Easing implementation & maintenance of academic static analyzers

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SemAntique
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Introduction

Motivation

Academic research around static analysis

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Ideal analyzer

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- Sound, precise and scalable

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  - Experimental evaluation
  - Onboarding

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- Debugging time-consuming

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- Maintenance necessary to build upon previous work

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⟹ Aiming for lowest possible implementation & maintenance costs

This talk

Since 2017 Development of the Mopsa static analysis platform

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This talk	shares our experience and approach in Mopsa

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⚠ Experience report; some things might be folklore.

Overview of Mopsa

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

`gitlab.com/mopsa/mopsa-analyzer`

Goals: explore new designs, ease development of (relational) analyses

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- Semantic rewriting
- Loose coupling
- Observability

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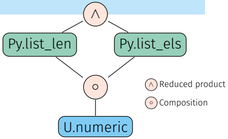
DAG of abstractions

- Relational domains
- Composition
- Cooperation



Contributors (2018–2024, chronological arrival order)

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

Works around Mopsa

Languages

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

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- Non-exploitability [PM24]

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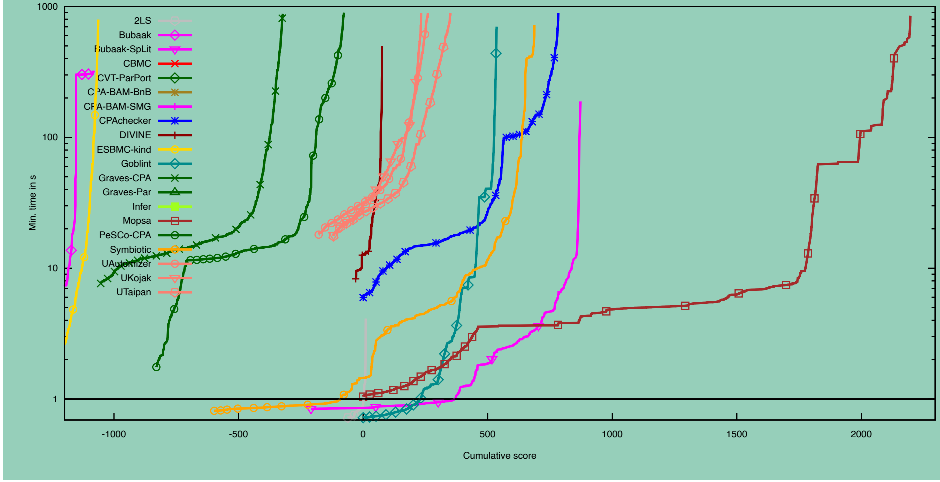
Properties

- **Absence of RTEs**
- Patch analysis [DM19]
- Endianness portability [DOM21]
- Non-exploitability [PM24]
- Sufficient precondition inference [MM24]

Works around Mopsa – II

Software Verification Competition

We won the “SoftwareSystems” track of SV-Comp 2024 [Mon+24]!



Outline

1 Providing transparent analysis results

2 Avoiding regressions

3 Easing debugging

4 A plug-in system of analysis observers

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
...
```

Raising the bar in static analyzer transparency

```
$ 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 $a^\# \not\sqsubseteq p^\#$ then
  add_alarm $a^\#$ $p^\#$
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```

$\rightsquigarrow$

```
if $a^\# \not\sqsubseteq p^\#$ 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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$$\text{Selectivity} = \frac{\#\text{checks proved safe}}{\#\text{checks}}$$

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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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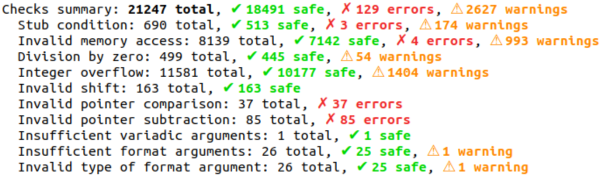
Analysis of coreutils `fmt`



```
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)
```

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

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2. Ignore silently

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4. Assume and report: f has any effect on its parameters

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Related topic: soundiness paper [Liv+15]

Avoiding regressions

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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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- 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
```

```
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
```

CI, tests & benchmarks

Detecting breaking changes using continuous integration

- `mopsa-diff` to compare with previous results

CI, tests & benchmarks

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  - * stubs can be added in marginal cases

Some benchmarks

See SV-Comp 2024 results.

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Benchmark	# Tests	Total LOC	Time	Precision
CWE121	2,508	234,930	3,064s	22.13%
CWE122	1,556	166,664	1,948s	25.84%
CWE124	758	93,372	961s	36.94%
CWE126	600	75,984	769s	46.83%
CWE127	758	89,022	963s	37.07%
CWE190	3,420	440,749	4,356s	78.13%
CWE191	2,622	340,884	3,236s	78.87%
CWE369	497	83,238	674s	70.42%
CWE415	190	17,990	228s	100.00%
CWE416	118	14,782	142s	67.80%
CWE469	18	1,520	22s	100.00%
CWE476	216	20,427	254s	100.00%

Table 1: Juliet benchmarks (non-relational configuration, no partitioning).

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Table 1: Juliet benchmarks (non-relational configuration, no partitioning).

Benchmark	Time	Selectivity	# checks
basename	33.79s	98.65%	11,731
comm	42.67s	97.32%	12,654
dircolors	34.82s	99.74%	20,062
dirname	21.68s	99.61%	11,307
echo	19.26s	99.43%	11,010
false	14.50s	99.72%	10,774
getlimits	34.62s	98.54%	11,711
hostid	18.05s	99.65%	11,303
id	32.69s	99.04%	12,338
link	23.03s	99.52%	11,572
logname	20.36s	99.66%	11,307
mkfifo	34.87s	99.20%	11,807

Table 2: `coreutils` benchmarks (fully symbolic arguments, relational analysis).

Easing debugging

Where static analyzers usually start from

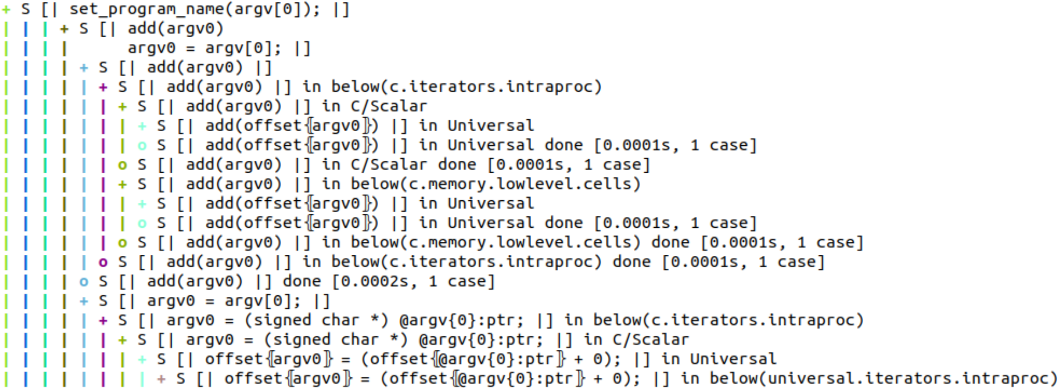
- Analysis output Too coarse

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
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| | | | 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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- Breakpoints

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  - Specific transfer function, analysis of subexpression

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  - Alarm: jumping back to statement generating first alarm

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Demo!

- Breakpoints
  - Program location
  - Specific transfer function, analysis of subexpression
  - Alarm: jumping <u>back</u> to statement generating first alarm
- Navigation

An interactive engine acting as abstract debugger

GDB-like interface to the abstract interpretation of the program

Demo!

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  - Specific transfer function, analysis of subexpression
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- Navigation
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An interactive engine acting as abstract debugger

GDB-like interface to the abstract interpretation of the program

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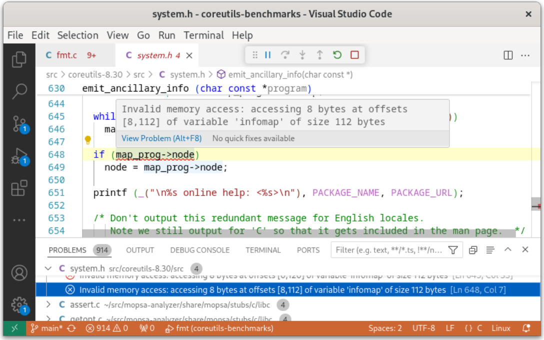
  - Full state
  - Projection on specific variables
- Some scripting capabilities

IDE support

- Language Server Protocol for linters (report alarms)


system.h - coreutils-benchmarks - Visual Studio Code
File
Edit
Selection
View
Go
Run
Terminal
Help
fmt.c 9+
system.h 4
src > coreutils-8.30 > src > system.h > emit_ancillary_info(char const *)
PROBLEMS 914
OUTPUT
DEBUG CONSOLE
TERMINAL
PORTS
Filter (e.g. text, **/*.ts, !**/n...
main*
914 0
0
fmt (coreutils-benchmarks)
Spaces: 2
UTF-8
LF
{} C
Linux

```
emit_ancillary_info (char const *program)

  whil
    ma

  if (map_prog->node)
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     Note we still output for 'C' so that it gets included in the man page.  */
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```
Invalid memory access: accessing 8 bytes at offsets
[8,112] of variable 'infomap' of size 112 bytes
```

View Problem (Alt+F8)   No quick fixes available

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assert.c ~/src/mopsa-analyzer/share/mopsa/stubs/c/libc 4

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IDE support

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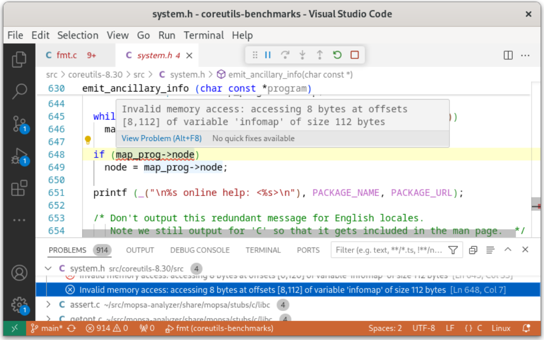
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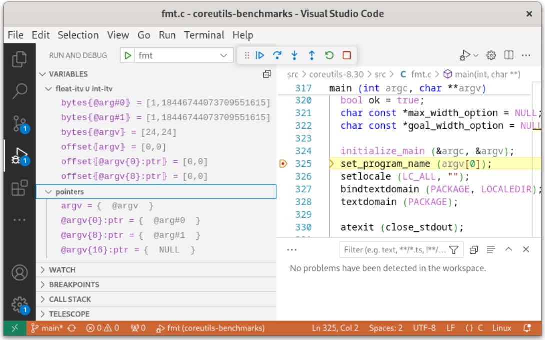
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fmt
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WATCH
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```
VARIABLES
  float-itv ∪ int-itv
    bytes{@arg#0} = [1,18446744073709551615]
    bytes{@arg#1} = [1,18446744073709551615]
    bytes{@argv} = [24,24]
    offset{argv} = [0,0]
    offset{@argv{0}:ptr} = [0,0]
    offset{@argv{8}:ptr} = [0,0]
  pointers
    argv = {  @argv  }
    @argv{0}:ptr = {  @arg#0  }
    @argv{8}:ptr = {  @arg#1  }
    @argv{16}:ptr = {  NULL  }
```

```
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  char const *max_width_option = NULL;
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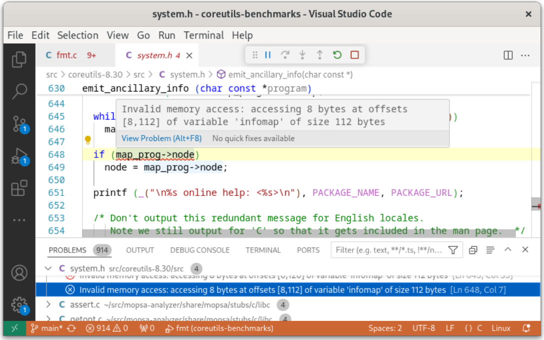
  set_program_name (argv[0]);
  setlocale (LC_ALL, "");
  bindtextdomain (PACKAGE, LOCALEDIR);
  textdomain (PACKAGE);

  atexit (close_stdout);
```

No problems have been detected in the workspace.

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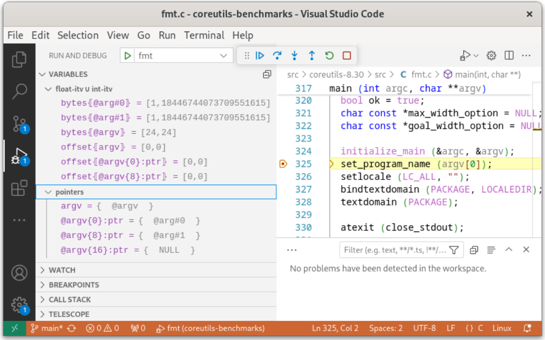
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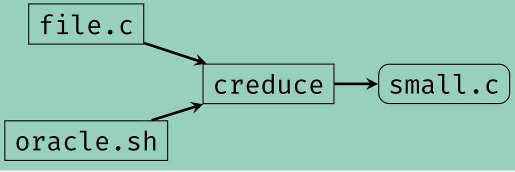
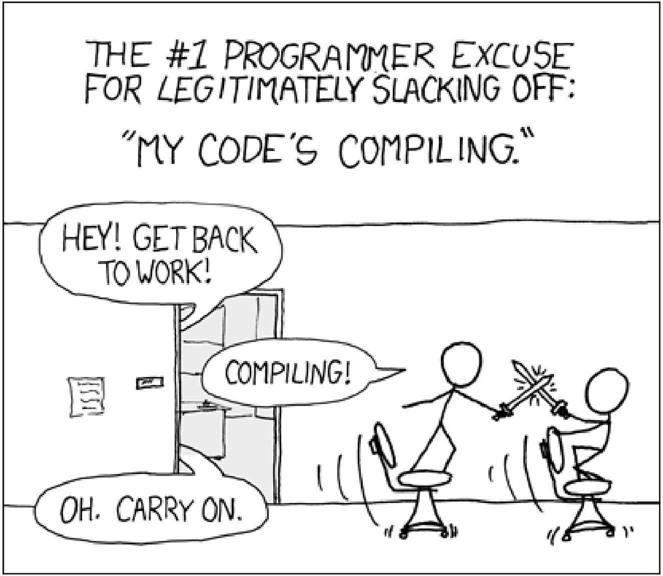
Automated testcase reduction using `creduce` [Reg+12]



Testcase reduction – II



Testcase reduction – III

Internal errors debugging

- Highly helpful to significantly reduce debugging time of runtime errors (Apron mishandlings, raised exceptions, …)
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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-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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- Logs: trace of interpretation performed by the analysis
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- **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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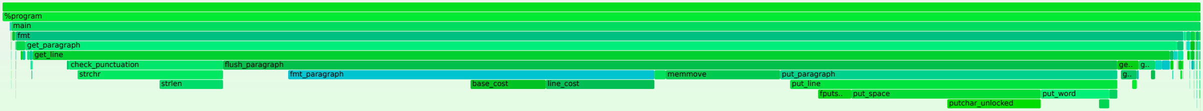

Mopsa analysis of coreutils fmt

Profiling – II

Apron vs PPLite on Coreutils touch

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

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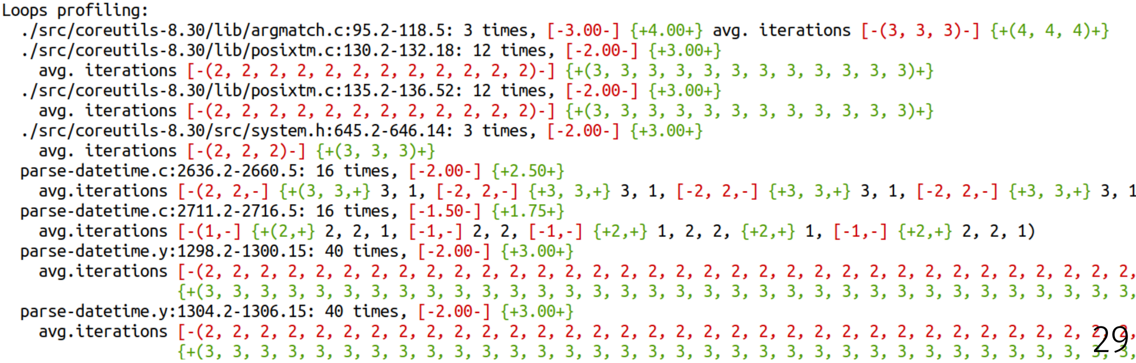

```
Loops profiling:
  ./src/coreutils-8.30/lib/argmatch.c:95.2-118.5: 3 times, [-3.00-] {+4.00+} avg. iterations [-(3, 3, 3)-] {+(4, 4, 4)+}
  ./src/coreutils-8.30/lib/posixtm.c:130.2-132.18: 12 times, [-2.00-] {+3.00+}
    avg. iterations [-(2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2)-] {+(3, 3, 3, 3, 3, 3, 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, 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, 3,
  parse-datetime.y:1304.2-1306.15: 40 times, [-2.00-] {+3.00+}
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                   {+(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, 3,
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Lots of folklore

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- Code maintenance time is still high (for me)

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- Non-regression testing of soundness & precision. CI on real-world software.
- Combination of existing techniques and new tools to debug & profile Mopsa
  “std. tools on the concrete execution of the *abstract interpreter*”
  ⇝ “new tools on abstract execution of *target program*”

Ongoing challenges

- Handling the exponential number of configurations
- Code maintenance time is still high (for me)
- Onboarding material

Conclusion

Our current approach

- Non-regression testing of soundness & precision. CI on real-world software.
- Combination of existing techniques and new tools to debug & profile Mopsa
  "std. tools on the concrete execution of the *abstract interpreter*"
  $\rightsquigarrow$ "new tools on abstract execution of *target program*"

Ongoing challenges

- Handling the exponential number of configurations
- Code maintenance time is still high (for me)
- Onboarding material
- Online availability, install-free tool testing

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