

Traversals of Object Structures: Specification and Efficient Implementation*

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Abstract

Separation of concerns and loose coupling of concerns are important issues in software engineering. In this paper we show how to separate traversal-related concerns from other concerns, how to loosely couple traversal-related concerns to the structural concern and how to efficiently implement traversal-related concerns. The stress is on the detailed description of our algorithms and the traversal-specifications they operate on.

Traversal of object structures is a ubiquitous routine in most types of information processing. Ad-hoc implementations of traversals lead to scattered and tangled code and in this paper we present a new approach, called *traversal strategies*, to succinctly modularize traversals. In our approach traversals are defined using a high-level directed graph description, which is compiled into a dynamic road map to assist run-time traversals. The complexity of the compilation algorithm is polynomial in the size of the strategy graph and the class graph of the given application. A prototype of the system has been developed and is being successfully used to implement traversals for Java and AspectJ [54] and for generating adapters for software components. Our previous approach, called *traversal specifications* [34, 46], was less general, less succinct, and its compilation algorithm was of exponential complexity in some cases. In an additional result we show that this bad behavior is inherent to the static traversal code generated by previous implementations, where traversals are carried out by invoking methods without parameters.

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1 Introduction

1.1 The Idea of Adaptive Traversals

The run-time state of application programs, particularly of object-oriented programs, can be represented as a directed graph, where objects are represented as nodes and field names are represented as edges. To a large extent, program execution can be viewed as traversing that graph. Examples of traversals are that sub-objects with certain properties are sought; or it may be desired to compute a function of certain sub-objects of a given object. In standard programming techniques, expressing traversals involves a strong commitment to the whole class structure traversed (since each hop in the traversal is explicitly coded as in “*a.b*”), even if the task to be performed by the traversal depends only on the start and the target objects.

We call a concern that deals with traversing objects for implementing some behavior of those objects a traversal-related concern. A typical program operating on large objects contains many traversal-related concerns. Those traversal concerns already exist at the design level and become more refined as we move from the design object structure to the implementation object structure. The ad-hoc way for an experienced programmer to implement a traversal concern is to write methods for each of the classes whose objects are traversed. Unfortunately, this leads to a scattered and tangled implementation because the code that implements the concern is spread across multiple classes and tangled with code from other concerns.

In this paper we propose a new paradigm, called *traversal strategies*, or *strategies* for short, which helps us to not only cleanly modularize traversal-related concerns but also to minimally bind them to the structural concern, i.e., strategies allow the programmer to specify traversals in a localized manner with minimal binding to the class structure. Informally, the idea is to specify the high-level topology of the traversal, in which only the key “milestones” are explicitly mentioned; given a concrete class structure, executable traversal code is compiled, with all details filled in.

Strategies are a generalized form of *traversal specifications*, which were introduced in a simple form in [34] and formally treated in a more general form in [46]. Succinct specifications of traversals are an integral part of Adaptive Programming (AP) [31].

For a simple example, using the current implementation of our system, the DJ Library (see section 7.2.2 and [44, 32, 2]), a Java programmer may write

```
ClassGraph objectStructure = new ClassGraph();
ClassA o = new ClassA(...);
String whereToGo = "from ClassA to ClassB";
SomeClass whatAndWhenToDo = new SomeClass(...);
objectStructure.traverse(o, whereToGo, whatAndWhenToDo);
```

which means that when the `traverse` method of class graph `objectStructure` is invoked with an object `o` of class `ClassA` as first argument, the constituents of `o` will be recursively scanned according to the instructions in `whereToGo` to find all sub-objects whose class is `ClassB`, executing what needs to be done in addition to the scanning as specified by `whatAndWhenToDo`. For example, `whatAndWhenToDo` may produce an array which contains all `ClassB` sub-objects of `o`. Note that an ad-hoc implementation

of the above code may cut across many classes and would be tangled with other code. The reader is warned that the current implementation requires that the start class of the traversal is mentioned explicitly in the strategy although it could be inferred from the object being traversed.

We analyse the expression `objectStructure.traverse(o,whereToGo,whatAndWhenToDo)` from the point of view of separation of concerns. The overall expression implements some traversal-related behavioral concern by weaving together several subconcerns. Adaptive Programming (AP) is a technology that improves the separation of traversal-related concerns by separating the concerns of `objectStructure`, `whereToGo` and `whatAndWhenToDo`. Concern `objectStructure` is expressed by a class graph similar to a UML class diagram. Concern `whereToGo` is expressed by a strategy that defines, together with `objectStructure`, a traversal through `o`. Concern `whatAndWhenToDo` is split into a list of (`whenToDo`, `whatToDo`) pairs and defines an enhancement to the traversal which might veto some of the subtraversals. The coupling between the concerns is quite loose: concern `whereToGo` often minimally duplicates information from `objectStructure`, and `whatAndWhenToDo` mentions only a few classes and relationships from `objectStructure`. Separation of concerns offers many engineering benefits such as software that is less scattered and tangled, and that is easier to reuse.

A traversal strategy (expressing: where to go) deals with how to traverse through objects. A traversal is a function that maps each object graph rooted at object `o` to a subgraph rooted at `o`. This subgraph may then be traversed using one of several techniques, e.g., depth-first traversal that we use with DJ. We use a language tailored to the traversal concern and sentences in this language we express as strings in Java programs. The simplest expression in our language is of the form “from `ClassA` to `ClassB`”. This means: given an object of class `ClassA` (a `ClassA`-object), select a subgraph of the `ClassA`-object that contains all `ClassB`-objects. The subgraph of the `ClassA`-object is not a minimum subgraph, but it is minimum relative to the information in the class graph without look-ahead in the object graph.

The traversal relies on the following primitive: Given an object graph of some class graph, and a root object o of class `ClassA` from which the traversal from `ClassA` to `ClassB` starts, we need to decide which objects to visit from o , i.e., we need to compute $first(o)$, the set of edges that we need to traverse from o . Function $first(o)$ contains all edges that *could* lead (according to the rules of the class graph) to an object that contains a `ClassB`-object. The “*could*” represents our lack of knowledge about the rest of the object graph [61]. More precisely, $first(o)$ contains all edges $e = o \xrightarrow{l} o'$ such that there exists an object rooted at o' that contains a `ClassB`-object and that satisfies a fixed set of constraints (expressed by the class graph).

The previous paragraph gives the simple, yet complete meaning of the traversal “from `ClassA` to `ClassB`” which can be easily generalized to more general traversal specifications. Adaptive programmers need to know only this meaning of traversals which is further detailed in [61] but the present paper is also for implementors and we are studying efficient implementations of this meaning in the case that the traversal strategy is a general directed graph.

Our goal is to make the traversal efficient; therefore we don't want to look ahead in the object graph to decide whether going through an edge in $first(o)$ will eventually lead us to a `ClassB`-object. We only look ahead in the class graph because it gives us meta-information about the shape of objects. So $first(o)$ will contain all those edges after which, according to the class graph information, there

is still a possibility of reaching a `ClassB`-object. We accept that for this particular object some of the traversals might result in a dead end. A source of confusion is that a traversal may traverse any number of paths from a `ClassA`-object to `ClassB`-objects especially if in the class graph there are several paths from `ClassA` to `ClassB`.

But in all those cases, the semantics is precisely defined and this has already been the case in our earlier paper [46] on a subset of the traversal strategy language discussed here. The semantics is also clearly defined in the case of multiple paths in the traversal strategy.

Back to our example: `whatAndWhenToDo` is called a visitor object. A visitor object is an ordinary object that has methods that are executed as objects of classes specified in the visitor class are visited by the traversal. Visitor objects are named after the Visitor design pattern [18] but are much simpler than visitor objects described by the Visitor design pattern because none of the scaffolding is needed. By scaffolding we mean writing an abstract visitor class that duplicates much information from the class graph.

One obvious advantage of strategies is that the traversal is created automatically; another advantage is that the traversal specification is loosely coupled to the class structure: it works for the case where all `ClassB` objects are directly contained in the `ClassA` object, as well as for the case where the `ClassB` objects are deeply buried in sub-objects of `ClassA` objects.

More specifically, the basic concept of strategies can be defined as follows. Given a class graph $G = (V, E)$, a strategy is a subgraph S of the transitive closure of G , that is, there may be an edge (v, u) in S only if u is reachable from v in G . Thus, each edge (u, v) in the strategy graph defines a set of paths in the class graph: the paths from node u to node v . The next step is observing that by the natural notion of concatenation, we get that each *path* in the strategy graph defines a set of paths in the class graph. Finally, using specially marked nodes in the strategy graph, called *source* and *target*, one can define a set of paths in the strategy graph: the paths from the source node to the target node. Since each path in the strategy graph defines a set of paths in the original class graph, we have that a strategy defines a set of paths in the class graph. The paths in the class graph are expansions of the paths in the strategy graph. A path p is an expansion of a path p' if p' can be obtained by deleting some elements from p .

We can apply the concept of expansion also to define the semantics of a traversal strategy directly at the object graph level. When a traversal reaches a target node in the object graph, the path traversed from the source, with suitable substitution of subclasses by superclasses, must be an expansion of an s - t path in the strategy graph. s is the source and t the target of the strategy. When a traversal reaches a final node in the object graph without being at a target node, the path traversed, with suitable substitution of subclasses by superclasses, must be a prefix of an expansion of an s - t path in the strategy graph. The prefix is the longest prefix such that there is still a possibility of reaching a target node as determined by the class graph. Thus, a strategy effectively selects a set of paths in an object graph, by specifying relatively little detail. The union of all those object graph paths selects a subgraph of the object graph.

This basic idea is extended in many respects, as described in Section 4. To give a more concrete flavor for the usefulness of strategies, let us demonstrate with the following simple example.

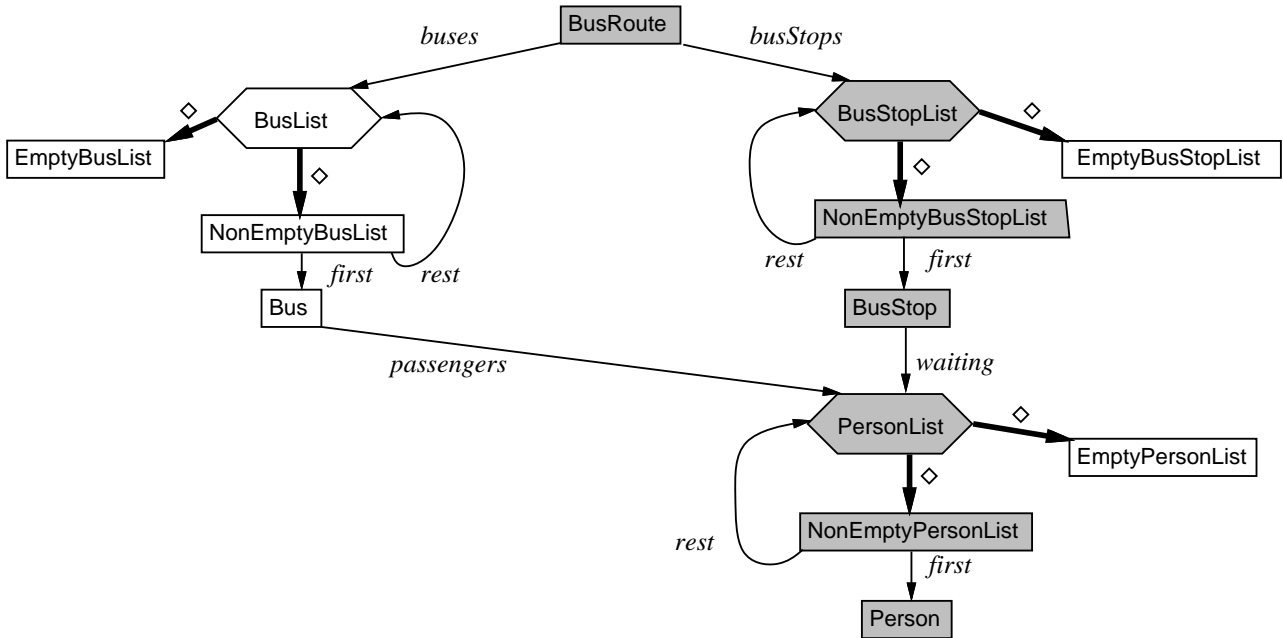


Figure 1: *Bus simulation class graph*. Squares and hexagons denote classes (concrete and abstract, respectively), regular arrows denote fields and are labeled by the field name, and heavy arrows (labeled with \diamond) denote the subclass relation (for the shading, see text).

1.2 Example

Consider a program simulating bus route management. For expressing class graphs, we use the graphical notation of our current implementation (called *DemeterJ*, [37]). Alternative notations would be the UML class diagram notation [7] or an XML schema notation [14]. For expressing behavior, we use standard Java and the DJ library [2]. Consider the class graph depicted in Fig. 1, which defines a data structure describing a bus route. A bus route object consists of two lists: a list of bus objects, each containing a list of passengers; and a list of bus stop objects, each containing a list of people waiting. Suppose that as a part of a simulation, we would like to determine the set of person objects corresponding to people waiting at any bus stop on a given bus route. The group of collaborating classes which is needed for this task is shaded in Fig. 1. To carry out the simulation, an object-oriented program should contain a method for each of these shaded classes. These methods that are scattered across several classes would traverse bus route objects. However, using the technique of strategies, one can solve the problem in a much more elegant way, by modularizing the code and keeping it in one place, rather than scattered through several classes and tangled with other code. We define a strategy graph with nodes `BusRoute`, `BusStop` and `Person` that are connected by an edge from `BusRoute` to `BusStop`, and an edge from `BusStop` to `Person`. (Note that this is a strategy graph because it is a subgraph of the transitive closure of the class graph.) In our formalism, the strategy can be expressed as follows.

- (1) from `BusRoute` via `BusStop` to `Person`

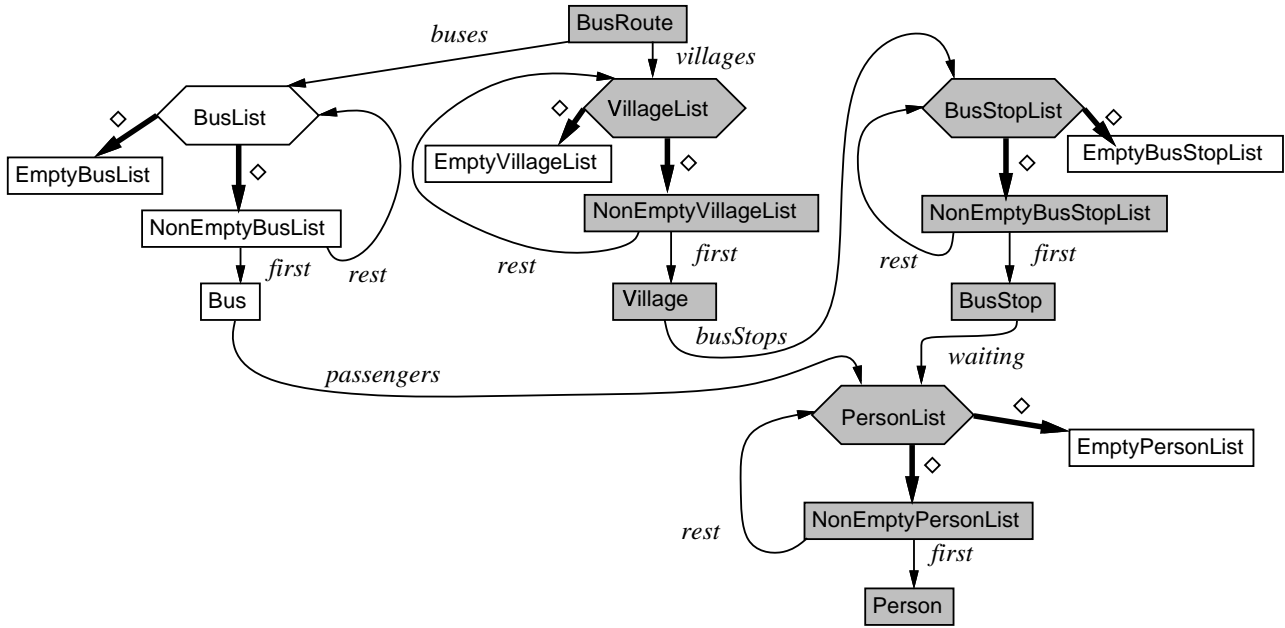


Figure 2: *Evolved bus simulation class graph.*

The benefit of strategies is apparent when considering the following scenario: Suppose that the bus route class has been modified so that the bus stops are grouped by villages. The revised class graph is depicted in Fig. 2. To implement the same requirement of finding all people waiting for a bus, an object-oriented program must now contain one method for each of the classes shaded in Fig. 2, and thus the previous object-oriented implementation becomes invalid. The traversal strategy (1), however, is up-to-date and does not require any rewriting. In fairness, the revision to the class graph must preserve the class names referred to in the traversal strategy and the meaning of the traversal strategy must be correct for the new class graph. When a class graph is changed, it is important to check the correctness of all traversal strategies that depend on that class graph. Sometimes it is necessary to refine the strategies to make them correct in the new class graph. But this is easier than updating all traversal methods manually [35].

The actual work on the objects is done by the so-called *visitor methods*: these are methods that can be associated with strategy points, specifying what to do when the traversal arrives at the object. The invocation order of the methods can be controlled for each object. Some standard visitor methods (e.g., printing, copying, testing for equality etc.) are provided as part of our implementation.

Strategies effectively filter out the noise in the class graph which is irrelevant to the implementation of the current task. For the class graph in Fig. 2, the simple strategy (1), which mentions only three classes, replaces methods for ten classes: `BusRoute`, `VillageList`, `NonEmptyVillageList`, `Village`, `BusStopList`, `NonEmptyBusStopList`, `BusStop`, `PersonList`, `NonEmptyPersonList`, `Person`.

To show how to program with strategies, we complete the Java program (using the DJ library) of finding all people waiting at any bus stop on a particular bus route.

```
class BusRoute {
```

```

// ...
ClassGraph cg = new ClassGraph();
String whereToGo2 = "from BusRoute via BusStop to Person";
void printWaitingPersons() {
    cg.traverse(this, whereToGo2, new PrintVisitor());
}
}

```

The program above defines a method called `printWaitingPersons` for the class `BusRoute`. This method will execute the traversal specified by traversal strategy (1), and it will print the object of class `BusRoute` using the visitor class `PrintVisitor`. Note that the definition of `printWaitingPersons` works without any change for both class graphs, which is the reason for calling it an *adaptive method* [32].

Notice that the adaptive method is expressed in plain Java using the DJ library of which we use the classes `ClassGraph` and `Visitor`, the super class of all visitor classes, such as `PrintVisitor`. A `ClassGraph`-object is a graph whose nodes are classes and whose edges are is-a and has-a relationships between classes. Class `ClassGraph` provides methods to create and maintain a class graph. The simplest way to create a `ClassGraph`-object is to call the constructor `ClassGraph()` without arguments which will create the class graph using Java reflection by taking all classes in the default package [44]. A traversal specification may be applied to both a `ClassGraph`-object and a Java object. From the point of view of a `ClassGraph`-object, a traversal specification is a subgraph of the transitive closure of the `ClassGraph`-object if it is applied to a class graph it selects a subset of the paths in the class graph. If applied to a Java object, a traversal specification defines a subgraph of the object graph representing the Java object.

In this implementation of adaptive programming with DJ the class graph and the traversals are computed dynamically. In previous implementations of adaptive programming for C++ [35] and Java [37, 12], the traversals are computed statically.

To show the details of visitors, we write a Java method that counts (instead of prints) all people waiting at any bus stop on a particular bus route. Because the traversals for `printWaitingPersons` and `countWaitingPersons` are identical, we reuse the same traversal strategy `whereToGo2`. We also reuse the class graph `cg`.

```

class BusRoute {
    // ...
    int countWaitingPersons() {
        Integer result = (Integer) cg.traverse(this, whereToGo2, new CountVisitor());
        return result.intValue();
    }
}
class CountVisitor extends Visitor {
    int c;
    public void start() { c=0; }
    public void before(Person o) { c++; }
    public Object getReturnValue() { return new Integer(c); }
}

```

}

Class `Visitor` has a simple interface: with the `start` method we say what needs to be done before the traversal starts. With the `getReturnValue` method we express what needs to be returned when the traversal completes. With a `before` method we express what needs to be done before we visit an object of a specific class. There are also `after` and `around` methods; the complete API is documented in [2]. The `before`, `after`, and `around` methods that are defined in a visitor class are invoked using the Java Reflection API.

1.3 New Contributions

The contributions of this paper are three-fold: an extension to the traversal specification language, a polynomial-time compilation algorithm for the extended language that is simpler than our earlier algorithm, and a lower bound result which explains the shortcomings of the previous algorithms. More specifically, we allow the underlying specification of a traversal to have any topology, generalizing the series-parallel and tree topologies considered previously, and we allow the use of a name map between the nodes in the strategy graph and in the class graph. This name map supports that different nodes in the strategy graph are mapped to the same node in the class graph. Section 9 provides a more detailed comparison of traversal strategies and traversal specifications.

The generalization of our previous algorithm to a larger class of graphs was not our primary goal for coming up with a better algorithm. It happened as a side-effect: as we made the algorithm more efficient and working for a larger class of series-parallel graph/class graph combinations, the algorithm also naturally worked for any kind of graph.

Our new polynomial-time algorithm presented in Section 5 has the beneficial property that it is simpler and easier to understand. Our earlier algorithm required an unintuitive check for the short-cut and zig-zag conditions. Those two conditions had to be checked to make sure that the traversal is correct. The short-cut and zig-zag conditions also prohibited many series-parallel graph/class graph combinations. We notice that this paper is related to two applications of Polya's inventors paradox[48]: 1. Although we solve a more general algorithmic problem at the programming tool level, the algorithm becomes simpler. 2. The algorithm supports better adaptive programming which is about solving problems for more general data structures than the one originally given, leading to simpler programs ([31], section 4.1.1).

The compilation algorithm generates code whose running time may be slightly worse than the running time of the code generated by previous compilation algorithms (when they apply), since the previous algorithm generated traversal methods which did not pass arguments at all. However, this minor penalty in running time is unavoidable if we want the size of the traversal code to be reasonably bounded: we prove in Section 6 that if no arguments are passed by the traversal methods, then there are cases where the number of distinct traversal methods must be exponential in the size of the strategy specification.

1.4 Algorithm Overview

For those readers who don't need to understand all the details behind the algorithms we give a brief overview. Given a strategy S and a class graph G , we need to provide an algorithm that decides which objects to visit from a node o in an object graph, i.e., we need to compute $first(o)$, the set of edges that we need to traverse from node o . $first(o)$ is computed based on answers to reachability questions in the class graph. To quickly answer the reachability questions we compute a new graph, called a traversal graph, which is basically the product of the two graphs S and G . The traversal graph stores the answers to the reachability questions that we will ask during the object traversal.

The traversal graph computation (Algorithm 1) is based on the following idea of a reduction: For traversal strategies of the form “from A to B”, the paths defined in the class graph can be represented by a subgraph of the class graph: Compute all edges reachable from A (called forward edges) and from which B can be reached (called backward edges). This computation is called *from-to computation*. Edges in the intersection of the forward and backward edges form the graph which represents the traversal. Any strategy can be reduced to this case but for a graph that is much larger than the original class graph. This larger graph, called the traversal graph, will contain as many copies of the class graph as the traversal strategy graph has edges. The size of the traversal graph will be reduced by a from-to computation. In other words, the from-to computation (which can be implemented, e.g., with a forward and a backward depth-first search) is fundamental to computing the traversal graph. The size of the traversal graph is a small polynomial in the size of the class graph and the strategy graph.

The traversal graph is non-deterministic in nature: from a node there might be two outgoing edges leading to a node with the same label. This non-determinism needs to be handled carefully in order to avoid an exponential blow-up in algorithm performance. The traversal methods algorithm (Algorithm 2) traverses an object graph, guided by a traversal graph. To deal with the non-determinism, we allow multiple tokens simultaneously to be put on the traversal graph to keep track of the legal traversal possibilities. As the traversal progresses the number of tokens on the traversal graph fluctuates. Fortunately, the number of tokens is bounded by the number of edges in the strategy graph.

As suggested by [45, 51], algorithms 1 and 2 are about computing intersections of sets of paths. Algorithm 1 is a variation on an algorithm to compute the cross product of two automata. The complications are in the constraint maps, the name maps and the more complex structure of the graphs (class graphs have two kinds of nodes and two kinds of edges).

1.5 Paper Organization

The remainder of this paper is organized as follows. In Section 2 we introduce the basic concepts, terminology and notation we use throughout the paper. In Section 3 we give a definition for the concept of traversals, based on [45]. In Section 4 we define the new concept of strategies. In section 5 we specify and analyze the algorithm which translates strategies into traversal code. In Section 6 we prove a lower bound for traversal methods that do not pass arguments. In Section 7 we comment about some practical aspects of the implementation of the strategies approach. In Section 8 we survey related work. In Section 9 we compare strategies with the earlier approach of traversal specifications.

In Section 10 we describe some applications of strategies. In Section 11 we describe our experiences using strategies and present some empirical evidence of how they are used. We give a few concluding thoughts in Section 12.

2 Preliminaries

In this section we formally define the basic concepts, terminology and notation we use throughout this paper. All notions in this section are standard, with the exception of Subsection 2.3.

2.1 Graphs and paths

A directed graph is a pair (V, E) where V is a set of *nodes*, and $E \subseteq V \times V$ is a set of *edges*. A directed labeled graph is a triple $G = (V, E, L)$ where V is a set of *nodes*, L is a set of *labels*, and $E \subseteq V \times L \times V$ is a set of *edges*. If $e = (u, l, v) \in E$, then u is the *source* of e , l is the *label* of e , and v is the *target* of e . We denote an edge (u, l, v) by $u \xrightarrow{l} v$.

Given a directed labeled graph $G = (V, E, L)$, a *node-path* is a sequence $p = \langle v_0 v_1 \dots v_n \rangle$, where $v_i \in V$ for $0 \leq i \leq n$, and $v_{i-1} \xrightarrow{l_i} v_i \in E$ for some $l_i \in L$ for all $0 < i \leq n$. Similarly, a *path* is a sequence $\langle v_0 l_1 v_1 l_2 \dots l_n v_n \rangle$ where $\langle v_0 \dots v_n \rangle$ is a node-path, and $v_{i-1} \xrightarrow{l_i} v_i \in E$ for all $0 < i \leq n$. Unlabeled graphs have only node-paths. Paths of the form $\langle v_0 \rangle$ are called *trivial*. The first node of a path (or a node-path) p is called the *source* of p , and the last node in p is called the *target* of p , denoted $\text{Source}(p)$ and $\text{Target}(p)$, respectively. The elements other than the source and the target of a path (nodes for a node-path, nodes and edges for a path) are the *interior* of the path. For a graph G , nodes u, v , and sets of nodes U, V , we define $P_G(u, v)$ to be the set of all paths in G with source u and target v and $P_G(U, V)$ to be the set of all paths in G with source in U and with target in V .

If $p_1 = \langle v_0 \dots l_i v_i \rangle$ and $p_2 = \langle v_i l_{i+1} \dots v_n \rangle$ are paths with the target of p_1 identical to the source of p_2 , we define the concatenation $p_1 \cdot p_2 = \langle v_0 \dots v_{i-1} l_i v_i l_{i+1} v_{i+1} \dots v_n \rangle$. Notice that $p_1 \cdot p_2$ contains only one copy of the meeting point v_i . Concatenation of node paths is defined similarly. Let P_1 and P_2 be sets of paths such that for some node v , $\text{Target}(p_1) = v$ for all $p_1 \in P_1$, and $\text{Source}(p_2) = v$ for all $p_2 \in P_2$. Then we define

$$P_1 \cdot P_2 = \{p_1 \cdot p_2 \mid p_1 \in P_1 \text{ and } p_2 \in P_2\} .$$

2.2 Class graphs and object graphs

In this paper we will be interested in special kinds of graphs, called class graphs and object graphs, defined as follows.

Fix a finite set \mathcal{C} of *class names*. Each class name is either *abstract* or *concrete*. Fix a finite set \mathcal{L} of *field names*. We sometimes call field names *labels*. We assume the existence of two distinguished symbols: $\text{this} \in \mathcal{L}$ and $\diamond \notin \mathcal{L}$. Class graphs model the class structure of object-oriented programs. Formally, *class graphs* are graphs $G = (V, E, L)$ such that

- $V \subseteq \mathcal{C}$, i.e., the nodes are class names.
- $L \subseteq \mathcal{L} \cup \{\diamond\}$, i.e., edges are labeled by field names or “ \diamond ”. Edges labeled by a field name are called *reference* edges, and edges labeled by \diamond are called *subclass* edges.
- For each $v \in V$, the field names of all edges going out from v are distinct (but there may be many edges labeled by \diamond going out from v).
- For each $v \in V$ such that v is concrete, $v \xrightarrow{\text{this}} v \in E$.
- The set of subclass edges is acyclic.

We shall use the (reflexive) notion of a *superclass*: given a class graph $G = (V, E, L)$, we say that $v \in V$ is a superclass of $u \in V$ if there is a (possibly empty) path of subclass edges from v to u . The collection of all super-classes of a class v is called the *ancestry* of v . Multiple inheritance conflicts are disallowed: we require that the following condition holds true.

Single Inheritance Condition: For all nodes v , if v has two super-classes u and w with outgoing edges labeled by the same label, then either u is in the ancestry of w or w is in the ancestry of u .

The *induced references* of a given class v is the set of all reference edges going out from its ancestry, with the usual overriding rule: for each label l used in edges going out from the ancestry of v , only the edge labeled l closest to v is in the induced references of v . The notion of “closest” is well defined by the Single Inheritance Condition above. Note that since a class is a superclass of itself, the induced edges include both the direct references and the inherited references.

Next, we define *object graphs*, which model the instantiations of class graphs. An object graph is a labeled directed graph $\Omega = (V', E', L')$, where nodes are called *objects*, and $L' \subseteq \mathcal{L}$. An object graph $\Omega = (V', E', L')$ is an *instance* of a class graph $G = (V, E, L)$ under a given function *Class* mapping objects to classes, if the following conditions are satisfied.

- For all objects $o \in V'$, $\text{Class}(o)$ is concrete.
- For each object $o \in V'$, the labels of edges going out from o is exactly the set of labels of the induced references of $\text{Class}(o)$. (In particular, this means that the edges going out from o have distinct labels.)
- For each edge $o \xrightarrow{l} o' \in E'$, $\text{Class}(o)$ has an induced reference edge $v \xrightarrow{l} u$ such that v is a superclass of $\text{Class}(o)$ and u is a superclass of $\text{Class}(o')$.

For the greater part of this paper, we shall assume that object graphs are acyclic. We discuss an extension to cyclic object graphs in Section 5.4.

2.3 Non-standard notions

In this paper, we assume that class graphs are *simple*, formally defined as follows.

Definition 2.1 A class graph $G = (V, E, L)$ is simple if

1. for all edges $u \xrightarrow{l} v \in E$, we have that $l = \diamond$ if and only if u is abstract, and
2. for all edges $u \xrightarrow{\diamond} v \in E$, we have that v is concrete.

The first requirement says that all edges going out from abstract classes are subclass edges and all edges going out from concrete classes are reference edges. This property is called *flatness*. Flatness helps us map paths in a class graph G to paths in an object graph which is an instance of G . The second requirement says that all subclass edges are coming into concrete classes; this helps us find all subclasses of a given class quickly. Note that no generality is lost by the assumption that class graphs are simple, as the following proposition asserts.

Proposition 2.1 Let $G = (V, E, L)$ be an arbitrary class graph. Then there exists a class graph $\text{Simplify}(G) = (V', E', L)$ such that an object graph Ω is an instance of G if and only if Ω is an instance of $\text{Simplify}(G)$. Moreover, $|V'| = O(|V|)$ and $|E'| = O(|E|^2)$.

The Simplify transformation is outlined in Appendix A.

Define a *concrete path* to be an alternating sequence of concrete class names and labels (excluding \diamond). We shall map paths in class graphs to concrete paths by omitting abstract classes and subclass edges. We refer to this mapping as the *natural correspondence*, and denote it by $X(p)$, where p is a path in a class graph G and $X(p)$ is the corresponding concrete path. Similarly, we denote the concrete path resulting from taking the sequence of class names and edge labels in an object graph path p' by $Y(p')$, and (overloading the term) we call this mapping also a *natural correspondence*. The motivation for these definitions is that if p is a path in a class graph G , then there is some object graph Ω which is an instance of G , and a path p' in Ω , such that $X(p) = Y(p')$.

For a class graph path set P , define $X(P) \stackrel{\text{def}}{=} \{X(p) \mid p \in P\}$.

3 Definition of traversals

We now arrive at the central topic of this paper: traversals of object graphs. Informally, a traversal is a (possibly infinite) set of concrete paths; when used in conjunction with an object graph, it results in a sequence of objects, called the *traversal history*. The traversal history is a depth-first traversal of the object graph along object paths agreeing with the given concrete path set. To make the traversal useful, each object has a special *visit* method attached to it; when an object is added to the traversal history, this method is invoked. (A more comprehensive discussion of the visitor programming pattern and visitor methods can be found in [18, 49, 50].)

But first, we define traversals formally. The definition here is adapted from the “simplified semantics” from [45]. We use a few technical notions. For a set of sequences $R \subseteq \Sigma^*$ for an alphabet Σ ,

define

$$\begin{aligned}\text{head}(R) &= \{x \in \Sigma \mid \exists \alpha.(x\alpha \in R)\} \\ \text{tail}(R, x) &= \{\alpha \mid x\alpha \in R \text{ for some } x \in \Sigma\}.\end{aligned}$$

Intuitively, $\text{head}(R)$ is the set of all first elements of R , and $\text{tail}(R, x)$ is the set of all “tails” of sequences of R that start with x (where a tail of a sequence is the whole sequence except its first element).

In the definition below, we assume that there exists a total order \prec on the set of field names \mathcal{L} (this assumption may be weakened somewhat). We first give the formal definition, then explain it in words.

Definition 3.1 (from [45]) *Fix a class graph G . If Ω is an acyclic object graph which is an instance of G , o an object in Ω , R a set of concrete paths corresponding to paths of G , and H a sequence of objects, then the judgment*

$$\Omega \vdash_s o : R \triangleright H$$

means that when traversing the object graph Ω starting with o , and guided by the concrete path set R , then H is the traversal history.¹ This judgment holds when it is derivable using the following rules:

$$\frac{}{\Omega \vdash_s o : R \triangleright \epsilon} \quad \text{if } \text{tail}(R, \text{Class}(o)) = \emptyset, \tag{1}$$

where ϵ denotes the empty history, and

$$\frac{\Omega \vdash_s o_i : \text{tail}(\text{tail}(R, \text{Class}(o)), l_i) \triangleright H_i \quad \forall i \in 1..n}{\Omega \vdash_s o : R \triangleright o \cdot H_1 \cdot \dots \cdot H_n} \quad \begin{array}{l} \text{if } \text{head}(\text{tail}(R, \text{Class}(o))) = \{l_i \mid i \in 1..n\}, \\ o \xrightarrow{l_i} o_i \text{ is in } \Omega, i \in 1..n, \text{ and} \\ l_j \prec l_k \text{ for } 1 \leq j < k \leq n. \end{array} \tag{2}$$

In other words, a traversal of an object graph Ω starting with an object o guided by a path set R , is done as follows. First, the first elements of the sequences of R are compared to $\text{Class}(o)$: sequences beginning with another element are immediately thrown out of consideration. If the remaining path set is not empty, then o becomes the first element of the history; it is followed by the histories resulting from starting a traversal from each descendent of o , guided by the remainder of the path set after “peeling off” the first two elements (corresponding to o and the edge going out to the descendent). Intuitively, this procedure is depth-first search on Ω with R used to determine how to prune the search. Please note that concatenation of traversal histories does not use the same definition as concatenation of paths; it is the usual concatenation of sequences.

Remarks. Note that the guarantee made by a traversal guided by a path set R is the following: A path p in the object graph is followed so long as there is a path in $q \in R$ such that q has a prefix which is equal to the current prefix of p (taking the $\text{Class}(o)$ instead of o in p). In other words, the decision whether the traversal takes a certain branch in the object graph depends only on the portion of the graph visited so far and on the current branch, and not on the links further ahead. This means, for example, that even if all paths in R end with the same class A , some of the traversal paths may end

¹The label s of the turnstile indicates “semantics.”

with a node o with $\text{Class}(o) \neq A$ just because the path to o is a prefix of a path in R . This relaxation is necessary to enable efficient implementation of traversals by looking only ahead in the class graph and not in the object graph as discussed earlier.

4 Strategies: Specification of traversals

In this section we define strategies, which are a graph-based language for expressing traversals. In Section 4.1 we give a basic definition of strategies and explain how strategies express traversals. Then, in Section 4.2, we give the full definition of strategies using the additional concept of a constraint map. This extended notion is the one we shall be using in the remainder of the paper. In Section 4.3, we discuss a few possible additional refinements of the concept of strategies.

4.1 Strategies

Traversals are defined in terms of sets of concrete paths. Strategies select class graph paths and then derive concrete paths by applying the natural correspondence. Intuitively, a strategy selects class graph paths by specifying a high-level topology which spans all paths in the selected set. Formally, strategies are defined as follows.

Definition 4.1 *A strategy \mathcal{S} is a triple $\mathcal{S} = (S, s, t)$, where $S = (C, D)$ is a directed unlabeled graph called the strategy graph, where C is the set of strategy graph nodes and D is the set of strategy graph edges, and $s, t \in C$ are the source and target of \mathcal{S} , respectively.*

The connection between strategies and class graphs is done by a name map, defined as follows.

Definition 4.2 *Let $S = (C, D)$ be a strategy graph and let $G = (V, E, L)$ be a class graph. A name map for S and G is a function $\mathcal{N} : C \rightarrow V$. If p is a sequence of strategy graph nodes, then $\mathcal{N}(p)$ is the sequence of class nodes obtained by applying \mathcal{N} to each element of p .*

The basic idea of strategies is that under a name map, a path in the strategy graph is an abstraction of a set of paths in the class graph. This is done by viewing each strategy graph edge $a \rightarrow b$ as representing the set of paths in the class graph starting with node $\mathcal{N}(a)$ and ending at node $\mathcal{N}(b)$. This representation naturally extends to paths in the strategy graph: A path in the strategy graph represents a set of paths in the class graph obtained by concatenating the sets of class graph paths obtained from each strategy graph edge.

We now make this intuition formal using the concept of path expansion, defined as follows.

Definition 4.3 *Given a nontrivial sequence p , a sequence is called an expansion of p if it can be obtained by inserting one or more elements between the elements of p . The only expansion of a trivial sequence is itself.*

Note that if p' is a path which is an expansion of another path p (possibly in another graph), then $\text{Source}(p) = \text{Source}(p')$ and $\text{Target}(p) = \text{Target}(p')$.

We now formally define the basic way strategies express paths in object graphs. Recall that $P_G(s, t)$ denotes that set of all paths in G starting at s and ending at t and X is the natural correspondence mapping class graph paths to concrete paths.

Definition 4.4 *Let $\mathcal{S} = (S, s, t)$ be a strategy, let $G = (V, E, L)$ be a class graph, and let \mathcal{N} be a name map for \mathcal{S} and G . Then*

$$\mathcal{S}[G, \mathcal{N}] = \left\{ X(p') \mid p' \in P_G(\mathcal{N}(s), \mathcal{N}(t)) \text{ and } \exists p \in P_{\mathcal{S}}(s, t) \text{ such that } p' \text{ is an expansion of } \mathcal{N}(p) \right\}.$$

Note that $\mathcal{S}[G, \mathcal{N}]$ is a set of concrete paths: intuitively, first a set of class graph paths is selected, and then the natural correspondence is applied to obtain concrete paths. These concrete paths can be used (playing the role of “ R ”) in Definition 3.1.

4.2 Using a constraint map

Strategies impose positive constraints on paths, in the sense that they specify which nodes must be traversed in which order. It turns out that it is quite useful to also have negative constraints: what nodes and edges cannot be used between the specified milestones. We formalize this idea with the concepts of element predicates and constraint maps.

Definition 4.5 *Given a class graph $G = (V, E, L)$, an element predicate EP for G is a predicate over $V \cup E$. Given a strategy graph S , a function \mathcal{B} mapping each edge of S to an element predicate for G is called a constraint map for S and G .*

(Of course, some predicate specification languages may be very hard to compute. For computational complexity purposes, we assume that there exists a parameter, denoted τ , such that given an element of G , determining whether it satisfies an element predicate can be done in no more than τ time units.)

The constraint map is used to specify, for each edge in the strategy graph, which elements of the class graph may be used in the traversal corresponding to that edge. Formally, we have the following definition.

Definition 4.6 *Let S be a strategy graph, let G be a class graph, let \mathcal{N} be a name map for S and G , and let \mathcal{B} be a constraint map for S and G . Given a strategy graph path $p = \langle a_0 a_1 \dots a_n \rangle$, we say that a class graph path p' is a satisfying expansion of p with respect to \mathcal{B} under \mathcal{N} if there exist nontrivial paths p_1, \dots, p_n such that $p' = \langle N(a_0) \rangle \cdot p_1 \cdot p_2 \cdots p_n$ and:*

1. For all $1 \leq i \leq n$, $\text{Source}(p_i) = \mathcal{N}(a_{i-1})$ and $\text{Target}(p_i) = \mathcal{N}(a_i)$.
2. For all $1 \leq i \leq n$, the interior elements of p_i satisfy the element predicate $\mathcal{B}(a_{i-1} \rightarrow a_i)$.

If $n = 0$, i.e., p is a trivial path $\langle a_0 \rangle$, then its only satisfying expansion is $\langle N(a_0) \rangle$.

Note that there may be many ways to decompose a path in accordance with Condition 1 in the definition above; a path p' is a satisfying expansion of a path p if for one of these decompositions, Condition 2 holds as well.² Note also that the element constraints are never applied to the ends of the

²Other definitions are possible, for example to require that a subpath ends when its target node is reached. We have found the non-deterministic definition above to be the most useful.

sub-paths. One consequence of our definition is that if $\mathcal{N}(a_{i-1}) = \mathcal{N}(a_i)$ then the single node path $\langle \mathcal{N}(a_i) \rangle$ always satisfies Condition 2, regardless of the element predicate $\mathcal{B}(a_{i-1} \rightarrow a_i)$.

Using the constraint map, we now define a more elaborate way in which a strategy expresses paths in object graphs.

Definition 4.7 *Let $\mathcal{S} = (S, s, t)$ be a strategy, let $G = (V, E, L)$ be a class graph, let \mathcal{N} be a name map for S and G , and let \mathcal{B} be a constraint map for S and G . Then $\mathcal{S}[G, \mathcal{N}, \mathcal{B}]$ is the set of concrete paths defined by*

$$\mathcal{S}[G, \mathcal{N}, \mathcal{B}] = \left\{ X(p') \mid p' \in P_G(\mathcal{N}(s), \mathcal{N}(t)) \text{ and} \right. \\ \left. \exists p \in P_S(s, t) \text{ such that } p' \text{ is a satisfying expansion of } p \text{ w.r.t. } \mathcal{B} \right\}.$$

Note that $\mathcal{S}[G, \mathcal{N}] = \mathcal{S}[G, \mathcal{N}, \mathcal{B}_{\text{TRUE}}]$ for the constraint map $\mathcal{B}_{\text{TRUE}}$ which maps all strategy graph edges to the trivial element predicate that is always TRUE.

4.3 Remarks

Encapsulated strategies. The way strategies are presented above, a constraint map can be specified only when the class graph is given, as the element predicates are expressed in terms of class graph nodes and edges. An important design consideration, however, is to encapsulate the constraint map with the strategy and use the name map as the only interface to the class graph; we call this approach “encapsulated strategies.” The advantage of encapsulated strategies is that they allow one to have a clean interface between the strategy and the class graph, captured completely by the name map.

We only outline the details of the concept here, since it is not central to the algorithmic issues we focus on in the remainder of this paper. The idea is that instead of letting the element predicates range over the (yet unspecified) class graph, they range over variables called *symbolic names*. Binding to actual class graph elements is done only later, when the name map is introduced. Technically, we have an additional level of indirection in the encapsulated strategy: instead of explicit references to the class graph elements in the constraint map, the element predicates are predicates over *symbolic nodes* and *symbolic edges*. These are denoted using a set \mathcal{M} of strings, which are used as place-holders for class names and labels (symbolic edges are constructed from a pair of symbolic node names and a symbolic label). More formally, an *encapsulated strategy* is a tuple $\mathcal{E} = (\mathcal{S}, \mathcal{M}, \mathcal{B}')$, where \mathcal{S} is a strategy, \mathcal{M} is a set of symbolic names, and \mathcal{B}' is a function mapping edges of the strategy graph to predicates over the symbolic elements. To support encapsulated strategies, the name map is extended to map also symbolic names to actual class names and label names in the class graph.

Wildcard notation in predicate specification. We left the issue of how to specify the predicates open. One naive way of doing it is to enumerate all elements to be used, or alternatively to enumerate all elements to be excluded (cf. “use-only” and “bypassing” clauses presented in Section 7). More expressive power is given by allowing wildcard symbols to be used in the predicate specification. For example, an element predicate may be FALSE for all elements of the form $* \xrightarrow{l} *$, which means that no edges labeled l can be traversed. The unique feature of this notation is that it allows the programmer

to refer to elements whose identity is not necessarily known at predicate-specification time. Even when using encapsulated strategies as above, the programmer can only refer to symbolic names, which are later mapped to only a subset of the elements of the actual class graph, while the wildcard notation is implicitly mapped to all elements in the class graph as appropriate.

There is a difference between the strategies used by the algorithm, on the one hand, and the examples and discussion of the system that has been implemented in the AP Library, on the other. In the former, strategy graph edges are general, with a restriction only on the cost of verifying the governing condition per vertex and per edge. In the latter, only a small set of predefined predicates are used (bypassing, only-through). The reason for this difference is that we wanted the abstract model to be easy to express and it turned out that a more general formulation is easier to express. The general model can easily handle the particular edge predicates actually in use in the AP Library. For the current applications the expressive power of the model used by the AP Library is sufficient. Indeed, when the class graph is known, all strategies can be simulated by single edge strategies using bypassing clauses bypassing sufficiently many nodes and edges in the class graph.

Cyclic graphs Strategy graphs may be cyclic and so may class graphs and object graphs. However for the purpose of dealing with traversals, it is sufficient to consider object trees. Non-object trees need to be addressed by appropriate visitors.

5 Compilation algorithm

In this section we show how to implement traversal strategies efficiently by compiling them into executable programs. Formally, the compilation problem is defined as follows.

Input: A strategy $\mathcal{S} = (S, s, t)$, a simple class graph $G = (V, E, L)$, a name map \mathcal{N} for S and G , and a constraint map \mathcal{B} for S and G .

Output: A set of methods such that for any object graph Ω , invoking the traversal method at an object o in Ω yields a traversal history H satisfying the judgment $\Omega \vdash_s o : \mathcal{S}[G, \mathcal{N}, \mathcal{B}] \triangleright H$.

Recall that $\mathcal{S}[G, \mathcal{N}, \mathcal{B}]$ is a path set which can guide traversals of object graphs directly. Our compilation consists of two algorithms. For an overview of the algorithms see section 1.4.

1. We first invoke an algorithm (called Algorithm 1 below) which uses \mathcal{S} , G , \mathcal{N} , and \mathcal{B} to construct a graph which expresses the traversal $\mathcal{S}[G, \mathcal{N}, \mathcal{B}]$ in a more convenient way; we call this graph the *traversal graph*, and denote it by $TG(\mathcal{S}, G, \mathcal{N}, \mathcal{B})$.
2. The traversal methods employ another algorithm (called below Algorithm 2), which uses $TG(\mathcal{S}, G, \mathcal{N}, \mathcal{B})$ —the result of Algorithm 1.

The remainder of this section is organized as follows. In Section 5.1 we describe Algorithm 1. In Section 5.2 we describe Algorithm 2. In Section 5.3 we analyze the computational complexity of the

algorithms. We conclude this section with numerous extensions and variants for the basic algorithm, listed in Section 5.4.

5.1 The traversal graph

In this section we explain how the *traversal graph* is computed, based on a strategy $\mathcal{S} = (S, s, t)$, a simple class graph $G = (V, E, L)$, a name map \mathcal{N} for S and G , and a constraint map \mathcal{B} for S and G . The traversal graph, denoted $TG(\mathcal{S}, G, \mathcal{N}, \mathcal{B})$, is created by a series of transformations based on the class graph, the strategy, the name map, and the constraint map. The basic idea is to replace each strategy graph edge by a copy of the class graph appropriately pruned down to elements that satisfy the edge's element predicate.

The reader may follow a running example presented in Figure 3 (DemeterJ code for the example is given in Appendix B).

Algorithm 1: Traversal graph computation. Let the strategy graph be $S = (C, D)$, and let the strategy graph edges be $D = \{e_1, e_2, \dots, e_k\}$.

1. Create a graph $G' = (V', E')$ by taking k copies of G , one for each strategy graph edge. Denote the i th copy as $G^i = (V^i, E^i)$. We will use the correspondence between each strategy graph edge e_i and G^i . The nodes in V^i and edges in E^i will be denoted with a superscript i , as in v^i, e^i etc. Each class graph node v corresponds to k nodes in V' , denoted v^1, \dots, v^k . We extend the Class mapping to apply to the nodes of G' by setting $\text{Class}(v^i) \stackrel{\text{def}}{=} v$, where $v^i \in V'$ and $v \in V$.
2. For each strategy graph edge $e_i = a \rightarrow b$: Let $\mathcal{N}(a) = u$ and $\mathcal{N}(b) = v$. Remove from G^i the elements which do not satisfy $\mathcal{B}(e_i)$. More precisely, set

$$\begin{aligned} V^i &\leftarrow \{u^i, v^i\} \cup \{w^i \mid \mathcal{B}(e_i)(w) = \text{TRUE}\} \text{ , and} \\ E^i &\leftarrow \left\{ u^i \xrightarrow{l} v^i \mid \mathcal{B}(e_i)(u \xrightarrow{l} v) = \text{TRUE} \right\} \cup \\ &\quad \left\{ u^i \xrightarrow{l} y^i \mid \mathcal{B}(e_i)(u \xrightarrow{l} y) = \mathcal{B}(e_i)(y) = \text{TRUE} \right\} \cup \\ &\quad \left\{ w^i \xrightarrow{l} v^i \mid \mathcal{B}(e_i)(w \xrightarrow{l} v) = \mathcal{B}(e_i)(w) = \text{TRUE} \right\} \cup \\ &\quad \left\{ w^i \xrightarrow{l} y^i \mid \mathcal{B}(e_i)(w \xrightarrow{l} y) = \mathcal{B}(e_i)(w) = \mathcal{B}(e_i)(y) = \text{TRUE} \right\} . \end{aligned}$$

3. (a) Add to E' a node s^* and, for each edge e_i going out from the source node s in S , an edge $s^* \rightarrow \mathcal{N}(s)^i$.
 (b) Add to E' a node t^* and, for each edge e_i coming into the target node t in S , an edge $\mathcal{N}(t)^i \rightarrow t^*$.
 (c) If $s = t$, add to V' a node $\mathcal{N}(s)^0$ and add to E' edges $s^* \rightarrow \mathcal{N}(s)^0$ and $\mathcal{N}(s)^0 \rightarrow t^*$.
4. (a) For each strategy graph node $a \in C$: Let $I = \{e_{i_1}, \dots, e_{i_n}\}$ be the set of strategy graph edges coming into a , and let $O = \{e_{o_1}, \dots, e_{o_m}\}$ be the set of strategy graph edges going out from a . Let $\mathcal{N}(a) = v \in V$. Add $n \cdot m$ edges $v^{i_j} \rightarrow v^{o_l}$ for $j = 1, \dots, n$ and $l = 1, \dots, m$. Call these edges *intercopy edges*.

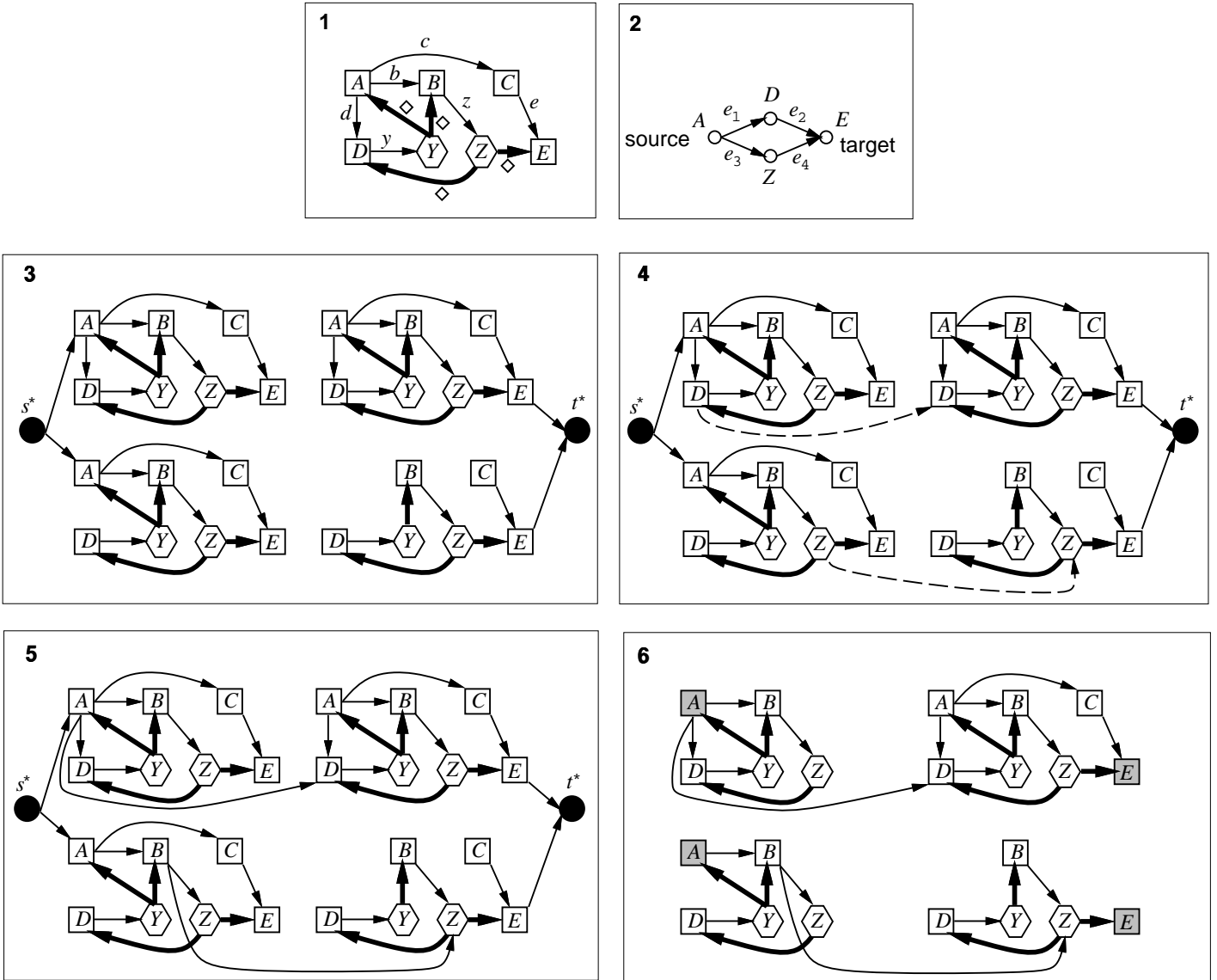


Figure 3: An example of traversal graph computation. 1: the input class graph. Edge labels are omitted from subsequent graphs. 2: The input strategy (the name map is indicated). In this example, the constraint map is as follows. $\mathcal{B}(e_1)(x) = \text{TRUE}$ and $\mathcal{B}(e_2)(x) = \text{TRUE}$ for all x ; $\mathcal{B}(e_3)(A \xrightarrow{d} D) = \text{FALSE}$ and $\mathcal{B}(e_3)(x) = \text{TRUE}$ for all $x \neq A \xrightarrow{d} D$; and $\mathcal{B}(e_4)(x) = \text{FALSE}$ if $x = A$ or if x is an edge incident to A , and $\mathcal{B}(e_4)(x) = \text{TRUE}$ otherwise. 3: G' after Steps 1, 2, and 3. 4: G' after Step 4a. Intercopy edges are dashed. 5: G' after Step 4. 6: The final traversal graph, as returned in Step 6. The shaded A nodes are the start set T_s , and the shaded E nodes are the finish set T_f .

- (b) For each node v^i in G' with an outgoing intercopy edge: Add edges $u^i \xrightarrow{l} v^j$ for all u^i such that $u^i \xrightarrow{l} v^i \in E^i$, and for all v^j which are reachable from v^i through intercopy edges only.
- (c) Remove all the intercopy edges added in Step 4a.
5. Mark all nodes and edges in G' which are both reachable from s^* and from which t^* is reachable, and remove unmarked nodes and edges from G' . Call the resulting graph $G'' = (V'', E'')$.
6. Return the following objects:
- The set of all nodes v such that $s^* \rightarrow v$ is an edge in G'' . This is the *start set*, denoted T_s .
 - The graph obtained from G'' after removing s^* and t^* and all their incident edges. This is the *traversal graph*, denoted $TG(\mathcal{S}, G, \mathcal{N}, \mathcal{B})$.
-

For the purpose of analysis, we also define the *finish set* of the traversal graph, denoted T_f , to be the set of all nodes v such that $v \rightarrow t^*$ is an edge in G'' .

Correctness

We now prove that Algorithm 1 is correct, in the sense that the set of paths in the traversal graph (from the start set of the finish set) is exactly the set of paths defined by the strategy. This property is formally stated in Lemma 5.2.

First, we show a basic property of paths in the traversal graph.

Lemma 5.1 *If p is a path in the traversal graph, then under the extended Class mapping, p is a path in the class graph.*

Proof: Note that for any edge $u^i \xrightarrow{l} v^j$ in the traversal graph, we have that the corresponding edge $u \xrightarrow{l} v$ is in the class graph. This can be verified by inspection: the only edges added to the graph which remain after Step 6 are added in Step 4. ■

By Lemma 5.1, we can apply the natural correspondence X to paths in the traversal graph to obtain concrete paths. This allows us to state the main property of the traversal graph in the following lemma.

Lemma 5.2 *Let \mathcal{S} be a strategy, let G be a class graph, let \mathcal{N} be a name map, and let \mathcal{B} be a constraint map. Let $TG = TG(\mathcal{S}, G, \mathcal{N}, \mathcal{B})$, let T_s be the start set and let T_f be the finish set generated by Algorithm 1. Then $X(P_{TG}(T_s, T_f)) = \mathcal{S}[G, \mathcal{N}, \mathcal{B}]$.*

Proof: Let $p \in P_{TG}(T_s, T_f)$ be a path in the traversal graph. To see that $X(p) \in \mathcal{S}[G, \mathcal{N}, \mathcal{B}]$, we decompose p according to the different copies of G it passes through. Intuitively, we take the maximal segments of p which are contained in the same copy of G , and the next node (which is in another copy). Formally, we decompose $p = \langle v_s \rangle \cdot p_1 \cdot p_2 \cdots p_n$ inductively by the following algorithm:

```

i ← 0; v ← head(p)
output v
while tail(p) ≠ ε

```

```

i ← i + 1
let j(i) be such that  $v \in G^{j(i)}$ 
// accumulate prefix of p until exiting  $G^{j(i)}$ 
pi ← ⟨v⟩
repeat
  p ← tail(p); l ← head(p)
  p ← tail(p); v' ← head(p)
  pi ← pi · ⟨vlv'⟩
  v ← v'
until tail(p) =  $\epsilon$  or  $v \notin G^{j(i)}$ 
output pi

```

Suppose that the algorithm above outputs v_s and n sub-paths p_1, \dots, p_n . For $i = 1, \dots, n$, let $v_{i-1} \rightarrow v_i = e_{j(i)}$ with $j(i)$ as defined by the algorithm, i.e., $e_{j(i)}$ is the edge in \mathcal{S} corresponding to the index of the copy of G through which p_i is passing. With this notation, consider the sequence of strategy graph nodes $q = \langle v_0 v_1 \dots v_n \rangle$. (If $n = 0$, let $q = \langle s \rangle$, where s is the source of \mathcal{S} .) By construction, q is a path in the strategy graph: this is because the only edges in the traversal graph which go from one copy of G to another are created in Step 4 of Algorithm 1, where an edge goes from G^i to G^j only if $\text{Target}(e_i) = \text{Source}(e_j)$. Next, note that since $\text{Source}(p) \in T_s$ we have by Step 3 and the definition of T_s that $\text{Class}(\text{Source}(p)) = \mathcal{N}(s)$, where s is the source of \mathcal{S} , and similarly, $\text{Class}(\text{Target}(p)) = \mathcal{N}(t)$ where t is the target of \mathcal{S} . Finally, note that p is a satisfying expansion of q with respect to \mathcal{B} . It therefore follows that $X(p) \in \mathcal{S}[G, \mathcal{N}, \mathcal{B}]$.

Suppose now that $p \in \mathcal{S}[G, \mathcal{N}, \mathcal{B}]$. By Definition 4.7, there exists a path p' in the strategy graph and a path p'' in the class graph such that $p = X(p'')$ and p'' is a satisfying expansion of p' . Hence p'' can be decomposed into sub-paths as in Definition 4.6. It is straightforward to verify from Definition 4.6 and the specification of the traversal graph, that $p'' \in P_{TG}(T_s, T_f)$. ■

5.2 Traversal methods algorithm

To carry out traversals, we attach a traversal method definition to each class. In this section we describe the algorithm of these methods.

Intuitively, the idea is to traverse the object graph while using the traversal graph as a road map that tells the traversal which of the possible branches to take. To do that, the algorithm maintains a set of tokens placed on the traversal graph. When a traversal method is invoked at an object, it gets the set of tokens as a parameter; the interpretation of a token placed on a node v in the traversal graph is roughly “the traversal made so far places **this** on v .” The fact that there may be more than one token simultaneously is a reflection of the fact that the path leading to an object in the object graph may be (under the natural correspondence Y) a prefix of several distinct paths in the $\mathcal{S}[G, \mathcal{N}, \mathcal{B}]$. This matters, because if there are several tokens, we might have more possibilities for selecting the next traversal step.

The traversal method is denoted below by $\text{Traverse}(T)$, where T is the set of tokens, i.e., a set of

nodes in the traversal graph. When the traversal method invokes the `visit` method at an object, that object is added to the traversal history. The description below is generic in the sense that the same method is used for all objects; it can be used for different traversals, using different traversal graphs.

We assume that each object can find its class name and can iterate through all its constituent fields at run time. This assumption can be fulfilled either by some minor preprocessing, or by “reflection” methods if they are available (e.g., [28]).

Algorithm 2: `Traverse(T)`, guided by a traversal graph TG .

1. Define a set of traversal graph nodes T' by

$$T' \leftarrow \left\{ v \mid \text{Class}(v) = \text{Class}(\text{this}) \text{ and } \exists u \in T \text{ such that } u = v \text{ or } u \xrightarrow{\diamond} v \text{ is an edge in } TG \right\} .$$

2. If $T' = \emptyset$, return.

3. Call `this.visit()`.

4. Let Q be the set of labels which appear both on edges going out from a node in T' in TG and on edges going out from `this` in the object graph. For each label $l \in Q$, let

$$T_l = \left\{ v \mid u \xrightarrow{l} v \in TG \text{ for some } u \in T' \right\} .$$

5. Call `this.l.Traverse(T_l)` for all $l \in Q$, ordered by “ \prec ”, the ordering of the labels.
-

Step 1 of Algorithm 2 makes sure that the token set corresponds to the class of the current object: the tokens in T placed on concrete classes appear in T' only if they are placed on a node corresponding to `Class(this)`. And the tokens in T placed on abstract classes are moved in T' to their subclass node whose class is `Class(this)` (if there is one; otherwise, they are simply discarded). In any event, all tokens in T' are placed on nodes corresponding to `Class(this)`.

An example run of the algorithm is given in Figure 4, based on the traversal graph of Figure 3. The following remarks help to understand Figure 4.

- a. For simplicity, child order is assumed alphabetical.
- b. In step 3, the traversal from B to D passes through the abstract class Z (and similarly in other steps).
- c. Step 4 could also derive a step to D if there were such a child, but there is no such child in the object graph.
- d. Step 6 represents the second child of the original token A in step 1. However, the token set is empty because the $A \rightarrow C$ edge is missing in copies 1 and 2 of the class graph. Note that in step 1 only the A in copies 1 and 2 is shaded. (An extension of the remark in the Figure.)
- e. The process hits a target node in steps 5 and 9.

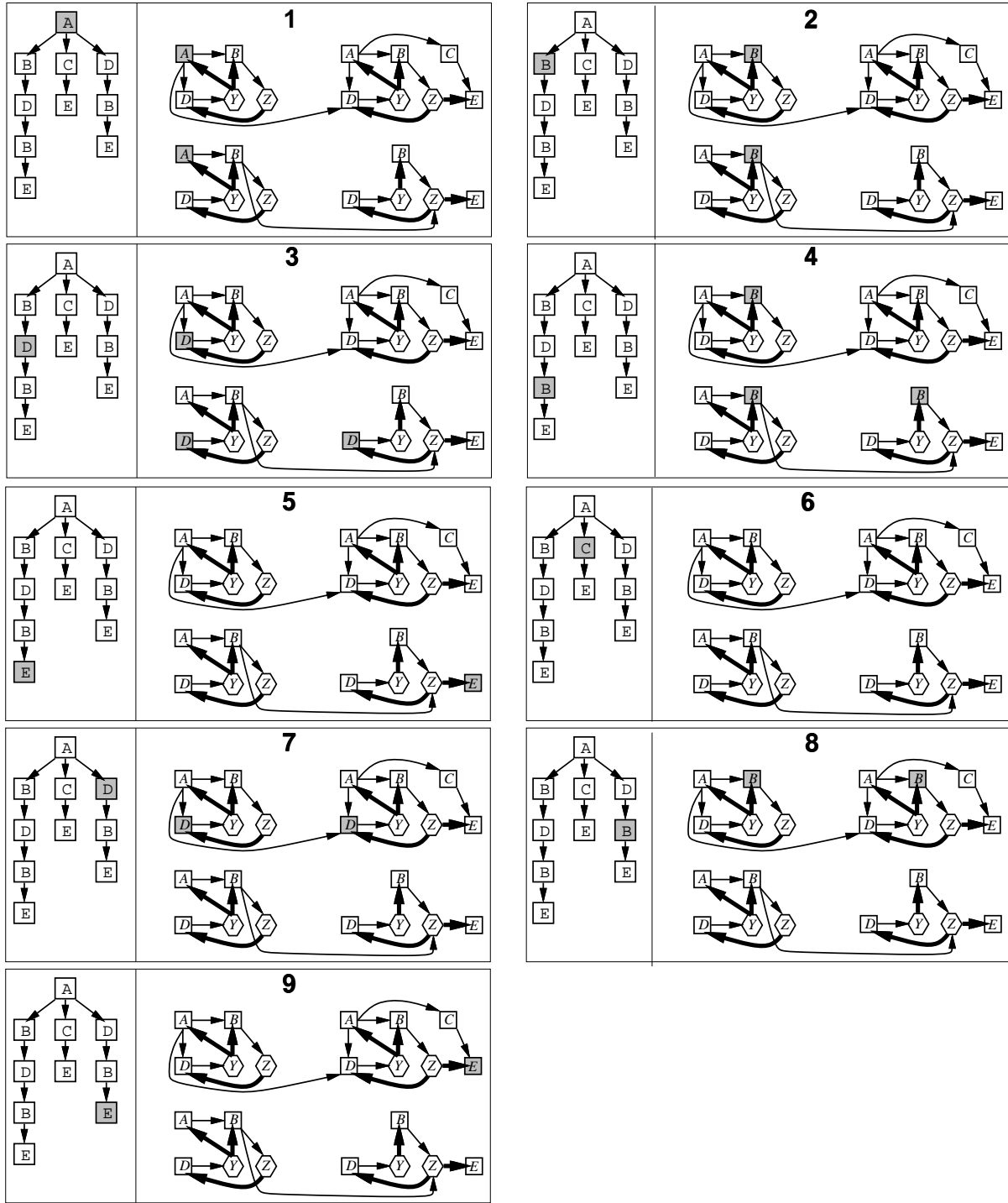


Figure 4: An example of an execution of traversal using the traversal of Fig. 3. At each step, the left hand side shows the object tree with the currently active object shaded, and the right hand side shows the traversal graph with the token set shaded. Note that in Step 6, the token set is empty because the traversal graph does not allow a transition from an A with a token in $4(1)$ to a C and hence the middle E object is not visited.

Correctness

The following lemma states the main property of the traversal algorithm.

Lemma 5.3 *Let Ω be an object tree, and let o be an object in Ω . Suppose that the `Traverse` methods are guided by a traversal graph TG with finish set T_f . Let $H(o, T)$ be the sequence of objects which invoke `visit` while $o.\text{Traverse}(T)$ is active, where T is a set of nodes in TG . Then*

$$\Omega \vdash_s o : X(P_{TG}(T, T_f)) \triangleright H(o, T) .$$

Proof: By induction on $|H(o, T)|$. For the base case, suppose that $H(o, T) = \epsilon$. By the algorithm, this can occur only if after Step 1, $T' = \emptyset$, which means that for all concrete nodes $v \in T$, $\text{Class}(v) \neq \text{Class}(o)$, and that no abstract node in T has a child whose class is $\text{Class}(o)$. It follows from Definition 3.1 that $\text{tail}(X(P_{TG}(T, T_f)), \text{Class}(o)) = \emptyset$ and hence $\Omega \vdash_s o : X(P_{TG}(T, T_f)) \triangleright \epsilon$, as required.

For the induction step, assume that $|H(o, T)| > 0$. Let l_1, \dots, l_n be the set of labels of traversal graph edges which start with a node in T' , and let $o_i = o.l_i$ for $i = 1, \dots, n$. In this case, by the algorithm we have that $H(o, T) = o \cdot H(o_1, T_1) \cdots H(o_n, T_n)$, where T_i is the set of traversal graph nodes v such that $u \xrightarrow{l_i} v$ for some $u \in T'$ and such that $o \xrightarrow{l_i} o'$ is an edge in the object graph. It is follows directly from the definitions that $X(P_{TG}(T_i, T_f)) = \text{tail}(\text{tail}(X(P_{TG}(T, T_f)), \text{Class}(o)), l_i)$, and hence, by the induction hypothesis, $\Omega \vdash_s o : X(P_{TG}(T_i, T_f)) \triangleright H(o_i, T_i)$ and we are done. \blacksquare

We summarize in the following theorem.

Theorem 5.4 *Let \mathcal{S} be a strategy, let G be a class graph, let \mathcal{N} be a name map, and let \mathcal{B} be a constraint map. Let TG be the traversal graph generated by Algorithm 1, and let T_s and T_f be the start and finish sets, respectively. Let Ω be an object tree and let o be an object in Ω . Let H be the sequence of nodes visited when $o.\text{Traverse}$ is called with argument T_s , guided by TG . Then*

$$\Omega \vdash_s o : X(\mathcal{S}[G, \mathcal{N}, \mathcal{B}]) \triangleright H .$$

Proof: By Lemma 5.3, the judgment $\Omega \vdash_s o : X(P_{TG}(T_s, T_f)) \triangleright H$ holds true. The claim of the theorem follows from the fact that $\mathcal{S}[G, \mathcal{N}, \mathcal{B}] = X(P_{TG(\mathcal{S}, G, \mathcal{N}, \mathcal{B})}(T_s, T_f))$ by Lemma 5.2, and from the definitions of the start set T_s and the finish set T_f . \blacksquare

From the theorem above it is clear how to start a traversal at an object o : Call $o.\text{Traverse}$ with argument T_s , where T_s is the start set of the traversal.

5.3 Computational complexity of the algorithm

It is easy to see that the time complexity of Algorithm 1 is polynomial in the size of its input. All steps run in time linear in the size of their input and output. Steps 1 and 2 take time linear in $|G'| = O(|\mathcal{S}| \cdot |G|)$ and in τ , where τ is the time bound for evaluating an element predicate for a given element. To bound the size of the traversal graph, let d_o be the maximal number of edges going out from a node in the class graph. Note that all edges added in Step 4 correspond to class graph edges. It follows that the number of going out edges added to a traversal graph node in Step 4 is d_o times

the number of copies of G in G' . Hence Step 4 may increase the size of the graph to $O(|\mathcal{S}|^2 \cdot |G| \cdot d_o)$ in the worst case. Steps 3a, 3b and 5 run in time linear in the size of $|G''| = O(|\mathcal{S}|^2 \cdot |G| \cdot d_o)$.

As for Algorithm 2, we note that the size of the argument T is bounded by the size of the strategy graph. This follows from the observation that in all recursive invocations of `Traverse` made by the algorithm, for all $v, u \in T$ we have that $\text{Class}(v) = \text{Class}(u)$. Since each copy of the class graph in the traversal graph contains at most one node of each class, it follows that the number of nodes in T is never more than the number of edges in the strategy graph.

The proper way to describe the complexity of Algorithm 2 is to express it in terms of the number of edges in the object graph and to consider the traversal graph size and the token set size as a constant. For each edge in the object graph we query a traversal graph edge and when the object graph edge is selected, we need to manipulate the token set. The complexity of Algorithm 2 is proportional to the number of edges in the object graph.³

5.4 Extensions

Multiple sources. As evident in the statement of Lemma 5.3, the initial set of nodes in the traversal graph from which the traversal starts can be arbitrary: the set of paths traversed would change, but in accordance with the traversal strategy, using an appropriate definition. In particular, one may have more than one start node in the strategy graph, which is interpreted as several optional “entry points”: it may be the case that the same traversal is sometimes started with a node of class A and at another time with a node of class B (or, more generally, with different nodes in the strategy graph). This situation of multiple sources can be easily handled by our algorithm: suppose that we have a set A of start nodes for the strategy. All we need to do is to change Step 3a of Algorithm 1 to be

3a'. Add edges $s^* \rightarrow \mathcal{N}(u)^i$ for each edge $e_i = u \rightarrow v \in D$, where $u \in A$.

Of course, in this case a traversal should start with invoking `Traverse` with argument A .

Multiple targets. Similarly, it may be the case that we don't need all traversal paths to end with the same target node. This can be useful, for example, if we want to traverse a tree of objects, rather than traverse all paths leading towards the same target. Using the same idea we had for multiple sources, it is simple to have multiple targets for a strategy: if we want to traverse all paths which may lead to any of the strategy graph nodes in a set B , all we need to do is to change Step 3b of Algorithm 1:

3b'. Add an edge (t^i, t^*) for each edge $e_i = (v, u) \in D$, where $u \in B$.

This extension is particularly useful when the target of the traversal is an abstract class: suppose we want to traverse to a class A which happens to be abstract. The natural interpretation is that the traversal should end at whatever subclass of A which happens to be in the object graph. However,

³Note that if we allow for users to call the initial traversal with arbitrary values of T (to allow multiple sources, see Section 5.4), then it may be the case, at the first call only, that $|T|$ is greater than the number of strategy graph edges.

with the semantics specified above, if the target of the strategy is A , then the object (whose class is concrete) substituting for A is *not* visited. To visit the object substituting for A regardless of its actual class, we can simply state that the target of the strategy is the set of all subclasses of A .

“Before,” “after” and “around” methods. The semantics presented in Section 3 imposes a pre-order of visiting the objects selected by the traversal, as evident in Algorithm 2: first the object is verified to be on a traversal path, then it is visited, and then the traversal proceeds down the tree. We call such visitor methods *before visitor methods*. It is sometimes useful to have the visitor methods invoked in post-order, namely first descend down the tree and then invoke the visitor method. These visitor methods are accordingly called *after visitor methods*. It is a simple exercise to adapt the definition of traversals to deal with after visitor methods.

Both before and after visitor methods are generalized by the notion of *around visitor methods*, whose code is interleaved with the traversal method code of Algorithm 2. This allows for before and after methods (which can communicate directly by shared data structures), and it also allows the visitor to directly manipulate the traversal, e.g., by invoking it multiple times, or by pruning it. This flexibility is very powerful, but its precise definition is involved, and is left for future work.

Cyclic object graphs. One of the apparent disadvantages of the approach presented in the current paper is that it deals only with tree (or forest) object graphs. This problem can be solved in many ways, depending on the intended semantics. In the current implementations, we use visitor methods to make sure that a visited node is not revisited in directed acyclic or in cyclic object graphs. The main point is that we already have all the machinery to carry out a depth-first traversal of a part of the object graph as selected by the strategy, so it is quite easy to vary the implementation slightly to accommodate for our needs. In a sense, what we need is a specialized around method (see above).

For example, one reasonable choice is that no object is visited twice. This can be easily implemented by associating a “visited” bit with each object (or alternatively a hash table), and using it as expected, namely to execute the following as the first step in the traversal method (Algorithm 2):

```
0. If this.visited = TRUE, return. Else this.visited ← TRUE.
```

where initially $o.visited = \text{FALSE}$ for all objects o .

6 The limits of static traversal code

One appealing approach to compiling executable code from traversal strategies is to use only static analysis: in this context, this means that only method invocations are used to traverse the graph, with no further computation while the program is running. The advantage of the static approach is that the run time overhead due to traversals is minimal; the possible disadvantages are larger compile time and higher space requirement for the executable code, but how large can they be? Early implementations of traversals were static, but they suffered from either being limited in scope [46, 45], or inefficient.

In particular, the automata-based algorithm presented in [45] may result in exponential compilation time and exponential number of traversal methods in the executable code.

In this section we show that this phenomenon is not accidental: for some strategies and class graphs, static compilation algorithms must output exponentially many methods, thereby making the space requirement of the code, as well as the running time of the compiler, infeasible in the worst case. We remark that our proof technique is similar to the standard technique of simulating non-deterministic finite automata in polynomial space and time [3].

To state the result formally, we first define the notion of static traversal compilation. We then give an example of a traversal strategy and a class graph where static compilation must result in an exponential number of methods. We remark that the strategy graph we use is not cyclic; in fact, a tree strategy is sufficient to prove the same result.

6.1 The target language

An algorithm is said to compile a traversal strategy and a class graph to *static traversal code* if it generates traversal code in a language which supports only method invocation without parameter passing. The target language of a static compilation algorithm is formally defined in [46, 45], and is given in Appendix C. Informally, a program attaches method definitions to each class, and a method body is a list of (qualified) method names. There are no arguments passed to the methods and no return values. Executing a method in a given object graph is done simply by unfolding the method definition. To perform a traversal starting with a given object, a special method attached to this object is invoked. When a method is invoked, the corresponding object may be added to the traversal history.

6.2 The lower bound

We now prove the main result of this section.

Theorem 6.1 *For any $n > 0$ there exists a traversal strategy \mathcal{S}_n with $|\mathcal{S}_n| = O(n)$ and a class graph G_n with $|G_n| = O(n)$ such that the number of methods in a static traversal code corresponding to \mathcal{S}_n and G_n is at least 2^n .*

Proof: By contradiction. Consider the strategy graph and the class graph depicted in Figure 5. Intuitively, starting with an object of class A , an object of class C_i can be visited only if it has an ancestor of class B_i . The strategy graph has $2n + 2$ nodes and $3n$ edges; The class graph has $2n + 3$ nodes and $4n + 2$ edges. Note that we can construct object trees where an A -object has any desired set of B -ancestors. We claim that in a static traversal code, there are at least 2^n methods attached to objects of class A . For suppose not. Then there exists a set $S_0 \subseteq \{C_1, C_2, \dots, C_n\}$ such that there is no method attached to A which consists of calls precisely to the methods in the objects pointed to by the elements of S_0 . Let I_0 be the set of indices in S_0 . Consider an object tree containing an object o with $\text{Class}(o) = A$ such that o has an ancestor of class B_i if and only if $i \in I_0$. Put differently, we think of an object tree which satisfies the following condition:

$$\{\text{Class}(o') \mid o' \text{ is an ancestor of } o\} \cap \{B_1, B_2, \dots, B_n\} = \{B_i \mid C_i \in S_0\} .$$

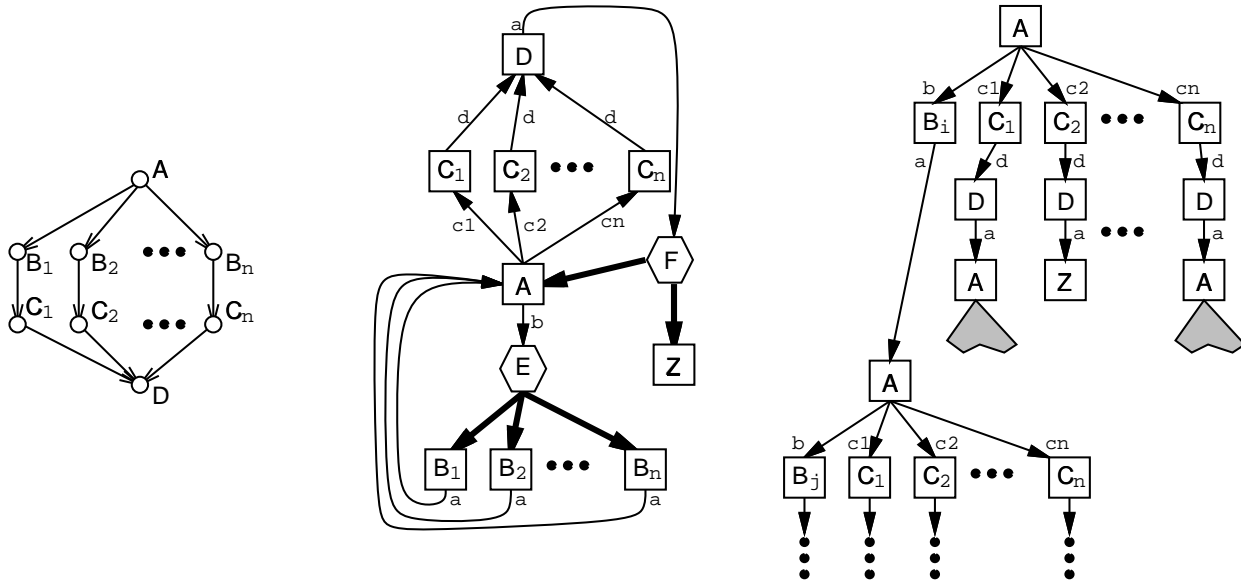


Figure 5: *Example considered in lower-bound proof. Left: the strategy graph. The source of the strategy is the node labeled A and the target is the node labeled D. Middle: the class graph. The name map is indicated by the node labels on the strategy graph. Right: a typical object tree. The shaded regions represent a recursive occurrence of the tree.*

As noted before, such an object graph exists. By definition, when o is invoked, it should call all its children whose class is in S_0 . But by assumption, no such method is attached to A . ■

We note that the strategy graph in the proof of Theorem 6.1 is acyclic (in fact, it is a series-parallel graph expressible in the syntax for traversal specifications of [45]). The proof extends directly to the case of tree strategies (see Section 5.4) by omitting the node corresponding to D in the strategy graph.

It may be instructive to see how the algorithm described in Section 5 avoids the exponential lower bound. In that algorithm, the traversal graph serves as a “road map,” and whenever a traversal method is called in an object o , it gets as an input argument a set of “tokens.” The token set reflects the current location of the traversal, i.e., what prefixes of paths have already been covered when the traversal reached o . This set controls the next traversal actions while being updated as the traversal continues. As the argument of Theorem 6.1 implies, the number of possible continuations of the traversal may be exponential; however, this only means that the number of possible configurations of the token set must be exponential, which can be achieved with an argument whose size is linear in the size of the strategy graph.

7 Implementation notes

In this section we describe some of the practical issues and design decisions taken in the course of development of DemeterJ [37], a prototype system based on the idea of strategies as described in this paper.

7.1 User-level representation

To aid specifying inputs, the system contains a graphical editor which allows the user to enter class and strategy graphs via an intuitive interface. The idea is that the class graph is either generated automatically from a given Java code, or that the user draws it manually. The representation we use is similar to that of UML [7]. In the next step, the user specifies a strategy graph by pointing at the class graph nodes. This method, aside for the obvious ease-of-use, also implicitly defines the name map: a strategy node is mapped to the class node from which it was derived. The constraint map predicates are defined by clicking on the undesired elements.

In addition to the graphical representation, an LL(1) grammar has been developed to support textual representation of strategies (see examples in Section 1 and in Appendix B). The syntax of strategies is given as an edge list between { and }, followed by an indication of the source and target nodes. Example:

```
{ A -> B B -> C C -> D } source: A target: D
```

is a three edge strategy. If a strategy's graph is a line graph, we may also use the from-to syntax:

```
from A via B via C to D
```

is equivalent.

In fact, the textual representation is a much more effective way to specify the constraint map. Specifically, each strategy edge may be followed by an element predicate expressed with any of the following forms:

```
bypassing { A, B }  
bypassing -> *, l, *  
only-through -> A, l, B
```

The first predicate is true for all elements except for nodes A and B. The second predicate is true for all elements except for edges whose label is l . The third predicate is false for all elements except for the edge $A \xrightarrow{l} B$.

7.2 Tool responsibilities

We have mentioned the tools DemeterJ, DJ Library, DAJ, AP Library all using the technology described in this paper. We briefly describe the responsibilities of those tools, how they relate and what their limits are.

7.2.1 AP Library

An experimental implementation of strategies, called the *AP library*, is used for a few years [1]. The AP Library is an implementation of the core concepts described in this paper: it includes an interface and implementation for the concepts of class graphs, traversal strategy graphs, traversal graphs and an algorithm to compute traversal graphs from class graphs and traversal strategy graphs.

The AP Library is used by DJ [2] (see Section 7.2.2) as well as by DAJ [53].

7.2.2 DJ Library: Traversals as objects

DemeterJ does the traversal compilation in a pre-processing stage, and requires the usage of a modified Java language. Traversal as objects (DJ) pursues a different avenue of implementation. The idea in DJ is to add traversals to Java without extending the language; instead, traversal is done using some predefined classes. More specifically, traversal graph objects are created by calling the constructor of the `TraversalGraph` class with a textual representation of the traversal strategy as a string argument. The `TraversalGraph` constructor implements the new algorithm described in this paper which translates a strategy and a class graph into a traversal graph which is interpreted when a traversal executes. A traversal graph object `t` is typically called by an expression of the form `t.traverse(o,v1,v2, ... ,vn)`, where `o` is the object to be traversed and $\langle v1, v2, \dots, vn \rangle$ is a vector of visitors. The DJ approach also allows to compute traversals at run-time.

We have implemented traversals as objects in a tool that integrates generic programming with adaptive programming. The tool is called DJ [2] and supports the adaptive definition of iterators that are used by generic algorithms. The tool works with the Java collection classes and offers the capability to use strategies to turn object graphs into lists.

DJ is slow because it relies heavily on reflection [44].

7.2.3 DemeterJ

DemeterJ is our oldest tool improving on our C++ implementation described in [35]. DemeterJ introduces the concept of adaptive methods which are basically a triple (class graph, strategy, visitor). DemeterJ uses an older version of the AP Library.

DemeterJ is often used after a project has been prototyped using the DJ library because DemeterJ produces fast code using the algorithms of this paper.

7.2.4 DAJ

DAJ (Demeter AspectJ) [53] is our latest tool and it takes AspectJ, rather than Java, as the starting point. DAJ uses the extension capabilities of AspectJ that allow additional declarations to be added to AspectJ. `TraversalGraphs`, `ClassGraphs`, `Visitors` and `Behaviors` can be declared in DAJ.

DAJ offers the benefit of having to learn only AspectJ and the concepts of `TraversalGraphs`, `ClassGraphs`, `Visitors` and `Behaviors` to program adaptively using traversal strategies. And DAJ generates fast code, using the AspectJ compiler. See Section 10 about how traversals fit into AspectJ.

8 Related work

It is surprising to see that despite the universality of traversals in programming, only very little work has been done in this direction although the pace is picking up (e.g., [29] and related papers by the same authors).

Until recently, the automation of traversal of object structures using succinct representations is unique to Demeter ([38], see above); the rising popularity of markup languages in general, and XML in particular, created a new interest in traversals. In this section we list some work relevant to traversals.

XML is a new standard for defining and processing markup languages for the web [9]. XML uses grammars (also called *document type definitions* or *schemas*) to define a markup language for a class of documents. To select subsets of XML document elements, the W3 Consortium recently introduced a language called XPath [11]. The way elements are selected in XPath is by navigation, somewhat resembling the way one selects files from an interactive shell, but with a much richer language. Recently [41], XPath has been proposed as input to a universal object model walker for arbitrary Java objects. XPath expressions are used to describe *sets of objects*, in the sense that the value of an expression is an *unordered* collection of objects *without duplicates*. This is in contrast to traversals, whose value is a set of *paths*, so that the objects of each path are explicitly ordered and may appear more than once, even on the same path. It is quite easy to implement XPath using strategies, using specialized “visitors.” The converse, however, does not hold, due to the lack of structure in XPath expression values. While XPath is a powerful language to address parts of an XML document, there are cases in which strategies can be used to select the same sets with *exponentially* shorter representation than the representation of XPath.

A bad example for XPath is (currently) as follows (XPath is in the process of being extended moving closer to the traversal strategy model to make this also easily expressible). Take a strategy graph with start node S and target node T and nodes A_i and B_i for i from 1 to n and nodes C_j for j from 1 to $n - 1$. There are edges from S to A_1 and B_1 ; from C_i to A_{i+1} and B_{i+1} and from A_i and B_i to C_i for i from 1 to $n - 1$; from A_n and B_n to T . Note that there exponentially many paths from S to T and if we want to express the T nodes that we want to select in XPath, we have to enumerate all those paths using the XPath notation. The size of the strategy graph solution is linear, while the size of the XPath solution is exponential.

This example may lead to exponential running times for some input objects both for the XPath and the traversal strategy case. It is the responsibility of the programmer to recognize this possibility and deal with it using appropriate visitor objects.

In the context of *object-oriented databases*, traversals are heavily used. Some automation of traversal was suggested in [42, 56, 40, 27, 23]. Roughly speaking, the idea in these papers is to traverse to a target without specifying the full path leading to it. Cast in our terms, one can view these techniques as a variant of line-graph strategies (i.e., strategy graphs with a single path) ; however, their goal is to allow the user to abbreviate the laborious specification of a full query, and their main concern is how to complete the abbreviation when it is ambiguous, sometimes using heuristics. Another complication these approaches confront is that queries are specified on-line and can therefore refer to run-time structures. By contrast, our approach ignores the ambiguity problem by traversing all qualified objects, and requires traversal specifications to refer only to compile-time structures. On the other hand, strategies allow for general graph specification, and entail (when combined with visitors) the power of a full-fledged programming language.

In the context of programming languages, traversals are frequently used as a part of *attribute grammars*, for traversing abstract syntax trees [60]. Using conventional programming techniques, the

details of traversals must be hard-coded in the attribute grammar; this fact makes attribute grammars hard to maintain, say in the case of some modifications in the grammar [25]. In the Eli system [19], this problem is addressed by separating the details of the grammar from the underlying algorithm, using traversal specifications which basically correspond to single edge strategy graphs. There are papers dealing with a more modular, component-based approach to attribute grammars, such as [17]. This allows traversals for different aspects or phases to be separated, partially addressing the concerns of scattering and tangling of traversal code. However, the mapping from specific attribute grammars to high-level attribute grammars needed in a modular attribute grammar approach could be expressed more conveniently with traversal strategies.

Meta-programming techniques have also been developed for traversals. For example, in [10], a simple kind of traversal (corresponding to a one layer tree graph) is used in a meta-program; this traversal scans all objects and executes the specified code at the desired targets.

The *Visitor* design pattern is discussed in many software-engineering works (e.g., [18]). While this approach identifies and isolates the task of traversal, no mechanism to automate the task and make it adaptive was previously proposed. Moreover, no formal treatment of traversal was offered. As a side remark from the software engineering perspective, we note that our approach of separating the traversal task from the class-structure of an object oriented program can be viewed as a special case of *aspect oriented programming* [26], where the idea is to try to align different conceptual aspects of programming with actual code modules.

Visitor generators have been around for a while (e.g., [24, 52, 8]), usually generating a default DepthFirst visitor with before and after hooks. Since these visitors only need to be manually specialized for selected types of the visited class hierarchy, they are adaptive to some degree. But visitor generators fall short of the accomplishments of our approach for the following reason: They don't take advantage of a high-level approach to specifying traversals and instead the generated visitor goes everywhere. For example, to implement a traversal "from A to B" with a visitor generator, we would have to specialize the visitor manually for all classes between A and B where we don't need to visit all outgoing edges. A visitor generator generates traversals of the form "from A to *" and then we have to simulate bypassing clauses using subclassing.

An important tool for aspect-oriented programming is AspectJ from Xerox PARC [54]. Generally speaking, AspectJ allows the programmer to manipulate *pointcuts*, which are a collection of points in the execution. In Section 10 we describe two applications of traversals to AspectJ. A traversal defines a structured set of join points (calls of the traversal methods) while in AspectJ a much richer set of join points is used. Visitors are advice on the traversals.

9 Comparison to traversal specifications

In this section, by \mathcal{L}_{OLD} we mean the traversal specification language of [34, 46] and by \mathcal{L}_{NEW} the traversal specification language for strategies presented in this paper.

The comparison between \mathcal{L}_{OLD} and \mathcal{L}_{NEW} is delicate but \mathcal{L}_{NEW} is an important improvement over \mathcal{L}_{OLD} . Some traversal specifications are equally easy to express in \mathcal{L}_{OLD} as in \mathcal{L}_{NEW} , other \mathcal{L}_{NEW}

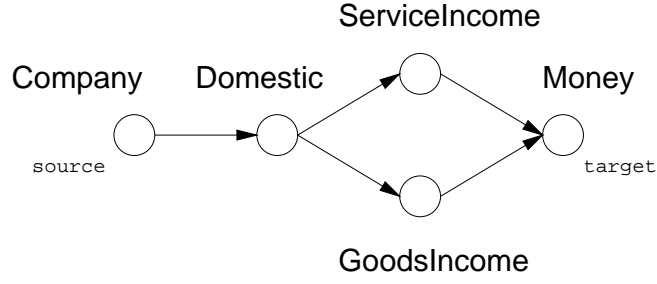


Figure 6: A series-parallel traversal strategy.

traversal specifications are impossible to express in \mathcal{L}_{OLD} and some traversal specifications expressed in \mathcal{L}_{NEW} can be expressed in \mathcal{L}_{OLD} but are exponentially longer.

We discuss the following three points in detail:

1. Any traversal specification in \mathcal{L}_{OLD} is a directed series-parallel graph [16] and can be expressed as a strategy in \mathcal{L}_{NEW} . In other words, we have upward compatibility. Example: The \mathcal{L}_{OLD} style traversal specification

$$[\text{Company}, \text{Domestic}] \cdot ([\text{Domestic}, \text{ServiceIncome}] \cdot [\text{ServiceIncome}, \text{Money}] \\ + [\text{Domestic}, \text{GoodsIncome}] \cdot [\text{GoodsIncome}, \text{Money}])$$

is expressed as the strategy shown in Figure 6. The translation maps each “from-to” part of the form $[X, Y]$ to an edge in the strategy.

2. Some of the traversal specifications in \mathcal{L}_{OLD} can be expressed much more succinctly as a strategy in \mathcal{L}_{NEW} . Consider the following \mathcal{L}_{OLD} traversal specification

$$[\text{Company}, \text{Domestic}] \cdot ([\text{Domestic}, \text{ServiceIncome}] \cdot [\text{ServiceIncome}, \text{Money}] \\ + [\text{Domestic}, \text{GoodsIncome}] \cdot [\text{GoodsIncome}, \text{Money}]) \\ + [\text{Company}, \text{Foreign}] \cdot [\text{Foreign}, \text{GoodsIncome}] \cdot [\text{GoodsIncome}, \text{Money}]$$

which duplicates $[\text{GoodsIncome}, \text{Money}]$. The traversal specification will traverse to all **Money** objects. The domestic and the foreign parts of the company are treated differently: for domestic parts we traverse both into **ServiceIncome** and **GoodsIncome** while for foreign parts we traverse only into **GoodsIncome**. In the corresponding traversal strategy given in Figure 7, this duplication is not needed.

Remembering the motivation that a traversal strategy with source s and target t defines a set of paths from s to t , we can always replace a strategy that is a dag by a set of paths that are merged together. Because the number of paths from s to t may be exponential in the size of the dag and there may be no shorter possibility than enumerating all of them, the old representation may be exponentially longer. Consider the following strategy with n nodes A_1, A_2, \dots, A_n . There are edges $A_i \rightarrow A_{i+1}$ for $i = 1, \dots, n - 1$ and edges $A_i \rightarrow A_{i+2}$ for $i = 1, \dots, n - 2$. Figure 8 shows this strategy with $n = 7$. The resulting graph is not series-parallel and the only way to express

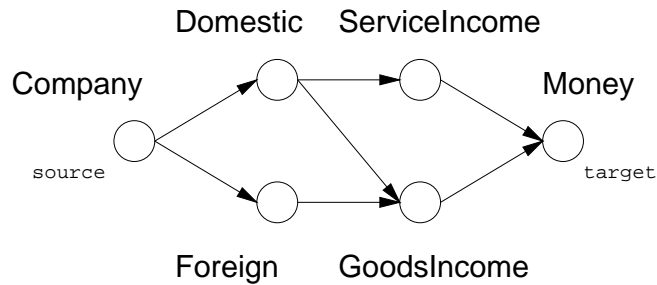


Figure 7: A non-series-parallel traversal strategy.

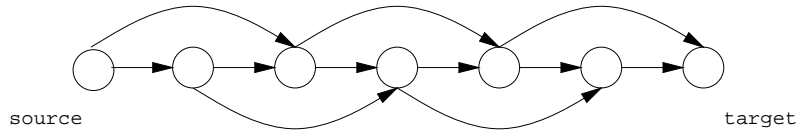


Figure 8: A non-series-parallel strategy with n nodes and $O(2^n)$ paths ($n = 7$ here).

the set of paths from source A_1 to target A_n using join and merge only is to enumerate a number of paths that grows exponentially in n . We can use a series-parallel construction for some of the paths but overall we will have an exponential number of paths and therefore a traversal strategy that grows exponentially in n .

3. There are cyclic strategies (expressed in \mathcal{L}_{NEW}) which cannot be simulated by \mathcal{L}_{OLD} . Consider the following traversal that cannot be simulated by a traversal specification in \mathcal{L}_{OLD} . For a given city, we want to find all other cities reachable through zero or more bus routes. Consider this specification in the context of the class graph in Figure 9. Using this class graph, we can start at a city and follow paths of the form

$$\langle \text{City (routes BusRoute cities City)}^* \rangle$$

to find all cities connected to it by bus routes only. We are not interested in the cities reachable through flights. We can use the cyclic strategy shown in Figure 10, which selects the desired City objects. But this cyclic strategy cannot be expressed by a series-parallel graph. We could try:

from City bypassing City via BusRoute bypassing City to City

but this allows only cities reachable through an immediate bus route.

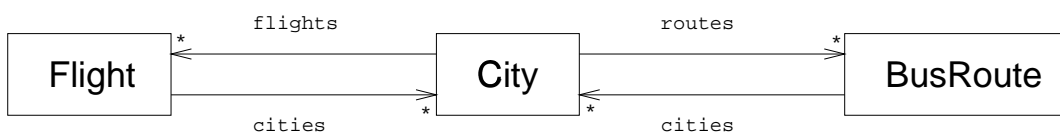


Figure 9: Class graph for a transportation network.

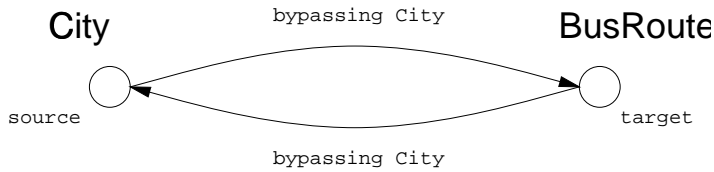


Figure 10: A cyclic strategy.

To summarize: the new notation is exponentially more expressive in some cases and combined with the exponential algorithmic improvement presented in this paper the new approach is considerably more efficient than the old approach.

10 Applications of traversal strategies

This paper focuses on succinctly defining behavior for traversing through object graphs and on efficient implementations of the traversals. However, our traversal theory (the expressive model and the efficient algorithms) are applicable in a much wider context which we outline in the following.

The traversal theory relies on three layers of graphs: top, middle and bottom. The bottom layer consists of trees that we want to traverse to select subtrees. Each bottom layer tree has a graph from the middle layer associated with it that contains meta-information about the bottom layer tree. The meta-information expresses that certain edges must or may exist. Each middle layer graph is associated with at least one top layer graph. The top layer graph is basically a sub graph of the transitive closure of the middle layer graph, decorated with additional information attached to the edges. The purpose of the top layer graph is to define sub trees of the bottom layer graphs. In other words, when the bottom layer graph is traversed, the top layer graph tells us at each node which outgoing edges to traverse. The purpose of the middle layer graph is to act as an abstraction barrier between the top and bottom layers. At the middle layer we program the specification given by the top layer and we use the middle layer to reduce the search space.

The top layer graphs are an abstraction A of the associated middle layer graphs and the middle layer graphs are an abstraction B of the associated bottom layer graphs. The abstractions A and B, however, are different. Abstraction A involves the transitive closure and abstraction B involves compatibility rules where relations at the middle layer imply relations at the bottom layer.

The traversal theory is also useful if we only use the top and the middle layer. In this case we are interested in defining succinctly a set of paths in the graph in the middle layer. Sometimes we are not interested in the details of the path set, just the subgraph or set of nodes that all those paths in the set cover.

This general description fits many practical situations of which we mention a few, all of them of interest to the emerging field of Aspect-Oriented Programming [15].

- The standard application: Top: strategy graph, Middle: class graph, Bottom: object trees. The strategy graph serves as a specification of a set of introductions of new traversal methods into the

class graph. This standard application is used extensively in DemeterJ and in DAJ [53]. DAJ is an extension of AspectJ [54] with traversals. DJ also falls into this standard application, however, the traversal behavior is created at run-time by specializing a generic traversal algorithm.

If we focus on the top and middle layer only, we need only our Algorithm 1, called the TraversalGraph algorithm, which is described later. One application of the TraversalGraph algorithm is to use it to succinctly specify a set of types. In AspectJ, type patterns could benefit from using strategies to specify a set of types succinctly.

A second application of the TraversalGraph algorithm is the adapter generation approach by Bart Wydaeghe and Wim Vanderperren [62, 63, 57]. The components that need to be connected might not match and therefore an adapter has to be generated. The idea is that a traversal graph that is constructed by the TraversalGraph algorithm succinctly describes all possible adapters from which the programmer can choose the most suitable one. The top layer graph represents the interactions of a high-level component and the middle layer graph represents the interactions of a low-level component that offers more detail than the other component asks for. The PacoSuite is a tool in which those ideas have been successfully implemented and tested in an industrial context. The application uses the full power of traversal strategies, including bypassing clauses and the name maps.

- The call graph application: Top: computational pattern, Middle: static call graph, Bottom: call tree.

Static call graph: It is derived from the program source as follows. The nodes correspond to methods and the edges to method invocation expressions (e.g. `a.foo(b,c)`) contained in the methods. There are two types of methods: concrete and abstract. A concrete method has an outgoing edge for every method the method calls or might call. Some of the outgoing edges are marked required and others are marked optional. The required edges are to calls of other methods that are reached unconditionally while optional edges correspond to calls that are reached conditionally (some conditional statement might prevent the execution of the call; e.g. an if, loop or switch statement). An abstract method has several outgoing edges marked as virtual edges. Each leads to one of the method calls that might happen as a result of the virtual method call. A static call graph has the shape of a class graph.

Dynamic call tree: It is a tree conforming to a static call graph. The nodes are calls of methods (called join points) and the edges represent immediate method call nesting. Conformance means that 1. the dynamic call graph can only contain instances of call sites appearing in the static call graph. 2. the dynamic call graph can only contain edges prescribed by the static call graph. 3. if in the static call graph a required edge exits a call site then the edge must be in the dynamic call graph. 4. a call of a virtual method is not shown in the dynamic call graph; instead it shows the concrete method that actually gets called. A dynamic call tree has the shape of an object tree where call nodes correspond to object nodes and immediately nested calls correspond to immediately nested objects.

As an example, consider the set of all method calls that might happen between a call to `f` and a call to `g`. For each of those method calls we would like to print some information and we would like to know how the join points are related. In other words, we want to know the structure of

the dynamic call tree between calls to `f` and calls to `g`. We would like to describe this slice of the dynamic call tree as from `jp1` to `jp2`, where `jp1 = call(* f(*))` and `jp2 = call(* g(*))`. Both `f` and `g` may return any type and both may have one argument of any type.

In a second example, we want to know for a thread and a resource type `R` all the `read`, `write`, `lock` and `unlock` calls that happen during the thread. Furthermore, we want to check, that none of those primitives call each other. For example, we want to disallow that a `write` calls `lock` directly.

We consider four kinds of nodes in the static call graph corresponding to calls of the four primitives.

```
jp_lock = call(R.lock())
jp_write = call(R.write())
jp_unlock = call(R.unlock())
jp_read = call(R.read())
```

`jp_start` is a node in the static call graph where the computation starts. We consider the following two strategies:

```
jps1 = from jp_start to {jp_lock, jp_write, jp_unlock, jp_read}

jps2 = from jp_start
      bypassing {jp_lock, jp_write, jp_unlock, jp_read}
      to {jp_lock, jp_write, jp_unlock, jp_read}
```

Notice that bypassing a node does not bypass that node if it is a start or end point.

The primitives don't call each other iff for the given static call graph, `jps1 = jps2`. This second example is interesting because it shows that strategies are useful to formulate architectural properties of call graphs at a high level of abstraction.

Finally, we present a use of the call graph application in serialization/marshalling which is a very common example of object traversal. A serializer is a tool transforming partial graphs of objects into a stream of bytes. In [39], simple traversal directives (which are single edge strategy graphs) are used to specify which parts of a compound object should be copied and which should be passed by reference when using remote method invocations. Our work on traversals is useful to current work in object serialization [47, 4, 21] in the following way: A common concern in serialization is how to generate serialization code with minimal impact on the code size of the application, or alternatively, how to arrange dynamic traversal with minimal run-time impact. We address this concern by showing in 6 that if the traversal methods are not generated carefully from a partial object specification (as described in this paper), one might end up with exponential code size. Our implementation of DJ shows how to arrange dynamic traversal and the DemeterJ implementation shows how to generate efficient code efficiently. We also show a general way to specify partial objects. This paper solves the problem where we use a marshalling language (our traversal strategy language) to specify partial object graphs.

11 Experience and empirical evidence

The algorithms described in this paper have been used extensively in our tools and tools developed by others. Surprisingly, both the exponential algorithmic improvements as well as the more general model don't seem to be so important for the applications where we used traversals. The earlier compilation algorithm, called the Xiao-algorithm, described in [46] worked very well in practice and the exponentially bad cases described in this paper did not seem to appear in practice. But the Xiao-algorithm was challenging to program and required occasionally the programmer to rewrite the traversal specifications in case the algorithm could not handle the combination of current strategy and class graph. The threat of slow performance and the lack of generality made us to switch to the algorithm described in this paper.

The remark that the Xiao algorithm worked well in practice is supported by the following statistics for DemeterJ. The entire tool uses 236 strategies of which only 32 strategies are multi-edge. This gives an average of 1.144 edges per strategy. The largest strategy had 4 edges. (It should be remarked that in a redesign of DemeterJ the average would be higher because, due to tool limitations, some strategies make use of bypassing instead of using more strategy edges. You can always simulate any strategy, in the context of a given class graph, by a single edge strategy that uses sufficiently many bypassing clauses.) Because strategies are small in DemeterJ, the efficiency of our new algorithm is not so important for the DemeterJ application. The complete set of strategies used in DemeterJ are available in [43].

The idea behind succinct specifications of mathematical structures [20] is to exploit regularity. If there is no regularity, succinctness will not work. In [20] boolean circuits are used to represent graphs succinctly. We instead use traversal strategies to define subgraphs succinctly. It is an interesting empirical evidence that traversal strategies are usually much shorter than the corresponding traversal graph that contains the expansion of the strategy for a specific class graph. We don't have numbers to support this evidence but we have used strategies extensively in the implementation of DemeterJ in DemeterJ. An industrial project at Verizon which uses DemeterJ was presented at the first International Conference on Aspect-Oriented Software Development (AOSD) in April 2002 [6] as an example of successful use of AOSD technology in industry. The traversal specifications worked very well in this project over a period of five years. The evolution history of the project is available on the web [5].

Further evidence that traversal strategies work, can be obtained from the successful use of the Demeter/C++ system [31] and its subsequent incarnations. Demeter/C++ has been used at Northeastern University since 1992, and in other places, including at Citibank, IBM, Bell Northern Research, Credit Suisse and at several universities. See [13] for an extensive description of the system and relevant references. The first version of Demeter allowed only very simple traversals (corresponding to single-edge strategy graphs with bypassing clauses), and generated code in C++. Demeter/C++ compiles traversals which can be described by a series-parallel graph, but only for a restricted set of class graph strategy combination.

Since 1996 the main development effort has focused on a system which generates Java code, called DemeterJ [37]. The current version of DemeterJ (formerly called Demeter/Java) and DJ support strategies as described in this paper. DAJ [53] is the latest addition to the Demeter tools which uses

AspectJ as the weaving language rather than our own and which exposes the weaving language to the application programmer. Those tools have been used in many projects and they worked best for large class graphs because in those the succinctness of strategies has the greatest benefits.

Hewlett-Packard has reported a positive experience in using the traversal/visitor style of programming for writing installation software for the HP printers family [30].

Finally, another empirical evidence is that the Law of Demeter [36] is still considered to be a good idea [22]. However, writing all of the methods needed to forward calls is boring and error prone. Traversal strategies may be used to specify the forwarding calls at a high level of abstraction.

12 Conclusion

Traversals are fundamental to object-oriented programming and programming in general. In order to process an object we need to traverse through a part of it and perform appropriate actions during the traversal. The importance of traversals of object structure is well recognized in the literature. For example, the Visitor design pattern [18] and its variants [58, 59, 24] attest to this fact. We believe that the notion of strategies is a significant contribution to software developers—both by providing a more intuitive and conceptually simpler programming model, and by automating the frequent-and-tedious task of programming traversals.

In this paper we have extended the state of knowledge regarding traversals by providing a general definition as well as an efficient implementation and a working prototype. We improve on all previous implementations and at the same time we present a model that is more general than previous traversal models. In addition, the lower bound result improves the understanding of the inherent properties of run-time traversals, whose implementation has been notoriously tricky.

U.S. patent 5,946,490 covers the algorithms in this paper.

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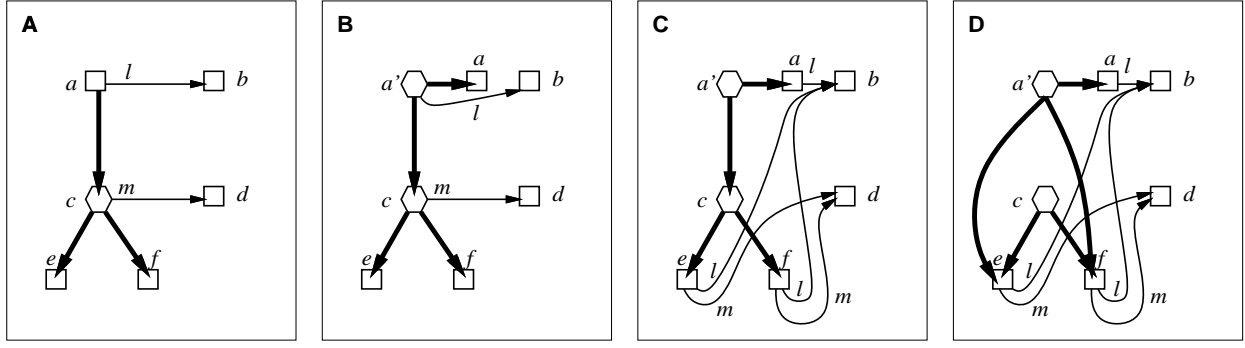


Figure 11: *An example of class graph simplification. A: the original class graph. Concrete classes are depicted as squares, and abstract classes are hexagons. Reference edges are regular, and subclass edges are heavy. B: after step 1. C: after step 2. D: after step 3.*

APPENDICES

A Class graph Simplification

In this appendix we prove Proposition 2.1. For the convenience of the reader, we reproduce it below.

Proposition 2.1. *Let $G = (V, E)$ be an arbitrary class graph. Then there exists a class graph $\text{Simplify}(G) = (V', E')$ such that an object graph Ω is an instance of G if and only if Ω is an instance of $\text{Simplify}(G)$. Moreover, $|V'| = O(|V|)$ and $|E'| = O(|E|^2)$.*

The proposition is proven by the following transformation algorithm (see example in Figure 11).

1. For each concrete class $v \in V$ with an outgoing subclass edge $v \xrightarrow{\diamond} u \in E$, add a new abstract node v' into V , along with the following changes of the edge set:

- Divert all edges coming into v to end at v' . That is,

$$E \leftarrow E \cup \{u \xrightarrow{l} v' \mid u \xrightarrow{l} v \in E\} \setminus \{u \xrightarrow{l} v \mid u \xrightarrow{l} v \in E\}$$

- Divert all subclass edges going out from v to originate at v' . That is,

$$E \leftarrow E \cup \{v' \xrightarrow{\diamond} u \mid v \xrightarrow{\diamond} u \in E\} \setminus \{v \xrightarrow{\diamond} u \mid v \xrightarrow{\diamond} u \in E\}$$

- Make v a subclass of v' :

$$E \leftarrow E \cup \{v' \xrightarrow{\diamond} v\}$$

When this step is completed, no concrete class has subclass edges going out from it.

2. For each concrete class v : add edges so that the set of edges going out from v is exactly the induced edges of v . Then, delete all reference edges going out from abstract classes.
3. Contract long inheritance chains. For each abstract class v : find all concrete classes u which can be reached from v using subclass edges only, and add a subclass edge $v \xrightarrow{\diamond} u$ if one does not exist already. Finally, delete all subclass edges leading to abstract classes.

Informally, Step 1 decouples the sub-classing role from concrete classes by introducing an additional abstract class for each class which has both subclass and reference edges going out from it.

Step 2 unfolds inherited reference edges by pushing them down the subclass hierarchy. This can be done efficiently by traversing the subclass edges in a top-down fashion, starting with nodes with no subclass edges coming into them, and “collecting” reference edges as we go down. Details are omitted.

Step 3 can be viewed as taking the transitive (non-reflexive) closure of the subclass relation. This step can be done in parallel with Step 2.

For the bound on the size of the resulting graph, note first that only Step 1 may change the number of nodes by at most doubling it. Next, note that since Steps 2 and 3 do not change the connectivity structure of the graph, we can deal with each connected component separately. Consider such a component with n nodes. Since it is connected, there are at least $n - 1$ nodes in the component before Steps 2 and 3. Since these steps do not introduce nodes or parallel edges, they may introduce at most $O(n^2)$ new edges. We may therefore conclude that the number of nodes in $\text{Simplify}(G)$ is at most doubled and the number of edges is at most squared.

B Code for the example in Figure 3

In this section we show how to program the example of Fig. 3 in DemeterJ [37]. We show how to write a program which traverses a given A-object according to the given strategy and also counts the number of E-objects found during the traversal.

The the code for the strategy given in pane 2 of Figure 3, including the name map and and the constraint map given below. The strategy is named S.

```
strategy
S = { A -> D
      D -> E
      A -> Z      bypassing -> A,d,D
      Z -> E      bypassing A
}
```

The notation for strategy graphs is an edge list, where each edge may have constraints associated with it. The default name map associates a strategy node with a class with the same label (this cannot be used if multiple strategy nodes are mapped to the same class).

The class graph code is annotated with some syntactic sugar to make it an LL(1) grammar which is given to the Java Compiler Compiler to create an object for a given input sentence. The code for the class graph of pane 1 of Figure 3 is as follows [31]:

```
A = "a" <b> B <c> C <d> D .
B = "b" <z> Z .
D = "d" <y> Y.
```

```

C = <e> E .
Y : A | B.
Z : D | E.
E = "e" .

```

Essentially, the graph is represented as a list of nodes, where each node is represented by a list of its outgoing edges.

To write the program which counts the number of E-objects contained in an A-object, we first define a visitor class:

```

CountingVisitor {
    int r;
    init (@ r = 0; @)
    before E (@ r++; @)
    return int (@ r; @)
}

```

This visitor class is encapsulating the counting behavior, including how to initialize (the `init` method) and what to return (the `return` method) after the traversal is complete.

Next we define a traversal/visitor combination `t`, called a traversal method `t`, using the strategy `S` we defined earlier and the `CountingVisitor` defined above. In general, a traversal method is a strategy combined with a list of parameter types (visitor classes). Finally, we define an adaptive method `CountCertainEs` for class `A` which defines with which subclass of `CountingVisitor` we want to do the work. In this case we use `CountingVisitor` itself.

```

A {
    traversal t(CountingVisitor v) { do S; }
    int CountCertainEs() = t(CountingVisitor);
}

```

We call `CountCertainEs` in class `Main` as follows.

```

A a = A.parse(System.in);
int result = a.CountCertainEs();

```

To summarize the adaptive programming approach used above, called the strategy/visitor style, we note that behavior is expressed in terms of strategies and visitors. Strategies are abstract path specifications, i.e., not attached to a particular class structure or visitor class. Visitors are specifications of behavior which needs to be executed while the paths are traversed. Strategies and visitors are combined in two steps: 1. First a strategy/visitor combination, called a traversal method, is defined. A traversal method is attached to a class and used to traverse an object graph. 2. A specific adaptive method is chosen from the traversal method by specifying which specific visitor subclasses to use.

The strategy/visitor style is a good approach to express behavior since strategies, visitors, traversal methods and adaptive methods are reusable and the resulting programs can be more easily evolved by changing strategies or visitors or class graphs. The coupling between strategies and visitors is loose,

much looser than in the tangled mess of the visitor design pattern described in [18] where the class graph information is spread all over.

C Target language for static compilation

Static traversal compilers compile strategies and class graphs into an object-oriented program where the sequence of methods invoked by an object depends only on the object structure and the method name (no parameter passing is allowed). Formally, the language is defined as follows.

A *program* in the target language is a partial function which maps a class name and a method name to a method. A method is a tuple of the form $\langle l_1.m_1, \dots, l_n.m_n \rangle$, where $l_1 \dots l_n \in \mathcal{L}$ and $m_1 \dots m_n$ are method names. When invoked, such a method executes by invoking $l_i.m_i$ in order. We distinguish two kinds of methods: *visiting* and *non-visiting*, prescribed by a predicate *visit* defined on the set of method names.

An invocation of a program is defined as follows. If Ω is an object graph, o a node in Ω , m a method name, P a program in the target language, and H a sequence of objects, then the judgment

$$\Omega \vdash_c o : m : P \triangleright H$$

means that when sending the message m to o , we get a traversal of the object graph Ω starting in o so that H is the traversal history. Formally, this holds when the judgment is derivable using the following rules:

$$\frac{\Omega \vdash_c o_i : m_i : P \triangleright H_i \quad \forall i \in 1..n}{\Omega \vdash_c o : m : P \triangleright o \cdot H_1 \cdot \dots \cdot H_n} \quad \text{if } P(\text{Class}(o), m) = \langle l_1.m_1 \dots l_n.m_n \rangle, \text{ and } \text{visit}(m), \text{ and } o \xrightarrow{l_i} o_i \text{ is in } \Omega \text{ for all } i \in 1..n.$$

and

$$\frac{\Omega \vdash_c o_i : m_i : P \triangleright H_i \quad \forall i \in 1..n}{\Omega \vdash_c o : m : P \triangleright H_1 \cdot \dots \cdot H_n} \quad \text{if } P(\text{Class}(o), m) = \langle l_1.m_1 \dots l_n.m_n \rangle, \text{ and } \neg \text{visit}(m), \text{ and } o \xrightarrow{l_i} o_i \text{ is in } \Omega \text{ for all } i \in 1..n.$$

The label c of the turnstile indicates “code”. Intuitively, the rule says that when sending the message m to o , we check if o understands the message, and if so, we invoke the method. The object o is added to the traversal history only if *visit*(m) is true. Notice that for $n = 0$, the rule is an axiom; in the case that *visit*(m) is true, it is simply

$$\frac{}{\Omega \vdash_c o : m : P \triangleright o} \quad \text{if } P(\text{Class}(o), m) = \langle \rangle$$

and if *visit*(m) is false, then it is

$$\frac{}{\Omega \vdash_c o : m : P \triangleright \epsilon} \quad \text{if } P(\text{Class}(o), m) = \langle \rangle,$$

where ϵ denotes the empty history.

Given a program in the target language, it is straightforward to generate, for example, a C++ or a Java program.