

CS 162 Programming languages

# Lecture 16: Solver-Aided Programming

Inspired by CSE507 from Emina Torlak

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# Outline of this lecture

- The classical way for using solvers
- Solver-aided programming
- Rosette constructs

# SAT

Boolean Satisfiability

Boolean  
Formula

① Variables

$x_1, x_2, x_3$   $\begin{cases} \text{"true"} / 1 \\ \text{"false"} / 0 \end{cases}$

② "not"  $\bar{x}_1$

$x_2$



# NP-complete Problems

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Stephen Cook 1971

SAT

Richard Karp 1972

3SAT

Independent Set

Hamiltonian Cycle

Vertex Cover

CLIQUE

Traveling-Salesman Problem(TSP)

Subset-Sum

.....

.....

About 1000 NP-complete problems have been discovered since.

# A classical way to use solvers

```
foo (int a) {  
  x = 10;  
  y = 5;  
}
```

$$x = 10 \wedge y = 5$$

```
foo (int a) {  
  if (a > 0)  
    x = 10;  
  else  
    y = 5;  
}
```

$$a > 0 \implies x = 10 \wedge a \leq 0 \implies y = 5$$

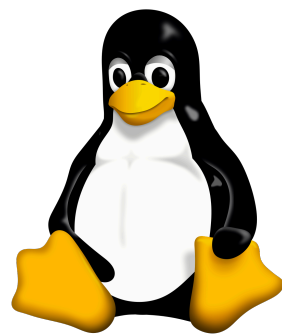
```
foo (int a) {  
  if (a > 0)  
    x = 10;  
  else  
    y = 5;  
  assert y > 4  
}
```

$$\begin{aligned} a > 0 &\implies x = 10 \wedge a \leq 0 \implies y = 5 \\ &\implies y > 4 \end{aligned}$$

# A classical way to use solvers



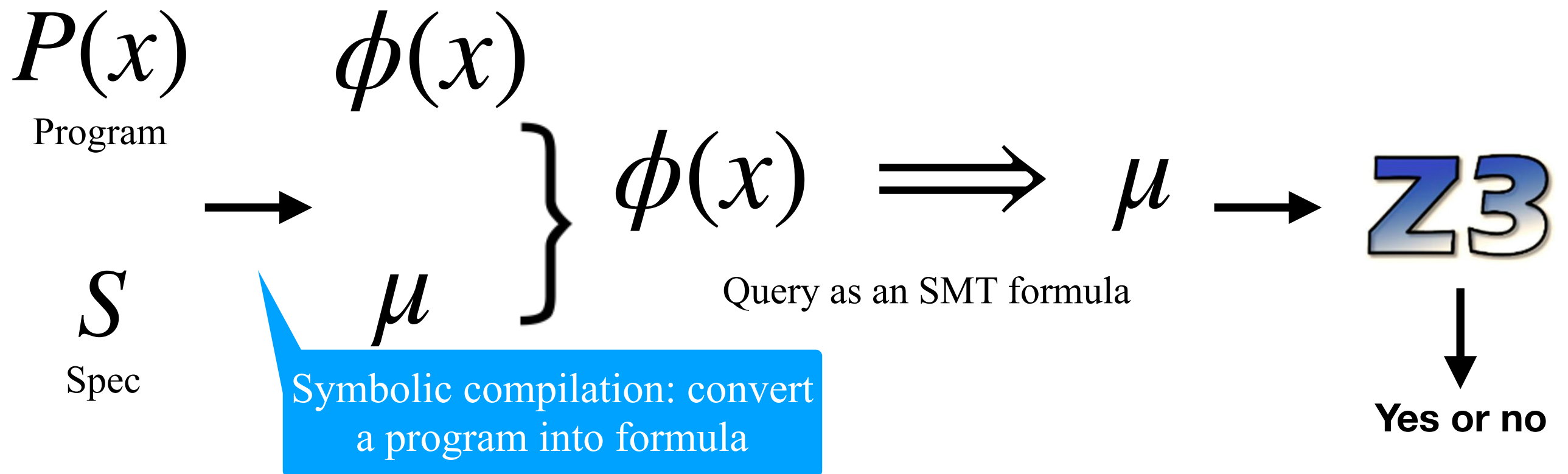
??



??

How to deal with complex systems?

# A classical way to use solvers



**Symbolic compilation can take years of effort!**

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

# Solver-aided programming

```
p(x) {  
  v = 12
```

```
p(x) {  
  v = ??
```

```
...
```

```
}
```

```
assert safe(x, p(x))
```

Find an input on which the program fails.

Localize bad parts of the program.

Find values that repair the failing run.

Find code that repairs the program.





# Solver-aided applications

## **Systems**

SOSP'19, OSDI'18,  
SOSP'17, OSDI'16

## **Blockchain**

ASE'20-a, ASE'20-b

## **Browser engines**

## **Biology**

POPL'14

## **Education**

## **Data science**

PLDI'18, PLDI'17

## **Robotics**

## **HPC**

ASPLOS'16, OSDI'18

## **Gaming**

## **Malware**

NDSS'17

## **Visualization**

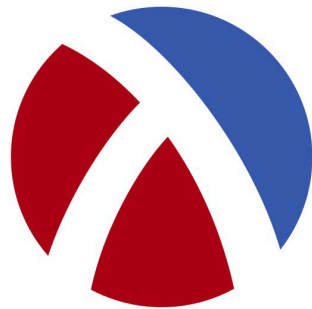
POPL'20

# Rosette constructs



Rosette

=



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:symbolic values

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

```
(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**

**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
```

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

```
> (eq? (same-x) (same-x))
#t
```

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

# Rosette constructs:symbolic values

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

```
(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**

**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
```

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

```
> (eq? (new-x) (new-x))
(= x$3 x$4)
```

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

# Rosette constructs: assert

**assert** checks that `expr` evaluates to a true value.

> (`assert` (`>= 2 1`)) ; passes

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

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

**symbolic values**

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

(`assert` `expr`)

**assertions**

> (`assert` (`>= x 1`))

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

**queries**

>

`(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.

# From assert to verify

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

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

```
(define (factored x)
  (* x (+ x 1) (+ x 2) (+ x 2)))
```

```
(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**

```
(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

Search for a binding of symbolic constants to concrete values that violates at least one of the assertions

`(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**

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

```
(define (factored 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 factored i)))
(evaluate i cex)
```

# Rosette constructs: debugging

Searches for a minimal set of expressions that are responsible for the observed failure

```
(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**

```
(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))))
```

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.



# Rosette constructs: synthesis

Search for a binding of symbolic constants to concrete values that satisfy the assertions

```
(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**

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

```
(define (factored x)
  (* (+ x (??)) (+ x 1) (+ x (??)) (+ x (??))))
```

Unknown is represented as ??

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

```
(define-symbolic i integer?)
```

```
(define binding
  (synthesize #:forall (list i)
    #:guarantee (same poly factored i)))
```

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

Thank you for taking CS162!