Static Analysis of Python Programs

A Type Abstract Domain for Python

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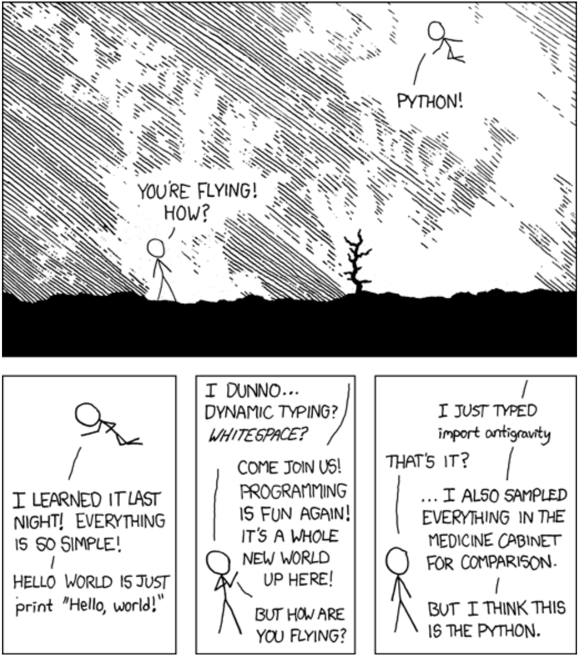
Introduction


YOU'RE FLYING! HOW?
PYTHON!
I LEARNED IT LAST NIGHT! EVERYTHING IS SO SIMPLE!
HELLO WORLD IS JUST print "Hello, world!"
I DUNNO... DYNAMIC TYPING? WHITESPACE?
COME JOIN US! PROGRAMMING IS FUN AGAIN! IT'S A WHOLE NEW WORLD UP HERE!
BUT HOW ARE YOU FLYING?
I JUST TYPED import antigravity
THAT'S IT?
... I ALSO SAMPLED EVERYTHING IN THE MEDICINE CABINET FOR COMPARISON.
BUT I THINK THIS IS THE PYTHON.

xkcd.com/353/

Python is a Dynamic Programming Language

It features:

- A concise and efficient syntax,
- Class-based objects,
- A large standard library,
- Dynamic typing: types are only known at runtime,
- Metaprogramming features:
  - Introspection,
  - Self-modification,
  - Metaclasses,
  - `eval`.

Python Example from the “os” Library

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Introspection, nominal types.

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Two notions of typing:

- Nominal, based on classes.
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Type of fspath?

str $\rightarrow$ str; bytes $\rightarrow$ bytes and any object having a method `__fspath__` returning str or bytes.

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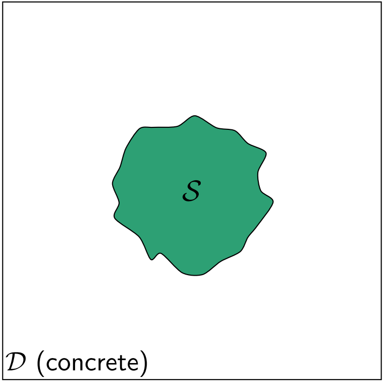
Goals

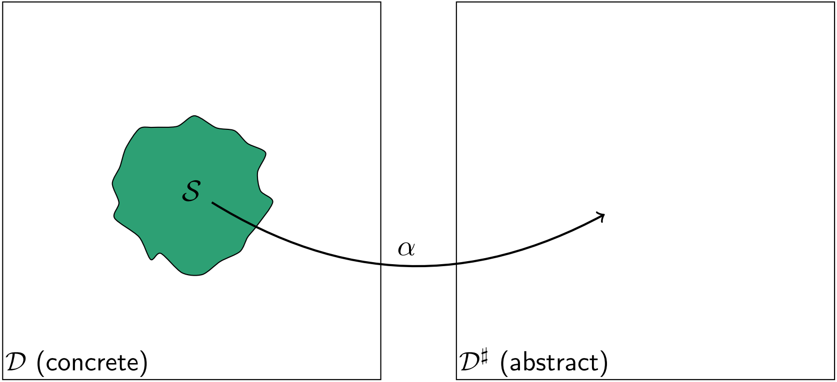
- Automatic analysis: no expert knowledge required.
- Sound analysis: if no bug is detected, none will occur.

Static Analysis by Abstract Interpretation 101



$\mathcal{D}^\sharp$ (abstract)

Static Analysis by Abstract Interpretation 101



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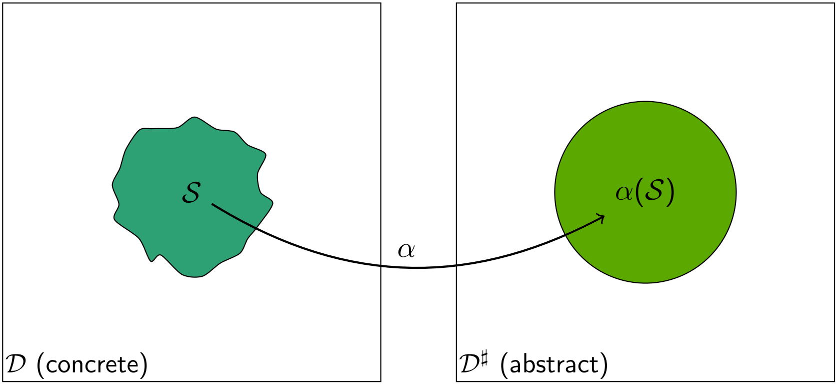

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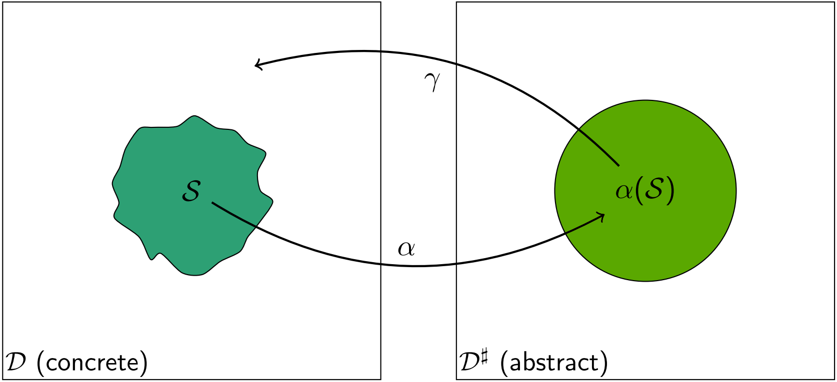

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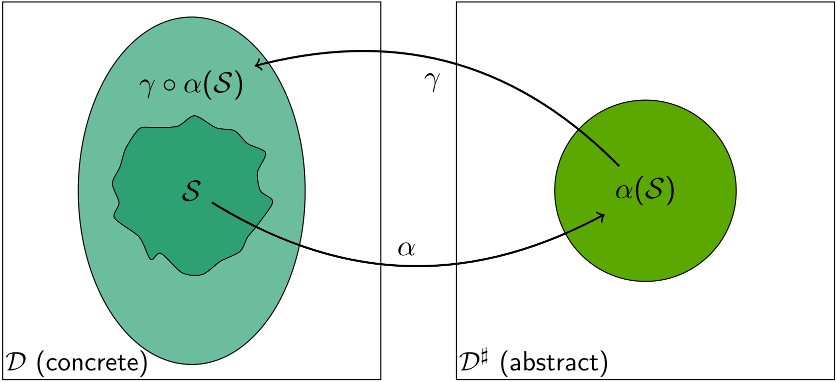

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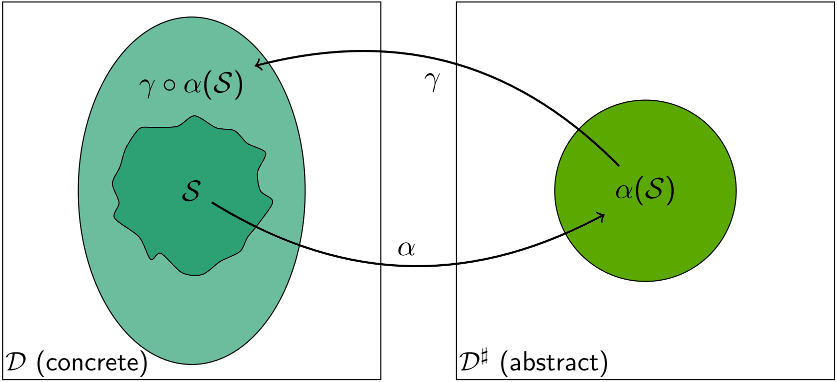

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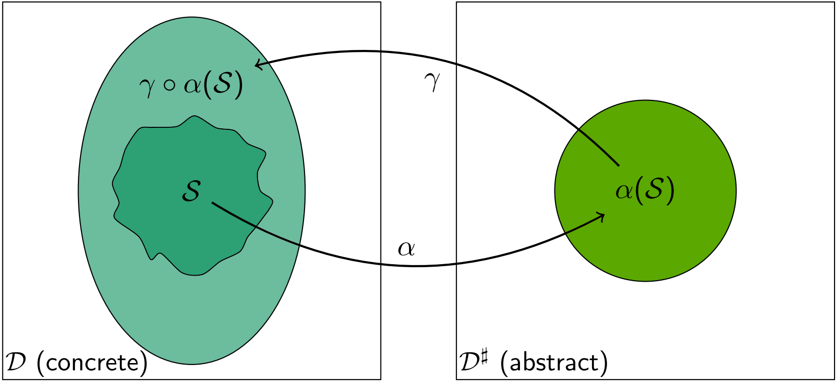

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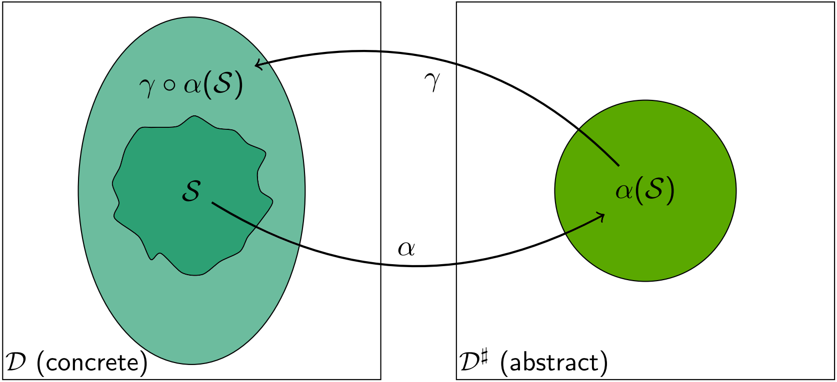

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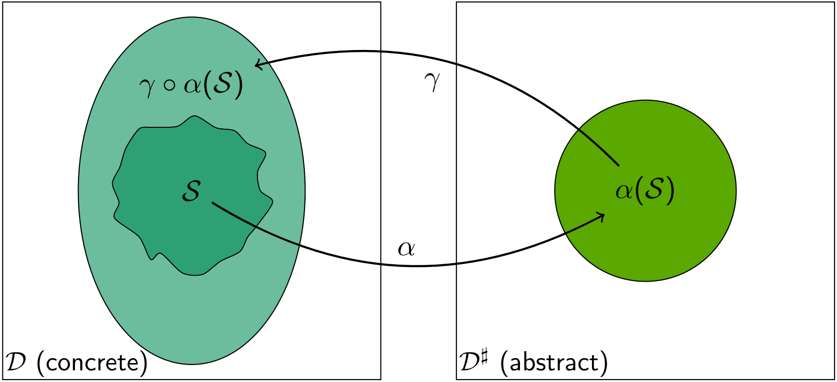

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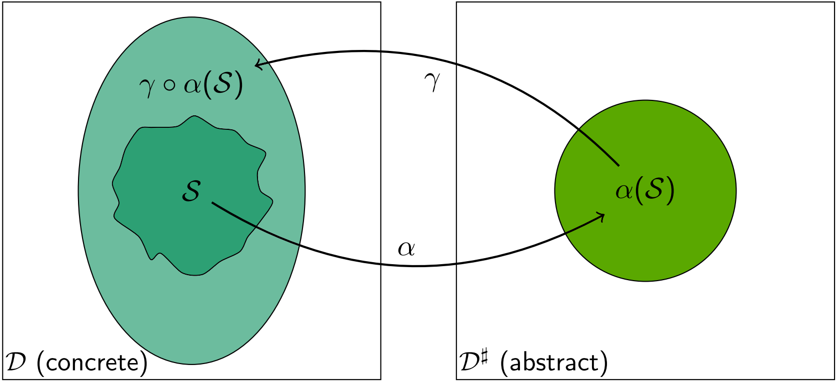

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- $\gamma \circ \alpha(\mathcal{S}) = \{\, 1, 2, 3, 4, 5 \,\}$

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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

Concrete Semantics – Motivation

Semantics? A mathematical description of the behavior of Python operators, acting like a collecting interpreter over program states.

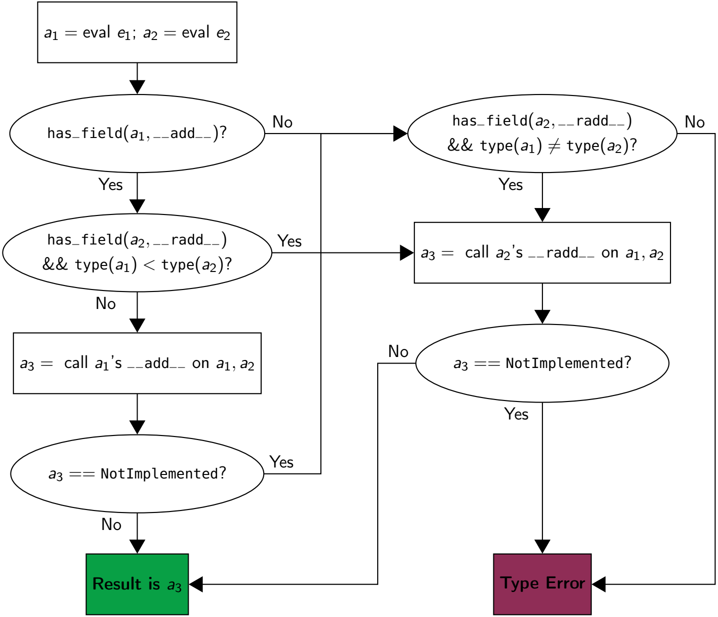
Why? To relate static analyses with the actual program behavior, and prove that our static analyses are sound.

Issues

- No standard.
- Size: Python is a huge language.
- Some parts are not formalized yet (`eval`, ...).
- Correctness: concrete semantics not implemented. But we can run our analysis on CPython's unittests.

$\Longrightarrow$ We need a concrete semantics, but this is not our endgoal.

Semantics – Example: $e_1 + e_2$



Semantics – Example: $e_1 + e_2$

$$
\begin{array}{l}
\mathbb{E}[\![\, e_1 + e_2 \,]\!]\,(f, \epsilon, \sigma) \stackrel{\text{def}}{=} \\
\quad \text{if } f \neq cur \text{ then } (f, \epsilon, \sigma) \text{ else} \\
\quad \text{letif } (f, \epsilon, \sigma, a_1) = \mathbb{E}[\![\, e_1 \,]\!]\,(f, \epsilon, \sigma) \text{ in} \\
\quad \text{letif } (f, \epsilon, \sigma, a_2) = \mathbb{E}[\![\, e_2 \,]\!]\,(f, \epsilon, \sigma) \text{ in} \\
\quad \text{if } hasattr(\sigma(a_1), \_\_add\_\_) \text{ then} \\
\quad\quad \text{if } hasattr(\sigma(a_2), \_\_radd\_\_) \wedge type(a_1) < type(a_2) \text{ then} \\
\quad\quad\quad \text{letif } (f, \epsilon, \sigma, a_r) = \mathbb{E}[\![\, a_2.\_\_radd\_\_(a_1) \,]\!] \text{ in} \\
\quad\quad\quad \text{if } \sigma(a_r) = \texttt{NotImpl} \text{ then } empty\_addr \circ \mathbb{S}[\![\, \texttt{raise TypeError} \,]\!](f, \epsilon, \sigma) \\
\quad\quad\quad \text{else } (f, \epsilon, \sigma, a_r) \\
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Type Abstract Domain

Features of the Analysis

Our goal: Detect uncaught exceptions, such as `TypeError`, `AttributeError`. Have a <u>sound</u> analysis.

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class A:
  def __init__(self):
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  def update(self, x):
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x = A()
c = x.val # c: int
y = x
# x, y point to the same address
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$\implies$ Handle addresses and aliasing.

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In addition, we can easily combine our analysis
with other analyses (value analysis, . . .).

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Abstract Addresses ($\mathbf{Addr}^\sharp$) have:

- A kind, representing the nominal type.
- A mode:
  - **weak**, meaning it summarizes multiple concrete addresses (only weak updates are possible on those addresses),
  - **strong**, abstracting one concrete address.

Description of the Type Abstract Domain

$\boxed{\text{Abstract environment (nominal types)} \qquad \mathcal{E}^\sharp = \mathbf{Id} \to \mathcal{P}(\mathbf{Addr}^\sharp)}$

Abstract Addresses ($\mathbf{Addr}^\sharp$) have:

- A kind, representing the nominal type.
- A mode:
  - **weak**, meaning it <u>summarizes</u> multiple concrete addresses (only weak updates are possible on those addresses),
  - **strong**, abstracting one concrete address.

We use the recency abstraction (Balakrishnan and Reps, "Recency-Abstraction for Heap-Allocated Storage").

Description of the Type Abstract Domain

$$\boxed{\text{Attribute abstraction (structural types)} \qquad \mathcal{S}^\sharp = \textbf{Addr}^\sharp \rightarrow \textbf{Attr}^\sharp}$$

Attribute abstraction (structural types) $\mathcal{S}^\sharp = \textbf{Addr}^\sharp \to \textbf{Attr}^\sharp$

Attribute under/over-approximation $\textbf{Attr}^\sharp = \mathcal{P}(\mathit{string})^2$

$$\gamma^\sharp_{\textbf{Attr}} : \begin{cases} \textbf{Attr}^\sharp & \to & \mathcal{P}(\mathcal{P}(\mathit{string})) \\ (u, o) & \mapsto & \{\, s \mid u \subseteq s \subseteq o \,\} \end{cases}$$

$$\gamma^\sharp_{\textbf{Attr}}(\{\, a \,\}, \{\, a, b, c \,\}) = \{\, \{\, a \,\}, \{\, a, b \,\}, \{\, a, c \,\}, \{\, a, b, c \,\} \,\}$$

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$$\text{let } \textbf{Obj } @, (\epsilon, \sigma) = \mathbb{E}^\sharp[\![\, e \,]\!]\,(\epsilon, \sigma) \text{ in}$$

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$$\mathbb{E}^\sharp[\![\, \texttt{object.\_\_new\_\_}(e) \,]\!]\, (\epsilon, \sigma) \stackrel{\text{def}}{=}$$

$$\quad \text{let } ee, (\epsilon, \sigma) = \mathbb{E}^\sharp[\![\, e \,]\!]\, (\epsilon, \sigma) \text{ in}$$

$$\quad \text{if } ee = \mathbf{Class}\ c \text{ then}$$

$$\qquad \text{let } \texttt{@}, (\epsilon, \sigma) = \mathbb{E}^\sharp[\![\, \text{alloc}(\mathbf{Inst}\ c) \,]\!]\, (\epsilon, \sigma) \text{ in } \mathbf{Obj}\ \texttt{@},\ (\epsilon, \sigma)$$

$$\quad \text{else empty\_eval} \circ \mathbb{S}^\sharp[\![\, \texttt{raise TypeError} \,]\!](\epsilon, \sigma)$$

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$$\mathbb{S}^\sharp [\![\, \texttt{object.\_\_setattribute\_\_}(x \in \textbf{Id}, attr \in string, e) \,]\!] (\epsilon, \sigma) \stackrel{\text{def}}{=}$$

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$$\text{let attr\_var} = \text{Var } (@_x, \text{attr}) \text{ in}$$

$$\text{if strong\_addr } @_x \text{ then}$$

$$\mathbb{S}^\sharp [\![\, \text{attr\_var} = e \,]\!] (\epsilon, \text{add\_under}(\sigma, @_x, \text{attr}))$$

$$\text{else}$$

$$\mathbb{S}^\sharp [\![\, \text{attr\_var} \stackrel{\text{weak}}{=} e \,]\!] (\epsilon, \text{add\_over}(\sigma, @_x, \text{attr}))$$

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

The polymorphism improves the precision.

A Modular List Domain

Ideas:

- Smash each list into one weak, abstract contents variable.
- The contents variable is built upon the list's abstract address.
- Delegate most of the work to the other domains.

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$$\mathbb{E}^\sharp[\![\, [e_1, \ldots, e_n]^{loc} \,]\!]\, s \stackrel{\text{def}}{=}$$

$$\textsf{let } @, \mathsf{s} = \mathbb{E}^\sharp[\![\, \mathsf{alloc}(\textbf{List } \mathit{loc}) \,]\!]\, s \textsf{ in}$$

$$\textsf{let } \mathsf{contents} = \mathsf{Var}(@, \texttt{"contents"}) \textsf{ in}$$

$$\textsf{let } \mathsf{s} = \mathbb{S}^\sharp[\![\, \mathsf{contents} \stackrel{\text{weak}}{=} e_n \,]\!] \circ \ldots \circ \mathbb{S}^\sharp[\![\, \mathsf{contents} \stackrel{\text{weak}}{=} e_1 \,]\!] s \textsf{ in}$$

$$\textbf{Obj } @, s$$

Lists and Polymorphisms

```
1 if *: l = [1, 2, 3]
2 else: l = [0.1, 0.2, 0.3]
3 x = l[0]
```

After line 1:

$l \mapsto \{ @_{list1} \}$

$@_{list1}.\text{content} \mapsto \{ @_{int} \}$

After line 2:

$l \mapsto \{ @_{list2} \}$

$@_{list2}.\text{content} \mapsto \{ @_{float} \}$

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After line 3 (join):

$$\begin{cases} l \mapsto \{ @_{list1}, @_{list2} \} \\ @_{list1}.\text{content} \mapsto \{ @_{int} \} \\ @_{list2}.\text{content} \mapsto \{ @_{float} \} \\ x \mapsto \{ @_{int}, @_{float} \} \end{cases}$$

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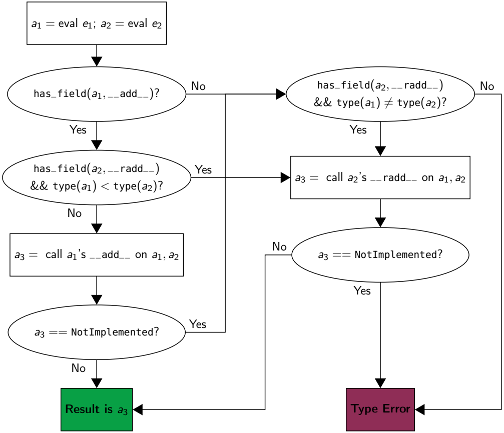
After unification and join:

$$\begin{cases} l \mapsto \{\, @_{list\{1,2\}} \,\} \\ @_{list\{1,2\}}.\text{content} \mapsto \{\, @_{int}, @_{float} \,\} \\ x \mapsto \{\, @_{int}, @_{float} \,\} \\ x \equiv @_{list\{1,2\}}.\text{content} \end{cases}$$

What about a context-insensitive analysis?

```
def f(e1, e2): return e1 + e2
```

f is valid whenever the evaluation hits the green box:



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Inlining most precise, but costly.

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Inlining most precise, but costly.

Towards function summaries a simple cache keeping the previous function analyses achieves up to 25x speedup on our benchmarks.

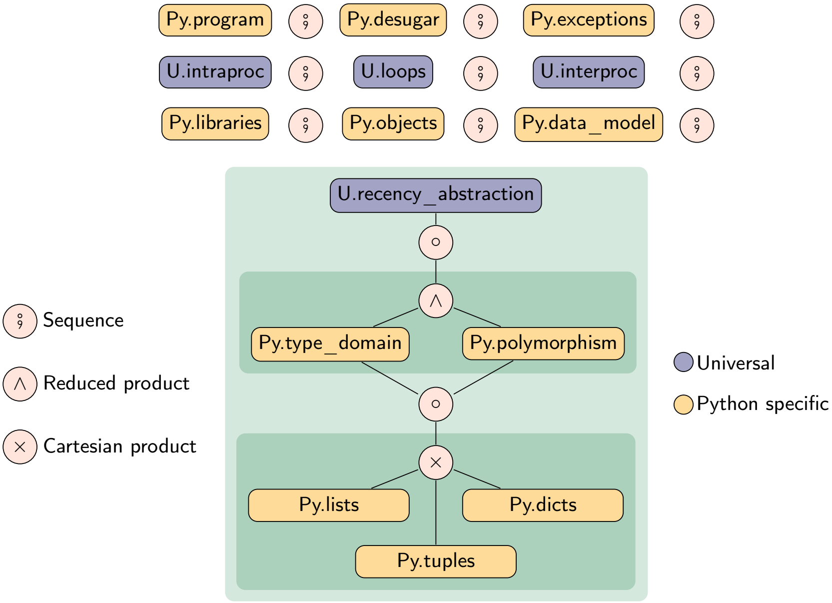
Experimental Evaluation

Modular **O**pen **P**latform for **S**tatic **A**nalysis[1]

- Modular abstract domains are small "blocks", handling everything from: abstract values to control-flow statements.
- Statements flow through these domains until one answers.
- The user can select the combination of abstract domains.
- Supports Python and C analysis (some parts are shared in a "universal" language).

[1] Journault et al. "Combinations of reusable abstract domains for a multilingual static analyzer". VSTTE19 Proceedings.

Implementation into MOPSA



Benchmarks

Official Python Benchmarks:

Name	LOC	Time (inlining)	Time (cache)	# Alarms	# False Alarms
fannkuch.py	59	0.07s	0.07s	0	0
float.py	63	0.10s	0.06s	0	0
spectral_n.py	74	3.9 s	0.33s	0	1
nbody.py	157	2.6s	1.5s	0	1
chaos.py	324	19s	5.9s	**1**	0
unpack_seq.py	458	5.6s	5.4s	0	0
hexiom.py	674	61.7m	2.2m	0	52

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unpack_seq.py	458	5.6s	5.4s	0	0
hexiom.py	674	61.7m	2.2m	0	52

[2] A real bug was found: a piece of currently unused code was working in Python 2.x, but not in Python 3.x.

Related Work

Related Work

JavaScript: more work has been done on JavaScript, including:

- Bodin et al.: semantics in Coq,
- Jensen, Møller, and Thiemann: Value Analysis for JavaScript.

Dynamic Analysis: Pyannotate and MonkeyType collect the types of a program at runtime. The types are valid for the explored trace.

Gradual Typing: annotated program parts are typechecked, while other parts have an unknown "top" type, from which any static type can be cast to and from. In Python: Mypy, Pyre.

Related Work II

Static Analysis of Python

- Fromherz et al[3]: a value analysis for Python (more costly). We have started a modular implementation of this analysis using our type domain.
- Typpete[4]: encodes type inference into a MaxSMT instance.
- Fritz & Hage[5]: performs a dataflow analysis.
- Pytype, tool from Google, performing a dataflow analysis.

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

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Our type analysis uniquely takes into account object mutability and control-flow.

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Conclusion

Conclusion & Future Work

We have developed a static type analysis for Python.

- More precise than the state-of-the-art static type analyses.
- Analyzes real-world benchmarks!
- Sound: it relates the analysis and the concrete semantics.

Future Work

- Support official type annotations (PEP 484).
- More efficient, summary-based function analysis.
- Handle libraries.
- Analyze real-world programs.

Appendix

Implementation into MOPSA

Implementation size:

- 5500 lines of OCaml for Python's semantics,
- 2500 for Python's type abstract domain,
- 2100 for Python's containers abstractions,
- 1800 for the universal language (loop & function analysis),
- 15000 for the modular framework.

Flow-sensitive analysis

Flow-sensitive Analysis Performed by induction over the syntax.

Using flow tokens to label continuation-passed states.

$\mathcal{F}^\sharp = \{\, cur, ret, brk, exn\ a, a \in \textbf{Addr}^\sharp \,\}$

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$$\mathbb{E}^\sharp[\![\, x \,]\!]\,(f \in \mathcal{F}^\sharp, \epsilon \in \mathcal{E}^\sharp, \sigma \in \mathcal{S}^\sharp) \stackrel{\text{def}}{=} \bigcup_{a^\sharp \in \epsilon(x)} \textbf{Obj}\ a^\sharp, (f, \epsilon[x \mapsto \{\, a^\sharp \,\}], \sigma)$$

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$$\text{letif } (\textbf{Obj}\ @, (f, \epsilon, \sigma)) = \mathbb{E}^\sharp[\![\, e \,]\!]\,(f, \epsilon, \sigma) \text{ in}$$

$$(f, \epsilon[x \mapsto @], \sigma)$$

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