A Multilanguage Static Analysis of Python/C Programs with Mopsa

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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.

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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Python's specificities

No standard

- CPython is the reference

  $\implies$ 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, a):
    if a[0] == "_": raise AttributeError("protected")
    return object.__getattribute__(self, a)

a = Protected(42)
a._priv # AttributeError raised
```

Python's specificities (II)

Dual type system

- Nominal (classes, MRO)

Fspath (from standard library)

```
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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Exceptions

Exceptions rather than specific values

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

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- 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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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

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

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Stateless domains: **list content**,

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

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

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A program analysis workflow

Averaging tasks

```
1  class Task:
2    def __init__(self, weight):
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4      self.weight = weight
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7    m = 0
8    for i in range(len(l)):
9      m = m + l[i].weight
10   m = m // (i + 1)
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13 l = [Task(randint(0, 20))
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```

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

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Stateless domains: list content, list length

Environment abstraction

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

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

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

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Attributes abstraction

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

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Environment abstraction

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

Conclusion

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

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

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

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- One AST to analyze them all
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- DAG of abstract domains
  - Composition
  - Cooperation

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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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Rewrite and analyze recursively

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init;
while(cond) {
  body;
  incr;
}
clean init
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for target in iterable: body
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Python.Desugar.Loops

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

Universal.Iterators.Loops

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A Concrete Example

Combining C and Python – example

counter.c

```c
typedef struct {
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static PyObject*
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```python
from counter import Counter
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How to analyze multilanguage programs?

Type annotations

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class Counter:
  def __init__(self): ...
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Rewrite into Python code

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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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- 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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```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

Multilanguage semantics

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- Builds upon the Python and C semantics
- Defines the API: calls between languages, value conversions

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- Shared heap, with disjoint, complementary views

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Limitations

Multilanguage semantics

Concrete definition

- Builds upon the Python and C semantics
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- Garbage collection not handled

Multilanguage semantics

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- Garbage collection not handled
- C access to Python objects only through the API (verified by Mopsa)

Multilanguage semantics

Concrete definition

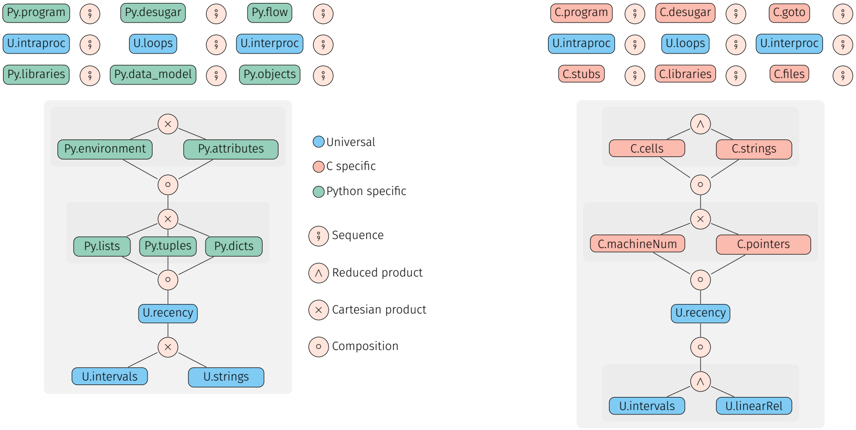
- Builds upon the Python and C semantics
- Defines the API: calls between languages, value conversions
- Shared heap, with disjoint, complementary views
- Boundary functions when objects switch views for the first time

Limitations

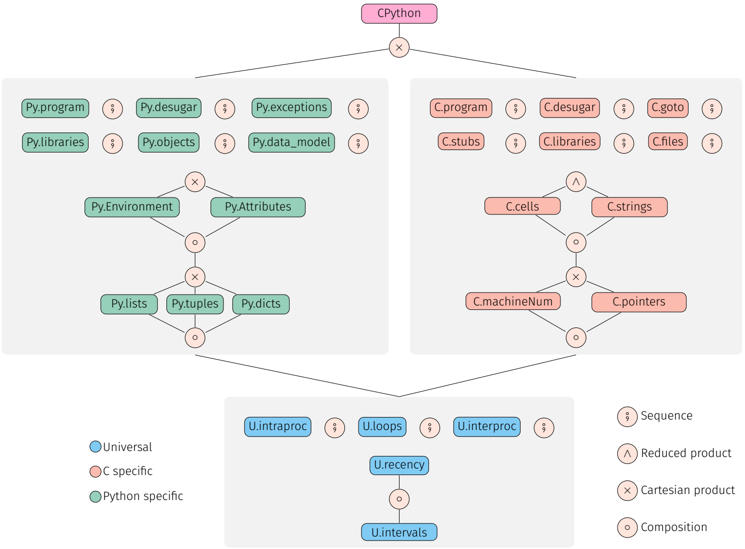
- Garbage collection not handled
- C access to Python objects only through the API (verified by Mopsa)
- Manual modelization from CPython's source code

Experimental Evaluation

From distinct Python and C analyses...



... to a multilanguage analysis!



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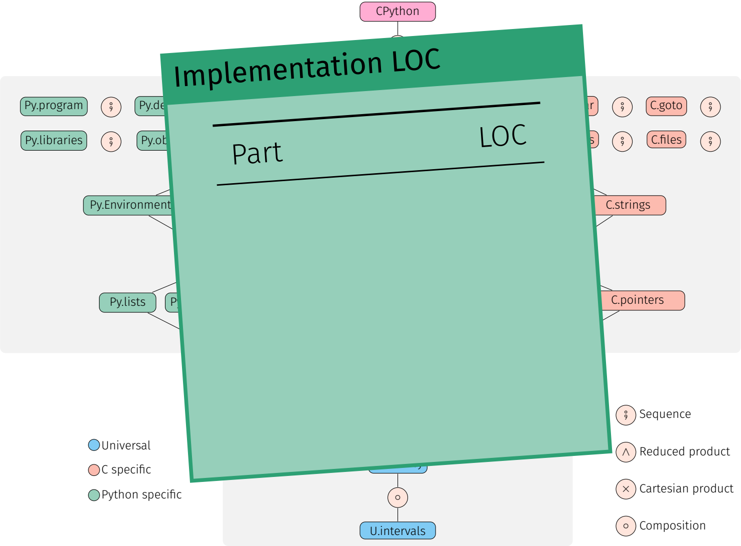
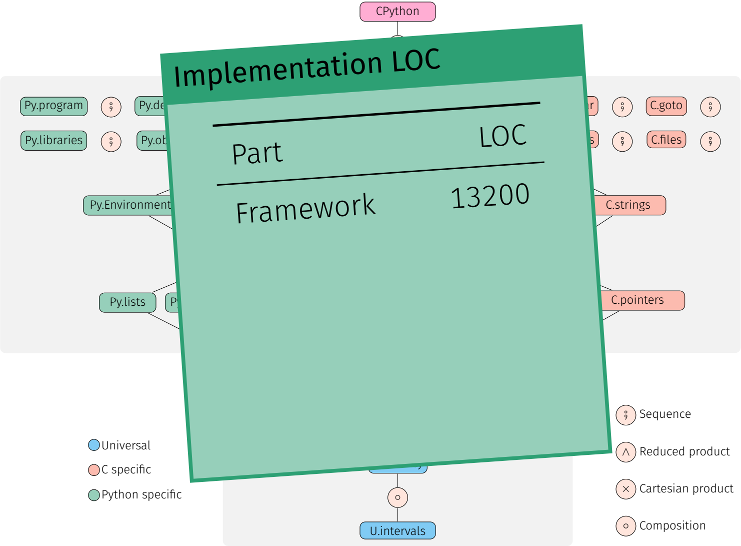


Implementation LOC

Part	LOC

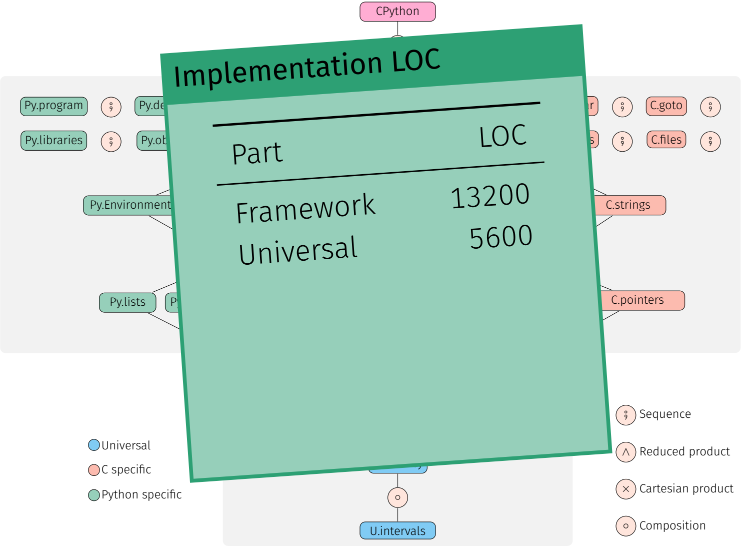
… to a multilanguage analysis!



Implementation LOC

Part	LOC
Framework	13200

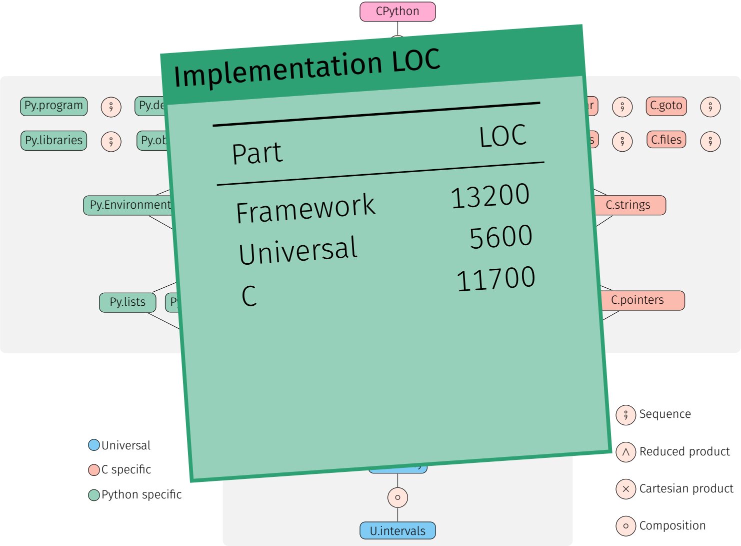
… to a multilanguage analysis!



Implementation LOC

Part	LOC
Framework	13200
Universal	5600

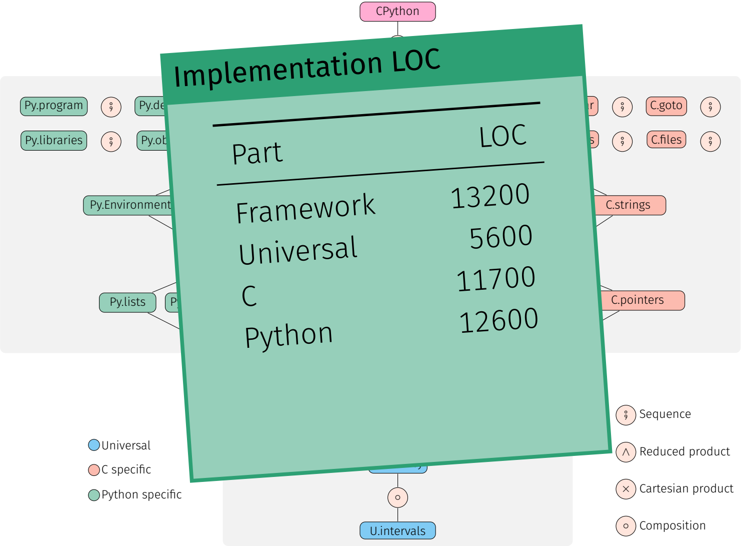
… to a multilanguage analysis!



Implementation LOC

Part	LOC
Framework	13200
Universal	5600
C	11700

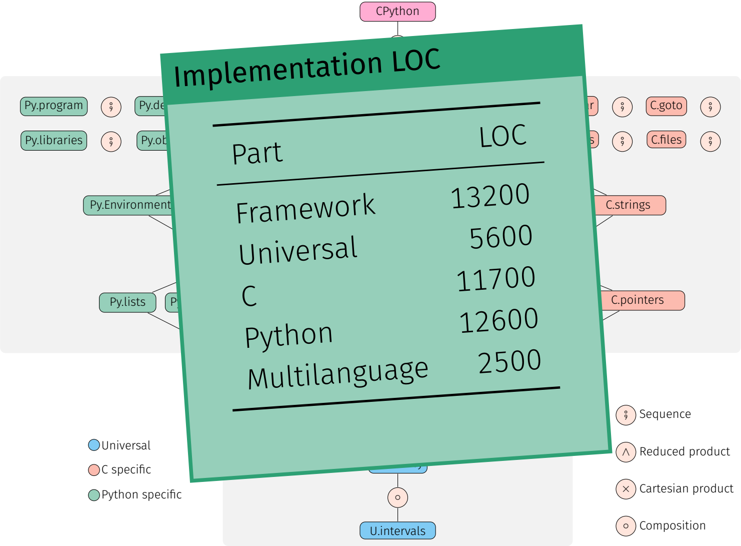
… to a multilanguage analysis!



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 $\leftrightsquigarrow$ 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

Related work

Theoretical frameworks

- Matthews and Findler[3] boundary functions as value conversions between two languages.
- Buro, Crole, and Mastroeni[4] generic framework for combining analyses of different languages.

[3] Matthews and Findler. "Operational semantics for multi-language programs". 2009.
[4] 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[5]
- Type inference of Java objects in C code[6]
- Extraction of C callbacks to Java[7]

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

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

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

[7] Lee, Lee, and Ryu. "Broadening Horizons of Multilingual Static Analysis: Semantic Summary Extraction from C Code for JNI Program Analysis". ASE 2020.

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

Contribution: multilanguage Python/C analysis

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Previous works

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

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Contribution: multilanguage Python/C analysis

Difficulties

- Concrete semantics
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Previous works

- Type/exceptions analyses for the JNI
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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

Future works

Multilanguage analyses

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

Future works

Multilanguage analyses

- 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

Questions

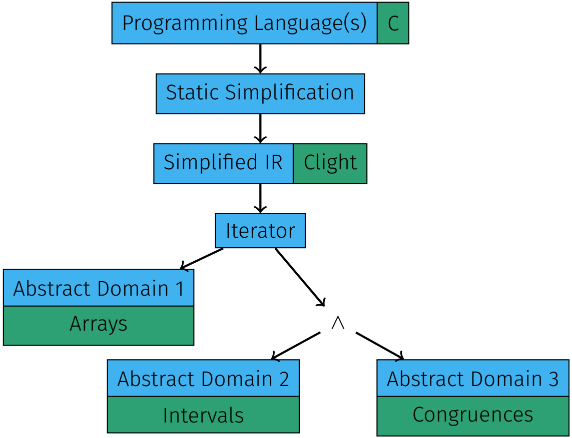
Raphaël Monat, Abdelraouf Ouadjaout, Antoine Miné

Binsec Seminar
26 November 2021

rmonat.fr

Table of backups

Usual implementations



Static simplification

- Infer's SIL IR for Java/C/C++
- May reduce the precision

Tree of abstract domains

No sharing (e.g., len(l), els(l), i)

Layered signatures

Different signatures throughout the abstract tree, and the iterator

Analysis of the multilanguage 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->counter += i;
  Py_RETURN_NONE;
}

static PyObject*
CounterGet(Counter *self)
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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()
```

$\mathbb{E}^{\#}_{\text{Py.call}}[\![\texttt{Counter()}]\!]\sigma^{\sharp}$

C

```
Pointers
 ⟨CounterCls,8,ptr⟩ : {PyType_Type}
 ⟨CounterCls,232,ptr⟩ : {Counter_methods}
```

Universal

```
Heap (Recency)
 @CounterCls @CounterIncr
 @CounterGet

Intervals
```

Python

```
Attributes
 @CounterCls ↦ {get, incr}

Environment
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 {@c function CounterGet}
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$$\mathbb{E}^{\#}_{\mathrm{C.call}}[\![\texttt{tp\_new\_wrapper}(\texttt{type}, \texttt{tuple(Counter)}, \texttt{NULL})]\!]\sigma^{\sharp}$$

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```

$\mathbb{E}^{\#}_{\text{C.call}}[\![\, \texttt{PyType\_GenericNew(CounterCls, NULL, NULL)} \,]\!]\sigma^{\sharp}$

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$\mathbb{E}^{\#}_{\text{C.cells}}[\![$ @I{CounterCls}->ob_type = CounterCls $]\!]\sigma^{\sharp}$

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$\mathbb{E}^{\#}_{\text{C.cells}}[\![\ \text{@I\{CounterCls\}->count} = 0\ ]\!]\sigma^{\sharp}$

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⟨@I{CounterCls},16,s32⟩ ↦ [0, 0]

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$^{c}\hookrightarrow_{p}$ (@I{CounterCls}, $\sigma^\sharp$)

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$\mathbb{S}^{\#}_{\mathrm{Py.env}}[\![\, c = \text{@I\{CounterCls\}} \,]\!]\sigma^{\sharp}$

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 {@c function CounterIncr}
 c ↦ {@I{CounterCls}}
```

Universal

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Heap (Recency)
 @CounterCls @CounterIncr
 @CounterGet @I{CounterCls}

Intervals
 ⟨@I{CounterCls},16,s32}⟩ ↦ [0, 0]
```

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$\mathbb{S}^{\#}_{\mathrm{Py}}[\![\, \mathtt{power = randrange(128)} \,]\!]\sigma^{\sharp}$

C

Pointers
⟨CounterCls,8,ptr⟩ : {PyType_Type}
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⟨@I{CounterCls},8,ptr⟩ : {CounterCls}

Universal

Heap (Recency)
@CounterCls @CounterIncr
@CounterGet @I{CounterCls}

Intervals
⟨@I{CounterCls},16,s32⟩ ↦ [0, 0]
power ↦ [0, 127]

Python

Attributes
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@CounterCls·incr ↦
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c ↦ {@I{CounterCls}}
power ↦ {@I{int}}

Example of recency abstraction

```python
class Task:
  def __init__(self, weight):
    if weight < 0: raise ValueError
    self.weight = weight

l = [Task(2), Task(1), Task(4), Task(5)]
```

Example of recency abstraction

$\left\{ @^\sharp(\text{Task}, r) \right.$

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class Task:
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Allocation:

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$$\left\{ @^\sharp(\mathrm{Task}, r) \cdot \mathrm{weight} \mapsto [2, 2] \right.$$

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Initialization:

Example of recency abstraction

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Allocation: $@^\sharp(\mathsf{Task}, r) \rightsquigarrow @^\sharp(\mathsf{Task}, o)$

Example of recency abstraction

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Allocation: $@^\sharp(\mathsf{Task}, r) \rightsquigarrow @^\sharp(\mathsf{Task}, o)$

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$$\left\{ \begin{array}{l} @^\sharp(\mathsf{Task}, r) \\ @^\sharp(\mathsf{Task}, o) \cdot \mathsf{weight} \mapsto [2, 2] \sqcup [1, 1] \end{array} \right.$$

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Example of recency abstraction

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Allocation: $@^\sharp(\text{Task}, r) \rightsquigarrow @^\sharp(\text{Task}, o)$

$$\left\{ @^\sharp(\text{Task}, r) \cdot \text{weight} \mapsto [2, 2] \right.$$

$$\left\{ \begin{array}{l} @^\sharp(\text{Task}, r) \cdot \text{weight} \mapsto [1, 1] \\ @^\sharp(\text{Task}, o) \cdot \text{weight} \mapsto [2, 2] \end{array} \right.$$

$$\left\{ \begin{array}{l} @^\sharp(\text{Task}, r) \cdot \text{weight} \mapsto [4, 4] \\ @^\sharp(\text{Task}, o) \cdot \text{weight} \mapsto [1, 2] \end{array} \right.$$

$$\left\{ \begin{array}{l} @^\sharp(\text{Task}, r) \\ @^\sharp(\text{Task}, o) \cdot \text{weight} \mapsto [1, 2] \sqcup [4, 4] \end{array} \right.$$

Example of recency abstraction

```python
class Task:
  def __init__(self, weight):
    if weight < 0: raise ValueError
    self.weight = weight

l = [Task(2), Task(1), Task(4), Task(5)]
```

Initialization:

$$@^\sharp(\mathrm{Task}, r) \cdot \mathrm{weight} \mapsto [2, 2]$$

$$@^\sharp(\mathrm{Task}, r) \cdot \mathrm{weight} \mapsto [1, 1]$$
$$@^\sharp(\mathrm{Task}, o) \cdot \mathrm{weight} \mapsto [2, 2]$$

$$@^\sharp(\mathrm{Task}, r) \cdot \mathrm{weight} \mapsto [4, 4]$$
$$@^\sharp(\mathrm{Task}, o) \cdot \mathrm{weight} \mapsto [1, 2]$$

$$@^\sharp(\mathrm{Task}, r) \cdot \mathrm{weight} \mapsto [5, 5]$$
$$@^\sharp(\mathrm{Task}, o) \cdot \mathrm{weight} \mapsto [1, 4]$$