Software Composition with Multiple Nested Inheritance

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Abstract. This paper introduces a programming language that makes it convenient to extend large software systems and even to compose them in a modular way. JX/MI supports *multiple nested inheritance*, building on earlier work on nested inheritance in the language JX. Nested inheritance permits modular, type-safe extension of a package (including nested packages and classes), while preserving existing type relationships. Multiple nested inheritance enables simultaneous extension of *two or more* classes or packages, composing their types and behavior while resolving conflicts with a relatively small amount of code. The utility of JX/MI is demonstrated by using it to construct two composable, extensible frameworks: a compiler framework for Java, and a peer-to-peer networking system. Both frameworks support composition of extensions. For example, two compilers adding different, domain-specific features to Java can be composed to obtain a compiler for a language that supports both sets of features.

1 Introduction

Software is frequently produced by combining and extending preexisting components; it is therefore valuable for programming languages to support code reuse, extension, and composition. Existing mechanisms like class inheritance and functors address the problem of code reuse and extension for small or simple extensions, but do not work well for larger bodies of code such as compilers or operating systems, which are composed of many mutually dependent classes, functions, and types. Better language support is needed to build these larger systems in an extensible way.

For example, a body of software written in an object-oriented language usually comprises many classes related through inheritance. Ordinary class inheritance can extend the software by adding new classes to the leaves of the class hierarchy, but in general, more significant changes may be needed to construct the extended software. For instance, all of the classes in some part of the class hierarchy may need (the same) additional field. Ordinary object-oriented languages provide no means to make this kind of extension in a modular fashion. The non-modular solution of copying and modifying the code is not acceptable because it duplicates code and makes maintenance of the copied code difficult as the original code evolves.

This paper introduces the language JX/MI, which supports the scalable, modular extension and composition of large software frameworks. JX/MI builds on previous work on the language JX, which supported scalable extension of software frameworks through *nested inheritance* [29]. Other language mechanisms such as virtual

classes [25], open classes [8], and aspects [22] also give some ability to extend a body of code with varying degrees of expressiveness and modularity. What JX/MI adds is the ability to *compose* several extensions to obtain a software system that combines their functionality.

The Polyglot compiler framework is an example of a software framework designed to be extended in sophisticated ways [31]. Polyglot is a Java compiler front end that can be extended to support domain-specific extensions to the Java language. For a given application domain, one might like to choose useful language features from a "menu" of available options, then compose the corresponding compilers to obtain a compiler for the desired language. However, previous language mechanisms gave no way to accomplish this composition while resolving the conflicts among the different extensions.

We identify the following requirements for extension and composition of software systems:

1. Orthogonal extension of the system with both new data types and new operations.
2. Modularity: The base system can be extended without modifying or recompiling its code.
3. Type safety: extensions cannot create run-time type errors.
4. Scalability: extensions should be *scalable*. The amount of code needed should be proportional to functionality added.
5. Non-destructive extension: The base system should still be available for use within the extended system.
6. Composability of extensions.

The first three of these requirements correspond to Wadler's *expression problem* [43]. The fourth requirement, scalability, is often but not necessarily satisfied by supporting separate compilation; it is important for extending large software. Non-destructive extension enables the extended system to interoperate with code and data of the base system, an important requirement for ensuring backward compatibility. Simple nested inheritance [29] addresses the first five requirements, but it does not support extension composition. In JX/MI, composition is accomplished through a new language feature, *multiple nested inheritance*, which builds on nested inheritance by adding the ability to write software by inheriting from several frameworks and thereby obtaining a composition of their functionality.

This paper describes multiple nested inheritance in the JX/MI language and our experience using it to compose software. Section 2 defines the problem of scalable extension and composition, considers a particularly difficult instantiation of this problem—the extension and composition of compilers—and gives an informal introduction to multiple nested inheritance and JX/MI. Multiple nested inheritance creates several interesting technical challenges, such as the problem of resolving conflicts among inherited frameworks; this topic and a detailed discussion of language semantics are presented in Section 3, explaining how conflicts are resolved among inherited frameworks. Section 4 then shows an example of using multiple nested inheritance in the construction of an extensible, composable compiler. The implementation of JX/MI is described in Section 5, and Section 6 describes experience using JX/MI to implement and compose extensions in the Polyglot compiler framework and in the Pastry framework for building

peer-to-peer systems. Related work is discussed in Section 7, and the paper concludes in Section 8.

2 Multiple nested inheritance for composition

Multiple nested inheritance supports scalable extension of a base system and composition of those extensions. To illustrate how multiple nested inheritance achieves this goal, we will consider the example of building a compiler with composable extensions. A compiler is of course not the only system for which extensibility is useful; other examples include user interface toolkits, operating systems, web browsers, and peer-to-peer networks. However, compilers are a particularly challenging domain because a compiler has several different interacting dimensions along which it can be extended.

2.1 Nested inheritance

Nested inheritance [29] is a virtual class mechanism that allows modular, scalable extension of a large body of code with new functionality. Nested inheritance was introduced by JX, an extension of the Java programming language; JX/MI extends JX with multiple nested inheritance. We begin by reviewing how nested inheritance supports extensibility.

Nested inheritance in JX/MI is inheritance of *namespaces*: that is, classes or packages. A package may contain several classes and packages, and a class may contain nested classes as well as methods and fields. A namespace may extend another namespace, inheriting all its members, including nested namespaces. As with ordinary inheritance, the meaning of code inherited from the base namespace is as if it were copied down from the base. A derived namespace may *override* any of the members it inherits, including nested classes and packages. Like virtual classes [24, 25, 14], when a nested namespace $T.C$ is overridden in T', a derived namespace of T, the overriding namespace $T'.C$ does not replace $T.C$, but instead refines (or *further binds*) it: $T'.C$ inherits members from $T.C$ as well as from $T'.C$'s explicitly named base namespaces (if any). In addition, $T'.C$ is also a subtype of $T.C$.

Type reinterpretation. The key feature of nested inheritance that enables scalable extensibility is type name resolution in the *inheriting context*. When the name of a class or package is inherited into a new namespace, the name is interpreted in its new context, rather than in the context in which it occurs in the program text. To illustrate this feature of JX/MI, Figure 1 shows a fragment of a simple compiler for the lambda calculus extended with pair expressions. This compiler translates the lambda calculus with pairs into the lambda calculus without pairs. Here, the class `base.Emitter` extends `Visitor`. In the context of the `base` package, `Visitor` is interpreted as `base.Visitor`. In the context of `pair`, which inherits the declaration of `Emitter` from `base`, `Visitor` refers to `pair.Visitor`. Thus, `pair.Emitter` extends `pair.Visitor` and inherits the `visitPair` method of `pair.Visitor`. Reinterpretation of supertype declarations provides a form of *virtual superclasses* [25, 11], permitting the subtyping relationships among the nested namespaces to be preserved

```
package base;

abstract class Exp {
  Type type;
  abstract Exp accept(Visitor v);
}
class Abs extends Exp {
  String x; Exp e; // λx.e
  Exp accept(Visitor v) {
    e = e.accept(v);
    return v.visitAbs(this);
  }
}
class Visitor {
  Exp visitAbs(Abs a) {
    return a;
  }
}
class TypeChecker extends Visitor
{
  Exp visitAbs(Abs a) { ... }
}
class Emitter extends Visitor {
  Exp visitAbs(Abs a) {
    print(...);
  }
}
class Compiler {
  void main() { ... }
}
```

```
package pair extends base;

class Pair extends Exp {
  Exp fst, snd;
  void accept(Visitor v) {
    fst.accept(v); snd.accept(v);
    return v.visitPair(this);
  }
}
class Visitor {
  Exp visitPair(Pair p) { return p; }
}
class TranslatePairs extends Visitor
{
  Exp visitPair(Pair p) {
    return ...;
    // (λx.λy.λf. f x y) ⟦p.fst⟧ ⟦p.snd⟧
  }
}
class Compiler {
  void main() {
    Exp e = parse();
    e.accept(new TypeChecker());
    e = e.accept(new TranslatePairs());
    e.accept(new Emitter());
  }
}
```

Fig. 1. Lambda calculus + pairs compiler

when inherited into a new enclosing namespace. This feature allows new members to be *mixed in* to a nested namespace by overriding its base namespace. JX/MI also allows the `extends` declaration of a class or interface to be overridden to extend a subtype of the original supertype.

This type name reinterpretation occurs with the formal parameter of the method `accept` as well. The class `pair.Pair` overrides the method `accept` of `base.Exp` with parameter type `Visitor`, which in this context means `pair.Visitor`. The method `pair.Pair.accept` can therefore access the parameter's `visitPair` method. Even though `pair.Visitor` is a subtype of `base.Visitor`, reinterpreting `Visitor` in contravariant positions such as formal parameter types is statically type-safe [29].

Mutually dependent classes. Compilers are composed of several sets of mutually dependent classes. For example, in the lambda compiler, the classes `Exp` and `Visitor` refer to one another. Extending one class at a time, as in ordinary class inheritance, does not work because the extended classes need to know about each other. With or-

dinary inheritance, the pair compiler could define `Pair` as a new subclass of `Exp`, but references within `Exp` to class `Visitor` would refer to the old version of `Visitor`, not the appropriate one that understands how to visit pairs.

For extensibility it is important to be able to extend an entire collection of classes together, reinterpreting names of types in the new, inheriting context. This capability is sometimes called *family polymorphism* [13], where a *family* is a set of mutually dependent classes. Virtual classes, mixin layers [39], and nested inheritance all provide some form of family polymorphism.

Classes need an expressive way to name each other, so that references from one class to another are reinterpreted correctly in inheriting contexts. In general, some references should be reinterpreted, while others should continue to refer to the same class. Nested inheritance uses *dependent classes* to allow naming of types within a family determined at run time. Nested inheritance introduced *prefix types* to permit one class to refer to another that is not nested within it; the prefix type P`[`T`]` refers to the innermost class (or package) enclosing T that is a subtype of P. The expressiveness of prefix types makes it possible in JX and JX/MI to extend a single class that is part of a family of related classes, without extending all of them: inheritance can operate at every level of the containment hierarchy. Related extensibility mechanisms such as virtual classes and mixin layers do not support this.

2.2 Extensibility requirements

Nested inheritance meets the first five of the requirements described in Section 1, making it a useful language for implementing extensible systems such as compiler frameworks:

Type-safe orthogonal extension. Compiler frameworks must support the addition of both new data types (abstract syntax, types, dataflow analysis values) and operations on those types (the compiler passes that transform and rewrite these data types). It is well known that there is a tension between extending types and extending the procedures that manipulate them [35]. Nested inheritance solves this problem because reinterpretation of type names in the inheriting context causes inherited methods to operate automatically on the data types as defined in the inheriting context.

Modularity and scalability. Extensions are subclasses (or subpackages) and hence are modular. Nested inheritance is also type-safe [29]. Extension is scalable for several reasons; one important reason is that the name of every method, field, and class provides a potential hook that can be used to extend behavior and data representations.

Nested inheritance does not affect the inherited code, so it is a non-destructive extension mechanism, unlike open classes [8] and aspects [22]. Therefore, inherited code and extended code can be used together in the same system, which is important in extensible compilers because the base language is often used as a target language in an extended compiler.

2.3 Composition

To support composition of extensions, JX/MI extends JX with multiple nested inheritance. Both classes and packages may be composed using multiple inheritance. Suppose that we had also extended the `base` package of Figure 1 to a `sum` package implementing a compiler for the base language extended with sum types. In that case, multiple nested inheritance permits the `pair` and `sum` packages to be composed as shown in Figure 2.

```
package sum extends base;

class Case extends Exp {
  Exp test, ifLeft, ifRight; ...
}
class Visitor {
  Exp visitCase(Case c) {
    return c;
  }
}
class TypeChecker extends Visitor
  { ... }
class TranslateSums extends Visitor
  { ... }
class Compiler {
  void main() { ... }
}
```

```
package pair_and_sum extends pair, sum;

// Resolve conflicting versions of main.
class Compiler {
  void main() {
    Exp e = parse();
    e.accept(new TypeChecker());
    e = e.accept(new TranslatePairs());
    e = e.accept(new TranslateSums());
    e.accept(new Emitter());
  }
}
```

Fig. 2. Compiler composition

The package `pair_and_sum` inherits all members of `pair` and `sum`. When two namespaces are composed, their common nested namespaces are also composed and their own nested namespaces are preserved. Since both `pair` and `sum` contain a class `Visitor`, the new class `pair_and_sum.Visitor` extends both `pair.Visitor` and `sum.Visitor`. By integrating the member classes of all its base classes, `pair_and_sum` compiler supports both product and sum types.

Both `pair.Compiler` and `sum.Compiler` define a method `main`; `pair_and_sum` resolves the conflict by overriding the `main` method, which is necessary in any case to define the order of compiler passes.

JX/MI provides only *shared* multiple inheritance: when a subclass (or subpackage) extends multiple base classes, perhaps implicitly by inheriting from multiple containing namespaces, the new subclass may share a common superclass of its immediate superclasses; however, instances of the subclass will not contain multiple subobjects for the common superclass. In our example, `pair_and_sum.Visitor` inherits from `base.Visitor` only once, like C++ virtual base classes.

We describe the semantics of multiple inheritance in more detail in the next section.

3 Semantics

This section gives an overview of the static and dynamic semantics of JX/MI. To conserve space, not all the features of the JX/MI language are discussed in detail; package inheritance, in particular, is discussed only briefly.

3.1 Dependent classes and prefix types

In the example of Figure 1, the name `Visitor` is syntactic sugar for the type `base[this.class].Visitor`. The type `this.class` is a dependent class, representing the statically unknown, but fixed, run-time class of the variable `this`. In general dependent class *p*`.class` represents the run-time class of the object referred to by the *final access path p*. An access path is final if it is a final local variable, including `this` and final formal parameters; a field access *p*`.f`, where *p* is a final access path and `f` is a final field of *p*; or a newly-constructed object `new` *T*`()`. The run-time class of the object specified by a final access path does not change.

The *prefix package* `base[this.class]` represents the enclosing package of `this.class` that is a subpackage of `base`. In the context of `pair` and its members, `base[this.class]` resolves to `pair`. More generally, the *prefix type* *P*`[`*T*`]` represents the innermost enclosing namespace of *T* that is a subtype of the non-dependent namespace *P*. Prefix types provide an unambiguous way to name enclosing classes and packages without the overhead of storing references to enclosing instances in each object, as is done in virtual classes. Indeed, if the enclosing namespace is a package, there are no run-time instances that could be used for this purpose.

Dependent classes and prefix types behave like any other class in JX/MI. In particular, instances of these types may be allocated, their static methods and fields may be accessed, and classes and packages may be selected from them.

Both dependent classes and prefixes of dependent classes are *exact types* [3]. Their run-time class is fixed, but statically unknown in general. To make type-checking decidable, a class may not extend an exact type, although it may extend a nested class of an exact type, as is done by the subclasses of `Visitor` and `Exp` in Figure 1. In addition, dependencies between the types of formal parameters of a method must be acyclic, and a dependent class cannot be dependent upon a field path whose declared type is also a field-dependent class. These restrictions prevent dependency cycles among dependent classes.

As a special case, the dependent class `this.class` may be used in a static context, even though the variable `this` is not in scope. In a static context `this.class` represents the namespace into which the code containing `this.class` is inherited.

To improve expressiveness and ease porting of Java programs to JX/MI, a *non-final* local variable *x* used in a method call may be coerced to *x*`.class` if *x* is not modified by any of the call's actual arguments, including the receiver. This condition ensures that on entry to the method, all types dependent on *x* are consistent; that is, the run-time class of *x* does not change between the time *x* is evaluated and method entry. Similar rules are used to coerce non-final variables in constructor calls, in `new` expressions, and in field assignments. The optimization is not performed for field paths since it is not safe for multi-threaded programs.

3.2 Type substitution

A method may have a formal parameter whose type depends upon another, including `this`. Such a method may only be called with a corresponding actual argument whose type depends upon another argument. For example, the class `base.Abs` in Figure 1 contains the call:

```
v.visitAbs(this_A);
```

to a method of `base.Visitor` with the signature:

```
void visitAbs(base[this_V.class].Abs a);
```

For clarity, each occurrence of `this` has been labeled with an abbreviation of its declared type.

To permit expressions that are not final access paths to be used as actual arguments, the type checker substitutes the actual argument types for dependent classes occurring in the formal parameter types. In this example, the receiver `v` has the type `base[this_A.class].Visitor`. Substituting this type for `this_V.class` in the formal parameter type `base[this_V.class].Abs` yields `base[base[this_A.class].Visitor].Abs`, which is equivalent to `base[this_A.class].Abs`.

To ensure soundness, substitution must satisfy the requirement that *exactness be preserved*; that is, when substituting into an exact type—a dependent class or a prefix of a dependent class—the resulting type must also be exact. This ensures that the run-time class or package represented by the type remains fixed. The substitution above is permitted since both `base[this_V.class]` and `base[this_A.class]` are exact.

However, if the type of `v` were just `base.Visitor`, then `v` might refer at run time to a `pair.Visitor` while at the same time `this_A` refers to a `base.Abs`. Substitution would yield `base[base.Visitor].Abs`, which simplifies to `base.Abs`. Since `base[this_A.class].Abs` is a subtype of `base.Abs`, the call would, incorrectly, be permitted, leading to a potential run-time type error. The problem is that there is no guarantee that the run-time classes of `this_A` and `v` both have the same enclosing `base` package. By requiring exactness be preserved, the substitution is illegal since `base` is not exact; therefore, the call to `visitAbs` where `v` is declared to be a `base.Visitor` is not permitted.

3.3 Intersection types

Multiple inheritance in JX/MI is implemented using intersection types [36, 9]. Rather than extend multiple superclasses, say T_1 and T_2, a class extends a single, implicit *intersection class type* $T_1 \,\&\, T_2$, which is a subclass (and subtype) of both T_1 and T_2. The declaration "`class D extends A1, A2`" is sugar for "`class D extends A1 & A2`".

The intersection type inherits all members of its base classes; however, its members cannot be overridden by the intersection class itself since the intersection is not declared explicitly in the program text; subclasses of the intersection type may override members.

```
class A {
  class B { }
  void m();
}

class A1 extends A {
  class B { }
  class C { }
  void m();
  void p();
}
```

```
class A2 extends A {
  class B { }
  class C { }
  void m();
  void p();
}

abstract class D extends A1, A2 { }
```

Fig. 3. Intersection type example

When two namespaces declare members with the same name, a *name conflict* may occur. How the conflict is resolved depends on where the name was introduced and whether the name refers to a nested class or to a method. If the name was introduced in a common ancestor of the intersected namespaces, the members with that name are assumed to be related. Otherwise, the name is assumed to refer to distinct members that coincidentally have the same name, but with possibly different semantics.

When two namespaces are intersected, their common nested namespaces are also intersected. In the code in Figure 3, both `A1` and `A2` contain a nested class `B` inherited from `A`. Since a common ancestor of `A1` and `A2` introduces `B`, the intersection type `A1 & A2` contains a nested class `(A1 & A2).B`, which is equivalent to `A1.B & A2.B`. The subclass `D` has an implicit nested class `D.B`, a subclass of `(A1 & A2).B`.

On the other hand, `A1` and `A2` both declare independent nested classes `C`. Even though these classes have the same name, they may have different semantics. The class `(A1 & A2).C` is *ambiguous*. In fact, `A1 & A2` contains two nested classes named `C`, one that is a subclass of `A1.C` and one a subclass of `A2.C`. Class `D` and its subclasses can specify which `C` is meant by exploiting the prefix type notation to resolve the ambiguity: `A1[D].C` refers to the `C` from `A1`, and `A2[D].C` refers to the `C` from `A2`. References to `C` within `A1` are interpreted as `A1[this.class].C`, and when inherited into `D`, these references refer to the `C` inherited from `A1`. Similarly, references to `C` within `A2` inherited into `D` refer to the `C` inherited from `A2`.

A similar situation occurs with the methods `A1.p` and `A2.p`. Again, `D` inherits both versions of `p`. Callers of `D.p` must resolve the ambiguity by up-casting the receiver to specify which one of the methods to invoke.

Finally, two or more intersected classes may declare methods with the same signature that override a method declared in a common base class. In this case, illustrated by the method `m` in Figure 3, the method in the intersection type is considered *abstract*. Subclasses of the intersection type (`D`, in the example), must override `m` to resolve the conflict, or else also be declared abstract.

Dependent classes and prefix types impose some restrictions on which types may be intersected. Intersecting two different exact types is not permitted, because members of the intersection type would be objects with more than one run-time class, which

is impossible. Since intersection types are used only in `extends` declarations, where the only variable in scope is `this` for the immediately enclosing class, this restriction does not limit expressiveness in practice. Similarly, a dependent type cannot be intersected with a non-dependent type unless the non-dependent type is a supertype of the dependent type (in which case, the intersection type is equivalent to just the subtype). Finally, two types conflict if any prefix of the types conflict; hence, subclasses of their intersection must be declared abstract. This restriction ensures that uses of prefix types inherited into the intersection type are meaningful.

3.4 Type equivalence

Prefix and intersection types permit a given type to be written in multiple ways. Type equivalence rules ensure types representing the same sets of run-time values are considered equal. We write $T \approx T'$ if types T and T' are equivalent.

The type constructor `&` is associative and commutative. In addition, if T_1 is a subtype of T_2, then $T_1 \,\&\, T_2 \approx T_1$. When two namespaces are intersected, members of their common nested namespaces are also intersected; thus, intersection types obey the following rule:

$$\frac{\Gamma \vdash T_1.C \quad \Gamma \vdash T_2.C}{\Gamma \vdash (T_1.C \,\&\, T_2.C) \approx (T_1 \,\&\, T_2).C} \qquad (\approx\text{-MEET-DIST})$$

The judgment $\Gamma \vdash T$ states that T is well-formed in typing context Γ.

The prefix type $P\texttt{[}T\texttt{]}$ is defined as the enclosing class of T that is a subtype of P:

$$\frac{\Gamma \vdash T \leq P \quad \Gamma \vdash P\texttt{[}T\texttt{]}}{\Gamma \vdash P\texttt{[}T\texttt{]} \approx T} \qquad (\approx\text{-PRE})$$

$$\frac{\Gamma \vdash P\texttt{[}T\texttt{]} \approx T' \quad \Gamma \vdash P\texttt{[}T.C\texttt{]}}{\Gamma \vdash P\texttt{[}T.C\texttt{]} \approx T'} \qquad (\approx\text{-PRE-NEST})$$

In JX/MI, unlike with virtual classes [14], it is possible to extend classes nested within other namespaces. Multiple nested classes or a mix of top-level and nested classes may be extended, resulting in an intersection of several types with different containers. This feature complicates equality of prefix types. Consider this example:

```
class A { class B { B x; } }
class A1 extends A { class B { B y = x; } }
class A2 extends A { class B { } }
class C extends A1.B, A2.B { }
```

The name `B` in `A.B` is interpreted as the type `A[this.class].B`. When inherited into `A1`, the name should resolve to an equivalent type, thus permitting the assignment from `x` to `y` in `A1.B`. In `A1.B`, the name `B` is interpreted as the type `A1[this.class].B`. Therefore, it must be that `A[this.class]` is equivalent to `A1[this.class]`. Similarly, `A[C]` $\approx$ `A1[C]` $\approx$ `A2[C]`. More generally, prefix types obey the following equivalence rule:

$$\frac{\Gamma \vdash P_1 \leq P_2 \quad \Gamma \vdash P_1\texttt{[}T\texttt{]} \quad \Gamma \vdash P_2\texttt{[}T\texttt{]}}{\Gamma \vdash P_1\texttt{[}T\texttt{]} \approx P_2\texttt{[}T\texttt{]}}$$

For an arbitrary prefix type $P\texttt{[}T\texttt{]}$, each superclass of T may have its own P prefix. The intersection of these prefixes is equivalent to $P\texttt{[}T\texttt{]}$. In the example above, each of the prefix types `A[C]`, `A1[C]`, and `A2[C]` is equivalent to the intersection type `A1&A2`. More formally, if $\mathit{supertypes}(\Gamma, T) = \{T_i \mid \Gamma \vdash T \leq T_i\}$, then

$$\frac{\{T_1, \ldots, T_n\} = \mathit{supertypes}(\Gamma, T) \quad (\forall i)\ \Gamma \vdash P\texttt{[}T_i\texttt{]}}{\Gamma \vdash P\texttt{[}T\texttt{]} \approx \&_i\, P\texttt{[}T_i\texttt{]}}$$

3.5 Constructors

As in Java, JX/MI initializes objects using constructors. JX/MI permits instances of dependent types to be allocated. Since the class being allocated may not be statically known, JX/MI allows the programmer to invoke a constructor of a superclass of the type being allocated. Constructors in JX/MI are inherited and can be overridden similarly to methods, ensuring the class represented by a dependent type implements a constructor with the same signature as the constructor invoked. The programmer can prevent a constructor from being inherited by declaring it `nonvirtual`; it is illegal to invoke a `nonvirtual` constructor on a dependent class.

A constructor for a given class must specify, using super constructor calls, how to invoke a constructor of each of the class's declared immediate superclasses. When a class explicitly extends multiple superclasses, it may share a common superclass. Invoking the shared constructor more than once may lead to inconsistent initialization of `final` fields, admitting the possibility of a run-time type error if the fields are used in dependent types.

To prevent this situation, if explicit multiple inheritance introduces sharing, JX/MI requires the new subclass (which introduced the sharing) to explicitly invoke a constructor of the shared superclass. The super constructor calls in the immediate subclasses of the shared class are not evaluated. This behavior is similar to that of constructors of shared virtual base classes in C++.

Sharing can also be introduced implicitly. For example, in Figure 4, the implicit class `D.C` is a subclass of `B1.C&B2.C` and shares the superclass `A`. Since `B1.C` and `B2.C` both inherit their `C()` constructor from `B.C`, both inherited constructors invoke the `A` constructor with the same arguments. There is no conflict and the compiler need only ensure that the constructor of `A` is invoked exactly once, before the body of `D.C`'s constructor is executed.

If, on the other hand, one or both of `B1` and `B2` overrode the `C()` constructor, then since `B1.C` and `B2.C` have different constructors with the same signature, one of them might change how the `C` constructor invokes `A(int)`. There is a conflict and `D` must override `C` to specify how `C()` should invoke the constructor of `A`.

3.6 Exact virtual types

One challenge for building extensible software systems is to provide extensible data processing, particularly when the input and output data have complex structure. Exten-

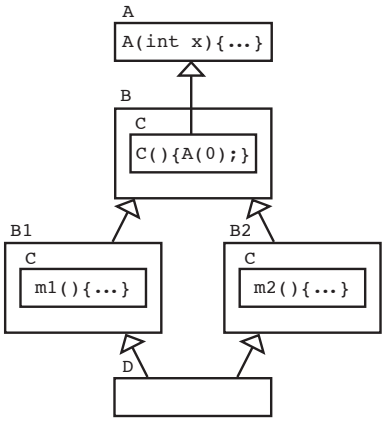

Fig. 4. Constructors in implicitly shared classes

sions to the software need to be able to scalably and modularly extend both the transformations performed on the data and the data being transformed. Compilers exhibit this difficulty, because compiler passes perform complex transformations on complex data structures representing program code. For scalable extensibility, it should not be necessary to change data transformers (e.g., compiler passes) if the extensions to the data representation do not interact with the transformation in question.

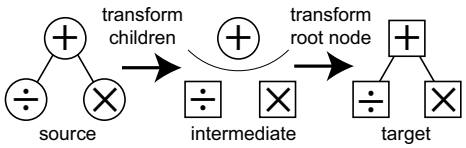

Fig. 5. AST transformation

A partial solution to this problem is the Visitor design pattern [16], which supports scalable extension of data processing. It allows boilerplate traversal of the input data structure to be factored out and shared. With minor extensions, visitors also support the generation of structured output data.

For example, consider an abstract syntax tree (AST) node representing a binary operation. As illustrated in Figure 5, most compiler passes for this kind of node would recursively transform the two child nodes representing operands, then invoke pass-specific code to transform the binary operation node itself, in general constructing a new node using the new children. This generic code can be shared by many passes.

However, the code for a given compiler pass might not be aware of the particular extended AST form used by a given compiler extension, and in general the source and target of the pass may be AST nodes for different languages—both, perhaps, extended versions of the base AST representation that the pass operates on. Because it is unaware

of any new children of the node added by extensions of the source language of the pass, it is hard to write a reusable compiler pass; the pass may fail to transform all the node's children. In the compiler example of Figure 1, a compiler pass transforms expressions in the lambda calculus extended with pairs into lambda calculus expressions without pairs. If this compiler pass is reused in a compiler in which expressions have additional type annotations, the source and target languages node will have children for these additional annotations, but the pass will not be aware of them and will fail to transform them.

To make a pass aware of any new children added by extensions of the source language, while preserving modularity, the solution is for the compiler to represent nodes in the intermediate form as trees with a root in the source language and children in the target language, corresponding to the middle tree of Figure 5. In the example of Figure 1, this can be done by creating, for both the source (i.e., `pair`) and target (i.e., `base`) language, packages `ast_struct` defining just the structure of each AST node. The `ast_struct` package is then extended to create source and target language packages for the actual AST nodes, and also to create a package *inside each visitor class* for the intermediate form nodes of that visitor's specific source and target language. This design is shown in Figure 6.

The key to making this design type-safe is a variant of virtual types [24, 25]—in this case, *virtual packages*, to link the packages together. In the `ast_struct` package, children of each AST node reside in a `child` virtual package. Like virtual types, virtual packages can be further bound in subclasses and subpackages. The `ast` package extends the `ast_struct` package and overrides `child` to bind it to the same `ast` package itself; the node classes in `ast` have children in the same package as their parent.

The `Visitor.tmp` package also extends the `ast_struct` package, but overrides `child` to bind it to the `target` package, which represents the target language of the visitor transformation. AST node classes in the `tmp` package have children in the `target` package, but parent nodes are in the `tmp` package; since `tmp` is a subpackage of `ast_struct`, nodes in this package have the same structure as nodes in the visitor's sibling `ast_struct` package. Thus, if the `ast_struct` package is overridden to add new children to an AST node class, the intermediate nodes in the `tmp` package will also contain those children.

Virtual types in JX/MI differ from those in languages from the BETA [24] family. First, virtual types in JX/MI are attributes of classes rather than of objects. Second, to enforce the requirement that exactness be preserved by substitution (see Section 3.2), virtual types and packages can be declared *exact*. For a given run-time container namespace T, the exact virtual type $T.C$ must be a fixed run-time class. Unlike a final-bound virtual type [24], an exact virtual type can be overridden in a subclass. For example, consider these declarations:

```
class A { }
class A2 extends A { }
class B { exact class T = A; }
class B2 extends B { exact class T = A2; }
```

The exact virtual type `B.T` is equivalent to the dependent class `new A().class`; that is, `B.T` contains only instances with run-time class `A`. Similarly, `B2.T` is equivalent to

```
package base.ast_struct;

exact package child = ast_struct;
abstract class Exp { }
class Abs extends Exp {
  String x; child.Exp e;
}
```

```
package base.ast
  extends ast_struct;

exact package child
  = base.ast[this.class];
abstract class Exp {
  abstract v.class.target.Exp
    accept(Visitor v);
  void childrenExp(Visitor v,
    v.class.tmp.Exp t) {
  }
}
```

```
package base;

class Visitor {
  // source language
  //   = base[this.class].ast
  // target language
  //   <= base.ast;
  exact package target = base.ast;
  package tmp extends ast_struct {
    exact package child = target;
  }
  ...
}
```

Fig. 6. Extensible rewriting example

`new A2().class`. If a variable `b` has declared type `B`, then an instance of `b.class.T` may have run-time class either `A` or `A2`, depending on the run-time class of `b`.

3.7 Packages

JX/MI supports inheritance of packages, including multiple inheritance. In fact, the most convenient way to use nested inheritance is usually at the package level, because large software is usually contained inside packages, not inside classes. Packages are treated like classes whose members are all static, and which lack constructors. The semantics of prefix packages and intersection packages are similar to those of prefix and intersection class types, described above. Since packages do not have run-time instances, the only exact packages are prefixes of a dependent class nested within the package.

4 Composing compilers

Using the language features just described we can construct a composable, extensible compiler.

Scalable, orthogonal extension of the base compiler with new data types and new operations is achieved through nested inheritance. Type name reinterpretation, made type-safe through dependent classes and prefix types, allows the entire base compiler to be extended and individual classes overridden to provide new functionality.

Because supertype declarations are interpreted in their inheriting context, new methods, fields, and member classes, added into an overridden class are automatically inherited into its subclasses. Overriding classes introduces entirely new versions of those classes. The original base classes are still available and need not be recompiled.

To support new syntax, an extended compiler need only introduce new abstract syntax node classes. If the base compiler uses the visitor design pattern, the base visitor interface can be extended with `visit` methods for the new nodes implementing default behavior, such as an identity transformation. Visitors for passes affected by the new syntax can be overridden to support it.

New passes can be added to the compiler by creating new visitor classes or by adding methods to the abstract syntax classes. Here again, default behavior can be added into the root class of all AST classes, and only those node types affected by the new pass need be overridden.

Independent compiler extensions can be composed using multiple nested inheritance with minimal effort. If the two compiler extensions are orthogonal, as for example with the product and sum type compilers of Section 2.3, then composing the extensions is trivial. If the language extensions have conflicting semantics, this will manifest as a name conflict when intersecting the classes within the two compilers. These name conflicts must be resolved to be able to instantiate the composed compiler.

5 Implementation

We implemented the JX/MI compiler in the Polyglot framework [31]. The compiler is a 2700-LOC (lines of code) extension of the JX compiler [29], itself a 22-kLOC extension of the Polyglot base Java compiler. (Note: blank and comment lines are not counted.)

5.1 Translating classes

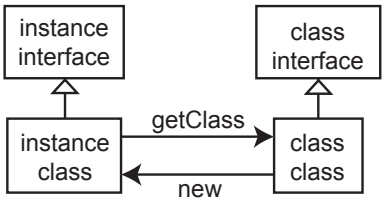

Fig. 7. Target classes and interfaces

The translation of JX/MI to Java is similar to the translation of JX to Java source code, described in [29]. As illustrated in Figure 7, each JX/MI class is represented by four classes: an *instance class*, an *instance interface*, a *class class*, and a *class interface*. The translation scheme described in the earlier paper has been extended to support intersection types and to make the generated code cleaner and more efficient.

References to a class or interface `C` are translated to references to `C`'s *instance interface*. The instance interface of `C` contains signatures for all instance methods of `C` as well as field getters and setters to allow access to fields from contexts where the actual run-time class is unknown. The instance interface of `C` extends the instance interface of

all of C's supertypes. Dependent classes, prefix types, and virtual types are translated to the instance interface of their most precise statically known simple supertype.

At run time, an object of the JX/MI class C is represented as a single object of the *instance class*, which implements the method interface of C. Instance classes are also generated for intersection classes. For non-intersection classes, the instance class of C extends the instance class of C's explicit superclass, which may be an intersection class. The instance class of an intersection class extends the instance class of the common ancestor of the intersected classes. Such an ancestor exists, since all classes are subclasses of Object. An instance class for C contains, or inherits from its superclass, all fields declared in C or inherited from any of the superclasses of C.

For every JX/MI class, there is a singleton *class class* object instantiated at run time. Every instance class contains a reference to its class class. Static methods are translated to instance methods of the class class to allow static methods to be invoked on dependent types, where the actual run-time class is unknown. To support super calls in the presence of multiple inheritance, instance methods are translated to methods of the class class. The instance class contains short one-line methods to dispatch to the implementation of the method in the appropriate class class. The class class also provides functions for accessing run-time type information to implement instanceof and casts, for constructing instances of the class, and for accessing the class class of prefixes and members classes, including virtual types. The code generated for expressions that dispatch on a dependent class—new x.class() expressions, for example—evaluates the dependent class's access path to locate the class class for the type. For prefix types, the class class is used to navigate to the prefix of the type.

The class class implements the *class interface* of each of the class's supertypes. The class interface contains signatures for all static methods of the class and also a factory method for each constructor.

5.2 Translating packages

To support package inheritance and composition, the representation of a package p includes a *package interface* and a *package class* that implements the interface, analogous to the class interface and class class. The package class provides type information about the package at run time and access to the class class or package class singletons of its members and prefixes. Both the package class and package interface of p are members of package p; packages have no instance classes or instance interfaces.

5.3 Java compatibility

Since JX/MI is translated to Java, the generated code can only use single inheritance. To interact with Java code, a JX/MI class may have only one most-specific Java superclass. The generated instance class is a subclass of this Java class. Because the instance interface is not a subtype of any Java class (except Object), when passing JX/MI objects to a method expecting a Java class, the object must be cast from the instance interface type to the expected Java supertype.

6 Experience

6.1 Polyglot

Following the approach described in Section 4, we ported the Polyglot compiler framework and several Polyglot-based extensions, all written in Java, to JX/MI. The Polyglot base compiler is a 31.9 kLOC program that performs semantic checking on Java source code and outputs equivalent Java source code. Special design patterns make Polyglot highly extensible [29]; more than a dozen research projects have used Polyglot to implement various extensions to Java (e.g., JPred [28], JMatch [23], as well as JX and JX/MI). For this work we ported six extensions ranging in size from 200 to 3000 LOC.

The port of the base compiler was our first attempt to port a large program to JX/MI, and was completed by one of the authors within a few days, excluding time to fix bugs in the JX and JX/MI compilers. Porting of each of the extensions took from one hour to a few days. Much of the porting effort could be automated, with most files requiring only modification of `import` statements. Porting issues are described below.

The ported base compiler is 28.0 kLOC. The code becomes shorter because it eliminates factory methods and other extension patterns necessary to make the Java version extensible, but which are not needed in JX/MI. We eliminated only extension patterns that were obviously unnecessary, and could remove additional code with more effort.

The number of type downcasts in each extension is reduced in JX/MI. For example, `coffer` went from 192 to 102 downcasts. The reduction is due to (1) use of dependent types, obviating the need for casts to access methods and fields introduced in extensions, and (2) removal of old extension mechanism code. Receivers of calls to conflicting methods sometimes needed to be upcast to resolve the ambiguities; there are 19 such upcasts in the port of `coffer`.

Table 1. Ported Polyglot extensions

Name	Extends Java 1.4 ...	LOC original	LOC ported
`polyglot`	with nothing	31888	27984
`param`	with infrastructure for parameterized types	513	540
`coffer`	with resource management facilities similar to Vault [10]	2965	2642
`j0`	with pedagogical features	679	436
`pao`	to treat primitives as objects	415	347
`carray`	with constant arrays	217	122
`covarRet`	to allow covariant method return types	228	214

The extensions are summarized in Table 1. The parsers for the base compiler, extensions, and compositions were generated from CUP [19] or Polyglot parser generator (PPG) [31] grammar files. Because PPG supports only single grammar inheritance, grammars were composed manually; line counts do not include parser code.

Table 2 shows lines of code needed to compose each pair of extensions, producing working compilers that implemented a composed language. The `param` extension was not composed because it is an *abstract extension* containing infrastructure for parameterized types, and it does not change the language semantics; however, `coffer` extends the `param` extension.

Table 2. Polyglot composition results: lines of code

	`j0`	`pao`	`carray`	`covarRet`
`coffer`	63	86	34	66
`j0`		46	34	37
`pao`			34	53
`carray`				31

The data show that all the compositions can be implemented with very little code; further, most added code straightforwardly resolves trivial name conflicts, such as between the methods that return the name and version of the compiler. Only three of ten compositions (`coffer & pao`, `coffer & covarRet`, and `pao & covarRet`) required resolution of nontrivial conflicts, for example, resolving conflicting code for checking method overrides. The code to resolve these conflicts is no more 10 lines in each case.

6.2 Pastry

We also ported the FreePastry peer-to-peer framework [37] version 1.2 to JX/MI and composed a few Pastry applications. The sizes of the original and ported Pastry extensions are shown in Table 3. Excluding bundled applications, FreePastry is 7100 lines of Java code.

Host nodes in Pastry exchange messages that can be handled in an application-specific manner. In FreePastry, network message dispatching is implemented with `instanceof` statements and casts. We changed this code to use more straightforward method dispatch instead, thus making dispatch extensible and eliminating several downcasts. Messages are dispatched to several protocol-specific handlers. For example, there is a handler for the routing protocol, another for the join protocol, and others for any applications built on top of the framework. The Pastry framework allows applications to choose to use one of three different messaging layer implementations: an RMI layer, a wire layer that uses sockets or datagrams, and an in-memory layer in which nodes of the distributed system are simulated in a single JVM. Family polymorphism enforced by the JX/MI type system statically ensures that messages associated with a given handler are not delivered to another handler and that objects associated with a given transport layer are not used by code for a different layer implementation.

Pastry implements a distributed hash table interface. Beehive [33] and PC-Pastry extend Pastry with caching functionality. PC-Pastry [33] uses a simple passive caching algorithm, where lookups are cached on nodes along the route from the requesting node to a node containing a value for the key. Beehive actively replicates objects throughout

the network according to their popularity. We introduced a package ("`cache`") containing functionality in common between Beehive and PC-Pastry; the CorONA RSS feed aggregation service [34] was modified to extend the `cache` package rather than Beehive.

Using multiple nested inheritance, the modified CorONA was composed first with Beehive, and then with PC-Pastry, creating two applications providing the CorONA RSS aggregation service but using different caching algorithms. Each composition of CorONA and a caching extension contains a single `main` method and some configuration constants to initialize the cache manager data structures. The CorONA–Beehive composition also overrides some CorONA message handlers to keep track of each cached object's popularity. We also implemented and composed test drivers for the CorONA extension, but line counts for these are not included since the original Java code did not include them.

Table 3. Ported Pastry extensions and compositions

Name	LOC original	LOC ported
Pastry	7082	7363
Beehive	3686	3634
PC-Pastry	695	630
CorONA	626	591
`cache`	N/A	140
CorONA–Beehive	N/A	68
CorONA–PC-Pastry	N/A	28

The JX/MI code for FreePastry is 7400 LOC, 300 lines longer than the original Java code. The additional code consists primarily of interfaces introduced to implement network message dispatching. The Pastry extensions had similar message dispatching overhead; since code in common between Beehive and PC-Pastry was factored out into the `cache` extension, the size of the ported extensions is smaller. The size reduction in CorONA is partially attributed to moving code from the CorONA extension to the CorONA–Beehive composition.

6.3 Porting Java to JX/MI

Porting Java code to JX/MI was usually straightforward, but certain common issues are worth discussing.

Type names. In JX/MI, unqualified type names are syntactic sugar for members of `this.class` or a prefix of `this.class`, e.g., `Visitor` might be sugar for `base[this.class].Visitor`. In Java, unqualified type names are sugar for fully qualified names; thus, `Visitor` would resolve to `base.Visitor`. To take full advantage of the extensibility provided by JX/MI, fully qualified type names sometimes must be changed to be only partially qualified.

In particular, `import` statements in most compilation units are rewritten to allow names of other classes to resolve to dependent types. For example, in Polyglot the import statement `import polyglot.ast.*;` was changed to `import ast.*;` so that imported classes resolve to classes in `polyglot[this.class].ast` rather than in `polyglot.ast`.

Final access paths. To make some expressions pass the type checker, it was necessary to declare some variables final to allow them to be coerced to dependent classes. In many cases, non-final access paths used in method calls could be coerced automatically by the compiler, as described in Section 3.1. However, non-final field accesses were not coerced automatically because the field might be updated (possibly by another thread) between evaluation and method entry. The common workaround is to save non-final fields in a final local variable and then to use that variable in the call.

This issue was not as problematic as originally expected. In fact, in 30 kLOC of ported Polyglot code, only three such calls needed to be modified. In most other cases, the actual method receiver type was of the form P`[`p`.class]`$.Q$ and the formal parameter types were of the form P`[this.class]`$.R$. Even if an actual argument were updated between its evaluation and method entry its new value is a class enclosed by the same run-time namespace P`[`p`.class]` as the receiver, ensuring that the call is safe.

Path aliasing The port of Pastry and its extensions made more extensive use of field-dependent classes than the Polyglot port. Several casts needed to be inserted in the JX/MI code for Pastry to allow a type dependent upon one access path to be coerced to a type dependent upon another path. Often, the two paths refer to the same object, ensuring the cast will always succeed. Implementing a simple local alias analysis should eliminate the need for many of these casts.

7 Related work

There has been great interest in the past several years in mechanisms for providing greater extensibility in object-oriented languages. object-oriented languages with additional extensibility. Nested inheritance uses ideas from many of these other mechanisms to create a powerful and relatively transparent mechanism for code reuse.

Virtual classes. Nested classes in JX/MI are similar to virtual types and virtual classes [24, 25, 20, 14]. Virtual types were originally developed for the language BETA [24, 25], primarily for generic programming rather than for extensibility.

Although virtual types in BETA were not statically type safe, Ernst's generalized BETA (gbeta) language [11, 12] uses path-dependent types, similar to dependent classes in JX/MI, to ensure static type safety. Type-safe virtual classes using path-dependent types were formalized by Ernst et al. [14]. However, virtual classes may only have one enclosing instance; for this reason, a class may not extend a more deeply nested virtual class. This can limit the ability to extend components of a larger system.

Virtual classes in gbeta support *family polymorphism* [13]: two virtual classes enclosed by distinct objects cannot be statically confused. Because nested classes in JX/MI

are attributes of their enclosing class, rather than an enclosing object, nested inheritance supports *class-based family polymorphism*. With family polymorphism, each object defines a family of mutually dependent classes; with class-based family polymorphism, each dependent class defines a family. By using prefix types, any member of the family can be used to name the family; with virtual classes all family members must be named from a single "family object".

Scala [32] is another language that supports scalable extensibility and family polymorphism through a statically safe virtual type mechanism based on path-dependent types. However, Scala's path-dependent type *p*.`type` is a singleton type containing only the value named by access path *p*; in JX/MI, *p*.`class` is not a singleton. For instance, `new x.class(...)` creates a new object of type `x.class` distinct from the object referred to by `x`. This difference gives JX/MI more flexibility, while preserving type soundness. Scala has no analogue to prefix types nor does it provide virtual superclasses, mitigating the scalability of the extension mechanisms provided.

Concord [21] also provides a type-safe variant of virtual classes. In Concord, mutually dependent classes are organized into *groups*, which can be extended via inheritance. References to other classes within a group are made using types dependent on the current group, `MyGrp`, similarly to how prefix types are used in JX/MI. Relative supertype declarations provide functionality similar to virtual superclasses. Groups in Concord cannot be nested, nor can groups be multiply inherited.

Class hierarchy composition. Tarr et al. [42] define a specification language for composing class hierarchies. Rules specify how to merge "concepts" in the different hierarchies. Multiple nested inheritance supports composition with a rule analogous to merging concepts by name.

Snelting and Tip [40] present an algorithm for composing class hierarchies and a semantic interference criterion. If the hierarchies are *interference-free*, the composed system preserves the original behavior. JX/MI reports a conflict if composed class hierarchies have a *static interference*, but makes no effort to detect dynamic interference.

Multiple inheritance and mixins. Cardelli [7] presents a formal semantics of multiple inheritance. Intersection types are due to Reynolds [36] and were used by Compagnoni and Pierce to model multiple inheritance [9].

The distinction between name conflicts among methods introduced in a common base class and among methods introduced independently with possibly different semantics was made as early as 1982 by Borning and Ingalls [1]. Many languages, such as C++ [41] and Self [18], treat all name conflicts as ambiguities to be resolved by the caller. Some languages [26, 2, 38] allow methods to be renamed or aliased.

A *mixin* [2, 15], also known as an *abstract subclass*, is a class parameterized on its superclass. Mixins are able to provide uniform extensions, such as adding new fields or methods, to a large number classes. Mixins can be simulated using explicit multiple inheritance. JX/MI provides additional mixin-like functionality by allowing the superclass of an existing base class to be changed or fields and methods to be added by overriding the class's superclass through extension of the superclass's container. Additionally, nested inheritance allows the implicit subclasses of the new base class to be instantiated without writing any additional code. Mixins have no analogous mechanism.

Since mixins are composed linearly, a class may not be able to access a member of a given super-mixin because the member is overridden by another mixin. Explicit multiple inheritance imposes no ordering on composition of superclasses. Both gbeta [12] and Scala [32] support mixin composition. Similarly to multiple nested inheritance, composition of mixins in these languages combines nested classes.

Self types and matching. Bruce et al. [5, 3] introduce *matching* as an alternative to subtyping, with a *self type*, or `MyType`, representing the type of the method's receiver. The dependent class `this.class` is similar but represents only the class referred to by `this` and not its subclasses. Type systems with `MyType` decouple subtyping and subclassing; in PolyTOIL and LOOM, a subclass *matches* its base class but is not a subtype. With nested inheritance, subclasses are subtypes. In [6, 4], Bruce and Vanderwaart propose *type groups* as a means to aggregate and extend mutually dependent classes, similarly to Concord's group construct.

Open classes. An *open class* [8] is a class to which new methods can be added without needing to edit the class directly, or recompile code that depends on the class. Nested inheritance provides similar functionality through class overriding in an extended container. Nested inheritance provides additional extensibility that open classes do not, such as the "virtual" behavior of constructors, and the ability to extend an existing class with new fields that are automatically inherited by its subclasses.

Aspect-oriented programming. Aspect-oriented programming (AOP) [22] is concerned with the management of *aspects*, functionality that cuts across modular boundaries. Nested inheritance provides aspect-like extensibility; an extension of a container may implement functionality that cuts across the class boundaries of the nested classes. Aspects modify existing class hierarchies, whereas nested inheritance creates a new class hierarchy, allowing the new hierarchy to be used alongside the old. Caesar [27] is an aspect-oriented language that also supports family polymorphism, permitting application of aspects to mutually recursive nested types.

8 Conclusions

This paper introduces multiple nested inheritance and shows that it is an effective language mechanism for extending and composing large bodies of software. Extension and composition are scalable, because new code needs to be written only to implement new functionality or to resolve conflicts between composed classes and packages. Novel features like prefix types and exact virtual types offer important expressive power.

Multiple nested inheritance has been implemented in an extension of Java called JX/MI. Using JX/MI, we implemented a compiler framework for Java, and showed that different domain-specific compiler extensions can easily be composed, resulting in a way to construct compilers by choosing from available language implementation components. We demonstrated the utility of multiple nested inheritance outside the compiler domain by porting the FreePastry peer-to-peer system to JX/MI. The effort required to port Java programs to JX/MI is not large. Ported programs were smaller, required fewer type casts, and supported more extensibility and composability.

We have informally described here the static and dynamic semantics of JX/MI. We have not shown that this type system is sound; however, it appears feasible to extend the previous proof for the soundness of JX [30].

Multiple nested inheritance is a powerful and convenient mechanism for building highly extensible software. We expect it to be useful for a wide variety of applications.

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