A Multilanguage Static Analysis of Python/C Programs with Mopsa

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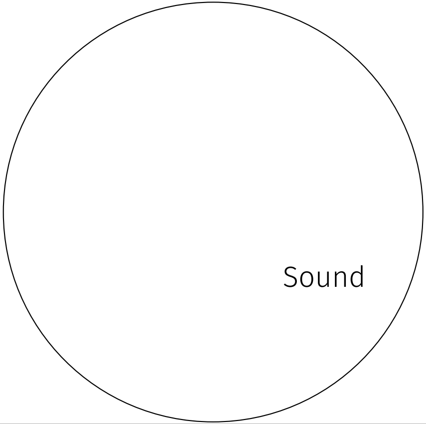
7 July 2022

rmonat.fr

Introduction

Program verification



All true errors
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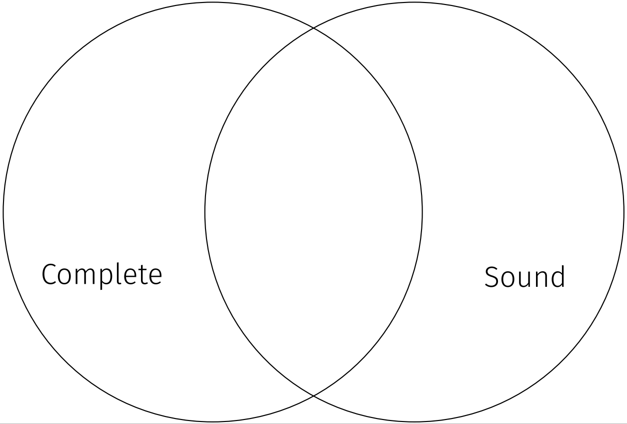
Program verification

All reported errors are true errors



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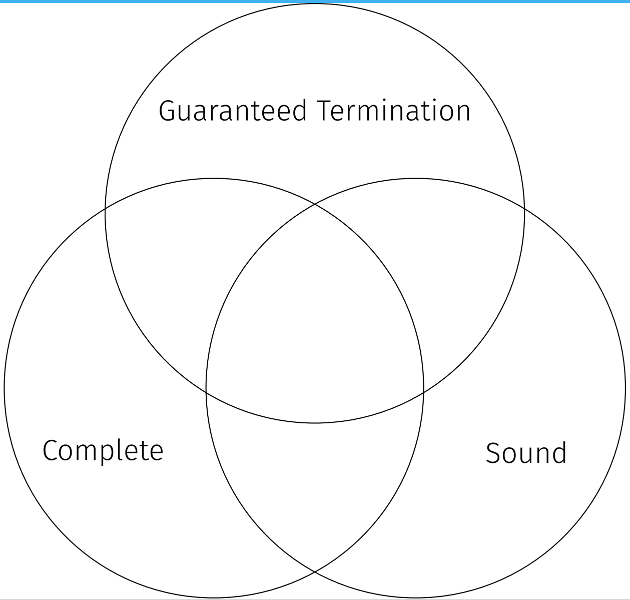

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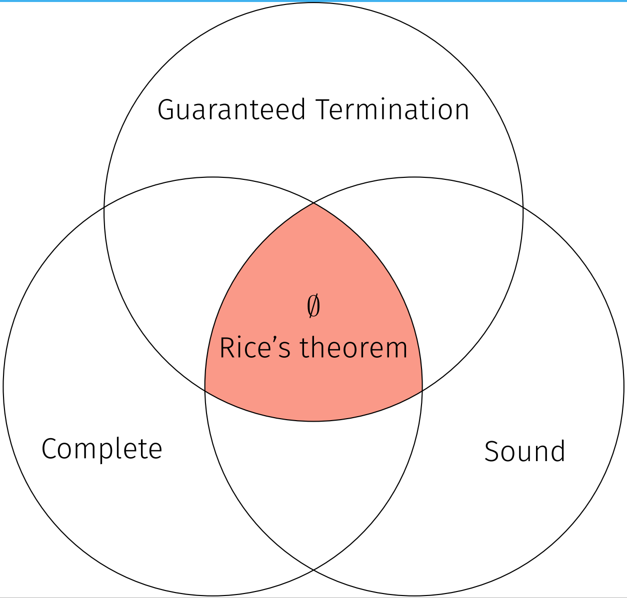

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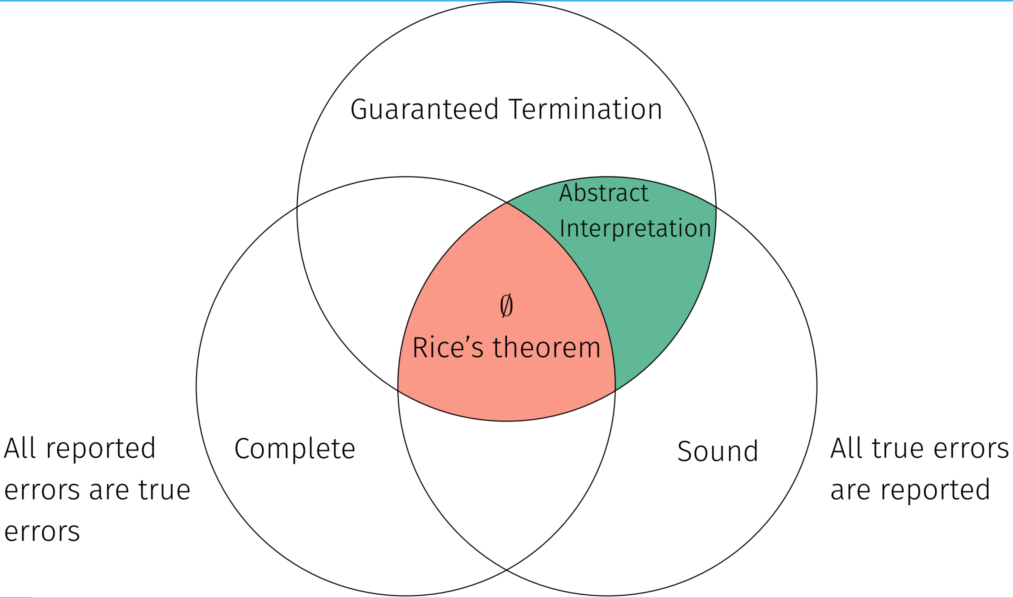


Conservative static program analysis

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

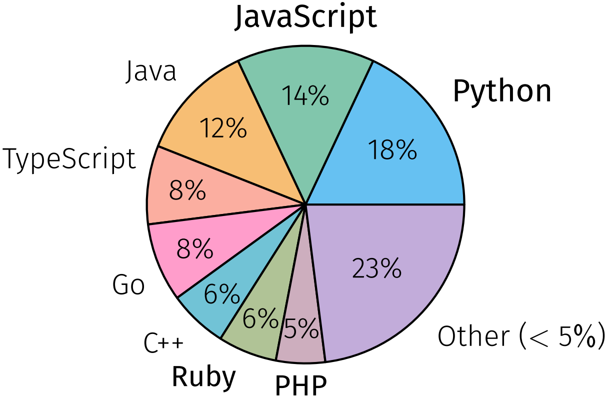
Inference of program properties such as the absence of run-time errors.

Semantic based on a formal modelization of the language.

Automatic no expert knowledge required.

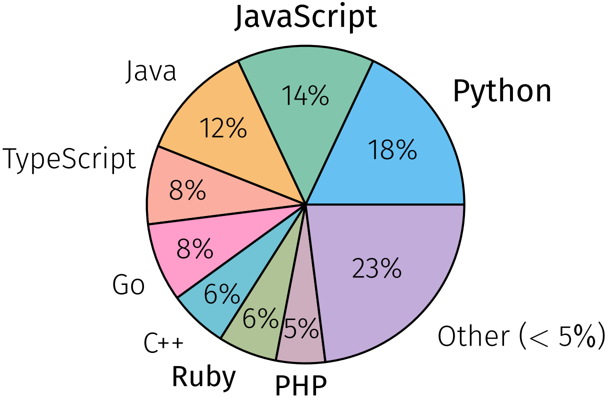
Sound covers all possible executions.

Dynamic programming languages



Most popular languages on GitHub

Dynamic programming languages



Most popular languages on GitHub

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

- 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

1 Introduction

2 A Taste of Python

3 Mopsa

4 Towards a Multilanguage Semantics

5 Implementation & Experimental Evaluation

6 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("...")
    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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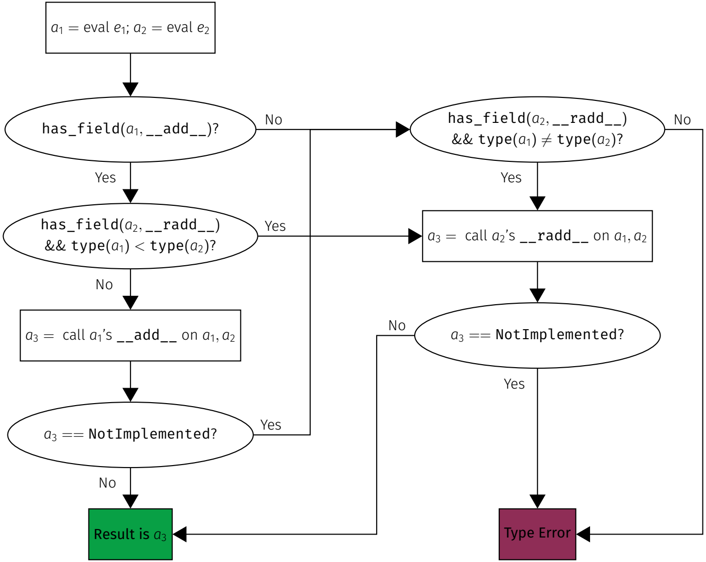
Example Semantics – binary operators



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/`

Mopsa

A program analysis workflow

Averaging numbers

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

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

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8  l = [randint(0, 20)
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Proved safe?

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

Searching for a loop invariant (l. 4)

Environment abstraction

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

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Stateless domains: **list content**,

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Numeric abstraction (intervals)

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

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

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Numeric abstraction (polyhedra)

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

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

A program analysis workflow

Averaging tasks

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

Proved safe?

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

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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)

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

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Attributes abstraction

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

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Conclusion

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

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

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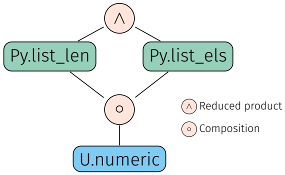

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Dynamic, semantic iterators with delegation

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

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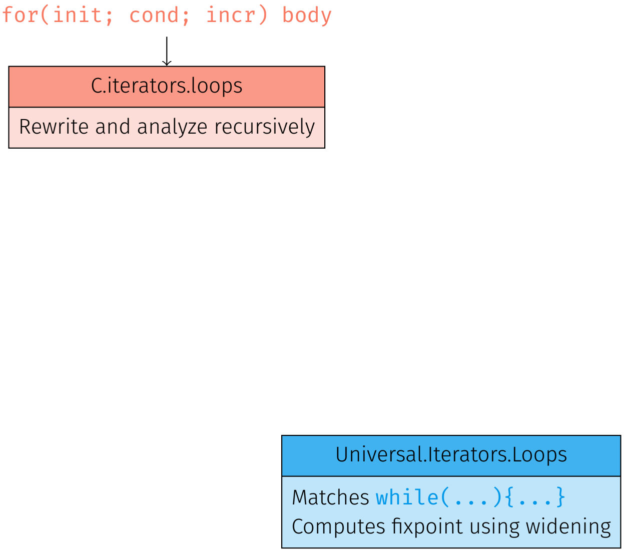

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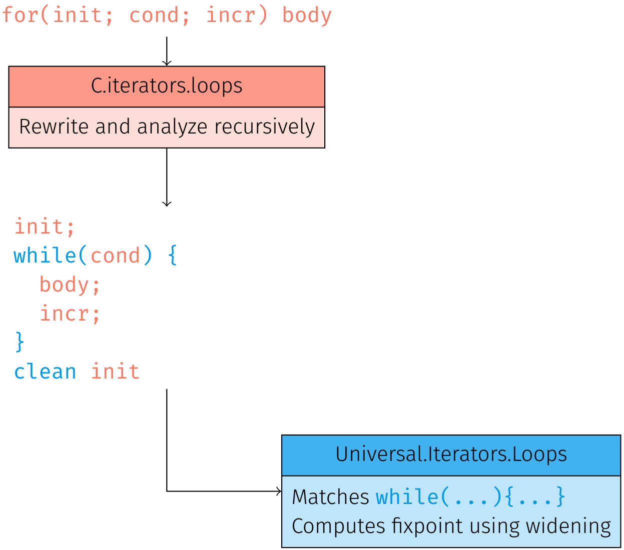

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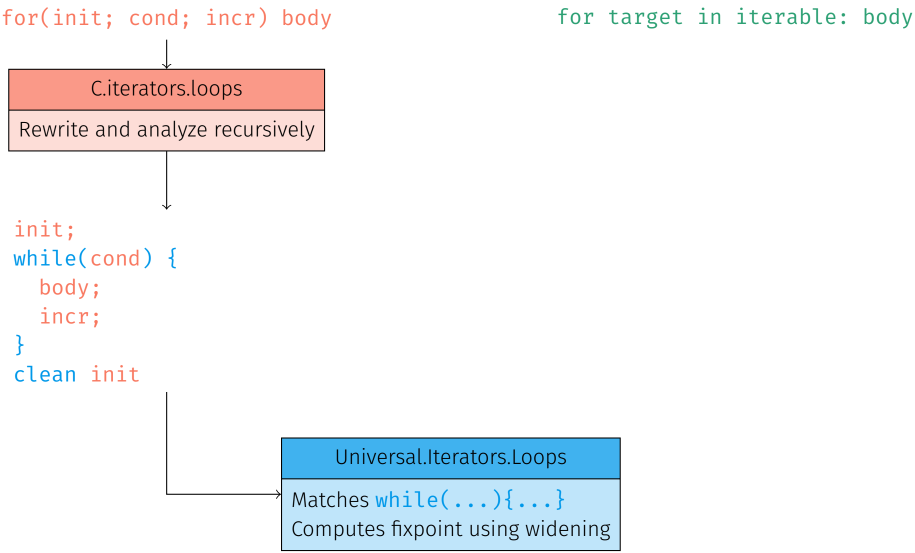

Dynamic, semantic iterators with delegation

```
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

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

Python.Desugar.Loops

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

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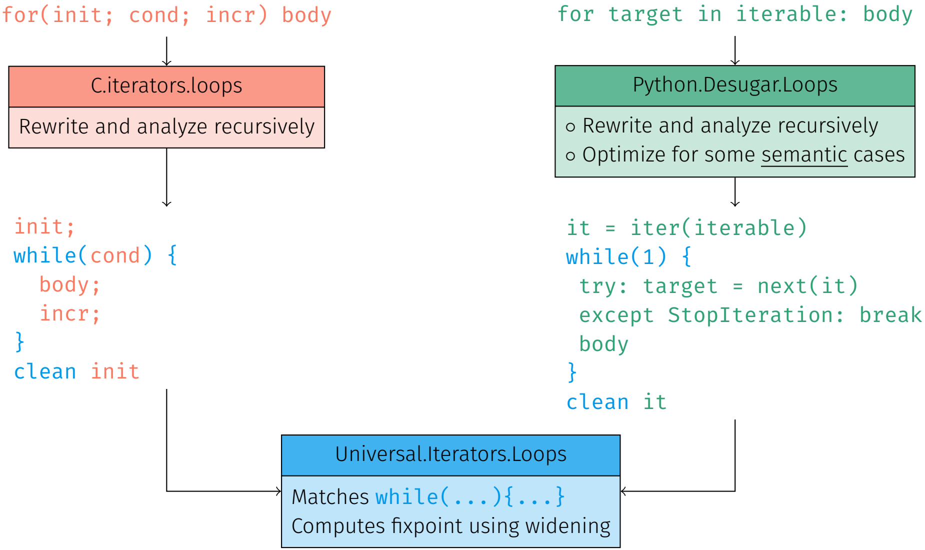

Towards a Multilanguage Semantics

Multilanguage code – example

counter.c

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    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);
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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)
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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

Multilanguage code – example

counter.c

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

static PyObject*
CounterIncr(Counter *self, PyObject *args)
{
    int i = 1;
    if(!PyArg_ParseTuple(args, "|i", &i))
        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

```python
class Counter:
  def __init__(self): ...
  def incr(self, i: int = 1): ...
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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

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

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

How to analyze multilanguage programs?

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Rewrite into Python code

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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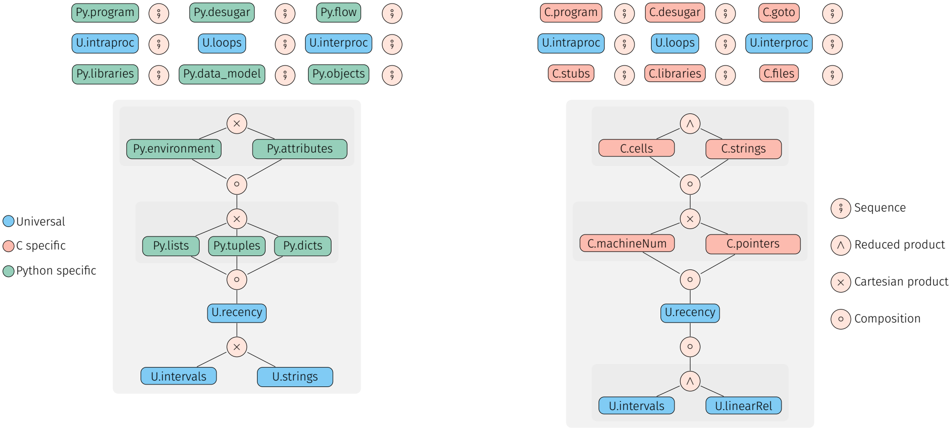
State separation $\rightsquigarrow$ reduced synchronization

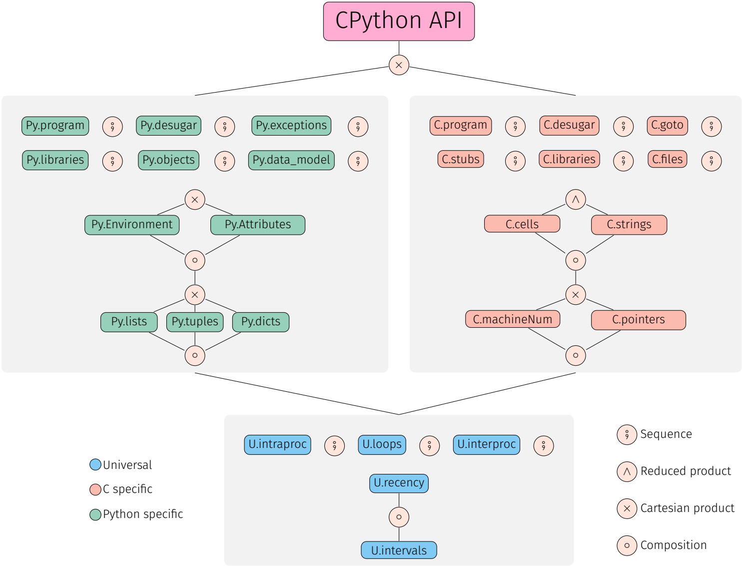
- Observation: structures are directly dereferenceable by one language only
- Switch to other language otherwise (`c.incr()` $\rightsquigarrow$ `self->count += 1`)
  Additional hypothesis: C accesses to Python objects through the API
- Synchronization: only when objects change language for the first time

Implementation & Experimental Evaluation

From distinct Python and C analyses...



... to a multilanguage analysis!



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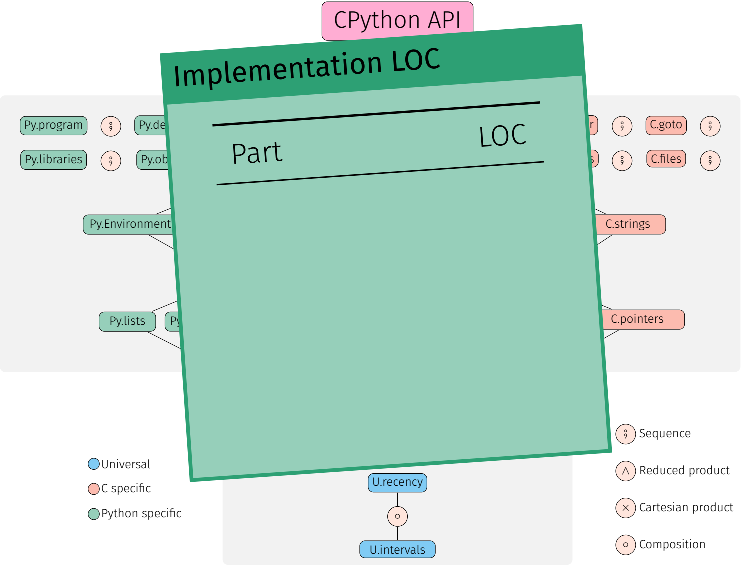

Implementation LOC

Part	LOC

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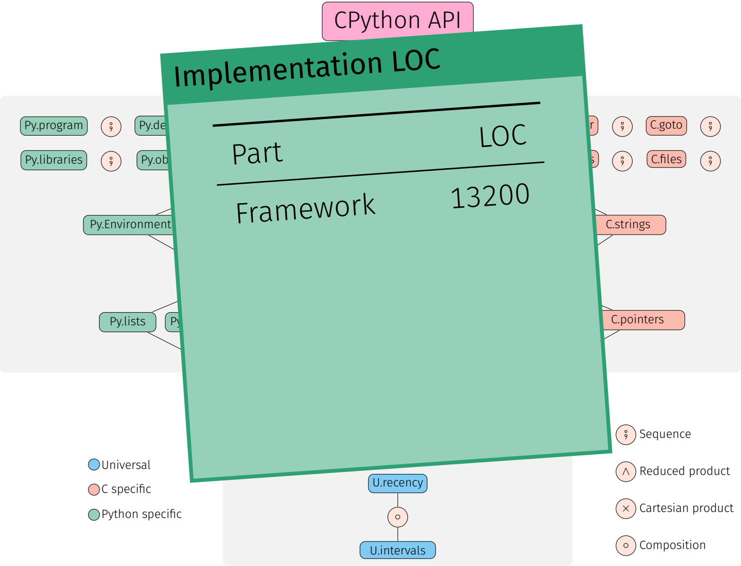
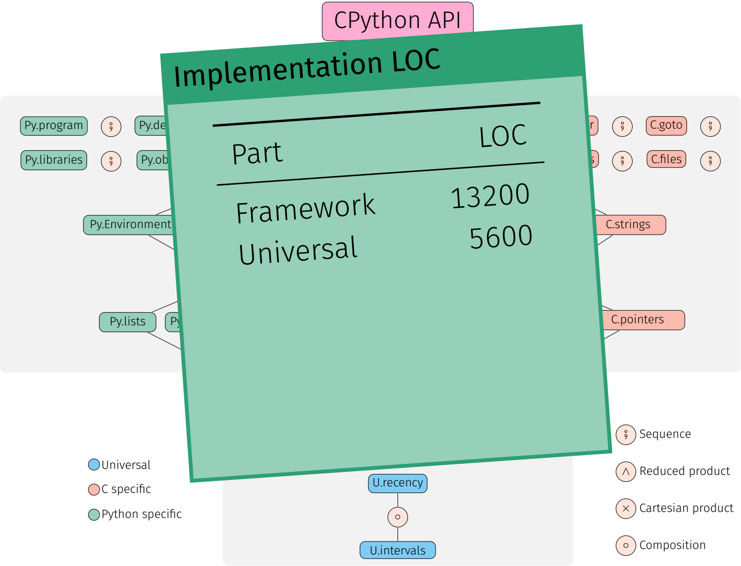


Implementation LOC

Part	LOC
Framework	13200

… to a multilanguage analysis!



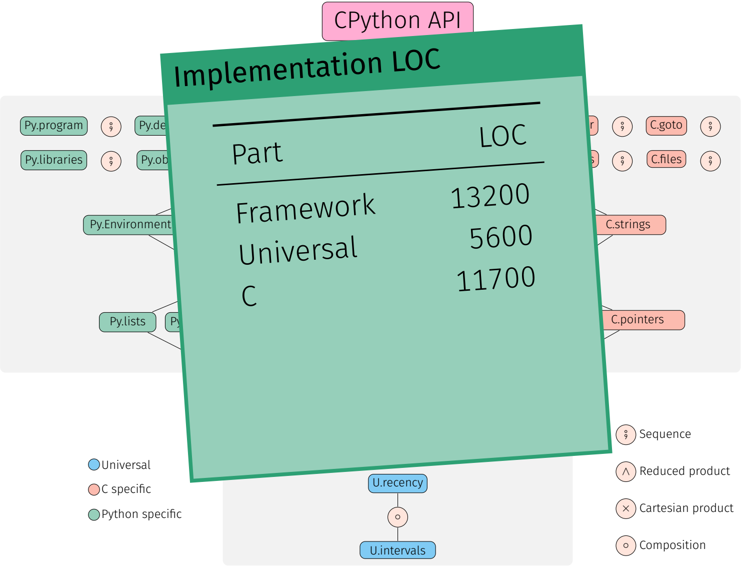
Implementation LOC

Part	LOC
Framework	13200
Universal	5600

... to a multilanguage analysis!

Implementation LOC

Part	LOC
Framework	13200
Universal	5600
C	11700



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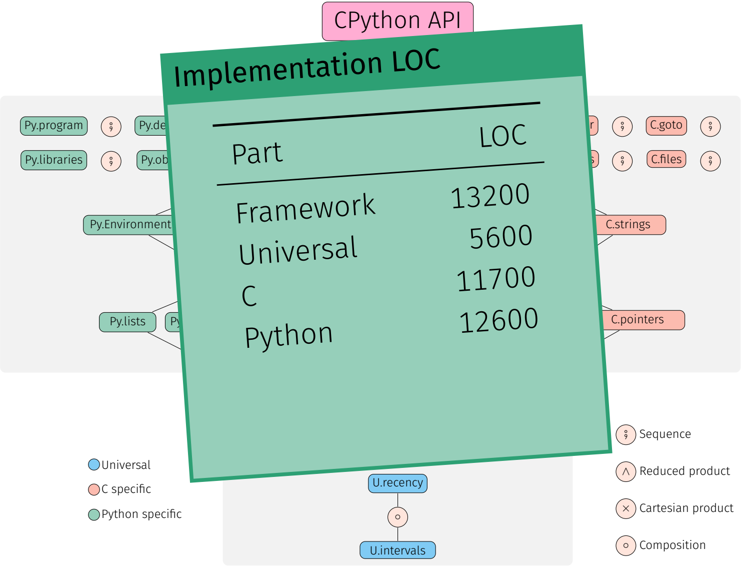

Implementation LOC

Part	LOC
Framework	13200
Universal	5600
C	11700
Python	12600

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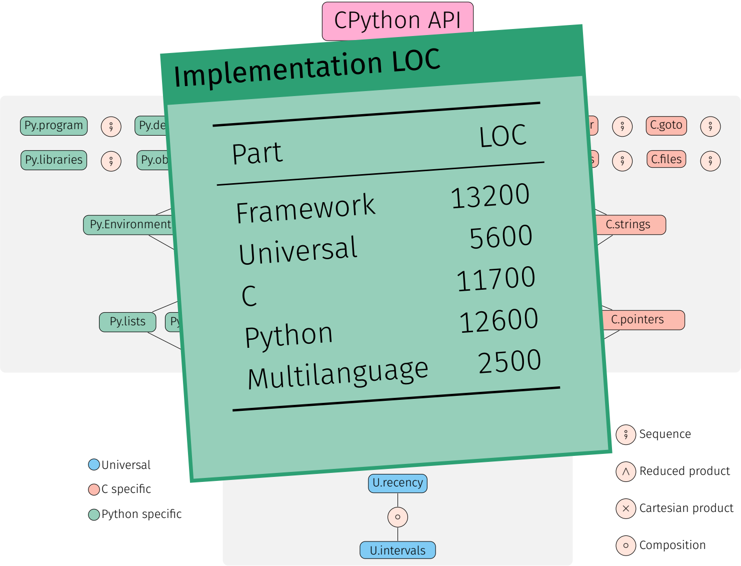

Implementation LOC

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	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

- Type/exceptions analyses for the JNI
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Previous works

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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)

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Future work

I'll be a permanent researcher at Inria Lille from September 2022

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- Make static analysis more user-friendly
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$\rightsquigarrow$ I would be glad to set up new collaborations!

A Multilanguage Static Analysis of Python/C Programs with Mopsa

Questions

Raphaël Monat, Abdelraouf Ouadjaout, Antoine Miné

Software Languages Lab, VUB
7 July 2022

rmonat.fr

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