A Multilanguage Static Analysis of Python/C Programs with Mopsa

Raphaël Monat, Abdelraouf Ouadjaout, Antoine Miné

Facebook TAV
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rmonat.fr

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 cover all possible executions.

Dynamic programming languages

Growing popularity

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

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- `eval`.

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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())
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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`

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

Outline

Mopsa

A program analysis workflow

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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```

Searching for a loop invariant (l. 4)

Environment abstraction

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

Proved safe?

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

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Stateless domains: **list content**,

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Numeric abstraction (intervals)

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

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

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

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

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Numeric abstraction (polyhedra)

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

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

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))]
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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

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

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

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Attributes abstraction

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

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Stateless domains: list content, list length

Environment abstraction

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

Conclusion

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

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

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

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Modular **O**pen **P**latform for **S**tatic **A**nalysis[2]

`gitlab.com/mopsa/mopsa-analyzer`

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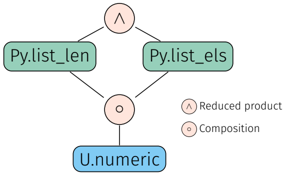

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Dynamic, semantic iterators with delegation

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

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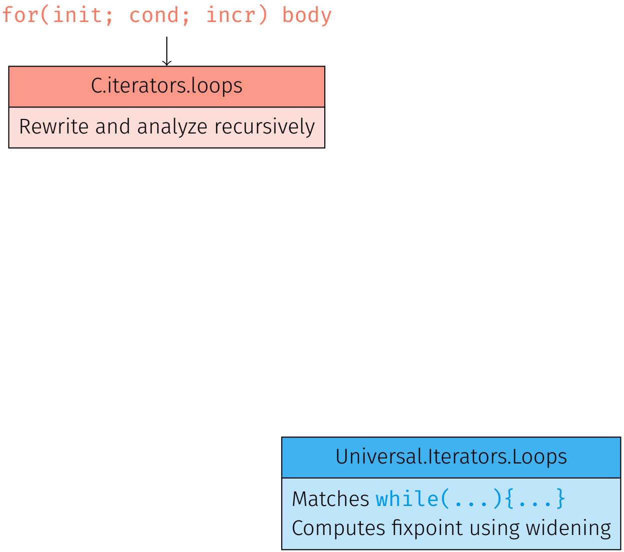

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C.iterators.loops

Rewrite and analyze recursively

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

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for(init; cond; incr) body
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```
for target in iterable: body
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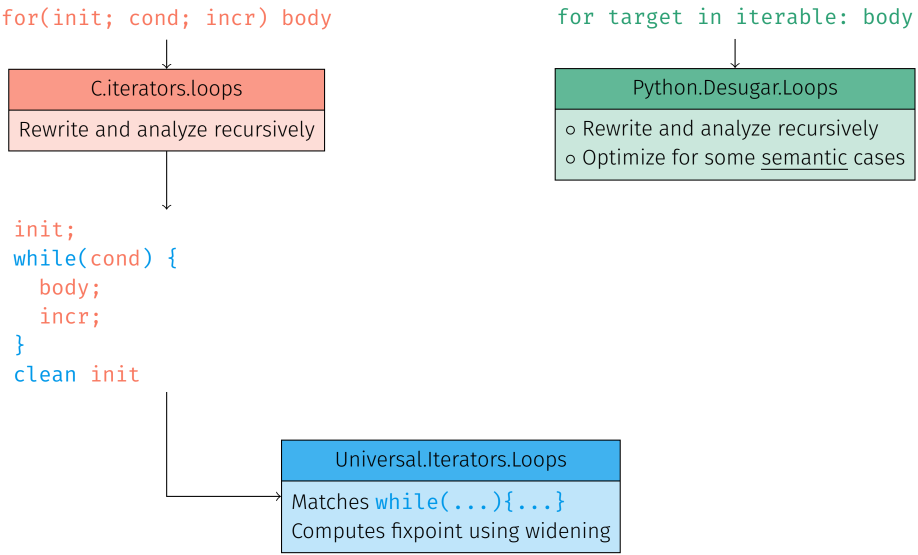

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Python.Desugar.Loops

- 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, target
```

Universal.Iterators.Loops

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

A Concrete Example

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;
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static PyObject*
CounterGet(Counter *self)
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    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)
c.incr()
r = c.get()
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- $32 \leq \texttt{power} \leq 64$: 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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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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Type annotations

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- Some effects can't be written in pure Python (e.g., read-only attributes)

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- Switch from one language to the other just as the program does

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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

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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()
```

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
```

Concrete Multilanguage Semantics

Multilanguage semantics

Concrete definition

- Builds upon the Python and C semantics

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- Defines the API: calls between languages, value conversions

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Limitations

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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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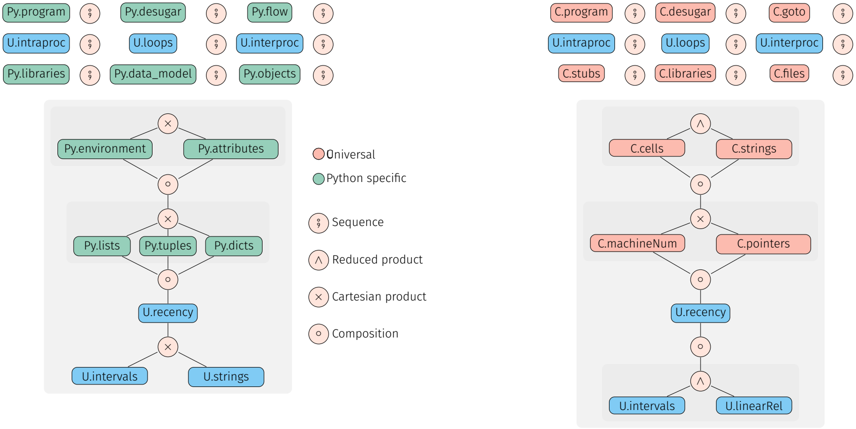
- Boundary functions when objects switch views for the first time

Limitations

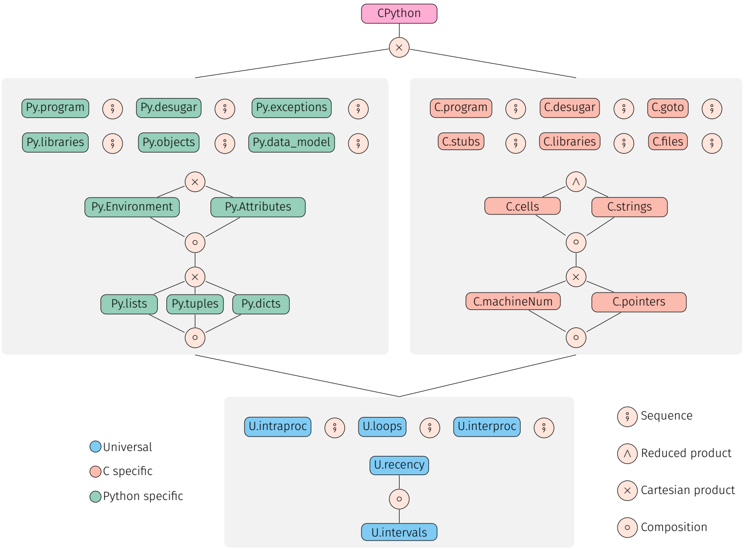
- Garbage collection not handled
- C access to Python objects only through the API (verified by Mopsa)
- Manual modelization from CPython's source code

Implementation & Experimental Evaluation

From distinct Python and C analyses...



... to a multilanguage analysis!



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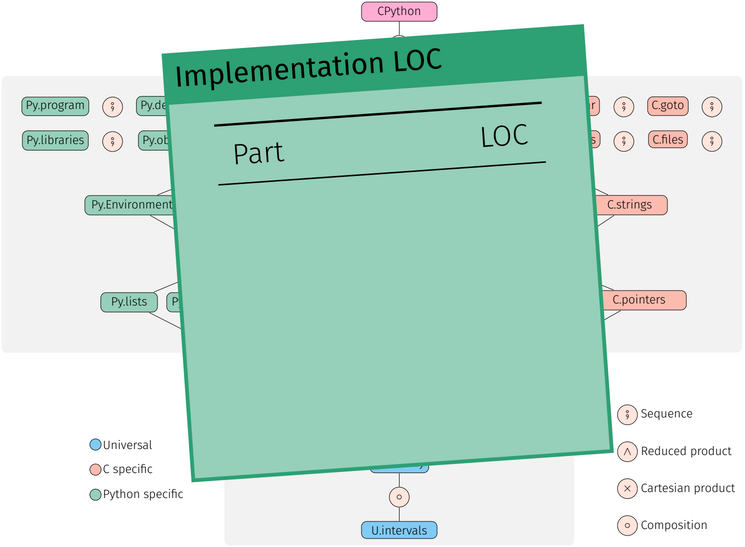
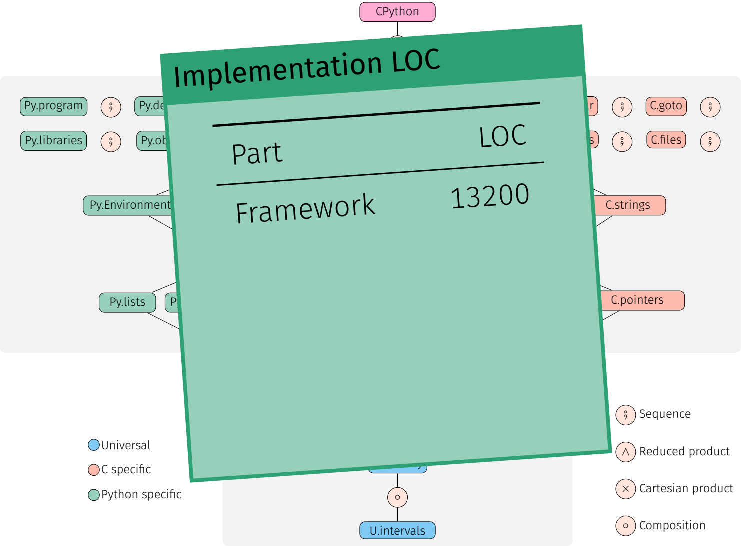


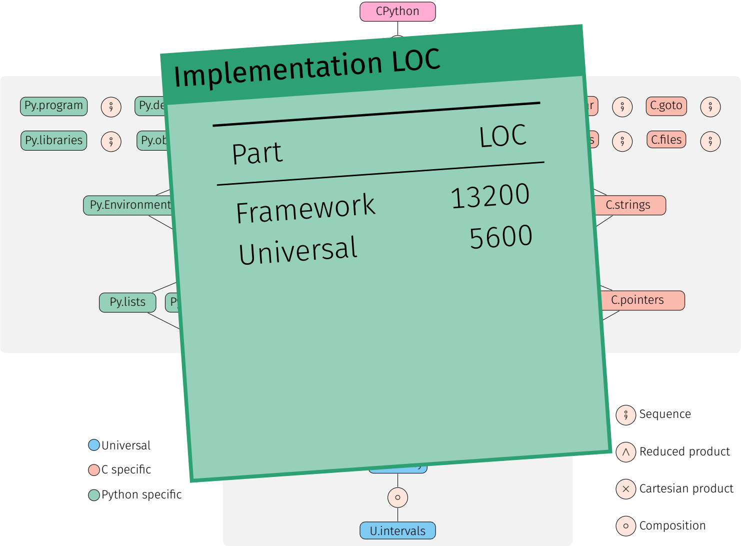
… to a multilanguage analysis!



Implementation LOC

Part	LOC
Framework	13200

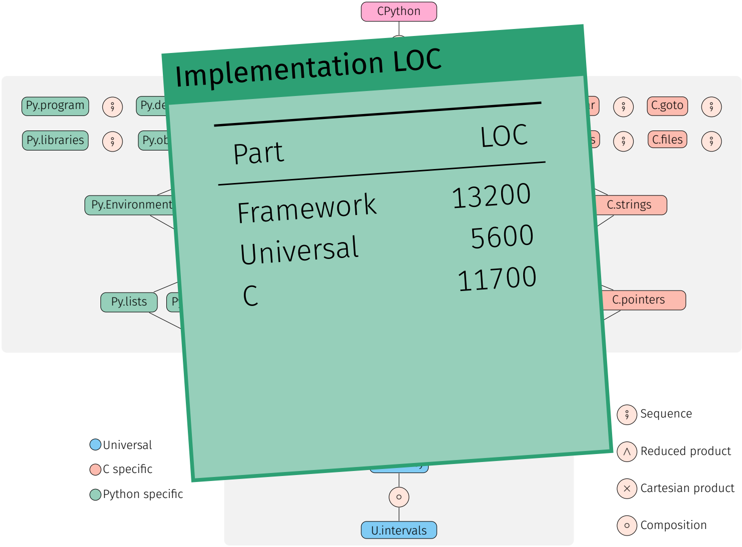
… to a multilanguage analysis!



Implementation LOC

Part	LOC
Framework	13200
Universal	5600

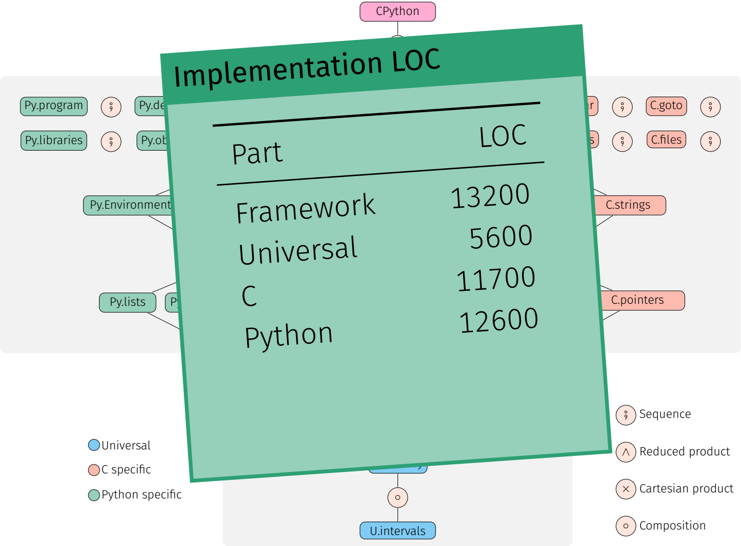
... to a multilanguage analysis!



Implementation LOC

Part	LOC
Framework	13200
Universal	5600
C	11700

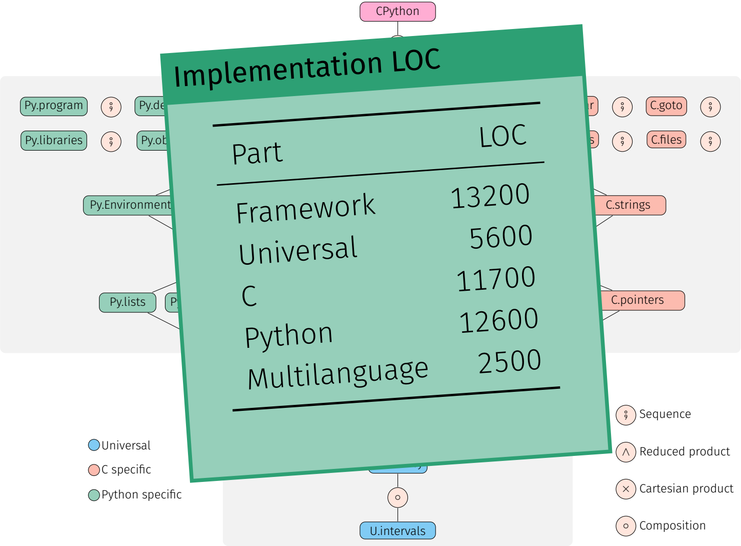
… to a multilanguage analysis!



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	|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

Conclusion

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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Previous works

- Type/exceptions analyses for the JNI
- No detection of runtime errors in C

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- Type/exceptions analyses for the JNI
- No detection of runtime errors in C

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 works

Multilanguage analyses

- Other interoperability frameworks (Cffi, Swig, Cython)
- Bigger applications

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- Other interoperability frameworks (Cffi, Swig, Cython)
- Bigger applications

Library analyses

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

A Multilanguage Static Analysis of Python/C Programs with Mopsa

Looking for

- RA / Postdoc position
- Starting fall 2022
- In the UK or Europe
- `raphael.monat@lip6.fr`

Raphaël Monat, Abdelraouf Ouadjaout, Antoine Miné

Facebook TAV
1 December 2021

rmonat.fr