A Multilanguage Static Analysis of Python Programs with Native C Extensions

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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
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

Infer run-time errors (or other semantic properties).

Automatic no expert knowledge required.

Semantic based on a formal modelization of the language.

Sound cover all possible executions.

Static Analysis by Abstract Interpretation

How does an abstract interpreter work?

- Execution in approximate, computable domains,
- Program ⇝ Abstract state ⇝ Semantic property (alarms),
- Combine abstract domains to gain precision.

sum_indexed.py

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$$\texttt{s} \geq 0$$

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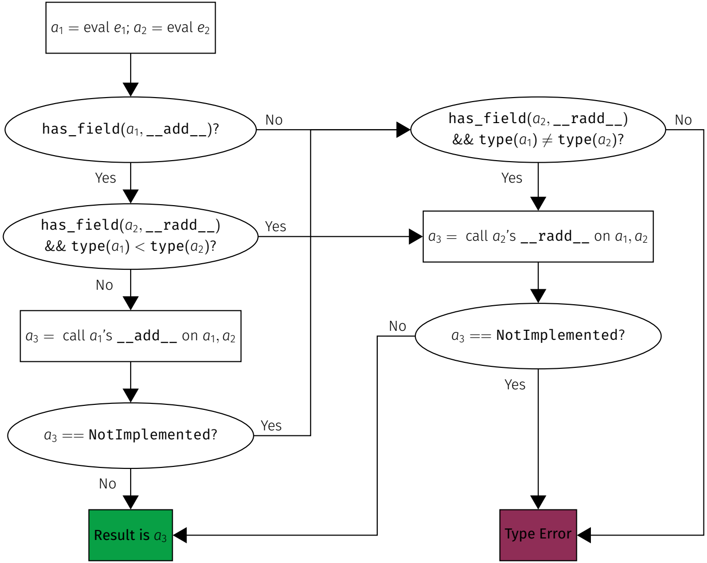
- `eval`.

Python is Complex! Semantics of $e_1 + e_2$



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

`has_field`(a_1, `__add__`)?

Yes

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

No

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

$a_3 ==$ `NotImplemented`?

No

Result is a_3

No

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

Yes

Yes

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

Yes

$a_3 ==$ `NotImplemented`?

No

Yes

Type Error

No

Combining C and Python

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- Different object representations (Python objects, C structs)
- Different runtime-errors (exceptions in Python),
- Garbage collection.

Outline

1. Introduction
2. A Concrete Example
3. Interlude: the Mopsa Static Analyzer
4. Multilanguage Analysis
5. Conclusion

A Concrete Example

Combining C and Python – Counter Example

counter.c

```c
typedef struct {
    PyObject_HEAD;
    int counter;
} 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)
{
    return Py_BuildValue("i", self->counter);
}
```

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```python
from counter import Counter
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⇒ Demo!

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- $\texttt{power} \leq 30 \Rightarrow \texttt{r} = 2^{\texttt{power}}$
- $\texttt{power} = 31 \Rightarrow \texttt{r} = -2^{31}$
- $32 \leq \texttt{power} \leq 62$: OverflowError: signed integer is greater than maximum
- $\texttt{power} \geq 63$: 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): ...
    def get(self) -> int: ...
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- Typeshed: type annotations for the standard library.

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Rewrite into Python code

```
class Counter:
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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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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.

Interlude: the Mopsa Static Analyzer

Project’s target: experiment new development ideas

Modular Open Platform for Static Analysis

- Multi-language support (C and Python)

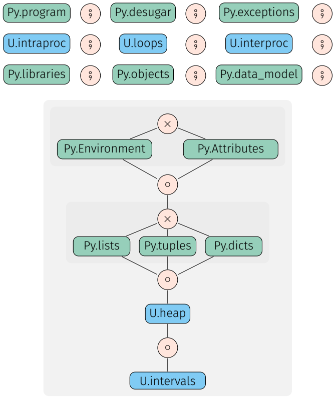
Expressiveness	Keep the original AST of the program.
Reusability	Reuse abstractions among languages.

- Flexible architecture

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

Multilanguage Analysis

Towards a Multilanguage Configuration



Py.program ⨟ Py.desugar ⨟ Py.exceptions ⨟

U.intraproc ⨟ U.loops ⨟ U.interproc ⨟

Py.libraries ⨟ Py.objects ⨟ Py.data_model ⨟

×

Py.Environment Py.Attributes

∘

×

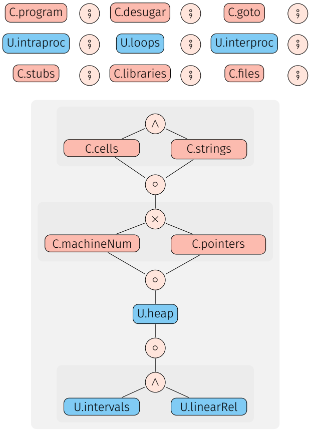
Py.lists Py.tuples Py.dicts

∘

U.heap

∘

U.intervals



C.program ⨟ C.desugar ⨟ C.goto ⨟

U.intraproc ⨟ U.loops ⨟ U.interproc ⨟

C.stubs ⨟ C.libraries ⨟ C.files ⨟

∧

C.cells C.strings

∘

×

C.machineNum C.pointers

∘

U.heap

∘

∧

U.intervals U.linearRel

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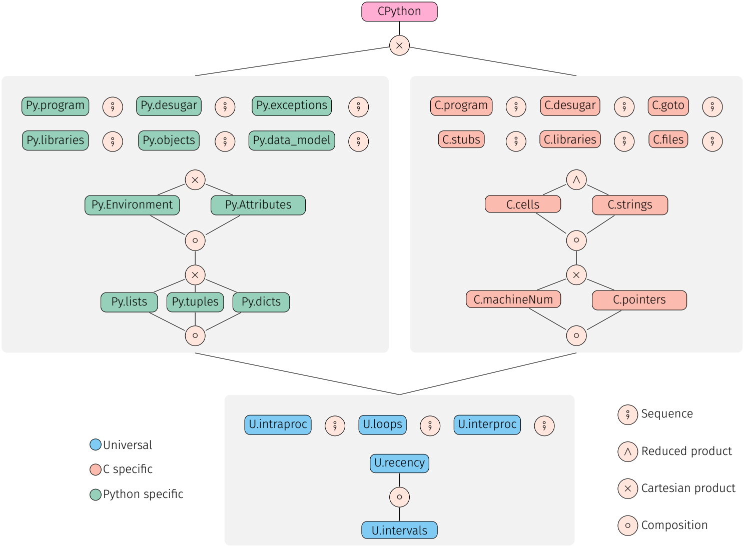

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from counter import Counter
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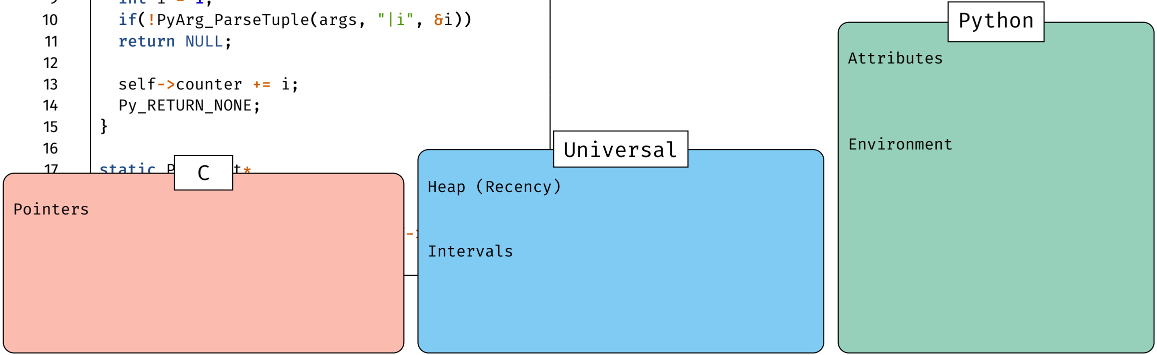

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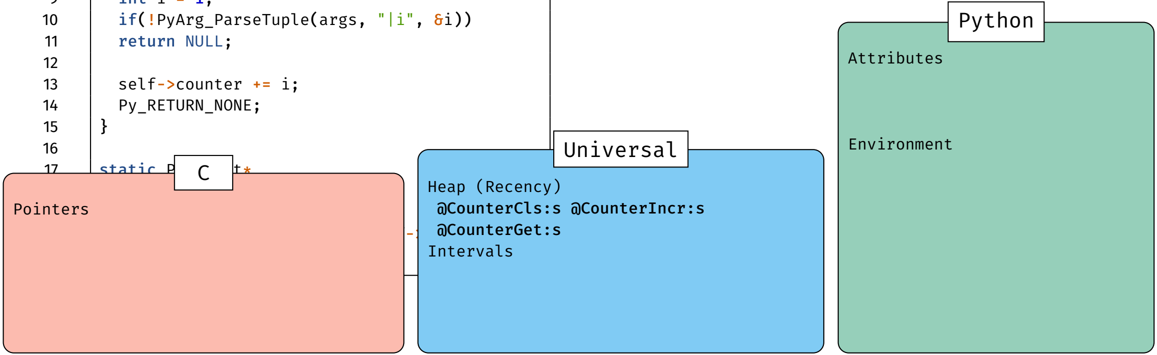

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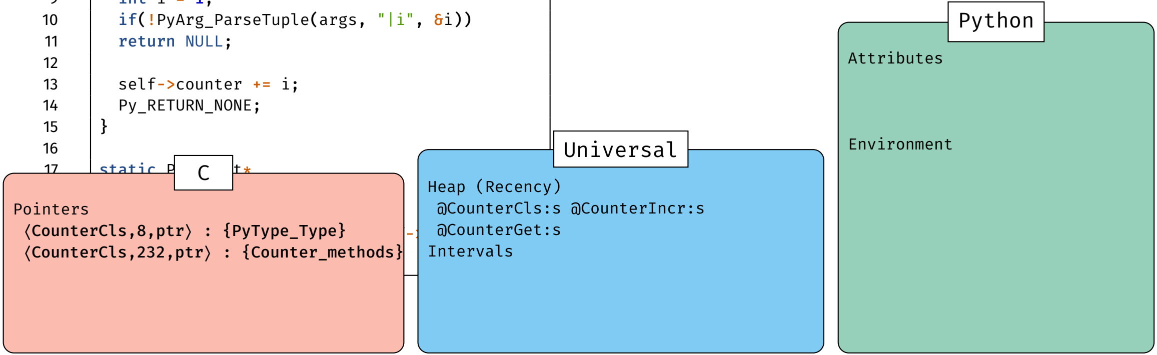

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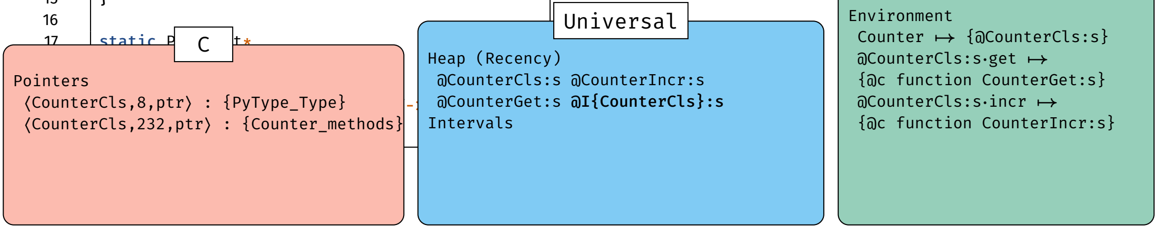

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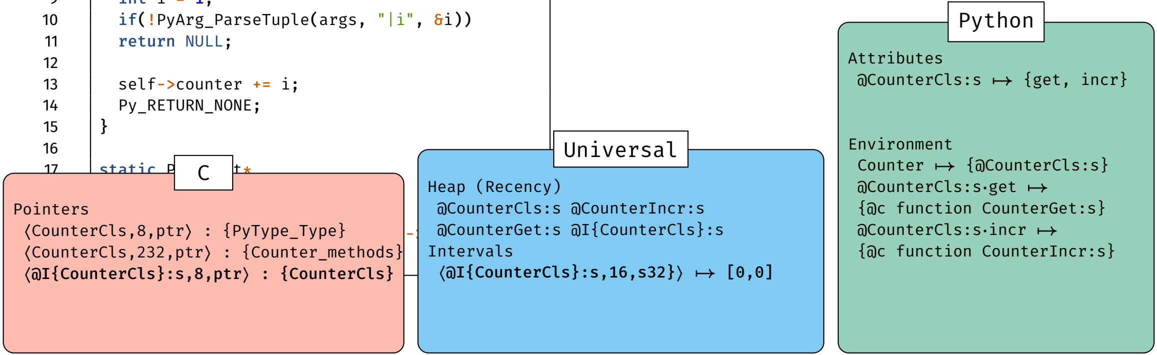

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@CounterGet:s @I{CounterCls}:s
Intervals
⟨@I{CounterCls}:s,16,s32}⟩ ↦ [0,0]

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```

C

Pointers

⟨CounterCls,8,ptr⟩ : {PyType_Type}

⟨CounterCls,232,ptr⟩ : {Counter_methods}

⟨@I{CounterCls}:s,8,ptr⟩ : {CounterCls}

Universal

Heap (Recency)

@CounterCls:s @CounterIncr:s

@CounterGet:s @I{CounterCls}:s

Intervals

⟨@I{CounterCls}:s,16,s32}⟩ ↦ [0,0]

Python

Attributes

@CounterCls:s ↦ {get, incr}

@I{CounterCls}:s ↦ ∅

Environment

Counter ↦ {@CounterCls:s}

@CounterCls:s·get ↦

{@c function CounterGet:s}

@CounterCls:s·incr ↦

{@c function CounterIncr:s}

c ↦ {@I{CounterCls}:s}

Analysis of the Example

counter.c

```c
typedef struct {
  PyObject_HEAD;
  int counter;
} 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 P t*
```

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

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

Universal

Heap (Recency)
@CounterCls:s @CounterIncr:s
@CounterGet:s @I{CounterCls}:s
Intervals
⟨@I{CounterCls}:s,16,s32}⟩ ↦ [0,0]

Python

Attributes
@CounterCls:s ↦ {get, incr}
@I{CounterCls}:s ↦ ∅

Environment
Counter ↦ {@CounterCls:s}
@CounterCls:s·get ↦
{@c function CounterGet:s}
@CounterCls:s·incr ↦
{@c function CounterIncr:s}
c ↦ {@I{CounterCls}:s}

Analysis of the Example

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C

Pointers

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

Universal

Heap (Recency)

@CounterCls:s @CounterIncr:s
@CounterGet:s @I{CounterCls}:s **@I{int}:w**

Intervals

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

Python

Attributes

@CounterCls:s ↦ {get, incr}
@I{CounterCls}:s ↦ ∅

Environment

Counter ↦ {@CounterCls:s}
@CounterCls:s·get ↦
{@c function CounterGet:s}
@CounterCls:s·incr ↦
{@c function CounterIncr:s}
c ↦ {@I{CounterCls}:s}
power ↦ {@I{int}:w}

Analysis of the Example

counter.c

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typedef struct {
  PyObject_HEAD;
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```

C

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

Universal

```
Heap (Recency)
 @CounterCls:s @CounterIncr:s
 @CounterGet:s @I{CounterCls}:s @I{int}:w
Intervals
 ⟨@I{CounterCls}:s,16,s32}⟩ ↦ [0,0]
 power ↦ [0,127]
```

Python

```
Attributes
 @CounterCls:s ↦ {get, incr}
 @I{CounterCls}:s ↦ ∅

Environment
 Counter ↦ {@CounterCls:s}
 @CounterCls:s·get ↦
 {@c function CounterGet:s}
 @CounterCls:s·incr ↦
 {@c function CounterIncr:s}
 c ↦ {@I{CounterCls}:s}
 power ↦ {@I{int}:w}
```

Analysis of the Example

counter.c

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C

Pointers
- ⟨CounterCls,8,ptr⟩ : {PyType_Type}
- ⟨CounterCls,232,ptr⟩ : {Counter_methods}
- ⟨@I{CounterCls}:s,8,ptr⟩ : {CounterCls}
- **args : {@tuple[1]:s}**
- **self : {@I{CounterCls}:s}**

Universal

Heap (Recency)
- @CounterCls:s @CounterIncr:s **@tuple[1]:s**
- @CounterGet:s @I{CounterCls}:s @I{int}:w

Intervals
- ⟨@I{CounterCls}:s,16,s32⟩ ↦ [0,0]
- power ↦ [0,127]
- **@tuple[1]:s·[0] ↦ [0,2^{127} − 1]**

Python

Attributes
- @CounterCls:s ↦ {get, incr}
- @I{CounterCls}:s ↦ ∅

Environment
- Counter ↦ {@CounterCls:s}
- @CounterCls:s·get ↦ {@c function CounterGet:s}
- @CounterCls:s·incr ↦ {@c function CounterIncr:s}
- c ↦ {@I{CounterCls}:s}
- power ↦ {@I{int}:w}
- **@tuple[1]:s·[0] ↦ {@I{int}:w}**

Combining C and Python – Current analyses

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

Conclusion

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An analysis of Python programs with C modules

- Combining previous C and Python analyses,

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- These abstractions co-exist and collaborate.

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Future work

Conclusion

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- Combining previous C and Python analyses,
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Future work

- Analyze larger applications,

Conclusion

An analysis of Python programs with C modules

- Combining previous C and Python analyses,
- Allocated objects are shared in the memory,
- Each language has different abstractions,
- These abstractions co-exist and collaborate.

Future work

- Analyze larger applications,
- Validate typeshed’s annotations,

Conclusion

An analysis of Python programs with C modules

- Combining previous C and Python analyses,
- Allocated objects are shared in the memory,
- Each language has different abstractions,
- These abstractions co-exist and collaborate.

Future work

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