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

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Dagstuhl #25242
11 June 2025

Inria

Introduction

whoami

Research Scientist at Inria Lille.

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Research Interests

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- Static analysis: C, Python, multi-language paradigms

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Research Interests

- Static analysis: C, Python, multi-language paradigms
- Formal methods for public administrations

A Program Analysis Trichotomy

Sound	All errors in program reported by analyzer

A Program Analysis Trichotomy

All errors reported by analyzer are replicable in program

Complete

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A Program Analysis Trichotomy

Guaranteed Termination

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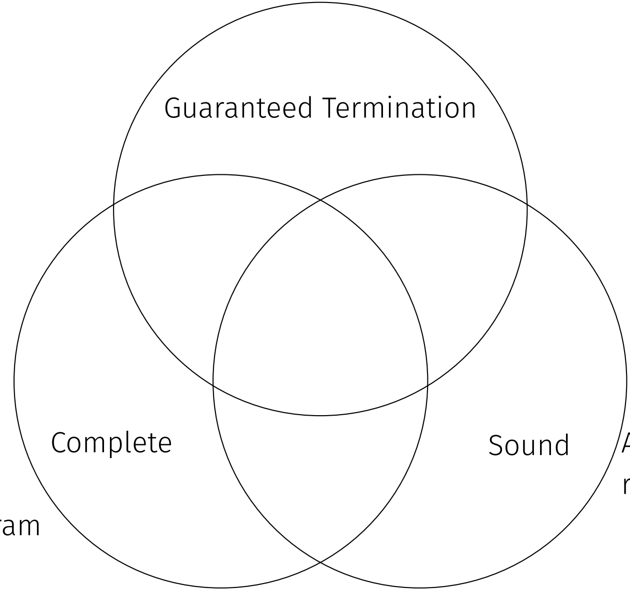
A Program Analysis Trichotomy



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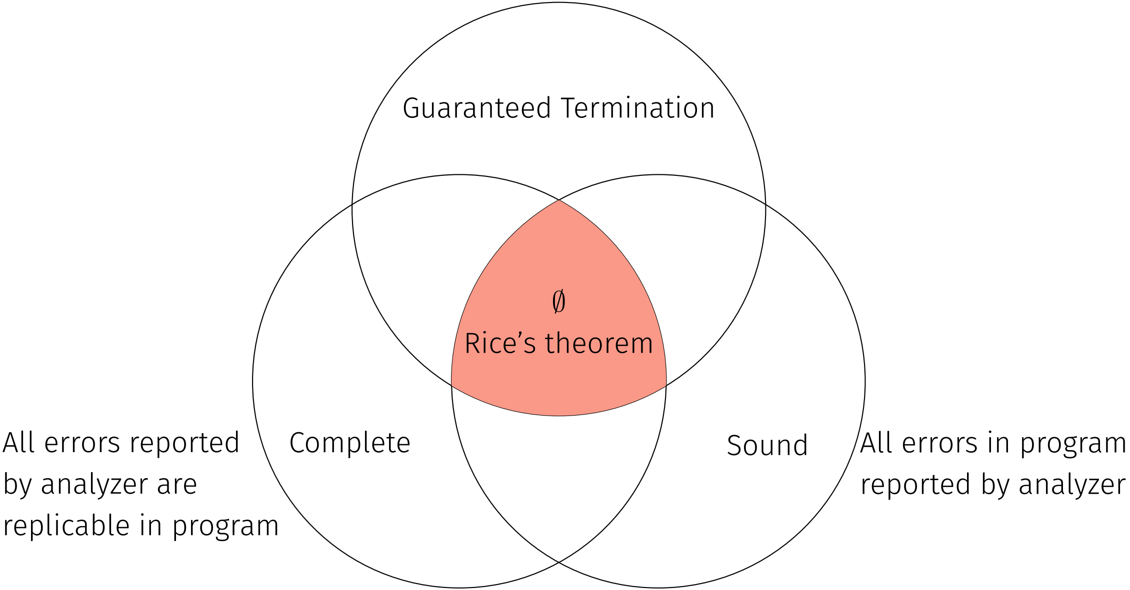

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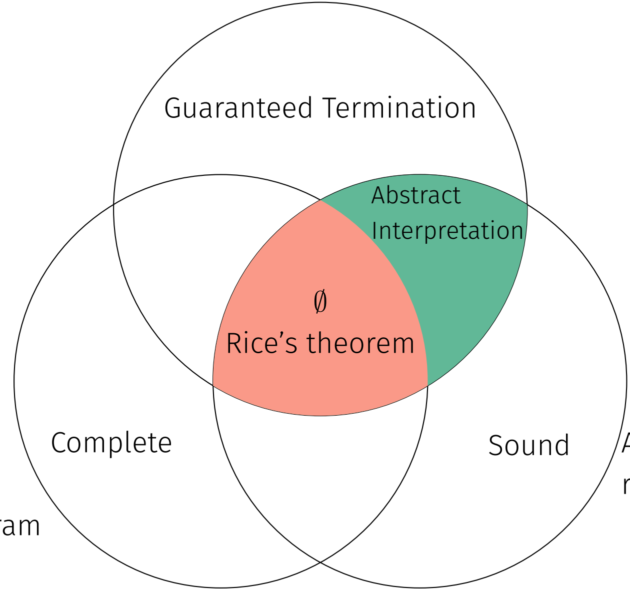

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All errors in program reported by analyzer

Motivation

Academic research around static analysis

Academic research around static analysis

Ideal analyzer

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- Sound, precise and scalable

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- Eases research:
  - Implementation
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- Maintenance necessary to build upon previous work

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

Outline

1. An overview of Mopsa
2. Avoiding regressions
3. Easing debugging
   - Developer-friendly interfaces
   - Testcase reduction
4. 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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Currently, fully context-sensitive analyses

Contributors (2018–2025, chronological arrival order)

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

Mopsa design

Analysis = composition of abstract domains

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unified domain signature $\Longrightarrow$ iterators are abstract domains

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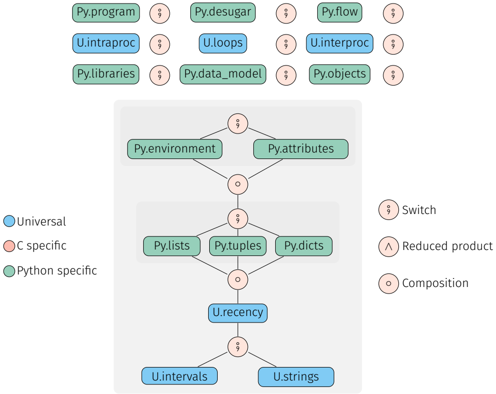

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Properties

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

Software Verification Competition [Mon+24]

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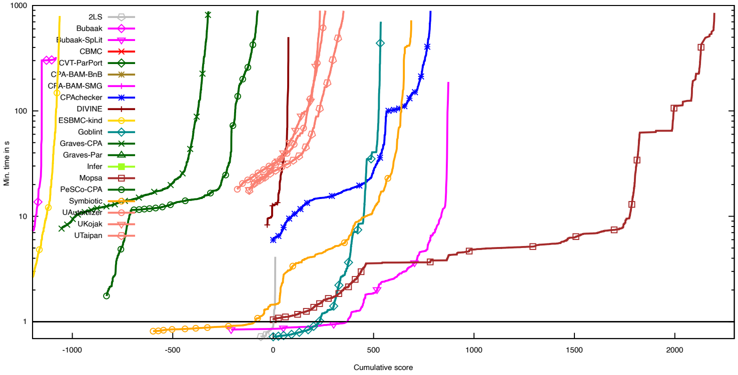

Avoiding regressions

Detour: providing transparent analysis results

Raising the bar in static analyzer transparency

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

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

```
$ static-analysis-tool file
...
No errors found
```

Raising the bar in static analyzer transparency

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$ static-analysis-tool file
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What has been checked? What has not?

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

if $a^\# \not\sqsubseteq p^\#$ **then**
  add_alarm $a^\#$ $p^\#$

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

$$\texttt{if}\ a^\# \not\sqsubseteq p^\#\ \texttt{then}\ \ \texttt{add\_alarm}\ a^\#\ p^\# \quad\rightsquigarrow\quad \texttt{if}\ a^\# \not\sqsubseteq p^\#\ \texttt{then}\ \ \texttt{add\_alarm}\ a^\#\ p^\#\ \ \texttt{else}\ \ \texttt{add\_safe\_check}\ p^\#$$

Mopsa’s approach to being transparent – example

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$$\text{Selectivity} = \frac{\#\text{checks proved safe}}{\#\text{checks}}$$

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```c
int main() {
  int n = _mopsa_rand_s32();
  int y = -1;
  for(int x = 0; x < n; x++)
    y++;
}
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Stmt
x++
y++
Selectivity

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Stmt	Itv
x++	Safe
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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Mopsa's approach to being transparent – output

Benefits of the approach

- Easy to implement
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- ~~Program size~~ ⇝ "expression complexity"

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

Soundness assumptions, through an example

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

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1. Crash

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1. Crash ✗
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Related topic: soundiness paper [Liv+15]

Avoiding regressions

Leveraging analysis transparency

Avoiding regressions

$\Longrightarrow$ check for precision changes

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$\Longrightarrow$ check for precision changes

Benchmarks with precision oracles

- Know whether a given alarm should be raised
- Based on manual analysis, not scalable
- NIST's Juliet Benchmarks, SV-Comp labeling of tasks (coarse)
- Can provide absolute precision measure

Avoiding regressions

$\Longrightarrow$ **check for precision changes**

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Otherwise: relative precision measures, rely on our selectivity computation.

Comparing analysis reports

`mopsa-diff` script, used to compare:

- analysis report(s): either single output or set of outputs
- usecases: different configurations, different versions of Mopsa

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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
- parse-datetime.y:610.8-41: alarm: Invalid memory access
- 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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- Reusing all benchmarks from our experimental evaluations

CI, tests & benchmarks

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Benchmark selection

Our benchmarks are

CI, tests & benchmarks

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  - * stubs can be added in marginal cases

Easing debugging

Developer-friendly interfaces

Where static analyzers usually start from

- Analysis output Too coarse

Where static analyzers usually start from

- Analysis output — Too coarse
- 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
| | | | | | | o S [| add(offset⦃argv0⦄) |] in Universal done [0.0001s, 1 case]
| | | | | | o S [| add(argv0) |] in below(c.memory.lowlevel.cells) done [0.0001s, 1 case]
| | | | | 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)
| | | | | | + S [| argv0 = (signed char *) @argv{0}:ptr; |] in C/Scalar
| | | | | | | + 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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  - Alarm: jumping back to statement generating first alarm
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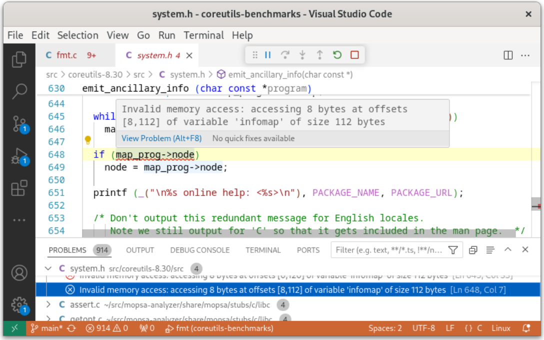
  - Projection on specific variables
- Some scripting capabilities

IDE support

- Language Server Protocol for linters (report alarms)



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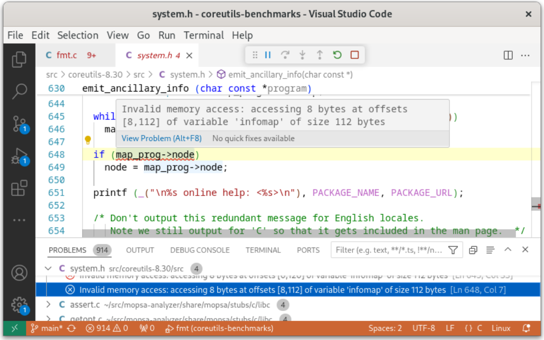
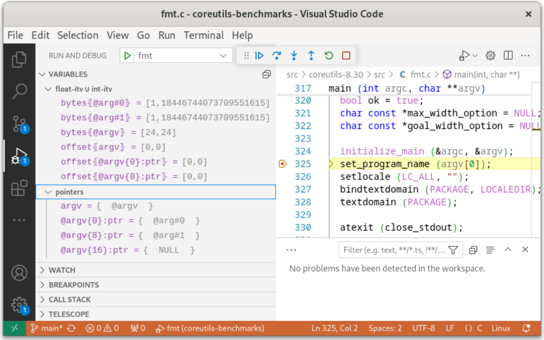
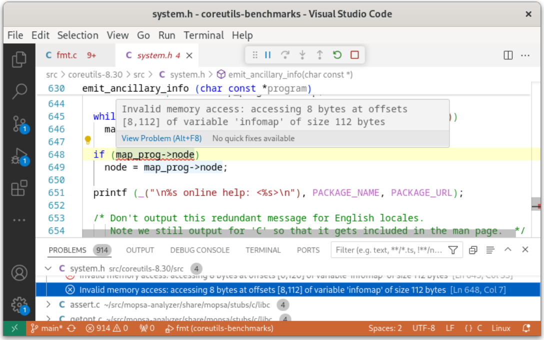
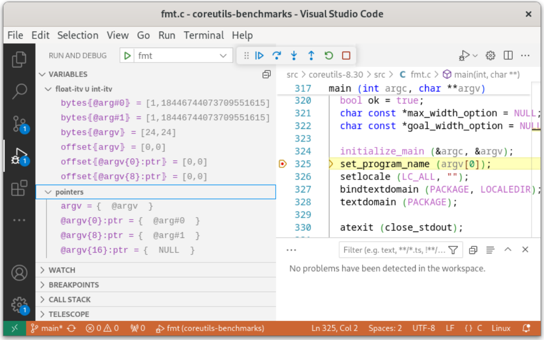




IDE support

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





Easing debugging

Testcase reduction

Motivation

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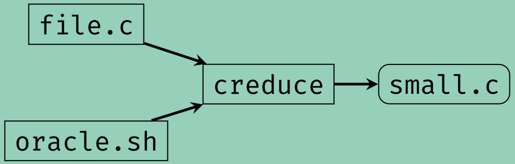
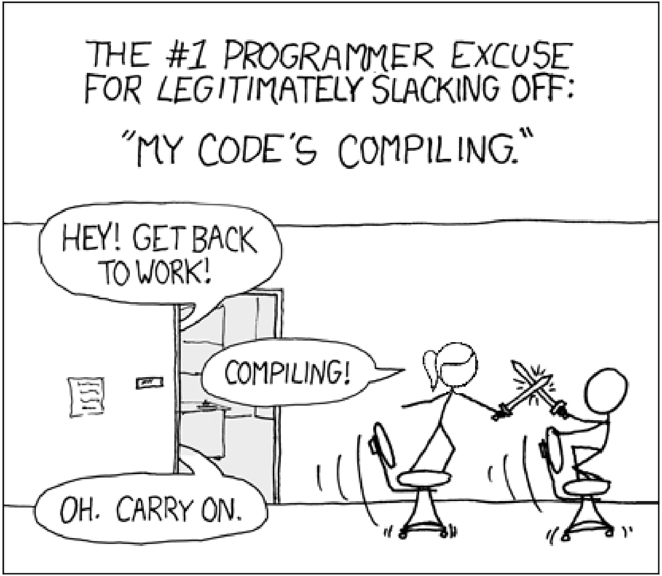
Automated testcase reduction using `creduce` [Reg+12]



Testcase reduction – II



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` reduces a specific file

One mitigation: generate a pre-processed, standalone file

Painful operation on large projects such as **`coreutils`**

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```
mopsa-c mopsa.db -make-target=fmt
```

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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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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:
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```

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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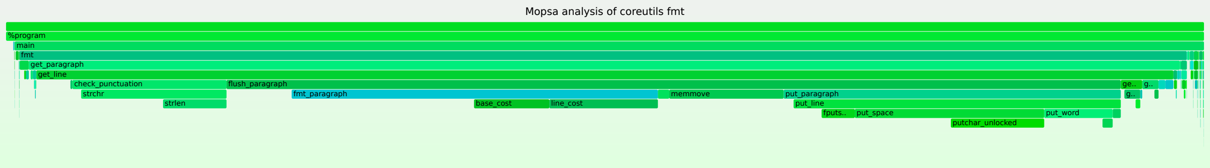

Profiling – II

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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, 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, 3,
  parse-datetime.y:1304.2-1306.15: 40 times, [-2.00-] {+3.00+}
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- Larger usability improvements?

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