Computer-Aided Reasoning for Software

CSE507

Solver-Aided Programming I

Topics

What is this course about?

Course logistics

Getting started with solver-aided programming!

welcome

about

Tools for building better software, more easily

more reliable,
efficient, secure

Tools for building **better software**, more easily

Tools for building **better software**, more easily

automated verification and synthesis based on satisfiability solvers

"solver-aided tools"

goal

By the end of this course, you'll be able to build solver-aided tools for any domain!

biology

systems

education

security

hardware

databases

networking

low-power computing

high-performance computing

logistics

Topics, structure, people

People

Zachary Tatlock
PLSE
CSE 201

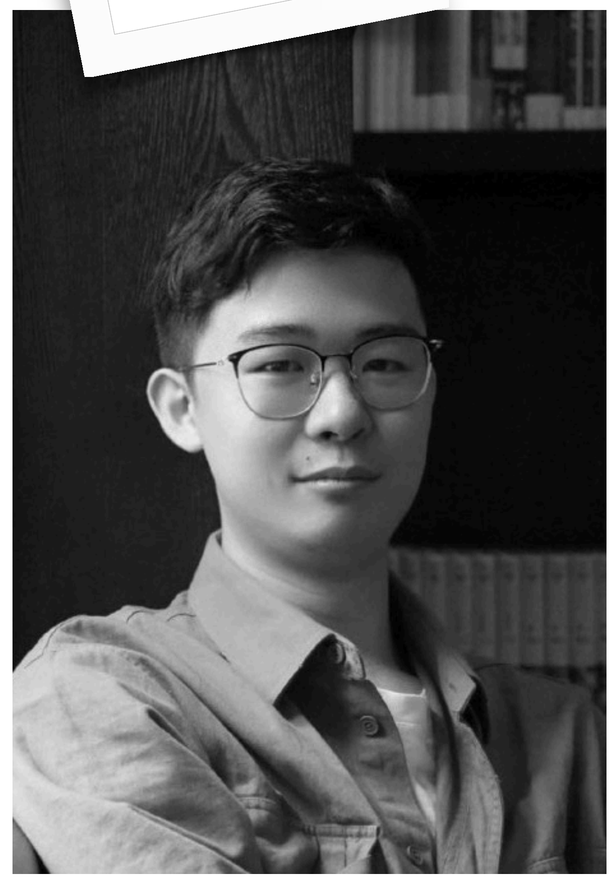
Sirui Lu
PLSE
OH TBD

People

Instructor

Zachary Tatlock
PLSE
CSE 201

TA



Sirui Lu
PLSE
OH TBD

Students!

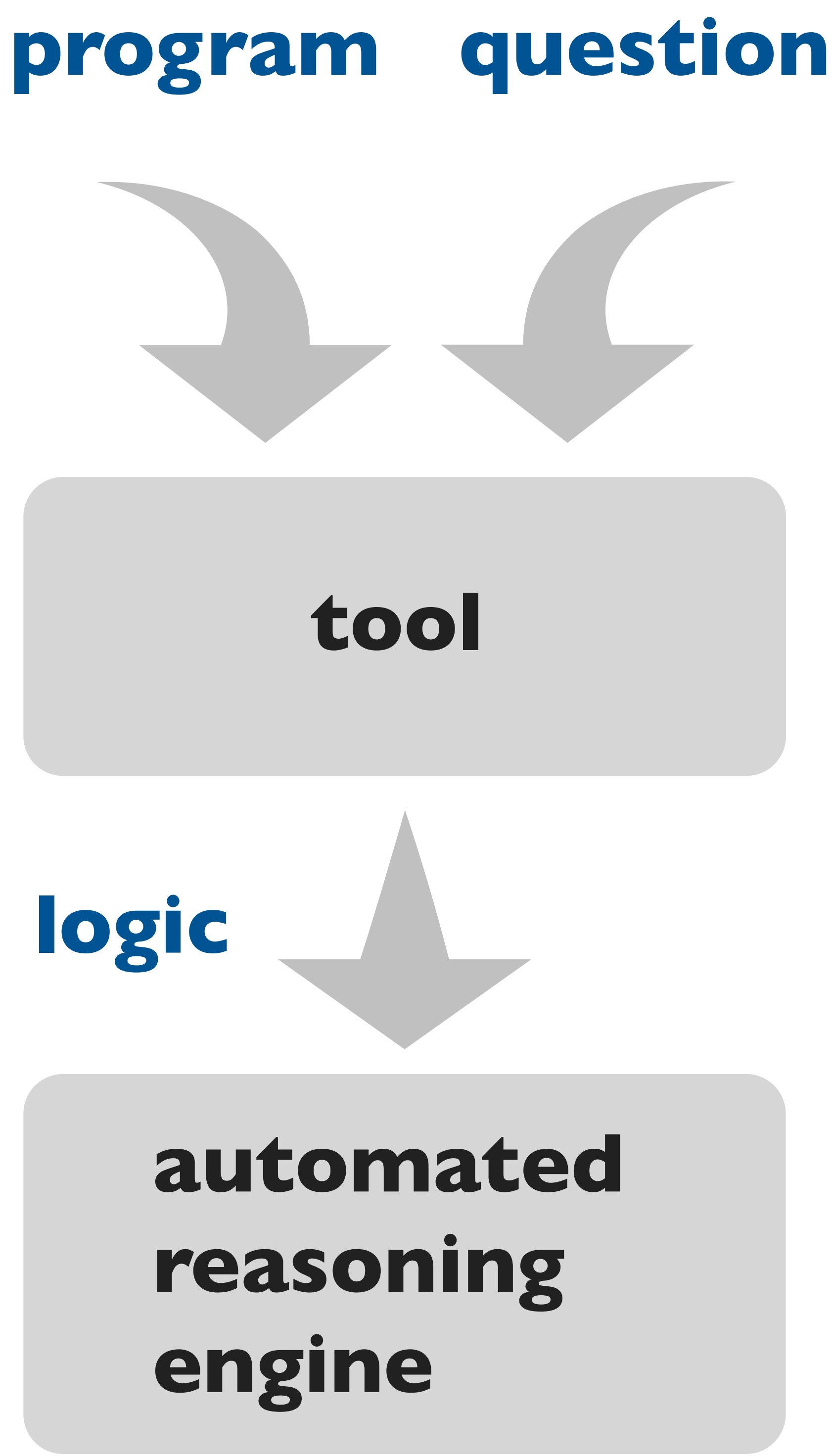
Your name
Research area

People

The Creator

Emina Torlak
PLSE → AWS

Course overview



Course overview

program **question**

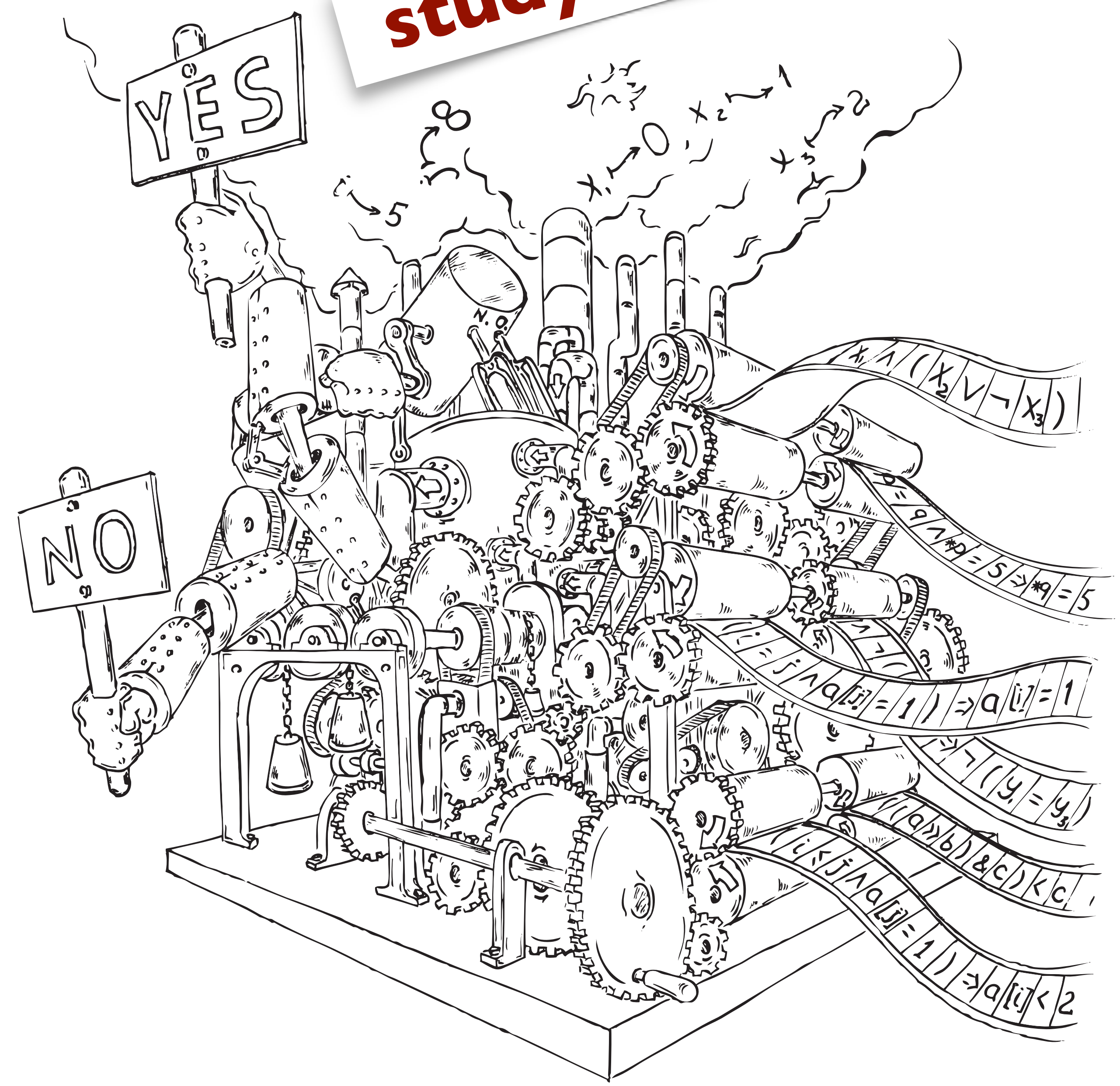
verifier, synthesizer

build! (part II)

logic

SAT, SMT, model finders

study (part I)



Drawing from "Decision Procedures" by Kroening & Strichman

Grading

3 homework assignments (75%)

- conceptual problems & proofs (TeX)
- implementations (Racket, Dafny, Alloy)
- completed with a partner ("whiteboard discussion" w/ others OK)

Course project (25%)

- build a computer-aided reasoning tool for a domain of your choice
- teams of 2-3 people
- see the course web page for timeline, deliverables and other details

study (part I)

build! (part II)

Reading and references

Recommended readings posted on the course web page

- Complete each reading before the lecture for which it is assigned
- If multiple papers are listed, only the first is required reading

Recommended text books

- Bradley & Manna, The Calculus of Computation
- Kroening & Strichman, Decision Procedures

Advice for doing well in 507

Come to class (prepared)

- Lecture slides are enough to teach from, but not enough to learn from

Participate

- Ask and answer questions

Meet deadlines

- Turn homework in on time
- Start homework and project sooner than you think you need to
- Follow instructions for submitting code (we have to be able to run it)
- No proof should be longer than a page (most are ~1 paragraph)

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

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.

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

ROSETTE

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

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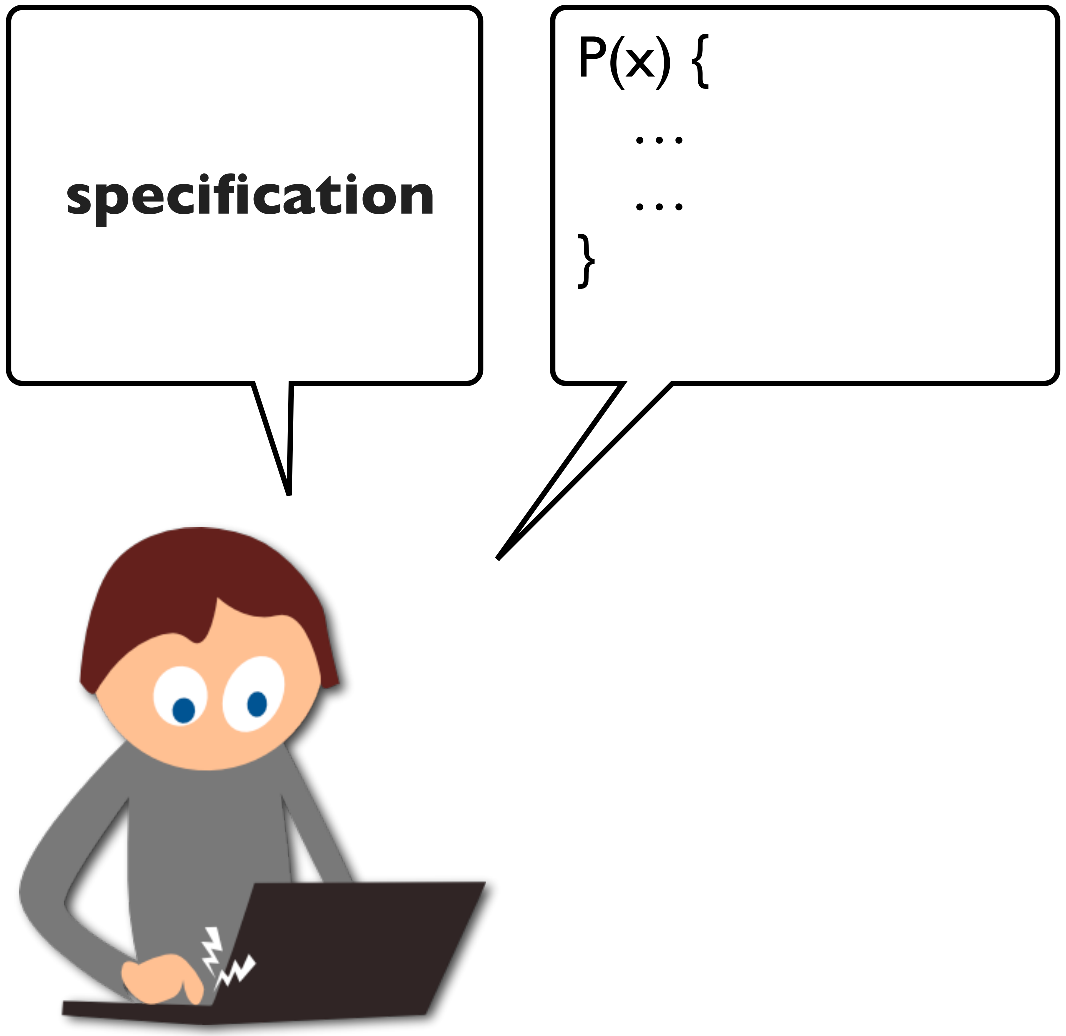
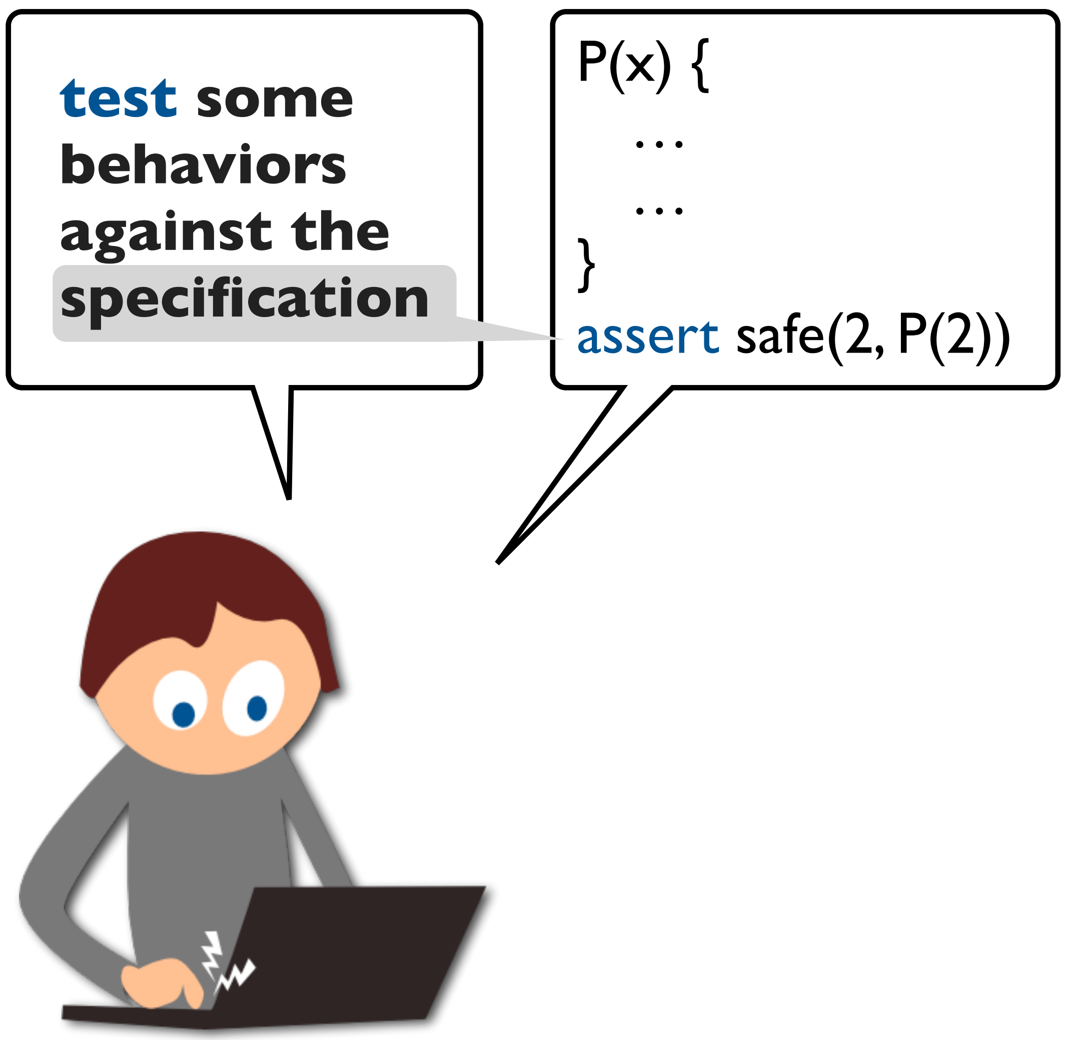
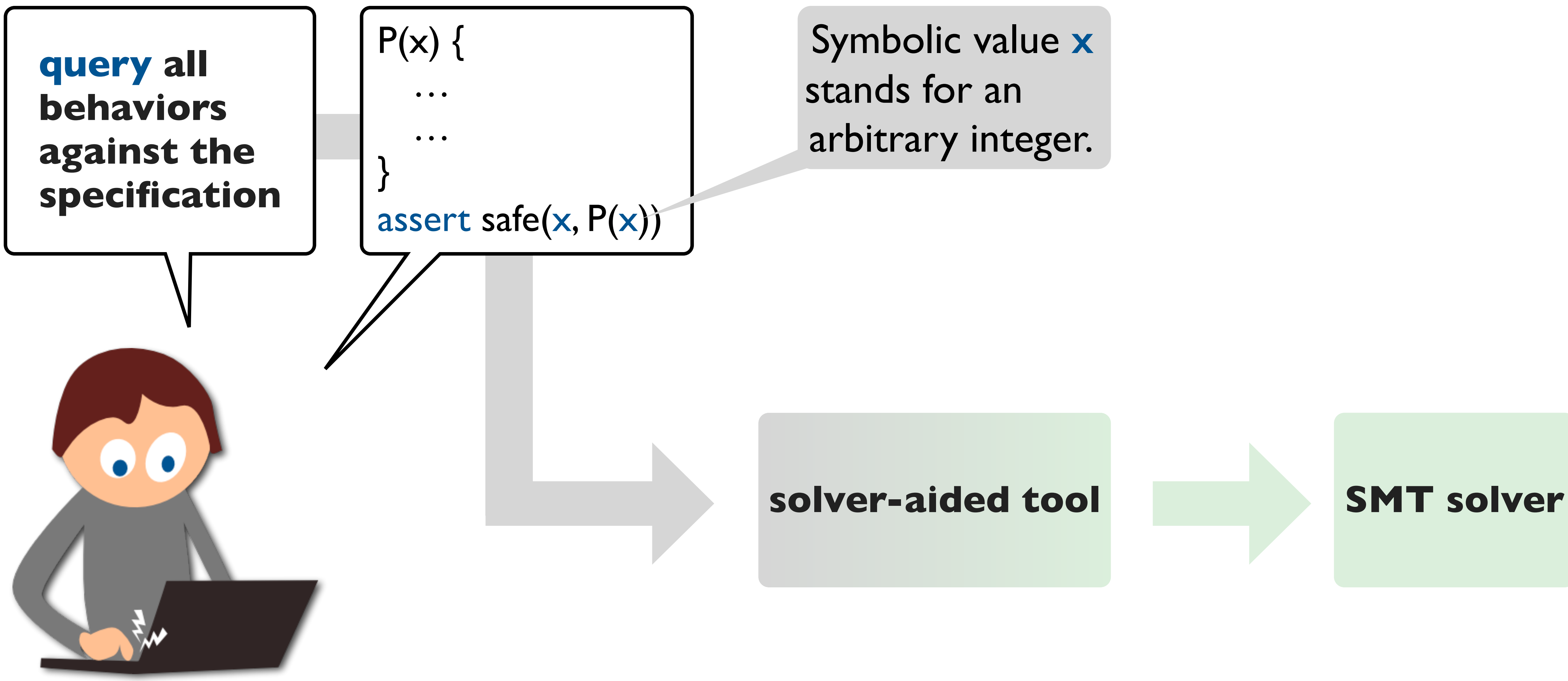
Classic programming: from spec to code



Classic programming: test behaviors

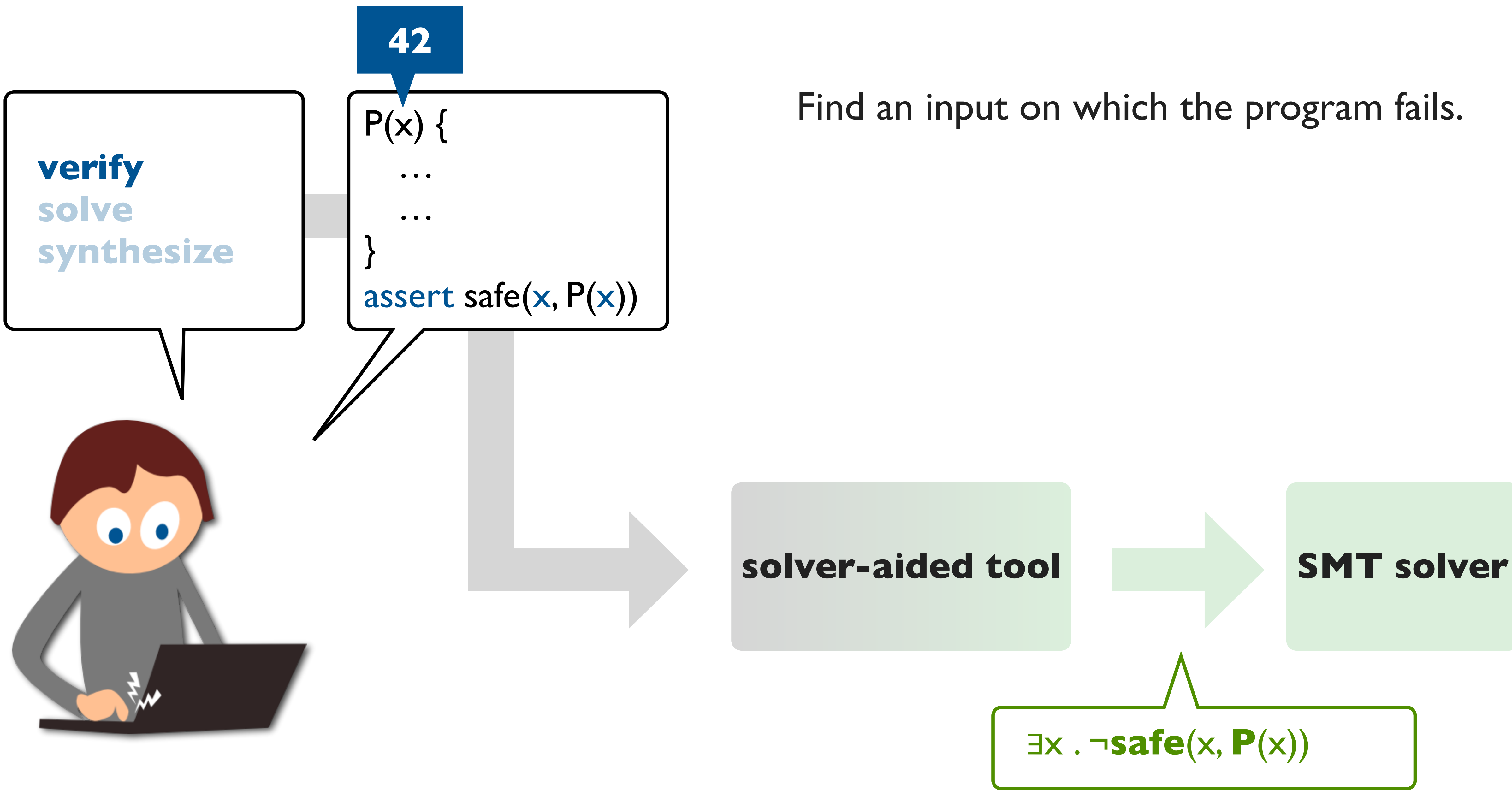


Solver-aided programming: *query* behaviors



Solver-aided programming: verify

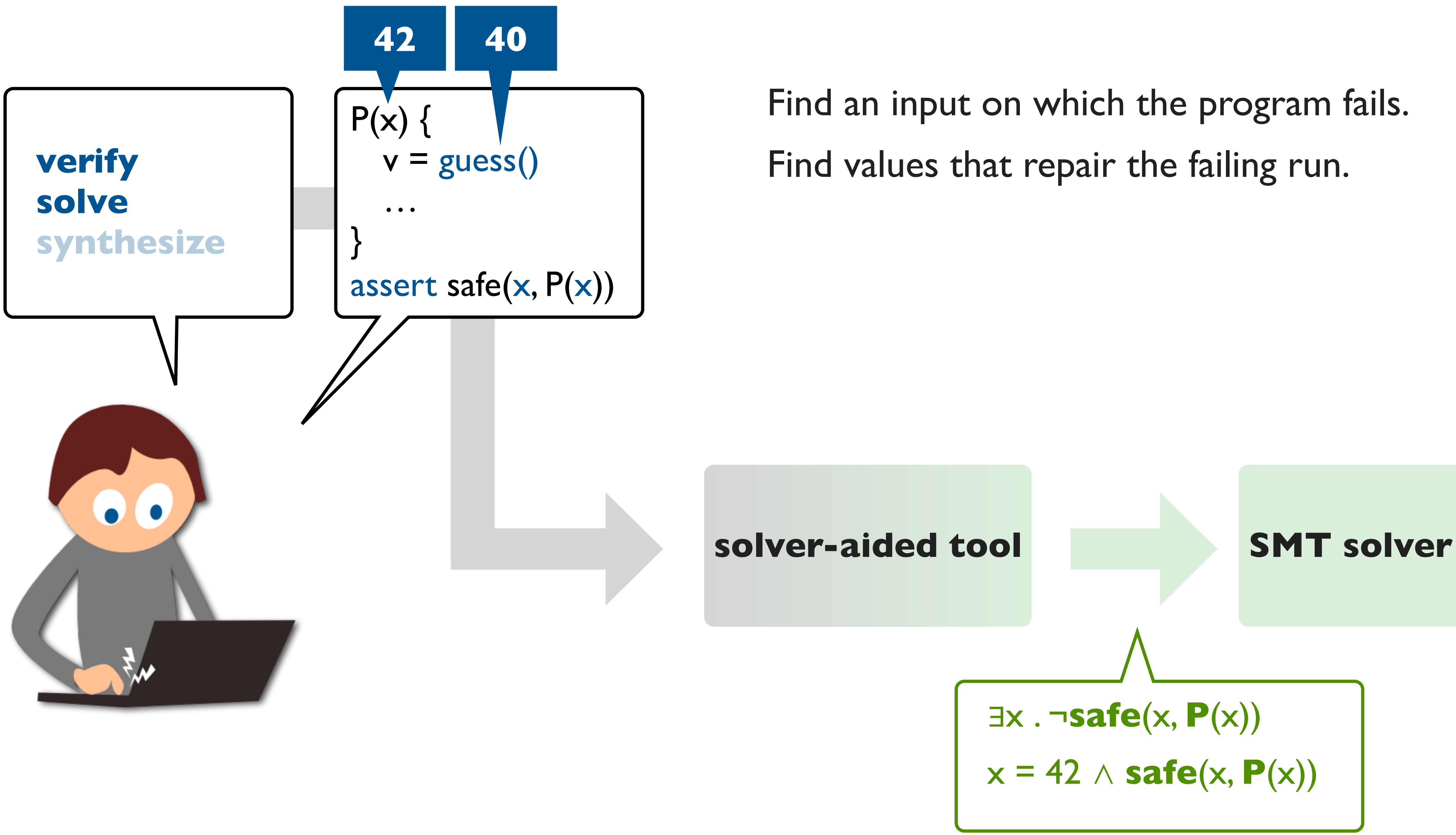
Find an input on which the program fails.



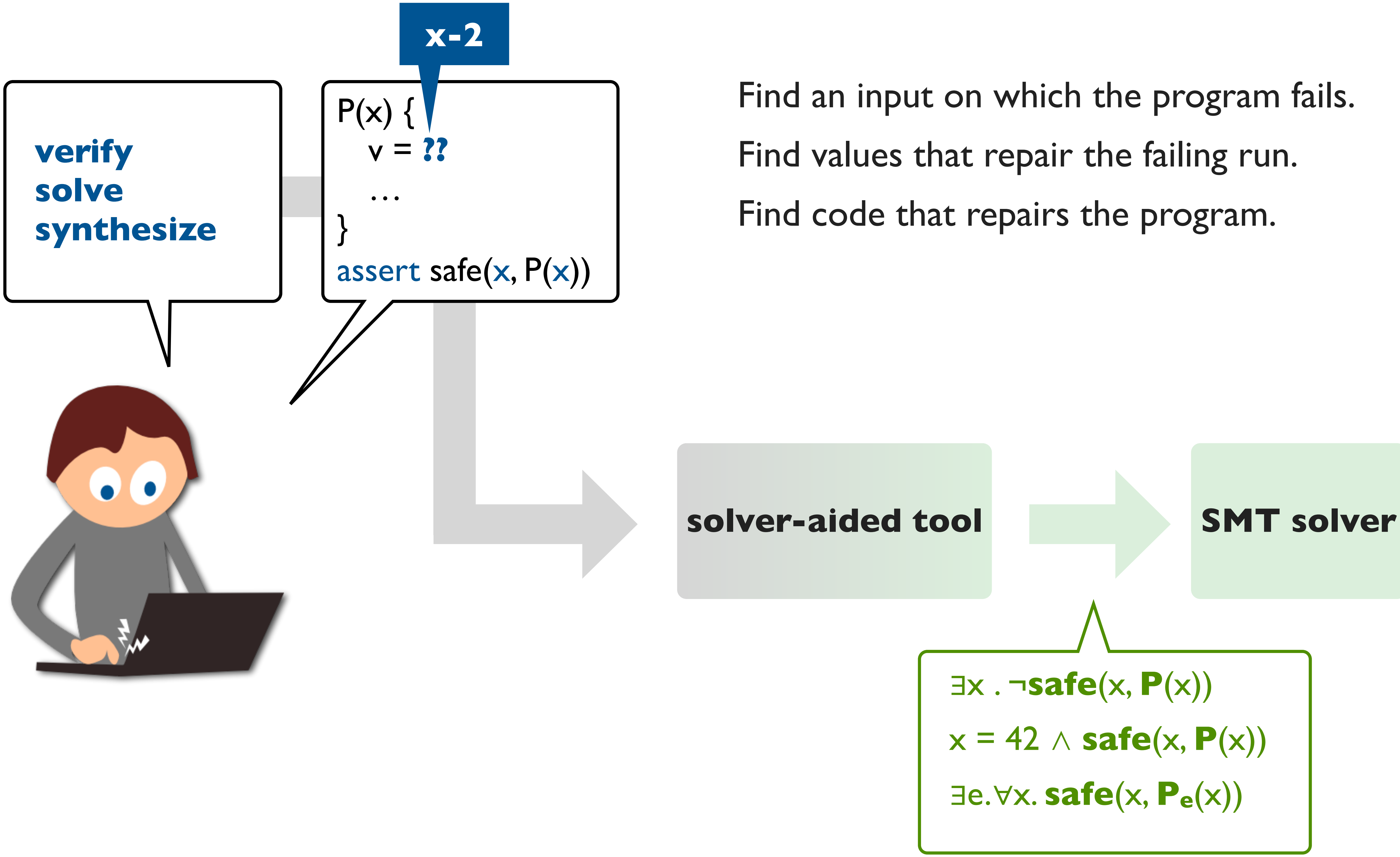
Solver-aided programming: solve

Find an input on which the program fails.

Find values that repair the failing run.



Solver-aided programming: synthesize

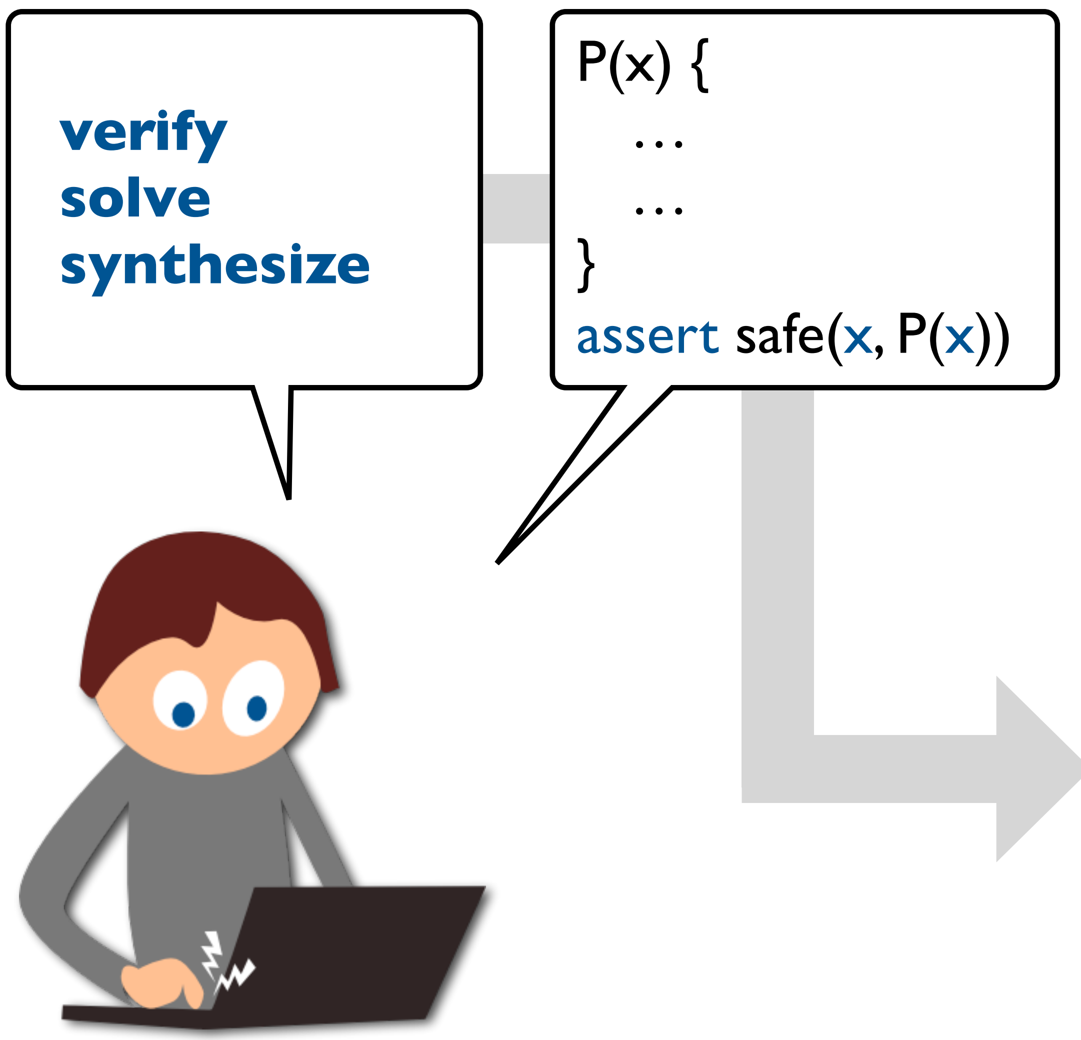


Find an input on which the program fails.

Find values that repair the failing run.

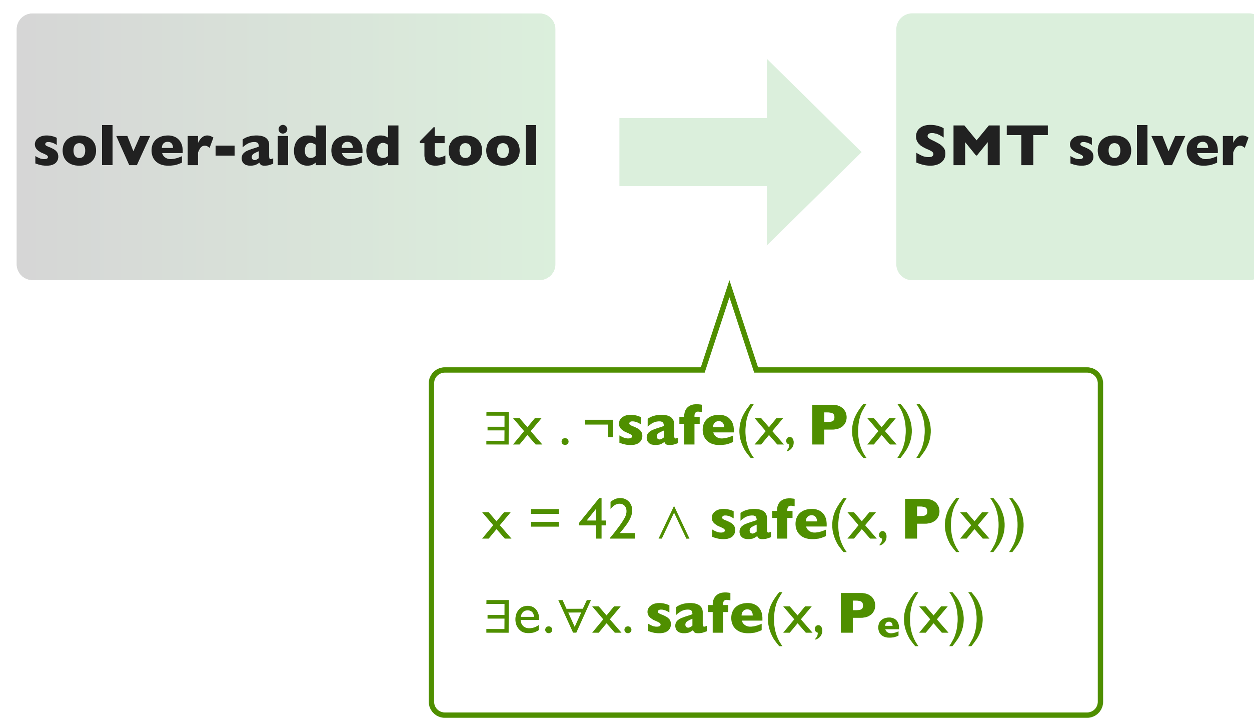
Find code that repairs the program.

Solver-aided programming: workflow



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

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



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ROSETTE

symbolic values
assertions
assumptions
queries

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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

```
(assume expr)
```

assumptions

```
(verify 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

```
(assume expr)
```

assumptions

```
(verify expr)
(solve expr)
(synthesize
  #:forall expr
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```

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

```
(assume expr)
```

assumptions

```
(verify expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

queries

Rosette constructs by example

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

```
(assert expr)
```

```
(assume expr)
```

```
(verify expr)
(solve expr)
(synthesize
  #:forall expr
  #:guarantee expr)
```

demo

https://courses.cs.washington.edu/courses/cse507/21au/doc/bvudiv2.rkt

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*

https://courses.cs.washington.edu/courses/cse507/23au/doc/gotchas.rkt

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)))
(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

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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? #:length 5)
> (define-symbolic xl i integer?)
> (define ys (take xs xl))
> (verify
   (begin
     (assume (<= 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

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- 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
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- 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

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- 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

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- 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
```

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ROSETTE

emina.github.io/rosette/

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Summary

Today

- Course overview & logistics
- Getting started with solver-aided programming

Next lecture

- Going pro with solver-aided programming