Mopsa Tutorial

Raphaël Monat

`rmonat.fr/lipari24/`

Lipari Summer School
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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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One AST to rule them all

- Multilanguage support
- Expressiveness
- Reusability

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Unified domain signature

- Semantic rewriting
- Loose coupling
- Observability

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DAG of abstractions

- Relational domains
- Composition
- Cooperation

A motivating example

Averaging numbers

```python
def average(l):
  m = 0
  for i in range(len(l)):
    m = m + l[i]
  m = m // (i + 1)
  return m

l = [randint(0, 20)
  for i in range(randint(5, 10))]
m = average(l)
```

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Environment abstraction

$m \mapsto @^{\sharp}_{\texttt{int}^{\sharp}} \quad i \mapsto @^{\sharp}_{\texttt{int}^{\sharp}}$

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Stateless domains: **list content**,

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Numeric abstraction (intervals)

$m \in [0, +\infty) \quad \underline{\text{els}}(l) \in [0, 20] \quad i \in [0, +\infty)$

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Stateless domains: list content, **list length**

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Numeric abstraction (polyhedra)

$m \in [0, +\infty)$ $\quad \underline{\mathrm{els}}(l) \in [0, 20]$

$0 \leq i < \underline{\mathrm{len}}(l)$ $\quad 5 \leq \underline{\mathrm{len}}(l) \leq 10$

A motivating example

Averaging tasks

```python
class Task:
  def __init__(self, weight):
    if weight < 0: raise ValueError
    self.weight = weight

def average(l):
  m = 0
  for i in range(len(l)):
    m = m + l[i].weight
  m = m // (i + 1)
  return m

l = [Task(randint(0, 20))
  for i in range(randint(5, 10))]
m = average(l)
```

Proved safe?

- `m // (i+1)`
- `l[i].weight`

Searching for a loop invariant

Stateless domains: list content, list length

Environment abstraction

$m \mapsto @^\sharp_{\texttt{int}^\sharp}$ $\quad i \mapsto @^\sharp_{\texttt{int}^\sharp}$ $\quad \underline{\text{els}}(l) \mapsto @^\sharp_{\texttt{Task}}$

$\underline{@^\sharp_{\texttt{Task}} \cdot \texttt{weight}} \mapsto @^\sharp_{\texttt{int}^\sharp}$

Numeric abstraction (polyhedra)

$m \in [0, +\infty)$

$0 \leq i < \underline{\text{len}}(l) \quad 5 \leq \underline{\text{len}}(l) \leq 10$

$0 \leq \underline{@^\sharp_{\texttt{Task}} \cdot \texttt{weight}} \leq 20$

Attributes abstraction

$@^\sharp_{\texttt{Task}} \mapsto (\{\, \texttt{weight} \,\}, \emptyset)$

Contributors (2018–2024, chronological arrival order)

- A. Miné
- A. Ouadjaout
- M. Journault
- A. Fromherz
- D. Delmas
- R. Monat
- G. Bau
- F. Parolini
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Slides inspired from many contributors, mistakes are my own.

Works around Mopsa

Languages

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

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- Absence of RTEs

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Properties

- **Absence of RTEs**
- Patch analysis [DM19]

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- **Absence of RTEs**
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- Non-exploitability [PM24]

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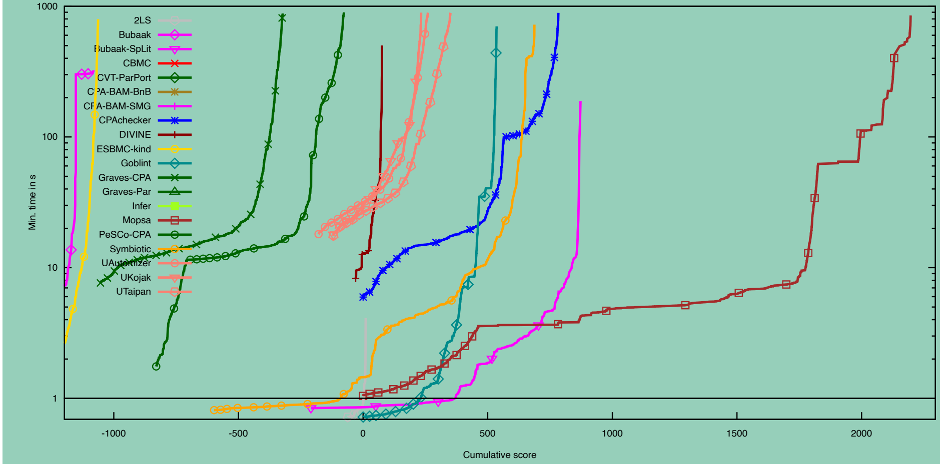
Properties

- **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]!



Ocaml tidbits

Mopsa is implemented in OCaml.

- Curried functions: `f x y z` $\rightsquigarrow f(x, y, z)$

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- Algebraic datatypes and pattern matching

```
type 'a option = None | Some of 'a

match e with
| None -> e1
| Some y -> e2 y
```

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Polymorphism = Type Variables

Outline

1. Introduction
2. Architecture of Mopsa
3. Current analyses in Mopsa
4. Easing development
5. Conclusion

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New users welcome!

Feel free to reach out in the future!

Architecture of Mopsa

Defining analyses

Mopsa design

Analysis = composition of abstract domains

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unified domain signature $\Longrightarrow$ iterators are abstract domains

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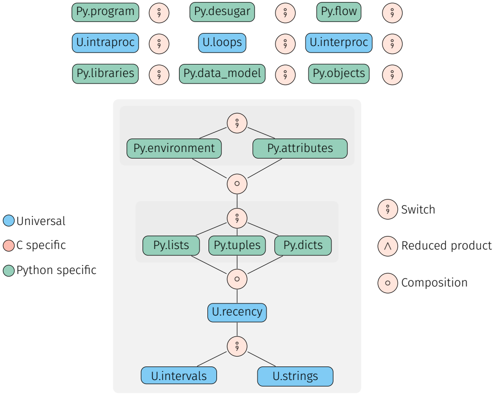

Py.program ⨾ Py.desugar ⨾ Py.flow ⨾
U.intraproc ⨾ U.loops ⨾ U.interproc ⨾
Py.libraries ⨾ Py.data_model ⨾ Py.objects ⨾

⨾
Py.environment
Py.attributes
∘
⨾
Py.lists
Py.tuples
Py.dicts
∘
U.recency
⨾
U.intervals
U.strings

🔵 Universal
🔴 C specific
🟢 Python specific

⨾ Switch
∧ Reduced product
∘ Composition

Abstract state & domain signature

Which type can we give to the abstract state?

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- `Cases.singleton : 'r -> 'a flow -> ('a, 'r) cases`

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  `>>$ : ('a,'r) cases -> ('r -> 'a flow -> ('a,'s) cases) -> ('a,'s) cases`

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  `>>$ : ('a,'r) cases -> ('r -> 'a flow -> ('a,'s) cases) -> ('a,'s) cases`
- Side note: this is a monad

Abstract state & domain signature – II

The manager: interroperating the whole analysis and local domains

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- Local domain has a private `type t`

Abstract state & domain signature – II

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Abstract state & domain signature – II

The manager: interroperating the whole analysis and local domains

$$\left.\begin{array}{l}\blacktriangleright \text{ Local domain has a private } \texttt{type t} \\ \blacktriangleright \text{ Whole abstract state of } \texttt{type 'a}\end{array}\right\} \Longrightarrow \texttt{type ('a, t) man}$$

Abstract state & domain signature – II

The manager: interroperating the whole analysis and local domains

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$\Big\} \Longrightarrow$ `type ('a, t) man`

From global analysis to local domain

- Get the domain's data

  `get : 'a -> t`
- Set the domain's data

  `set : t -> 'a -> 'a`

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From local domain to global analysis

- Analyze a given expression
- Analyze a given statement

  `man.exec stmt` $\sigma \Leftrightarrow \mathbb{S}^\sharp[\![\,\text{stmt}\,]\!]\sigma$

Signatures later

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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
val eval : expr -> ('a, t) man -> 'a flow -> 'a eval option
```

- `('a, t) man` manager

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- `'a flow` abstract state

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- option: domains return `None` for unsupported statements/expressions.

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- option: domains return `None` for unsupported statements/expressions.
  - `'a post = ('a, unit) cases`. DNF of abstract states.

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- `'a flow` abstract state
- 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
```

Architecture of Mopsa

Delegation-based support of multiple languages

Iterators to handle multiple languages

Traditional approaches

Desugar/compile programs to an intermediate representation (IR)

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

1

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Mopsa

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

Mopsa

- No loss of precision from the frontend[1]

---

[1] By default, 3-address code may result in precision loss [NP18]

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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- No loss of precision from the frontend[1]
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- A single AST type which can be extended for new languages

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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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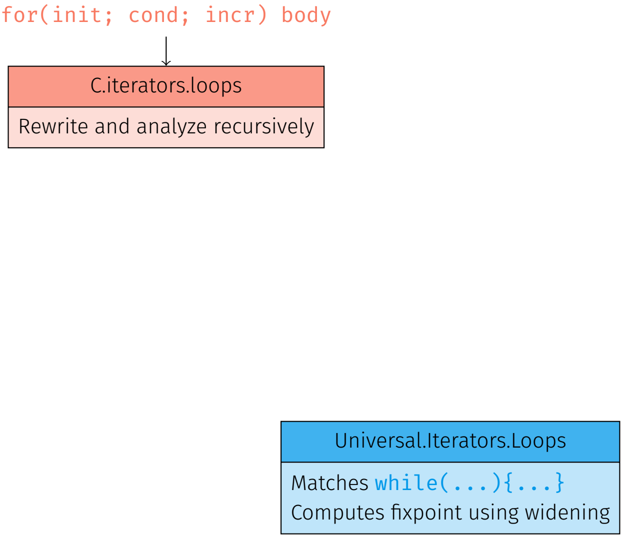

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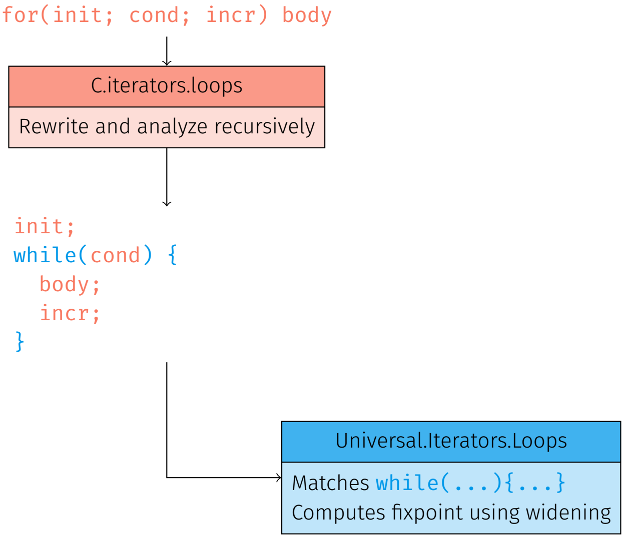

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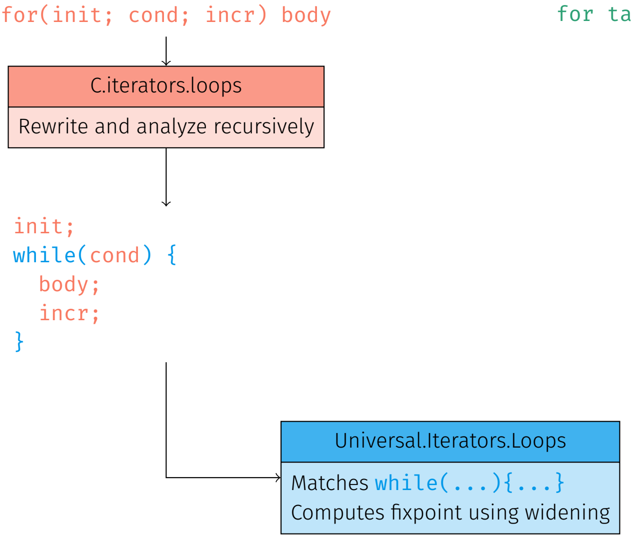

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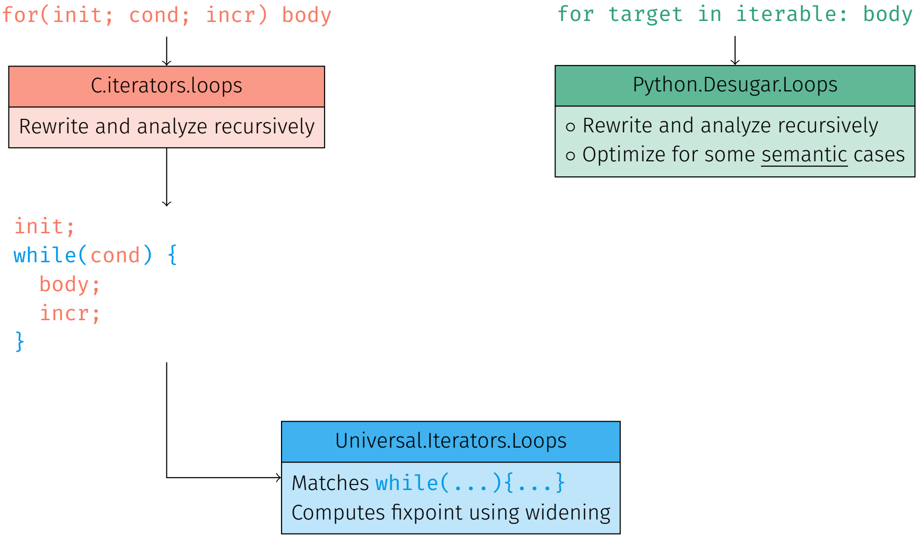

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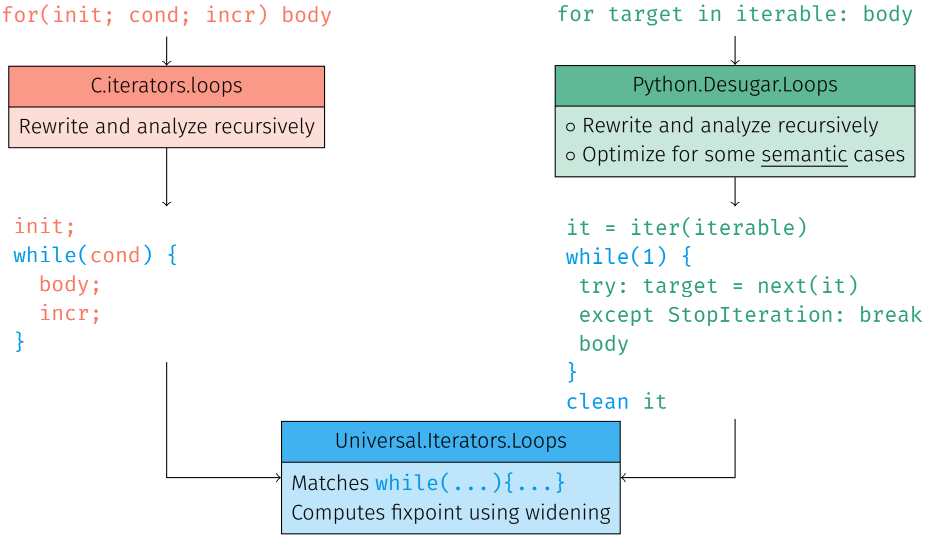

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Python.Desugar.Loops

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- Optimize for some semantic cases

```
it = iter(iterable)
while(1) {
 try: target = next(it)
 except StopIteration: break
 body
}
clean it
```

Universal.Iterators.Loops

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Architecture of Mopsa

Stateful domains through numerical examples

Numerical abstract values

$$\mathcal{P}(\mathcal{V} \to \mathbb{Z})$$

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$$\mathcal{P}(\mathcal{V} \to \mathbb{Z}) \underbrace{\underset{\alpha}{\overset{\gamma}{\leftrightarrows}}}_{\text{Cartesian abstraction}} \mathcal{V} \to \mathcal{P}(\mathbb{Z})$$

$$\alpha : \begin{cases} \mathcal{P}(\mathcal{V} \to \mathbb{Z}) & \to & \mathcal{V} \to \mathcal{P}(\mathbb{Z}) \\ \sum & \mapsto & \lambda v.\{\, \sigma(v) \mid \sigma \in \sum \,\} \end{cases} \qquad \gamma : \begin{cases} \mathcal{V} \to \mathcal{P}(\mathbb{Z}) & \to & \mathcal{P}(\mathcal{V} \to \mathbb{Z}) \\ f & \mapsto & \{\, \sigma \mid \forall v \in \mathcal{V}, \sigma(v) \in f(v) \,\} \end{cases}$$

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$\Longrightarrow$ We can define abstract operations on <u>values only</u>.

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The `nonrel` combinator will lift values to the mapping.

Numerical abstract values – II

Value signature

```
module type VALUE = sig
type t

val name : string

val bottom: t
val top: t

val subset: t -> t -> bool
val join: t -> t -> t
val meet: t -> t -> t
val widen: 'a ctx -> t -> t -> t
val constant : constant -> typ -> t
val binop : operator -> typ -> t -> typ ->
  t -> typ -> t
val filter : bool -> typ -> t -> t

val backward_binop : operator -> typ ->
  t -> typ -> t -> typ -> t -> t * t
val compare : operator -> bool -> typ ->
  t -> typ -> t -> (t * t)

val print: printer -> t -> unit
end
```

Implementations for intervals, congruences, powerset of integers

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Implementations for intervals, congruences, powerset of integers

They all abstract the same object

Relational domains

Motivational example

```
// Hyp: a array, of size l ∈ [10, 20]
s = 0;
for(int i = 0; i < l; i++) {
  s += a[i];
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$0 \leq i < l$, ✓

Architecture of Mopsa

Leveraging relational abstract domains

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C expression

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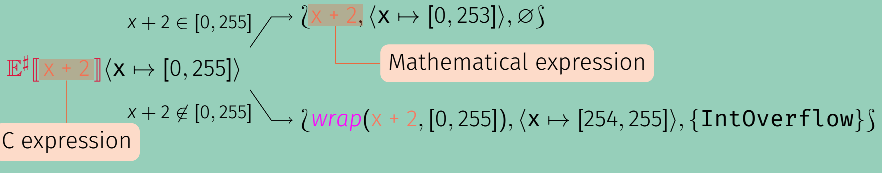

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$x + 2 \in [0,255]$ ⟶ $\wr\, x+2, \langle x \mapsto [0,253]\rangle, \varnothing \,\wr$

Mathematical expression

$x + 2 \notin [0,255]$ ⟶ $\wr\, \mathit{wrap}(x+2, [0,255]), \langle x \mapsto [254,255]\rangle, \{\texttt{IntOverflow}\} \,\wr$

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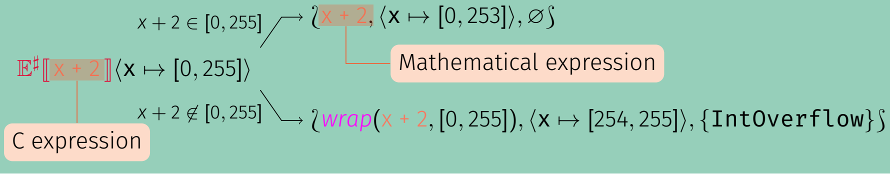

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N.B: expression evaluation required here

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C.Memory.Machine_Numbers

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let eval exp man flow =
  match exp.ekind with
  | E_var v -> Some (Cases.singleton exp flow)
  | E_binop(op, e1, e2) ->
    man.eval e1 flow >>$ fun n1 flow ->
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    let vmin, vmax = rangeof exp.etyp in
    let nexp = mk_binop n1 op n2 in
    let ret = assume (mk_in nexp vmin vmax) man flow
        ~fthen:(fun flow ->
            let flow = safe_c_integer_overflow flow in
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Variables do not overflow

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Evaluate `e1` and bind each case ⟅`n1`⟆

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Evaluate **e2** and bind each case ⦇**n2**⦈

Partition on condition
$\mathtt{nexp} \in [\mathtt{vmin}, \mathtt{vmax}]$

Abstracting containers (strings, arrays) lengths

Consider a variable-length container a.

Motivational example, with polyhedra

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// Hyp: a container
s = 0;
for(int i = 0; i < container_length(a); i++) {
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Convention: ghost variables are underscored.

Abstracting containers (strings, arrays) lengths – II

Universal.Toy.String_length

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let exec stmt man flow = let range = srange stmt in match skind stmt with
  | S_assign ({ekind = E_var (s, _); etyp=T_string}, e) ->
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Return ⊥, with alarm metadata

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NB: in case of dynamic allocations, ghost variables are a bit more complicated

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Variable-length containers have unbounded size

Not abstracting their contents $\Longrightarrow$ Non-terminating analysis

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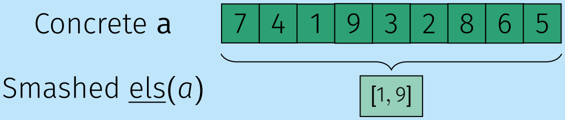

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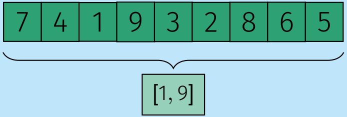

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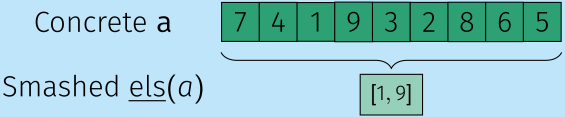

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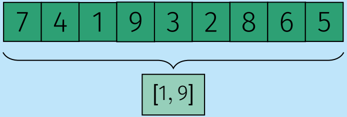

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$$\mathbb{S}^\sharp[\![\, c \overset{\text{weak}}{=} e \,]\!]s \overset{\text{def}}{=} s \sqcup \mathbb{S}^\sharp[\![\, c = e \,]\!](s)$$

Abstracting containers (strings, arrays) contents – II

What about weak read?

`r = a[3]`, assuming $\underline{\text{els}}(a) \in [1, 9]$.

$r \in [1, 9]$, and similarly with non-relational domains.

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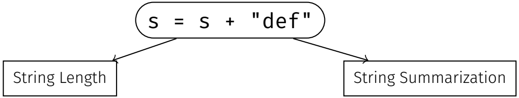
✓ $\mathbb{S}^\sharp[\![\texttt{expand}(\underline{\text{els}}(a), r)]\!](1 \leq \underline{\text{els}}(a) \leq i) = 1 \leq \underline{\text{els}}(a) \leq i \wedge 1 \leq r \leq i$

Intuitively: expand copies constraints. Cf. [Gop+04]

The perils of reduced products with shared relational domains



`s = s + "def"`

String Length

String Summarization

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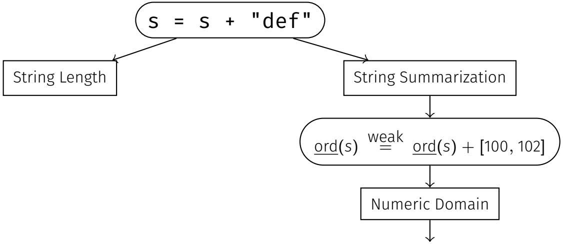

$\underline{\text{ord}}(s)$: smashed ASCII codes of s.

$$\sigma_2^\sharp = (\underline{\text{len}}(s) = 3 \land 97 \leq \underline{\text{ord}}(s) \leq 102)$$

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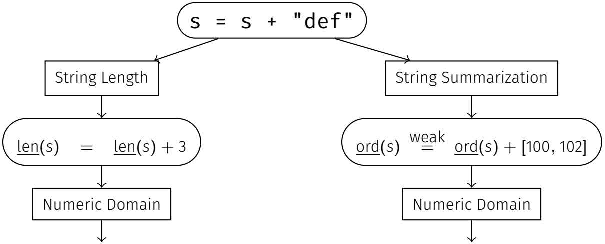

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$\underline{\text{ord}}(s) \overset{\text{weak}}{=} \underline{\text{ord}}(s) + [100, 102]$

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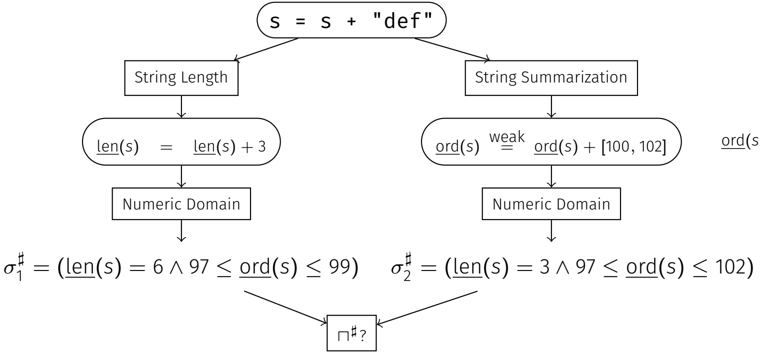

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$\sqcap^\sharp$?

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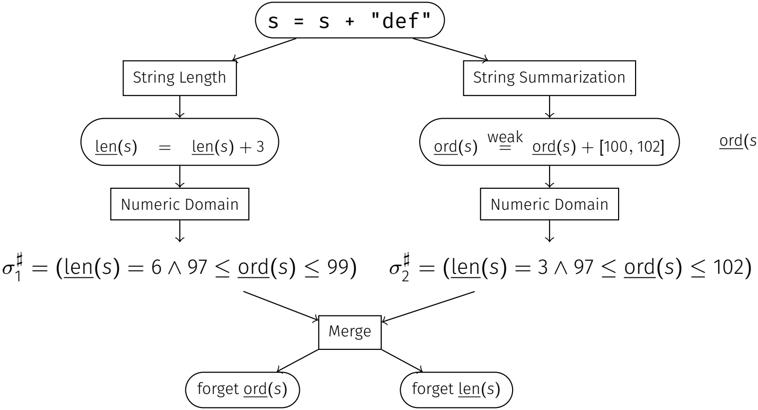

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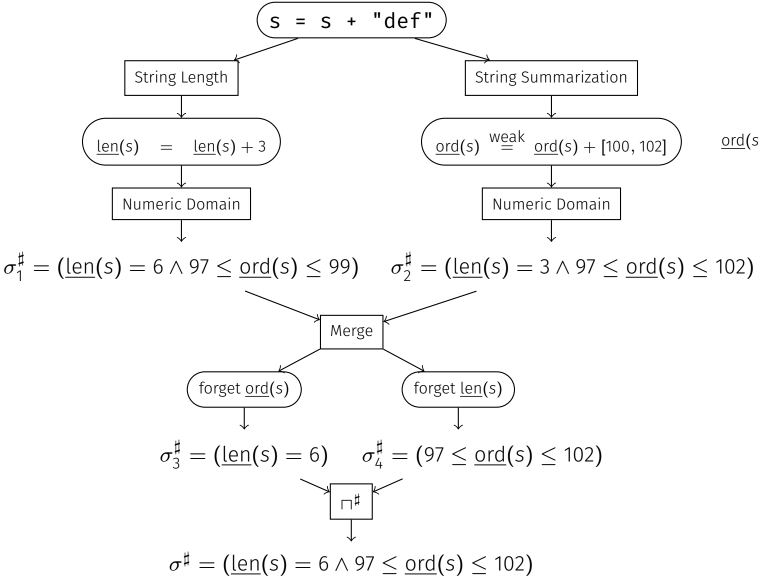

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$\sigma_4^\sharp = (97 \leq \underline{\text{ord}}(s) \leq 102)$

$\sqcap^\sharp$

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- Reduced product with sharing needs `merge` operator

Architecture of Mopsa

Domains & their combinators

Hasse diagram of domains

Domain

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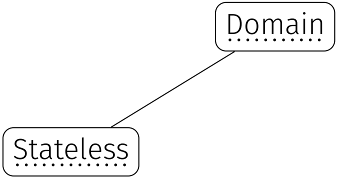
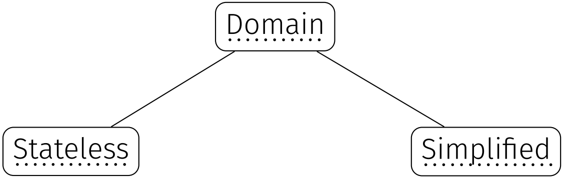


Domain

Stateless

Hasse diagram of domains

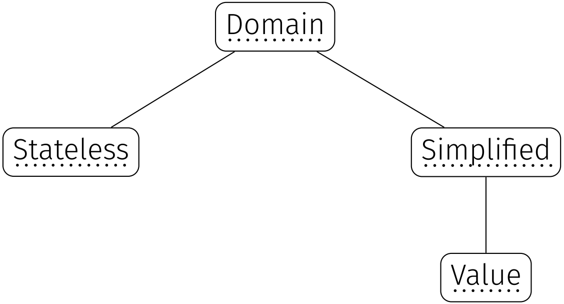


Domain

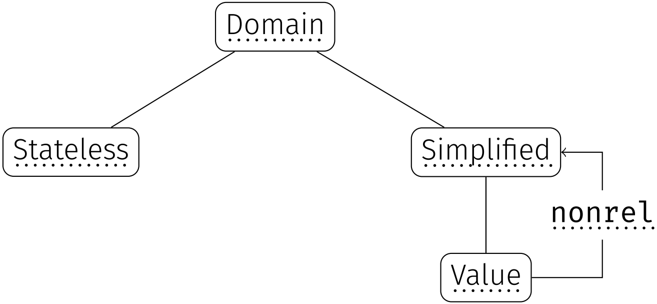
Stateless

Simplified

Hasse diagram of domains



Hasse diagram of domains



Domain

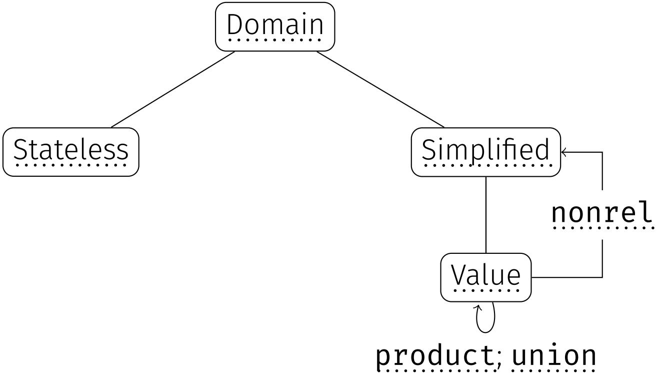
Stateless

Simplified

nonrel

Value

Hasse diagram of domains



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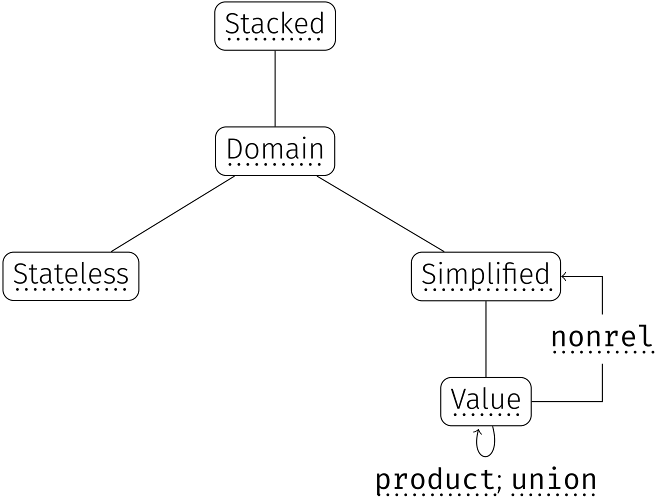

Stacked

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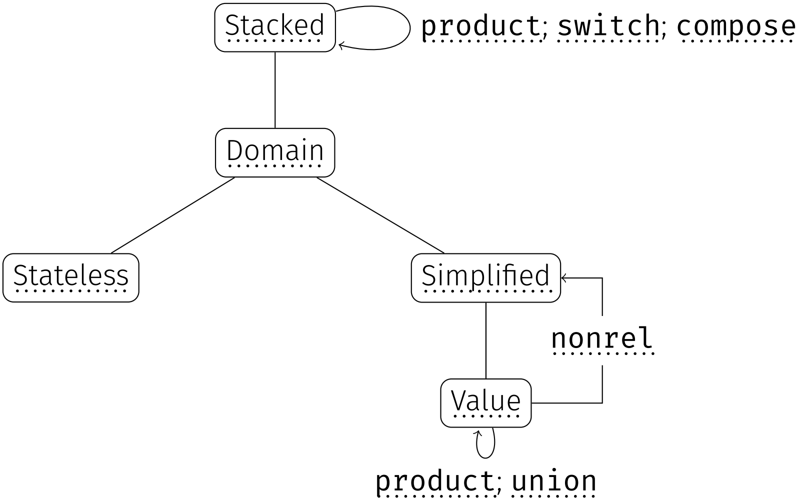

Combinators

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Switch

- Pointwise lattice lifting
- For $\texttt{tf} \in \{\texttt{eval}, \texttt{exec}\}$:

```
Switch(D1, D2).tf args =
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match o_r with
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```

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Compose

- Similar to switch
- Lattice operators can trigger operations on underlying domains

Architecture of Mopsa

Transparency in static analysis

Raising the bar in static analyzer transparency

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

Raising the bar in static analyzer transparency

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

Mopsa’s approach to being transparent – implementation

C.Memory.Machine_Numbers

```
let eval exp man flow =
  match exp.ekind with
  | E_var v -> Some (Cases.singleton exp flow)
  | E_binop(op, e1, e2) ->
    man.eval e1 flow >>$ fun n1 flow ->
    man.eval e2 flow >>$ fun n2 flow ->
    let vmin, vmax = rangeof exp.etyp in
    let nexp = mk_binop n1 op n2 in
    let ret = assume (mk_in nexp vmin vmax) man flow
        ~fthen:(fun flow ->
            let flow = safe_c_integer_overflow flow in
            Cases.singleton nexp flow)
        ~felse:(fun flow ->
            let nexp' = mk_wrap nexp vmin vmax in
            let flow = raise_alarm IntegerOverflow flow ~~in~~
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Standard: report alarm
Stored as metadata in `'a flow`

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Transparent: mark that
`e1 + e2` does not overflow

Standard: report alarm
Stored as metadata in `'a flow`

Mopsa’s approach to being transparent – example

Mopsa’s approach to being transparent

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

Mopsa’s approach to being transparent – example

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

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int main() {
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    y++;
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Stmt
`x++`
`y++`
Selectivity

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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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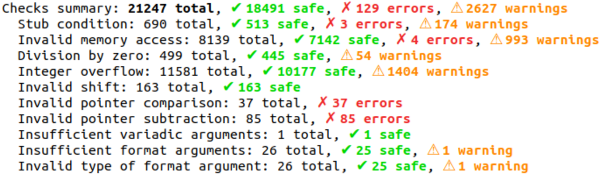
Analysis of coreutils `fmt`



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

1. Crash

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

Current analyses in Mopsa

Control-flow tokens

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int i = 0;
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$cur \mapsto i \in [1, 99]$

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More details: [Mon21, section 2.4.3]

Control-flow tokens – II

Universal.Iterators.Loops

```
let exec stmt man flow = match stmt.skind with
  | S_break ->
    Some (Cases.return () (Flow.rename T_cur T_break man.lattice flow))

  | S_while (cond, body) ->
    Some (
      lfp man cond body (Flow.rm T_break flow) flow >>% fun lfp_flow ->
      man.exec (mk_assume (mk_not cond)) lfp_flow >>% fun lfp_flow ->
      let lfp_flow = Flow.add T_cur (Flow.get T_break man.lattice lfp_flow)
                     man.lattice lfp_flow in
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Standard flow transferred to *brk*

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Standard flow transferred to *brk*

At loop end:
join *brk* and *cur* into *cur*

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- Checks for run-time errors
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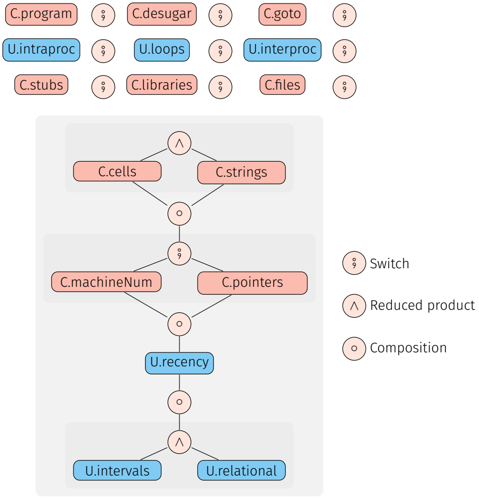

C.program ⨟ C.desugar ⨟ C.goto ⨟
U.intraproc ⨟ U.loops ⨟ U.interproc ⨟
C.stubs ⨟ C.libraries ⨟ C.files ⨟

⨟ Switch

∧ Reduced product

∘ Composition

Pointer domain

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```
char a[10] = "hello";
int i = _mopsa_rand(0,9);
char *p = &(a[i]); /* ⟨p ↦ {a}⟩, ⟨i ∈ [0, 9] ∧ offset(p) = i⟩ */
```

Cells domain

A low-level memory abstraction [Min06a]

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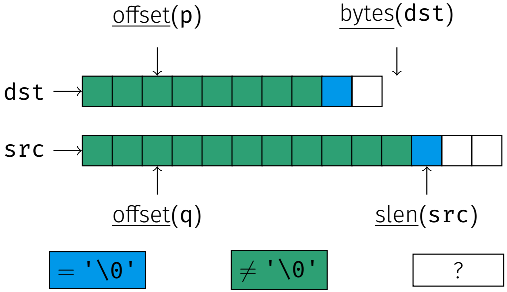

String length domain

The switch utility

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val switch : (expr list * ('a Flow.flow -> ('a,'r) cases)) list ->
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Transfer function of `base[offset] = rhs`

```
switch [
  (* set0 case *)
  (* Offset condition: offset ∈ [0, length] *)
  (* RHS condition: rhs = 0 *)
  (* Transformation: length := offset; *)
  [ mk_in offset zero length range;
    mk_eq rhs zero range ],
  man.exec (mk_assign length offset range)
  ;

  (* setnon0 case *)
  (* Offset condition: offset = length *)
  (* RHS condition: rhs ≠ 0 *)
  (* Transformation: length := [offset + 1, size]; *)
  [ mk_eq offset length range;
    mk_ne rhs zero range ],
  assign_length_interval (add offset one range) size
  ;
```

```
  (* First unchanged case *)
  (* Offset condition: offset ∈ [0, length - 1] *)
  (* RHS condition: rhs ≠ 0 *)
  (* Transformation: nop; *)
  [ mk_in offset zero (pred length range) range;
    mk_ne rhs zero range ],
  (fun flow -> Post.return flow)
  ;

  (* Second unchanged case *)
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  (* RHS condition: ⊤ *)
  (* Transformation: nop; *)
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strlen contract

```
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 * requires: valid_string_or_fail(__s);
 * ensures : return ∈ [0, size(__s) - 1];
 * ensures : __s[return] == 0;
 * ensures : ∀ int i ∈ [0, return - 1]: __s[i] != 0;
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Quantifier interpretation: delegated to domains

Some benchmarks

See SV-Comp 2024 results.

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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%
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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).

Current analyses in Mopsa

Python analysis

Python analysis overview

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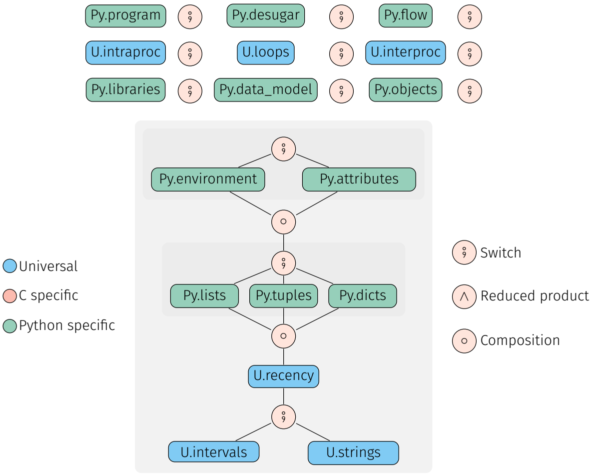

Py.program ⨟ Py.desugar ⨟ Py.flow ⨟
U.intraproc ⨟ U.loops ⨟ U.interproc ⨟
Py.libraries ⨟ Py.data_model ⨟ Py.objects ⨟

⨟
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∘
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🔵 Universal
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Python’s dual type system

Fspath (from standard library)

```python
class Path:
  def __fspath__(self): return 42

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Attribute abstraction + ghost variables

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Attribute abstraction

Using an under and an over-approximation

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Concretization

$$\gamma^\sharp_{\mathsf{ObjS}} : \begin{cases} \mathsf{ObjS}^\sharp & \rightarrow & \mathcal{P}(\mathcal{P}(string)) \\ (l, \top) & \mapsto & \{\, s \in \mathcal{P}(string) \mid l \subseteq s \,\} \\ (l, u) & \mapsto & \{\, s \in \mathcal{P}(string) \mid l \subseteq s \subseteq u \,\} \end{cases}$$

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Example

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- Also used in Type Analysis for JavaScript [JMT09]

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$$\left\{ \begin{array}{l} @^\sharp(\text{Task}, r) \mapsto \emptyset, \emptyset \\ \boldsymbol{\underline{@^\sharp(\text{Task}, o) \cdot \text{weight}} \mapsto [1, 2] \sqcup [4, 4]} \end{array} \right.$$

Recency abstraction – II

```python
class Task:
  def __init__(self, weight):
    if weight < 0: raise ValueError
    self.weight = weight

l = [Task(2), Task(1), Task(4), Task(5)]
```

Return of ghost variables

Composed on top of address, for attribute “weight”:

$$\underline{@^\sharp(\text{Task}, r) \cdot \text{weight}} \mapsto [2, 2]$$

Initialization:

$$\left\{ \underline{@^\sharp(\text{Task}, r) \cdot \text{weight}} \mapsto [2, 2] \right.$$

$$\left\{ \begin{array}{l} \underline{@^\sharp(\text{Task}, r) \cdot \text{weight}} \mapsto [1, 1] \\ \underline{@^\sharp(\text{Task}, o) \cdot \text{weight}} \mapsto [2, 2] \end{array} \right.$$

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$$\left\{ \begin{array}{l} \underline{\boldsymbol{@^\sharp(\text{Task}, r) \cdot \text{weight}}} \boldsymbol{\mapsto [5, 5]} \\ \underline{@^\sharp(\text{Task}, o) \cdot \text{weight}} \mapsto [1, 4] \end{array} \right.$$

Recency abstraction – III

Task creation

```
class Task:
  def __init__(self, weight):
    if weight < 0: raise ValueError
    self.weight = weight

m = [1, 2]
l = [Task(i) for i in m]
l.append(Task(3))
```

Type analysis

Nominal types used in abstract addresses. No need for allocation-site in `Tasks`. But helpful for lists!

Recency abstraction – III

Task creation

```python
class Task:
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    if weight < 0: raise ValueError
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Use allocation sites for `range` objects.

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Type analysis

Nominal types used in abstract addresses. No need for allocation-site in `Tasks`. But helpful for lists!

Value analysis

Use allocation sites for `range` objects.

Variable allocation policies

- Type-based (nominal) and/or location-based partitioning.
- Different configurations depending on type/value analysis.

Comparison of the type and value analyses

Name	LOC	Type Analysis					Non-relational Value Analysis				
		Time	Mem.	Exceptions detected			Time	Mem.	Exceptions detected		
				Type	Index	Key			Type	Index	Key
`nbody.py`	157	1.5s	3MB	0	22	1	5.7s	9MB	0	**1**	1
`scimark.py`	416	1.4s	12MB	1	1	0	3.4s	27MB	1	**0**	0
`richards.py`	426	13s	112MB	1	4	0	17s	149MB	1	**2**	0
`unpack_seq.py`	458	8.3s	7MB	0	0	0	9.4s	6MB	0	0	0
`go.py`	461	27s	345MB	33	20	0	2.0m	1.4GB	33	20	0
`hexiom.py`	674	1.1m	525MB	0	46	3	4.7m	3.2GB	0	**21**	3
`regex_v8.py`	1792	23s	18MB	0	2053	0	1.3m	56MB	0	**145**	0
`processInput.py`	1417	10s	64MB	7	7	1	12s	85MB	7	**4**	1
`choose.py`	2562	1.1m	1.6GB	12	22	7	2.9m	3.7GB	12	**13**	7
Total	9294	4.0m	2.8GB	59	2214	12	13m	9.1GB	59	228	12

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scimark.py	416								1	**0**	0
richards.py	426								1	**2**	0
unpack_seq.py	458								0	0	0
go.py	461								3	20	0
hexiom.py	674	1							0	**21**	3
regex_v8.py	1792								0	**145**	0
processInput.py	1417								7	**4**	1
choose.py	2562	1.			22	7	2.9m	3.7GB	12	**13**	7
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Conclusion

The non-relational value analysis

- ▶ does not remove false type alarms
- ▶ significantly reduces index errors
- ▶ is $\simeq 3\times$ costlier

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scimark.py	416	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	**0**	0
richards.py	426	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	**2**	0
unpack_seq.py	458	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0	0
go.py	461	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3	20	0
hexiom.py	674	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	**21**	3
regex_v8.py	1792	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	**145**	0
processInput.py	1417	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	7	**4**	1
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Heuristic packing and relational analyses

- ▶ Static packing, using function's scope
- ▶ Rules out all 145 alarms of **`regex_v8.py`** (1792 LOC) at 2.5× cost

Selectivity of the non-relational value analysis

Name	Attributes	Types	Indexes	Keys	Values	Overflows	Divisions
`scimark.py`	746/746	844/844	**2**/5		**29**/30	**21**/43	**20**/21
`richards.py`	**352**/353	389/389	**2**/4		**2**/3		2/2
`unpack_seq.py`	807/807	1210/1210			1/1		
`go.py`	**664**/697	728/728	**2**/20		7/7	**6**/12	**4**/6
`hexiom.py`	598/598	672/672	**10**/32	**0**/3	**23**/24		
`regex_v8.py`	7357/7357	8349/8349	**1913**/2057		63/63		
`processInput.py`	**617**/619	**790**/792	12/12	**0**/1	**0**/1	2/2	
`choose.py`	**2519**/2521	**2997**/2999	**28**/39	**4**/8	**9**/24	**7**/17	

Selectivity of the analysis on some classes of exceptions

Selectivity = Number of proved safe operations / Total number of checks

An empty cell denotes a program where the kind of exception cannot happen

Current analyses in Mopsa

Python+C analysis

Python+C analysis overview

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

- Performance (numpy)
- System libraries (pygit2)

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- Different values ($\mathbb{Z}$ vs. `Int32`)
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Our approach

- **Combined** analysis of C, Python and interface code
- Previous works [TM07; FF08; LLR20] : JNI $\overset{\text{⚠}}{\rightsquigarrow}$ Java, low precision

Multilanguage code – example

counter.c

```c
typedef struct {
    PyObject_HEAD;
    int count;
} Counter;

static PyObject*
CounterIncr(Counter *self, PyObject *args)
{
    int i = 1;
    if(!PyArg_ParseTuple(args, "|i", &i))
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    self->count += i;
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```python
from counter import Counter
from random import randrange

c = Counter()
power = randrange(128)
c.incr(2**power-1)
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High-level idea

Difficulty: shared memory

- Each language may change the memory state, and has a different view of it

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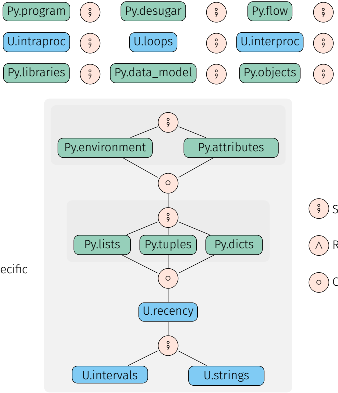
- Mopsa supports shared abstractions

From distinct Python and C analyses. . .

🔵 Universal
🔴 C specific
🟢 Python specific



Py.program ⨟ Py.desugar ⨟ Py.flow ⨟
U.intraproc ⨟ U.loops ⨟ U.interproc ⨟
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∧ Reduced product

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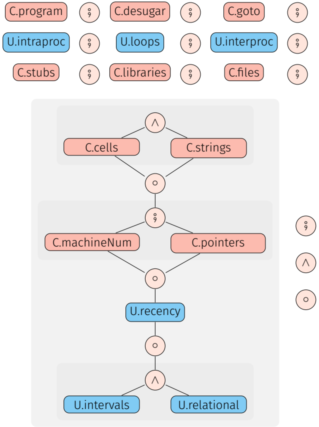

C.program ⨟ C.desugar ⨟ C.goto ⨟
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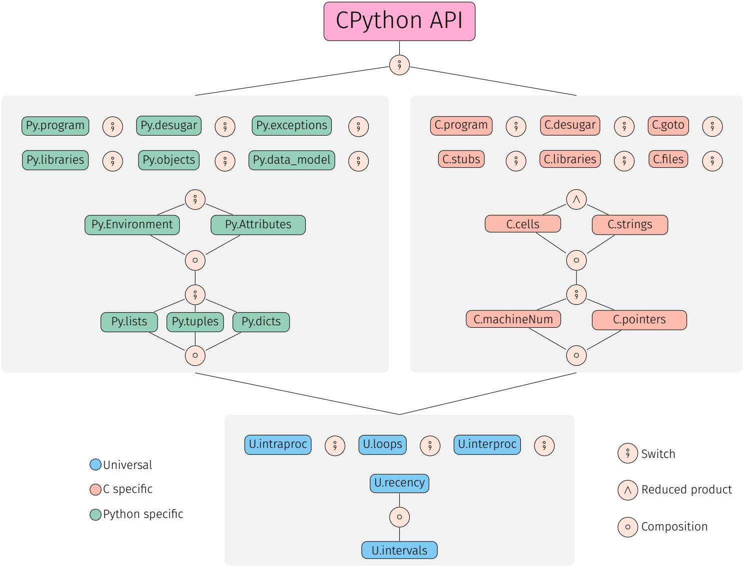
From distinct Python and C analyses. . . to a multilanguage analysis!



CPython API

⨾

Py.program ⨾ Py.desugar ⨾ Py.exceptions ⨾
Py.libraries ⨾ Py.objects ⨾ Py.data_model ⨾

⨾
Py.Environment Py.Attributes
∘
⨾
Py.lists Py.tuples Py.dicts
∘

C.program ⨾ C.desugar ⨾ C.goto ⨾
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∧
C.cells C.strings
∘
⨾
C.machineNum C.pointers
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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

Easing development

General advice around static analysis development

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Easing development

CI, tests & benchmarks

CI, tests & benchmarks

Detecting breaking changes using continuous integration

- `mopsa-diff` to compare with previous results

CI, tests & benchmarks

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- Reusing all benchmarks from our experimental evaluations

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- unmodified*
  - Underscores practicality of our approach

CI, tests & benchmarks

Detecting breaking changes using continuous integration

- `mopsa-diff` to compare with previous results
- Reusing all benchmarks from our experimental evaluations

Benchmark selection

Our benchmarks are

- third-party real code
- open-source – for the sake of reproducible science
- unmodified*
  - Underscores practicality of our approach
  - * stubs can be added in marginal cases

Comparing analysis reports

`mopsa-diff` script

- compares analysis report(s): either single output or set of outputs

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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: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
```

Easing development

Static analyzer interfaces

Where static analyzers usually start from

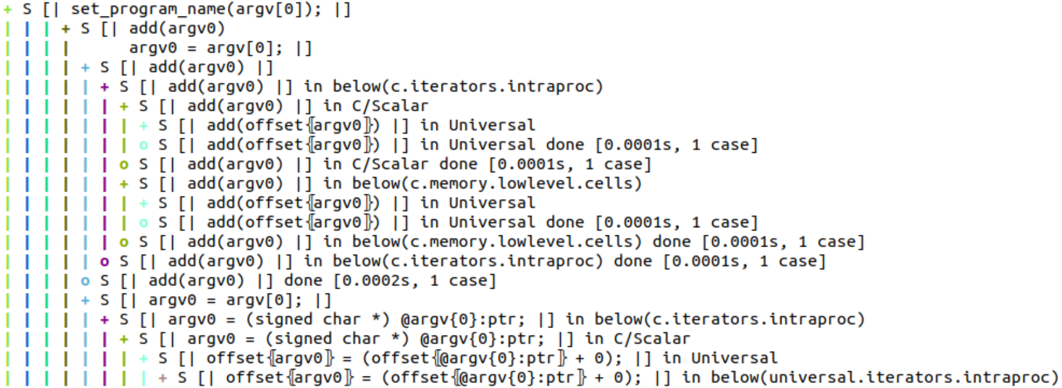
- Analysis output Too coarse

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)
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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

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Demo!

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- Breakpoints

An interactive engine acting as abstract debugger

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- Breakpoints
  - Program location

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- Observation of the abstract state

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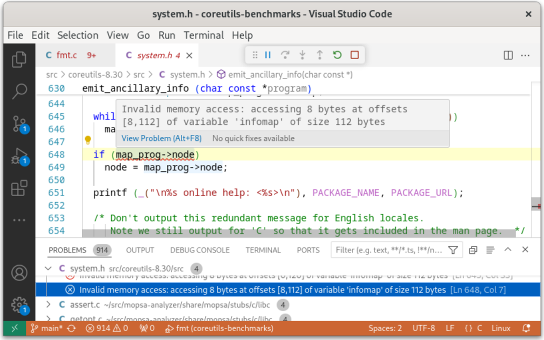
- Observation of the abstract state
  - Full state
  - Projection on specific variables
- Some scripting capabilities

IDE support

- Language Server Protocol for linters (report alarms)



```
630  emit_ancillary_info (char const *program)
644
645    whil
646      ma
647
648    if (map_prog->node)
649      node = map_prog->node;
650
651    printf (_("\n%s online help: <%s>\n"), PACKAGE_NAME, PACKAGE_URL);
652
653    /* Don't output this redundant message for English locales.
654       Note we still output for 'C' so that it gets included in the man page.  */
```

```
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

system.h src/coreutils-8.30/src 4

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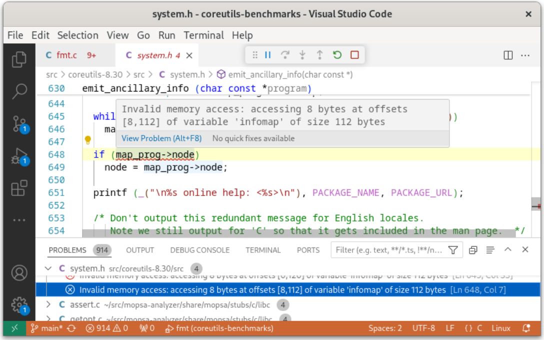

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  whil                                                         ))
    ma

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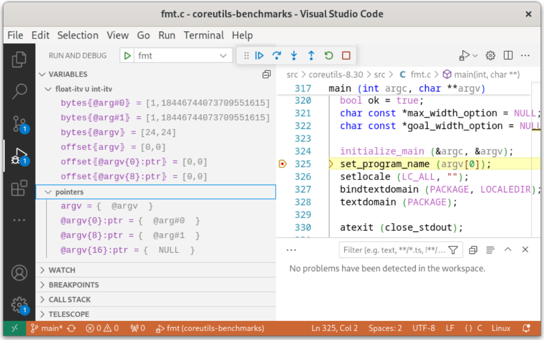

```
float-itv ∪ int-itv
  bytes⟦@arg#0⟧ = [1,18446744073709551615]
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pointers
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```

```
main (int argc, char **argv)
  bool ok = true;
  char const *max_width_option = NULL;
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  initialize_main (&argc, &argv);
  set_program_name (argv[0]);
  setlocale (LC_ALL, "");
  bindtextdomain (PACKAGE, LOCALEDIR);
  textdomain (PACKAGE);

  atexit (close_stdout);
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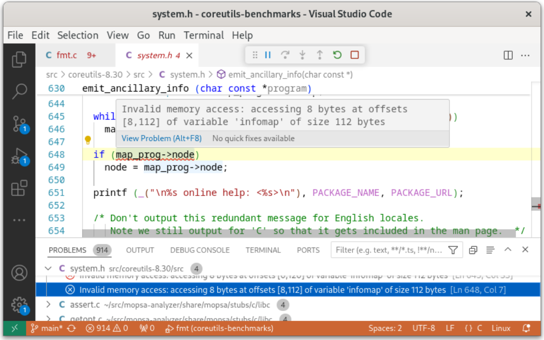
No problems have been detected in the workspace.

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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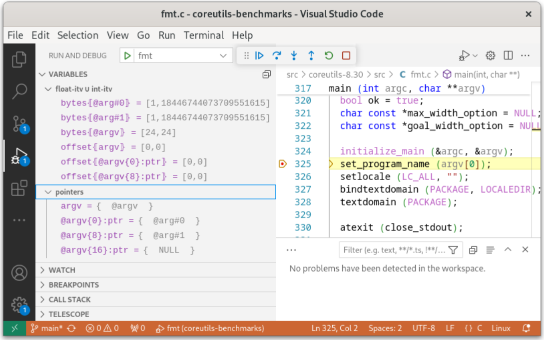

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Easing development

Plug-ins to observe the analysis

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

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```
./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
```

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

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Goblint: ensure that at least one branch of a conditional is analyzed.

Detection of imprecise analysis

Warns when assignments to top are performed

Simplifies the search for sources of large imprecision

Profiling

Standard profiling

Measures which parts of Mopsa are the most time-consuming

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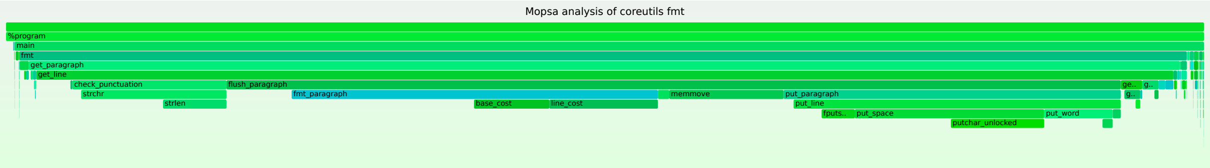

Easing development

Testcase reduction

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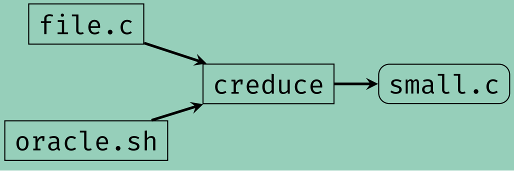
Automated testcase reduction using `creduce` [Reg+12]



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- Highly helpful to significantly reduce debugging time of runtime errors (Apron mishandlings, raised exceptions, …)

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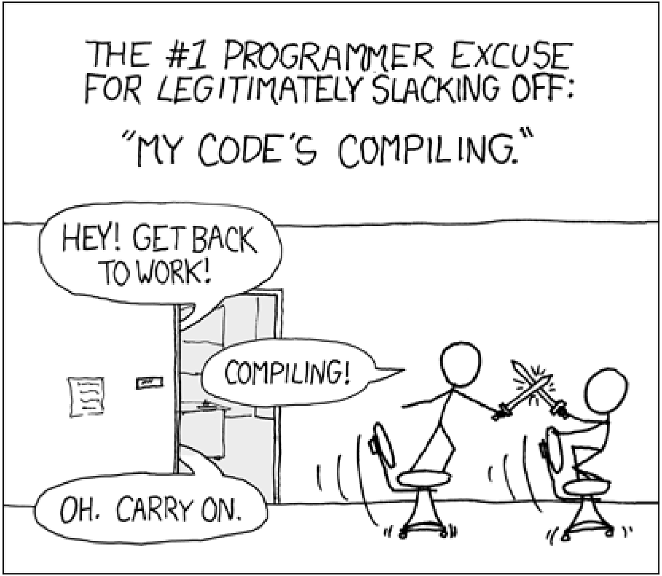
Differential-configuration debugging

```
$ 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

Testcase reduction – III



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` leverages the compilation database

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

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- Option to generate a single, preprocessed file

Conclusion

Some other approaches

External fixpoint engine

- Mopsa: each iterator (loops, gotos, calls) defines its fixpoint computation.

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Systematic relationship between concrete and abstract domains

- See e.g, Michelland, Zakowski, and Gonnord [MZG24], Keidel and Erdweg [KE19]

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Systematic relationship between concrete and abstract domains

- See e.g, Michelland, Zakowski, and Gonnord [MZG24], Keidel and Erdweg [KE19]
- Lighter than a formally verified analyzer? [Jou+15]

Recap

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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- </> Expressiveness
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Unified domain signature

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DAG of abstractions

- Relational domains
- Composition
- Cooperation

Recap

Modular Open Platform for Static Analysis [Jou+19]

`gitlab.com/mopsa/mopsa-analyzer`

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

One AST to rule them all

- Multilanguage support
- Expressiveness
- Reusability

Unified domain signature

- Semantic rewriting
- Loose coupling
- Observability

DAG of abstractions

- Relational domains
- Composition
- Cooperation

Feedback wanted!

Anonymous survey, or come and talk to me!

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