Lecture 15: Solver-Aided Programming

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Winter 2023

Torlak et. al. "A lightweight symbolic virtual machine for solver-aided host languages." PLDI'14

Outline of this lecture

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

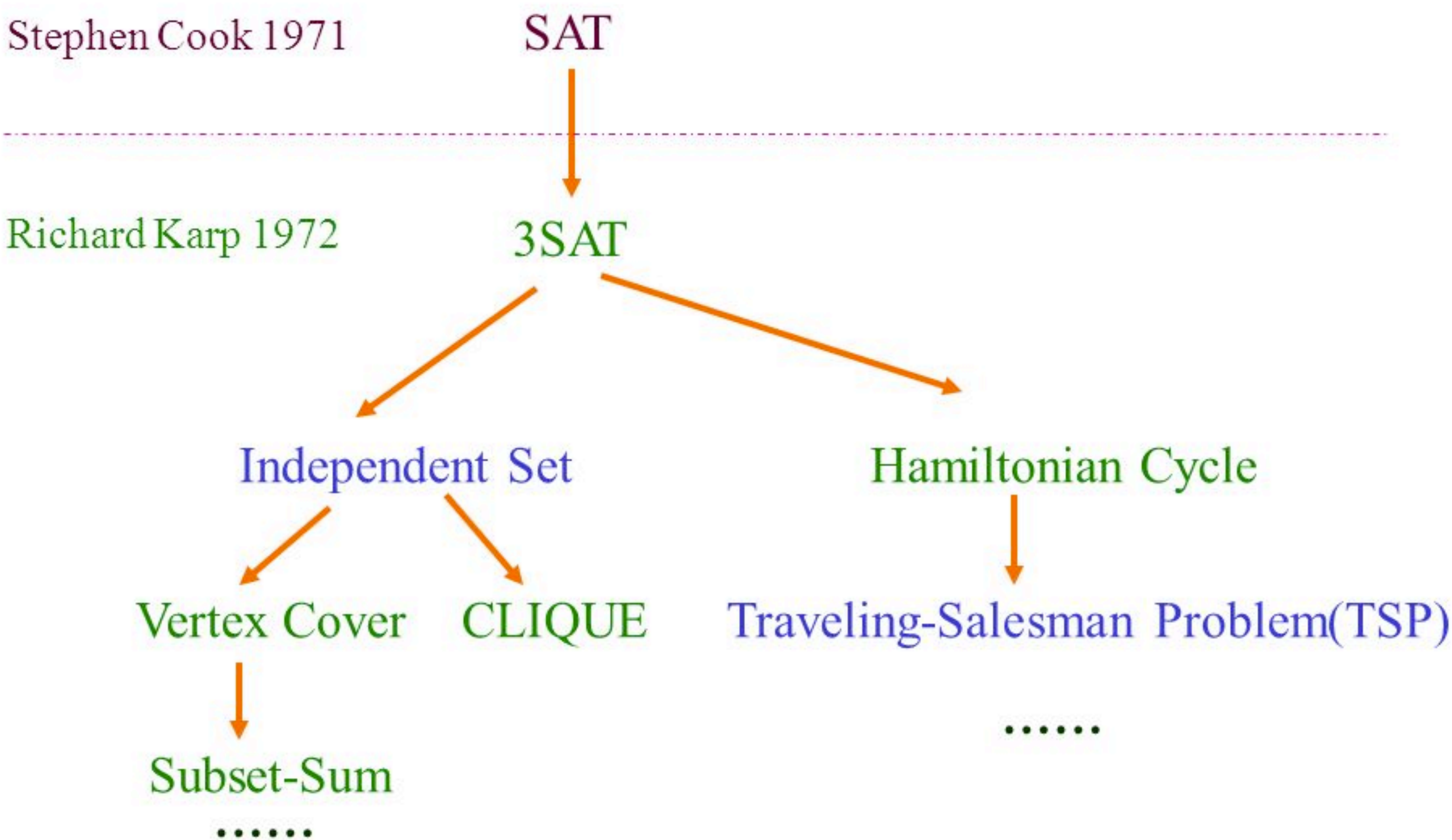
SAT

Boolean Satisfiability

Boolean Formula

1. Variables x_1 x_2 x_3 $\begin{cases} \text{"true"} / 1 \\ \text{"false"} / 0 \end{cases}$
2. "not" $\overline{x_1}$ x_2

NP-complete Problems



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;
}
```

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

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

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

$$\implies y > 4$$

A classical way to use solvers

$P(x)$

Program

S

Spec

$\longrightarrow$ $\left.\begin{matrix}\phi(x) \\ \\ \mu\end{matrix}\right\}$ $\phi(x) \implies \mu$ $\longrightarrow$ Z3 $\downarrow$ **Yes or no**

Query as an SMT formula

Symbolic compilation: convert a program into formula

Symbolic compilation can take years of effort!

A classical way to use solvers

??

??

How to deal with complex systems?

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

Gaming

HPC

ASPLOS'16, OSDI'18

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

A Lightweight Symbolic Virtual Machine for Solver-Aided Host Languages. Emina Torlak and Rastislav Bodik. PLDI'14

Rosette constructs:symbolic values

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

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

```
(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-x)
   (define-symbolic x integer?)
  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:symbolic values

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

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

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

> (new-x)
  x$0

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

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: 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**
(**assert** expr)	**assertions**
(**verify** expr) (**debug** [type ...+] expr) (**solve** expr) (**synthesize** #:forall expr #:guarantee expr)	**queries**

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

> (assert (>= x 1))

>

  (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 (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
```

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

symbolic values

```
(assert expr)
```

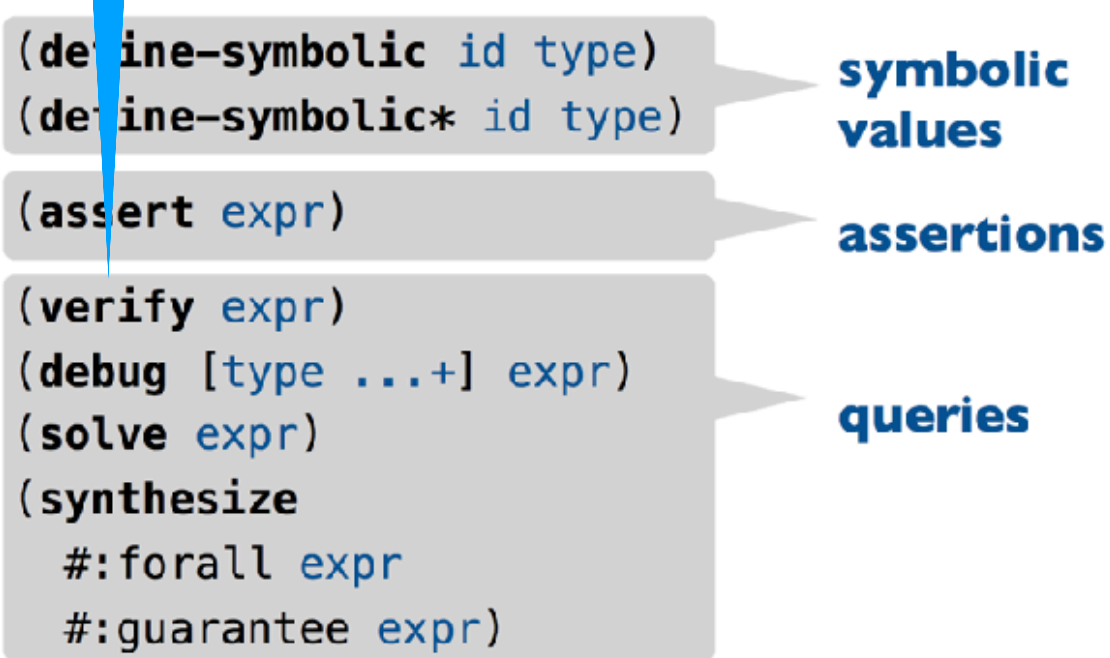
assertions

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

queries

Rosette constructs: verify

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




```
(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 (??))))

(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)))
```

Unknown is represented as ??

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

Thank you for taking CS162!