Static Type and Value Analysis by Abstract Interpretation of Python Programs with Native C Libraries

Raphaël Monat

PhD defense

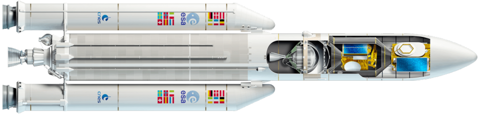
22 November 2021

Introduction

Software

Software is ubiquitous

- Transportation



Software

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- Transportation
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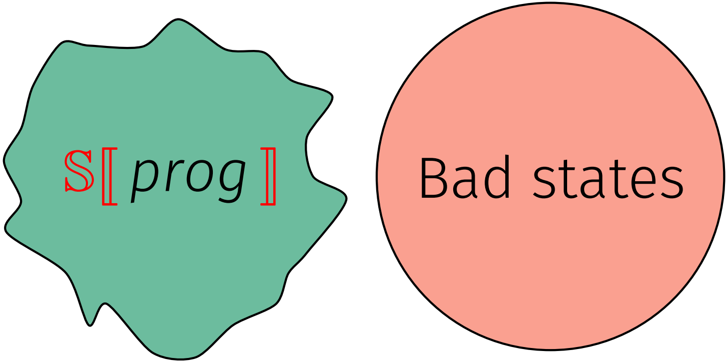
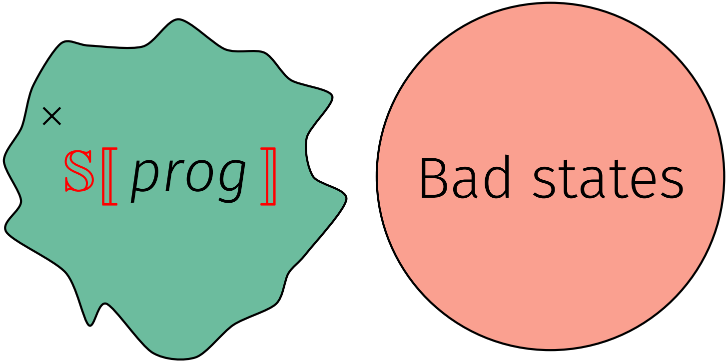
- …

Bugs

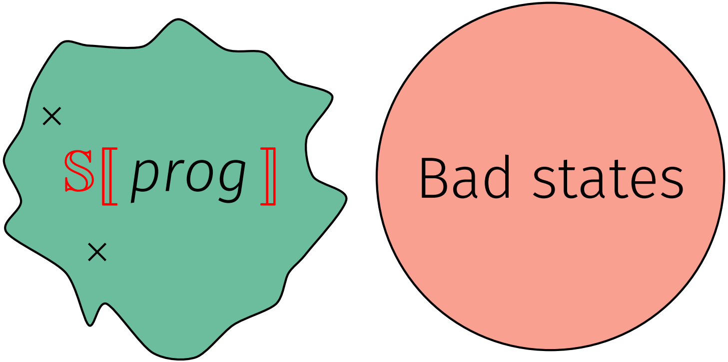
When a program does not work as intended

Software verification


$\mathbb{S}[\![prog]\!]$
Bad states



Cheap approach: test *prog*.



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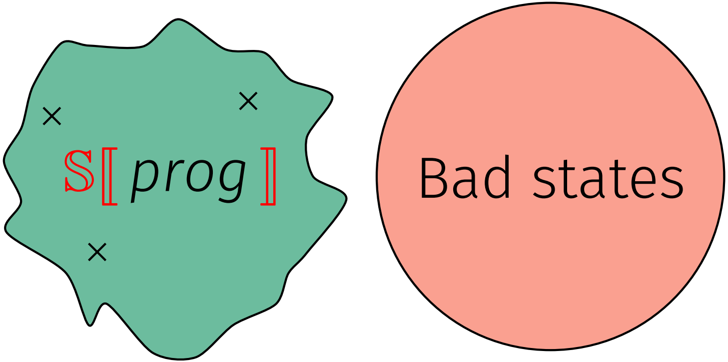

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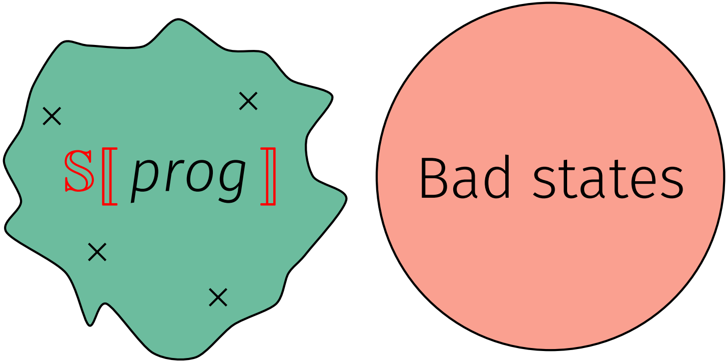

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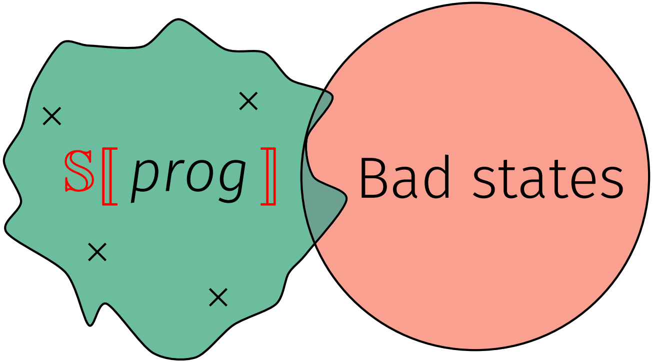

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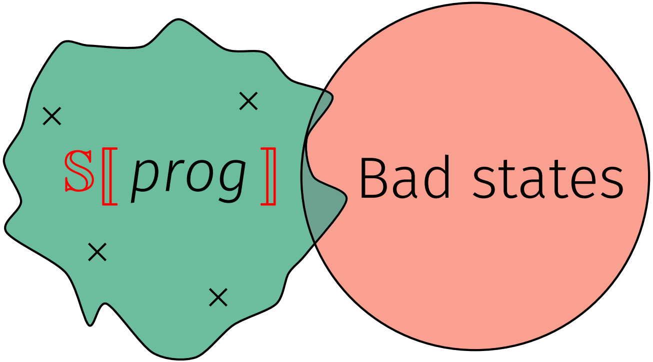

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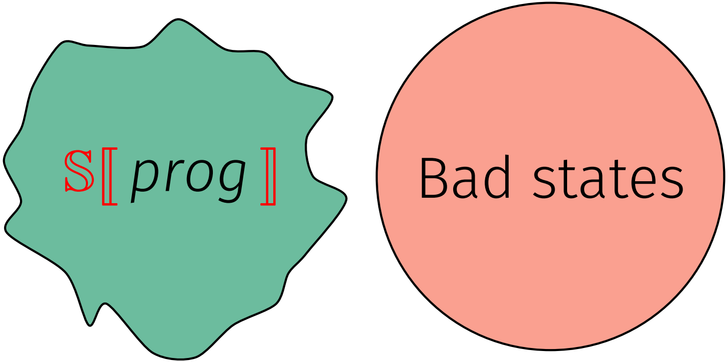

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Would there be a way to automatically prove programs correct?

An impossibility theorem

Rice's theorem (1953)

All non-trivial semantic properties of programs are undecidable.

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- Complete: all properties of the program can be derived.

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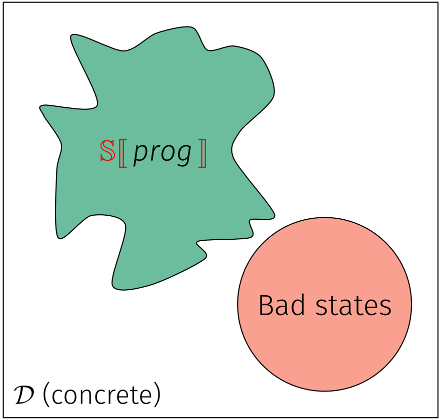
Mitigating Rice's theorem

Our choice: sound and automatic approaches.

Aimed at certifying programs correct.

Abstract interpretation – the big picture



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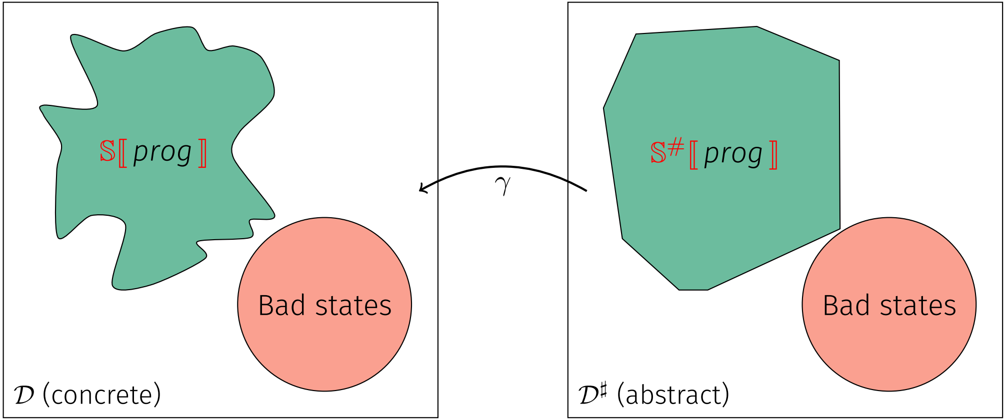

Program proved safe

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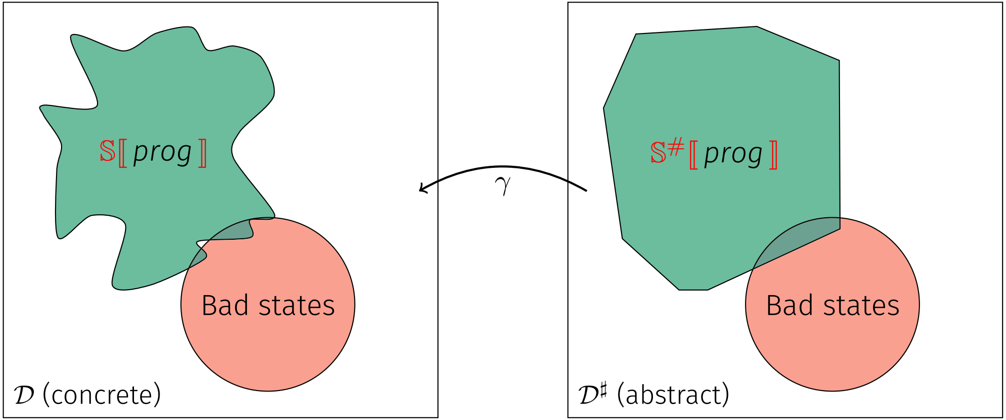

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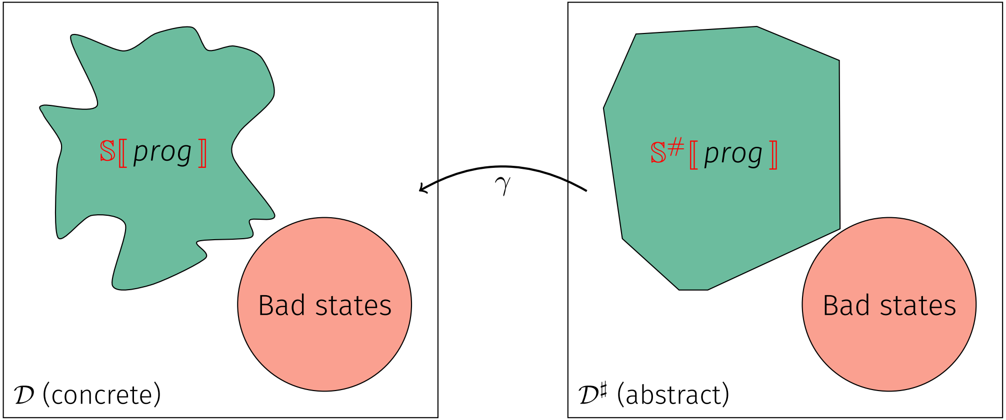

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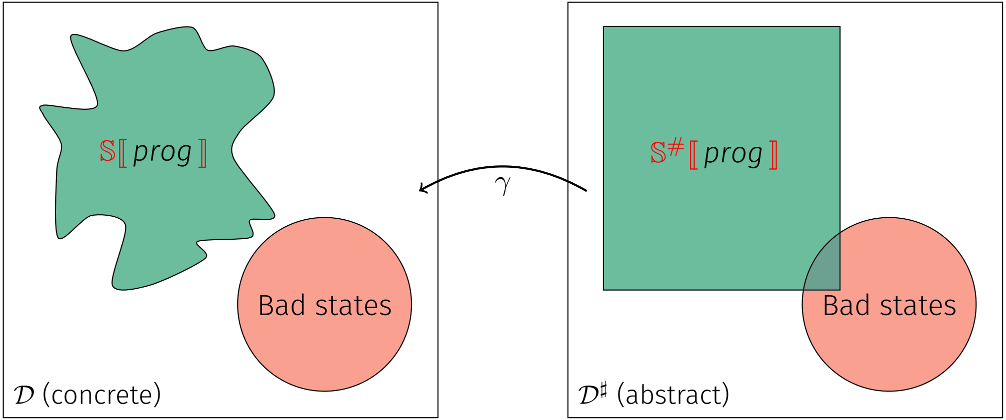

False alarm (Abstraction too coarse)

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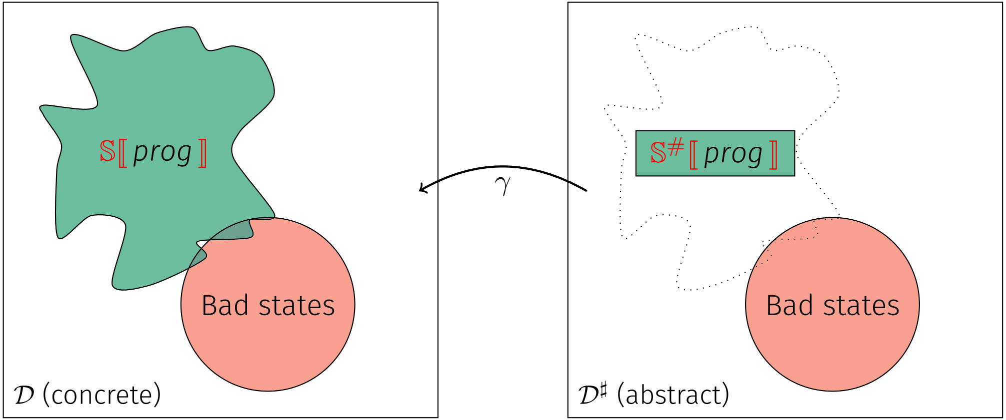

Unsound analysis
(shouldn't happen)

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Dynamic programming languages

Growing popularity

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

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- `eval`.

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State of the art

Well-established & industrialized analysis of static programming languages

- C: Polyspace (1999), Astrée (2003), Frama-C (2008)
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Why Python?

Used a lot in

- Scientific computing
- Scripts and automation

Outline

A Taste of Python

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("protected")
    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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Exceptions

Exceptions rather than specific values

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

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Complex desugaring into λ_π.

May incur losses of precision in the abstract interpreter.

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Moving to our own semantics

- Cost of understanding the code (vs CPython)
- Trust in the code (CPython's tests?)
- Insights of the papers

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Our approach

Interpreter-like semantics

Easily convertable to an abstract interpreter.

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Major extension of the work of Fromherz, Ouadjaout, and Miné[2]

- Separation between core and builtins
- $2.3\times$ more cases (`with` statement, bidirectional generators, …)
- Improved some cases ($+$, boolean casts of conditionals, data descriptors, …)

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Correctness

- Strived to make it auditable (with links to the source).
- Tested only through the abstract analysis yet (no concrete execution).

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Example – attribute access

$$\mathbb{E}_{\text{cur}}[\![\, x.s \,]\!](cur, e, h) \stackrel{\text{def}}{=} \qquad \texttt{LOAD\_ATTR PyObject\_GetAttr (slot\_tp\_getattr\_hook)}$$

$\text{letb } (cur, e, h), @_x = \mathbb{E}[\![\, x \,]\!](cur, e, h) \text{ in}$

$\text{letb } (cur, e, h), @_c = \mathbb{E}[\![\, mro\_search(type(@_x), \text{"}\texttt{\_\_getattribute\_\_}\text{"}) \,]\!](cur, e, h) \text{ in}$

$\text{letcases } (f, e, h), @_{x.s} = \mathbb{E}[\![\, @_c(@_x, s) \,]\!](cur, e, h) \text{ in}$

$\text{match } f \text{ with}$

- $exn\ @_{exc} \text{ when } isinstance(@_{exc}, \texttt{AttributeError}) \Rightarrow$

  $\text{let } (f, e, h), @_d = \mathbb{E}[\![\, mro\_search(type(@_x), \text{"}\texttt{\_\_getattr\_\_}\text{"}) \,]\!](f, e, h) \text{ in}$

  $\text{if } d \neq \bot \text{ then return } \mathbb{E}[\![\, @_d(@_x, s) \,]\!](cur, e, h)$

  $\text{else return } (f, e, h), \bot$

- $\_ \Rightarrow \text{return } (f, e, h), @_{x.s}$

Example – attribute access

$\mathbb{E}_{cur}[\![x.s]\!](cur, e, h) \stackrel{\text{def}}{=}$ `LOAD_ATTR PyObject_GetAttr (slot_tp_getattr_hook)`

$\text{letb } (cur, e, h), @_x = \mathbb{E}[\![x]\!](cur, e, h) \text{ in}$

$\mathbb{E}_{cur}[\![\texttt{object.\_\_getattribute\_\_}(obj, name)]\!](cur, e, h) \stackrel{\text{def}}{=}$ `tp_field _PyObject_GenericGetAttrWithDict`

$\text{letb } (cur, e, h), @_o = \mathbb{E}[\![obj]\!](cur, e, h) \text{ in}$

$\text{letb } (cur, e, h), @_n = \mathbb{E}[\![name]\!](cur, e, h) \text{ in}$

$\text{if } \neg isinstance(@_n, \text{str}) \text{ then return } \mathbb{S}[\![\texttt{raise TypeError}]\!](cur, e, h), \bot \text{ else}$

$\text{let } \texttt{str}(n) = \text{fst} \circ h(@_n) \text{ in}$

$\text{letcases } (f, e, h), @_{descr} = \mathbb{E}[\![mro\_search(type(@_o), n)]\!](f, e, h) \text{ in}$

$\text{if } @_{descr} \neq \bot \text{ then}$

$\text{if } hasattr(type(@_{descr}), \texttt{"\_\_get\_\_"}) \land$

$(hasattr(type(@_{descr}), \texttt{"\_\_set\_\_"}) \lor hasattr(type(@_{descr}), \texttt{"\_\_delete\_\_"})) \text{ then}$

$\text{return } \mathbb{E}[\![type(@_{descr}).\texttt{\_\_get\_\_}(@_{descr}, @_o, type(@_o))]\!](f, e, h)$

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$\mathbb{E}_{cur}[\![$ `type.__getattribute__` $(typ, name)]\!](cur, e, h) \stackrel{def}{=}$ `tp_field type_getattro`

$\quad$ letb $(cur, e, h), @_{typ} = \mathbb{E}[\![typ]\!](cur, e, h)$ in

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$\quad$ letb $(cur, e, h), @_{meta} = \mathbb{E}[\![\text{mro\_search}(type(@_{typ}), @_{name})]\!](cur, e, h)$ in

$\quad$ if $@_{meta} \neq \bot$ then

$\quad\quad$ if $hasattr(type(@_{meta}), \text{"\_\_get\_\_"}) \wedge$

$\quad\quad\quad (hasattr(type(@_{meta}), \text{"\_\_set\_\_"}) \vee hasattr(type(@_{meta}), \text{"\_\_delete\_\_"}))$ then

$\quad\quad\quad (@_{meta}, @_{typ}, type(@_{typ}))]\!](cur, e, h)$

Analyzing Python Programs

Goal

Detect runtime errors: uncaught raised exceptions

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Detect runtime errors: uncaught raised exceptions

Supported constructs

Our analysis supports:

- Objects
- Exceptions
- Dynamic typing
- Introspection
- Permissive semantics
- Dynamic attributes
- Generators
- `super`
- Metaclasses

Analysis | Overview

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Unsupported constructs

- Recursive functions
- `eval`
- Finalizers

Analysis | Domains required

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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1  def 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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Numeric abstraction (intervals)

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

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Numeric abstraction (intervals)

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

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

Analysis | Domains required

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Numeric abstraction (polyhedra)

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

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

Analysis | Domains required

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))]
15 m = average(l)
```

Proved safe?

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

Searching for a loop invariant (l. 4)

Stateless domains: list content, list length

Environment abstraction

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

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

Numeric abstraction (polyhedra)

$m \in [0, +\infty)$

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

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

Attributes abstraction

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

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(le
9      m = m + l[i].wei
10   m = m // (i + 1)
11   return m
12
13 l = [Task(randint(0,
14   for i in range(randint(5, 10))]
15 m = average(l)
```

Proved safe?

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

Searching for a loop invariant (l. 4)

Stateless domains: list content, list length

Environment abstraction

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

Conclusion

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

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

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

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Modular Open Platform for Static Analysis[3]

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

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

Mopsa | Dynamic, semantic iterators with delegation

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for(init; cond; incr) body
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Rewrite and analyze recursively

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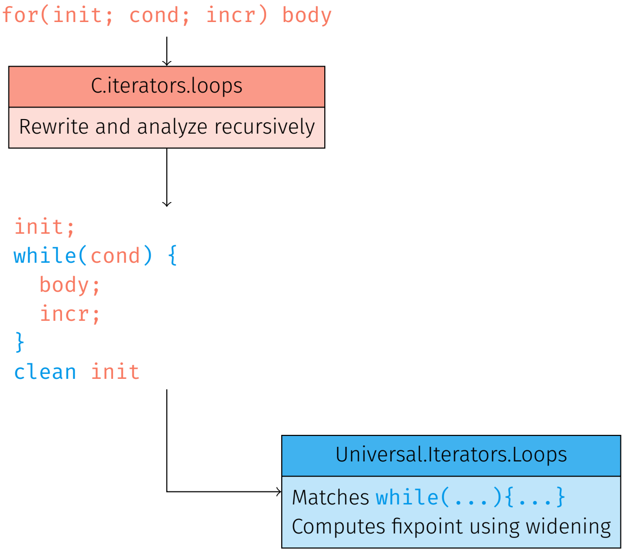

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```
for(init; cond; incr) body
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```
for target in iterable: body
```

C.iterators.loops

Rewrite and analyze recursively

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

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Python.Desugar.Loops

- Rewrite and analyze recursively
- Optimize for some semantic cases

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for target in iterable: body
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Python.Desugar.Loops

- Rewrite and analyze recursively
- Optimize for some semantic cases

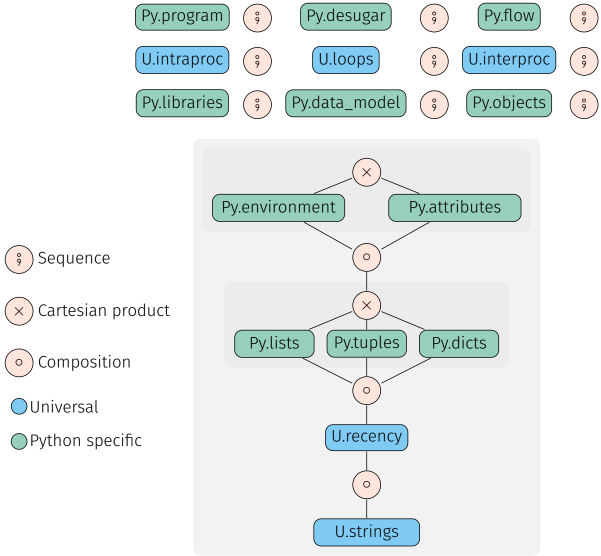
```
it = iter(iterable)
while(1) {
 try: target = next(it)
 except StopIteration: break
 body
}
clean it
```

Universal.Iterators.Loops

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

- Dynamicity:
  type inference first
- Flow-sensitive
- Context-sensitive

Types | Analysis



- Dynamicity: type inference first
- Flow-sensitive
- Context-sensitive

Types | Related work

- Similar in essence to TAJS.[4]
- Dataflow analysis by Fritz and Hage.[5]
- Typpete: SMT-based type inference.[6]
- Pytype, type inference tool used by Google.[7]
- RPython: efficient compilation of a static subset of Python.[8]
- Value analysis by Fromherz et al.[9]

---

[4] Jensen, Møller, and Thiemann. "Type Analysis for JavaScript". SAS 2009.

[5] Fritz and Hage. "Cost versus precision for approximate typing for Python". PEPM 2017.

[6] Hassan, Urban, Eilers, and Müller. "MaxSMT-Based Type Inference for Python 3". CAV 2018.

[7] Kramm et al. Pytype. 2019.

[8] Ancona, Ancona, Cuni, and Matsakis. "RPython: a step towards reconciling dynamically and statically typed OO languages". DLS 2007.

[9] Fromherz, Ouadjaout, and Miné. "Static Value Analysis of Python Programs by Abstract Interpretation". NFM 2018.

Types | Experimental evaluation

Name	LOC	Mopsa	⚠	Fritz & Hage	Pytype	Typpete	Fromherz et al.	RPython
bellman_ford.py	61	0.24s	0†	1.4s	0.99s	1.4s	2.4m	7.1s
float.py	63	82ms	0†	1.7s	0.92s	1.3s	0.84s	5.6s
coop_concat.py	64	43ms	0†	1.8s	0.81s	1.3s	20ms	🐞
crafting.py	132	0.41s	0†🔑	1.6s	0.97	1.7s	🐞	🐞
nbody.py	157	0.80s	1†🔑±	1.7s	1.3s	🐞	🐞	🐞
chaos.py	324	2.3s	0†±	13s	11s	🐞	🐞	🐞
scimark.py	416	0.55s	2†	8.5s	4.4s	🐞	🐞	🐞
richards.py	426	5.0s	2†±	38s	2.4s	🐞	🐞	7.8s
unpack_seq.py	458	4.2s	0±	1.1s	7.4s	2.7s	14s	🐞
go.py	461	15s	32†±	8.5s	3.4s	🐞	🐞	🐞
hexiom.py	674	22s	25†🔑±	🐞	4.2s	🐞	🐞	🐞
regex_v8.py	1792	15s	0†	4.9s	🕓	1.7m	🐞	🐞
processInput.py	1417	4.8s	7†🔑±	2.4s	11s	🐞	🐞	🐞
choose.py	2562	46s	17🔑†±	1.7s	15s	🐞	🐞	🐞

🐞 unsupported by the analyzer (crash) 🕓 timeout (after 1h)
Smashed exceptions: KeyError 🔑, IndexError †, ValueError ±

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Smashed exceptions: KeyError 🔑, IndexError †, ValueError ⋆

Conclusion

- Handling Python's dynamicity
- Good scalability (w.r.t. other semantic tools)

Thanks to Mopsa, switching from types to values is straightforward!

Monat, Ouadjaout, and Miné. “Value and allocation sensitivity in static Python analyses”.

Types ⇝ values | Configurations

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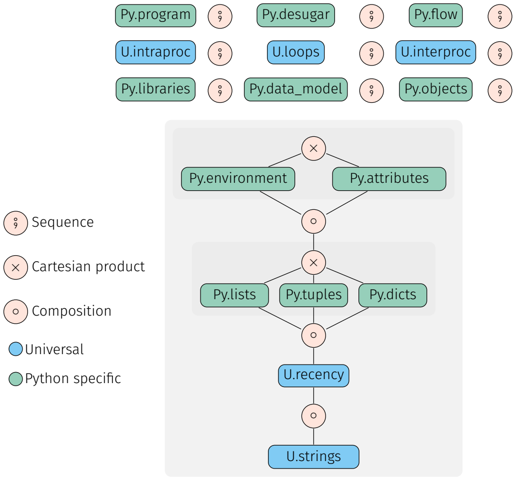

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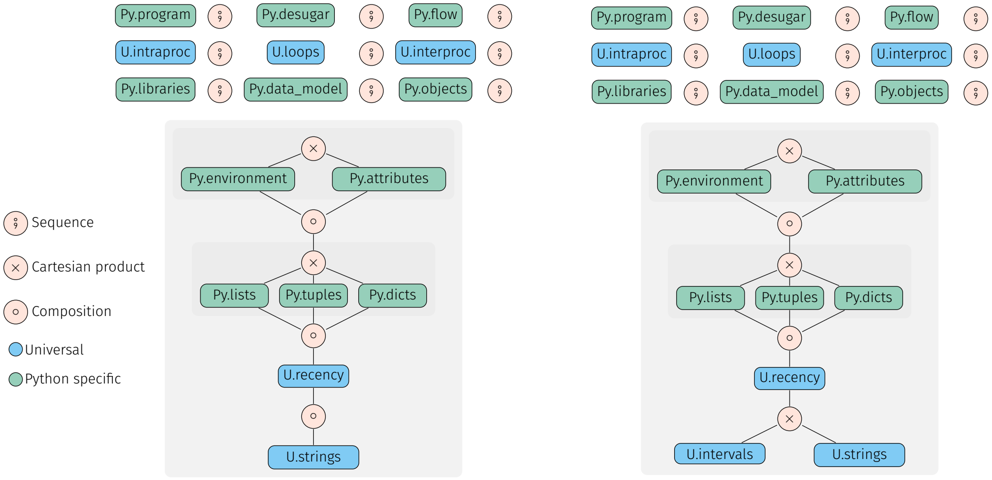

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Types ⇝ values | Comparing the analyses

Averaging tasks

```
1  class Task:
2    def __init__(self, weight):
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6  def average(l):
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13 l = []
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Type analysis

- ▶ `ValueError` (l. 3)

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Non-relational value analysis

`IndexError` (l. 9)

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- `IndexError` (l. 9)
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- `NameError` (l. 10)

Non-relational value analysis

`IndexError` (l. 9)

Relational value analysis

No alarm!

Types ⇝ values | Comparing the analyses (II)

Name	LOC	Type Analysis					Non-relational Value Analysis				
		Time	Mem.	Exceptions detected			Time	Mem.	Exceptions detected		
				Type	Index	Key			Type	Index	Key
nbody.py	157	1.5s	3MB	0	22	1	5.7s	9MB	0	**1**	1
scimark.py	416	1.4s	12MB	1	1	0	3.4s	27MB	1	**0**	0
richards.py	426	13s	112MB	1	4	0	17s	149MB	1	**2**	0
unpack_seq.py	458	8.3s	7MB	0	0	0	9.4s	6MB	0	0	0
go.py	461	27s	345MB	33	20	0	2.0m	1.4GB	33	20	0
hexiom.py	674	1.1m	525MB	0	46	3	4.7m	3.2GB	0	**21**	3
regex_v8.py	1792	23s	18MB	0	2053	0	1.3m	56MB	0	**145**	0
processInput.py	1417	10s	64MB	7	7	1	12s	85MB	7	**4**	1
choose.py	2562	1.1m	1.6GB	12	22	7	2.9m	3.7GB	12	**13**	7
Total	9294	4.0m	2.8GB	59	2214	12	13m	9.1GB	59	228	12

Name	LOC	Type Analysis					Non-relational Value Analysis				
		Time	Mem.	Exceptions detected			Time	Mem.	Exceptions detected		
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nbody.py	157	1.5								**1**	1
scimark.py	416	1.4								**0**	0
richards.py	426	13								**2**	0
unpack_seq.py	458	8.3								0	0
go.py	461	27s								20	0
hexiom.py	674	1.1m								**21**	3
regex_v8.py	1792	23s								**145**	0
processInput.py	1417	10s								**4**	1
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Total	9294	4.0m	2.8GB	59	2214	12	13m	9.1GB	59	228	12

Conclusion

The non-relational value analysis

- does not remove false type alarms
- significantly reduces index errors
- is $\simeq 3\times$ costlier

Types ⇝ values | Comparing the analyses (II)

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scimark.py	416	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**0**	0
richards.py	426	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**2**	0
unpack_seq.py	458	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0	0
go.py	461	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	20	0
hexiom.py	674	1.1m	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**21**	3
regex_v8.py	1792	23s	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**145**	0
processInput.py	1417	10s	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**4**	1
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Heuristic packing and relational analyses

- Static packing, using function's scope
- Rules out all 145 alarms of `regex_v8.py` (1792 LOC) at $2.5\times$ cost

The recency abstraction[10]

- Finite number of abstract addresses

[10] Balakrishnan and Reps. “Recency-Abstraction for Heap-Allocated Storage”. SAS 2006.
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- Also used in Type Analysis for JavaScript[11]

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Task creation

```python
class Task:
  def __init__(self, weight):
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m = [1, 2]
l = [Task(i) for i in m]
l.append(Task(3))
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Type analysis

Nominal types used in abstract addresses. No need for allocation-site in `Tasks`. But helpful for lists!

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Use allocation sites for `range` objects.

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Type analysis

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Value analysis

Use allocation sites for `range` objects.

Variable allocation policies

- Type-based (nominal) and/or location-based partitioning.
- Different configurations depending on type/value analysis.

List abstraction

- Summarization of the content (auxiliary variable)
- Auxiliary length variable

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- Summarization of the content (auxiliary variable)
- Auxiliary length variable

Dictionaries in Python

- Keys can be any object (JavaScript: strings or symbols)
- Key/value summarization currently used

Soundness

Two soundnesses

- Modelization of the semantics from CPython
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- Test only in the abstract
- Issue of overapproximations and unproved assertions

Unsupported constructs

- `eval`
- Recursive functions
- Finalizers

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Unsupported constructs

- `eval`
- Recursive functions
- Finalizers

Tests from previous works

- 450/586 tests supported
- 268/586 assertions proved

Official tests from CPython

- 325/416 tests supported (17 chosen files)
- 389/702 assertions proved

Analyzing Python Programs with C Libraries

Combining C and Python – motivation

One in five of the top 200 Python libraries contains C code

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- To bring better performance (numpy)

Combining C and Python – motivation

One in five of the top 200 Python libraries contains C code

- To bring better performance (numpy)
- To provide library bindings (pygit2)

Combining C and Python – motivation

One in five of the top 200 Python libraries contains C code

- To bring better performance (numpy)
- To provide library bindings (pygit2)

Pitfalls

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- Different runtime-errors (exceptions in Python)
- Garbage collection

Combining C and Python – first look

A combined static analysis of C/Python[12]

- Targeting C extensions using the CPython API

[12] Monat, Ouadjaout, and Miné. "A Multilanguage Static Analysis of Python Programs with Native C Extensions". SAS 2021.

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  - but each language has different abstractions

$\Rightarrow$ Share universal domains and synchronize abstractions

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Combining C and Python – example

counter.c

```c
typedef struct {
    PyObject_HEAD;
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static PyObject*
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    self->count += i;
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```python
from counter import Counter
from random import randrange

c = Counter()
power = randrange(128)
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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

Rewrite into Python code

```
class Counter:
  def __init__(self):
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  def get(self):
    return self.count
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    return self.count
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```

- No integer wrap-around in Python
- Some effects can't be written in pure Python (e.g., read-only attributes)

How to analyze multilanguage programs?

Type annotations

Rewrite into Python code

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
- Detect runtime errors in Python, in C, and at the boundary

Analysis result

counter.c

```c
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    int count;
} Counter;

static PyObject*
CounterIncr(Counter *self, PyObject *args)
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8  {
9      int i = 1;
10     if(!PyArg_ParseTuple(a
11        return NULL;
12
13     self->count += i;
14     Py_RETURN_NONE;
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19 {
20     return Py_BuildValue("
21 }
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count.py

```python
1  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
```

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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- Shared heap, with disjoint, complementary <u>views</u>
- <u>Boundary functions</u> when objects switch views for the first time

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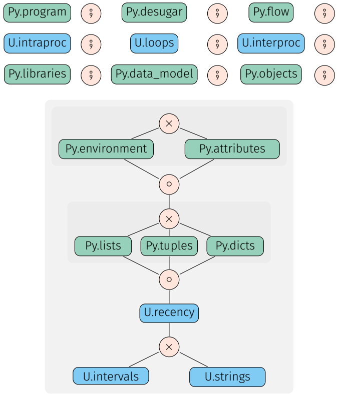
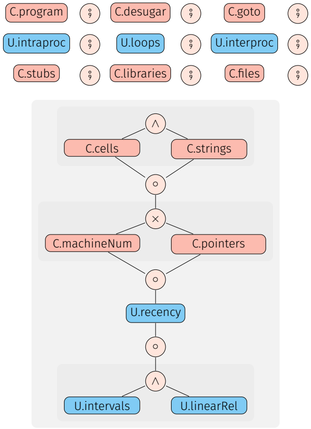
Limitations

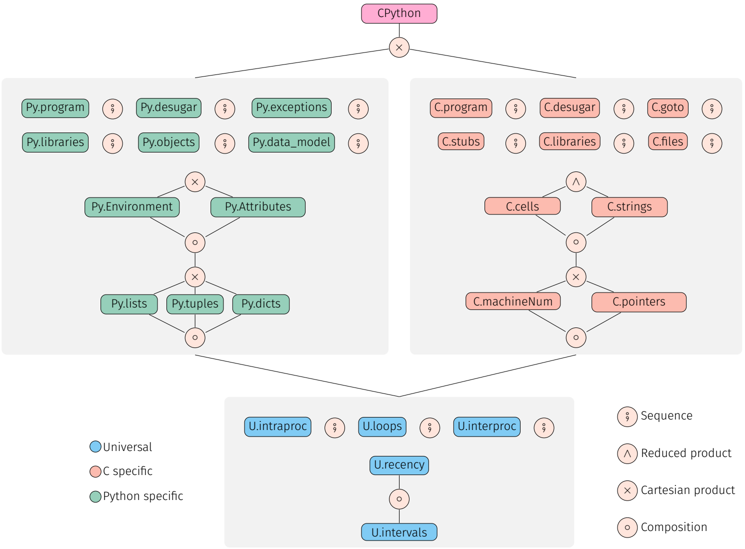
- Garbage collection not handled
- C access to Python objects only through the API (verified by Mopsa)
- Manual modelization from CPython's source code

From distinct Python and C analyses...





… to a multilanguage analysis!



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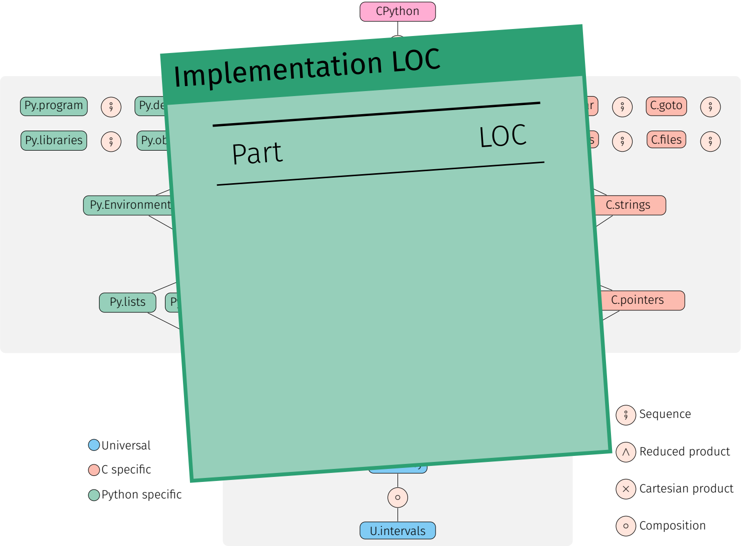


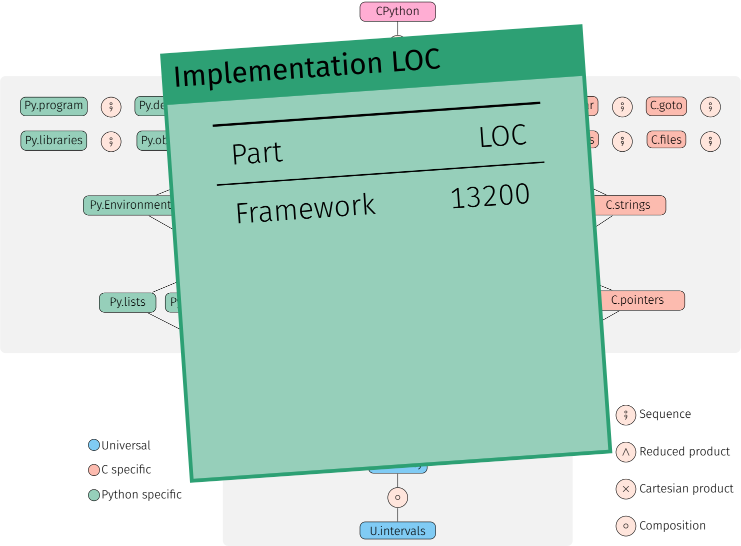
Implementation LOC

Part	LOC

… to a multilanguage analysis!

Implementation LOC

Part	LOC
Framework	13200



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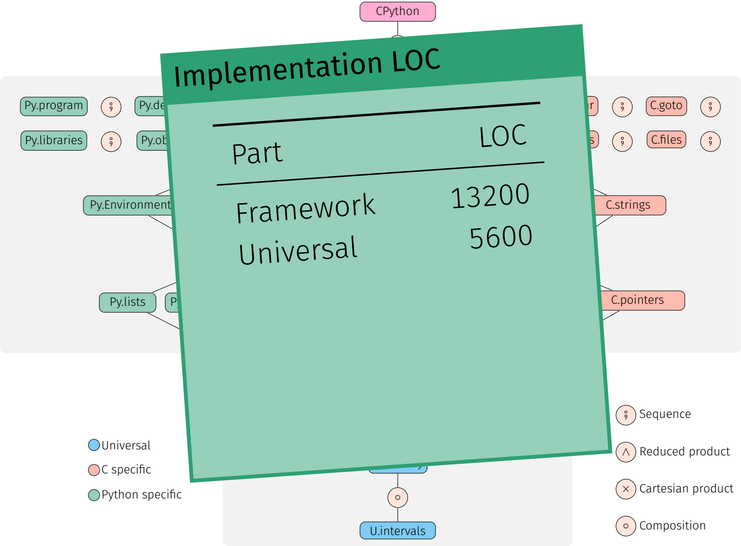

Implementation LOC

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Framework	13200
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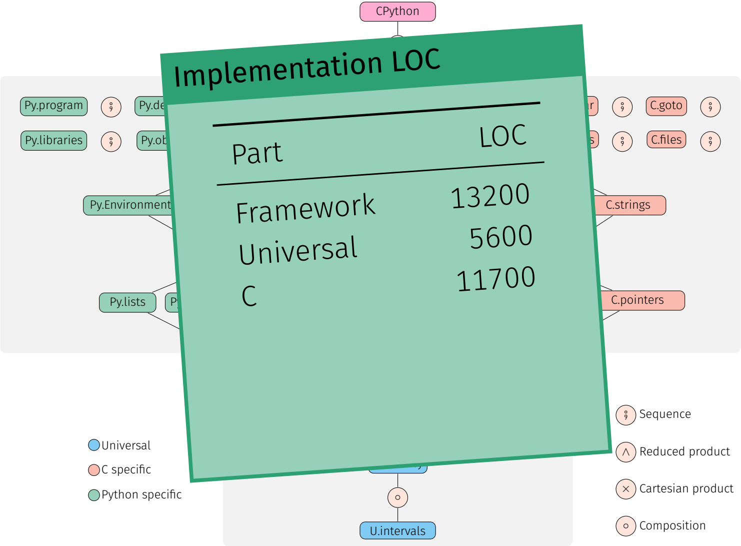

Implementation LOC

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Universal	5600
C	11700

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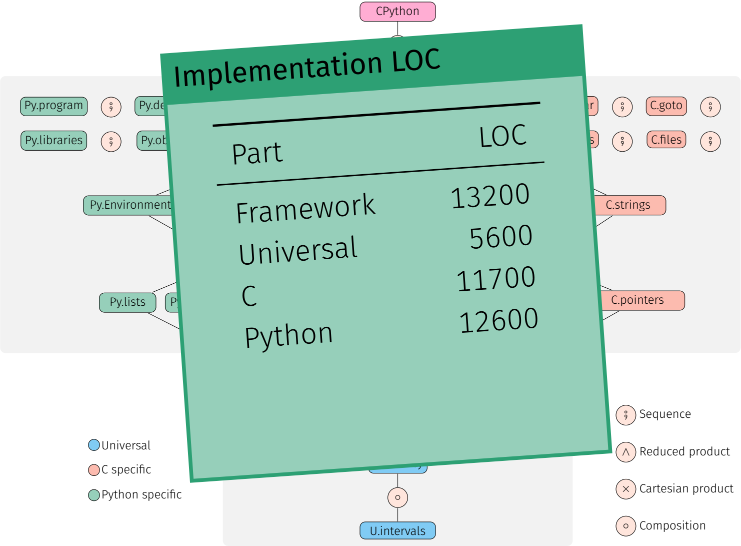

Implementation LOC

Part	LOC
Framework	13200
Universal	5600
C	11700
Python	12600

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Implementation LOC

Part	LOC
Framework	13200
Universal	5600
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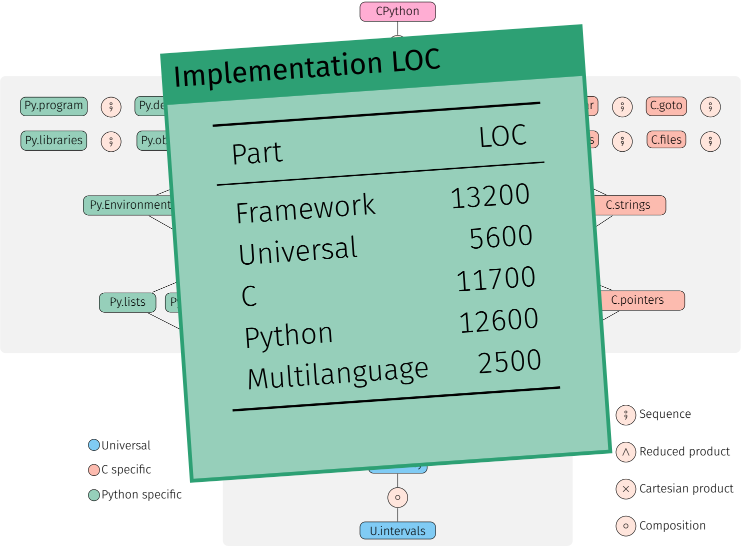
Python	12600
Multilanguage	2500



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

Related work

Theoretical frameworks

- Matthews and Findler[13] boundary functions as value conversions between two languages.
- Buro, Crole, and Mastroeni[14] generic framework for combining analyses of different languages.

[13] Matthews and Findler. “Operational semantics for multi-language programs”. 2009.
[14] 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[15]
- Type inference of Java objects in C code[16]
- Extraction of C callbacks to Java[17]

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

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

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

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

Conclusion

Contribution: concrete semantics of Python

Difficulties

- Size of the semantics
- CPython's source code

Contribution: concrete semantics of Python

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Previous works

- Executable semantics of Python
- Handcrafted tests

Contribution: concrete semantics of Python

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Previous works

- Executable semantics of Python
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Our results

- Semantics suitable for abstract interpretation
- Written and explained in the manuscript (70 cases)
- Backreferences to the source code
- Preliminary tests using CPython's suite

Contribution: type & value analyses of Python

Difficulties

- Dynamicity
- Dual type system
- Size of the semantics

[18] Monat, Ouadjaout, and Miné. "Static Type Analysis by Abstract Interpretation of Python Programs". ECOOP 2020.
[19] Monat, Ouadjaout, and Miné. "Value and allocation sensitivity in static Python analyses". SOAP@PLDI 2020.

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Our results

- Type analysis[18],
- Numeric value analysis & new sensitivities for the recency abstraction[19]
- Relational value analysis with packing (manuscript)
- Scale to small, real-world benchmarks

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Contribution: multilanguage Python/C analysis

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Our 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

Some future works

Executable concrete semantics

- Split soundness testing (CPython – concrete semantics – analyzer)
- Conformance tests

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- Beyond key/value summarization
- Empirical study of dictionary use (use of non-string keys)

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Multilanguage library analyses

- Other interoperability frameworks (Cffi, Swig, Cython)
- Infer Typeshed’s annotations
- Library analysis without client code

Static Type and Value Analysis by Abstract Interpretation of Python Programs with Native C Libraries

Questions

xkcd.com/353

Raphaël Monat

PhD defense
22 November 2021