# On the Unusual Effectiveness of Type-aware Operator Mutations for Testing SMT Solvers


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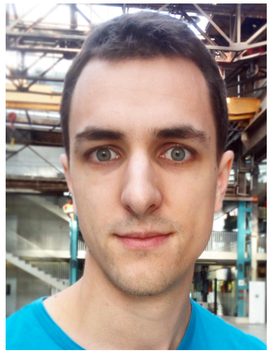
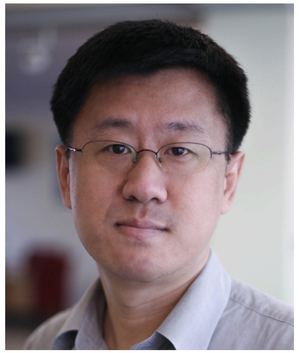
ETH Zurich, Switzerland

(*Equal contributions)




OOPSLA, 17 Nov, 2020, Online

# SMT Problem

$$\varphi : x > 0 \wedge x < 0$$

# SMT Problem

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**UNSAT**

# SMT Problem

$$\varphi : x > 0 \wedge x < 1$$

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$$\varphi : x > 0 \wedge x < 1$$

**SAT**

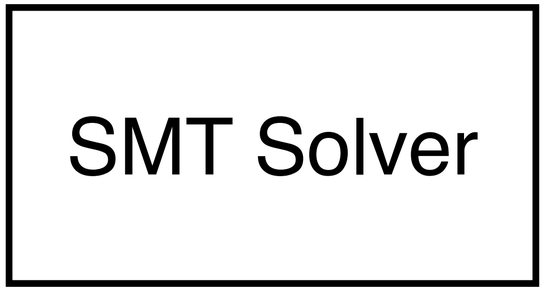
# SMT Problem

$$x = 0.5$$

$$\varphi : x > 0 \wedge x < 1$$

**SAT**

# SMT Solver



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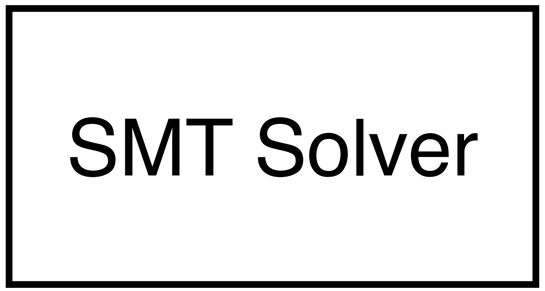
$$\varphi : x > 0 \wedge x < 1 \longrightarrow$$



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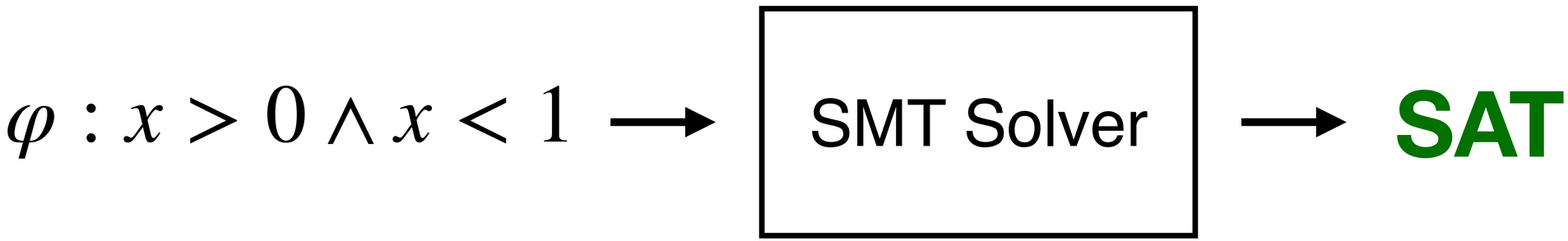

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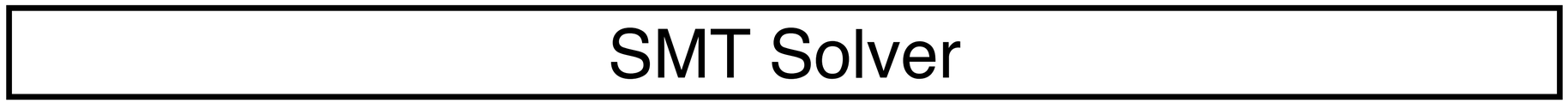

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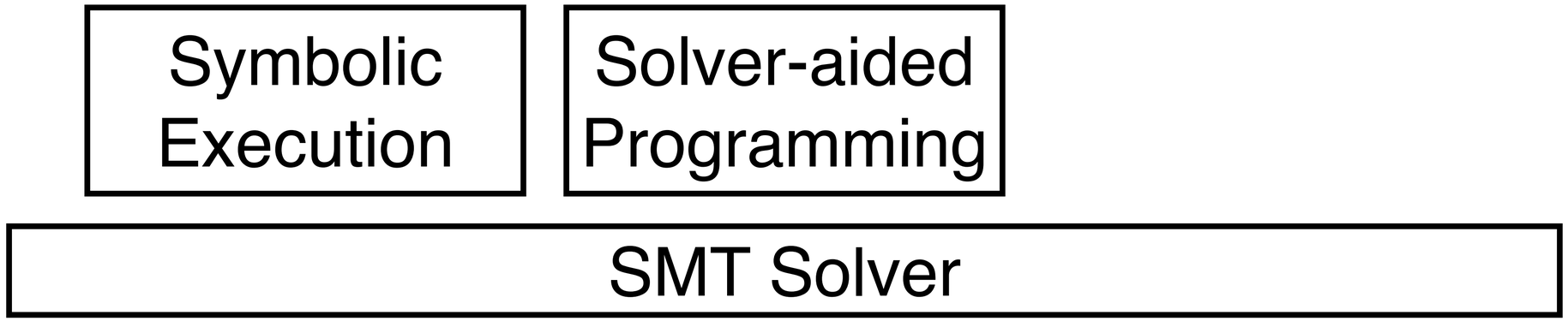

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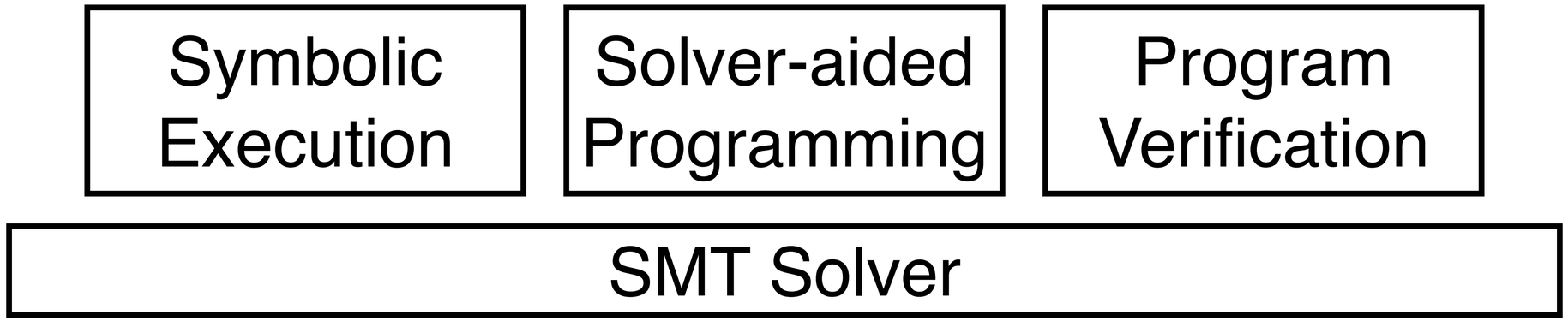
Symbolic Execution
Solver-aided Programming
Program Verification
SMT Solver

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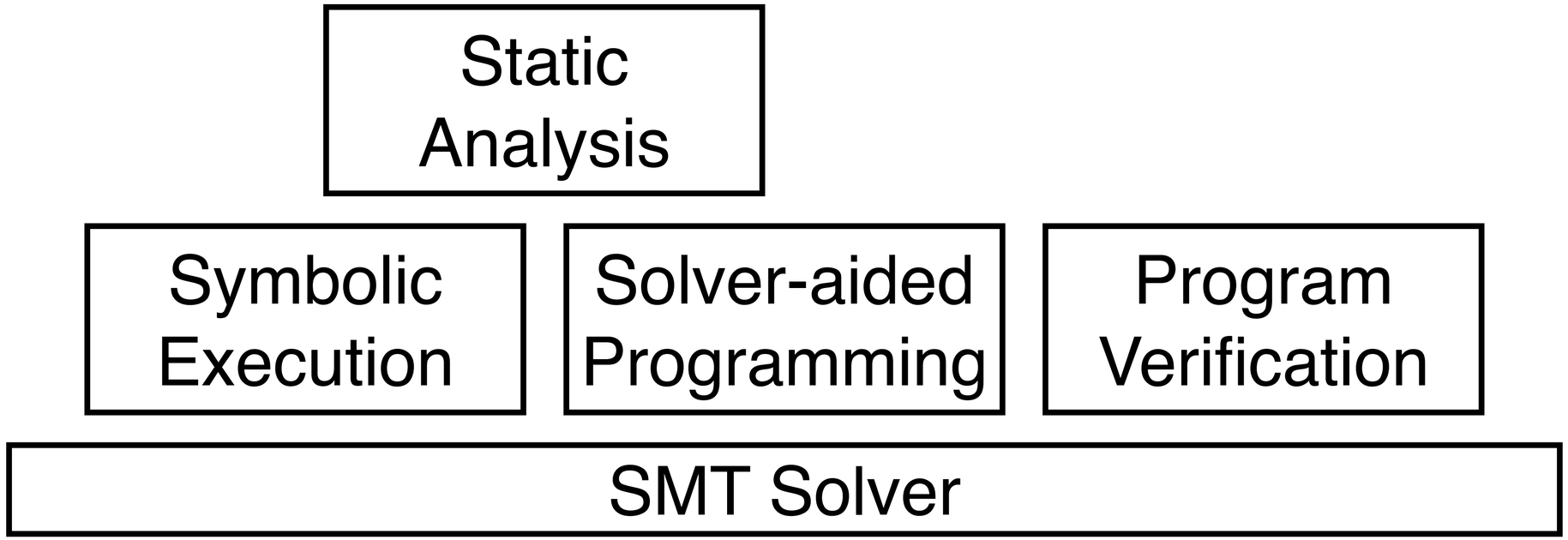
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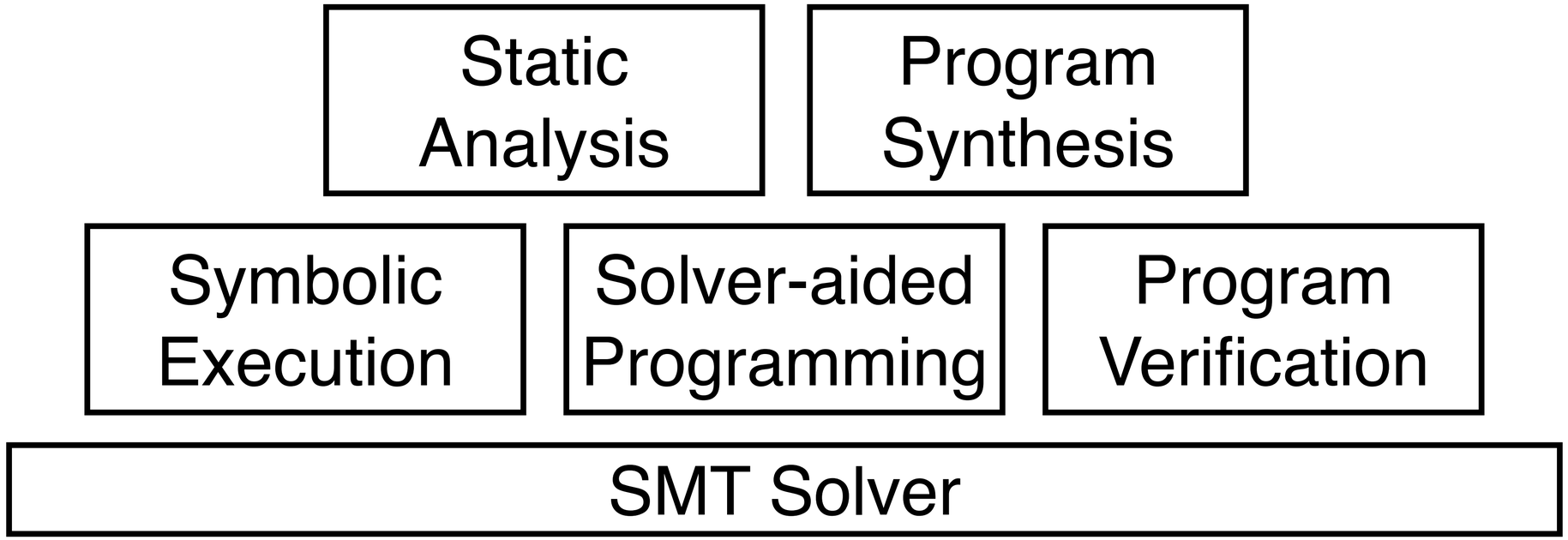
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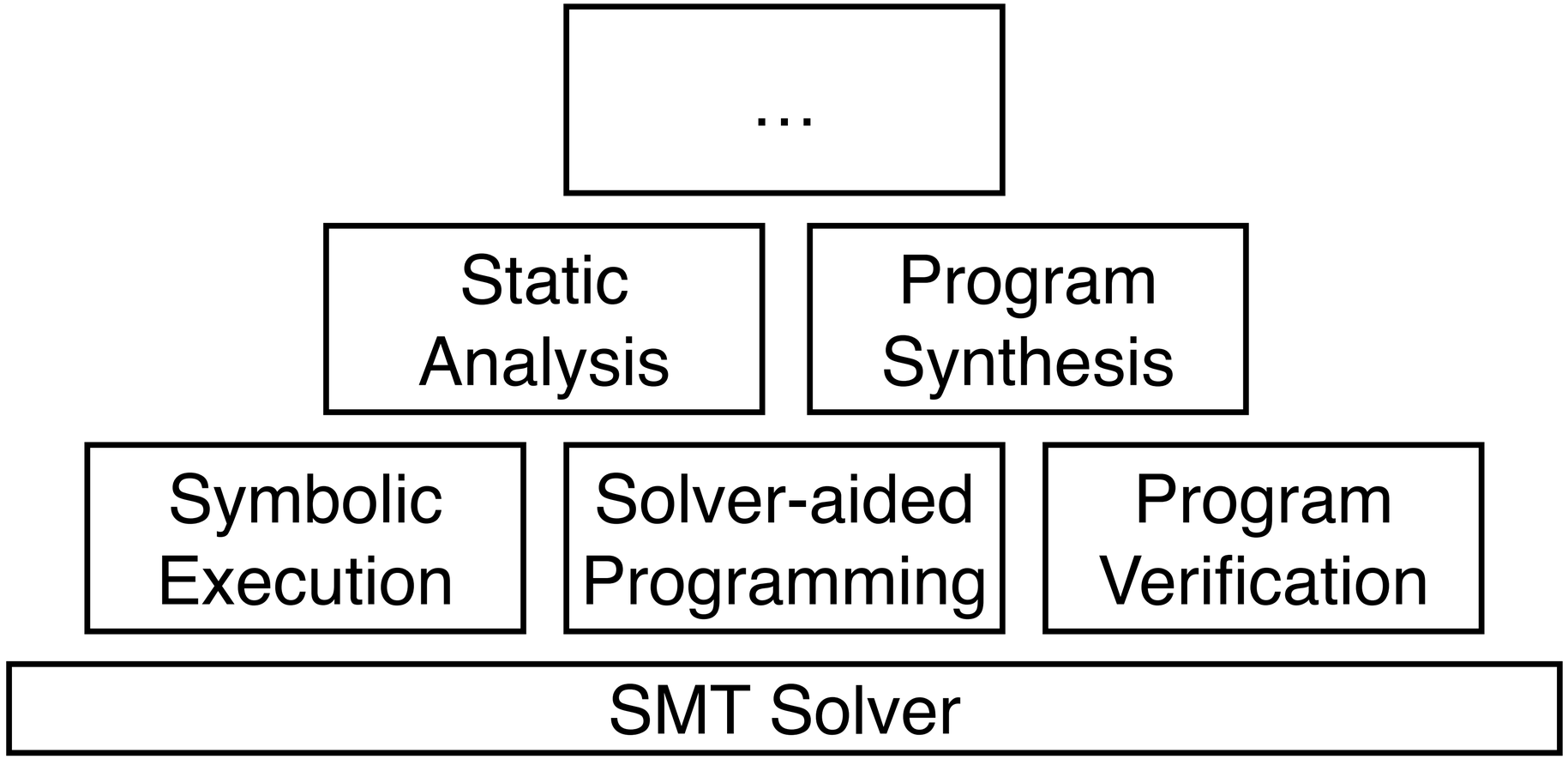
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https://github.com/Z3Prover/z3/issues/3973

# Related Work

| | Confirmed Bugs in Z3 | | Confirmed Bugs in CVC4 | |
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| **Approach** | soundness | all | soundness | all |
| StringFuzz [1] | 0 | 0 | - | - |
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SIMPLE BUT UNUSUAL EFFECTIVE APPROACH


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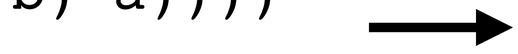

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https://github.com/Z3Prover/z3/issues/2715

# Empirical Evaluation

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- Seeds: SMT-LIB benchmarks (300k+ formulas)

# Bug Findings

| Status | Z3 | CVC4 | Total |
|---|---|---|---|
| Reported | 811 | 281 | 1,092 |
| Confirmed | 578 | 241 | 819 |
| Fixed | 521 | 164 | 685 |
| Duplicate | 85 | 18 | 106 |

Bug status as of 30 Oct 2020

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F

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| | soundness | all | soundness | all |
| StringFuzz | 0 | 0 | - | - |
| BanditFuzz | 0 | 0 | - | - |
| Bugariu et al. | 1 | 3 | 0 | 0 |
| YinYang | 24 | 36 | 5 | 8 |
| STORM | 17 | 21 | 0 | 0 |
| OpFuzz | 114 | 316 | 11 | 185 |

**OpFuzz found many more soundness bugs in Z3 and CVC4's default modes than all previous approaches**

# Z3 Soundness Bug #2832

```
$ cat bug.smt2
(declare-const a (_ BitVec 8))
(declare-const b (_ BitVec 8))
(declare-const c (_ BitVec 8))
(assert (= (bvxnor a b c)
           (bvxnor (bvxnor a b) c)))
(check-sat)

$ cvc4 bug.smt2
sat     ✔

$ z3 bug.smt2
unsat   ✘
```

https://github.com/Z3Prover/z3/issues/2832

# Z3 Soundness Bug #2832

```
$ cat bug.smt2
(declare-const a (_ BitVec 8))
(declare-const b (_ BitVec 8))
(declare-const c (_ BitVec 8))
(assert (= (bvxnor a b c)
           (bvxnor (bvxnor a b) c)))
(check-sat)

$ cvc4 bug.smt2
sat     ✔

$ z3 bug.smt2
unsat   ✘
```

https://github.com/Z3Prover/z3/issues/2832

# Z3 Soundness Bug #2832

```
(bvxnor a b c) ≠ (not (bvxor a b c))
```

# Z3 Soundness Bug #2832

**(bvxnor a b c) ≠ (not (bvxor a b c))**

```
(bvxnor true true true) = (not (bvxor true true true))
```

# Z3 Soundness Bug #2832

**(bvxnor a b c) ≠ (not (bvxor a b c))**

```
(bvxnor true true true) = (not (bvxor true true true))
(bvnxor (bvnxor true true) true)) = (not (bvxor (bvxor true true) true))
```

# Z3 Soundness Bug #2832

**(bvxnor a b c) ≠ (not (bvxor a b c))**

```
                (bvxnor true true true) = (not (bvxor true true true))
(bvnxor (bvnxor true true) true)) = (not (bvxor (bvxor true true) true))
                    (bvnxor true true) = (not (bvxor false true))
```

# Z3 Soundness Bug #2832

**(bvxnor a b c) ≠ (not (bvxor a b c))**

```
                (bvxnor true true true) = (not (bvxor true true true))
(bvnxor (bvnxor true true) true)) = (not (bvxor (bvxor true true) true))
                    (bvnxor true true) = (not (bvxor false true))
                                  true ≠ false
```

# Z3 Soundness Bug #2832

```
$ cat bug.smt2
(declare-const a (_ BitVec 8))
(declare-const b (_ BitVec 8))
(declare-const c (_ BitVec 8))
(assert (= (bvxnor a b c)
           (bvxnor (bvxnor a b) c)))
(check-sat)

$ cvc4 bug.smt2
sat     ✔

$ z3 bug.smt2
unsat   ✘
```

https://github.com/Z3Prover/z3/issues/2832

**Root Cause: Unsound rewriter**

# Z3 Soundness Bug #2830

```
$ cat bug.smt2
(declare-fun a () Int)
(declare-fun b (Int) Bool)
(assert (b 0))
(push)
(assert (distinct true (= a 0) (not (b 0))))
(check-sat)

$ cvc4 bug.smt2
unsat   ✔

$ z3 bug.smt2
sat     ✘
```

https://github.com/Z3Prover/z3/issues/2830

# Z3 Soundness Bug #2830

```
$ cat bug.smt2
(declare-fun a () Int)
(declare-fun b (Int) Bool)
(assert (b 0))
(push)
(assert (distinct true (= a 0) (not (b 0))))
(check-sat)

$ cvc4 bug.smt2
unsat   ✔

$ z3 bug.smt2
sat     ✘
```

https://github.com/Z3Prover/z3/issues/2830

**Root Cause: Last argument omitted in distinct operator**

# CVC4 Soundness Bug #3497

```
$ cat bug.smt2
(declare-fun x () String)
(declare-fun y () String)
(assert (= (str.indexof x y 1)
           (str.len x)))
(assert (str.contains x y))
(check-sat)

$ z3 bug.smt2
sat     ✔

$ cvc4 bug.smt2
unsat   ✘
```

https://github.com/CVC4/CVC4/issues/3497

# CVC4 Soundness Bug #3497

```
$ cat bug.smt2
(declare-fun x () String)
(declare-fun y () String)
(assert (= (str.indexof x y 1)
           (str.len x)))
(assert (str.contains x y))
(check-sat)

$ z3 bug.smt2
sat     ✔

$ cvc4 bug.smt2
unsat   ✘
```

https://github.com/CVC4/CVC4/issues/3497

# CVC4 Soundness Bug #3497

```
$ cat bug.smt2
(declare-fun x () String)
(declare-fun y () String)
(assert (= (str.indexof x y 1)
           (str.len x)))
(assert (str.contains x y))
(check-sat)

$ z3 bug.smt2
sat     ✔

$ cvc4 bug.smt2
unsat   ✘
```

```
(str.indexof x y 1) <= (str.len x)
```

https://github.com/CVC4/CVC4/issues/3497

# CVC4 Soundness Bug #3497

```
$ cat bug.smt2
(declare-fun x () String)
(declare-fun y () String)
(assert (= (str.indexof x y 1)
           (str.len x)))
(assert (str.contains x y))
(check-sat)

$ z3 bug.smt2
sat      ✔

$ cvc4 bug.smt2
unsat    ✘
```

https://github.com/CVC4/CVC4/issues/3497

```
(str.indexof x y 1) < (str.len x)
```

**Root Cause: Missed boundary condition**

# CVC4 Soundness Bug #3497

```
$ cat bug.smt2
(declare-fun x () String)
(declare-fun y () String)
(assert (= (str.indexof x y 1)
           (str.len x)))
(assert (str.contains x y))
(check-sat)

$ z3 bug.smt2
sat     ✔

$ cvc4 bug.smt2
unsat   ✘
```

**ajreynol** commented on Nov 26, 2019 — Member

Thanks a lot for the bug report, this is fixed in #3499.

https://github.com/CVC4/CVC4/issues/3497

# CVC4 Soundness Bug #4469

```
$ cat bug.smt2
(set-logic QF_AUFBVLIA)
(declare-fun a () Int)
(declare-fun b (Int) Int)
(assert (distinct (b a)
   (b (b a))))
(check-sat)

$ z3 bug.smt2
sat     ✔

$ cvc4 bug.smt2
unsat   ✘
```

https://github.com/CVC4/CVC4/issues/4469

# CVC4 Soundness Bug #4469

```
$ cat bug.smt2
(set-logic QF_AUFBVLIA)
(declare-fun a () Int)
(declare-fun b (Int) Int)
(assert (distinct (b a)
   (b (b a))))
(check-sat)

$ z3 bug.smt2
sat     ✔

$ cvc4 bug.smt2
unsat   ✘
```

https://github.com/CVC4/CVC4/issues/4469

# CVC4 Soundness Bug #3475

```
$ cat bug.smt2
(set-logic ALL)
(declare-fun x () Real)
(assert (< x 0))
(assert (not (= (/ (sqrt x) (sqrt x)) x)))
(check-sat)

$ z3 bug.smt2
sat   ✔

$ cvc4 bug.smt2
unsat ✘
```

https://github.com/CVC4/CVC4/issues/3475

# CVC4 Soundness Bug #3475

```
$ cat bug.smt2
(set-logic ALL)
(declare-fun x () Real)
(assert (< x 0))
(assert (not (= (/ (sqrt x) (sqrt x)) x)))
(check-sat)

$ z3 bug.smt2
sat   ✔

$ cvc4 bug.smt2
unsat ✘
```

```
Formula is satisfiable
negative x = -1
(/ sqrt(-1) sqrt(-1)) = 1
```

https://github.com/CVC4/CVC4/issues/3475

# CVC4 Soundness Bug #3475

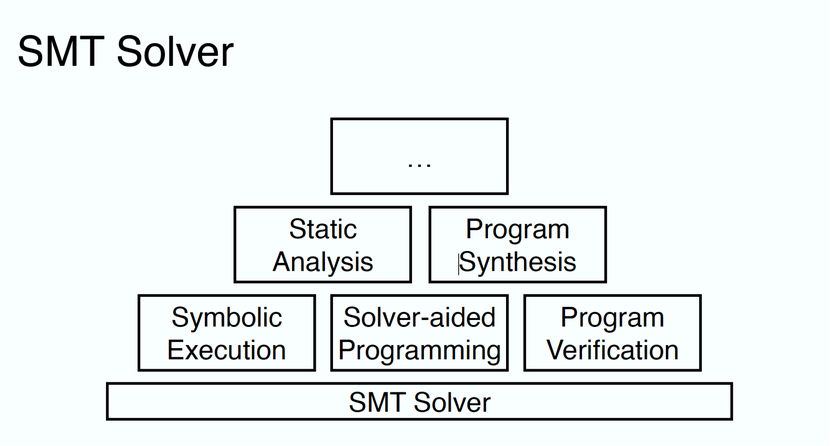
```
Simplification:
(sqrt x) = choice real y s.t. x*x = y
```

# CVC4 Soundness Bug #3475

```
Simplification:
(sqrt x) = choice real y s.t. x*x = y
```

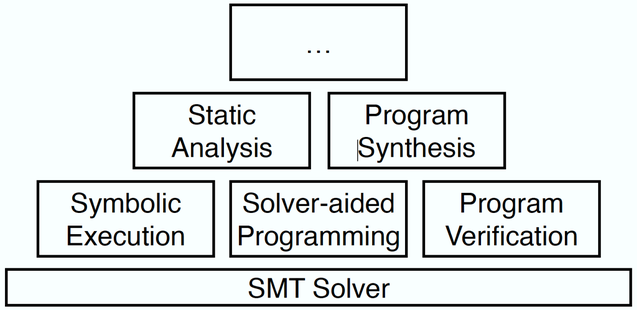
Problem: Inadmissible for negative y (since no real x exists)

# Summary


SMT Solver
…
Static Analysis
Program Synthesis
Symbolic Execution
Solver-aided Programming
Program Verification
SMT Solver

# Summary

## SMT Solver




## Type-aware operator mutation

```
$ cat > formula.smt2
(assert (forall ((a Int))
        (exist  ((b Int))
        (distinct (* 2 b) a))))
(check-sat)

$ cvc4 formula.smt2
sat

$ z3 formula.smt2
sat
```

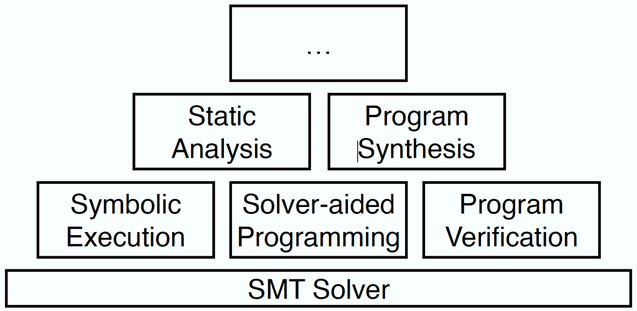
→

```
$ cat > bug.smt2
(assert (forall ((a Int))
        (exist  ((b Int))
        (= (* 2 b) a))))
(check-sat)

$ cvc4 bug.smt2
unsat ✔

$ z3 bug.smt2
sat    ✘
```

https://github.com/Z3Prover/z3/issues/3973

# Summary

## SMT Solver

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```
$ cat > formula.smt2
(assert (forall ((a Int))
        (exist  ((b Int))
        (distinct (* 2 b) a))))
(check-sat)

$ cvc4 formula.smt2
sat

$ z3 formula.smt2
sat
```

→

```
$ cat > bug.smt2
(assert (forall ((a Int))
        (exist  ((b Int))
        (= (* 2 b) a))))
(check-sat)

$ cvc4 bug.smt2
unsat ✔

$ z3 bug.smt2
sat    ✘
```

https://github.com/Z3Prover/z3/issues/3973

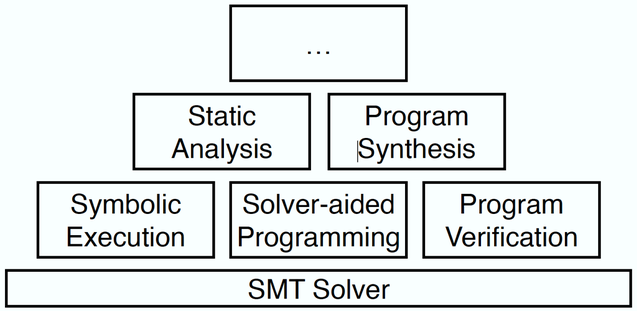
## Bug Findings

| Status | Z3 | CVC4 | Total |
|---|---|---|---|
| Reported | 811 | 281 | 1,092 |
| Confirmed | 578 | 241 | 819 |
| Fixed | 521 | 164 | 106 |
| Duplicate | 85 | 18 | 79 |

Bug status as of 30 Oct 2020

# Summary

## SMT Solver

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```
$ cat > formula.smt2
(assert (forall ((a Int))
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        (distinct (* 2 b) a))))
(check-sat)

$ cvc4 formula.smt2
sat

$ z3 formula.smt2
sat
```

→

```
$ cat > bug.smt2
(assert (forall ((a Int))
        (exist  ((b Int))
        (= (* 2 b) a))))
(check-sat)

$ cvc4 bug.smt2
unsat ✔

$ z3 bug.smt2
sat   ✘
```

https://github.com/Z3Prover/z3/issues/3973

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Bug status as of 30 Oct 2020

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```
$ cat bug.smt2
(declare-const a (_ BitVec 8))
(declare-const b (_ BitVec 8))
(declare-const c (_ BitVec 8))
(assert (= (bvxnor a b c)
           (bvxnor (bvxnor a b) c)))
(check-sat)

$ cvc4 bug.smt2
sat    ✔

$ z3 bug.smt2
unsat  ✘
```

https://github.com/Z3Prover/z3/issues/2832

### CVC4 Soundness Bug #3497

```
$ cat bug.smt2
(declare-fun x () String)
(declare-fun y () String)
(assert (= (str.indexof x y 1)
           (str.len x)))
(assert (str.contains x y))
(check-sat)

$ z3 bug.smt2
sat    ✔

$ cvc4 bug.smt2
unsat  ✘
```

(str.indexof x y 1) < (str.len x)

Root Cause: Missed boundary condition

https://github.com/CVC4/CVC4/issues/3497

### Z3 Soundness Bug #2830

```
$ cat bug.smt2
(declare-fun a () Int)
(declare-fun b (Int) Bool)
(assert (b 0))
(push)
(assert (distinct true (= a 0) (not (b 0))))
(check-sat)

$ cvc4 bug.smt2
unsat  ✔

$ z3 bug.smt2
sat    ✘
```

Root Cause: Last argument omitted in distinct operator

https://github.com/Z3Prover/z3/issues/2830

### CVC4 Soundness Bug #4469

```
$ cat bug.smt2
(set-logic QF_AUFBVLIA)
(declare-fun a () Int)
(declare-fun b (Int) Int)
(assert (distinct (b a)
   (b (b a))))
(check-sat)

$ z3 bug.smt2
sat    ✔

$ cvc4 bug.smt2
unsat  ✘
```

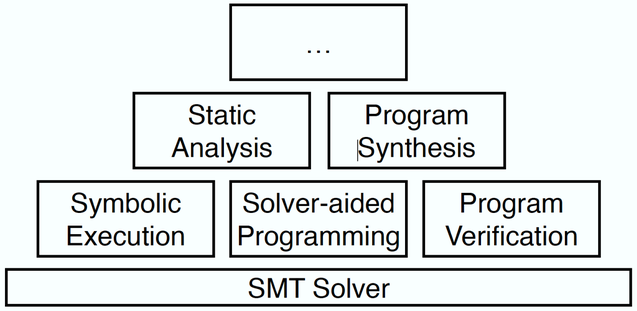
Labels: bug, major

https://github.com/CVC4/CVC4/issues/4469

# Summary

testsmt.github.io @testsmt

## SMT Solver

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```
$ cat > formula.smt2
(assert (forall ((a Int))
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        (distinct (* 2 b) a))))
(check-sat)

$ cvc4 formula.smt2
sat

$ z3 formula.smt2
sat
```

→

```
$ cat > bug.smt2
(assert (forall ((a Int))
        (exist  ((b Int))
        (= (* 2 b) a))))
(check-sat)

$ cvc4 bug.smt2
unsat ✔

$ z3 bug.smt2
sat   ✘
```

https://github.com/Z3Prover/z3/issues/3973

## Bug Findings

| Status | Z3 | CVC4 | Total |
|---|---|---|---|
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Bug status as of 30 Oct 2020

### Z3 Soundness Bug #2832

```
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(declare-const a (_ BitVec 8))
(declare-const b (_ BitVec 8))
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(assert (= (bvxnor a b c)
           (bvxnor (bvxnor a b) c)))
(check-sat)

$ cvc4 bug.smt2
sat    ✔

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unsat  ✘
```

https://github.com/Z3Prover/z3/issues/2832

### CVC4 Soundness Bug #3497

```
$ cat bug.smt2
(declare-fun x () String)
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(assert (= (str.indexof x y 1)
           (str.len x)))
(assert (str.contains x y))
(check-sat)

$ z3 bug.smt2
sat    ✔

$ cvc4 bug.smt2
unsat  ✘
```

(str.indexof x y 1) < (str.len x)

Root Cause: Missed boundary condition

https://github.com/CVC4/CVC4/issues/3497

### Z3 Soundness Bug #2830

```
$ cat bug.smt2
(declare-fun a () Int)
(declare-fun b (Int) Bool)
(assert (b 0))
(push)
(assert (distinct true (= a 0) (not (b 0))))
(check-sat)

$ cvc4 bug.smt2
unsat  ✔

$ z3 bug.smt2
sat    ✘
```

Root Cause: Last argument omitted in distinct operator

https://github.com/Z3Prover/z3/issues/2830

### CVC4 Soundness Bug #4469

```
$ cat bug.smt2
(set-logic QF_AUFBVLIA)
(declare-fun a () Int)
(declare-fun b (Int) Int)
(assert (distinct (b a)
   (b (b a))))
(check-sat)

$ z3 bug.smt2
sat    ✔

$ cvc4 bug.smt2
unsat  ✘
```

Labels: bug, major

https://github.com/CVC4/CVC4/issues/4469

# Yin-Yang Umbrella Release

OpFuzz + Semantic Fusion [PLDI ’20]

github.com/testsmt