The Mopsa static analysis platform, and our quest to ease implementation & maintenance

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rmonat.fr

ConVeY talk @ TUM
31 March 2025

Introduction

whoami

Research Scientist at Inria since Sep. 2022.

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Automated Verification of Catala Programs

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Motivation

Sheer quantity of programs and changes during their life:

Automated analyses will help scaling up

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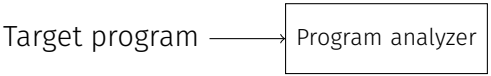

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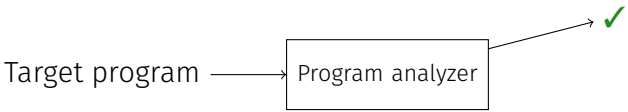

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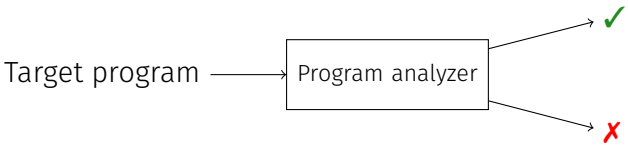

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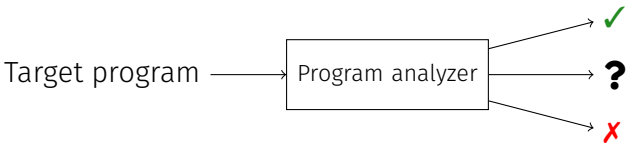

Turing & Rice to the Rescue

Sound All errors in program reported by analyzer

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All errors reported by analyzer are replicable in program

Complete

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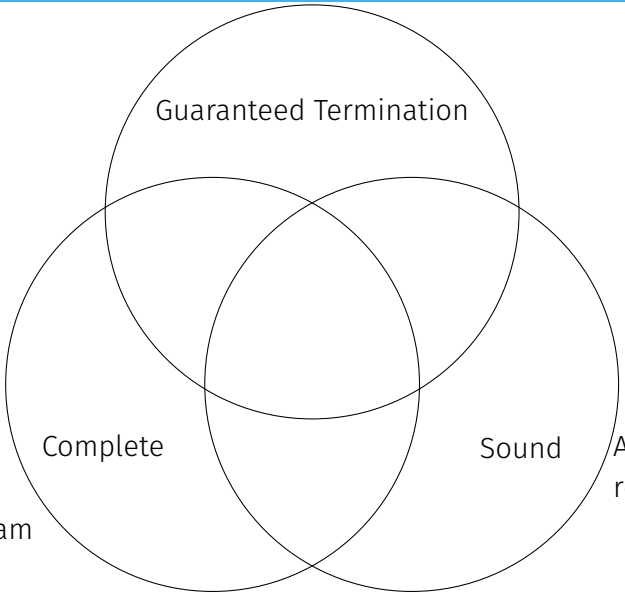

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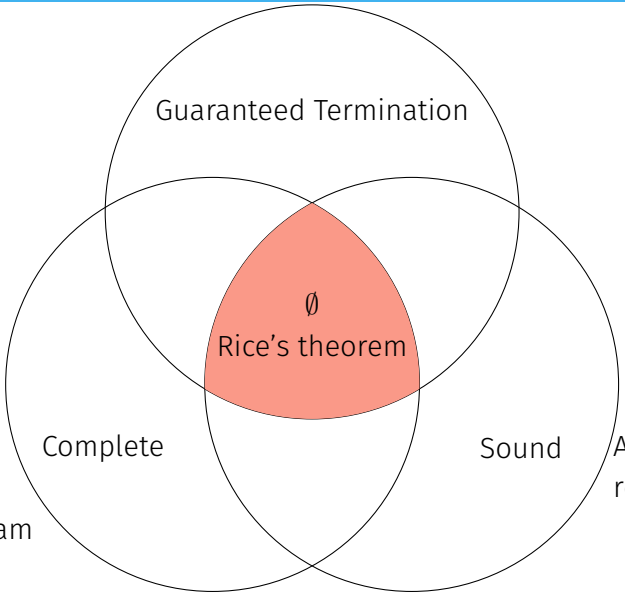

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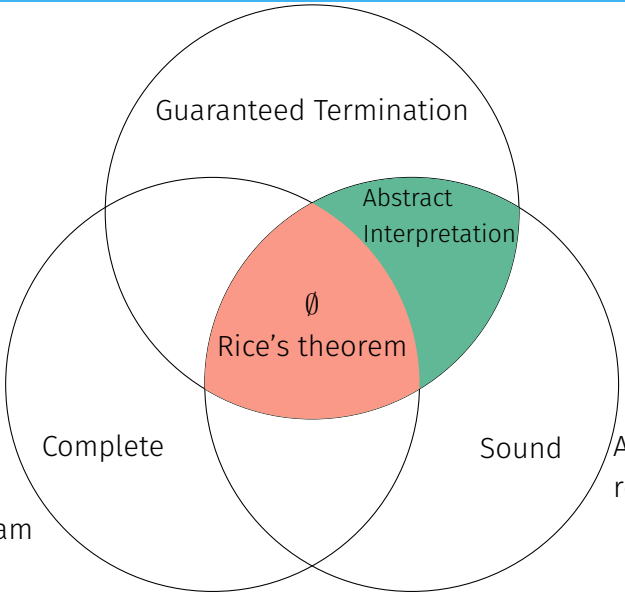

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Academic research around static analysis

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$\Longrightarrow$ Aiming for lowest possible implementation & maintenance costs

Outline

1. An overview of Mopsa
2. Providing transparent analysis results
3. Avoiding regressions
4. Easing debugging
5. A plug-in system of analysis observers

An overview of Mopsa

Modular **O**pen **P**latform for **S**tatic **A**nalysis [Jou+19]

`gitlab.com/mopsa/mopsa-analyzer` or `opam install mopsa`

Started by ERC Consolidator Grant (2016-2021) of Antoine Miné (LIP6, SU)

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- Can be used as an experimentation platform

Contributors (2018–2025, chronological arrival order)

- A. Miné
- A. Ouadjaout
- M. Journault
- A. Fromherz
- D. Delmas
- R. Monat
- G. Bau
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Maintainers in bold.

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Key design decisions

Analysis = composition of abstract domains

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unified domain signature $\Longrightarrow$ iterators are abstract domains

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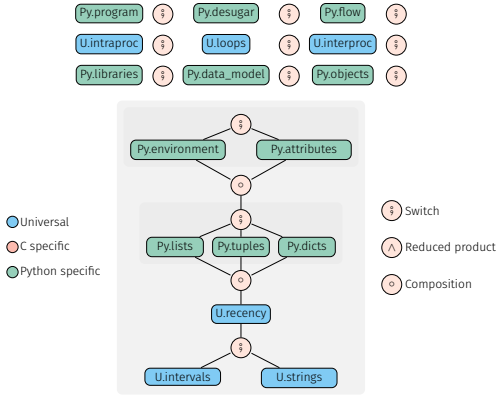

Iterators to handle multiple languages

Traditional approaches

Desugar/compile programs to an intermediate representation (IR)

Example: Infer's IR has five (!) constructors

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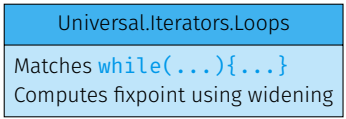
- Various programming paradigms supported!
- All constructs have to be handled – but rewritings are possible
- A single AST type which can be extended for new languages

Dynamic, semantic iterators with delegation



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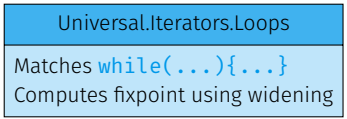
```
for(init; cond; incr) body
```



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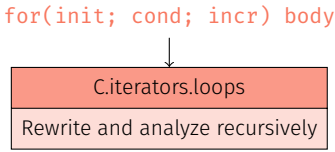

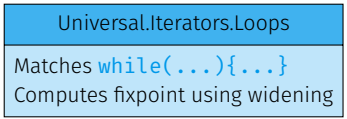

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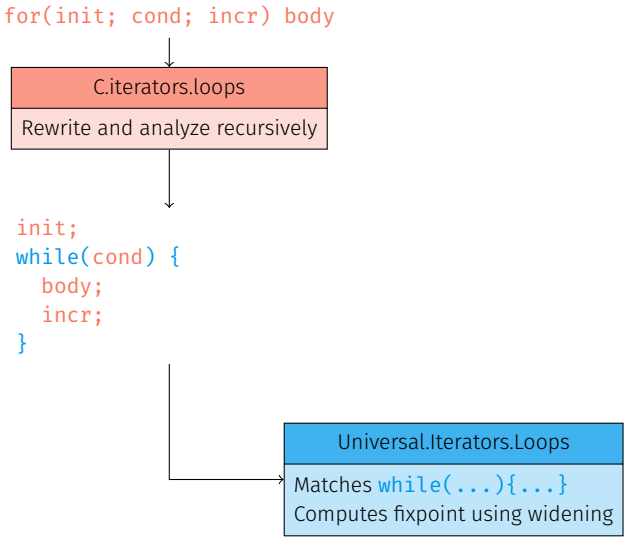

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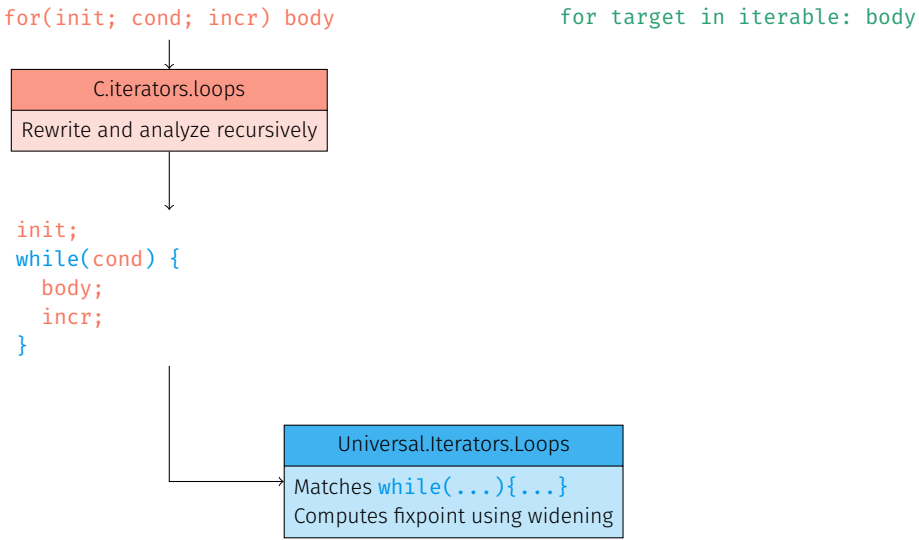

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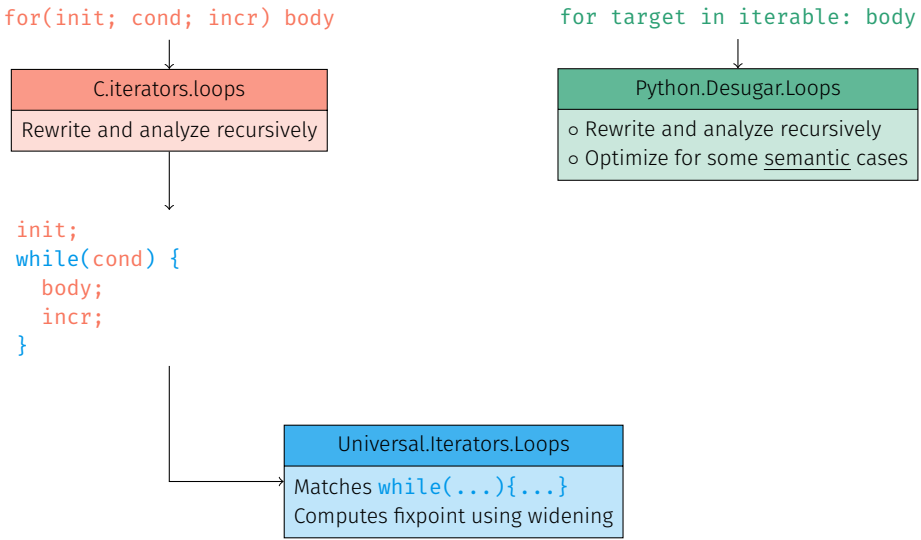

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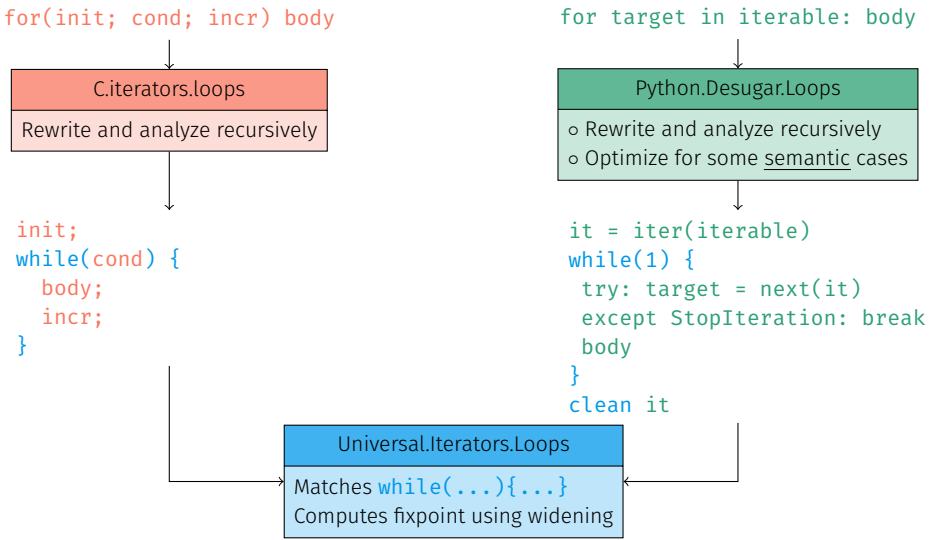

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Motivational example

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- Bindings from the convenient Apron library [JM09]

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Mopsa relies on rewriting, symbolic expressions and ghost variables

to leverage relational domains.

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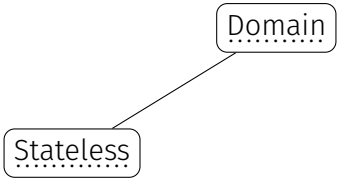

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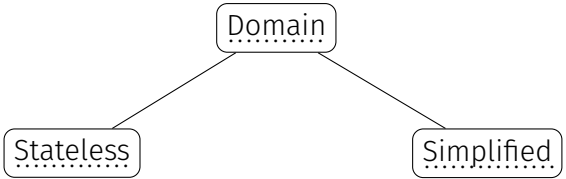

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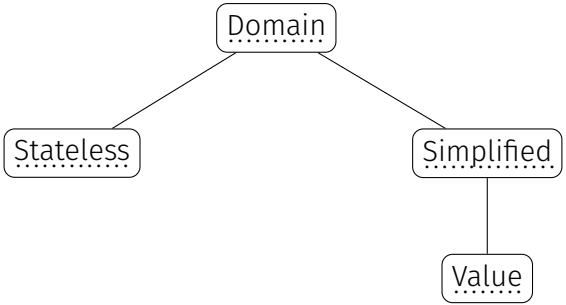

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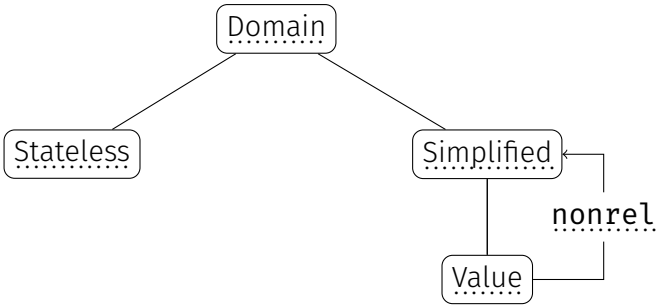

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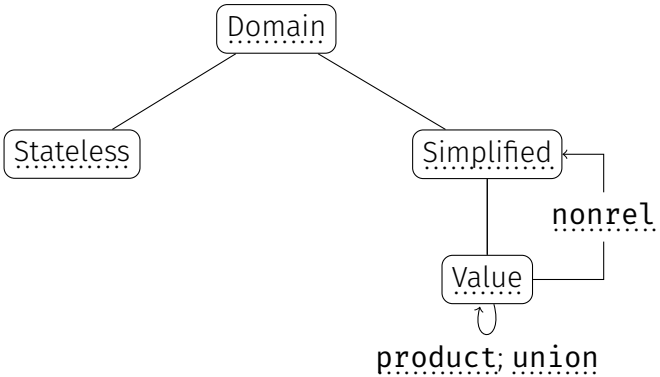

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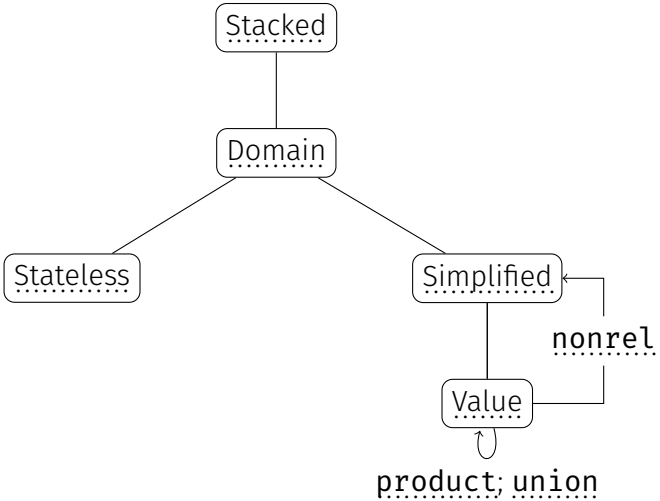

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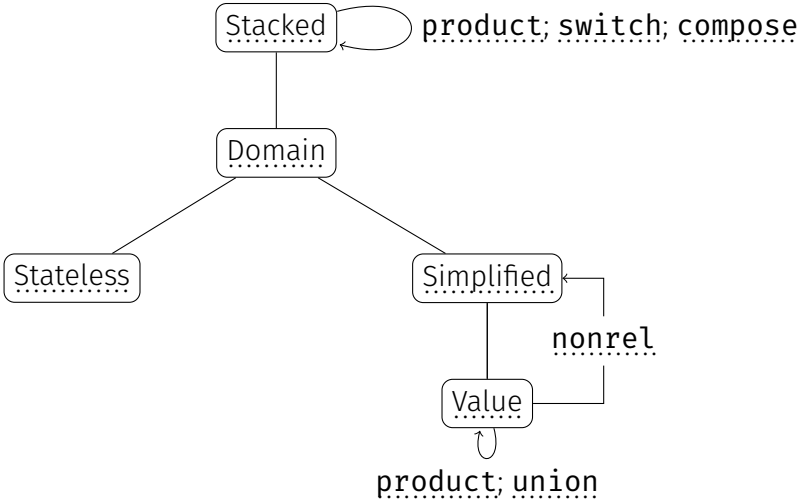

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Works around Mopsa

- Large support of `libc` through stubs

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- Check for all C runtime errors

Coreutils – Ouadjaout and Miné [OM20]

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- Ability to analyze real-world programs

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Benchmark	Time	Selectivity	# checks
basename	33.79s	98.65%	11,731
dirname	21.68s	99.61%	11,307
echo	19.26s	99.43%	11,010
false	14.50s	99.72%	10,774
pwd	22.04s	99.62%	11,502
rmdir	39.00s	99.22%	11,699
sleep	23.79s	99.46%	11,546
tee	35.69s	98.76%	12,057
timeout	32.28s	98.51%	12,420
true	9.55s	99.72%	10,774
uname	20.61s	99.52%	11,943
users	20.82s	99.06%	11,668
whoami	13.03s	99.66%	11,329

Multilanguage Analysis – Monat, Ouadjaout, and Miné [MOM21]

Assessment 20% of the 200 most popular Python libraries rely on C code

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Our approach: Combined analysis of C, Python and interface code

Library	C + Py. Loc	Tests	/test	# proved checks / # checks %	# checks
`noise`	1397	15/15	1.2s	99.7%	6690
`cdistance`	2345	28/28	4.1s	98.0%	13716
`llist`	4515	167/194	1.5s	98.8%	36255
`ahocorasick`	4877	46/92	1.2s	96.7%	6722
`levenshtein`	5798	17/17	5.3s	84.6%	4825
`bitarray`	5841	159/216	1.6s	94.9%	25566

Non-exploitability – Parolini and Miné [PM24]

- Focus on bugs that a user can trigger through program interaction

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Test suite	Domain	Analyzer	Alarms	Time
Coreutils	Intervals	MOPSA	4,715	1:17:06
		MOPSA-NEXP	1,217 (-74.19%)	1:28:42 (+15.05%)
	Octagons	MOPSA	4,673	2:22:29
		MOPSA-NEXP	1,209 (-74.13%)	2:43:06 (+14.47%)
	Polyhedra	MOPSA	4,651	2:12:21
		MOPSA-NEXP	1,193 (-74.35%)	2:30:44 (+13.89%)
Juliet	Intervals	MOPSA	49,957	11:32:24
		MOPSA-NEXP	13,906 (-72.16%)	11:48:51 (+2.38%)
	Octagons	MOPSA	48,256	13:15:29
		MOPSA-NEXP	13,631 (-71.75%)	13:41:47 (+3.31%)
	Polyhedra	MOPSA	48,256	12:54:21
		MOPSA-NEXP	13,631 (-71.75%)	13:21:26 (+3.50%)

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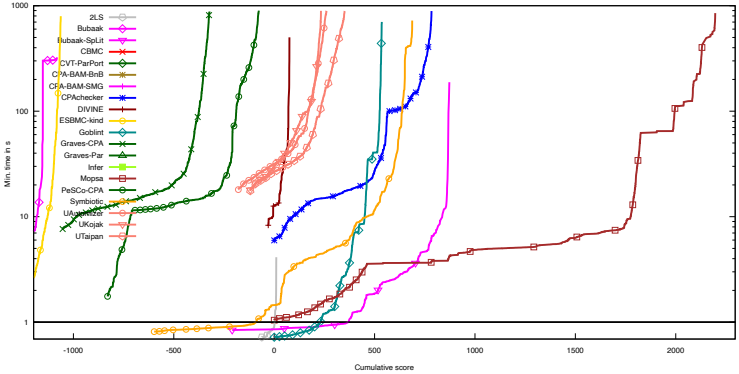

Summary of analyses

Languages
C [JMO18; OM20], Python [MOM20a; MOM20b]

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- **Absence of RTEs**
- Patch analysis [DM19]
- Endianness portability [DOM21]
- Non-exploitability [PM24]
- Sufficient precondition inference [MM24a; MM24b]

Providing transparent analysis results

Raising the bar in static analyzer transparency

```
$ static-analysis-tool file
```

Raising the bar in static analyzer transparency

```
$ static-analysis-tool file
...
```

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```
$ static-analysis-tool file
...
No errors found
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What has been checked? What has not?

Mopsa's approach to being transparent – at a high level

```
if a# ⋢ p# then
  add_alarm a# p#
```

Mopsa's approach to being transparent – at a high level

```
if a# ⋢ p# then
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```

```
if a# ⋢ p# then
  add_alarm a# p#
else
  add_safe_check p#
```

Mopsa's approach to being transparent – example

Mopsa's approach to being transparent

- Reporting status of all proofs / checks in every analyzed context

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```
1  int main() {
2    int n = _mopsa_rand_s32();
3    int y = -1;
4    for(int x = 0; x < n; x++)
5      y++;
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```

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Stmt
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y++
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Stmt	Itv
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y++	Alarm
Selectivity	50%

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Stmt	Itv	Poly
x++	Safe	Safe
y++	Alarm	Safe
Selectivity	50%	100%

Mopsa's approach to being transparent – output

Benefits of the approach

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- Easy to implement

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Analysis of coreutils `fmt`

```
Checks summary: 21247 total, ✔ 18491 safe, ✗ 129 errors, ⚠ 2627 warnings
  Stub condition: 690 total, ✔ 513 safe, ✗ 3 errors, ⚠ 174 warnings
  Invalid memory access: 8139 total, ✔ 7142 safe, ✗ 4 errors, ⚠ 993 warnings
  Division by zero: 499 total, ✔ 445 safe, ⚠ 54 warnings
  Integer overflow: 11581 total, ✔ 10177 safe, ⚠ 1404 warnings
  Invalid shift: 163 total, ✔ 163 safe
  Invalid pointer comparison: 37 total, ✗ 37 errors
  Invalid pointer subtraction: 85 total, ✗ 85 errors
  Insufficient variadic arguments: 1 total, ✔ 1 safe
  Insufficient format arguments: 26 total, ✔ 25 safe, ⚠ 1 warning
  Invalid type of format argument: 26 total, ✔ 25 safe, ⚠ 1 warning
```

Mopsa's approach to being transparent – soundness assumptions

Soundness assumptions, through an example

```
extern int f(int *x)
```

Mopsa's approach to being transparent – soundness assumptions

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`extern int f(int *x)`, handling gradations

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1. Crash

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Mopsa's approach to being transparent – soundness assumptions

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Related topic: soundiness paper [Liv+15]

Avoiding regressions

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$\Longrightarrow$ check for precision changes

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Benchmarks with precision oracles

- Know whether a given alarm should be raised
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Otherwise: relative precision measures, rely on our selectivity computation.

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`mopsa-diff` script, used to compare:

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```
--- baseline/touch-many-symbolic-args-a4.json
+++ pplite/touch-many-symbolic-args-a4.json

- time: 589.0760
+ time: 675.1761

+ parse-datetime.y:1399.44-46: alarm: Invalid memory access
- parse-datetime.y:965.56-71: alarm: Invalid memory access
- parse-datetime.y:980.25-52: alarm: Invalid memory access
- parse-datetime.y:1003.23-50: alarm: Invalid memory access
- parse-datetime.y:921.56-71: alarm: Invalid memory access
- parse-datetime.c:1733.2-8: alarm: Invalid memory access
- parse-datetime.y:781.26-41: alarm: Invalid memory access
- parse-datetime.y:772.23-38: alarm: Invalid memory access
- parse-datetime.y:755.23-38: alarm: Invalid memory access
- parse-datetime.y:973.25-52: alarm: Invalid memory access
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- parse-datetime.y:743.25-40: alarm: Invalid memory access
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```

```
139 reports compared
avg. time change       +52.065s
avg. speedup                -36%
new alarms                    2
removed alarms               32
new assumptions               0
removed assumptions           0
new successes                 0
new failures                  0
```

Detecting breaking changes using continuous integration

- `mopsa-diff` to compare with previous results

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  - * stubs can be added in marginal cases

Easing debugging

Where static analyzers usually start from

- Analysis output

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- Printing abstract state using builtins — Not interactive

Where static analyzers usually start from

- Analysis output — Too coarse
- Printing abstract state using builtins — Not interactive
- Interpretation trace — Can be dozens of gigabytes of text

```
+ S [| set_program_name(argv[0]); |]
| | + S [| add(argv0)
| | |       argv0 = argv[0]; |]
| | | + S [| add(argv0) |]
| | | | + S [| add(argv0) |] in below(c.iterators.intraproc)
| | | | | + S [| add(argv0) |] in C/Scalar
| | | | | | + S [| add(offset⟦argv0⟧) |] in Universal
| | | | | | o S [| add(offset⟦argv0⟧) |] in Universal done [0.0001s, 1 case]
| | | | | o S [| add(argv0) |] in C/Scalar done [0.0001s, 1 case]
| | | | | + S [| add(argv0) |] in below(c.memory.lowlevel.cells)
| | | | | | + S [| add(offset⟦argv0⟧) |] in Universal
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| | | | o S [| add(argv0) |] in below(c.iterators.intraproc) done [0.0001s, 1 case]
| | | o S [| add(argv0) |] done [0.0002s, 1 case]
| | | + S [| argv0 = argv[0]; |]
| | | | + S [| argv0 = (signed char *) @argv{0}:ptr; |] in below(c.iterators.intraproc)
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| | | | | | + S [| offset⟦argv0⟧ = (offset⟦@argv{0}:ptr⟧ + 0); |] in Universal
| | | | | | | + S [| offset⟦argv0⟧ = (offset⟦@argv{0}:ptr⟧ + 0); |] in below(universal.iterators.intraproc)
```

An interactive engine acting as abstract debugger

GDB-like interface to the abstract interpretation of the program

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Demo!

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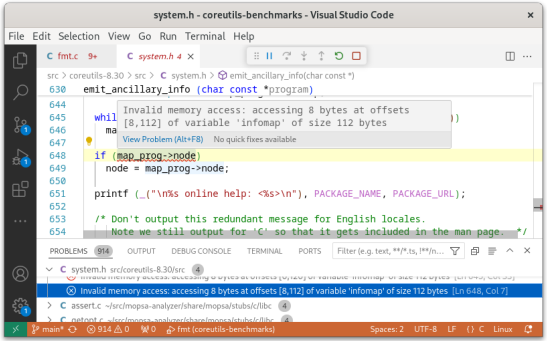
- Navigation
- Observation of the abstract state
  - Full state
  - Projection on specific variables
- Some scripting capabilities

IDE support

- Language Server Protocol for linters (report alarms)



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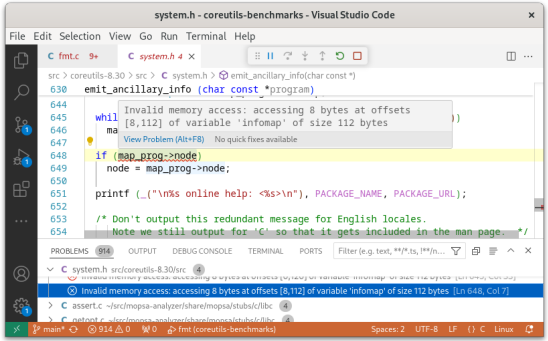
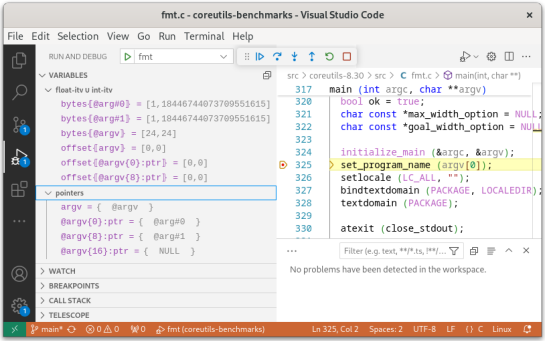
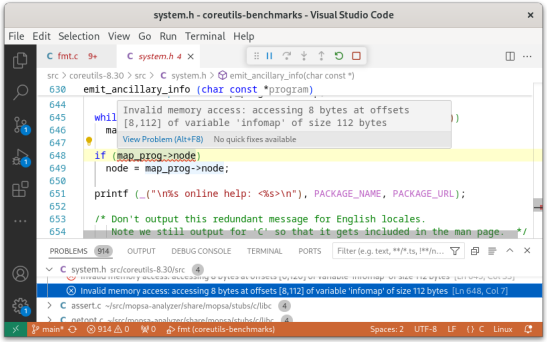
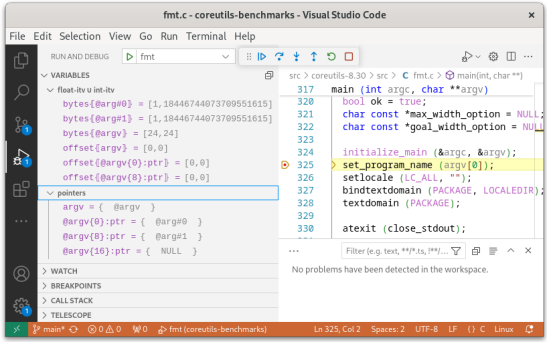




IDE support

- Language Server Protocol for linters (report alarms)
- Debug Adapter Protocol providing interactive engine interface
- Both protocols introduced by VSCode, supported by multiple IDEs





Testcase reduction

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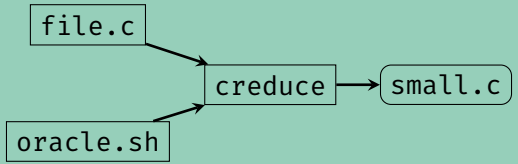
Automated testcase reduction using `creduce` [Reg+12]




THE #1 PROGRAMMER EXCUSE FOR LEGITIMATELY SLACKING OFF:
"MY CODE'S COMPILING."
HEY! GET BACK TO WORK!
COMPILING!
OH. CARRY ON.

Testcase reduction – III

Internal errors debugging

- Highly helpful to significantly reduce debugging time of runtime errors (Apron mishandlings, raised exceptions, ...)
- Has been applied to coreutils programs, SV-Comp programs of 10,000+ LoC

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Reference	Origin	Original LoC	Reduced LoC	Reduction
Issue 76	SV-Comp	28,737	18	99.94%
Issue 81	SV-Comp	15,627	8	99.95%
Issue 134	SV-Comp	17,411	10	99.94%
Issue 135	SV-Comp	7,016	12	99.83%
M.R. 130	`coreutils`	77,981	20	99.97%
M.R. 145	`coreutils`	77,427	19	99.98%

Testcase reduction – IV

Differential-configuration debugging

```
$ mopsa-c -config=confA.json file.c
Alarm: assertion failure
$ mopsa-c -config=confB.json file.c
No alarm
```

Has been used to simplify cases in externally reported soundness issues

Handling multi-file projects

`creduce` limited to reducing a specific file

Mitigation: generate a pre-processed, standalone file

Painful operation on large projects such as `coreutils`

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Mopsa supports multi-file C projects

- `mopsa-build`

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```
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- Option to generate a single, preprocessed file

A plug-in system of analysis observers

Hooks: a plug-in system of analysis observers

Hooks	
Observe analyzer state	before/after any expression/statement analysis

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Current hooks

- Logs: trace of interpretation performed by the analysis
- Thresholds for widening
- **Coverage**
- **Heuristic unsoundness/imprecision detection**
- **Profiling**

Coverage hooks

Coverage

- Global metric for the analysis' results
- Good to detect issues in the instrumentation of the fully context-sensitive analysis

No symbolic argument

```
./src/coreutils-8.30/src/fmt.c:
    'main' 76% of 72 statements analyzed
    'set_prefix' 100% of 12 statements analyzed
    'same_para' 100% of 1 statement analyzed
    'get_line' 100% of 30 statements analyzed
    'fmt' 100% of 7 statements analyzed
    'base_cost' 100% of 16 statements analyzed
    'line_cost' 100% of 10 statements analyzed
    'get_prefix' 100% of 18 statements analyzed
```

Symbolic arguments

```
./src/coreutils-8.30/src/fmt.c:
    'main' 100% of 72 statements analyzed
```

Heuristic unsoundness/imprecision detection

Detection of unsound transfer functions

Bottom shouldn't appear after some statements (such as assignments)

Detection of imprecise analysis

Warns when top expressions are created

Simplifies the search for sources of large imprecision (esp. with rewritings)

Profiling

Standard profiling

Measures which parts of Mopsa are the most time-consuming

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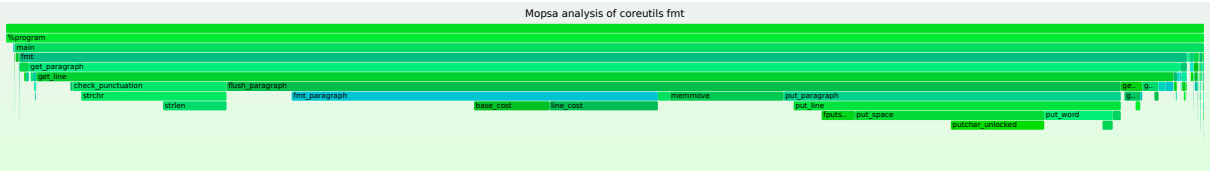

Apron vs PPLite on Coreutils touch

- PPLite is 14% slower but more precise (11 alarms removed). Why?

Profiling – II

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```
Loops profiling:
  ./src/coreutils-8.30/lib/argmatch.c:95.2-118.5: 3 times, [-3.00-] {+4.00+} avg. iterations [-(3, 3, 3)-] {+(4, 4, 4)+}
  ./src/coreutils-8.30/lib/posixtm.c:130.2-132.18: 12 times, [-2.00-] {+3.00+}
    avg. iterations [-(2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2)-] {+(3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3)+}
  ./src/coreutils-8.30/lib/posixtm.c:135.2-136.52: 12 times, [-2.00-] {+3.00+}
    avg. iterations [-(2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2)-] {+(3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3)+}
  ./src/coreutils-8.30/src/system.h:645.2-646.14: 3 times, [-2.00-] {+3.00+}
    avg. iterations [-(2, 2, 2)-] {+(3, 3, 3)+}
  parse-datetime.c:2636.2-2660.5: 16 times, [-2.00-] {+2.50+}
    avg.iterations [-(2, 2,-] {+(3, 3,+} 3, 1, [-2, 2,-] {+3, 3,+} 3, 1, [-2, 2,-] {+3, 3,+} 3, 1, [-2, 2,-] {+3, 3,+} 3, 1
  parse-datetime.c:2711.2-2716.5: 16 times, [-1.50-] {+1.75+}
    avg.iterations [-(1,-] {+(2,+} 2, 2, 1, [-1,-] 2, 2, [-1,-] {+2,+} 1, 2, 2, {+2,+} 1, [-1,-] {+2,+} 2, 2, 1)
  parse-datetime.y:1298.2-1300.15: 40 times, [-2.00-] {+3.00+}
    avg.iterations [-(2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2,
                   {+(3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3,
  parse-datetime.y:1304.2-1306.15: 40 times, [-2.00-] {+3.00+}
    avg.iterations [-(2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2,
                   {+(3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3, 3,
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Conclusion

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DAG of abstractions

- Relational domains
- Composition
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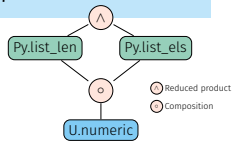

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