Yices 1.0: An Efficient SMT Solver

AFM'06 Tutorial

Leonardo de Moura (joint work with Bruno Dutertre)

$\{$demoura, bruno$\}$@csl.sri.com.

Computer Science Laboratory

SRI International

Menlo Park, CA

Satisfiability Modulo Theories (SMT)

- SMT is the problem of determining satisfiability of formulas modulo background theories.
- Examples of background theories:
  - linear arithmetic: $x + 1 \leq y$
  - arrays: $a[i := v_1][j] = v_2$
  - uninterpreted functions: $f(f(f(x))) = x$
  - datatypes: $car(cons(v_1, v_3)) = v_2$
  - bitvectors: $concat(bv_1, bv_2) = bv_3$
- Example of formula:

$$i - 1 = j + 2, f(i + 3) \neq f(j + 6)$$

Applications of SMT

- Extended Static Checking
- Equivalence Checking (Hardware)
- Bounded Model Checking (e.g., sal-inf-bmc)
- Predicate Abstraction
- Symbolic Simulation
- Test Case Generation (e.g., sal-atg)
- AI Planning & Scheduling
- Embedded in Theorem Provers (e.g., PVS)

Yices

- Yices is an SMT Solver developed at SRI International.
- Yices is not ICS.
- It is used in SAL, PVS, and CALO.
- It is a complete reimplementation of SRI’s previous SMT solvers.
    - It has a new architecture, and uses new algorithms.
    - Counterexamples and Unsatisfiable Cores.
    - Incremental: push, pop, and retract.
    - Weighted MaxSAT/MaxSMT.
- Supports all theories in SMT-LIB and much more.

Supported Features

- Uninterpreted functions
- Linear real and integer arithmetic
- Extensional arrays
- Fixed-size bit-vectors
- Quantifiers
- Scalar types
- Recursive datatypes, tuples, records
- Lambda expressions
- Dependent types

Using Yices

- Starting yices shell: `./yices -i`
- Batch mode:
  - Yices format: `./yices ex1.ys`
  - SMT-LIB format: `./yices -smt ex1.smt`
  - Dimacs format: `./yices -d ex1.cnf`
- Increasing verbosity level: `./yices -v 3 ex1.ys`
- Producing models: `./yices -e ex1.ys`

First Example

```
(define f::(-> int int))
(define i::int)
(define j::int)
(assert (= (- i 1) (+ j 2)))
(assert (/= (f (+ i 3)) (f (+ j 6))))
```

$\longrightarrow$ unsat

Check

- `assert` gets only trivial inconsistencies.
- `(check)` should be used to test satisfiability.

```
(define x::int)
(define y::int)
(define z::int)
(assert (= (+ (* 3 x) (* 6 y) z) 1))
(assert (= z 2))
(check)
```

$\longrightarrow$ unsat

Extracting Models

- `./yices -e ex3.ys`

```
(define x::int)
(define y::int)
(define f::(-> int int))
(assert (/= (f (+ x 2)) (f (- y 1))))
(assert (= x (- y 4)))
(check)
```

$\longrightarrow$ sat

```
(= x -2)
(= y 2)
(= (f 0) 1)
(= (f 1) 3)
```

Extracting Unsatisfiable Cores

- `./yices -e ex4.ys`

```
(define f::(-> int int))
(define i::int)
(define j::int)
(define k::int)
(assert+ (= (+ i (* 2 k)) 10))
(assert+ (= (- i 1) (+ j 2)))
(assert+ (= (f k) (f i)))
(assert+ (/= (f (+ i 3)) (f (+ j 6))))
(check)
```

$\longrightarrow$ unsat

```
unsat core ids: 2 4
```

Lemma Learning

- SMT (and SAT) solvers have a search engine:
  - Case-split
  - Propagate
  - Conflict $\leadsto$ Backtrack
- Each conflict generates a Lemma:
  - It prevents a conflict from happening again.

Retracting Assertions

- Assertions asserted with `assert+` can be retracted.
- Lemmas are reused in the next call to `(check)`.
  - Yices knows which lemmas are safe to reuse.

```
(assert+ (= (+ i (* 2 k)) 10))
(assert+ (= (- i 1) (+ j 2)))
(assert+ (= (f k) (f i)))
(assert+ (/= (f (+ i 3)) (f (+ j 6))))
(check)
```

$\longrightarrow$ unsat

```
(retract 2)
(check)
```

$\longrightarrow$ sat

Stacking logical contexts

- `(push)`
  - Saves the current logical context on the stack.
- `(pop)`
  - Restores the context from the top of the stack.
  - Pops it off the stack.
  - Any changes between the matching `push` and `pop` commands are flushed.
  - The context is restored to what it was right before the push.
- Applications (depth-first search):
  - Symbolic Simulation
  - Extended Static Checking

Weighted MaxSAT

- `./yices -e ex5.ys`

```
(assert+ (= (+ i (* 2 k)) 10)             10)
(assert+ (= (- i 1) (+ j 2))              20)
(assert+ (= (f k) (f i))                  30)
(assert+ (/= (f (+ i 3)) (f (+ j 6))) 15)
(max-sat)
```

$\longrightarrow$ sat

```
unsatisfied assertion ids: 4
(= i 10) (= k 0) (= j 7) (= (f 0) 11)
(= (f 10) 11) (= (f 13) 12)
cost: 10
```

Type checking

- By default, Yices assumes the input is correct.
- It may crash if the input has type errors.
- You can force Yices to “type check” the input:
  - `./yices -tc ex1.ys`
  - Performance penalty.
- Idea: use `-tc` only when you are developing your front-end for Yices.

Other useful commands

- `(reset)` – reset the logical context.
- `(status)` – display the status of the logical context.
- `(echo [string])` – prints the string [string].

Function (Array) Theory

- Yices (like PVS) does not make a distinction between arrays and functions.
- Function theory handles:
  - Function updates.
  - Lambda expressions.
  - Extensionality

Function (Array) Theory (cont.)

- Example: `./yices f1.ys`

```
(define A1::(-> int int))
(define A2::(-> int int))
(define v::int) (define w::int)
(define x::int) (define y::int)
(define g::(-> (-> int int) int))
(define f::(-> int int))
(assert (= (update A1 (x) v) A2))
(assert (= (update A1 (y) w) A2))
(assert (/= (f x) (f y)))
(assert (/= (g A1) (g A2)))
(check)
```

$\longrightarrow$ unsat

Lambda expressions

- Example: `./yices -e f2.ys`

```
(define f::(-> int int))
(assert (or (= f (lambda (x::int) 0))
            (= f (lambda (x::int) (+ x 1)))))
(define x::int)
(assert (and (>= x 1) (<= x 2)))
(assert (>= (f x) 3))
(check)
```

$\longrightarrow$ sat

```
(= x 2) (= (f 2) 3)
```

Recursive datatypes

- Similar to PVS and SAL datatypes.
- Useful for defining: lists, trees, etc.
- Example: `./yices dt.ys`

```
(define-type list
    (datatype (cons car::int cdr::list) nil))
(define l1::list)
(define l2::list)
(assert (not (nil? l2)))
(assert (not (nil? l1)))
(assert (= (car l1) (car l2)))
(assert (= (cdr l1) (cdr l2)))
(assert (/= l1 l2))
```

$\longrightarrow$ unsat

Fixed-size bit-vectors

- It is implemented as a satellite theory.
- Straightforward implementation:
  - Simplification rules.
  - Bit-blasting for all bit-vector operators but equality.
  - “Bridge” between bit-vector terms and the boolean variables.
- Example: `./yices -e bv.ys`

```
(define b::(bitvector 4))
(assert (= b (bv-add 0b0010 0b0011)))
(check)
```

$\longrightarrow$ unsat

```
(= b 0b0101)
```

Dependent types

- Useful for stating properties of uninterpreted functions.
- Alternative to quantifiers.
- Example: `./yices -e d.ys`

```
(define x::real)
(define y::int)
(define floor::(-> x::real
    (subtype (r::int) (and (>= x r)
                           (< x (+ r 1))))))
(assert (and (> x 5) (< x 6)))
(assert (= y (floor x)))
(check)
```

$\longrightarrow$ sat

```
(= x 11/2) (= y 5) (= (floor 11/2) 5)
```

Quantifiers

- Main approach: egraph matching (Simplify)
  - Extension for offset equalities and terms.
  - Several triggers (multi-patterns) for each universally quantified expression.
  - The triggers are fired using a heuristic that gives preference to the most conservative ones.
- Fourier Motzkin elimination to simplify quantified expressions.
- Instantiation heuristic based on:

  What's Decidable About Arrays?,

  A. R. Bradley, Z. Manna, and H. B. Sipma, VMCAI'06.

Quantifiers (cont.)

- Yices may return `unknown` for quantified formulas.
- The model should be interpreted as a “potential model”.
- Tuning egraph matching:
  - `-mi <num>` – Maximum number of quantifier instantiations.
  - `-mp <num>` – Maximum number of patterns per quantifier.
  - `-pc <num>` – Pattern generation heuristic (0: liberal, 2: conservative).
- Advice: try conservative setting first.

Quantifiers: example

- `./yices q.ys`

```
(define f::(-> int int))
(define g::(-> int int))
(define a::int)
(assert (forall (x::int) (= (f x) x)))
(assert (forall (x::int) (= (g (g x)) x)))
(assert (/= (g (f (g a))) a))
(check)
```

$\longrightarrow$ unsat

C API

- Yices distribution comes with a C library.
- Two different APIs:
  - `yices_c.h`
  - `yicesl_c.h` (Lite version).

Conclusion

- Yices is an efficient and flexible SMT solver.
  - Yices supports all theories in SMT-LIB and much more.
  - It is being used in SAL, PVS, and CALO.
- Yices is not ICS.
- Yices is freely available for end-users.
  - `http://yices.csl.sri.com`
- Supported Platforms:
  - Linux
  - Windows: Cygwin & MinGW
  - Mac OSX