Static Analysis by Abstract Interpretation of Dynamic Programming Languages

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Introduction

Static Analysis

- Detect bugs in programs
- Without having to execute them

Static Analysis

- Detect bugs in programs
- Without having to execute them

. . . by Abstract Interpretation

- Keep possible environments using overapproximations
- Sound analysis: if no bug is detected, no bug will occur
- Automatic analysis: no interaction with expert user needed

Dynamic Programming Languages

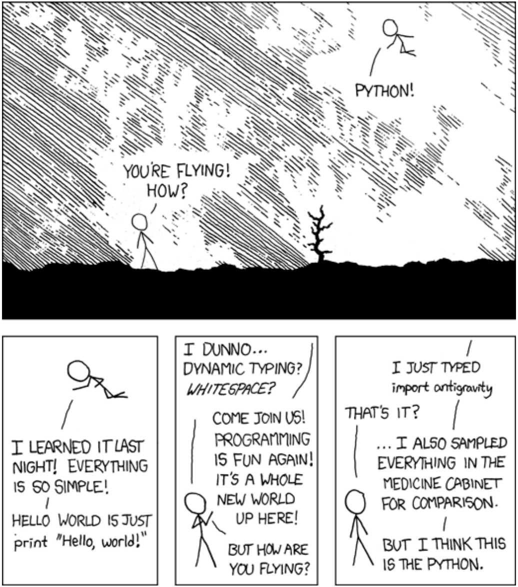
- Simple syntax, high-level features
- Dynamic typing: types are only known at runtime
- Introspection
- Self-modification
- Eval

Examples: JavaScript, Python, . . .

Static analyses are especially helpful – and difficult – on dynamic programming languages.

Python

Why?



Source: xkcd (`https://xkcd.com/353/`)

Semantics of Python

- ✗ No standard (and no formal semantics) defining Python.
- CPython's implementation is the definition.
- We use a slight modification of the semantics of Fromherz, Ouadjaout, and Miné[1].

[1] Fromherz, Ouadjaout, and Miné. "Static Value Analysis of Python Programs by Abstract Interpretation". NASA Formal Methods - 10th International Symposium, NFM 2018, Newport News, VA, USA, April 17-19, 2018, Proceedings.

Semantics of +

$$\mathbb{E}[\![e_1 + e_2]\!](f, \epsilon, \sigma) \stackrel{\text{def}}{=}$$

$\quad$ if $f \neq cur$ then $(f, \epsilon, \sigma, addr_{\text{None}})$ else

$\quad$ letif $(f_1, \epsilon_1, \sigma_1, a_1) = \mathbb{E}[\![e_1]\!](f, \epsilon, \sigma)$ in

$\quad$ letif $(f_2, \epsilon_2, \sigma_2, a_2) = \mathbb{E}[\![e_2]\!](f_1, \epsilon_1, \sigma_1)$ in

$\quad$ if $has\_field(a_1, \_\_add\_\_, \sigma_2)$ then

$\quad\quad$ letif $(f_3, \epsilon_3, \sigma_3, a_3) = \mathbb{E}[\![a_1.\_\_add\_\_(a_2)]\!](f_2, \epsilon_2, \sigma_2)$ in

$\quad\quad$ if $\sigma_3(a_3) = (\_, \texttt{NotImpl})$ then

$\quad\quad\quad$ if $has\_field(a_2, \_\_radd\_\_, \sigma_3) \wedge typeof(a_1) \neq typeof(a_2)$ then

$\quad\quad\quad\quad$ letif $(f_4, \epsilon_4, \sigma_4, a_4) = \mathbb{E}[\![a_2.\_\_radd\_\_(a_1)]\!](f_3, \epsilon_3, \sigma_3)$ in

$\quad\quad\quad\quad$ if $\sigma_4(a_4) = (\_, \texttt{NotImpl})$ then $\texttt{TypeError}(f_4, \epsilon_4, \sigma_4)$

$\quad\quad\quad\quad$ else $(f_4, \epsilon_4, \sigma_4, a_4)$

$\quad\quad\quad$ else $\texttt{TypeError}(f_3, \epsilon_3, \sigma_3)$

$\quad\quad$ else $f_3, \epsilon_3, \sigma_3, a_3$

$\quad$ else if $has\_field(a_2, \_\_radd\_\_, \sigma_2) \wedge typeof\, a_1 \neq typeof\, a_2$ then

$\quad\quad$ letif $(f_3, \epsilon_3, \sigma_3, a_3) = \mathbb{E}[\![a_2.\_\_radd\_\_(a_1)]\!](f_2, \epsilon_2, \sigma_2)$ in

$\quad\quad$ if $\sigma_3(a_3) = (\_, \texttt{NotImpl})$ then $\texttt{TypeError}(f_3, \epsilon_3, \sigma_3)$

$\quad\quad$ else $(f_3, \epsilon_3, \sigma_3, a_3)$

$\quad$ else $\texttt{TypeError}(f_2, \epsilon_2, \sigma_2)$

Evaluate e_1

slight modification from Fromherz, Ouadjaout, and Miné, "Static Value Analysis of Python Programs by Abstract Interpretation"

Semantics of $+$

$$
\begin{array}{l}
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\quad \text{if } f \neq cur \text{ then } (f, \epsilon, \sigma, addr_{\text{None}}) \text{ else} \\
\quad \text{letif } (f_1, \epsilon_1, \sigma_1, a_1) = \mathbb{E}[\![e_1]\!](f, \epsilon, \sigma) \text{ in} \\
\bullet\ \text{letif } (f_2, \epsilon_2, \sigma_2, a_2) = \mathbb{E}[\![e_2]\!](f_1, \epsilon_1, \sigma_1) \text{ in } \bullet \\
\quad \text{if } has\_field(a_1, \_\_add\_\_, \sigma_2) \text{ then} \\
\qquad \text{letif } (f_3, \epsilon_3, \sigma_3, a_3) = \mathbb{E}[\![a_1.\_\_add\_\_(a_2)]\!](f_2, \epsilon_2, \sigma_2) \text{ in} \\
\qquad \text{if } \sigma_3(a_3) = (\_, \texttt{NotImpl}) \text{ then} \\
\qquad\quad \text{if } has\_field(a_2, \_\_radd\_\_, \sigma_3) \wedge typeof(a_1) \neq typeof(a_2) \text{ then} \\
\qquad\qquad \text{letif } (f_4, \epsilon_4, \sigma_4, a_4) = \mathbb{E}[\![a_2.\_\_radd\_\_(a_1)]\!](f_3, \epsilon_3, \sigma_3) \text{ in} \\
\qquad\qquad \text{if } \sigma_4(a_4) = (\_, \texttt{NotImpl}) \text{ then } \texttt{TypeError}(f_4, \epsilon_4, \sigma_4) \\
\qquad\qquad \text{else } (f_4, \epsilon_4, \sigma_4, a_4) \\
\qquad\quad \text{else } \texttt{TypeError}(f_3, \epsilon_3, \sigma_3) \\
\qquad \text{else } f_3, \epsilon_3, \sigma_3, a_3 \\
\quad \text{else if } has\_field(a_2, \_\_radd\_\_, \sigma_2) \wedge typeof\, a_1 \neq typeof\, a_2 \text{ then} \\
\qquad \text{letif } (f_3, \epsilon_3, \sigma_3, a_3) = \mathbb{E}[\![a_2.\_\_radd\_\_(a_1)]\!](f_2, \epsilon_2, \sigma_2) \text{ in} \\
\qquad \text{if } \sigma_3(a_3) = (\_, \texttt{NotImpl}) \text{ then } \texttt{TypeError}(f_3, \epsilon_3, \sigma_3) \\
\qquad \text{else } (f_3, \epsilon_3, \sigma_3, a_3) \\
\quad \text{else } \texttt{TypeError}(f_2, \epsilon_2, \sigma_2)
\end{array}
$$

Evaluate e_2

slight modification from Fromherz, Ouadjaout, and Miné, “Static Value Analysis of Python Programs by Abstract Interpretation”

Semantics of +

$$\mathbb{E}[\![e_1 + e_2]\!](f, \epsilon, \sigma) \stackrel{\text{def}}{=}$$

$\text{if } f \neq cur \text{ then } (f, \epsilon, \sigma, addr_{\text{None}}) \text{ else}$

$\text{letif } (f_1, \epsilon_1, \sigma_1, a_1) = \mathbb{E}[\![e_1]\!](f, \epsilon, \sigma) \text{ in}$

$\text{letif } (f_2, \epsilon_2, \sigma_2, a_2) = \mathbb{E}[\![e_2]\!](f_1, \epsilon_1, \sigma_1) \text{ in}$

● $\text{if } has\_field(a_1, \_\_add\_\_, \sigma_2) \text{ then}$ ●

$\quad \text{letif } (f_3, \epsilon_3, \sigma_3, a_3) = \mathbb{E}[\![a_1.\_\_add\_\_(a_2)]\!](f_2, \epsilon_2, \sigma_2) \text{ in}$

$\quad \text{if } \sigma_3(a_3) = (\_, \texttt{NotImpl}) \text{ then}$

$\quad\quad \text{if } has\_field(a_2, \_\_radd\_\_, \sigma_3) \land typeof(a_1) \neq typeof(a_2) \text{ then}$

$\quad\quad\quad \text{letif } (f_4, \epsilon_4, \sigma_4, a_4) = \mathbb{E}[\![a_2.\_\_radd\_\_(a_1)]\!](f_3, \epsilon_3, \sigma_3) \text{ in}$

$\quad\quad\quad \text{if } \sigma_4(a_4) = (\_, \texttt{NotImpl}) \text{ then } \texttt{TypeError}(f_4, \epsilon_4, \sigma_4)$

$\quad\quad\quad \text{else } (f_4, \epsilon_4, \sigma_4, a_4)$

$\quad\quad \text{else } \texttt{TypeError}(f_3, \epsilon_3, \sigma_3)$

$\quad \text{else } f_3, \epsilon_3, \sigma_3, a_3$

$\text{else if } has\_field(a_2, \_\_radd\_\_, \sigma_2) \land typeof\, a_1 \neq typeof\, a_2 \text{ then}$

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$\quad \text{else } (f_3, \epsilon_3, \sigma_3, a_3)$

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If e_1 has method $\_\_add\_\_$

slight modification from Fromherz, Ouadjaout, and Miné, "Static Value Analysis of Python Programs by Abstract Interpretation"

Semantics of +

$\mathbb{E}[\![e_1 + e_2]\!](f, \epsilon, \sigma) \stackrel{\text{def}}{=}$

and if $\_\_add\_\_$ does not return `NotImpl`

$$
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\quad \text{if } f \neq cur \text{ then } (f, \epsilon, \sigma, addr_{\texttt{None}}) \text{ else} \\
\quad \text{letif } (f_1, \epsilon_1, \sigma_1, a_1) = \mathbb{E}[\![e_1]\!](f, \epsilon, \sigma) \text{ in} \\
\quad \text{letif } (f_2, \epsilon_2, \sigma_2, a_2) = \mathbb{E}[\![e_2]\!](f_1, \epsilon_1, \sigma_1) \text{ in} \\
\quad \text{if } has\_field(a_1, \_\_add\_\_, \sigma_2) \text{ then} \\
\qquad \text{letif } (f_3, \epsilon_3, \sigma_3, a_3) = \mathbb{E}[\![a_1.\_\_add\_\_(a_2)]\!](f_2, \epsilon_2, \sigma_2) \text{ in} \\
\qquad \bullet \text{ if } \sigma_3(a_3) = (\_, \texttt{NotImpl}) \text{ then } \bullet \\
\qquad\quad \text{if } has\_field(a_2, \_\_radd\_\_, \sigma_3) \wedge typeof(a_1) \neq typeof(a_2) \text{ then} \\
\qquad\qquad \text{letif } (f_4, \epsilon_4, \sigma_4, a_4) = \mathbb{E}[\![a_2.\_\_radd\_\_(a_1)]\!](f_3, \epsilon_3, \sigma_3) \text{ in} \\
\qquad\qquad \text{if } \sigma_4(a_4) = (\_, \texttt{NotImpl}) \text{ then } \texttt{TypeError}(f_4, \epsilon_4, \sigma_4) \\
\qquad\qquad \text{else } (f_4, \epsilon_4, \sigma_4, a_4) \\
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\quad \text{else if } has\_field(a_2, \_\_radd\_\_, \sigma_2) \wedge typeof\, a_1 \neq typeof\, a_2 \text{ then} \\
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\quad \text{else } \texttt{TypeError}(f_2, \epsilon_2, \sigma_2)
\end{array}
$$

slight modification from Fromherz, Ouadjaout, and Miné, "Static Value Analysis of Python Programs by Abstract Interpretation"

Semantics of +

return the result of the $\_\_add\_\_$ call

$$
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\quad \text{letif } (f_2, \epsilon_2, \sigma_2, a_2) = \mathbb{E}[\![\, e_2 \,]\!](f_1, \epsilon_1, \sigma_1) \text{ in} \\
\quad \text{if } has\_field(a_1, \_\_add\_\_, \sigma_2) \text{ then} \\
\qquad \text{letif } (f_3, \epsilon_3, \sigma_3, a_3) = \mathbb{E}[\![\, a_1.\_\_add\_\_(a_2) \,]\!](f_2, \epsilon_2, \sigma_2) \text{ in} \\
\qquad \text{if } \sigma_3(a_3) = (\_, \texttt{NotImpl}) \text{ then} \\
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\end{array}
$$

slight modification from Fromherz, Ouadjaout, and Miné, "Static Value Analysis of Python Programs by Abstract Interpretation"

Semantics of $+$

otherwise, if e_1 and e_2 have different types

$$
\begin{array}{l}
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\quad \text{letif } (f_1, \epsilon_1, \sigma_1, a_1) = \mathbb{E}[\![\, e_1 \,]\!] (f, \epsilon, \sigma) \text{ in} \\
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\qquad\quad \bullet \text{ if } has\_field(a_2, \_\_radd\_\_, \sigma_3) \wedge typeof(a_1) \neq typeof(a_2) \text{ then } \bullet \\
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\end{array}
$$

slight modification from Fromherz, Ouadjaout, and Miné, "Static Value Analysis of Python Programs by Abstract Interpretation"

Semantics of +

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$\quad\quad\quad\quad$ ● letif $(f_4, \epsilon_4, \sigma_4, a_4) = \mathbb{E}[\![\, a_2.\_\_radd\_\_(a_1) \,]\!]\,(f_3, \epsilon_3, \sigma_3)$ in ●

$\quad\quad\quad\quad$ if $\sigma_4(a_4) = (\_, \texttt{NotImpl})$ then $\texttt{TypeError}(f_4, \epsilon_4, \sigma_4)$

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$\quad$ else if $has\_field(a_2, \_\_radd\_\_, \sigma_2) \wedge typeof\, a_1 \neq typeof\, a_2$ then

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call the reflected method __*radd*__

slight modification from Fromherz, Ouadjaout, and Miné, "Static Value Analysis of Python Programs by Abstract Interpretation"

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$\quad$ else $\texttt{TypeError}(f_2, \epsilon_2, \sigma_2)$

raise a type error if nothing works

slight modification from Fromherz, Ouadjaout, and Miné, "Static Value Analysis of Python Programs by Abstract Interpretation"

Typing

fspath returns "the file system representation of the path."

Excerpt (and simplification) from Python's stdlib (os.py:1022).

```
def fspath(p):
  if isinstance(p, (str, bytes)):
    return p
  elif hasattr(p, "__fspath__"):
    res = p.__fspath__()
    if isinstance(res, (str, bytes)):
      return res
    else:
      raise TypeError("...")
  else:
    raise TypeError("...")
```

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Two kinds of typing:

- nominal typing (`isinstance`)
- duck typing (`hasattr`)

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Signature?

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```

Two kinds of typing:

- nominal typing (`isinstance`)
- duck typing (`hasattr`)

Signature?

$\alpha \to \alpha,\ \alpha \in \{\, \textit{str}, \textit{bytes} \,\}$

Typing

fspath returns "the file system representation of the path."

Excerpt (and simplification) from Python's stdlib (`os.py`:1022).

```
def fspath(p):
  if isinstance(p, (str, bytes)):
    return p
  elif hasattr(p, "__fspath__"):
    res = p.__fspath__()
    if isinstance(res, (str, bytes)):
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    else:
      raise TypeError("...")
  else:
    raise TypeError("...")
```

Two kinds of typing:

- nominal typing (`isinstance`)
- duck typing (`hasattr`)

Signature?

$\alpha \to \alpha,\ \alpha \in \{\, \mathit{str}, \mathit{bytes} \,\}$

Objects having method *__fspath__*, itself returning type α

Typing +

$$
\begin{aligned}
&\mathbb{E}[\![e_1 + e_2]\!](f, \epsilon, \sigma) \stackrel{\text{def}}{=} \\
&\quad \text{if } f \neq cur \text{ then } (f, \epsilon, \sigma, addr_{\texttt{None}}) \text{ else} \\
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$\Longrightarrow$ difficult to type + modularly

Type-based analysis of Python

Current state of the type analysis

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def fspath(p):
  if isinstance(p, (str, bytes)):
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    res = p.__fspath__()
    if isinstance(res, (str, bytes)):
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    else:
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  else:
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class FSPath:
  def __fspath__(self):
    return 42
```

```
r1 = fspath('a')
r2 = fspath(b'path')
r3 = fspath(FSPath())
```

- `r1:` `str`
- `r2:` `bytes`
- r3: TypeError raised

In the works: a partially modular interprocedural analysis

What kind of interprocedural analysis?

- Inlining

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- **Summary-based, top-down analysis**

Summaries keep the results of the previous analyses (a bit similar to memoization).

Digression: implementation into MOPSA

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

- Modular abstract domains for: abstract values, control-flow, ...
- Statements flow through abstract domains until one answers
- User selects the combination of abstract domains
- Currently, subsets of C and Python are supported

Future work

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- Other modular interprocedural analyses

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- Multilingual analysis (Python and C)
  - Analyze both Python code and CPython calls
  - Similarly, some Python libraries use a lot of C code

Appendix

Other Type Analyses

Program	Fritz and Hage	Pytype	Typpete	MOPSA - types
Analysis method	Dataflow analysis	Unclear	SMT-solver	AI
class_attr_ok	✓	✗	✳	✓
class_pre_store	✓	✓	✓	✓
default_args_class	✓	✓	✓	✓
except_clause	✗	✳	✓	✓
fspath	✗	✗	✳	✓
magic	✓	✓	✓	✳
polyfib	✳	✗	✳	✳
poly_lists	✳	✓	✳	✓
vehicle	✓	✓	✓	✳
widening	✓	✗	✳	✓

✓ sound and precise

✳ sound but false alarm

✗ unsound

Other Type Analyses

- Typpete [2]: uses an SMT solver to perform type inference

[2]Hassan et al. "MaxSMT-Based Type Inference for Python 3". CAV (2).

[3]Fritz and Hage. "Cost versus precision for approximate typing for Python". Proceedings of the 2017 ACM SIGPLAN Workshop on Partial Evaluation and Program Manipulation, PEPM 2017, Paris, France, January 18-20, 2017.

Other Type Analyses

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Other Type Analyses

- Typpete [2]: uses an SMT solver to perform type inference
- Work of Fritz and Hage[3]: analysis written in terms of data-flow equations
- Pytype: from engineers at Google, no technical reference

[2] Hassan et al. "MaxSMT-Based Type Inference for Python 3". CAV (2).

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Value Analysis of Python

Value Analysis[4]:

- incomparable with our analysis (due to the relationality)

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Value Analysis[4]:

- incomparable with our analysis (due to the relationality)
- generally more precise information, more costly
- support for large Python library more difficult to implement

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