Computer-Aided Reasoning for Software

CSE507

Solver-Aided Programming I

Emina Torlak
emina@cs.washington.edu

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

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!

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systems

security

biology

education

networking

hardware

databases

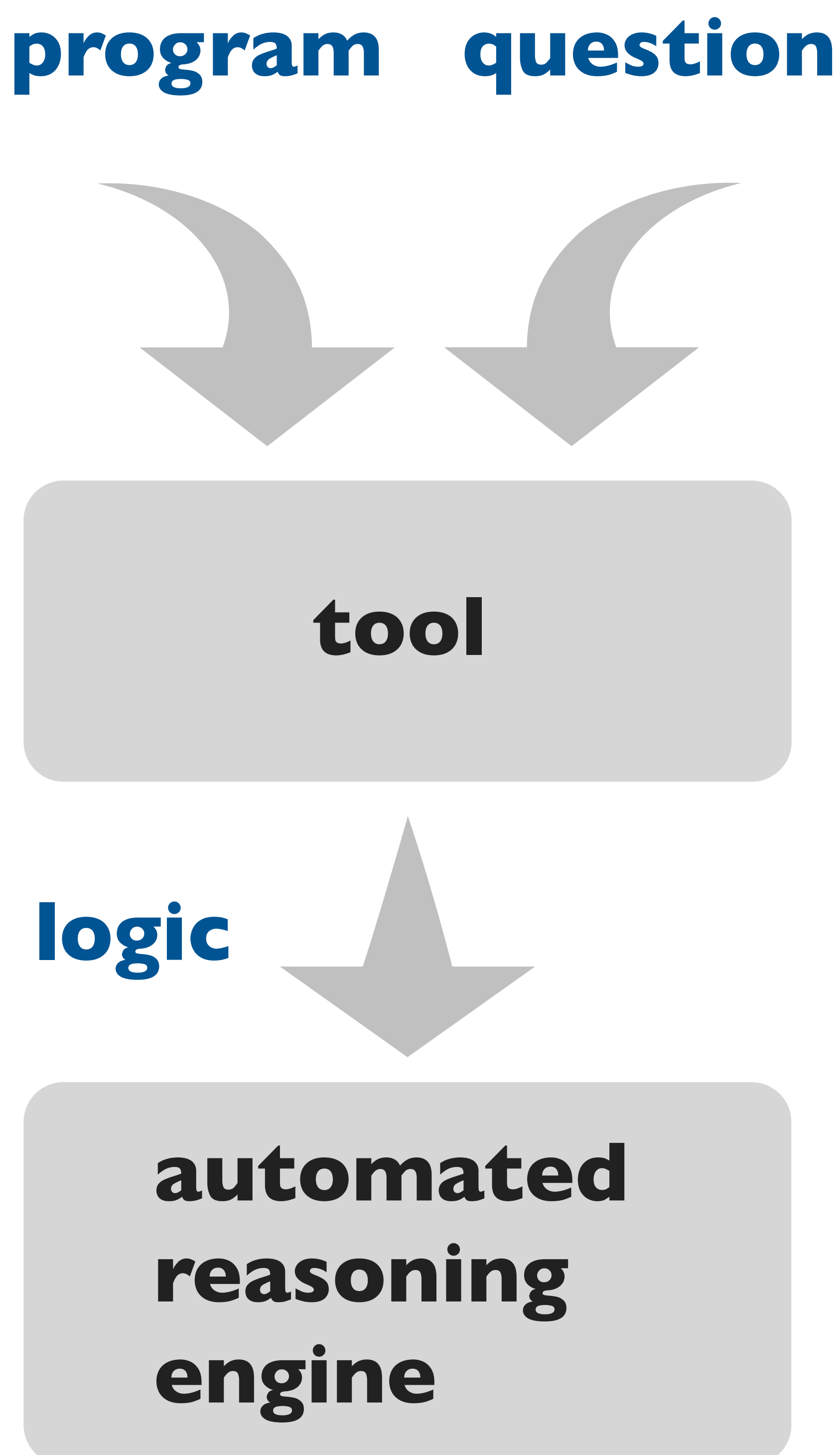
low-power computing

high-performance computing

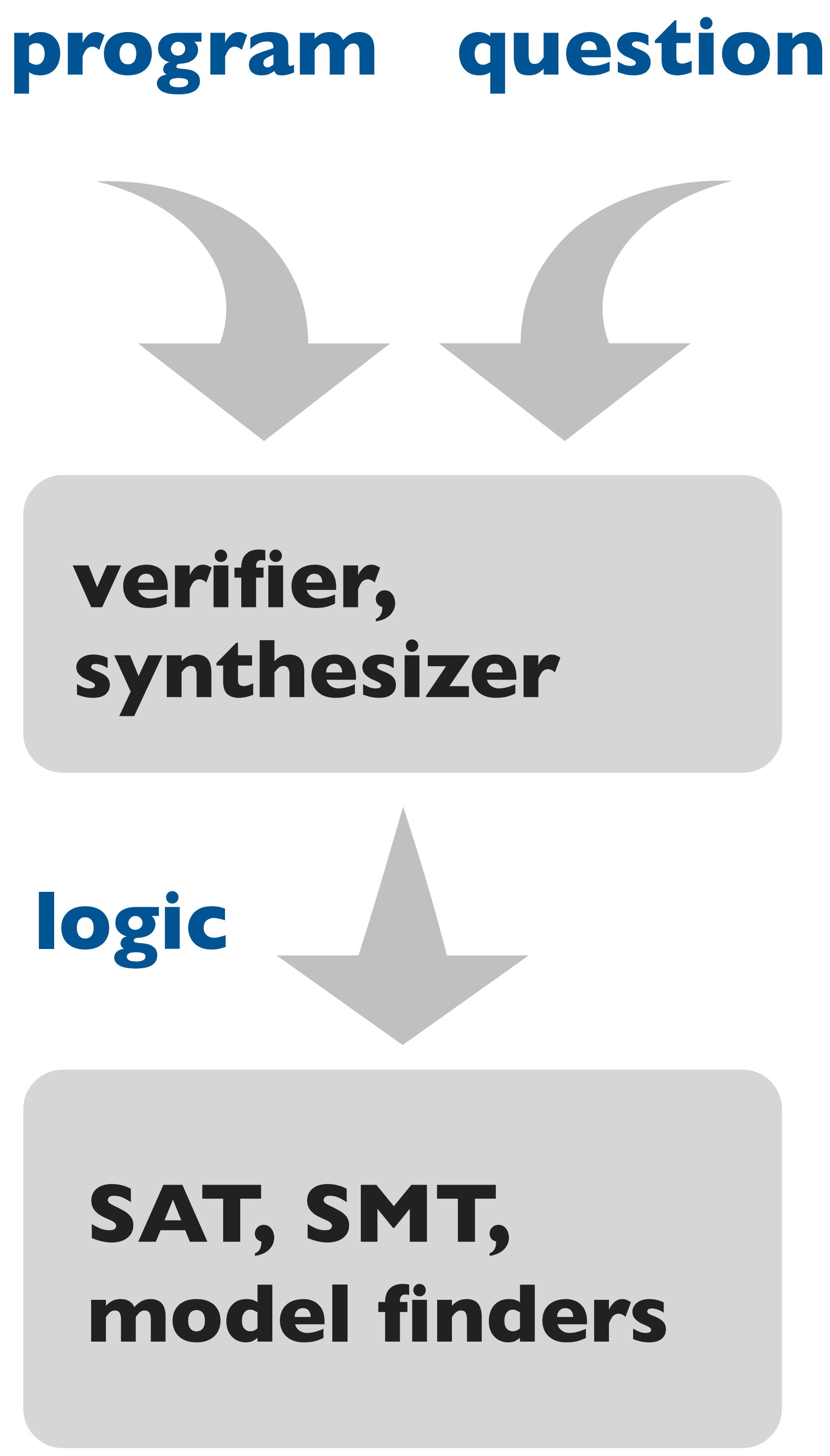
logistics

Topics, structure, people

Course overview



Course overview



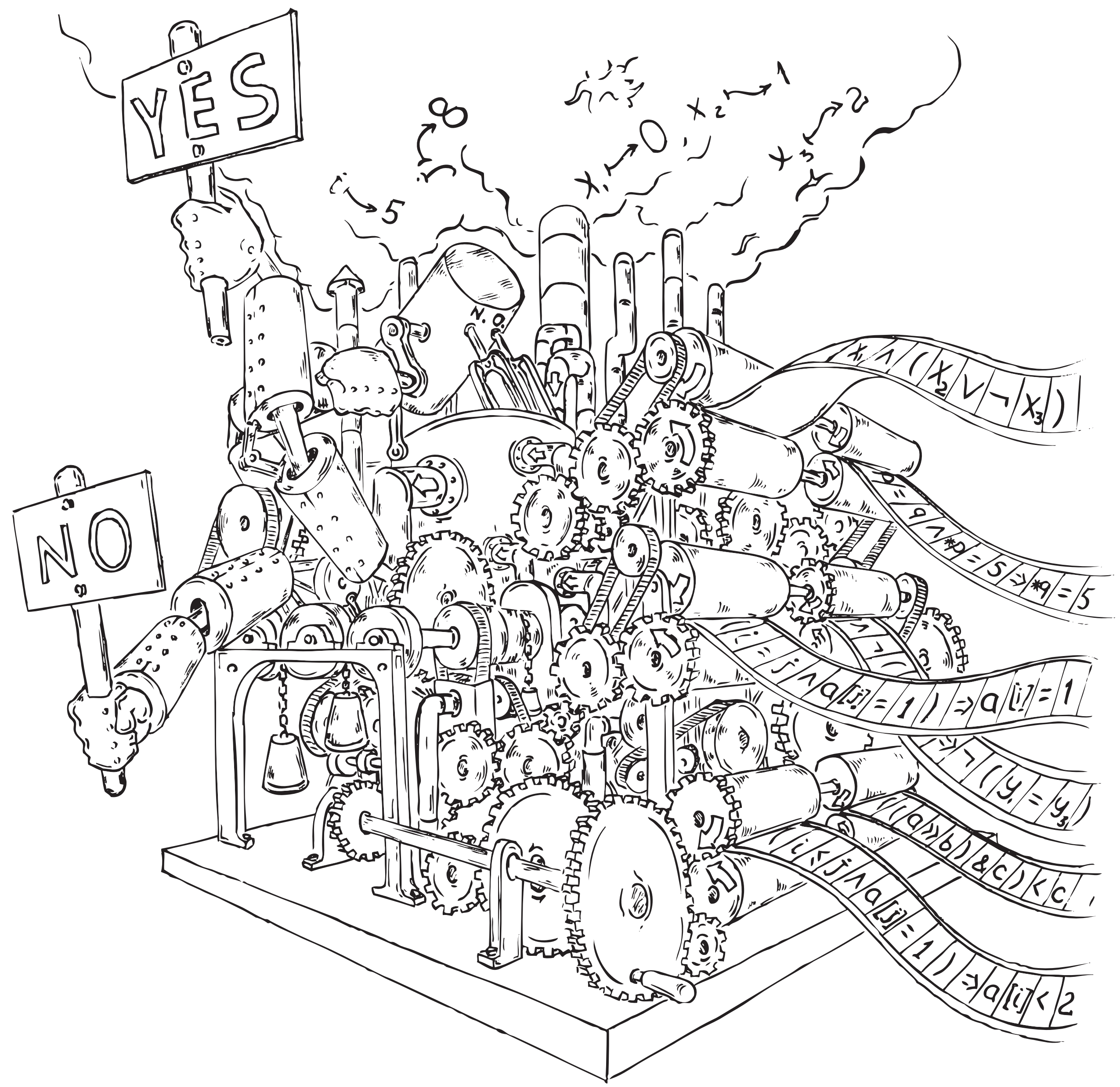
Course overview

program **question**

verifier, synthesizer

logic

SAT, SMT, model finders



Drawing from “Decision Procedures” by Kroening & Strichman

Course overview

program **question**

verifier, synthesizer

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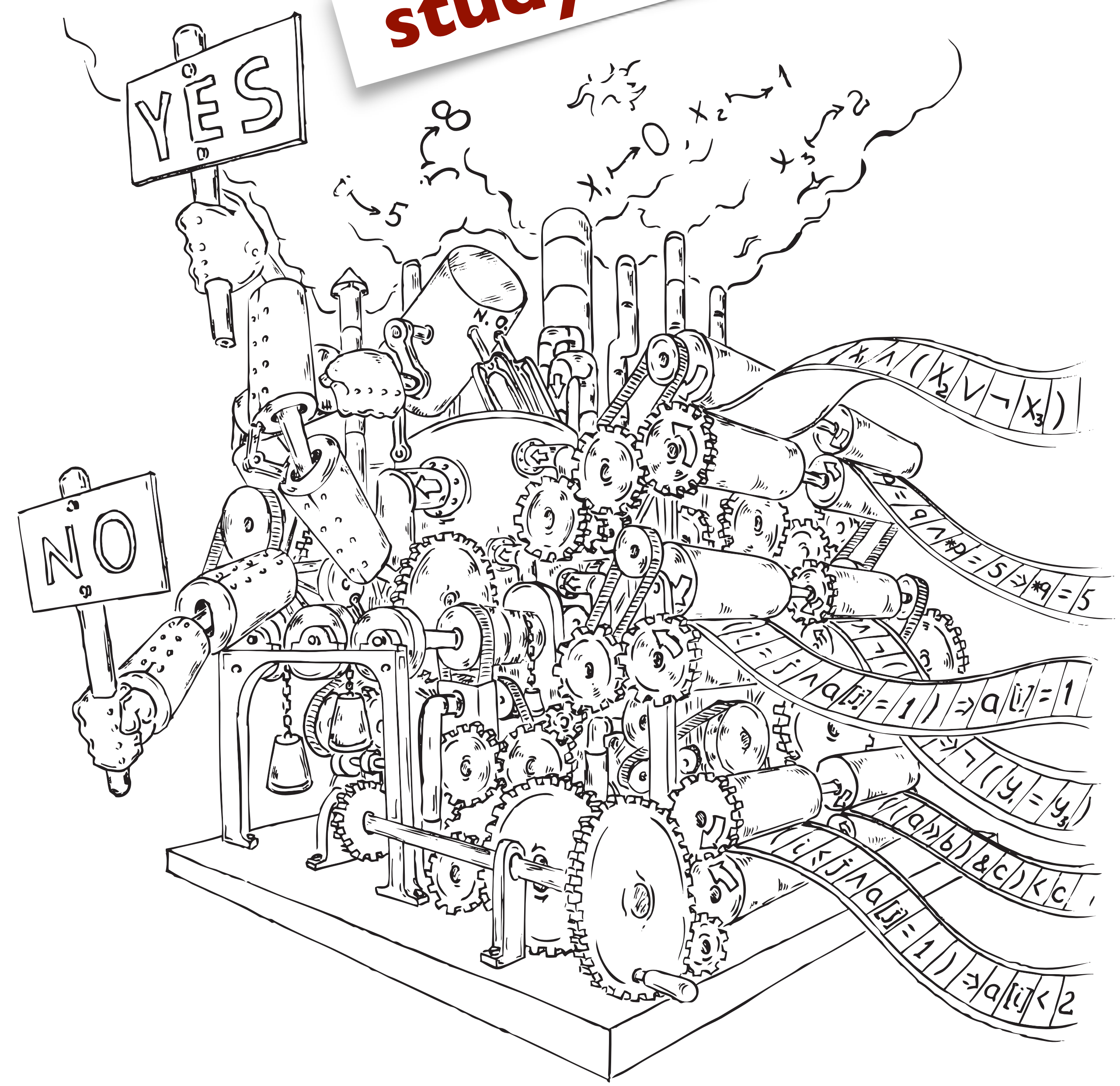
SAT, SMT, model finders

study (part I)



Drawing from "Decision Procedures" by Kroening & Strichman

Course overview

program **question**

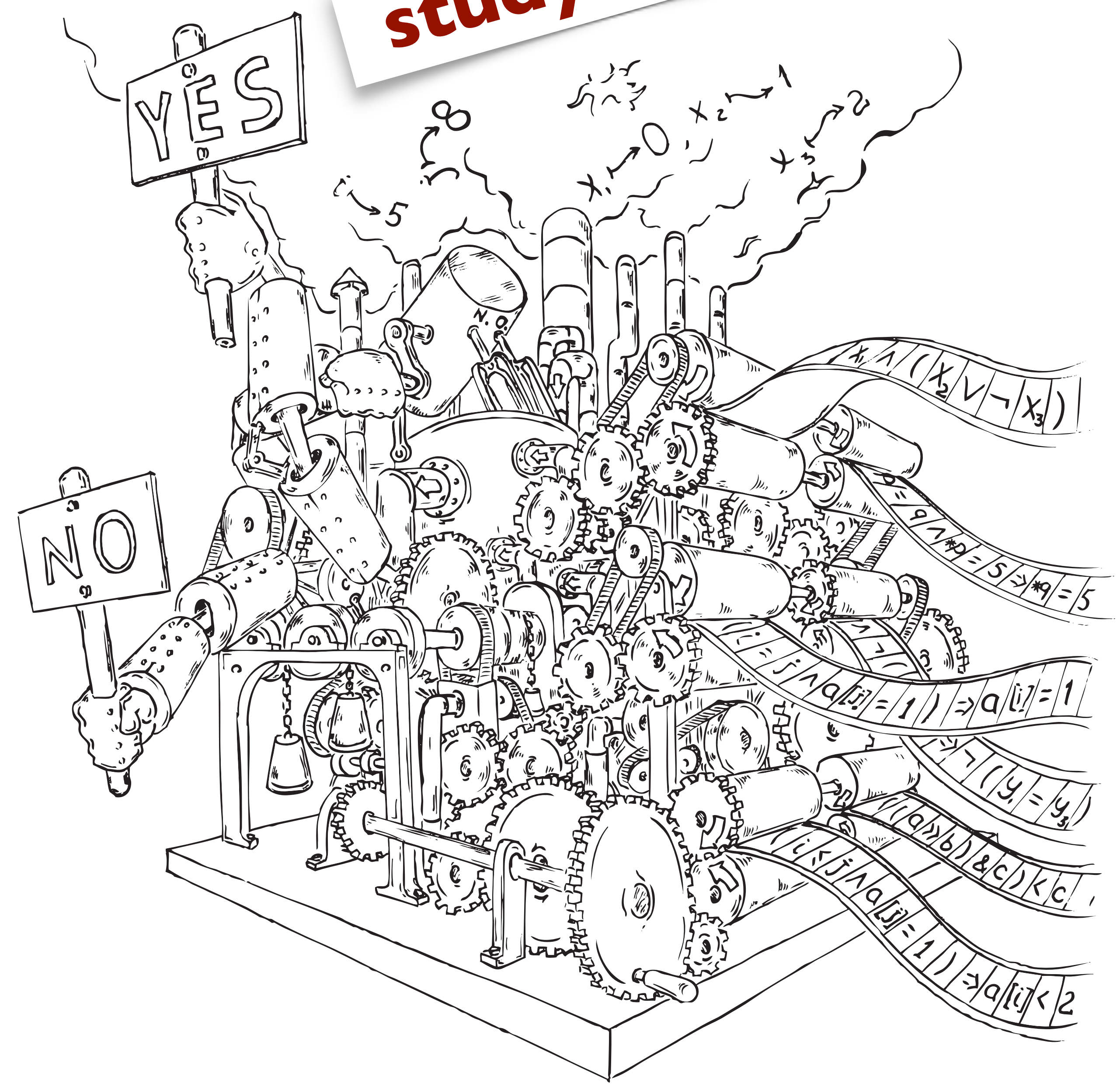
verifier, synthesizer

build! (part II)

logic

SAT, SMT, model finders

study (part I)



Drawing from "Decision Procedures" by Kroening & Strichman

Grading

study (part I)

3 individual homework assignments (75%)

- conceptual problems & proofs (TeX)
- implementations (Racket, Dafny, Alloy)
- completed on your own (may discuss HWs with course staff only)

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

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

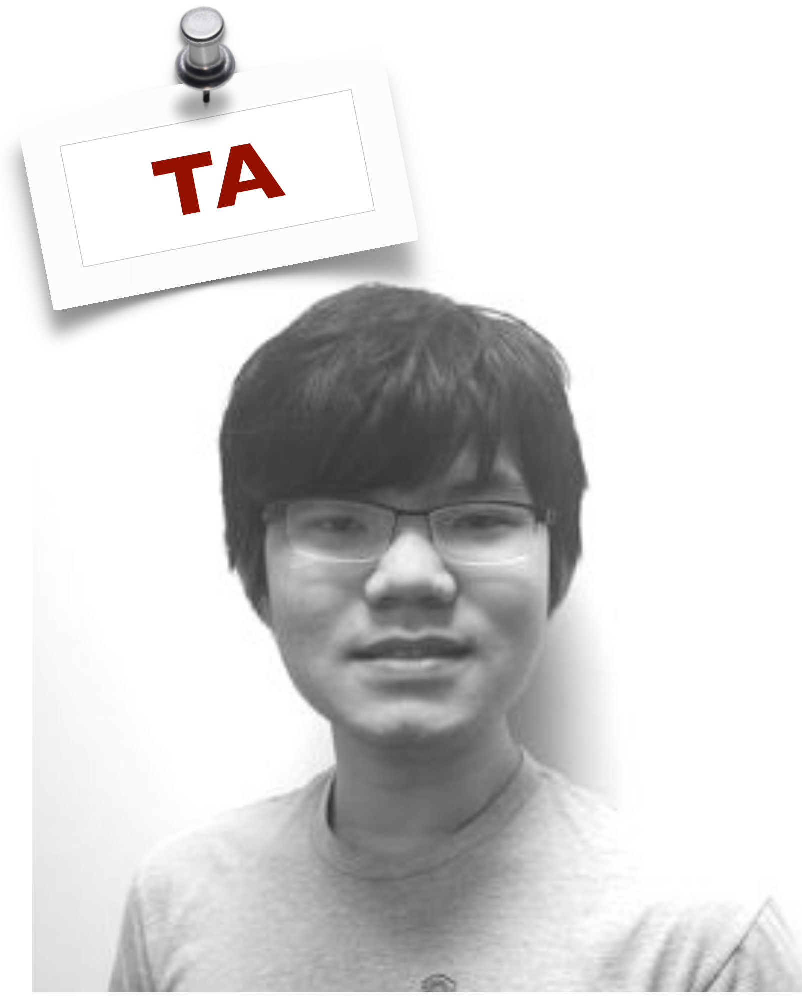
- Ask and answer questions

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)

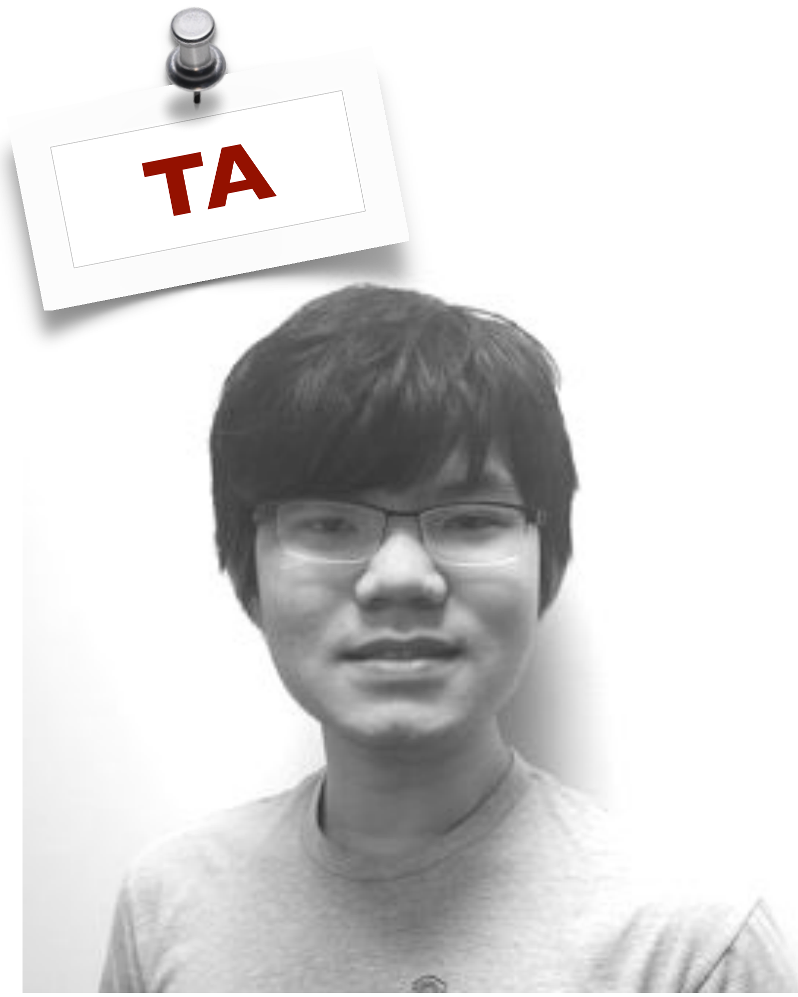
People

Emina Torlak
PLSE
CSE 596



Sorawee Porncharoenwase
PLSE
CSE2 253
OH W 1-2pm

People



students!

Your name
Research area

Emina Torlak
PLSE
CSE 596
By appointment

Sorawee Porncharoenwase
PLSE
CSE2 253
OH W 1-2pm

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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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.

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

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.

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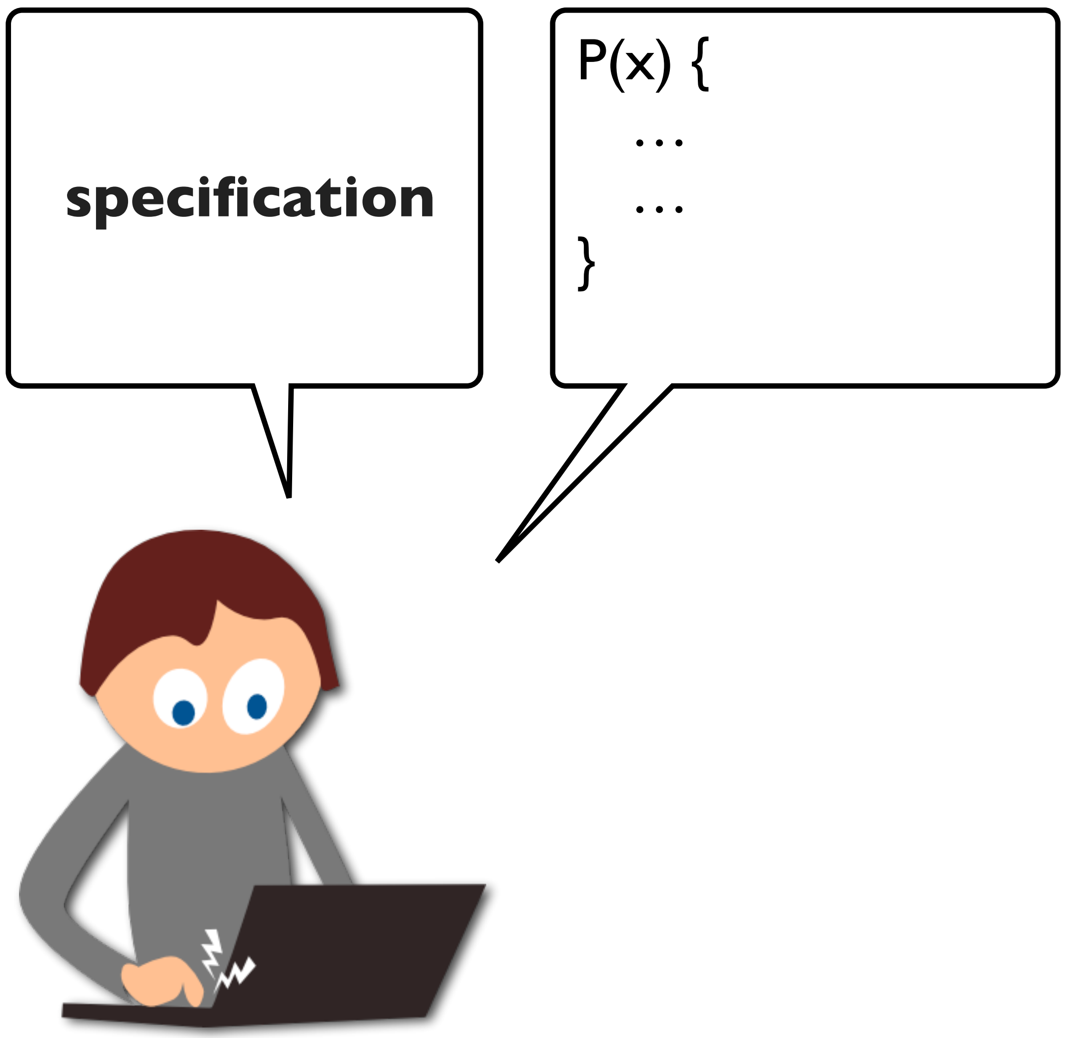
ROSETTE

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

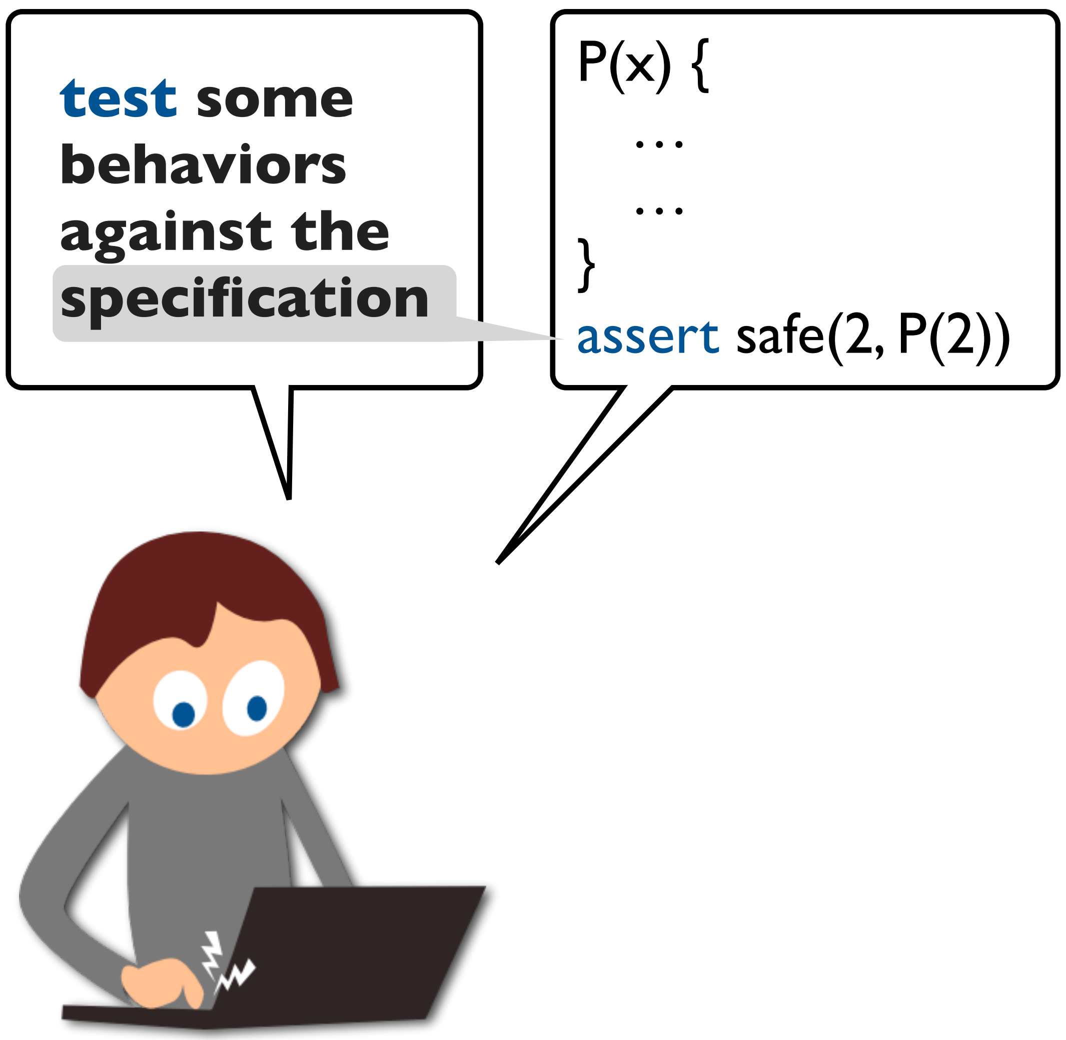
How to use a solver-aided language: the **workflow**, constructs and gotchas.

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

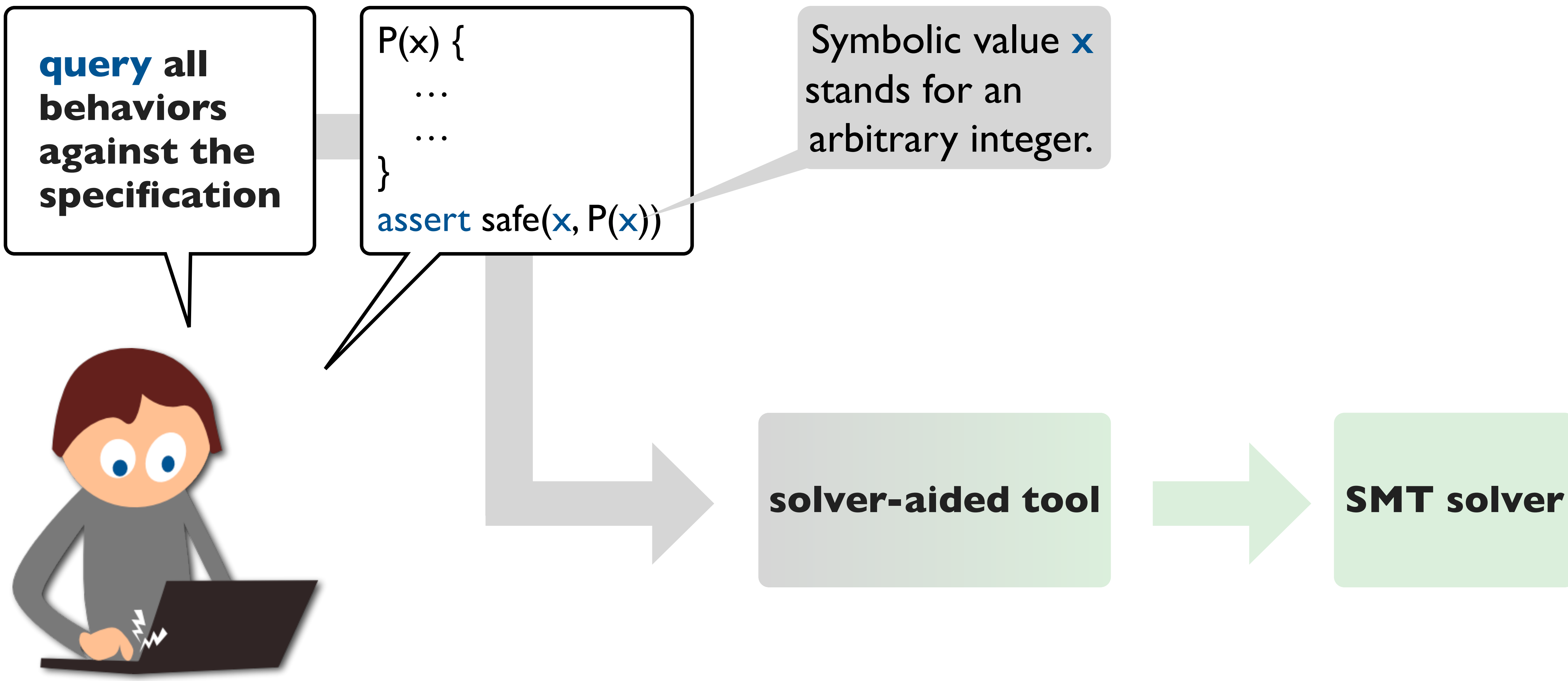
Classic programming: from spec to code



Classic programming: test behaviors

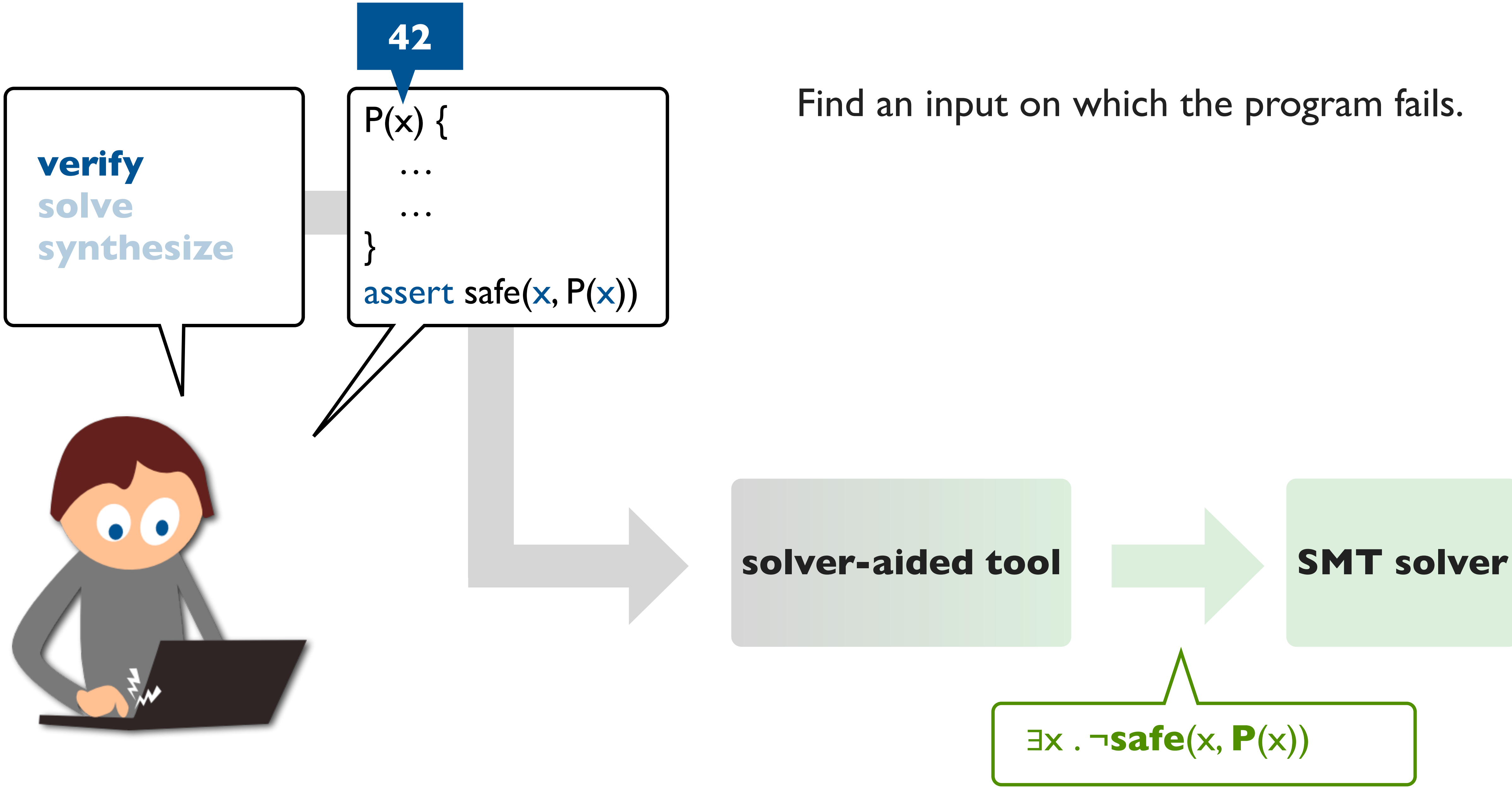


Solver-aided programming: *query* behaviors



Solver-aided programming: verify

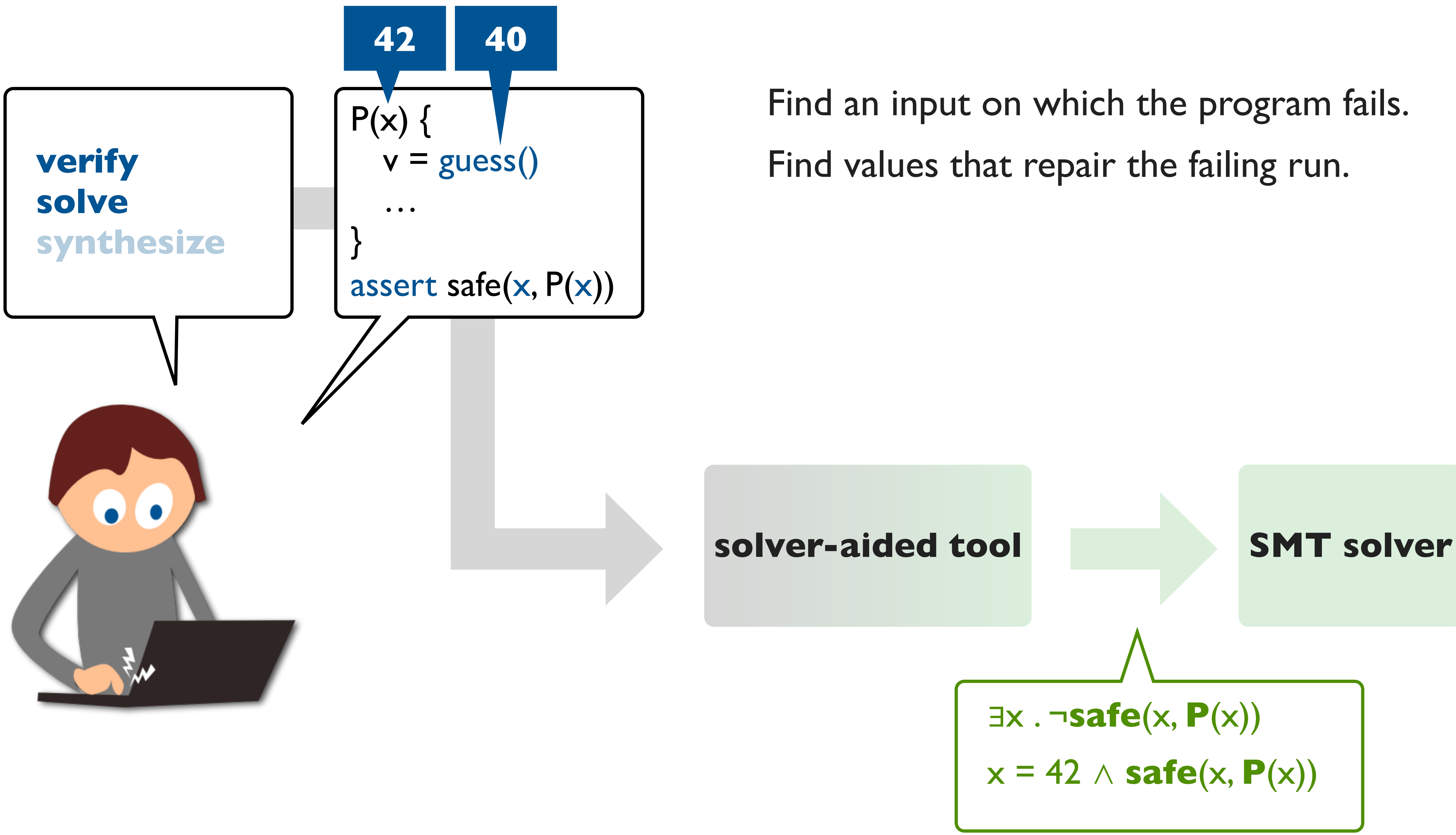
Find an input on which the program fails.



Solver-aided programming: solve

Find an input on which the program fails.

Find values that repair the failing run.

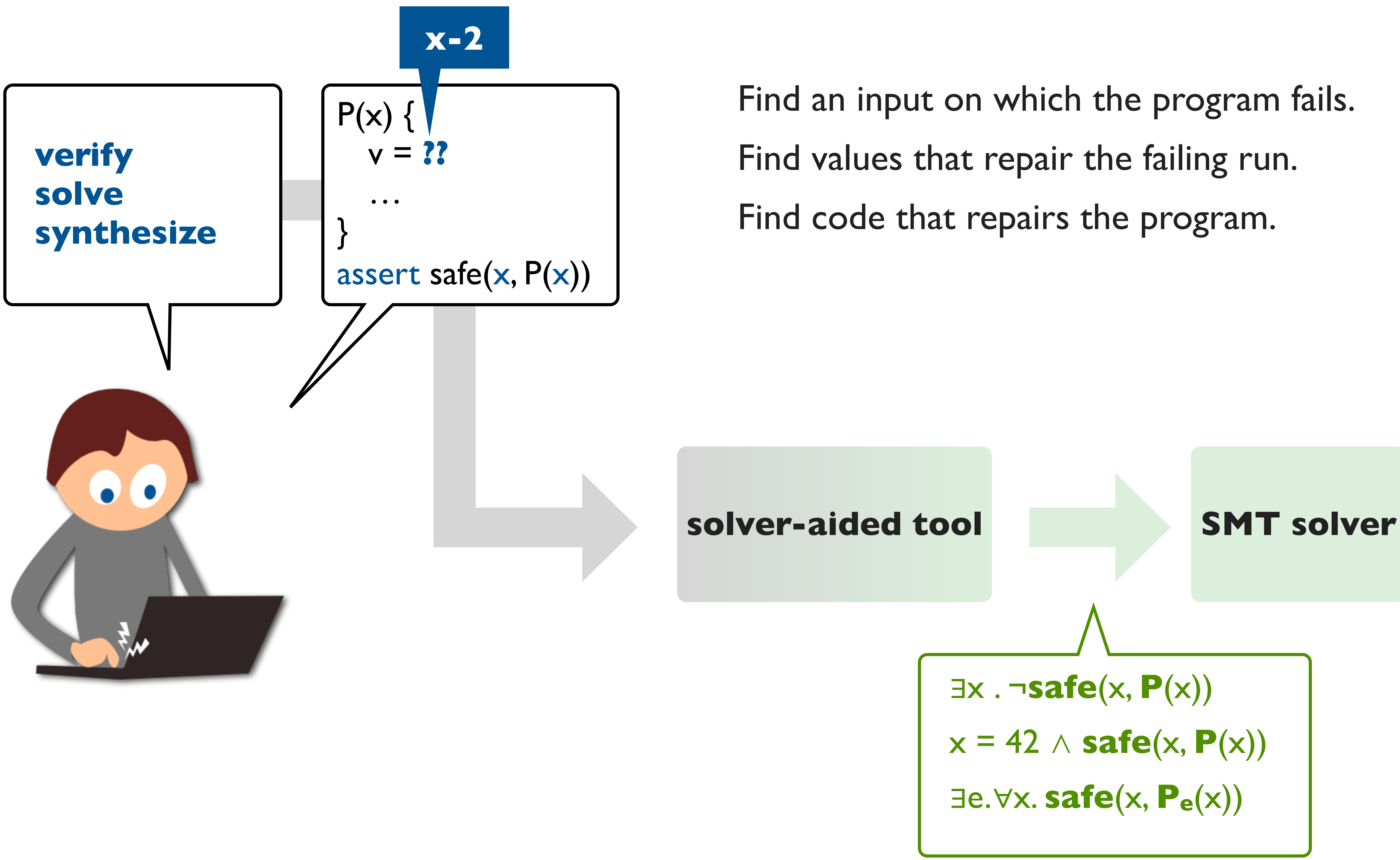


Solver-aided programming: synthesize

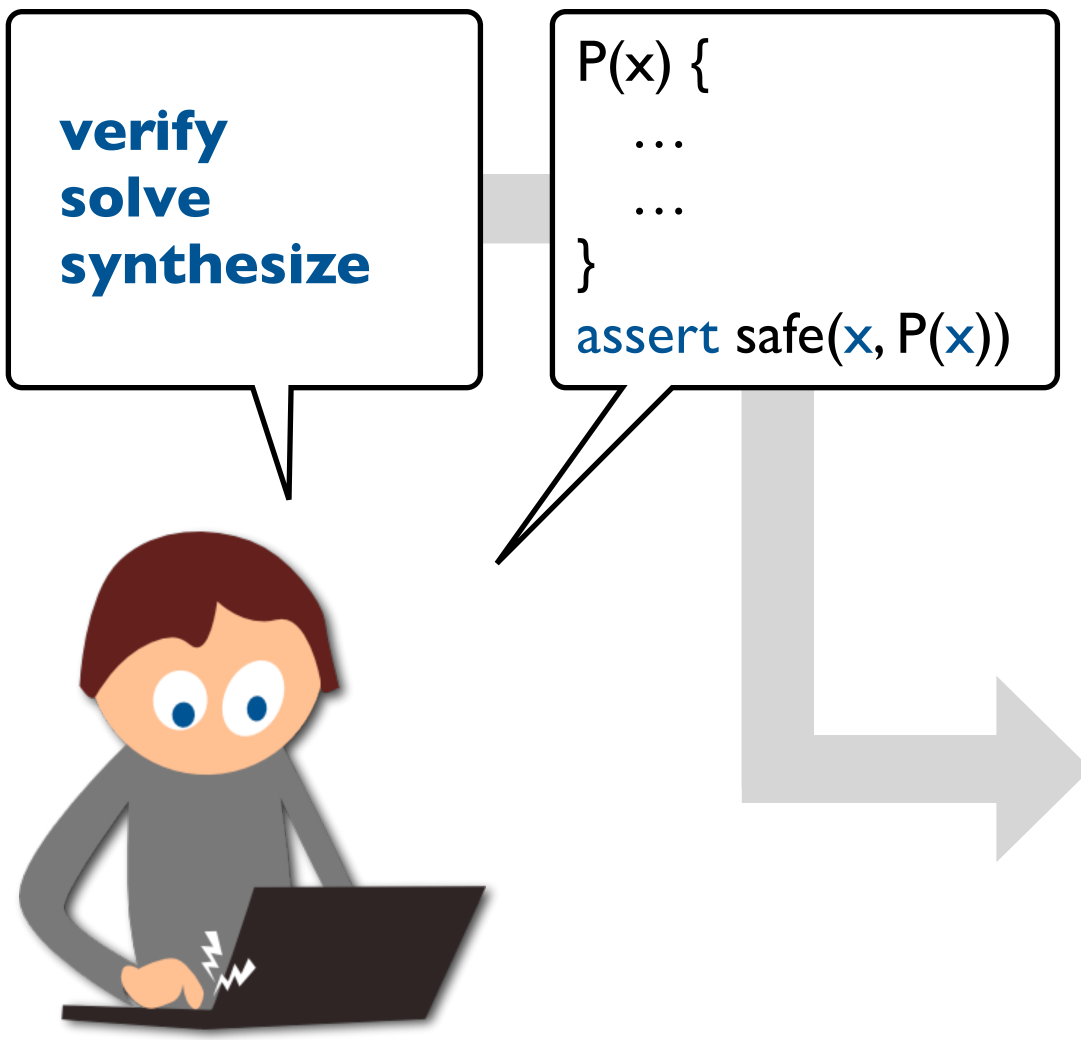
Find an input on which the program fails.

Find values that repair the failing run.

Find code that repairs the program.

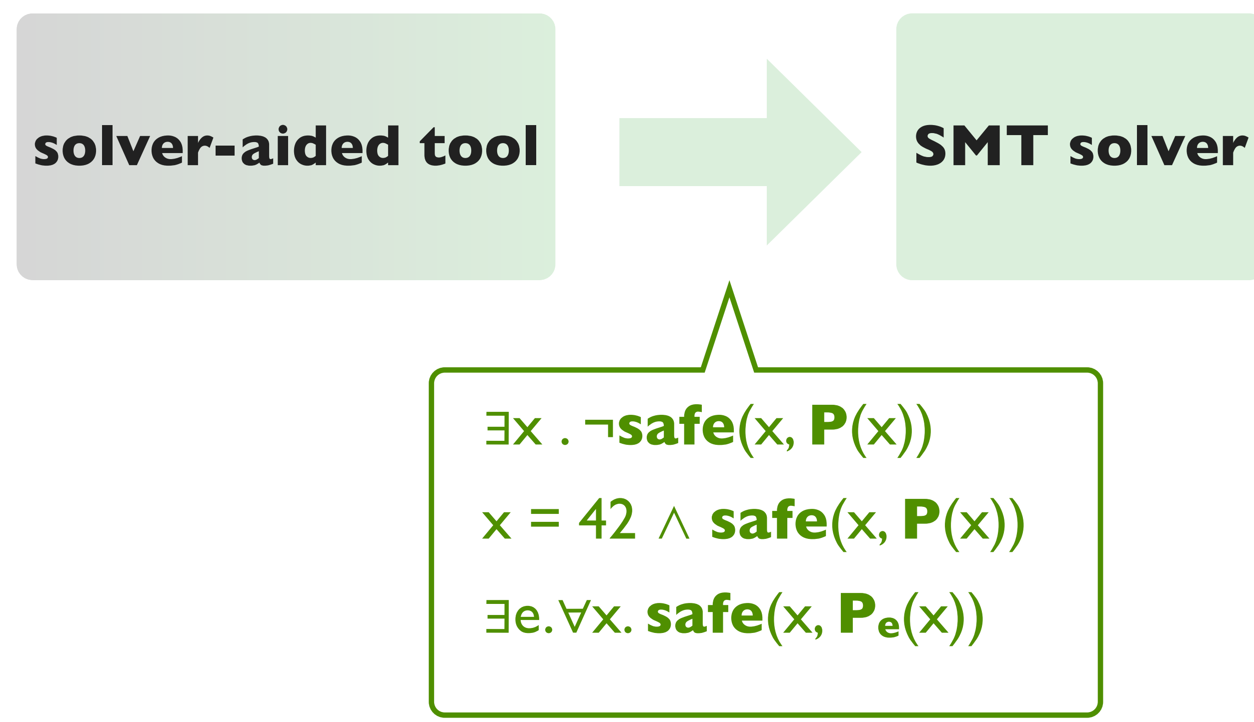


Solver-aided programming: workflow



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

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



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

ROSETTE

symbolic values
assertions
assumptions
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

```
(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
  #: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

```
(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
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```

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/cse507/21au/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

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Unsafe features

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

Common pitfalls and gotchas: reasoning precision

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

Common pitfalls and gotchas: reasoning precision

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```
; 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

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```
; 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

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- Determines if integers and reals are approximated using k-bit words or treated as infinite-precision values.
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```
; 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

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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))))
```

Common pitfalls and gotchas: unbounded loops

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> (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

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

Common pitfalls and gotchas: unbounded loops

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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)))
```

Common pitfalls and gotchas: unbounded loops

Reasoning precision

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> (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

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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)))]))
```

Common pitfalls and gotchas: unbounded loops

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

Common pitfalls and gotchas: unbounded loops

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> (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

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> (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

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

Common pitfalls and gotchas: unsafe features

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(ite* (⊢ (= 0 k) 1) (⊢ (= 1 k) 2)))
```

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

Common pitfalls and gotchas: unsafe features

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

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hash-ref: no value found for key
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> (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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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.

Summary

Today

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

Next lecture

- Going pro with solver-aided programming