A Multilanguage Static Analysis of Python/C Programs with Mopsa

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Dagstuhl
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Introduction

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

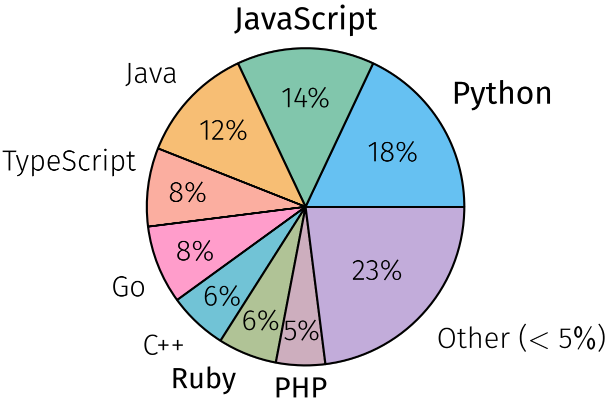
```c
#include <string.h>

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

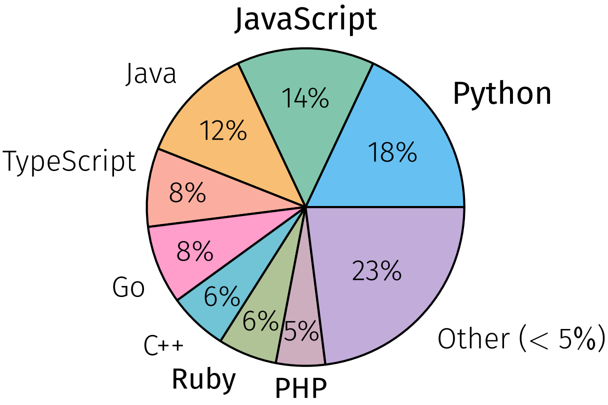
Inference	of program properties such as the absence of run-time errors.
Semantic	based on a formal modelization of the language.
Automatic	no expert knowledge required.
Sound	covers all possible executions.

Dynamic programming languages



Most popular languages on GitHub

Dynamic programming languages



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Features

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

Combining C and Python – motivation

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

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Pitfalls

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Pitfalls

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

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- To bring better performance (numpy)
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Pitfalls

- Different values ($\mathbb{Z}$ vs. `Int32`)
- Shared memory state

Outline

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("...")
    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, Cassels, Haahr, Moon, Playford, and Withington. "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`

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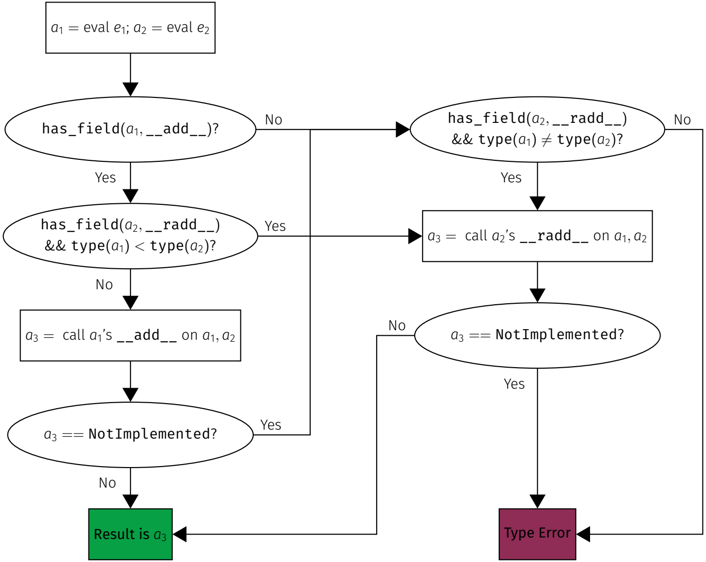
Example Semantics – binary operators



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(f"{x} + {y} = {x + y}")
  return x + y
c = 2 |padd| 3
```

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

Overview of our value analysis for Python

Goal

Detect runtime errors: uncaught raised exceptions

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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

Mopsa

A program analysis 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**,

Environment abstraction

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

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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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$\boldsymbol{\underline{\mathrm{len}}(l) \in [5, 10]}$ $\quad \boldsymbol{i \in [0, 10]}$

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Numeric abstraction (polyhedra)

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

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

A program analysis 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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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

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

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

Numeric abstraction (polyhedra)

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

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

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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

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

Conclusion

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

…)

$[\ldots, +\infty)$

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Modular **O**pen **P**latform for **S**tatic **A**nalysis[1]

`gitlab.com/mopsa/mopsa-analyzer`

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- One AST to analyze them all
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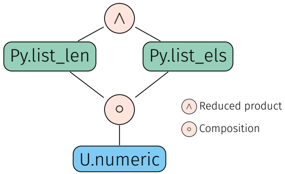

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Dynamic, semantic iterators with delegation

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

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for(init; cond; incr) body
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↓

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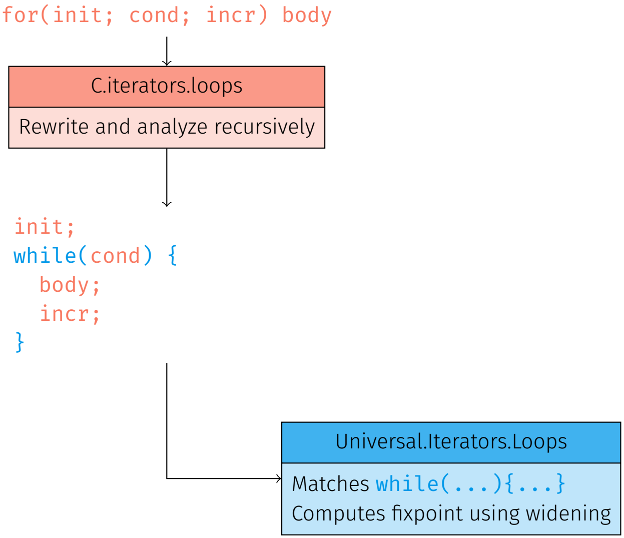

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Python.Desugar.Loops

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- Optimize for some semantic cases

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Python.Desugar.Loops

- Rewrite and analyze recursively
- Optimize for some <u>semantic</u> cases

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

Universal.Iterators.Loops

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Expression rewriting

$\mathbb{S}^{\#}_{env}[\![\, m = m + l[i].weight \,]\!]^{\#}_{env}\sigma^{\sharp}$

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$\mathbb{S}^{\#}_{env}\llbracket\, m = m + l[i].weight \,\rrbracket^{\#}_{env}\sigma^{\sharp}$

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$\longleftarrow \langle @^{\sharp}_{Task,\mathsf{r}}, \perp\rangle, \sigma^{\sharp}$

$\rightarrow \mathbb{E}^{\#}_{object}[\![\, \mathtt{object.\_\_getattribute\_\_}(l[i], "weight") \,]\!]\sigma^{\sharp}$

$\rightarrow \mathbb{E}^{\#}_{heap}[\![\, get\_field(l[i], "weight") \,]\!]\sigma^{\sharp}$

$\rightarrow \mathbb{E}^{\#}_{env}[\![\, l[i] \cdot weight \,]\!]\sigma^{\sharp}$

$\longleftarrow \langle @^{\sharp}_{\mathtt{int}^{\sharp}}, \underline{\mathrm{int}}(\underline{@^{\sharp}_{Task,\mathsf{r}} \cdot weight})\rangle, \sigma^{\sharp}$

Towards a Multilanguage Analysis

Multilanguage code – example

counter.c

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

static PyObject*
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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)
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

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- $\texttt{power} = 31 \Rightarrow \texttt{r} = -2^{31}$
- $32 \leq \texttt{power} \leq 64$: 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

```python
class Counter:
  def __init__(self): ...
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- Typeshed: type annotations for the standard library, used in previous work: Monat, Ouadjaout, and Miné. "Static Type Analysis by Abstract Interpretation of Python Programs". ECOOP 2020.

How to analyze multilanguage programs?

Type annotations

Rewrite into Python code

```
class Counter:
  def __init__(self):
    self.count = 0
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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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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

High-level idea

Difficulty: shared memory

- Two distinct visions of a shared state
- Synchronization? We could perform a full state translation, but
  - the cost would be high in the analysis
  - <u>some</u> abstractions can be shared between Python and C

High-level idea

Difficulty: shared memory

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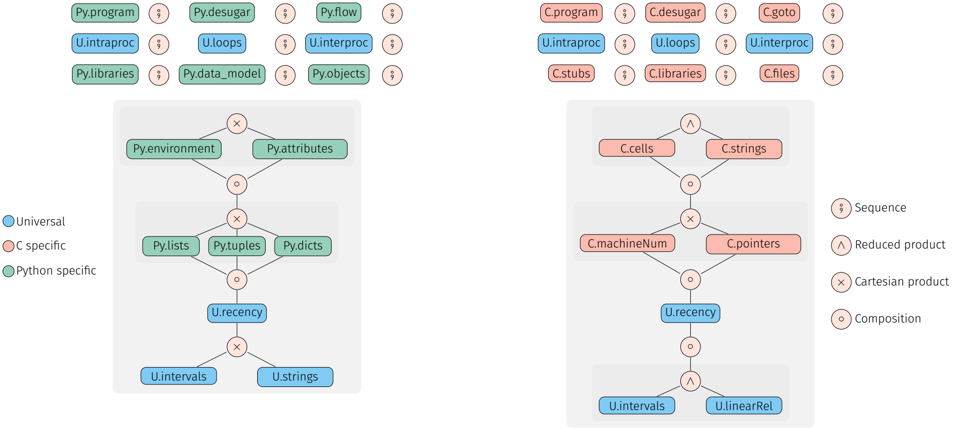
State separation $\leadsto$ reduced synchronization

- Observation: structures are directly dereferenceable by one language only
- Switch to other language otherwise (`c.incr()` $\leadsto$ `self->count += 1`)

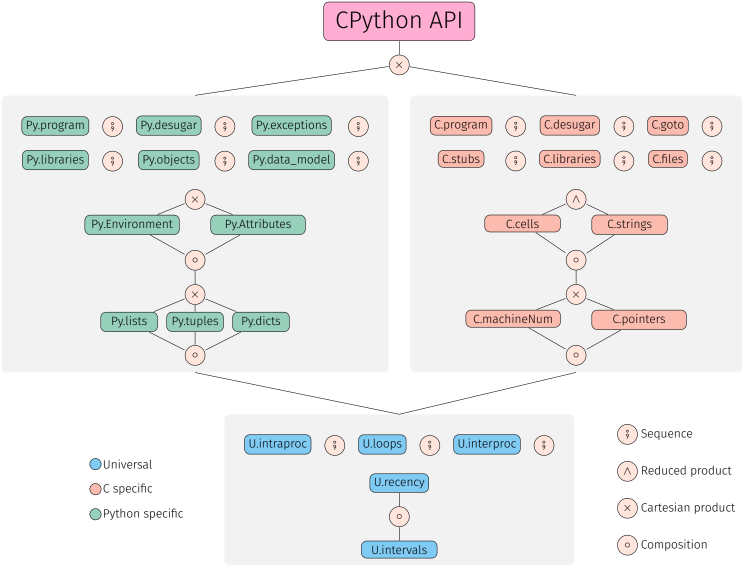
  Additional hypothesis: C accesses to Python objects through the API
- Synchronization: only when objects change language for the first time

Implementation & Experimental Evaluation

From distinct Python and C analyses...



... to a multilanguage analysis!



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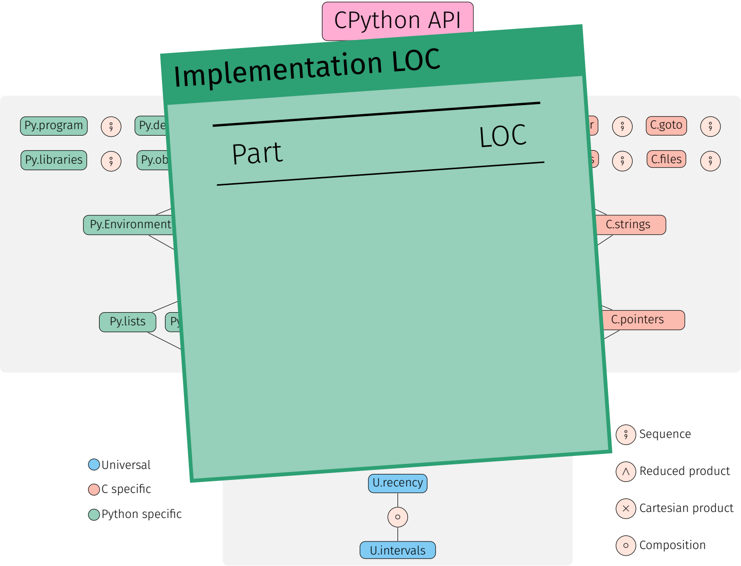


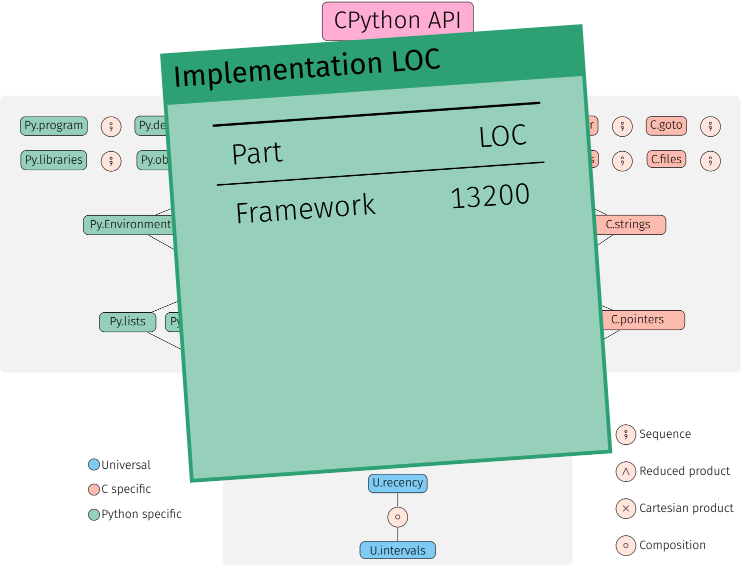
Implementation LOC

Part	LOC

... to a multilanguage analysis!

Implementation LOC

Part	LOC
Framework	13200



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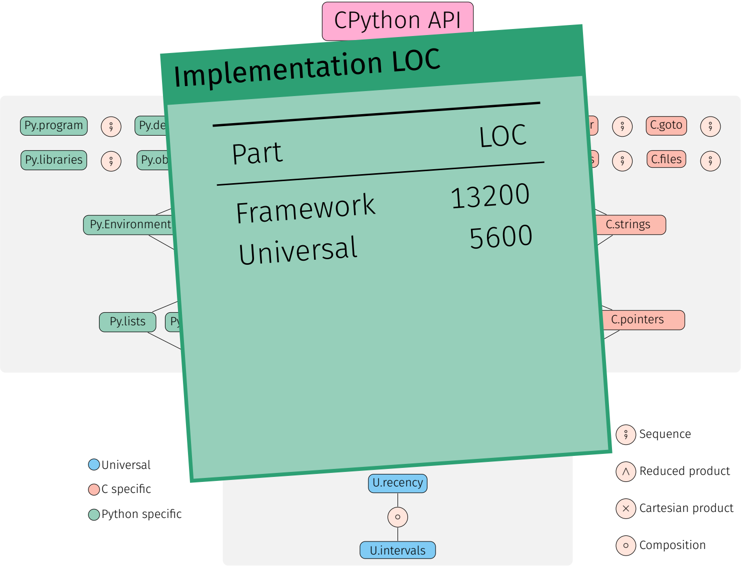

Implementation LOC

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Universal	5600

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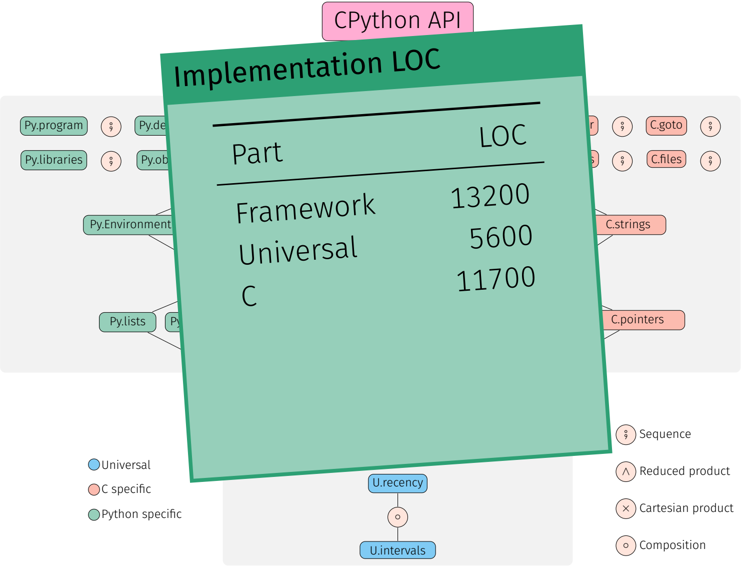

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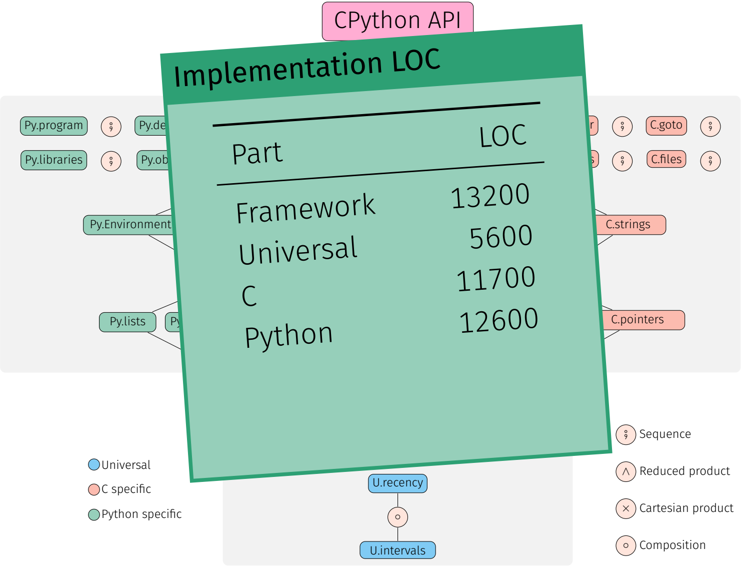

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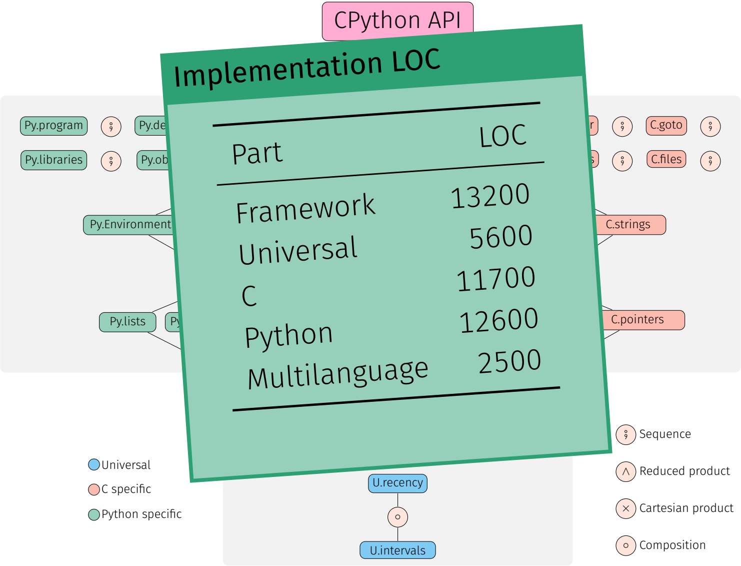

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Universal	5600
C	11700
Python	12600
Multilanguage	2500

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	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

Conclusion

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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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Previous works

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- No detection of runtime errors in C

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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

A Multilanguage Static Analysis of Python/C Programs with Mopsa

Questions

Raphaël Monat, Abdelraouf Ouadjaout, Antoine Miné

Dagstuhl
11 July 2023