A Notion of Dynamic Interface for Depth-Bounded Object-Oriented Packages

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Abstract. Programmers using software components have to follow protocols that specify when it is legal to call particular methods with particular arguments. For example, one cannot use an iterator over a set once the set has been changed directly or through another iterator. We formalize the notion of dynamic package interfaces (DPI), which generalize state-machine interfaces for single objects, and give an algorithm to statically compute a sound abstraction of a DPI. States of a DPI represent (unbounded) sets of heap configurations and edges represent the effects of method calls on the heap. We introduce a novel heap abstract domain based on depth-bounded systems to deal with potentially unboundedly many objects and the references among them. We have implemented our algorithm and show that it is effective in computing representations of common patterns of package usage, such as relationships between viewer and label, container and iterator, and JDBC statements and cursors.

1 Introduction

Modern object-oriented programming practice uses packages to encapsulate components, allowing programmers to use these packages through well-defined application programming interfaces (APIs). While programming languages such as Java or C# provide a clear specification of the static APIs of components in terms of classes and their (typed) methods, there is usually no specification of the dynamic behavior of packages that constrain the temporal ordering of method calls on different objects. For example, one should invoke the lock and unlock methods of a lock object in alternation; any other sequence raises an exception. More complex constraints connect method calls on objects of different classes. For example, in the Java Database Connectivity (JDBC) package, a ResultSet object, which contains the result of a database query executed by a Statement object, should first be closed before its corresponding Statement object can execute a new query.

In practice, such temporal constraints are not formally specified, but explained through informal documentation and examples, leaving programmers susceptible to bugs in the usage of APIs. Being able to specify dynamic interfaces for components that

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capture these temporal constraints. Clarify constraints imposed by the package on client code. Moreover, program analysis tools may be able to automatically check whether the client code invokes the component correctly according to such an interface.

Previous work on mining dynamic interfaces through static and dynamic techniques has mostly focused on the single-object case (such as a lock object) [2, 9–11, 19], and rarely on more complex collaborations between several different classes (such as JDBC clients) interacting through the heap [13, 15, 16]. In this paper, we propose a systematic, static approach for extraction of dynamic interfaces from existing object-oriented code. Our work is closely related to the Canvas project [16]. Our new formalization can express structures than could not be expressed in previous work (i.e. nesting of graphs).

More precisely, we work with packages, which are sets of classes. A configuration of a package is a concrete heap containing objects from the package as well as references among them. A dynamic package interface (DPI) specifies, given a history of constructor and method calls on objects in the package, and a new method call, if the method call can be executed by the package without causing an error. In analogy with the single-object case, we are interested in representations of DPIs as finite state machines, where states represent sets of heap configurations and transitions capture the effect of a method call on a configuration. Then, a method call that can take the interface to a state containing erroneous configurations is not allowed by the interface, but any other call sequence is allowed.

The first stumbling block in carrying out this analogy is that the number of states of an object, that is, the number of possible valuations of its attributes, as well as the number of objects living in the heap, can both be unbounded. As in previous work [10, 16], we can bound the state space of a single object using predicate abstraction, that tracks the abstract state of the object defined by a set of logical formulas over its attributes. However, we must still consider unboundedly many objects on the heap and their inter-relationships. Thus, in order to compute a dynamic interface, we must address the following challenges.

1. The first challenge is to define a finite representation for possibly unbounded heap configurations and the effect of method calls. For single-object interfaces, states represent a subset of finitely-many attribute valuations, and transitions are labeled with method names. For packages, we have to augment this representation for two reasons. First, the number of objects can grow unboundedly, for example, through repeated calls to constructors, and we need an abstraction to represent unbounded families of configurations. Second, the effect of a method call may be different depending on the receiver object and the arguments, and it may update not only the receiver and other objects transitively reachable from it, but also other objects that can reach these objects.

2. The second challenge is to compute, in finite time, a dynamic interface using the preceding representation. For single-object interfaces [2, 10], interface construction roughly reduces to abstract reachability analysis against the most general client (a program that non-deterministically calls all available methods in a loop). For packages, it is not immediate that abstract reachability analysis will terminate, as our abstract domains will be infinite, in general.
We address these challenges as follows. First, we describe a novel shape domain for finitely representing infinite sets of heap configurations as recursive unfoldings of nested graphs. Technically, our shape domain combines predicate abstraction [14, 17], for abstracting the internal state of objects, with sets of depth-bounded graphs represented as nested graphs [20]. Each node of a nested graph is labelled with a valuation of the abstraction predicates that determine an equivalence class for objects of a certain class.

Second, we describe an algorithm to extract the DPI from this finite state abstraction based on abstract reachability analysis of depth-bounded graph rewriting systems [21]. We use the insight that the finite state abstraction can be reinterpreted as a numerical program. The analysis of this numerical program yields detailed information about how a method affects the state of objects when it is called on a concrete heap configuration, and how many objects are effected by the call.

We have implemented our algorithm on top of the Picasso abstract reachability tool for depth-bounded graph rewriting systems. We have applied our algorithm on a set of standard benchmarks written in a Java-like OO language, such as container-iterator, JDBC query interfaces, etc. In each case, we show that our algorithm produces an intuitive DPI for the package within a few seconds. This DPI can be used by a model checking tool to check conformance of a client program using the package to the dynamic protocol expected by the package.

2 Overview: A Motivating Example

We illustrate our approach through a simple example.

Example. Figure 1 shows two classes Viewer and Label in a package, adapted from [13], and inspired by an example from Eclipse’s ContentView and IBaseLabelProvider classes. A Label object throws an exception if its run or dispose method is called after the dispose method has been called on it. There are different ways that this exception can be raised. For example, if a Viewer object sets its f reference to the same Label object twice, after the second call to set, the Label object, which is already disposed, raises an exception. As another example, for two Viewer objects that have their f reference attributes point to the same Label object, when one of the objects calls its done method, if the other object calls its done method an exception will be raised. An interface for this package should provide possible configurations of the heap when an arbitrary client uses the package, and describe all usage scenarios of the public methods of the package that do not raise an exception.

Dynamic Package Interface. Intuitively, an interface for a package summarizes all possible ways for a client to make calls into the package (i.e., create instances of classes in the package and call their public methods). In the case of single-objects, where all attributes are scalar-valued, interfaces are represented as finite-state machines with transitions labeled with method calls [2,10,19]. Each state s of the machine represents a set \[[s]\] of states of the object, where a state is a valuation to all the attributes. (In case there are infinitely many states, the methods of [2,10] abstract the object relative to a finite set of predicates, so that the number of states is finite.) An edge \[ s \rightarrow t \] indicates that calling the method \( m() \) from any state in \( [s] \) takes the object to a state in \( [t] \). Some states of
class Viewer {
    Label f;
    public void Viewer() {
        f := null;
    }
    public void run() {
        if (f != null) f.run();
    }
    public void done() {
        if (f != null) f.dispose();
    }
    public void set(Label l) {
        if (f != null) f.dispose();
        f := l;
    }
}

class Label {
    boolean disposed;
    public void Label() {
        disposed := false;
    }
    protected void run() {
        if (disposed) throw new Exception();
    }
    protected void dispose() {
        if (disposed) throw new Exception();
        disposed := true;
    }
}

Fig. 1. A package consisting of Viewer and Label classes and its two abstract heaps

the machine are marked as errors: these represent inconsistent states, and method calls leading to error states are disallowed.

Below, we generalize such state machines to packages.

States: Ideals over Shapes. The first challenge is that the notion of a state is more complex now. First, there are arbitrarily many states: for each \(n\), we can have a state with \(n\) instances of Label (e.g., when a client allocates \(n\) objects of class Label); moreover, we can have more complex configurations where there are arbitrarily many viewers, each referring to a single Label, where the Label may have disposed = true or not. We call sets of (potentially unbounded) heap configurations abstract heaps.

Our first contribution is a novel finite representation for abstract heaps. We represent abstract heaps using a combination of parametric shape analysis [17] and ideal abstractions for depth-bounded systems [21]. As in shape analysis, we fix a set of unary
predicates, and abstract each object w.r.t. these predicates. For example, we track the predicate $\text{disposed}(l)$ to check if an object $l$ of type Label has disposed set to true. Additionally, we track references between objects by representing the heap as a nested graph whose nodes represent predicate abstractions of objects and whose edges represent references from one object to another. Unlike in parametric shape analysis, references are always determinate and the abstract domain is therefore still infinite.

Figure 1(c) shows an abstract heap $H_0$ for our example. There are five nodes in the abstract heap. Each node is labelled with the name of its corresponding class and a valuation of predicates, and represents an object of the specified class whose state satisfies the predicates. Some nodes have an identifier in square brackets in order to easily refer to them. For instance, $V_{nd}$ represents a Viewer object and $L_d$ represents a Label object for which disposed is true. Edges between nodes show field references: the edge between the $V_d$ and $L_d$ objects that is labeled with $f$ shows that objects of type $V_d$ have an $f$ field referring to some object of type $L_d$. Finally, nodes and subgraphs can be marked with a "*". Intuitively, the "*" indicates an arbitrary number of copies of the pattern within the scope of the "*". For example, since $V_d$ is starred, it represents arbitrarily many (including zero) Viewer objects sharing a Label object of type $L_d$. Similarly, since the subgraph over nodes $V_d$ and $L_d$ is starred, it represents configurations with arbitrarily many Label objects, each with (since $V_d$ is starred as well) arbitrarily many viewers associated with it.

Figure 1(d) shows a second abstract heap $H_{err}$. This one has two extra nodes in addition to the nodes in $H_0$, and represents erroneous configurations in which the Label object is about to throw an exception in one of its methods. (We set a special error-bit whenever an exception is raised, and the node with object type $L_{err}$ represents an object where that bit is set.)

Technically (see Sections 5.2 and 5.3), nested graphs represent ideals of downward-closed sets (relative to graph embedding) of configurations of depth-bounded predicate abstractions of the heap. While the abstract state space is infinite, it is well-structured, and abstract reachability analysis can be done [1, 12, 20].

**Transitions: Object Mappings.** Suppose we get a finite set $S$ of abstract heaps represented as above. The second challenge is that method calls may have parameters and may change the state of the receiver object as well as objects reachable from it or even objects that can reach the receiver. As an example, consider a set container object with some iterators pointing to it. Removing an element through an iterator can change the state of the iterator (it may reach the end), the set (it can become empty), as well as other iterators associated with the set (they become invalidated and may not be used to traverse the set). Thus, transitions cannot simply be labeled with method names, but must also indicate which abstract objects participate in the call as well as the effect of the call on the abstract objects. The interface must describe the effect of the heap in all cases, and all methods. In our example, we can enumerate 14 possible transitions from $H_0$. To complete the description of an interface, we have to (1) show how a method call transforms the abstract heap, and (2) ensure that each possible method call from each abstract heap in $S$ ends up in an abstract heap also in $S$.

Consider invoking the $\text{set}$ method of a viewer in the abstract heap $H_0$. There are several choices: one can choose in Figure 1(c) an object of type $V_d$, $V_{nd}$, or $V_0$ as the
callee, and pass it an object of type $L_d$ or $L_{nd}$. Note that the method call captures the scenario in which one representative object is chosen from each node and the method is executed. Recall that, because of stars, a single node may represent multiple objects. Figure 2(a) shows how the abstract heap is transformed if we choose a viewer pointing to a label which is not disposed as the callee and pass it a disposed label as argument. The box on the left specifies the source heap before the method call and the box on the right specifies the destination heap after the method call. A representative object in a method call is graphically shown by a rounded box and has a role name that prefixes its object type. The source heap includes three representative objects with role names: callee, arg0, and scope0. The callee and arg0 role names determine the callee object and the parameter object of the method call, respectively. The scope0 is a Label object that is in the scope of the method call: i.e., the method call affects its type or the valuation of its predicates. Lastly, there is a fourth object in the left box that is not a single representative, but a starred object $V_*$ that represents all viewers other than the callee object that reference the object with role scope0. The following properties hold: First, both the source and the destination of the transition are $H_0$, hence, the method call transforms objects in the abstract heap $H_0$ back to $H_0$. Second, any object in $H_0$ that is not mentioned in the source box is untouched by the method call. Third, each object in the left box is mapped to another representative object in the right box: The
representative objects can be traced via their role names while the other objects via the arrows that specifies their new types (to model non-determinism, such an arrow can be a multi-destination arrow). Thus, $V.set(L_a)$ transforms the callee object by changing its reference $f$ to the $L_a$ object that was the parameter of the method call. The object $L$ that the callee referenced before the method call get the value of its disposed predicate changed to true after the method call. All other objects represented by $V$, that reference $L$ continue referencing that object.

The second transition, in Figure 2(b), shows what happens if set is called on $V_a$ with any label. This time, an error occurs, since the method call tries to dispose an already disposed label. This is indicated by a transformation to the error node $H_{err}$, and thus, is not allowed in the interface.

Algorithm for Interface Computation. Our second contribution is an algorithm and a tool for computing the dynamic package interfaces in form of a state machine, as described above. Conceptually, the DPI of a package is computed in two steps: (i) computing the covering set of the package, which includes all possible configurations of the package, in a finite form; and (ii) computing the object mappings of the package using the covering set.

Computing the Covering Set. We introduce three layers of abstraction to obtain an overapproximation of the covering set of a package in a finite form. First, using a fixed set of predicates over the attributes of classes, we introduce a predicate abstraction layer. Second, we remove from this predicate abstraction those reference attributes of classes that can create a chain of objects with an unbounded length; these essentially correspond to recursive data structures, such as linked lists. We call these two abstraction layers the depth-bounded abstraction. The soundness of depth-bounded abstraction follows soundness arguments similar to the ones for classic abstract interpretation. However, unlike the classic abstract interpretation of non-object-oriented programs, the depth-bounded abstraction of object-oriented packages does not in general result in a finite representation; e.g., we may still have an unbounded number of iterator and set objects, with each iterator object being connected to exactly one set object.

Our third abstraction layer, namely, ideal abstraction, ensures a finite representation of the covering set of a package. The domain of ideal abstraction is essentially the same as the domain of nested graphs. The key property of this abstraction layer is that it can represent an unbounded number of depth-bounded objects as the union of a finite set of ideals, each of which itself is represented finitely. The soundness of this abstraction layer follows from the general soundness result for the ideal abstraction of depth-bounded systems [21].

To compute the covering set of a package, we use a notion of most general client. Intuitively, the most general client [10] runs in an infinite loop; in each iteration of the loop, it non-deterministically either allocates a new object, or picks an already allocated object, a public method of the object, a sequence of arguments to the method, and invokes the method call on the object. Using a widening operator over the sequence of the steps of the most general client, our algorithm is able to determine when the nesting level of an object needs to be incremented. Our algorithm terminates due to the fact that the ideal abstraction is a well-structured transition system.
Computing the Object Mappings. The object mappings are computed using the covering set as starting point. To compute the object mappings we let the most general client run one more time using the covering set as starting state of the system. During that run we record what effect the transitions have. For a particular transition we record, among other information, what are the starting and ending abstract heaps and the corresponding unfolded, representative objects. The nodes of the unfolded heap configurations are tagged with their respective roles in the transition. Finally, we record how the objects are modified and extract the mapping of the object mapping.

In our example, there are two maximal nodes: \( H_0 \) and \( H_{err} \), where \( H_{err} \) denotes the error configurations. \( H_0 \) and \( H_{err} \) together represent the covering set of the package. Accordingly, the interface shows that \( H_0 \) captures the “most general” abstract heap in the use of this package; each “correct” method call corresponds to an object mapping over \( H_0 \). We omit showing the remaining 12 object mappings of the interface.

3 Concrete Semantics

We now present a core OO language.

Syntax. For a set of symbols \( X \) (including variables), we denote by \( \text{Exp}.X \) and \( \text{Pred}.X \) the set of expressions and predicates respectively, constructed with symbols drawn from \( X \). We assume there are two special variables \( \text{this} \) and \( \text{null} \).

In our language, a package consists of a collection of class definitions. A class definition consists of a class name, a constructor method, a set of fields, and a set of method declarations partitioned into public and protected methods. A constructor method has the same name as the class, a list of typed arguments, and a body. We assume fields are typed with either a finite scalar type (e.g., Boolean), or a class name. The former are called scalar fields and the latter reference fields. Intuitively, reference fields refer to other objects on the heap. Methods consist of a signature and a body. The signature of a method is a typed list of its arguments and its return value. The body of a method is given by a control flow automaton over the fields of the class. Intuitively, any client can invoke public methods, but only other classes in the package can invoke protected ones.

A control flow automaton (CFA) over a set of variables \( X \) and a set of operations \( \text{Op}.X \) is a tuple \( F = (X, Q, q_0, q_f, T) \), where \( Q \) is a finite set of control states, \( q_0 \in Q \) (resp. \( q_f \in Q \)) is a designated initial state (resp. final state), and \( T \subseteq Q \times \text{Op}.X \times Q \) is a set of edges labeled with operations.

For our language, we define the set \( \text{Op}.X \) of operations over \( X \) to consist of: (i) assignments \( \text{this}.x ::= e \), where \( x \in X \) and \( e \in \text{Exp}.X \); (ii) assumptions, \( \text{assume}(p) \), where \( p \in \text{Pred}.((\{\text{this}\} \cup X) \); (iii) construction \( \text{this}.x = \text{new}(C(\vec{a})) \), where \( C \) is a class name and \( \vec{a} \) is a sequence in \( \text{Exp}.X \), and (iv) method calls \( \text{this}.x := \text{this}.y.m(\vec{a}) \), where \( x, y \in X \).

Formally, a class \( C = (A, c, M_p, M_t) \), where \( A \) is the set of fields, \( c \) is the constructor, \( M_p \) is the set of public methods, and \( M_t \) is the set of protected methods. We use \( C \) also for the name of the class. A package \( P \) is a set of classes.

We make the following assumptions. First, all field and method names are disjoint. Second, each class has an attribute \( \text{ret} \) used to return values from a method to its callers. Third, all CFAs are over disjoint control locations. Fourth, a package is well-typed, in
that assignments are type-compatible, called methods exist and are called with the right number and types of arguments, etc. Finally, it is not clear how the pushdown system and depth-bounded system mix and whether there exists an bqo that may accommodate both. Therefore, we omit recursive method calls from our the analysis.

A client \( I \) of a package \( P \) is a class with exactly one method \( \text{main} \), such that (i) for each \( x \in I.A \), we have the type of \( x \) is either a scalar or a class name from \( P \), (ii) in all method calls \( \text{this} \cdot x = \text{this} \cdot y \cdot m(\bar{a}) \), \( m \) is a public method of its class, and (iii) edges of \( \text{main} \) can have the additional non-deterministic assignment \( \text{havoc}(\text{this} \cdot x) \). An OO program is a pair \((P, I)\) of a package \( P \) and a client \( I \).

Concrete Semantics. We give the semantics of an OO program as a labeled transition system. A transition system \( S = (X, X_0, \rightarrow) \) consists of a set \( X \) of states, a set \( X_0 \subseteq X \) of initial states, and a transition relation \( \rightarrow \subseteq X \times X \). We write \( x \rightarrow x' \) for \((x, x') \in \rightarrow \).

Fix an OO program \( S = (P, I) \). It induces a transition system \((\text{Conf}, U_0, \rightarrow)\), with configurations \( \text{Conf} \), initial configurations \( U_0 \), and transition relation \( \rightarrow \) as follows.

Let \( O \) be a countably infinite set of object identifiers (or simply objects) and let \( \text{class} : O \rightarrow P \cup \{I, \text{null}\} \) be a function mapping each object identifier to its class. A configuration \( u \in \text{Conf} \) is a tuple \((O, \text{this}, q, \nu, st)\), where \( O \subseteq O \) is a finite set of currently allocated objects, \( \text{this} \in O \) is the current object (i.e., the receiver of the call to the method currently executed), \( q \) is the current control state, which specifies the control state of the CFA at which the next operation will be performed, \( \nu \) is a sequence of triples of object, variable, and control location (the program stack), and \( st \) is a store, which maps an object and a field to a value in its domain. We require that \( O \) contains a unique \text{null} object \text{null} with \text{class} (\text{null}) = \text{nil}. We denote by \( \text{Conf} \) the set of all configurations \( S \).

The set of initial configurations \( U_0 \subseteq \text{Conf} \) is the set of configurations \( u_0 = (\{\text{null}, o_1\}, \text{this}, \text{main}, \text{q}_0, \text{e}, st) \) such that (i) \( \text{class}(o_1) = I \), (ii) the current object \( \text{this} = o_1 \), (iii) the value of all reference fields of all objects in the store is \text{null} and all scalar fields take some default value in their domain, and (iv) the control state is the initial state of the CFA of the main method of \( I \) and the stack is empty.

Given a store, we write \( st(e) \) and \( st(p) \) for the value of an expression \( e \) or predicate \( p \) evaluated in the store \( st \), computed the usual way.

The transitions in \( \rightarrow \) are as follows. A configuration \((O, \text{this}, q, \nu, st)\) moves to configuration \((O', \text{this}', q', \nu', st')\) if there is an edge \((q, op, q')\) in the CFA of \( q \) such that

- \( op = \text{this} \cdot x := e \) and \( O' = O, \text{this}' = \text{this}, \nu' = \nu, \) and \( st' = st[(\text{this}, x) \mapsto st(e)] \).
- \( op = \text{assume}(p) \) and \( O' = O, \text{this}' = \text{this}, \nu' = \nu, st(p) = 1, \) and \( st' = st \).
- \( op = \text{this} \cdot x := \text{this} \cdot y \cdot m(\bar{a}) \) and \( O' = O, \text{this}' = \text{this}, \nu' = (\text{this}, x, q') \nu, \) and \( q' = m \cdot \text{q}_0, \) and the formal arguments of \( m \) are assigned values \( st(\bar{a}) \) in the store.
- \( op = \text{new}(C(\bar{a})) \) and \( O' = O \sqcup \{o\} \) for a new object \( o \) with \( \text{class}(o) = C \), \( \text{this}' = o, \nu' = (\text{this}, x, q') \nu, \) and \( q' = c \cdot \text{q}_0, \) and the formal arguments of \( c \) are assigned values \( st(\bar{a}) \) in the store.
- \( op = \text{havoc}(\text{this} \cdot x) \); \( O' = O, \text{this}' = \text{this}, \) and \( st' = st[(\text{this}, x) \mapsto \nu] \), where \( \nu \) is some value chosen non-deterministically from the domain of \( x \).

Finally, if \( q \) is the final node of a CFA and \( \nu = (o, x, q) \nu', \) and the configuration \((O, \text{this}, q, \nu, st)\) moves to \((O, o, q, \nu', st')\), where \( st' = st[o \cdot x \mapsto st(\text{this} \cdot \text{ret})] \). If none of the rules apply, the program terminates.
To model error situations, we assume that each class has a field `err` which is initially 0 and set to 1 whenever an error is encountered (e.g., an assertion is violated). An error configuration is a configuration $u$ in which there exists an object $o \in u.O$ such that $o.err = 1$. An OO program is safe if it does not reach any error configuration.

**Example 1** Figure 3 depicts two configurations for a set of objects belonging to a “set and iterator” package. For the sake of brevity, we do not show the code for this package, but the functionality of the package is standard. The package has three classes, namely, Set, Iterator, and Elem. The Elem class can create a linked list to store the elements of a Set object. An Iterator object is used to traverse the elements of its corresponding Set object via its pos attribute as an index. It can also remove an element of the Set object through its remove method. An Iterator object can perform these operations only if it has the same version as its corresponding Set object. The Iterator version is stored in the iver field and the Set version in sver. In this example, we focus on the remove method. The remove method of an Iterator object invokes the delete method of its corresponding Set object, passing its pos attribute as a parameter. The delete method, in turn, deletes the pos-th Elem object that is accessible through its head attribute. The version attributes of both the Iterator and Set objects are incremented, while the version attributes of other Iterator objects remain the same. The two configurations in Figure 3 are abbreviated to show only the information relevant to this example.

The configuration

$$u = \{(s, i_1, i_2, e_1, e_2), s, ((i_1, iver), 2), ((i_2, iver), 2), \cdots\},$$

depicted in Figure 3(a), is one of the configurations during the execution of $i_2$.remove, namely the configuration immediately after executing this.iter.of.delete(this.pos).

After a number of steps, the computation reaches configuration

$$u' = \{(s, i_1, i_2, e_1, e_2), s, e, ((i_1, iver), 2), ((i_2, iver), 3), \cdots\},$$

depicted in Figure 3(b), which is the configuration after $o_2$.remove() has completed and the control has returned to the client, l. At $u'$, $i_2$ still has the same version $(i_2, iver)$ as $s$, (s.sver), but $i_1$ has a different version now. Thus, $i_1$ cannot traverse or remove an element of $s$ any more.
4 Dynamic Package Interface (DPI)

For a package \( P \), its dynamic package interface is essentially a set of nested object graphs representing heap configurations together with a set of object mappings over them, one for each distinct method invocation.

Each nested object graph represents an unbounded number of heap configurations. An object mapping for a method invocation specifies how the objects of a source heap configuration are transformed to the objects of a destination heap configuration. Object mappings use an extended notion of object graphs with role labelling to identify the callee and the arguments of the method calls. Up to isomorphism, the set of object mappings of a DPI specify the effect of all possible public method calls on distinct heap configurations of a package.

In the remainder of this section, in Section 4.1, we present the notions of nested object graphs and cast nested object graphs, followed by the notion of object mapping, in Section 4.2. In Section 4.3, we present DPI formally.

4.1 Nested Object Graphs

A nested object graph \( H \) over a package \( P \) is a tuple \((AL, AR, O, l, st, nl)\) with

- \( AL \) and \( AR \): sets of object labels and reference fields, respectively,
- \( O \): a set of object nodes identifiers,
- \( st : (O \times AR) \rightarrow O \) the reference edge function,
- \( l : O \rightarrow AL \) the object labelling function,
- \( nl : O \rightarrow \mathbb{N}_0 \), the nesting level function.

We call an object node with nesting level zero an object instance and otherwise call it an abstract object. An abstract object represents an unbounded number of object instances. If an object node is connected via a reference label to another object node in \( st \), it means that one or more object instances (depending on their relative nesting levels) in the source node have reference attributes pointing to an object instance in the destination node. We denote by \( \text{class} \) the function from \( AL \) to \( P \) that extracts the class information from a label.

A nested object graph is well-formed if: \( \forall (o_1, r, o_2), \text{st}(o_1, r) = o_2 \Rightarrow nl(o_1) \geq nl(o_2) \). This constraint is necessary because it should not be possible for an object instance to reference more than one object instance with the same reference attribute.

Example 2 Let us consider the graph in Figure 1(c) which is a nested object graph. Let the object node labelled with \([V_{nd}]\)Viewer be denoted by \( x \), then \( V_{nd} \) is the identifier that we use to refer to \( x \) in the description, and we have \( l(x) = \text{Viewer} \), which tells the class of \( x \) and the predicates and their valuation (none in this case). Finally, we have \( nl(x) = 2 \).

A cast nested object graph \( G \) over \( P \) is a tuple \((AL, AR, O, l, st, n, nl)\) where

- \((AL, AR, O, l, st, nl)\) is a nested object graph over \( P \),
- \( R \) is a set of object role labels, and
Example 3 Let us consider the graph inside the box in the left hand side of Figure 2(a), which is a cast nested object graph whose source is \( H_k \subseteq \) object node labelled with object graph Notation. 4.2 Object Mapping as a node in the graphs. can be seen as a projection of the internal state of the most general client on the objects Therefore, we omit this information in nested object graphs. The roles in abstract graphs in the heap. That is, the object instance of the most general client itself is not represented \( \forall r_1, r_2 \in R, n(r_1) = n(r_2) \Rightarrow r_1 = r_2 \). Henceforth, we consider only well-formed nested object graphs and well-formed cast nested object graphs. We denote the set of all nested object graphs and the set of all cast nested object graphs over \( P \) as \( \mathcal{H}_P \) and \( \mathcal{G}_P \), respectively.

In our analysis, each cast nested object graph \( G \in \mathcal{G}_P \) corresponds to a unique nested object graph \( H \in \mathcal{H}_P \), as we will see in the next section. We assume the source function \( \text{src}: \mathcal{G}_P \to \mathcal{H}_P \), which determines the nested object graph of a cast nested object graph.

The DPI shows the state of the system (i.e., the package together with its most general client) at the call and return points of public methods in the package. In those states, the stack of the client is empty and this always refers to the most general client. Therefore, we omit this information in nested object graphs. The roles in abstract graphs can be seen as a projection of the internal state of the most general client on the objects in the heap. That is, the object instance of the most general client itself is not represented as a node in the graphs.

4.2 Object Mapping

Notation. For a package \( P \), we denote by \( \mathcal{M}_P \) the set of all its public methods: \( \mathcal{M}_P = \bigcup_{C \in P} C.\mathcal{M}_P \). For a public method \( m(C_1, \ldots, C_n) \) of a class \( C \), we define its signature as \( \text{sig}(m) = \{(C, \text{callee}), (C_1, \text{arg}_0), \ldots, (C_n, \text{arg}_0)\} \).

An object mapping of a method \( m \in \mathcal{M}_P \) is a tuple \( (m, G, G', k) \) where \( G, G' \in \mathcal{G}_P \), \( k \subseteq G.O \times G'.O \) is a relation, and the following conditions are satisfied:

- \( G \) includes object instances for \( \text{sig}(m) \):
  \[ \forall (C, s) \in \text{sig}(m), \ \exists o \in G.O, \ \text{class}(G.o) = C \land G.n.o = s; \]
- \( \text{dom}(k) = G.O; \)
- \( k \) preserves the class of an object: \( \forall (o_1, o_2) \in k, \ \text{class}(G.o_1) = \text{class}(G'.o_2); \)
- \( k \) is functional on object instances: \( \forall (o_1, o_2), (o_1, o_3) \in k, \ \text{G.nl}(o_1) = 0 \Rightarrow o_2 = o_3; \)
- \( k \) preserves the nesting level of object instances:
  \[ \forall (o_1, o_2) \in k, \ G.nl(o_1) = 0 \Leftrightarrow G'.nl(o_2) = 0; \]
– $k$ preserves the role names of object instances:
\[
\forall (o_1, o_2) \in k, \ G.nl(o_1) = 0 \Rightarrow G.nl(o_1) = G'.nl(o_2).
\]

For a set $M \subseteq \mathcal{G}_P$, by $\text{Maps}_P(M)$ we denote the set of all object mappings $(m, G, G', k)$ of package $P$ such that $G, G' \in M$.

An object mapping is a compact representation of the effect that a method call has on the objects of a package. The mapping specifies how objects are transformed by the method call. A pair $(o_1, o_2) \in k$ indicates that each concrete object represented by the abstract object $o_1$ might become part of the target abstract object $o_2$. The total number of concrete objects is always preserved. Because nested object graphs can represent more than one concrete state, there can be more than one object mapping associated with a given method call and source graph, as well as multiple target objects for each source object in the source graph of one object mapping.

Example 4 Let us consider the two cast nested object graphs inside the boxes in the left and right hand side of Fig. 2(a). Denote these two graphs by $G$ and $G'$. Figure 2(a) then represents the object mapping: $(\text{set}, G, G', ((V, V), (L_a, L_a), (L, L), (V, V)))$.

Note that in addition to callee and arg role names, the object mapping in Figure 2(a) also uses scope role names, which labels an object instance that is not part of the signature of the method. The scope role names are used to label all such object instances. One last type of role names that are used by object mappings is new role names, which label the objects that are created by a method call. To improve the readability of some figures we omit abstract objects that are not modified. We show only the objects part of the connected component affected by the call.

4.3 Definition: DPI

A DPI of a package $P$ is a tuple $(\mathcal{H}, \mathcal{G}, \Omega, E)$ where

– $\mathcal{H} \subseteq \mathcal{H}_P$ is a finite set of nested object graphs,
– $\mathcal{G} \subseteq \mathcal{G}_P$ is a finite set of cast nested object graphs,
– $\Omega \subseteq \text{Maps}_P(\mathcal{G})$ the set of object mappings; and
– $E \subseteq \mathcal{H}$ the set of error nested object graphs.

The DPI $(\mathcal{H}, \mathcal{G}, \Omega, E)$ is well-formed if:

1. the castgraphs come from $\mathcal{H}$: $\forall G \in \mathcal{G}, \ src(G) \in \mathcal{H}$
2. it is safe: $\forall (m, G, G') \in \Omega, \ src(G) \in (\mathcal{H} - E)$; and
3. it is complete in that a non-error covering nested object graph has a mapping for all methods:

\[
\forall H \in (\mathcal{H} - E), \ \forall o \in H.O, \ \forall m \in \text{class}(G.l(o)).M_p, \ \exists (m, G, G') \in \Omega, \ src(G) = H.
\]

Well-formed DPs characterize the type of interface that we are interested in computing for OO packages. Following the analogy between a DPI and an FSM, the set of nested object graphs correspond to the “states” of the state machine and the set of object mappings correspond to the “transitions”. Section 5 describes how a well-formed
DPI can be computed for a package soundly via an abstract semantics that simulates the concrete semantics of Section 3. Henceforth by a DPI, we mean a well-formed DPI.

A DPI can be understood in two ways. The first interpretation comes directly from the abstract OO program semantics of Section 5. The second interpretation views the DPI as a counter program. In this program each $H \in \mathcal{H}$ has a control location and for each node in $H.O$ there is a counter variable. The value of a counter keeps track of the number of concrete objects that are represented by the corresponding abstract object node. Object mappings can be translated into updates of the counters. Further details of that interpretation can be found in Section 5.4 and [4].

5 Abstract Semantics for Computing DPI

In this section, we present the abstraction layers that we use to compute the DPI of a package. Section 5.2 presents our depth-bounded abstract domain, which ensures that any chain of objects of a package has a bounded depth when represented in this domain. Section 5.3 presents our ideal abstract domain, which additionally ensures that any number of objects of a package are represented finitely. Section 5.4 describes how the DPI of a package can be computed by encoding the ideal abstract interpretation of a package as a numerical program.

5.1 Preliminaries

For a transition system $S = (X, X_0, \rightarrow)$, we define the post operator as $\text{post}(S) : \mathcal{P}(X) \rightarrow \mathcal{P}(X)$ with $\text{post}(S)(Y) = \{ x' \in X \mid \exists x \in Y. x \rightarrow x' \}$. The reachability set of $S$, denoted $\text{Reach}(S)$, is defined by $\text{Reach}(S) = \text{lfp}^\infty (\lambda Y. X_0 \cup \text{post}(S)(Y))$.

A quasi-ordering $\leq$ is a reflexive and transitive relation $\leq$ on a set $X$. In the following $X(\leq)$ is a quasi-ordered set. The downward closure (resp. upward closure) of $Y \subseteq X$ is $\downarrow Y = \{ x \in X \mid \exists y \in Y. x \leq y \}$ (resp. $\uparrow Y = \{ x \in X \mid \exists y \in Y. y \leq x \}$). A set $Y$ is downward-closed (resp. upward-closed) if $Y = \downarrow Y$ (resp. $Y = \uparrow Y$). An element $x \in X$ is an upper bound for $Y \subseteq X$ if for all $y \in Y$ we have $y \leq x$. A nonempty set $D \subseteq X$ is directed if any two elements in $D$ have a common upper bound in $D$. A set $I \subseteq X$ is an ideal of $X$ if $I$ is downward-closed and directed. A quasi-ordering $\leq$ on a set $X$ is a well-quasi-ordering (wqo) if any infinite sequence $x_0, x_1, x_2, \ldots$ of elements from $X$ contains an increasing pair $x_i \leq x_j$ with $i < j$.

A well-structured transition system (WSTS) is a tuple $S = (X, X_0, \rightarrow, \leq)$ where $(X, X_0, \rightarrow)$ is a transition system and $\leq \subseteq X \times X$ is a wqo that is monotonic with respect to $\rightarrow$, i.e., for all $x_1, x_2, y_1, t$ such that $x_1 \leq y_1$ and $x_1 \rightarrow x_2$, there exists $y_2$ such that $y_1 \rightarrow y_2$ and $x_2 \leq y_2$. The covering set of a well-structured transition system $S$, denoted $\text{Cover}(S)$, is defined by $\text{Cover}(S) = \downarrow \text{Reach}(S)$.

5.2 Depth-Bounded Abstract Semantics

We now present an abstract semantics for OO programs. Given an OO program $S$, our abstract semantics of $S$ is a transition system $S^\# = (\text{Conf}^\#, \mathcal{U}^\#, \rightarrow^\#)$ that is obtained by an abstract interpretation [5] of $S$. Typically, the system $S^\#$ is still an infinite state
system. However, the abstraction ensures that $S_n^u$ belongs to the class of depth-bounded systems [12]. Depth-bounded systems are well-structured transition systems that can be effectively analyzed [20], and this will enable us to compute the dynamic package interface.

**Heap Predicate Abstraction.** We start with a heap predicate abstraction, following shape analysis [14][17]. Let $AP$ be a finite set of *unary abstraction predicates* from $\text{Pred}((x) \cup C.A)$ where $x$ is a fresh variable different from this and null. For a configuration $u = (O,.; st)$ and $o \in O$, we write $u \models p(o)$ iff $st[x \mapsto o](p) = 1$. Further, let $AR$ be a subset of the reference fields in $C.A$. We refer to $AR$ as *binary abstraction predicates*. For an object $o \in O$, we denote by $AR(o)$ the set $AR \cap \text{class}(o).A$.

The concrete domain $D$ of our abstract interpretation is the powerset of configurations $D = \mathcal{P}(Conf)$, ordered by subset inclusion. The abstract domain $D_h^u$ is the powerset of abstract configurations $D_h^u = \mathcal{P}(Conf^u)$, again ordered by subset inclusion. An abstract configuration $u^h \in Conf^u$ is like a concrete configuration except that the store is abstracted by a finite labelled graph, where nodes are object identifiers, edges correspond to the values of reference fields in $AR$, and node labels denote the evaluation of objects on the predicates in $AP$. That is, the abstract domain is parameterized by both $AP$ and $AR$.

Formally, an abstract configuration $u^h \in Conf^u$ is a tuple $(O, this, q, v, q, st)$ where $O \subseteq O$ is a finite set of object identifiers, $this \in O$ is the current object, $q \in F.Q$ is the current control location, $v$ is a finite sequence of triples $(o, x, q)$ of objects, variables, and control location, $\eta : O \times AP \to \mathbb{B}$ is a predicate valuation, and $st$ is an abstract store that maps objects in $o \in O$ and reference fields $a \in AR(o)$ to objects $st(p, a) \in O$. Note that we identify the elements of $Conf^u$ up to isomorphic renaming of object identifiers.

The meaning of an abstract configuration is given by a concretization function $\gamma_h : Conf^u \to D$ defined as follows: for $u^h \in Conf^u$ we have $u^h \models \gamma_h(u^h)$ iff (i) $u^h.O = u.O$; (ii) $u^h.this = u.this$; (iii) $u^h.q = u.q$; (iv) $u^h.v = u.v$; (v) for all $o \in u.O$ and $p \in AP$, $u^h.p(o, p) = 1$ iff $u \models p(o)$; and (vi) for all objects $o \in O$, and $a \in AR(o)$, $u^h.st(o,a) = u^h.st(o,a)$. We lift $\gamma_h$ pointwise to a function $\gamma_h : D_h^u \to D$ by defining $\gamma_h(u^h) = \bigcup \{ \gamma_h(u^h) \mid u^h \in U^u \}$. Clearly, $\gamma_h$ is monotone. It is also easy to see that $\gamma_h$ distributes over meets because for each configuration $u$ there is, up to isomorphism, a unique abstract configuration $u^h$ such that $u \in \gamma_h(u^h)$. Hence, let $\alpha_h : D \to D_h^u$ be the unique function such that $\alpha_h$ forms a Galois connection between $D$ and $D_h^u$, i.e., $\alpha_h(U) = \bigcap \{ U^u \mid U \subseteq \gamma_h(U^u) \}$.

The abstract transition system $S_h^u = (Conf^u, U_0^u, \to_h^u)$ is obtained by setting $U_0^u = \alpha_h(U_0)$ and defining $\to_h^u \subseteq Conf^u \times Conf^u$ as follows. Let $u^h, v^h \in Conf^u$. We have $u^h \to_h^u v^h$ iff $v^h \in \alpha_h \circ \text{post}.S \circ \gamma_h(u^h)$.

**Theorem 1.** The system $S_h^u$ simulates the concrete system $S$, i.e., (i) $U_0 \subseteq \gamma_h(U_0^u)$ and (ii) for all $u, v \in Conf$ and $u^h \in Conf^u$, if $u \in \gamma_h(u^h)$ and $u \to v$, then there exists $v^h \in Conf^u$ such that $u^h \to_h^u v^h$ and $v \in \gamma_h(v^h)$.

**Proof. (Sketch)** We can use the framework of abstract interpretation [6] to prove the theorem. By definition, $(\alpha_h, \gamma_h)$ forms a Galois connection between $D$ and $D_h^u$. Furthermore, $u^h \to_h^u v^h$ iff $v^h \in \alpha_h \circ \text{post}.S \circ \gamma_h(u^h)$. 

**Depth-Boundedness.** Let \( u^h \in \text{Conf}^h \) be an abstract configuration. A simple path of length \( n \) in \( u^h \) is a sequence of distinct objects \( \pi = o_1, \ldots, o_n \) in \( u^h,O \) such that for all \( 1 \leq i < n \), there exists \( a_i \) with \( u^h.st(o_i, a_i) = o_{i+1} \) or \( u^h.st(o_{i+1}, a_i) = o_i \) (the path is not directed). We denote by \( \text{lsp}(u^h) \) the length of the longest simple path of \( u^h \). We say that a set of abstract configurations \( U^h \subseteq \text{Conf}^h \) is depth-bounded if \( U^h \) is bounded in the length of its simple paths, i.e., there exists \( k \in \mathbb{N} \) such that \( \forall u^h \in U^h, \text{lsp}(u^h) \leq k \) and the size of the stack \( |u^h.v| \leq k \).

We show that under certain restrictions on the binary abstraction predicates \( AR \), the abstract transition system \( S^h_h \) is a well-structured transition system. For this purpose, we define the embedding order on abstract configurations. An embedding for two configurations \( u^h, v^h : \text{Conf}^h \) is a function \( h : u^h,O \rightarrow v^h,O \) such that the following conditions hold: (i) \( h \) preserves the class of objects: for all \( o \in u^h.O \), \( \text{class}(o) = \text{class}(h(o)) \); (ii) \( h \) preserves the current object, \( h(u^h\.this) = v^h\.this \); (iii) \( h \) preserves the stack, \( h(u^h.v) = v^h.v \) where \( h \) is the unique extension of \( h \) to stacks; (iv) \( h \) preserves the predicate valuation: for all \( o \in u^h.O \) and \( p \in AP \), \( u^h.p(h(o), p) \) iff \( v^h.p(h(o), p) \); and (v) \( h \) preserves the abstract store, i.e., for all \( o \in u^h.O \) and \( a \in AR(o) \), we have \( h(u^h.st(o, a)) = v^h.st(h(o), a) \). The embedding order \( \preceq : \text{Conf}^h \times \text{Conf}^h \) is then as follows: for all \( u^h, v^h : \text{Conf}^h \), \( u^h \preceq v^h \) iff \( u^h \) and \( v^h \) share the same current control location \( (u^h.q = v^h.q) \) and there exists an injective embedding of \( u^h \) into \( v^h \).

**Lemma 1.** (1) The embedding order is monotonic with respect to abstract transitions in \( S^h_h = (\text{Conf}^h, U^h_0, \rightarrow^h_h) \). (2) Let \( U^h \) be a depth-bounded set of abstract configurations. Then \( (U^h, \preceq) \) is a wqo.

**Proof.** The first part follows from the definitions. For the second part, we can reduce it to the result from \([4]\). We just need to encode the stack into the graph. The stack itself can be easily encoded as a chain with special bottom and top node. The assumption that the stack is bounded guarantees that can still apply \([4]\) Lemma 2.

If the set of reachable configurations of the abstract transition system \( S^h_h \) is depth-bounded, then \( S^h_h \) induces a well-structured transition system.

**Theorem 2.** If \( \text{Reach}(S^h_h) \) is depth-bounded, then \( (\text{Reach}(S^h_h), U^h_0, \rightarrow^h_h, \preceq) \) is a WSTS.

**Proof.** The theorem follows from Lemma \([1]\) and \([12]\) Theorem 2.

In practice, we can ensure depth-boundedness of \( \text{Reach}(S^h_h) \) syntactically by choosing the set of binary abstraction predicates \( AR \) such that it does not contain reference fields that span recursive data structures. Such reference fields are only allowed to be used in the defining formulas of the unary abstraction predicates. Recursive data structures can be dealt with only if they are private to the package, i.e., not exposed to the user. In that case the predicate abstraction can use a more complex domain that understand such shapes, e.g., \([17]\). In the next section, we assume that the set \( \text{Reach}(S^h_h) \) is depth-bounded and we identify \( S^h_h \) with its induced WSTS.

**Example 5** Figure \([2]\) depicts the two corresponding, depth-bounded abstract configurations of the concrete configurations in Figure \([3]\) The objects are labelled with their corresponding unary predicates. A labelled arrow between two objects specifies that the
corresponding binary predicate between two objects holds. The set of unary abstraction predicates consists of:

- \( \text{empty}(x) \equiv x.\text{size} = 0 \)
- \( \text{sync}(x) \equiv x.\text{iver} = x.\text{iter_of.sver} \)
- \( \text{mover}(x) \equiv x.\text{pos} < x.\text{iter_of.size} \)
- \( \text{positive}(x) \equiv x.e > 0 \)

The set of binary abstraction predicates is \( \mathcal{A}_R = \{\text{iter_of}\} \). If we had also included \( \text{head} \) and \( \text{next} \) in \( \mathcal{A}_R \), the resulting abstraction would not have been depth bounded.

### 5.3 Ideal Abstraction

In our model, the errors are local to objects. Thus, we are looking at the control-state reachability question. This means that the set of abstract error configurations is upward-closed with respect to the embedding order \( \preceq \), i.e., we have \( U^\#_{\text{err}} = \uparrow U^\#_{\text{err}} \). From the monotonicity of \( \preceq \) we therefore conclude that \( \text{Reach}(S^\#_h) \cap U^\#_{\text{err}} = \emptyset \) if and only if \( \text{Cover}(S^\#_h) \cap U^\#_{\text{err}} = \emptyset \). This means that if we analyze the abstract transition system \( S^\#_h \) modulo downward closure of abstract configurations, this does not incur an additional loss of precision. We exploit this observation as well as the fact that \( S^\#_h \) is well-structured to construct a finite abstract transition system whose configurations are given by downward-closed sets of abstract configurations. We then show that this abstract transition system can be effectively computed.

Every downward-closed subset of a wqo is a finite union of ideals. In previous work \cite{21}, we formalized an abstract interpretation coined \emph{ideal abstraction}, which exploits this observation to obtain a generic terminating analysis for computing an over-approximation of the covering set of a WSTS. We next show that ideal abstraction applies to the depth-bounded abstract semantics by providing an appropriate finite representation of ideals and how to use it to compute the DPI. The abstract domain \( D^\#_{\text{idl}} \) of the ideal abstraction is given by downward-closed sets of abstract configurations, which we represent as finite sets of ideals. The concrete domain is \( D^h \). The ordering on the abstract domain is subset inclusion. The abstraction function is downward closure.

Formally, we denote by \( \text{Idl}(\text{Conf}^\#) \) the set of all depth-bounded ideals of abstract configurations with respect to the embedding order. Define the quasi-ordering \( \subseteq \) on \( \mathcal{P}_{\text{fin}}(\text{Idl}(\text{Conf}^\#)) \) as the point-wise extension of \( \preceq \) from the ideal completion \( \text{Idl}(\text{Conf}^\#) \) of \( \text{Conf}^\#(\preceq) \) to \( \mathcal{P}_{\text{fin}}(\text{Idl}(\text{Conf}^\#)) \):

\[
I_1 \subseteq I_2 \iff \forall I_1 \in I_2. \exists I_2 \in I_1, I_1 \subseteq I_2
\]
The abstract domain $D_{\text{idl}}^h$ is the quotient of $\mathcal{P}_{\text{fin}}(\text{Idl}(\text{Conf}^h))$ with respect to the equivalence relation $\subseteq \cap \subseteq^{-1}$. For notational convenience we use the same symbol $\subseteq$ for the quasi-ordering on $\mathcal{P}_{\text{fin}}(\text{Idl}(\text{Conf}^h))$ and the partial ordering that it induces on $D_{\text{idl}}^h$. We further identify the elements of $D_{\text{idl}}^h$ with the finite sets of maximal ideals, i.e., for all $L \in D_{\text{idl}}^h$ and $I_1, I_2 \in L$, if $I_1 \subseteq I_2$ then $I_1 = I_2$. The abstract domain $D_{\text{idl}}^h$ is defined as $\mathcal{P}_{\text{fin}}(\text{Idl}(\text{Conf}^h))$. The concretization function $\gamma_{\text{idl}} : D_{\text{idl}}^h \to D_{\text{idl}}^h$ is $\gamma_{\text{idl}}(I) = \bigcup I$. Further, define the abstraction function $\alpha_{\text{idl}} : D_{\text{idl}}^h \to D_{\text{idl}}^h$ as $\alpha_{\text{idl}}(U^h) = \{ I \in \text{Idl}(\text{Conf}^h) | I \subseteq I^h \}$. From the ideal abstraction framework $\text{[21]}$, it follows that $(\alpha_{\text{idl}}, \gamma_{\text{idl}})$ forms a Galois connection between $D_{\text{idl}}^h$ and $D_{\text{idl}}^h$. The overall abstraction is then given by the Galois connection $(\alpha, \gamma)$ between $D$ and $D_{\text{idl}}^h$, which is defined by $\alpha = \alpha_{\text{idl}} \circ \alpha_{\text{fin}}$ and $\gamma = \gamma_{\text{idl}} \circ \gamma_{\text{fin}}$. We define the abstract post operator $\text{post}^h$ of $S$ as the most precise abstraction of $\text{post} \cdot S$ with respect to this Galois connection, i.e., $\text{post}^h \cdot S = \alpha \circ \text{post} \circ \gamma$.

In the following, we assume the existence of a sequence widening operator $\nabla_{\text{idl}} : \text{Idl}(\text{Conf}^h)^* \to \text{Idl}(\text{Conf}^h)^*$, i.e., $\nabla_{\text{idl}}$ satisfies the following two conditions: (i) covering condition: for all $I \in \text{Idl}(\text{Conf}^h)^*$, if $\nabla_{\text{idl}}(I)$ is defined, then for all $I$ in $I$, $I \subseteq \nabla_{\text{idl}}(I)$; and (ii) termination condition: for every ascending chain $(I_i)_{i \in \mathbb{N}}$ in $\text{Idl}(\text{Conf}^h)$, the sequence $I_0 = I_0, I_1 = \nabla_{\text{idl}}(I_0 \ldots I_n)$, for all $i > 0$, is well-defined and an ascending stabilizing chain.

The ideal abstraction induces a finite labeled transition system $\text{S}^h_{\text{idl}}$ whose configurations are ideals of abstract configurations. There are special transitions labeled with $\epsilon$, which we refer to as abstracting transitions. We call $\text{S}^h_{\text{idl}}$ the abstract covering system of $\text{S}^h$. This is because the set of reachable configurations of $\text{S}^h_{\text{idl}}$ over-approximates the covering set of $\text{S}^h$, i.e., $\text{Cover}(\text{S}^h_{\text{idl}}) \subseteq \gamma_{\text{idl}}(\text{Reach}(\text{S}^h_{\text{idl}}))$. Furthermore, the directed graph spanned by the non-covering transitions of $\text{S}^h_{\text{idl}}$ is acyclic.

Formally, we define $\text{S}^h_{\text{idl}} = (\text{I}_{\text{idl}}, I_0, \rightarrow^h_{\text{idl}})$ as follows. The initial configurations $I_0$ are given by $I_0 = \alpha_{\text{idl}}(U^h_0)$. The set of configurations $\text{I}_{\text{idl}} \subseteq \text{Idl}(\text{Conf}^h)$ and the transition relation $\rightarrow^h_{\text{idl}} \subseteq \text{I}_{\text{idl}} \times \text{I}_{\text{idl}}$ are defined as the smallest sets satisfying the following conditions: (1) $I_0 \subseteq I_{\text{idl}}$; and (2) for every $I \in \text{I}_{\text{idl}}$, let $\text{paths}(I)$ be the set of all sequences of ideals $I_0 \ldots I_n$ with $n \geq 0$ such that $I_0 \in I_0, I_n = I$, and for all $0 \leq i < n, I_i \rightarrow^h_{\text{idl}} I_{i+1}$. Then, for every path $I = I_0 \ldots I_n \in \text{paths}(I)$, if there exists $i < n$ such that $I_i \subseteq I_{i+1}$, then $I \rightarrow^h_{\text{idl}} I_{i+1}$. Otherwise, for all $I' \in \text{post}^h \cdot S \circ \gamma_{\text{idl}}(I)$, let $J' = \nabla_{\text{idl}}(I' \cdot I')$ where $I'$ is the subsequence of all ideals $I_i$ in $I$ with $I_i \subseteq I'$, then $J' \in \text{I}_{\text{idl}}$ and $I \rightarrow^h_{\text{idl}} J'$.

**Theorem 3.** The abstract covering system $\text{S}^h_{\text{idl}}$ is computable and finite.

**Proof. (Sketch)** Following the result from $\text{[21]}$, we can effectively compute an inductive overapproximation $C$ of the covering set of $\text{S}^h_{\text{idl}}$. From $\text{[20]}$ Lemma 15, we have a finite representation of $C$. Finally, $\rightarrow^h_{\text{idl}}$ can be effectively computed as we will see in the remainder of the section.

Define the relation $\rightarrow^h_{\text{idl}} \subseteq \text{I}_{\text{idl}} \times \text{I}_{\text{idl}}$ as $\rightarrow^h_{\text{idl}} = \rightarrow^h_{\text{idl}} \cup \epsilon_{\text{idl}} \circ \rightarrow^h_{\text{idl}}$. We now state our main soundness theorem.

**Theorem 4.** [Soundness] The abstract covering system $\text{S}^h_{\text{idl}}$ simulates $S$, i.e., (i) $U_0 \subseteq \gamma(I_0)$ and (ii) for all $I \in \text{I}_{\text{idl}}$ and $u, v \in \text{Reach}(S)$, if $u \in \gamma(I)$ and $u \rightarrow v$, then there exists $J \in \text{I}_{\text{idl}}$ such that $v \in \gamma(J)$ and $I \rightarrow^h_{\text{idl}} J$. 
Proof. (Sketch) The abstract covering system is just a lifting of the original transition system to a finite-state system by partitioning the states into a finite number of sets given by the incomparable ideals in covering set or an overapproximation of it. The lifting relies on the monotonicity property of the underlying WSTS to ensure simulation. The transition relation \( \rightarrow_{\text{idl}}^\# \) maps states from ideal to ideal while ensuring that the target ideal contains at least one larger state.

In the rest of this section, we explain how we represent ideals of abstract configurations and how the operations for computing the abstract covering system are implemented.

Representing Ideals of Abstract Configurations. The ideals of depth-bounded abstract configurations are recognizable by regular hedge automata [20]. We can encode these automata into abstract configurations \( I^\# \) that are equipped with a nesting level function.

Formally, a quasi-ideal configuration \( I^\# \) is a tuple \((O, \text{this}, q, v, \eta, st, nl)\) where \( nl : O \rightarrow \mathbb{N} \) is the nesting level function and \((O, \text{this}, q, v, \eta, st)\) is an abstract configuration, except that \( \eta \) is only a partial function \( \eta : O \times AP \rightarrow \mathbb{B} \). We denote by \( QIdlConf^{\#} \) the set of all quasi-ideal configurations. We call \( I^\# = (O, \text{this}, q, v, \eta, st, nl) \) simply an ideal configuration, if \( \eta \) is total and for all \( o \in O, a \in AR(o), nl(o) \geq nl(st(o, a)) \). We denote by \([I^\#]\) the inherent abstract configuration \((O, \text{this}, q, v, \eta, st)\) of an ideal configuration \( I^\# \). Further, we denote by \( IdlConf^{\#} \) the set of all ideal configurations and by \( IdlConf^0 \) the set of all ideal configurations in which all objects have nesting level 0. We call the latter finitary ideal configurations.

Meaning of Quasi-Ideal Configurations. An inclusion mapping between quasi-ideal configurations \( I^\# = (O, \text{this}, q, v, \eta, st, nl) \) and \( J^\# = (O', \text{this}', q', v', \eta', st', nl') \) is an embedding \( h : O \rightarrow O' \) that satisfies the following additional conditions: (i) for all \( o \in O, nl(o) \leq nl'(h(o)) \); (ii) \( h \) is injective with respect to level 0 vertices in \( O' \); for all \( o_1, o_2 \in O, o' \in O', h(o_1) = h(o_2) = o' \) and \( nl'(o') = 0 \) implies \( o_1 = o_2 \); and (iii) for all distinct \( o_1, o_2, o \in O \), if \( h(o_1) = h(o_2) \), and \( o_1 \) and \( o_2 \) are both neighbors of \( o \), then \( nl'(h(o_1)) = nl'(h(o_2)) > nl'(h(o)) \).

We write \( I^\# \leq_h J^\# \) if \( q = q' \) and \( h \) is an inclusion mapping between \( I^\# \) and \( J^\# \). We say that \( I^\# \) is included in \( J^\# \), written \( I^\# \leq J^\# \), if \( I^\# \leq_h J^\# \) for some \( h \).

We define the meaning \([I^\#]\) of a quasi-ideal configuration \( I^\# \) as the set of all inherent abstract configurations of the finitary ideal configurations included in \( I^\# \):

\[
[I^\#] = \{ [J^\#] \mid J^\# \in IdlConf^0 \land J^\# \leq I^\# \}
\]

We extend this function to sets of quasi-ideal configurations, as expected.

Proposition 1. Ideal configurations exactly represent the depth-bounded ideals of abstract configurations, i.e., \( [I^\#] \in IdlConf^0 \), \( I^\# \leq J^\# \) iff \( [I^\#] \subseteq [J^\#] \).

Since the relation \( \leq \) is transitive, we also get:

Proposition 2. For all \( I^\#, J^\# \in QIdlConf^0 \), \( I^\# \leq J^\# \) iff \( [I^\#] \subseteq [J^\#] \).
It follows that inclusion of (quasi-)ideal configurations can be decided by checking for the existence of inclusion mappings, which is an \( \text{NP-complete} \) problem.

Quasi-ideal configurations are useful as an intermediate representation of the images of the abstract post operator. They can be thought of as a more compact representation of sets of ideal configurations. In fact, any quasi-ideal configuration can be reduced to an equivalent finite set of ideal configurations. We denote the function performing this reduction by \( \text{reduce} : \text{QIdlConf}^\# \rightarrow \mathcal{P}_{\text{fin}}(\text{IdlConf}^\#) \) and we extend it to sets of quasi-ideal configurations, as expected.

**Example 6** Figure 5 depicts the two corresponding, ideal abstract configurations of the two depth-bounded abstract configurations in Figure 4. The nesting level of each object is shown by the number next to it. When the abstract configurations in Figure 4 are considered as finitary ideal configurations, then they are included in their corresponding ideal configurations in Figure 5. The two inclusion mappings between the corresponding configurations in Figure 4 and Figure 5 are \( \{(i_1,s_1),(i_2,s_2),(s,s^\#),(e_1,e^\#),(e_2,e^\#)\} \).

Note that since the nesting level of \( s^\# : \text{Set} \) in both ideal configurations is zero, it is not possible to define inclusion mapping when there are more than one concrete set object. However, if the nesting levels of the set and iterator objects are incremented, then such an inclusion mapping can be defined.

**Computing the Abstract Post Operator.** We next define an operator \( \text{Post}^\#.S \) that implements the abstract post operator \( \text{post}^\#.S \) on ideal configurations. In the following, we fix an ideal configuration \( I^\# = (O,\text{this},q,y,st,nl) \) and a transition \( t = (q,\text{op},q') \) in \( S \). For transitions not enabled at \( I^\# \), we set \( \text{Post}^\#.S.t(I^\#) = \emptyset \).

We reduce the computation of abstract transitions \( [I^\#] \rightarrow u^\# \) to reasoning about logical formulas. For efficiency reasons, we implicitly use an additional Cartesian abstraction [3] in the abstract post computation that reduces the number of required theorem prover calls. For a set of variables \( X \), we assume a symbolic weakest precondition operator \( \text{wp} : \text{Op}.(C.A) \times \text{Pred}._{\text{X} \cup C.A} \rightarrow \text{Pred}._{\text{X} \cup C.A} \) that is defined as usual. In addition, we need a symbolic encoding of abstract configurations into logical formulas. For this purpose, define a function \( \Gamma : O \rightarrow \text{Pred}._{(O \cup \text{C.A})} \) as follows: given \( o \in O \), let \( O(o) \) be the subset of objects in \( O \) that are transitively reachable from \( o \) in the abstract
store st, then $\Gamma(o)$ is the formula

$$\Gamma(o) = \text{distinct}(O(o) \cup O(this)) \land \text{this} = \text{this} \land \text{null} = \text{null} \land$$

$$\bigwedge_{o' \in O(o), O(this)} \left( \bigwedge_{p \in AP} \eta(o', p) \cdot p(o') \land \bigwedge_{a \in AR(o')} o'.a = st(o'.a) \right)$$

where $\eta(o', p) \cdot p(o') = \begin{cases} p(o') & \text{if } \eta(o', p) = 1 \\ \neg p(o') & \text{if } \eta(o', p) = 0. \end{cases}$

Now, let $J^\#$ be the set of all quasi-ideal configurations $J^\# = (O, this, q', v, \eta', st', nl)$ that satisfy the following conditions:

- $\Gamma(this) \land q$ is satisfiable, if $op = \text{assume}(q)$;
- for all $o \in O, p \in AP$, if $\Gamma(o) \models \text{wp}(op, p(o))$, then $\eta'(o, p) = 1$, else if $\Gamma(o) \models \text{wp}(op, \neg p(o))$, then $\eta'(o, p) = 0$, else $\eta'(o, p)$ is undefined;
- for all $o, o' \in O, a \in AR(o), a \in AR(o')$, if $\Gamma(o) \land \Gamma(o') \models \text{wp}(op, o.a = o')$, then $st'(o, a) = o'$, else if $\Gamma(o) \land \Gamma(o') \models \text{wp}(op, o.a \neq o')$, then $st'(o, a) \neq o'$.

Then define $\text{Post}^\#(s.t(I^\)) = \text{reduce}(J^\#)$.

### 5.4 Computing the Dynamic Package Interface

We now describe how to compute the dynamic package interface for a given package $P$. The computation proceeds in three steps. First, we compute the OO program $S = (P, I)$ that is obtained by extending $P$ with its most general client $I$. Next, we compute the abstract covering system $S^\#$ of $S$ described as Sections 5.2 and 5.3. We assume that the user provides sets of unary and binary abstraction predicates $AP$, respectively, $AR$ that define the heap abstraction. Alternatively, we can use heuristics to guess these predicates from the program text of the package. For example, we can add all branch conditions in the program description as predicates. Finally, we extract the package interface from the computed abstract covering system. We describe this last step in more detail.

We can interpret the abstract covering system as a numerical program. The control locations of this program are the ideal configurations in $S^\#$. With each abstract object occurring in an ideal configuration we associate a counter. The value of each counter denotes the number of concrete objects represented by the associated abstract object. While computing $S^\#$, we do some extra bookkeeping and compute for each transition of $S^\#$ a corresponding numerical transition that updates the counters of the counter program. These updates capture how many concrete objects change their representation from one abstract object to another. A formal definition of such numerical programs can be found in [4].

The dynamic package interface $\text{DPI}(P)$ of $P$ is a numerical program that is an abstraction of the numerical program associated with $S^\#$. The control locations of $\text{DPI}(P)$ are the ideal configurations in $S^\#$ that correspond to call sites, respectively, return sites to public methods of classes in $P$, in the most general client. A connecting path in $S^\#$ for a pair of such call and return sites (along with all covering transitions connecting ideal configurations on the path) corresponds to the abstract execution of a single
method call. We refer to the restriction of the numerical program \( S^g_{\text{id}} \) to such a path and all its covering transitions as a **call program**. Each object mapping of \( \text{DPI}(P) \) represents a summary of one such call program. Hence, an object mapping of \( \text{DPI}(P) \) describes, both, how a method call affects the state of objects in a concrete heap configuration and how many objects are affected.

Note that a call program may contain loops because of loops in the method executed by the call program. The summarization of a call program therefore requires an additional abstract interpretation. The concrete domain of this abstract interpretation is given by transitions of counter programs, i.e., relations between valuations of counters. The concrete fixed point is the transitive closure of the transitions of the call program. The abstract domain provides an appropriate abstraction of numerical transitions. How precisely the package interface captures the possible sequences of method calls depends on the choice of this abstract domain and how convergence of the analysis of the call programs is enforced. We chose a simple abstract domain of **object mappings** that distinguishes between a constant number, respectively, arbitrary many objects transitioning from an abstract object on the call site of a method to another on the return site. However, other choices are feasible for this abstract domain that provide more or less information than object mappings.

# 6 Experiences

We have implemented our system by extending the Picasso tool\[^{21}\]. Picasso uses an ideal abstraction to compute the covering sets of depth-bounded graph rewriting systems. Our extension of Picasso computes a dynamic package interface from a graph rewriting system that encodes the semantics of the method calls in a package\[^{1}\].

For a graph-rewriting system that represents a package, our tool first computes its covering set. Using the elements of the covering set, it then performs unfolding over them with respect to all distinct method calls to derive the object mappings of the DPI of the package. The computation of the covering elements and the object mappings are carried out as described in the previous section.

In addition to the Viewer and Label example, described in Section\[^{2}\] we have experimented with other examples: a set and iterator package, which we used as our running example in the previous sections, and the JDBC statement and result package. In the remainder of this section, we present the DPIs for these packages.

**Set and Iterator.** We considered a simple implementation of the **Set** and **Iterator** classes in which the items in a set are stored in a linked list. The **Iterator** class has the usual **next**, **hasNext**, and **remove** methods. The **Set** class provides a method **iterator**, which creates an **Iterator** object associated with the set, and an **add** method, which adds a data element to the set. The interface of the package is meant to avoid raising exceptions of types **NoSuchElementException** and **ConcurrentModificationException**. A **NoSuchElementException** is raised whenever the **next** method is called on an iterator of an empty list. A **ConcurrentModificationException** is raised whenever an iterator

\[^{1}\] Our tool and the full results of our experiments can be found at: [http://pub.ist.ac.at/~zufferey/picasso/dpi/index.html](http://pub.ist.ac.at/~zufferey/picasso/dpi/index.html)
accesses the set after the set has been modified, either through a call to the add method of the set or through a call to the remove method of another iterator. An iterator that removes an element can still safely access the set afterwards. (Similar restrictions apply to other Collection classes that implement Iterable.)

We used the following predicates. The unary abstraction predicate empty($s$) determines whether the size of a Set object $s$ is zero or not. For Iterator objects, we specified two predicates that rely on the attributes of both the Set and the Iterator classes. The predicate sync($i$) holds for an Iterator object $i$ that has the same version as its associated Set object. The predicate mover($i$) specifies that the position of an Iterator object $i$ in the list of its associated Set object is less than the size of the set.

Our algorithm computes the maximal configurations $H_0$, shown in Figure 6(a). There are also four error abstract heap configurations, which correspond to different cases in which one of the two exceptions is raised for an Iterator object. Figure 6(b) and 6(c) show the object mappings of two transitions. For the sake of clarity, we have omitted the name of the reference attribute iter of in the mappings. While both transitions invoke the remove() method on an Iterator object whose mover and sync predicates are true, they have different effects because they capture different concrete heaps represented by the same abstract heap $H_0$. The first transition shows the case when the callee object remains a mover, i.e., its pos field does not refer to the last element of the list. The second transition shows the case when the callee object becomes a non-mover; i.e., before the call to remove, its pos field refers to the last element of the linked list. In both transitions, the other Iterator objects that reference the same Set object all become unsynced. Some of these objects remain movers while some of them become non-movers. In both cases, the callee remains synced. There are two other symmetric transitions that capture the cases in which the Set object becomes empty.

JDBC (Java Database Connectivity) is a Java technology that enables access to databases of different types. We looked at three classes of JDBC for simple query access to databases: Connection, Statement, and ResultSet. A Connection object provides a means to connect to a database. A Statement object can execute an SQL query statement through a Connection object. A ResultSet object stores the result of the execution of a Statement object. All objects can be closed explicitly. If a Statement object is closed, its corresponding ResultSet object is also implicitly closed. Similarly, if a Connection object is closed, its corresponding Statement objects are implicitly closed, and so are the open ResultSet objects of these Statement objects. Java documentation states: “By default, only one ResultSet object per Statement object can be open at the same time. Therefore, if the reading of one ResultSet object is interleaved with the reading of another, each must have been generated by different Statement objects. All execution methods in the Statement interface implicitly close a statement’s current ResultSet object if an open one exists.”

Figure 7(a) shows the maximal abstract heap $H_0$ computed by our tool. It represents all safe configurations in which the Connection object is either open or closed. Each type of object has a corresponding “open” predicate that specifies whether it is open or not. The node $c$ is of particular interest, as it demonstrates the preciseness of our algorithm: It has the same nesting level as the node $b$, which means that an open Statement object can have at most one open ResultSet object associated with it. We omit showing
(a) Abstract heap configuration $H_0$ of the set-iterator package using predicates: $\textit{empty}(s) \equiv s.\text{size} = 0$, $\textit{synch}(i) \equiv i.\text{iter}\_of\_sver$, and $\textit{mover}(i) \equiv i.\text{pos} < i.\text{iter}\_of\_size$.

(b) Object mapping for $d$.\textit{remove}()

(c) Another possible object mapping for $d$.\textit{remove}()

Fig. 6. Set-iterator DPI: The abstract heap of the package together with two of its object mappings
abstract heaps capturing erroneous configurations. Lastly, Figure 7(b) shows the object mapping for the close method call on an open Statement object with an open ResultSet object. The mapping takes the Statement object and the open ResultSet object to their corresponding closed objects. All other objects remain the same.

7 Conclusions

We have formalized DPIs for OO packages with inter-object references, developed a novel ideal abstraction for heaps, and given a sound and terminating algorithm to compute DPIs on the (infinite) abstract domain. In contrast to previous techniques for multiple objects based on mixed static-dynamic analysis [13,15], our algorithm is guaranteed to be sound. While our algorithm is purely static, an interesting future direction is to effectively combine it with dual, dynamic [7,8,15] and template-based [18] techniques.
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