

Path-sensitive Type Analysis with Backward Analysis for Quality Assurance of Dynamic Typed Language Code

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Abstract

Precise and fast static type analysis for dynamically typed language is very difficult. This is mainly because the lack of static type information makes it difficult to approximate all possible values of a variable. Actually, the existing static type analysis methods are imprecise or slow.

In this paper, we propose a novel method to improve the precision of static type analysis for Python code, where a backward analysis is used to obtain the path-sensitivity. By doing so, our method aims to obtain more precise static type information, which contributes to the overall improvement of static analysis.

To show the effectiveness of our method, we conducted a preliminary experiment to compare our method implementation and the existing analysis tool with respect to precision and time efficiency. The result shows our method provides more precise type analysis with fewer false positives than the existing static type analysis tool. Also it shows our proposed method increases the analysis time, but it is still within the range of practical use.

1 Introduction

Static analysis for dynamically typed languages has the problem that it is difficult to achieve both of precision and scalability. This is mainly because the lack of static type information makes it more difficult to approximate all possible values of a variable than in statically typed ones. For example, Monat et al., [1], a state-of-the-art analysis, is not capable of path-sensitive analysis. Pyre [2], another state-of-the-art one, has the problem that annotation must be given manually to achieve inter-procedural and scalable analysis.

In this paper, we propose a novel method to improve the precision of static type analysis for Python code, where a backward analysis is used to obtain the path-sensitivity. The backward analysis is performed on demand, so the path-sensitive analysis is performed selectively and intensively only where a detailed analysis is needed, which enables more precise and efficient analysis.

Our proposed method consists of two steps. In the first step, a flow-sensitive static type analysis is performed forwardly (based on the method of TAJIS [3]), which roughly overapproximates the type candidates of a variable. This overapproximation has the effect of reducing the number of the subsequent backward analyses. The next step performs the backward analysis for a part of variables, based on the result of the first step, to check whether there exists an execution path under a type candidate. When the execution path does not exist, the type candidate is discarded. Thus, path-sensitivity can be acquired by checking the existence (feasibility) of the execution path.

To show the effectiveness of our method, we conducted a preliminary experiment to compare our method implementation and the existing analysis tool with respect to precision and time efficiency. The result shows our method provides more precise type analysis with fewer false positives than the existing static type analysis tool. Also it shows our proposed method increases the analysis time, but it is still within the range of practical use for real-world medium-sized programs.

The contributions of this paper are as follows:

- We propose a novel precise static type analysis method with a path-sensitivity.
- We formalize the backward analysis for type analysis.
- We demonstrate the usefulness of our method through our method implementation and the preliminary experiment.

2 Background

2.1 Static Analysis

Static analysis is a technique of analyzing whether a program behaves correctly or not without executing the program itself, by approximating the behavior of the program. To achieve this, it is essential to approximate the state of the program in execution. This is because distinguishing all possible states of a program separately would result in a state explosion. And the more precise this approximation is, the more precise the results of the

```

1 class Create:
2     def run(self): ...
3
4 class Select:
5     def run(self): ...
6     def add_where(self): ...
7
8 def run_sql(mode):
9     # 'mode' is 'CREATE' or 'SELECT'
10    if mode == CREATE:
11        sql = Create()
12    else:
13        sql = Select()
14
15    ...
16
17    if mode == SELECT:
18        sql.add_where() # never called for 'Create'
19
20    sql.run()

```

Figure 1: The existing type analysis [1] produces a false positive result “`add_where` can be called even for the instance of `Create`” for this code due to insufficient path-sensitivity.

analysis will be, since it represents the behavior closer to the actual one of the program. However, precise approximation consumes a large amount of time and space resources, resulting in low scalability and the inability to analyze large codes. In particular, type analysis plays a very important role in static analysis for dynamically typed languages. This is because it is easier to make more precise approximations when the type information of variables is available. For this reason, when performing static analysis for dynamically typed language code, it is common to perform type analysis to determine the type of a variable. However, the existing methods do not perform path-sensitive type analysis and hence they are imprecise.

2.2 Path Sensitivity

Path-sensitivity in static analysis means that individual analysis result is computed separately for each (feasible) execution path. Although path-sensitive analysis is more precise, it requires a separate state for each execution path, which reduces its scalability as described in Sec. 2.1. Therefore, to obtain path-sensitivity, some technique for scalability is also required.

3 Problem Setting

To clarify our problem setting, this section provides our motivating example (Fig. 1), for which the existing type analysis [1] produces incorrect analysis result.

Fig. 1 is an example code, for which Monat et al. [1] produces a false positive analysis due to insufficient path-sensitivity. In this code, there are two classes: `Create`

and `Select`, both of which have `run` method. In addition, only `Select` class has `add_where` method. In `run_sql` function, instances of these classes are created according to the value of the argument `mode`, and the method `run` of the instance is called at line 20. However, at line 17, iff the value of `mode` is `SELECT`, that is, iff the type of `sql` is `Select` class, `add_where` method is called. Note that, according to the condition of the `if` statement at line 17, the type of `sql` at line 18 is always `Select` class. Thus, `add_where` method would be never called for the instances of `Create` class.

Unfortunately, a state-of-the-art research [1], which performs static type analysis for Python programs based on abstract interpretation, cannot correctly analyze this code and gives a wrong attribute error (false positive), that is, “`add_where` can be called even for the instance of `Create`”. Because the research [1] does not perform path-sensitive analysis, it merges the two states of the true/false branch paths after analyzing `if` statements and continues its analysis. Therefore, after the analysis of the `if` statement at line 10 to 13, the variable `sql` is analyzed as an instance of `Create` or `Select` class. Here, the analysis can refine the value of the variable `mode` from the conditional expression at line 17, but it cannot refine the type of the variable `sql`, since the analysis does not know the fact that the type of `sql` is `Select` iff `mode` is `SELECT`. Therefore, at line 18, the variable `sql` is analyzed as an instance of `Create` or `Select` class, which results in a (wrong) attribute error because there is no `add_where` method in `Create` class.

However, as we have just discussed above, this is a wrong error that never occurs when the program is executed. As we can see from the above example, existing type analysis tools are unable to perform path-sensitive type analysis for Python programs, resulting in false positives.

4 Proposed Method

This section provides an overview of our proposed method, and an example analysis for the motivating example in Fig. 1.

4.1 Overview of Proposed Method

Our proposed method consists of two steps: the forward analysis and the backward analysis. The forward analysis has the effect that it roughly overapproximates down the type candidates of a variable, while the backward analysis has the effect that it obtains a path-sensitivity. Thresher [4] and so on perform the backward analysis to obtain path-sensitivity, but the purpose of Thresher is pointer analysis, not type analysis. So one of the contributions of our proposed method is that it is the first one, to our knowledge, that performs the backward analysis for type analysis.

Now we define “query” as a constraint created by the relationship between variables and types, and also defines “witness” as an execution path that leads to a code location of current interest for a given initial query. The backward analysis adds constraints to the query, which must be satisfied to pass through the witness. Then, when the query becomes unsatisfiable in the repeated addition of constraints (i.e., when a contradiction arises in the constraints), we can conclude that there is no execution path that produces the relationship between the variable and the type represented by the initial query, and for this situation, we say “there is no witness that satisfies the initial query.” This implies we obtain path-sensitive type analysis result, since we eliminate infeasible execution paths in the backward analysis.

4.2 A Concrete Example of Backward Analysis

This section gives a concrete example of backward analysis for our motivating example in Fig. 1. We assume here that, in the forward analysis, we have already obtained the fact that the type of `sql` at line 18 is `Create` or `Select` class.

4.2.1 Initial Query is “the Type of `sql` at Line 18 is `Create` Class

First, we set the initial query to “the type of `sql` is `Create` class.” In fact, there is no execution path where the variable `sql` becomes of type `Create` class at line 18, so the backward analysis reveals that this query is *refuted*.

1. The initial query just before line 18 is:

$$sql \mapsto \hat{sql} \wedge \hat{sql} == \text{Create}$$

where $sql \mapsto \hat{sql}$ intuitively means the abstract value of the variable `sql` is \hat{sql} , and the constraint $\hat{sql} == \text{Create}$ must be satisfied.

2. Then, the conditional expression in the `if` statement at line 17 is added to the query

$$sql \mapsto \hat{sql} \wedge \hat{sql} == \text{Create} \\ \wedge mode \mapsto \hat{mode} \wedge \hat{mode} == \text{SELECT}$$

3. Then, the confluence of the `if` statement branches is reached at line 10. The two paths are analyzed separately: one through `then` clause and the other through `else` clause. In either case, the constraint obtained from the conditional expressions in the clause is added to the query when the analysis leaves the clause (i.e., when the analysis in the clause is finished), not when the analysis enters the clause.

3-1 The case through `then` clause:

- (a) The assignment at line 11 does not change the query.
- (b) The conditional expression at line 10 changes the query as follows:

$$sql \mapsto \hat{sql} \wedge \hat{sql} == \text{Create} \\ \wedge mode \mapsto \hat{mode} \wedge \hat{mode} == \text{SELECT} \\ \wedge \hat{mode} == \text{CREATE}$$

The value of the variable `mode` cannot be `SELECT` and `CREATE` at the same time, and thus this query is refuted. Therefore, the analysis knows there is no witness of passing through the `then` clause at line 10 to 13, that satisfies the initial query “the type of the variable `sql` is `Create` class.”

3-2 The case through `else` clause:

- (a) The assignment at line 10 changes the query as follows:

$$sql \mapsto \hat{sql} \wedge \hat{sql} == \text{Create} \\ \wedge mode \mapsto \hat{mode} \wedge \hat{mode} == \text{SELECT} \\ \wedge \hat{sql} == \text{Select}$$

The type of the variable `sql` cannot be `Create` and `Select` class at the same time, and thus this query is refuted. Therefore, the analysis knows there is no witness of passing through the `else` clause at line 10 to 13, that satisfies the initial query “the type of the variable `sql` is `Create` class.”

As the result, `Create` can be removed from the type of the variable `sql` just before line 18, since the type of the variable `sql` at line 18 turns out to be only `Select` class, and thus the analysis eliminates the attribute error at line 18. So, our proposed method can perform precise analysis by employing path-sensitive analysis with the backward analysis.

5 Formal Definition of Analysis

5.1 Formal Definition of Forward Analysis

Our forward analysis is flow-sensitive and path-insensitive, and is used to roughly overapproximate down the type candidates. This allows the backward analysis to be performed at fewer locations, which is expected to significantly increase the speed of the analysis.

In our proposed method (Fig. 2), the type (*Type*) is defined as a primitive type or a class (*Type_c*) declared in the program. The forward analysis is intended for type analysis, but it is also defined to allow primitives as abstract values, since this allows for more precise analysis.

primitives	$p \in Prim ::= None True False 0$ $ 1 \dots 1.0 \dots "foo" \dots$	$\llbracket \cdot \rrbracket^\# : Stmt \rightarrow (\widehat{State} \hookrightarrow \widehat{State})$
variables	$x, y, z \in Var$	$\llbracket x = p \rrbracket^\#(\hat{\sigma}) = \hat{\sigma}[x \mapsto p]$
attributes	$attr \in Attr$	$\llbracket x = y \rrbracket^\#(\hat{\sigma}) = \hat{\sigma}[x \mapsto \hat{\sigma}y]$
class types	$\tau_c \in Type_c ::= class\ Foo \dots$	$\llbracket x = y \oplus z \rrbracket^\#(\hat{\sigma}) = \hat{\sigma}[x \mapsto \hat{\sigma}y \sqcup \hat{\sigma}z]$
types	$\tau \in Type ::= BOOL INT FLOAT$ $ STR \tau_c$	$\llbracket x = y.attr \rrbracket^\#(\hat{\sigma}) = \hat{\sigma}[x \mapsto \bigcup_{\hat{a}_y \in \hat{\sigma}y} \hat{\sigma}getmem^\#(\hat{a}_y, attr)]$
abstract addresses	$\hat{a} \in \widehat{Addr}$	$\llbracket y.attr = x \rrbracket^\#(\hat{\sigma}) = \hat{\sigma}[getmem^\#(\hat{a}_y, attr) \mapsto \hat{\sigma}x]$ <i>for $\hat{a}_y \in \hat{\sigma}y$</i>
abstract memories	$\hat{m} \in \widehat{Mem} = Var \cup (\widehat{Addr} \times Attr)$	$\llbracket x = new\ y() \rrbracket^\#(\hat{\sigma}) = \hat{\sigma}[x \mapsto instance(\hat{\sigma}y)]$
abstract values	$\hat{v} \in \widehat{Val} = \widehat{Addr} \cup Type \cup Prim$	$\llbracket s_1; s_2 \rrbracket^\#(\hat{\sigma}) = \llbracket s_2 \rrbracket(\llbracket s_1 \rrbracket(\hat{\sigma}))$
abstract states	$\hat{\sigma} \in \widehat{State} = \widehat{Mem} \hookrightarrow \mathcal{P}(\widehat{Val})$	$\llbracket if(x)\ s_1\ else\ s_2 \rrbracket^\#(\hat{\sigma}) = \llbracket s_1 \rrbracket(\hat{\sigma}) \cup^\# \llbracket s_2 \rrbracket(\hat{\sigma})$

Figure 2: Concrete domain and abstract domain in the forward analysis.

For example, suppose that there is a variable `index` to access a list element. If primitives are not allowed as abstract values, there is no way to analyze what element of the list is being accessed. However, if primitives are allowed as abstract values, there are some cases where the analysis knows it, e.g., the case there is a conditional `func(1[index])` in the program. Thus, primitives as abstract values allow for more precise analysis, since it increases the cases where the element-sensitive analysis is available.

Now we define the abstract semantics based on abstract interpretation (Fig 3). In Fig 3, we provide the definitions for typical statements in Python. For the literal assignments ($x = p$), the variable x in the left-hand-side (LHS) is defined as to map to the primitive p in the right-hand-side (RHS). For the alias assignments ($x = y$), the variable x in LHS is defined as to map to the abstract values mapped by the variable y . Similarly, for binary-operator assignments ($x = y \oplus z$), it is defined as to map to the abstract values calculated in RHS.

For attribute read ($x = y.attr$), the variable x in LHS is defined as to map to abstract values ($\hat{\sigma} getmem^\#(\hat{a}_y, attr)$) mapped by the attribute $attr$ for all abstract addresses (\hat{a}_y) of objects mapped by the variable y . Similarly, for attribute write ($y.attr = x$), the attribute $attr$ for all abstract addresses of objects mapped by the variable y is defined as to map to abstract values mapped by the variable x . For instance creation ($x = new\ y()$), the variable x in LHS is defined as to map to the instance of the class object y .

The sequence ($s_1; s_2$) is defined as to analyze in order from s_1 to s_2 , while the conditional branch (`if(x) s_1 else s_2`) is defined as to merge the analysis results of the two branch paths.

In summary, the above abstract semantics are used to compute the abstract states of variables and the at-

$$\begin{aligned}
getmem^\# & : (\widehat{Addr} \times Attr) \hookrightarrow \widehat{Mem} \\
instance & : Type_c \rightarrow \widehat{Addr} \\
\sqcup & : (\mathcal{P}(\widehat{Val}) \times \mathcal{P}(\widehat{Val})) \rightarrow \mathcal{P}(\widehat{Val}) \\
\cup^\# & : (\widehat{State} \times \widehat{State}) \rightarrow \widehat{State}
\end{aligned}$$

Figure 3: Abstract semantics definition based on abstract interpretation.

tributes of objects in the forward analysis. The rough type analysis results obtained by this formalization are then refined by the backward analysis as defined in the next section (Sec. 5.2).

5.2 Formal Definition of Backward Analysis

The backward analysis checks each possible execution path and updates the constraints in the query to refute the query. This section defines the rules for the updates for all statements as Hoare logic.

As shown in Fig. 4, the query is represented by two

symbolic values	$\hat{x}, \hat{y}, \hat{z}, \hat{attr} \in \widehat{Var}$
symbolic expressions	$\hat{e} \in \widehat{Expr} ::= \hat{x} \hat{v} p \hat{e}_1 \oplus \hat{e}_2$ $ \hat{e}_1 == \hat{e}_2$
heap constraints	$H ::= True x \mapsto \hat{x}$ $ \hat{y}.attr \mapsto \hat{attr} H_1 * H_2$
pure constraints	$P ::= True \hat{e} P_1 \wedge P_2 $
query	$Q ::= False H \wedge P Q_1 \vee Q_2$

Figure 4: Defining domains for backward analysis.

Disjunction	$\frac{\langle Q'_1 \rangle s \langle Q_1 \rangle \quad \langle Q'_2 \rangle s \langle Q_2 \rangle}{\langle Q'_1 \vee Q'_2 \rangle s \langle Q_1 \vee Q_2 \rangle}$
Sequence	$\frac{\langle Q'_1 \rangle s_1 \langle Q'_1 \rangle \quad \langle Q'_1 \rangle s_2 \langle Q_1 \rangle}{\langle Q'_1 \rangle s_1; s_2 \langle Q_1 \rangle}$
IfElse	$\frac{\langle Q_1 \rangle s_1 \langle Q \rangle \quad \langle Q_2 \rangle s_2 \langle Q \rangle}{\langle (Q_1 \wedge x) \vee (Q_2 \wedge !x) \rangle \text{if}(x) s_1 \text{else } s_2 \langle Q \rangle}$
Constant	$\frac{}{\langle P \wedge \hat{x} == p \rangle x = p \langle P \rangle}$
Alias	$\frac{}{\langle (y \mapsto \hat{x} \wedge P) \rangle x = y \langle x \mapsto \hat{x} \wedge P \rangle}$
Binop	$\frac{\langle y \mapsto \hat{y} * z \mapsto \hat{z} \wedge P \wedge \hat{x} == \hat{y} \oplus \hat{z} \rangle}{\begin{array}{l} x = y \oplus z \\ \langle x \mapsto \hat{x} \wedge P \rangle \end{array}}$
AttrRead	$\frac{}{\langle y \mapsto \hat{y} * \hat{y}.attr \mapsto \hat{x} \wedge P \rangle \begin{array}{l} x = y.attr \\ \langle x \mapsto \hat{x} \wedge P \rangle \end{array}}$
AttrWrite	$\frac{}{\langle x \mapsto attr \wedge P \rangle \begin{array}{l} y.attr = x \\ \langle y \mapsto \hat{y} * \hat{y}.attr \mapsto attr \wedge P \rangle \end{array}}$
New	$\frac{h = y \mapsto \hat{y} \quad c = \bigvee_{\tau'_c \in \tau_c} (\hat{y} == \tau'_c)}{\langle h \wedge attr == undef \wedge c \wedge \hat{x} == \hat{y} \rangle \begin{array}{l} x = new y() \\ \langle h * x \mapsto \hat{x} \wedge P \rangle \end{array}}$

Figure 5: Defining analysis rule for the backward analysis.

kind of constraints: heap constraints and pure constraints. Heap constraints (e.g., $sql \mapsto \hat{sql}$ in Sec. 4.2) are used to relate a variable in the program (e.g., `sql` in Fig. 1), to a symbolic value (e.g., \hat{sql} in Sec. 4.2), while pure constraints (e.g., $\hat{sql} == \text{Create}$ in Sec. 4.2) are used to represent the constraints on symbolic values like “the variable `sql` must be of type `Create`.” Some pure constraints (e.g., $\hat{mode} == \text{CREATE}$ shown in Sec. 4.2) come from the analysis of conditionals like `if` statements.

Fig. 5 defines the analysis rules for the backward analysis as Hoare logic similar to the definitions in Thresher [4]. However, because this is the backward analysis, unlike ordinary Hoare logic, it is necessary to read the rules in the direction of post-constraints to pre-constraints. So, for a rule of the form $\langle Q \rangle s \langle Q' \rangle$, given a post-constraint Q' and a statement s , Q can be deduced from Q' , if executing statement s from a state satisfying Q produces a state satisfying Q' .

The first three rules in Fig. 5 are independent of the kind of statements. The rule Disjunction analyzes each

query represented by OR (\vee) individually. The rule Sequence indicates that backward analysis can be performed one statement at a time, starting with the last statement. Finally, the rule IfElse analyzes each path one by one when the path branches. As shown by the rules Disjunction and IfElse, the backward analysis analyzes each path one by one when a case split occurs, so it is necessary to analyze these branches more efficiently, and this is future work.

The remaining six rules in Fig. 5 define the rules corresponding to the kind of statements. The common point to all these six assignment rules is that the mapping from the LHS variable (the assigned variable) to the symbolic value (e.g., $x \mapsto \hat{x}$) is erased in the pre-constraint, since the mapping is the result of the assignment, and thus the mapping is useless in the pre-constraint. The rule Constant for constant assignments adds the constraint $(\hat{x} == p)$ ¹ that the symbolic value must be equal to the primitive value on RHS. The rule Alias for variable assignments ($x = y$) replaces the symbolic values mapped by the variable on RHS with the symbolic values (\hat{x}) mapped by the variable on LHS (so, the pre-condition includes $y \mapsto \hat{x}$). The rule Binop for binary-operator assignments adds the constraint $(\hat{x} == \hat{y} \oplus \hat{z})$ that the symbolic value of the variable in LHS after assignment must be equal to the calculated result of binary-operation in RHS before assignment. The rules AttrRead and AttrWrite both replaces the symbolic value similar to the rule Alias. Finally, the rule New adds the two constraints. One is $\hat{x} == \hat{y}$ that the types in LHS and RHS must be equal, and the other is that the new object’s attribute is *undef* ($attr == undef$).

6 Implementation and Preliminary Experiment

6.1 Implementation

We implemented our proposed method in Java based on Ariadne² and Thresher³. Ariadne is a Python extension of WALA⁴, which is a static analysis framework mainly for Java programs.

Note here that there are some Python programs that Ariadne does not support, so the following preprocessing was performed on the Python programs when used in the experiment (Sec. 6.2):

- Adding `import` statements for mock modules

¹At a glance, this rule seems wrong, as the value of the variable x before assignment is generally not p . However, this rule is correct and sound technically, since this rule works to refute the query by adding the constraint $\hat{x} == p$ to the pre-constraint, which actually holds in the post-constraint. Similar techniques are used in other rules.

²<https://wala.github.io/ariadne/>

³<https://github.com/cuplv/thresher>

⁴https://wala.sourceforge.net/wiki/index.php/Main_Page

- Replacing list comprehensions with `for`-loops
- Replacing `for-else` statements with `while-else` statements
- Explicitly specifying with an extra keyword argument that an actual argument is with the asterisk (*), as Ariadne just ignores the star information. (e.g., `func(*a) ⇒ func(*a, PYPSTA_STARED_ARG=a)`)
- Replacing some compound assignment operators with not compound assignment operators, while preserving the behavior (e.g., `a//=3; ⇒ a=a//3;`)

Although the formalization given in Sec. 5 is intra-procedural one, our implementation can perform inter-procedural analysis. Our implementation handles the function calls as follows:

- Function calls in the forward analysis:
 - When a function is called, the control of analysis is transferred to the inside of the function for further analysis. The abstract values of formal parameters become the abstract values of actual arguments in the analysis results at the time of the function call.
 - When the callee function returns, the control of analysis is transferred to the caller’s function call location. If there is a return value, the function’s return abstract value becomes the abstract value of the return expression.
- Function calls in the backward analysis:
 - When a function is called, the function call location is pushed to the stack, and then the control of analysis is transferred to the inside of the function and the analysis is continued from the function tail. If there are multiple function tails, the analysis is performed separately for each function tail.
 - When the function entry point is reached:
 1. If the stack is not empty, the control of the analysis is transferred to the function call location popped from the stack for further backward analysis.
 2. If the stack is empty, the analysis is performed separately for all possible callers obtained from the call graph.

In the experiment, the stack height was limited to 3. This is the same height as that used in Thresher [4].

To analyze the programs that use the standard library, we created and used *summaries* of the standard library, based on the *typedshed* project⁵. The *typedshed* project

is Python standard library and built-in functions with type annotations. This has also been used in previous studies such as Pyre [2]. However, the granularity of the abstract states obtained from the summaries is a “type”, which is coarser than that of the abstract values defined in the forward analysis, so the precision of the analysis may be reduced. To avoid this, we created handwritten summaries for some functions in the standard library and built-in functions.

To speed up the backward analysis, some optimizations are performed such as simplifying constraints in the middle of the analysis and skipping statements that do not affect the constraints.

6.2 Preliminary Experiment

Our preliminary experiment aims to answer the following research questions:

- RQ1: How precise are the analysis results of our proposed method compared to the existing methods?
- RQ2: What is the difference in analysis time of our proposed method compared to existing methods?

The environment used in the experiment is: Windows 10 Home, Intel Core i7-1065G7 CPU@1.30GHz (4-cores) and 32GB RAM.

Monat et al., [1] is employed as a comparison study for both of RQ1 and RQ2. We used two kinds of benchmarks: synthetic programs and real-world applications. The synthetic benchmarks are ones that the authors created, the ones used in Monat et al., [1] and Ariadne. The real-world benchmarks are the ones used in Monat et al., [1]. However, some real-world benchmarks in [1] were not supported by [1]. In such a case, we modified them so as to be analyzed in [1].

6.2.1 RQ1: How precise are the analysis results of our proposed method compared to the existing methods?

This experiment examines the number of false positives in each analysis result. Here, since all benchmarks do not produce errors at runtime, all errors detected by static analysis become false positives. So, we just count the number of errors detected in the analysis.

Also, since some errors (`KeyError`, `IndexError`, `ValueError`) are not counted in [1], and there are many potential errors that cannot be avoided for sound static analysis, we excluded the errors in the result of the experiment.

Table. 1 shows the result of the experiment, where program names with an asterisk (*) indicate synthetic benchmarks. The column “refuted” indicates the number of false positives generated by the forward analysis that could be analyzed as wrong errors by the backward analysis. Numbers in parentheses indicate the number of false

⁵<https://github.com/python/typedshed>

Table 1: Precision in the experiment

	LOC	our method		[1]
		FP	(refuted)	FP
dict.py*	9	0	1	1
mutation.py	10	0	0	0
for.py*	10	1	0	1
branch.py*	12	0	1	1
sql.py*	29	0	1	1
loop.py*	29	0	1	0
fannkuch.py	54	0	0	0
float.py	60	8(8)	0	8(8)
coop_con.py	65	0	0	0
spectral.py	74	0	0	1
craft.py	132	0	0	0
nbody.py	156	0	0	1
chaos.py	309	0	14(14)	0
richards.py	423	2(2)	25(374)	2(2)
unpack_seq.py	457	0	0	0

positive where the same false positive is counted twice for two different call-contexts (context-sensitive false positives). In our method, the backward analysis is performed at least these numbers of times.

There are false positives in both of our proposed method and Monat et al., [1] method for three programs, and, for all the three cases, the number of false positives of our proposed method are equal to those of Monat et al., [1] method. For most programs used in the experiment, using only the forward analysis, not the backward analysis, gave sufficiently high precise results. Because of this, there are few programs that are refuted by the backward analysis. Nevertheless, the result shows that the backward analysis for both synthetic and real-world programs refutes extra false positives and thus the backward analysis improves the precision.

The reason for the false positive in `for.py*` is because our proposed method analyzed the path that never executes the inside of the loop, even though it could be statically known that the inside of the loop is always executed at least once. To correctly analyze this, for example, we must add a constraint such that “the number of elements is greater than zero on the path through the inside of the loop” for the objects (lists, etc.) to be iterated in the `for` statement. However, this is not defined in the current backward analysis rules and this is also future work.

Also in `float.py`, both our proposed method and [1] gave a false positive. Fig. 6 is the code snippet from `float.py`. Each element of the variable `points` is initialized with `None` at line 2, and then all elements become instances of the `Point` class in the loop at line 3 to 4. However, our current analysis (and also Monat’s analysis) only knows that the variable `i` is of type `int`, and cannot know that all elements of the list are updated. Thus, the analysis thinks the list variable `points` can

```

1 def benchmark(n):
2     points = [None] * n
3     for i in range(n):
4         points[i] = Point(i)
5     for p in points:
6         p.normalize()
7     return maximize(points)

```

Figure 6: Example code where our proposed method gave a false positive

contain `None` as an element, and it gives a wrong attribute error (false positive) for the `normalize` attribute access at line 6, since `None` does not have the attribute `normalize`. Intuitively, it is statically known that the variable `p` cannot be of type `None`, but the analysis does not know this due to the lack of some rules in the backward analysis. For this case, we need the rule that generates the constraint on the variable `i` and `p` such as “the variable `i` has the values of the range of `range(n)`, i.e., a series of integers from 0 to `n-1` with no duplicates.”

The one of cause of the false positives in `richards.py` is an exception. The analysis cannot statically know that the exception is never raised on all possible paths. Such errors are a limitation of our proposed method as a static analysis. Of course, if the code that can raise an exception is a dead code, the backward analysis can refute it.

In `chaos.py` and `richards.py`, many types are refuted in the backward analysis. This is because the methods that gave an error are called in many contexts, and the backward analysis is done for each of those contexts.

The current rules in the backward analysis do not support some syntax rules, such as the accessing of container data types, loops, etc, which are generally not statically resolvable. However, there are some cases where they are statically resolvable like Fig. 6. So we need to refine the rules in the backward analysis so as to generate more detailed constraints for these syntax rules. This is future work.

6.2.2 RQ2: What is the Difference in Analysis Time of the Proposed Method Compared to Existing Methods?

Table. 2 shows the result of the experiment of analysis time, where the average time of three runs for each benchmark program is listed. The programs used in the experiment are all the real-world ones, since the synthetic ones are all too small. For all programs, the analysis time of our proposed method is more than that of Monat et al., [1]. In particular, the backward analysis on programs such as `richards.py` took significantly more analysis time than other programs, since the backward analysis is performed so many times for `richards.py` as shown in Table. 1. However, we consider the analysis time is still within the range of practical use even for the programs that requires a lot of times of the backward analysis (177

Table 2: The result of the experiment of analysis time for real-world programs

	LOC	our method(s)	[1](s)
mutation.py	10	1.05	0.021
fannkuch.py	54	1.25	0.077
float.py	60	7.92	0.083
coop_con.py	65	1.18	0.032
spectral.py	74	1.37	0.22
craft.py	132	1.40	0.43
nbody.py	156	1.50	0.028
chaos.py	309	12.83	2.77
richards.py	423	177.72	6.25
unpack_seq.py	457	9.19	5.35

seconds in Table. 2).

As shown in Sec. 6.1, there are some syntax rules not supported by Ariadne, so we needed to preprocess (i.e., modify) such Python codes for the experiment, but we found that the analysis generates false positives for some preprocessed codes due to this preprocessing (although they are refuted in the backward analysis). So the more syntax rules Ariadne supports, the less preprocessing we need to do, which leads to even fewer false positives in the forward analysis. This reduces the number of the backward analysis, resulting in faster analysis.

Of course, a further reduction of the analysis time is necessary, as a lot of times of the backward analysis is the root cause of the analysis time increase. For example, sharing the constraints among different backward analyses may make it easier to merge multiple path information, which may result in shorter analysis time. This is future work.

7 Related Work

7.1 Type Analysis

Monat et al. [1], Pyre [2], mypy [5], pytype [6], etc. are tackling the problem on static type analysis and static type checking for Python. The article [7] is the previous report by the authors of [1] and gave a detailed description of the abstract interpretation. Monat et al. [1] is almost mostly precise based on Python semantics, but it has the problem that it does not perform the path-sensitive analysis as described in Sec. 3. Flow [8] is a static type analysis method for JavaScript, and the study [2] is the type analysis tool for Python based on Flow [8]. The study [2] is path-sensitive, but there are some limitations, for example, manual type annotations are required and its precision is not enough. A detailed comparison of mypy and pytype is given in the article [9]. In particular, mypy cannot correctly analyze the code without annotations, and pytype cannot correctly analyze the code in Fig. 1 due to the lack of path-sensitivity.

7.2 Static Analysis for Dynamically Typed Languages

In addition to the studies [1] and [7], Fromherz et al. [10], PySA [11], PyCG [12] and NoCFG [13] are also static analysis tools for Python code. The study [1] is based on [10], which performs the static analysis using the abstract interpretation based on TAJs [3]. However, the study [10] is path-insensitive. PySA is a static taint analysis tool based on the technique of Pyre, but it has the problem that it cannot correctly analyze the code without annotations as well as Pyre, and it is path-insensitive. PyCG and NoCFG are static call graph generators for Python code. NoCFG utilizes the type inference in the call graph generation. Both analyses in PyCG and NoCFG are flow-insensitive and path-insensitive, and thus their analyses are imprecise.

TAJS [14, 3] and TAJSV_R [15] are static type analysis tools for JavaScript code. TAJs is widely used as a framework of the static type analysis for JavaScript, but it has the problem that it is not scalable and path-insensitive. The study [14] uses the techniques like the parameter-sensitivity and the loop specialization to more precisely analyze the abstract values of the variables. These techniques can be applied to the forward analysis of our proposed method to improve the precision. TAJSV_R is based on TAJs, and improves the field-sensitivity for JavaScript objects by the backward analysis. However, the result of type analysis is path-insensitive, since it is based on TAJs. This problem may be resolved by the path-sensitive type analysis in our proposed method.

7.3 Static Analysis using Backward Analysis

Like our proposed method, Thresher [4], TAJSV_R [15] and SUPA [16] use the backward analysis to improve the precision. Thresher refines the result of pointer analysis by the formalization based on Hoare logic (our proposed method also uses a similar formalization based on Hoare logic). SUPA aims to perform fast flow-sensitive pointer analysis, and also uses the backward analysis to refine the pointer information. They are the same as our proposed method in that they use the backward analysis, but differ in their intended purposes: the pointer analysis in Thresher and SUPA, and the type analysis for dynamically typed languages in our proposed method.

8 Conclusion

This paper proposed a novel method to improve the precision of static type analysis for dynamically typed languages. To improve precision, our proposed method performs a path-sensitive analysis with the backward analysis. The backward analysis analyzes the paths one at a

time on demand, which enables fast path-sensitive analysis.

The preliminary experiment shows our proposed method improved the precision, compared to the existing static type analysis tool. Also it shows our proposed method increases the analysis time, but it is still within the range of practical use.

Our future work includes even higher precision by defining the detailed rules in the backward analysis for container data types and loops, and even shorter analysis time by sharing the constraints among different backward-analyses.

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