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

Raphaël Monat – SyCoMoRES team, Lille

`rmonat.fr`

CUPLV
4 April 2025

Introduction

whoami

Research Scientist at Inria since Sep. 2022.

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Motivation

Sheer quantity of programs and changes during their life:

Automated analyses will help scaling up

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Target program

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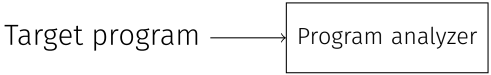

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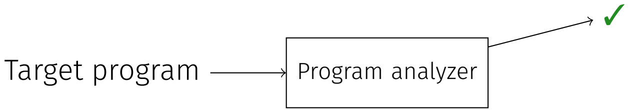

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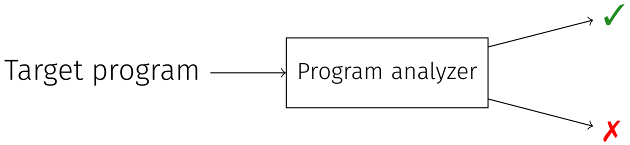

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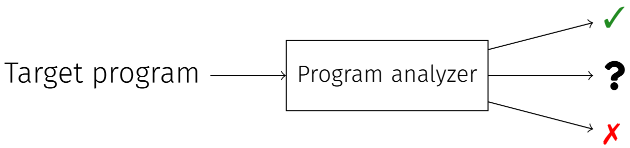

Turing & Rice to the Rescue

Sound All errors in program reported by analyzer

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All errors reported by analyzer are replicable in program

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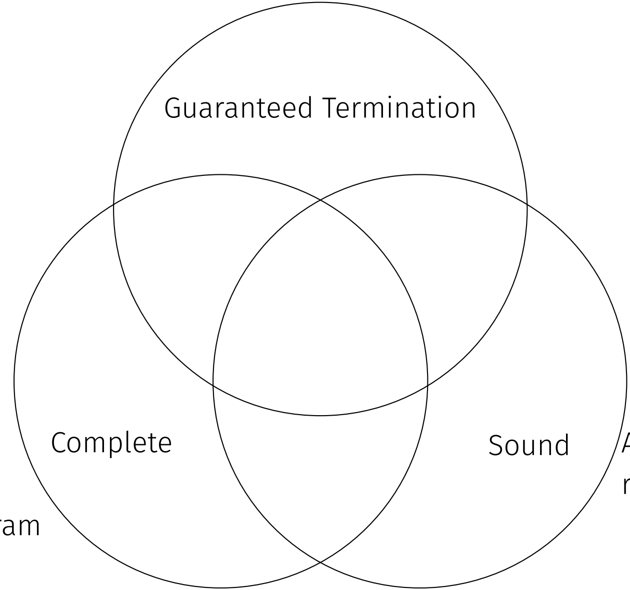

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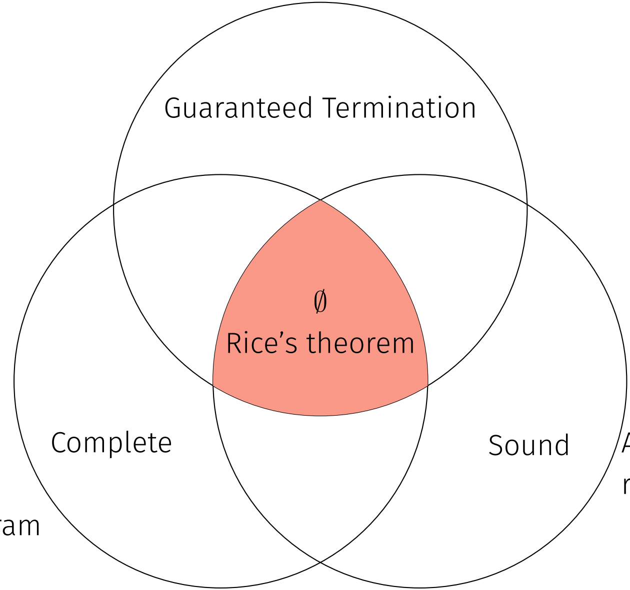

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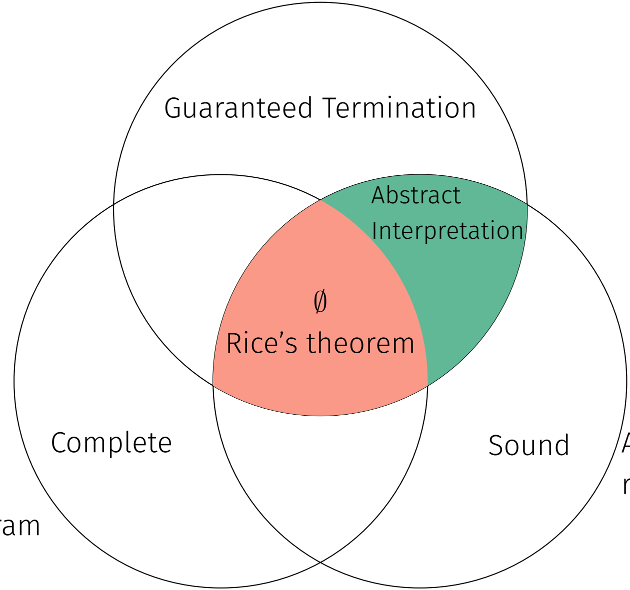

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$\Longrightarrow$ Aiming for lowest possible implementation & maintenance costs

Outline

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`

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Contributors (2018–2025, chronological arrival order)

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- A. Ouadjaout
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- 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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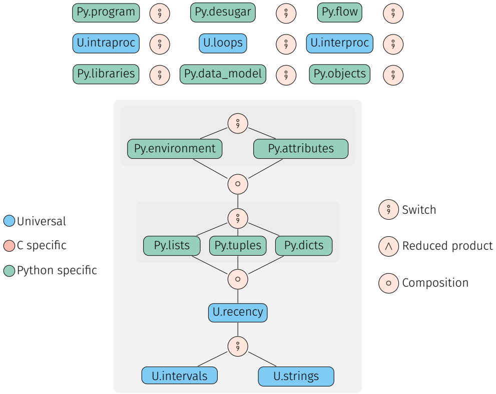

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Traditional approaches

Desugar/compile programs to an intermediate representation (IR)

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- 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

Universal.Iterators.Loops
Matches `while(...){...}`
Computes fixpoint using widening

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for(init; cond; incr) body
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↓

C.iterators.loops

Rewrite and analyze recursively

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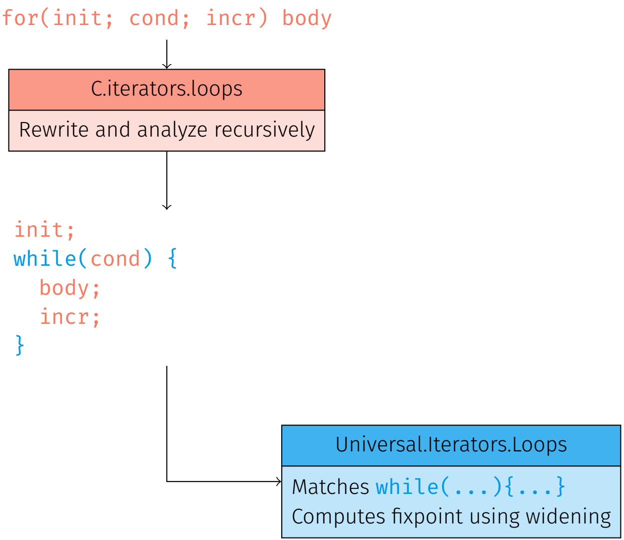

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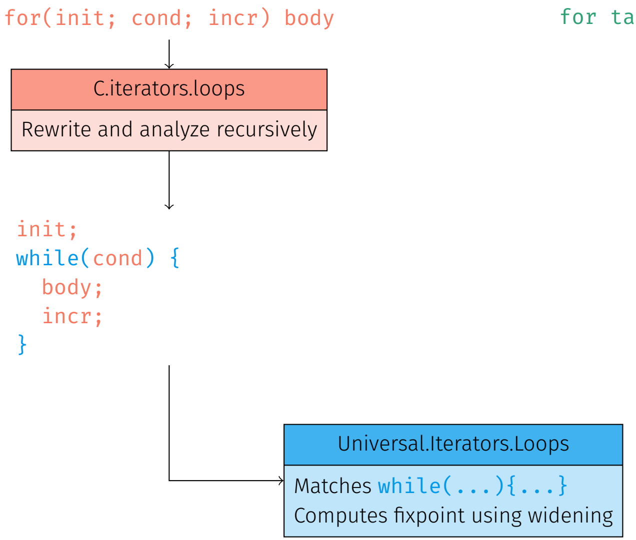

`for target in iterable: body`

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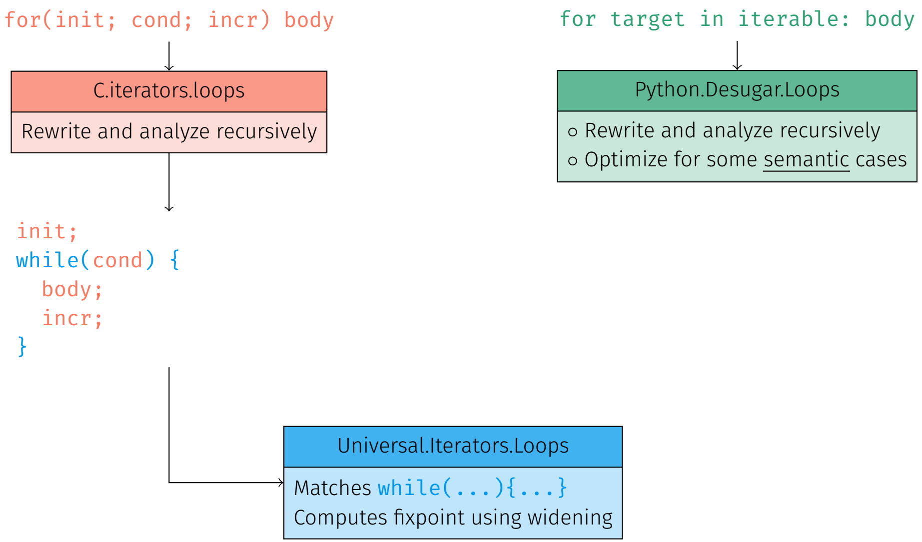

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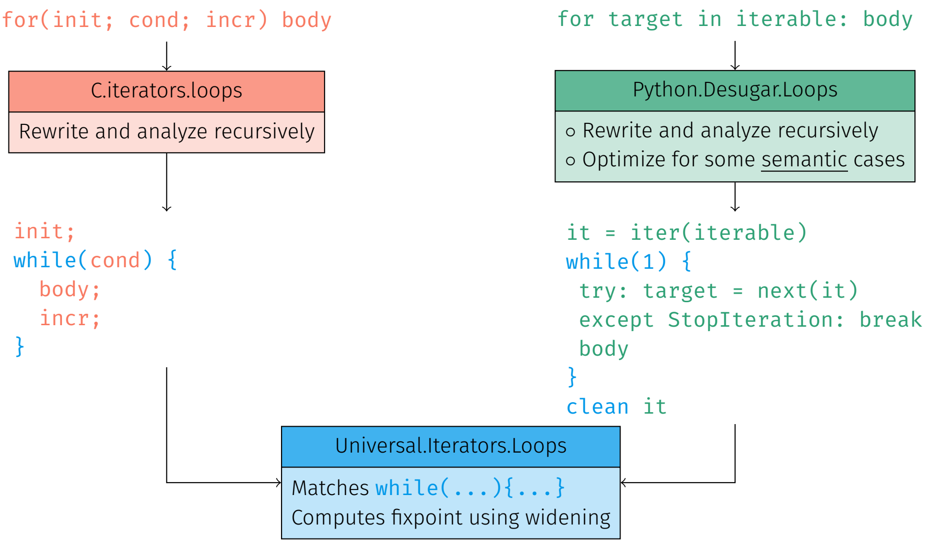

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Motivational example

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// Hyp: a array of size len(a) ∈ [10, 20]
s = 0;
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- Bindings from the convenient Apron library [JM09]

Relational domains in Mopsa

Difficulties arising from relational domains

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Mopsa relies on rewriting, symbolic expressions and ghost variables

to leverage relational domains.

An overview of Mopsa

Works around Mopsa

Coreutils – Ouadjaout and Miné [OM20]

- Large support of `libc` through stubs

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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	$\frac{\text{\# proved checks}}{\text{\# checks}}$ %	# 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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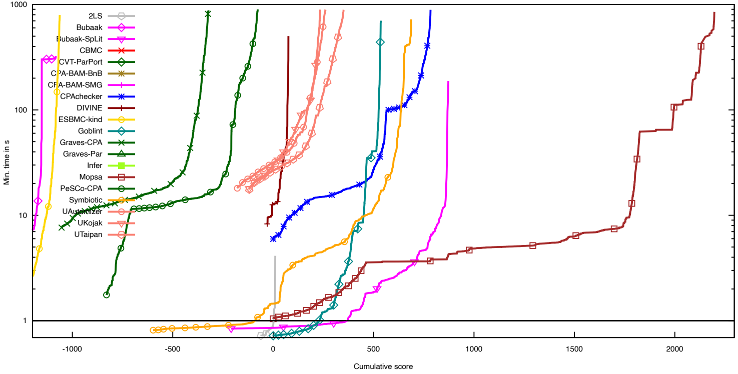

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- Endianness portability [DOM21]
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- Sufficient precondition inference [MM24a; MM24b]

Implementation details

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Mopsa is implemented in OCaml.

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match e with
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Polymorphism = Type Variables

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   - add new custom domains. Can rely on predefined `Lattices`.

A zoology of domains and combinators in Mopsa

Domain

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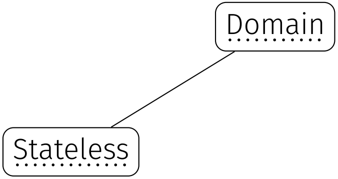

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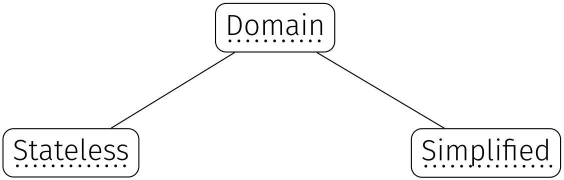

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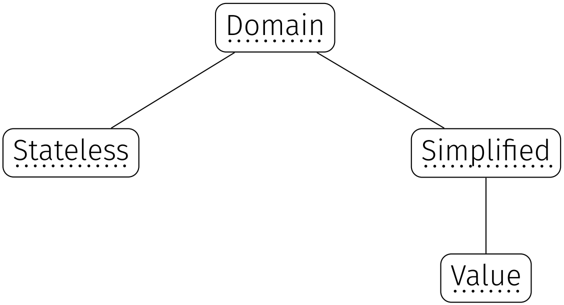

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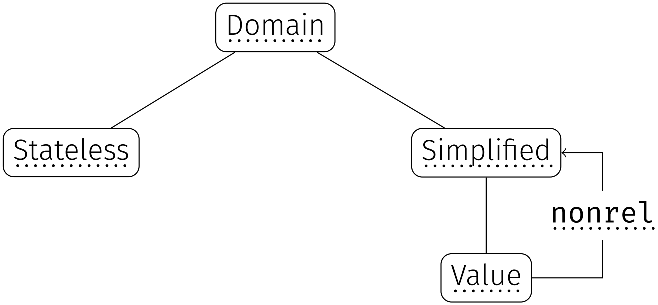

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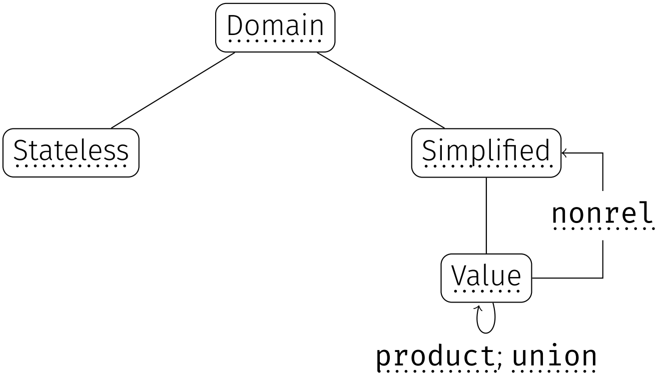

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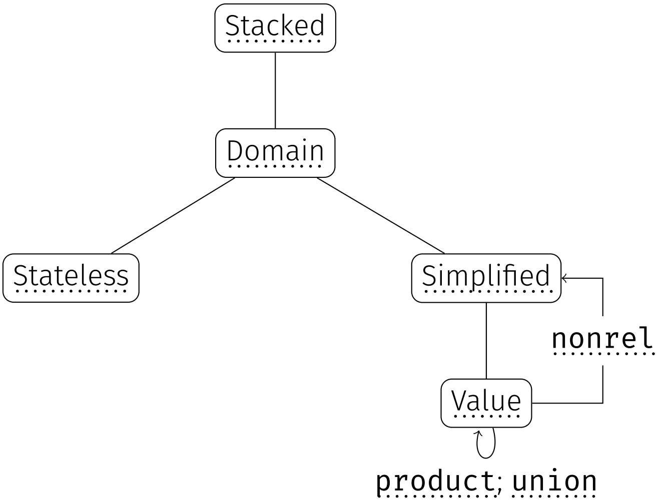

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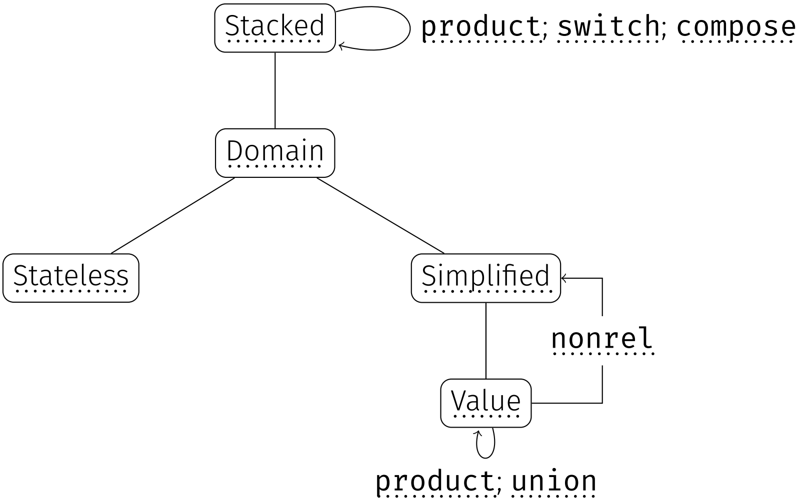

Abstract state & domain signature

Which type can we give to the abstract state?

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- Side note: this is a monad

Abstract state & domain signature – II

The manager: interroperating the whole analysis and local domains

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From global analysis to local domain

- Get the domain's data

```
get : 'a -> t
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- Analyze a given statement
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Signatures later

Also: lattice operators

Abstract state & domain signature – III

Utilities

```
type ('a, 'r) cases (* ≃ DNF of 'a flow * 'r *)

type 'a eval = ('a, expr) cases
type 'a post = ('a, unit) cases

(* Manager, allowing interaction between a
   domain ('t) and whole analysis ('a) *)
type ('a, 't) man = {
  get : 'a -> 't;
  set : 't -> 'a -> 'a;
  exec : stmt -> 'a flow -> 'a post;
  eval : expr -> 'a flow -> 'a eval;
  (* [...] *)
}
```

Domain type overview

```
module type DOMAIN = sig

type t
(* private, opaque data of the domain *)
val name : string

val join : t -> t -> t (* and other lattice operators *)

(* Transfer functions *)
val exec : stmt -> ('a, t) man -> 'a flow -> 'a post option
val eval : expr -> ('a, t) man -> 'a flow -> 'a eval option

(* [...] *)
end
```

Focus on the domain-local transfer functions

```
val exec : stmt -> ('a, t) man -> 'a flow -> 'a post option
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- `('a, t) man` manager

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- option: domains return `None` for unsupported statements/expressions.
  - `'a post = ('a, unit) cases`. DNF of abstract states.
  - `'a eval = ('a, expr) cases`. DNF of abstract states and symbolic expressions. Useful for rewriting, esp. for relational analyses

Example: loop iterator

Iterators are stateless domains:

- `type t = unit`, trivial lattice operators

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Universal.Iterators.Loops

```
let rec lfp man cond body flow_init flow =
  man.exec (mk_block [mk_assume cond; body]) flow >>$ fun () flow' ->
  if man.lattice.subset (man.lattice.join flow_init flow') flow
  then Cases.singleton () flow'
  else lfp man cond body flow_init (man.lattice.widen flow flow')

let exec stmt man flow = match stmt.skind with
  | S_while (cond, body) ->
    Some (lfp man cond body flow flow >>$ fun () lfp_flow ->
          man.exec (mk_assume (mk_not cond)) lfp_flow)
  | _ -> None
```

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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...
No errors found
```

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No errors found
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What has been checked? What has not?

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

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

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

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int main() {
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  int y = -1;
  for(int x = 0; x < n; x++)
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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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Mopsa's approach to being transparent – output

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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

Mopsa's approach to being transparent – soundness assumptions

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1. Crash

Mopsa's approach to being transparent – soundness assumptions

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Mopsa's approach to being transparent – soundness assumptions

Soundness assumptions, through an example

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Related topic: soundiness paper [Liv+15]

Easing debugging

Developer-friendly interfaces

Where static analyzers usually start from

- Analysis output Too coarse

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- Printing abstract state using builtins — Not interactive

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- 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)
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| | | | + 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
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```

An interactive engine acting as abstract debugger

GDB-like interface to the abstract interpretation of the program

An interactive engine acting as abstract debugger

GDB-like interface to the abstract interpretation of the program

Demo!

An interactive engine acting as abstract debugger

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- Breakpoints

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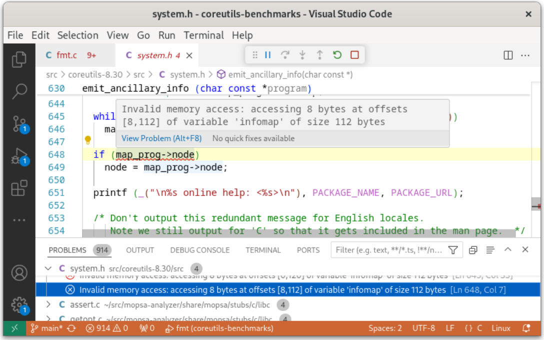
  - Projection on specific variables
- Some scripting capabilities

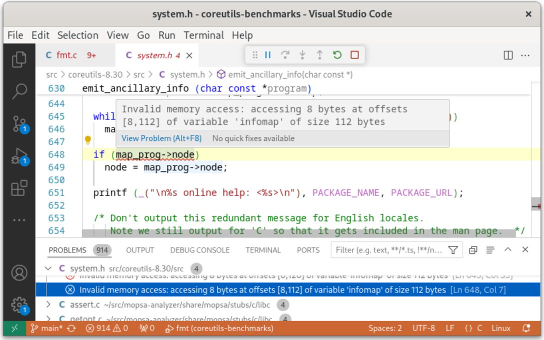
IDE support

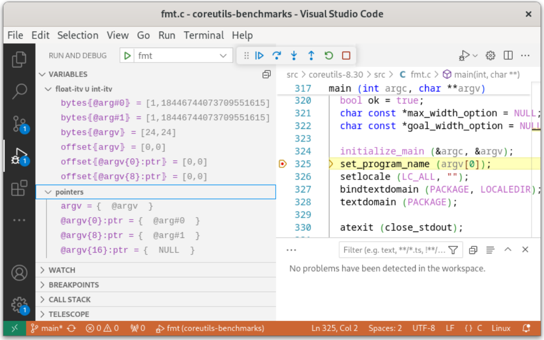
- Language Server Protocol for linters (report alarms)



IDE support

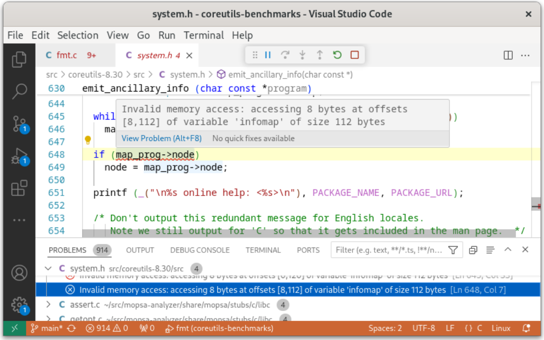
- Language Server Protocol for linters (report alarms)
- Debug Adapter Protocol providing interactive engine interface

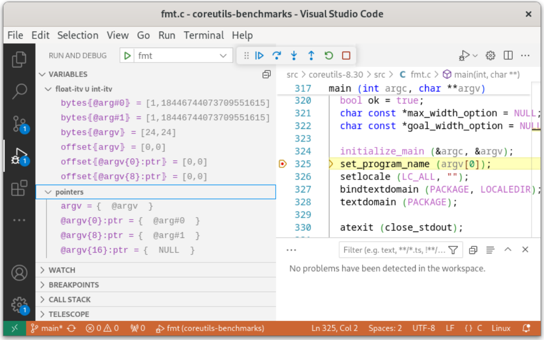




IDE support

- 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

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Motivation

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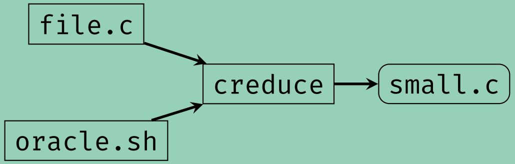
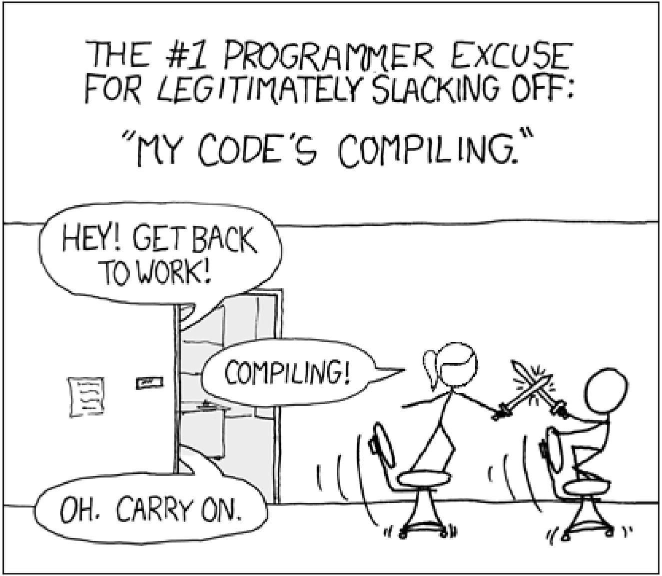
Automated testcase reduction using `creduce` [Reg+12]




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

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- 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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- Option to generate a single, preprocessed file

Conclusion

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Lots of folklore

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

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

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DAG of abstractions

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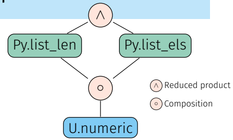

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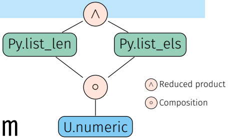

Mopsa Questions? Do Get in Touch!

`raphael.monat@inria.fr` `mopsa.zulipchat.com`

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