Recaf: Java Dialects as Libraries

Aggelos Biboudis  
CWI, The Netherlands  
University of Athens, Greece  
biboudis@di.uoa.gr

Pablo Inostroza  
CWI, The Netherlands  
pvaldera@cwi.nl

Tijs van der Storm  
CWI & University of Groningen  
The Netherlands  
storm@cwi.nl

Abstract

Mainstream programming languages like Java have limited support for language extensibility. Without mechanisms for syntactic abstraction, new programming styles can only be embedded in the form of libraries, limiting expressiveness.

In this paper, we present Recaf, a lightweight tool for creating Java dialects; effectively extending Java with new language constructs and user defined semantics. The Recaf compiler generically transforms designated method bodies to code that is parameterized by a semantic factory (Object Algebra), defined in plain Java. The implementation of such a factory defines the desired runtime semantics.

We applied our design to produce several examples from a diverse set of programming styles and two case studies: we define i) extensions for generators, asynchronous computations and asynchronous streams and ii) a Domain-Specific Language (DSL) for Parsing Expression Grammars (PEGs), in a few lines of code.

Categories and Subject Descriptors  
D.3.3 [Programming Languages]: Language Constructs and Features;  
D.3.2 [Programming Languages]: Language Classifications—Extensible languages

Keywords  
language virtualization, object algebras, transformation, extensible languages

1. Introduction

Programming languages are as expressive as their mechanisms for abstraction. Most mainstream languages support functional and object-based abstractions, but it is well-known that some programming patterns or idioms are hard to encapsulate using these standard mechanisms. Examples include complex control-flow features, asynchronous programming, or embedded DSLs. It is possible to approximate such features using library-based encodings, but this often leads to code that is verbose and tedious to maintain.

Consider the example of a simple extension for automatically closing a resource in Java\textsuperscript{1}:

```java
void method receiving a closure, like
Consumer<Closeable> block)
```

Such a language feature abstracts away the boilerplate needed to correctly close an IO resource, by automatically closing the resource whenever the execution falls out of the scope of the block.

Unfortunately, in languages like Java, defining such constructs as a library is limited by inflexible statement-oriented syntax, and semantic aspects of (non-local) control-flow. For instance, one could try to simulate using a method receiving a closure, like \texttt{void using(Closeable r, Consumer<Closeable> block)}. However, the programmer can now no longer use non-local control-flow statements (e.g., break) within the closure block, and all variables will become effectively final as per the Java 8 closure semantics. Furthermore, encodings like this disrupt the conventional flow of Java syntax, and lead to an atypical, inverted code structure. More sophisticated idioms lead to even more disruption of the code (case in point is “call-back hell” for programming asynchronous code).

In this work we present Recaf\textsuperscript{2}, a lightweight tool\textsuperscript{3} to extend Java with custom dialects. Extension writers do not have to alter Java’s parser or write any transformation rules. The Recaf compiler generically transforms an extended version of Java, into code that builds up the desired semantics. Hence, Recaf is lightweight: the programmer can define a dialect without stepping outside the host language.

Recaf is based on two key ingredients:

- Syntax extension: Java’s surface syntax is liberated to allow the definition of new language constructs, as long as they follow the pattern of existing control-flow or declaration constructs. (For instance, the using construct follows the pattern of Java’s for-each.) A pattern that is

\textsuperscript{1} similar to C#’s using construct, or Java’s try-with-resources

\textsuperscript{2} As in recaffeinating coffee which describes the process of enhancing its caffeine content [7].

\textsuperscript{3} The code is available at https://github.com/cwi-swat/recaf.
used, drives a corresponding transformation that Recaf performs.

- Semantics extension: a single, syntax-directed transformation maps method bodies (with or without language extensions) to method calls on polymorphic factories which construct objects encapsulating the user-defined or customized semantics.

The factories are developed within Java as Object Algebras [20], which promote reusability and modular, type-safe extension of semantic definitions.

The combination of the two aforementioned key points enables a range of application scenarios. For instance, Recaf can be used to: extend Java with new syntactic constructs (like using), modify or instrument the semantics of Java (e.g., to implement aspects like tracing, memoization), replace the standard Java semantics with a completely different semantics (e.g., translate Java methods to Javascript source code), embed DSLs into Java (e.g., grammars, or GUI construction), define semantics-parametric methods which support multiple interpretations, and combine any of the above in a modular fashion (e.g., combine using with a tracing aspect). Developers can define the semantics of new and existing constructs and create DSLs for their daily programming needs. Language designers can experiment with new features, by quickly translating their denotations in plain Java. In other words, Recaf brings the vision of “languages as libraries” to mainstream, object-oriented programming languages.

The contributions of this paper are summarized as follows:

- We present a transformation of Java statement Abstract Syntax Trees (ASTs) with extended syntax to virtualize their semantics, and we show how the semantics can be defined as Object Algebras (Section 3).
- We generalize the transformation to virtualize Java expressions, widening the scope of user defined semantics (Section 4).
- We describe the implementation of Recaf, and how it deals with certain intricacies of the Java language (Section 5).
- We evaluate the expressiveness of Recaf with two case studies: i) providing language support for generators and asynchronous computations and ii) creating a DSL for parser combinators (Section 6).

The results of the case studies and directions for future work are discussed in Section 7.

2. Overview

2.1 Recaffeinating Java with Recaf

Figure 1 gives a bird's eye overview of Recaf. It shows how the using extension is used and implemented using Recaf. The top shows a snippet of code illustrating how the programmer would use a Recaf extension, in this case consisting of the using construct. The programmer writes an ordinary method, decorated with the recaf modifier to trigger the source-to-source transformation. To provide the custom semantics, the user also declares a recaf field, in scope of the recaf method. In this case, the field alg is initialized to be a Using object, defined over the concrete type String.

The downward arrow indicates Recaf’s source-to-source transformation which virtualizes the semantics of statements by transforming the Recaf code fragment to the plain Java code at the bottom. Each statement in the user code is transformed into calls on the alg object. The using construct itself is mapped to the Using method. The Using class shown in the call-out, defines the semantics for using. It extends a class (BaseJava) capturing the ordinary semantics of Java, and defines a single method, also called using. This particular Using method defines the semantics of the using construct as an interpreter of type IExec.

In addition to using a recaf field to specify the semantics of a recaf method, it is also possible to decorate a formal parameter of a method with the recaf modifier. This allows binding of the semantics at the call site of the method itself. Thus, Recaf supports three different binding times for the semantics of a method: static (using a static field), at object construction time (using an instance field), and late binding (method parameter). Recaf further makes the distinction between statement-only virtualization and full virtualization. In the latter case, expressions are virtualized too. This mode is enabled by using the recaff keyword, instead of recaf.

Section 4 provides all the details regarding the difference.

2.2 Object Algebras

The encoding used for the using class in Figure 1 follows the design pattern of Object Algebras [20] which has already been applied to numerous cases in the literature [1, 12, 21]. Object Algebras can be seen as an object-oriented encoding of tagless interpreters [4]. Instead of defining a language’s abstract syntax using concrete data structures, it is defined using generic factories: a generic interface declares generic methods for each syntactic construct. Implementations of such interfaces define a specific semantics by creating se-
### 3. Statement Virtualization

In this section we describe the first level of semantic and syntactic polymorphism offered by Recaf, which restricts virtualization and syntax extension to statement-like constructs.

#### 3.1 μJava

μJava is a simplified variant of Java used for exposition in this paper. In μJava all variables are assumed to be final, there is no support for primitive types nor void methods, and all variable declarations have initializers. Figure 2 shows the abstract syntax of μJava statements and method bodies in the form of Object Algebra interfaces.

<table>
<thead>
<tr>
<th>μJava Method Signature</th>
<th>Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>R method(S s)</code></td>
<td><code>MuJavaMethod&lt;R, S&gt;</code></td>
</tr>
<tr>
<td><code>S expr(Supplier&lt;Void&gt; e)</code></td>
<td><code>MuJavaMethod&lt;S, Void&gt;</code></td>
</tr>
<tr>
<td><code>S if(Supplier&lt;Boolean&gt; c, S s1, S s2)</code></td>
<td><code>MuJavaMethod&lt;S, S&gt;</code></td>
</tr>
<tr>
<td><code>S seq(S s1, S s2)</code></td>
<td><code>MuJavaMethod&lt;S, S&gt;</code></td>
</tr>
</tbody>
</table>

Both interfaces are parametric in two generic types, `R` and `S`, `R` represents the return type of the method, and `S` the semantic type of statements. The method `Method` in `MuJavaMethod` mediates between the denotation of statements (`S`) and the return type `R` of the virtualized method. The programmer of a Recaf method needs to ensure that `R` returned by `Method` corresponds to the actual return type declared in the method. Note that `R` does not have to be bound to the same concrete type in both `MuJavaMethod` and `μJava`. This means that the return type of a virtualized method can be different than the type of expressions expected by `Return`.

The `MuJava` interface assumes that expressions are represented using the standard Java `Supplier` type, which represents thunks. Java expressions may perform arbitrary side-effects; semantic objects representing operations like pretty printing, evaluation, and so on.

Object Algebras are a simple solution to the expression problem [31]. As such they provide type-safe, modular extensibility along two axes: adding new data variants and adding new operations over them without changing existing code. For instance, the `using` algebra extends the base Java semantics with a new syntactic construct. On the other hand, the generic interface representing the abstract syntax of Java can also be implemented again, to obtain a different semantics. In the remainder of this paper we define the algebras as Java 8 interfaces with default methods to promote additional flexibility for modularly composing semantic modules.

#### 3.2 Transforming Statements

The transformation for μJava is shown in Figure 3, and consists of two transformation functions `M` and `J`, respectively transforming method bodies and statements. The transformation folds over the syntactic structure of μJava, compositionally mapping each construct to its virtualized representation. Both functions are subscripted by the expression `a`, which represents the abstract algebra that is used to construct the semantics. The value of `a` is determined by the `recaf` modifier on a field or formal parameter.

As an example consider the code shown on the left of Figure 4. The equivalent code after the Recaf transformation is shown on the right. The semantics of the code is now virtualized via the algebra object `a`. The algebra `a` may implement the same semantics as ordinary Java, but it can also customize or completely redefine it.

#### 3.3 Statement Syntax

Statement syntax is based on generalizing the existing control-flow statement syntax of Java. Informally speaking, wherever Java requires a keyword (e.g., `for`, `while` etc.), Recaf allows...
The type parameter
The direct style interpreter for $\mu$
This grammar defines a potentially infinite family of new lan-
tween the evaluation of the semantic objects, returned by the
return
structs to semantic objects of type $IExec$
interface
prises):
MuJavaBase<R>
extends
is declared as follows:
3.4 Direct Style Semantics
the use of an identifier. This identifier will then, by conven-
tion, correspond to a particular method with the same name
in the semantic algebra.
The following grammar describes the syntax extensions
of statements ($S$) for $\muJava$:
$$S ::= x; e; \quad \text{Return-like}$$
$$x (T; x; e) S \quad \text{For-each like}$$
$$x (e) \{S\} \quad \text{While-like}$$
$$x \{S\} \quad \text{Try-like}$$
$$x T x = e; \quad \text{Declaration-like}$$
This grammar defines a potentially infinite family of new lan-
guage constructs, by using identifiers ($x$) instead of keywords.
Each production is a generalization of existing syntax. For
instance, the first production, follows syntax of return $e$, with
the difference that an exclamation mark is needed after the
identifier $x$ to avoid ambiguity. The second production is like
for–each, the third like while, and the fourth follows the pat-
tern of if without else. Finally, the last production supports
custom declarations, where the first identifier $x$ represents the
keyword.
Transforming the extension into an algebra simply uses the
keyword identifier $x$ as a method name, but follows the same
transformation rules as for the corresponding, non-extended
constructs. The transformation rules are shown in Figure 5.  

3.4 Direct Style Semantics
The direct style interpreter for $\muJava$ is defined as the inter-
face $\muJavaBase$, implementing it using default methods and
is declared as follows:
```java
interface $\muJavaBase$<R> extends $\muJava$<R, IExec> { ... }
```
The type parameter $R$ represents the return type of the method.
$S$ is bound to the type $IExec$, which represents thunks (clo-
sures):
```java
interface IExec { void exec(); }
```
The algebra $\muJavaBase$ thus maps $\muJava$ statement con-
structs to semantic objects of type $IExec$. Most of the state-
ments in $\muJava$ have a straightforward implementation. Non-
local control-flow (i.e., return), however, is implemented us-
ing exception handling.

The method $\text{Method}$ ties it all together and mediates be-
tween the evaluation of the semantic objects, returned by the
algebra, to the actual return type of the method:
```java
default $R\text{Method}(IExec s)\{ 
  try { s.exec(); }
  catch (Return r) { return (R)r.value; }
  catch (Throwable e) { throw new RuntimeException(e); }
  return null;
}
```
Since the mapping between the statement denotation and the
actual return type of a method is configurable it is not part
of $\muJavaBase$ itself. This way, $\muJavaBase$ can be reused with
different $\text{Method}$ implementations.

Example: Maybe
As a simple example, similar to the using
extension introduced in Section 1, consider a maybe construct,
to unwrap an optional value (of type java.util.Optional). In
a sense, maybe literally overrides the semicolon, similar to the
bind operator of Haskell. Syntactically, the maybe operator
follows the declaration-like syntax. It is defined as follows:
```java
interface $\mu$Maybe<R> extends $\muJavaBase$<R> { 
  default <T> IExec Maybe(Supplier<Optional<T>> x,
    Function<T, IExec> s) { 
    return () -> {
      Optional<T> opt = x.get();
      if (opt.isPresent()) s.apply(opt.get()).exec();
    }
  }
}
```
The $\text{Maybe}$ method returns an $IExec$ closure that evaluates
the expression (of type Optional), and if the optional is not empty,
executes the body of maybe.

3.5 Continuation-Passing Style Semantics
The direct style base interpreter can be used for many exten-
sions like using or maybe. However, language constructs that re-
quire non-local control-flow semantics require a continuati-
ion-passing style (CPS) interpreter. This base interpreter can be
used instead of the direct style interpreter for extensions like
coroutines, backtracking, call/cc etc. It also shows how Ob-
ject Algebras enables the definition of two different semantics
for the same syntactic interface.

The cps style interpreter is defined as the interface
$\muJavaCPS$, similarly to $\muJavaBase$:
```java
interface $\mu$JavaCPS<R> extends $\muJava$<R, SD<R>> { ... }
```
The $\muJavaCPS$ algebra maps $\muJava$ abstract syntax to CPS
denotations ($SD$), defined as follows:
```java
interface SD<R> { void accept(K<R> r, K0 s); }
```
$SD$ is a functional interface that takes as parameters a return
and a success continuation. The return continuation $r$ is of
type $K<R>$ (a consumer of $R$) and contains the callback in
the case a statement is the return statement. The success con-
tinuation is of type $K0$ (a thunk) and contains the callback in
the case the execution falls off without returning.

To illustrate the CPS interpreter, consider the following
code that defines the semantics of the $if$–else statement:
The previous section discussed virtualization of declaration and control-flow statements. In this section we widen the scope of Recaf for virtualizing expressions as well.

### 4. Full Virtualization

The previous section discussed virtualization of declaration and control-flow statements. In this section we widen the scope of Recaf for virtualizing expressions as well.

#### 4.1 Expression Virtualization

Until now we have dissected the MuJava interface of Figure 2. That interface still does not support virtualized expressions since it requires the concrete type Supplier in expression positions. To enable full virtualization, we have to use the algebraic interfaces shown in Figure 7, where expressions are represented by the generic type E. MuExpJava specifies the semantic objects for MuJava expressions. The interface MuStmJava is similar to MuJava, but changes the concrete Supplier arguments to the generic type E.

Compared to full Java, the expression sub language of MuJava makes some additional simplifying assumptions: there are no assignment expressions, no super calls, no array creation, no static fields or methods, no package qualified names, and field access and method invocation require an explicit receiver. For brevity, we have omitted infix and prefix expressions.

To support expression virtualization, the transformation of statements is modified according to the rules of Figure 8. The function \(\delta\) folds over the expression structure and creates the corresponding method calls on the algebra \(\mu\). Consider, for example, how full virtualization desugars the MuJava code fragment for (Integer x: y) println(x + 1):

```java
a.For(a.Var("y", y), Integer x
  a.Add(a.Var("x", x), a.Lit(1))));
```

Note how the HOAS representation of binders carries over to expression virtualization, through the var constructor. The additional string argument to var is not essential, but provides additional meta data to the algebra.

Recaf does not currently support new syntactic constructs for user defined expression constructs. We assume that in most cases ordinary method abstraction is sufficient\(^4\). The examples below thus focus on instrumenting or replacing the semantics of ordinary MuJava expressions.

#### 4.2 An Interpreter for MuJava Expressions

Just like statements, the base semantics of MuJava expressions is represented by an interpreter, this time conforming to the

---

\(^4\) The only situation where a new kind of expression would be useful is when arguments of the expression need to be evaluated lazily, as in short-circuiting operators.
As an example, consider an aspect defining tracing of the
IEval
The class of the object whose field is requested, is discovered
values of variables during method execution. The algebra ex-
interface
super
and then calls the
 overridden
Var
and then, the reflective method
overridden, they implement the additional behavior, and dele-
expression virtual-
Example: Aspects
interface
Figure 8. Transforming statements (modified) and expressions.

interface MuExpJava, shown in Figure 7. This interpreter binds
E to the closure type IEval:

As IEval is not polymorphic, we do not make any assumptions
about the type of the returned object. The interpreter is fully
dynamically typed, because Java’s type system is not expres-
denotations, even if the Recaf transformation would have had
access to the types of variables and method signatures.

The evaluation of expressions is straightforward. Field
access, object creation (new), and method invocation, however
are implemented using reflection. For instance, the following
code defines the semantics for field lookup:

default IEval Field(IEval x, String f) {
    return () -> {
Object o = x.eval();
Class<?> clazz = o.getClass();
return clazz.getField(f).get(o);
    }
}

The class of the object whose field is requested, is discovered
at runtime, and then, the reflective method getField is invoked
in order to obtain the value of the field for the requested
object.

Example: Aspects A useful use case for expression virtual-
ization is defining aspect-like instrumentation of expression
evaluation. The algebra methods of the base interpreter are
overridden, they implement the additional behavior, and dele-
gate to the parent’s implementation with the super keyword.
As an example, consider an aspect defining tracing of the
values of variables during method execution. The algebra ex-
tends the base interpreter for Java expressions and overrides
the var definition, for variable access. Figure 9 shows how the
 overridden var method uses the variable name and the actual
received value passed to print out the tracing information,
and then calls the super implementation.

Figure 9. Intercepting field accesses for policy based access control.

Example: Library embedding In the following example we
demonstrate library embedding of a simple constraint solving language, Choco [24], a Java library for constraint
programming. Choco’s programming model is heavily based
on factories nearly for all of its components, from variable
creation, constraint declaration over variables, to search
strategies.

We have developed a Recaf embedding which translates a
subset of Java expressions to the internal constraints of Choco,
which can then be solved. The solve algebra defines the var
extension to declare constraint variables. The solve! state-
ment posts constraints to Choco’s solver. This embedding
illustrates how the expression virtualization allows the ex-
tension developer to completely redefine (a subset of) Java’s
expression syntax.

recaf Solve alg = new Solve();
recaff Iterable<Map<String, Integer>> example() {
    var 0, 5, IntVar x;
    var 0, 5, IntVar y;
    solve! x + y < 5;
}

5. Implementation of Recaf

All Recaf syntactic support is provided by Rascal [14], a language for source code analysis and transformation. Ras-
cal features built-in primitives for defining grammars, tree
traversal and concrete syntax pattern matching. Furthermore,
Rascal’s language workbench features [9] allow language de-
velopers to define editor services, such as syntax highlighting
or error marking, for their languages.

5.1 Generically Extensible Syntax for Java

Section 3.3 introduced generic syntax extensions in the
context of μJava, illustrating how the base syntax could be
augmented by adding arbitrary keywords, as long as they
conform to a number of patterns, e.g. while- or declaration-
like. We implemented these patterns and a few additional
ones for full Java using Rascal’s declarative syntax rules.
These rules modularly extend the Java grammar, defined in
Rascal’s standard library using productions for each case that
we identify as an extensibility point: return-like, declaration-
like, for-like, switch-like (as a for) and try-like.
5.2 Transforming Methods

Recaf source code transformation transforms any method that has the recaf or recaff modifier. If the modifier is attached to the method declaration, the algebra is expected to be declared as field in the enclosing scope (class or interface). If the modifier is attached to a method’s formal parameter, that parameter itself is used instead. Furthermore, if the recaff modifier is used, expressions are transformed as well.

The transformation is defined as Rascal rewrite rules that match on a Java statement or expression using concrete-syntax pattern matching. This means that the matching occurs on the concrete syntax tree directly, having the advantage of preserving comments and indentation from the Recaf source file. As an example, the following rule defines the transformation of the while-statement:

```
Expr stm2alg((Stm)\texttt{while}(\langle Expr \texttt{c}\rangle)(\langle Stm \texttt{s}\rangle),\texttt{Id} a,\texttt{Names} ns) = (\texttt{Expr'})\langle Id \texttt{a}\rangle.\texttt{while}(\langle Expr \texttt{c}\rangle,\langle Expr \texttt{s}\rangle);
```

This rewrite rule uses the actual syntax of the Java while statement as the matching pattern and returns an expression that calls the while method on the algebra a. The condition c and the body s are transformed in the when-clause (where := indicates binding through matching). The function injectExpr either transforms the expression c, in the case of transformations annotated with the recaff keyword, or creates closures of type Supplier otherwise. The body s is transformed calling recursively \texttt{stm2alg}.

The ns parameter represents the declared names that are in scope at this point in the code and is the result of a local name analysis needed to correctly handle mutable variables. Local variables introduced by declarations and for-loops are mutable variables in Java, unless they are explicitly declared as final. This poses a problem for the HOAS encoding we use for binders: the local variables become parameters of closures, but if these parameters are captured inside another closure, they have to be (effectively) final. To correctly deal with this situation, variables introduced by declarations or for-loops are wrapped in explicit reference objects, and the name is added to the Names set. Whenever such a variable is referenced in an expression it is unwrapped. For extensions that introduce variables it is unknown whether they should be mutable or not, so the transformation assumes they are final, as a default. In total, the complete Recaf transformation consists of 790 SLOC.

5.3 Recaf Runtime

The Recaf runtime library comes with two base interpreters of Java statements, similar to \texttt{MuJavaBase} and \texttt{MuJavaCPS}, and an interpreter for Java Expressions. In addition to return, the interpreters support the full non-local control-flow features of Java, including (labeled) break, continue and throw. The CPS interpreter represents each of those as explicit continuations in the statement denotation (50), whereas the direct style interpreter uses exceptions.

The main difference between \texttt{MuExpBase} and the full expression interpreter is handling of assignments. We model mutable variables by the interface \texttt{IRef}, which defines a setter and getter to update the value of the single field that it contains. The \texttt{IRef} interface is implemented once for local variables, and once for fields. The latter uses reflection to update the actual object when the setter is called. In addition to the \texttt{Var(String, Object)} constructor, the full interpreter features the constructor \texttt{Ref(String, IRef<?>)} to model mutable variables. The expression transformation uses the local name analysis (see above) to determine whether to insert \texttt{Var} or \texttt{Ref} calls.

Since the Recaf transformation is syntax-driven, some Java expressions are not supported. For instance, since the expression interpreter uses reflection to call methods, statically overloaded methods are currently unsupported (because it is only possible to dispatch on the runtime type of arguments). Another limitation is that Recaf does not support static method calls, fields references or package qualified names. These three kinds of references all use the same dot-notation syntax as ordinary method calls and field references. However, the transformation cannot distinguish these different kinds, and interprets any dot-notation as field access or method invocation with an explicit receiver. We consider a type-driven transformation for Recaf as an important direction for future work.

6. Case Studies

6.1 Spicing up Java with Side-Effects

The Dart programming language recently introduced \texttt{sync*}, \texttt{async} and \texttt{async*} methods, to define generators, asynchronous computations and asynchronous streams [18] without the typical stateful boilerplate or inversion of control flow. Using Recaf, we have implemented these three language features for Java, based on the CPS interpreter, closely following the semantics presented in [18].

Generators. The extension for generators is defined in the \texttt{Iter} class. The \texttt{Iter} class defines \texttt{Method} to return a plain \texttt{Java Iterable<R>}. When the \texttt{iterator()} is requested, the statement denotations start executing. The actual implementation of the generator is defined in the client code using two new constructs. The first is \texttt{yield!}, which produces a single value in the iterator. Its signature is \texttt{SD<R> Yield(ISupply<Resizable>)}\footnote{\texttt{Supply} is a thunk which has a throws clause.}. Internally, \texttt{yield!} throws a special \texttt{Yield} exception to communicate the yielded element to a main iterator effectively pausing the generator. The \texttt{Yield} exception contains both the element, as well as the current continuation, which is stored in the iterator. When the next value of the iterator is requested, the saved continuation is invoked to resume the generator process. The second construct is \texttt{yieldFrom...}
which flattens another iterable into the current one. Its signature is $\text{SD<R> YieldFrom(ISupply<Iterable<R>> x)}$ and it is implemented by calling $\text{ForEach(x, e \rightarrow Yield() \rightarrow e)}$. In the code snippet below, we present a recursive implementation of a range operator, using both $\text{yield!}$ and $\text{YieldFrom!}$:

```java
recaf Iterable<Integer> range(int s, int n) {
    if (n > 0) {
        yield! s;
        yieldFrom! range(s + 1, n - 1);
    }
}
```

Async. The implementation of async methods also defines Method, this time returning a $\text{Future<R>}$ object. The only syntactic extension is the $\text{await}$ statement. Its signature is $\langle T \rangle \text{ Await(Supplier<CompletableFuture<T>>, Function<T, SD<R>>)}$, following the syntactic template of for-each. The $\text{await}$ statement blocks until the argument future completes. If the future completes normally, the argument block is executed with the value returned from the future. If there is an exception, the exception continuation is invoked instead. $\text{Await}$ literally passes the success continuation to the future’s whenComplete method. The Async extension supports programming with asynchronous computations without having to resort to call-backs. For instance, the following method computes the string length of a web page, asynchronously fetched from the web.

```java
recaf Future<Integer> task(String url) {
    await String html = fetchAsync(url);
    return html.length();
}
```

Async*. Asynchronous streams (or reactive streams) support a straightforward programming style on observables, as popularized by the Reactive Extensions [16] framework. The syntax extensions to support this style are similar to $\text{yield!}$ and $\text{YieldFrom!}$ constructs for defining generators. Unlike the $\text{yield!}$ for generators, however, $\text{yield!}$ now produces a new element asynchronously. Similarly, the $\text{YieldFrom!}$ statement is used to splice on asynchronous stream into another. Its signature reflects this by accepting an $\text{Observable}$ object (defined by the Java variant of Reactive Extensions, RxJava): $\text{SD<R> YieldFrom(ISupply<Observable<R>> x)}$. Reactive streams offer one more construct: $\text{awaitFor!}$, which is similar to the ordinary for-each loop, but “iterates” asynchronously over a stream of observable events. Hence, its signature is $\langle T \rangle \text{ SD<R> AwaitFor(ISupply<Observable<T>>, Function<T, SD<R>>>}$. Whenever, a new element becomes available on the stream, the body of the $\text{awaitFor!}$ is executed again. An async* method will return an Observable.

Here is a simple method that prints out intermediate results arriving asynchronously on a stream. After the result is printed, the original value is yielded, in a fully reactive fashion.

```java
recaf <X> Observable<X> print(Observable<X> src) {
    awaitFor (X x: src) {
        System.out.println(x);
        yield! x;
    }
}
```

6.2 Parsing Expression Grammars (PEGs)

To demonstrate language embedding and aspect-oriented language customization we have defined a DSL for Parsing Expression Grammars (PEGs) [11]. The abstract syntax of this language is shown in Figure 10. The lit! construct parses an atomic string, and ignores the result. let is used to bind intermediate parsing results. For terminal symbols, the regexp construct can be used. The language overloads the standard sequencing and return constructs of Java to encode sequential composition, and the result of a parsing process. The constructs choice, opt, star, and plus correspond to the usual regular EBNF operators. The choice combinator accepts a list of alternatives (alt). The Kleene operators bind a variable $x$ to the result of parsing the argument statement $S$, where the provided expression $e$ represents the result if parsing of $S$ fails.

The PEG language can be used by considering methods as nonterminals. A PEG method returns are parser object which returns a certain semantic value type. A simple example of parsing primary expression is shown in Figure 11. The method primary returns an object of type $\text{Parser}$ which produces an expression $\text{Exp}$. Primaries have two alternatives: constant values and other expressions enclosed in parentheses. In the first branch of the $\text{choice}$ operator, the regexp construct attempts to parse a numeric value, the result of which, if successful, is used in the $\text{return}$ statement, returning an $\text{Int}$ object representing the number. The second branch, first parses an open parenthesis, then binds the result of parsing an additive expression (implemented in a method called $\text{addSub}$) to $e$, and finally parses the closing parenthesis. When all three parses are successful, the $\text{e}$ expression is returned. Note that the $\text{return}$ statements return expressions, but the result of the method is a parser object.

Standard PEGs do not support left-recursive productions, so nested expressions are typically implemented using loops. For instance, additive expression could be defined as $\text{addSub ::= mulDiv (("+"|"-") mulDiv)*}$. Here’s how the $\text{addSub}$ method could define this grammar using the PEG embedding:

```java
recaf <Exp> addSub() {
    let Exp l = mulDiv();
    star Exp e = (1) {
        regexp String o = "+\-\? \?
        let Exp r = mulDiv();
        return new Bin(o, e, r);
    }
    return e;
}
```

The first statement parses a multiplicative expression. The star construct creates zero or more binary expressions, from
the operator (e), the left-hand side (e) and the right-hand side (r). If the body of the star fails to recognize a + or − sign, the e will be bound to the initial seed value l. The constructed binary expression will be fed back into the loop as e through every subsequent iteration.

The (partial) PEG for expressions shown above and in Figure 11 does support any kind of whitespace between elements of an expression. Changing the PEG definitions manually to parse intermediate layout, however, would be very tedious and error-prone. Exploiting the Object Algebra-based architecture, we add the layout handling as a modular aspect, by extending the PEG algebra and overriding the methods that construct the parsers.

For instance, to insert layout in between sequences, the PEG subclass for layout overrides the seq as follows:

```java
<T, U> Parser<T> Seq(Parser<T> p1, Parser<U> p2) {
    return PEG.super.Seq(p1, PEG.super.Seq(layout, p2));
}
```

Another concern with standard PEGs is exponential worst-case runtime performance. The solution is to implement PEGs as packrat parsers [10], which run in linear time by memoizing intermediate parsing results. Again, the base PEG language can be modularly instrumented to turn the returned parsers into memoizing parsers.

7. Discussion

Static Type Safety

The Recaf source-to-source transformation assumes certain type signatures on the algebras that define the semantics. For instance, the transformation of binding constructs (declarations, for-each, etc.) expects Function types in certain positions of the factory methods. If a method of a certain signature is not present on the algebra, the developer of a Recaf method will get a static error at the compilation of the generated code.

The architecture based on Object Algebras provides type-safe, modular extensibility of algebras. Thus, the developer of semantics may enjoy full type-safety in the development of extensions. The method signatures of most of the examples and case-studies accurately describe the expected types and do not require any casts.

On the other hand, the statement evaluators represent expressions as opaque closures, which are typed in the expected result such as Supplier<Boolean> for the if-else statement. At the expression level, however, safety guarantees depend on the denotation types themselves. More generally, semantics, like the Java base expression interpreter, however, are defined in terms of closures returning Object. The reason is that Java's type system is not expressive enough to represent them otherwise (lacking features such as higher-kinded types and implicits). As a result, potentially malformed expressions are not detected at compile-time.

Another consequence of this limitation is that the Supply-based statement interpreters described in Section 3 cannot be combined out-of-the-box with expression interpreters in the context of Full Virtualization, as both interpreters must be defined in terms of generic expressions. Fortunately, the Supply-based statement interpreters can be reused by applying the Adapter pattern [29]. In the runtime library, we provide an adapter that maps a Supplier-based algebra to one that is generic in the expression type. As we have discussed earlier, this is unsafe by definition. Thus, although we can effectively integrate statement and expression interpreters, we lose static type guarantees for the expressions.

To conclude, Recaf programs are type-correct when using Statement Virtualization, as long as they generate type-correct Java code. However, in the context of Full Virtualization, compile-time guarantees are overridden as the expressions are fully generic, and therefore, no static assumptions on the expressions can be made.

Runtime Performance. The runtime performance depends on the implementation of the semantics. The base interpreters are admittedly naive, but for the purpose of this paper they illustrate the modularity and reusability enabled by Recaf for building language extensions on top of Java. The Dart-like extensions, reuse the CPS interpreter. As such they are too slow for production use (closure creation to represent the program increases heap allocations). But these examples illustrate the expressiveness of Recaf's embedding method: a very regular syntactic interface (the algebra), may be implemented by an
8. Related Work

Syntactic and semantic extensibility of programming languages has received a lot of attention in literature, historically going back to Landin’s, “Next 700 Programming Languages” [15]. In this section we focus on work that is related to Recaf from the perspective of semantic language virtualization, languages as libraries, and semantic language customization.

Language Virtualization. Language virtualization allows the programmer to redefine the meaning of existing constructs and define new ones for a programming language. Well-known examples include LINQ [17]) that offers query syntax over custom data types, Haskell’s do-notation for defining custom monadic evaluation sequences, and Scala’s for-comprehensions. Scala Virtualized [25] and Lightweight Modular Staging (LMS) [26] are frameworks to redefine the meaning of almost the complete Scala language. However, these frameworks rely on the advanced typing mechanisms of Scala (higher-kinded types and implicits) to implement concrete implementations of DSL embeddings. Additionally, compared to Scala, Java does not have support for delimited continuations so we rely on a CPS interpretation to mitigate that. Recaf scopes virtualization to methods, a choice motivated by the statement-oriented flavor of the Java syntax, and inspired by how the async, sync* and async* modifiers are scoped in Dart [18] and async in C# [2].

Another related approach is the work on F#’s computation expressions [22] which allow the embedding of various computational idioms via the definition of concrete computation builder objects, similar to our Object Algebras. The F# compiler desugars ordinary F# expressions to calls into the factory, in an analogous way to the transformation employed by Recaf. Note that the semantic virtualization capabilities offered by computation expressions are scoped to the expression level. Both, Recaf and F# support custom operators, however in F# they are not supported in control flow statements [27]. Carette et al. [4] construct CPS interpreters among others. In Recaf we use the same approach to enable control-flow manipulation extensions.

Languages as Libraries. Recaf is a framework for library-based language extension. The core idea of “languages as libraries” is that embedded languages or language extensions exist at the same level as ordinary user code. This is different, for instance, from extensible compilers (e.g., [19]) where language extensions are defined at the meta level.

The SugarJ system [8] supports language extension as a library, where new syntactic constructs are transformed to plain Java code by specifying custom rewrite rules. The Racket system supports a similar style of defining library-based languages by transformation, leveraging a powerful macro facility and module system [28]. A significant difference to Recaf is that in both SugarJ and Racket, the extension developer writes the transformations herself, whereas in Recaf the transformation is generic and provided by the framework.

Language Customization. Language extension is only one of the use cases supported by Recaf. Recaf can also be used to instrument or modify the base semantics of Java. Consequently, Recaf can be seen as specific kind of meta object protocol [13], where the programmer can customize the dynamic semantics of a programming language, from within the host language itself. OpenC++ [5] introduced such a feature for C++, allowing the customization of member access, method invocation and object creation.

9. Conclusion

In this paper we have presented Recaf, a lightweight tool to extend both the syntax and the semantics of Java methods just by writing Java code. Recaf is based on two techniques. First, the Java syntax is generalized to allow custom language constructs that follow the pattern of the regular control-flow statements of Java. Second, a generic source-to-source transformation translates the source code of methods into calls to factory objects that represent the desired semantics. Furthermore, formulating these semantic factories as Object Algebras enables powerful patterns for composing semantic definitions and language extensions.

Acknowledgments

We thank the anonymous reviewers for their constructive comments. We are grateful to Nick Palladinos, Jouke Stoel and Vasilis Karakostas for their valuable suggestions. Research carried out by the first author was supported by the CWI Internships program.
References


