

# CS 433 Automated Reasoning 2021

## Lecture 4: Encoding into reasoning problems

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# Topic 4.1

## Z3 solver

# Solver basic interface

- ▶ Input : formula
- ▶ Output: sat/unsat

If satisfiable, we may ask for a satisfying assignment.

## Exercise 4.1

*What can we ask from a solver in case of unsatisfiability?*

## Z3: SMT solver

- ▶ Written in C++
- ▶ Provides API in C++ and Python
- ▶ We will initially use python interface for quick ramp up
- ▶ Later classes we will switch to C++ interface

## Installing Z3 (Ubuntu-18.04)

```
$sudo apt-get install z3
```

Not tested on 20.04

**Commentary:** You may also try `$pip3 install python3-z3`

## Locally Installing a version of Z3 (Linux)

Let us install z3-4.7.1. You may choose another version.

- ▶ Download

```
https://github.com/Z3Prover/z3/releases/download/z3-4.7.1/z3-4.7.1-x64-ubuntu-16.04.zip
```

- ▶ Unzip the file in some folder. Say

```
/path/z3-4.7.1-x64-ubuntu-16.04/
```

- ▶ Update the following environment variables

```
$export LD_LIBRARY_PATH=$LD_LIBRARY_PATH:/path/z3-4.7.1-x64-ubuntu-16.04/bin  
$export PYTHONPATH=$PYTHONPATH:/path/z3-4.7.1-x64-ubuntu-16.04/bin/python
```

- ▶ After the setup the following call should throw no error

```
$python3 /path/z3-4.7.1-x64-ubuntu-16.04/bin/python/example.py
```

## Topic 4.2

### Using solver

## Steps of using Z3 via python interface

```
from z3 import *           # load z3 library

p1 = Bool("p1")           # declare a Boolean variable
p2 = Bool("p2")

phi = Or( p1, p2 )        # construct the formula
print(phi)                # printing the formula

s = Solver()              # allocate solver
s.add( phi )              # add formula to the solver
r = s.check()             # check satisfiability
if r == sat:
    print("sat")
else:
    print("unsat")        # save the script test.py
                           # run \python3 test.py
```



## Get a model

```
r = s.check()
if r == sat:
    m = s.model()      # read model
    print(m)          # print model
else:
    print("unsat")
```

### Exercise 4.2

What happens if we run `m = s.model()` in the `unsat` case?

## Solve and print model

```
from z3 import *

# packaging solving and model printing
def solve( phi ):
    s = Solver()
    s.add( phi )
    r = s.check()
    if r == sat:
        m = s.model()
        print(m)
    else:
        print("unsat")

# we will use this function in later slides
```

## Pointer and variable

There is a distinction between the Python variable name and the propositional variable it holds.

```
from z3 import *      # load z3 library

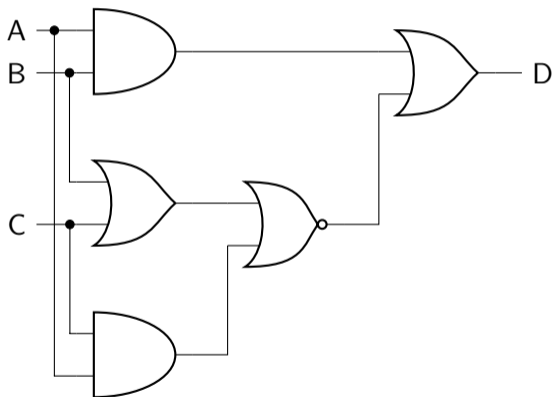
x = Bool("y")        # creates Propositional variable y

z = x                 # python pointer z also holds variable y
```

## Exercise: encoding Boolean circuit

### Exercise 4.3

Using Z3, find the input values of A, B, and C such that output D is 1.



We know you can do it! Please do not shout the answer. Please make computer find it.

## Topic 4.3

### Solver engineering

## Design of solvers: context vs. solver

Any complex software usually has a context object.

The context consists of a **formula store** containing the constructed formulas.

Z3 Python interface **instantiates a default context**. Therefore, we do not see it explicitly.

A `Solver` is a solving instance. There can be **multiple solvers** in a context.

The `Solver` solves only the added formula.

## Formula handling

```
a = Bool('a')
b = Bool('b')
ab = And( a, b )

# accessing sub-formulas
print(ab.arg(0))
print(ab.arg(1))

# accessing the symbol at the head
ab_decl = ab.decl()
name = ab_decl.name()
if name == "and":
    print("Found an And")
```

## Topic 4.4

### Theory formulas



## Solving rational(real) arithmetic

```
x = Real('x')  
y = Real('y')  
phi = And(x + y > 5, x > 1, y > 1)  
solve(phi)
```

For linear arithmetic  
Real == rational

## Solving integer arithmetic

```
x = Int('x')
y = Int('y')
phi = And(x + y > 5, x > 1, y > 1)
solve( phi )
```

## Exercise: bounded model checking

### Exercise 4.4

*Using Z3, find the inputs  $x$  and  $y$  such that the assert fails.*

```
int foo( int x, int y ) {  
    int z = 3*x + 2*y - 3;  
    if( y > 0 )  
        assert( z != 0 );  
}
```

## Solving bit precise

```
x = BitVec('x',32) # declare name and bit length
y = BitVec('y',32)
phi = And(x + y > 5, x > 1, y > 1)
solve( phi )
```

- ▶ Bit lengths must match in an operation
- ▶ Largely solved by **bit blasting**
- ▶ Far more expensive to solve!

converting Bit-vector formulas into Boolean formulas by replacing vectors by bits and operation by circuits.

## Exercise : observe overflow behavior

### Exercise 4.5

*Give a bit-vector formula that is satisfiable due to overflow of addition, but in infinite precision it is unsatisfiable.*

## Uninterpreted functions

```
x = Int('x')
y = Int('y')

# declaring Int -> Int function
h = Function('h', IntSort(), IntSort() )

phi = And( h( x ) > 5, h( y ) < 2 )

solve( phi )
```

## Exercise:

### Exercise 4.6

*Give a satisfying model of the following formula*

$$g(x, y) < 0 \wedge g(y, x) > 0 \wedge y = x$$

## Uninterpreted sorts

```
u = DeclareSort('U') # declaring new sort

c = Const('c', u) # declaring a constant of the sort

f = Function('f', u, u) # declaring a function of the sort

# declaring a predicate of the sort
P = Function('P', u, BoolSort())

phi = And( f(c) == c, P( f(c) ), Not( P(c) ) )

solve( phi )
```

### Exercise 4.7

*Get model after dropping the third atom. Interpret the model.*

**Commentary:** Hint: the solver also chooses domains for the uninterpreted sorts, and the models of the functions are presented in terms of the domains.



## Topic 4.5

### Quantified formulas

## Quantifiers

```
u = DeclareSort('U')
H = Function('Human', u, BoolSort() )
M = Function('Mortal', u, BoolSort() )

# Humans are mortals
x = Const('x', u )
all_mort = ForAll( x, Implies( H(x), M(x) ) )

s = Const('Socrates', u )
thm = Implies( And( H(s), all_mort ), M(s) )

solve( Not(thm) ) # negation of a valid theorem
                  # is unsatisfiable
```

## Exercise: solving quantified formulas

### Exercise 4.8

*Prove/disprove if the following statement is valid.*

*There is someone such that if the one drinks, then everyone drinks*

### Exercise 4.9

*Write a formula that only accepts infinite models. Encode the formula in Z3 and get model.*

## Quantified formula handling

```
u = DeclareSort('U')
H = Function('Human', u, BoolSort() )
M = Function('Mortal', u, BoolSort() )
x = Const( 'x', u )
y = Const( 'y', u )

all_mort = ForAll( x, Implies( H(x), M(x) ) )
print(all_mort.body())
# Output: Implies(Human(Var(0)), Mortal(Var(0)))
# Var(0) is FOL variable
# Naming quantified variables using DeBruijn index

alt = ForAll( x, Exists( y, Implies( H(x), M(y) ) ) )
print(alt.body().body())
# Output: Implies(Human(Var(1)), Mortal(Var(0)))
```

## Topic 4.6

### SMT2 format

# API vs Input language

- ▶ Each solver has their own API
- ▶ We need a **common input** format for
  - ▶ interoperability and
  - ▶ database of problems

## Standard format for SMT solvers

SMT2 is a standard input format for SMT solvers.

`http://smtlib.cs.uiowa.edu/language.shtml`

- ▶ Formulas are written in prefix notation (why?)

`(>= (* 2 x) (+ y z))`

- ▶ There is a simple type system. Similar to Z3 API.
- ▶ Solver interacts like a stack

# File format

An SMT2 file has five parts

1. Preamble declarations
2. Sort declarations
3. Variable declarations
4. Asserting formulas
5. Solving commands



## Preamble declaration

- ▶ Set configurations of the solvers

```
(set-logic QF_UFLIA) ;setting Theory/Logic
```

```
(set-option :produce-proofs true) ;enable proof generation if input is unsat
```

## Sort declarations

- ▶ Declare new sorts of the variables

```
(declare-sort symbol numeral)
```

### Example 4.1

```
(declare-sort U 0) ; new sort with no parameters  
(declare-sort Arr 2) ; new sort with two parameters
```

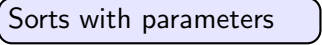
## Variable declarations

- ▶ Declare variables and functions that may be used in the formulas

```
(declare-fun symbol (sort*) sort)
```

### Example 4.2

```
(declare-fun x () Int) ;declare variable  
(declare-fun f (Int) Int) ;declare a function with one argument  
(declare-fun g (Int Int) Int) ;declare a function with two arguments  
(declare-fun h ((Arr U Int) Int) Int);declare a function with two argument
```



Sorts with parameters

# Asserting formulas

- ▶ Formulas are asserted in a sequence

## Example 4.3

```
(assert (>= (* 2 x) (+ y z)))  
(assert (< (f x) (g x x)))  
(assert (> (f y) (g x x)))
```

# Commands

- ▶ Commands are the actions that solver needs to do

## Example 4.4

```
(check-sat) ; checks if the conjunction of asserted formula is sat  
(get-model) ; returns a model if the formulas are sat
```

## Stack interaction

The standard is designed to be interactive

- ▶ Asserted formulas are pushed in the stack of the solver
- ▶ `(push)` command places marker on the stack
- ▶ `(pop)` removes the formulas upto the last marker

### Example 4.5

```
(push)
(assert (= x y))
(check-sat)
(pop)
```

*After the pop the solver state goes back to the last push. Useful in interactive use of solver.*

## Full example

```
(set-logic QF_UFLIA)
(set-option :produce-proofs true)
(declare-fun x () Int)
(declare-fun y () Int)
(declare-fun z () Int)
(declare-fun f (Int) Int)
(declare-fun g (Int Int) Int)
(assert (>= (* 2 x) (+ y z)))
(assert (< (f x) (g x x)))
(assert (> (f y) (g x x)))
(check-sat)
(get-model)
(push)
(assert (= x y))
(check-sat)
(pop)
(exit)
```

`http://rise4fun.com/z3`



# Topic 4.7

## Problems

## Exercise : Python programming

### Exercise 4.10

Write a Python program that generates a random graph in a file `edges.txt` for  $n$  nodes and  $m$  edges, which are given as command line options.

Please store edges in `edges.txt` as the following sequence of tuples

10,12

30,50

....

### Exercise 4.11

Write a program that reads a directed graph from `edges.txt` and finds the number of **strongly connected components** in the graph

### Exercise 4.12

Write a program that reads a directed graph from `edges.txt` and finds the cliques of size  $k$ , which is given as a command line option.

# Proving theorems

## Exercise 4.13

*Prove/disprove the following theorems using a solver*

- ▶ *Sky is blue. Space is black. Therefore sky and space are blue or black.*
- ▶ *Hammer and chainsaw are professional tools. Professional tools and vehicles are rugged. Therefore, hammers are rugged.*

## Write a function: find positive variables

### Exercise 4.14

*Find the set of Boolean variables that occur only positively in a propositional logic formula.*

*An occurrence of a variable is positive if there are even number of negations from the occurrence to the root of the formula.*

*Examples:*

*Only  $q$  occurs positively in  $p \wedge \neg(\neg q \wedge p)$ .*

*$p$  occurs positively in  $\neg\neg p$ .*

*$p$  does not occur positively in  $\neg p$ .*

*$p$  and  $q$  occur positively in  $(p \vee \neg r) \wedge (r \vee q)$ .*

## Write a function: compute linear coefficient

### Exercise 4.15

*Find coefficient of each variable in a linear term. If the term is non-linear, throw an exception.*

*Examples:*

*$x - 2x + y + 4$  should return  $[4, -1, 1]$  if variables are ordered  $[x, y]$ .*

*$x - x + 4y - 2(2y)$  should return  $[0, 0, 0]$  if variables are ordered  $[x, y]$ .*

*$(x + 1) * y$  should throw an exception*

## Write a function: find quantifier alternation depth

### Exercise 4.16

*Compute quantifier alternations depth of a sentence.*

*Maximum number of quantifier type switches is any path from an atom to the root.*

*Examples: quantifier alternations depth of*

$\forall x. \exists y. E(x, y)$  *is 1.*

$\forall x. \exists y. \forall z. E(x, y, z)$  *is 2.*

$\forall x. \forall y. E(x, y)$  *is 0.*

$\forall x. ( (\exists y. H(x, y)) \Rightarrow G(x) )$  *is 0.* ( $\exists$  under negation is  $\forall$  and vice-versa)

$\forall x. ( (\exists y. H(x, y)) \Rightarrow \exists z. G(x, z) )$  *is 1.*

## Write a function: find unrelated constraints

### Exercise 4.17

*Consider a formula  $F$  consists of only a conjunction of atoms. Find the partitions of  $F$  that have disjoint set of uninterpreted symbols.*

*Examples:*

*$x = y \wedge x = z \wedge P(u)$  has two unrelated subsets  $\{x = y, x = z\}$  and  $\{P(u)\}$*

*$x + y = 3 \wedge z + u \geq 10$  has two unrelated subsets  $\{x + y = 3\}$  and  $\{z + u \geq 10\}$ , while they have a common interpreted symbol  $+$ .*

## Write a function: find maximum occurring symbol

### Exercise 4.18

Consider a formula  $F$ . Find the uninterpreted symbol in  $F$  that occurs most often.

Examples:

$x$  occurs most often in  $g(g(x, x), g(x, x))$ .

$f$  occurs most often in  $f(x, y) = f(x, b) \wedge f(2, 3) > 10$ .

$D$  occurs most often in  $\exists x.(D(x) \Rightarrow D(x + 1))$ . *quantified variables are not counted.*



## Write a function: find common symbols

### Exercise 4.19

Consider formulas  $F_1$  and  $F_2$ . Find uninterpreted symbols that occur both in  $F_1$  and  $F_2$ .

Examples:

$\{x, f\}$  occurs  $f(x) > 3$  and  $f(y) < x$ , but not  $y$

$\{f\}$  occurs  $f(x) > 3$  and  $\forall x.f(x) > y$ , but not  $x$  and  $y$ .

$\{f, x\}$  occurs  $f(x) > 3$  and  $x > 20 \vee \forall x.f(x) > y$ . *quantified variables are not counted.*

# Integer vs. Reals

## Exercise 4.20

*Consider the following constraints*

$$3x - y \geq 2 \wedge 3y - z \geq 3 \wedge 3 \geq x + y$$

*Solve the above constraints using SMT solver under the following theories*

- ▶ *Reals (QF\_LRA)*
- ▶ *Int (QF\_LIA)*

End of Lecture 4