Flexible Type-Safe Linking of Components for Java-like Languages*

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Abstract. We define a framework of components based on Java-like languages, where components are binary mixin modules. Basic components can be obtained from a collection of classes by compiling such classes in isolation; for allowing that, requirements in the form of type constraints are associated with each class. Requirements are specified by the user who, however, is assisted by the compiler which can generate missing constraints essential to guarantee type safety.
Basic components can be composed together by using a set of expressive typed operators; thanks to soundness results, such a composition is always type safe.
The framework is designed as a separate layer which can be instantiated on top of any Java-like language; to show the effectiveness of the approach, an instantiation on a small Java subset is provided, together with a prototype implementation.
Besides safety, the approach achieves great flexibility in reusing components for two reasons: (1) type constraints generated for a single component exactly capture *all possible* contexts where it can be safely used; (2) composition of components is not limited to conventional linking, but is achieved by means of a set of powerful operators typical of mixin modules.

1 Introduction

It has been argued that the notion of software component is so general that cannot be defined in a precise and comprehensive way [14]. For instance, [25] provides three different definitions, that adopt different levels of abstraction. However, most researchers would agree that the following features are essential prerequisites for component technology: *modularity*, *type safety*, and *independence* from a particular programming language.
Modules and components share several common characteristics. The important software engineering principle of maximizing cohesion and minimizing dependencies of code applies as well to modules and to components. Furthermore, both modules and components are meant as units of composition which can be developed independently.
Type safety is an important property which guarantees a correct integration between components; separate development of components requires explicit interfaces not only for the provided services, but also for the requirements which ensure safe assembly of components. In order to maximize reuse, required interfaces should capture as many as possible contexts where a component can be safely used.
While modules are often tied to a specific programming language, components are usually meant as binary units, and therefore should not depend on a particular programming language; of course, basic components still need to be constructed by using some programming language. For instance, .NET assemblies do not strongly rely on any particular language, but can be created,

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for instance, both from C# and Haskell code. However assembling components is a process which should involve only binary units and, therefore, is expected to be language independent. The benefits of this independence are a better integration and interoperability of components, especially when the binary form is some kind of intermediate language.
Among the several varieties of modules which can be found in programming languages or have been proposed in literature, *mixin modules* are one of the closest approximations of the notion of software component.
Module systems based on the notion of mixin module offer a framework largely independent from the core language with well-established and clean foundations [9, 5, 27, 21, 7, 16]. Differently to parametric modules, like, for instance, ML functors, which offer only one composition operator roughly corresponding to function application, mixin modules are equipped with a richer set of operators that support *mutual recursion* across module boundaries and declaration of *virtual* entities which can be redefined via an *overriding* operator. For this reason, mixin modules seem a good starting point for defining a language independent framework for flexible composition and reuse of components in a type safe way. The main difference between a mixin module and a component is that the former is modeled as a collection of classes in source form, while the latter is modeled as a collection of classes in binary form. Of course, in practice there are other differences which we deliberately do not model in this paper: for instance, in general a component is a collection of more heterogeneous entities including not only code, but also resources like, for instance, multimedia data.[1]
Nowadays component technology is mainly based on mainstream object-oriented languages; nevertheless, object-oriented languages alone fail to provide important features for developing and assembling components. Compositional compilation is not supported by mainstream object-oriented languages, even though this property is important for allowing separate development of components: users should be able to obtain a basic component from a collection of classes by simply compiling such classes in total isolation. Furthermore, linking is the only available mechanism for manipulating and assembling binary components.
In this paper, we investigate how to build a framework for component-oriented programming based on Java-like languages. The framework is meant as a logically separate layer constructed on top of the Java-like language used for creating basic components.
In the framework, components are modeled as mixin modules in binary form, by following and further developing the approach presented in [6]. Furthermore, separate development of components is possible by adopting the type technology we have developed for Java-like languages in a previous work [2] based on the two notions of *polymorphic type constraint* and *polymorphic bytecode*. Polymorphic type constraints allow the specification of the minimal requirements needed by a component for being safely used; compilation in total isolation of classes into components is achieved by generating polymorphic bytecode, a bytecode annotated with type variables which can be instantiated according to the context where a component is deployed.
The framework allows separate compilation of classes into basic components starting from the declarations of such classes in a Java-like language and from the specification of the requirements needed by the classes. Then, components in polymorphic bytecode can be assembled together in a type safe way by means of five composition operators: *bind*, *merge*, *renaming*, *unbind*, and *restrict*.
Other interesting features of the framework are the following:

– Since specifying the requirements needed by a class can be a tedious activity, the framework assists the programmer by generating those constraints which have not been explicitly specified by the user, but are nevertheless necessary for guaranteeing a type safe composition. The

[1] We refer to [25], Section 4.1.4, for more details.

interface obtained in this hybrid way is then permanently associated with the polymorphic bytecode of the class in the components.
- Classes in a component are all implicitly considered *virtual*, that is, their definition can be later replaced when composing the component with others.
- In addition to composition operators typical of mixin modules [9, 7], the framework provides two novel operators[2] *bind* and *unbind*, designed for better supporting unanticipated software evolution.

The paper is organized as follows. Section 2 is a gentle introduction to the framework; some examples are used for explaining its main features and its ability to support software reuse and unanticipated software evolution. In Section 3 we formally define the framework, by listing the ingredients the underlying Java-like language should provide. We give reduction semantics and typing rules, and show soundness of the type system. In Section 4 we show how the framework can be instantiated on top of a simple language which is basically Featherweight Java [17]. Section 5 is devoted to the implementation of the framework: a prototype is available[3] for testing most of the examples shown in Section 2. Finally, Section 6 outlines related work, summarizes paper contribution and draws directions for future developments.
A preliminary presentation of the ideas developed in this paper can be found in [4].

2 A Gentle Introduction to Components

This section is a brief introduction to our component-oriented system: its main features are presented through some simple, but still meaningful, examples showing its expressive power.
Even though our operators handle components in binary form (more precisely, in polymorphic bytecode), in the examples we write components in source format for readability. In particular, we choose Java as source language, but all code could be easily rewritten in, say, C#.

2.1 Basic Components

Let us start our introduction with an example[4] of declaration of basic component:

```
component LinkedList = {
  deferred class N;
  class List {
    requires { N(N); }
    N first;
    void addFirst(){first=new N(first);}
  }
  class Node{
    requires { & N; }
    N next;
    Node(N n){next=n;}
    N getNext(){return next;}
  }
}
```

[2] Which, however, can be encoded in lower-level operators of module calculi such as CMS [7]; see end of Sect.3.1 for details.
[3] `http://www.disi.unige.it/person/LagorioG/SmartJavaComp/`
[4] For simplicity, we will keep the examples small and avoid access modifiers.

A basic component is a collection of declarations of classes which are either *deferred*, that is, whose definition has to be provided later, like `N`, or *defined* inside the component, like `List` and `Node`. Class definitions are those in the Java-like language under consideration, enriched by a `requires` part which specifies *type constraints* on deferred classes, which of course also depend on the language. In the example, constraint `N(N)` means that class `N` is required to have a constructor applicable to an argument of type `N`, whereas constraint `&N` means that class `N` must exist. Other forms of constraints are subtyping constraints and constraints requiring a class to have a field of a certain type or a method applicable to certain argument types; moreover, constraints are *polymorphic* in the sense that types can be type variables, as will be illustrated below.

As shown below, deferred classes can be bound to a definition by means of the *bind* and *merge* operators. Within this example, the intuition is that `N` *could be* `Node`; indeed, if we replaced all occurrences of `N` with `Node`, then we would obtain the classic example of single-linked lists with a header node. However, having used a deferred class instead of the already defined class `Node` allows us to bind `N` to something more specific than `Node` later, for instance a class `DoubleNode` (which, presumably, extends `Node`).

This particular use of a deferred class allows one to simulate type mechanisms as *mytype* [11], or `ThisClass` of LOOJ [10], where *mytype* can be used inside a method of a class to refer to the class itself, and, similarly to what happens with *this*, is redirected to the proper subclass when the method is inherited..

However, our approach allows a step further: `N` can be bound to *any class* that satisfies the type constraints declared in class `List` and `Node`, and not just to a subclass of `Node`. For instance, class `Node` simply requires an existing definition for `N`, since `N` is used in `Node` only as a type, while the correctness of `List` relies on a stricter constraint[5] asking `N` to provide a constructor which takes an argument of type `N` (hence, with a single parameter whose type is a supertype of `N`).

Note that constraints are declared at the level of each class definition, rather than at the level of the component declaration. As we will see, this is due to the fact that classes declared in components are all *virtual:* for instance, a new component could be derived from `LinkedList` by overriding the declaration of `Node`. In this case, the constraints associated with `Node`, and only those, are analogously replaced.

Component `LinkedList` supports an important feature for promoting component-oriented programming: each class is explicitly equipped not only with the interface of the provided services (what is usually, and improperly, called the provided interface), but also with the interface of the required features (what is usually, and improperly, called the required interface). Indeed, provided and required interfaces for classes `List` and `Node` can be easily extracted from their code:

```
class List {
  requires { N(N); }
  provides { N first; void addFirst(); }
}
class Node{
  requires { & N; }
  provides { N next; Node(N n); N getNext(); }
}
```

Providing the required interface should allow compilation of a component in *total isolation* (no other sources or binary files are needed) and composition with other components (already in

[5] Indeed, the constraint `N(N)` implies `& N`.

binary form) in a *type safe* manner. To this end, the required interface should specify, on the one hand, all the requirements on deferred classes which are needed to compile the component; on the other hand, it should not specify requirements which are not strictly necessary, in order to allow safe composition with as many other components as possible. For Java-like languages, this can be achieved by using the approach we propose based on type constraints, whereas cannot be achieved by using other forms of required interfaces. For instance, compilation in isolation of the component above cannot be achieved by using the approach based on only subtyping constraints adopted for Java generics; there is no way to guarantee that class `N` has a constructor which is type compatible with the call in method `addFirst` by simply requiring class `N` to extend some already defined class or interface.

Conversely, an approach where the required interface has to specify for each deferred class its expected signature (that is, constructor, field and method signatures), as done, e.g., in our previous work [6], is too restrictive in the other respect, since it rejects components which do not match this type but can still be linked in a safe way with the given component. We will illustrate better this point in the following when introducing the merge operator.

Since specifying required interfaces by listing all the needed type constraints may be a tedious and error prone activity, the specification of required interfaces is assisted by the compiler: the most general constraints which are required by a component, but are not explicitly specified by the programmer, are automatically generated and added to the required interface. In this way the compiled code will contain the complete required interface, including both the user constraints and the missing ones inferred by the compiler.

Some kinds of type constraints written by the user are expanded by the compiler in a more verbose form; for instance the type constraint `N(N)` required by the user in class `List` is automatically expanded into `constructor(N,<N>,<'a>)`, where `'a` is a freshly generated type variable, and angle brackets enclose list of types. The same form of constraint is generated by the compiler, if the user-defined constraint is omitted.

The constraint `constructor(N,<N>,<'a>)` requires that class `N` has a constructor with a parameter of type `'a` which is selected whenever a constructor of `N` is invoked with an actual argument of type `N` (therefore, among the parameter types of all constructors of `N` with one parameter, `'a` is the least such that `N<='a`).

The same type variable `'a` is used for annotating the corresponding constructor invocation in the polymorphic bytecode. Note that constructor invocations in standard Java bytecode are always annotated with class names, while annotations in polymorphic bytecode include type variables as well.

Keeping track of the polymorphic bytecode annotation `'a` in the constraint `constructor(N,<N>,<'a>)` is *essential* for deploying components in a compositional way. When the deployer (see Section 5) verifies the constraint `constructor(N,<N>,<'a>)`, it can also substitute the annotation `'a` in the polymorphic bytecode with the proper class name.

Similar considerations apply for those two kinds of constraints dealing with field access and method invocation, respectively.

Type variables can be used by the user as well, for imposing more general requirements (see for instance the merge example in Section 2.3). Furthermore, the user can always specify constraints which are not strictly necessary to guarantee type safety, but that are needed for contractual reasons.

For instance, in class `List` the user could specify the requirement `N <= Node` which requires `N` to be a subclass of `Node`, even though this condition is not necessary for the type safety of the code of the class. The required interface generated with the code will contain both the user-defined constraint `N <= Node` and the inferred constraint `constructor(N,<N>,<'a>)`.

As shown in the following, the generated required interface will be used together with the provided interface, to check type safety of component composition.
Note that the type variables which occur in the constraints are all existentially quantified and their scope is limited to the required interface; that is, the required interface for class `List` could be more properly written as follows:

```
class List {
  requires { ∃ 'a.constructor(N,<N>,<'a>); }
  ...
}
```

The fact that the provided interface might contain type variables as well merely depends on the underlying programming language: for instance, only Java 5.0 and later versions allow generic classes and polymorphic methods.

2.2 Soft and hard links

Classes can be referenced through either *qualified class names* or *simple class names* (that is, unqualified class names). Let us consider for instance the following component:

```
component AComponent = {
  deferred class Elem;
  class C{
    Elem e;
    List@LinkedList l;
    void m(C c){...} ...
  }
}
```

The qualified name `List@LinkedList` is used for referencing class `List` at component[6] `LinkedList`; indeed, class `List` cannot be correctly referenced through its simple name, since it is neither defined, nor deferred in component `AComponent`. On the other hand, class `C` and `Elem` can be correctly referenced through their simple class names because they are declared inside `AComponent`. These two notations reflect two different ways of referencing classes: a *soft link* to a class is any of its unqualified occurrences except those which introduce the declaration of either the class itself, or any of its constructors, whereas a *hard link* to a class is any of its qualified occurrences. The difference between soft and hard links is methodological: soft links are allowed to be redirected (through the composition operators), whereas hard links permanently refer to a fixed class in a fixed component. [7]

2.3 Open and Closed Components

A component with deferred classes, as `LinkedList`, is called *open*; analogously, a component with no deferred classes is called *closed*.
There are two different composition operators for deriving closed components from open ones: *bind* and *merge*.

[6] To avoid ambiguities with the syntax used by Java-like languages for member accesses, we prefer to avoid the dot notation for components.
[7] See more in Section 2.7.

Bind A closed component can be obtained by binding the deferred classes of some open component to declarations in the same component. For instance, a new component `ClosedLinkedList` could be obtained from `LinkedList` by binding `N` to `Node`, since class `Node` satisfies all required constraints on `N`:

```
component ClosedLinkedList=bind(LinkedList,N->Node);
```

The component we obtain in this way is equivalent to (that obtained compiling) the following, where we have copied the definition of `LinkedList` and replaced each occurrence of `N` by `Node`.

```
component ClosedLinkedList = {
  class List {
    requires { Node(Node); }
    Node first;
    void addFirst(){first=new Node(first);}
  }
  class Node {
    requires { & Node; }
    Node next;
    Node(Node n) {next=n;}
    Node getNext() {return next;}
  }
}
```

Now classes `List` and `Node` can be used:

```
List@ClosedLinkedList l=new List()@ClosedLinkedList;
```

When closing a component, all type constraints in the class types must be verified, otherwise a type error is issued.[8] For instance, the expression `bind(LinkedList,{N->List})` is not type correct, since `List` does not satisfy the constraint `List(List)`.
Note that the constraints in `ClosedLinkedList` cannot be removed by the compiler even though they are clearly satisfied. Indeed, a closed component is not permanently "sealed", but can be reopened using operators *restrict* and *unbind*, which will be discussed in Section 2.5. So, for instance, the required and provided interfaces for classes in `ClosedLinkedList` are

```
class List {
  requires { Node(Node); }
  provides { Node first; void addFirst(); }
}
class Node{
  requires { & Node; }
  provides { Node next; Node(Node n); Node getNext(); }
}
```

Merge Assume we want to extend the code in `LinkedList` in order to support doubly linked lists. This extension can be isolated in a separate component:

```
component Double = {
```

[8] For constraint verification see also Section 2.6.

```
  deferred class N, List, Node;
  class DoubleList extends List {
    requires { N(N,'a); 'a List.first; N<='a; 'a N.next; 'a 'a.prev; }
    N last;
    void addLast() {
      N n = new N(last, null);
      if (first==null) first = n;
      if (last!=null) last.next = n;
      last = n;
    }
    void addFirst() {
      N n=new N(null, first);
      if (first!=null) first.prev = n;
      first = n;
      if (last==null) last=n;
    }
  }
class DoubleNode extends Node {
  requires {Node(N); }
  N prev;
  DoubleNode(N n) {super(n);}
  DoubleNode(N p,N n) {super(n); prev=p;}
  N getPrev() { return prev; }
  }
}
```

Before explaining how the merge operator behaves, let us focus on the user requirements in `DoubleList`: class `N` must have a constructor with two parameters of type `N` and `'a` (`N(N,'a)`), class `List` is expected to have a field `first` of type `'a` (`'a List.first`) such that `'a` is a supertype of `N` (`N<='a`), and type `'a` is required to have a field `prev` of type `'a` (`'a.prev='a`). Note that, as anticipated above, the type variable `'a` is used for expressing requirements more general[9] than those we could express with a required interface which specifies for each deferred class its expected signature. Indeed, in this case we should have fixed for instance the type of field `f` in `List`, e.g., requiring this type to be `N`, whereas in fact any supertype of `N` would work as well.
A new component `DoubleLinkedList` can be defined by merging `LinkedList` with `Double`:

```
component DoubleLinkedList=merge(LinkedList,Double);
```

In `DoubleLinkedList` the two deferred classes `List` and `Node` of component `Double` are bound to the corresponding declarations in `LinkedList`, whereas class `N` remains deferred (indeed binding of deferred classes is by name matching). Note that, while it is possible to merge components with deferred classes having the same name, name conflicts for defined classes are not allowed. Finally, it is possible to bind `N` to `DoubleNode` in `DoubleLinkedList`:

```
component ClosedDoubleLinkedList = bind(DoubleLinkedList,N->DoubleNode);
// this below would be a type error, since DoubleList requires N to satisfy N(N,'a)
//
// component ClosedDoubleLinkedList = bind(DoubleLinkedList, N->Node) ; // ERROR
```

[9] For sake of simplicity we have omitted to specify the most general requirements as they would be inferred by the compiler.

2.4 Renaming Facilities

Since binding of deferred classes is by name matching, a renaming operator might be useful in some circumstances.
For instance, if in `Double` the two deferred classes `List` and `Node` were named `L` and `Nd`, respectively, then a renaming would be necessary before merging `LinkedList` with `Double`.

```
component DoubleLinkedList = merge(LinkedList,rename(Double,{L->List,Nd->Node}));
```

The *rename* operator allows renaming of a single class name at time, therefore the expression `rename(Double,{L->List,Nd->Node})` is just a convenient shortcut for the more verbose one:

```
rename(rename(Double,L->List),Nd->Node)
```

Renaming of more classes is accomplished sequentially from left to right. Both deferred and defined classes can be renamed. Since the operator allows only bijective renamings, the newly introduced name must be unused in order to avoid conflicts.

2.5 Unbind and Restrict

Let us consider again component `ClosedLinkedList` as defined in Section 2.3. As already noted, the constraints on class `Node` cannot be removed by the compiler without compromising type safety. This is due to the fact that it is possible to derive an open component from a closed one by making some class deferred. This can be accomplished by using either the *unbind* or the *restrict* operator.
The unbind operator can be considered the inverse of bind; for instance, as `ClosedLinkedList` could be derived from `LinkedList` with the bind operator, the opposite could be obtained by deriving `LinkedList` from `ClosedLinkedList` with the unbind operator.

```
component LinkedList=unbind(ClosedLinkedList,Node->N)
```

The class to be unbound (`Node` in the example) must be defined in the component while the new name (`N` in the example) must be unused. The effect consists in adding the deferred class `N` and replacing all soft links to `Node` with `N`.
This example shows also that requirements cannot be safely removed by the compiler; indeed, requirements on `Node` specified in `ClosedLinkedList` cannot be simplified, since after applying the unbind operator, soft links to the defined class `Node` could be redirected to some deferred class (`N` in the example).
The unbind operator offers an effective way to deal with unanticipated code modification; although unanticipated code modification should be better addressed when designing and developing components, unbind gives a chance to recover from this problem when composing third party components whose design did not take into account some unforeseen opportunities of reuse.
The restrict operator provides another mean for opening closed components. It is mainly used jointly with the merge operator to override class declarations. For instance, a new component could be obtained from `ClosedLinkedList` by overriding the definition of `Node` with that contained in component `AnotherNode`:

```
component AnotherNode = {
  class Node {
```

```
    Node next;
    int elem;
    Node(Node n) {next=n;}
    Node(Node n,int e) {next=n;elem=e;}
    Node getNext() {return next;}
    int getElem() {return elem;}
  }
}
component ClosedIntLinkedList = merge(AnotherNode,restrict(ClosedLinkedList, Node));
```

First, the restrict operator makes class `Node` in `ClosedLinkedList` deferred by removing its declaration. Then the new declaration of `Node` in `AnotherNode` is added by the merge operator. Now it should be clear why type constraints must always be kept: if we had removed the constraint `Node(Node)` from the type of `ClosedLinkedList`, then we would not be able to correctly typecheck the definition of `ClosedIntLinkedList`.
Note the difference between the unbind and the restrict operator: for class `C` defined in component `Comp`, `unbind(Comp, C->U)` does not remove the declaration of `C`, but redirects soft links to `C` to an unused class `U`; `restrict(Comp,C)`, instead, makes class `C` deferred by removing its declaration, but does not redirect soft links to `C`. Hence `rename(restrict(Comp,C),C->U)` is still different from `unbind(Comp, C->U)` since in the latter the definition of `C` is kept.
As for renaming, convenient shortcuts are provided for unbinding and restricting multiple classes. A preferential merge operator resolving conflicts between class declarations can be obtained as a more powerful form of syntactic shortcut:

`merge(M1 < M2)` is an abbreviation for `merge(restrict(M1,C1,..,Cn),M2)`

where `C1,..,Cn` are all the classes defined in both components.

2.6 Constraint satisfaction and earlier error detection

Constraint satisfaction ensures that components can be deployed compositionally. If type safety is the main concern, then the simplest way to achieve it is to check that type constraints are all satisfied just when components are deployed into an application. However, this approach has the drawback that type errors cannot be detected at an earlier stage when components are defined. For instance, let us consider the declaration of the following open component:

```
component Vain = {
  requires {D<=C}
  deferred class D;
  class C extends D {
    C m() { return new D(); }
  }
}
```

The body of method `m` is type correct if we require that `D` is a subtype of `C`; however, if satisfaction of `D<=C` is checked only at deployment time rather than at compilation time, the compiler does not detect that class `C` is inherently flawed. Indeed, class `C` extends `D`, therefore `C<=D` holds and `D<=C` can never be satisfied. As a matter of fact, component `Vain` is rather useless, since there is no way to correctly bind `D` to a class declaration.
An approach where constraint satisfaction is checked at compile time, and not only at deployment time, allows earlier error detection, but is more challenging, since the compiler relies only

on partial type information, that is, that contained in the component to be compiled in isolation. Indeed, sometimes it is not easy to predict that a component cannot be correctly used in any deployment context. For instance, the type inference algorithm defined in [2] is smart enough to reject the declaration of `Vain` above; however, it is not so smart to reject all component declarations with unsatisfiable constraints. However, the algorithm ensures that deployment of components is always type safe, therefore it is not possible to build an application with components with unsatisfiable constraints.

2.7 Qualified Class Names

As already explained, classes can be referenced through qualified names:

```
component AnotherList = {
  class List {
    requires { Node@AComponent(Node@AComponent); }
    Node@AComponent first;
    void addFirst(){first=new Node@AComponent(first);}
  }
}
```

Component `AnotherList` explicitly depends on component `AComponent` which is expected to define a class `Node` satisfying the constraint specified in class `List`. The qualified name `Node@AComponent` establishes a hard link to class `Node` defined in `AComponent`; differently to what happens for soft links, composition operators do not allow[10] code to change dependencies introduced by hard links. Therefore, class `List` as defined in `AnotherList` will always depend on class `Node` in `AComponent` in any possible context where it will be reused.
Hard links can also reference classes defined in the same component where they are used.

```
component YetAnotherList = {
  class List {
    requires { Node@YetAnotherList(Node@YetAnotherList); }
    Node@YetAnotherList first;
    void addFirst(){first=new Node@YetAnotherList(first);}
  }
  class Node{
    requires { & Node@YetAnotherList; }
    Node@YetAnotherList next;
    Node(Node@YetAnotherList n){next=n;}
    Node@YetAnotherList getNext(){return next;}
  }
}
```

In component `YetAnotherList` all hard links to `Node` are permanently bound to the definition of `Node` in the same component and can no longer be unbound.
While it is not possible to transform a hard link into a soft link, the opposite can be achieved via the bind operator. For instance, `YetAnotherList` could be equivalently obtained from `ClosedLinkedList`:

```
component YetAnotherList = bind(ClosedLinkedList,Node->Node@YetAnotherList);
```

[10] The motivation for this limitation is methodological rather than technical.

Similarly to what happens for SML and OCaml modules, class names can only be qualified by a component name and not by a component expression: for instance, `Node@merge(LinkedList,Double)` is not syntactically correct. This restriction avoids to make compositional compilation of components too complex.

2.8 Generativity versus Transparency

Let us consider the following two component declarations:

```
component ClosedLinkedList = bind(LinkedList, N->Node)
component ClosedLinkedList2 = bind(LinkedList, N->Node)
```

Should the two types `List@ClosedLinkedList` and `List@ClosedLinkedList2` be considered equivalent? A similar question arises in ML module system where both answers are considered reasonable. Following ML terminology, we may say that the two types `List@ClosedLinkedList` and `List@ClosedLinkedList2` are equivalent if the two components `ClosedLinkedList` and `ClosedLinkedList2` are considered to be *transparent*, whereas the two types are incompatible if the two components are considered to be *generative*.
Avoiding transparent components makes the type system less expressive but also more complex. Let us consider, for instance, the following artificial example:

```
component M1 = {
  deferred class C;
  class A {}
  class B extends C {}
}
component M2 = merge({class C{int i;}}, M1);
component M3 = merge({class C{boolean b;}}, M1);
```

Let us assume that `M2` and `M3` are transparent modules. Clearly, `C@M2` and `C@M3` cannot be equivalent types since they are defined by two different class declarations. On the other hand, types `A@M2` and `A@M3` correspond to the same class declaration (derived from `M1`) as well as `B@M2` and `B@M3`. However, types `A@M2` and `A@M3` can be safely considered equivalent, but not `B@M2` and `B@M3`.
For simplicity, in this paper we consider only generative components, but allowing transparent components is certainly an important feature for supporting software reuse which, therefore, deserves future investigation.

2.9 The Expression Problem

In this last part of the section we show the expressive power of our component framework by considering as "benchmark" the classical *expression problem* (or *extensibility problem*). For convenience we use a slightly more complex variation of Torgersen's example [26]; we refer to the same paper for a comprehensive treatment of the expression problem which would be out of scope in this paper.
The approach we take here is the classical data-centered one, which is more intuitive and simpler, but also less suitable for adding new methods. Our goal is to show that a component-based framework allows addition of new methods to existing classes without modifying available code, and this can be achieved without any need to extend the language used for writing classes (Java in our case). The additional cost is just the introduction of a deferred class. There are many

approaches which, instead, try to solve the problem by proposing language extensions (see, e.g., [8, 13]).
What follows is an implementation of a type `Exp` of simple integer expressions built on top of literals and addition. The only available methods are `clone()`, which allows cloning of an expression, and `print()`, which displays the expression on the screen.[11]

```
component Expr = {
  deferred class E;
  interface Exp {
    E clone();
    void print();
  }
  class Lit implements Exp {
    requires { Lit(int); int Lit.value; Lit<=E; }
    int value;
    Lit(int v) {value=v;}
    E clone() {return new Lit(value);}
    void print() {System.out.print(value);}
  }
  class Add implements Exp {
    requires { Add(E,E); E Add.left; E Add.right; Add<=E; void E.print(); }
    E left,right;
    Add(E l,E r) {left=l; right=r;}
    E clone() {return new Add(left,right);}
    void print() {
      left.print();
      System.out.print('+');
      right.print();
    }
  }
}
```

The code of the component is very similar to a standard data-centered implementation one would write in a Java package, with the only difference that all occurrences of `Exp`, except those immediately following the keyword `implements`, are replaced with the deferred class `E`. The reason is that some code extensions might require the specialization of `Exp` when used as a type, whereas replacing the interface `Exp` by another could break correctness of classes `Lit` and `Add` (see below). Hence, we introduce two separate names.
The constraints on deferred class `E` require `E` to be a supertype of `Lit` and `Add`, and to have a method `void print()`.
The component can be used by a client (for instance a parser) by means of the bind operation.

```
component Client = {
  deferred class Exp, Lit, Add;
  class Producer { // typically, the parser
    requires { Lit(int); Add(Lit,Lit); Add<=Exp; }
    Exp produce() {return new Add(new Lit(2),new Lit(3));}
  }
```

[11] Again, for simplicity we do not write the most general requirements as they would be inferred by the compiler.

```
}
component Application = bind(merge(Expr, Client), {E->Exp});
```

For instance, the execution of the following well-typed statement

```
new Producer@Application().produce().clone().print();
```

displays 2+3 on the screen, as expected.
Since we have chosen a data-centered approach, adding a new method is more challenging than adding a new kind of expressions. For instance, let us consider the problem of adding a new method `eval()` for evaluating expressions.
We can confine the extension into a new component:

```
component Eval = {
  deferred class E, Exp, Lit, Add;
  interface EvalExp extends Exp {
    int eval();
  }
  class EvalLit extends Lit implements EvalExp {
    requires { Lit(int); int Lit.value; }
    EvalLit(int v) {super(v);}
    int eval() {return value;}
  }
  class EvalAdd extends Add implements EvalExp {
    requires { Add(E,E); 'a Add.left; 'a Add.right; int 'a.eval(); }
    EvalAdd(E l,E r) {super(l,r);}
    int eval() {return left.eval()+right.eval();}
  }
}
```

The constraints on deferred classes require `Lit` to have a constructor with parameter `int`, and a field `value` of type `int`[12], and `Add` to have a constructor applicable to two arguments of type `E`, and two fields `left`, `right` of a certain type which, in turn, has a method `int eval()`.
A first tentative for instantiating the parameters of `Eval` would consist in directly merging `Eval` with `Expr` and, then, binding `E` to `EvalExp`. However, this is not type correct, since, for instance, class `Lit` in `Expr` requires the constraint `Lit <= E` and this would not hold if we replace `E` with `EvalExp`. The problem can be solved by redirecting references to `Lit` and `Add` to `EvalLit` and `EvalAdd`, respectively. This can be accomplished by unbinding `Lit` and `Add` in component `Expr`.

```
component EvalExpr = merge(Eval, unbind(Expr, {Lit->EvalLit,Add->EvalAdd}));
component Application2 =
  merge(bind(EvalExpr, E->EvalExp),
        rename(Client, {Exp->EvalExp, Lit->EvalLit, Add->EvalAdd}));
```

As already mentioned, in this last example the deferred class `E` plays an essential role. Indeed, a composition analogous to the above would not be possible with the closed version of `Expr` (obtained from `Expr` by binding `E` to `Exp`). In this case we would need to redirect `Exp` (instead of `E`) to `EvalExp` in `ClosedEvalExpr`, but unfortunately this redirection is not type safe, since both `Lit` and `Add` fail to implement `EvalExp`. Now we can execute the following code:

[12] For simplicity here we assume that there is just one kind of numeric type `int`.

```
EvalExp@Application2 e = new Producer@Application2().produce().clone();
e.print();
System.out.println(" = "+e.eval());
Exp@Application e2=e; // type error
```

to print `2+3 = 5` on the screen. Note that the last line of the code is not type safe since `Exp@Application` and `Exp@Application2` cannot be compatible, even if we allowed transparent components: interface `Exp` in `Application` declares method `Exp clone()`, whereas interface `Exp` in `Application2` (which is the direct supertype of `EvalExp@Application2`) declares method `EvalExp clone()`.

3 A Framework of Components

In this section, we define a parametric framework for components which can be instantiated on top of a programming language providing some syntactic categories and judgments. We use a Java-oriented terminology, since our aim is to instantiate the framework on Java-like languages (in particular, in the next section we present an instantiation on Featherweight Java [17]). However, the framework could in principle be applied more in general, thinking of "class" as "language entity" and of "binary" as abstract intermediate language.

3.1 Syntax and reduction rules

In order to define syntax and reduction semantics of our component language, we first list the syntactic categories the used programming languages must provide; the list of required judgments will be given when describing the type system.

- Simple class names (c). Given simple class names, *class names* $\mathtt{n}$ (see Fig.1) will be either simple class names or qualified class names of shape $\mathsf{c}@\mathtt{M}$, where $\mathtt{M}$ is a component name.
- (Source) class definitions (cd^{s}). We assume that each source class definition introduces a simple class name c that can be extracted by a function *out*. Moreover, $\mathit{in}(\mathsf{cd}^{\mathsf{s}})$ should denote the set of all soft links in cd^{s}. Finally, $\mathit{close}_{\mathtt{M}}(\mathsf{cd}^{\mathsf{s}})$, $\mathsf{cd}^{\mathsf{s}}[\mathsf{c}'/\mathit{in}\ \mathsf{c}]$, and $\mathsf{cd}^{\mathsf{s}}[\mathsf{c}'/\mathsf{c}]$ should denote the class definition obtained from cd^{s} by: qualifying simple class names by $\mathtt{M}$; replacing soft links to c by c'; and replacing all unqualified occurrences of c by c'.
  Sequences of source class definitions $\mathsf{cd}^{\mathsf{s}}{}_1 \ldots \mathsf{cd}^{\mathsf{s}}{}_n$ will also be denoted by S.

If $\mathsf{S} = \mathsf{cd}^{\mathsf{s}}{}_1 \ldots \mathsf{cd}^{\mathsf{s}}{}_n$, then $\mathit{out}(\mathsf{S}) = \mathit{out}(\mathsf{cd}^{\mathsf{s}}{}_1) \cup \ldots \cup \mathit{out}(\mathsf{cd}^{\mathsf{s}}{}_n)$ denotes the set of all classes defined in S. The other functions are extended to sequences analogously. Recall that a soft link to a class is expected to be any of its unqualified occurrences except those which introduce the declaration of either the class itself, or any of its constructors (see the concrete definition for FJ given in Fig.7 in Sect.4). Besides simple class names, a class definition can contain qualified class names, that is, hard links to classes defined in other components.
For instance, in `component M={class C{ C(){...} C@M m(C c){...}}}` only the last occurrence of `C` is a soft link to `C`, whereas `C@M` is a hard link, that is, a link permanently anchored to the declaration of `C` inside `M`.
The syntax used for creating and composing components is given in Fig.1. We assume that order in sequences is immaterial and use a bar notation for sequences following the same conventions as in [17] (for instance, $\overline{\mathsf{c}}$ stands for $\mathsf{c}_1 \ldots \mathsf{c}_n$).
An application program corresponds to an executable application obtained by assembling together and deploying some components as specified in the environment `MDS`, and by providing a main expression e^{s} from which execution must start in the context of components `MDS`.

$\mathtt{n}$	$::= \mathtt{c} \mid \mathtt{c@M}$	class name
$\mathtt{P}$	$::= (\mathtt{MDS}, \mathsf{e}^{\mathsf{s}})$	application program
$\mathtt{MDS}$	$::= \{\overline{\mathtt{MD}}\}$	(source) component environment
$\mathtt{MD}$	$::= \mathtt{M} = \mathtt{ME}$	component declaration
$\mathtt{ME}$	$::= \mathtt{M} \mid \mathtt{BM} \mid \mathtt{merge}(\mathtt{ME}_1, \mathtt{ME}_2) \mid \mathtt{restrict}(\mathtt{ME}, \mathtt{c}) \mid \mathtt{rename}(\mathtt{ME}, \mathtt{c} \mapsto \mathtt{c}') \mid \mathtt{bind}(\mathtt{ME}, \mathtt{d} \mapsto \mathtt{n}) \mid \mathtt{unbind}(\mathtt{ME}, \mathtt{c} \mapsto \mathtt{d})$	component expression
$\mathtt{BM}$	$::= \{\overline{\mathtt{c}}; \mathsf{S}\}$	basic component

where: component/class names declared in MDS/BM are distinct; $in(\mathsf{S}) \subseteq \overline{\mathtt{c}} \cup out(\mathsf{S})$ in BM

Fig. 1. Syntax

A component environment is a sequence of component declarations (possibly mutually dependent), each one associated with a distinct name.

A basic component BM is a sequence of class names (the deferred classes), followed by a sequence of class definitions. We assume that all class names (deferred or defined) introduced in BM are distinct, and that class definitions can only contain soft links to classes which are explicitly declared in BM, either in $\overline{\mathtt{c}}$ or in S.

Classes in components are all implicitly considered *virtual*, that is defined class names are not associated permanently with a class definition, but their definition can be changed when composing components.

Composition operators include `merge`, `restrict`, `rename`, `bind`, and `unbind`. The reduction relations over programs, component environments, declarations and expressions are defined by the rules defined in Figure 2. For simplicity, we use the same symbol for the reduction relations over the four different set of terms, since such sets are mutually disjoint.

Values for component expressions are basic components BM, whereas a component declaration M = ME is expected to reduce to a declaration of a basic component M = BM. Analogously, component environments are expected to reduce to environments of basic components.

Note that the reduction semantics is provided only to be able to express soundness of composition of components (formally, a component environment MDS) w.r.t. global compilation of the corresponding classes, that is, the collection of classes which we get by reducing and then deploying (see below) MDS (Theorem 3 at the end of this Section). This allows a modular proof of soundness of component composition, by relying on type soundness of the used programming language. However, in the real scenario (see Section 5) a component expression is not reduced at the source level, but rather binary components are generated by first compiling in total isolation basic components, and then by combining binary components into more complex components in a context where all components needed for composition are already available. This is modeled by the type system in the following.

Rule (*prog*) corresponds to the intuition that the component environment of the program needs first to be reduced to a collection of declarations of basic components; then, the reduced component environment is closed by completing simple class names with their corresponding qualified version, and, finally, in the context of the class definitions extracted from the elaborated component environment, the reduction of e^{s} can start (*prog2*) according to the reduction relation $\rightarrow_{core}$ at the level of the programming language.

The auxiliary functions *classes* and *close* are trivially defined by

$$(prog)\ \frac{\mathtt{MDS} \to \mathtt{MDS}'}{(\mathtt{MDS}, \mathsf{e}^{\mathsf{s}}) \to (\mathtt{MDS}', \mathsf{e}^{\mathsf{s}})}$$

$$(prog2)\ \frac{(\mathsf{S}, \mathsf{e}^{\mathsf{s}}) \to_{core} (\mathsf{S}, \mathsf{e}^{\mathsf{s}\prime})}{(\{\overline{\mathtt{M} = \mathtt{BM}}\}, \mathsf{e}^{\mathsf{s}}) \to (\{\overline{\mathtt{M} = \mathtt{BM}}\}, \mathsf{e}^{\mathsf{s}\prime})}\ \mathsf{S} \equiv \mathit{classes}(\mathit{close}(\{\overline{\mathtt{M} = \mathtt{BM}}\}))$$

$$(mdecs)\ \frac{\mathtt{MD} \to \mathtt{MD}'}{\{\overline{\mathtt{M} = \mathtt{BM}}\ \mathtt{MD}\ \mathtt{MDS}\} \to \{\overline{\mathtt{M} = \mathtt{BM}}\ \mathtt{MD}'\ \mathtt{MDS}\}}$$

$$(mdecs2)\ \frac{}{\{\overline{\mathtt{M} = \mathtt{BM}}\ \mathtt{MD}\ \mathtt{MDS}\} \to \{\overline{\mathtt{M} = \mathtt{BM}}\ \mathtt{MD}'\ \mathtt{MDS}\}}\ \begin{array}{l}\mathtt{MD}' \equiv \mathtt{MD}[\overline{\mathtt{BM}/\mathtt{M}}] \\ \mathtt{MD}' \not\equiv \mathtt{MD}\end{array}$$

$$(mdec)\ \frac{\mathtt{ME} \to \mathtt{ME}'}{\mathtt{M} = \mathtt{ME} \to \mathtt{M} = \mathtt{ME}'}$$

$$(merge)\ \frac{}{\mathtt{merge}(\{\overline{\mathsf{c}}_1; \mathsf{S}_1\}, \{\overline{\mathsf{c}}_2; \mathsf{S}_2\}) \to \{\overline{\mathsf{c}}; \mathsf{S}_1\mathsf{S}_2\}}\ \begin{array}{l}\overline{\mathsf{c}} = \overline{\mathsf{c}}_1\overline{\mathsf{c}}_2 \setminus \mathit{out}(\mathsf{S}_1\mathsf{S}_2) \\ \mathit{out}(\mathsf{S}_1) \cap \mathit{out}(\mathsf{S}_2) = \emptyset\end{array}$$

$$(restrict)\ \frac{}{\mathtt{restrict}(\{\overline{\mathsf{c}}; \mathsf{S}\ \mathsf{cd}^{\mathsf{s}}\}, \mathsf{c}) \to \{\overline{\mathsf{c}}\ \mathsf{c}; \mathsf{S}\}}\ \mathit{out}(\mathsf{cd}^{\mathsf{s}}) = \mathsf{c}$$

$$(rename)\ \frac{}{\mathtt{rename}(\{\overline{\mathsf{c}}; \mathsf{S}\}, \mathsf{c} \mapsto \mathsf{c}') \to \{\overline{\mathsf{c}}; \mathsf{S}\}[\mathsf{c}'/\mathsf{c}]}\ \begin{array}{l}\mathsf{c} \in \overline{\mathsf{c}} \cup \mathit{out}(\mathsf{S}) \\ \mathsf{c}' \notin \overline{\mathsf{c}} \cup \mathit{out}(\mathsf{S})\end{array}$$

$$(bind)\ \frac{}{\mathtt{bind}(\{\overline{\mathsf{c}}\ \mathsf{d}; \mathsf{S}\}, \mathsf{d} \mapsto \mathtt{n}) \to \{\overline{\mathsf{c}}; \mathsf{S}[\mathtt{n}/\mathsf{d}]\}}\ \mathtt{n} \text{ qualified or } \mathtt{n} \in \mathit{out}(\mathsf{S})$$

$$(unbind)\ \frac{}{\mathtt{unbind}(\{\overline{\mathsf{c}}; \mathsf{S}\}, \mathsf{c} \mapsto \mathsf{d}) \to \{\overline{\mathsf{c}}\ \mathsf{d}; \mathsf{S}[\mathsf{d}/\mathit{in}\ \mathsf{c}]\}}\ \begin{array}{l}\mathsf{c} \in \mathit{out}(\mathsf{S}) \\ \mathsf{d} \notin \overline{\mathsf{c}} \cup \mathit{out}(\mathsf{S})\end{array}$$

Fig. 2. Reduction rules

$$\begin{array}{r}\mathit{classes}(\overline{\mathtt{M} = \{\overline{\mathsf{c}}; \mathsf{S}\}}) = \overline{\mathsf{S}} \\ \mathit{close}(\overline{\mathtt{M} = \{\overline{\mathsf{c}}; \mathsf{S}\}}) = \overline{\mathtt{M} = \{\overline{\mathsf{c}}; \mathit{close}_{\mathtt{M}}(\mathsf{S})\}}\end{array}$$

The definition of $\mathit{close}_{\mathtt{M}}$, though trivial as well (simple class names are qualified by $\mathtt{M}$), depends on the used language; Figure 7 in Sect.4 contains the instantiation for FJ.

In a component environment, component declarations are sequentially processed from left to right. The leftmost declaration $\mathtt{MD}$ which is not fully reduced yet is selected, and, either a reduction step can be applied to $\mathtt{MD}$ (*mdecs*), or some name $\mathtt{M}_i$ of previously declared components can be substituted with the corresponding basic expression (*mdecs2*). Note that even though the two rules are not mutually exclusive, the reduction relation turns out to be confluent. The side condition $\mathtt{MD}' \not\equiv \mathtt{MD}$ avoids loops, whereas $\mathtt{MD}[\overline{\mathtt{BM}/\mathtt{M}}]$ denotes parallel substitution of $\mathtt{M}_i$ with $\mathtt{BM}_i$, for $i \in 1..n$, in $\mathtt{MD}$. The inductive definition of such substitution is standard, except for the following case:

$$\{\overline{\mathsf{c}}; \mathsf{S}\}[\overline{\mathtt{BM}/\mathtt{M}}] = \{\overline{\mathsf{c}}; \mathsf{S}\}.$$

Substitution is not propagated inside components, since hard links are allowed to establish mutual dependencies between components.
Rule (*mdec*) is straightforward.
We denote by $\mathsf{S}[\mathtt{c}'/\mathit{in}\ \mathtt{c}]$ the class definitions obtained from S by replacing every soft link to $\mathtt{c}$ by $\mathtt{c}'$. Recall that soft links to $\mathtt{c}$ are all occurrences of $\mathtt{c}$ except those which either occur in qualified names, or introduce the declaration of either $\mathtt{c}$, or one of its constructors.
Finally, $\overline{\mathsf{c}}[\mathtt{c}'/\mathtt{c}]$ denotes the replacement of $\mathtt{c}$ with $\mathtt{c}'$ in $\overline{\mathsf{c}}$, if present, and $\mathsf{S}[\mathtt{c}'/\mathtt{c}]$ denotes the replacement of simple class name $\mathtt{c}$ (but not of qualified names of shape $\mathtt{c@M}$) with $\mathtt{c}'$. That is, $\overline{\mathsf{c}}[\mathtt{c}'/\mathtt{c}]$ differs from $\mathsf{S}[\mathtt{c}'/\mathit{in}\ \mathtt{c}]$ since it also replaces declaring occurrences. Again, the precise definitions of $\_[\_/\mathit{in}\ \_]$ and $\_[\_/\_]$ depend on the used language.
The reduction relation for component expressions is defined as the compatible closure of the corresponding rules, since, for brevity, we have omitted the usual congruence rules. Even though it is not deterministic, the reduction relation is clearly confluent by orthogonality.
Merging two basic components (*merge*) corresponds to just putting together their class definitions ($\mathsf{S}_1\,\mathsf{S}_2$), provided that there are no conflicts, whereas the deferred classes are those of the two components which do not match with a defined class ($\overline{\mathsf{c}}_1\overline{\mathsf{c}}_2 \setminus \mathit{out}(\mathsf{S}_1\mathsf{S}_2)$); note that deferred classes are shared.
The restrict operator (*restrict*) removes the definition of a class $\mathtt{c}$ in a basic component, and makes $\mathtt{c}$ a deferred class.
The rename operator (*rename*) performs a bijective renaming of a class $\mathtt{c}$ into $\mathtt{c}'$ in a basic component `BM`: $\mathtt{c}$ must be either a deferred or a defined class in `BM`, whereas $\mathtt{c}'$ must be new, that is, neither deferred nor defined in `BM`. Recall that qualified names are not affected by the substitution.
The bind operator (*bind*) replaces all soft links to a deferred class[13] with the name of a defined class of the same component or with a qualified class name. Conversely, the unbind operator (*unbind*) replaces all soft links to a defined class with a new deferred class.
As final remark, note that all the composition operators can be expressed as a combination of operators in (mixin) module calculi, such as CMS [7]. Indeed, `merge` (called *link* in [7]) and `restrict` are exactly the corresponding operators of the CMS version with virtual components, whereas `rename`, `bind` and `unbind` can all be obtained as special instances of the CMS *reduct* operator which allows independent renaming of input and output names (in `rename` names which are both input and output are renamed in the same way, and only bijective renamings are considered; in `bind` an input name is renamed to an output name; finally, in `unbind` an input name is renamed to a fresh name). Hence, the semantics of our component language could be equivalently given by translation into CMS. However, we preferred here a direct semantics since it is more intuitive for most readers. Note also that `unbind` operator, which seems at a first sight to change the inner structure of a component, actually can safely be expressed by module operators which consider a component as a black box, relying on the CMS distinction between (external) names and (internal) variables which we have omitted here for simplicity: that is, only the input name is changed, whereas the variable used in internal code is kept. This model exactly reflects what happens at the implementation level.

3.2 Type system

We describe now types and typing rules for our component language. First, we list the additional syntactic categories and judgments the used programming language must provide.

[13] Note that all soft links to a deferred class are just all unqualified occurrences of $\mathtt{c}$.

– Binary class definitions (cd^{b}). We assume functions *out*, *in*, $close_{\mathtt{M}}$, $\_[\_/in\ \_]$ and $\_[\_/\_]$ analogous to those assumed on source class definitions. Sequences of binary class definitions $\mathsf{cd}^{\mathsf{b}}_1 \ldots \mathsf{cd}^{\mathsf{b}}_{\mathsf{n}}$ will be also denoted by B.
– Class signatures (δ), which can be thought of as the type information which can be extracted from a class definition (the class definition deprived of body). We assume functions *out*, *in*, $close_{\mathtt{M}}$, $\_[\_/in\ \_]$ and $\_[\_/\_]$ to be defined on class signatures as well. Sequences of class signatures are also denoted by Δ.
– Global compilation $\vdash_{core} \mathsf{S} : \Delta|\mathsf{B}$, to be read: the program (sequence of class definitions) S has class signatures Δ and compiles to the sequence of binary class definitions B.
– Type constraints (γ), which express requirements needed by a class for its correct functioning, e.g., that a given class has a field of a given type. We assume functions *in*, $close_{\mathtt{M}}$, $\_[\_/in\ \_]$ and $\_[\_/\_]$ to be defined on constraints as well. Sequences of type constraints will be denoted also by Γ.
– Compositional compilation (of a class), $\vdash_{core} \mathsf{cd}^{\mathsf{s}} : \Gamma|\delta|\mathsf{cd}^{\mathsf{b}}$, to be read: The class definition cd^{s} has signature δ and compiles to cd^{b} under the type constraints in Γ.
– Linking, $\Delta \vdash_{core} \Gamma|\mathsf{cd}^{\mathsf{b}} \rightsquigarrow \Gamma'|\mathsf{cd}^{\mathsf{b}\prime}$, to be read: In the class signatures Δ the type constraints Γ are consistent and can be simplified into Γ', and the binary cd^{b} becomes $\mathsf{cd}^{\mathsf{b}\prime}$.

Types for our component language are given in Fig.3. Note that the type system for the component language models not only typechecking of component declarations, but, even more importantly, how these component declarations generate new binary components via compilation of defined classes and, possibly, linking of binary components already present. In other words, the type system models the semantics of our component framework at the binary level, as it is implemented in the prototype we have developed. As a consequence, types play also the role of binaries, as we stress by the double terminology in the figure below.

$\mathcal{M}$	$::= (\mathtt{M}_1, \mathtt{MT}_1) \ldots (\mathtt{M}_n, \mathtt{MT}_n)$	component type environment (binary component environment)
$\mathtt{MT}$	$::= \{\overline{\mathtt{c}}; \overline{\mathtt{CT}}\}$	component type (binary component)
$\mathtt{CT}$	$::= \Gamma\|\delta\|\mathsf{cd}^{\mathsf{b}}$	class type (binary class)

where: component/class names declared in $\mathcal{M}/\mathtt{MT}$ distinct; $out(\delta) = out(\mathsf{cd}^{\mathsf{b}})$ in $\mathtt{CT}$

Fig. 3. Types

A *component type environment* is a sequence of pairs consisting of a component name and a component type, where all component names are assumed to be distinct. A *component type* contains the information needed to safely use a component in a context, and consists of a sequence of deferred classes and a sequence of *class types*. A class type models the binary code corresponding to a (defined) class, such as a `.class` file in Java; however, here binaries contain, besides the class signature (the provided interface of the class), also the constraints (the required interface). We assume that in each class type the class signature and the binary class are coherent in the sense that they declare the same class name, and that all classes declared in a component type (both deferred and defined) are distinct.
The functions *out*, *in*, $\_[\_/in\ \_]$ and $\_[\_/\_]$, whose definition depends on the used language, are extended in the obvious componentwise way to class types. Recall that $in(\mathtt{CT})$ is expected to denote the set of all soft links in $\mathtt{CT} = \Gamma|\delta|\mathsf{cd}^{\mathsf{b}}$ (that is, all simple class names in in Γ, δ, and cd^{b}, except those which introduce the declaration of a class, or any of its constructors).

Typing rules are given in Fig.4. A program (*prog*) is well typed if its component environment has a component type environment $\mathcal{M}$ that can be turned into a well formed *closed* component type environment $\mathcal{M}'$. If so, then the class signatures Δ extracted from $\mathcal{M}'$ are used for typing the main expression e^{s}. The judgment $\Delta \vdash_{core} \mathsf{e}^{\mathsf{s}} : \mathtt{c}$ depends on the used language.

$$(prog)\ \frac{\vdash \mathtt{MDS} : \mathcal{M} \qquad \vdash \mathcal{M} \rightsquigarrow_{close} \mathcal{M}' \qquad \Delta \vdash_{core} \mathsf{e}^{\mathsf{s}} : \mathtt{c}}{\vdash (\mathtt{MDS}, \mathsf{e}^{\mathsf{s}})\diamond}\ \Delta \equiv classTypes(\mathcal{M}')$$

$$(mdecs)\ \frac{\emptyset \vdash \mathtt{MD}_1 : (\mathtt{M}_1, \mathtt{MT}_1)\ \ \cdots (\mathtt{M}_i, \mathtt{MT}_i)^{i\in 1..n-1} \vdash \mathtt{MD}_n : (\mathtt{M}_n, \mathtt{MT}_n)}{\vdash \overline{\mathtt{MD}} : \overline{(\mathtt{M}, \mathtt{MT})}}$$

$$(mdec)\ \frac{\mathcal{M} \vdash \mathtt{ME} : \mathtt{MT}}{\mathcal{M} \vdash \mathtt{M} = \mathtt{ME} : (\mathtt{M}, \mathtt{MT})}$$

$$(mtype)\ \frac{\overline{\delta} \vdash \Gamma_i|\mathsf{cd}_{\mathsf{i}}^{\mathsf{b}} \diamond\ \ \forall\, i \in 1..n}{\vdash \{\overline{\mathtt{c}}; \overline{\Gamma|\delta|\mathsf{cd}^{\mathsf{b}}}\}\diamond}\ \ in(\Gamma_i|\delta_i|\mathsf{cd}_{\mathsf{i}}^{\mathsf{b}}) \subseteq \overline{\mathtt{c}} \cup out(\overline{\delta})\ \forall\, i \in 1..n$$

$$(mname)\ \frac{}{\mathcal{M} \vdash \mathtt{M} : \mathtt{MT}}\ (\mathtt{M}, \mathtt{MT}) \in \mathcal{M}$$

$$(basic)\ \frac{\vdash_{core} \mathsf{cd}_{\mathsf{i}}^{\mathsf{s}} : \Gamma_i|\delta_i|\mathsf{cd}_{\mathsf{i}}^{\mathsf{b}}\ \forall i \in 1..n \qquad \vdash \{\overline{\mathtt{c}}; \overline{\Gamma|\delta|\mathsf{cd}^{\mathsf{b}}}\}\diamond}{\mathcal{M} \vdash \{\overline{\mathtt{c}}; \overline{\mathsf{cd}^{\mathsf{s}}}\} : \{\overline{\mathtt{c}}; \overline{\Gamma|\delta|\mathsf{cd}^{\mathsf{b}}}\}}$$

$$(merge)\ \frac{\mathcal{M} \vdash \mathtt{ME}_i : \{\overline{\mathtt{c}}_i; \overline{\mathtt{CT}}_i\}, i = 1, 2 \qquad \vdash \{\overline{\mathtt{c}}; \overline{\mathtt{CT}}_1\overline{\mathtt{CT}}_2\}\diamond}{\mathcal{M} \vdash \mathtt{merge}(\mathtt{ME}_1, \mathtt{ME}_2) : \{\overline{\mathtt{c}}; \overline{\mathtt{CT}}_1\overline{\mathtt{CT}}_2\}}\ \begin{array}{l}\overline{\mathtt{c}} = \overline{\mathtt{c}_1}\ \overline{\mathtt{c}_2} \setminus out(\overline{\mathtt{CT}}_1\overline{\mathtt{CT}}_2) \\ out(\overline{\mathtt{CT}}_1) \cap out(\overline{\mathtt{CT}}_2) = \emptyset\end{array}$$

$$(restrict)\ \frac{\mathcal{M} \vdash \mathtt{ME} : \{\overline{\mathtt{c}}; \overline{\mathtt{CT}}\ \Gamma|\delta|\mathsf{cd}^{\mathsf{b}}\}}{\mathcal{M} \vdash \mathtt{restrict}(\mathtt{ME}, \mathtt{c}) : \{\overline{\mathtt{c}}\ \mathtt{c}; \overline{\mathtt{CT}}\}}\ out(\delta) = \mathtt{c}$$

$$(rename)\ \frac{\mathcal{M} \vdash \mathtt{ME} : \{\overline{\mathtt{c}}; \overline{\mathtt{CT}}\}}{\mathcal{M} \vdash \mathtt{rename}(\mathtt{ME}, \mathtt{c} \mapsto \mathtt{c}') : \{\overline{\mathtt{c}}; \overline{\mathtt{CT}}\}[\mathtt{c}'/\mathtt{c}]}\ \begin{array}{l}\mathtt{c} \in \overline{\mathtt{c}} \cup out(\overline{\mathtt{CT}}) \\ \mathtt{c}' \notin \overline{\mathtt{c}} \cup out(\overline{\mathtt{CT}})\end{array}$$

$$(bind)\ \frac{\mathcal{M} \vdash \mathtt{ME} : \{\overline{\mathtt{c}}\ \mathtt{d}; \overline{\mathtt{CT}}\} \qquad \vdash \{\overline{\mathtt{c}}; \overline{\mathtt{CT}}[\mathtt{n}/\mathtt{d}]\}\diamond}{\mathcal{M} \vdash \mathtt{bind}(\mathtt{ME}, \mathtt{d} \mapsto \mathtt{n}) : \{\overline{\mathtt{c}}; \overline{\mathtt{CT}}[\mathtt{n}/\mathtt{d}]\}}\ \mathtt{n} \text{ qualified or } \mathtt{n} \in out(\overline{\mathtt{CT}})$$

$$(unbind)\ \frac{\mathcal{M} \vdash \mathtt{ME} : \{\overline{\mathtt{c}}; \overline{\mathtt{CT}}\}}{\mathcal{M} \vdash \mathtt{unbind}(\mathtt{ME}, \mathtt{c} \mapsto \mathtt{d}) : \{\overline{\mathtt{c}}\ \mathtt{d}; \overline{\mathtt{CT}}[\mathtt{d}/in\ \mathtt{c}]\}}\ \begin{array}{l}\mathtt{c} \in out(\overline{\mathtt{CT}}) \\ \mathtt{d}\ \notin \overline{\mathtt{c}} \cup out(\overline{\mathtt{CT}})\end{array}$$

Fig. 4. Typing rules

All auxiliary rules and functions needed for (*prog*) are defined in Figure 5. Function *classBin* is not directly used in the typing rules, but is needed for stating the soundness result (see Theorem 3 below). When closing a component type environment (first rule), all simple class names appearing in the component types are qualified by the corresponding component name, as happens in the reduction rule for programs. Indeed, the functions *close* and $close_{\mathtt{M}}$ are the static counterpart of the (deliberately overloaded) functions used in the dynamic semantics. Then it must be checked that the resulting types are well formed closed component types w.r.t. the class

$$\frac{classTypes(\overline{\mathtt{MT}'}) \vdash \mathtt{MT}'_i \diamond_{closed} \ \ \forall i \in 1..n}{\vdash \overline{(\mathtt{M}, \mathtt{MT})} \rightsquigarrow_{close} \overline{(\mathtt{M}, \mathtt{MT}')}} \ \mathtt{MT}'_i = close_{\mathtt{M}_i}(\mathtt{MT}_i) \ \forall\, i \in 1..n$$

$$\frac{\Delta \vdash_{core} \Gamma_i|\mathsf{cd}_\mathsf{i}^\mathsf{b} \rightsquigarrow \emptyset|\mathsf{cd}_\mathsf{i}^{\mathsf{b}'} \ \forall i \in 1..n}{\Delta \vdash \{\emptyset; \overline{\Gamma|\delta|\mathsf{cd}^\mathsf{b}}\}\diamond_{closed}}$$

$$\begin{aligned}
classTypes(\overline{(\mathtt{M}, \mathtt{MT})}) &= \overline{classTypes(\mathtt{MT})} \\
classTypes(\{\overline{\mathsf{c}}; \overline{\Gamma|\delta|\mathsf{cd}^\mathsf{b}}\}) &= \overline{\delta} \\
classBin(\overline{(\mathtt{M}, \mathtt{MT})}) &= \overline{classBin(\mathtt{MT})} \\
classBin(\{\overline{\mathsf{c}}; \overline{\Gamma|\delta|\mathsf{cd}^\mathsf{b}}\}) &= \overline{\mathsf{cd}^\mathsf{b}} \\
close_{\mathtt{M}}(\{\overline{\mathsf{c}}; \overline{\Gamma|\delta|\mathsf{cd}^\mathsf{b}}\}) &= (\{\overline{\mathsf{c}}; \overline{close_{\mathtt{M}}(\Gamma)|close_{\mathtt{M}}(\delta)|close_{\mathtt{M}}(\mathsf{cd}^\mathsf{b})}\})
\end{aligned}$$

Fig. 5. Auxiliary rules and functions

signatures extracted from all component types. This means (second rule) that all constraints must be satisfied by the class signatures, that is, they all simplify to the empty set of constraints. Rules (*mdecs*) and (*mdec*) are standard.

Rule (*mtype*) defines well formed, but not necessarily closed, component types. Indeed, it checks whether all constraints of a component type MT are consistent w.r.t. the class signatures extracted from MT; therefore it is sufficient that the set of constraints provably simplifies to some other set of constraints (possibly the same; if Γ cannot be simplified than it is unsatisfiable). The notation $\Delta \vdash \Gamma|\mathsf{cd}^\mathsf{b}\diamond$ is an abbreviation for $\Delta \vdash_{core} \Gamma|\mathsf{cd}^\mathsf{b} \rightsquigarrow \Gamma'|\mathsf{cd}^{\mathsf{b}'}$ for some $\Gamma', \mathsf{cd}^{\mathsf{b}'}$. Note that this judgment is not strictly necessary for ensuring the soundness of the type system (indeed, mutual consistency of all components is checked again in rule (prog)) at deployment type, nevertheless it is used in rules (*basic*), (*merge*), and (*bind*) for guaranteeing earlier error detection.

In rule (*basic*), the type of a basic component is inferred by separately typechecking each class definition, obtaining the constraints on the used classes, the signature of the declared class, and the corresponding binary class. Recall that the formal definition of the judgment $\vdash_{core} \mathsf{cd}^\mathsf{s} : \Gamma|\delta|\mathsf{cd}^\mathsf{b}$ depends on the used programming language. Then, the obtained component type must be checked (judgment $\vdash \{\overline{\mathsf{c}}; \overline{\Gamma|\delta|\mathsf{cd}^\mathsf{b}}\}\diamond$) in order to detect internal inconsistencies that would prevent the component to be effectively deployable in any context.

In rule (*merge*), the operator can be safely applied only if the arguments have no conflicting class definitions. As in (*basic*), the resulting component type is required to be well formed, since in the merged components some constraint of a component operand could be inconsistent w.r.t. some of the class declared in the other operand.

In rule (*restrict*), the operator can be safely applied only if the class to be removed is actually defined in the component. The resulting component type is then obtained by removing the corresponding class type from the component type of the argument and by adding the class to the sequence of deferred classes. In this case, no checking on the resulting component type is needed, since the operation cannot introduce any sort of inconsistencies.

In rule (*rename*), the operator can be safely applied only if the class to be renamed is either a defined or a deferred class of the component, and the new name does not coincide with any class of the component. The resulting component type is obtained by correspondingly renaming the component type of the argument. Like it happens for (*restrict*), no checking on the resulting component type is needed.

In rule (*bind*), the operator can be safely applied only if `d` is deferred; if so, then `d` is bound to `n`. The resulting component type is obtained by replacing all soft links to `d` with `n` in the component type of the argument, and by removing `d` from the sequence of deferred classes. As in (*basic*) and (*merge*), the resulting component type is required to be well formed.
In rule (*unbind*), the operator can be safely applied only if `c` is a defined class and `d` does not coincide with any either defined or deferred class of the component. The resulting component type is obtained by replacing all soft links to `c` by `d` in the component type of the argument, and by adding `d` in the sequence of deferred classes. As for the restrict and the rename operator, no inconsistencies can be introduced, therefore the resulting component type does not need to be checked.
Also note that constraint checking in the above rules is sometimes redundant, due to the fact that, as already explained, constraints are checked but not simplified in rules (*basic*), (*merge*), and (*bind*). However, a more efficient implementation of the system could be obtained by keeping trace of the constraints which are already satisfied.
The relevance of the type system presented until now is that it supports *compositional compilation* of components. This means that it is possible for the programmer to write classes and compile them into components in isolation, and then to compose and deploy components by just checking that mutual assumptions are satisfied, without any need for code re-inspection. This means that the framework truly supports components, that is, mixin modules in binary form.
Of course, we have to show that the compositional approach, where we first compile components in isolation and then combine and deploy them by checking their compatibility, is *sound*. That is, it gives the same result we would have obtained by not using components at all, but by compiling together all the classes obtained by reducing and then flattening components. Theorem 3 below states that this property holds under the assumption that compositional compilation of classes provided by the used language is sound w.r.t. global compilation.
The theorem can be proved by means of subject reduction and unique normal form properties stated in Theorem 1 and 2, respectively.
In the following, we assume that the used language satisfies the following assumption.

Assumption 1 (Soundness of compositional compilation of the used language) *If* $\vdash_{core} \mathsf{cd}_\mathsf{i}^\mathsf{s} : \Gamma_i|\delta_i|\mathsf{cd}_\mathsf{i}^\mathsf{b}$ *and* $\overline{\delta} \vdash_{core} \Gamma_i|\mathsf{cd}_\mathsf{i}^\mathsf{b} \rightsquigarrow \emptyset|\mathsf{cd}_\mathsf{i}^{\mathsf{b}\prime}$, *for* $i \in 1..n$
then $\vdash_{core} \overline{\mathsf{cd}^\mathsf{s}} : \overline{\delta}|\overline{\mathsf{cd}^\mathsf{b}}$.

Theorem 1 (Subject reduction). *If* $\vdash \mathtt{MDS} : \mathcal{M}$, $\mathtt{MDS} \rightarrow \mathtt{MDS}'$, *then* $\vdash \mathtt{MDS}' : \mathcal{M}$.

Theorem 2 (Unique normal form). *If* $\vdash \mathtt{MDS} : \mathcal{M}$, *then* $\mathtt{MDS} \xrightarrow{*} \mathtt{MDS}'$ *for a unique* $\mathtt{MDS}'$ *having shape* $\{\overline{\mathtt{M} = \mathtt{BM}}\}$.

Theorem 3. *If* $\vdash \mathtt{MDS} : \mathcal{M}$, *and* $\vdash \mathcal{M} \rightsquigarrow_{close} \mathcal{M}'$, *then* $\mathtt{MDS} \xrightarrow{*} \mathtt{MDS}'$ *for a unique* $\mathtt{MDS}' \equiv \{\overline{\mathtt{M} = \mathtt{BM}}\}$, *and* $\vdash_{core} classes(close(\mathtt{MDS}')) : \mathsf{B}|\Delta$ *with* $\mathsf{B} = classBin(\mathcal{M}')$ *and* $\Delta = classTypes(\mathcal{M}')$.

Theorem 3 states that, if by composing components we have obtained a new component which is a collection of class binary definitions and class signatures $\mathsf{B}|\Delta$, then such a component could be equivalently obtained from direct global compilation of the corresponding collection of classes (that is, those obtained by reducing the component expressions). This result implies as a corollary that composition of components is type safe, provided that the type system for the used language is sound.

4 Instantiation on Featherweight Java

In this section we show how to instantiate the framework introduced in the previous section on top of a simple programming language. To this end, we provide a concrete definition for (most of) the various ingredients required in Sect.3. The definitions are basically those in [2], to which we refer for the omitted formal definitions and detailed comments, slightly adapted to exactly fit in our framework.

$$
\begin{array}{rll}
\mathsf{cd}^{\mathsf{s}} ::= \texttt{class c extends n \{ req fds mds}^{\mathsf{s}}\texttt{ \}} \mid \quad (\mathsf{c} \neq \texttt{Object}) & & \text{class definition} \\
\mathsf{req} ::= \texttt{requires } \{\gamma_1 \ldots \gamma_n\} & & \text{requirements} \\
\mathsf{fds} ::= \mathtt{n}_1\ \mathsf{f}_1 \ldots \mathtt{n}_n\ \mathsf{f}_n & & \text{field declarations} \\
\mathsf{mds}^{\mathsf{s}} ::= \mathsf{md}^{\mathsf{s}}{}_1 \ldots \mathsf{md}^{\mathsf{s}}{}_n & & \text{method declarations} \\
\mathsf{md}^{\mathsf{s}} ::= \mathsf{mh}\ \{\texttt{return } \mathsf{e}^{\mathsf{s}}\texttt{;}\} & & \text{method declaration} \\
\mathsf{mh} ::= \mathtt{n}_0\ \mathsf{m}(\mathtt{n}_1\ \mathsf{x}_1, \ldots, \mathtt{n}_n\ \mathsf{x}_n) & & \text{method header} \\
\mathsf{e}^{\mathsf{s}} ::= \mathsf{x} \mid \mathsf{e}^{\mathsf{s}}.\mathsf{f} \mid \mathsf{e}^{\mathsf{s}}{}_0.\mathsf{m}(\mathsf{e}^{\mathsf{s}}{}_1, \ldots, \mathsf{e}^{\mathsf{s}}{}_n) \mid \texttt{new } \mathtt{n}(\mathsf{e}^{\mathsf{s}}{}_1, \ldots, \mathsf{e}^{\mathsf{s}}{}_n) \mid (\mathtt{n})\mathsf{e}^{\mathsf{s}} & & \text{expression}
\end{array}
$$

where field/method/parameter names declared in $\mathsf{fds}/\mathsf{mds}^{\mathsf{s}}/\mathsf{mh}$ are distinct

---

Fig. 6. FJ (source) class definitions

First of all, we give in Fig.6 the syntax of (source) class definitions cd^{s}. The source language we consider is very similar to Featherweight Java [17] (indeed, we call it FJ) and is a functional subset of Java with no primitive types. However there are some differences between the two languages: requirements on classes, in the form of type constraints, can be added by the user; class constructors are implicitly declared; finally class names can be either simple or *qualified* as `c@M` which denotes the class `c` in component `M`.
Note that an important feature of components is that the classes they contain are considered values when components are assembled, hence components do not have any observable state, even though objects and classes can be stateful in Java.
Every class definition can contain constraint, instance field and method declarations and has only one implicit constructor whose parameters correspond to all class fields (both inherited and declared) in the order of declaration. Constraints γ specify the requirement interface of a class, and are formally defined and explained in the sequel. In class definitions we assume that the name of the class `c` cannot be `Object`.
Expressions are variables, field access, method invocation, instance creation and casting; the keyword `this` is considered a special variable. Finally, in order to simplify the presentation, we assume that in each single declaration (either of fields, or methods, or parameters) the introduced names are distinct.
Fig.7 contains the definitions of the functions on class definitions assumed for giving syntax and reduction rules of the component language in Sect.3.1.
We describe now the additional ingredients assumed for defining the type system of the component language in Sect.3.2. Fig.8 contains the syntax of binary class definitions. Our notion of bytecode is abstract, since the only differences between source code and bytecode of interest here are the annotations needed by the JVM verifier. Moreover, note that our bytecode is polymorphic, in the sense that these annotations can be type variables. We have omitted straightforward the definitions of functions *out*, *in*, $\_[\_/\mathit{in}\ \_]$ and $\_[\_/\_]$ on binary classes, class signatures and type constraints, since they are analogous to those defined in Fig. 7 for source classes.

$out(\texttt{class c extends n \{ req fds mds}^{\mathsf{s}}\texttt{ \}}) = \{\mathsf{c}\}$

$in(\texttt{class c extends n \{ req fds mds}^{\mathsf{s}}\texttt{ \}}) = in(\mathsf{n}) \cup in(\mathsf{req}) \cup in(\mathsf{fds}) \cup in(\mathsf{mds}^{\mathsf{s}})$
$in(\mathsf{x}) = \emptyset, in(\mathsf{f}) = \emptyset, in(\mathsf{m}) = \emptyset$
$in(\mathsf{c}) = \{\mathsf{c}\}, in(\mathtt{M.c}) = \emptyset$
all other cases are trivial (union)

$close_{\mathtt{M}}(\texttt{class c extends n \{ req fds mds}^{\mathsf{s}}\texttt{ \}}) =$
$\quad \texttt{class } close_{\mathtt{M}}(\mathsf{c}) \texttt{ extends } close_{\mathtt{M}}(\mathsf{n}) \texttt{ \{ } close_{\mathtt{M}}(\mathsf{req})\ close_{\mathtt{M}}(\mathsf{fds})\ close_{\mathtt{M}}(\mathsf{mds}^{\mathsf{s}})\texttt{ \}}$
$close_{\mathtt{M}}(\mathsf{x}) = \mathsf{x}, close_{\mathtt{M}}(\mathsf{f}) = \mathsf{f}, close_{\mathtt{M}}(\mathsf{m}) = \mathsf{m}$
$close_{\mathtt{M}}(\mathsf{c}) = \mathtt{M.c}, close_{\mathtt{M}_1}(\mathtt{M}_2\mathtt{.c}) = \mathtt{M}_2\mathtt{.c}$
all other cases are trivial (propagation)

$\texttt{class c}''\texttt{ extends n \{ req fds mds}^{\mathsf{s}}\texttt{ \}}[\mathsf{c}'/\mathsf{c}] =$
$\qquad \texttt{class c}''[\mathsf{c}'/\mathsf{c}]\texttt{ extends n}[\mathsf{c}'/\mathsf{c}]\texttt{ \{ req}[\mathsf{c}'/\mathsf{c}]\ \mathsf{fds}[\mathsf{c}'/\mathsf{c}]\ \mathsf{mds}^{\mathsf{s}}[\mathsf{c}'/\mathsf{c}]\texttt{ \}}$
$\mathsf{x}[\mathsf{c}'/\mathsf{c}] = \mathsf{x}, \mathsf{f}[\mathsf{c}'/\mathsf{c}] = \mathsf{f}, \mathsf{m}[\mathsf{c}'/\mathsf{c}] = \mathsf{m},$
$\mathsf{c}[\mathsf{c}'/\mathsf{c}] = \mathsf{c}', \mathsf{c}''[\mathsf{c}'/\mathsf{c}] = \mathsf{c}''$ if $\mathsf{c}'' \not\equiv \mathsf{c}, \mathtt{M.c}[\mathsf{c}'/\mathsf{c}] = \mathtt{M.c}$
all other cases are trivial (propagation)

$\texttt{class c}''\texttt{ extends n \{ req fds mds}^{\mathsf{s}}\texttt{ \}}[\mathsf{c}'/in\ \mathsf{c}] =$
$\qquad \texttt{class c}''\texttt{ extends n}[\mathsf{c}'/\mathsf{c}]\texttt{ \{ req}[\mathsf{c}'/\mathsf{c}]\ \mathsf{fds}[\mathsf{c}'/\mathsf{c}]\ \mathsf{mds}^{\mathsf{s}}[\mathsf{c}'/\mathsf{c}]\texttt{ \}}$

Fig. 7. Auxiliary functions for FJ

cd^{b}	$::= \texttt{class c extends n \{ fds mds}^{\mathsf{b}}\texttt{ \}}$	class definition
$\mathsf{mds}^{\mathsf{b}}$	$::= \mathsf{md}^{\mathsf{b}}{}_1 \ldots \mathsf{md}^{\mathsf{b}}{}_n$	method declarations
md^{b}	$::= \mathsf{mh}\ \{\texttt{return e}^{\mathsf{b}}\texttt{;}\}$	method declaration
e^{b}	$::= \mathsf{x} \mid \mathsf{e}^{\mathsf{b}}[\mathsf{t.f}\ \mathsf{t}'] \mid \mathsf{e}_0^{\mathsf{b}}[\mathsf{t.m}(\bar{\mathsf{t}})\mathsf{t}'](\mathsf{e}_1^{\mathsf{b}} \ldots \mathsf{e}_n^{\mathsf{b}}) \mid \texttt{new } [\mathsf{n}\ \bar{\mathsf{t}}](\mathsf{e}_1^{\mathsf{b}} \ldots \mathsf{e}_n^{\mathsf{b}}) \mid (\mathsf{n})\mathsf{e}^{\mathsf{b}} \mid \ll \mathsf{n}, \mathsf{t} \gg \mathsf{e}^{\mathsf{b}}$	expression

where fds and mh are defined in Fig.6 and method names declared in $\mathsf{mds}^{\mathsf{b}}$ are distinct

Fig. 8. FJ binary class definitions

δ	$::= (\mathsf{c}, \mathsf{n}, \mathsf{fss}, \mathsf{mss}) \mid \mathsf{c}$	class signature
fss	$::= \overline{\mathsf{fs}}$	field signatures
fs	$::= \mathsf{n\ f}$	field signature
mss	$::= \overline{\mathsf{ms}}$	method signatures
ms	$::= \mathsf{n\ m}(\bar{\mathsf{n}})$	method signature
γ	$::= \mathsf{t} \leq \mathsf{t}' \mid \exists \mathsf{n} \mid \phi(\mathsf{t}, \mathsf{f}, \mathsf{t}') \mid \mu(\mathsf{t}, \mathsf{m}, \bar{\mathsf{t}}, (\mathsf{t}', \bar{\mathsf{t}}')) \mid \kappa(\mathsf{n}, \bar{\mathsf{t}}, \bar{\mathsf{t}}') \mid \mathsf{n} \sim \mathsf{t}$	constraint
t	$::= \mathsf{n} \mid \alpha$	expression type

Fig. 9. FJ class signatures and type constraints

Class signatures and type constraints are defined in Fig.9. Class signatures are the type information which can be extracted from a class definition and consist of a simple class name (the name of the declared class), a class name (the name of the parent class), a sequence of *field signatures* (type and name of declared fields) and a sequence of *method signatures* (return type, name and parameter types of declared methods). Constraints have the following informal meaning:

- $\mathtt{t} \leq \mathtt{t}'$ means "$\mathtt{t}$ is a subtype of $\mathtt{t}'$".
- $\exists \mathtt{n}$ means "$\mathtt{n}$ is defined".
- $\phi(\mathtt{t}, \mathtt{f}, \mathtt{t}')$ means "$\mathtt{t}$ provides field $\mathtt{f}$ with type $\mathtt{t}'$".
- $\mu(\mathtt{t}, \mathtt{m}, \bar{\mathtt{t}}, (\mathtt{t}', \bar{\mathtt{t}}'))$ means "$\mathtt{t}$ provides method $\mathtt{m}$ applicable to arguments of type $\bar{\mathtt{t}}$, with return type $\mathtt{t}'$ and parameters of type $\bar{\mathtt{t}}'$.
- $\kappa(\mathtt{n}, \bar{\mathtt{t}}, \bar{\mathtt{t}}')$ means "$\mathtt{n}$ provides constructor applicable to arguments of type $\bar{\mathtt{t}}$, with parameters of type $\bar{\mathtt{t}}'$".
- $\mathtt{n} \sim \mathtt{t}$ means "$\mathtt{n}$ and $\mathtt{t}$ are comparable" (this constraint is generated when compiling a cast).

Note that both the constraints $\mu(\mathtt{t}, \mathtt{m}, \bar{\mathtt{t}}, (\mathtt{t}', \bar{\mathtt{t}}'))$ and $\kappa(\mathtt{n}, \bar{\mathtt{t}}, \bar{\mathtt{t}}')$ subsume the constraint $\bar{\mathtt{t}} \leq \bar{\mathtt{t}}'$.
We omit the formal definition of global compilation $\vdash_{core} \mathsf{S} : \Delta | \mathsf{B}$ (see [2]), which is basically a reformulation of the standard type system for FJ [17]. Rules defining compositional compilation of classes are given in Fig.10. They use a *local environment* Π of shape $(\mathtt{x}_1, \mathtt{n}_1) \ldots (\mathtt{x}_n, \mathtt{n}_n)$. Note that the type constraints which are generated for a class are both those inferred for typechecking its fields and methods and those explicitly added by the user.
We write $type(\mathsf{fds})$ and $type(\mathsf{mds^s})$ to denote the set of field signatures and the set of method signatures extracted from the field declarations fds and from the method declarations $\mathsf{mds^s}$, respectively. The straightforward definition of *type* has been omitted.
We refer to [2] for an algorithmic definition of linking $\Delta \vdash_{core} \Gamma | \mathsf{cd^b} \rightsquigarrow \Gamma' | \mathsf{cd^{b'}}$. Basically, this judgment holds if the binary class $\mathsf{cd^b}$, equipped with constraints Γ, can be safely linked to a context of other classes whose type information is described by class signatures Δ. In this case, constraints Γ are simplified to Γ' and bytecode of the class is simplified correspondingly, by basically eliminating constraints which hold in Δ and replacing some type variables with class names. Checking the linking judgment also includes checking sanity constraints in Δ, such as that there are no cycles in the inheritance hierarchy and overriding rules are satisfied. Finally, we again refer to [2] for the proof that Assumption 1 holds for FJ.
As a last comment, note that, even though the instantiation outlined in this section and fully formally defined in [2] considers a very small Java subset excluding Java specific features like, for instance, field hiding, method overloading, and `super`, this is mainly for simplicity. Indeed, it has already been extensively shown [18, 3, 20, 19] how to extend the compositional compilation technique to more significant subsets of Java by introducing more sophisticated forms of constraints.

5 Implementation

In this section we discuss how we have implemented a prototype compiler for the framework we have presented; it can be downloaded (along with its sources and some examples) at:

`http://www.disi.unige.it/person/LagorioG/SmartJavaComp/`

This compiler supports a superset of the language modeled in this paper; in addition to some syntactic shortcuts it supports primitive types, assignments, implicit use of `this`, the literal `null`, `void` methods, constructor overload and basic statements. All examples shown in the

$$\textit{(class)}\ \frac{\vdash \mathsf{fds} : \Gamma \qquad \mathsf{c} \vdash \mathsf{mds^s} : \Gamma' | \mathsf{mds^b}}{\vdash_{core} \texttt{class c extends n \{ req fds mds}^{\mathsf{s}}\ \texttt{\} } : \Gamma^r, \Gamma, \Gamma', \exists\, \mathtt{n} | (\mathsf{c}, \mathtt{n}, \mathsf{fss}, \mathsf{mss}) | \texttt{class c extends n \{ fds mds}^{\mathsf{b}}\ \texttt{\}}}\ \begin{array}{l}\mathsf{req} = \{\texttt{requires}\ \Gamma^r\} \\ \mathit{type}(\mathsf{mds^s}) = \mathsf{mss} \\ \mathit{type}(\mathsf{fds}) = \mathsf{fss}\end{array}$$

$$\textit{(fields)}\ \frac{\vdash \mathsf{fd}_i : \Gamma_i \qquad \forall i \in 1..n}{\vdash \mathsf{fd}_1\ \ldots \mathsf{fd}_n : \Gamma_1, \ldots, \Gamma_n}\ n \neq 1 \qquad \textit{(field)}\ \frac{}{\vdash \mathtt{n\ f} : \exists\, \mathtt{n}}$$

$$\textit{(methods)}\ \frac{\mathsf{c} \vdash \mathsf{md^s}_i : \Gamma_i | \mathsf{md^b}_i \qquad \forall i \in 1..n}{\mathsf{c} \vdash \mathsf{md^s}_1\ \ldots \mathsf{md^s}_n : \Gamma_1 \ldots \Gamma_n | \mathsf{md^b}_1\ \ldots \mathsf{md^b}_n}\ n \neq 1$$

$$\textit{(method)}\ \frac{\mathtt{x}_1{:}\mathtt{n}_1 \ldots \mathtt{x}_n{:}\mathtt{n}_n, \mathtt{this}{:}\mathsf{c} \vdash \mathsf{e^s} : \mathsf{t} \mid \Gamma \mid \mathsf{e^b}}{\mathsf{c} \vdash \mathtt{n}_0\ \mathtt{m}(\mathtt{n}_1\ \mathtt{x}_1 \ldots \mathtt{n}_n\ \mathtt{x}_n)\ \{\texttt{return e}^{\mathsf{s}}\texttt{;}\} : \Gamma, \mathsf{t} \leq \mathtt{n}_0, \exists\, \mathtt{n}_i{}^{i \in 0..n} | \mathtt{n}_0\ \mathtt{m}(\mathtt{n}_1\ \mathtt{x}_1 \ldots \mathtt{n}_n\ \mathtt{x}_n)\ \{\texttt{return e}^{\mathsf{b}}\texttt{;}\}}$$

$$\textit{(parameter)}\ \frac{\Pi = (\mathtt{x}_1, \mathtt{n}_1) \ldots (\mathtt{x}_n, \mathtt{n}_n)}{\Pi \vdash \mathtt{x} : \mathtt{n}_i \mid \Lambda \mid \mathtt{x}}\ \mathtt{x} = \mathtt{x}_i \qquad \textit{(field access)}\ \frac{\Pi \vdash \mathsf{e^s} : \mathsf{t} \mid \Gamma \mid \mathsf{e^b}}{\Pi \vdash \mathsf{e^s.f} : \alpha \mid \Gamma, \phi(\mathsf{t}, \mathsf{f}, \alpha) \mid \mathsf{e^b[t.f}\ \alpha\mathsf{]}}\ \alpha \text{ fresh}$$

$$\textit{(meth inv)}\ \frac{\begin{array}{c}\Pi \vdash \mathsf{e^s}_0 : \mathsf{t}_0 \mid \Gamma_0 \mid \mathsf{e}^{\mathsf{b}}_0 \\ \Pi \vdash \mathsf{e^s}_i : \mathsf{t}_i \mid \Gamma_i \mid \mathsf{e}^{\mathsf{b}}_{\mathsf{i}} \quad \forall i \in 1..n\end{array}}{\Pi \vdash \mathsf{e^s}_0.\mathsf{m}(\mathsf{e^s}_1 \ldots \mathsf{e^s}_n) : \beta \mid \Gamma_0, \Gamma_1, \ldots, \Gamma_n, \mu(\mathsf{t}_0, \mathsf{m}, \bar{\mathsf{t}}, (\beta, \bar{\alpha})) \mid \mathsf{e}^{\mathsf{b}}_0[\mathsf{t}_0.\mathsf{m}(\bar{\alpha})\beta](\mathsf{e}^{\mathsf{b}}_1, \ldots, \mathsf{e}^{\mathsf{b}}_{\mathsf{n}})}\ \beta,\bar{\alpha} \text{ fresh}$$

$$\textit{(new)}\ \frac{\Pi \vdash \mathsf{e^s}_i : \mathsf{t}_i \mid \Gamma_i \mid \mathsf{e}^{\mathsf{b}}_{\mathsf{i}}\ \forall i \in 1..n}{\Pi \vdash \mathtt{new\ n}(\mathsf{e^s}_1, \ldots, \mathsf{e^s}_n) : \mathtt{n} \mid \Gamma_1, \ldots, \Gamma_n, \kappa(\mathtt{n}, \bar{\mathsf{t}}, \bar{\alpha}) \mid \mathtt{new}\ [\mathtt{n}\ \bar{\alpha}](\mathsf{e}^{\mathsf{b}}_1 \ldots \mathsf{e}^{\mathsf{b}}_{\mathsf{n}})}\ \bar{\alpha} \text{ fresh}$$

$$\textit{(cast)}\ \frac{\Pi \vdash \mathsf{e^s} : \mathsf{t} \mid \Gamma \mid \mathsf{e^b}}{\Pi \vdash (\mathtt{n})\mathsf{e^s} : \mathtt{n} \mid \Gamma, \mathtt{n} \sim \mathsf{t} \mid \ll \mathsf{c}, \mathsf{t} \gg \mathsf{e^b}}$$

Fig. 10. Compositional compilation of classes for FJ

paper, except the ones which uses Java interfaces, can be tested. Interface support is not ready at the time of writing, but we are working on it.
Our prototype consists of two programs:

- the compiler, which generates `.bc` component binary files from `.sjc` component source files, and
- the deployer, which assembles component binary files into standard `.jar` files. These resulting JAR files are directly executable on any JVM (Java Virtual Machine).

A `.sjc` file contains a single component declaration `MD` as in Fig.1, where the language used for writing class definitions is the small Java subset described above. A `.bc` file (a binary component) corresponds to a component type `MT` as in Fig.3, hence is (roughly) a collection of Java classes in polymorphic bytecode format, each one equipped with its constraints. The compiler implements typing rules in Fig.4. In particular, a basic component is compiled by compiling in isolation any class definition, by implementing the type system for separate compilation defined in [2], extended to the considered language.
Component declarations where unbound component names appear only in qualified names can be compiled in total isolation. On the other hand, component declarations which depend on other components can be compiled only if these components are already available in binary form (this corresponds to the $\mathcal{M}$ component type environment used in the typing rules). In this case, our compiler acts also as a linker, that is, it generates a new `.bc` file by also using those binary files. When components are compiled, type constraints are checked for consistency; unfortunately, some errors could be undetected as long as components remain open. Luckily, verification of constraints is complete in case of closed components [2].
Because binary components contain polymorphic bytecode, they cannot be directly loaded, much less executed, by a standard JVM. In order to obtain a standard Java "executable" (that is, a JAR archive containing a proper *manifest*) from a set of `.bc` binary files, we must *deploy* them (this corresponds to the step of closing a component type environment $\mathcal{M}$ in rule (prog) in Fig.4). The deployer can assemble components into a single executable, after having checked that these components complete each other without clashing; that is, when:

- the collection of Java class signatures extracted from these components is well-formed (class hierarchy is acyclic and there is no bad overriding/overloading);
- all type constraints of components are satisfied (and therefore simplify to the empty set of constraints) in this environment of class signatures.

These checks, as those made by the compiler for checking consistency of components, correspond to the judgment $\Delta \vdash_{core} \Gamma|\mathsf{B} \rightsquigarrow \Gamma'|\mathsf{B}'$, which is dependent on the used programming language (note that this judgment also includes checking well-formedness of Δ); our compiler and deployer implement the definition given in Sect.4.

6 Conclusion

We have presented a parametric framework of components for Java-like languages where a component is a collection of (binary) classes, each one equipped with type constraints on used classes. These type constraints guarantee *safe* linking (that is, composition and deployment) of components; moreover, linking is *flexible*, in the sense that type constraints are abstract enough to never reject safe compositions, and components can be combined by a set of powerful (mixin) module operators.
A concrete instantiation of the framework can be provided by giving a suitable intermediate language: Java bytecode or .NET intermediate language does not allow fully adaptive components

since, roughly speaking, they do not abstract away from all the possible contexts where open components can be safely used. However, as shown in [2], it is possible to define more abstract binary languages which are adequate to this aim. Our work until now, both in [2] and in the prototype accompanying this paper, has focused on extending Java bytecode, by adding type variables and type constraints. However, instantiations based on .NET intermediate language are feasible and interesting as well; moreover, they would be even more appealing in the sense that, being .NET an intermediate language which does not rely on a particular source language, the corresponding component framework would allow interoperability among components written in any language which targets .NET. We plan to further investigate this possibility in further work.

Basic components are constructed, as mentioned above, in a particular programming language. Again, the framework can be instantiated on any source programming language which allows compilation in isolation of classes in the given binary language.

The semantics of the component language is defined in terms of reduction into basic components, that is, collection of class declarations. The type system guarantees subject reduction and unique normal form for component expressions; moreover, composition of components is proved to be equivalent to global compilation of all their classes, hence to be type safe.

To show the effectiveness of the approach, we have provided a complete formal description of an instantiation of the framework on Featherweight Java [17], which uses the type system for compositional compilation in [2]. Moreover, we have developed a prototype implementation on a small Java subset, which implements a large extension of this type system.

In literature there exist several proposals to better support component programming in object-oriented languages.

MzScheme [15] and Jiazzi [22] components are mixins which can be statically linked, in a way similar to our approach. MzScheme is built on top of Scheme and is not statically typed; Jiazzi is inspired by MzScheme, but it is defined on top of Java, and is statically typed.

Other related papers propose language level abstractions for component-oriented programming allowing components to be first-class entities. ComponentJ [23], ArchJava [1], and ACOEL [24] are Java-like component-oriented languages, where components can be dynamically composed by explicitly connecting their *ports*. Ports basically play the role of required and provided interfaces in our framework.

ComponentJ promotes black-box object-oriented component programming style, by avoiding inheritance in favor of object composition.

ArchJava is an extension of Java with component classes; its type system allows for static checking of structural conformance between architecture and implementation.

ACOEL is an extensional language for supporting black-box components which uses mixins and virtual types to build adaptable applications.

Finally, Zenger [28] follows a more scalable approach, by proposing a component model where components are composed by type-safe high-level composition operators.

Differently to our approach, all the works above are less focused on the problem of programming language independence and interoperability of binary components.

There are several short term enhancements on the design of the component language which could be considered: for instance, the simpler extensions of adding an hiding operator for making classes private, and a freeze operator for making classes non virtual (classes statically bound), or the more involved extension to support transparent components.

Long term future work includes at least two important directions. First, our binary components are linkable units, but not loadable units, that is, they cannot be replaced or serviced after application execution has started. Hence, we plan to study the possibility of considering a different semantics for the composition operators based on dynamic rather static linking, following the

approach taken by Buckley and Drossopoulou [12] who have defined a model for a virtual machine able to execute polymorphic bytecode.
Second, in order to make the framework usable in practice and software reuse effective much work still have to be done: an appropriate GUI should be designed in order to assist the user while analysing, composing, and deploying components. Furthermore, black-box components approach, as followed here, make difficult the task of reusing code if type information in the provided and required interfaces are not coupled with assertions expressing semantic properties.

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