MODEL-BASED API TESTING FOR SMT SOLVERS

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SMT Workshop 2017, July 22 – 23
Heidelberg, Germany

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SMT Solvers

- highly complex
- usually serve as back-end to some application
- **key requirements:**
  - correctness
  - robustness
  - performance

⟶ **full verification** difficult and still an open question

⟶ solver development relies on **traditional testing** techniques

Testing of SMT Solvers

State-of-the-art:

- unit tests
- regression test suite
- grammar-based black-box input fuzzing with **FuzzSMT** [SMT'09]
  - generational input fuzzer for SMT-LIB v1
  - patched for SMT-LIB v2 compliance
  - generates random but valid SMT-LIB input
  - **especially effective in combination with delta debugging**
  - ◇ **not possible** to test solver features not supported by the input language

This work: model-based API fuzz testing

⟶ generate random valid **API call sequences**

Model-Based API fuzz testing

$\longrightarrow$ generate random valid **API call sequences**

- Previously: **model-based API testing framework for SAT** [TAP'13]
  - implemented for the SAT solver Lingeling
  - allows to test random solver configurations (option fuzzing)
  - allows to replay erroneous solver behavior

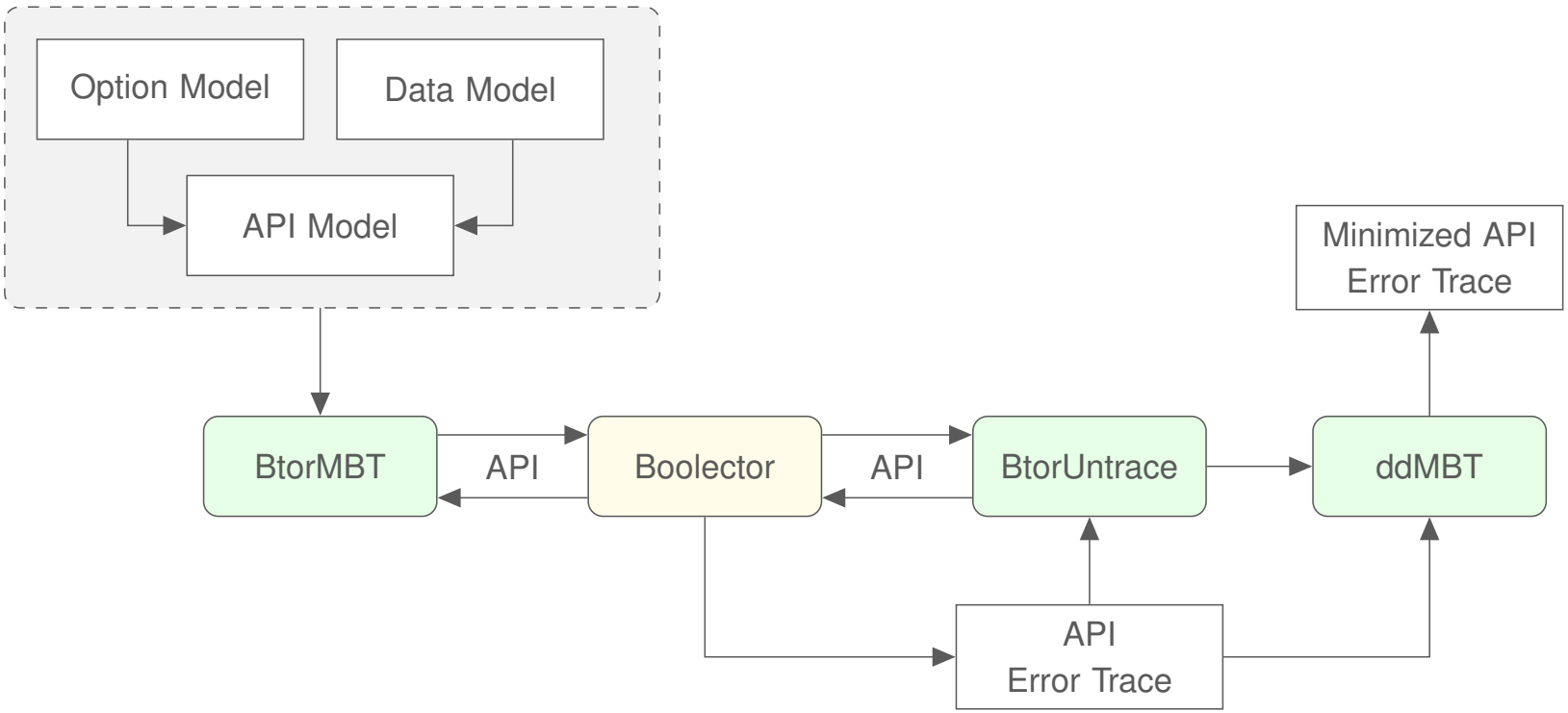
  $\longrightarrow$ results **promising** for other solver back-ends

- Here: **model-based API testing framework for SMT**
  - lifts SAT approach to SMT
  - implemented for the SMT solver Boolector
  - tailored to Boolector
  - for QF_(AUF)BV with non-recursive first-order lambda terms

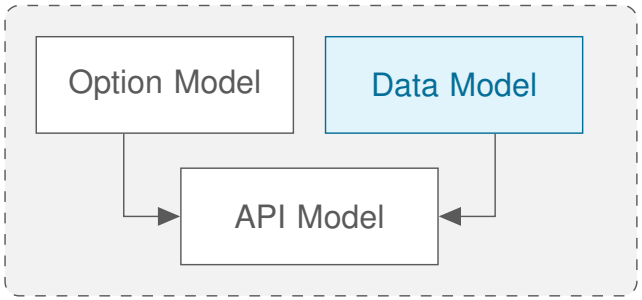
  $\longrightarrow$ **effective** and promising for other SMT solvers

  $\longrightarrow$ more general approach left to **future work**

Workflow


Option Model
Data Model
API Model
Minimized API
Error Trace
BtorMBT
API
Boolector
API
BtorUntrace
ddMBT
API
Error Trace

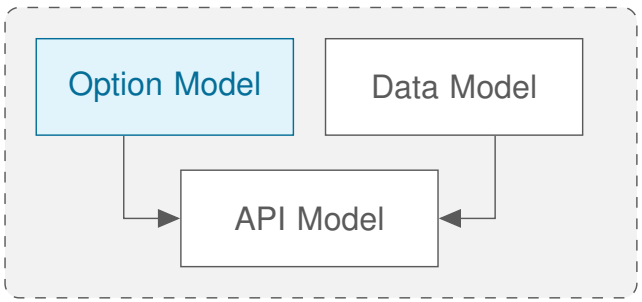
Models



Data Model

- ■ SMT-LIB v2
- □ quantifier-free bit-vectors
- □ arrays
- □ uninterpreted functions
- □ lambda terms

Models



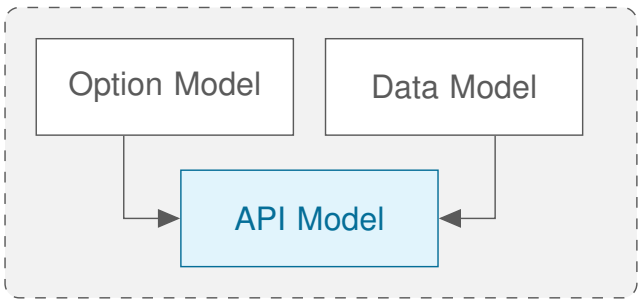
Option Model

- default values
- min / max values
- (in)valid combinations
- solver-specific

Boolector:

- multiple solver engines
- 70+ options (total)
- query all options (+ min, max and default values) via API

Models



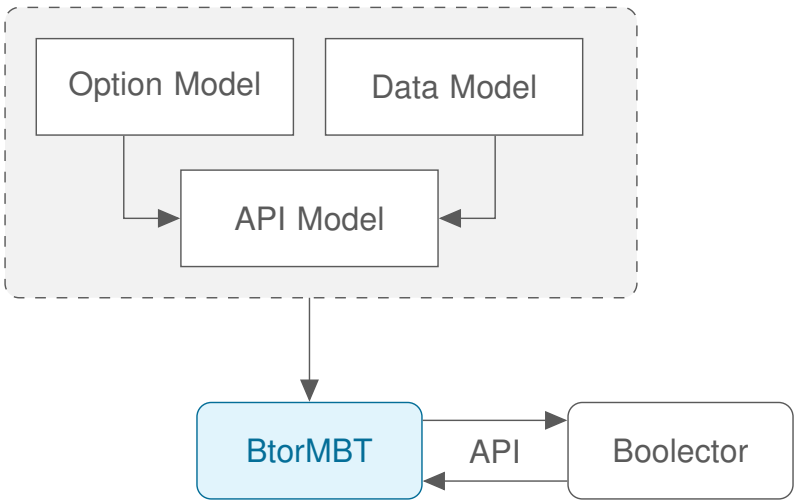
API model

- full feature set available via API
- finite state machine

Boolector:

- full access to complete solver feature set
- 150+ API functions

BtorMBT

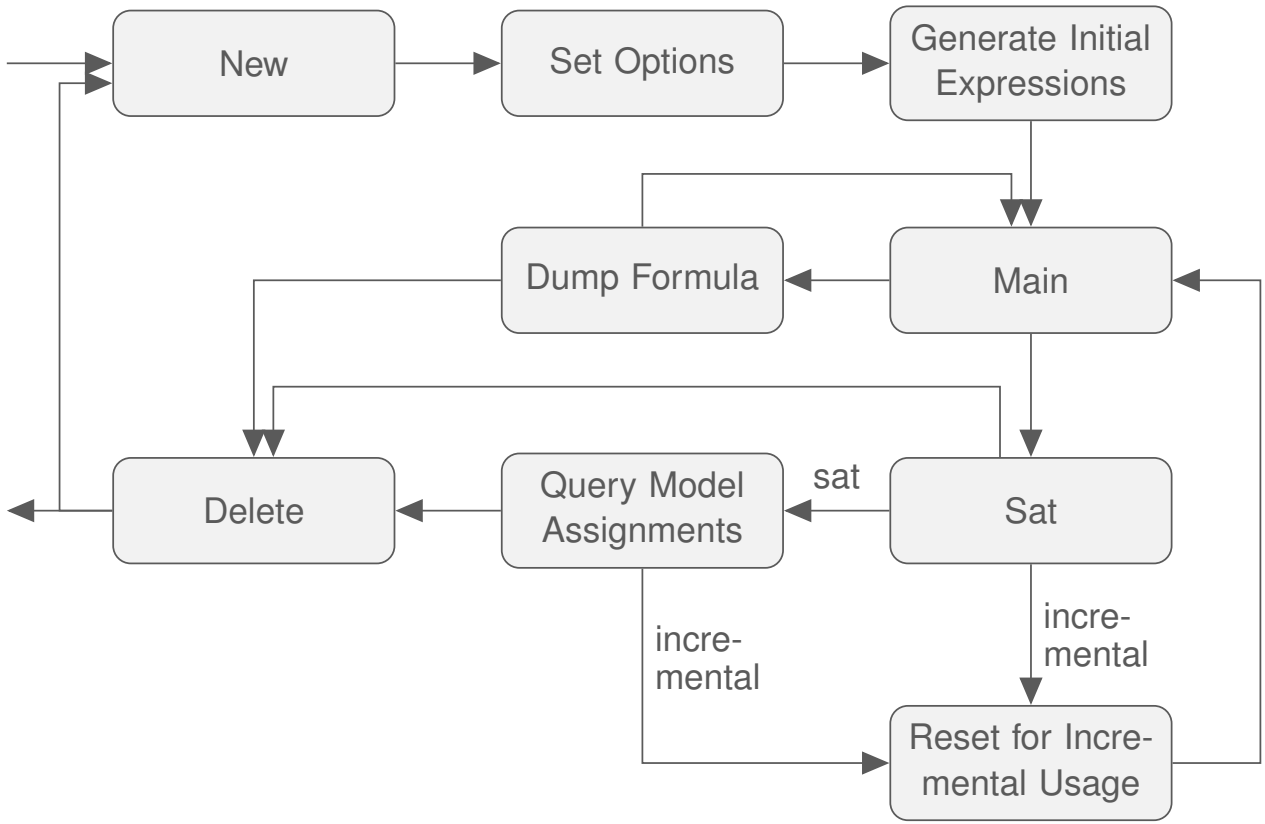


- ■ test case generation engine
- ■ API fuzz testing tool
- ■ implements API model

- □ dedicated tool for testing random configurations of Boolector
- □ integrates Boolector via C API
- □ fully supports all functionality provided via API

BtorMBT

API Model



BtorMBT

Option Fuzzing

- multiple solver engines
- configurable with 70+ options (total)
- several SAT solvers as back-end

1. choose logic (QF_BV, QF_ABV, QF_UFBV, QF_AUFBV)
2. choose solver engine (depends on logic)
3. choose configuration options and their values
   - ☐ within their predefined value ranges
   - ☐ based on option model

   $\longrightarrow$ exclude invalid combinations

   $\longrightarrow$ choose more relevant options with higher probability (e.g. incrementality)

BtorMBT

Expression Generation

- generate **inital set** of expressions
  1. randomly sized shares of inputs
     - ☐ Boolean variables
     - ☐ bit-vector constants and variables
     - ☐ uninterpreted function symbols
     - ☐ array variables
  2. non-input expressions
     - combine inputs and already generated non-input expressions
     - with operators

  $\longrightarrow$ until a max number of initial expressions is reached

- randomly generate **new** expressions after initialization
  - ☐ choose expressions from the initial set with lower probability
  - ☐ to increase expression depth

BtorMBT

Dump Formula

- output format: BTOR, SMT-LIB v2 and AIGER

- BTOR and SMT-LIB v2:
  1. dump to temp file
  2. parse temp file (into temp Booletor instances)
  3. check for parse errors

- AIGER
  - QF_BV only

  $\longrightarrow$ currently no AIGER parser

  $\longrightarrow$ dump to stdout without error checking

BtorMBT

Solver-Internal Checks

- model validation for **satisfiable** instances
  - after each SAT call that concludes with satisfiable
- check failed assumptions for **unsatisfiable** instances
  - in case of incremental solving
  - determine the set of inconsistent (failed) assumptions
  - check if failed assumptions are indeed inconsistent
- check internal state of cloned instances
  - data structures
  - allocated memory
- automatically enabled in debug mode

BtorMBT

Shadow Clone Testing

- **full** clone
  - ☐ exact disjunct copy of solver instance
  - ☐ exact same behavior
  - ☐ deep copy

  $\longrightarrow$ includes (bit-blasted) AIG layer and SAT layer

  $\longrightarrow$ requires SAT solver to support cloning

- **term layer** clone
  - ☐ term layer copy of solver instance
  - ☐ does not guarantee exact same behavior

$\longrightarrow$ shadow clone testing to test **full** clones

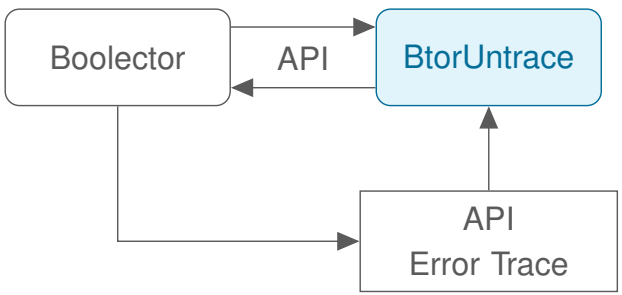
BtorMBT

Shadow Clone Testing

1. generate shadow clone (initialization)
   - ☐ may be initialized anytime prior to the first SAT call
   - ☐ is randomly released and regenerated multiple times
   - ☐ solver checks internal state of the freshly generated clone
2. shadow clone mirrors every API call
   - ☐ solver checks state of shadow clone after each call
3. return values must correspond to results of original instance

$\longrightarrow$ enabled at random

BtorUntrace



- replay API traces
- reproduce solver behavior
  - failed test cases
  - faulty behavior outside of API testing framework

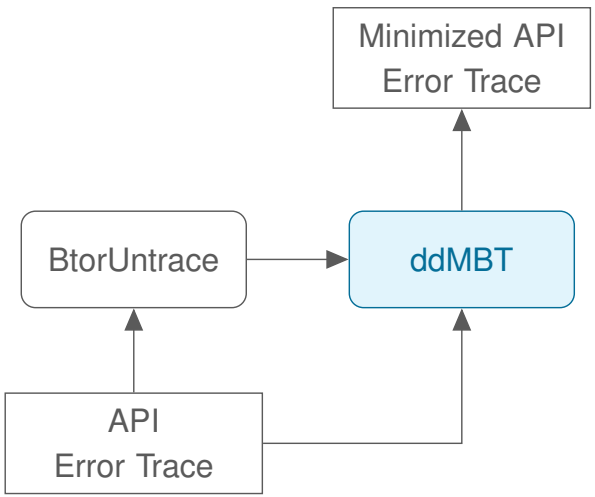
→ without the need for the original (complex) setup of the tool chain

- for traces generated by Boolector
- integrates Boolector via C API

Example API Trace

```
1  new
2  return b1
3  set_opt b1 1 incremental 1
4  set_opt b1 14 rewrite-level 0
5  bitvec_sort b1 1
6  return s1@b1
7  array_sort b1 s1@b1 s1@b1
8  return s3
9  array b1 s3@b1 array1
10 return e2@b1
11 var b1 s1@b1 index1
12 return e3@b1
13 var b1 s1@b1 index2
14 return e4@b1
15 read b1 e2@b1 e3@b1
16 return e6@b1
17 read b1 e2@b1 e4@b1
18 return e8@b1
19 eq b1 e3@b1 e4@b1
20 return e9@b1
21 ne b1 e6@b1 e8@b1
22 return e-10@b1
23 assert b1 e9@b1
24 assume b1 e-10@b1
25 sat b1
26 return 20
27 failed b1 e-10@b1
28 return true
29 sat b1
30 return 10
31 release b1 e2@b1
32 release b1 e3@b1
33 release b1 e4@b1
34 release b1 e6@b1
35 release b1 e8@b1
36 release b1 e9@b1
37 release b1 e-10@b1
38 release_sort b1 s1@b1
39 release_sort b1 s3@b1
40 delete b1
```

ddMBT



- minimize trace file
- while preserving behavior when replayed with BtorUntrace
- based on solver exit code and error message
- works in rounds

1. remove lines (divide and conquer)
2. substitute terms with fresh variables
3. substitute terms with expressions of same sort

Experimental Evaluation

Configurations

- **BtorMBT** as included with Boolector 2.4
  - $\longrightarrow$ Boolector compiled with support for Lingeling, PicoSAT, MiniSAT
- **FuzzSMT** patched for SMT-LIB v2 compliance
- with and without option fuzzing
  - $\longrightarrow$ randomly choosing solver engines and SAT solvers enabled even when option fuzzing disabled

Experimental Evaluation

Throughput

- important measure of **efficiency** and **effectiveness**
  - $\longrightarrow$ high throughput: test cases too trivial
  - $\longrightarrow$ low throughput: test cases too difficult

  goal: as many good test cases in as little time as possible

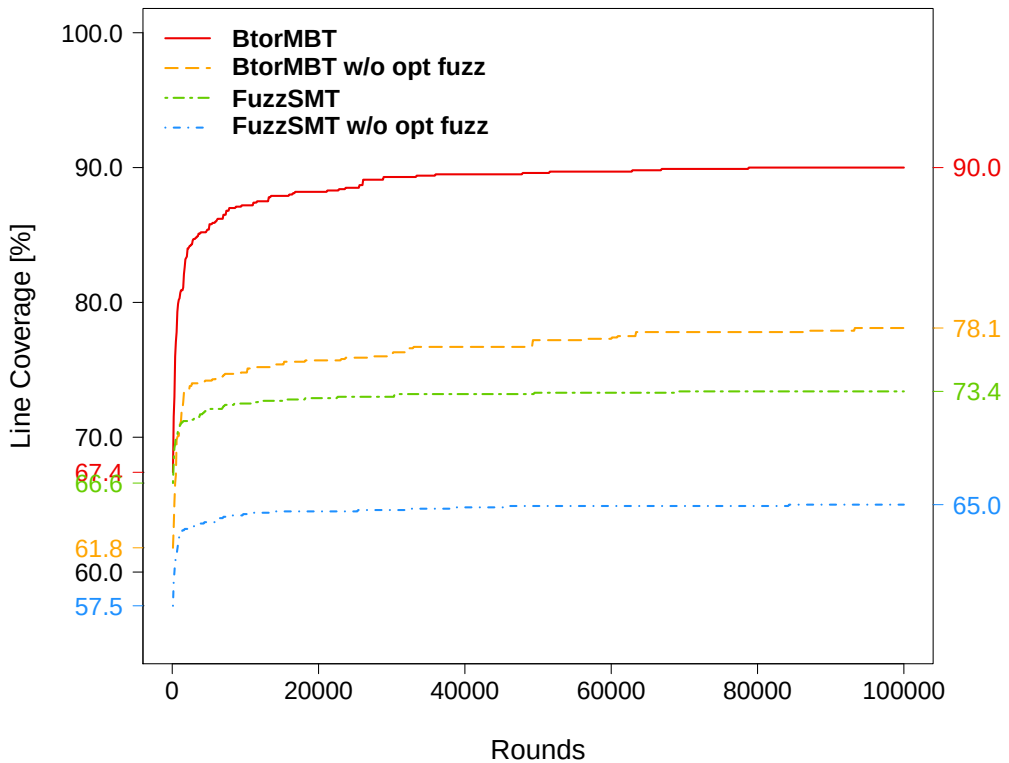
- 100k runs
- solver timeout: 2 seconds

- **BtorMBT:** 45 rounds / second
  - $\longrightarrow$ **+20%** throughput without shadow clone testing
  - $\longrightarrow$ **20%** of SAT calls incremental
  - $\longrightarrow$ **25%** of solved instances is satisfiable

- **FuzzSMT:** 7 rounds / second

Experimental Evaluation

Code Coverage (gcc gcov)



	BtorMBT	BtorMBT w/o opt fuzz
10k	87 %	75 %
100k	90 %	78 %

$\longrightarrow$ >98% API coverage

	FuzzSMT	FuzzSMT w/o opt fuzz
10k	73 %	62 %
100k	74 %	65 %

$\longrightarrow$ >52% API coverage

(incomplete SMT-LIB v2 support)

Experimental Evaluation

Defect Insertion

Test configurations:

- **4626** faulty configurations (total)
- **TC_A** randomly inserted abort statement (2305 configurations)
- **TC_D** randomly deleted statement (2321 configurations)

- ☐ all configurations are faulty configurations
- ☐ 100k runs (BtorMBT) and 10k runs (FuzzSMT)
- ☐ solver timeout: 2 seconds

Experimental Evaluation

Defect Insertion

Rounds		BtorMBT		BtorMBT w/o opt fuzz		FuzzSMT		FuzzSMT w/o opt fuzz	
		Found	[%]	Found	[%]	Found	[%]	Found	[%]
100k	TC_A (2305)	2088	90.6	1789	77.6				
	TC_D (2321)	1629	70.2	1366	58.9				
	TC (4626)	**3717**	**80.4**	**3155**	**68.2**				
10k	TC_A (2305)	2028	88.0	1719	74.6	1735	75.3	1523	66.1
	TC_D (2321)	1510	65.1	1277	55.0	1304	56.2	1153	49.7
	TC (4626)	**3538**	**76.5**	**2996**	**64.8**	**3039**	**65.7**	**2676**	**57.8**

$\longrightarrow$ success rates for TC_A roughly correspond to code coverage

Conclusion

- model-based API testing tool set for Boolector
- generates random valid sequences of API calls
- allows to test random solver configurations on random input formulas

Future Work:

- let BtorMBT take over API tracing
- more balanced ratio of sat to unsat instances
- maximize code coverage with symbolic execution techniques
- solver-independent model-based api testing framework

References I

[SMT'09] R. Brummayer and A. Biere. Fuzzing and Delta-Debugging SMT Solvers. In Proc. of the 7th International Workshop on Satisfiability Modulo Theories (SMT'09), 5 pages, ACM, 2009.

[TAP'13] C. Artho, A. Biere and M. Seidl. Model-Based Testing for Verification Back-Ends. In Proc. of the 7th International Conference on Tests and Proofs (TAP 2013), LNCS volume 7942, pages 39–55, Springer, 2013.