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

Raphaël Monat, Abdelraouf Ouadjaout, Antoine Miné

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SORBONNE UNIVERSITÉ

Introduction

Whoami

- Member of APR, LIP6, Sorbonne Université & CNRS
- September 2018 – August 2021: PhD Student
- September 2021 – August 2022: ATER

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Static Program Analysis

average.py

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

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

TypeError: unsupported operand type(s) for '+': 'int' and 'str'

argslen.c

```c
#include <string.h>

int main(int argc, char *argv[]) {
  int i = 0;
  for (char **p = argv; *p; p++) {
    strlen(*p); // valid string
    i++; // no overflow
  }
  return 0;
}
```

No alarm

Specifications of the analyzer

Inference of program properties such as the absence of run-time errors.

Automatic no expert knowledge required.

Semantic based on a formal modelization of the language.

Sound cover all possible executions.

Dynamic programming languages

Growing popularity

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

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

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- Object orientation,
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- `eval`.

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Outline

1. Introduction
2. A Taste of Python
3. Analyzing Python Programs
4. Analyzing Python Programs with C Libraries
5. Conclusion

A Taste of Python

Python’s specificities

No standard

- CPython is the reference

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

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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)

```python
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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- **Structural (attributes)**

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Exceptions

Exceptions rather than specific values

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

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Guth. "A formal semantics of Python 3.3". 2013

Implementation within the K framework.

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Complex desugaring into λ_π.

May incur losses of precision in the abstract interpreter.

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Different goal

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

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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

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

$$
\begin{aligned}
&\text{letb } (cur, e, h), @_x = \mathbb{E}[\![x]\!](cur, e, h) \text{ in} \\
&\text{letb } (cur, e, h), @_c = \mathbb{E}[\![\mathit{mro\_search}(\mathit{type}(@_x), \text{"}\texttt{\_\_getattribute\_\_}\text{"})]\!](cur, e, h) \text{ in} \\
&\text{letcases } (f, e, h), @_{x.s} = \mathbb{E}[\![@_c(@_x, s)]\!](cur, e, h) \text{ in} \\
&\text{match } f \text{ with}
\end{aligned}
$$

- $\mathit{exn}\ @_{exc} \text{ when } \mathit{isinstance}(@_{exc}, \texttt{AttributeError}) \Rightarrow$
  $\text{let } (f, e, h), @_d = \mathbb{E}[\![\mathit{mro\_search}(\mathit{type}(@_x), \text{"}\texttt{\_\_getattr\_\_}\text{"})]\!](f, e, h) \text{ in}$
  $\text{if } d \neq \bot \text{ then return } \mathbb{E}[\![@_d(@_x, s)]\!](cur, e, h)$
  $\text{else return } (f, e, h), \bot$
- $\_ \Rightarrow \text{return } (f, e, h), @_{x.s}$

Example – attribute access

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

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

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

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

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

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

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

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

$\text{if } @_{descr} \neq \bot \text{ then}$

$\text{if } hasattr(type(@_{descr}), \text{"}\texttt{\_\_get\_\_}\text{"}) \wedge$

$(hasattr(type(@_{descr}), \text{"}\texttt{\_\_set\_\_}\text{"}) \vee hasattr(type(@_{descr}), \text{"}\texttt{\_\_delete\_\_}\text{"})) \text{ then}$

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

Example – attribute access

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

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

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

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

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

$\mathbb{E}_{cur}[\![$ `type.__getattribute__`$(typ, name)]\!](cur, e, h) \stackrel{def}{=}$ `tp_field type_getattro`

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

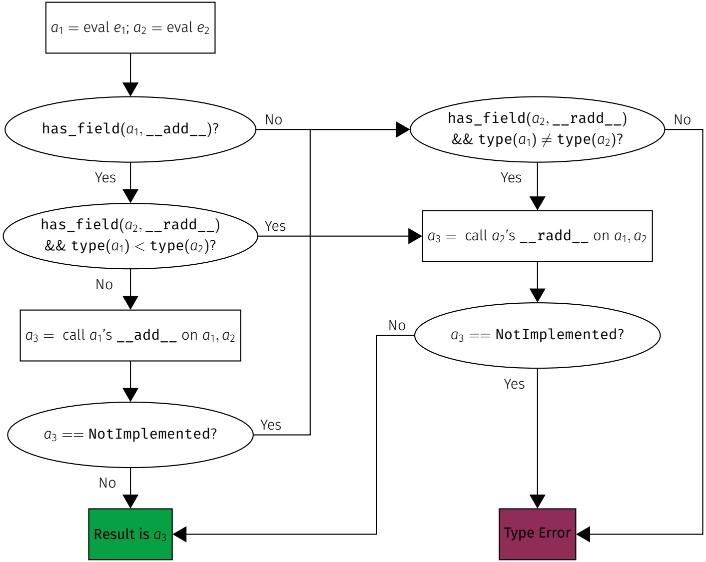
if $@_{meta} \neq \bot$ then

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

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

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

Example – binary operators



Crazy Python

Custom infix operators

```
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/`

Analyzing Python Programs

Goal

Detect runtime errors: uncaught raised exceptions

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Detect runtime errors: uncaught raised exceptions

Supported constructs

Our analysis supports:

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

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Unsupported constructs

- Recursive functions
- `eval`
- Finalizers

Analysis | Domains required

Avering 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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```
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3    for i in range(len(l)):
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5    m = m // (i + 1)
6    return m
7
8  l = [randint(0, 20)
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```

Searching for a loop invariant (l. 4)

Environment abstraction

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

Proved safe?

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

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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)

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

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

Analysis | Domains required

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

Proved safe?

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

Searching for a loop invariant (l. 4)

Stateless domains: list content, list length

Environment abstraction

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

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

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Attributes abstraction

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

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Stateless domains: list content, list length

Environment abstraction

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

Conclusion

- Different domains depending on the precision
- Use of auxiliary variables (<u>underlined</u>)

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

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

Attributes abstraction

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

Modular Open Platform for Static Analysis[3]

[3] Journault, Miné, Monat, and Ouadjaout. “Combinations of reusable abstract domains for a multilingual static analyzer”. VSTTE 2019.

Modular Open Platform for Static Analysis[3]

- One AST to analyze them all
  - Multilanguage support
  - Expressiveness
  - Reusability

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- Unified domain signature
  - Semantic rewriting
  - Loose coupling
  - Observability

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  - Multilanguage support
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  - Reusability
- Unified domain signature
  - Semantic rewriting
  - Loose coupling
  - Observability
- DAG of abstract domains
  - Composition
  - Cooperation

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

Mopsa | Dynamic, semantic iterators with delegation

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for(init; cond; incr) body
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↓

C.iterators.loops

Rewrite and analyze recursively

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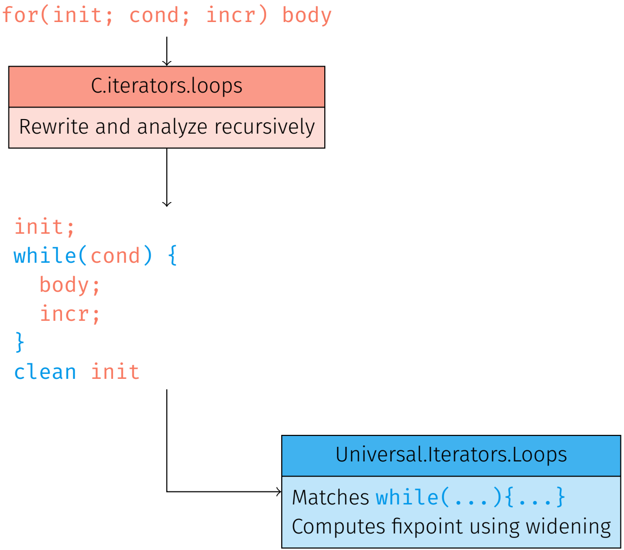
Computes fixpoint using widening

Mopsa | Dynamic, semantic iterators with delegation



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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

```
for target in iterable: body
```

Mopsa | Dynamic, semantic iterators with delegation

```
for(init; cond; incr) body
```

↓

C.iterators.loops

Rewrite and analyze recursively

↓

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

→

Universal.Iterators.Loops

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

Computes fixpoint using widening

```
for target in iterable: body
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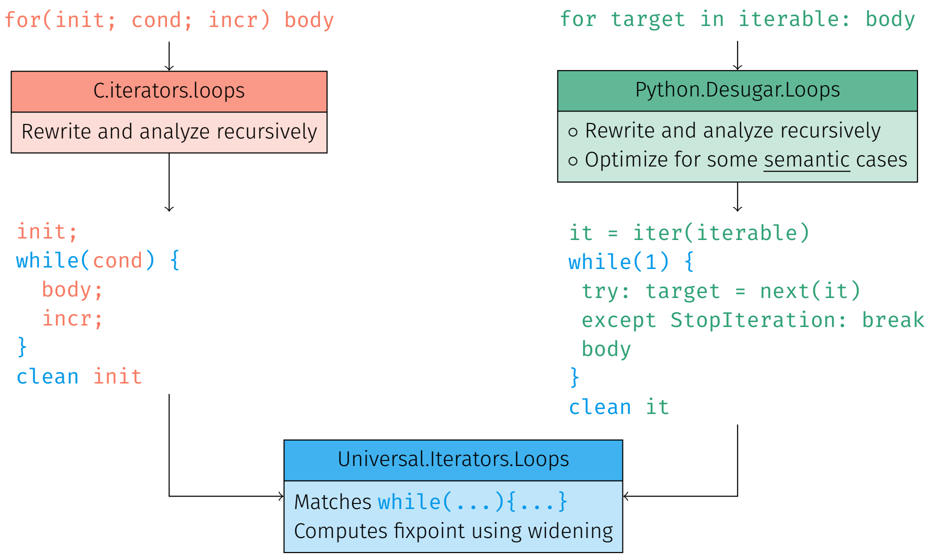
↓

Python.Desugar.Loops

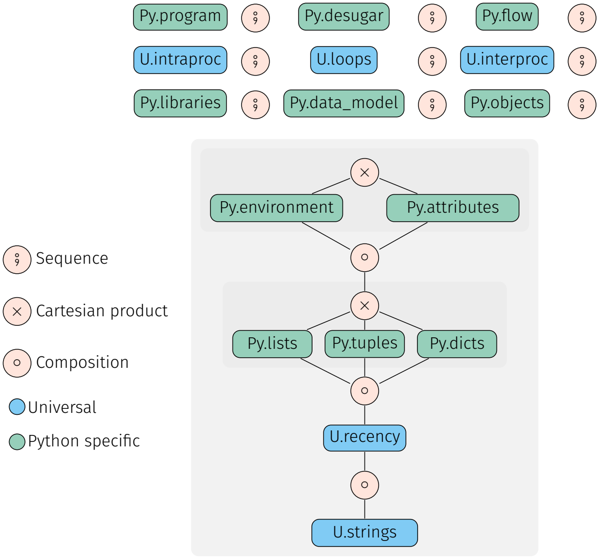
- Rewrite and analyze recursively
- Optimize for some semantic cases

Mopsa | Dynamic, semantic iterators with delegation



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

Types | Analysis



- Dynamicity: type inference first
- Flow-sensitive
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Types | Related work

- Similar in essence to TAJS.[4]
- Dataflow analysis by Fritz and Hage.[5]
- Typpete: SMT-based type inference.[6]
- Pytype, type inference tool used by Google.[7]
- RPython: efficient compilation of a static subset of Python.[8]
- Value analysis by Fromherz et al.[9]

---

[4] Jensen, Møller, and Thiemann. "Type Analysis for JavaScript". SAS 2009.
[5] Fritz and Hage. "Cost versus precision for approximate typing for Python". PEPM 2017.
[6] Hassan, Urban, Eilers, and Müller. "MaxSMT-Based Type Inference for Python 3". CAV 2018.
[7] Kramm et al. Pytype. 2019.
[8] Ancona, Ancona, Cuni, and Matsakis. "RPython: a step towards reconciling dynamically and statically typed OO languages". DLS 2007.
[9] 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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go.py	461						🐞	🐞
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Conclusion

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

🐞 unsupported by the analyzer (crash) ⏱ timeout (after 1h)
Smashed exceptions: KeyError 🔑, IndexError †, ValueError ±

Types $\rightsquigarrow$ values | Configurations

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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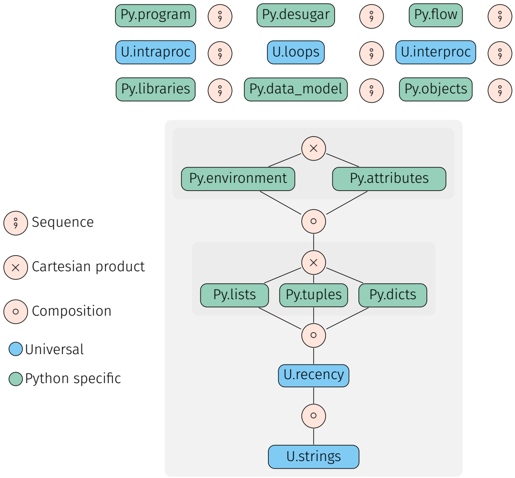

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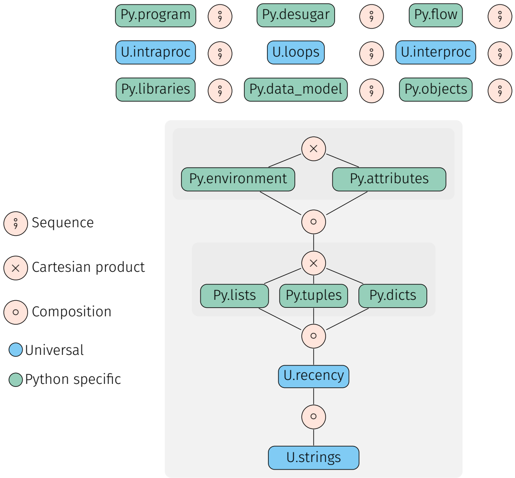

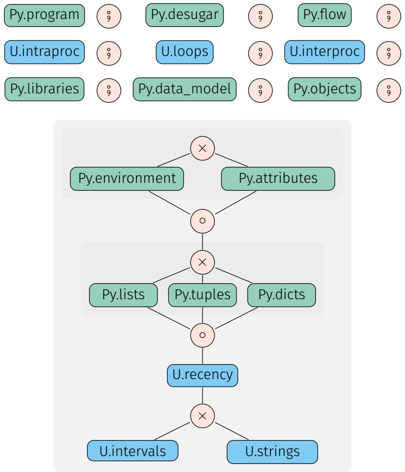

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Types ⇝ values | Comparing the analyses

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)):
15   l.append(Task(randint(0, 20)))
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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

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]	**1**	1
scimark.py	416	1.4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**0**	0
richards.py	426	13	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**2**	0
unpack_seq.py	458	8.3	[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

Types ⇝ values | Comparing the analyses (II)

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		Time	Mem.	Exceptions detected: Type	Index	Key	Time	Mem.	Exceptions detected: 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
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The non-relational value analysis

- does not remove false type alarms
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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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- `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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Pitfalls

- 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[10]

- Targeting C extensions using the CPython API

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

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  - allocated objects are <u>shared</u> in the memory
  - but each language has <u>different abstractions</u>

$\Rightarrow$ 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

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```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, used in the single-language analysis before

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Type annotations

Rewrite into Python code

```
class Counter:
  def __init__(self):
    self.count = 0
  def get(self):
    return self.count
  def incr(self, i=1):
    self.count += i
```

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- No integer wrap-around in Python

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- 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

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Drawbacks of the current approaches

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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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static PyObject*
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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 }
```

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```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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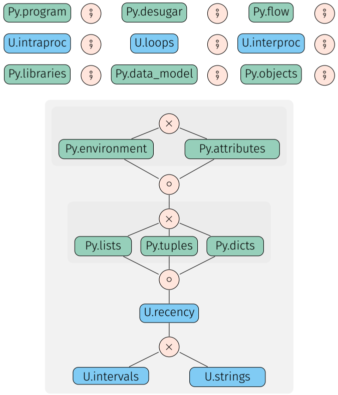
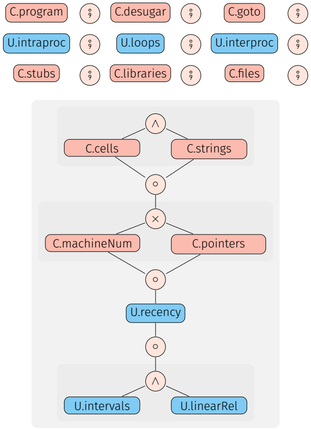
Limitations

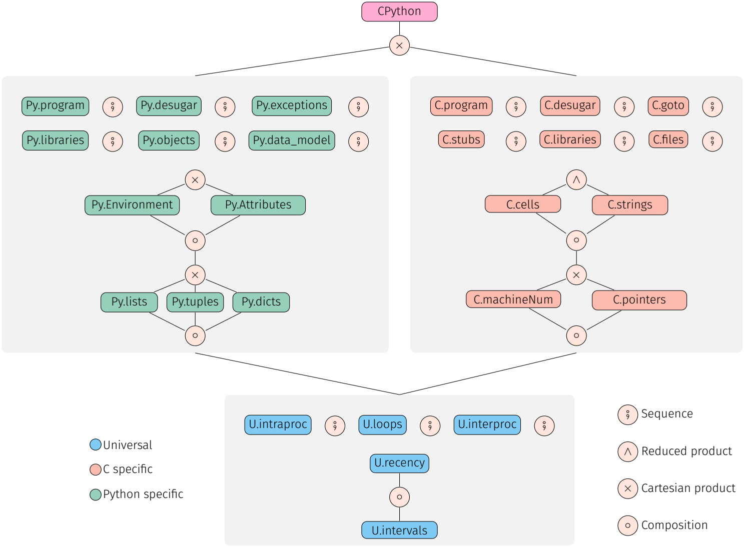
- Garbage collection not handled
- C access to Python objects only through the API (verified by Mopsa)
- Manual modelization from CPython's source code

From distinct Python and C analyses...





... to a multilanguage analysis!



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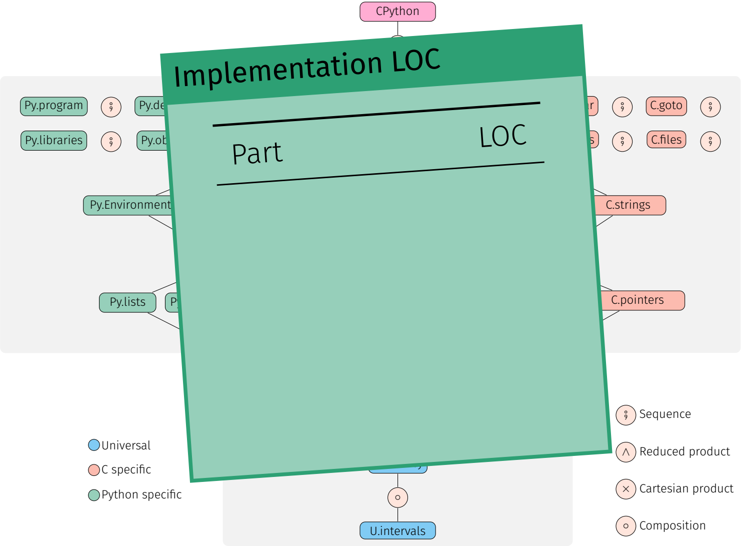
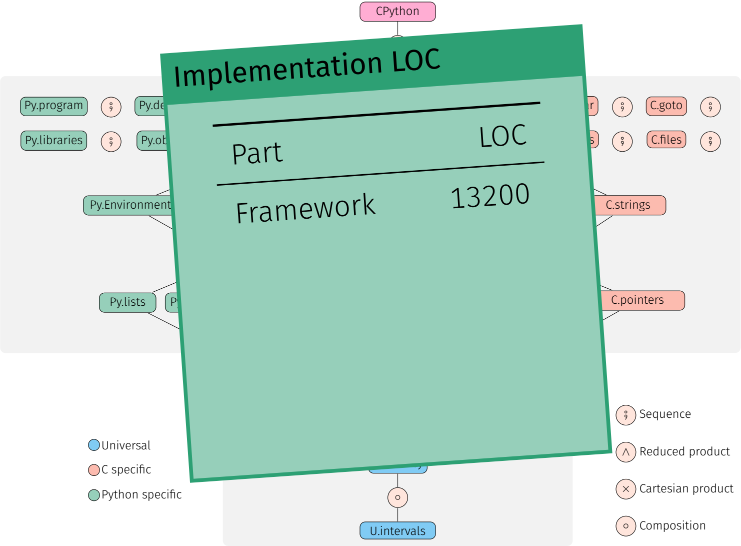


Implementation LOC

Part	LOC

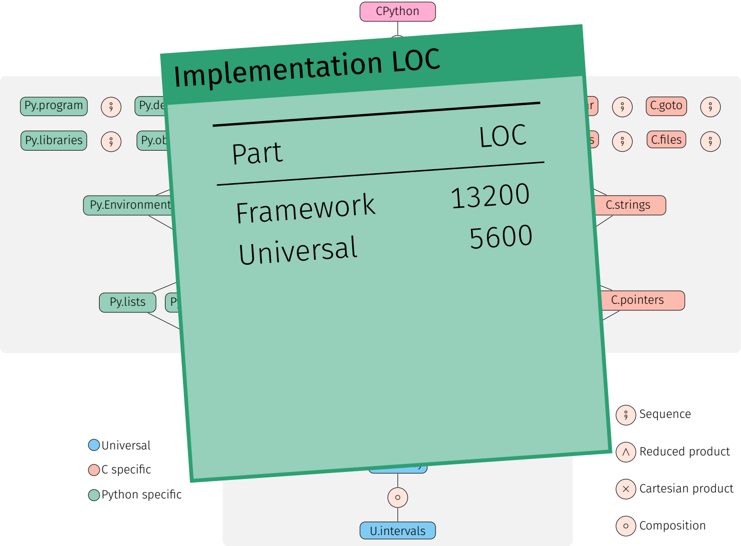
… to a multilanguage analysis!



Implementation LOC

Part	LOC
Framework	13200

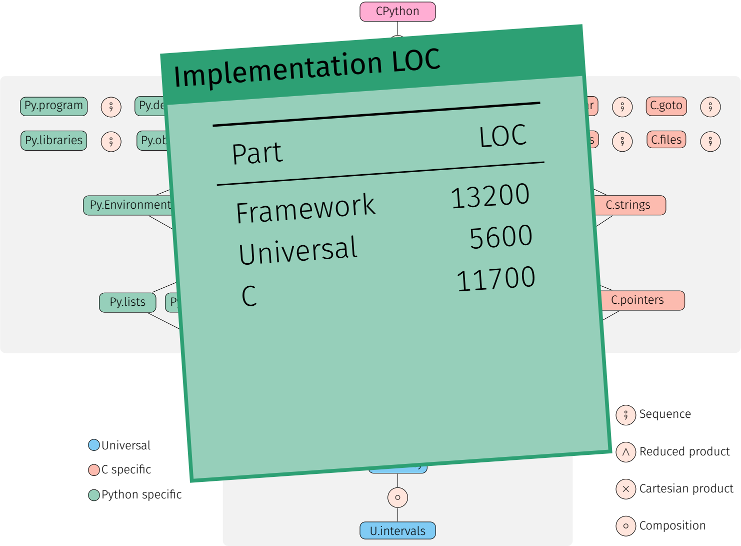
... to a multilanguage analysis!



Implementation LOC

Part	LOC
Framework	13200
Universal	5600

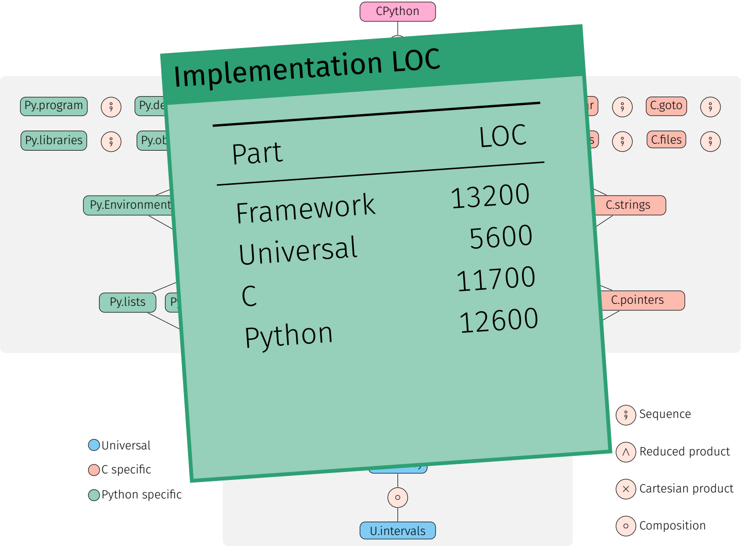
… to a multilanguage analysis!



Implementation LOC

Part	LOC
Framework	13200
Universal	5600
C	11700

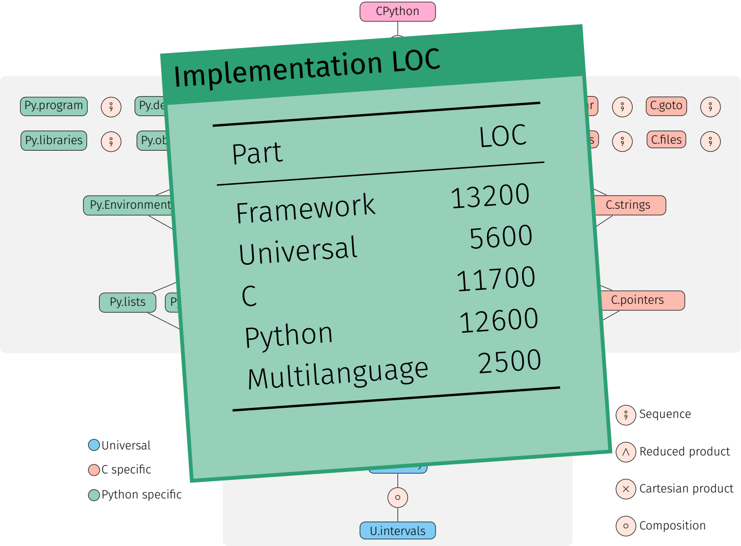
... to a multilanguage analysis!



Implementation LOC

Part	LOC
Framework	13200
Universal	5600
C	11700
Python	12600

… to a multilanguage analysis!



Implementation LOC

Part	LOC
Framework	13200
Universal	5600
C	11700
Python	12600
Multilanguage	2500

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	$\lvert C \rvert$	$\lvert Py \rvert$	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[11] boundary functions as value conversions between two languages.
- Buro, Crole, and Mastroeni[12] generic framework for combining analyses of different languages.

[11] Matthews and Findler. "Operational semantics for multi-language programs". 2009.
[12] 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[13]
- Type inference of Java objects in C code[14]
- Extraction of C callbacks to Java[15]

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

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

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

[15] 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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- Executable semantics of Python
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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

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

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Our results

- Type analysis[16],
- Numeric value analysis & new sensitivities for the recency abstraction[17]
- Relational value analysis with packing (manuscript)
- Scale to small, real-world benchmarks

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Contribution: multilanguage Python/C analysis

Difficulties

- Concrete semantics
- Memory interaction

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Previous works

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- No detection of runtime errors in C

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

Formalizing complex semantics

Use a concrete semantics framework such as

- Skeletal semantics
- Interaction trees

In order to

- Formalize the concrete semantics of Python
- Automatically generate static analyzers

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Improving the scalability of static analyses

- Incremental analyses
- Variable packing refinment algorithm
- Compositional analyses

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

Questions

xkcd.com/353

Raphaël Monat, Abdelraouf Ouadjaout, Antoine Miné

MTV Seminar
16 February 2022