Solver-aided programming: getting started

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

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

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

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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.

ROSETTE

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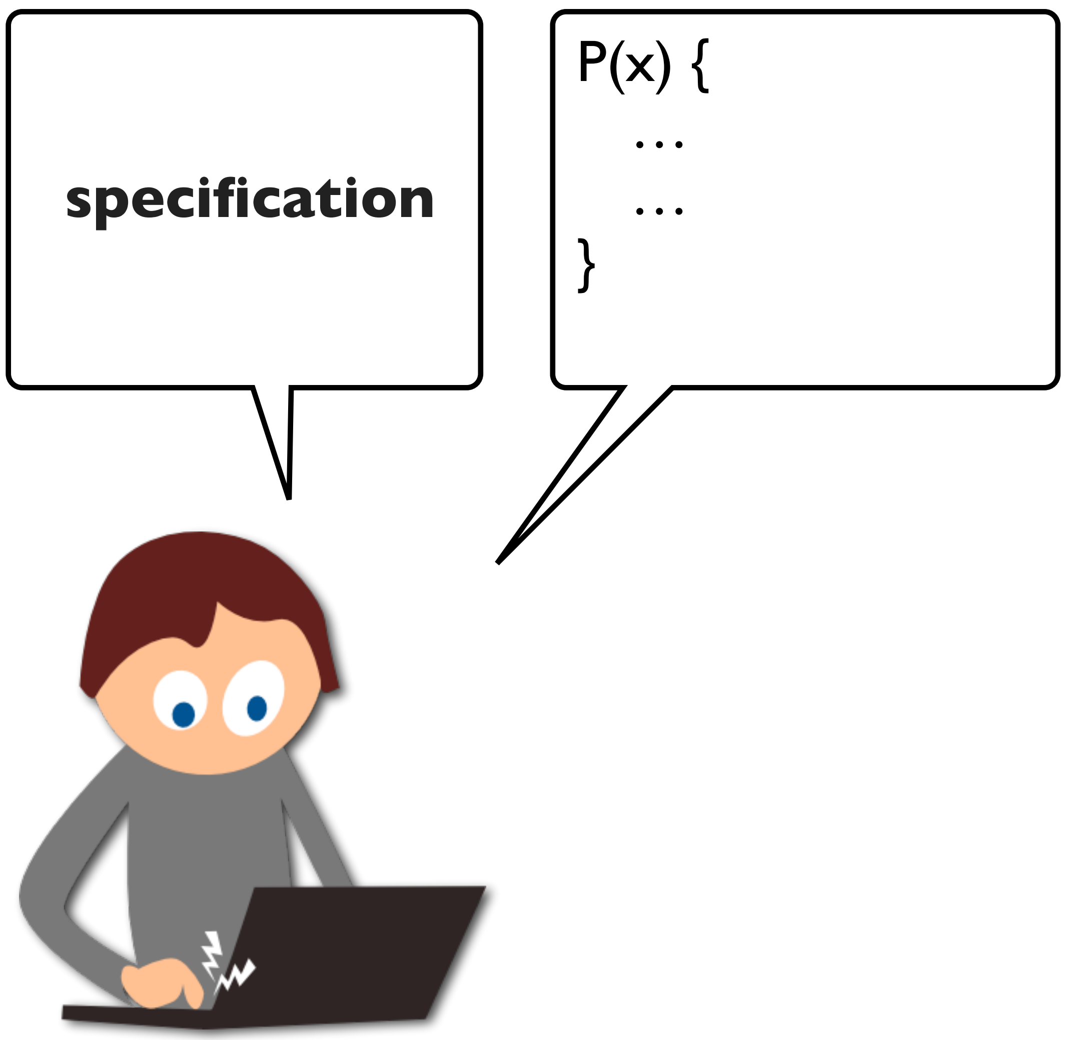
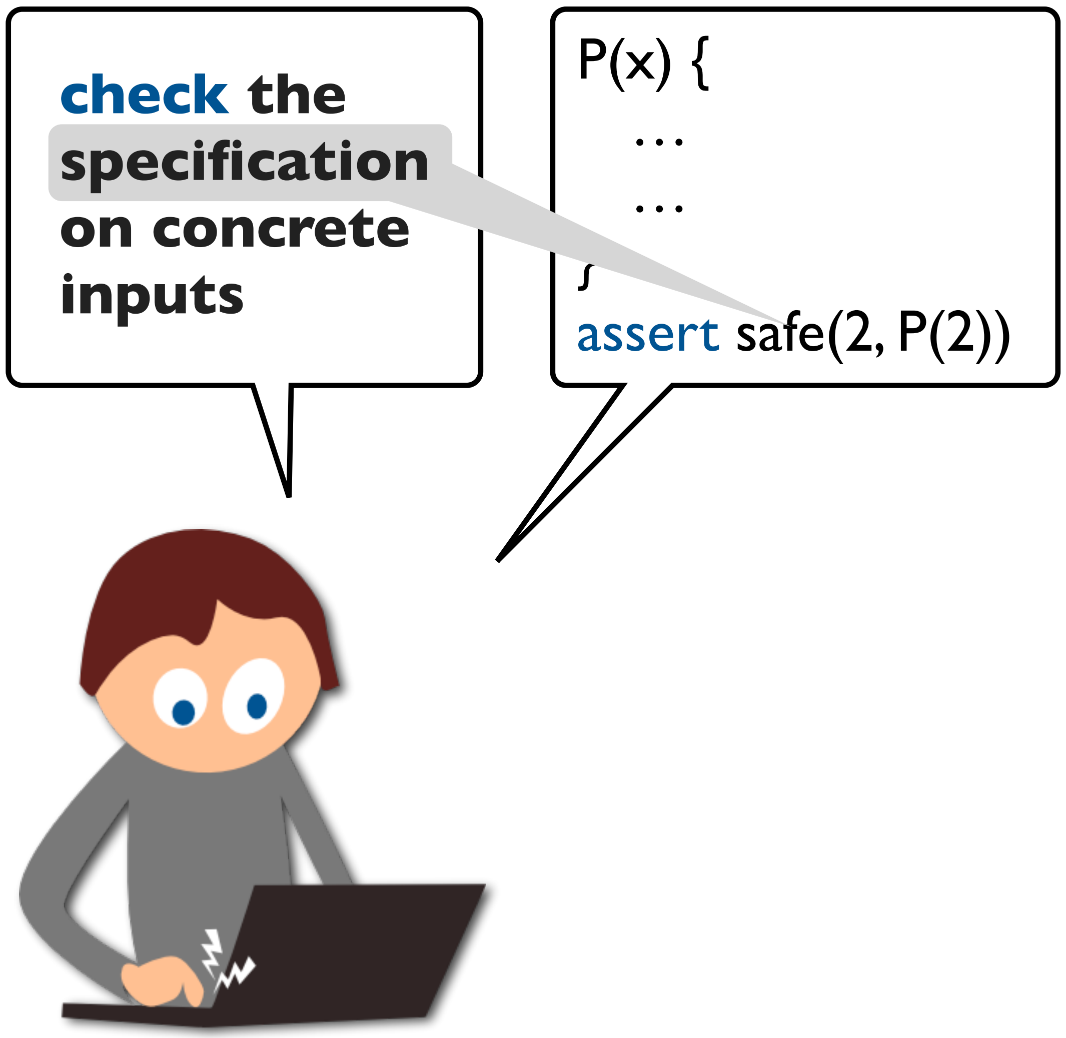
Classic programming: from spec to code



Classic programming: check code against spec



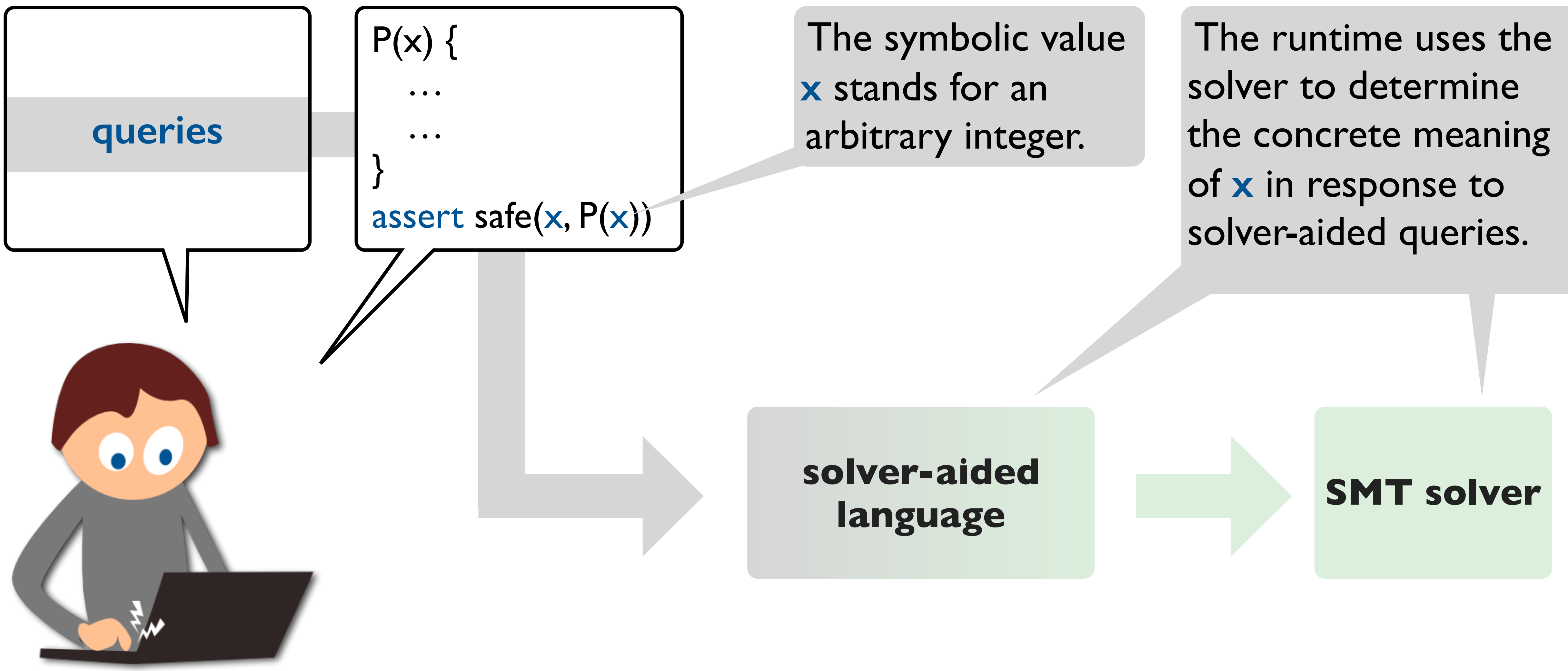
Solver-aided programming: add *symbolic values*

check the specification on symbolic inputs

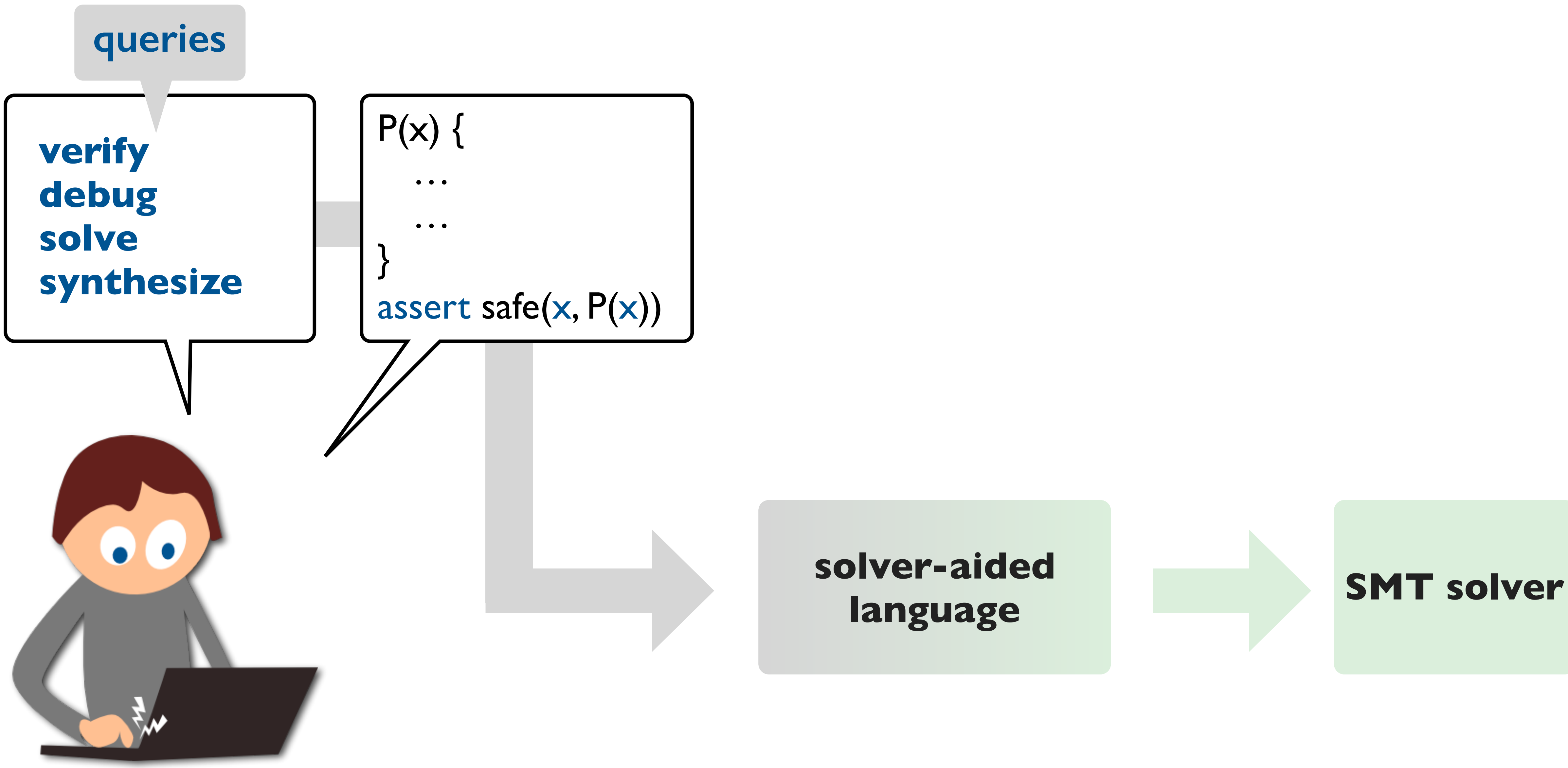
```
P(x) {
   …
   …
}
assert safe(x, P(x))
```

The symbolic value **x** stands for an arbitrary integer.

Solver-aided programming: *query* code against spec

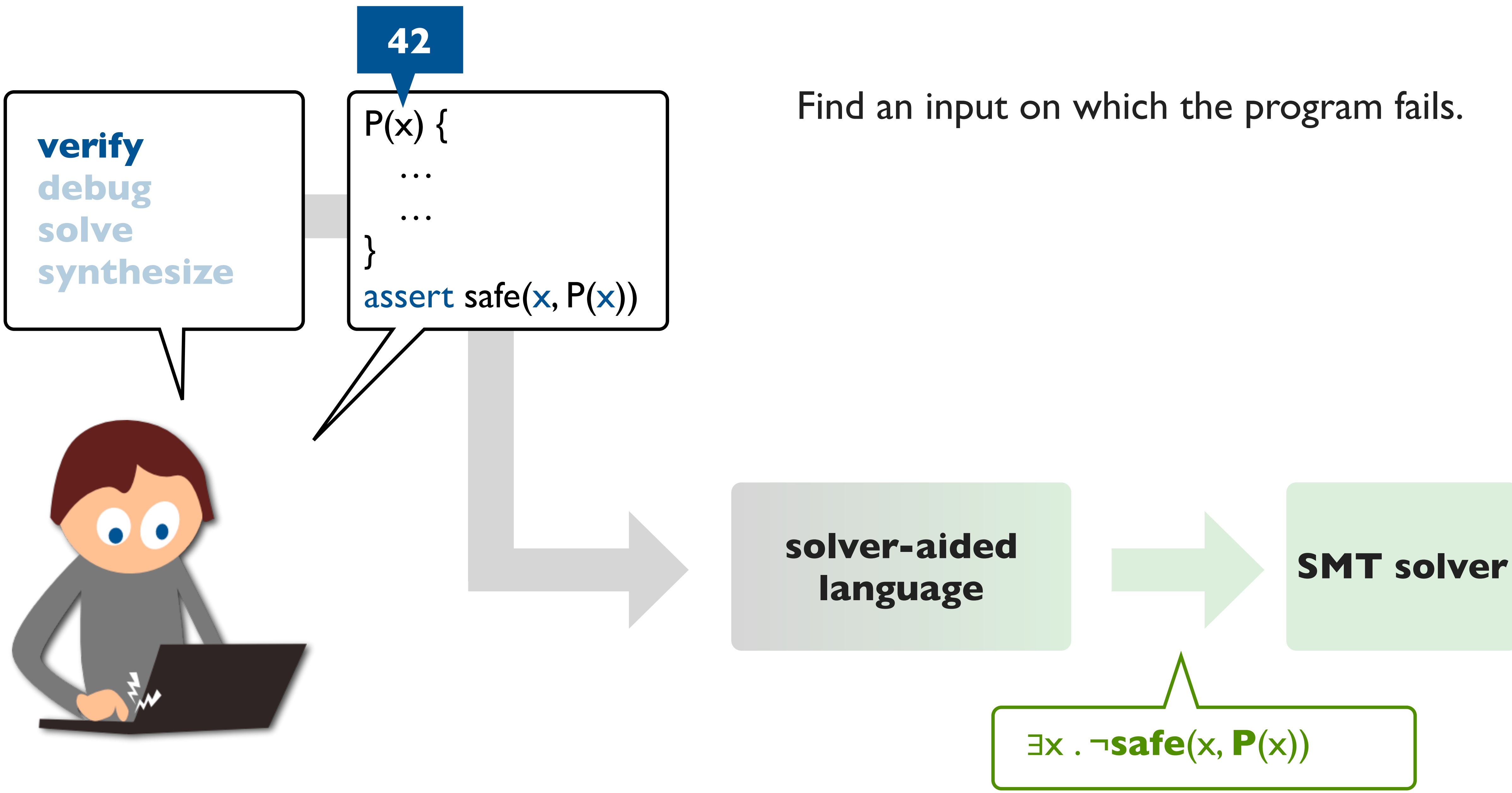


Solver-aided programming: *query* code against spec



Solver-aided programming: *verify* code against spec

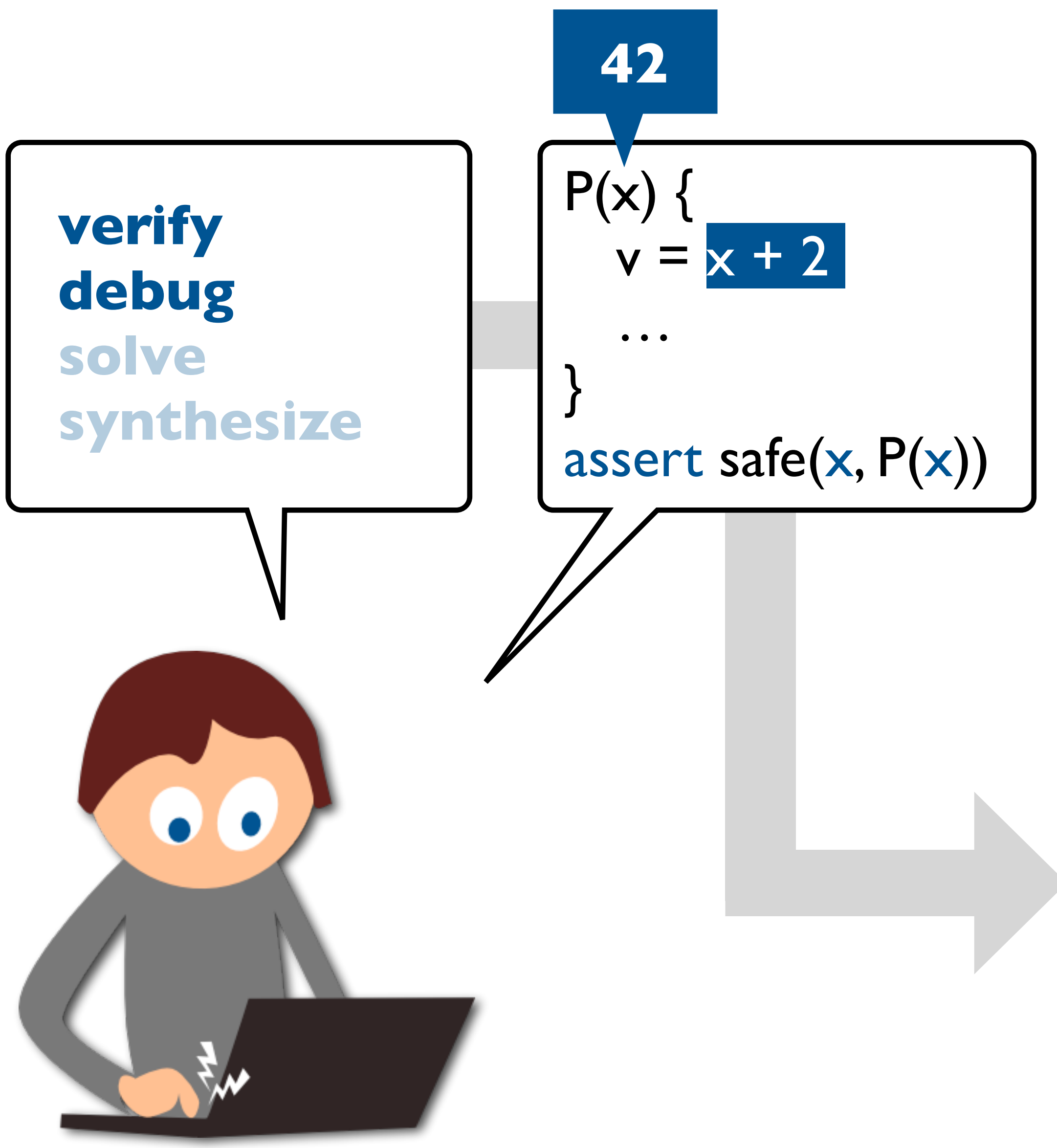
Find an input on which the program fails.

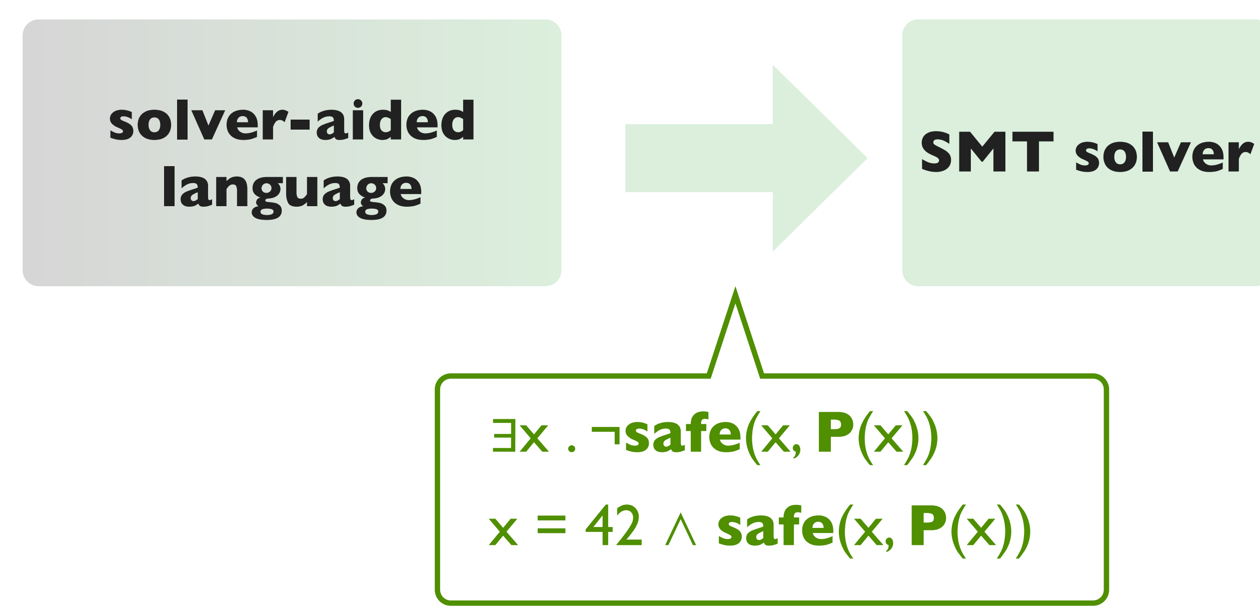


Solver-aided programming: *debug* code against spec

Find an input on which the program fails.

Localize bad parts of the program.



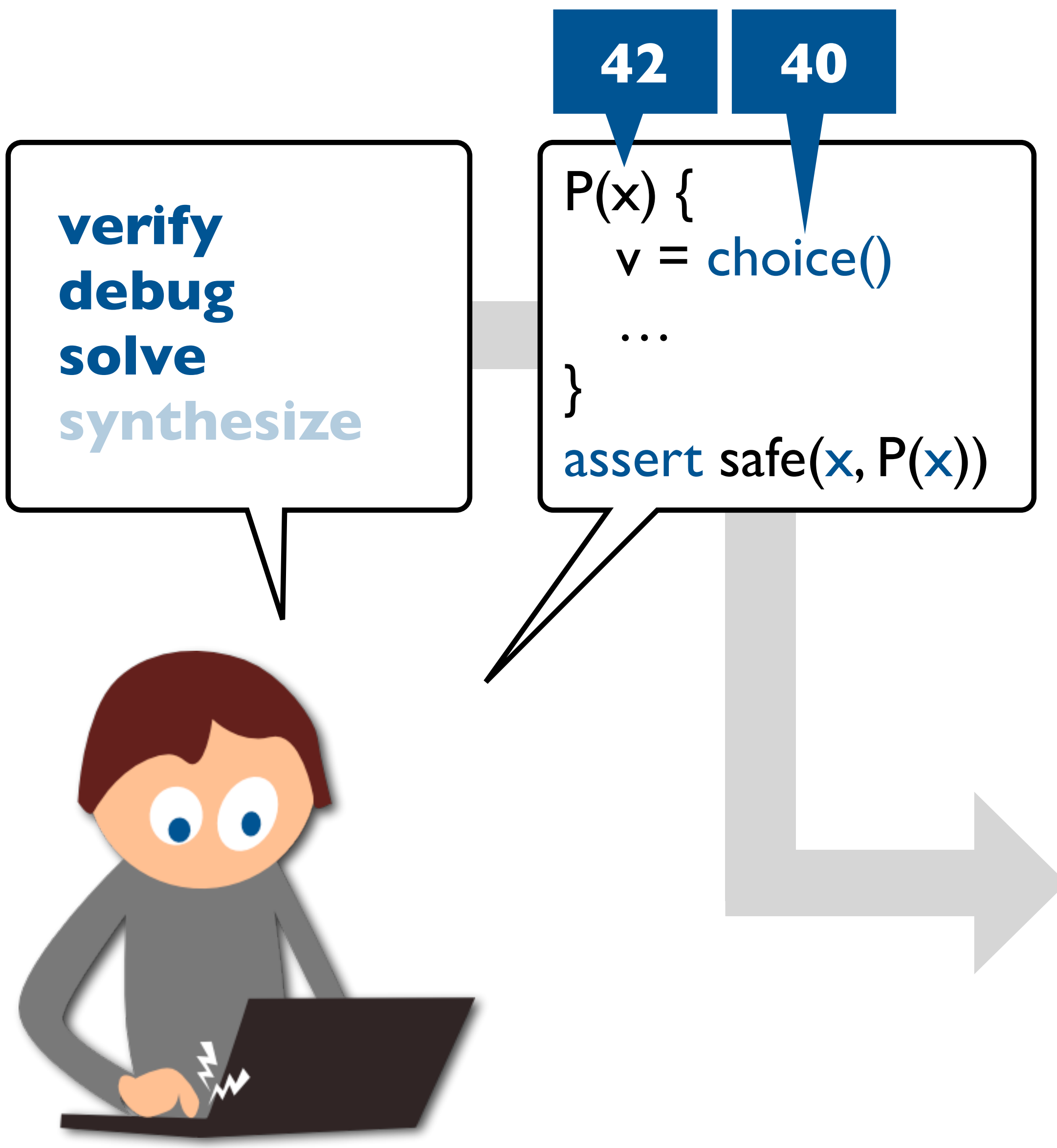


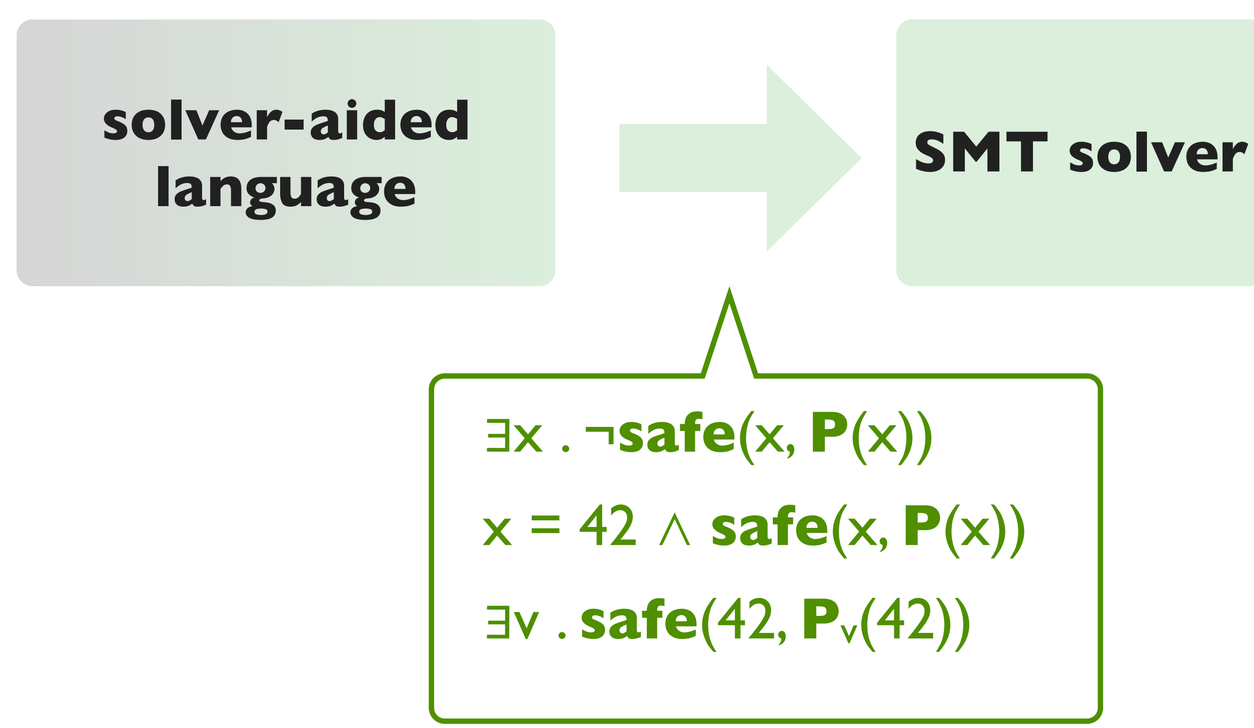
Solver-aided programming: *solve* for values from spec

Find an input on which the program fails.

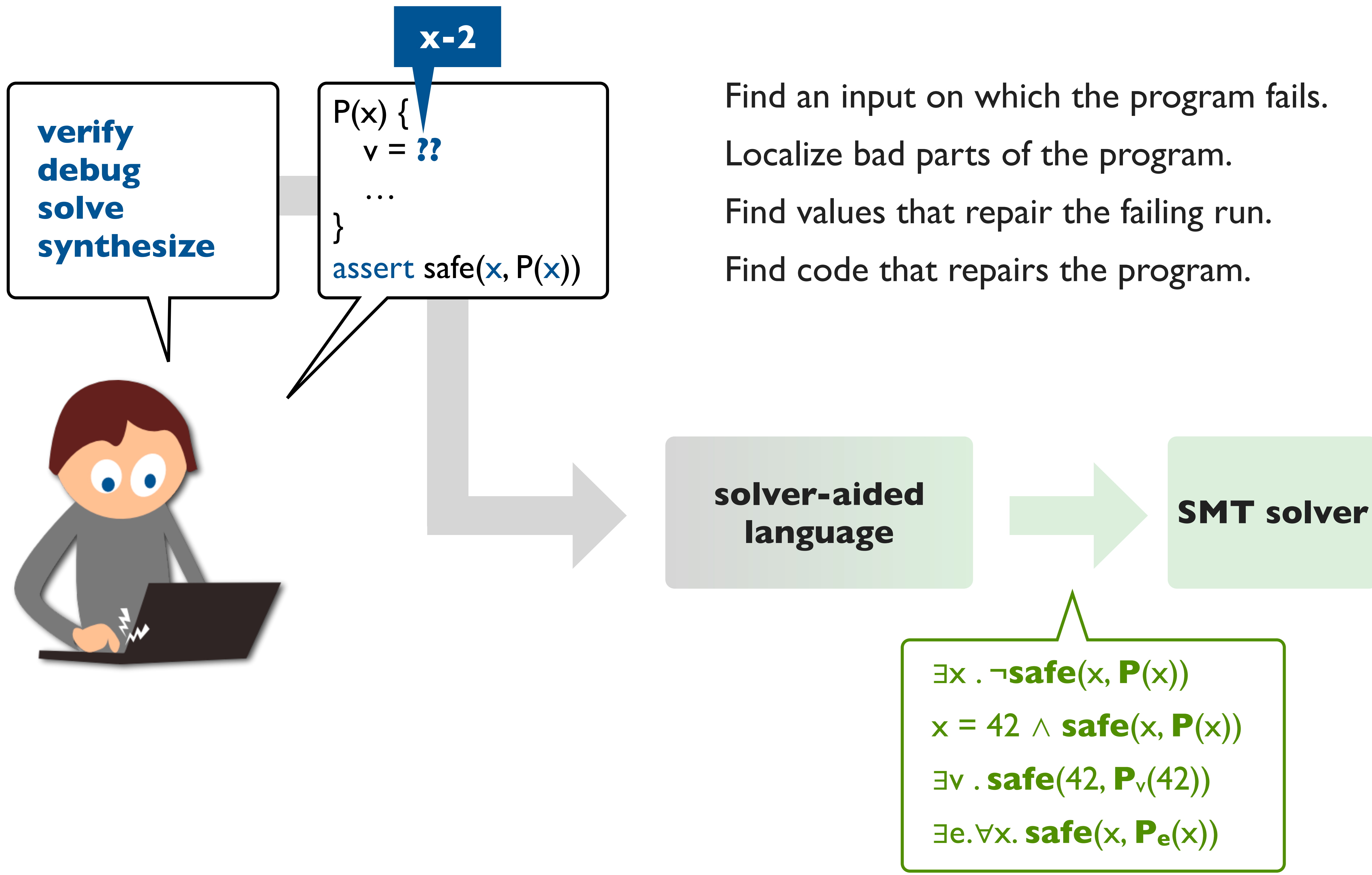
Localize bad parts of the program.

Find values that repair the failing run.





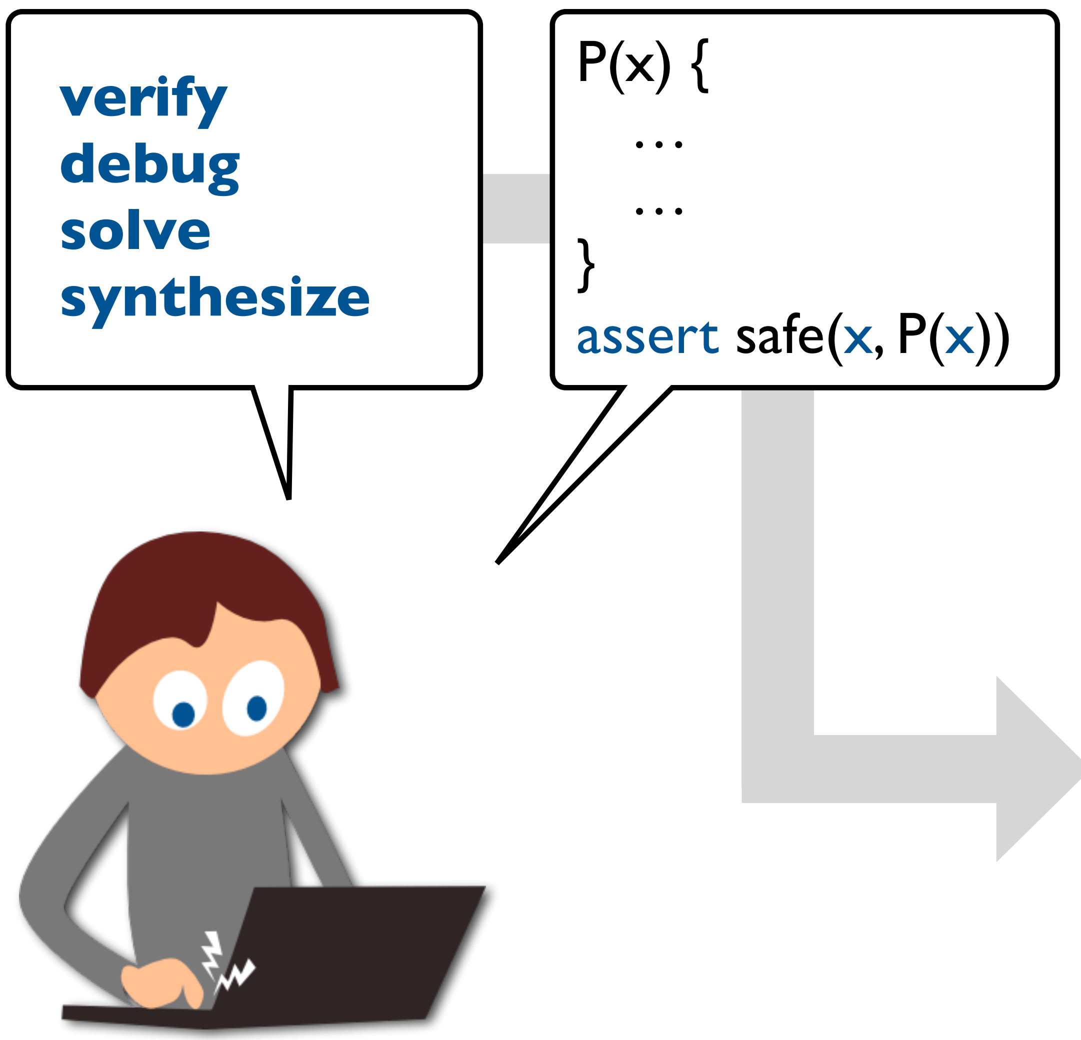
Solver-aided programming: *synthesize* code from spec

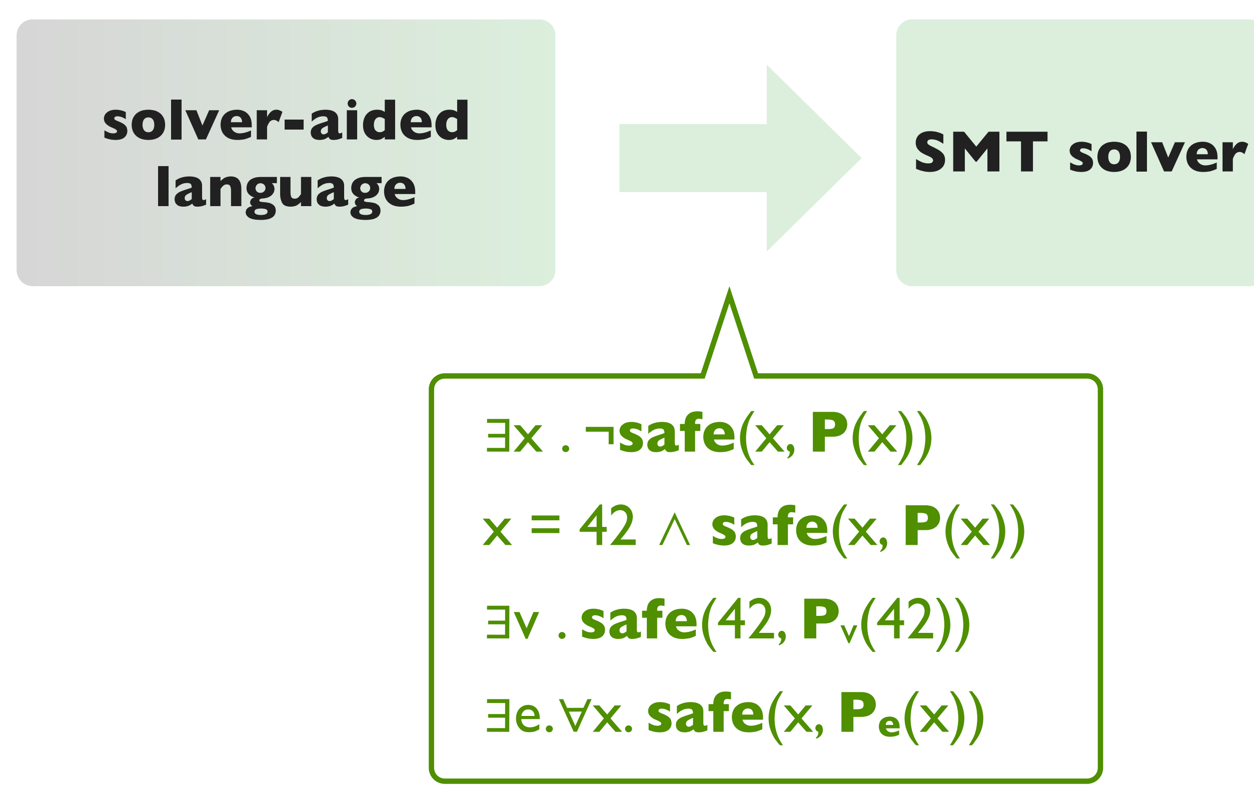


Solver-aided programming: workflow

Use **assertions** and **symbolic values** to express the specification.

Ask **queries** about program behavior (on arbitrary inputs) with respect to the specification.





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

ROSETTE

symbolic values
assertions
queries

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.

Rosette extends Racket with solver-aided constructs

= +

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

symbolic values

```
(assert expr)
```

assertions

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

queries

Rosette extends **Racket** with solver-aided constructs

"A programming language for creating new programming languages"

= +

A modern descendent of Scheme and Lisp with powerful macro-based meta programming.

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

symbolic values

```
(assert expr)
```

assertions

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

queries

Rosette extends **Racket** with solver-aided constructs

```
#lang rosette
```

=

```
#lang racket
```

+

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

symbolic values

```
(assert expr)
```

assertions

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

queries

Rosette constructs: define-symbolic

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

define-symbolic creates a fresh symbolic *constant* of the given type and binds it to the variable id.

```
> (define-symbolic x integer?)
```

Rosette constructs: define-symbolic

A type that is efficiently supported by SMT solvers: booleans, integers, reals, bitvectors, uninterpreted functions.

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

(assert expr)

(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

define-symbolic creates a fresh symbolic *constant* of the given type and binds it to the variable id.

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> (define-symbolic x integer?)
```

Rosette constructs: define-symbolic

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

define-symbolic creates a fresh symbolic *constant* of the given type and binds it to the variable id.

```
> (define-symbolic x integer?)
> (+ 1 x 2 3)
(+ 6 x)
```

Symbolic values of a given type can be used just like concrete values of that type.

Rosette constructs: define-symbolic

A type that is efficiently supported by SMT solvers: booleans, integers, reals, bitvectors, uninterpreted functions.

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

(assert expr)

(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

define-symbolic creates a fresh symbolic *constant* of the given type and binds it to the variable id.

```
> (define (same-x)
    (define-symbolic x integer?)
    x)
> (same-x)
x
> (same-x)
x
> (eq? (same-x) (same-x))
#t
```

id is bound to the *same* constant every time **define-symbolic** is evaluated.

Symbolic values of a given type can be used just like concrete values of that type.

Rosette constructs: define-symbolic*

A type that is efficiently supported by SMT solvers: booleans, integers, reals, bitvectors, uninterpreted functions.

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

define-symbolic* creates a fresh symbolic *constant* of the given type and binds it to the variable id.

```
> (define (new-x)
    (define-symbolic* x integer?)
    x)
> (new-x)
x$0
> (new-x)
x$1
> (eq? (new-x) (new-x))
(= x$2 x$3)
```

id is bound to a *different* constant every time **define-symbolic*** is evaluated.

Symbolic values of a given type can be used just like concrete values of that type.

Rosette constructs: creating complex symbolic values

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

define-symbolic(*) can be used to create *bounded* symbolic instances of complex data types.

Rosette constructs: creating complex symbolic values

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

define-symbolic(*) can be used to create *bounded* symbolic instances of complex data types.

```
> (define-symbolic* xs integer? [4])
> xs
(list xs$0 xs$1 xs$2 xs$3)
```

A concrete list of 4 symbolic integers; this is just a short-hand for evaluating **define-symbolic*** 4 times and collecting the results into a list.

Rosette constructs: creating complex symbolic values

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

define-symbolic(*) can be used to create *bounded* symbolic instances of complex data types.

```
> (define-symbolic* xs integer? [4])
> xs
(list xs$0 xs$1 xs$2 xs$3)
> (define-symbolic* len integer?)
> (take xs len)
{[(= 0 len$0) ()]
 [(= 1 len$0) (xs$0)]
 [(= 2 len$0) (xs$0 xs$1)]
 [(= 3 len$0) (xs$0 xs$1 xs$2)]}
```

A symbolic list of length up to 4, consisting of symbolic integers.

Rosette constructs: assert

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

assert checks that expr evaluates to a true value.

```
> (assert (>= 2 1)) ; passes
> (assert (< 2 1))  ; fails
assert: failed
```

Rosette constructs: assert

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

assert checks that expr evaluates to a true value.

```
> (assert (>= 2 1)) ; passes
> (assert (< 2 1))  ; fails
assert: failed
```

```
> (define-symbolic* x integer?)
> (assert (>= x 1))
```

Symbolic expr gets added to the assertion store. Its meaning (true or false) is eventually determined by the solver in response to queries.

Rosette constructs: assert

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

assert checks that expr evaluates to a true value.

```
> (assert (>= 2 1)) ; passes
> (assert (< 2 1))  ; fails
assert: failed
```

```
> (define-symbolic* x integer?)
> (assert (>= x 1))
> (asserts)
(list (<= 1 x$0) ...)
```

Symbolic expr gets added to the assertion store. Its meaning (true or false) is eventually determined by the solver in response to queries.

Rosette constructs: from assert to verify

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Do poly and fact produce the same output on all inputs?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))


; some tests ...
> (same poly fact 0)  ; pass
> (same poly fact -1) ; pass
> (same poly fact -2) ; pass
```

Rosette constructs: verify

verify searches for a binding of symbolic constants to concrete values that causes at least one assertion in expr to fail.

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Do poly and fact produce the same output on all inputs?

```
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(define (same p f x)
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; some tests ...
> (same poly fact 0)  ; pass
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> (same poly fact -2) ; pass
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Rosette constructs: verify

verify searches for a binding of symbolic constants to concrete values that causes at least one assertion in expr to fail.

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Do poly and fact produce the same output on all inputs?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (define-symbolic i integer?)
> (verify (same poly fact i)))
```

Rosette constructs: verify

verify searches for a binding of symbolic constants to concrete values that causes at least one assertion in expr to fail.

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

No! The solver finds a concrete *counterexample* to the assertion in same.

Do poly and fact produce the same output on all inputs?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (define-symbolic i integer?)
> (verify (same poly fact i)))
(model [i -6])
```

Rosette constructs: verify

verify searches for a binding of symbolic constants to concrete values that causes at least one assertion in expr to fail.

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

We can store bindings in variables and evaluate arbitrary expressions against them.

Do poly and fact produce the same output on all inputs?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (define-symbolic i integer?)
> (define cex
    (verify (same poly fact i)))
> (evaluate i cex)
-6
```

Rosette constructs: verify

verify searches for a binding of symbolic constants to concrete values that causes at least one assertion in expr to fail.

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

The assertions encountered while evaluating expr are removed from the asserts store once a query (such as **verify**) completes.

Do poly and fact produce the same output on all inputs?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (define-symbolic i integer?)
> (define cex
    (verify (same poly fact i)))
> (asserts)
(list)
```

Rosette constructs: from verify to debug

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Why do poly and fact output different values on the input -6?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))
```

Rosette constructs: from verify to debug

debug searches for a minimal set of expressions of the given types that cause the evaluation of expr to fail.

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Why do `poly` and `fact` output different values on the input -6?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))
```

Rosette constructs: debug

debug searches for a minimal set of expressions of the given types that cause the evaluation of expr to fail.

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

To use **debug**, require the debugging libraries, mark fact as the candidate for debugging, save the module to a file, and issue a **debug** query.

Why do poly and fact output different values on the input -6?

```
(require rosette/query/debug
         rosette/lib/render)

(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define/debug (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))
```

```
> (render ; visualize the result
   (debug [integer?]
     (same poly fact -6)))
```

Rosette constructs: debug

debug searches for a minimal set of expressions of the given types that cause the evaluation of expr to fail.

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

To use **debug**, require the debugging libraries, mark `fact` as the candidate for debugging, save the module to a file, and issue a **debug** query.

Why do `poly` and `fact` output different values on the input -6?

```
(require rosette/query/debug
         rosette/lib/render)

(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define/debug (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (render ; visualize the result
   (debug [integer?]
     (same poly fact -6)))
```

Rosette constructs: from debug to solve

Can we repair `fact` on the input -6 as suggested by **debug**?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))
```

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Rosette constructs: from debug to solve

solve searches for a binding of symbolic constants to concrete values that causes all assertions in expr to pass.

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Can we repair `fact` on the input -6 as suggested by **debug**?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* x (+ x 1) (+ x 2) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))
```

Rosette constructs: solve

solve searches for a binding of symbolic constants to concrete values that causes all assertions in expr to pass.

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Can we repair fact on the input -6 as suggested by **debug**?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (define-symbolic* c1 c2 c3 integer?)
 (* (+ x c1) (+ x 1) (+ x c2) (+ x c3)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (solve (same poly fact -6))
```

Rosette constructs: solve

solve searches for a binding of symbolic constants to concrete values that causes all assertions in expr to pass.

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Yes! The solver finds concrete values for c1, c2, and c3 that work for the input -6.

Can we repair fact on the input -6 as suggested by **debug**?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (define-symbolic* c1 c2 c3 integer?)
 (* (+ x c1) (+ x 1) (+ x c2) (+ x c3)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (solve (same poly fact -6))
(model [c1$0 -66] [c2$0 7] [c3$0 7])
```

Rosette constructs: solve many with define-symbolic*

solve searches for a binding of symbolic constants to concrete values that causes all assertions in expr to pass.

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Solving same for multiple inputs: note the behavior of **define-symbolic***.

Can we repair fact on multiple inputs individually?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (define-symbolic* c1 c2 c3 integer?)
 (* (+ x c1) (+ x 1) (+ x c2) (+ x c3)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (solve (begin
          (same poly fact -6)
          (same poly fact 12)))
(model [c1$1 -66] [c2$1 7] [c3$1 7]
       [c1$2 2508] [c2$2 -11] [c3$2 -11])
```

Rosette constructs: solve many with define-symbolic

solve searches for a binding of symbolic constants to concrete values that causes all assertions in expr to pass.

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Solving same for multiple inputs: note the behavior of **define-symbolic**.

Can we repair fact on multiple inputs simultaneously?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (define-symbolic c1 c2 c3 integer?)
 (* (+ x c1) (+ x 1) (+ x c2) (+ x c3)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (solve (begin
           (same poly fact -6)
           (same poly fact 12)))
(model [c1 2] [c2 3] [c3 0])
```

Rosette constructs: from solve to synthesize

Can we repair `fact` on all inputs as suggested by **solve**?

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (define-symbolic c1 c2 c3 integer?)
 (* (+ x c1) (+ x 1) (+ x c2) (+ x c3)))

(define (same p f x)
 (assert (= (p x) (f x))))
```

Rosette constructs: synthesize

synthesize searches for a binding that causes all assertions in **#:guarantee** expr to pass for all bindings of the symbolic constants in the **#:forall** expr.

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Can we repair fact on all inputs as suggested by **solve**?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (define-symbolic c1 c2 c3 integer?)
 (* (+ x c1) (+ x 1) (+ x c2) (+ x c3)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (define-symbolic* i integer?)
> (synthesize
   #:forall i
   #:guarantee (same poly fact i))
```

Rosette constructs: synthesize

synthesize searches for a binding that causes all assertions in **#:guarantee** expr to pass for all bindings of the symbolic constants in the **#:forall** expr.

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

Yes! The solver finds concrete values for c1, c2, and c3 that work for every input i.

Can we repair fact on all inputs as suggested by **solve**?

```
(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (define-symbolic c1 c2 c3 integer?)
 (* (+ x c1) (+ x 1) (+ x c2) (+ x c3)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (define-symbolic* i integer?)
> (synthesize
   #:forall i
   #:guarantee (same poly fact i))
(model [c1 3] [c2 0] [c3 2])
```

Rosette constructs: synthesize

synthesize searches for a binding that causes all assertions in **#:guarantee** expr to pass for all bindings of the symbolic constants in the **#:forall** expr.

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

To generate code, require the sketching library, save the module to a file, and issue a **synthesize** query.

Can we repair fact on all inputs as suggested by **solve**?

```
(require rosette/lib/synthax)

(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* (+ x (??)) (+ x 1) (+ x (??)) (+ x (??))))

(define (same p f x)
 (assert (= (p x) (f x))))


> (define-symbolic* i integer?)
> (print-forms ; print the generated code
   (synthesize
    #:forall i
    #:guarantee (same poly fact i)))
```

Rosette constructs: synthesize

synthesize searches for a binding that causes all assertions in **#:guarantee** expr to pass for all bindings of the symbolic constants in the **#:forall** expr.

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

```
(assert expr)
```

```
(verify expr)
(debug [type ...+] expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

To generate code, require the sketching library, save the module to a file, and issue a **synthesize** query.

Can we repair fact on all inputs as suggested by **solve**?

```
(require rosette/lib/synthax)

(define (poly x)
 (+ (* x x x x) (* 6 x x x)
    (* 11 x x) (* 6 x)))

(define (fact x)
 (* (+ x 3) (+ x 1) (+ x 0) (+ x 2)))

(define (same p f x)
 (assert (= (p x) (f x))))


> (define-symbolic* i integer?)
> (print-forms ; print the generated code
   (synthesize
    #:forall i
    #:guarantee (same poly fact i)))
```

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.

Common pitfalls and gotchas

Reasoning precision

Unbounded loops

Unsafe features

"A gotcha is a valid construct in a system, program or programming language that works as documented but is counter-intuitive and almost invites mistakes because it is both easy to invoke and unexpected or unreasonable in its outcome."

—*Wikipedia*

Common pitfalls and gotchas: reasoning precision

Reasoning precision

Unbounded loops

Unsafe features

- Determines if integers and reals are approximated using k-bit words or treated as infinite-precision values.
- Controlled by setting `current-bitwidth` to an integer k > 0 or #f for approximate or precise reasoning, respectively.

Common pitfalls and gotchas: reasoning precision

Reasoning precision

Unbounded loops

Unsafe features

- Determines if integers and reals are approximated using k-bit words or treated as infinite-precision values.
- Controlled by setting `current-bitwidth` to an integer k > 0 or #f for approximate or precise reasoning, respectively.

```
; default current-bitwidth is #f
> (define-symbolic x integer?)
> (solve (assert (= x 64)))
```

Common pitfalls and gotchas: reasoning precision

Reasoning precision

Unbounded loops

Unsafe features

- Determines if integers and reals are approximated using k-bit words or treated as infinite-precision values.
- Controlled by setting `current-bitwidth` to an integer k > 0 or #f for approximate or precise reasoning, respectively.

```
; default current-bitwidth is #f
> (define-symbolic x integer?)
> (solve (assert (= x 64)))
(model [x 64])
```

Common pitfalls and gotchas: reasoning precision

Reasoning precision

Unbounded loops

Unsafe features

- Determines if integers and reals are approximated using k-bit words or treated as infinite-precision values.
- Controlled by setting `current-bitwidth` to an integer k > 0 or #f for approximate or precise reasoning, respectively.

```
; default current-bitwidth is #f
> (define-symbolic x integer?)
> (solve (assert (= x 64)))
(model [x 64])
> (verify (assert (not (= x 64))))
```

Common pitfalls and gotchas: reasoning precision

Reasoning precision

Unbounded loops

Unsafe features

- Determines if integers and reals are approximated using k-bit words or treated as infinite-precision values.
- Controlled by setting `current-bitwidth` to an integer k > 0 or #f for approximate or precise reasoning, respectively.

```
; default current-bitwidth is #f
> (define-symbolic x integer?)
> (solve (assert (= x 64)))
(model [x 64])
> (verify (assert (not (= x 64))))
(model [x 64])
```

Common pitfalls and gotchas: reasoning precision

Reasoning precision

Unbounded loops

Unsafe features

- Determines if integers and reals are approximated using k-bit words or treated as infinite-precision values.
- Controlled by setting `current-bitwidth` to an integer k > 0 or #f for approximate or precise reasoning, respectively.

```
; default current-bitwidth is #f
> (define-symbolic x integer?)
> (solve (assert (= x 64)))
(model [x 64])
> (verify (assert (not (= x 64))))
(model [x 64])

> (current-bitwidth 5)
> (solve (assert (= x 64)))
```

Common pitfalls and gotchas: reasoning precision

Reasoning precision

Unbounded loops

Unsafe features

- Determines if integers and reals are approximated using k-bit words or treated as infinite-precision values.
- Controlled by setting `current-bitwidth` to an integer k > 0 or #f for approximate or precise reasoning, respectively.

```
; default current-bitwidth is #f
> (define-symbolic x integer?)
> (solve (assert (= x 64)))
(model [x 64])
> (verify (assert (not (= x 64))))
(model [x 64])

> (current-bitwidth 5)
> (solve (assert (= x 64)))
(model [x 0])
> (verify (assert (not (= x 64))))
(model [x 0])
```

Common pitfalls and gotchas: unbounded loops

Reasoning precision

Unbounded loops

Unsafe features

- Loops and recursion must be *bounded* (aka *self-finitizing*) by
  - concrete termination conditions, or
  - upper bounds on size of iterated (symbolic) data structures.
- Unbounded loops and recursion run forever.

Common pitfalls and gotchas: unbounded loops

Reasoning precision

Unbounded loops

Unsafe features

- Loops and recursion must be *bounded* (aka *self-finitizing*) by
  - concrete termination conditions, or
  - upper bounds on size of iterated (symbolic) data structures.
- Unbounded loops and recursion run forever.

```
(define (search x xs)
  (cond
    [(null? xs) #f]
    [(equal? x (car xs)) #t]
    [else (search x (cdr xs))]))

> (define-symbolic xs integer? [5])
> (define-symbolic xl i integer?)
> (define ys (take xs xl))
> (verify
   (when (<= 0 i (- xl 1))
     (assert (search (list-ref ys i) ys))))
```

Common pitfalls and gotchas: unbounded loops

Reasoning precision

Unbounded loops

Unsafe features

- Loops and recursion must be *bounded* (aka *self-finitizing*) by
  - concrete termination conditions, or
  - upper bounds on size of iterated (symbolic) data structures.
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```
(define (search x xs)
  (cond
    [(null? xs) #f]
    [(equal? x (car xs)) #t]
    [else (search x (cdr xs))]))

> (define-symbolic xs integer? [5])
> (define-symbolic xl i integer?)
> (define ys (take xs xl))
> (verify
   (when (<= 0 i (- xl 1))
     (assert (search (list-ref ys i) ys))))
(unsat)
```

Terminates because `search` iterates over a bounded structure.

Common pitfalls and gotchas: unbounded loops

Reasoning precision

Unbounded loops

Unsafe features

- Loops and recursion must be *bounded* (aka *self-finitizing*) by
  - concrete termination conditions, or
  - upper bounds on size of iterated (symbolic) data structures.
- Unbounded loops and recursion run forever.

```
(define (factorial n)
  (cond
    [(= n 0) 1]
    [else (* n (factorial (- n 1)))]))
```

Common pitfalls and gotchas: unbounded loops

Reasoning precision

Unbounded loops

Unsafe features

- Loops and recursion must be *bounded* (aka *self-finitizing*) by
  - concrete termination conditions, or
  - upper bounds on size of iterated (symbolic) data structures.
- Unbounded loops and recursion run forever.

```
(define (factorial n)
  (cond
    [(= n 0) 1]
    [else (* n (factorial (- n 1)))]))

> (define-symbolic k integer?)
> (solve
    (assert (> (factorial k) 10)))
```

Common pitfalls and gotchas: unbounded loops

Reasoning precision

Unbounded loops

Unsafe features

- Loops and recursion must be *bounded* (aka *self-finitizing*) by
  - concrete termination conditions, or
  - upper bounds on size of iterated (symbolic) data structures.
- Unbounded loops and recursion run forever.

```
(define (factorial n)
  (cond
    [(= n 0) 1]
    [else (* n (factorial (- n 1)))]))

> (define-symbolic k integer?)
> (solve
    (assert (> (factorial k) 10)))
```

Unbounded because `factorial` termination depends on k.

Common pitfalls and gotchas: unbounded loops

Reasoning precision

Unbounded loops

Unsafe features

- Loops and recursion must be *bounded* (aka *self-finitizing*) by
  - concrete termination conditions, or
  - upper bounds on size of iterated (symbolic) data structures.
- Unbounded loops and recursion run forever.

Bound the recursion with a concrete guard.

```
(define (factorial n g)
  (assert (>= g 0))
  (cond
    [(= n 0) 1]
    [else (* n (factorial (- n 1) (- g 1)))]))
```

Common pitfalls and gotchas: unbounded loops

Reasoning precision

Unbounded loops

Unsafe features

- Loops and recursion must be *bounded* (aka *self-finitizing*) by
  - concrete termination conditions, or
  - upper bounds on size of iterated (symbolic) data structures.
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Bound the recursion with a concrete guard.

```
(define (factorial n g)
  (assert (>= g 0))
  (cond
    [(= n 0) 1]
    [else (* n (factorial (- n 1) (- g 1)))]))

> (define-symbolic k integer?)
> (solve
    (assert (> (factorial k 3) 10)))
```

Common pitfalls and gotchas: unbounded loops

Reasoning precision

Unbounded loops

Unsafe features

- Loops and recursion must be *bounded* (aka *self-finitizing*) by
  - concrete termination conditions, or
  - upper bounds on size of iterated (symbolic) data structures.
- Unbounded loops and recursion run forever.

Bound the recursion with a concrete guard.

```
(define (factorial n g)
  (assert (>= g 0))
  (cond
    [(= n 0) 1]
    [else (* n (factorial (- n 1) (- g 1)))]))

> (define-symbolic k integer?)
> (solve
    (assert (> (factorial k 3) 10)))

(unsat)
```

UNSAT because the bound is too small to find a solution.

Common pitfalls and gotchas: unbounded loops

Reasoning precision

Unbounded loops

Unsafe features

- Loops and recursion must be *bounded* (aka *self-finitizing*) by
  - concrete termination conditions, or
  - upper bounds on size of iterated (symbolic) data structures.
- Unbounded loops and recursion run forever.

Bound the recursion with a concrete guard.

```
(define (factorial n g)
  (assert (>= g 0))
  (cond
    [(= n 0) 1]
    [else (* n (factorial (- n 1) (- g 1)))]))

> (define-symbolic k integer?)
> (solve
    (assert (> (factorial k 4) 10)))

(model
  [k 4])
```

Make sure the bound is large enough …

Common pitfalls and gotchas: unsafe features

Reasoning precision

Unbounded loops

Unsafe features

- Rosette *lifts* only a core subset of Racket to operate on symbolic values. This includes all constructs in `#lang rosette/safe`
- Unlifted constructs can be used in `#lang rosette` but require care: the programmer must determine when it is okay for symbolic values to flow to unlifted code.

Common pitfalls and gotchas: unsafe features

Reasoning precision

Unbounded loops

Unsafe features

- Rosette *lifts* only a core subset of Racket to operate on symbolic values. This includes all constructs in `#lang rosette/safe`
- Unlifted constructs can be used in `#lang rosette` but require care: the programmer must determine when it is okay for symbolic values to flow to unlifted code.

```
; vectors are lifted
> (define v (vector 1 2))
> (define-symbolic k integer?)
> (vector-ref v k)
```

Common pitfalls and gotchas: unsafe features

Reasoning precision

Unbounded loops

Unsafe features

- Rosette *lifts* only a core subset of Racket to operate on symbolic values. This includes all constructs in `#lang rosette/safe`
- Unlifted constructs can be used in `#lang rosette` but require care: the programmer must determine when it is okay for symbolic values to flow to unlifted code.

```
; vectors are lifted
> (define v (vector 1 2))
> (define-symbolic k integer?)
> (vector-ref v k)
(ite* (⊢ (= 0 k) 1) (⊢ (= 1 k) 2)))
```

Common pitfalls and gotchas: unsafe features

Reasoning precision

Unbounded loops

Unsafe features

- Rosette *lifts* only a core subset of Racket to operate on symbolic values. This includes all constructs in `#lang rosette/safe`
- Unlifted constructs can be used in `#lang rosette` but require care: the programmer must determine when it is okay for symbolic values to flow to unlifted code.

```
; vectors are lifted
> (define v (vector 1 2))
> (define-symbolic k integer?)
> (vector-ref v k)
(ite* (⊢ (= 0 k) 1) (⊢ (= 1 k) 2)))

; hashes are unlifted
> (define h (make-hash '((0 . 1)(1 . 2))))
> (hash-ref h k)
```

Common pitfalls and gotchas: unsafe features

Reasoning precision

Unbounded loops

Unsafe features

- Rosette *lifts* only a core subset of Racket to operate on symbolic values. This includes all constructs in `#lang rosette/safe`
- Unlifted constructs can be used in `#lang rosette` but require care: the programmer must determine when it is okay for symbolic values to flow to unlifted code.

```
; vectors are lifted
> (define v (vector 1 2))
> (define-symbolic k integer?)
> (vector-ref v k)
(ite* (⊢ (= 0 k) 1) (⊢ (= 1 k) 2)))

; hashes are unlifted
> (define h (make-hash '((0 . 1)(1 . 2))))
> (hash-ref h k)
hash-ref: no value found for key
  key: k
```

Common pitfalls and gotchas: unsafe features

Reasoning precision

Unbounded loops

Unsafe features

- Rosette *lifts* only a core subset of Racket to operate on symbolic values. This includes all constructs in `#lang rosette/safe`
- Unlifted constructs can be used in `#lang rosette` but require care: the programmer must determine when it is okay for symbolic values to flow to unlifted code.

```
; vectors are lifted
> (define v (vector 1 2))
> (define-symbolic k integer?)
> (vector-ref v k)
(ite* (⊢ (= 0 k) 1) (⊢ (= 1 k) 2)))

; hashes are unlifted
> (define h (make-hash '((0 . 1)(1 . 2))))
> (hash-ref h k)
hash-ref: no value found for key
  key: k
> (hash-set! h k 3)
> (hash-ref h k)
```

Common pitfalls and gotchas: unsafe features

Reasoning precision

Unbounded loops

Unsafe features

- Rosette *lifts* only a core subset of Racket to operate on symbolic values. This includes all constructs in `#lang rosette/safe`
- Unlifted constructs can be used in `#lang rosette` but require care: the programmer must determine when it is okay for symbolic values to flow to unlifted code.

```
; vectors are lifted
> (define v (vector 1 2))
> (define-symbolic k integer?)
> (vector-ref v k)
(ite* (⊢ (= 0 k) 1) (⊢ (= 1 k) 2)))

; hashes are unlifted
> (define h (make-hash '((0 . 1)(1 . 2))))
> (hash-ref h k)
hash-ref: no value found for key
  key: k
> (hash-set! h k 3)
> (hash-ref h k)
3
```

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

ROSETTE

emina.github.io/rosette/

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