Static Type and Value Analysis by Abstract Interpretation of Python Programs with Native C Libraries

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MPRI lecture

31 January 2021

SORBONNE UNIVERSITÉ

Introduction

Goals of the lecture

Whoami

- MPRI 2017-2018
- PhD 2018-2021
- Currently ATER

Lecture

- A recent take at the PhD, from the other side...
- Around the analysis of Python.

Dynamic programming languages

Growing popularity

JavaScript #1, Python #2 on GitHub[1]

[1] https://octoverse.github.com/#top-languages

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New features

- Object orientation,
- Dynamic typing,
- Dynamic object structure,
- Introspection operators,
- `eval`.

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State of the art

Well-established & industrialized analysis of static programming languages

- C: Polyspace (1999), Astrée (2003), Frama-C (2008)
- Java: Julia (2010)

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Why Python?

Used a lot in

- Scientific computing
- Scripts and automation

Outline

What can we prove?

Average

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

What can we prove?

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Highly polymorphic function. More context would help!

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```python
average([1,2,3])
average([])
average(range(2, 10, 3))
average({0: 3.14, 1: 2.78})
```

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average([1,2,3])
try: average([])
except NameError: pass
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Detect raised exceptions interrupting the execution.

A Taste of Python

Python's specificities

No standard

- CPython is the reference

$\implies$ manual inspection of the source code and handcrafted tests

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  $\Longrightarrow$ manual inspection of the source code and handcrafted tests

Operator redefinition

- Calls, additions, attribute accesses
- Operators eventually call overloaded `__methods__`

Protected attributes

```python
class Protected:
  def __init__(self, priv):
    self._priv = priv
  def __getattribute__(self, attr):
    if attr[0] == "_": raise AttributeError("protected")
    return object.__getattribute__(self, attr)

a = Protected(42)
a._priv # AttributeError raised
```

Python's specificities (II)

Dual type system

- Nominal (classes, MRO)

Fspath (from standard library)

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

def fspath(p):
  if isinstance(p, (str, bytes)):
    return p
  elif hasattr(p, "__fspath__"):
    r = p.__fspath__()
    if isinstance(r, (str, bytes)):
      return r
  raise TypeError

fspath("/dev" if random() else Path())
```

Barrett et al. "A Monotonic Superclass Linearization for Dylan". OOPSLA 1996

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Exceptions

Exceptions rather than specific values

- `1 + "a"` ⇝ `TypeError`
- `l[len(l) + 1]` ⇝ `IndexError`

Fspath (from standard library)

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Complex desugaring into λ_π.

May incur losses of precision in the abstract interpreter.

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Semantics of Python, using a Python framework, developped concurrently.

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These works focus on the concrete semantics. This is not our endgoal.

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Moving to our own semantics

- Cost of understanding the code (vs CPython)
- Trust in the code (CPython's tests?)
- Insights of the papers

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Our approach

Interpreter-like semantics

Easily convertable to an abstract interpreter.

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Our approach

Interpreter-like semantics

Easily convertable to an abstract interpreter.

Major extension of the work of Fromherz, Ouadjaout, and Miné[2]

- Separation between core and builtins
- 2.3$\times$ more cases (`with` statement, bidirectional generators, ...)
- Improved some cases ($+$, boolean casts of conditionals, data descriptors, ...)

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Correctness

- Strived to make it auditable (with links to the source).
- Tested only through the abstract analysis yet (no concrete execution).

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Example – attribute access

$\mathbb{E}_{cur}[\![x.s]\!](cur, e, h) \stackrel{\text{def}}{=}$ `LOAD_ATTR PyObject_GetAttr (slot_tp_getattr_hook)`

$$\text{letb } (cur, e, h), @_x = \mathbb{E}[\![x]\!](cur, e, h) \text{ in}$$

$$\text{letb } (cur, e, h), @_c = \mathbb{E}[\![mro\_search(type(@_x), \texttt{"\_\_getattribute\_\_"})]\!](cur, e, h) \text{ in}$$

$$\text{letcases } (f, e, h), @_{x.s} = \mathbb{E}[\![@_c(@_x, s)]\!](cur, e, h) \text{ in}$$

$$\text{match } f \text{ with}$$

- $exn\ @_{exc} \text{ when } isinstance(@_{exc}, \texttt{AttributeError}) \Rightarrow$

  $\text{let } (f, e, h), @_d = \mathbb{E}[\![mro\_search(type(@_x), \texttt{"\_\_getattr\_\_"})]\!](f, e, h) \text{ in}$

  $\text{if } d \neq \bot \text{ then return } \mathbb{E}[\![@_d(@_x, s)]\!](cur, e, h)$

  $\text{else return } (f, e, h), \bot$

- $\_ \Rightarrow \text{return } (f, e, h), @_{x.s}$

Example – attribute access

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letb $(cur, e, h), @_x = \mathbb{E}[\![x]\!](cur, e, h)$ in

$\mathbb{E}_{cur}[\![$ `object.__getattribute__`$(obj, name)]\!](cur, e, h) \stackrel{\text{def}}{=}$ `tp_field _PyObject_GenericGetAttrWithDict`

letb $(cur, e, h), @_o = \mathbb{E}[\![obj]\!](cur, e, h)$ in

letb $(cur, e, h), @_n = \mathbb{E}[\![name]\!](cur, e, h)$ in

if $\neg isinstance(@_n, \text{str})$ then return $\mathbb{S}[\![$ `raise TypeError` $]\!](cur, e, h), \perp$ else

let `str`$(n) = \text{fst} \circ h(@_n)$ in

letcases $(f, e, h), @_{descr} = \mathbb{E}[\![mro\_search(type(@_o), n)]\!](f, e, h)$ in

if $@_{descr} \neq \perp$ then

if $hasattr(type(@_{descr}),$ "`__get__`"$) \wedge$ $(hasattr(type(@_{descr}),$ "`__set__`"$) \vee hasattr(type(@_{descr}),$ "`__delete__`"$))$ then

return $\mathbb{E}[\![type(@_{descr}).$`__get__`$(@_{descr}, @_o, type(@_o))]\!](f, e, h)$

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letb $(cur, e, h), @_{typ} = \mathbb{E}[\![typ]\!](cur, e, h)$ in

letb $(cur, e, h), @_{name} = \mathbb{E}[\![name]\!](cur, e, h)$ in

letb $(cur, e, h), @_{meta} = \mathbb{E}[\![$ mro_search$(type(@_{typ}), @_{name})]\!](cur, e, h)$ in

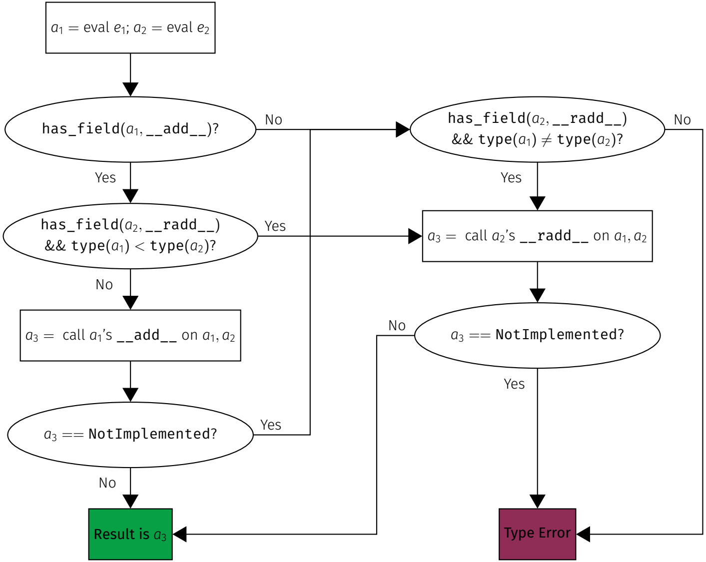
if $@_{meta} \neq \bot$ then

if hasattr$(type(@_{meta}),$"__get__"$) \wedge$

(hasattr$(type(@_{meta}),$"__set__"$) \vee$ hasattr$(type(@_{meta}),$"__delete__")) then

$\ldots (@_{meta}, @_{typ}, type(@_{typ}))]\!](cur, e, h)$

Example – binary operators



Crazy Python

Custom infix operators

```python
class Infix(object):
    def __init__(self, func): self.func = func
    def __or__(self, other): return self.func(other)
    def __ror__(self, other): return Infix(lambda x: self.func(other, x))

instanceof = Infix(isinstance)
b = 5 |instanceof| int

@Infix
def padd(x, y):
  print("{x} + {y} = {x + y}")
  return x + y
c = 2 |padd| 3
```

Credits `tomerfiliba.com/blog/Infix-Operators/`

The Mopsa Analysis Platform

Workflow

Averaging numbers

```
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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Proved safe?

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

Searching for a loop invariant (l. 4)

Environment abstraction

$m \mapsto @^\sharp_{\mathtt{int}^\sharp} \quad i \mapsto @^\sharp_{\mathtt{int}^\sharp}$

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Stateless domains: **list content**,

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Numeric abstraction (intervals)

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

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

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Numeric abstraction (polyhedra)

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

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

Workflow

Averaging tasks

```
1  class Task:
2    def __init__(self, weight):
3      if weight < 0: raise ValueError
4      self.weight = weight
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6  def average(l):
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8    for i in range(len(l)):
9      m = m + l[i].weight
10   m = m // (i + 1)
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13 l = [Task(randint(0, 20))
14   for i in range(randint(5, 10))]
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```

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- `l[i].weight`

Searching for a loop invariant (l. 4)

Stateless domains: list content, list length

Environment abstraction

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

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

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Environment abstraction

$m \mapsto @^\sharp$ … i … $@^\sharp$ … $@^\sharp_{\texttt{Task}}$

Conclusion

- Different domains depending on the precision
- Use of auxiliary variables (underlined)

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

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Overview

Modular Open Platform for Static Analysis[3]

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- One AST to analyze them all
  - Multilanguage support
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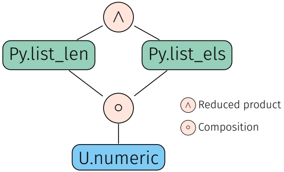

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Dynamic, semantic iterators with delegation

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

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for(init; cond; incr) body
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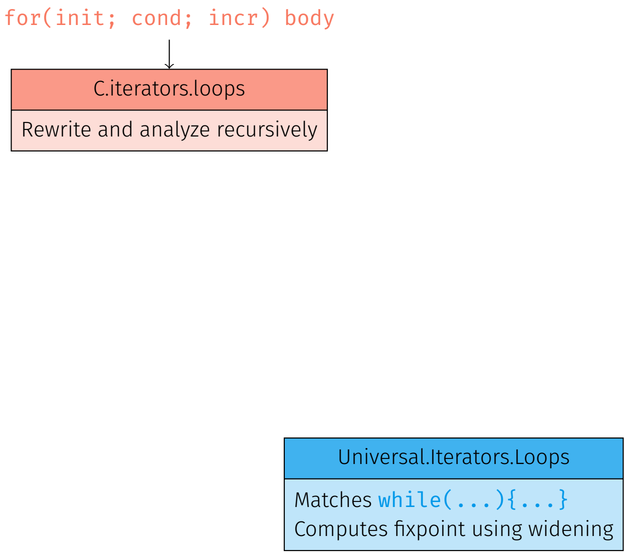

Dynamic, semantic iterators with delegation

```
for(init; cond; incr) body
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C.iterators.loops

Rewrite and analyze recursively

```
init;
while(cond) {
  body;
  incr;
}
clean init
```

Universal.Iterators.Loops

Matches `while(...){...}`

Computes fixpoint using widening

Dynamic, semantic iterators with delegation

`for(init; cond; incr) body`

`for target in iterable: body`

C.iterators.loops

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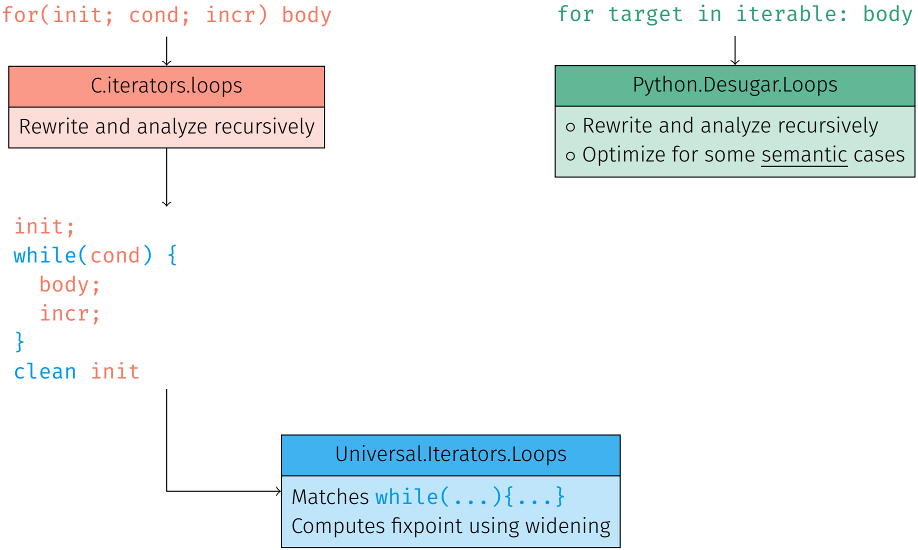

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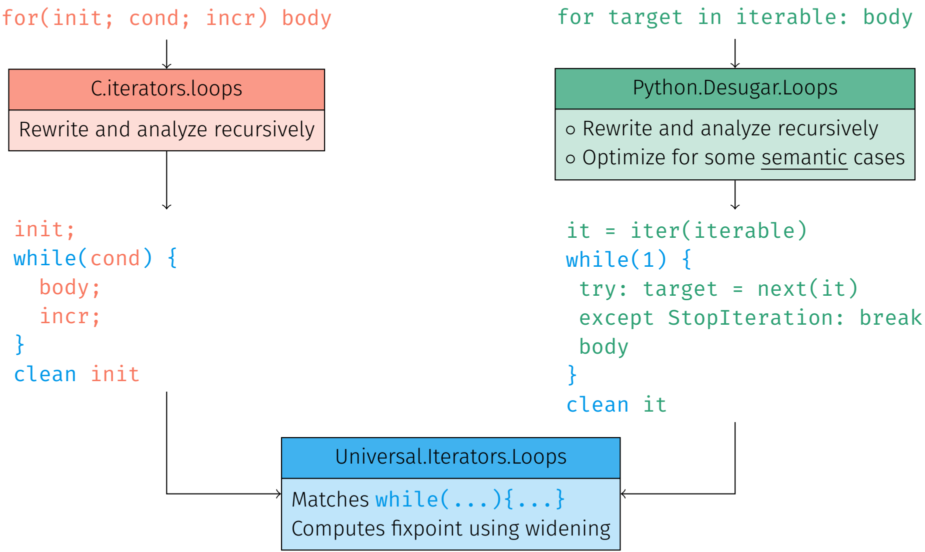

Hooks as observers of the analysis

Idea

Observe analyzer's state before/after any eval/exec

Hook signature

```
module type STATELESS_HOOK =
sig
  val name : string
  val init : 'a ctx -> unit

  val on_before_exec : stmt -> ('a,'a) man  -> 'a flow -> unit
  val on_after_exec :  stmt -> ('a,'a) man -> 'a flow -> ('a, unit) cases -> unit

  val on_before_eval : expr -> ('a,'a) man -> 'a flow -> unit
  val on_after_eval : expr -> ('a,'a) man -> 'a flow -> ('a, expr) cases -> unit

  val on_finish : ('a,'a) man -> 'a flow -> unit
end
```

Example of hooks: Logs

Logs

- Display the evaluation tree
- Optionally, display the abstract state at each point

```
+ S [| r = []; |]
| + E [| [] : py |]
| | + E [| alloc(list, STRONG) : addr |]
| | o E [| alloc(list, STRONG) : addr |] = @list:3ae881f4d:s : addr done [0.0001s, 1 case]
| | * reaching dependent_len.py:8.4-6
| | + S [| @list:3ae881f4d:s.list_length = 0; |]
| | | + E [| 0 : int |]
| | | o E [| 0 : int |] = 0 : int done [0.0001s, 1 case]
| | | * reaching dependent_len.py:8.4-6
| | | + S [| @list:3ae881f4d:s.list_length = 0; |] in below(universal.iterators.intraproc)
| | | o S [| @list:3ae881f4d:s.list_length = 0; |] in below(universal.iterators.intraproc) done [0.0001s, 1 case]
| | o S [| @list:3ae881f4d:s.list_length = 0; |] done [0.0001s, 1 case]
| o E [| [] : py |] = ⟪@list:3ae881f4d:s⟫ : py done [0.0002s, 1 case]
o S [| r = []; |] done [0.0002s, 1 case]
```

Example of hooks: Coverage

Coverage

- Global metric for the analysis' results
- Good to detect dead code, and soundness issues

```
def sum(l):
  s = 0
  for x in l:
    s += x
  return s

r2 = sum(['a', 'b', 'c'])
r1 = sum([1, 2, 3])
```

Example of hooks: Profiling

Motivation

- `perf`, `memtrace` too low-level and global
- Higher-level view by profiling at the analyzed program's level
- Inlining and nested loops $\implies$ analysis time $\not\propto$ program size

Product

```python
def p(l1, l2):
    r = []
    for x in l1:
        for y in l2:
            r.append((x, y))
    return r

r1 = p([1,2,3], [4,5,6])
r2 = p(['a', 'b'], ['c', 'd'])
```

Loop Profiler

```
nested.py:3.4-6.4: 2 times,
                   # iterations (3, 3)
nested.py:4.8-6.4: 6 times,
                   # iterations (3, 1, 1, 3, 1, 1)
```

Function Profiler

```
p          0.0544s(total)   x2
```

Analyzing Python Programs

Analyses overview

Goal

Detect runtime errors: uncaught raised exceptions

Analyses overview

Goal

Detect runtime errors: uncaught raised exceptions

Supported constructs

Our analysis supports:

- Objects
- Exceptions
- Dynamic typing
- Introspection
- Permissive semantics
- Dynamic attributes
- Generators
- `super`
- Metaclasses

Analyses overview

Goal

Detect runtime errors: uncaught raised exceptions

Supported constructs

Our analysis supports:

- Objects
- Exceptions
- Dynamic typing
- Introspection
- Permissive semantics
- Dynamic attributes
- Generators
- `super`
- Metaclasses

Unsupported constructs

- Recursive functions
- `eval`
- Finalizers

Attribute abstraction

Non-deterministic attribute handling

```
class A: pass

a = A()
a.x = 42
if *: a.y = 3
r = a.x * a.y
```

Attribute abstraction

Non-deterministic attribute handling

```
1 class A: pass
2
3 a = A()
4 a.x = 42
5 if *: a.y = 3
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```

After line 5: `a` may have attribute `y`.

Attribute abstraction

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After line 6, either

- `a` must have attribute `y`
- or an `AttributeError` has been raised

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After line 5: `a` may have attribute `y`.

After line 6, either

- `a` must have attribute `y`
- or an `AttributeError` has been raised

$\Longrightarrow$ We need both an under and an over-approximation of the attributes.

Attribute abstraction (II)

Using an under and an over-approximation

$\text{ObjS}^\sharp = \{ (u, o) \mid u \in \mathcal{P}(string), o \in \mathcal{P}(string) \cup \{ \top \}, u \subseteq o \vee o = \top \}$

Attribute abstraction (II)

Using an under and an over-approximation

$$\mathsf{ObjS}^\sharp = \{\, (u, o) \mid u \in \mathcal{P}(string), o \in \mathcal{P}(string) \cup \{\, \top \,\}, u \subseteq o \vee o = \top \,\}$$

Concretization

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

Attribute abstraction (II)

Using an under and an over-approximation

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Example

$$\gamma^\sharp_{\mathsf{ObjS}}(\{ x \}, \{ x, y, z \}) = \{ \{ x \}, \{ x, y \}, \{ x, z \}, \{ x, y, z \} \}$$

Attribute abstraction (III)

Non-deterministic attribute handling

```
class A: pass

a = A()
a.x = 42
if *: a.y = 3
r = a.x * a.y
```

How to lift the attribute abstraction?

Attribute abstraction (III)

Non-deterministic attribute handling

```
class A: pass

a = A()
a.x = 42
if *: a.y = 3
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```

How to lift the attribute abstraction? $\mathcal{V} \to \mathsf{ObjS}^\sharp$?

Attribute abstraction (III)

Non-deterministic attribute handling

```
1 class A: pass
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How to lift the attribute abstraction? $\mathcal{V} \to \mathsf{ObjS}^\sharp$?

After line 5, $a \mapsto \{ x \}, \{ x, y \}$?

Attribute abstraction (III)

Non-deterministic attribute handling

```
1 class A: pass
2
3 a = A(); b = a
4 b.x = 42
5 if *: a.y = 3
6 r = a.x * a.y
```

How to lift the attribute abstraction? $\mathcal{V} \to \mathsf{ObjS}^\sharp$?

After line 5, $a \mapsto \{ x \}, \{ x, y \}$?

Different variables may point to a same object, we need a memory abstraction:

$\mathsf{Addr}^\sharp \to \mathsf{ObjS}^\sharp$

Handling memory

N.B: already mentionned by Xavier Rival in lesson 10.

A finite set of abstract addresses $\mathbf{Addr}^\sharp$

Handling memory

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A finite set of abstract addresses $\mathbf{Addr}^\sharp$(why finite?)

Handling memory

N.B: already mentionned by Xavier Rival in lesson 10.

A finite set of abstract addresses **Addr**$^\sharp$(why finite?)

```
class A: pass

n = random_int()
for i in range(n):
  a = A()
  a.val = i
```

Handling memory

N.B: already mentionned by Xavier Rival in lesson 10.

A finite set of abstract addresses **Addr**$^\sharp$(why finite?)

```python
class A: pass

n = random_int()
for i in range(n):
  a = A()
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```

Need to handle unbounded allocations.

Allocation site abstraction

- $\text{Addr}^\sharp = \text{Loc}$
- Weak updates on abstract addresses

Attribute addition

```python
class A: pass

a = A()
a.x = 42
```

After line 3: $@_3^\sharp \mapsto \emptyset, \emptyset$

Weak update line 4:

$(@_3^\sharp \mapsto \{x\}, \{x\}) \sqcup^\sharp (@_3^\sharp \mapsto \emptyset, \emptyset) =$

Allocation site abstraction

- $\mathsf{Addr}^\sharp = \mathsf{Loc}$
- Weak updates on abstract addresses

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class A: pass

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After line 3: $@_3^\sharp \mapsto \emptyset, \emptyset$

Weak update line 4:

$$(@_3^\sharp \mapsto \{x\}, \{x\}) \sqcup^\sharp (@_3^\sharp \mapsto \emptyset, \emptyset) = @_3^\sharp \mapsto \emptyset, \{x\}$$

Allocation site abstraction

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Weak update line 4:

$(@_3^\sharp \mapsto \{x\}, \{x\}) \sqcup^\sharp (@_3^\sharp \mapsto \emptyset, \emptyset) = @_3^\sharp \mapsto \emptyset, \{x\}$

How to perform precise operations?

The recency abstraction[4]

- Precise analysis of object initialization

[4] Balakrishnan and Reps. "Recency-Abstraction for Heap-Allocated Storage". SAS 2006.
[5] Jensen, Møller, and Thiemann. "Type Analysis for JavaScript". SAS 2009.

The recency abstraction[4]

- Precise analysis of object initialization
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The recency abstraction[4]

- Precise analysis of object initialization
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  - through a recency criterion: $(l, \boldsymbol{r})$ most recent allocation (with strong updates)
    $(l, \boldsymbol{o})$ older addresses (summarized)

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    $(l, \boldsymbol{o})$ older addresses (summarized)
- Initially designed for analysis of low-level code (binaries, C)
- Also used in Type Analysis for JavaScript[5]

[4] Balakrishnan and Reps. "Recency-Abstraction for Heap-Allocated Storage". SAS 2006.
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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!

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Value analysis

Use allocation sites for `range` objects.

Handling memory | Recency abstraction (II)

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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.

Handling memory | Recency abstraction (III)

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

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

Handling memory | Recency abstraction (III)

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class Task:
  def __init__(self, weight):
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```

$$\left\{ @^\sharp(\text{Task}, r) \mapsto \emptyset, \emptyset \right.$$

Allocation:

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class Task:
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$$\left\{ @^\sharp(\mathrm{Task}, r) \mapsto \{\,\mathrm{weight}\,\}, \{\,\mathrm{weight}\,\} \right.$$

Initialization:

Handling memory | Recency abstraction (III)

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class Task:
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Allocation: $@^\sharp(\text{Task}, r) \rightsquigarrow @^\sharp(\text{Task}, o)$

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Analysis of `l[0].x = 3`? What about `l[3].x = 3`?

How to perform a numerical analysis?

Handling memory | Recency abstraction (IV)

How to perform a numerical analysis?

Auxiliary variables for attributes: $\textbf{Addr}^\sharp \times \mathit{string} \subseteq \mathcal{V}$

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$\{@^\sharp(\mathrm{Task}, r)$

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```

Allocation:

How to perform a numerical analysis?

Auxiliary variables for attributes: $\mathbf{Addr}^\sharp \times \mathit{string} \subseteq \mathcal{V}$

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

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Allocation: $@^\sharp(\text{Task}, r) \rightsquigarrow @^\sharp(\text{Task}, o)$

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

Initialization:

How to perform a numerical analysis?

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

Handling memory | Recency abstraction (IV)

How to perform a numerical analysis?

Auxiliary variables for attributes: $\mathbf{Addr}^\sharp \times \mathit{string} \subseteq \mathcal{V}$

```python
class Task:
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Auxiliary variables for attributes: $\textbf{Addr}^\sharp \times \textit{string} \subseteq \mathcal{V}$

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

List abstraction

- Summarization of the content (auxiliary variable)
- Auxiliary length variable

Container abstractions

List abstraction

- Summarization of the content (auxiliary variable)
- Auxiliary length variable

Dictionaries in Python

- Keys can be any object (JavaScript: strings or symbols)
- Key/value summarization currently used
- To be combined with an attribute-like abstraction for strings?

Python List Abstraction

- Smash each list into one weak, abstract contents variable.
- The contents variable is built upon the list's abstract address.
- Delegate to memory and numeric domains.

$$\mathbb{E}^\#[\![\, [e_1, \ldots, e_n]^{loc} \,]\!] s \stackrel{\text{def}}{=}$$

$$\quad \text{let } s, @ = \mathbb{E}^\#[\![\, \text{alloc}(\textbf{List}\ loc) \,]\!] s \text{ in}$$

$$\quad \text{let contents} = \text{mk\_var}\ @\ \text{"contents" in}$$

$$\quad \mathbb{S}^\#[\![\, \text{contents} \stackrel{\text{weak}}{=} e_n \,]\!] \circ \ldots \circ \mathbb{S}^\#[\![\, \text{contents} = e_1 \,]\!] s, @$$

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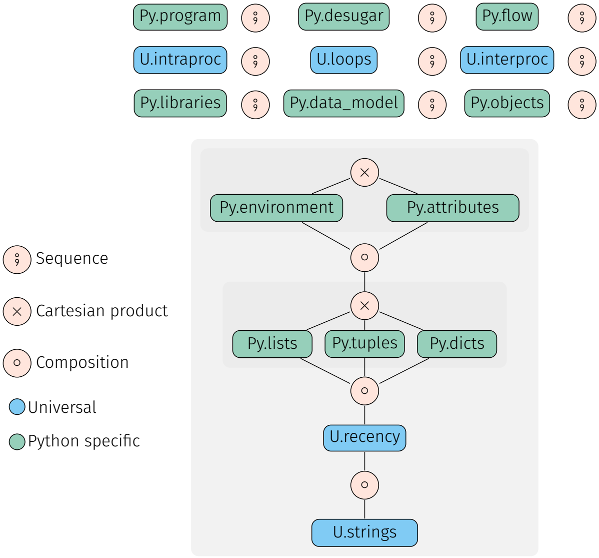
Demo!

Types | Analysis

- Dynamicity:
  type inference first
- Flow-sensitive
- Context-sensitive

Types | Analysis



- Dynamicity:
  type inference first
- Flow-sensitive
- Context-sensitive

- Similar in essence to TAJS.[6]
- Dataflow analysis by Fritz and Hage.[7]
- Typpete: SMT-based type inference.[8]
- Pytype, type inference tool used by Google.[9]
- RPython: efficient compilation of a static subset of Python.[10]
- Value analysis by Fromherz et al.[11]

---

[6] Jensen, Møller, and Thiemann. "Type Analysis for JavaScript". SAS 2009.
[7] Fritz and Hage. "Cost versus precision for approximate typing for Python". PEPM 2017.
[8] Hassan, Urban, Eilers, and Müller. "MaxSMT-Based Type Inference for Python 3". CAV 2018.
[9] Kramm et al. Pytype. 2019.
[10] Ancona, Ancona, Cuni, and Matsakis. "RPython: a step towards reconciling dynamically and statically typed OO languages". DLS 2007.
[11] Fromherz, Ouadjaout, and Miné. "Static Value Analysis of Python Programs by Abstract Interpretation". NFM 2018.

Types | Experimental evaluation

Name	LOC	Mopsa	⚠	Fritz & Hage	Pytype	Typpete	Fromherz et al.	RPython
bellman_ford.py	61	0.24s	0†	1.4s	0.99s	1.4s	2.4m	7.1s
float.py	63	82ms	0†	1.7s	0.92s	1.3s	0.84s	5.6s
coop_concat.py	64	43ms	0†	1.8s	0.81s	1.3s	20ms	🐛
crafting.py	132	0.41s	0†🔑	1.6s	0.97	1.7s	🐛	🐛
nbody.py	157	0.80s	1†🔑±	1.7s	1.3s	🐛	🐛	🐛
chaos.py	324	2.3s	0†±	13s	11s	🐛	🐛	🐛
scimark.py	416	0.55s	2†	8.5s	4.4s	🐛	🐛	🐛
richards.py	426	5.0s	2†±	38s	2.4s	🐛	🐛	7.8s
unpack_seq.py	458	4.2s	0±	1.1s	7.4s	2.7s	14s	🐛
go.py	461	15s	32†±	8.5s	3.4s	🐛	🐛	🐛
hexiom.py	674	22s	25†🔑±	🐛	4.2s	🐛	🐛	🐛
regex_v8.py	1792	15s	0†	4.9s	🕓	1.7m	🐛	🐛
processInput.py	1417	4.8s	7†🔑±	2.4s	11s	🐛	🐛	🐛
choose.py	2562	46s	17🔑†±	1.7s	15s	🐛	🐛	🐛

🐛 unsupported by the analyzer (crash) 🕓 timeout (after 1h)

Smashed exceptions: KeyError 🔑, IndexError †, ValueError ±

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richards.py	426	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	🐞	7.8s
unpack_seq.py	458	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	14s	🐞
go.py	461	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	🐞	🐞
hexiom.py	674	[illegible]	[illegible]	[illegible]	[illegible]	🐞	🐞	🐞
regex_v8.py	1792	15s	0†	4.9s	🕓	1.7m	🐞	🐞
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Smashed exceptions: KeyError 🔑, IndexError †, ValueError ≛

Conclusion

- Handling Python's dynamicity
- Good scalability (w.r.t. other semantic tools)

Thanks to Mopsa, switching from types to values is straightforward!

Monat, Ouadjaout, and Miné. "Value and allocation sensitivity in static Python analyses".

Types ⇝ values | Configurations

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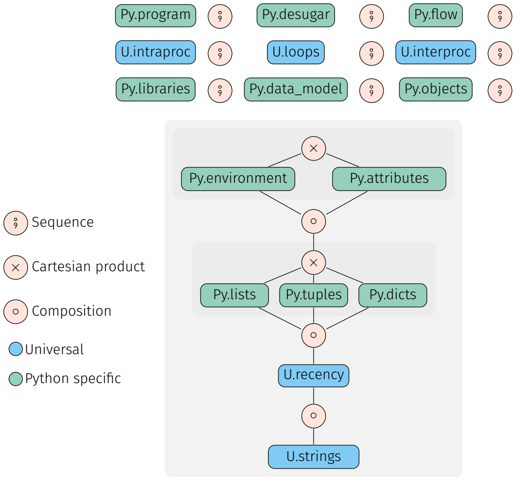

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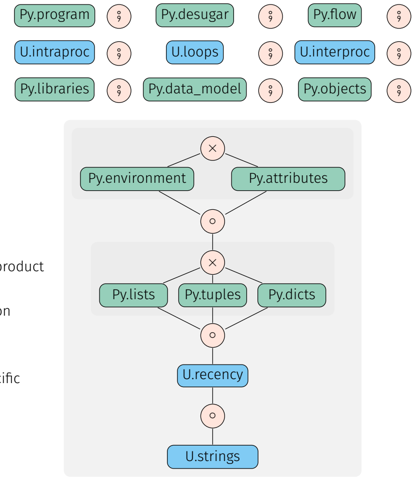

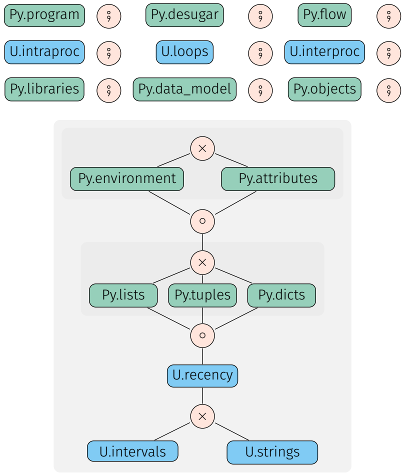

⨾ Sequence

× Cartesian product

∘ Composition

Universal

Python specific

Monat, Ouadjaout, and Miné. “Value and allocation sensitivity in static Python analyses”.

Types ⇝ values | Comparing the analyses

Averaging tasks

```
1  class Task:
2    def __init__(self, weight):
3      if weight < 0: raise ValueError
4      self.weight = weight
5
6  def average(l):
7    m = 0
8    for i in range(len(l)):
9      m = m + l[i].weight
10   m = m // (i + 1)
11   return m
12
13 l = []
14 for i in range(randint(5, 10)):
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16 m = average(l)
```

Type analysis

- `ValueError` (l. 3)

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Non-relational value analysis

`IndexError` (l. 9)

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Non-relational value analysis

`IndexError` (l. 9)

Relational value analysis

No alarm!

Types ⇝ values | Comparing the analyses (II)

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

Types ⇝ values | Comparing the analyses (II)

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	1.5[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**1**	1
scimark.py	416	1.4[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**0**	0
richards.py	426	13[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**2**	0
unpack_seq.py	458	8.3[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0
go.py	461	27s	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	20	0
hexiom.py	674	1.1m	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**21**	3
regex_v8.py	1792	23s	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**145**	0
processInput.py	1417	10s	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**4**	1
choose.py	2562	1.1m	[illegible]	[illegible]	22	7	2.9m	3.7GB	12	**13**	7
Total	9294	4.0m	2.8GB	59	2214	12	13m	9.1GB	59	228	12

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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		Time	Mem.	Exceptions detected			Time	Mem.	Exceptions detected		
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nbody.py	157	1.5								**1**	1
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richards.py	426	13								**2**	0
unpack_seq.py	458	8.3								0	0
go.py	461	27								20	0
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- ▶ does not remove false type alarms
- ▶ significantly reduces index errors
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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 $2.5\times$ 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

Soundness

Two soundnesses

- Modelization of the semantics from CPython
- Implementation of this semantics within Mopsa

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- Test only in the abstract
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Unsupported constructs

- `eval`
- Recursive functions
- Finalizers

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Unsupported constructs

- `eval`
- Recursive functions
- Finalizers

Tests from previous works

- 450/586 tests supported
- 268/586 assertions proved

Official tests from CPython

- 325/416 tests supported (17 chosen files)
- 389/702 assertions proved

Analyzing Python Programs with C Libraries

Combining C and Python – motivation

One in five of the top 200 Python libraries contains C code

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- Different values (arbitrary-precision integers in Python, bounded in C)
- Different object representations (Python objects, C structs)
- Different runtime-errors (exceptions in Python)
- Garbage collection

Combining C and Python – first look

A combined static analysis of C/Python[12]

- Targeting C extensions using the CPython API

[12] Monat, Ouadjaout, and Miné. "A Multilanguage Static Analysis of Python Programs with Native C Extensions". SAS 2021.

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$\Rightarrow$ Share universal domains and synchronize abstractions

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Combining C and Python – 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))
       return NULL;

    self->count += i;
    Py_RETURN_NONE;
}

static PyObject*
CounterGet(Counter *self)
{
    return Py_BuildValue("i", self->count);
}
```

count.py

```python
from counter import Counter
from random import randrange

c = Counter()
power = randrange(128)
c.incr(2**power-1)
c.incr()
r = c.get()
```

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```

- $\texttt{power} \leq 30 \Rightarrow \texttt{r} = 2^{\texttt{power}}$
- $32 \leq \texttt{power} \leq 64$: OverflowError: signed integer is greater than maximum
- $\texttt{power} \geq 64$: OverflowError: Python int too large to convert to C long

Combining C and Python – 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))
       return NULL;

    self->count += i;
    Py_RETURN_NONE;
}

static PyObject*
CounterGet(Counter *self)
{
    return Py_BuildValue("i", self->count);
}
```

count.py

```python
from counter import Counter
from random import randrange

c = Counter()
power = randrange(128)
c.incr(2**power-1)
c.incr()
r = c.get()
```

- $\texttt{power} \leq 30 \Rightarrow \texttt{r} = 2^{\texttt{power}}$
- $\texttt{power} = 31 \Rightarrow \texttt{r} = -2^{31}$
- $32 \leq \texttt{power} \leq 64$: OverflowError: signed integer is greater than maximum
- $\texttt{power} \geq 64$: OverflowError: Python int too large to convert to C long

How to analyze multilanguage programs?

Type annotations

```
class Counter:
  def __init__(self): ...
  def incr(self, i: int = 1): ...
  def get(self) -> int: ...
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- Typeshed: type annotations for the standard library

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- No raised exceptions $\implies$ missed errors
- Only types
- Typeshed: type annotations for the standard library, used in the single-language analysis before

How to analyze multilanguage programs?

Type annotations

Rewrite into Python code

```
class Counter:
  def __init__(self):
    self.count = 0
  def get(self):
    return self.count
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- No integer wrap-around in Python

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    self.count += i
```

- No integer wrap-around in Python
- Some effects can’t be written in pure Python (e.g., read-only attributes)

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Type annotations

Rewrite into Python code

Drawbacks of the current approaches

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Our approach

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- Analyze both the C and Python sources

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Type annotations

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- Not automatic: manual conversion
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Our approach

- Analyze both the C and Python sources
- Switch from one language to the other just as the program does
- Reuse previous analyses of C and Python
- Detect runtime errors in Python, in C, and at the boundary

Analysis result

counter.c

```c
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    int count;
} Counter;

static PyObject*
CounterIncr(Counter *self, PyObject *args)
{
    int i = 1;
    if(!PyArg_ParseTuple(args, "|i", &i))
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```python
from counter import Counter
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c = Counter()
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Analysis result

counter.c

```c
1  typedef struct {
2      PyObject_HEAD;
3      int count;
4  } Counter;
5
6  static PyObject*
7  CounterIncr(Counter *self,
8  {
9      int i = 1;
10     if(!PyArg_ParseTuple(a
11        return NULL;
12
13     self->count += i;
14     Py_RETURN_NONE;
15 }
16
17 static PyObject*
18 CounterGet(Counter *self)
19 {
20     return Py_BuildValue("
21 }
```

count.py

```python
1  from counter import Counter
2  from random import randrange
```

```
⚠Check #430:
./counter.c: In function 'CounterIncr':
./counter.c:13.2-18: warning: Integer overflow

 13:    self->count += i;
        ^^^^^^^^^^^^^^^^
 '(self->count + i)' has value [0,2147483648] that is larger
   than the range of 'signed int' = [-2147483648,2147483647]
 Callstack:
       from count.py:8.0-8: CounterIncr


✗ Check #506:
count.py: In function 'PyErr_SetString':
count.py:6.0-14: error: OverflowError exception

 6: c.incr(2**p-1)
    ^^^^^^^^^^^^^^
 Uncaught Python exception: OverflowError: signed integer is greater than maximum
 Uncaught Python exception: OverflowError: Python int too large to convert to C long
 Callstack:
       from ./counter.c:17.6-38::convert_single[0]: PyParseTuple_int
       from count.py:7.0-14: CounterIncr
 +1 other callstack
```

Multilanguage semantics

Concrete definition

- Builds upon the Python and C semantics

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- Garbage collection not handled

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- C access to Python objects only through the API (verified by Mopsa)

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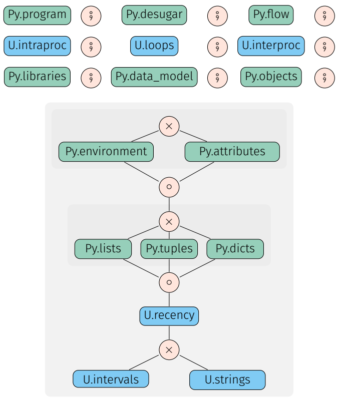
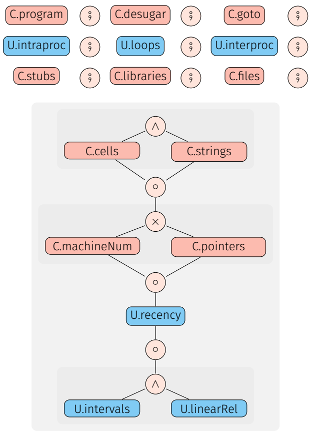
- Shared heap, with disjoint, complementary views
- Boundary functions when objects switch views for the first time

Limitations

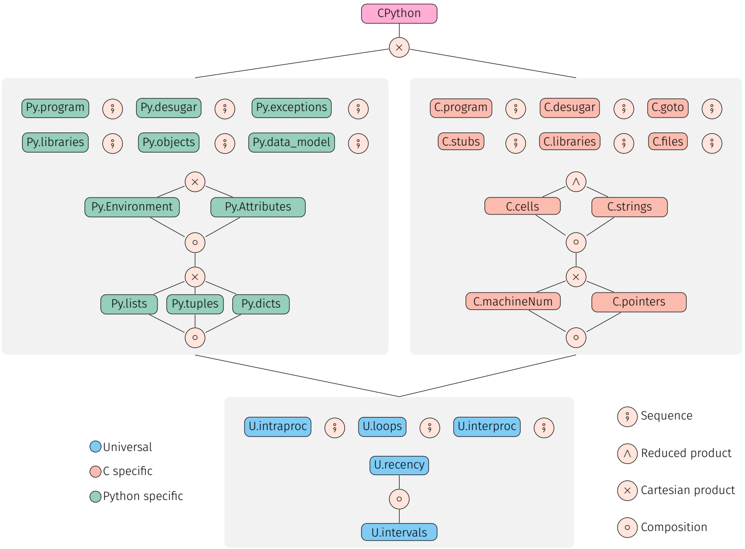
- Garbage collection not handled
- C access to Python objects only through the API (verified by Mopsa)
- Manual modelization from CPython's source code

From distinct Python and C analyses...





... to a multilanguage analysis!



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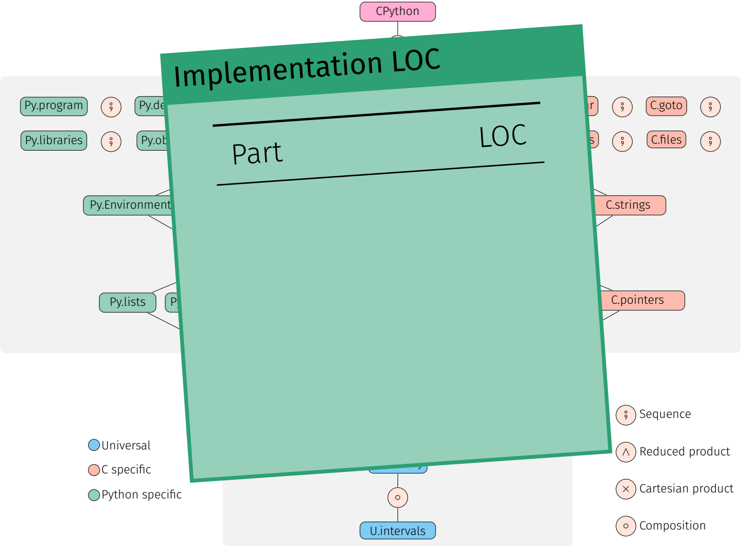
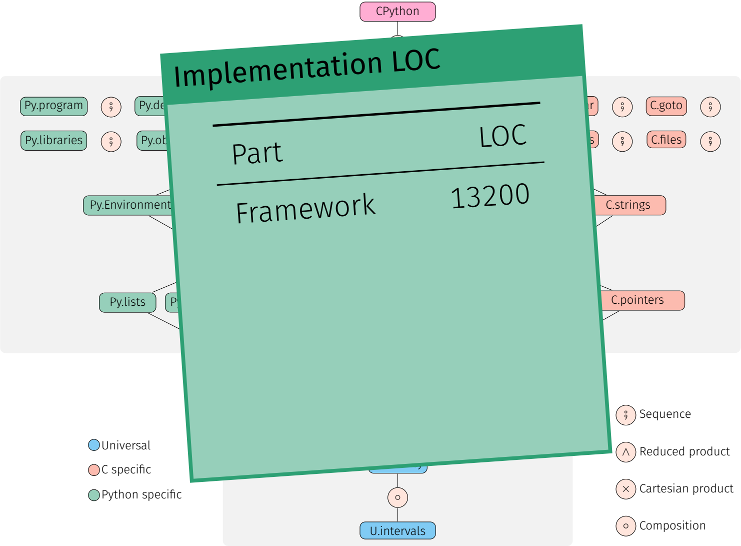


Implementation LOC

Part	LOC

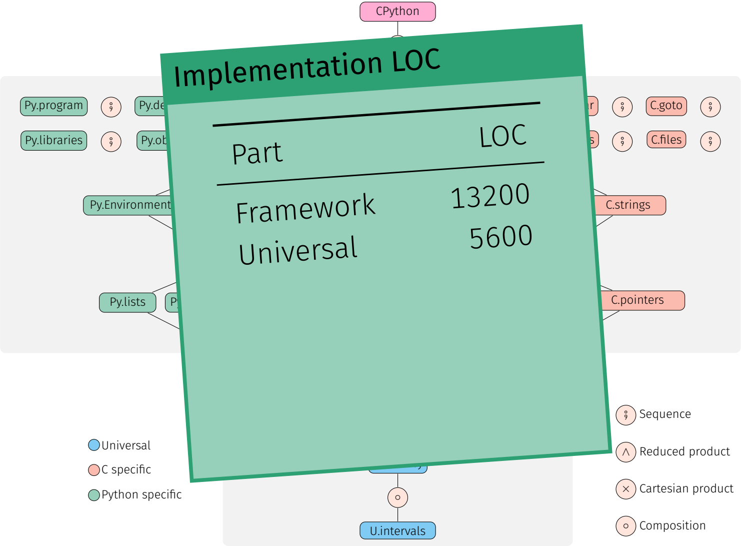
… to a multilanguage analysis!



Implementation LOC

Part	LOC
Framework	13200

… to a multilanguage analysis!



Implementation LOC

Part	LOC
Framework	13200
Universal	5600

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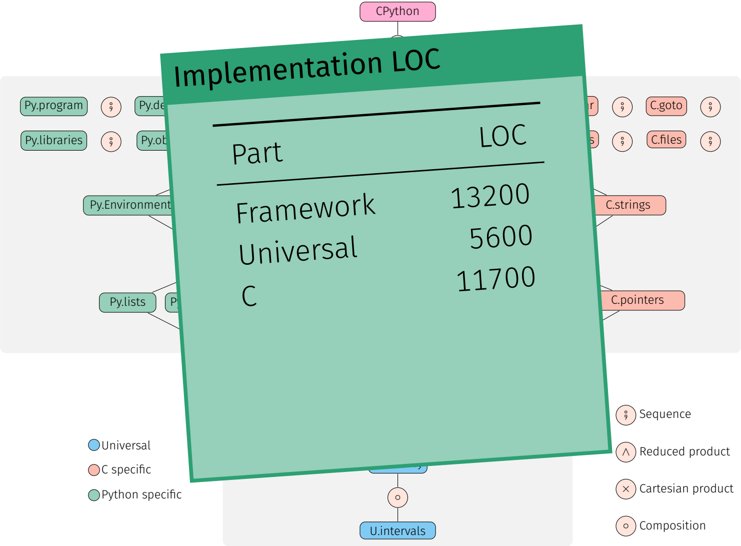
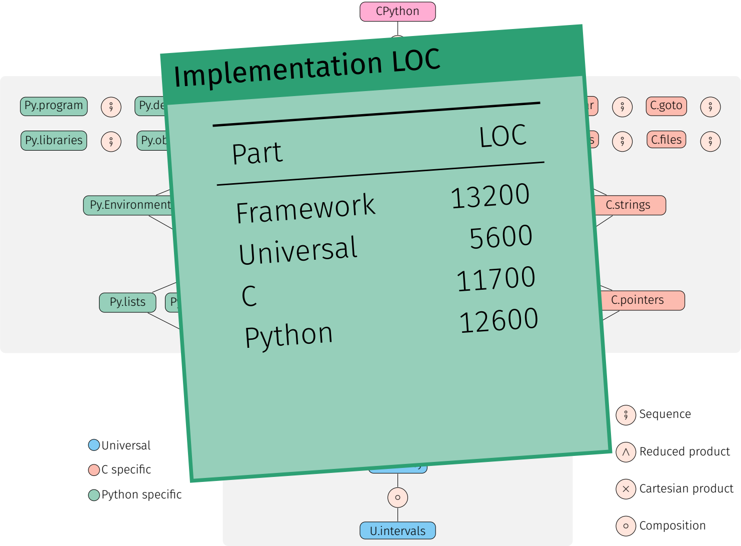


Implementation LOC

Part	LOC
Framework	13200
Universal	5600
C	11700

… to a multilanguage analysis!



Implementation LOC

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Universal	5600
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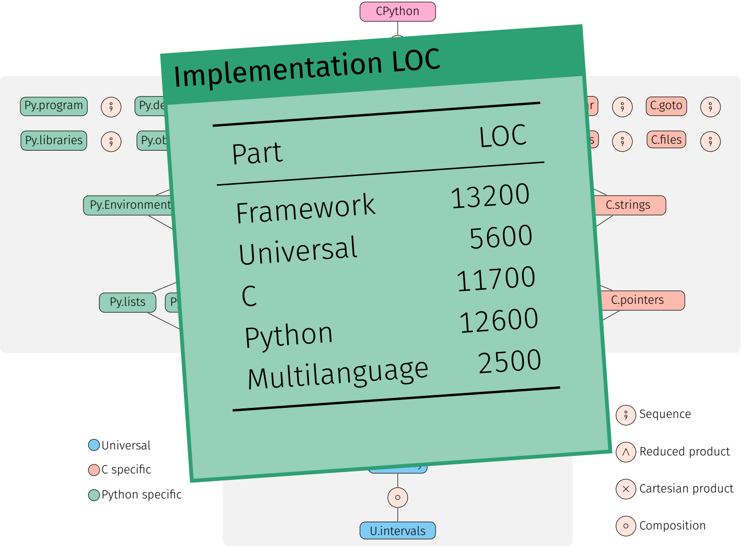
Python	12600

… to a multilanguage analysis!



Implementation LOC

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Python	12600
Multilanguage	2500

Analysis of the multilanguage 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))
  return NULL;

  self->counter += i;
  Py_RETURN_NONE;
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static PyObject*
CounterGet(Counter *self)
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count.py

```python
from counter import Counter
from random import randrange

c = Counter()
power = randrange(128)
c.incr(2**power-1)
c.incr()
r = c.get()
```

$\mathbb{E}^{\#}_{\text{Py.call}}[\![\, \texttt{Counter()} \,]\!]\sigma^{\sharp}$

C

Pointers
⟨CounterCls,8,ptr⟩ : {PyType_Type}
⟨CounterCls,232,ptr⟩ : {Counter_methods}

Universal

Heap (Recency)
@CounterCls @CounterIncr
@CounterGet

Intervals

Python

Attributes
@CounterCls ↦ {get, incr}

Environment
Counter ↦ {@CounterCls}
@CounterCls·get ↦
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$\mathbb{E}^{\#}_{\text{C.call}}[\![\,$ tp_new_wrapper(type, tuple(Counter), NULL) $]\!]\sigma^{\#}$

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$\mathbb{E}^{\#}_{\text{C.call}} [\![\texttt{PyType\_GenericNew(CounterCls, NULL, NULL)}]\!] \sigma^{\sharp}$

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 @CounterCls @CounterIncr
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$\mathbb{E}^{\#}_{\text{C.cells}}[\![\, \texttt{@I\{CounterCls\}->ob\_type} = \texttt{CounterCls} \,]\!]\sigma^{\sharp}$

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```

$\mathbb{E}^{\#}_{\text{C.cells}}[\![$ @I{CounterCls}->count = 0 $]\!]\sigma^{\sharp}$

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```

Universal

```
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Intervals
 ⟨@I{CounterCls},16,s32}⟩ ↦ [0, 0]
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${}^{c}\hookrightarrow_{p}(@I\{CounterCls\}, \sigma^{\sharp})$

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```

$\mathbb{S}^{\#}_{\text{Py.env}}[\![\, c = \text{@I\{CounterCls\}} \,]\!]\sigma^{\sharp}$

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 ⟨@I{CounterCls},8,ptr⟩ : {CounterCls}
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$\mathbb{S}^{\#}_{\text{Py}} [\![\text{power} = \text{randrange}(128)]\!] \sigma^{\sharp}$

C

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Pointers
 ⟨CounterCls,8,ptr⟩ : {PyType_Type}
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 ⟨@I{CounterCls},8,ptr⟩ : {CounterCls}
```

Universal

```
Heap (Recency)
 @CounterCls @CounterIncr
 @CounterGet @I{CounterCls}

Intervals
 ⟨@I{CounterCls},16,s32⟩ ↦ [0, 0]
 power ↦ [0, 127]
```

Python

```
Attributes
 @CounterCls ↦ {get, incr}
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Environment
 Counter ↦ {@CounterCls}
 @CounterCls·get ↦
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 {@c function CounterIncr}
 c ↦ {@I{CounterCls}}
 power ↦ {@I{int}}
```

Benchmarks

Corpus selection

- ▶ Popular, real-world libraries available on GitHub, averaging 412 stars.
- ▶ Whole-program analysis: we use the tests provided by the libraries.

Library	|C|	|Py|	Tests						Assertions	Py ⇝ C
`noise`	722	675	15/15	18s	99.6%	(4952)	100.0%	(1738)	0/21	6.5
`ahocorasick`	3541	1336	46/92	54s	93.1%	(1785)	98.0%	(4937)	30/88	5.4
`levenshtein`	5441	357	17/17	1.5m	79.9%	(3106)	93.2%	(1719)	0/38	2.7
`cdistance`	1433	912	28/28	1.9m	95.3%	(1832)	98.3%	(11884)	88/207	8.7
`llist`	2829	1686	167/194	4.2m	99.0%	(5311)	98.8%	(30944)	235/691	51.7
`bitarray`	3244	2597	159/216	4.2m	96.3%	(4496)	94.6%	(21070)	100/378	14.8

$\frac{\text{safe C checks}}{\text{total C checks}}\%$

total C checks

average # transitions between Python and C per test

Theoretical frameworks

- Matthews and Findler[13] boundary functions as value conversions between two languages.
- Buro, Crole, and Mastroeni[14] generic framework for combining analyses of different languages.

[13] Matthews and Findler. “Operational semantics for multi-language programs”. 2009.
[14] Buro, Crole, and Mastroeni. “On Multi-language Abstraction - Towards a Static Analysis of Multi-language Programs”. SAS 2020.

Related work (II)

Around the Java Native Interface (JNI)

Static translation of some of C's effects, injected back into the Java analysis.

- Effects of C code on Java heap modelized using JVML[15]
- Type inference of Java objects in C code[16]
- Extraction of C callbacks to Java[17]

- Modular analyses
- No numeric information
- Missing C runtime errors

[15] Tan and Morrisett. "Ilea: inter-language analysis across Java and C". OOPSLA 2007.

[16] Furr and Foster. "Checking type safety of foreign function calls". 2008.

[17] Lee, Lee, and Ryu. "Broadening Horizons of Multilingual Static Analysis: Semantic Summary Extraction from C Code for JNI Program Analysis". ASE 2020.

Conclusion

Contribution: concrete semantics of Python

Difficulties

- Size of the semantics
- CPython's source code

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Previous works

- Executable semantics of Python
- Handcrafted tests

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Our results

- Semantics suitable for abstract interpretation
- Written and explained in the manuscript (70 cases)
- Backreferences to the source code
- Preliminary tests using CPython's suite

Contribution: type & value analyses of Python

Difficulties

- Dynamicity
- Dual type system
- Size of the semantics

[18] Monat, Ouadjaout, and Miné. "Static Type Analysis by Abstract Interpretation of Python Programs". ECOOP 2020.
[19] Monat, Ouadjaout, and Miné. "Value and allocation sensitivity in static Python analyses". SOAP@PLDI 2020.

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- JS: type and constant analysis
- Python: no scalability or support of dynamicity

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Our results

- Type analysis[18],
- Numeric value analysis & new sensitivities for the recency abstraction[19]
- Relational value analysis with packing (manuscript)
- Scale to small, real-world benchmarks

[18] Monat, Ouadjaout, and Miné. "Static Type Analysis by Abstract Interpretation of Python Programs". ECOOP 2020.
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Contribution: multilanguage Python/C analysis

Difficulties

- Concrete semantics
- Memory interaction

Monat, Ouadjaout, and Miné. "A Multilanguage Static Analysis of Python Programs with Native C Extensions". SAS 2021

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- Type/exceptions analyses for the JNI
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- Concrete semantics
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Previous works

- Type/exceptions analyses for the JNI
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Our results

- Careful separation of the states and modelization of the API
- Lightweight domain on top of off-the-shelf C and Python analyses
- Shared underlying abstractions (numeric, recency)
- Scale to small, real-world libraries (using client code)

Monat, Ouadjaout, and Miné. “A Multilanguage Static Analysis of Python Programs with Native C Extensions”. SAS 2021

Some future works

Executable concrete semantics

- Split soundness testing (CPython – concrete semantics – analyzer)
- Use skeletal semantics or interaction trees framework
- Conformance tests

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Dictionary abstractions

- Beyond key/value summarization
- Empirical study of dictionary use (use of non-string keys)

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Multilanguage library analyses

- Infer Typeshed's annotations
- Library analysis without client code

Static Type and Value Analysis by Abstract Interpretation of Python Programs with Native C Libraries

Questions

xkcd.com/353

Raphaël Monat

MPRI lecture
31 January 2021