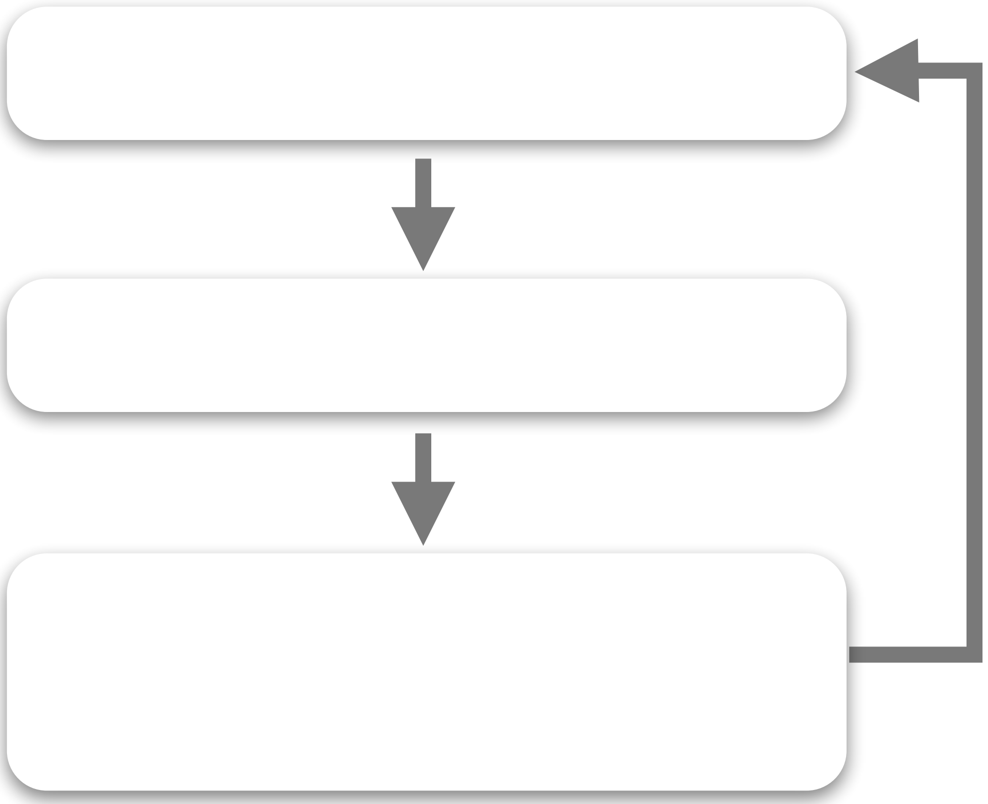


wanted

more solver-aided tools …

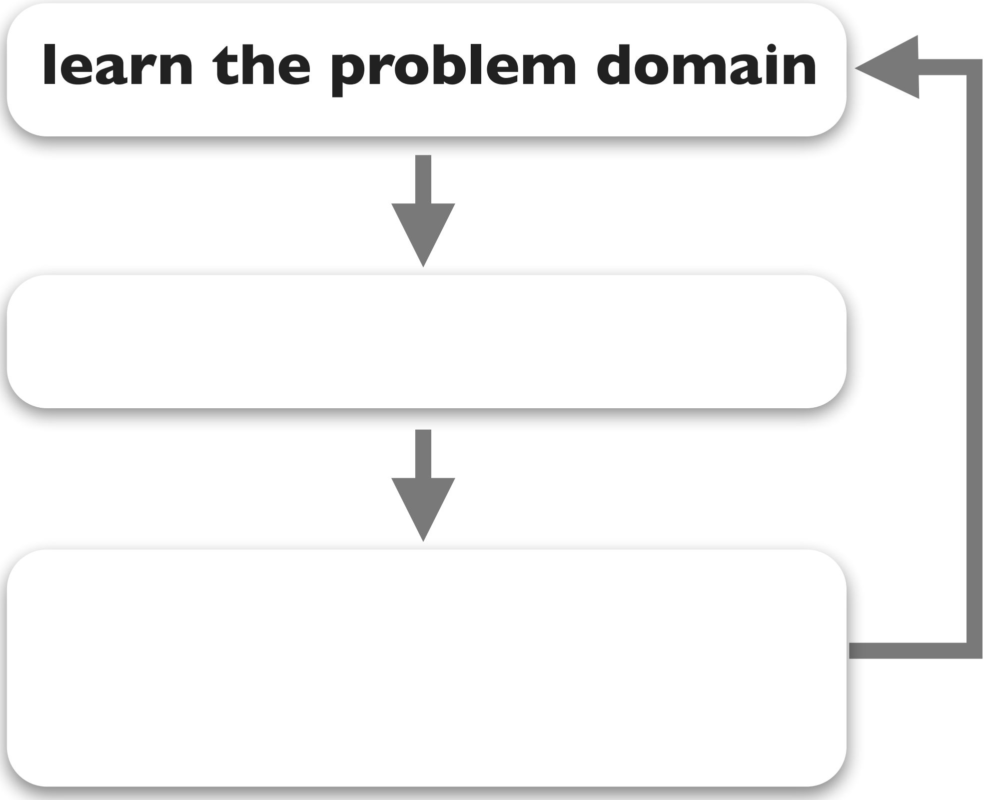


Building solver-aided tools: state-of-the-art

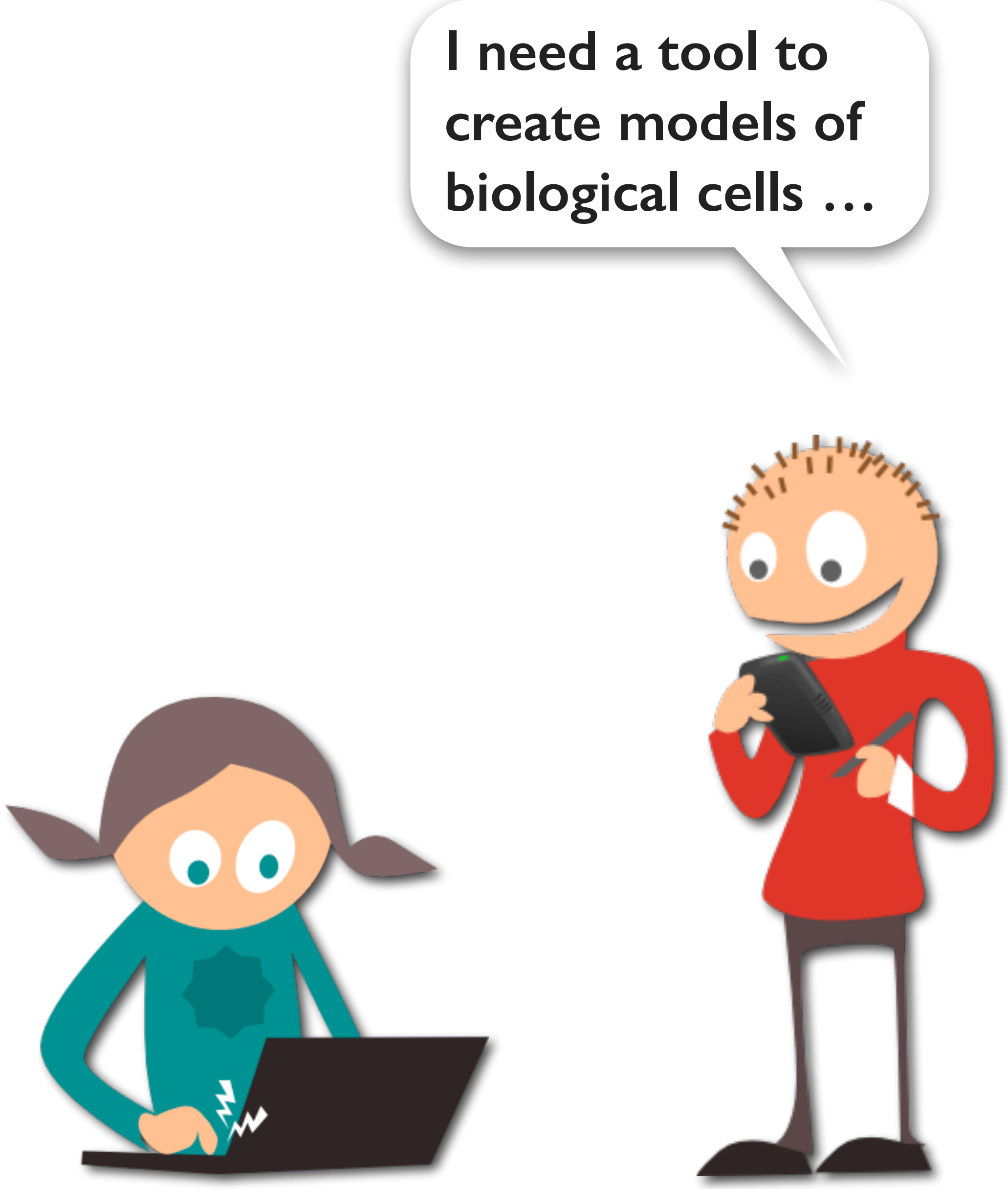


tools expert

Building solver-aided tools: state-of-the-art



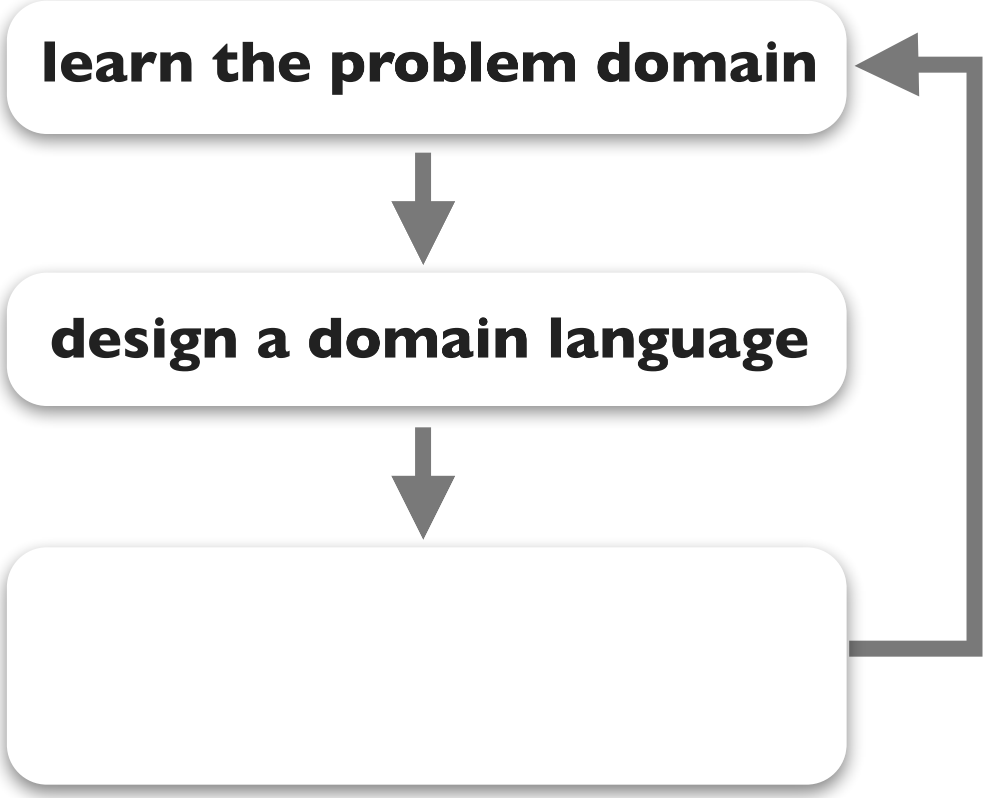
learn the problem domain



tools expert

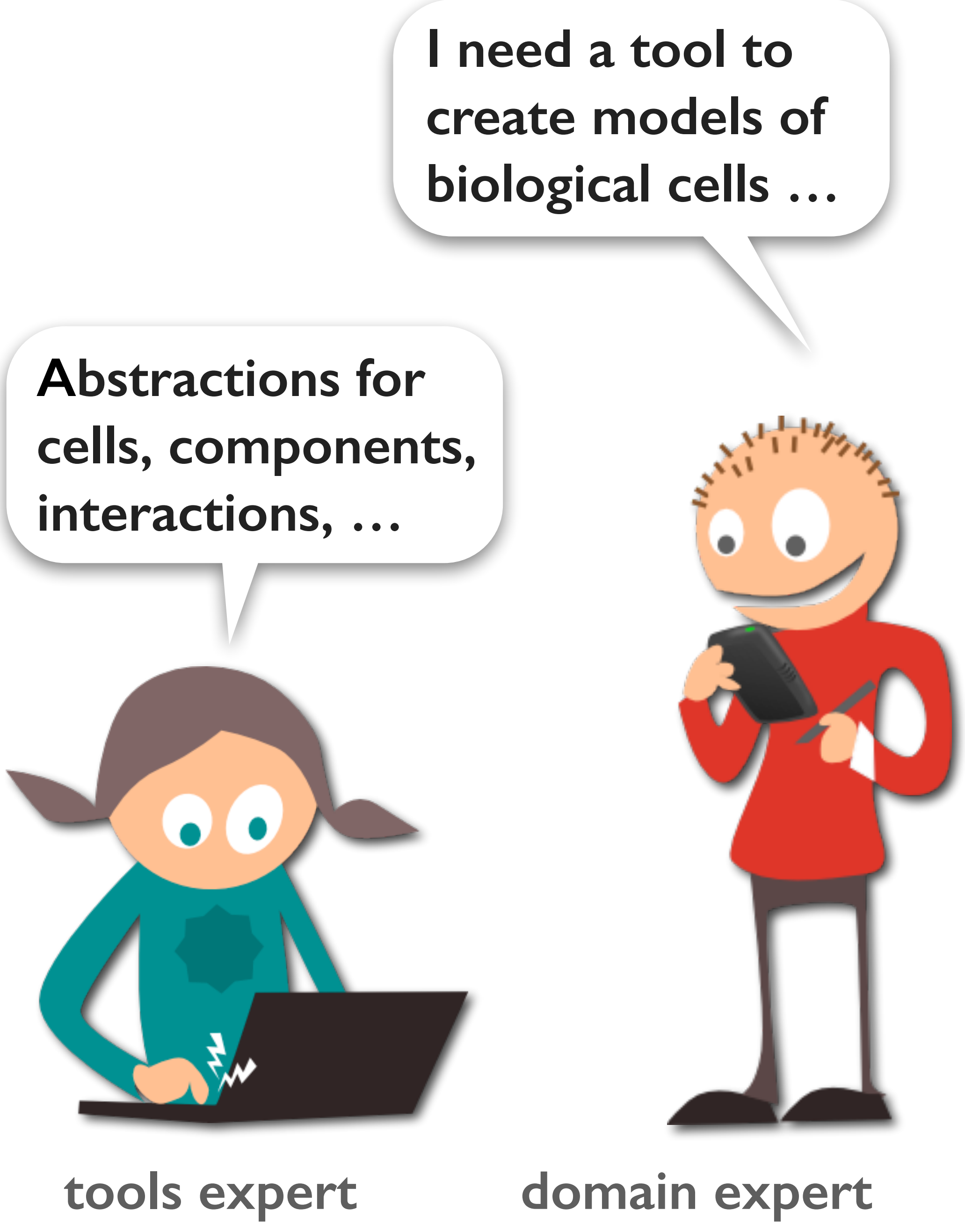
domain expert

Building solver-aided tools: state-of-the-art

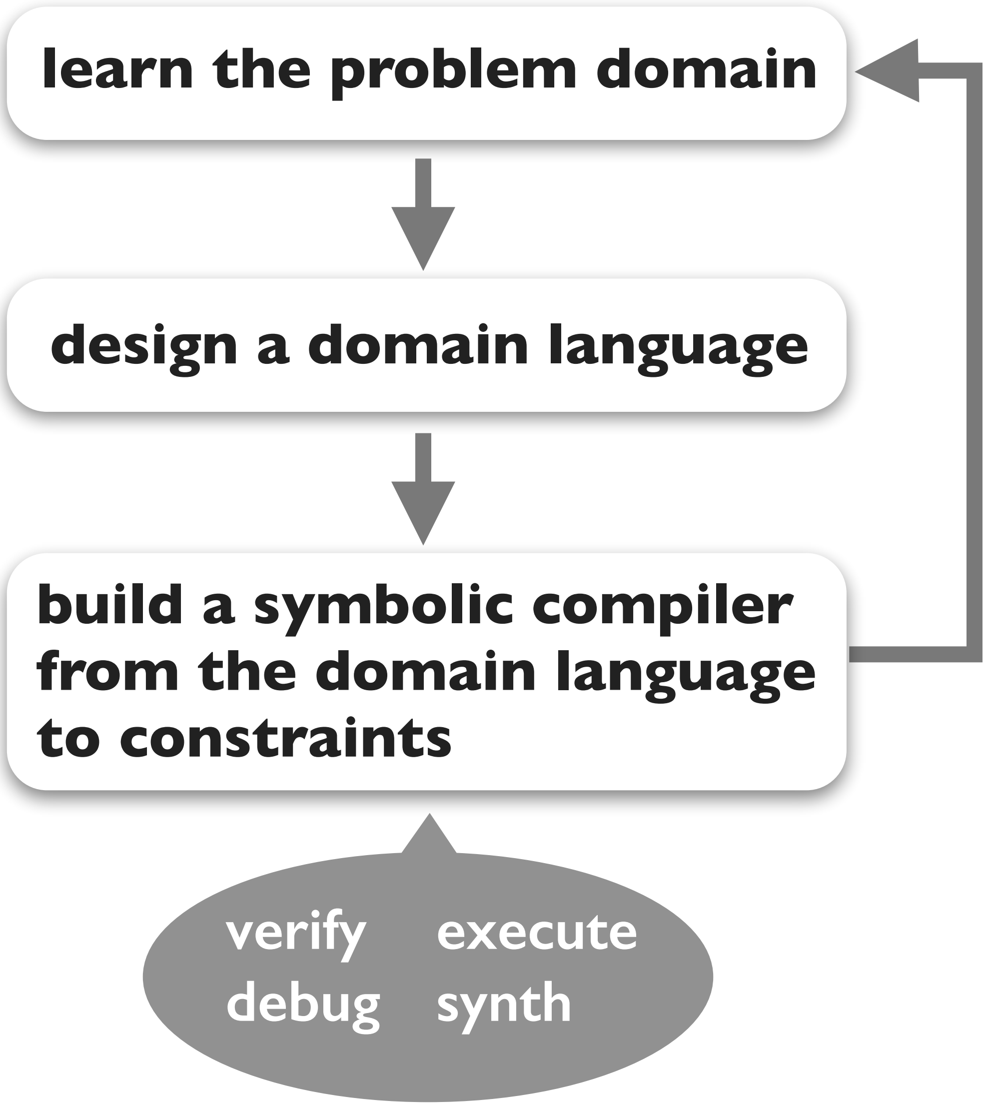


learn the problem domain

design a domain language



Building solver-aided tools: state-of-the-art



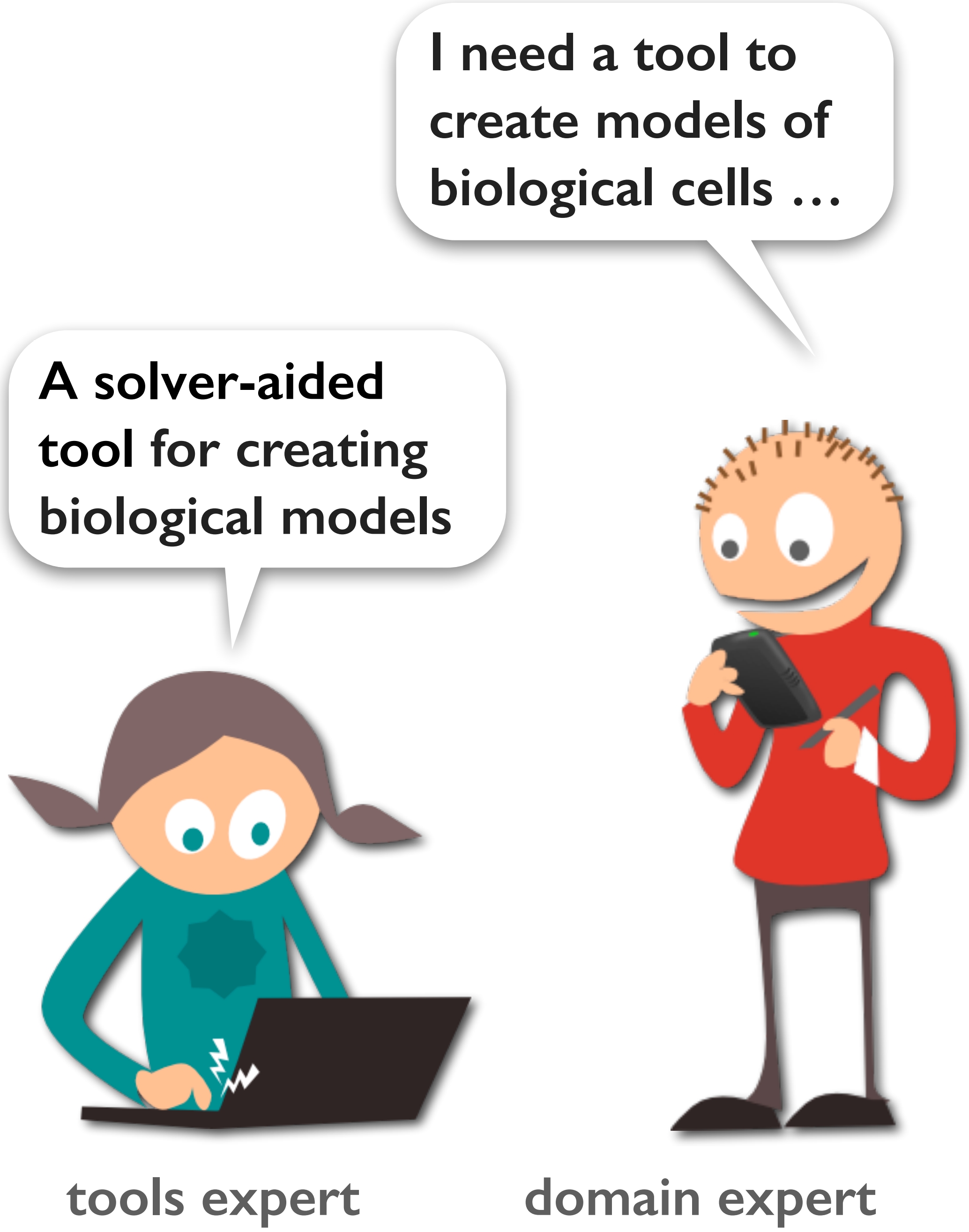
learn the problem domain

design a domain language

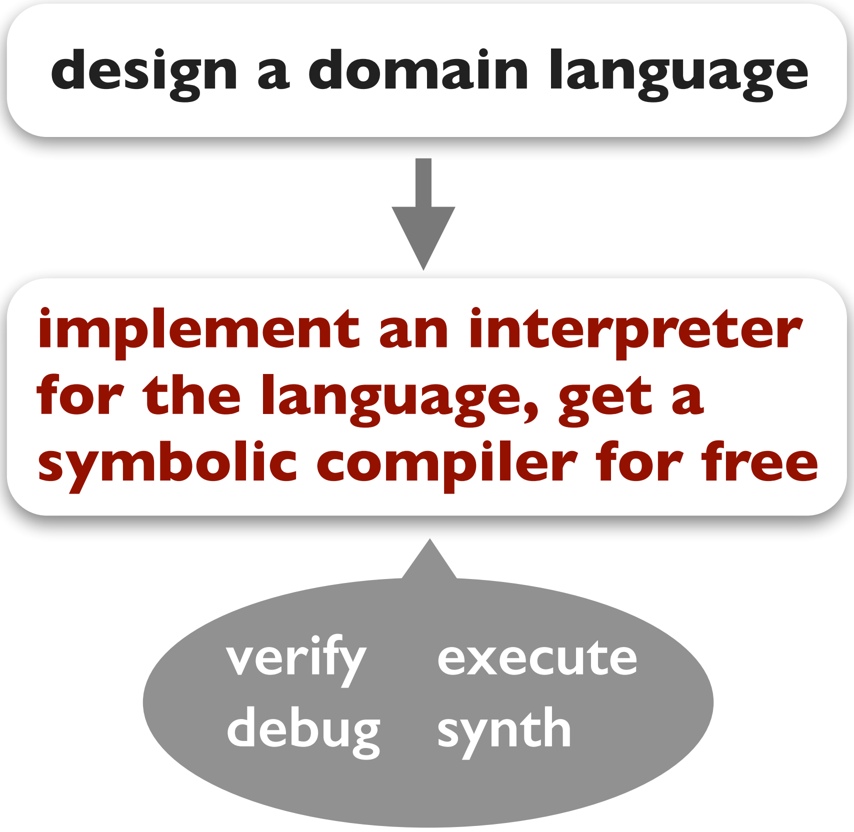
build a symbolic compiler from the domain language to constraints

verify execute debug synth

months or years of work



Can we do better?



design a domain language

weeks

implement an interpreter for the language, get a symbolic compiler for free

verify execute
debug synth

domain expert

Can we do better?

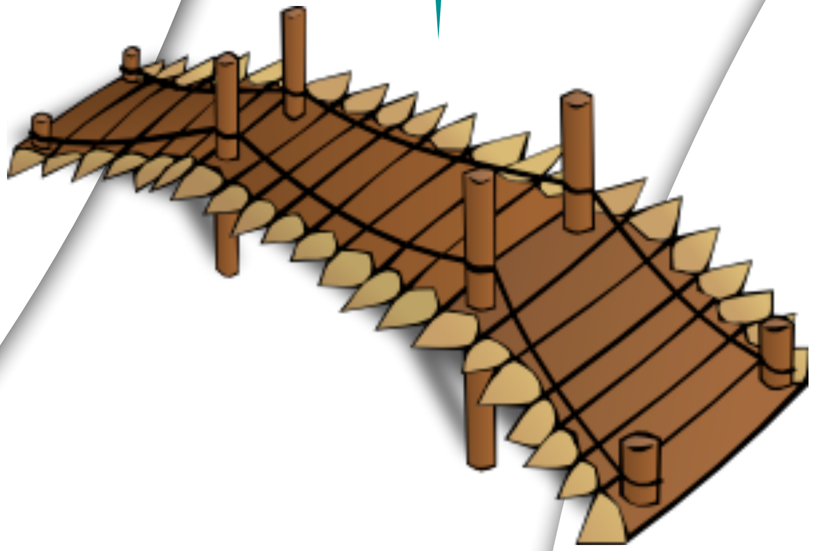
a solver-aided domain-specific language (SDSL)

design a domain language

implement an interpreter for the language, get a symbolic compiler for free

weeks

verify execute
debug synth



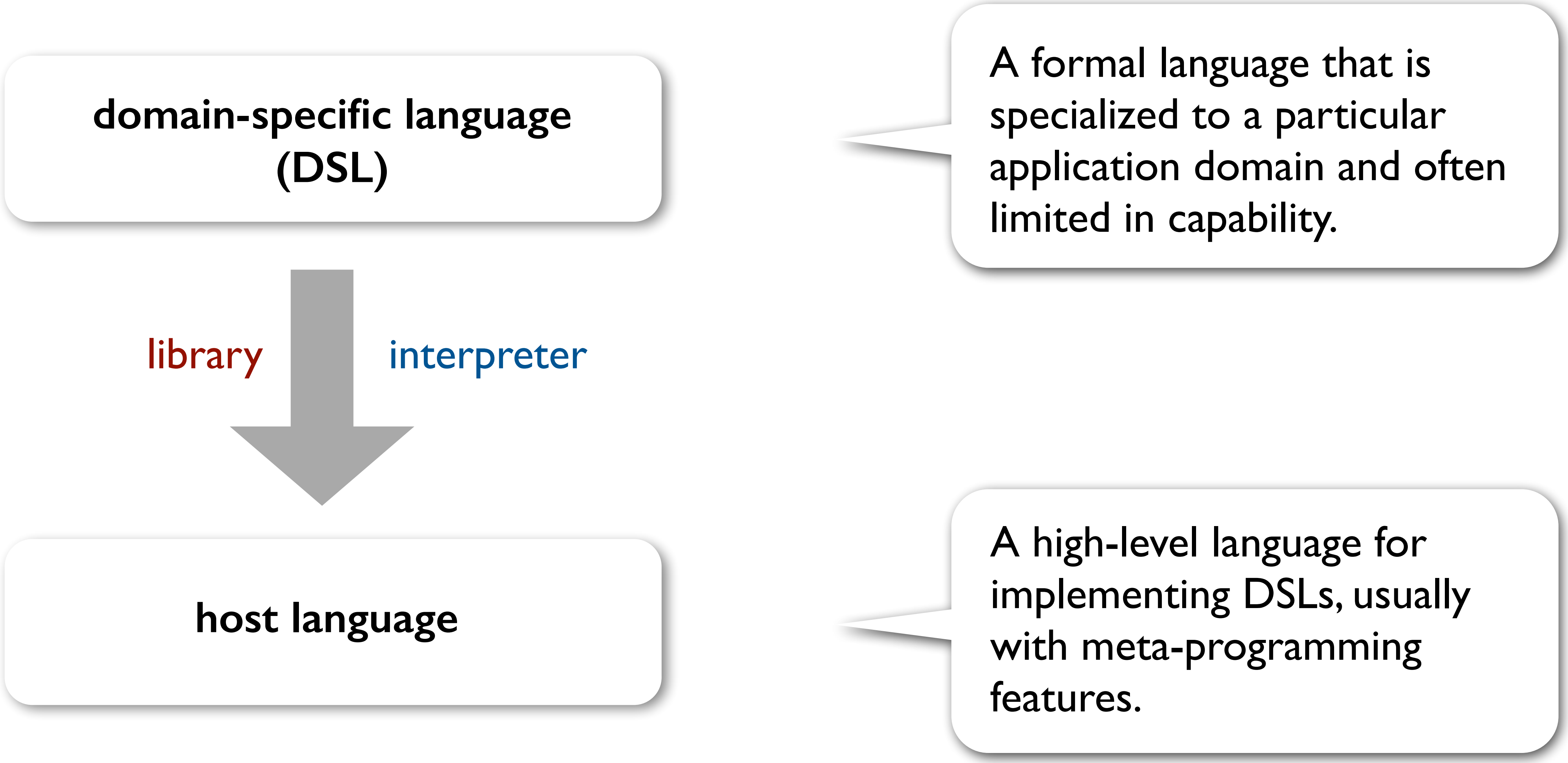
a solver-aided host language

domain expert

design

solver-aided languages

Layers of languages



domain-specific language (DSL)

library

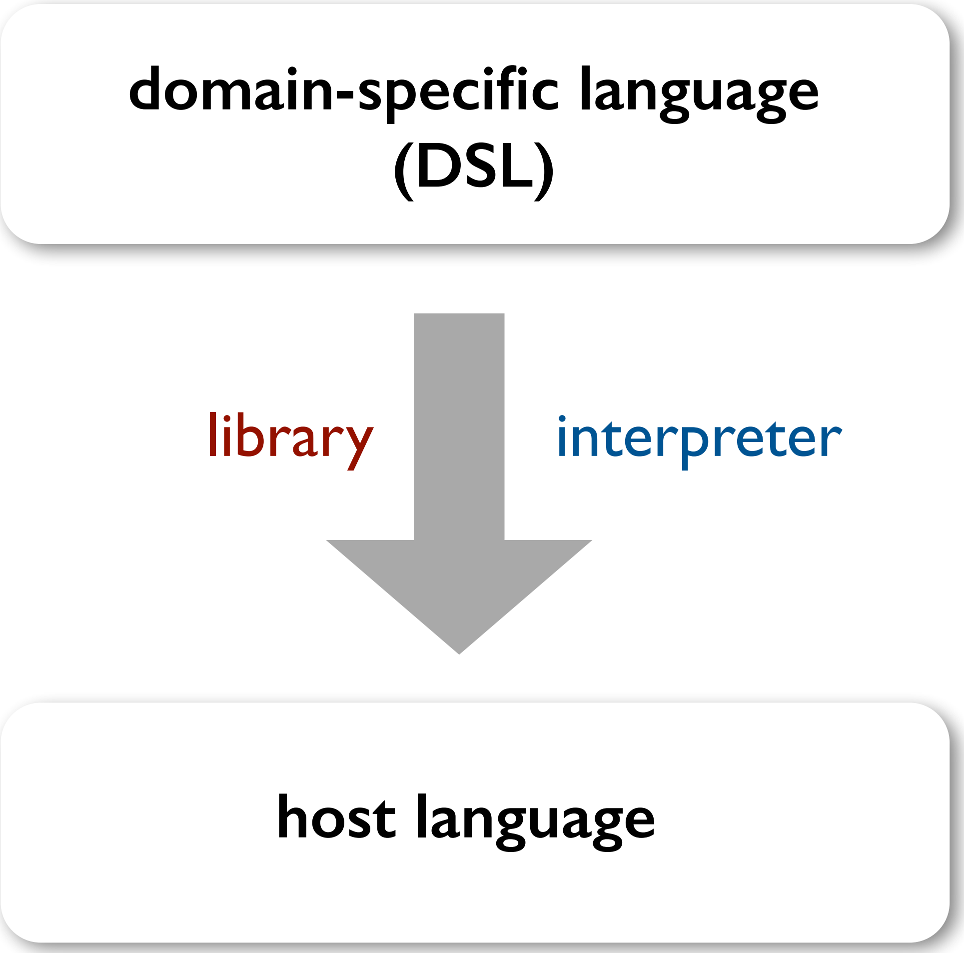
interpreter

host language

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

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

Layers of languages



domain-specific language (DSL)

library

interpreter

host language

artificial intelligence
Church, BLOG

databases
SQL, Datalog

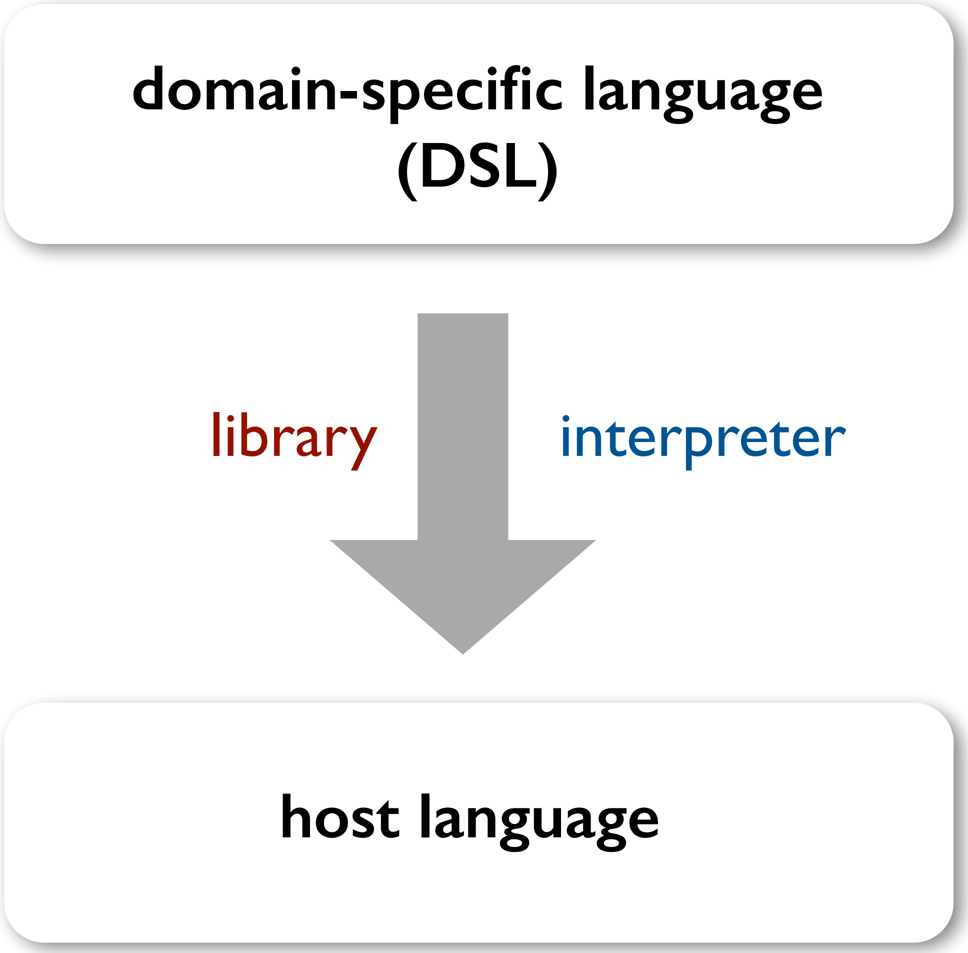
hardware design
Bluespec, Chisel, Verilog, VHDL

math and statistics
Eigen, Matlab, R

layout and visualization
LaTex, dot, dygraphs, D3

Scala, Racket, JavaScript

Layers of languages



domain-specific language (DSL)

library

interpreter

host language

Eigen / Matlab

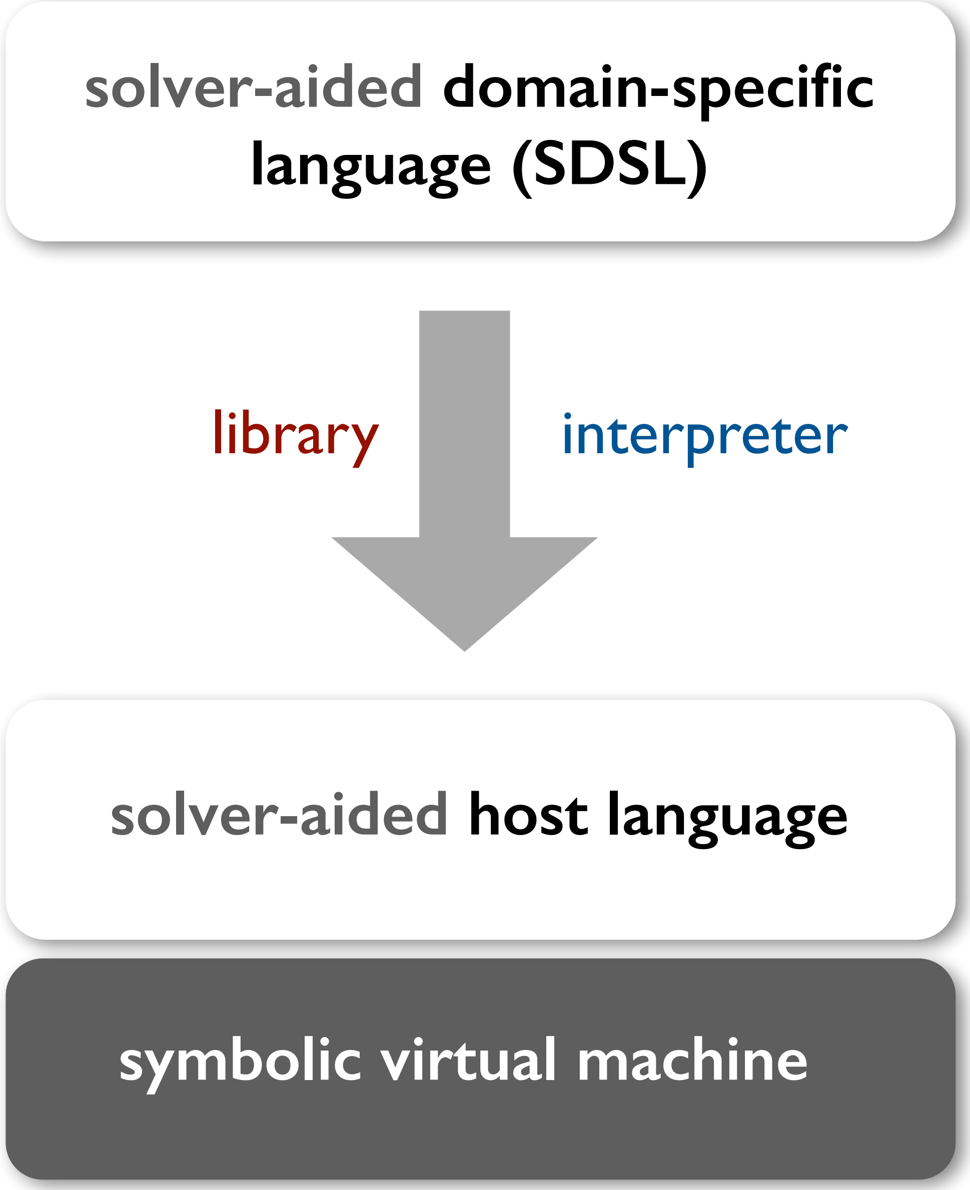
```
C = A * B
```

[associativity]

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 solver-aided languages



solver-aided **domain-specific language (SDSL)**

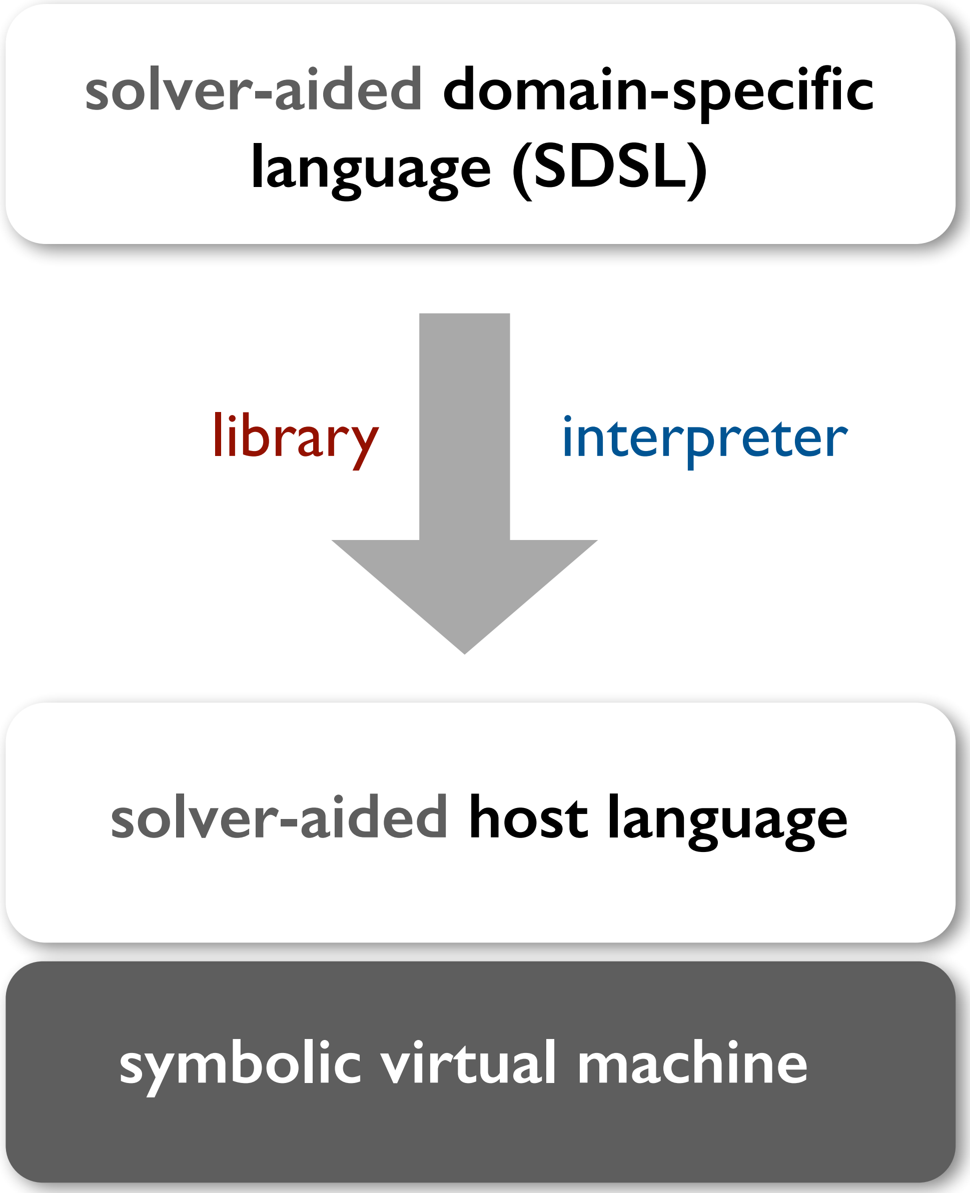
library

interpreter

solver-aided **host language**

symbolic virtual machine

Layers of solver-aided languages



solver-aided **domain-specific language (SDSL)**

library

interpreter

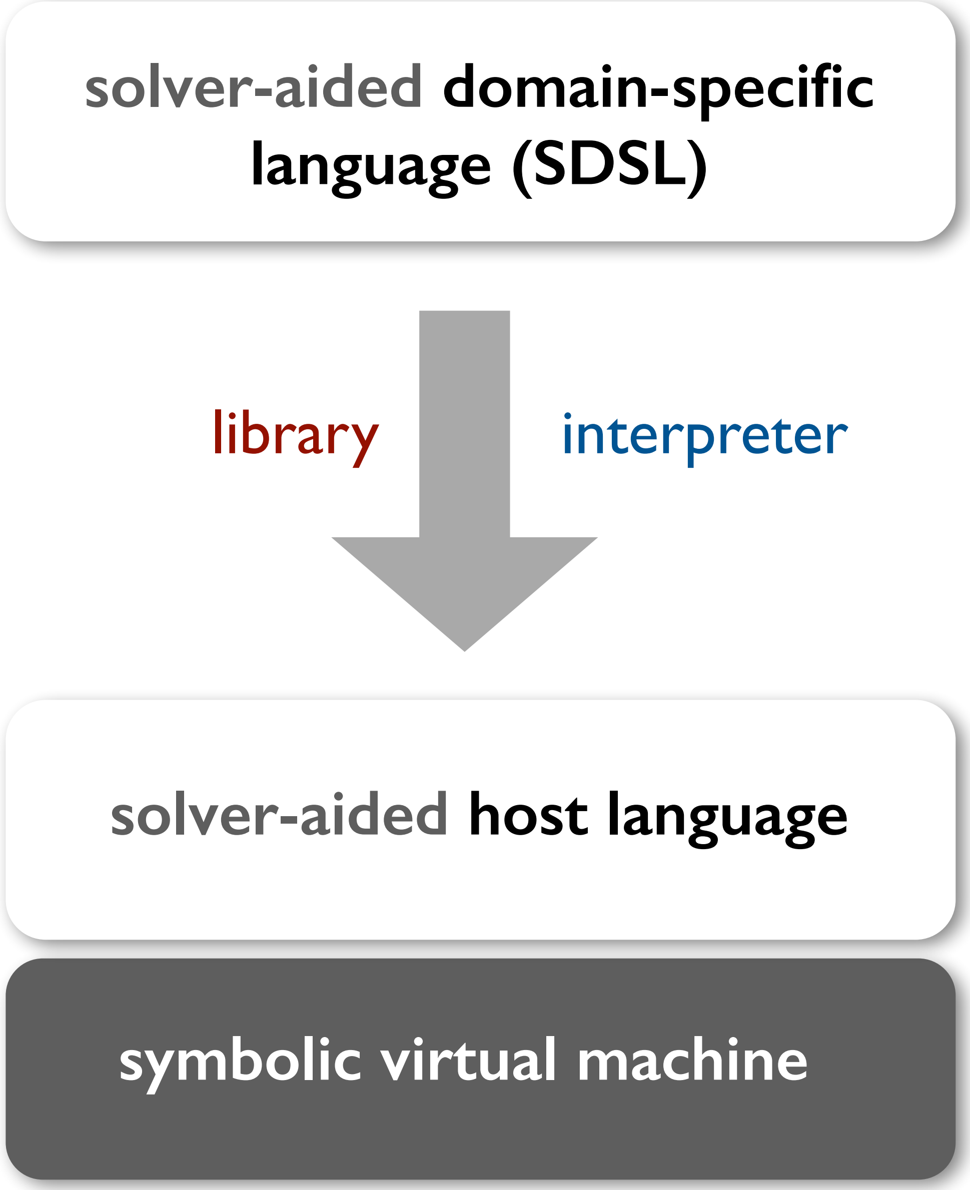
solver-aided **host language**

symbolic virtual machine

ROSETTE

[Torlak & Bodik, **Onward'13, PLDI'14**]

Layers of solver-aided languages



solver-aided **domain-specific language (SDSL)**

library

interpreter

solver-aided **host language**

symbolic virtual machine

spatial programming
Chlorophyll

data-parallel programming
SynthCL

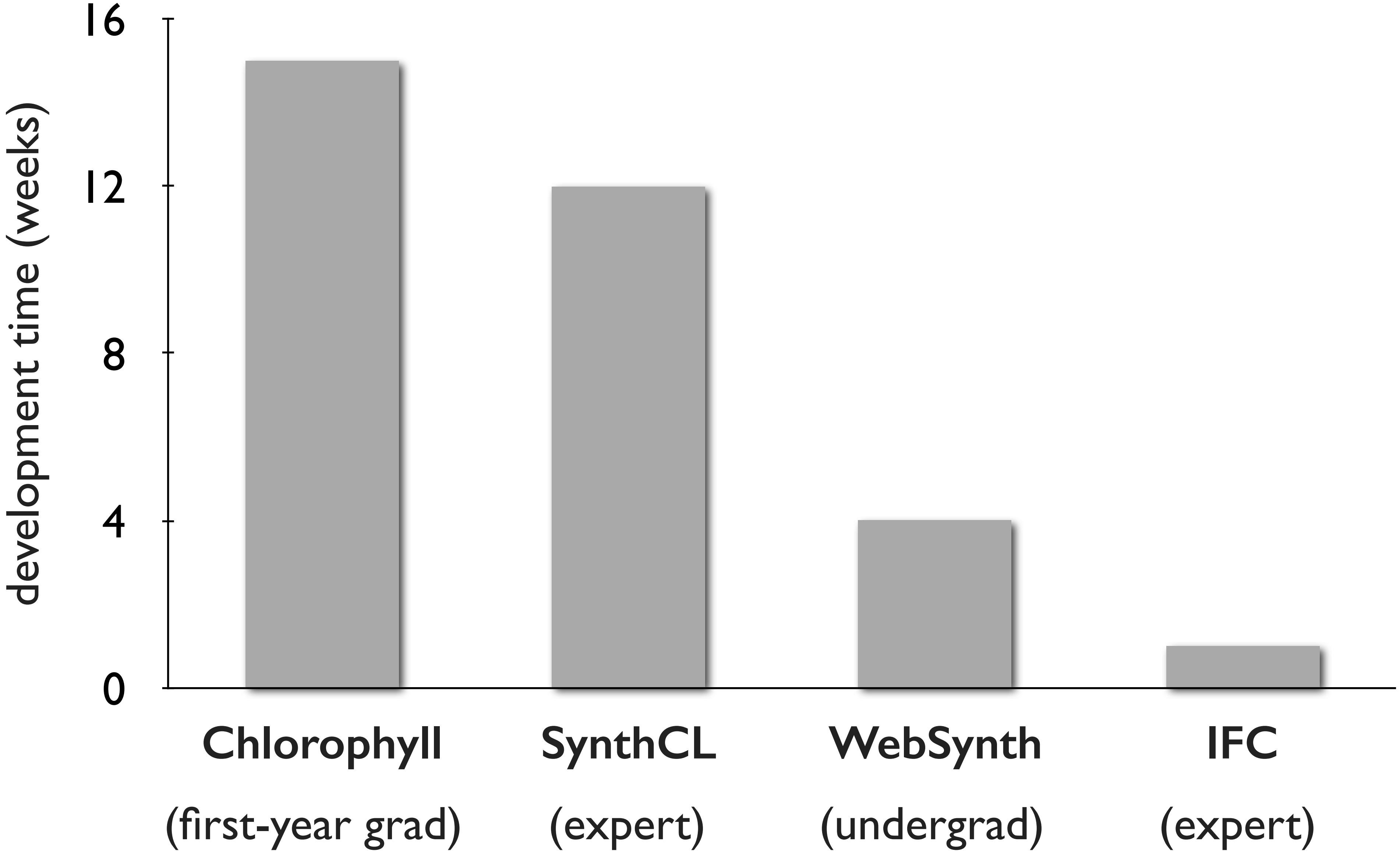
web scraping
WebSynth

secure stack machines
IFC

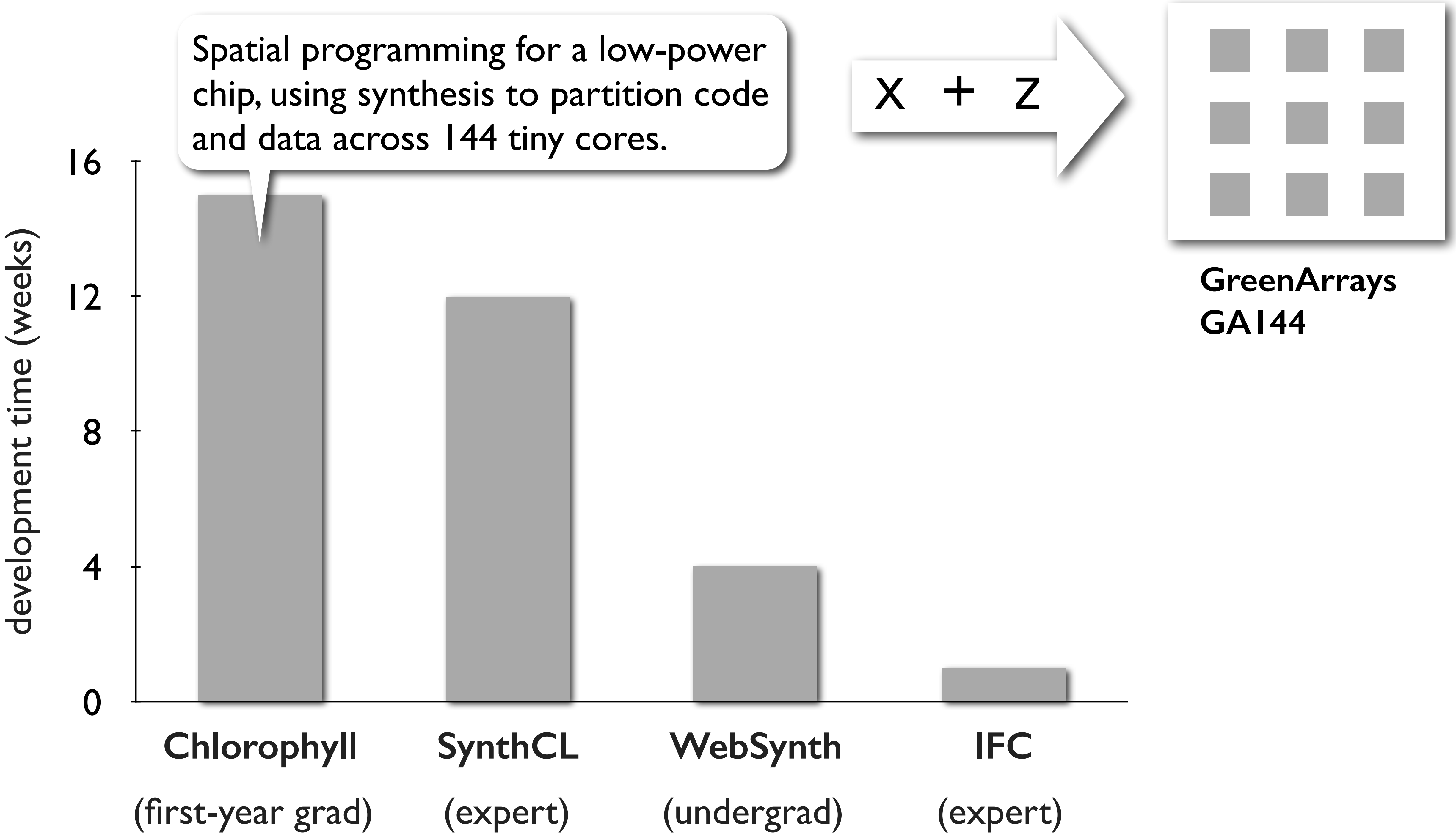
ROSETTE

[Torlak & Bodik, **Onward'13, PLDI'14**]

SDSLs developed with ROSETTE



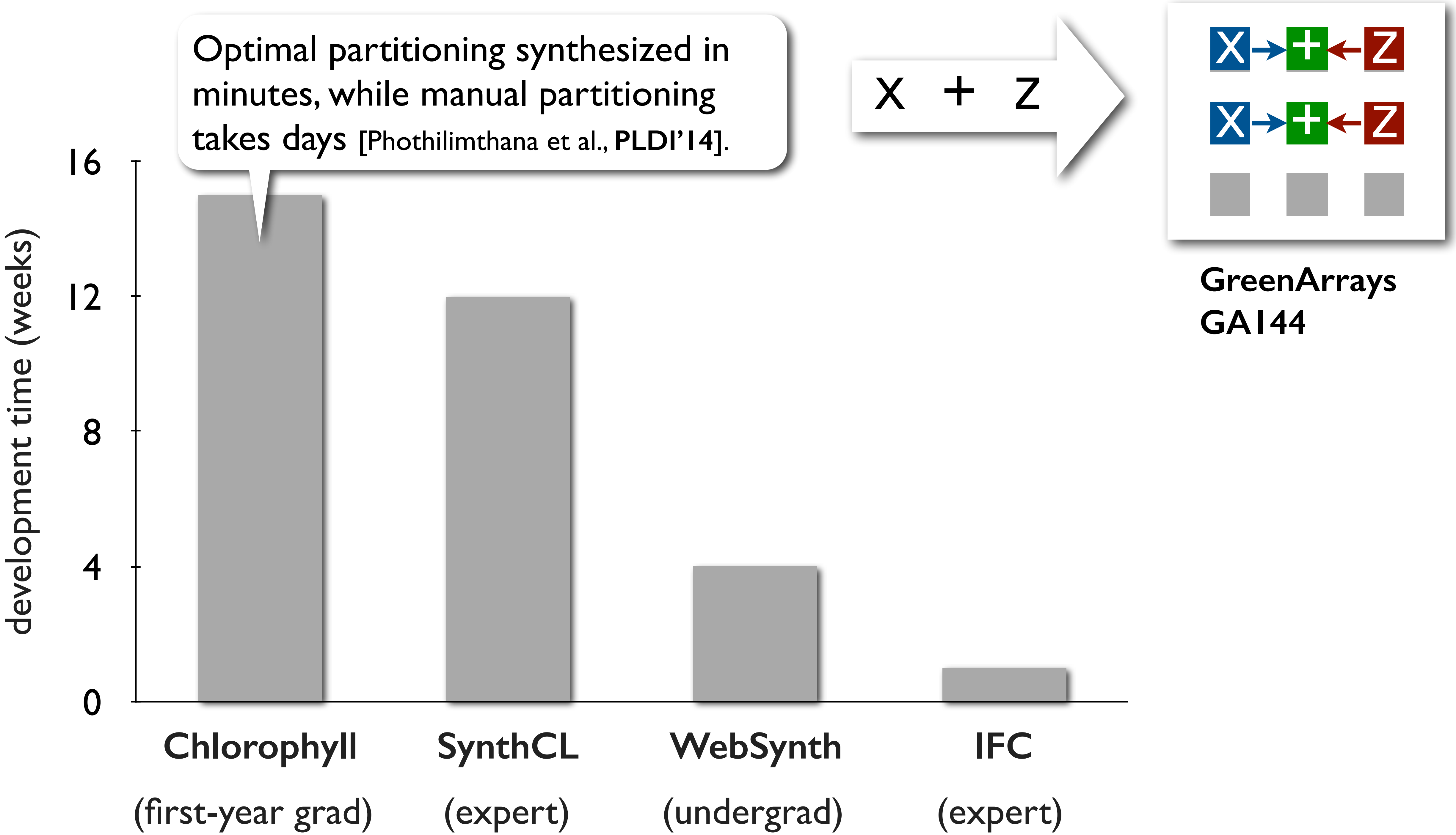
SDSLs developed with ROSETTE



Spatial programming for a low-power chip, using synthesis to partition code and data across 144 tiny cores.

GreenArrays GA144

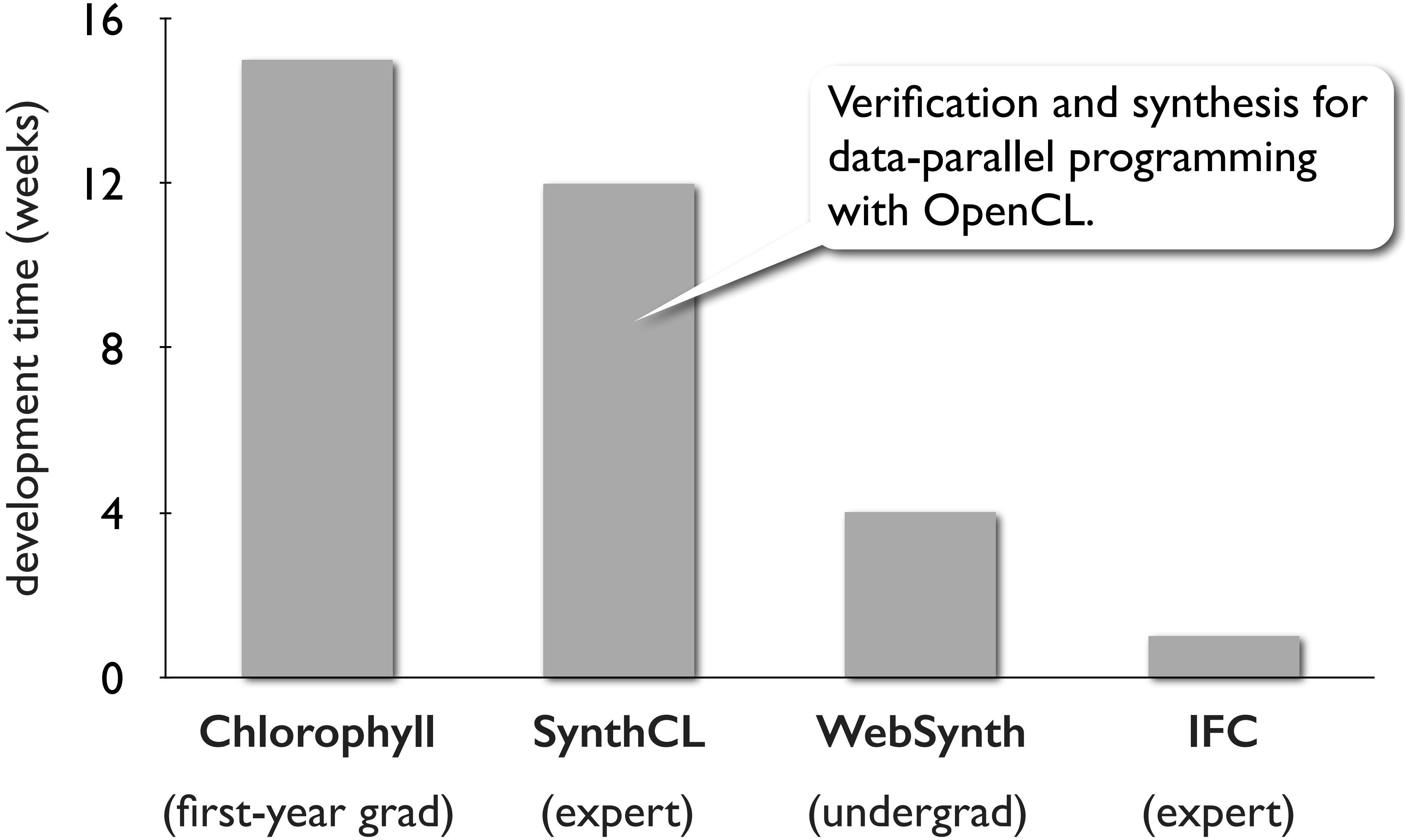
SDSLs developed with ROSETTE



Optimal partitioning synthesized in minutes, while manual partitioning takes days [Phothilimthana et al., **PLDI'14**].

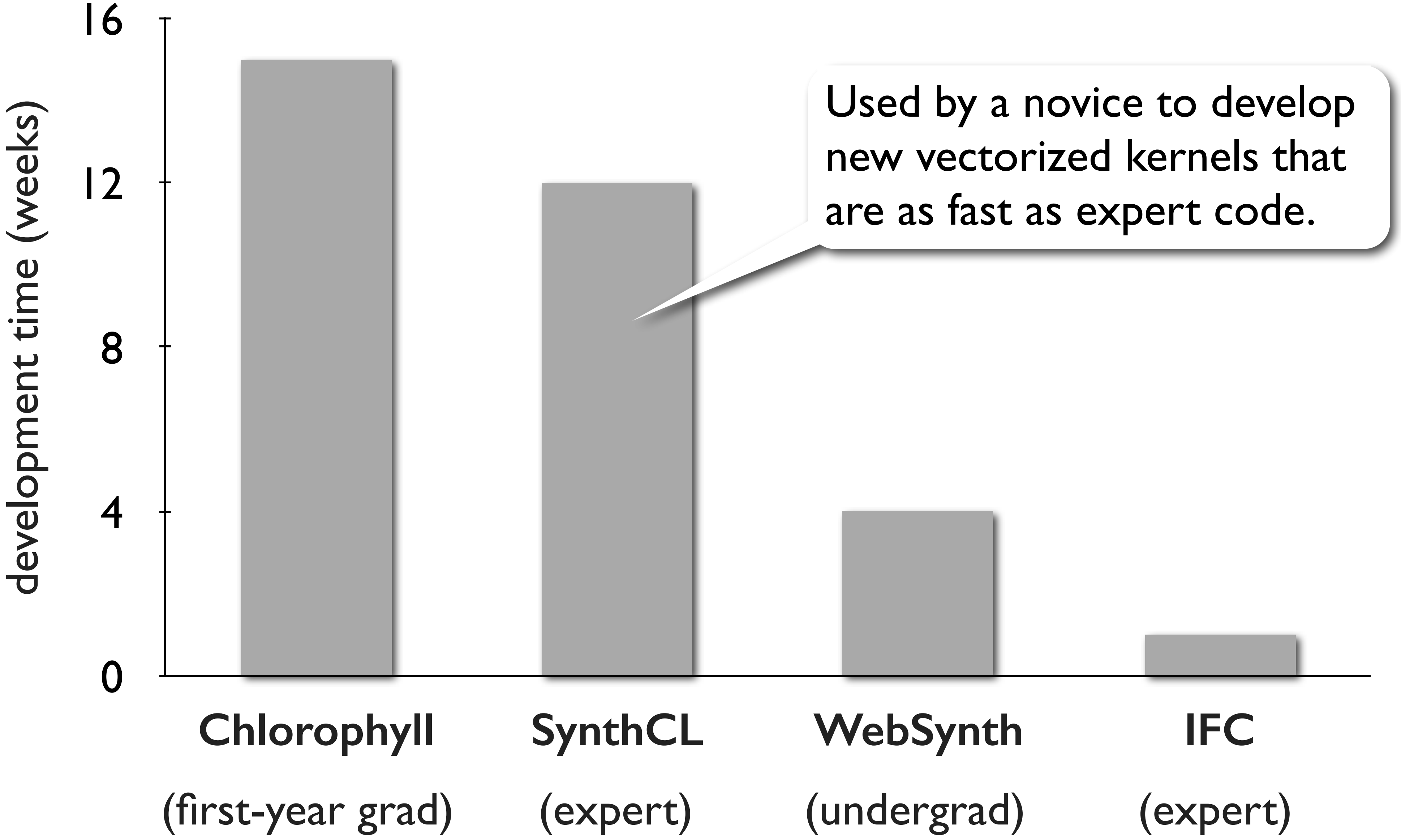
GreenArrays GA144

SDSLs developed with ROSETTE



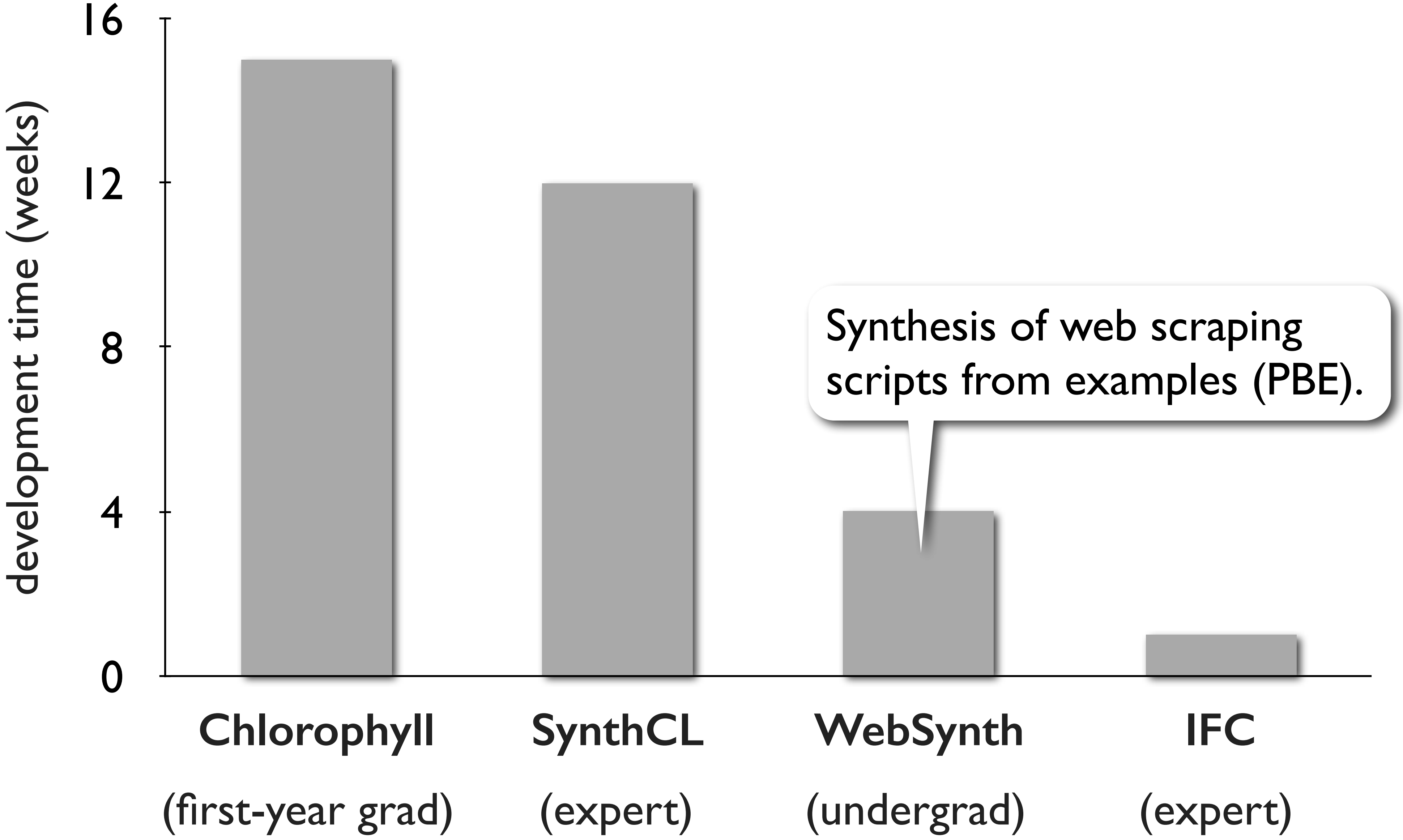
Verification and synthesis for data-parallel programming with OpenCL.

SDSLs developed with ROSETTE



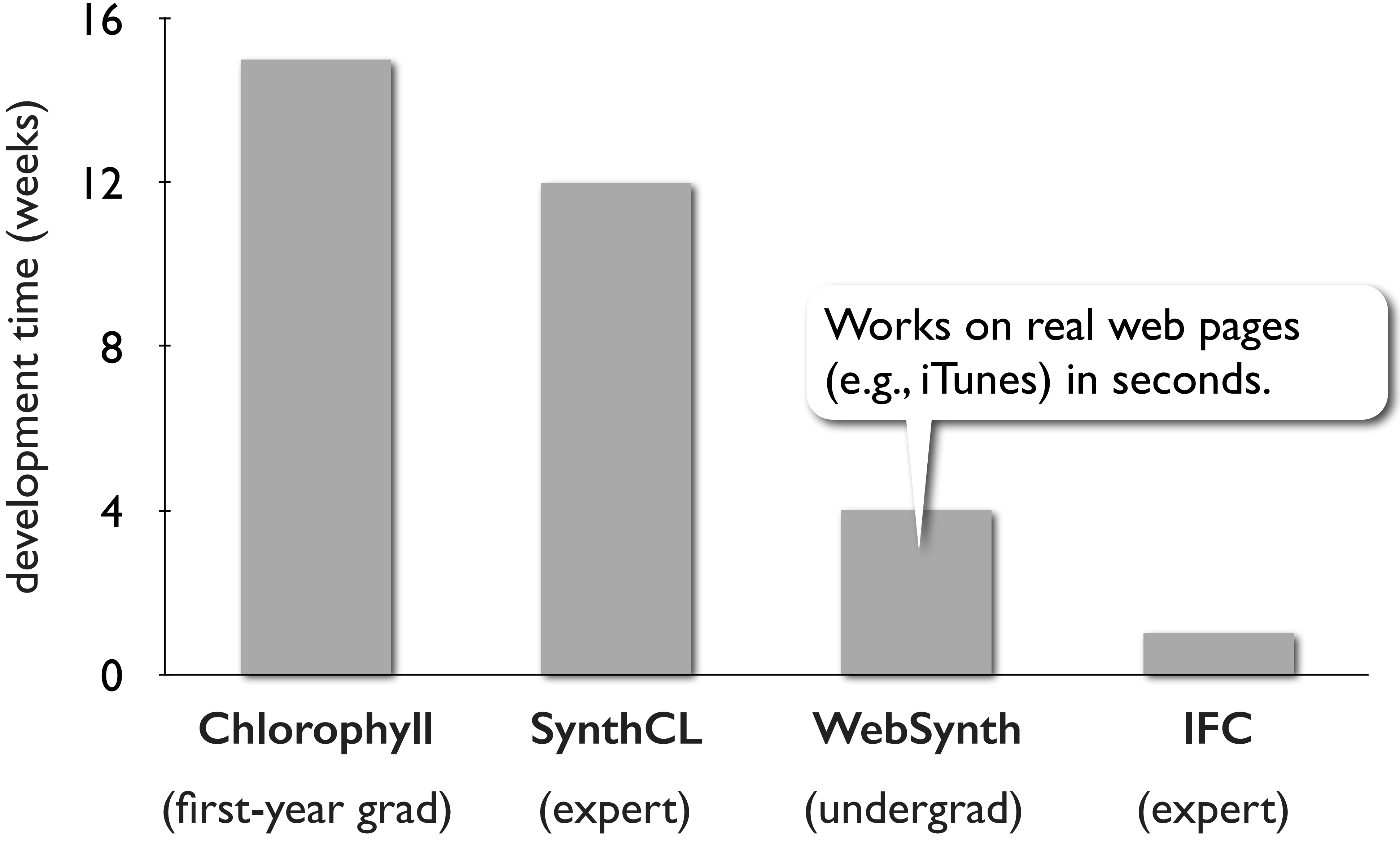
Used by a novice to develop new vectorized kernels that are as fast as expert code.

SDSLs developed with ROSETTE



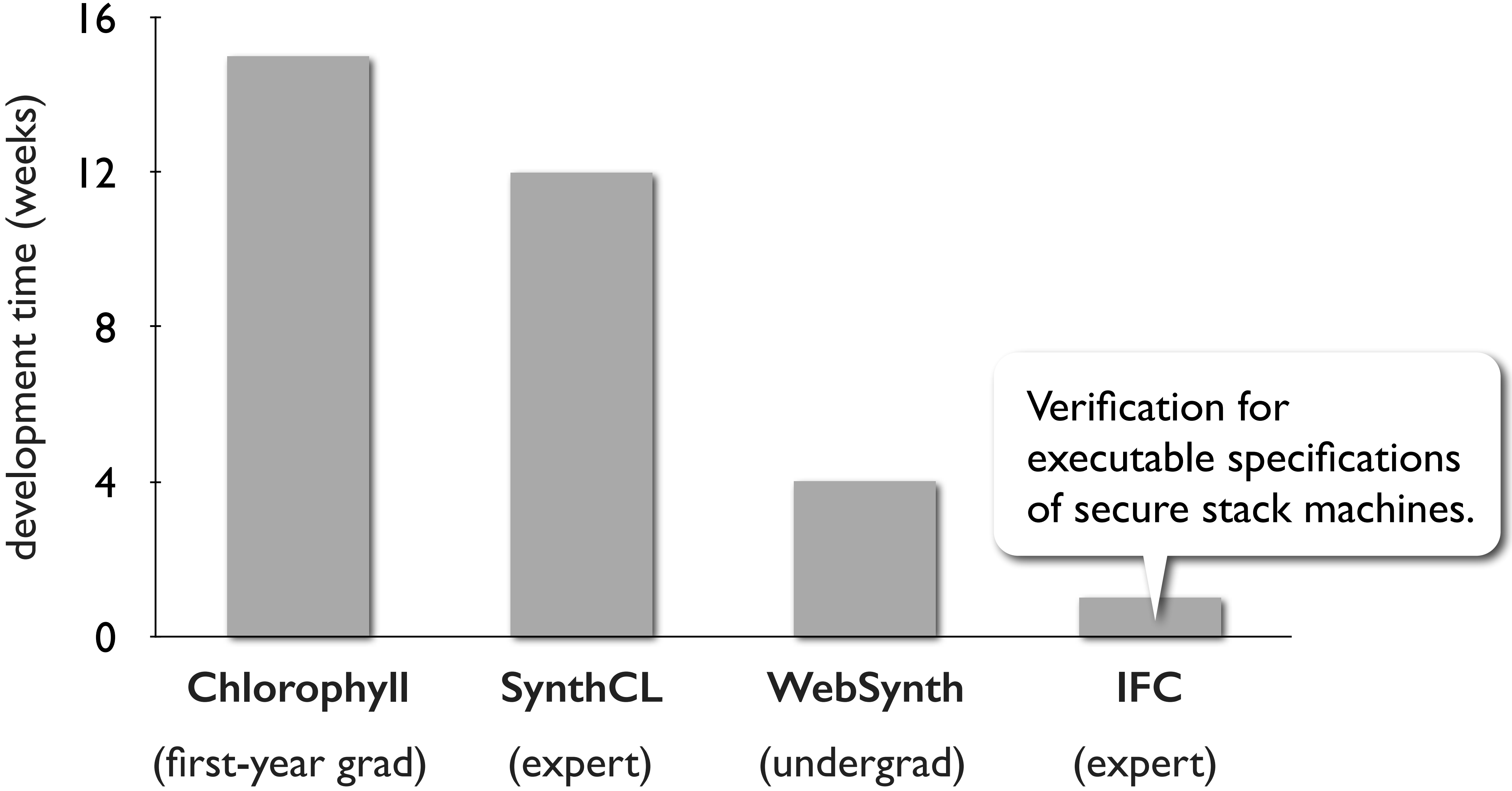
Synthesis of web scraping scripts from examples (PBE).

SDSLs developed with ROSETTE



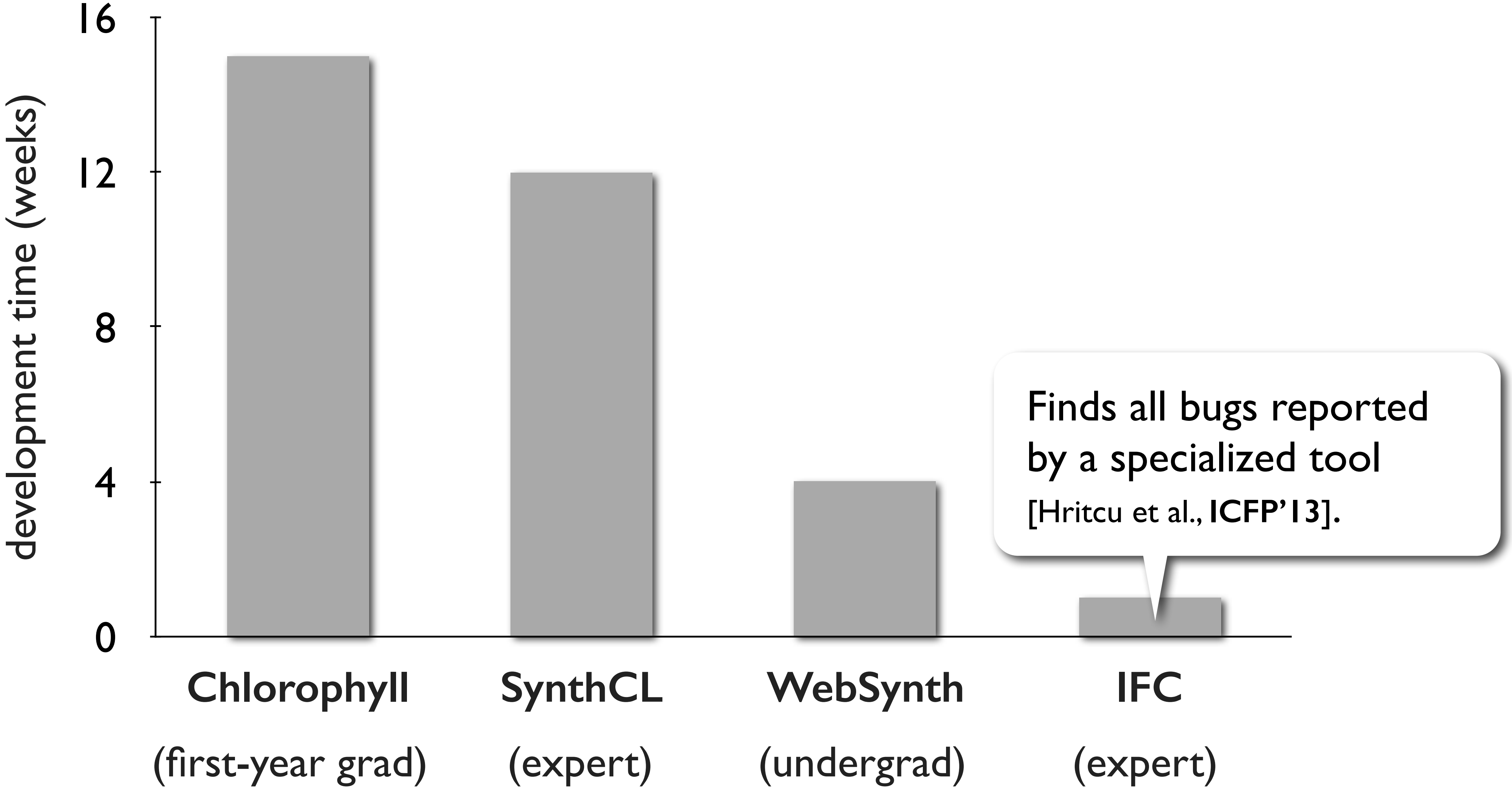
Works on real web pages (e.g., iTunes) in seconds.

SDSLs developed with ROSETTE



Verification for executable specifications of secure stack machines.

SDSLs developed with ROSETTE



Finds all bugs reported by a specialized tool [Hritcu et al., **ICFP'13**].

Anatomy of a solver-aided host language

Modern descendent of Scheme with macro-based metaprogramming.

Racket

Anatomy of a solver-aided host language

```
(define-symbolic id type)

(assert expr)

(verify expr)
(debug [expr] expr)
(solve expr)
(synthesize [expr] expr)
```

Anatomy of a solver-aided host language

symbolic constants

```
(define-symbolic id type)

(assert expr)

(verify expr)
(debug [expr] expr)
(solve expr)
(synthesize [expr] expr)
```

ROSETTE

Anatomy of a solver-aided host language

symbolic constants

```
(define-symbolic id type)
```

assertions

```
(assert expr)
```

```
(verify expr)
(debug [expr] expr)
(solve expr)
(synthesize [expr] expr)
```

ROSETTE

Anatomy of a solver-aided host language

symbolic constants

```
(define-symbolic id type)
```

assertions

```
(assert expr)
```

queries

```
(verify expr)
(debug [expr] expr)
(solve expr)
(synthesize [expr] expr)
```

ROSETTE

Anatomy of a solver-aided host language

symbolic constants

```
(define-symbolic id type)
```

assertions

```
(assert expr)
```

queries

```
(verify expr)
(debug [expr] expr)
(solve expr)
(synthesize [expr] expr)
```

∃ v . property(**P**(v))

ROSETTE

Anatomy of a solver-aided host language

symbolic constants

```
(define-symbolic v number?)
```

assertions

```
(assert expr)
```

queries

```
(verify expr)
(debug [expr] expr)
(solve expr)
(synthesize [expr] expr)
```

∃ v . property(**P**(v))

ROSETTE

Anatomy of a solver-aided host language

symbolic constants

```
(define-symbolic v number?)
```

assertions

```
(assert (odd? (P v)))
```

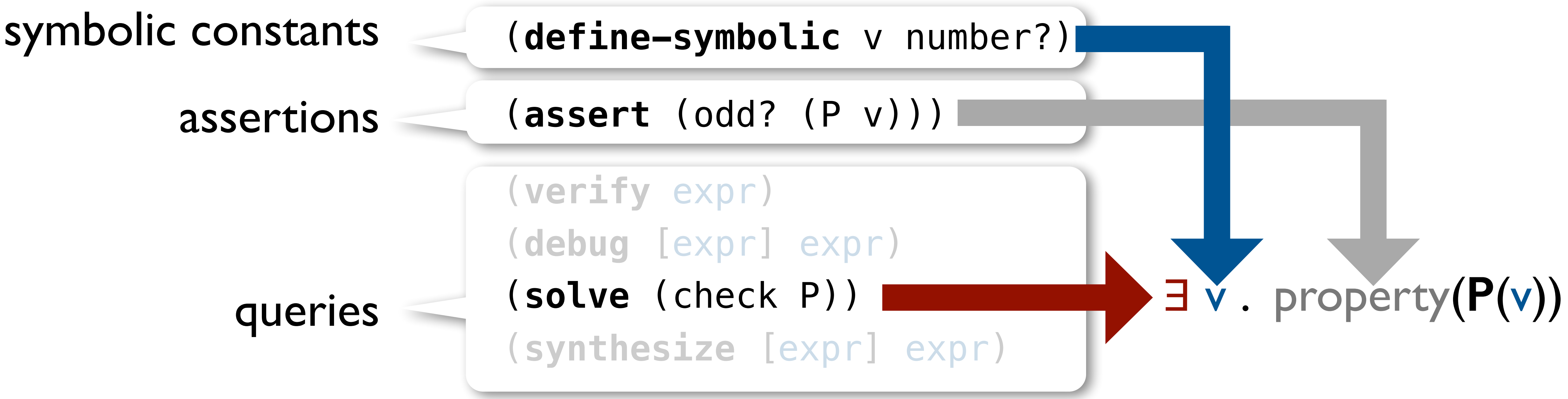
queries

```
(verify expr)
(debug [expr] expr)
(solve expr)
(synthesize [expr] expr)
```

∃ v . property(P(v))

ROSETTE

Anatomy of a solver-aided host language



symbolic constants

```
(define-symbolic v number?)
```

assertions

```
(assert (odd? (P v)))
```

queries

```
(verify expr)
(debug [expr] expr)
(solve (check P))
(synthesize [expr] expr)
```

$\exists\, v\ .\ \text{property}(\mathbf{P}(v))$

ROSETTE

A tiny example SDSL

```
def bvmax(r0, r1) :
  r2 = bvge(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 SDSL

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

test debug
verify synth

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

A tiny example SDSL: ROSETTE

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

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

A tiny example SDSL: ROSETTE

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

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

parse

```
(define bvmax
 `((2 bvge 0 1)
   (3 bvneg 2)
   (4 bvxor 0 2)
   (5 bvand 3 4)
   (6 bvxor 1 5)))
```

A tiny example SDSL: ROSETTE

```
def bvmax(r0, r1) :
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(define bvmax
 `((2 bvge 0 1)
   (3 bvneg 2)
   (4 bvxor 0 2)
   (5 bvand 3 4)
   (6 bvxor 1 5)))
```

`(out opcode in ...)`

A tiny example SDSL: ROSETTE

```
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  r2 = bvge(r0, r1)
  r3 = bvneg(r2)
  r4 = bvxor(r0, r2)
  r5 = bvand(r3, r4)
  r6 = bvxor(r1, r5)
  return r6

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

interpret

```
(define bvmax
 `((2 bvge 0 1)
   (3 bvneg 2)
   (4 bvxor 0 2)
   (5 bvand 3 4)
   (6 bvxor 1 5)))
```

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

```
(define (interpret prog inputs)
  (make-registers prog inputs)
  (for ([stmt prog])
    (match stmt
      [(list out opcode in ...)
       (define op (eval opcode))
       (define args (map load in))
       (store out (apply op args))]))
  (load (last)))
```

A tiny example SDSL: ROSETTE

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

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

```
(define bvmax
 `((2 bvge 0 1)
   (3 bvneg 2)
   (4 bvxor 0 2)
   (5 bvand 3 4)
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```

0	-2
1	-1
2	
3	
4	
5	
6	

interpret

```
(define (interpret prog inputs)
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A tiny example SDSL: ROSETTE

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```
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interpret

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(define bvmax
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2	
3	
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5	
6	

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

0	-2
1	-1
2	
3	
4	
5	
6	

interpret

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0	-2
1	-1
2	0
3	
4	
5	
6	

interpret

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(define (interpret prog inputs)
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```

```
(define bvmax
 `((2 bvge 0 1)
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```

0	-2
1	-1
2	0
3	0
4	-2
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6	-1

interpret

```
(define (interpret prog inputs)
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  r6 = bvxor(r1, r5)
  return r6

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

```
(define bvmax
 `((2 bvge 0 1)
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```

0	-2
1	-1
2	0
3	0
4	-2
5	0
6	-1

interpret

```
(define (interpret prog inputs)
  (make-registers prog inputs)
  (for ([stmt prog])
    (match stmt
      [(list out opcode in ...)
       (define op (eval opcode))
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  (load (last)))
```

A tiny example SDSL: ROSETTE

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

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

```
(define bvmax
 `((2 bvge 0 1)
   (3 bvneg 2)
   (4 bvxor 0 2)
   (5 bvand 3 4)
   (6 bvxor 1 5)))
```

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

```
(define (interpret prog inputs)
  (make-registers prog inputs)
  (for ([stmt prog])
    (match stmt
      [(list out opcode in ...)
       (define op (eval opcode))
       (define args (map load in))
       (store out (apply op args))]))
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```

A tiny example SDSL: ROSETTE

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

> verify(bvmax, max)
```

query

```
(define-symbolic n0 n1 number?)
(define inputs (list n0 n1))
(verify
  (assert (= (interpret bvmax inputs)
             (apply max inputs))))
```

A tiny example SDSL: ROSETTE

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

> verify(bvmax, max)
```

query

Creates two fresh symbolic constants of type number and binds them to variables n0 and n1.

```
(define-symbolic n0 n1 number?)
(define inputs (list n0 n1))
(verify
  (assert (= (interpret bvmax inputs)
             (apply max inputs))))
```

A tiny example SDSL: ROSETTE

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

> verify(bvmax, max)
```

query

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

```
(define-symbolic n0 n1 number?)
(define inputs (list n0 n1))
(verify
  (assert (= (interpret bvmax inputs)
             (apply max inputs))))
```

A tiny example SDSL: ROSETTE

```
def bvmax(r0, r1) :
  r2 = bvge(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

```
(define-symbolic n0 n1 number?)
(define inputs (list n0 n1))
(verify
  (assert (= (interpret bvmax inputs)
             (apply max inputs))))
```

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

A tiny example SDSL: ROSETTE

```
def bvmax(r0, r1) :
  r2 = bvge(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

```
(define-symbolic n0 n1 number?)
(define inputs (list n0 n1))
(verify
  (assert (= (interpret bvmax inputs)
             (apply max inputs))))
```

A tiny example SDSL: ROSETTE

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

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

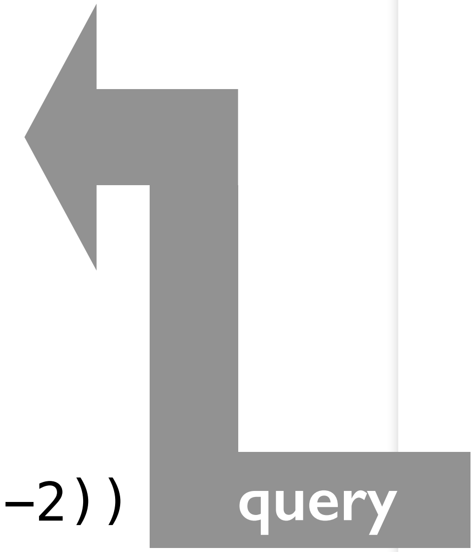
query

```
(define inputs (list 0 -2))
(debug [input-register?]
  (assert (= (interpret bvmax inputs)
             (apply max inputs))))
```

A tiny example SDSL: ROSETTE

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

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



```
(define inputs (list 0 -2))
(debug [input-register?]
  (assert (= (interpret bvmax inputs)
             (apply max inputs))))
```

A tiny example SDSL: ROSETTE

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

> synthesize(bvmax, max)
```

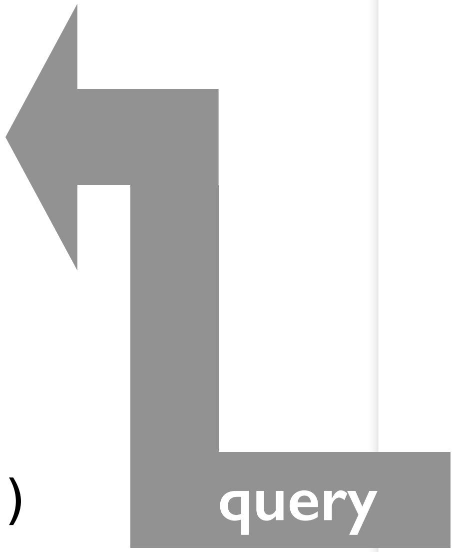
query

```
(define-symbolic n0 n1 number?)
(define inputs (list n0 n1))
(synthesize [inputs]
  (assert (= (interpret bvmax inputs)
             (apply max inputs))))
```

A tiny example SDSL: ROSETTE

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

> synthesize(bvmax, max)
```

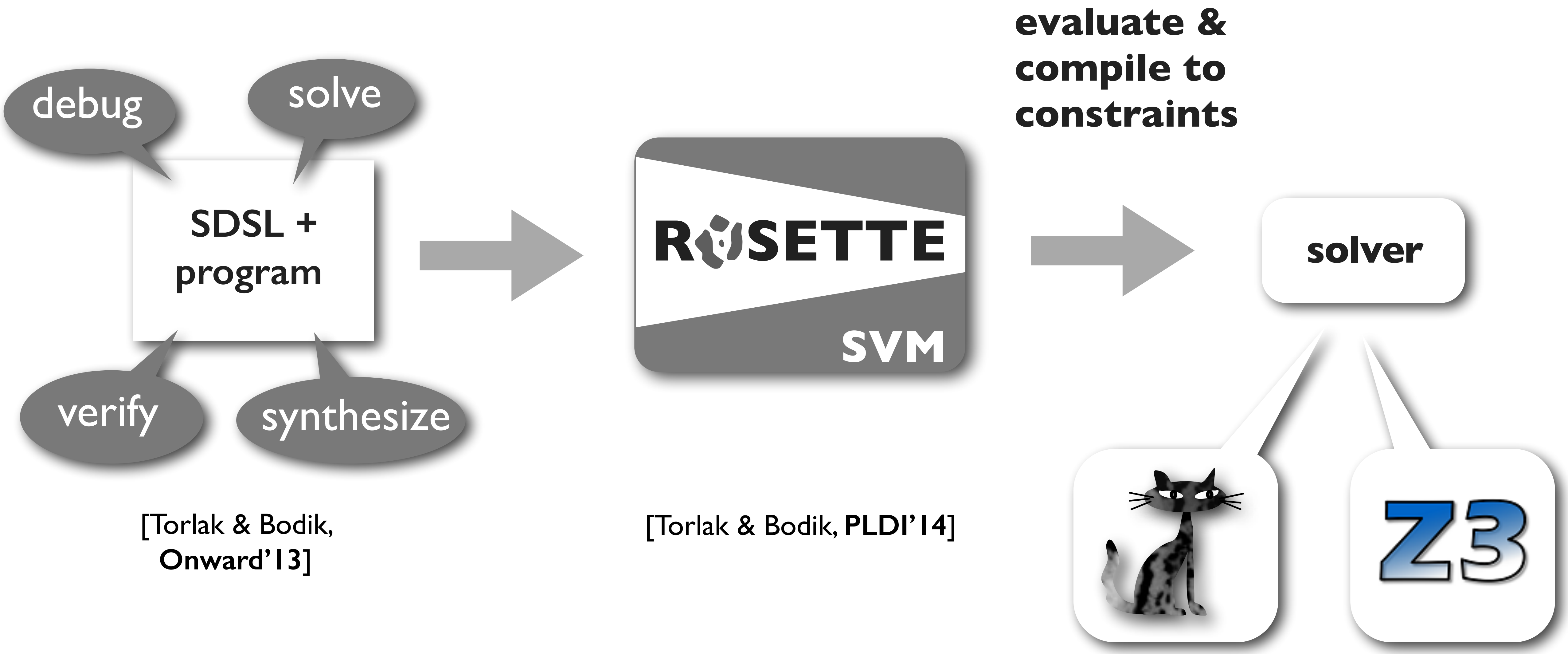


```
(define-symbolic n0 n1 number?)
(define inputs (list n0 n1))
(synthesize [inputs]
  (assert (= (interpret bvmax inputs)
             (apply max inputs))))
```

tech

symbolic virtual machine (SVM)

Anatomy of a symbolic virtual machine



debug

solve

SDSL + program

verify

synthesize

[Torlak & Bodik, **Onward'13**]

ROSETTE

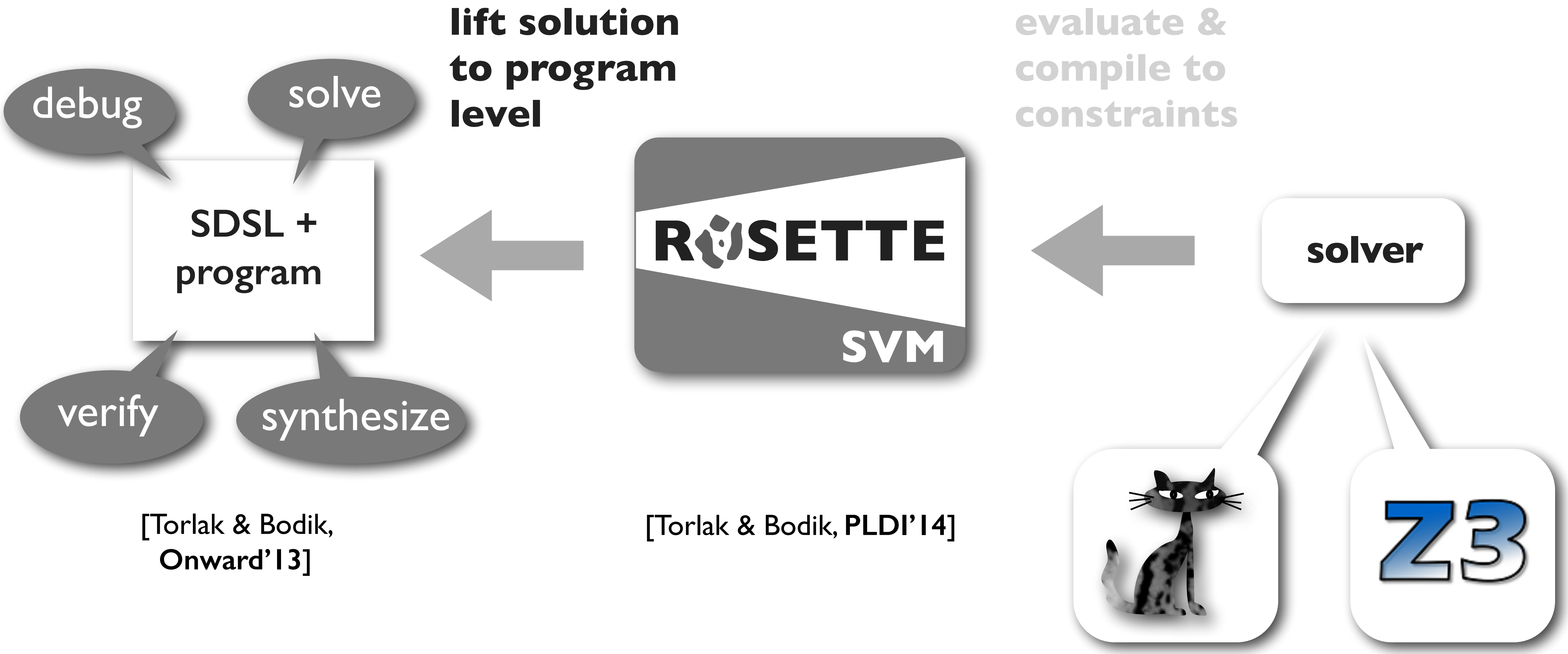
SVM

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

evaluate & compile to constraints

solver

Anatomy of a symbolic virtual machine



lift solution to program level

evaluate & compile to constraints

debug

solve

SDSL + program

verify

synthesize

ROSETTE

SVM

solver

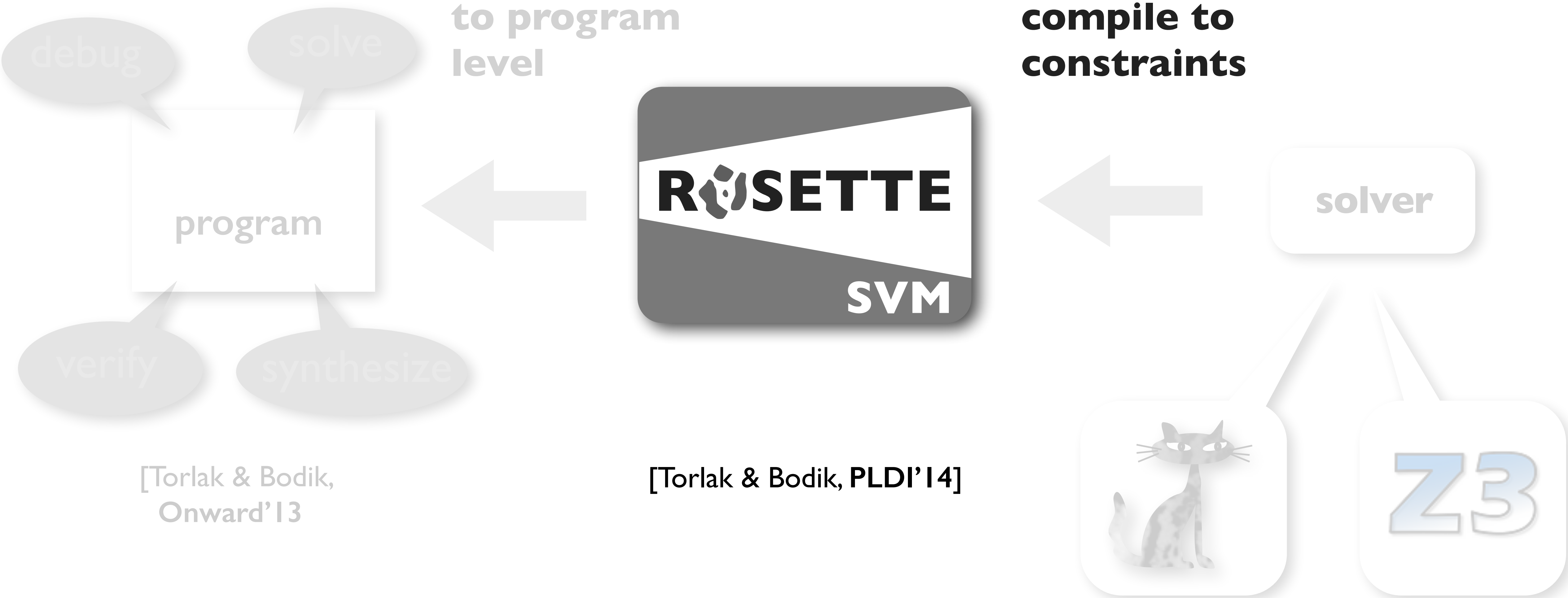
[Torlak & Bodik, **Onward'13**]

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

Anatomy of a symbolic virtual machine

lift solution to program level

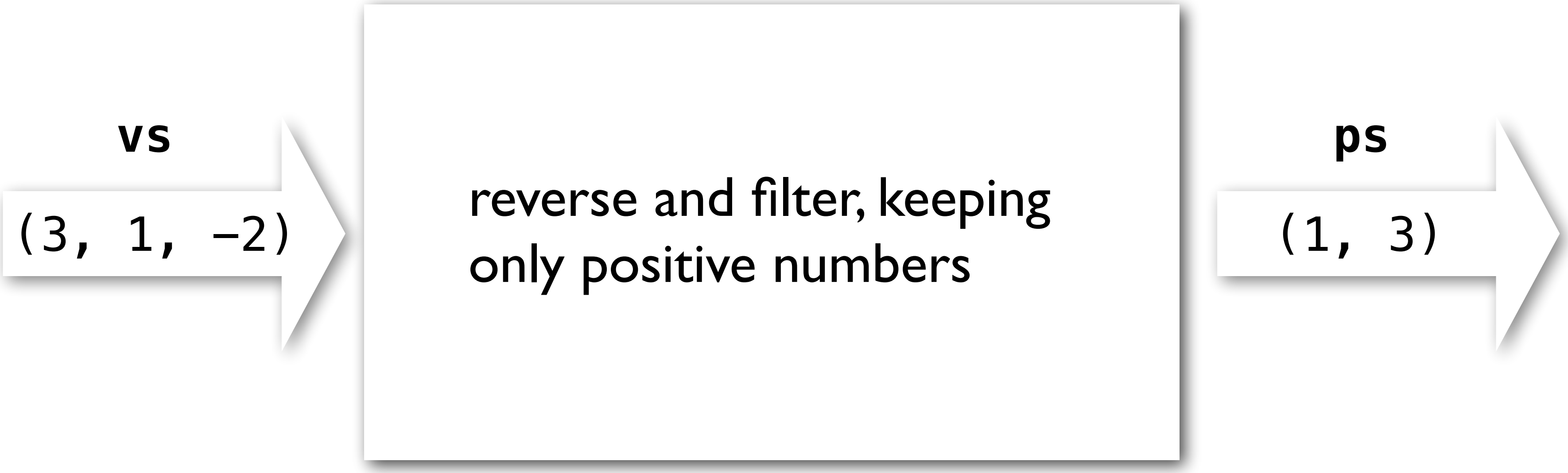
evaluate & compile to constraints



[Torlak & Bodik, Onward'13]

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

Translation to constraints by example



`vs`

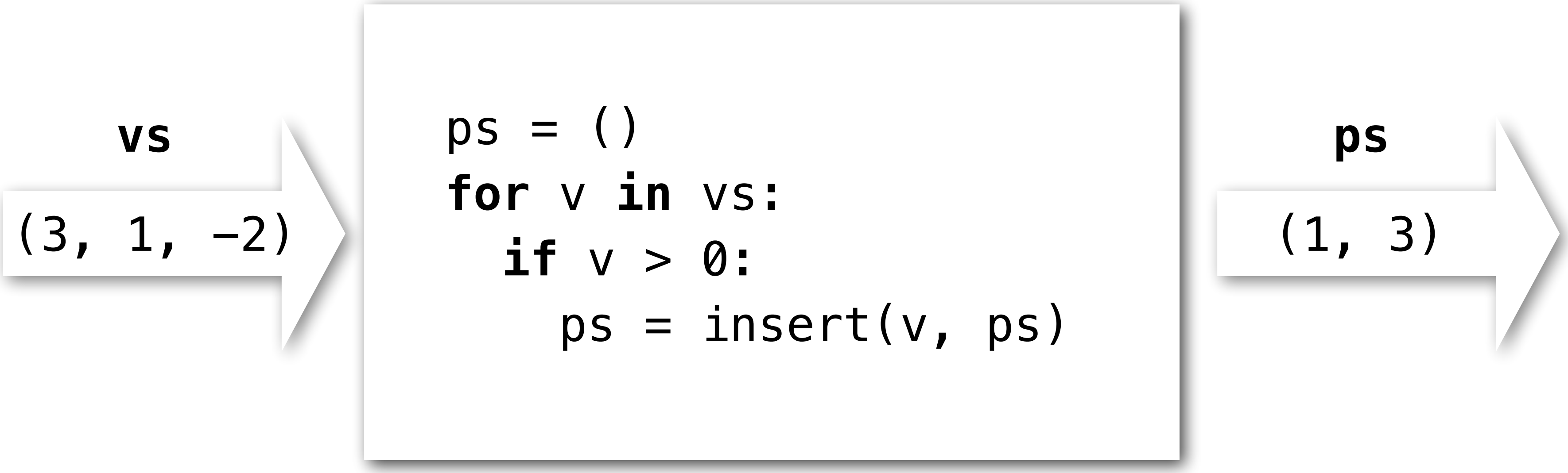
`(3, 1, −2)`

reverse and filter, keeping only positive numbers

`ps`

`(1, 3)`

Translation to constraints by example



vs

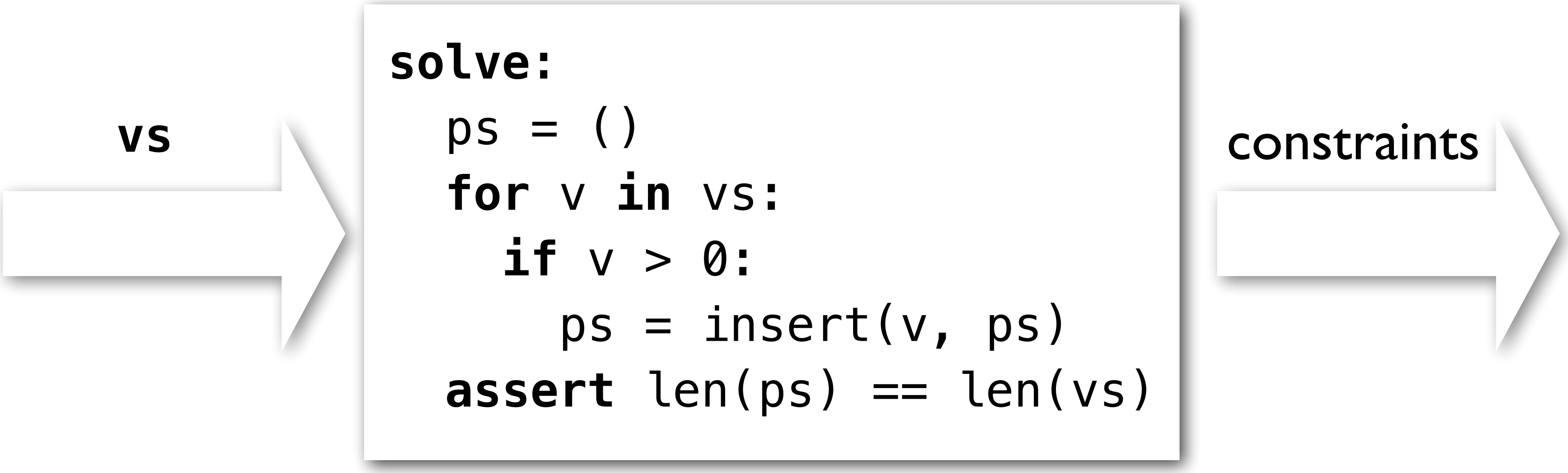
`(3, 1, −2)`

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

ps

`(1, 3)`

Translation to constraints by example

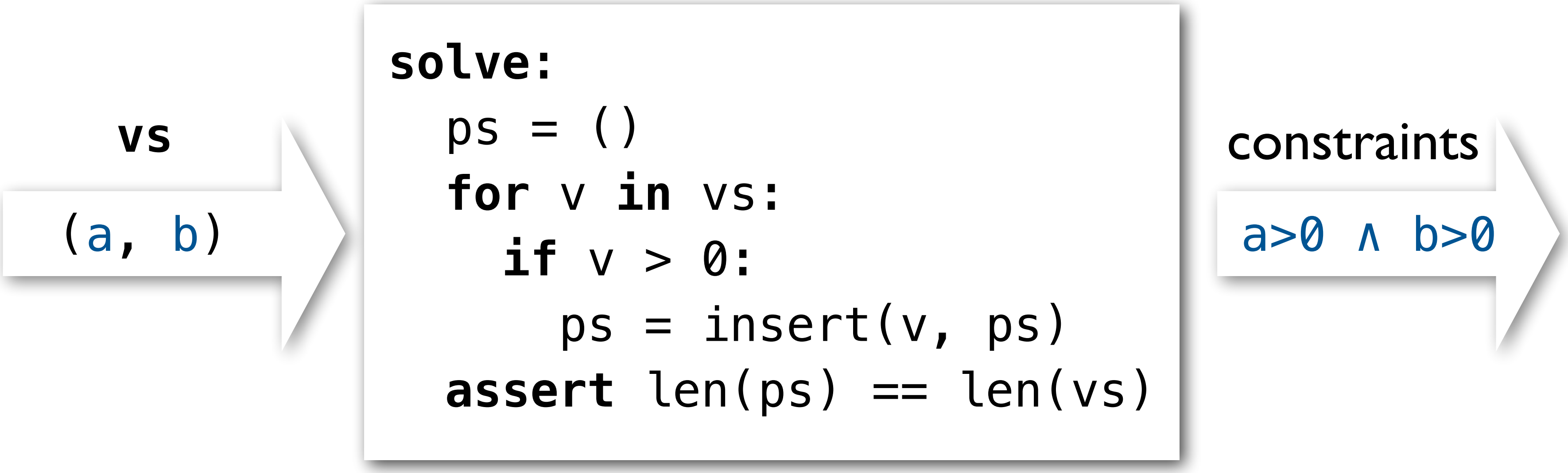


`vs`

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

constraints

Translation to constraints by example



vs

`(a, b)`

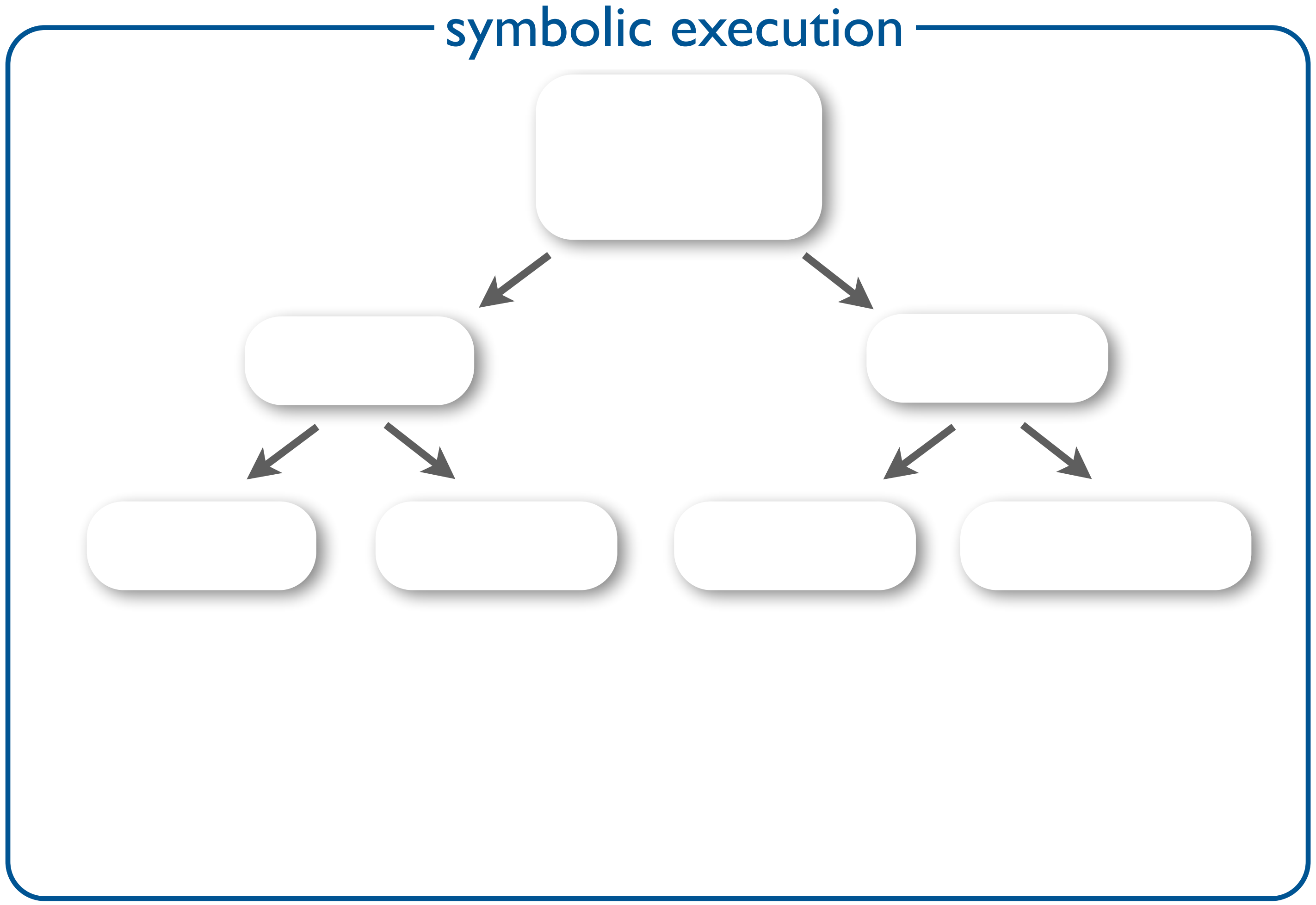
```
solve:
  ps = ()
  for v in vs:
    if v > 0:
      ps = insert(v, ps)
  assert len(ps) == len(vs)
```

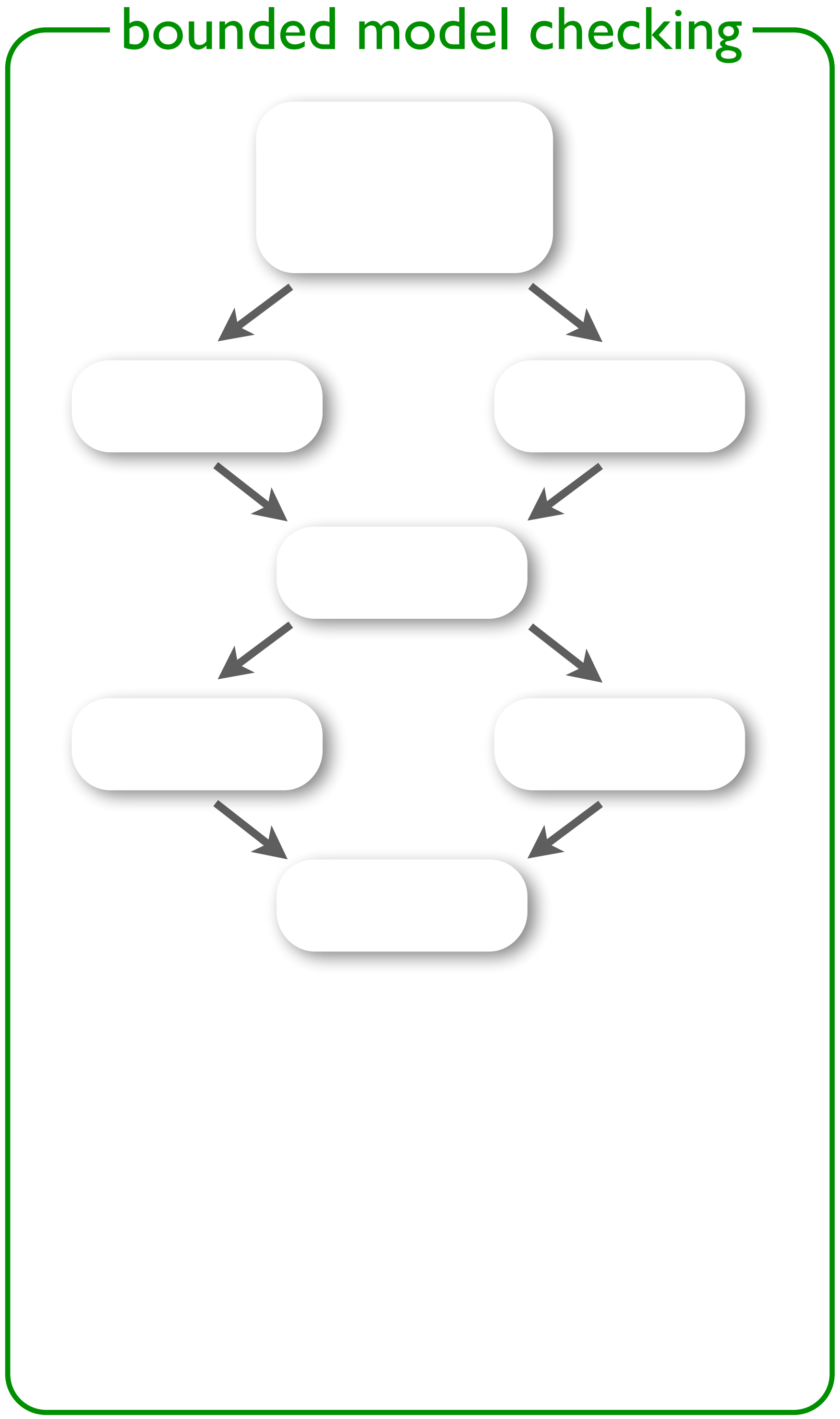
constraints

`a>0 ∧ b>0`

Design space of precise symbolic encodings

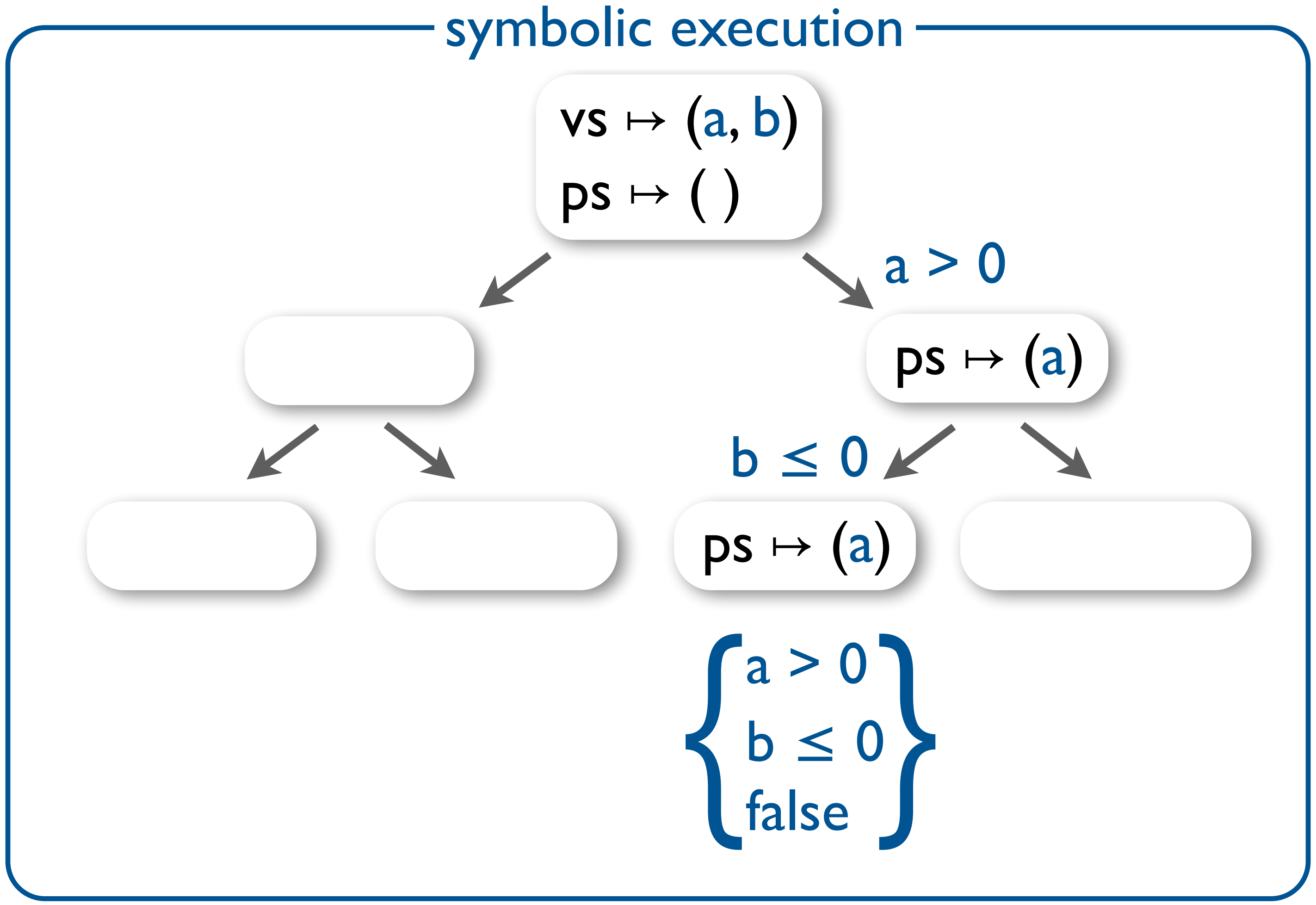
```
solve:
  ps = ()
  for v in vs:
    if v > 0:
      ps = insert(v, ps)
  assert len(ps) == len(vs)
```





Design space of precise symbolic encodings

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



symbolic execution

vs ↦ (a, b)
ps ↦ ( )

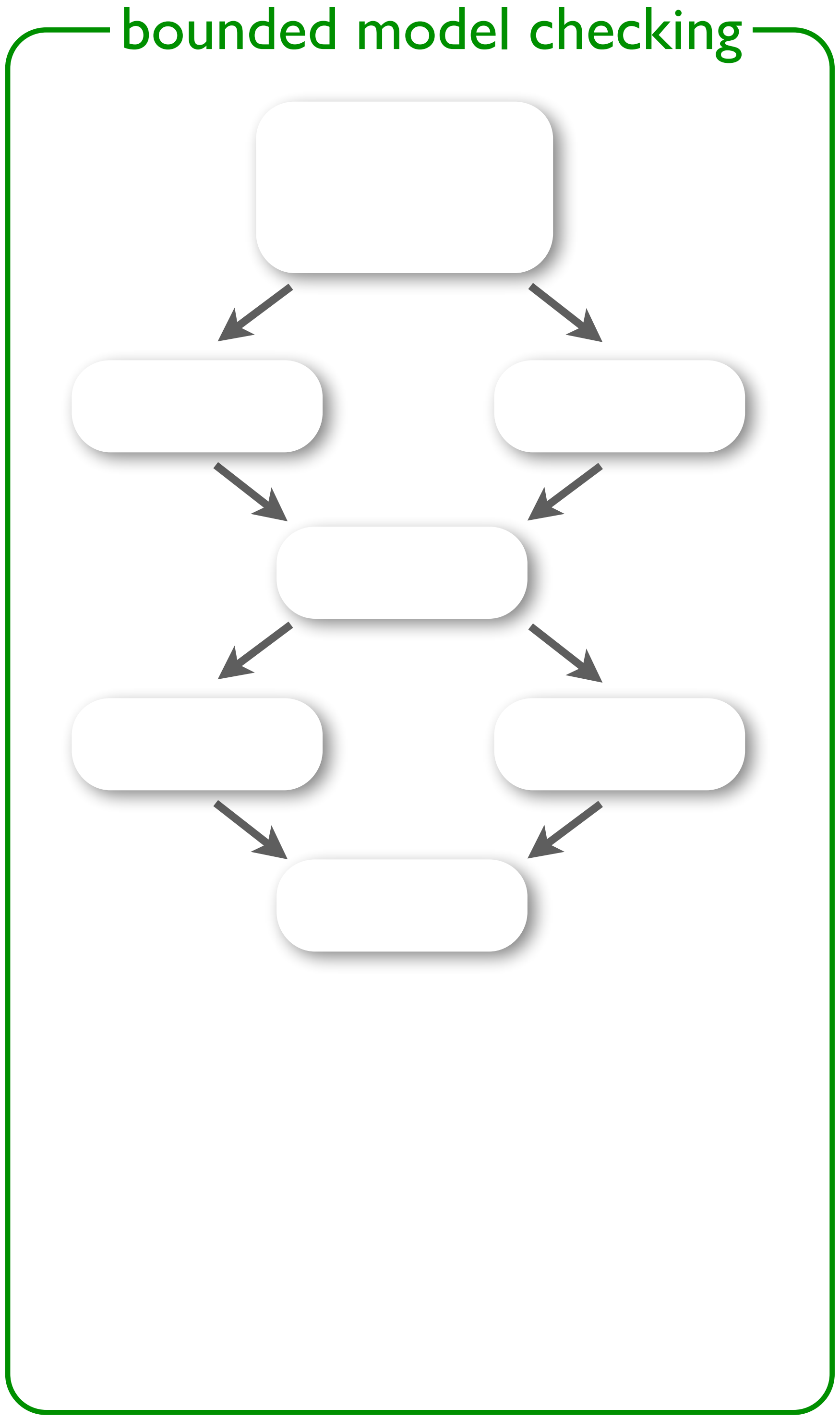
a > 0

ps ↦ (a)

b ≤ 0

ps ↦ (a)

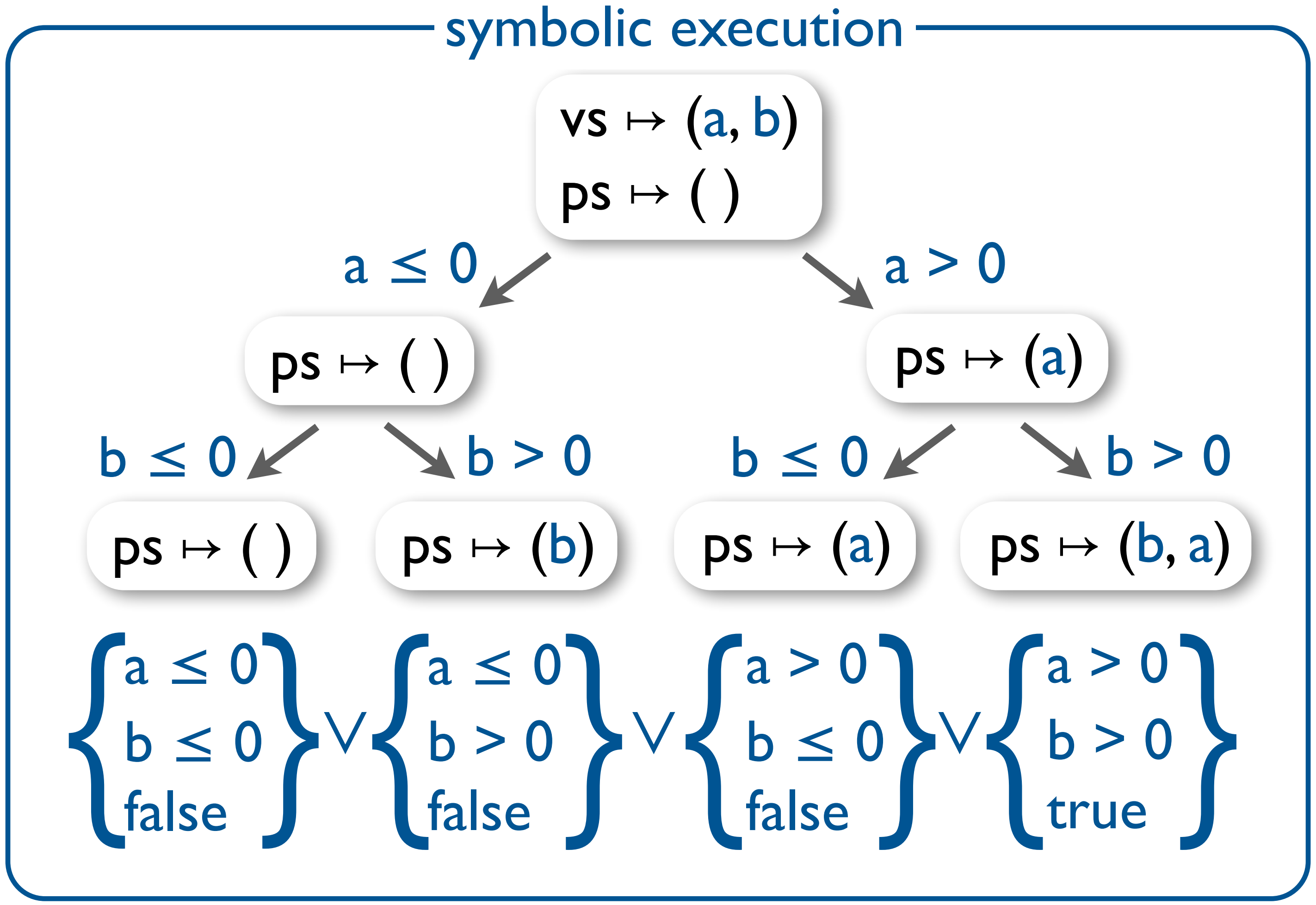
$\left\{\begin{array}{l} a > 0 \\ b \leq 0 \\ \text{false} \end{array}\right\}$



bounded model checking

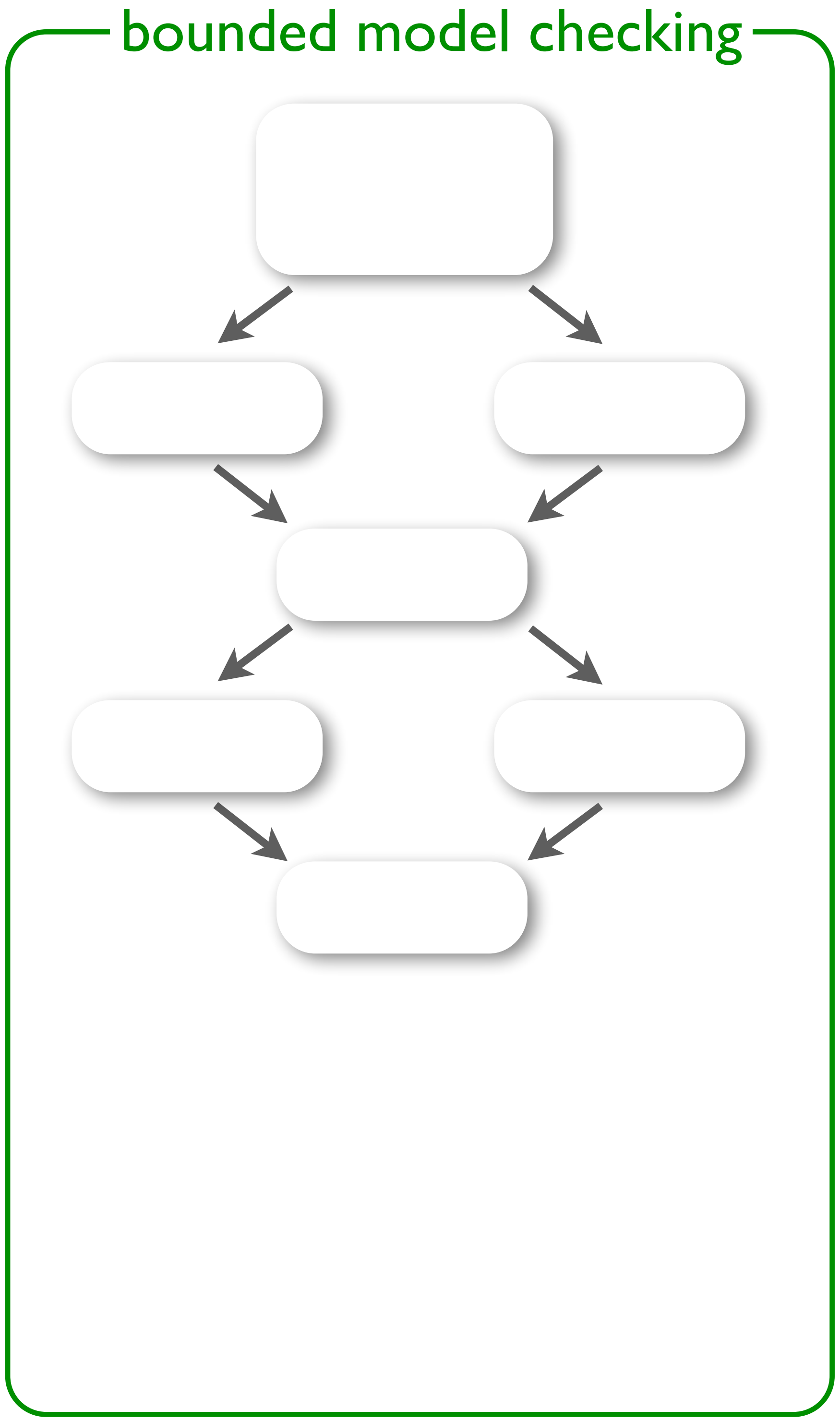
Design space of precise symbolic encodings

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



symbolic execution

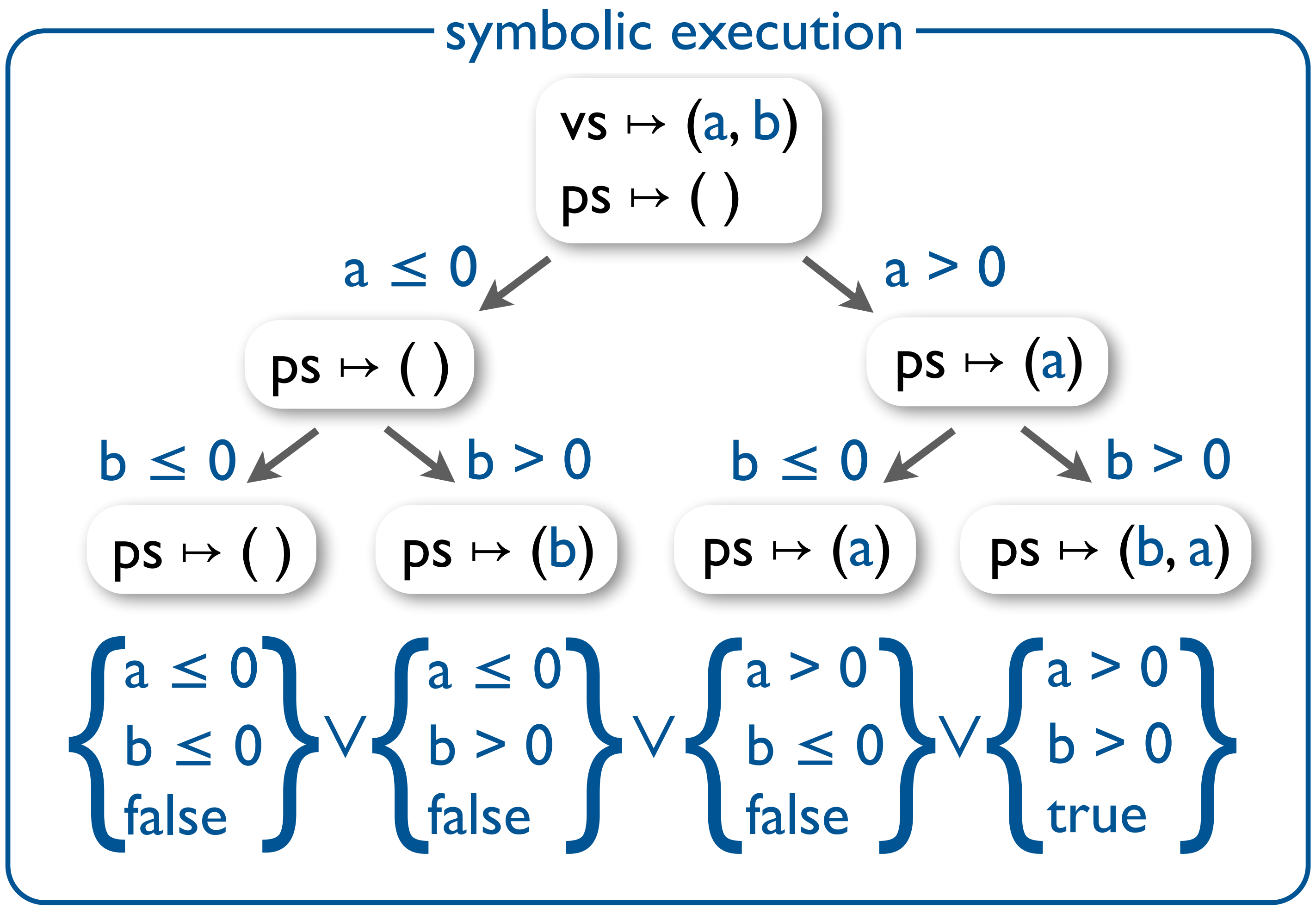
$$\left\{\begin{matrix} a \le 0 \\ b \le 0 \\ \text{false} \end{matrix}\right\} \vee \left\{\begin{matrix} a \le 0 \\ b > 0 \\ \text{false} \end{matrix}\right\} \vee \left\{\begin{matrix} a > 0 \\ b \le 0 \\ \text{false} \end{matrix}\right\} \vee \left\{\begin{matrix} a > 0 \\ b > 0 \\ \text{true} \end{matrix}\right\}$$



bounded model checking

Design space of precise symbolic encodings

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



symbolic execution

vs ↦ (a, b)
ps ↦ ( )

$a \le 0$ → ps ↦ ( )

$a > 0$ → ps ↦ (a)

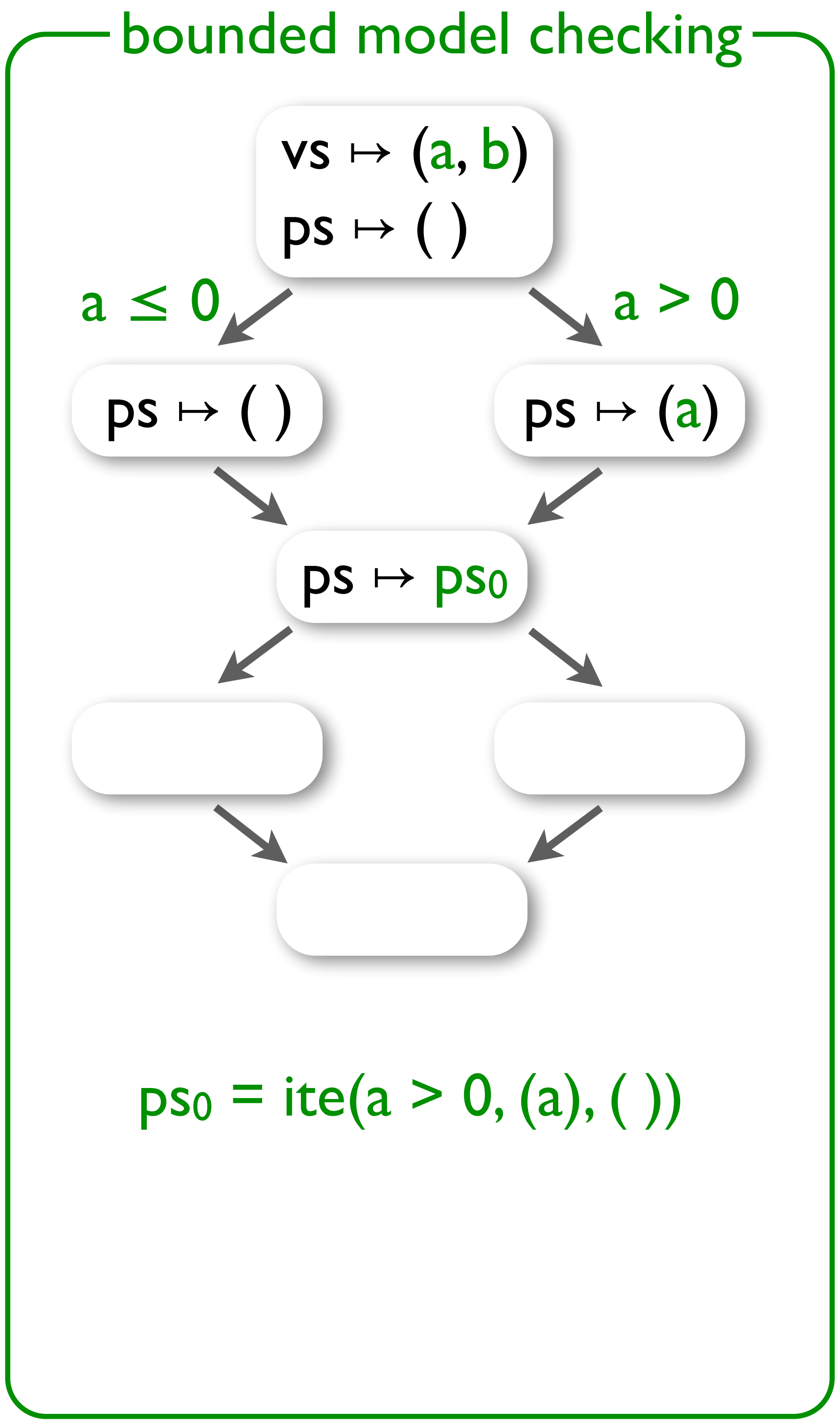
$b \le 0$ → ps ↦ ( )

$b > 0$ → ps ↦ (b)

$b \le 0$ → ps ↦ (a)

$b > 0$ → ps ↦ (b, a)

$$\left\{\begin{matrix} a \le 0 \\ b \le 0 \\ \text{false} \end{matrix}\right\} \vee \left\{\begin{matrix} a \le 0 \\ b > 0 \\ \text{false} \end{matrix}\right\} \vee \left\{\begin{matrix} a > 0 \\ b \le 0 \\ \text{false} \end{matrix}\right\} \vee \left\{\begin{matrix} a > 0 \\ b > 0 \\ \text{true} \end{matrix}\right\}$$



bounded model checking

vs ↦ (a, b)
ps ↦ ( )

$a \le 0$ → ps ↦ ( )

$a > 0$ → ps ↦ (a)

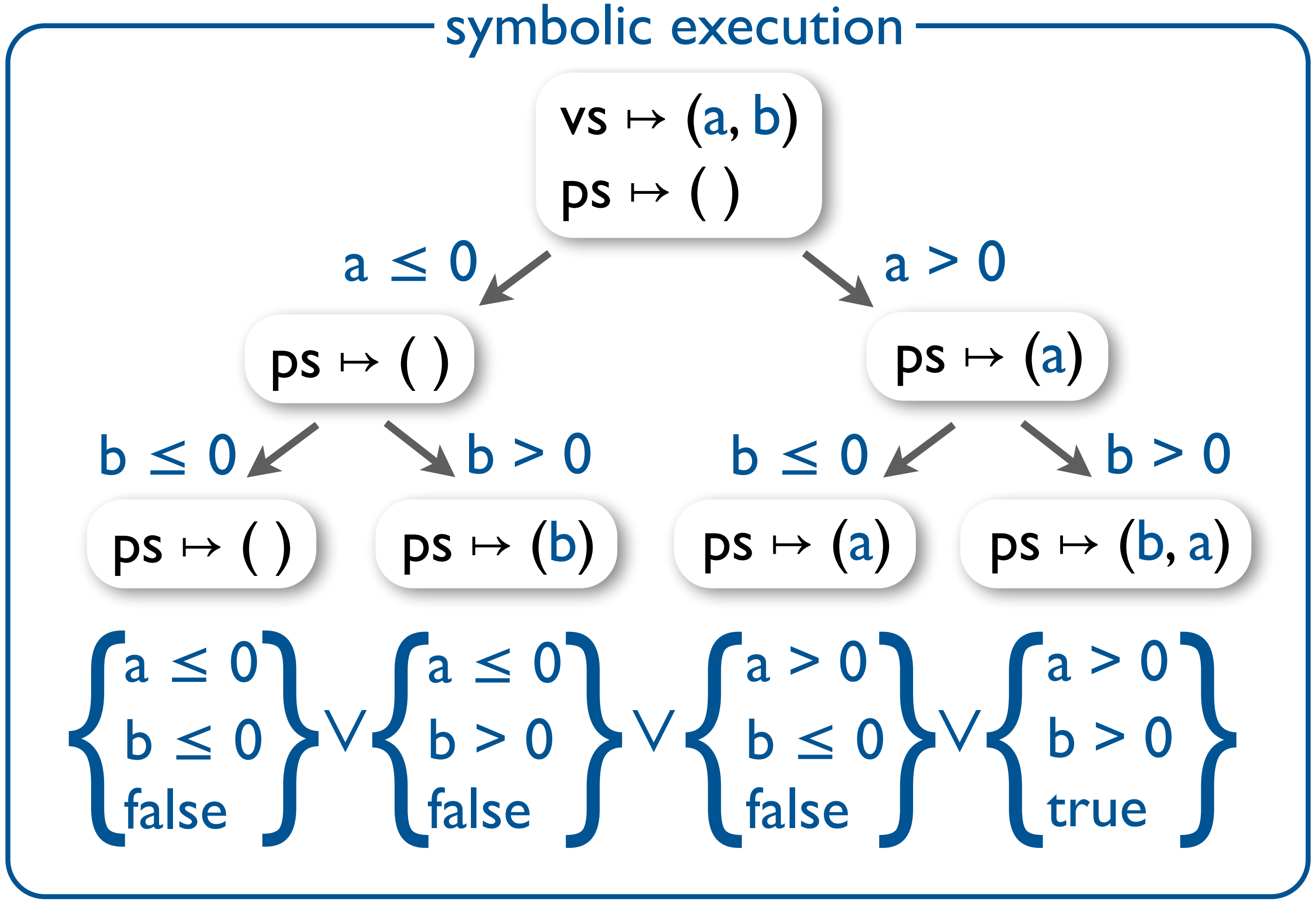
ps ↦ ps_0

ps_0 = ite(a > 0, (a), ( ))

Design space of precise symbolic encodings

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

symbolic execution



vs ↦ (a, b)
ps ↦ ( )

a ≤ 0: ps ↦ ( )

a > 0: ps ↦ (a)

b ≤ 0: ps ↦ ( )

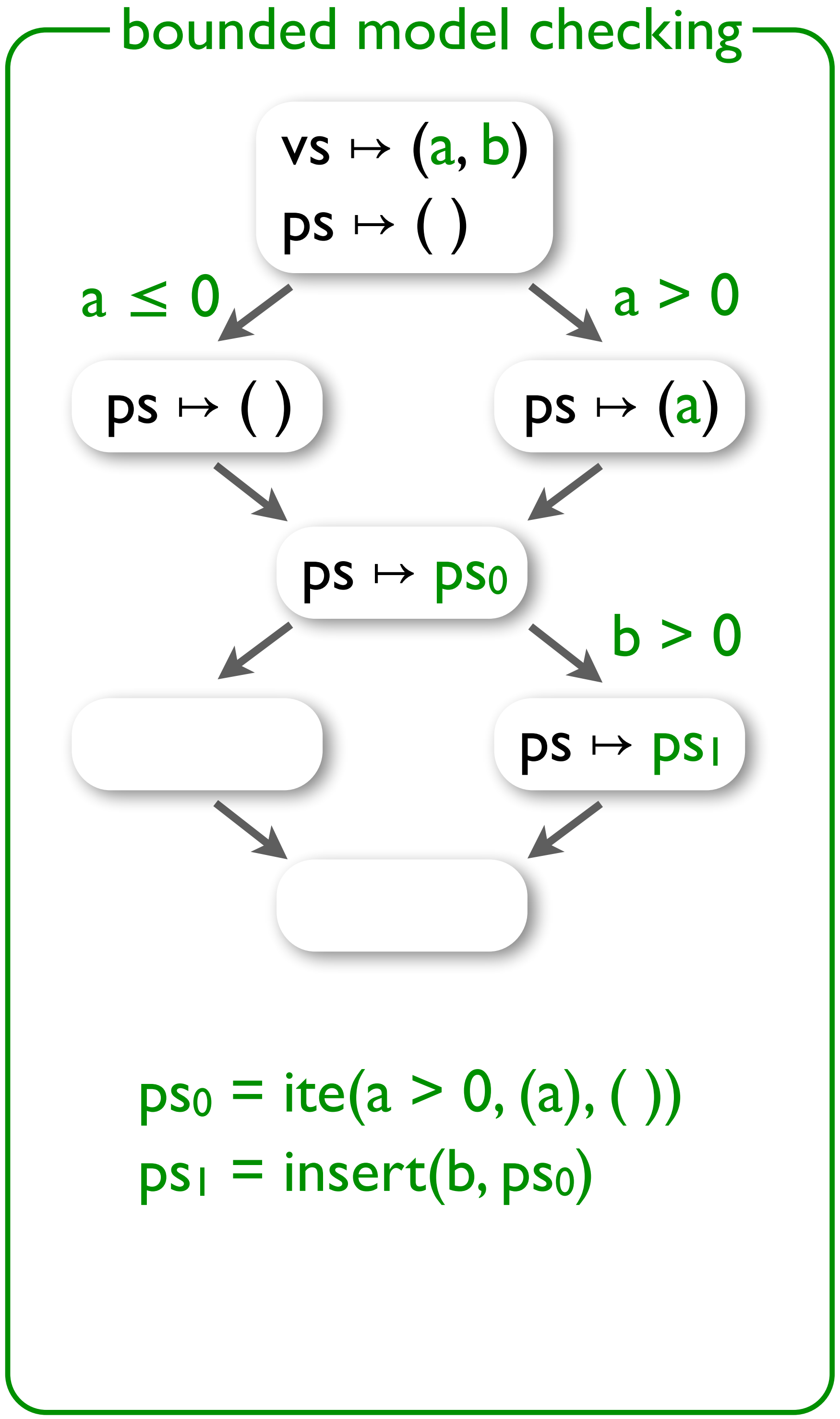
b > 0: ps ↦ (b)

b ≤ 0: ps ↦ (a)

b > 0: ps ↦ (b, a)

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

bounded model checking



vs ↦ (a, b)
ps ↦ ( )

a ≤ 0: ps ↦ ( )

a > 0: ps ↦ (a)

ps ↦ ps_0

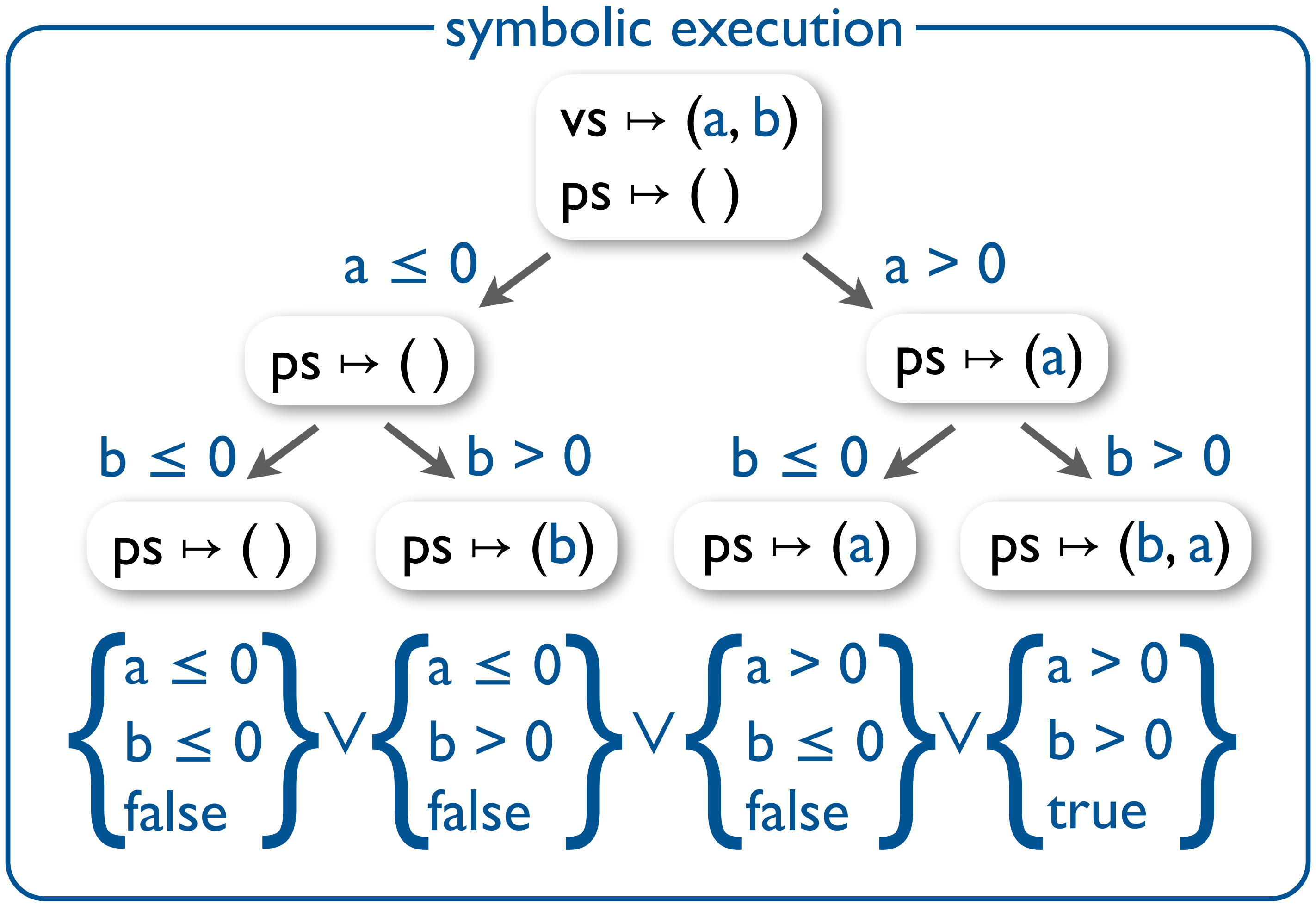
b > 0: ps ↦ ps_1

ps_0 = ite(a > 0, (a), ( ))

ps_1 = insert(b, ps_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)
```



symbolic execution

$vs \mapsto (a, b)$
$ps \mapsto (\,)$

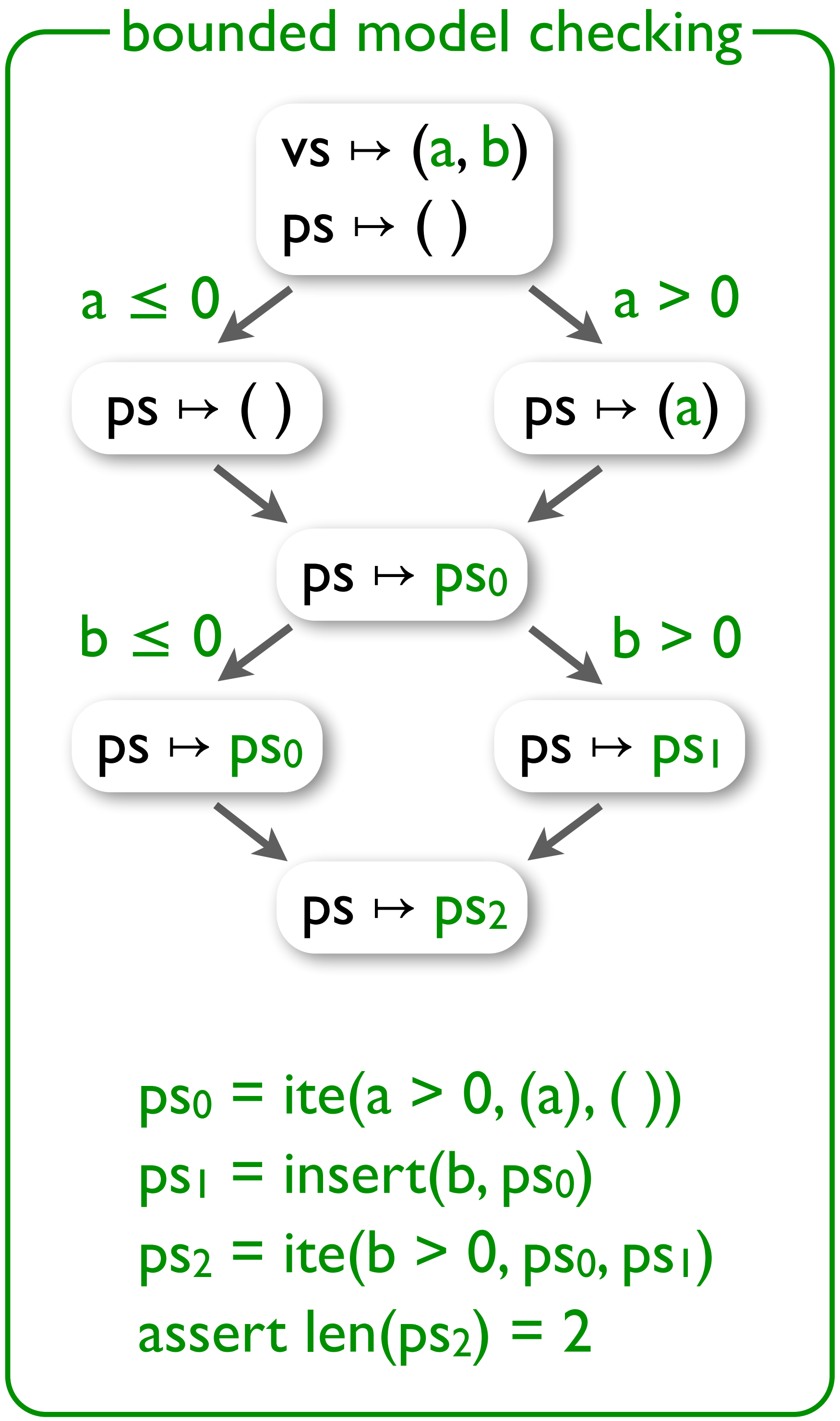
$a \le 0$ | $a > 0$

$ps \mapsto (\,)$ | $ps \mapsto (a)$

$b \le 0$ | $b > 0$ | $b \le 0$ | $b > 0$

$ps \mapsto (\,)$ | $ps \mapsto (b)$ | $ps \mapsto (a)$ | $ps \mapsto (b, a)$

$$\left\{\begin{array}{l} a \le 0 \\ b \le 0 \\ \text{false} \end{array}\right\} \vee \left\{\begin{array}{l} a \le 0 \\ b > 0 \\ \text{false} \end{array}\right\} \vee \left\{\begin{array}{l} a > 0 \\ b \le 0 \\ \text{false} \end{array}\right\} \vee \left\{\begin{array}{l} a > 0 \\ b > 0 \\ \text{true} \end{array}\right\}$$



bounded model checking

$vs \mapsto (a, b)$
$ps \mapsto (\,)$

$a \le 0$ | $a > 0$

$ps \mapsto (\,)$ | $ps \mapsto (a)$

$ps \mapsto ps_0$

$b \le 0$ | $b > 0$

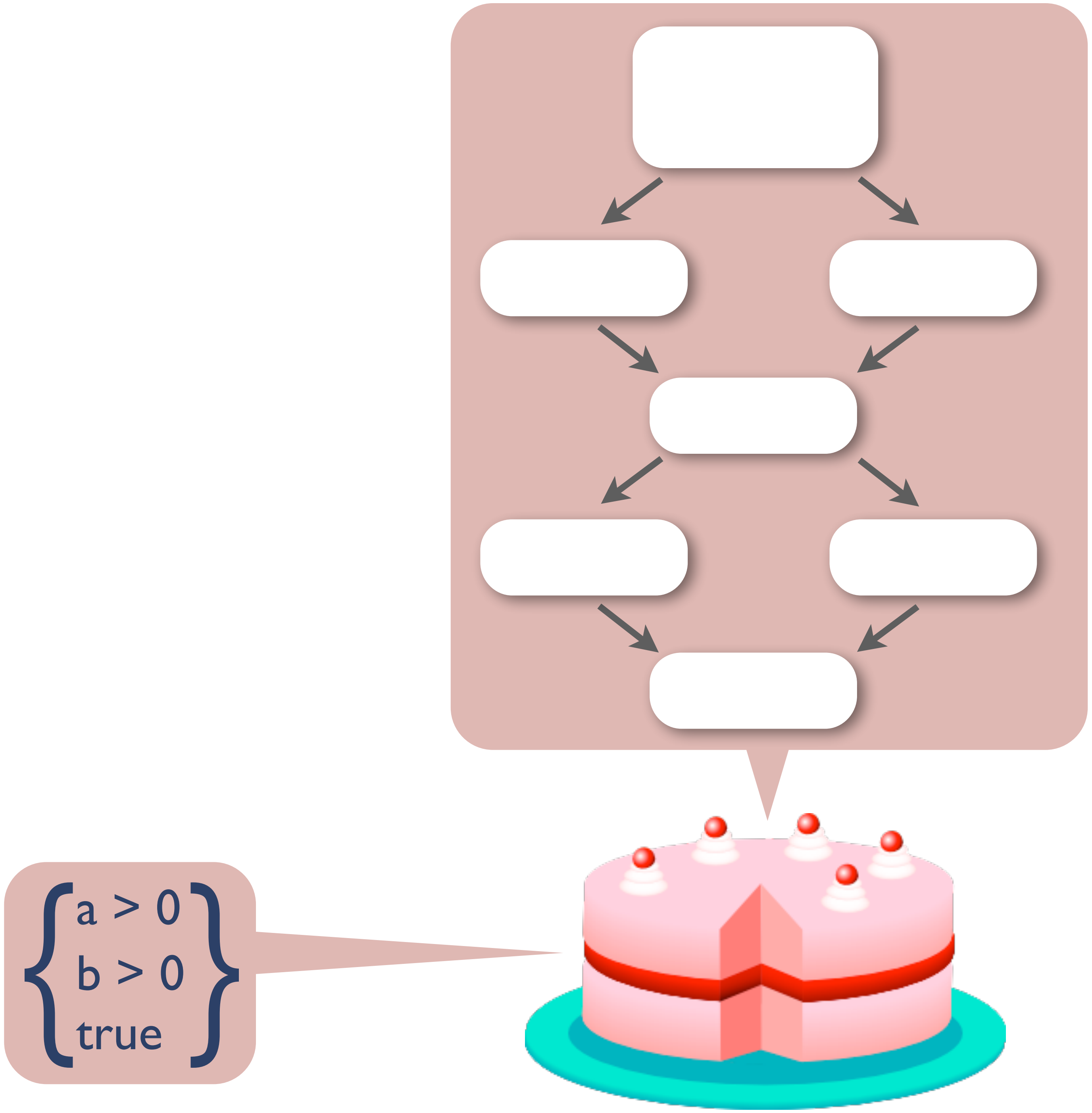
$ps \mapsto ps_0$ | $ps \mapsto ps_1$

$ps \mapsto ps_2$

$ps_0 = \text{ite}(a > 0, (a), (\,))$
$ps_1 = \text{insert}(b, ps_0)$
$ps_2 = \text{ite}(b > 0, ps_0, ps_1)$
$\text{assert len}(ps_2) = 2$

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)
```



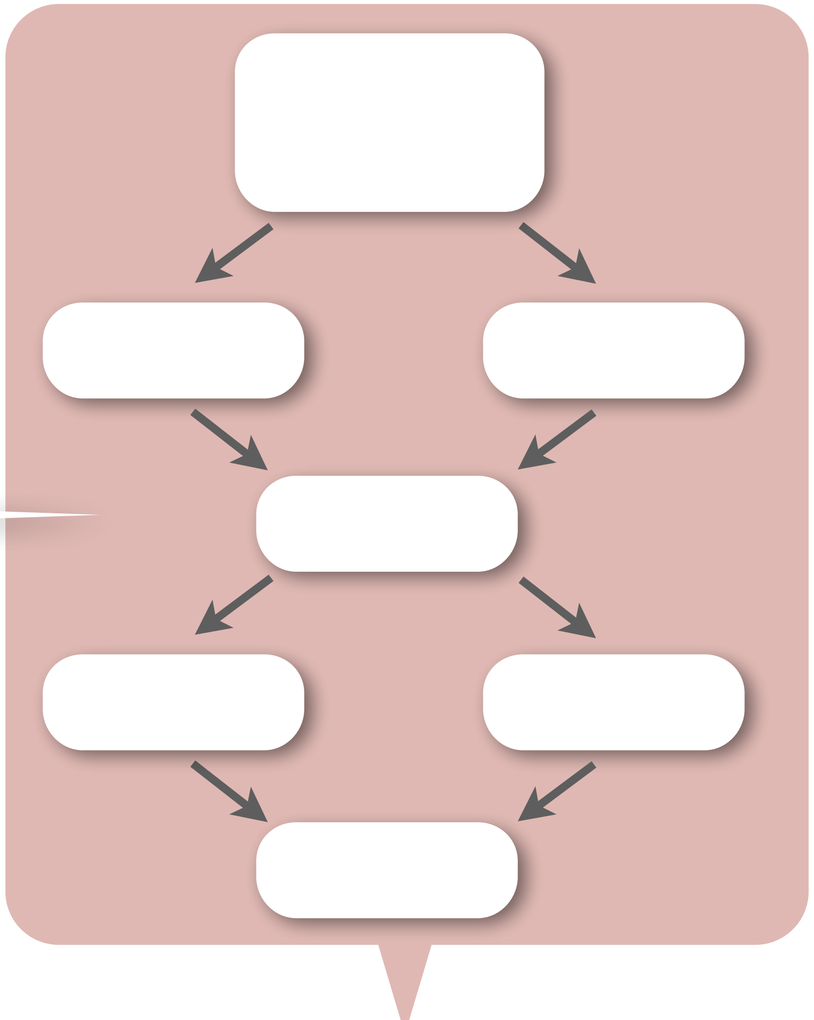
$$\left\{\begin{matrix} a > 0 \\ b > 0 \\ \text{true} \end{matrix}\right\}$$

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)
```

Merge values of

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



$$\left\{\begin{matrix} a > 0 \\ b > 0 \\ \text{true} \end{matrix}\right\}$$

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)
```

Merge values of

- primitive types: symbolically
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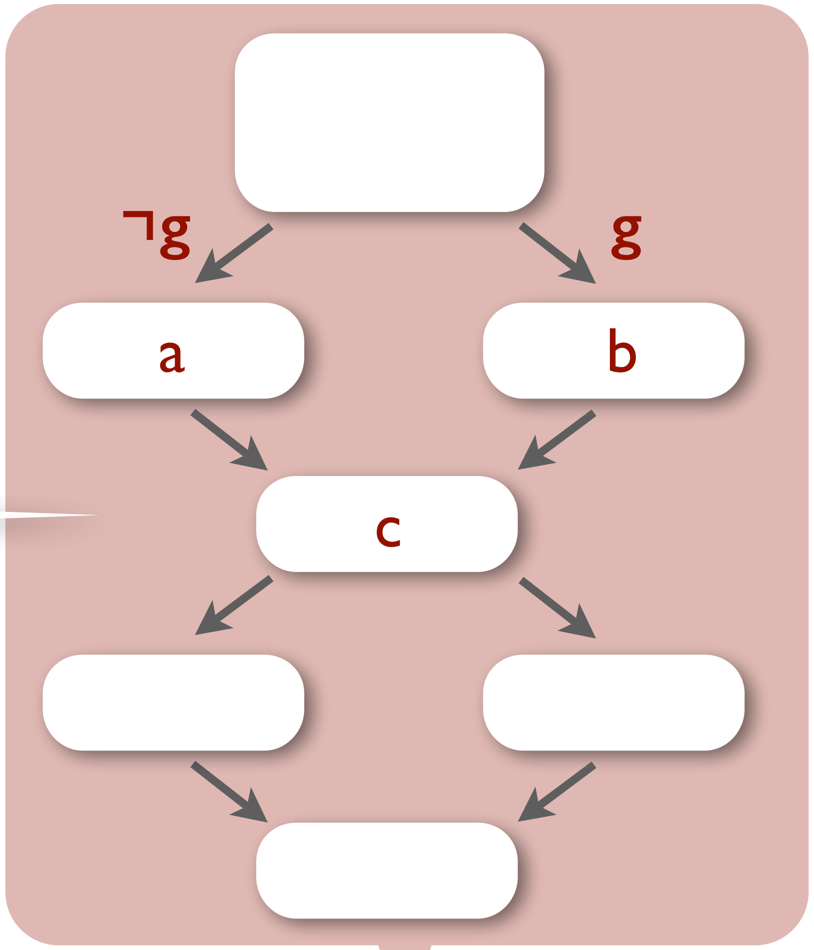


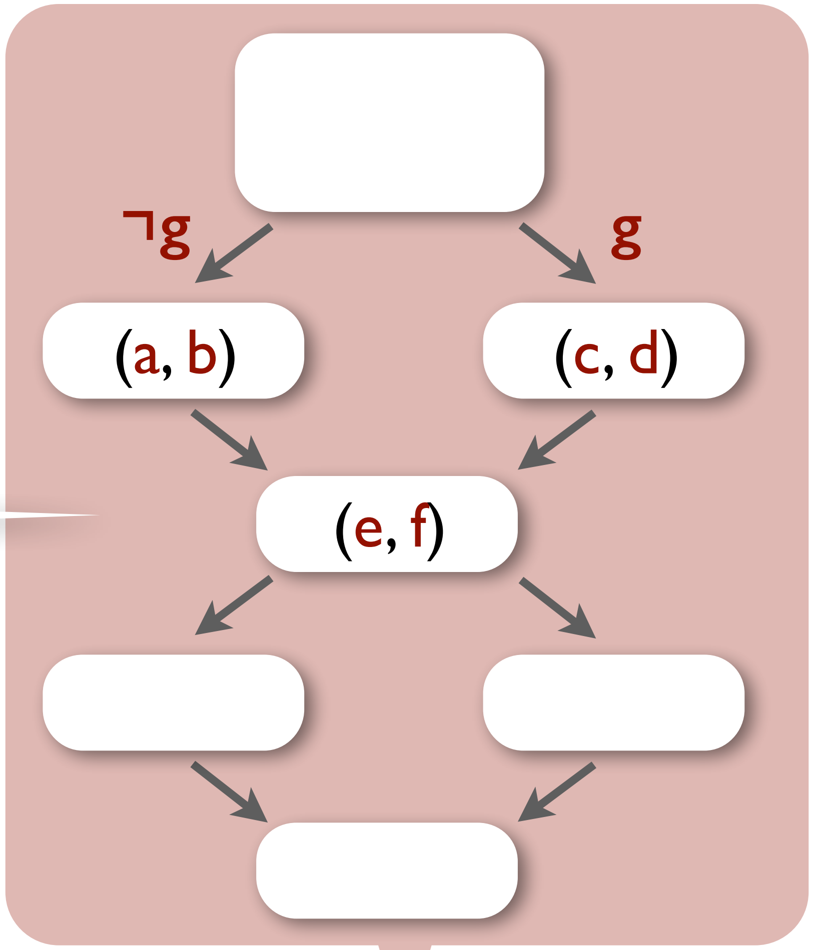
$$\left\{\begin{array}{l} a > 0 \\ b > 0 \\ \text{true} \end{array}\right\}$$

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)
```

Merge values of

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



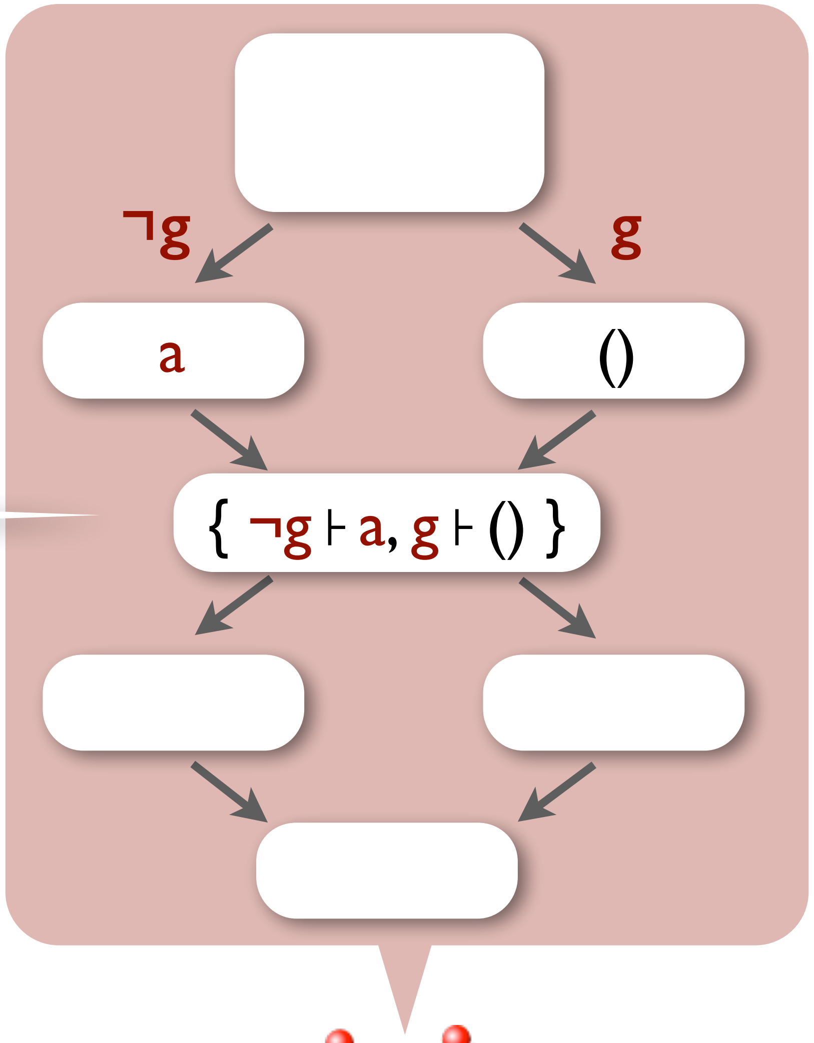
$$\left\{\begin{array}{l} a > 0 \\ b > 0 \\ \text{true} \end{array}\right\}$$

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)
```

Merge values of

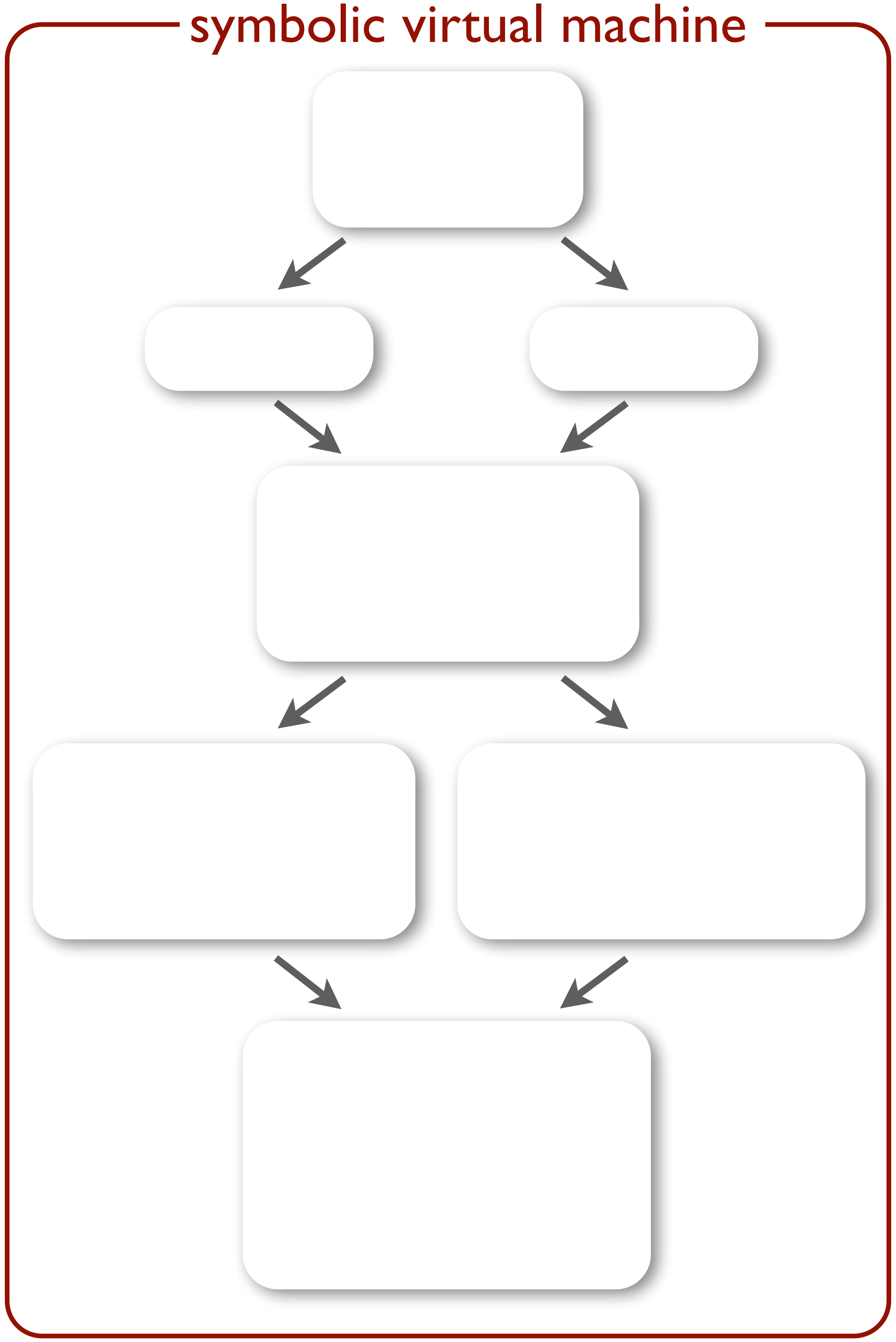
- primitive types: symbolically
- immutable types: structurally
- all other types: via unions



$$\left\{\begin{array}{l} a > 0 \\ b > 0 \\ \text{true} \end{array}\right\}$$

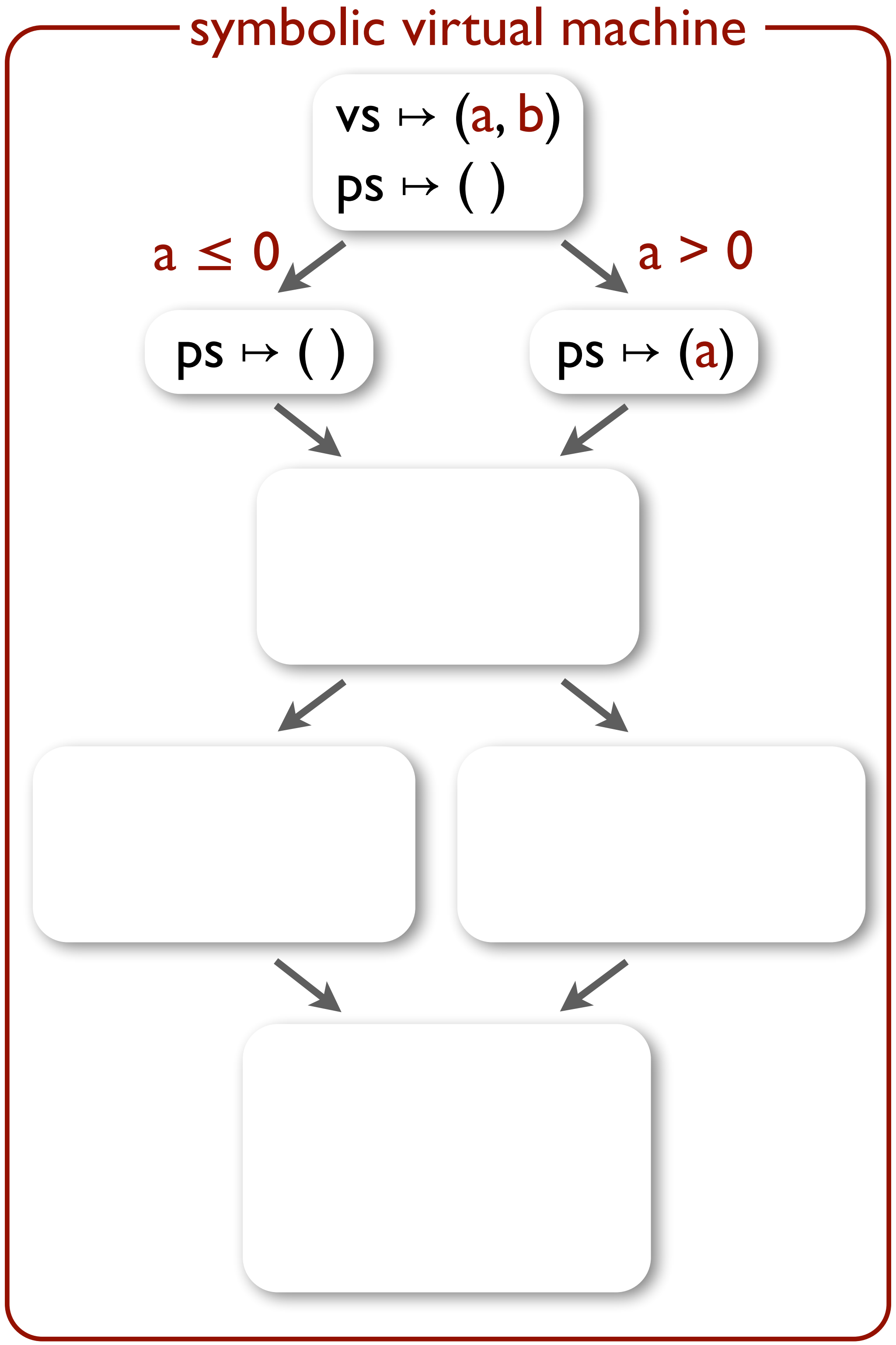
A new design: type-driven state merging

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



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)
```

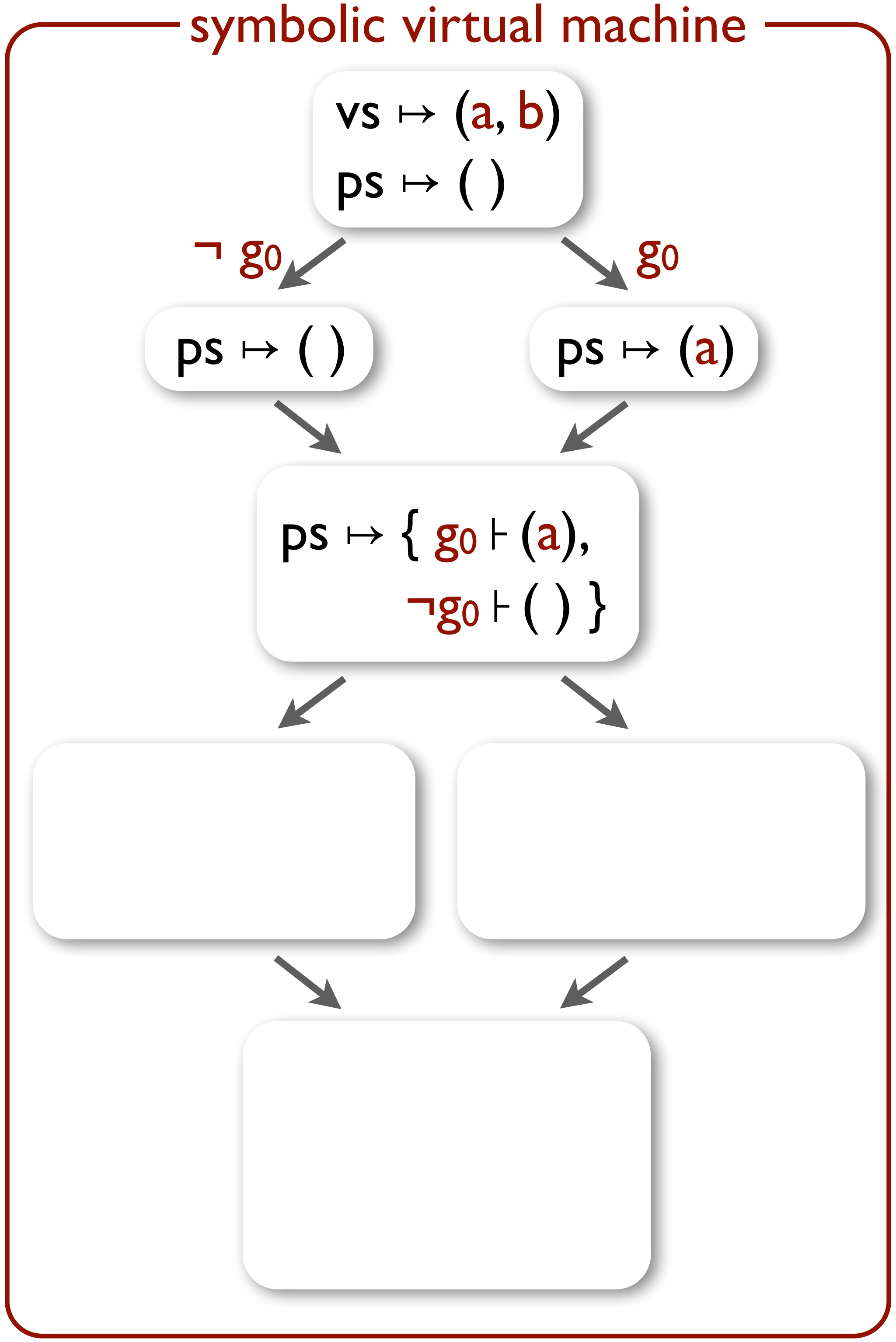


A new design: type-driven state merging

```
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 and exhaustive guards.

$g_0 = a > 0$



symbolic virtual machine

$vs \mapsto (a, b)$
$ps \mapsto (\,)$

$\neg\, g_0$

g_0

$ps \mapsto (\,)$

$ps \mapsto (a)$

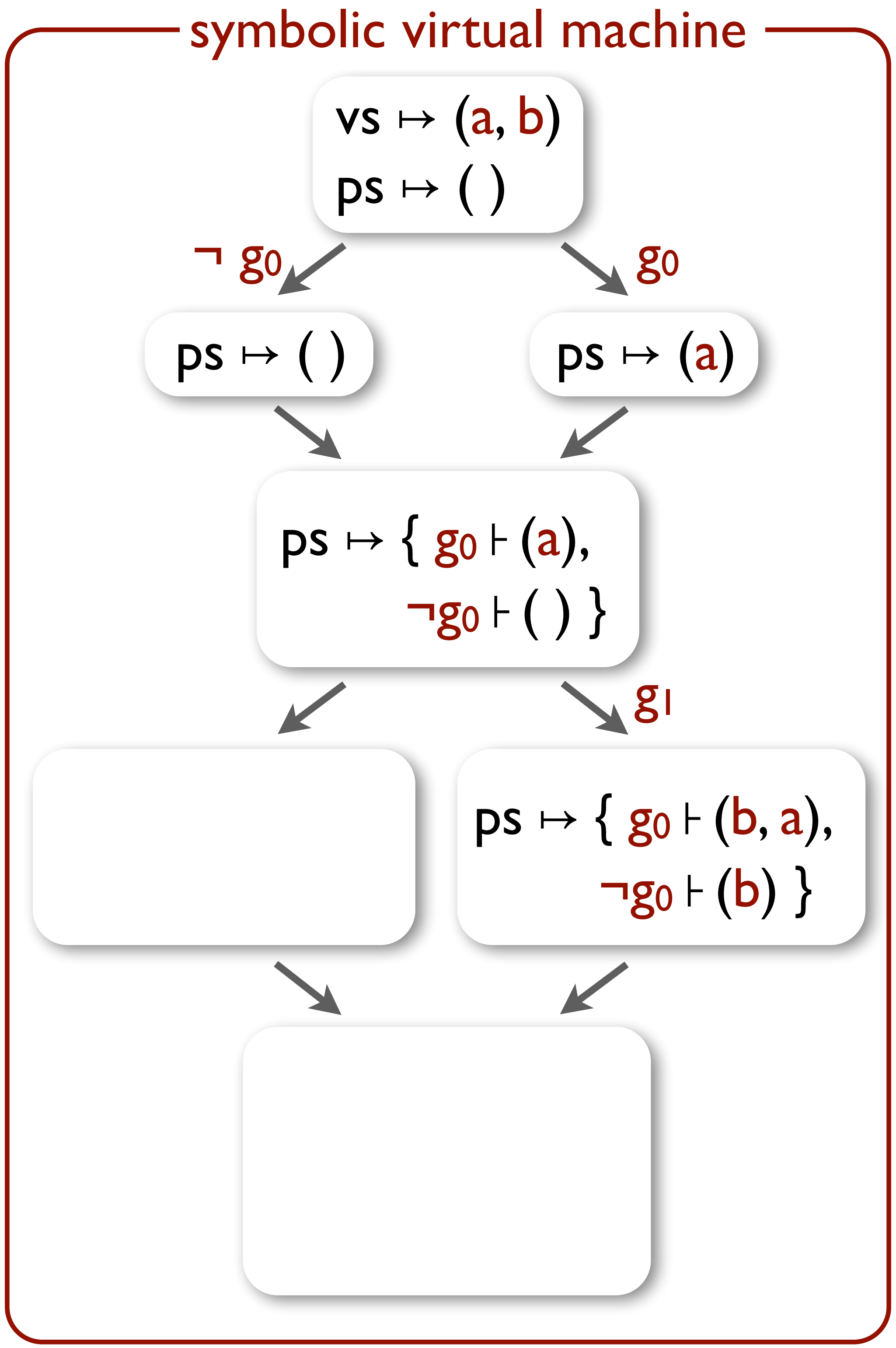
$ps \mapsto \{\, g_0 \vdash (a),$
$\neg g_0 \vdash (\,) \,\}$

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)
```

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

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



symbolic virtual machine

$vs \mapsto (a, b)$
$ps \mapsto (\,)$

$\neg\, g_0$

g_0

$ps \mapsto (\,)$

$ps \mapsto (a)$

$ps \mapsto \{\, g_0 \vdash (a),$
$\neg g_0 \vdash (\,) \,\}$

g_1

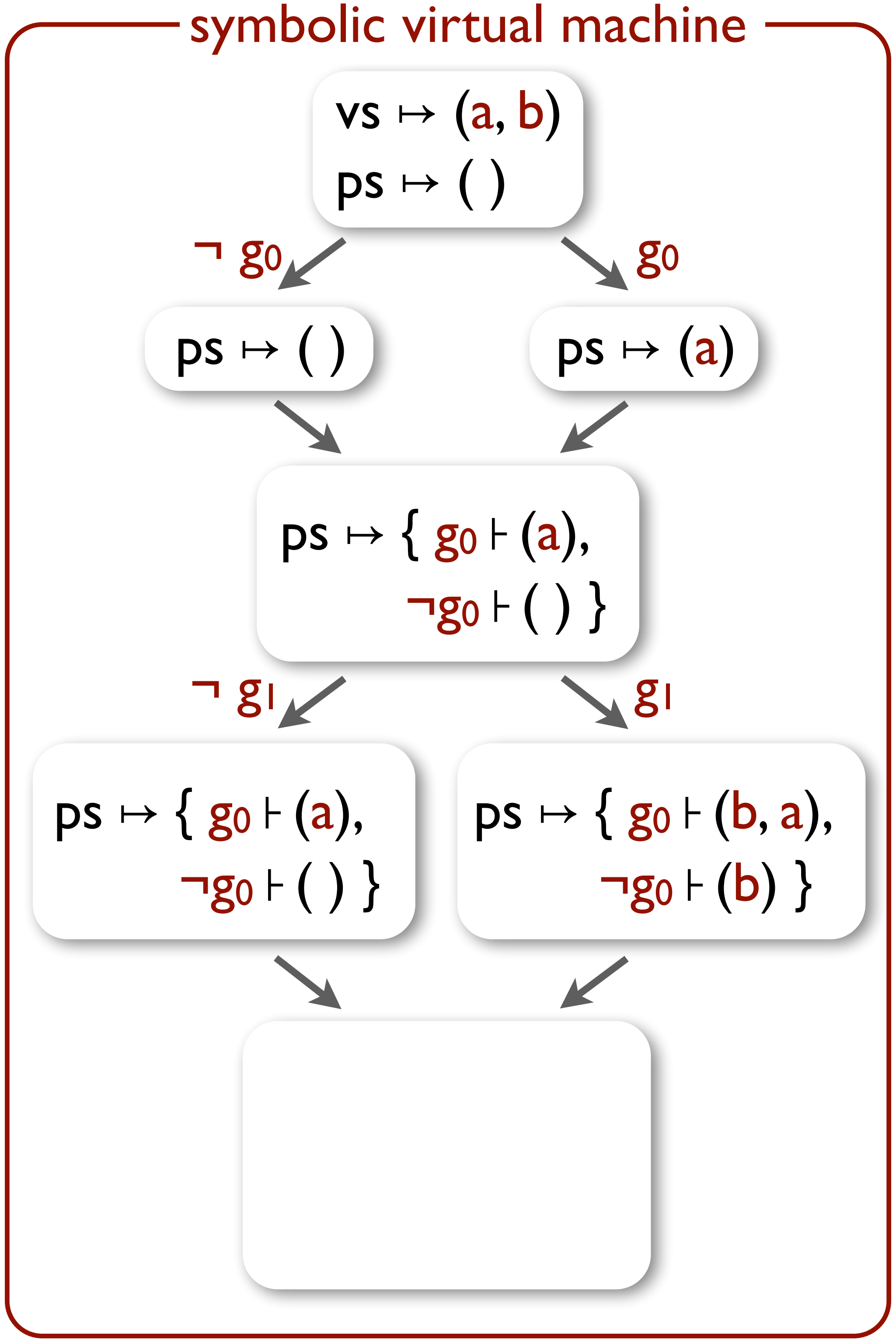
$ps \mapsto \{\, g_0 \vdash (b, a),$
$\neg g_0 \vdash (b) \,\}$

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)
```

$g_0 = a > 0$

$g_1 = b > 0$



symbolic virtual machine

$vs \mapsto (a, b)$

$ps \mapsto (\,)$

$\neg\, g_0$ $\quad$ g_0

$ps \mapsto (\,)$ $\quad$ $ps \mapsto (a)$

$ps \mapsto \{\, g_0 \vdash (a),\ \neg g_0 \vdash (\,) \,\}$

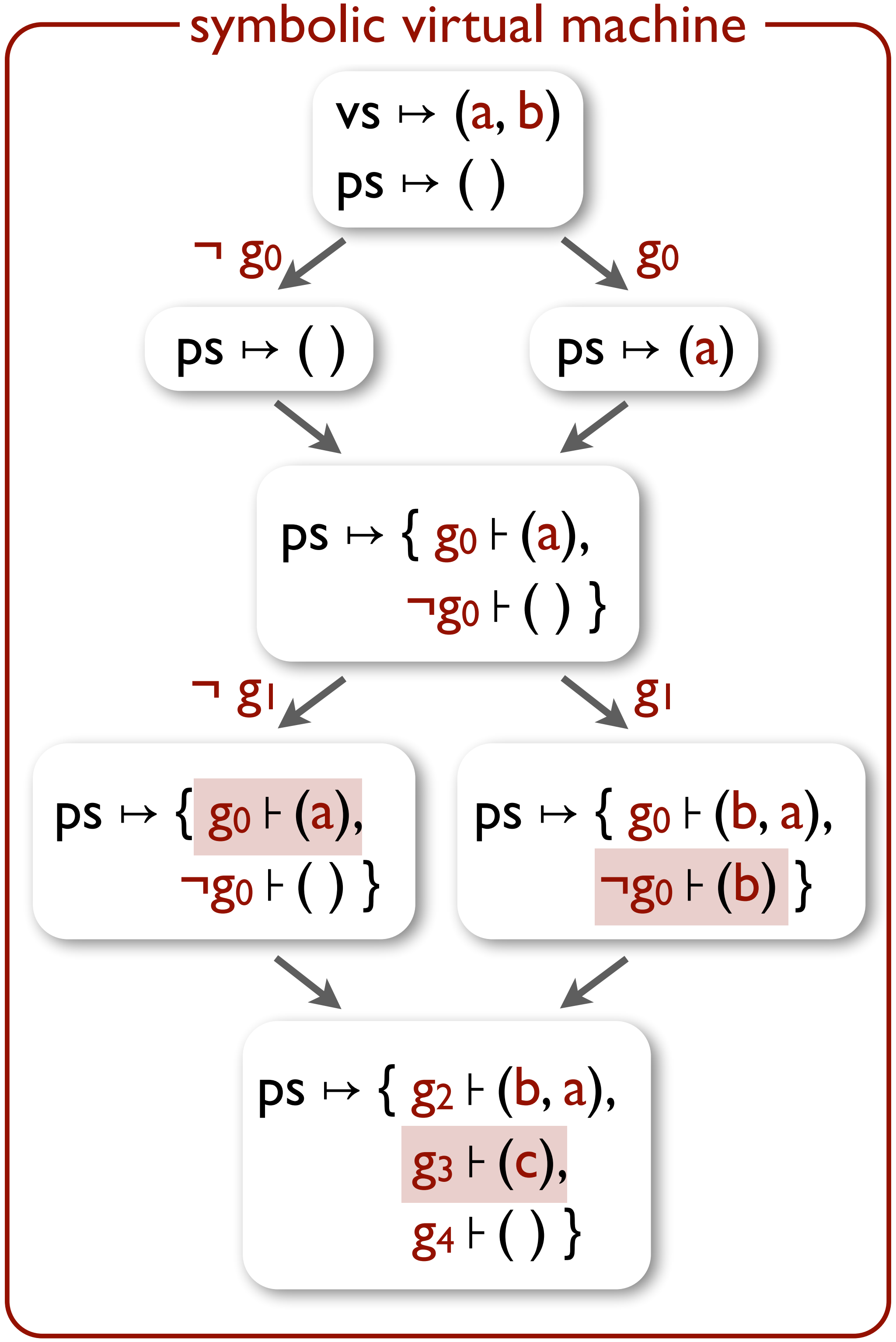
$\neg\, g_1$ $\quad$ g_1

$ps \mapsto \{\, g_0 \vdash (a),\ \neg g_0 \vdash (\,) \,\}$ $\quad$ $ps \mapsto \{\, g_0 \vdash (b, a),\ \neg g_0 \vdash (b) \,\}$

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)
```

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



symbolic virtual machine

$vs \mapsto (a, b)$
$ps \mapsto (\,)$

$\neg g_0$ | g_0

$ps \mapsto (\,)$ | $ps \mapsto (a)$

$ps \mapsto \{ g_0 \vdash (a), \neg g_0 \vdash (\,) \}$

$\neg g_1$ | g_1

$ps \mapsto \{ g_0 \vdash (a), \neg g_0 \vdash (\,) \}$ | $ps \mapsto \{ g_0 \vdash (b, a), \neg g_0 \vdash (b) \}$

$ps \mapsto \{ g_2 \vdash (b, a), g_3 \vdash (c), g_4 \vdash (\,) \}$

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)
```

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

$g_0 = a > 0$

$g_1 = b > 0$

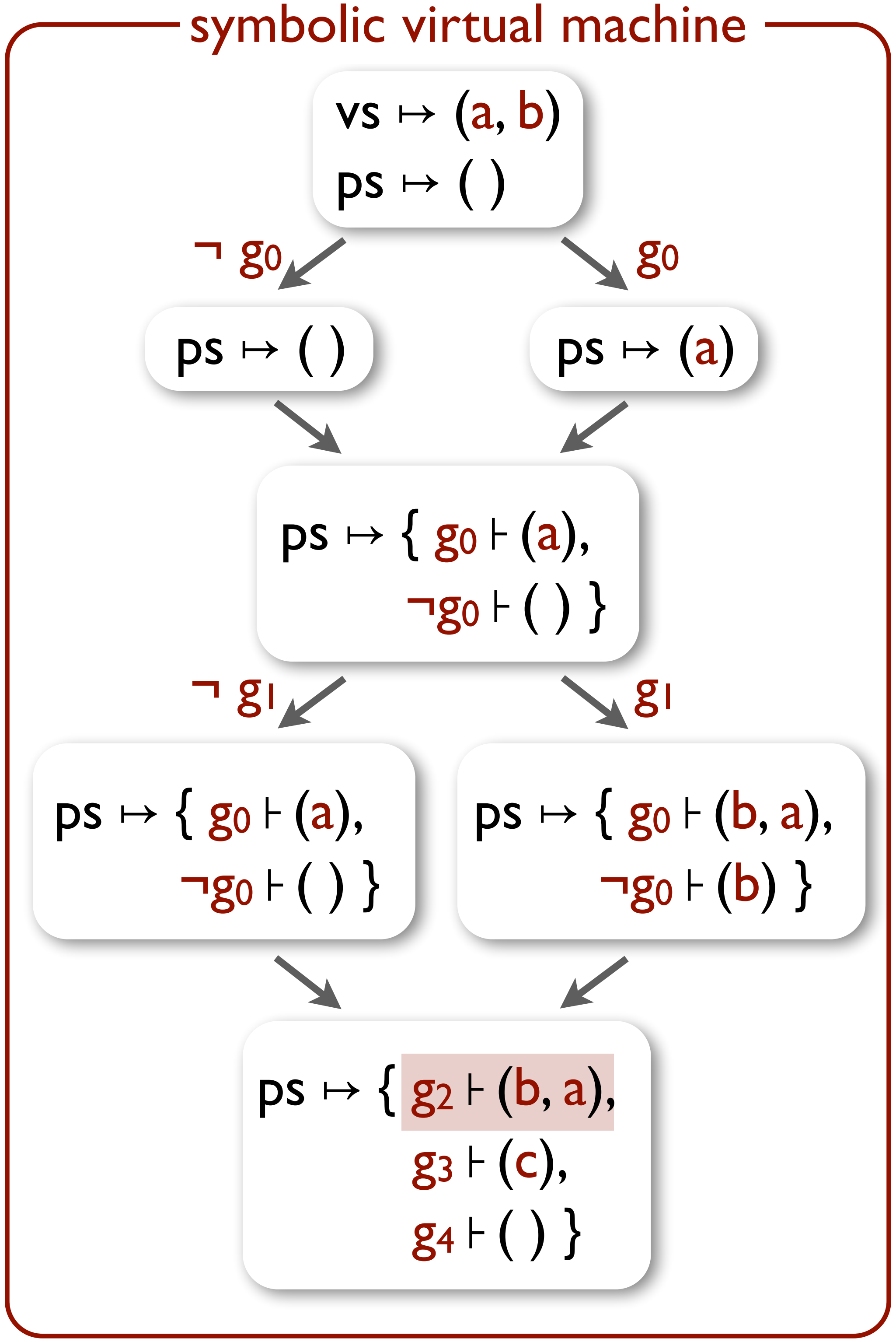
$g_2 = g_0 \wedge g_1$

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

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

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

assert g_2



symbolic virtual machine

$vs \mapsto (a, b)$
$ps \mapsto (\,)$

$\neg\, g_0$ / g_0

$ps \mapsto (\,)$ / $ps \mapsto (a)$

$ps \mapsto \{\, g_0 \vdash (a),\ \neg g_0 \vdash (\,) \,\}$

$\neg\, g_1$ / g_1

$ps \mapsto \{\, g_0 \vdash (a),\ \neg g_0 \vdash (\,) \,\}$ / $ps \mapsto \{\, g_0 \vdash (b, a),\ \neg g_0 \vdash (b) \,\}$

$ps \mapsto \{\, g_2 \vdash (b, a),\ g_3 \vdash (c),\ g_4 \vdash (\,) \,\}$

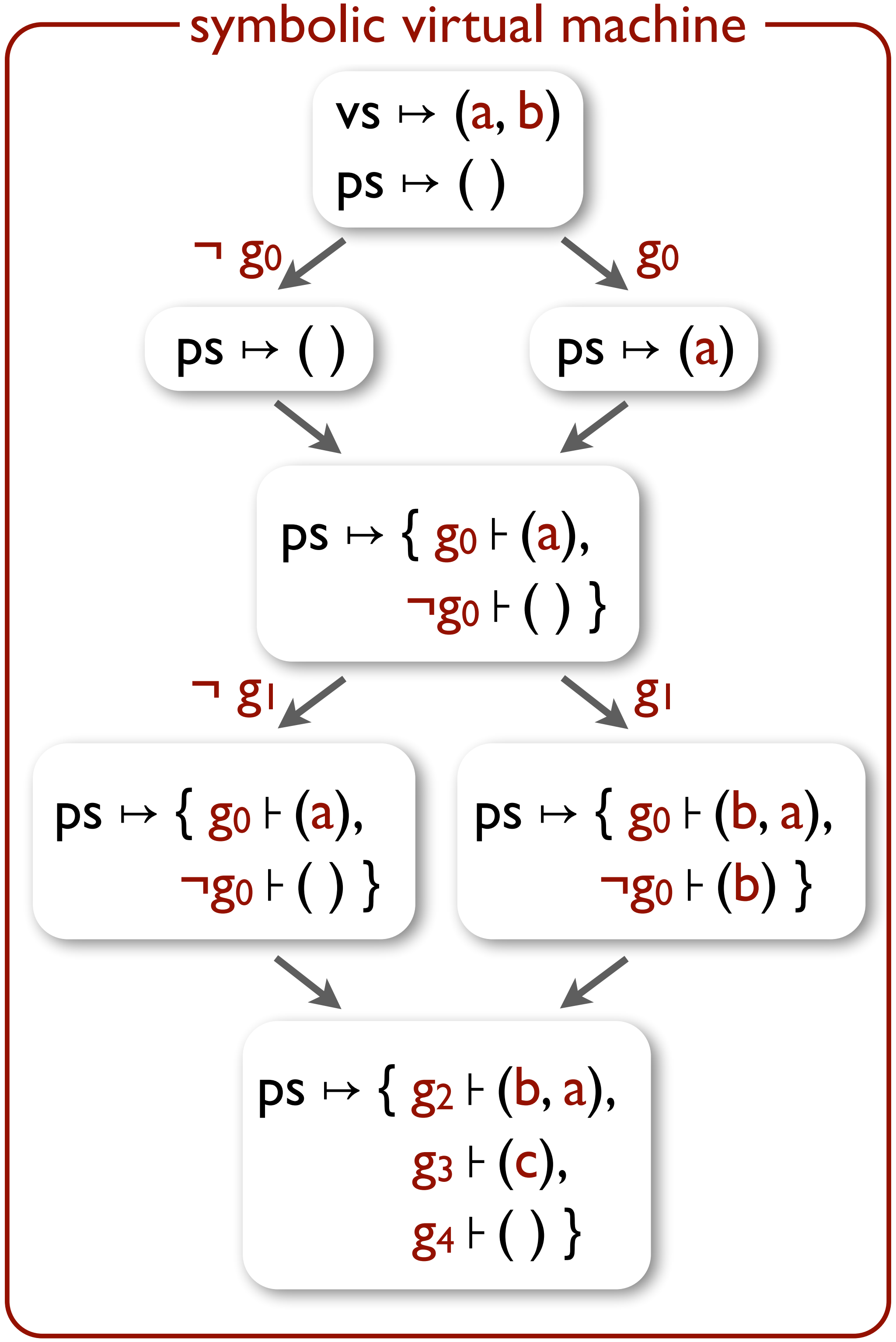
A new design: type-driven state merging

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

polynomial encoding

partial evaluation

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



symbolic virtual machine

$vs \mapsto (a, b)$
$ps \mapsto (\,)$

$\neg\, g_0$

g_0

$ps \mapsto (\,)$

$ps \mapsto (a)$

$ps \mapsto \{\, g_0 \vdash (a),\ \neg g_0 \vdash (\,) \,\}$

$\neg\, g_1$

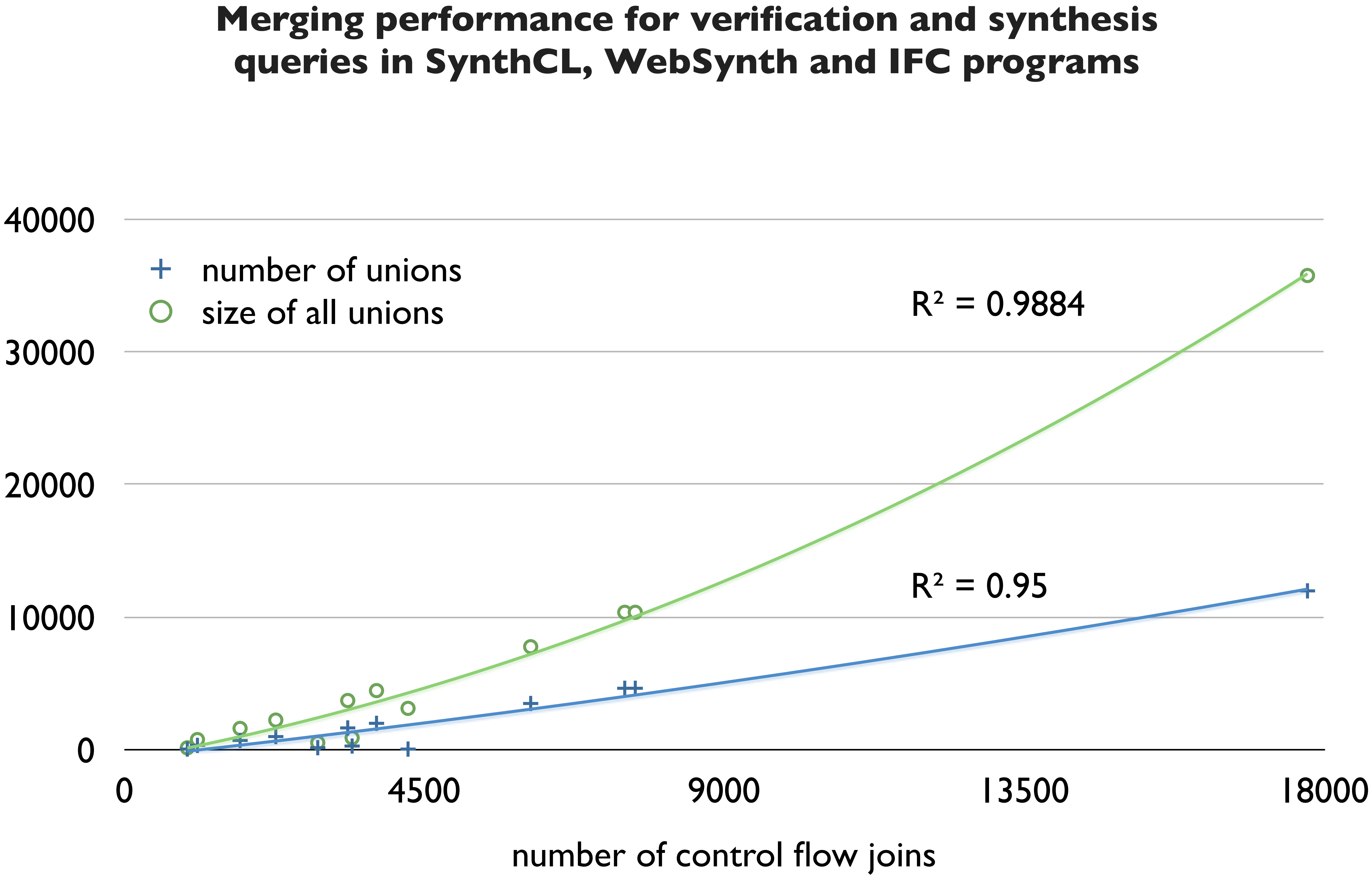
g_1

$ps \mapsto \{\, g_0 \vdash (a),\ \neg g_0 \vdash (\,) \,\}$

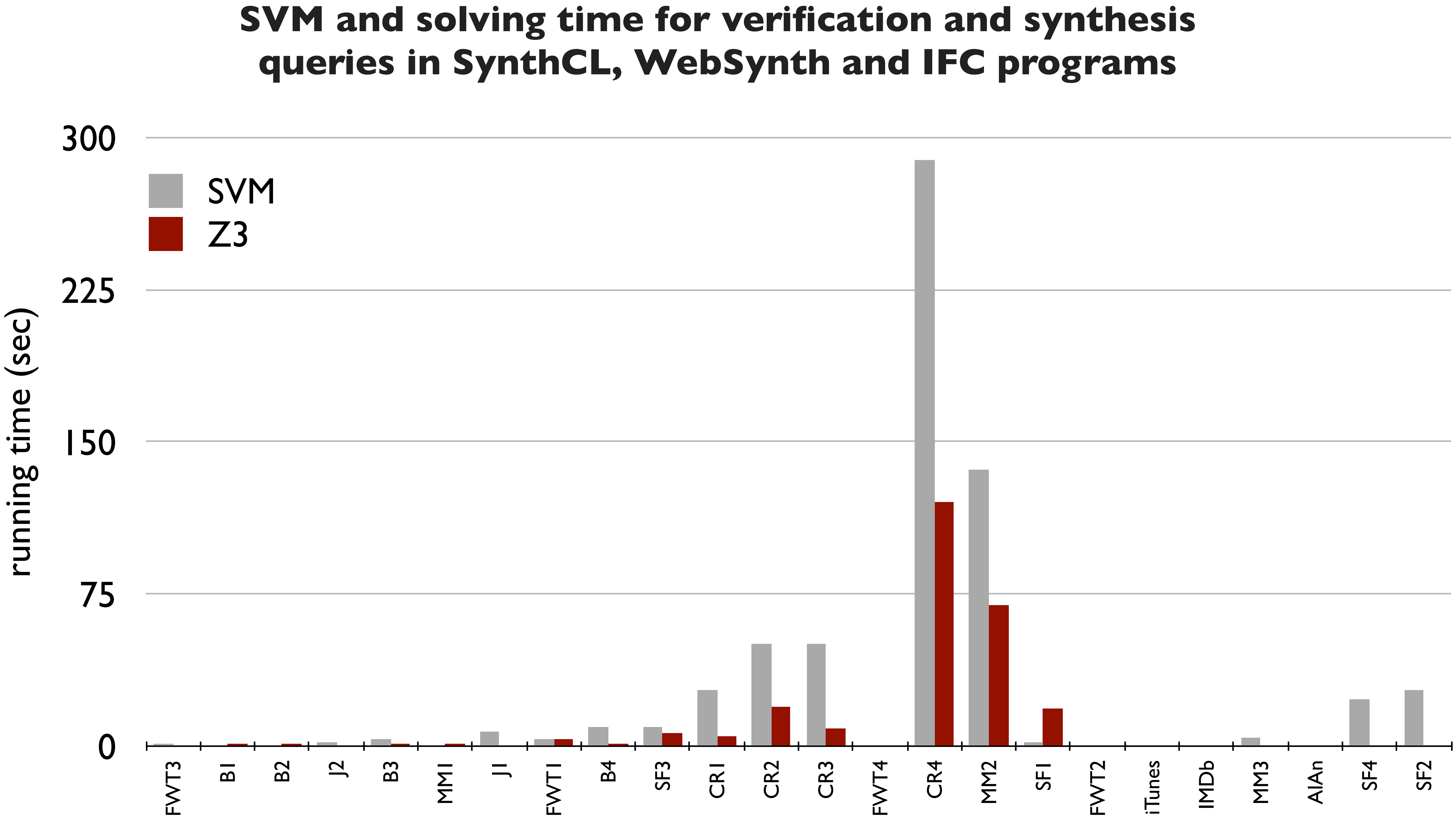
$ps \mapsto \{\, g_0 \vdash (b, a),\ \neg g_0 \vdash (b) \,\}$

$ps \mapsto \{\, g_2 \vdash (b, a),\ g_3 \vdash (c),\ g_4 \vdash (\,) \,\}$

Effectiveness of type-driven state merging

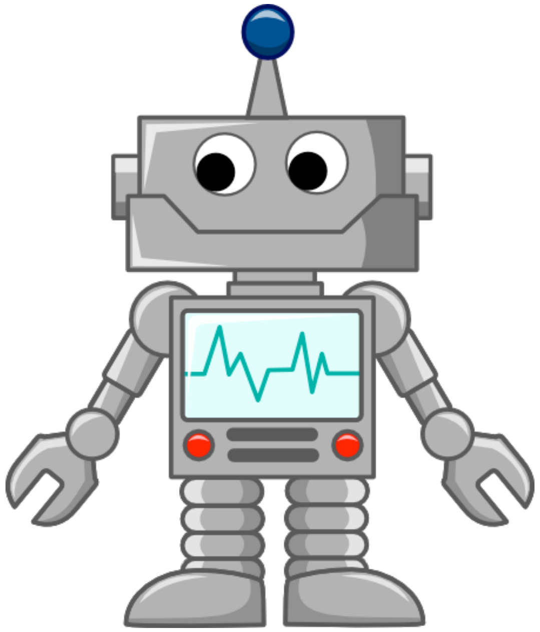


Effectiveness of type-driven state merging



demo

a little SDSL for finite state automata



thanks

thanks

ROSETTE

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