# A Multilanguage Static Analysis of Python/C Programs with Mopsa

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Sycomores Seminar
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rmonat.fr




# 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.

**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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## New features

- Object orientation,
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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

```
1  class Protected:
2    def __init__(self, priv):
3      self._priv = priv
4    def __getattribute__(self, attr):
5      if attr[0] == "_": raise AttributeError("...")
6      return object.__getattribute__(self, attr)
7
8  a = Protected(42)
9  a._priv # AttributeError raised
```

# Python's specificities (II)

## Dual type system

- Nominal (classes, MRO)

Fspath (from standard library)

```
1  class Path:
2    def __fspath__(self): return 42
3
4  def fspath(p):
5    if isinstance(p, (str, bytes)):
6      return p
7    elif hasattr(p, "__fspath__"):
8      r = p.__fspath__()
9      if isinstance(r, (str, bytes)):
10       return r
11   raise TypeError
12
13 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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## Dual type system

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## Exceptions

Exceptions rather than specific values

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

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**Pitfalls**

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

# Outline

# Mopsa

# A program analysis workflow

Averaging numbers

```
1  def average(l):
2    m = 0
3    for i in range(len(l)):
4      m = m + l[i]
5    m = m // (i + 1)
6    return m
7
8  l = [randint(0, 20)
9    for i in range(randint(5, 10))]
10 m = average(l)
```

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Searching for a loop invariant (l. 4)

**Environment abstraction**

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

Proved safe?

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

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Stateless domains: **list content**,

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

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

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**Numeric abstraction (polyhedra)**

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

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

# A program analysis workflow

Averaging tasks

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1  class Task:
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```

Proved safe?

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Searching for a loop invariant (l. 4)

Stateless domains: list content, list length

## Environment abstraction

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

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

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## Attributes abstraction

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

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**Conclusion**

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

# Overview of Mopsa

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

`gitlab.com/mopsa/mopsa-analyzer`

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

## Modular Open Platform for Static Analysis[2]

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- One AST to analyze them all
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  - Expressiveness
  - Reusability

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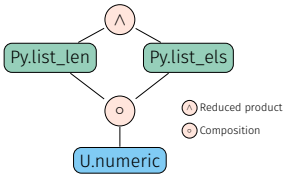


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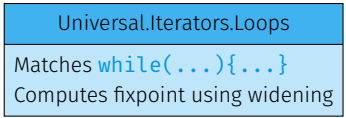

# Dynamic, semantic iterators with delegation

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

| Universal.Iterators.Loops |
| --- |
| Matches `while(...){...}`<br>Computes fixpoint using widening |

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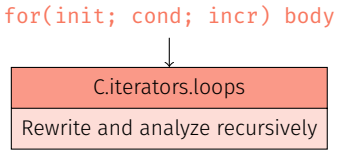


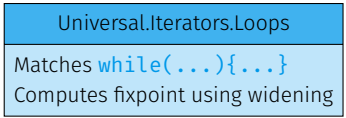

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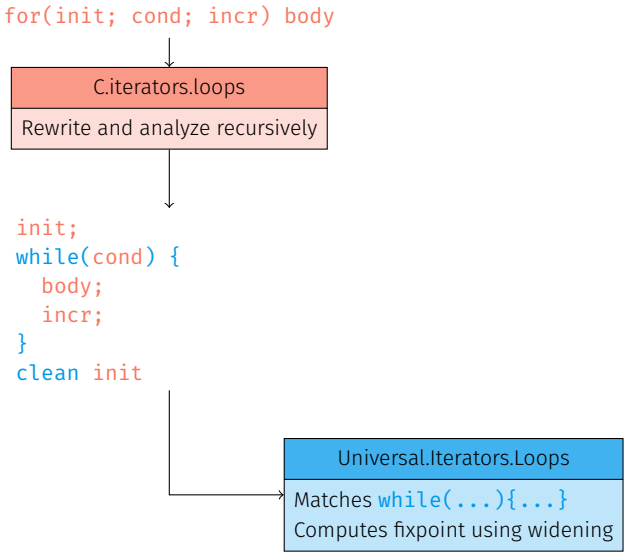

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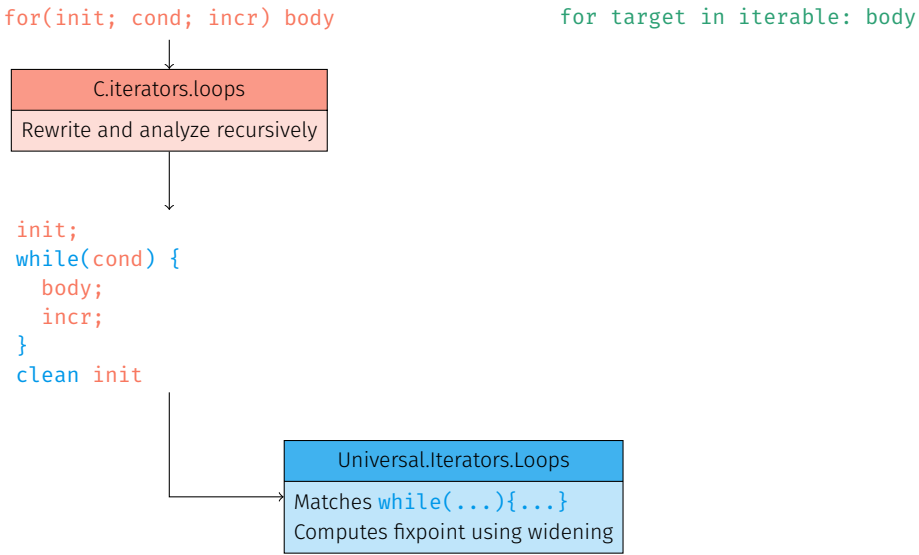

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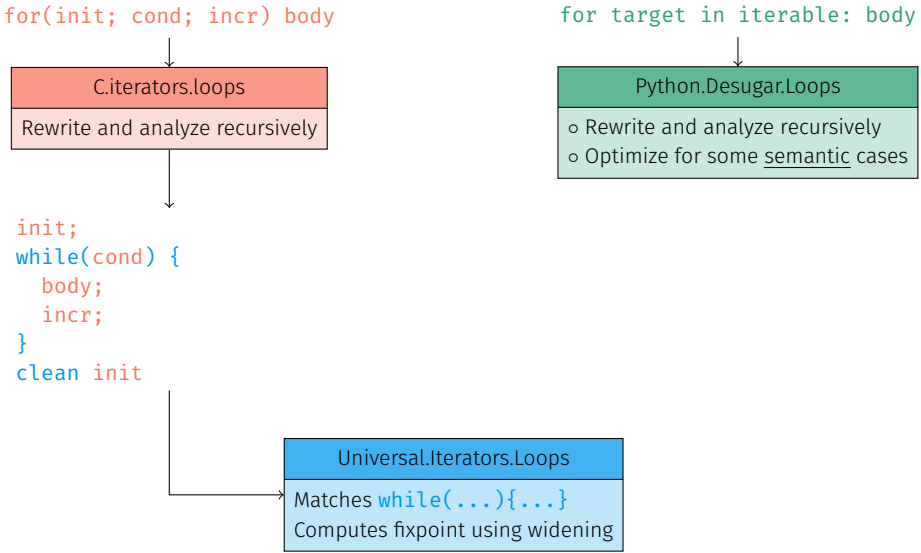

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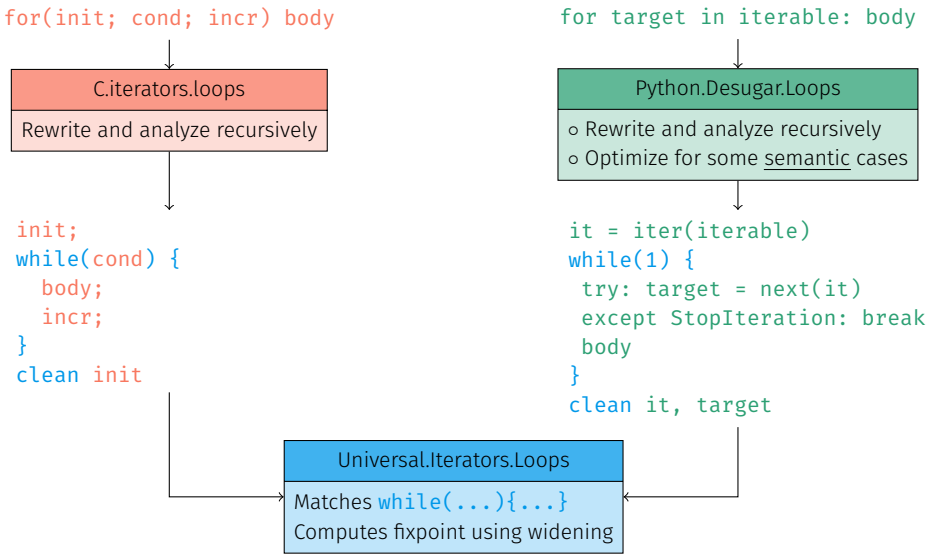

# A Concrete Example

# 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;
}

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)
c.incr()
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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
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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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# How to analyze multilanguage programs?

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- 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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- Reuse previous analyses of C and Python
- Detect runtime errors in Python, in C, and at the boundary

# Analysis result

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()
```

# Analysis result

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from counter import Counter
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⚠ 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

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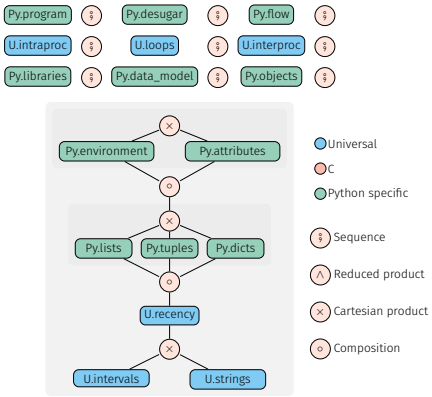
- Boundary functions when objects switch views for the first time

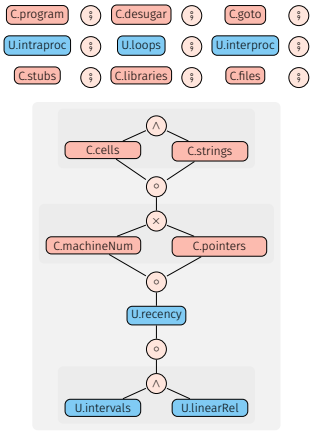
## Limitations

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

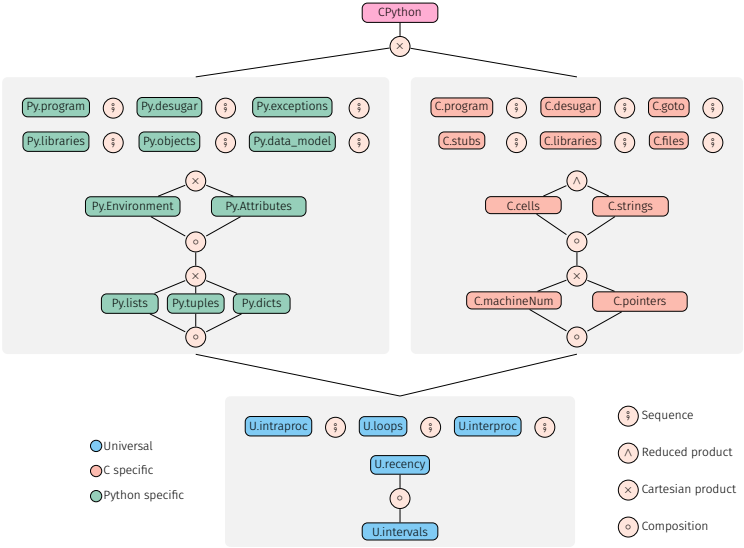
# Implementation & Experimental Evaluation

# From distinct Python and C analyses...



# … to a multilanguage analysis!



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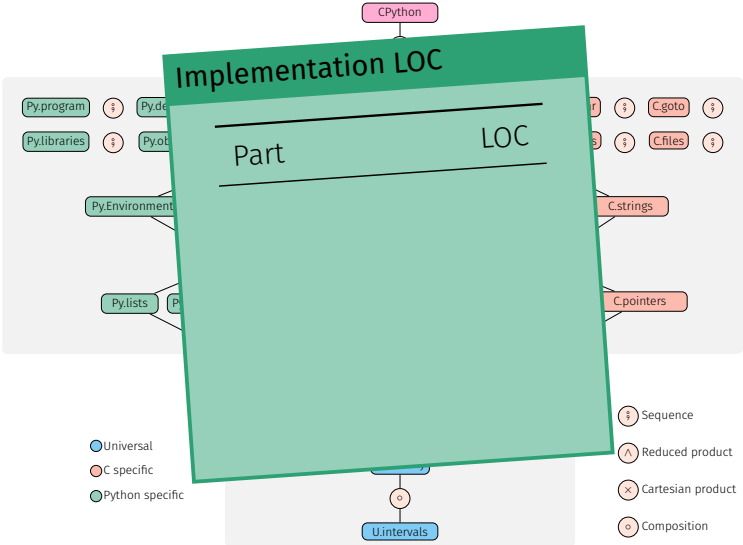

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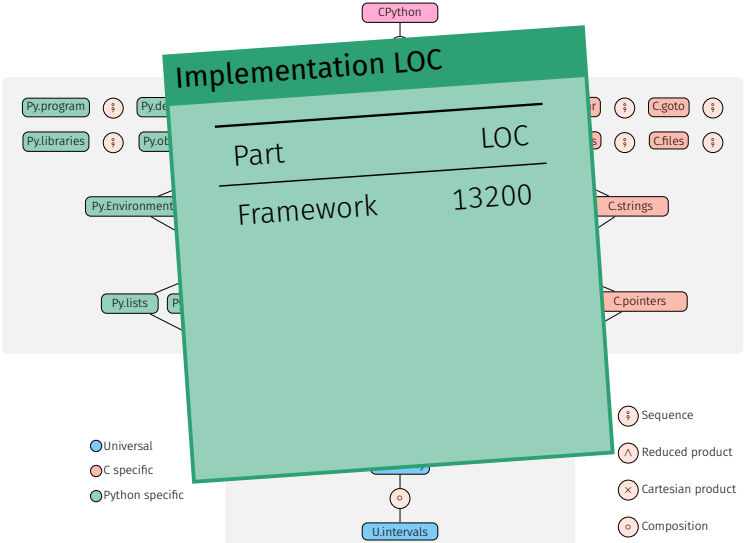
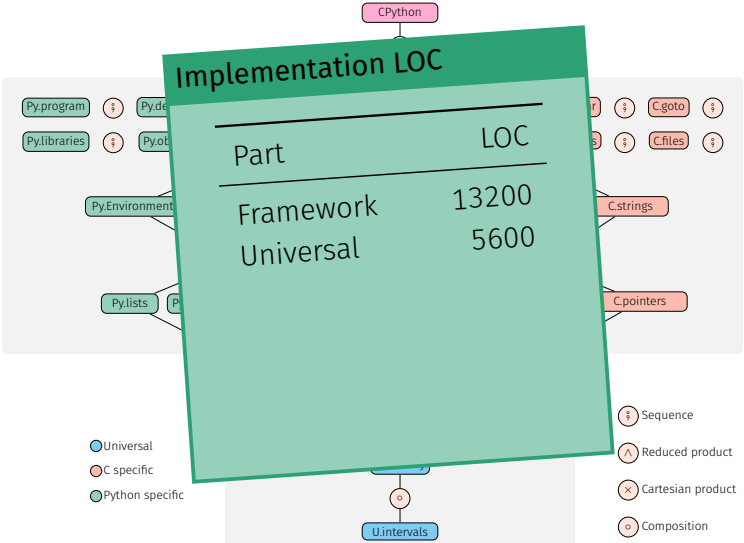



## Implementation LOC

| Part | LOC |
|---|---|
| Framework | 13200 |

# … to a multilanguage analysis!




## Implementation LOC

| Part | LOC |
|---|---|
| Framework | 13200 |
| Universal | 5600 |

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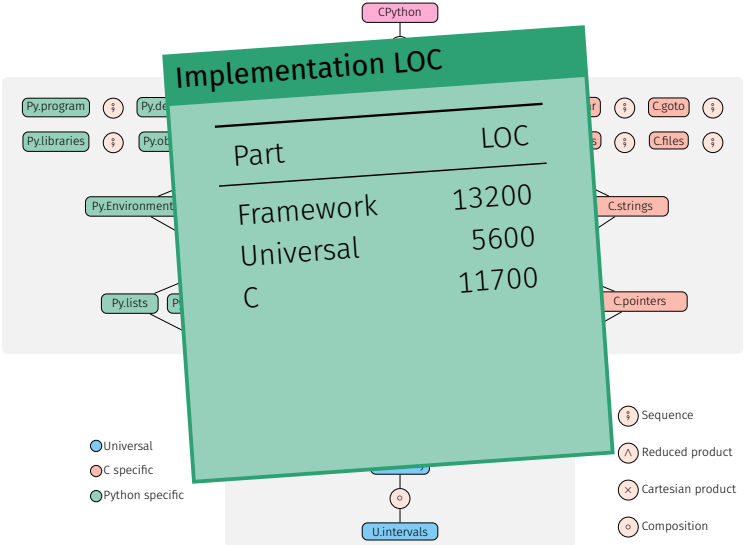


## Implementation LOC

| Part | LOC |
|---|---|
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| Universal | 5600 |
| C | 11700 |

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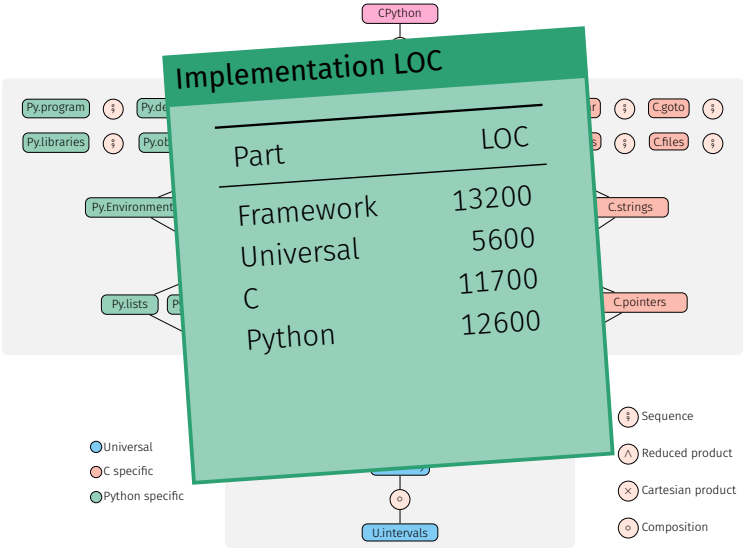


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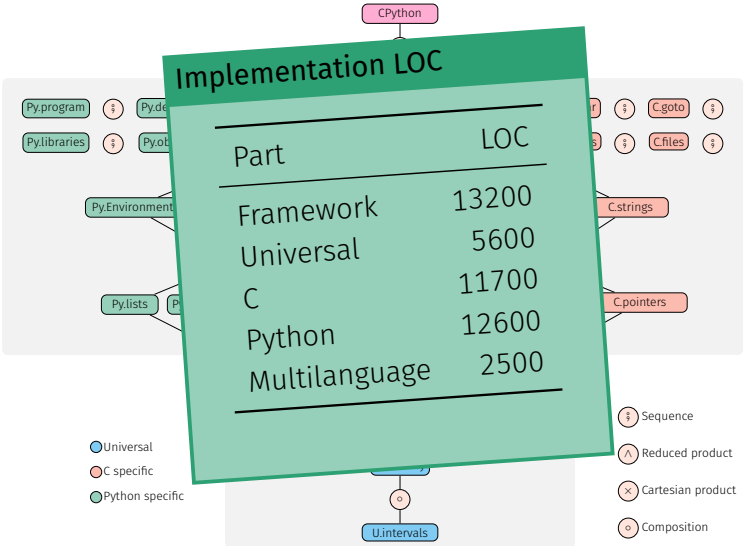


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| C | 11700 |
| Python | 12600 |
| Multilanguage | 2500 |

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

# Future works

## Multilanguage analyses

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

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- Bigger applications

## Library analyses

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

# A Multilanguage Static Analysis of Python/C Programs with Mopsa

# Questions

Raphaël Monat, Abdelraouf Ouadjaout, Antoine Miné

Sycomores Seminar
31 January 2022

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