4. SMT Technology

Prof. Roberto Amadini

Department of Computer Science and Engineering, University of Bologna, Italy

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SMT Solvers

- Given a theory $\mathcal{T}$, a $\mathcal{T}$-solver is a procedure for deciding whether a conjunction of $\mathcal{T}$-literals is satisfiable
  - $\mathcal{T} =$ EUF, arithmetic, arrays, bit-vectors,...
- We can define a SMT solver as a collection of $\mathcal{T}_i$-solvers for different theories $\mathcal{T}_i$
  - Maybe combinations of these theories
- SMT solvers can handle formulas involving variables of different sort
  - sort $\approx$ type (Integer, Real, Array, String, ...)
- The user interacts with SMT solver through queries
  - e.g., to check the satisfiability of a formula or add new formulas

SMT Solvers

- Nowadays plenty of SMT solvers available
    - Especially used for software analysis applications
- Some of them are "special-purpose"
    - E.g., only for solving bit-vectors or non-linear arithmetic formulas
- Some others more "general-purpose"
    - They can handle disparate theories
    - We shall see 2 of them: Z3 and CVC5

Z3

- Z3 is a well-known SMT solver with specialized algorithms for efficiently tackling several theories
  - First paper describing Z3: De Moura, L., and N. Bjørner. "*Z3: An efficient SMT solver*" TACAS 2008
- Z3 is open source: `https://github.com/z3prover/z3`
- It provides APIs for common programming languages
  - E.g., Z3Py
  - `https://ericpony.github.io/z3py-tutorial/guide-examples.htm`
- Let's see some of the Z3 main features
  - From `https://theory.stanford.edu/~nikolaj/programmingz3.html`

Z3Py Example

```python
from z3 import *
Tie, Shirt = Bools('Tie Shirt')
s = Solver()
s.add(
  Or(Tie, Shirt),
  Or(Not(Tie), Shirt),
  Or(Not(Tie), Not(Shirt))
)
print(s.check())
print(s.model())
```

- The solver check if $(Tie \vee Shirt) \wedge (\neg Tie \vee Shirt) \wedge (\neg Tie \vee \neg Shirt)$ is satisfiable, and in case prints a model
  - Is this formula satisfiable?

`tie_shirt.py`

Z3Py Example

```
from z3 import *
Tie, Shirt = Bools('Tie Shirt')
s = Solver()
s.add(
  Or(Tie, Shirt),
  Or(Not(Tie), Shirt),
  Or(Not(Tie), Not(Shirt))
)
print(s.check())
print(s.model())
```

- The solver check if $(Tie \vee Shirt) \wedge (\neg Tie \vee Shirt) \wedge (\neg Tie \vee \neg Shirt)$ is satisfiable, and in case prints a model
  - Is this formula satisfiable?

```
sat
[Tie = False, Shirt = True]
```

Z3 Sorts

- Z3 handles different sorts apart from built-in `Bool`, e.g.
  - `Int`
  - `Real`
  - `BitVec`
  - `Array`
  - `String`

- Formulas are terms of `Bool` sort. They may include (un-)interpreted functions and constants. E.g., in:

```
B = BoolSort() ; Z = IntSort()
f = Function('f', B, Z) ; g = Function('g', Z, B)
a = Bool('a')
solve(g(1+f(a)))
```

  we have $f : \mathbb{B} \to \mathbb{Z}, g : \mathbb{Z} \to \mathbb{B}, a \in \mathbb{B}$, with $\mathbb{B} = \{\mathit{true}, \mathit{false}\}$ and we ask if $g(1 + f(a))$ is satisfiable

Example

```
Z = IntSort()
f = Function('f', Z, Z)
x, y, z = Ints('x y z')
A = Array('A', Z, Z)
fml = Implies(x + 2 == y,
              f(Store(A, x, 3)[y-2]) == f(y-x+1))
solve(Not(fml))
```

Here `fml` corresponds to formula:

$$x + 2 = y \implies f(\mathit{write}(A, x, 3)[y - 2]) = f(y - x + 1)$$

so `Not(fml)` is:

$$x + 2 = y \ \wedge \ f(\mathit{write}(A, x, 3)[y - 2]) \neq f(y - x + 1)$$

Is `Not(fml)` satisfiable?

`not_fml.py`

Arithmetic theory

- Arithmetical constraints are clearly fundamental. Z3 has different procedures according to which fragment of arithmetic is used:

Logic	Description	Solver	Example
LRA	Linear Real Arithmetic	Dual Simplex [28]	$x + \frac{1}{2}y \leq 3$
LIA	Linear Integer Arithmetic	Cuts + Branch	$a + 3b \leq 3$
LIRA	Mixed Real/Integer	[7, 12, 14, 26, 28]	$x + a \geq 4$
IDL	Integer Difference Logic	Floyd-Warshall	$a - b \leq 4$
RDL	Real Difference Logic	Bellman-Ford	$x - y \leq 4$
UTVPI	Unit two-variable / inequality	Bellman-Ford	$x + y \leq 4$
NRA	Polynomial Real Arithmetic	Model based CAD [42]	$x^2 + y^2 < 1$
NIA	Non-linear Integer Arithmetic	CAD + Branch [41]	$a^2 = 2$
		Linearization [15]	

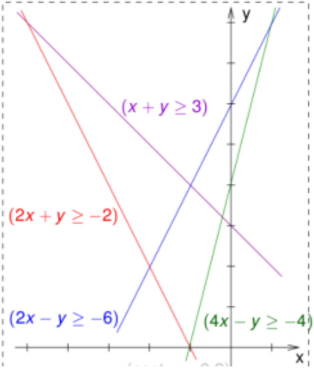
CAD = Cylindrical Algebraic Decomposition

- If we need to precisely model finite precision arithmetic, then using fixed-width bit-vectors is probably a better choice
  - Z3 handles bit-vectors with eager SAT encoding (bit-blasting)

Example

$$\begin{aligned}\varphi \stackrel{\text{def}}{=} \; & (\neg A_1 \lor (2x + y \geq -2)) \\ \land \; & (\;\; A_1 \lor (x + y \geq 3)) \\ \land \; & (\neg A_2 \lor (4x - y \geq -4)) \\ \land \; & (\;\; A_2 \lor (2x - y \geq -6))\end{aligned}$$

```
from z3 import *
x, y = Ints('x y')
A1, A2 = Bools('A1 A2')
s = Solver()
s.add(Or(Not(A1), 2*x + y >= -2))
s.add(Or(A1, x + y >=  3))
s.add(Or(Not(A2), 4*x - y >= -4))
s.add(Or(A2, 2*x - y >= -6))
print(s.check())
print(s.model())
```

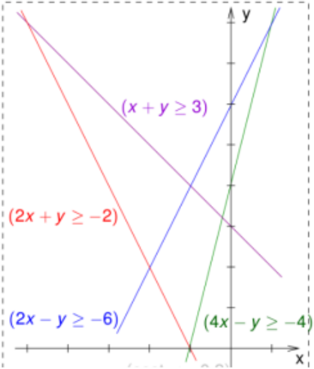


ex_lia.py

Example

$$
\begin{aligned}
\varphi \stackrel{\text{def}}{=} \quad & (\neg A_1 \vee (2x + y \geq -2)) \\
\wedge \quad & (\ \ A_1 \vee (x + y \geq 3)) \\
\wedge \quad & (\neg A_2 \vee (4x - y \geq -4)) \\
\wedge \quad & (\ \ A_2 \vee (2x - y \geq -6))
\end{aligned}
$$

```python
from z3 import *
x, y = Ints('x y')
A1, A2 = Bools('A1 A2')
s = Solver()
s.add(Or(Not(A1), 2*x + y >= -2))
s.add(Or(A1, x + y >=  3))
s.add(Or(Not(A2), 4*x - y >= -4))
s.add(Or(A2, 2*x - y >= -6))
print(s.check())
print(s.model())
```




```
[A1 = True, x = -1, A2 = False, y = 1]
```

(note we are not optimizing here)

Other theories

- Z3 offers a number of other theories:
  - Arrays
    - Via reduction to EUF
  - Floating points
    - Via reduction to Bit-vectors
  - Algebraic Datatypes
    - Captures the theory of finite trees
  - String and Sequences
    - Theory of free monoids + specific operations (length, replace, ...)

Incremental solving

- Z3 allows incremental solving via push and pop operations
  - This creates local scopes: assertions added within a “push” are retracted on the matching “pop”
  - CP solvers don’t have (yet?) this capability!

```
p, q, r = Bools('p q r')
s = Solver()
s.add(Implies(p,q))
s.add(Not(q))
print(s.check())  # sat:   p->q /\ !q
s.push()
s.add(p)          # unsat: p->q /\ !q /\ p
print(s.check())
s.pop()           # sat:   p->q /\ !q
print(s.check())
```

Z3 and optimization

- Z3 enables OMT via the `Optimize` module in 2 ways:
  - By specifying an objective function
  - Via soft constraints
- The objective function is either a linear arithmetical term or a bit-vector term
- Soft constraints are assertions that the solver can ignore. The goal is maximizing the satisfied soft constraints
  - MaxSMT
- Soft constraints might have an optional weight. In this case the goal is minimizing the sum of the weights of unsatisfied constraints

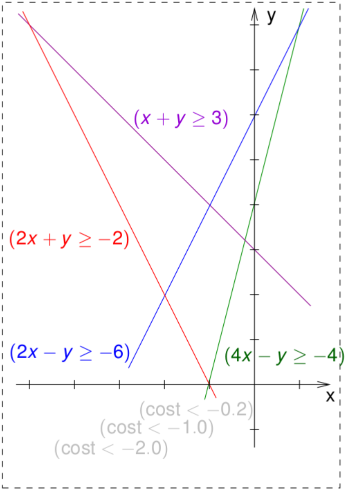
Example

[w. pure-literal filt. $\Longrightarrow$ partial assignments]

- OMT($\mathcal{LRA}$) problem:

$$
\begin{array}{rl}
\varphi \stackrel{\text{def}}{=} & (\neg A_1 \vee (2x + y \geq -2)) \\
\wedge & (A_1 \vee (x + y \geq 3)) \\
\wedge & (\neg A_2 \vee (4x - y \geq -4)) \\
\wedge & (A_2 \vee (2x - y \geq -6)) \\
\wedge & (\text{cost} < -0.2) \\
\wedge & (\text{cost} < -1.0) \\
\wedge & (\text{cost} < -2.0) \\
\text{cost} \stackrel{\text{def}}{=} & x
\end{array}
$$

- $$\mu = \left\{ \begin{array}{l} A_1, \neg A_1, \quad A_2, \neg A_2, \\ (4x - y \geq -4), \\ (x + y \geq 3), \\ (2x + y \geq -2), \\ (2x - y \geq -6) \\ (\text{cost} < -0.2) \\ (\text{cost} < -1.0) \\ (\text{cost} < -2.0) \end{array} \right\}$$



Example

```python
from z3 import *
x, y = Reals('x y')
A1, A2 = Bools('A1 A2')
s = Optimize()
s.add(Or(Not(A1), 2*x + y >= -2))
s.add(Or(A1, x + y >= 3))
s.add(Or(Not(A2), 4*x - y >= -4))
s.add(Or(A2, 2*x - y >= -6))
z = s.minimize(x)
print(s.check())
print(s.model())
print(z.value())
```

omt.py

Example

```
from z3 import *
x, y = Reals('x y')
A1, A2 = Bools('A1 A2')
s = Optimize()
s.add(Or(Not(A1), 2*x + y >= -2))
s.add(Or(A1, x + y >= 3))
s.add(Or(Not(A2), 4*x - y >= -4))
s.add(Or(A2, 2*x - y >= -6))
z = s.minimize(x)
print(s.check())
print(s.model())
print(z.value())

sat
[A1 = True, y = 2, x = -2, A2 = False]
-2
```

CVC

- Many other SMT solvers exist apart from Z3
  - https://smt-comp.github.io/2023/
- A well-known family of SMT solvers is CVC* (*Cooperating Validity Checker*), a saga originated at Stanford University
  - CVC (2002)
  - CVC Lite (2004)
  - CVC3 (2007)
  - CVC4 (2011)
  - CVC5 (2022): Barbosa, H., et al. "*cvc5: A Versatile and Industrial-Strength SMT Solver.*" International Conference on Tools and Algorithms for the Construction and Analysis of Systems 2022.

CVC5

- CVC5 is a major improvement of CVC4 1.8 (final CVC4 version)
  - New APIs, theories, solvers and procedures
- It provides strong performance on industrial use cases
- It is open-source: `https://github.com/cvc5/cvc5`
  - Releases: `https://github.com/cvc5/cvc5/releases`
- It can be programmed via APIs (C++,Java,Python) or executed in interactive mode
  - Documentation: `https://cvc5.github.io/docs/cvc5-0.0.11`
  - Optimization not supported, but they're working on that: `https://arxiv.org/abs/2404.16122`

SMT-LIB

- What solver should we use? Z3? CVC5? Both? None of them?
  - Yices2, Vampire, Bitwuzla, (Opti)MathSAT, ...
- Clearly each SOTA solvers has strengths and weaknesses, selecting the best of them for an unforeseen SMT formula is not trivial
  - Algorithm Selection problem
- Surely we shouldn't write $n > 1$ programs for solving the same formula with n solvers
  - *Model once, solve everywhere*
- Need for standardization

SMT-LIB

- SMT-LIB initiative started in 2003 to:
  - Provide rigorous descriptions of SMT theories
  - Develop and promote common languages for SMT solvers.
  - Connect developers, researchers and users of the SMT community
  - Establish and make available benchmarks for SMT solvers.
  - Collect and promote software tools useful to the SMT community
- SMT-LIB website: `https://smtlib.cs.uiowa.edu/`
- SMT-LIB 2.7 specifications (February 5, 2025): `https://smt-lib.org/papers/smt-lib-reference-v2.7-r2025-02-05.pdf`

SMT-LIB language

- SMT-LIB uses a parenthesized prefix notation (similar to LISP)
  - Designed to be machine-readable rather than human-readable
  - E.g. `(= (+ a b) c)` or `(< (f x) (g y z))`
- 3 main components: theory declarations, logic declarations, scripts
- SMT-LIB theories are defined by sorts and functions
  - Predicates $\equiv$ `Bool`-valued functions
  - E.g., theory of Ints, Reals, ...
- SMT-LIB logic $=$ Theory declarations $+$ restrictions on formulas
  - E.g., `QF_IDL` logic is based on theory of Ints and restricts (in)equalities to be of the form $x - y \bowtie k$ with $\bowtie \in \{=, \neq, <, \leq, \geq, >\}$

Theory of integers

```
(theory Ints

 :smt-lib-version 2.6
 :smt-lib-release "2017-11-24"
 :written-by "Cesare Tinelli"
 :date "2010-04-17"
 :last-updated "2015-04-25"
 :update-history
 "Note: history only accounts for content changes, not release changes.
  2015-04-25 Updated to Version 2.5.
 "

 :sorts ((Int 0))

 :funs ((NUMERAL Int)
        (- Int Int)                  ; negation
        (- Int Int Int :left-assoc)  ; subtraction
        (+ Int Int Int :left-assoc)
        (* Int Int Int :left-assoc)
        (div Int Int Int :left-assoc)
        (mod Int Int Int)
        (abs Int Int)
        (<= Int Int Bool :chainable)
        (<  Int Int Bool :chainable)
        (>= Int Int Bool :chainable)
        (>  Int Int Bool :chainable)
       )
```

Integer difference logic

```
(logic QF_IDL

 :smt-lib-version 2.6
 :smt-lib-release "2017-11-24"
 :written-by "Cesare Tinelli"
 :date "2010-04-30"
 :last-updated "2015-04-25"
 :update-history
 "Note: history only accounts for content changes, not release changes.
  2015-04-25 Updated to Version 2.5.
 "

 :theories ( Ints )

 :language
 "Closed quantifier-free formulas with atoms of the form:
  - q
  - (op (- x y) n),
  - (op (- x y) (- n)), or
  - (op x y)
  where
    - q is a variable or free constant symbol of sort Bool,
    - op is <, <=, >, >=, =, or distinct,
    - x, y are free constant symbols of sort Int,
    - n is a numeral.
 "
)
```

SMT-LIB syntax

- `set-logic` specifies the logic
  - E.g. `(set-logic QF_IDL)` or `(set-logic QF_LRA)`

- `declare-fun` introduces a new function symbol, so it can be used to declare variables too (variables $\equiv$ uninterpreted constants)
  - E.g., function `(declare-fun f (Int Int) Bool)` or variable `(declare-fun x () Real)`
  - Command `(declare-const x () Real)` is also available

- `assert` specifies formulas, and `check-sat` checks the satisfiability of all the specified formulas
  - E.g.,`(assert (= (+ a b) c))`

- Others: `(set-option :produce-models true)`, `(get-model)`, `(get-unsat-core (x))`, . . .

SMT-LIB script

- This is an example of SMT-LIB script, i.e., a sequence of commands

```
(set-logic QF_LRA)
(set-option :produce-models true)
(declare-fun x () Real)
(declare-fun y () Real)
(declare-fun A1 () Bool)
(declare-fun A2 () Bool)
(assert (or (not A1) (>= (+ (* 2 x) y) (- 2))))
(assert (or A1 (>= (+ x y) 3)))
(assert (or (not A2) (>= (- (* 4 x) y) (- 4))))
(assert (or A2 (>= (- (* 2 x) y) (- 6))))
(check-sat)
(get-model)
```

- It encodes $A1 \Rightarrow 2x + y \geq -2 \ \wedge \ \neg A1 \Rightarrow x + y \geq 3 \ \wedge \ A2 \Rightarrow 4x - y \geq -4 \ \wedge \ \neg A2 \Rightarrow 2x - y \geq -6$

ex_lra.smt2

SMT-LIB script

```
$ z3 ex_lra.smt2
sat
(
  (define-fun A1 () Bool true)
  (define-fun y  () Real (/ 13.0 5.0))
  (define-fun x  () Real (- (/ 3.0 5.0)))
  (define-fun A2 () Bool false)
)

$ cvc5 ex_lra.smt2
sat
(
  (define-fun x  () Real (/ 4 3))
  (define-fun y  () Real (/ 28 3))
  (define-fun A1 () Bool false)
  (define-fun A2 () Bool true)
)
```

Assertion stack

- SMT solvers react to commands by modifying an assertion stack
- Each stack element is called level and consists of a set of assertions
  - formulas + declarations/definitions of sorts and functions
- By default a new assertion always belongs to the current level
  - In the example above, only 1 level
- Levels can be added and removed with `push` and `pop` commands
  - pop removes all level assertions, including declarations/definitions

Incremental solving

```
(declare-fun x () Real)
(declare-fun y () Real)

(push 1)
(declare-fun A () Bool)
(assert (or (not A) (>= (+ (* 2 x) y) (- 2))))
(assert (or A (>= (- (* 4 x) y) (- 4))))
(check-sat)
(get-model)
(pop 1)

(declare-fun A () Int)
(assert (or (< A 0) (>= (- (* 4 x) y) (- 4))))
(assert (or (>= A 0) (< (- (* 2 x) y) (- 6))))
(check-sat)
(get-model)
```

ex_lra2.smt2

Incremental solving

- In the above example we have 2 levels
- After `(push 1)`, one decision level including declarations for Boolean variable `A` and $\{A \Rightarrow 2x + y \geq -2, A \Rightarrow 4x - y \geq -4\}$ is pushed on assertion stack
  - Then we check for satisfiability and ask for a model
- After `(pop 1)`, the last decision level is removed from the stack, so `A` can be declared again, this time with a different sort (`Int`)
  - Then we check again for satisfiability and ask for a model

Incremental solving

```
$ cvc5 -i --produce-models ex_lra2.smt2

sat
(
  (define-fun x () Real (/ (- 9) 8))
  (define-fun y () Real (/ (- 1) 2))
  (define-fun A () Bool false)
)
sat
(
  (define-fun x () Real 0.0)
  (define-fun y () Real 8.0)
  (define-fun A () Int (- 1))
)
```

SMT-LIB and optimization

- Standard SMT-LIB does not have an explicit support to optimization
- One possible workaround is to implement an offline OMT approach
  - SMT solvers as black-boxes
- SMT solver should be in incremental mode avoiding to restart each time a new bound is found
- In binary search mode, one should use push/pop primitives

Offline OMT($\mathcal{LRA}$)

Algorithm 1 Offline OMT($\mathcal{LA}(\mathbb{Q})$) Procedure based on Mixed Linear/Binary Search.

```
Require: ⟨φ, cost, lb, ub⟩ {ub can be +∞, lb can be −∞}
l ← lb; u ← ub; PIV ← ⊤; M ← ∅
φ ← φ ∪ {¬(cost < l), (cost < u)}
while (l < u ) do
    if (BinSearchMode()) then {Binary-search Mode}
        pivot ← ComputePivot(l, u)
        PIV ← (cost < pivot)
        φ ← φ ∪ {PIV}
        ⟨res, μ⟩ ← SMT.IncrementalSolve(φ)
        η ← SMT.ExtractUnsatCore(φ)
    else {Linear-search Mode}
        ⟨res, μ⟩ ← SMT.IncrementalSolve(φ)
        η ← ∅
    end if
    if (res = SAT) then
        ⟨M, u⟩ ← Minimize(cost, μ)          } u = current best bound
        φ ← φ ∪ {(cost < u)}
    else {res = UNSAT }
        if (PIV ∉ η) then                    } Linear search completed
            l ← u
        else
            l ← pivot                        } Updating binary search pivot
            φ ← φ \ {PIV}
            φ ← φ ∪ {¬PIV}
        end if
    end if
end while
return ⟨M, u⟩
```

From R. Sebastiani, S. Tomasi: *Optimization Modulo Theories with Linear Rational Costs*. ACM Trans. Comput. Log. 16(2): 12:1-12:43 (2015)

SMT-LIB $\Longleftrightarrow$ MiniZinc

- One may think to SMT-LIB as the SMT equivalent of MiniZinc language for CP problems
- SMT-LIB is actually "*lower-level*", more similar to FlatZinc language
  - MiniZinc models, together with optional data and solver-specific redefinitions, are compiled into FlatZinc instances
- Translating SMT-LIB $\rightarrow$ MiniZinc is quite straightforward, except that MiniZinc does not support all the standard SMT-LIB theories
  - E.g., theory of arrays and strings not officially supported by MiniZinc
  - Global constraints likely lost
- One can translate SMT-LIB $\rightarrow$ FlatZinc, if target solver is known or simply ignored

SMT-LIB $\Longleftrightarrow$ MiniZinc

- An early proposal to convert FlatZinc $\rightarrow$ SMT-LIB by Bofill et al. is fzn2smt, used by Yices SMT solver in MiniZinc Challenges 2010–2013
  - Based on obsolete MiniZinc versions and no longer maintained
- A prototypical converter SMT-LIB $\rightarrow$ MiniZinc called smt2mzn-str was developed by G. Gange for solving string constraints
  - String support in MiniZinc is still experimental
- Contaldo et al. proposed 2 compilers STM-LIB $\leftrightarrow$ FlatZinc called fzn2omt and omt2fzn
  - Contaldo, F. et al. "*From MiniZinc to Optimization Modulo Theories, and Back*". CPAIOR 2020.
  - They use the default MiniZinc $\rightarrow$ FlatZinc decomposition for global constraints and SMT-LIB with optimization extensions

Writing SMT-LIB

- From SMT-LIB standard: *"...Preferring ease of parsing over human readability is reasonable in this context not only because SMT-LIB benchmarks are meant to be read by solvers but also because they are produced in the first place by automated tools like verification condition generators or translators..."*
- One may write a SMT-LIB instance manually...
  - Tricky prefix notation, impractical for large instances
- ...or define an ad hoc script producing a SMT-LIB instance
  - E.g., Bash or Python script
- ...or define the instance with Z3 and then use Z3's API to generate a corresponding SMT-LIB instance
  - E.g., Z3Py + `to_smt2()` method of `Solver` class
  - Easier writing, no need to define ad hoc script
  - Translation may introduce additional variables

Z3Py Example

```
from z3 import *
Tie, Shirt = Bools('Tie Shirt')
s = Solver()
s.add(
  Or(Tie, Shirt),
  Or(Not(Tie), Shirt),
  Or(Not(Tie), Not(Shirt))
)
print(s.to_smt2())
print(s.dimacs())
```

- to_smt2 returns the SMT-LIB instance for solver's assertions
- dimacs returns the DIMACS instance for solver's assertions

tie_shirt.py

SMT-LIB output

```
; benchmark generated from python API
(set-info :status unknown)
(declare-fun Shirt () Bool)
(declare-fun Tie () Bool)
(assert
  (or Tie Shirt))
(assert
  (let (($x8 (not Tie)))
  (or $x8 Shirt)))
(assert
  (let (($x8 (not Tie)))
  (or $x8 (not Shirt))))
(check-sat)
```

- Note the introduction of $x8, a local variable defined through the let binder

DIMACS output

```
p cnf 2 3
1 2 0
-1 2 0
-1 -2 0
c 1 Tie
c 2 Shirt
```

- Header `p cnf 2 3` means CNF formula with 2 variables and 3 clauses
- Follows one clause per line, terminated with `0`
  - `1 2 0` is the clause $x_1 \lor x_2$
  - `-1 2 0` is the clause $\neg x_1 \lor x_2$
  - `-1 -2 0` is the clause $\neg x_1 \lor \neg x_2$
- Each line that begins with `c` is a comment

Exercises

- CVC5 + IDL Theory project: write C++ code
  https://github.com/cvc5/cvc5/blob/idl-lab/project.md
- Define SMT-LIB specifications for well-known NP-Hard problems (subset-sum, knapsack, TSP, ...) and solve with different SMT solvers
- Take some MiniZinc models and manually translate to SMT-LIB
  https://github.com/MiniZinc/minizinc-benchmarks
  - compare with fzn2omt translation
    https://github.com/PatrickTrentin88/fzn2omt

Resources

- Z3 solver
  - *Programming Z3*. N. Bjørner, L. de Moura, L. Nachmanson, and C. Wintersteiger https://theory.stanford.edu/~nikolaj/programmingz3.html
  - https://ericpony.github.io/z3py-tutorial/guide-examples.htm
- CVC5 solver
  - https://cvc5.github.io/
  - https://github.com/cvc5/cvc5
- SMT-LIB initiative
  - https://smtlib.cs.uiowa.edu/
  - https://smtlib.cs.uiowa.edu/papers/smt-lib-reference-v2.6-r2017-07-18.pdf