Static Type Analysis by Abstract Interpretation of Python Programs

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Raphaël Monat, Abdelraouf Ouadjaout, Antoine Miné

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`https://rmonat.fr/ecoop20/`

Introduction

Python, from a PL perspective

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- `eval`.

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Python Example from the “os” Library

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def fspath(p):
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Introspection, nominal types.

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Static Analysis by Abstract Interpretation

Motivation

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- At “compile time”, before the program execution.

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Goals

- Automatic analysis: no expert knowledge required.
- Sound analysis: if no bug is detected, none will occur.

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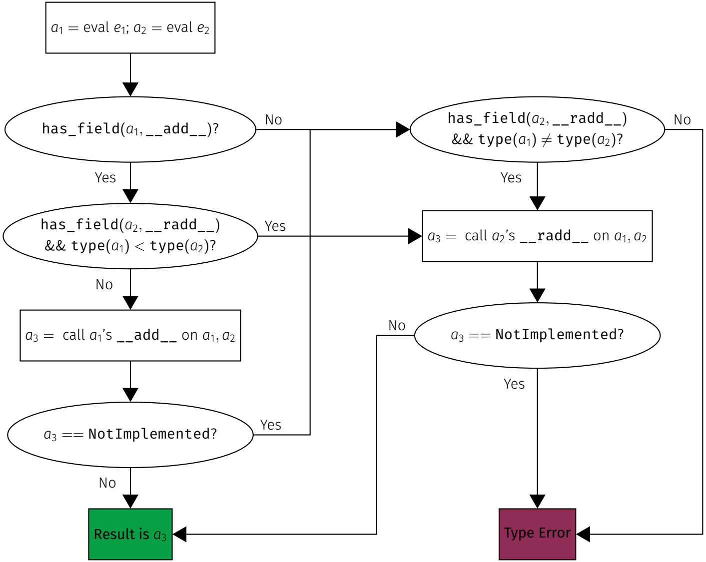
We present a type abstract domain for Python…
but first let us take a look at Python's semantics.

Concrete Semantics of Python

Semantics – Example: $e_1 + e_2$



Semantics – Example: $e_1 + e_2$

```
$\mathbb{E}[\![ e_1 + e_2 ]\!] (f, \epsilon, \sigma) \overset{\text{def}}{=}$
    if $f \neq cur$ then $(f, \epsilon, \sigma)$ else
    letif $(f, \epsilon, \sigma, a_1) =$ $\mathbb{E}[\![ e_1 ]\!] (f, \epsilon, \sigma)$ in
    letif $(f, \epsilon, \sigma, a_2) =$ $\mathbb{E}[\![ e_2 ]\!] (f, \epsilon, \sigma)$ in
    if $hasattr(\sigma(a_1), \_\_add\_\_)$ then
        if $hasattr(\sigma(a_2), \_\_radd\_\_) \land type(a_1) < type(a_2)$ then
            letif $(f, \epsilon, \sigma, a_r) =$ $\mathbb{E}[\![ a_2.\_\_radd\_\_(a_1) ]\!]$ in
            if $\sigma(a_r) = \texttt{NotImpl}$ then $empty\_addr \circ \mathbb{S}[\![ \texttt{raise TypeError} ]\!](f, \epsilon, \sigma)$
            else $(f, \epsilon, \sigma, a_r)$
        else letif $(f, \epsilon, \sigma, a_r) =$ $\mathbb{E}[\![ a_1.\_\_add\_\_(a_2) ]\!]$ in
            if $\sigma(a_r) = \texttt{NotImpl}$ then
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Type Analysis of Python

Features of the Analysis

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def dint(x):
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try: z2 = dint('a')
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```python
class A:
  def __init__(self): self.v = 0
x = A()
y = x.v # y: int
z = x
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Bravenboer and Smaragdakis. “Exception Analysis and Points-to Analysis: Better Together”. ISSTA 2009

Simplified Analysis: Example

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class Path:
  def __fspath__(self): return 42

p = "/dev" if random() else Path()

def fspath(p):
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- Addresses & aliasing[1]: $\mathsf{Addr}^\sharp \overset{\text{def}}{=} \mathsf{Location} \times \{\, \mathsf{r}, \mathsf{o} \,\}$

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- Flow-sensitive analysis: state partitioning by flow tokens

$$\mathcal{F}^\sharp \overset{\text{def}}{=} \{\, cur, ret, brk, cont, exn \;\; @^\sharp, @^\sharp \in \mathbf{Addr}^\sharp \,\}$$

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Dynamic attribute addition changes types	Immutable types
Similar, relational domain	Parametric polymorphism
More costly, context-sensitive interprocedural analysis	Functions are analyzed in isolation
Top-down analysis	Bottom-up analysis

Extensions of the Analysis

Relational Type Equality Domain

```
def get_sep(s):
  if isinstance(s, str): return '/'
  elif isinstance(s, bytes): return b'/'
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if *: r = '/dev/null'
else: r = b'/dev/null'
sep = get_sep(r)
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$$\underbrace{\begin{cases} r \in \{\, @_{str} \,\} \\ sep \in \{\, @_{str} \,\} \end{cases}}_{\text{if branch}} \sqcup \underbrace{\begin{cases} r \in \{\, @_{bytes} \,\} \\ sep \in \{\, @_{bytes} \,\} \end{cases}}_{\text{else branch}} = \begin{cases} r \in \{\, @_{str}, @_{bytes} \,\} \\ sep \in \{\, @_{str}, @_{bytes} \,\} \end{cases}$$

Relational Type Equality Domain

```
def get_sep(s):
  if isinstance(s, str): return '/'
  elif isinstance(s, bytes): return b'/'
  else: raise TypeError

if *: r = '/dev/null'
else: r = b'/dev/null'
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```

$$\underbrace{\begin{cases} r \in \{ @_{str} \} \\ sep \in \{ @_{str} \} \end{cases}}_{\text{if branch}} \sqcup \underbrace{\begin{cases} r \in \{ @_{bytes} \} \\ sep \in \{ @_{bytes} \} \end{cases}}_{\text{else branch}} = \begin{cases} r \in \{ @_{str}, @_{bytes} \} \\ sep \in \{ @_{str}, @_{bytes} \} \end{cases} \wedge \; r \equiv sep$$

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Then, we can analyze `res = r + sep` without false alarms.

The polymorphism improves the precision.

Interprocedural Analysis

What about a context-insensitive analysis?

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def f(e1, e2): return e1 + e2
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`e1.__add__` can be any function

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$\implies$ We focus on a context-sensitive analysis.

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Inlining most precise, but costly.

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def f(e1, e2): return e1 + e2
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$\implies$ We focus on a context-sensitive analysis.

Inlining most precise, but costly.

Towards function summaries a simple cache keeping the previous function analyses achieves up to 7x speedup on our benchmarks.

Experimental Evaluation

Implementation into Mopsa

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

- Modular abstract domains are small “blocks”.
- The user can select the combination of abstract domains.
- Supports Python and C analysis
  (some parts are shared in a “universal” language).

Available now: `https://gitlab.com/mopsa/mopsa-analyzer`

---

[2] Journault et al. “Combinations of reusable abstract domains for a multilingual static analyzer”. VSTTE 2019.

Features and Limitations

Our tool is sound; it supports:

- Objects
- Exceptions
- Dynamic typing
- Introspection
- Permissive semantics
- Dynamic attributes

Currently, it does not support:

- Recursive functions
- `super`
- metaclasses
- `eval`

Related Work on Python Analysis

- Dataflow analysis by Fritz and Hage[3].
- Sound Typpete: SMT-based type inference[4].
- Pytype, type inference tool used by Google.[5].
- RPython: efficient compilation of a static subset of Python[6].
- Sound Value Analysis by Fromherz et al[7].

---

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

[4] Hassan et al. "MaxSMT-Based Type Inference for Python 3". CAV 2018.

[5] Kramm et al. Pytype. 2019.

[6] Ancona et al. "RPython: a step towards reconciling dynamically and statically typed OO languages". DLS 2007.

[7] Fromherz et al. "Static Value Analysis of Python Programs by Abstract Interpretation". NFM 2018.

Experimental Evaluation

Name	LOC	Conf. 1	Conf. 2	⚠	Fritz & Hage	Pytype	Typpete	Fromherz et al.	RPython
🐇 bellman_ford.py	61	0.17s	0.24s	0†	1.4s	0.99s	1.4s	2.4m	7.1s
🐍 float.py	63	0.13s	82ms	0†	1.7s	0.92s	1.3s	0.84s	5.6s
🐇 coop_concat.py	64	45ms	43ms	0†	1.8s	0.81s	1.3s	20ms	🐞
🐍 spectral_norm.py	74	0.32s	0.19s	1	1.6s	0.98s	🐞	🐞	🐞
🐇 crafting.py	132	0.48s	0.41s	0†🔑	1.6s	0.97	1.7s	🐞	🐞
🐍 raytrace.py	411	3.5s	1.5s	7⚓	36s	2.8s	🐞	🐞	🐞
🐍 scimark.py	416	0.85s	0.55s	2†	8.5s	4.4s	🐞	🐞	🐞
🐍 richards.py	426	11s	5.0s	2†⚓	38s	2.4s	🐞	🐞	7.8s
🐍 unpack_seq.py	458	13s	4.2s	0⚓	1.1s	7.4s	2.7s	14s	🐞
🐍 go.py	461	4.0m	15s	32†⚓	8.5s	3.4s	🐞	🐞	🐞
🐍 hexiom.py	674	6.9m	22s	25†🔑⚓	🐞	4.2s	🐞	🐞	🐞
🐍 regex_v8.py	1792	8.2m	15s	0†	4.9s	🕒	1.7m	🐞	🐞
ⓕ processInput.py	1417	6.1s	4.8s	7†🔑⚓	2.4s	11s	🐞	🐞	🐞
ⓕ choose.py	2562	8.6m	46s	17🔑†⚓	1.7s	15s	🐞	🐞	🐞

Sound tool. 🐞 unsupported by the analyzer. 🕒 timeout (1h). Smashed Exceptions: KeyError 🔑, IndexError †, ValueError ⚓.

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A new static type analysis for Python:

- Takes into account dynamic Python features.

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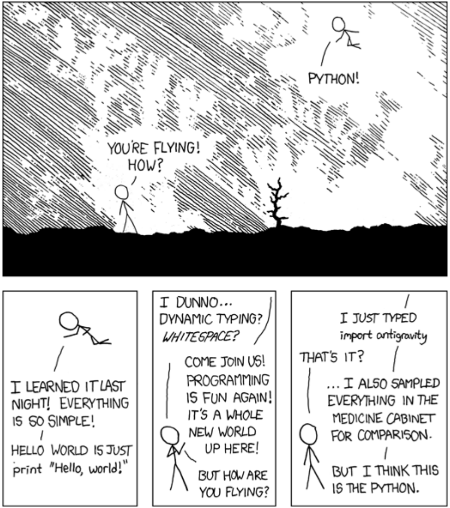
- Summary-based function analysis.
- Handle libraries.
- Analyze bigger programs.

Thank you! Questions?



`xkcd.com/353/`