Abstract

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Chapter 1

Introduction

Object-oriented programming languages have been adopted widely over the past two decades. As of March 2022, the top five positions of the TIOBE index are occupied by Python, C, Java, C++ and C#. Four of these languages (with the exception of C) are considered object-oriented and, as the index suggests, are widely adopted and used in large-scale commercial products.

1.1 Properties of Object-Oriented Programming Languages

According to [1], *object-oriented* programming languages are the languages where the main unit of abstraction is an *object*. Objects encapsulate *data*, which are the values of some type. Some languages, e.g. Java and C++, distinguish between *primitive types*, which represent low-level constructs like numbers or boolean values, and *object types*, which represent a composite type. Objects may also contain operations on the said data, known as *methods*. Methods can take parameters and may return a value.

Objects should also obey certain definitive properties. As [1] suggests, ” the extent to which a particular language satisfies these properties defines how much of an object-oriented language it is.” These properties are:

- Encapsulation - an object should expose a well-defined interface through which it should be consumed. The irrelevant details of how an object implements this interface should be *hidden* from the consumer.
- Inheritance - is a mechanism through which objects can share functionality and extend the behavior of other objects. Inheritance is a complex mechanism and its implementation differs from language to language. As per [1], ”Inheritance enables programmers to reuse the definitions of previously defined structures. This clearly reduces the amount of work required in producing”.
- Polymorphism - a possibility to define operations on objects in such a way, that they can accept and return values of multiple types.
- Dynamic (or late [2]) binding - the implementation of the method to be run on an object is chosen at runtime. This implies that the implementation that is used during the runtime of a program may be *different* from that of a type that is known statically (i.e. at compile time)

1.2 Criticism

Together with increasing adoption, OO programming techniques and languages have gained a substantial amount of valid criticism. Mansfield [3] mentions most of these complaints, ultimately claiming that ”...with OOP-inflected programming languages, computer software becomes more verbose, less readable, less descriptive, and harder to modify and maintain". Many of these criticisms are being turned into recommendations, such as the famous "Design patterns: elements of reusable object-oriented software" [4]. However, such recommendations are not the part of the language specification and thus can not be enforced by the language compiler. This leads to these recommendations often being misinterpreted or overused, especially by beginners.

1.3 Analysis Tools

To mitigate this complexity and enforce good practices, developers have created a lot of software tools. These tools can be divided into two categories: **dynamic** analyzers and **static** analyzers.

Dynamic analyzers (also known as *profilers*) inspect the state of the program as it is being executed. Dynamic analyzers collect important information about the program execution, such as CPU utilization and memory consumption and present it in the human-readable form. This information is crucial in applications where the performance plays an important role. Unfortunately, the tools require the program under analysis to be executed, which can be expensive or even impossible, e.g. when the program is to be run on dedicated hardware.

On the contrary, **static** analyzers inspect the source code of the program (or one of its intermediate representations) *without executing it* to locate common errors, anti-patterns and deviations from the accepted style conventions. Executing such tools isn't usually time-consuming or otherwise expensive, which is why they are a crucial part of continuous integration (CI) pipelines and integrated development environments (IDEs). Despite being prone to false positives, static analysis tools can pinpoint the location of the error with greater precision.

Unlike dynamic analyzers, static analyzers operate on the source code, which allows them to inspect the program from a higher-level perspective. This means that static analyzers can improve the error reporting of programming language compilers, discover more problems, and even automatically fix them.

Prior to analysis, many static analysis tools convert the source of the target language into some intermediate representation. This is done for several reasons. In general, this is done to extract the information from the source code that is relevant for analysis needs. Another common use case for employing an intermediate representation would be to make the static analyzer work with more than one target language. In this case the representation serves as a common ground for the various analyzers. The examples of intermediate representation are LLVM [5] and Jimple [6] (used in SOOT [7]).

1.4 Research Objective

In this thesis we present an implementation of a module for a static analyzer of object-oriented programs which takes the program representation in Elegant Objects (EO) [8] as an input and produces simple error messages as output. EO is an intermediate representation based on ϕ-calculus, a formal model that is intended to unify the varying semantics of object-oriented languages. It also claims to be a language with minimum verbosity, providing the minimum necessary set of operations. The combination of a strict formal ground and a reduced feature set make EO a powerful intermediate representation for a static analyzer that should be able to capture many bugs specific to OO programs. This thesis describes the proof-of-concept implementation of detecting the two defects of the ”fragile base class” [9] family: ”unanticipated mutual recursion” and ”unjustified assumption in modifier”.

The rest of this thesis is structured as follows: chapter 2 covers the existing work of finding bugs in OO programs, chapter 3 describes the semantics of EO and how it can represent object-oriented programs, chapter 4 describes the implementation of the analyzer, chapter 5 covers the evaluation of the implementation, including testing and benchmarks and, finally, chapter 6 concludes the thesis.

Chapter 2

Literature Review

Static analysis of object-oriented programs is a well-studied area. However, most of the effort in these studies was focused on analysing specific languages.

One of these areas is the . This area is crucial for this thesis, because it motivates the existence of the tool we are trying to create. Another area of interest may be ”attempts to establish a formal foundation for object-oriented languages”. This is the area where we may find how EO intersects with other similar works in the area and what sets it apart.

2.1 Navigation

2.2 Methods & Criteria

2.3 Fragile Base Class Problem

2.4 Intermediate Representations for Static Analyzers

2.5 Formalizations of Object-oriented Programming

Chapter 3

Methodology

This chapter presents the formal basis required to understand the implementation part. Section 3.1 briefly describes the relevant parts of φ-calculus: its syntax and semantics. Section 3.2 explains how φ-calculus maps to EO, the intermediate representation the analyzers operate on. Section 3.3 shows how to encode basic object-oriented constructs (classes, methods, inheritance) by means of EO. Sections 3.4 and 3.5.1 explain their respective defect type and how it can be detected in an EO program.

3.1 φ-calculus

EO is a programming language that implements φ-calculus, a formal model for object-oriented programming languages initially introduced by Bugayenko [8]. In this thesis we use a refinement of φ-calculus proposed by Kudasov and Sim [10].

3.1.1 Objects and attributes

At the heart of φ-calculus lies the concept of **object**.

Definition 1 (Objects and attributes)**.** An **object** is a set of pairs $[\![n_0 \mapsto o_0, n_1 \mapsto o_1, \ldots, n_i \mapsto o_i, \ldots]\!]$, where n_i is a unique identifier and o_i is an object. Such pairs are known as **attributes**. The first element is the **attribute name** the second element is the **attribute value**. An empty set $[\![]\!]$ is also a valid object. An attribute where the second element is $[\![]\!]$ is called **void** or **free**. Otherwise, it is known as **attached**.

Attributes of object can be accessed by their names via the dot notation:

$$[\![x \mapsto y]\!].x \leadsto y$$

In this case, this would reduce to just object y, which is defined elsewhere. $\leadsto$ means ”is reduced to” or ”evaluates to”.

3.1.2 Application

Application can be used to create a new object where the values of the some or all free attributes are set. In other words, application can be used to create *closed* objects from *abstract* objects.

Definition 2 (Abstract and closed objects)**.** If an object has one or more free attributes it is called **abstract** or **open**. Otherwise, it is called **closed**.

For example, object a in 3.2 corresponds to a point in a two-dimensional space with coordinates $x = 1, y = 2$. The objects 1 and 2 can be defined in terms of φ-calculus, however the definition itself is out of the scope of this thesis.

$$point := [\![x \mapsto [\![]\!], y \mapsto [\![]\!]]\!] \tag{3.1}$$

$$a := point(x \mapsto 1, y \mapsto 2) \tag{3.2}$$

$$a \rightsquigarrow [\![x \mapsto 1, y \mapsto 2]\!] \tag{3.3}$$

3.1.3 Locators

The revisision of φ-calculus by Kudasov and Sim [10] also defines special objects called **locators**, which are denoted as ρ^i, where $i \in \mathbb{N}$. Locators allow objects to reference other objects relatively to the object where the locator is used. For example, this can be used to (but is not limited to) encode definition of attributes in terms of other attributes of this object. Suppose there is an object x:

$$x := [\![a \mapsto \rho^0.b, b \mapsto c]\!]$$

The expression $x.a$ would be reduced to the value of object c. This happens because $x.a$ references $x.b$ via ρ^0, which means the immediate enclosing object. In more complicated examples, like 3.4.

$$x := [\![a \mapsto [\![c \mapsto \rho^1.b]\!], b \mapsto d]\!] \tag{3.4}$$

$$x.a.c \rightsquigarrow d \tag{3.5}$$

ρ can be used to define attributes of inner objects in terms of attributes of outer objects, or even outer objects themselves.

3.1.4 φ-attribute

Objects can define a special attribute with name φ. This attribute redirects attribute access to its value when the enclosing object does not have an attribute with such a name (fig. 3.6).

$$a := [\![d \mapsto y]\!] \tag{3.6}$$

$$x := [\![\varphi \mapsto a, c \mapsto g]\!] \tag{3.7}$$

$$x.d \rightsquigarrow x.\varphi.d \rightsquigarrow y \tag{3.8}$$

If the attribute is present both in the object and its φ-attribute, the attribute in the object takes precedence:

$$\begin{aligned} a &:= [\![d \mapsto y]\!] \\ x &:= [\![\varphi \mapsto a, \mathbf{d} \mapsto g]\!] \\ x.d &\rightsquigarrow g \end{aligned}$$

In 3.7, Bugayenko [8] refers to object *a* as **decorated object**, where the ”decorated” part refers to the decorator pattern described in [4, Chapter 4]. This technique of extending an object is also known as *delegation* [11] in object-oriented languages.

3.1.5 Complete example

Tying everything together, figure 3.1 shows how φ-calculus can be used to compute Fibonacci numbers.

$$
\begin{array}{l}
\mathit{fib} := [\![\\
\quad n \mapsto [\![]\!], \\
\quad \varphi \mapsto \rho^0.n.\mathit{less}(n \mapsto 2).\mathit{if}(\\
\quad\quad \mathit{ifTrue} \mapsto n, \\
\quad\quad \mathit{ifFalse} \mapsto \\
\quad\quad \mathit{fib}(n \mapsto \rho^0.n.\mathit{sub}(n \mapsto 1)) \\
\quad\quad .\mathit{add}(n \mapsto \mathit{fib}(n \mapsto \rho^0.n.\mathit{sub}(n \mapsto 2) \\
\quad) \\
\quad) \\
\quad) \\
\quad]\!]
\end{array}
$$

Figure 3.1: Fibonacci numbers in φ-calculus

3.2 EO

EOLANG, or simply EO, is a programming language created by Bugayenko [8] which is a direct implementation of φ-calculus with some extensions. However, their implementation contains features that are irrelevant to the scope of this thesis. Moreover, there is a notable difference between Bugayenko version of EO and ϕ-calculus by [10] in the definition of locators (or ”parent objects”). In the work by Bugayenko locators are *attributes*, whereas in [10] they are *objects*. Consequently, in this thesis, similarly to the φ-calculus, we are going to use a different version of EO which is a direct translation of the calculus defined in 3.1. The table of translation is shown in figure 3.2.

	φ-calculus	EO

Objects	$obj := [\![a \mapsto x, b \mapsto y]\!]$	`[] > obj`
		`x > a`
		`y > b`

Free Attrubutes	$point := [\![x \mapsto [\![]\!], y \mapsto [\![]\!]]\!]$	`[x y] > point`
Application	$a := point(x \mapsto 1, y \mapsto 2)$	`point 1 2 > a`

φ-attribute	$x := [\![\varphi \mapsto a, c \mapsto g]\!]$	`[] > x`
		`a > @`
		`g > c`

Fibonacci example	Fig. 3.1	`[n] > fib`
		`($.n.less 2).if > @`
		`n`
		`(fib ($.n.sub 1)).add`
		`(fib ($.n.sub 2))`

ρ^0	ρ^0	`$`
ρ^1	ρ^1	`^`
ρ^3	ρ^3	`^.^.^`

Figure 3.2: Mapping φ-calculus to EO

3.3 Describing object-oriented programs with EO

Before analyzing programs written in object-oriented programming languages, it is necessary to translate them into EO while preserving the semantics of the original language. This chapter presents a simplified version of such an encoding that is assumed by analyzers described in this thesis.

3.3.1 Classes

Classes are modelled as closed EO objects. Class-level (i.e. ”static”) attributes become attributes of the class object. Constructor is represented by an attribute-object ”new” of the class object. This object may take parameters to produce an instance of the object.

All instance attributes and methods are defined inside the object returned by the ”new” object. Inheritance is modelled as decoration in EO. So, a full example of EO translation would look like this. Class instances (a.k.a objects in Java) are created by applying the ”new” object to the required parameters.

3.3.2 Methods

Methods are modelled as EO objects, similarly to classes. These objects can take parameters. Instance methods are required to accept a special **self** attribute in addition to other parameters. This parameter is used to pass an instance of the object calling the method (hence the name - ”self”). ”self” parameter can be used to call instance methods inside other instance methods.

The return value of the method is represented by the value of the φ attribute (”@” symbol in EO). In order to call the instance method we need to instantiate the object first. Then we can call the method by accessing the instance's attribute with the method name and passing the instance object to it as the first argument.

3.4 Detecting Unanticipated Mutual Recursion

3.4.1 Problem Statement

Unanticipated mutual recursion is a problem that occurs as a result of unconstrained inheritance. Suppose we have an object named Base with two methods - *f* and *g*. Method *g* calls method *f*, whereas *f* does not.

Then, there is a class called Derived that extends Base and redefines the method *f* in a way that it calls *g*. When we call a method *f* on an instance of Derived, we get a stack overflow error: method *f* calls method *g*, method *g* calls method *f* and so on (figure 3.3).

It is important to note that we are not interested in detecting mutual recursion between the two methods of the same class. We are only interested the cases where mutual recursion occurs as a result of redefining one of the methods of the superclass. The example in fig. 3.4 shows the class with two mutually-recursive methods ”isOdd” and ”isEven”. In this case the recursion is anticipated and necessary, so it is not a defect.

3.4.2 Proposed solution

The solution to the problem lies in detecting the cycles in the call-graphs of all the objects. For each class-object in the program, do the following:

1. Detect the decorated class-object, all methods, and for each method in the class detect all the methods it calls. If the method that is called exists in the

```java
class Base {

    int f(int v) {
        return v;
    }

    int g(int v) {
        return this.f(v);
    }
}

class Derived extends Base {
    @Override
    int f(int v) {
        return this.g(v);
    }
}
```

(a) Java

```
[] > base
  [self v] > f
    v > @
  [self v] > g
    self.f > @
      self
      v
[] > derived
  base > @
  [self v] > f
    self.g > @
      self
      v
```

(b) EO

Figure 3.3: Example of unanticipated mutual recursion

```java
class NumericOps {
    boolean isEven(int n) {
        if (n == 0) {
            return true;
        } else {
            return
                this.isOdd(n - 1);
        }
    }

    boolean isOdd(int n) {
        if (n == 0) {
            return false;
        } else {
            return
                this.isEven(n - 1);
        }
    }

}
```

(a) Java

```
[] > numeric_ops
  [self n] > is_even
    ($.n.eq 0).if > @
      1
      $.self.is_odd
        $.self
        ($.n.sub 1)
  [self n] > is_odd
    ($.n.eq 0).if > @
      0
      $.self.is_even
        $.self
        ($.n.sub 1)
```

(b) EO

Figure 3.4: Example without unanticipated mutual recursion.

class-object, mark it as *resolved*. Otherwise, mark it as *partially-resolved*. The set of mappings between the methods of the class and the methods that each of the methods calls is considered a *partial call-graph* of the object.

2. After that the tree is traversed again to convert all the partially-resolved calls to fully resolved calls. To do that we need to calculate the *complete call-graph* of the object, which contains the methods from the object itself, as well as the methods from the decorated object. This is done by *extending* the partial call-graph of the decorated object with the partial call-graph of the decorating objects. Hereinafter we use the terms **child** and **parent** to refer to the decorating object and the decorated object respectively. The extension procedure is defined as follows:

    (a) if the method is present in the parent call-graph, but is absent in the child call-graph, it is left as is.

    (b) if the method is present in the child call-graph but does not exist in the parent call-graph, it is added to the parent call-graph.

    (c) if the method is present both in the child call-graph and the parent call-graph, all the occurrences of the method in the parent call-graph are replaced by the child's version of the method.

3. After the object's call-graph is resolved, perform the depth-first search [12] to find the cycles in the complete call-graph. After all the cycles are found, exclude the cycles that contain only the methods from the same object.

3.5 Detecting Unjustified Assumption in Subclass

3.5.1 Problem Statement

This defect [9, Section 3.3] occurs when the superclass is refactored by *inlining* the calls to the method that can be redefined by the subclass. The term inlining refers to replacing the method call with its body. Consider an example (Fig. 3.5). Class *M* extends class *C*, redefining method *l* to weaken its precondition. Consequently, the precondition in method *m* of class *M* is also weakened, because it relies on calling the method *l*.

Now, suppose that class *C* comes from some external library, and class *M* is defined in the user code. Library maintainer decides to refactor class *C* by inlining the call to *l* in method *m* (Fig. 3.6). Observe what happens to the class *M*. Now that *m* in class base has an assert, the redefinition of method *n* in class *M* has its precondition strengthened as compared to its version in class *C*. Therefore, the seemingly safe refactoring in base class broke the invariants in the subclasses. The name of the defect come from the fact that the subclasses usually *M assume* that the method *m* should be implemented in terms of method *l*. The examples in fig. 3.5 and 3.6 show that such an assumption is indeed not justified, and the maintainers of class *C* can change it as they deem fit.

3.5.2 Proposed Solution

We propose the following approach for detecting the methods where inlining of the calls may lead to breaking changes in subclasses:

1. An *initial* representation of the program is produced. This representation is a tree-like data structure which preserves the nesting relations between

```java
class C {
    int l(int v) {
        assert (v < 5);
        return v;
    }

    int m(int v) {
        return this.l(v);
    }

    int n(int v) {
        return v;
    }
}

class M extends C {
    int l(int v) {
        return v;
    }

    int n(int v) {
        return this.m(v);
    }
}
```

(a) Java

```
[] > c
  [self v] > l
    seq > @
      assert (v.less 5)
      v
  [self v] > m
    self.l self v > @
  [self v] > n
    v > @

[] > m
  c > @
  [self v] > l
    v > @
  [self v] > n
    self.m self v > @
```

(b) EO

Figure 3.5: Example of unjustified assumption in subclass (before revision)

```
class C {
    int l(int v) {
        assert (v < 5);
        return v;
    }

    int m(int v) {
        assert (v < 5);
        return v;
    }

    int n(int v) {
        return v;
    }
}

class M extends C {
    int l(int v) {
        return v;
    }

    int n(int v) {
        return this.m(v);
    }
}
```

(a) Java

```
[] > c
  [self v] > l
    seq > @
      assert (v.less 5)
      v
  [self v] > m
    self.l self v > @
  [self v] > n
    v > @

[] > m
  c > @
  [self v] > l
    v > @
  [self v] > n
    self.m self v > @
```

(b) EO

Figure 3.6: Example of unjustified assumption in subclass (after revision)

objects. So, the objects which contain other objects are the roots of their respective subtrees, whereas the container objects are the subtrees or leaves.

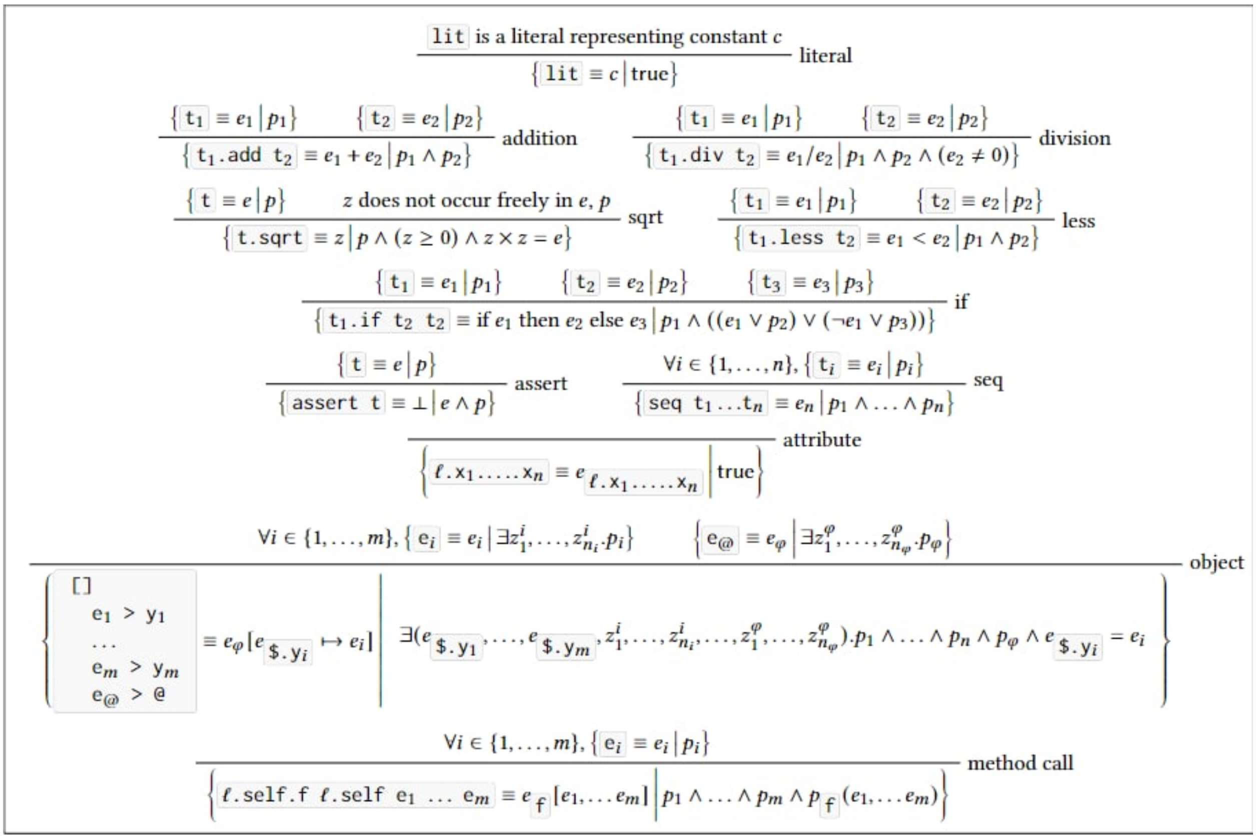
2. We produce a *revision* of the initial program representation where all the calls to the methods are inlined.

3. In both versions, for each of the class-objects, for each method in the class-object, a set of*properties* is inferred. These properties can be thought of as an implicit contract [13] of each method. In addition to the implicit properties, the explicit properties which come in the form of *assert* statements in the source code are also taken into account. In order to infer the properties of the method, partial interpretation of its body is performed. The interpretation is limited to basic numeric operations, numeric and boolean values and method calls. The inference rules are described in greater detail in fig. 3.7.

4. After all the properties are inferred, the following predicate should hold true for both the initial and the revised versions:

$$P_{init} \Rightarrow P_{rev}$$

   If it doesn't hold for some class-object, it means that the revision of one of its superclasses introduces a breaking change, which weakens the precondition of some its methods.



$$\frac{\texttt{lit}\ \text{is a literal representing constant}\ c}{\{\texttt{lit} \equiv c \mid \text{true}\}}\ \text{literal}$$

$$\frac{\{\texttt{t}_1 \equiv e_1 \mid p_1\} \qquad \{\texttt{t}_2 \equiv e_2 \mid p_2\}}{\{\texttt{t}_1\texttt{.add t}_2 \equiv e_1 + e_2 \mid p_1 \wedge p_2\}}\ \text{addition} \qquad \frac{\{\texttt{t}_1 \equiv e_1 \mid p_1\} \qquad \{\texttt{t}_2 \equiv e_2 \mid p_2\}}{\{\texttt{t}_1\texttt{.div t}_2 \equiv e_1/e_2 \mid p_1 \wedge p_2 \wedge (e_2 \neq 0)\}}\ \text{division}$$

$$\frac{\{\texttt{t} \equiv e \mid p\} \qquad z\ \text{does not occur freely in}\ e, p}{\{\texttt{t.sqrt} \equiv z \mid p \wedge (z \geq 0) \wedge z \times z = e\}}\ \text{sqrt} \qquad \frac{\{\texttt{t}_1 \equiv e_1 \mid p_1\} \qquad \{\texttt{t}_2 \equiv e_2 \mid p_2\}}{\{\texttt{t}_1\texttt{.less t}_2 \equiv e_1 < e_2 \mid p_1 \wedge p_2\}}\ \text{less}$$

$$\frac{\{\texttt{t}_1 \equiv e_1 \mid p_1\} \qquad \{\texttt{t}_2 \equiv e_2 \mid p_2\} \qquad \{\texttt{t}_3 \equiv e_3 \mid p_3\}}{\{\texttt{t}_1\texttt{.if t}_2\ \texttt{t}_2 \equiv \text{if}\ e_1\ \text{then}\ e_2\ \text{else}\ e_3 \mid p_1 \wedge ((e_1 \vee p_2) \vee (\neg e_1 \vee p_3))\}}\ \text{if}$$

$$\frac{\{\texttt{t} \equiv e \mid p\}}{\{\texttt{assert t} \equiv \bot \mid e \wedge p\}}\ \text{assert} \qquad \frac{\forall i \in \{1, \ldots, n\}, \{\texttt{t}_i \equiv e_i \mid p_i\}}{\{\texttt{seq t}_1 \ldots \texttt{t}_n \equiv e_n \mid p_1 \wedge \ldots \wedge p_n\}}\ \text{seq}$$

$$\frac{}{\left\{\ell\texttt{.x}_1\texttt{.}\ldots\texttt{.x}_n \equiv e_{\ell\texttt{.x}_1\texttt{.}\ldots\texttt{.x}_n} \,\middle|\, \text{true}\right\}}\ \text{attribute}$$

$$\frac{\forall i \in \{1, \ldots, m\}, \{\texttt{e}_i \equiv e_i \mid \exists z^i_1, \ldots, z^i_{n_i}.p_i\} \qquad \left\{\texttt{e}_@ \equiv e_\varphi \,\middle|\, \exists z^\varphi_1, \ldots, z^\varphi_{n_\varphi}.p_\varphi\right\}}{\left\{\begin{array}{l}\texttt{[]} \\ \quad \texttt{e}_1\ \texttt{>}\ \texttt{y}_1 \\ \quad \ldots \\ \quad \texttt{e}_m\ \texttt{>}\ \texttt{y}_m \\ \quad \texttt{e}_@\ \texttt{>}\ \texttt{@}\end{array} \equiv e_\varphi[e_{\texttt{\$.y}_i} \mapsto e_i] \,\middle|\, \exists(e_{\texttt{\$.y}_1}, \ldots, e_{\texttt{\$.y}_m}, z^i_1, \ldots, z^i_{n_i}, \ldots, z^\varphi_1, \ldots, z^\varphi_{n_\varphi}).p_1 \wedge \ldots \wedge p_n \wedge p_\varphi \wedge e_{\texttt{\$.y}_i} = e_i\right\}}\ \text{object}$$

$$\frac{\forall i \in \{1, \ldots, m\}, \{\texttt{e}_i \equiv e_i \mid p_i\}}{\left\{\ell\texttt{.self.f}\ \ell\texttt{.self e}_1\ \ldots\ \texttt{e}_m \equiv e_{\texttt{f}}[e_1, \ldots e_m] \,\middle|\, p_1 \wedge \ldots \wedge p_m \wedge p_{\texttt{f}}(e_1, \ldots e_m)\right\}}\ \text{method call}$$

Figure 3.7: Rules for property inference in detection of unjustified assumption in subclass.

Chapter 4

Implementation

This chapter analyzes specifics of Odin (short for Object Dependency INspector) - a static analyzer of EO source code. Section 4.1 covers the tools and technologies used in the project. Section 4.2 gives a brief overview of the project file structure. Section 4.3 goes over the implementation of EO parser used in the project. Section 4.4 discusses the ways we can represent the elements of object-oriented programs in EO. Sections 4.5 and 4.6 describe the implementations of the analysis algorithms applied to structured EO code. Finally, section 4.7 summarizes this chapter.

4.1 Development Environment

Odin is a project written entirely in **Scala** [1] - a modern programming language with support for high-level concepts such as structural pattern matching [14] and algebraic data types [15]. Scala is compiled into Java Virtual Machine (JVM) byte code. This allows Odin to be used as a library in any other project compatible with JVM, be it Scala or Java. In addition, programs compiled to JVM byte code

[1] https://www.scala-lang.org/

can be run without changes on any device that can run Java Virtual Machine.

The project uses a build tool called **sbt** [2], which allows compiling multiple Scala modules at once. A distinctive feature of **sbt** is the ability to cross-compile Scala code so that it is compatible with many versions of Scala and Java. It also supports a variety of plugins that improve the development process. The plugins used by Odin are **scalafmt** [3], an automatic source code formatter, and **scalafix** [4] , a linter and code analyzer with support for project-wide refactorings.

Odin is published as a **JAR** [5] and can be downloaded from the **Maven Central** repository [6].

The source code of the project is available on **Github** [7]. It also provides the instructions on how to launch and contribute to the project.

4.2 Module Structure

Odin is a project consisting of multiple modules. The main modules are:

- Core, which contains the definition for EO AST (Abstract Syntax Tree). This AST is used as an input to all analysis algorithms.
- Analyses, which contains the implementations of various analyzers.
- Backends, which contains algorithms that transform EO AST into something else. The only backend so far is a plain text backend: it transforms EO AST into its syntactically correct equivalent in EO source code. This backend can

[2] https://www.scala-sbt.org/

[3] https://scalameta.org/scalafmt/

[4] https://scalacenter.github.io/scalafix/

[5] https://docs.oracle.com/javase/7/docs/technotes/guides/jar/jar.html

[6] https://search.maven.org/search?q=g:org.polystat.odin

[7] https://github.com/polystat/odin

also be interpreted as a pretty-printer of EO code and is widely used as such in other modules.

- Parser, which contains a parser (also known as a syntactic analyzer) of EO source code. It is used to convert different EO representations (e.g. plain text or XML encoding) into the EO AST defined in Core module.

4.3 Parser

The parser used in Odin implements a slightly altered version of EO specification defined by Bugayenko [8]. In particular, it relaxes constraints on whitespace between tokens and the number of newlines and comments between definitions. This is done to reduce the complexity of producing source code pieces for testing and debugging.

The parser was created using **cats-parse** library [8] for Scala. It provides a parser-combinator [16] approach to building recursive-descent parsers. Recursive-descent parsers are known for their worst-case exponential complexity. This problem can not be avoided in general. However, cats-parse mitigates it by explicitly marking all the places in the parser definition that can cause such spikes in complexity.

4.4 Analyses

This section describes each of the analysis algorithms in greater detail. First, we will describe the steps that are performed prior to each of the defect-specific analyses: parsing and detecting the significant features of EO programs - objects,

[8] https://github.com/typelevel/cats-parse

methods and extension clauses. Then we will describe the algorithms for detecting each of the covered defects: unanticipated mutual recursion and unjustified assumption in subclass. Finally, we will conclude the chapter by describing the shortcomings of each of the algorithms.

4.4.1 Preprocessing

Before running on

4.4.2 Unanticipated Mutual Recursion

4.4.3 Unjustified Assumption Analysis

Chapter 5

Evaluation and Discussion

This chapter provides the evaluation of the resulting implementation. Section 5.1 outlines the limitations of the EO-based static analysis. Section 5.2 describes how the analyzers were tested. Finally, section 5.3 describes the result of comparing EO-based static analyzers with their counerparts for other programming languages.

5.1 Limitations

5.2 Testing

5.3 Comparisons

Chapter 6

Conclusion

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