Murxla: A Modular and Highly Extensible API Fuzzer for SMT Solvers

Aina Niemetz

joint work with Mathias Preiner and Clark Barrett

AHA Meeting, March 2, 2022

Stanford University

Satisfiability Modulo Theories (SMT) Problem

Given a FOL formula and a combination of theories

$$((x \ll 01) \geq 00) \land (x < 01) \land ((\mathrm{read}(\mathrm{write}(a, x, x), x \cdot 10) = x + 01)$$

$x, 00, 01, 10$ ... Bit-Vectors of size 2 a ... Array

is there an assignment to x such that this formula evaluates to **true**?

SMT Solvers

- **Tools to solve the SMT Problem**
  - back-ends in higher-level tool chains
  - complex and large pieces of software
    - Bitwuzla: $\sim$ 90k LOC
    - cvc5: $\sim$ 300k LOC
    - z3: $\sim$ 500k LOC
  - **strong requirements:**
    - performance
    - robustness
    - correctness

SMT Solvers

- **Tools to solve the SMT Problem**
  - back-ends in higher-level tool chains
  - complex and large pieces of software
    - Bitwuzla: ∼ 90k LOC
    - cvc5: ∼ 300k LOC
    - z3: ∼ 500k LOC
  - **strong requirements:**
    - performance
    - robustness
    - correctness

SMT Solvers

- **Tools to solve the SMT Problem**
  - back-ends in higher-level tool chains
  - complex and large pieces of software
    - Bitwuzla: $\sim$ 90k LOC
    - cvc5: $\sim$ 300k LOC
    - z3: $\sim$ 500k LOC
  - **strong requirements:**
    - performance
    - robustness
    - correctness
  - **traditional testing:**
    - unit testing
    - maintaining a regression test suite
    - insufficient for achieving high levels of robustness
  - random stress testing (**fuzzing**)

Fuzz Testing SMT Solvers

SMT solvers provide **two** interfaces:

- textual interface (SMT-LIB)
    - input fuzzing
- application programming interface (API)
    - API fuzzing

Fuzz Testing SMT Solvers

SMT solvers provide **two** interfaces:

- textual interface (SMT-LIB)
  - input fuzzing

full knowledge of input structure

- application programming interface (API)
  - API fuzzing

Fuzz Testing SMT Solvers

SMT solvers provide **two** interfaces:

full knowledge of input structure

- ▶ textual interface (SMT-LIB)
  - ▶ input fuzzing
  - ▷ generate valid SMT-LIB input
  - + significantly less effort
  - − no solver-specific features
- ▶ application programming interface (API)
  - ▶ API fuzzing
  - ▷ link against solver library
  - ▷ generate valid sequences of solver API calls
  - + solver-specific features
  - + subsumes input fuzzing (except parser)
  - − more involved

Input vs. API Fuzzing

```
Solver slv;
Sort sort_int = slv.getIntegerSort(), "x");   // Int
Term x = slv.mkConst(sort_int);               // (declare-fun x () Int)
Term y = slv.mkConst(sort_int, "y");          // (declare-fun y () Int)
slv.assertFormula(slv.mkTerm(DISTINCT, x, y); // (assert (distinct x y))
slv.checkSat();                               // (check-sat)
Term p = slv.mkTerm(PLUS, x, y);              // (+ x y)
Term v = slv.getValue(p);                     // (get-value ((+ x y)))
Term e = slv.mkTerm(EQUAL, p, v);             // ???
slv.checkSatAssuming(e);                      // (check-sat-assuming (???))
```

Murxla

Murks ...	a German (rather informal) word for a *botch* or *screw-up*
⇩	
Murxla ...	a tool to find *Murks*es (bugs) in SMT solvers via API fuzzing

Murxla

Murks …	a German (rather informal) word for a *botch* or *screw-up*
⇩	
Murxla …	a tool to find *Murks*es (bugs) in SMT solvers via API fuzzing

What do we consider a bug?

- soundess issues
  - solver answers *unsat* when input is *sat*
  - solver answers *sat* when input is *unsat*
- crashes (assertion failures, segmentation faults, ...)
- performance regressions

Murxla

... a model-based API Fuzzer for SMT solvers

Murxla

... a $\boxed{\text{model-based API Fuzzer}}$ for SMT solvers

$\Downarrow$

lifts grammar-based input
fuzzing to API level

- semantic (data) model
  - defines constructs (theories, sorts, operators, commands)
  - based on SMT-LIBv2
- API model
  - defines the usage of the solver API itself
- options model
  - defines solver configuration options and valid combinations

Murxla

... a model-based API Fuzzer $\overset{++}{\vee}$ for $\overset{\text{all}^{*}}{\vee}$ SMT solvers

- model-based **API fuzzer**
  - generates valid sequences of solver API calls
- **Tracer**
  - records API call sequences as an API trace
- **Delta Debugger**
  - minimizes API traces while preserving the original behavior
- **Untracer**
  - replays API traces to reproduce original behavior

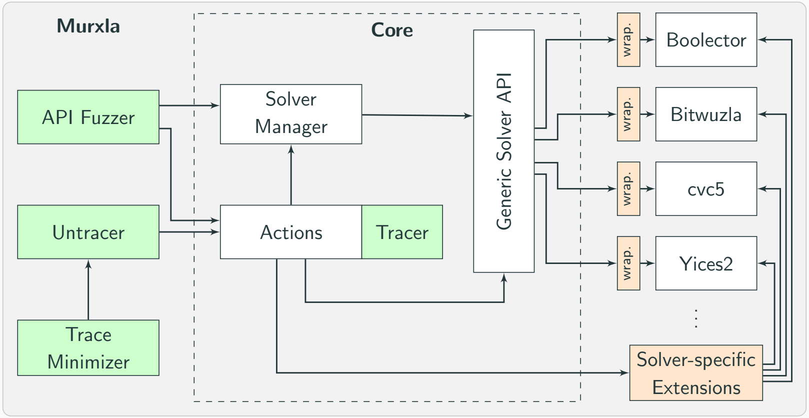
* Provided they allow being integrated into a C++ tool.

Murxla

… a model-based API Fuzzer $\overset{++}{\curlyvee}$ for $\overset{\text{all}^*}{\curlyvee}$ SMT solvers

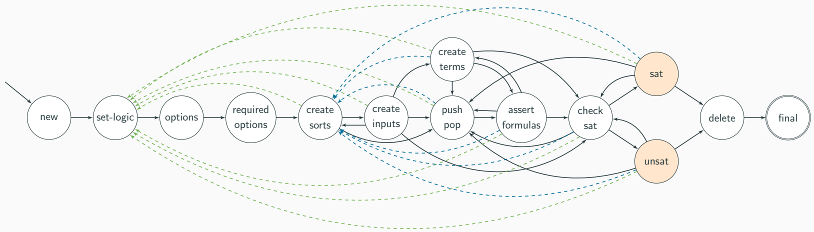
- **translate** API traces to **SMT-LIBv2**
  - ▷ if trace doesn't contain solver-specific extensions
  - ▷ especially useful for minimized traces
  - ▷ can then be further reduced with ddSMT
- **generate** SMT-LIBv2 input
  - ▷ can be used as SMT-LIB input fuzzer with any solver binary
- **cross-check** two solver instances
  - ▷ two integrated solvers under test
  - ▷ one integrated solvers vs. a solver via the SMT-LIBv2 interface

Murxla Architecture

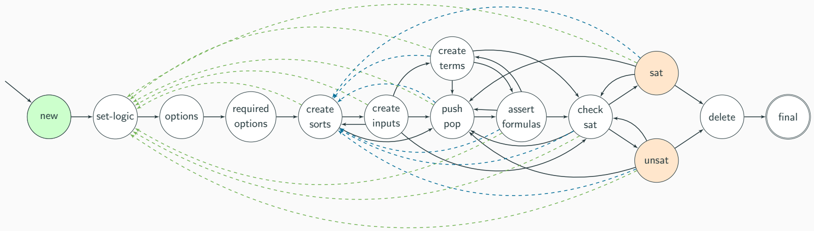


API Fuzzer

- weighted finite state machine
- transition executes action
- actions are recorded/traced
- step through until solver crashes, time limit or final state is reached

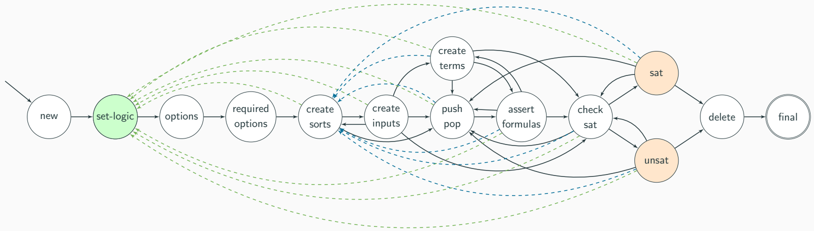


API Trace



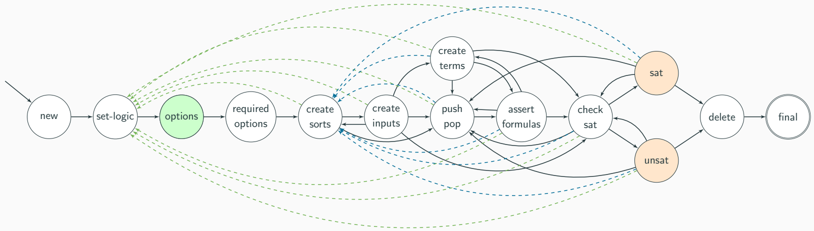
```
74761 new
```

API Trace



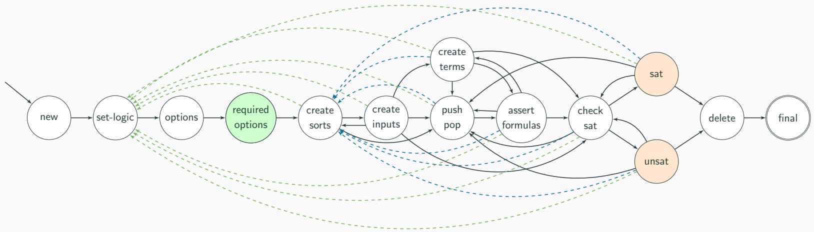
```
74761 new
65471 set-logic QF_BV
```

API Trace



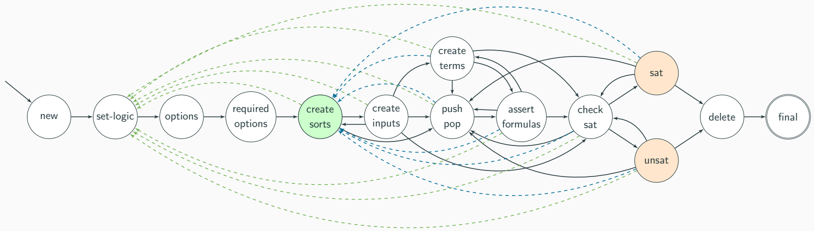
```
74761 new
65471 set-logic QF_BV
```

API Trace



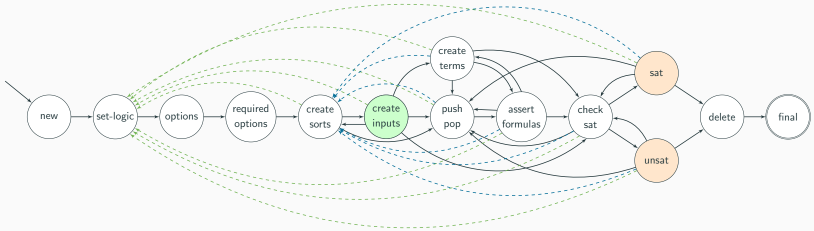
```
74761 new
65471 set-logic QF_BV
```

API Trace



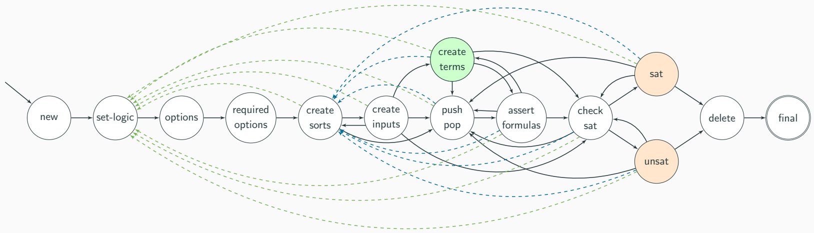
```
74761 new
65471 set-logic QF_BV
33949 mk-sort SORT_BOOL
      return s1
64345 mk-sort SORT_BV 8
      return s2
```

API Trace



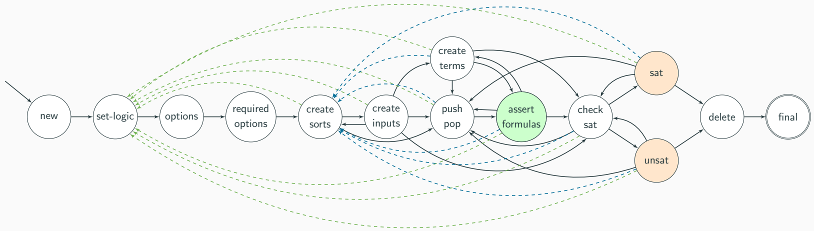
```
74761 new                      89712 mk-const s2 "b"
65471 set-logic QF_BV                return t2
33949 mk-sort SORT_BOOL
      return s1
64345 mk-sort SORT_BV 8
      return s2
49391 mk-const s2 "a"
      return t1
```

API Trace



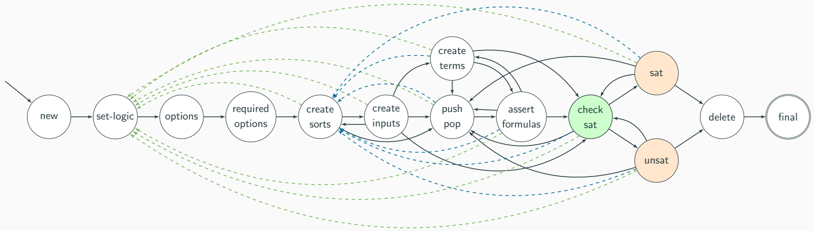
```
74761 new                       89712 mk-const s2 "b"
65471 set-logic QF_BV                 return t2
33949 mk-sort SORT_BOOL         6548 mk-term OP_EQUAL SORT_BOOL 2 t1 t2
      return s1                      return t3 s1
64345 mk-sort SORT_BV 8
      return s2
49391 mk-const s2 "a"
      return t1
```

API Trace



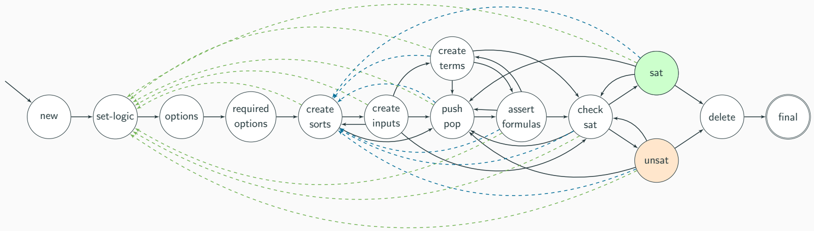
```
74761 new                            89712 mk-const s2 "b"
65471 set-logic QF_BV                       return t2
33949 mk-sort SORT_BOOL              6548 mk-term OP_EQUAL SORT_BOOL 2 t1 t2
      return s1                           return t3 s1
64345 mk-sort SORT_BV 8              20351 assert-formula t3
      return s2
49391 mk-const s2 "a"
      return t1
```

API Trace



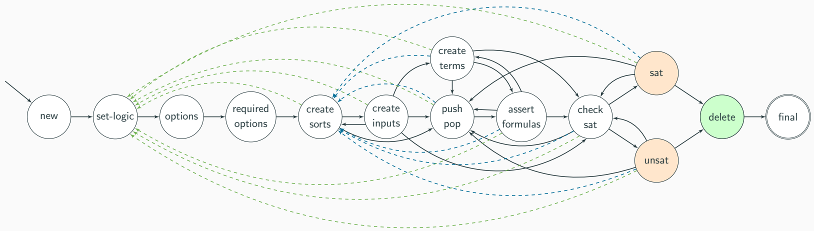
```
74761 new
65471 set-logic QF_BV
33949 mk-sort SORT_BOOL
      return s1
64345 mk-sort SORT_BV 8
      return s2
49391 mk-const s2 "a"
      return t1
89712 mk-const s2 "b"
      return t2
6548 mk-term OP_EQUAL SORT_BOOL 2 t1 t2
     return t3 s1
20351 assert-formula t3
47017 check-sat
```

API Trace



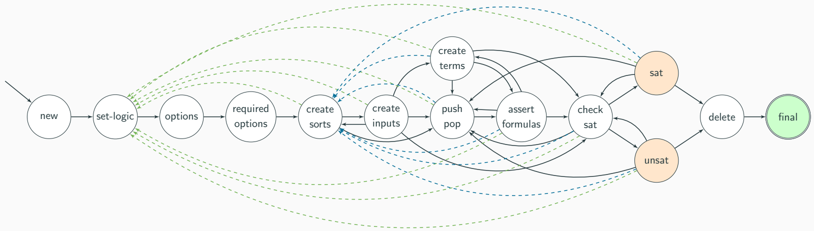
```
74761 new                          89712 mk-const s2 "b"
65471 set-logic QF_BV                    return t2
33949 mk-sort SORT_BOOL            6548 mk-term OP_EQUAL SORT_BOOL 2 t1 t2
      return s1                         return t3 s1
64345 mk-sort SORT_BV 8            20351 assert-formula t3
      return s2                    47017 check-sat
49391 mk-const s2 "a"
      return t1
```

API Trace



```
74761 new                         89712 mk-const s2 "b"
65471 set-logic QF_BV                   return t2
33949 mk-sort SORT_BOOL           6548 mk-term OP_EQUAL SORT_BOOL 2 t1 t2
      return s1                        return t3 s1
64345 mk-sort SORT_BV 8           20351 assert-formula t3
      return s2                   47017 check-sat
49391 mk-const s2 "a"             74496 delete
      return t1
```

API Trace



```
74761 new                          89712 mk-const s2 "b"
65471 set-logic QF_BV                    return t2
33949 mk-sort SORT_BOOL            6548 mk-term OP_EQUAL SORT_BOOL 2 t1 t2
      return s1                         return t3 s1
64345 mk-sort SORT_BV 8            20351 assert-formula t3
      return s2                    47017 check-sat
49391 mk-const s2 "a"              74496 delete
      return t1
```

Trace Minimizer

Original: 157 Lines

```
91764 new
45977 set-logic QF_AUFSNIA
  848 set-option produce-difficulty true
  848 set-option strings-exp true
43555 set-option incremental false
22267 set-option produce-unsat-cores true
50067 mk-sort SORT_STRING
      return s1
92374 mk-const s1 "_x0"
      return t1
29153 mk-value s1 ""
      return t2
89065 mk-const s1 "_x1"
      return t3
        .
        .
        .
94281 assert-formula t32
17138 assert-formula t46
77242 assert-formula t43
10259 assert-formula t24
37044 assert-formula t55
28759 check-sat
81533 cvc5-get-difficulty
10993 get-unsat-core
```

Minimized: 25 Lines (16%)

```
91764 new
848 set-option produce-difficulty true
50067 mk-sort SORT_STRING
return s1
92374 mk-const s1 "_x0"
return t1
29153 mk-value s1 ""
return t2
23432 mk-term OP_STR_SUFFIXOF SORT_BOOL 2 t1 t1
return t20 s2
532 mk-term str.tolower SORT_STRING 1 t1
return t23 s1
51711 mk-term OP_EQUAL SORT_BOOL 2 t20 t20
return t24 s2
63692 mk-term OP_STR_SUFFIXOF SORT_BOOL 2 t1 t2
return t25 s2
30349 mk-term OP_NOT SORT_BOOL 1 t20
return t27 s2
81085 mk-term OP_AND SORT_BOOL 2 t27 t24
return t28 s2
29866 mk-term OP_AND SORT_BOOL 2 t28 t20
return t32 s2
94281 assert-formula t32
28759 check-sat
10993 get-unsat-core
```

```
Fatal failure within cvc5::UnsatCore cvc5::SolverEngine::getUnsatCoreInternal() at cvc5/src/smt/solver_engine.cpp:1295
Check failure
    pepf != nullptr
Aborted (core dumped)
```

Evaluation

- **Input Fuzzers**
  - **Storm** [Mansur et al., ESEC/FSE'20]
    - mutates Boolean structure
  - **TypeFuzz** [Park et al., OOPSLA'21]
    - hybrid approach (mutational with generative elements)
    - for integers, reals strings
- **Model-Based API Fuzzers**
  - **BtorMBT** [Niemetz et al., SMT 2017]
    - tailored to (exclusively) Boolector
    - covers all features of Boolector except quantifiers
    - rigorously applied during development and for every release
    - recent fuzzing campaigns found no issues in covered code

Evaluation

Murxla vs. BtorMBT (Boolector)

Murxla			BtorMBT		
L [%]	F [%]	I [#]	L [%]	F [%]	I [#]
81.1	87.5	18	72.3	80.6	0

Murxla vs. Input Fuzzers (cvc5, QF_SLIA)

Murxla			Storm			Murxla-cc			TypeFuzz		
L [%]	F [%]	I [#]	L [%]	F [%]	I [#]	L [%]	F [%]	I [#]	L [%]	F [%]	I [#]
37.8	52.5	7	20.2	34.3	0	21.5	36.3	1	17.4	30.8	0

I	...	Number of issues
F	...	Function coverage
L	...	Line coverag
Murxla-cc	...	cross-checking configuration (Z3 vs cvc5)

1 hour, with 1 second time limit per round

Evaluation

Murxla with/without Option Fuzzing

Option	Bitwuzla			Boolector			cvc5			Yices2		
Fuzzing	L [%]	F [%]	I [#]	L [%]	F [%]	I [#]	L [%]	F [%]	I [#]	L [%]	F [%]	I [#]
no	47.4	63.9	7	68.5	79.2	6	38.9	56.8	11	37.0	42.4	1
yes	62.9	75.8	23	81.1	87.7	13	49.1	66.8	21	-	-	

I . . .	Number of issues
F . . .	Function coverage
L . . .	Line coverage

1 hour, with 1 second time limit per round

Conclusion

- Murxla is a tool for fuzzing and debugging SMT solvers
- quick and effective in finding issues
  - even for logics subjected to month-long fuzzing campaigns
- found many issues while finalizing the tool
  - more than 100 issues in cvc5 alone
- being integrated into development workflow of Bitwuzla and cvc5

References

A. Niemetz, M. Preiner and A. Biere. Model-Based API Testing for SMT Solvers. In Proc. of SMT'17, pages 3–14, 2017. http://ceur-ws.org/Vol-1889/paper1.pdf

M. N. Mansur, M. Christakis, V. Wüstholz and F. Zhang. Detecting critical bugs in SMT solvers using blackbox mutational fuzzing. In Proc. of ESEC/FSE'20, pages 701–712, ACM, 2020. https://doi.org/10.1145/3368089.3409763

J. Park, D. Winterer, C. Zhang and Z. Su. Generative type-aware mutation for testing SMT solvers. In Proc. of OOPSLA'21, pages 1–19, ACM, 2021. https://doi.org/10.1145/3485529