SOFTWARE—PRACTICE AND EXPERIENCE
Softw. Pract. Exper. 2008; **38**:33–73
Published online 29 May 2007 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/spe.821

An efficient and flexible toolkit for composing customized method dispatchers[‡,§]

A. Cunei[*,†] and J. Vitek

Department of Computer Science, Purdue University, West Lafayette, IN 47907, U.S.A.

SUMMARY

The standard dispatching mechanisms built into programming languages sometimes fail to satisfy the needs of the programmer. In the case of Java, the need for more flexibility has led to the development of a number of tools, including visitors and multi-method extensions, that each add some particular functionality, but lack the generality necessary to support user-defined dispatching mechanisms. In this paper we advocate a more modular approach to dispatching, and we present a tool, PolyD, that allows the programmer to design custom dispatching strategies and to parametrize many aspects of the dispatching process. PolyD exhibits excellent performance and compares well against existing tools. Copyright © 2007 John Wiley & Sons, Ltd.

Received 19 October 2006; Revised 17 February 2007; Accepted 20 February 2007

KEY WORDS: dispatching; multimethods; visitor pattern; Java

1. INTRODUCTION

Object-oriented programming revolves around organizing data and code as distinct objects that communicate using messages. When a message is received by one object, the object responds in its own way, by using one of the available methods. The message is 'dispatched', meaning that one of the methods is selected and invoked as a result of the arrival of the message. However, the details of the dispatching process and in particular of the method selection, can vary considerably.

[*]Correspondence to: Antonio Cunei, Department of Computer Science, Purdue University, 305 N. University Street, West Lafayette, IN 47907, U.S.A.
[†]E-mail: cunei@cs.purdue.edu
[‡]PolyD can be freely downloaded from the PolyD home page at http://www.ovmj.org/polyd.
[§]A preliminary version of this work was presented at the 20th ACM SIGPLAN International Conference on Object-Oriented Programming, System, Languages and Applications (OOPSLA 2005), 16–20 October 2005, San Diego, CA, U.S.A. Section 6 has been added, consisting of entirely new material.

Contract/grant sponsor: National Science Foundation; contract/grant numbers: HDCCSR-0341304 and CAREER-0093282

If, for instance, compile-time information is used exclusively in order to select the correct method, the only runtime action required will be the method invocation, a situation referred to as static resolution. Much more frequently, however, dynamic dispatching is used instead, meaning that the actual runtime class of one or more objects is used in the selection process. Most typed languages, including Java, rely on a combination of static resolution and *single dispatching*, in which the runtime selection of the method is based on the class of a single, distinguished, argument. The remaining arguments of the message are only inspected statically in order to resolve overloaded methods. Other languages implement a *multiple dispatching* mechanism, in which the runtime class of multiple objects is considered in order to select the most appropriate method [1–3]. Multiple dispatching, together with its generalization to predicate dispatching, has been studied in the context of extensions to Java [4–8] and from the point of view of static type-checking [9–11]. Multiple dispatching is an elegant tool that can help to solve programming problems that would otherwise require more complex workarounds. For instance, the classic Visitor pattern is a convoluted substitute for a straightforward double dispatching [12].

The goal of PolyD is to provide a *modular framework for user-defined dispatching mechanisms for Java*. We argue that when programmers are faced with the need for a dispatching mechanism distinct from what is provided by the language, a tool such as PolyD provides them with a more efficient, flexible, and easy to use solution than hand-coded mechanisms. The term 'modular' refers here to *composable in a modular manner:* we want to be able to build dispatching mechanisms by using either off-the-shelf or custom-written components, and combining them in order to obtain the desired functionality. By emphasizing separation and modularity between the message send and the actual dispatching mechanism PolyD allows the programmer to select different dispatching mechanisms in different parts of the code, to modify their choice of dispatcher during development or even at runtime, and to customize various aspect of the standard dispatchers provided.

In order to be practical, the design of PolyD is constrained by the following requirements. The framework should be *non-intrusive*. This means that changes to the syntax of Java or the tool-chain (i.e. source compiler, debugger, bytecode format) are not acceptable. The solution should be *portable* in the sense that it should run on any implementation of Java and thus virtual machine (VM) changes are ruled out. Dispatchers should be *modular*, allowing users to redefine either the implementation of the client methods, target methods, or of the dispatcher independently without requiring recompilation. The framework should be sufficiently *flexible* to allow the user to modify the semantics of the standard dispatchers bundled with the tool. This paper presents the following main contributions.

- The idea of a modular approach to dispatching, enabling a greater flexibility in the choice of the dispatching mechanisms.
- The design and implementation of the PolyD dispatching framework, which allows new dispatchers to be defined and used in the standard Java execution environment with minimal effort.
- A multi-method dispatcher for Java that has good performance and scales better than other tools when increasing the number of methods involved. An original handling of `null` values is also described.
- A tool that can be used as a teaching aid to show how different dispatching mechanisms cause the same code to behave differently.
- Examples of applications for which PolyD is useful.
- A performance evaluation of PolyD , comparing it against other tools.

DOI: 10.1002/spe

2. MOTIVATING EXAMPLE

To see a practical example of the impact of the dispatching strategy on the code organization, consider the following, concrete example. The Ovm project, developed at Purdue University, is an open source framework for building language runtimes that includes an ahead-of-time compiler and tools for manipulating bytecode [13]. Ovm transforms incoming bytecode to an intermediate representation called OvmIR that is the common input of all execution modes (interpret/compile). We will first give some background on the issues involved in writing bytecode (or OvmIR) manipulation tools, then we discuss issues specific to dispatching.

2.1. A bytecode manipulation framework

In Ovm each intermediate representation instruction corresponds to a subclass of the `Instruction` class. Analyses written for the framework use the flyweight pattern [14] to avoid the need for multiple instances of the same instruction class. An `InstructionBuffer` class maintains the current program counter and interprets constants referenced from the bytecode stream. This technique allows instruction objects to retrieve and interpret their immediate operands without any state of their own. For example, the concrete instruction `GETFIELD` subclasses the abstract class `FieldAccess`. `FieldAccess` provides a method `getSelector()` to return information about the name and type of the field being accessed. The state required by the method is encapsulated in the instruction buffer argument. This design follows the Flyweight pattern, allowing the `InstructionSet` class to hold a single instance of each concrete instruction.

Each instruction implements the methods `size()` (to return its size in bytes), and `getOpcode()`. Further behavior is added by appropriate subclasses. Thus, manipulations of the OvmIR can rely on the type checker to prevent some errors, for instance trying to use a constant pool index as a jump target. The core of the instruction hierarchy used within Ovm is shown in Figure 1. Such hierarchy reflects properties of the Java bytecode instruction set and is based on pragmatic considerations, not on any systematic analysis of features of all conceivable instructions of stack machines.

It turns out to be very inconvenient to model all of the features of bytecode using single inheritance. For example, `FlowChange` is an interface which is implemented by the concrete instruction `RET` (return) that inherits from `LocalAccess`. Another example is the `Throwing` interface that is implemented by all instructions that can throw exceptions.

2.2. Dispatching over instructions

The software architecture of Ovm has evolved over time. Originally, the instruction objects used dedicated methods to perform bytecode manipulation. The use of dedicated methods had the disadvantage that every additional analysis or processing step required changes to each instruction class. Thus, each of the instructions was extended with an `accept()` method and various analyses were written as visitors operating on the instructions.

In order to make code factoring easier, the instructions were arranged in the hierarchy of Figure 1 to factor out commonalities between the instructions. The visitors that implement the various analyses are able to take advantage of the instruction hierarchy; the visit methods can be refactored using the hierarchical visitor pattern [15]. For example, our access modifier inference tool does not need to

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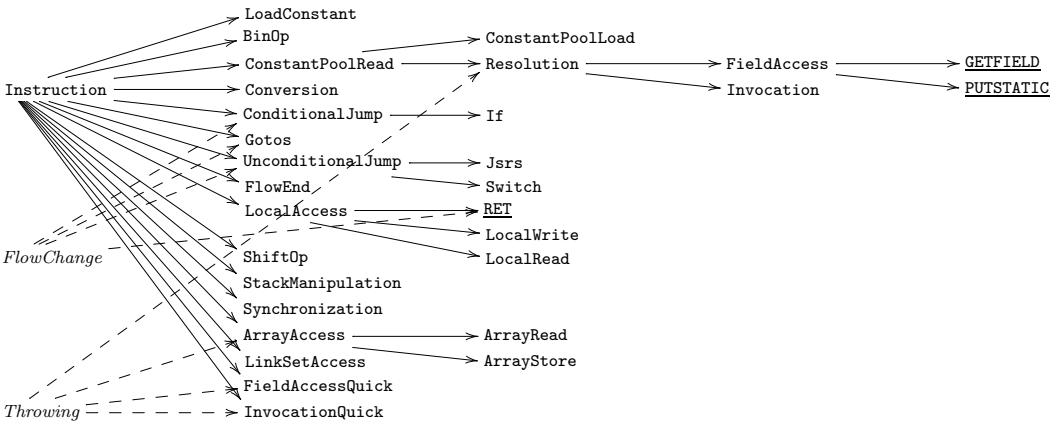

Figure 1. The instruction hierarchy. OvmIR consists of 237 concrete instructions (`RET`, `GETFIELD`, and `PUTSTATIC` are the only ones shown). Italics indicate interfaces, all others are abstract classes (some parts omitted for clarity).

distinguish between Java's four field access operations (`GETFIELD`, `PUTFIELD`, `GETSTATIC`, and `PUTSTATIC`). Using the hierarchical visitor pattern, we only need to implement a visit method for the abstract `FieldAccess` instruction class. In order to make the hierarchical visitor pattern work, a helper method that redirects calls from `visit(PUTSTATIC i)` to `visit(FieldAccess i)` is required. For an instruction, such as `GETFIELD`, the parent class of all hierarchical visitors would have the following method:

```
void visit(GETFIELD i) {
   visit((FieldAccess) i);
}
```

The sole purpose of this method is to redispatch calls that are not implemented by the specific visitor to the parent type. This is a useful technique, as it allows us to factor out implementations applicable to a group of instructions. Writing this indirection code, while conceptually trivial, turns out to be cumbersome. Each time the instruction hierarchy evolves, the base-classes of the visitors need to be rewritten. With over 200 instruction classes it is difficult to track changes in the hierarchy. The use of the visitor pattern requires that every analysis supplies visit methods for *all* instructions. Thus, every change in the hierarchy of the instruction set requires updates to several visitors.

The problem was solved by replacing the use of visitors with the Walkabout pattern [16]. The Walkabout declares visit methods just like visitors, but instead of performing double-dispatch with `accept()` methods in the instruction objects, the appropriate visit methods are found by reflection. In Ovm, hundreds of `accept()` methods were removed from the instruction objects and hundreds of `visit()` methods that were either abstract (visitor interface), empty (default base class), or indirecting to other visit methods (hierarchical visitor) became obsolete. The plain Walkabout was

DOI: 10.1002/spe

subsequently replaced with the Runabout [12], an alternate implementation of the same pattern that relies on dynamic bytecode generation in order to achieve higher performance.

2.3. The meaning of 'most appropriate'

While the Runabout considerably simplified the structure of Ovm a number of more subtle issues arose, originated by the algorithm chosen to select a suitable visit method in the various circumstances. Consider the following example, taken from the Ovm code that adds write barriers:

```
void visit(PUTFIELD i) {...
 if (...)
  ...replaceInstruction().
        addPUTFIELD_WITH_BARRIER_REF();
}
void visit(PUTFIELD_WITH_BARRIER_REF i) { }
```

The code replaces, when appropriate, some occurrences of the `PUTFIELD` bytecode. However, some empty visit methods are necessary in order to restrict the manipulation to instances of `PUTFIELD`, while excluding instance of its subclass `PUTFIELD_WITH_BARRIER_REF`. While the hierarchy used makes sense in many other parts of the code, in this particular case we would rather have the opportunity to use a 'non-subsumptive' visitor, in order to make the code clearer and more maintainable, even if the hierarchy changes and new subclasses are added. The 'most appropriate' method for the developer, in this case, would not be the one selected by the Runabout.

Other problems related to the method selection arise because of the complex hierarchy, which includes subclasses and subinterfaces, used to organize the set of instructions. The Runabout arbitrarily gives preference to `visit` methods encountered following the chain of superclasses over `visit` methods found through superinterfaces. Such a resolution algorithm caused several headaches during the development of Ovm, since it is difficult to track exactly which visit method will be called in all circumstances.

Even more tricky is the question of visitor-style dispatching when inheritance is used to organize visitors themselves. Consider the following example, taken from an Ovm bug report:

```
class C { }
class D extends C { }
class BR extends VisitorTool {
 void visit(D _) { }
}
class DR extends BR {
 void visit(C _) { }
}
```

What is the semantics that should be applied if a message `visit(new D())` is sent to an instance of `DR`? The role of the visitor tool is to discover the dynamic type of the parameter, and to invoke the 'most appropriate' method, but there are actually various choices, of which the tool selects just one.

DOI: 10.1002/spe

For instance, the developer might design the various subclasses as successive refinements that together describe the visitor. In that case `visit(D)` in `BR` should be applied, being the most specific according to the argument type. On the other hand, the developer might regard every new subclass as an entirely new layer of implementation; in that case the `visit(C)` in `DR` should be preferred, as it is able to deal with a `new D()` and is more appropriate in the sense that it is defined in a more specific subclass. Some developers might be interested in distinguishing between the two cases according to the static type of the argument, or other factors.

In other words, developers require a degree of flexibility in the selection of the 'most appropriate' method that is not granted by current tools. The lack of flexibility in the choice of the dispatching policy impacts adversely on the usability of the tool, on the ability of developers to give the desired structure to their code, and ultimately on code maintainability.

3. TOWARDS A MODULAR APPROACH TO DISPATCHING

The lack of flexibility in the existing tools is what prompted our research for a more versatile solution, and the subsequent development of PolyD. Rather than developing multiple tools, each suitable for individual situations, we explore how different approaches can be integrated within a single framework, and how the dispatching mechanism can be modularized in order to achieve the necessary degree of flexibility. We argue that such an approach is not limited to our current implementation, but it is in fact a general technique, applicable to object-oriented languages, that offers more powerful dispatching features to programmers.

3.1. Modular dispatching mechanisms: a general approach

Having multiple, but independent, dispatching mechanisms has the potential to be inefficient in many ways. First of all, if different calling formats or conventions are used it becomes difficult to replace one dispatching strategy with another at a later stage. Second, every dispatcher is implemented from scratch, despite the fact that parts of their inner workings are likely to be similar. Finally, the programmer has no direct way to customize relevant aspects of the dispatching process.

In order to make the dispatching procedure more general and efficient, we will instead use a modular approach, so that individual components can be replaced and customized. By abstracting and separating common elements, it becomes easier to add custom dispatching mechanisms, to alter their operation, to replace them in a modular fashion, and to obtain new functionalities operating directly at the dispatching level. By provide the scaffolding and let the users 'fill in the blanks', the ease of use for users is improved.

We will use the term 'dispatcher' to refer to any component that implements a specific dispatching mechanism, be it a part of the built-in language runtime or an additional API. In order to describe our modular approach to dispatching, we will progress in stages by decomposing dispatchers into their basic components. As a note on terminology, we will talk about the 'class' of arguments, even though 'type' would be more appropriate since some arguments could be primitive values rather than objects. Such a usage reflects the terminology used in the reflective API of Java, in which even primitives have a `Class` descriptor.

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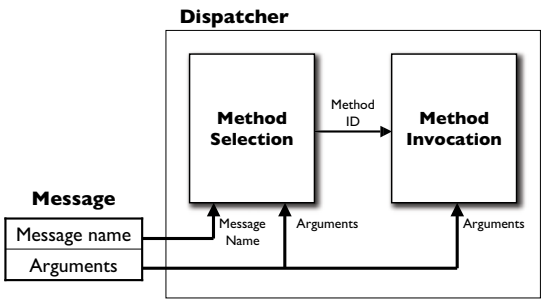

Figure 2. Basic structure of a dispatcher.

3.1.1. Selection and invocation

Let us consider the structure of a generic dispatcher. The fundamental steps that every dispatcher, regardless of its exact operation, needs to perform at runtime are the selection of one of the available methods, according to the supplied arguments, and the invocation of the method selected. Figure 2 reflects this first subdivision in the internal structure, and the flow of data at runtime during message dispatching.

In the most general case the dynamic selection of a method can potentially use not just the class to which the arguments belong, but their values as well. For instance, one of the message arguments could contain an index used to select from a set of available methods. Considering the abstract structure of dispatchers, we can make no assumptions about the specific method selection strategy in use. Conceivably, the choice of the method could depend on external factors or on the execution history. Different methods could be selected for successive identical messages with identical arguments. The selection could even be completely random.

3.1.2. Modularizing the selection module

While, in general, it is not possible to anticipate the way in which the selection module will choose one of the available methods, the dynamic dispatching strategies that are normally used in programming languages rely solely on the classes of the arguments, and always select the same method given the set of available methods and the list of argument classes. Such a deterministic behavior, together with the computational cost of finding the most appropriate methods, leads naturally to a further modularization in the dispatcher structure, reflecting the introduction of a caching mechanism and a further confinement of the method selection policy.

The method selection module can be divided into two separate parts. The ‘dispatching policy’ component will contain the core logic of the method choice, while a ‘selection interface’ component will deal with the implementation aspects, including caching. The general structure of a dispatcher assumes therefore the form shown in Figure 3, while the detailed internal structure of the caching method selection module is shown in Figure 4.

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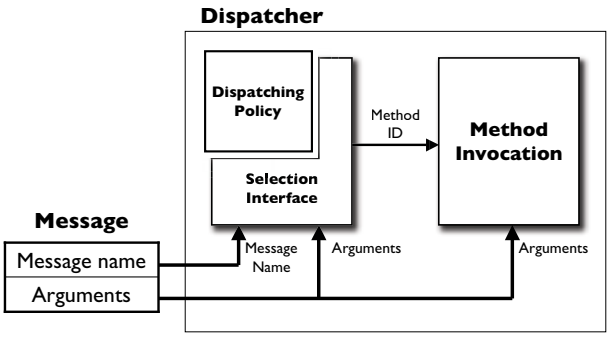

Figure 3. Separating policy from caching and invocation.

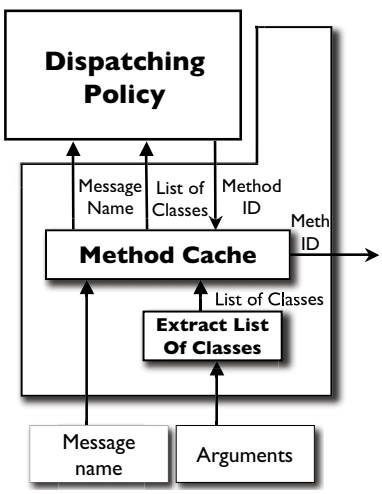

Figure 4. Caching the method selection.

An aspect worth emphasizing is that, by concentrating on the efficient implementation of the cache and the method invocation, all the dispatcher implemented according to this structure will share a high dispatching efficiency after the initial warm-up stage. Subtle implementation details such as cache synchronization issues, present in multithreaded code, are also removed from the core dispatching logic and can be dealt with just once for the whole system. The mechanism enables developers to add new dispatching policies without putting an excessive emphasis on the optimization of their code, while focusing instead on other aspects such as correctness and code maintainability. The range of dispatchers made available by PolyD all share a high dispatching efficiency owing to the use of the modular approach described here.

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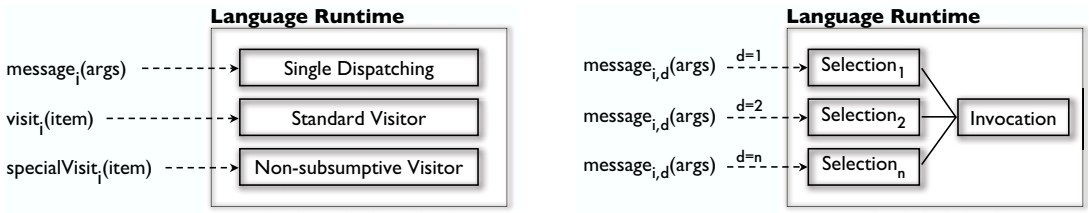

Figure 5. Dispatching mechanisms: (a) separate dispatching subsystems; (b) a more homogenous structure.

3.2. Composing dispatchers

Having introduced a first modular structure for dispatchers, we can consider how different modules can co-exist, and the effects on the code that uses the resulting dispatchers. To avoid ambiguities in the terminology, we will talk about 'composing dispatchers' referring to the process of assembling a dispatcher on a conceptual level, by combining the modules that implement the features of interest. We will talk instead about 'constructing dispatchers' or 'building dispatchers', later in the text, referring to the actual production of the dynamically generated bytecode that implements the desired dispatcher from the specification. The process is detailed in Section 6.

The separation between method selection and method invocation suggests a first approach to the modular composition of dispatchers. In the simplest case, the invocation consists of little more than jumping to the method code, but it might also involve code loading or other operations. One implementation of the invocation module can be shared among multiple dispatchers. If that invocation module is modified or optimized, all of the dispatchers will benefit from the new implementation. As a first step, we can replace distinct dispatchers, shown in Figure 5(a), with the structure shown in Figure 5(b).

A single call format. In order to make the use of different dispatchers more symmetrical, different call formats are replaced by a single format, in which the chosen dispatching mechanism is involved in the message sending operation, potentially as a runtime argument. By using a single and consistent mechanism for using the different dispatchers in the client code, it becomes possible to replace dispatchers during development, or even dynamically at runtime. This can be of interest considering that, in the same way in which classes can be loaded dynamically, new dispatching policies suitable for specific class hierarchies can be loaded dynamically as well. The new dispatchers can then be used without any need for client code recompilation.

In a sense, moving from a fixed dispatcher for each call to a parametric call site, in which the dispatcher is a dynamic factor, is similar to the gain in flexibility obtained by moving from strict overloading to true dynamic dispatching: we gain the ability to decide dynamically not just that we want the 'most appropriate' method for those arguments, but also what 'most appropriate' means at that moment.

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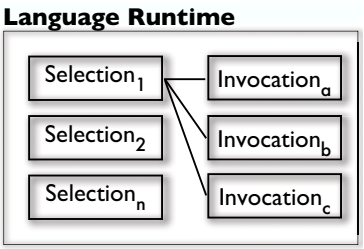

Figure 6. Modular composition of dispatchers.

Having the ability to observe the behavior of the same code using different dispatchers is also interesting from an educational point of view. Except for simple examples, determining the effects that overloading, or multiple dispatching, or different techniques have on more complex programs is not trivial. As we shall see later, PolyD allows students to actually run the same code using different mechanisms, and to compare critically the results.

Multiple invocation policies. While the basic invocation module only needs to call the selected method, there is no reason why multiple invocation policies should not be implemented. For instance, one invocation policy could keep track of the methods calls in order to profile the program, a different one could log all the arguments and the return values for debugging purposes, and yet another one could transparently apply security checks.

By creating custom invocation policies, or adapting existing ones, new features can be introduced at the level of the method call without having to deal with the complexity of the rest of the dispatcher. Having the ability to alter the invocation stage, in other words, allows the programmer to address cross-cutting concerns that are typical of aspect-oriented programming, without requiring a static code weaving. The new situation is reflected in Figure 6.

3.3. Method selection

An aspect that was not immediately obvious in Figure 4 is the determination of the set of available methods from which the dispatching policy draws the most appropriate element. The dynamic content of the message arguments is only part of the information used by a dispatcher to locate the correct method. The information available statically at each call site, namely the 'static class' that each argument appears to have at that point in the code, also plays a factor. In the case of pure overloading, for instance, the static information is the only information used to perform the selection. The diagram in Figure 7 shows the two-stage selection process commonly used in object-oriented languages.

We can reorganize the selection process shown in Figure 7 as displayed in Figure 8. The specific selection algorithms are encapsulated in the dispatching policy component, while the remaining implementation aspects, including obtaining information for the call site and storing the statically preselected set, are demanded to a common framework. This code organization is well reflected by the simple Dispatching Policy API of PolyD, described later in Section 4.13. Further details on the static preselection mechanism are available in Section 4.13.1.

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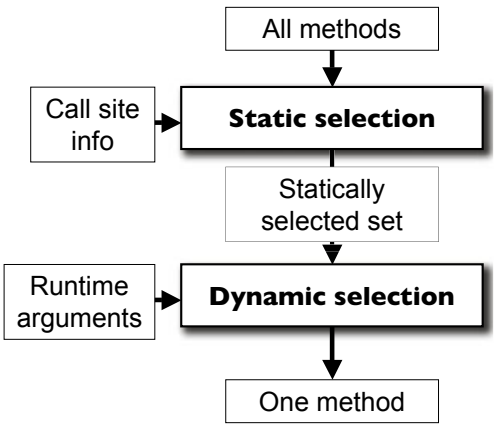

Figure 7. Static and dynamic method selection.

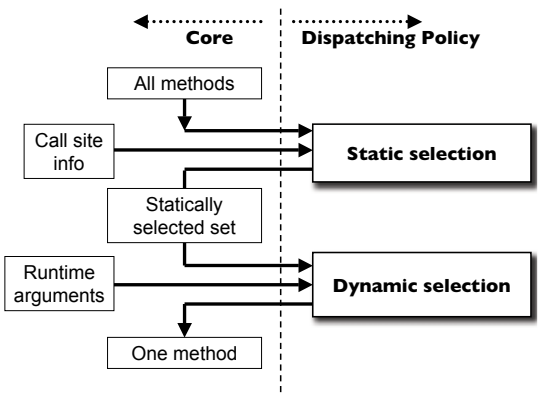

Figure 8. Separating selection from implementation.

3.4. More open choices

The dispatchers built into programming languages rely on a series of design choices, which cannot be altered by the programmer. We allow the programmer to customize some of those choices, allowing a greater degree of flexibility. Among the most obvious choices are the handling of inheritance (whether to allow multiple code inheritance, for instance), and the treatment of ambiguities. Regarding the latter, ambiguities can be rejected, or precedence lists can be used to resolve them (as in the case of CLOS/C++).

DOI: 10.1002/spe

There are also other, possibly less obvious facets of the dispatching process that are also usually fixed. However, there is no intrinsic reason to deny to developers the ability to alter those aspects in the way that they see fit. We will now discuss briefly two notable aspects, and in Section 4 we will show how they can be controlled in our framework, PolyD.

3.4.1. Null arguments

One area in which the design of the dispatching mechanism involves elements of arbitrary choice is the handling of `null` arguments. In the standard Java language, `null` belongs to a special nameless type (there is no associated keyword). While it is not possible to associate `null` with any class, `null` is always a legal argument when an object is expected, so the dispatcher must be ready to deal with that special case. Since there is no runtime class to base a method selection on, the implementation can adopt different strategies.

A possible choice is considering all `null` argument invalid, causing the dispatching code to fail, for instance throwing an exception. That behavior is similar to the way in which Java natively operates while dispatching on a single receiver. The rationale is that it is not legal to send a message to `null` since the value does not represent a valid object. In the case of multimethods, however, the position is less tenable. If all arguments to all calls are involved while performing the dispatching, `null` values would be disallowed as arguments altogether, which is an unreasonable restriction.

A different approach, with several sub-cases, consists in specifying a way to obtain a default behavior if one or more of the arguments are `null`. One possible choice is to select the method with the most specific applicable combination of classes (if unique). This strategy, used by Java when resolving overloading, is linked to the idea that the null type is a subtype of every other type in the system. For example, consider the classes `A`, `B`, `C`, and `D`, with `D` subclass of `C`, `C` of `B`, and `B` of `A`, and the following definitions:

```
static void alpha(A x) { result("A"); }
static void alpha(B x) { result("B"); }
static void alpha(D x) { result("D"); }

alpha(null);
--> Result is "D"
```

The most specific method, according to the resolution mechanisms used by Java, was chosen. Let us suppose that class `D2` is also a subclass of `C`, adding another method:

```
static void alpha(D2 x) { result("D2"); }

alpha(null);
Over.java:10: reference to alpha is ambiguous, both
method alpha(D) in Over and method alpha(D2) in Over
match
 alpha(null);
 ^1 error
```


DOI: 10.1002/spe

In this case the compiler is unable to find a single most specific method, and compilation aborts. That only happens when Java statically knows that the argument is `null`. While conceptually correct, this strategy is not always the best choice on a practical level. In Java `null` is not a real object, and it is not possible to write methods that accept specifically `null` arguments. The presence of `null` indicates instead a special situation that should be handled appropriately, and a different strategy might be desirable. One option is specifying a particular default method that should be used. An alternative is looking for the most general method applicable for a certain combination of classes. Other strategies can also be devised, depending on the specific circumstances.

3.4.2. Missing methods

Some dispatching policies cannot determine statically whether a message will always find a valid matching method. For example, a 'non-subsumptive' dispatcher must examine the exact dynamic type of the arguments to determine whether any method can be applied. Similarly, other strategies may need a special way to handle messages with no matching methods. There are various possible alternatives: ignoring the message, throwing an exception, or taking some user-defined action. The exact definition of the handler is an additional customizable element in the definition of a dispatcher.

We have until now discussed the ways in which dispatchers can be made more modular and customizable. These ideas should now be put into practice by creating a concrete modular dispatching infrastructure. The next section describes the implementation and the features of PolyD, our flexible dispatching framework.

4. PolyD

PolyD is a pure Java tool that, using dynamic bytecode generation, allows the user to define customized dispatching policies, altering many aspects of message dispatching that are usually predetermined and that cannot be easily changed.

In other words, by using PolyD it is possible to define a set of methods and invoke them according to user-defined criteria. For example, PolyD can be used to implement a visitor-like mechanism, or general multiple dispatching, or more unusual dispatching policies. PolyD makes it possible to personalize many aspects of the dispatching process: the handling of null arguments, of missing methods, of ambiguities, of the method invocation, and so on.

As an added advantage, PolyD only uses standard Java, and does not require special syntax, special bytecode, preprocessors, or custom VMs. The performance of the tool is well-suited to real-life applications: for unary methods (methods with a single argument) PolyD has performance similar, or even better, than the Runabout [12] and the Sprintabout [17]; for other arities we find that PolyD scales better than MultiJava [8] and JMMF [4] (more details on these tools are available in Section 8).

Let us start with an introductory example.

4.1. QuickStart

Let us assume that we want to describe the effect of a `Person` dancing in a given `Place`. Using PolyD we shall define a suitable dispatcher that selects the appropriate method. In this example

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we will use multiple dispatching, although different policies could be used. Java 1.5 annotations are used to denote PolyD specifications, called 'tags' in the text.

PolyD cleanly separates the interface that specifies the messages from the implementing methods. This is the interface definition:

```
@PolyD
@DispatchingPolicy (MultiDisp.class)
interface Dance {
  void dance(Person p,Place q);
}
```

The `@PolyD` tag is used as a marker to introduce a PolyD interface. The `@DispatchingPolicy` tag informs the framework that all specified methods will use that dispatching policy. We can now write the implementing methods:

```
class Impl {
 void dance(Dancer p, Stage q) {
  printComment("Dance is an expression of art!");
 }
 void dance(Person p, Stage q) {
 printComment("What is that guy doing on the stage?");
 }
 void dance(Person p, Place q) {
 printComment("That person is dancing. Strange.");
 }
}
```

The methods describe three possible responses to various combinations of arguments. The dispatcher can now be used:

```
Person joe     = new Person();
Place  office  = new Place();
Person nureyev = new Dancer();
Place  bolshoi = new Stage();

Dance d = PolyD.build(Dance.class,new Impl());

d.dance(joe,bolshoi);
d.dance(nureyev,bolshoi);
d.dance(nureyev,office);


> What is that guy doing on the stage?
> Dance is an expression of art!
> That person is dancing. Strange.
```


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Note that in all three cases the arguments to `dance()` are statically a `Person` and a `Place`, but nothing more specific. However, since multiple dispatching is used in this example, dynamically the most appropriate methods are chosen. We could try, in contrast, to use overloading in the same example:

```
@PolyD
@DispatchingPolicy (Overloading.class)
interface Dance2 extends Dance {}
Dance d = PolyD.build(Dance2.class,new Impl());
```

The result is now

```
> That person is dancing. Strange.
> That person is dancing. Strange.
> That person is dancing. Strange.
```

The same client code can be used with both dispatchers, obtaining a different behavior according to the different policy.

4.2. More features

PolyD imposes no restrictions about the number of arguments, the type of the return value, or the use of primitive types in methods and prototypes. The interfaces can define any number of prototypes, each using different dispatchers. Multiple bodies can be specified with a single interface, enhancing the opportunities for code reuse and suggesting a 'mixin-like' approach:

```
Dance d = PolyD.build(Dance.class,body1,body2,body3);
```

All of the methods available in the various bodies will be combined to satisfy the prototypes declared in the interface. It is also possible to share one body among multiple dispatchers, and to call the same group of methods using different names.

The standard dispatching policies available are multiple dispatching, overloading, and a 'non-subsumptive' policy that only calls a method if the classes of the arguments match exactly those of the method parameters. The policy that implements multiple dispatching policy also offers a form of symmetric multiple inheritance, treating equally interfaces and classes (MultiJava, in contrast, only deals with subclasses; this restriction, however, is used to facilitate modular typechecking [18]). It is possible to define personalized dispatching policies using a simple API, described later. Similarly, it is possible to define custom invocation policies, which define the operations that should be performed when a method is called. For instance the policy can log all method calls, or inspect the arguments on-the-fly for debugging purposes or security checks, or gather statistics.

It is possible to specify exactly what should happen if null arguments are encountered (an aspect that is rarely customizable in programming languages), restrict the interpretation of the dynamic class of arguments in order to implement variations on the 'super' concept, and define custom handlers for messages that cannot be satisfied by any methods according to the dispatching policy in use. A Runabout emulation layer is also included, which allows existing programs that use that tool to take advantage of the new features without sacrificing compatibility. Figure 9 shows a more complex example of a PolyD interface. All of the features shown in that example are explained in detail in the following sections.

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```
@PolyD
@DispatchingPolicy(MultiDisp.class)
@InvocationPolicy(DebuggingInvocation.class)
public interface Dance {
  Person test(long i,@IfNull(Place.class) Place p);

  @Preload({
   @Seq({Person.class,Office.class}),
   @Seq({Worker.class,Workplace.class})
  })
  void dance(Person p,Place q);

  int four(String a,char c,Object o,Place p);

  @Name("dance")
  @DispatchingPolicy(NonSubsump.class)
  @OnMissing(Missing.IGNORE)
  void nonSubsumpDance(Person a,Place b);

  @Name("dance")
  void danceSuper(@As(Person.class) Person a,Place b);

  @Name("visit")
  void visitAsPlace(@As(Place.class) Place p);
}
```

Figure 9. A more complex PolyD interface.

4.3. Building a dispatcher

The construction of a dispatcher takes place using `PolyD.build()`. As previously mentioned, it is possible to use multiple bodies for every interface, as follows:

```
Interf d=PolyD.build(Interf.class,a,b,c);
```

where `a`, `b`, and `c` are instances of three different classes. The methods of all those classes are combined to build the final dispatcher. Only the methods specified in the interface are used to build the dispatcher; other methods in the bodies are treated as support methods. The classes used for the bodies are not required to implement the interface.

A method specified in the interface, with a certain name and arity, causes all public methods with same name and arity to be included in the custom dispatcher. Multiple methods with same name and arity can be specified in the interface. For instance:

```
@PolyD
@DispatchingPolicy (MultiDisp.class)
interface Several {
  void test(A a, X x);
```


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```
  void test(X x, B b);
}
```

The method `test()` will be usable on arguments that respect the shown combinations, but not others. The methods used in the interface can be of arbitrary arity, and use and return any values, including primitives.

4.4. `@DispatchingPolicy`

The tag `@DispatchingPolicy` is mandatory, and specifies the way in which one method is selected when the dispatcher is used. The tag can be added to the interface or to individual prototypes. The tag on individual prototypes overrides the specification for the whole interface. If all prototypes are individually tagged, the tag on the interface is optional. Methods with the same name can be resolved, if desired, in different ways. For example:

```
@PolyD
interface Several {
  @DispatchingPolicy(Overloading.class)
   void test(A a);
  @DispatchingPolicy(MultiDisp.class)
   void test(C b);
}
```

If `C` and `A` are not related, the behavior is obvious. If, just to make a convoluted example, `C` is a subclass of `A`, the policy in use depends on which of the two prototypes is chosen by Java, according to its own overloading mechanism. If the argument is statically known to be at least a `C`, multiple dispatching will be used, otherwise overloading is used instead. The standard dispatching policies available are listed in the following subsections. Section 4.13 explains how to create custom policies.

`ovm.polyd.policy.MultiDisp`. The policy implements a fully symmetric multiple dispatching, considering inheritance through subclasses and subinterfaces as equivalent. Consequently, the policy also implements a form of multiple inheritance simply by specifying different methods that accept instances of different classes or interfaces that have a common descendant.

If a dispatcher contains a method which uses this policy, and the call `PolyD.build()` is completed successfully, all subsequent method invocations will always find a matching method. In other words, there will never be a `MissingMethodException`. The policy is also able to detect most ambiguities at dispatcher building time, although some might be undetectable at this stage because of Java's dynamic loading. For example, a class and an interface that appear unrelated might acquire a common descendant at any point in time, generating a late ambiguity. The conflict, however, can be discovered during the first dispatching that involves the new class; an exception will be thrown. If the list of combinations of arguments that are to be used with a certain method is known in advance, then all ambiguities can be detected at dispatcher building time (see Section 4.11). While our default implementation of multidispatching makes sure that only a single method will ever be eligible for a certain combination of arguments, other policies can be easily created to use instead of precedence lists or any other resolution technique.

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ovm.polyd.policy. Overloading. The policy mimics the usual static resolution adopted by Java on the list of arguments. All ambiguities are detected statically (partly by Java itself) and, if the call `PolyD.build()` completes successfully, no `MissingMethodException` will ever be thrown.

ovm.polyd.policy. NonSubsump. The resolution rule used by the `NonSubsump` policy uses the method implementation whose list of parameter classes matches *exactly* the list of classes of supplied arguments. So, if we have a method defined on '`FieldAccess`', for example, the method will be called on instances of `FieldAccess` but not on instances of its subclasses. If a call is made and the policy cannot find an implementation that matches exactly, the call is ignored. Such behavior can be altered if desired, as explained in the following sections.

ovm.polyd. MissingMethodException. Some dispatching policies might be unable to establish at dispatcher building time that all subsequent method calls will be successful. If a dispatching policy is unable to find a suitable method for a given combination of arguments, a `MissingMethodException` is thrown by default, although every policy can define a custom response.

4.5. `@OnMissing`

The tag `@OnMissing` is used to describe the preferred handling of those messages that have no matching method according to the policy in use. If a tag is specified for the whole interface, and a different one is specified for a single prototype, the local one overrides the global selection. The options accepted are as follows.

ovm.polyd.Const.Missing. STANDARD. The handling of the error situation is demanded to the `onMissing()` method contained in the selected dispatching policy. It is possible to customize this aspect by creating a subclass of the desired policy and overriding `onMissing()`. This option is the default.

ovm.polyd.Const.Missing. IGNORE. When a message does not match any method, the call is ignored. If the method is supposed to return a value of some sort, a dummy result is returned instead (zero, or null, or false).

ovm.polyd.Const.Missing. WARN. As above, but a warning message is additionally printed on the standard error stream.

ovm.polyd.Const.Missing. FAIL. The request for a message that does not match any available method (according to the selected dispatching policy) causes an exception `MissingMethodException` to be thrown.

ovm.polyd.Const.Missing. ABORT. If a matching method cannot be found, execution aborts.

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4.6. `@InvocationPolicy`

In PolyD it is possible to specify additional actions that should be executed when a method is called. A special invocation policy can be attached to the whole interface or to individual prototypes. If no invocation policy is specified, the method is simply called; this is the default policy and also the faster mechanism. The use of a custom invocation policy imposes some overhead during dispatching.

`ovm.polyd.policy. PlainInvocation.` Only supplied as an example, the `PlainInvocation` policy performs a simple invocation and returns the result supplied by the called method. This policy can be used as a template to create customized invocation policies.

`ovm.polyd.policy. DebuggingInvocation.` By adding this invocation policy to any interface or prototype, all method calls will be logged to the standard output stream, together with their arguments and their return values.

4.7. `@IfNull`

The value `null` has no class associated to it, and it is not possible to extract the list of classes of the arguments necessary to determine which method is the more appropriate one according to the given policy. When one or more arguments can be `null`, PolyD offers different ways to specify the default behavior. The tag `@IfNull` can be added to an argument of a prototype in order to specify the class that should be used when that argument is `null`. For example,

```
void test(long i,@IfNull(Place.class)Place p);
```

The class used in the `@IfNull` must be equal or an arbitrary subclass of the corresponding argument. Independent `@IfNull` tags can be added to the various parameters. The use of this construct adds just a marginal overhead to the dispatching cost, and it is the most convenient solution when good efficiency is desired. If a more general mechanism is desired instead, it is possible to use the `remapNull()` facility, described at the end of Subsection 4.13.1.

4.8. `@As`

In PolyD it is possible to override the dynamic interpretation of the class of arguments using the `@As` tag. For example:

```
void dance(@As(Person.class) Person a,Place b);
```

The class specified by the tag can be identical to any superclass of the class of the parameter, as long as compatible methods are present in the supplied bodies. When the dispatching policy receives the list of dynamic types of the arguments, while dispatching a message, the types of the argument marked with `@As` will be replaced with the classes indicated. The main application of the `@As` tag is the implementation of a generalized form of 'super', which can also be applied in cases of multiple inheritance or multiple dispatching. In that sense, specifying an `@As` class is similar to the qualified super form available in C++. In PolyD, however, the class can be any ancestor of the class of the

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parameter, and not necessarily a direct superclass. Multiple `@As` tags can be specified for the different parameters. While this construct is sufficient to replicate the functionality of 'super' for individual prototypes, it might be more practical to define a more general 'super' mechanism. That can be achieved by defining a custom dispatching policy that selects, depending on the context, the correct method.

4.9. `@Name`

It can be useful to bind together prototypes and methods even if their names differ. That can be obtained by using the `@Name` tag, as in the following example:

```
interface W {
  void msg(A a,B b);
  ...
  @Name("msg")
  @DispatchingPolicy(OtherPolicy.class)
  void other(A a,B b);
}
```

The two prototypes `msg()` and `other()` will both use the same implementation methods, but use different dispatching policies. The prototype `other()` will use the bodies named `msg`, thanks to the tag `@Name`. In general, the tag `@Name` can be applied to prototypes in the interface as well as to individual methods within the bodies, allowing the user to mix and match interfaces and bodies as needed.

The tag `@Name` is particularly useful in conjunction with the `@As` tag in order to implement forms similar to 'super'. For example,

```
interface W {
  void msg(A a,B b);
  ...
  @Name("msg")
  void msgSuper(A a,@As(A.class)B b);
}
```

The implementations of `msg()` will also be accessible through the name msgSuper(), but in that case the second argument, because of the `@As` tag, will be interpreted as having dynamic type `A`; the dynamic dispatching will be performed accordingly.

4.10. `@Self`

Because bodies and prototypes can be mixed and matched while building prototypes, each body has, in itself, no knowledge of the characteristics of the dispatcher it belongs to. Indeed, it might belong to more than one at once. `@Self` variables retrieve this information: at dispatcher build time each variable marked with `@Self` is initialized to the dispatcher just built, if the type of the variable corresponds to the interface of that dispatcher.

`@Self` variables allow a method to call another method using the same dispatcher that was used to reach the current method in the first place. For example,

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```
class Body {
  @Self Interf self;

  void m(B x) {
   self.m2(x);
  }
}
```

In the above example, the variable `self` will be automatically initialized when a dispatcher is created using the interface `Interf`, as in

```
PolyD.build(Interf.class,new Body());
```

There can be multiple variables tagged with `@Self`, and they may refer to different interfaces. If a single body is shared among multiple dispatchers (which use distinct interfaces), each variable will be initialized when the dispatcher corresponding to that interface is built. For instance,

```
class Body {
  @Self OverloadingInterface over;
  @Self MultidispInterface multi;

  void m(B x) {
   over.m2(x);
   multi.m2(x);
  }
}
Body b=new Body();
y=PolyD.build(OverloadingInterface.class,b);
z=PolyD.build(MultidispInterface.class,b);
y.m(...)
```

4.11. `@Preload`

Each dispatching policy is free to decide how much checking should be performed statically (at dispatcher building time) or rather dynamically. For example, the standard policy `MultiDisp` performs an extensive static checking making sure that, if the dispatcher is built successfully, all successive method invocations will always find a matching method. The `MultiDisp` policy also tries to discover as many ambiguities in the method definitions as possible.

Java, however, is founded on dynamic class loading, and that implies that new classes may introduce new ambiguities or conflicts at a later stage according to the rules of each particular dispatching policy. Consequently, some of the checks could require a lazy approach, performed after the main dispatcher construction. Such additional checks are only required for messages involving new classes, and the results are still saved by the caching subsystem, so the overhead is limited. If the classes that will be used to dispatch messages are known in advance, and it is preferable to force an early detection of potential error conditions, the tag `@Preload` can be used to force the same checks in an eager fashion. This is an example of `@Preload` in action:

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```
@Preload({
  @Seq({Person.class,Office.class}),
  @Seq({Worker.class,Workplace.class}),
  @Seq({Dancer.class,Place.class}),
  @Seq({Dancer.class,Office.class})
})
void dance(Person p,Place q);
```

The specified combinations of classes will be checked and preloaded eagerly in the method cache of the dispatcher. Notably, Relaxed MultiJava [19] also performs a lazy checking, and has a preloader tool that works similarly to the mechanism here described.

4.12. `@Raw`

The `@Raw` tag can be used to pass arguments directly from the call site to the method selector. Such arguments will be removed from the argument list prior to the actual method call. Only objects or integers can be used as raw arguments.

Raw arguments can be used, for example, to identify specific call sites, even if the regular method arguments are the same; that information can be used to implement general forms of 'super'. For instance, let us have a class `C` subclass of `B`, and `B` subclass of `A`:

```
interface W {
  void visit(@Raw Class c, @Raw Class d, A a);
}
class X {
 void visit(C a) {
  ...
  next.visit(X.class,C.class,a);
 }
 void visit(A a) {
  ...
  next.visit(X.class,A.class,a);
 }
}
class Y {
 void visit(B a) {
  ...
  next.visit(Y.class,B.class,a);
 }
}
```

In this example, the first two arguments to the visit message identify the specific call site, so that the method selector can decide which one is the appropriate 'next' method to call. The raw arguments are used by the selector and removed, while the third argument is passed on to the following visit method.

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Another possible application of raw arguments is marking the remaining arguments in order to modify their interpretation. For instance, an `enum` class can define multiple states, and each raw specification can modify the following argument:

```
d.message(WHITE,a,RED,b,RED,c,WHITE,d);
```

The raw arguments are separated and passed to the method selection. Once the correct method is selected, taking into account the given argument modifiers, the proper `message(a,b,c,d)` will be called.

4.13. Custom policies

It is possible, in PolyD, to define personalized dispatching and invocation policies. The API is rather simple and the standard policies can be used as templates to develop new ones. This section can be used as a general reference about the main aspects involved.

4.13.1. Dispatching policies

Each dispatching policy defines different aspects of the method selection and dispatching. The following are the main calls involved in the policy definition.

`compatibleSet`. The routine `compatibleSet` performs a static preselection, finding in the supplied set of methods those that can are applicable for a given call site, for this dispatching policy. This routine can also be used to perform a consistency check on the set of supplied methods, discovering duplicate methods, violation in covariance rules, ambiguities, conflicts, and so on. If the selection performed by the dispatching policy is entirely dynamic, `compatibleSet` can just return the whole method array given as argument, without performing any preselection. In this case it is not necessary to override, in the user-defined policy, the default implementation.

The list of classes corresponds to the classes that can be determined statically for a given call site. However, such a list is not necessarily the actual list of specific static types of the arguments, but it depends on what Java can discriminate according to the list of prototypes in the interface used to build the dispatcher. An example is required to make this aspect clear. Let us assume that we have a class `A`, its subclass `B`, and a subclass of the latter `C`:

```
interface I {
 void m(A,B);
 void m(B,C);
}
...
 d.m(c,c);
 d.m(b,c);
 d.m(b,b);
 d.m(a,b);
```


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Even if we know statically that `c` is of class `C`, `b` of `B`, and `a` of `A`, the four call sites will only be discriminated according to what Java knows according to the interface. The first two calls will be determined statically to be `(B,C)`, the last two `(A,B)`. It is important to keep this aspect present when implementing a policy that has a component of static resolution. PolyD is constrained in any case to respect the overloading semantics of the Java language.

Summarizing the mechanism: the set of methods that can possibly be invoked through each of the prototype in the interface, according to the usual Java semantics, is calculated when the dispatcher is constructed. This set is then passed to the dispatching policy, which can decide to reduce it according to its own rules, performing a static preselection. For instance, the overloading dispatching policy return a set containing exactly one of those methods. The returned set is then used as the set of candidates among which to perform the dynamic selection, during dispatching.

`bestMatch`. The dynamic counterpart of the previous call is the method `bestMatch`, which determines in the preselected set the one and only method that is more appropriate for the list of classes supplied, representing the actual dynamic classes of the arguments supplied by the message. The function should return the index in the array of methods corresponding to the best match for the given classes. If no suitable method is found, `bestMatch` returns -1.

`handleMissing()`. The default behavior in case a suitable method cannot be found is specified by the method `OnMissing`, defined in each dispatching policy. Such method can be overridden in order to implement the most appropriate handler for the specific case. The routine `handleMissing()` accepts as arguments the list of classes that caused the special handling and the set of applicable methods (which can have various names because of the `@Name` tag).

`disableCaching`. The standard method caching mechanism offered by PolyD is disabled for this policy if this method returns `true`. This enables the definition of policies that select different methods at different times for the same combination of argument classes. It can also be useful for debugging the policy.

4.13.2. `remapNull()`

A general mechanism used to handle `null` arguments is offered by the `remapNull()` routine. When a `null` argument is encountered during dispatching, and no `@IfNull` clause is specified for the corresponding parameter, control is transferred to the `remapNull()` routine associated with the dispatching policy in use. The routine `remapNull()` can be used, for instance, to find the most general method that applies, or the most specific one, or to take whatever action the programmer sees fit. The routine is supplied the unexpected sequence of argument classes, including nulls, and the list of methods that are applicable to that call site. The result, if the remapping is successful, is a new combination of classes, appropriate to the context, that will be used to resume the dispatching process. If no custom behavior is defined, a `NullPointerException` is thrown by default.

4.13.3. Invocation policy

The structure of an invocation policy is rather simple. A single method `invoke()` needs to be defined:

```
public Object invoke(Object obj,Method m,Object[] args)
```


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The method should perform all the additional operations required by this policy and call the supplied method of the given object using the given arguments. If some of the arguments are primitives, they are wrapped and unwrapped following the conventions used by the `invoke()` method of the reflective Java API.

4.14. Compatibility with pre-1.5 Java

By default PolyD uses Java annotations, and generates bytecode compatible with Java 1.5. However, a pre-1.5 version of PolyD is also automatically generated from the main source tree. All of the features described thus far are therefore also available to older Java VMs, using a suitable API. When accessed through this API, PolyD behaves as a general dispatching library that does not require annotations, and that can be used in conjunction with other Java tools and frameworks.

The calls required to use PolyD through this API are slightly more verbose than the ones that use annotations directly, but they are conceptually no more complicated. In the following examples some casts will be omitted for the sake of clarity.

4.14.1. Descriptors

The construction of dispatchers using the pre-1.5 compatible API relies on descriptors, which are used to accumulate the kind of information that PolyD usually obtains exploring the annotations on interfaces and bodies. A new descriptor is created as follows:

```
Descriptor d1=new Descriptor(Interf.class,
      new Class[] {BodyA.class,BodyB.class});
```

This descriptor will be used to construct a dispatcher that uses the interface `Interf` and two bodies of class `BodyA` and `BodyB`. The dispatching policy can be added to the descriptor as follows:

```
d1.setDispatching(MultiDisp.class);
```

Similarly, the interface-wide handler for missing methods and invocations policy are set using calls similar to the following example:

```
d1.setInvocation(DebuggingInvocation.class);
d1.setMissingHandling(Missing.Ignore);
```

The properties of each individual method can be set by extracting reflectively the method reference, and then using the appropriate calls as follows:

```
mt=Dance.class.getMethod("visit",new Class[]{Place.class});
d3.setMethodDispatching(mt,MultiDisp.class);
d3.setMethodName(mt,"lxn");
d3.setMissingHandling(mt,Missing.Ignore);
d3.setMethodPreload(mt2,new Class[][]
   {{String.class,Object.class},{Object.class,Place.class}});
d3.setMethodAsClasses(mt2,new Class[]{Place.class,null});
d3.setMethodNullDefaults(mt3,new Class[]{null,Object.class,null});
```


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The calls are self-explanatory, and mirror the annotations already described. For the calls `setMethodAsClasses()` and `setmethodNullDefaults()`, each position in the array is `null` at the position in which no default is specified. The last property that can be specified is the use of `@Self` variables:

```
f=Body.class.getField("self");
d3.setSelfField(f);
```

Once the descriptor is ready, it is possible to proceed with the creation of the actual dispatcher, using the facilities described in the following sections.

4.14.2. Factories

The more direct way to create a dispatcher is the use of a factory. The creation of factories, and the creation of new dispatchers, is illustrated by the following example:

```
Factory fact=d5.register();
Interf disp1=f1.getDispatcher1(bod1);
Interf disp2=f1.getDispatcher1(bod2);
```

This approach minimizes the time required to build a new dispatcher. If the descriptor was created specifying one body the method `getDispatcher1()` should be used, if two bodies are used then use `getDispatcher2()` and so on up to `getDispatcher4()`. If more than four bodies are used, the method `getDispatcherN()` will accept an array of bodies. It is the responsibility of the programmer to pass to `getDispatcher()` bodies that are compatible with the list of classes used to build the descriptor. If the requirement is not satisfied, the dispatcher creation will fail by throwing an exception `DispatcherCreationException`.

4.14.3. Registered dispatchers

If, owing to the structure of the client, it is not possible or practical to pass around a factory, it is still possible to create dispatchers after the `register()` operation as follows:

```
d5.register();
...
Interf disp1=buildFromDescriptor(Interf.class,bod1);
Interf disp2=buildFromDescriptor(Interf.class,bod2);
```

After a descriptor is registered in the system, the creation of a new dispatcher using `buildFromDescriptor()` will look for the more recently registered descriptor associated with the supplied interface and classes of bodies, and will use the corresponding implementation to build new dispatchers. The mechanism is functionally equivalent to the use of factories, except for the speed penalty involved in looking up into the internal maps to find the correct implementation.

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5. RUNABOUT EMULATION

In order to verify the usability of PolyD as a general tool, we have integrated the framework into existing applications. The first large application was Ovm, the open source framework for building language runtimes developed at Purdue University. The source of the project comprises about 400 000 lines of code (plus libraries), and many of the internal operations of the framework are organized in a visitor-like fashion. The second application we considered was Kacheck/J, an encapsulation checker for Java that analyzes the use of confined types in programs [20]. In order to integrate PolyD in the existing code base, we have developed a Runabout emulation layer exploiting the ability of PolyD to integrate new dispatching strategies into its structure with minimal effort.

The core method resolution strategy of the Runabout was converted into a custom dispatching policy for PolyD, reproducing faithfully the mode of operation of the original tool. The new policy consists of less than 150 lines of code. In order to ease debugging, two new invocation policies were added in order, respectively, to perform a customized logging and to keep a count of all the creations of new dispatchers and the number of times each of them is used. The two new invocation policies had less than 50 and 75 lines of code, respectively. Using these extremely simple modules, the existing dispatching engine of PolyD was very easily converted into a functional replica of the Runabout, while making no modification to the dispatching core. Using this emulation layer, PolyD, was then integrated into the applications that we mentioned earlier. As discussed later in the paper, the resulting performance was comparable to the original and occasionally even demonstrated some gain. The additional features of PolyD (e.g. the custom invocation policies) are made available to the applications without requiring relevant changes to the client code.

6. IMPLEMENTATION

All of the features described in the previous sections are implemented within PolyD by dynamically generating the bytecode corresponding to the classes and methods necessary to obtain the desired combination of dispatching features. Such dynamically generated bytecode is tailored as needed following a general structure designed for high execution speed, making use of a specially designed method cache that contributes to the efficiency of PolyD. The inner workings of the system will now be described in some detail. We will initially describe the overall ideas behind the system, show some examples, illustrate the operation of the dynamically generated bytecode, and finally describe the way in which that bytecode is constructed.

6.1. Assembling and using the dispatcher

The operation of PolyD can be logically divided into two parts, corresponding to the static and dynamic handling of method dispatching in a regular compiler for a statically typed object-oriented language.

The first step, the dispatcher construction, is performed when the `build()` function is invoked. During this stage, all of the initial checks for consistency, the applicable method preselections, and additional verifications are performed right before generating on-the-fly the bytecode that implements that particular dispatcher. The method cache is created and initialized, unless the dispatching policy

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explicitly requests it to be disabled. If preloading information is available, the corresponding cache entries are generated, and possible errors detected. The second way in which PolyD operates is the actual dispatching of a message, performed at runtime. When a message is sent to the dispatcher built in the previous stage, control is assumed by one of the various adapter subroutines contained in the dynamically generated bytecode. Such subroutines, optimized for the policies and features specified for each dispatcher prototype, determine the most appropriate method corresponding to the combinations of arguments encountered, taking care of `null` arguments and special conditions. Once the best method has been determined, that information is saved in the dispatching cache, and the call is made.

6.2. Dispatcher construction

The overall idea of implementing a dispatcher is to create an 'adapter' class interposed between the method call, as performed by Java through the prototypes declared in the dispatcher interface, and the concrete methods contained in the various bodies that compose the dispatcher implementation. The adapter class 'implements', in the Java sense of the word, the interface that we specify for our dispatcher, associating an adapter subroutine with each of the prototypes defined in the dispatcher interface.

Each of the adapter subroutines is optimized as applicable for the specific combination of policies and features associated with the prototype, taking advantage of the information collected at dispatcher construction time. In particular, at build time the dispatching policy will supply the set of implementing methods that are applicable for each prototype; this information can be used to restrict the amount of work that the dispatcher needs to perform at runtime. In certain cases, several prototypes can share the same adapter subroutine. Figure 10 shows an example of an adapter class, generated for one sample dispatcher and decompiled for illustrative purposes by using the Jad Java decompiler [21] (some of the code has been omitted for clarity).

In the example, the dispatcher interface specifies two prototypes, `void dance(Person person, Place place)` and `void visit(Place place)`. The code that performs the dispatching is contained in the class `PolyD$A0`, and the two prototypes are implemented with a method each. The simple implementation of the adapter subroutine for `visit()`, in the first part of Figure 10, shows a minimal example of the code executed when a simple message with one argument is dispatched. When further features are used in the definition of a dispatcher, the generated code becomes accordingly more complicated in order to accommodate all of the various requirements.

6.2.1. Example of an adapter subroutine

Looking at the adapter subroutine for `visit()`, the class of the single argument is initially extracted and converted into a hash code. This is accomplished by converting it into a numeric value with `hashCode()`, and then extracting the lower order bits. The result is then used to perform a lookup into the hash table of the methods already cached. The hash table maps the classes of the arguments to cases within a switch block, each of which corresponds to one implementing method among those statically determined to be applicable for that prototype.

If no value is found in the hash table (the entry in the `quick_map` array is zero), or if the associated key for that entry in the array is not our class (because of a collision in the hash table), the hash table

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```
// An example of the dynamically generated bytecode,
// decompiled using the Jad decompiler. Only a small
// subset of the PolyD features are used in this example.
package ovm.polyd;
// [..imports..]

public final class PolyD$A0
    implements DanceAux1
{
    ComboA instance_ovm_polyd_test14_ComboA_1;
    ComboB instance_ovm_polyd_test14_ComboB_2;
    ComboC instance_ovm_polyd_test14_ComboC_3;
    private static final int quick_map_0[];
    private static final Class keys0_map_0[];
    private static final Class keys1_map_0[];
    private static final MultiHash2 map_0;
    private static final int quick_map_1[];
    private static final Class keys0_map_1[];
    private static final MultiHash1 map_1;

    public final void visit(Place place)
    {
        Class class1;
        int i = (class1 = place.getClass()).hashCode() & 0x7f;
        int j = class1 != keys0_map_1[i] ? map_1.findCode(i, class1) : quick_map_1[i];
        switch(j != 0 ? j : map_1.lookupAndUpdate(i, class1))
        {
        case 0: // '\0'
        default:
            map_1.methGroup.theDispatcher.onMissing(new Class[] {
                class1
            }, map_1.methGroup.bodies);
            return;
        case 1: // '\001'
            instance_ovm_polyd_test14_ComboA_1.visit(place);
            return;
        case 2: // '\002'
            instance_ovm_polyd_test14_ComboA_1.visit((Factory)place);
            return;
        case 3: // '\003'
            ComboB.visit((Park)place);
            return;
        case 4: // '\004'
            ComboB.visit((Disco)place);
            break;
        }
    }

//
```

Figure 10. Decompiled example of adapter class.

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```
    public final void dance(Person person, Place place)
    {
        Class class1;
        Class class2;
        int i = (class1 = ovm/polyd/test14/Person).hashCode() * 37 + (class2 = place.getClass()).hashCode() & 0x7f;
        int j = class1 != keys0_map_0[i] || class2 != keys1_map_0[i] ? map_0.findCode(i, class1, class2) : quick_map_0[i];
        switch(j != 0 ? j : map_0.lookupAndUpdate(i, class1, class2))
        {
        case 0: // '\0'
        default:
            map_0.methGroup.onMissing(new Class[] {
                class1, class2
            });
            return;
        case 1: // '\001'
            instance_ovm_polyd_test14_ComboA_1.dance(person, (Park)place);
            return;
        case 2: // '\002'
            instance_ovm_polyd_test14_ComboA_1.dance(person, (Workplace)place);
            return;
        case 3: // '\003'
            instance_ovm_polyd_test14_ComboA_1.dance((Worker)person, (Park)place);
            return;
        case 4: // '\004'
            instance_ovm_polyd_test14_ComboA_1.dance(person, place);
            return;
        case 5: // '\005'
            instance_ovm_polyd_test14_ComboB_2.dance(person, (Disco)place);
            return;
        case 6: // '\006'
            instance_ovm_polyd_test14_ComboB_2.dance((Worker)person, (Disco)place);
            return;
        case 7: // '\007'
            instance_ovm_polyd_test14_ComboB_2.dance((Worker)person, (Workplace)place);
            break;
        }
    }
    public static final void SPECIAL$$STATIC$$INIT(List list)
    {
        Iterator iterator = list.iterator();
        map_0 = new MultiHash2(quick_map_0 = new int[128], keys0_map_0 = new Class[128], keys1_map_0 = new Class[128],
                               (MethodGroup)iterator.next());
        map_1 = new MultiHash1(quick_map_1 = new int[128], keys0_map_1 = new Class[128], (MethodGroup)iterator.next());
    }
}

// The Factory associated with the code above. This is all the
// code that is executed when building new dispatchers for this dispatcher
// prototype, once the bytecode has been generated and cached.
// In this example the fields aux1 and super1 are marked with @Self.
package ovm.polyd;
import ovm.polyd.test14.ComboA;
import ovm.polyd.test14.ComboB;
import ovm.polyd.test14.ComboC;
public final class Factory$A0 extends Factory
{
    public Object getDispatcher3(Object obj, Object obj1, Object obj2)
    {
        PolyD.A0 a0 = new PolyD.A0();
        a0.instance_ovm_polyd_test14_ComboA_1 = (ComboA)obj;
        a0.instance_ovm_polyd_test14_ComboB_2 = (ComboB)obj1;
        a0.instance_ovm_polyd_test14_ComboC_3 = (ComboC)obj2;
        ((ComboA)obj).super1 = a0;
        ((ComboC)obj2).aux1 = a0;
        return a0;
    }
}
```

Figure 10. Continued.

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collision chain is explored by calling `findCode()`. If no value is found, the slow path is invoked by calling `lookupAndUpdate()`, which will call the dynamic component of the dispatching policy and cache the result.

Once the appropriate index in the switch statement has been determined, the corresponding method is called using as a receiver one of the implementing bodies that were originally supplied to the `build()` function while building the dispatcher, unless the called method happens to be static. In this example a simple call is made; however, if a special invocation policy is requested, the appropriate additional code is generated to perform the call. If no suitable method can be found by the dispatcher, the `onMissing()` method is invoked.

6.2.2. Avoiding cache synchronization

An interesting aspect worth of comment is that there is no explicit synchronization along the fast path in the adapter subroutine. The reason why the code works correctly is that the hash table is filled lazily and, once something is stored in the key arrays or the `quick_map` array, it is never changed again. If the entry in the key arrays for a certain hash value has been initialized, but the corresponding `quick_map` entry is not, then a zero value is found, and `lookupAndUpdate()` is called. If the entry in the key arrays has not been initialized, or does not match the current class, then `findCode()` is called.

The routine `lookupAndUpdate()` is actually synchronized, and will inspect the arrays once again from within the synchronized section before proceeding with any updates. The routine `findCode()` relies again on a similar principle, applied this time to the collision chain: either the correct value is found, or zero is returned (if no entry is found or if the collision chain is being altered concurrently). If the desired class is not found, once again we fall into `lookupAndUpdate()`, which offers us the synchronization necessary to avoid overlapping concurrent updates of the hash table. To summarize, apart from the few cases in which a combination of argument classes has not been cached yet, during normal operation the method cache will only be read from without requiring any synchronization, therefore enhancing the dispatching efficiency.

6.3. Customizations

The simple layout shown in the example can become a lot more complicated when more features of PolyD are used. Modifier tags such as `@As`, `@Null`, and `@Raw`, lead to appropriate changes to the dispatcher code, which are applied while the code is automatically generated. For instance, `@Null` causes an additional test to be inserted right after the class of an argument is extracted. Using `@Raw` causes some arguments to be passed to the method selection logic, including `lookupAndUpdate()`, although those arguments are removed before the method call. Methods that use multiple arguments require the hash table to make use of multiple `quick_map` arrays in order to associate method indices to tuples of classes rather than single classes, and the size of the arrays is tuned appropriately.

The overall scheme of the adapter is generally preserved, but certain parts of the routine are customized as needed. However, nothing, at least in principle, prevents us from using entirely different implementations of the adapter subroutines in different cases, depending on the convenience of using each approach for varying circumstances. The use of dynamic code generation is fundamental in allowing us to obtain this degree of flexibility.

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6.4. Factories

For certain applications it is necessary to generate a large number of new dispatchers. In our example, Ovm creates about 230 000 new dispatchers just to compile a simple 'hello world' program. It would be extremely time-consuming to generate new bytecode each time a new dispatcher is encountered; therefore, it becomes imperative to decouple the bytecode generation from the actual dispatcher instantiation.

This is accomplished by introducing, for each adapter class, a separate factory, also generated on-the-fly. An example of the additional factory class is shown in the second part of Figure 10. Each factory is associated with a dispatcher interface, and stored in a separate cache.

When a new dispatcher is created by calling `PolyD.build()`, the cache is inspected to see whether an existing dynamically generated class can be reused. As described in the previous sections, different sequences of bodies can be combined in order to create different implementations for the same dispatcher interface. Therefore, the exact sequence of classes of the implementing bodies is used together with the dispatcher interface when searching the cache for the corresponding dynamically generated code.

If no associated bytecode can be found, the actual generation of the Java bytecode takes place. That step, however, is preceded by an inspection of the implementing bodies for consistency and completeness. This verification is described in the next section. Once the system has verified that the sequence of implementing bodies does, in fact, constitute a valid implementation for the dispatcher, the bytecode for the adapter class and the corresponding factory is generated, and inserted into the implementation cache.

Once the bytecode is known, either because it was found in the cache or because it has just been generated, all that remains to create a new dispatcher is to call the factory, an example of which is shown in Figure 10. The dispatcher construction consists of allocating a new instance, linking to the dispatcher the implementing bodies, and setting up the `@Self` fields. The implementing bodies will then be used as targets for the redirected messages while performing the dynamic dispatching, as shown in the second part of Figure 10 in the adapter subroutine for `dance(Person person, Place place)`.

6.5. Verification and code generation

Before the code can be generated, as mentioned above, it is crucial to verify the specification of the dispatcher and the content of all the implementing bodies, and verify, as far as possible, whether a dispatcher can be successfully built. This involves verifying whether the requested dispatcher would be complete, in the sense that every prototype has a matching implementation, and consistent, so that there are no conflicts or obvious ambiguities in the supplied implementations.

As a first step, all the information is collected, either from the description built using the pre-1.5 compatible descriptors or by inspecting the Java 1.5 annotations in the dispatcher prototype and the various bodies. Once that is done, the methods and prototypes are grouped by name and arity. The `@Name` tags, if present, are used rather than the original name so that prototypes and implementing methods can be matched, even if their names differ. The arguments marked with `@Raw` are skipped while calculating the arity. If a prototype has no corresponding method of equal arity/name then an

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error is generated. If a method has no matching prototype, then it is just a support method not used for dispatching, and it is ignored.

The methods are then inspected for consistency against the prototypes. The return value covariance is verified: each time a method can be called through a certain prototype, its return value must be equal to, or a subclass of, the return value specified in the prototype. This is necessary in order to conform to Java typing rules. At the end of the inspection, each prototype must have at least one corresponding applicable implementation, otherwise an error is generated. The reinterpretation of the arguments imposed by the `@As` tags is also taken into account while performing the comparisons.

Once all the checks are passed, we know the set of implementation methods that can actually be reached through each individual prototype. Such sets form the basis of the selection coded in each adapter subroutine, which we implement in the form of a switch statement, although different approaches are also possible.

The adapter code, and the corresponding factory, can then finally be generated. Notably, when calling the implementing methods from the adapter subroutines, we have to contend with the way in which overloading is used by Java in order to disambiguate methods. Additional casts are therefore inserted for some or all of the message arguments in order to force the correct method to be invoked.

7. PERFORMANCE

The performance levels offered by PolyD for single-argument methods are competitive with those of related, but less general, tools, as will be shown shortly. In the case of multiple-argument methods, we find that PolyD can offer higher dispatching speeds than other multidispatching tools, exhibiting a dramatically better performance when increasing the number of methods. We now briefly describe the implementation mechanism, and subsequently discuss the benchmarking tests.

7.1. Efficiency of the implementation

The implementation of PolyD has been tuned to offer performance levels suitable for concrete, realistic uses. PolyD was integrated and tested in real applications, in particular in the Ovm framework, which comprises about 400 000 lines of code and makes intense use of visitor-like dispatching. In order to maximize the dispatching efficiency, PolyD combines a reflective approach with dynamic bytecode generation and caching, getting inspiration by its single-argument predecessor, the Runabout. In the case of PolyD, the construction of the dynamically generated bytecode is made considerably more complicated by the many parametric aspects involved. Our code generator relies on the ASM framework [22].

Great effort was spent in minimizing the time required for message dispatching and for the construction of new dispatchers. The dispatching fast path is quite short and consists of just a handful of bytecode instructions. The creation of new dispatchers takes place by simply instantiating the synthetic class and setting up a few fields. A fast dispatcher creation time is particularly important if a large number of dispatchers are generated, as was the case for the applications that we tested. During the creation of a new VM for a short test program the Ovm compiler creates about 230 000 dispatchers, which are collectively used approximately 5 900 000 times. The Kacheck/J tool, used to parse the rt.jar file from a Sun JDK, creates about 285 000 dispatchers, and uses them about 9 400 000 times.

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Execution time (sec.)	*Kacheck client VM*	*Kacheck server VM*	*Ovm server VM*
PolyD	21.707	22.921	104.165
Runabout	22.201	22.966	104.297

Kacheck: 285,656 dispatchers created
9,384,595 invocations

Ovm: 226,620 dispatchers created
5,864,145 invocations

Figure 11. Speed comparison between Kacheck/Js and Ovm.

7.2. Benchmarking

We evaluated the performance of our implementation by adapting two existing applications, using PolyD as the core infrastructure for the visitor-style dispatching. The execution time of the PolyD version was then compared with the Runabout version of the same applications. In addition, a number of microbenchmarks were run comparing PolyD against Runabout, Sprintabout, Dynamic Dispatcher, MultiJava, the Java Multi-Method Framework (JMMF), and plain visitors (references on these systems are available in Section 8). All benchmarks were run on an AMD Athlon^{TM} XP1900+ at 1600 MHz, 1 GB of RAM, running Red Hat Linux (kernel 2.4.20), and Sun's JDK 1.5.0 in server mode. All of the timings shown in the tables and the graphs are averages of at least ten runs.

The first application used for the test is Kacheck/J, an encapsulation checker that analyzes the use of confined types in programs in Java programs. The performance of the PolyD version of the application was found to be similar or, in some cases slightly better, than the performance of the Runabout version. Figure 11 shows a comparison of the running time required by Kacheck/J to detect encapsulated types in the rt.jar file contained in Sun's 1.4.2-03 JDK. Similar figures were found for the Ovm framework: the numbers in Figure 11 refer to the execution time of the ahead-of-time compiler while processing a test program (with all the libraries), up to the code generation stage.

Detailed tests were also performed using microbenchmarks, in particular comparing the relative performance of PolyD and other tools when dealing with visitors, or multimethods, defined over a progressively larger hierarchy of classes. PolyD was compared against MultiJava and JMMF when dealing with unary, binary, and ternary methods. The expected result was that PolyD, as a result of its hashing core, should scale well moving towards more complex systems. The experimental results, shown in Figures 12 and 13, confirm our intuition.

MultiJava, which relies on a chain of `instanceof` tests, has a good efficiency when just a few methods are involved, but the longer sequence of tests causes a severe performance degradation when a higher number of methods are involved. The graphs show the timings obtained using JDK 1.5.0 in server mode using a flat hierarchy, in which a single superclass has a number of direct subclasses, or a deep hierarchy, in which all classes are arranged in a chain. Using a flat hierarchy, for unary methods PolyD achieves a higher dispatching speed than MultiJava when more than about 50 methods are defined. For binary methods, PolyD is faster when dealing with more than about 15 methods. Using

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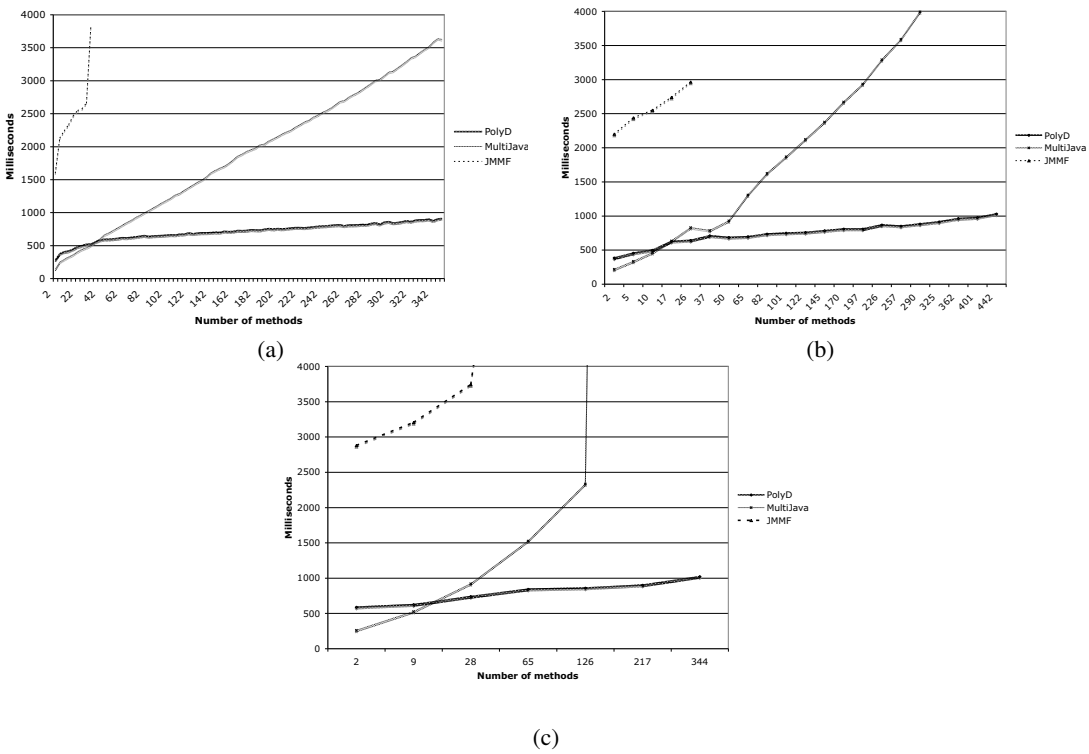

Figure 12. Dispatching time results for PolyD, MultiJava, and JMMF, using a flat hierarchy, shown on a linear scale: (a) unary methods; (b) binary methods; (c) ternary methods.

a deep hierarchy the performance of MultiJava degrades even more rapidly, and PolyD shows better dispatching speed when using as few as nine methods in the unary case, as shown in Figure 15.

JMMF, which operates reflectively, exhibited much slower dispatching times. We encountered some unexpected exceptions using JMMF for certain method combinations, and that is reflected in the missing samples in the graphs. The benchmarks show that PolyD, in addition to its extensive features set, is also an efficient solution for general multiple dispatching, scaling much better than other tools when dealing with complex systems.

Regarding the visitor-like tools, Figures 14 and 15 compare PolyD against the Runabout, the Sprintabout, and other tools. The Dynamic Dispatcher and JMMF required a considerably longer time to complete the tests than the other tools, and their graph is out of scale. Figure 16 displays the relative performance of PolyD, Runabout, and Sprintabout when a larger number of methods are involved.

The results of the overall dispatching efficiency of the three tools are comparable. That should not be too surprising considering that they all rely on class hashing and on method caching to speed up performance. PolyD exhibits a good level of performances despite having to cater for a much more

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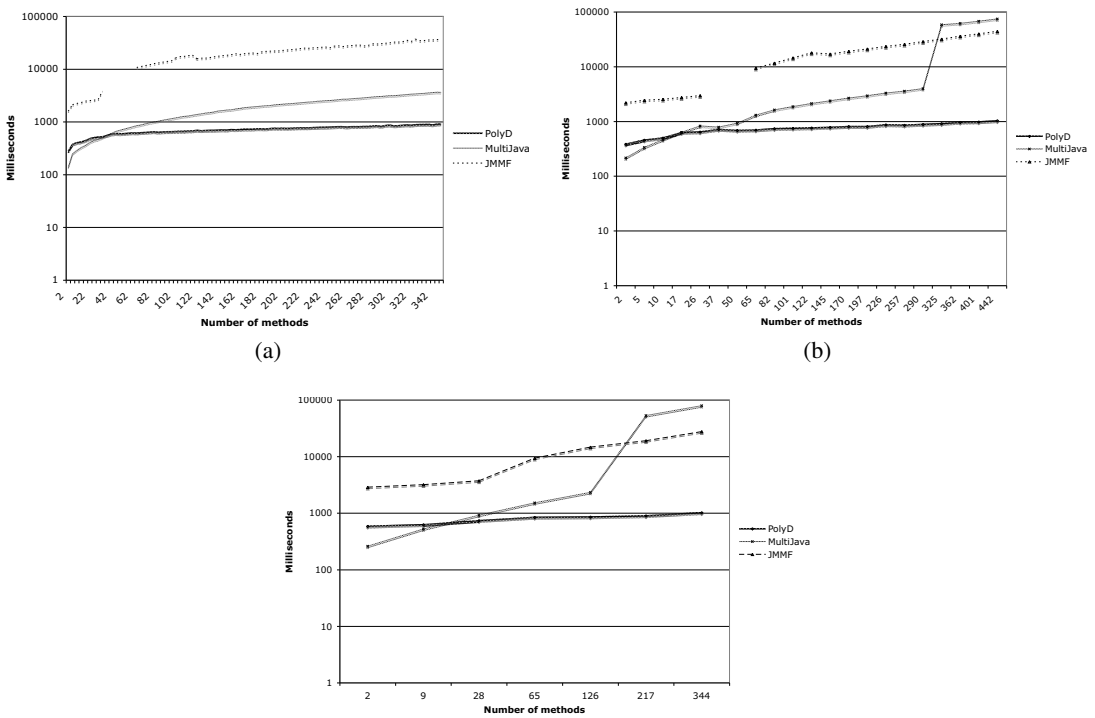

Figure 13. Dispatching time results for PolyD, MultiJava and JMMF, using a flat hierarchy, shown on a logarithmic scale: (a) unary methods; (b) binary methods; (c) ternary methods.

general system. The experimental measurements confirm that PolyD can be used as a more general, and equally efficient, replacement for existing visitor-like tools.

8. RELATED WORK

A number of tools have been developed to extend the native dispatching mechanism offered by Java. A relevant class of tools aims to provide features similar to the classic Visitor pattern [14], but improving on the implementation. Palsberg and Jay [16] were the first to suggest that the use of a reflective approach would obviate the need for `accept()` methods, implementing the Walkabout. Bravenboer and Visser [23] improved on the idea by adding a cache in order to reduce the cost of reflective lookups, as these were extremely costly in early implementations of Java. Grothoff [12] further improved efficiency by using runtime bytecode generation; his tool is known as the Runabout. A similar approach, albeit with lower performance, was also used by the Dynamic Dispatcher [24].

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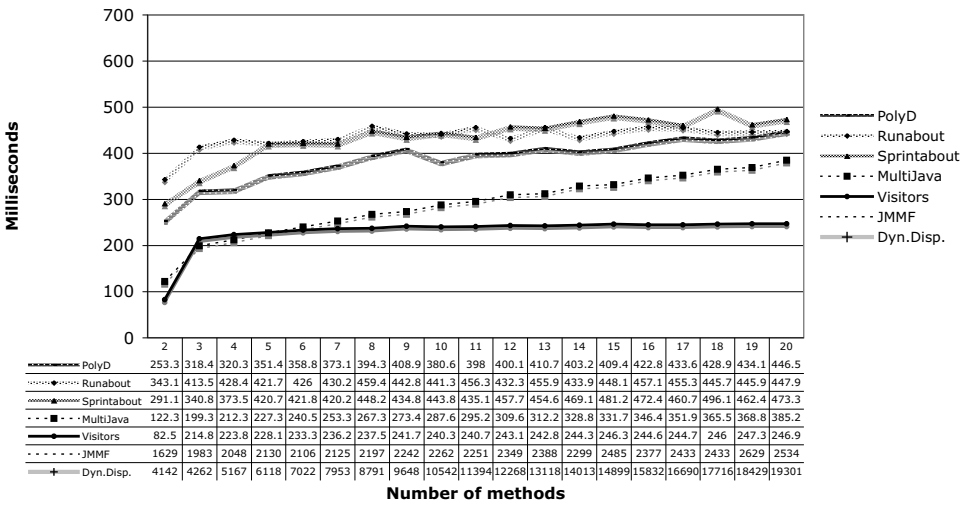
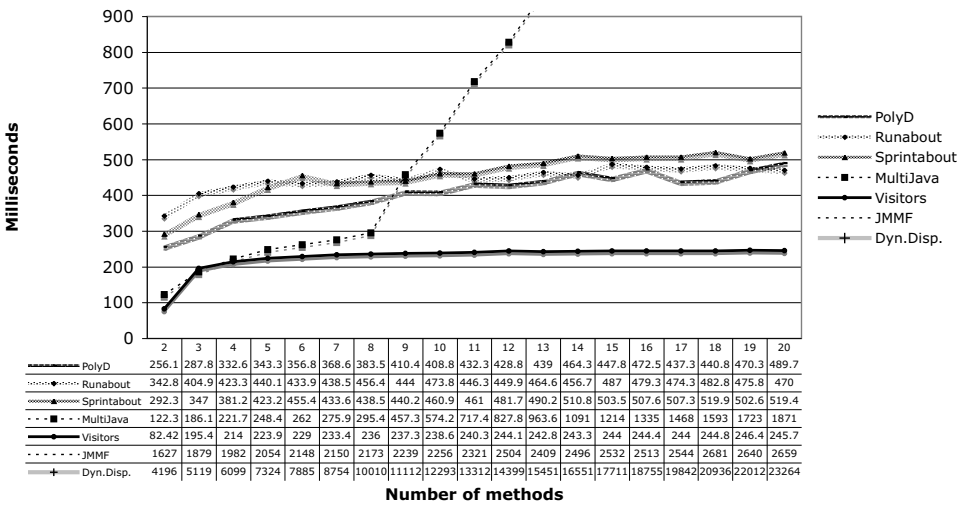


	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
PolyD	253.3	318.4	320.3	351.4	358.8	373.1	394.3	408.9	380.6	398	400.1	410.7	403.2	409.4	422.8	433.6	428.9	434.1	446.5
Runabout	343.1	413.5	428.4	421.7	426	430.2	459.4	442.8	441.3	456.3	432.3	455.9	433.9	448.1	457.1	455.3	445.7	445.9	447.9
Sprintabout	291.1	340.8	373.5	420.7	421.8	420.2	448.2	434.8	443.8	435.1	457.7	454.6	469.1	481.2	472.4	460.7	496.1	462.4	473.3
MultiJava	122.3	199.3	212.3	227.3	240.5	253.3	267.3	273.4	287.6	295.2	309.6	312.2	328.8	331.7	346.4	351.9	365.5	368.8	385.2
Visitors	82.5	214.8	223.8	228.1	233.3	236.2	237.5	241.7	240.3	240.7	243.1	242.8	244.3	246.3	244.6	244.7	246	247.3	246.9
JMMF	1629	1983	2048	2130	2106	2125	2197	2242	2262	2251	2349	2388	2299	2485	2377	2433	2433	2629	2534
Dyn.Disp.	4142	4262	5167	6118	7022	7953	8791	9648	10542	11394	12268	13118	14013	14899	15832	16690	17716	18429	19301

Figure 14. Speed comparison of seven dispatching tools (flat hierarchy).



	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
PolyD	256.1	287.8	332.6	343.3	356.8	368.6	383.5	410.4	408.8	432.3	428.8	439	464.3	447.8	472.5	437.3	440.8	470.3	489.7
Runabout	342.8	404.9	423.3	440.1	433.9	438.5	456.4	444	473.8	446.3	449.9	464.6	456.7	487	479.3	474.3	482.8	475.8	470
Sprintabout	292.3	347	381.2	423.2	455.4	433.6	438.5	440.2	460.9	461	481.7	490.2	510.8	503.5	507.6	507.3	519.9	502.6	519.4
MultiJava	122.3	186.1	221.7	248.4	262	275.9	295.4	457.3	574.2	717.4	827.8	963.6	1091	1214	1335	1468	1593	1723	1871
Visitors	82.42	195.4	214	223.9	229	233.4	236	237.3	238.6	240.3	244.1	242.8	243.3	244	244.4	244	244.8	246.4	245.7
JMMF	1627	1879	1982	2054	2148	2150	2173	2239	2256	2321	2504	2409	2496	2532	2513	2544	2681	2640	2659
Dyn.Disp.	4196	5119	6099	7324	7885	8754	10010	11112	12293	13312	14399	15451	16551	17711	18755	19842	20936	22012	23264

Figure 15. Speed comparison of seven dispatching tools (deep hierarchy).

DOI: 10.1002/spe

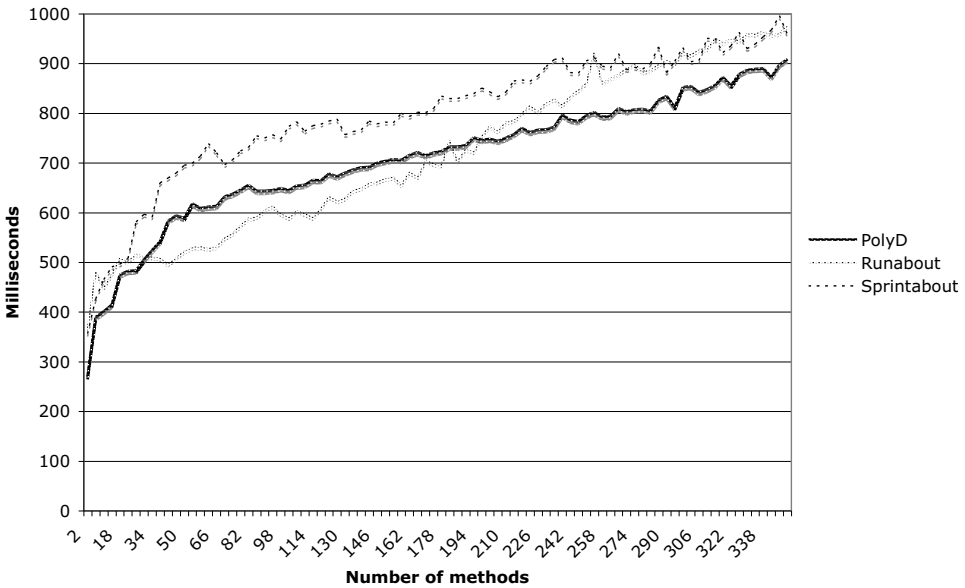


Figure 16. Speed comparison of PolyD, Runabout, and Sprintabout where a larger number of methods are involved (flat hierarchy).

The mechanism used by the Runabout was refined by Forax *et al*. [17] in the Sprintabout. Their tool, akin to PolyD, uses a table-based dispatcher. Visitors have been proposed as a native language feature, in the Peripaton language [25].

Several projects add multiple dispatching to Java, either by supplying the feature in the form of a library or by requiring special syntax, preprocessors, or VMs. MultiJava [8] uses a special syntax and a preprocessor. It also does not dispatch following interfaces and subinterfaces, but is limited to single inheritance. JMMF [4] works solely using reflection, but suffers from low performance. The system described by Dutchyn *et al*. [26] changes the semantics of Java dispatching, and uses a custom VM.

Other notable Java tools or proposals advocate alternate forms of dispatching, although none of them relies on pure Java: JPred [7] implements a general form of predicate dispatching (also see [27]); Boyland and Castagna [5] use parasitic methods to implement a restricted form of multimethods; Tuple [28] implements multidispatching as dispatching on tuples; Baumgartner *et al*. [29] suggest the addition of multimethods and retroactive abstraction to Java; Nice [30] and Kiev [31] are two Java derivatives that include multimethod features. Proposals for adding multidispatching to other languages also exist. For example, Foote *et al*. [32] add multimethods to Smalltalk-80. Handling dispatching in the case of `null` can be accommodated by the MultiJava notion of 'value dispatch', and the languages based on predicate dispatch can also naturally handle the case.

PolyD separates the dispatching concerns from the main program code, and as such it can be seen as a specialized aspect-oriented system. In this way, the functionalities offered by PolyD could be

DOI: 10.1002/spe

made part of a general aspect framework as, for instance, XAspects [33]. The CLOS system [34] uses multimethods and allows programmers to customize the ambiguity resolution, therefore enabling the customization of one aspect of the dispatching process. The Fred/Socrates system [35] brings together elements of predicate dispatching and aspect-oriented programming, allowing the programmer to define multiple 'branches', corresponding to a given message, selected using boolean predicates but which can also be refined in stages. However, in Fred both the predicate and the body are part of the code that describes each branch. PolyD, conversely, totally segregates the selection logic, allowing for instance the same bodies to be selected through different policies. In that sense, PolyD is more clearly a specialized aspect language in which the dispatching concern is clearly confined, rather than being distributed throughout the code.

Open classes and the extensibility problem, also known as the expression problem, are extensively discussed in literature [13,36–38].

9. FUTURE WORK

We are planning several enhancements and further developments of our framework. In terms of improvements to the current code base, the dispatching core can be optimized when a small number of methods are involved and a sequence of tests can replace the method lookup for the specific policy in use. This would allow us to implement, for instance, multiple dispatching more efficiently for fewer methods, while retaining the considerable advantages of hashing when building larger systems. Other minor improvements are also planned in order to optimize performance when dealing with final classes, and in other particular cases.

More general developments are also planned. PolyD currently allows the user to select, via a modular policy, the 'most appropriate' method according to the classes of the arguments as obtained using the reflective features of Java. We are considering defining a parallel reflective API, enabling the user to define an independent, user-defined, pseudo-class hierarchy. This should facilitate easy prototyping of more unusual forms of inheritance (e.g. virtual types), together with their dispatching mechanisms.

10. CONCLUSIONS

Object-oriented programming languages adopt predefined message dispatch strategies that compromise between the performance and flexibility requirement needs of most applications. While pragmatic, this approach leaves programmers with the responsibility of hand coding their own dispatchers when the default mechanisms fall short. A number of tools attempt to ease such task by adding specific dispatching extensions. In this paper, we proposed a more general solution based on a modular approach to dispatching. We put our ideas into practice by developing a flexible dispatching framework for Java that enables programmers to define customized dispatching strategies that are better suited for the task at hand.

We have shown that our implementation, PolyD, is a tool that can replace, offering a more general solution, both visitor-derived and multimethod tools. The performance of PolyD is comparable to, and often exceeds, that of the Runabout and related tools, while at the same time offering more flexibility. When used as a multidispatching package, PolyD scales better than MultiJava and JMMF, showing a dramatic improvement over both tools when the number of methods increases. The PolyD framework is a pure Java solution that uses the standard Java runtime, bytecode, and syntax.

DOI: 10.1002/spe

The extensive set of features offered by PolyD encompasses many aspects of the dispatching process that are not customizable in comparable systems, including a custom handling of missing methods, of null arguments, of method selection, and of method invocation. The dispatchers generated by PolyD share a common, efficient dispatching core, which ensures a high dispatching performance. In conclusion, we claim that PolyD is a flexible, general, and efficient framework that can free developers from the limitations of conventional dispatching mechanisms.

PolyD can be freely downloaded from www.ovmj.org/polyd.

ACKNOWLEDGEMENTS

The authors wish to thank Christian Grothoff, Rémi Forax, Etienne Duris, James Noble, Jeremy Manson, and James Baker for contributing to this work with discussions, documentation, and ideas. We also thank the anonymous reviewers for their useful and insightful comments.

This work was partially supported by NSF Grants HDCCSR-0341304 and CAREER-0093282.

REFERENCES

1. Barrett K, Cassels B, Haahr P, Moon DA, Playford K, Withington PT. A monotonic superclass linerization for Dylan. *Proceedings OOPSLA'96 Conference on Object-Oriented Programming Systems, Languages, and Applications. ACM SIGPLAN Notices* 1996; **31**:69–82.
2. DeMichiel LG, Gabriel RP. The common lisp object system: An overview. *Proceedings of the 1987 European Conference on Object-Oriented Programming (ECOOP'87)*, Paris, France (*Lecture Notes in Computer Science*, vol. 276). Springer: Berlin, 1987; 151–170.
3. Chambers C. Object-oriented multi-methods in Cecil. *Proceedings of the 1992 European Conference on Object-Oriented Programming (ECOOP'92)*, Utrecht, The Netherlands (*Lecture Notes in Computer Science*, vol. 615). Springer: Berlin, 1992; 33–56.
4. Forax R, Duris E, Roussel G. Java multi-method framework. *International Conference on Technology of Object-Oriented Languages and Systems (TOOLS'00)*, Sydney, Australia. IEEE Computer Society Press: Los Alamitos, CA, 2000.
5. Boyland J, Castagna G. Parasitic methods: An implementation of multi-methods for Java. *Proceedings of the ACM SIGPLAN 1997 Conference on Object-Oriented Programming Systems, Languages and Applications. ACM SIGPLAN Notices* 1997; **32**(10):66–76.
6. Chambers C, Chen W. Efficient multiple and predicate dispatching. *Proceedings of the ACM SIGPLAN 1999 Conference on Object-Oriented Programming Systems, Languages and Applications. ACM SIGPLAN Notices* 1999; **34**(10):238–255.
7. Millstein T. Practical predicate dispatch. *Proceedings of the ACM SIGPLAN 2004 Conference on Object-Oriented Programming Systems, Languages and Applications. ACM SIGPLAN Notices* 2004; **39**(11):345–264.
8. Clifton C, Millstein T, Leavens GT, Chambers C. Multijava: Design rationale, compiler implementation, and applications. *ACM Transactions on Programming Languages and Systems* 2006; **28**(3):517–575.
9. Chambers C, Leavens GT. Typechecking and modules for multi-methods. *Proceedings of the ACM SIGPLAN 1994 Conference on Object-Oriented Programming Systems, Languages and Applications. ACM SIGPLAN Notices* 1994; **29**(10):1–15.
10. Agrawal R, DeMichiel LG, Lindsay BG. Static type checking of multi-methods. *Proceedings of the ACM SIGPLAN 1991 Conference on Object-Oriented Programming Systems, Languages and Applications. ACM SIGPLAN Notices* 1991; **26**(11):113–128.
11. Bourdoncle F, Merz S. Type-checking higher-order polymorphic multi-methods. *Conference Record of the 24th ACM SIGPLAN–SIGACT Symposium on Principles of Programming Languages (POPL'97)*, New York, NY, 1997. ACM Press: New York, 1997; 302–315.
12. Grothoff C. Walkabout revisited: The runabout. *Proceedings of the 2003 European Conference on Object-Oriented Programming (ECOOP'03)*, Darmstadt, Germany, 21–25 July 2003 (*Lecture Notes in Computer Science*, vol. 2743), Cardelli L (ed.). Springer: Berlin, 2003; 103–125.
13. Palacz K, Baker J, Flack C, Grothoff C, Yamauchi H, Vitek J. Engineering a customizable intermediate representation. *Proceedings of the ACM SIGPLAN Workshop on Interpreters, Virtual Machines and Emulators (IVME'03)*, San Diego, CA, June 2003. ACM Press: New York, 2003.

DOI: 10.1002/spe

14. Gamma E, Helm R, Johnson R, Vlissides J. *Design Patterns: Elements of Reusable Object-Oriented Software*. Addison-Wesley: Reading, MA, 1995.
15. Nordberg ME III. Variations on the visitor pattern. *Proceedings of The Joint Pattern Languages of Programs (PLoP)*. Addison-Wesley: Reading, MA, 1996.
16. Palsberg J, Jay CB. The essence of the visitor pattern. *Proceedings of the 22nd IEEE International Conference on Computer Software and Applications (COMPSAC)*, Vienna, Austria. IEEE Computer Society Press: Los Alamitos, CA, 1998; 9–15.
17. Forax R, Duris E, Roussel G. Reflection-based implementation of Java extensions: The double-dispatch use-case. *Proceedings of the 2005 ACM Symposium on Applied Computing*, New York, 2005. ACM Press: New York, 2005.
18. Millstein TD, Chambers C. Modular statically typed multimethods. *Journal of Information and Computation* 2002; **175**(1):76–118.
19. Millstein T, Reay M, Chambers C. Relaxed MultiJava: Balancing extensibility and modular typechecking. *Proceedings of the ACM SIGPLAN 2003 Conference on Object-Oriented Programming Systems, Languages and Applications. ACM SIGPLAN Notices* 2003; **38**(11):224–240.
20. Grothoff C, Palsberg J, Vitek J. Encapsulating objects with confined types. *Proceedings of the 2001 Object-Oriented Programming Systems, Languages and Applications (OOPSLA'01)*. ACM Press: New York, 2001; 241–255.
21. The Jad decompiler home page. http://www.kpdus.com/jad.html [27 March 2007].
22. Bruneton É, Lenglet R, Coupaye T. ASM: A code manipulation tool to implement adaptable systems. *Proceedings of the ASF (ACM SIGOPS France) Journées Composants 2002: Systèmes à composants adaptables et extensibles (adaptable and extensible component systems)*, Grenoble, France, November 2002. ACM Press: New York, 2002.
23. Bravenboer M, Visser E. Guiding visitors: Separating navigation from computation. *Technical Report UU-CS-2001-42*, Institute of Information and Computing Sciences, Utrecht University, 2001.
24. Büttner F, Radfelder O, Lindow A, Gogolla M. Digging into the visitor pattern. *Proceedings of the 16th International Conference on Software Engineering and Knowledge Engineering (SEKE'2004)*, Banff, Alberta, Canada, June 2004; 135–141.
25. VanDrunen T, Palsberg J. Visitor-oriented programming. *Proceedings of the 11th ACM SIGPLAN International Workshop on Foundations of Object-Oriented Languages (FOOL-11)*, Venice, Italy, January 2004.
26. Dutchyn C, Lu P, Szafron D, Bromling S, Holst W. Multi-dispatch in the Java virtual machine: Design and implementation. *Proceedings of the 6th Usenix Conference on Object-Oriented Technologies and Systems (COOTS'2001)*. USENIX Association: Berkeley, CA, 2001; 77–92.
27. Ernst MD, Kaplan C, Chambers C. Predicate dispatching: A unified theory of dispatch. *Proceedings of the 1998 European Conference on Object-Oriented Programming (ECOOP'87)*, Brussels, Belgium (*Lecture Notes in Computer Science*, vol. 1445). Springer: New York, 1998; 186–211.
28. Leavens GT, Millstein TD. Multiple dispatch as dispatch on tuples. *Proceedings of the ACM SIGPLAN 1998 Conference on Object-Oriented Programming Systems, Languages and Applications. ACM SIGPLAN Notices* 1998; **33**(10):374–387.
29. Baumgartner G, Jansche M, Läufer K. Half & Half: Multiple dispatch and retroactive abstraction for Java. *Technical Report OSU-CISRC-5/01-TR08*, Department of Computer Science, The Ohio State University, March 2002.
30. The Nice language home page. http://nice.sourceforge.net [27 March 2007].
31. The Kiev language home page. http://web.archive.org/web/20060111125014/http://kiev.forestro.com/index.html [11 January 2006].
32. Foote B, Johnson RE, Noble J. Efficient multimethods in Smalltalk-80. *Proceedings of the European Conference on Object-Oriented Programming (ECOOP'05)*, Glasgow, Scotland, July 2005. Springer: Berlin, 2005.
33. Shonle M, Lieberherr KJ, Shah A. *XAspects: An Extensible System for Domain Specific Aspect Languages*, Anaheim, CA, 2003. ACM Press: New York, 2003; 28–37.
34. Bobrow DG, DeMichiel LG, Gabriel RP, Keene SE, Kicsales G, Moon DA. Common lisp object system specification: X3J13 document 88-002R. *ACM SIGPLAN Notices* 1988; **23**.
35. Orleans D. Incremental programming with extensible decisions. *Proceedings of the 1st International Conference on Aspect-Oriented Software Development*, Enschede, The Netherlands, 2002. ACM Press: New York, 2002.
36. Zenger M, Odersky M. Independently extensible solutions to the expression problem. *Technical Report IC/2004/33*, École Polytechnique Fédérale de Lausanne, 2004.
37. Krishnamurthi S, Felleisen M, Friedman DP. Synthesizing object-oriented and functional design to promote re-use. *Proceedings of the 1998 European Conference on Object-Oriented Programming (ECOOP'98)*, Brussels, Belgium, July 1998 (*Lecture Notes in Computer Science*, vol. 1445). Springer: Berlin, 1998; 91–113.
38. Torgersen M. The expression problem revisited: Four new solutions using generics. *Proceedings of the 2004 European Conference on Object-Oriented Programming (ECOOP'04)* (*Lecture Notes in Computer Science*, vol. 3086). Springer: Berlin, 2004; 123–143.

DOI: 10.1002/spe