A Multilanguage Static Analysis of Python Programs with Native C Extensions

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rmonat.fr/sas21

Introduction

Static Program Analysis

sum.py

```python
def sum(l):
  s = 0
  for x in l:
    s += x
  return s

r1 = sum([1, 2, 3])
r2 = sum(['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.

Python

- #2 language on Github[1],

[1] `https://octoverse.github.com/#top-languages`

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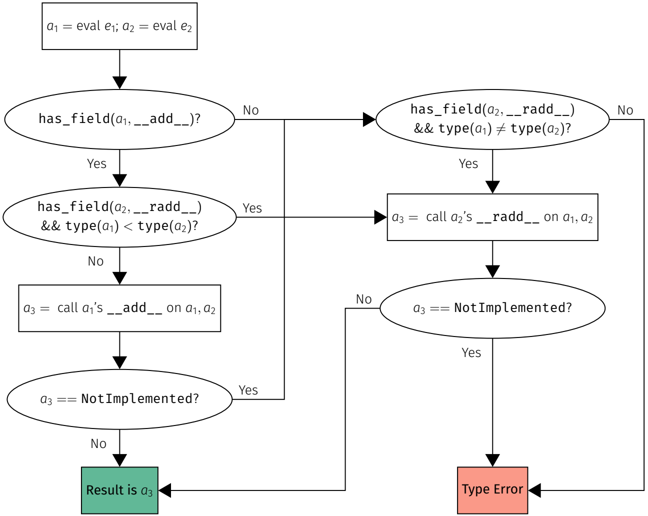

$a_1 =$ eval e_1; $a_2 =$ eval e_2

has_field(a_1, __add__)?

No

has_field(a_2, __radd__) && type(a_1) $\neq$ type(a_2)?

No

Yes

Yes

has_field(a_2, __radd__) && type(a_1) $<$ type(a_2)?

Yes

$a_3 =$ call a_2's __radd__ on a_1, a_2

No

$a_3 =$ call a_1's __add__ on a_1, a_2

No

$a_3 ==$ NotImplemented?

Yes

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Yes

No

Result is a_3

Type Error

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

Outline

1. Introduction
2. A Concrete Example
3. Concrete Multilanguage Semantics
4. Mopsa, a Multilanguage Analyzer
5. Experimental Evaluation
6. Conclusion

A Concrete Example

Combining C and Python – Counter 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))
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    self->count += i;
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```python
from counter import Counter
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- $\texttt{power} = 31 \Rightarrow \texttt{r} = -2^{31}$
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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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  used in previous work: Monat et al. “Static Type Analysis by Abstract Interpretation of Python Programs”. ECOOP 2020.

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Rewrite into Python code

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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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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.

Our approach

counter.c

```c
 1  typedef struct {
 2      PyObject_HEAD;
 3      int count;
 4  } Counter;
 5
 6  static PyObject*
 7  CounterIncr(Counter *self, PyObject *args)
 8  {
 9      int i = 1;
10      if(!PyArg_ParseTuple(args, "|i", &i))
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("i", self->count);
21  }
```

count.py

```python
1  from counter import Counter
2  from random import randrange
3
4  c = Counter()
5  power = randrange(128)
6  c.incr(2**power-1)
7  c.incr()
8  r = c.get()
```

```
⚠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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- Builds upon the Python and C semantics.

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$\Longrightarrow$ details in the paper.

Mopsa, a Multilanguage Analyzer

Our Framework: MOPSA

Modular **O**pen **P**latform for **S**tatic **A**nalysis

- Multi-language support (C and Python)

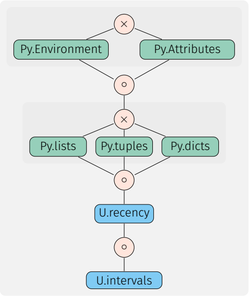
Expressiveness	Keep the original AST of the program.
Reusability	Reuse abstractions among languages.

- Flexible architecture

Loose coupling	Divide into interchangeable components.
Composition	Create complex components from simpler ones.
Cooperation	Components can communicate and delegate tasks.
Observability	Pluggable hooks observe the analysis.

From distinct Python and C analyses...

Py.program ⨟ Py.desugar ⨟ Py.exceptions ⨟
U.intraproc ⨟ U.loops ⨟ U.interproc ⨟
Py.libraries ⨟ Py.objects ⨟ Py.data_model ⨟



×
Py.Environment Py.Attributes
∘
×
Py.lists Py.tuples Py.dicts
∘
U.recency
∘
U.intervals

C.program ⨟ C.desugar ⨟ C.goto ⨟
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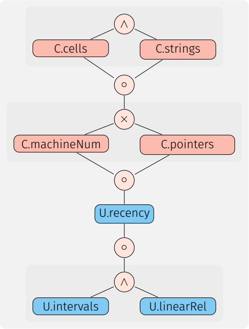
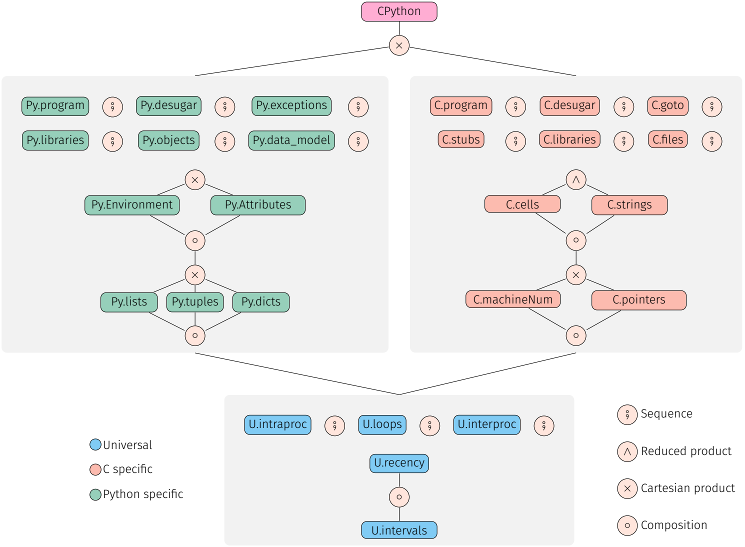


∧
C.cells C.strings
∘
×
C.machineNum C.pointers
∘
U.recency
∘
∧
U.intervals U.linearRel

… to a multilanguage analysis!



🔵 Universal

🔴 C specific

🟢 Python specific

⨾ Sequence

∧ Reduced product

× Cartesian product

∘ Composition

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

C

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

Universal

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

Intervals
```

Python

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Attributes
 @CounterCls ↦ {get, incr}


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

Python

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


Environment
 Counter ↦ {@CounterCls}
 @CounterCls·get ↦
 {@c function CounterGet}
 @CounterCls·incr ↦
 {@c function CounterIncr}
```

Analysis of the 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)
{
```

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()
```

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

Python

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Universal

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

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C

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

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

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Universal

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Intervals
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 power ↦ [0, 127]
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 Counter ↦ {@CounterCls}
 @CounterCls·get ↦
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 @CounterCls·incr ↦
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 c ↦ {@I{CounterCls}}
 power ↦ {@I{int}}
```

Experimental Evaluation

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

$\underbrace{\quad}_{\frac{\text{safe C checks}}{\text{total C checks}}\%}$

$\underbrace{\quad}_{\text{total C checks}}$

$\underbrace{\quad}_{\text{average \# transitions between Python and C per test}}$

Conclusion

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Static translation of some of C’s effects, injected back into the Java analysis.

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Future work

- Analyze larger applications,
- Validate typeshed's annotations,
- Apply to other multilanguage settings (JNI).