Reflection in Attribute Grammars

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Abstract

This paper shows how reflection on (undecorated) syntax trees used in attribute grammars can significantly reduce the amount of boiler-plate specifications that must be written. It is implemented in the Silver attribute grammar system in the form of a `reflect` function mapping syntax trees and other values into a generic representation and a `reify` function for the inverse mapping. We demonstrate its usefulness in several ways. The first is in an extension to Silver itself that simplifies writing language extensions for the ableC extensible C specification by allowing language engineers to specify C-language syntax trees using the concrete syntax of C (with typed holes) instead of writing abstract syntax trees. Secondly, a scrap-your-boilerplate style substitution mechanism is described. The third use is in serialization and de-serialization of the interface files Silver generates to support separate compilation; a custom interface language was replaced by a generic reflection-based implementation. Finally, an experimental implementation of staged interpreters for a small staged functional language is discussed.

CCS Concepts • **Software and its engineering → Translator writing systems and compiler generators**.

Keywords attribute grammars, reflection, meta-programming

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1 Introduction

Strong static type systems are lightweight, yet effective, formal methods for ensuring that run-time type errors cannot happen when executing type-correct programs, and many find the benefits of type safety outweigh the restrictions that such systems necessarily impose. Some meta-programming languages and systems enjoy the benefits of strong static typing, *e.g.* the Kiama [Sloane 2011] system embedded in Scala, the Java-based JastAdd [Ekman and Hedin 2007] attribute grammar system, and the Silver [Van Wyk et al. 2010] attribute grammar system used in the work presented here. The type systems in these ensure that all object-language syntax trees are well-sorted, that is, they correspond to the context free grammar defining the language.

But as many have observed, for example in the "scrap-your-boilerplate" work [Lämmel and Jones 2003], this often comes at a price. Transformations over syntax trees from syntactically rich languages are cumbersome to express recursively; for example, implementing a program transformation that rewrites $x + 0$ to x requires code or specifications not only for the case of addition, but for all other constructs in the language. For these other constructs the specification simply duplicates each construct with its rewritten components, leading to lots of uninteresting, cumbersome boilerplate code. Other (non-boilerplate) challenges in language development include the construction of non-trivial syntax trees and their serialization/de-serialization to/from strings.

One approach to this problem is to use a form of *reflection* [Demers and Malenfant 1995]. In our approach, a (well-sorted) syntax tree is reflected into a generic form over which transformations such as the one described above can be more easily written. This ease of writing is traded for the loss of some type-safety as well-sortedness is not guaranteed when constructing or manipulating object-language trees in this form. This paper presents a technique for bringing reflection of undecorated syntax trees (those without attributes) to attribute grammars and evaluates it on several examples.

Motivating Example: The reflection system presented here is implemented in Silver and some example uses are in an extensible specification of C, ableC [Kaminski et al. 2017a], all of which are written in Silver. Consider a language extension introducing an exponent operator to C that should translate, for example, `x ** y` to the code shown in Figure 1. Constructing the syntax tree of this translation by directly using abstract syntax is quite tedious and imposes barriers to entry for new language developers who must learn the numerous productions in the ableC abstract syntax grammar to become productive. Instead it is desirable to extend the meta-language allowing abstract syntax trees to be constructed

```
1  ({ float _res = 1;
2     for (int _i = 0; _i < y; _i++) {
3       _res *= x;
4     }
5     _res; })
```

Figure 1. The translation of an exponent expression `x ** y`, where `x` is a `float` and `y` is an `int`. Note this uses a statement-expression (`({...; ...;})`), a C extension supported by GCC and other compilers, to embed a statement in an expression.

using the actual concrete syntax of the object-language, as is done in systems such as Stratego [Visser 2002].

An example of this is shown on the left in Figure 2. Here the extension developer introduces a new production (named `exponent`) for an exponent operator that extends the ableC host language, and specifies that exponent constructs translate down (via the `forwards to` specification [Van Wyk et al. 2002]) to a syntax tree like the one in Figure 1. Some attributes (such as `pp`, the "pretty-printed" version of the construct) may be defined directly on the new production, while all other attributes (such as a translation to machine code) are automatically computed on the forwarded-to tree.

Object-language concrete syntax, in this case C, is written here as an expression in Silver using a "quote" production that wraps a piece of code in the object-language for which the abstract syntax tree should be constructed; `ableC_Expr{...}` beginning on line 6 of Figure 2 is an example of a quote production that introduces an `Expr` term from the C language. Sometimes portions of the desired tree are not fixed but instead should be constructed using Silver code. Such holes in the tree may be filled in using "antiquote" productions that escape from the object-language syntax back to Silver expressions, such as `$TypeExpr` on line 7. This line specifies the declaration and initialization of `_res` seen on line 1 of Figure 1. The specification on the right of Figure 2 is what is needed when writing the abstract syntax directly to specify this same single line. Since Silver itself is an extensible language, language developers may easily construct a version of Silver tailored to their object-language by introducing these productions (such the ableC extension to Silver used here, referred to as Silver-ableC.)

The reflection system presented here is used to simplify the implementation of this extension to Silver for using object-language concrete syntax in specifying trees. Computing the translation for quote productions such as `ableC_Expr` presents a difficulty without reflection; we must generate the abstract syntax for the Silver expression which, when compiled and evaluated, will construct the specified object-language syntax tree. In systems like Stratego this process may be accomplished by the use of rewrite rules; this is permitted as terms have a uniform/generic representation, and weak typing allows for an incremental transformation of object-language into meta-language abstract syntax. However in a strongly typed system such as Silver, object-language trees are strongly distinguished from meta-language expressions that construct trees; thus a direct transformation is required from the former to the latter.

One approach is to define a translation-to-Silver attribute on all nonterminals of the object-language attribute grammar, on each production writing an equation that constructs the Silver expression for a call to that production. With nearly 500 abstract productions in the ableC specification doing this would require writing a tremendous amount of boilerplate code. An important observation is that the desired translation does not depend on the semantics of particular productions, but rather is only based on the name of the production and number of children. Thus, some approach is demanded for dealing with a generic representation of an abstract syntax tree, rather than performing a computation on the tree itself.

There are other, similar problems that can best be expressed as generic analyses on trees. For example consider serializing/de-serializing between a tree and a string; this can easily be done with a uniform untyped term representation, but not so easily with a tree represented by a variety of nonterminals. Thus we want a general-purpose mechanism that can represent a tree in a generic way, and convert between well-sorted trees and this generic representation.

Reflection in Silver: Problems of this nature benefit from some form of reflection in the meta-language. The reflection capability developed here consists of two primary functions:

- `reflect`: which converts a well-sorted syntax tree in Silver into a generic tree representation of type `AST`.
- `reify`: which converts generic `AST` trees back to their original form. This requires run-time type checking and may fail if the generic form does not correspond to a well-sorted object-language tree. Thus `reify` returns a value of type `Either<String a>`: either a string error message or the tree of the correct type (represented by type variable `a`).

Transformations and analyses on `AST` trees are implemented by specifying attributes and their defining equations. This leads to specifications that are much less verbose with much less boilerplate code.

This follows a common thread found in a wide variety of reflective systems; one in which data can be viewed in two ways. The first is through the regular type system of the language, be it Java objects or Silver well-sorted syntax trees. The second view is a more generic one in which values of different types or sorts can be viewed in a uniform way; this may be by reflective methods in Java available to work on an `Object` super-type (`Field.get`, `Method.invoke`, etc.) or, in our case here, though the `reflect` transformation into a generic `AST` representation.

```
1  abstract production exponent
2  top::Expr ::= base::Expr exp::Expr
3  {
4    top.pp = base.pp ++ "␣**␣" ++ exp.pp;
5    forwards to
6      ableC_Expr {
7        ({$TypeExpr{base.typerep.typeExpr} _res = 1;
8          for ($TypeExpr{exp.typerep.typeExpr} _i = 0;
9               _i < $Expr{exp}; _i++) {
10           _res *= $Expr{base};
11         }
12         _res;})
13     };
14 }
```

```
1  declStmt(
2    variableDecls(
3      nilStorageClass(),
4      base.typerep.typeExpr,
5      consDeclarator(
6        declarator(
7          name("_res"),
8          baseTypeExpr(),
9          justInitializer(
10           exprInitializer(
11             integerConstant(
12               "1", false,
13               noIntSuffix()))))),
14       nilDeclarator()))
```

Figure 2. An example using Silver-ableC to implement an exponent expression in ableC. On the right is shown the tedious code that would be written using only plain Silver, for just line 7 of the exponent production on the left.

Contributions: The primary contributions of the paper are enumerated below.

- We integrate reflection and attribute grammars using a special AST nonterminal and a bidirectional `reflect`/`reify` transformation between AST trees and well-sorted object-language syntax trees; discussing the system design in Section 3 and its implementation in Section 8.
- We demonstrate the use of reflection in mapping object-language concrete syntax to the Silver constructs that would construct it, supporting specifications like those in Figure 2. This saved almost 18,000 lines of specification over several ableC extension specifications, amounting to 40% of the code base by character count. The code generation for many extensions was complex enough that they would likely not have been implemented using the direct method of specifying translation as shown on the right in Figure 2. (Section 4)
- We demonstrate the use of reflection in attribute grammars to implement "scrap your boilerplate"-style [Lämmel and Jones 2003] substitutions of particular subtrees within much larger abstract syntax trees. This saved over 2,500 lines of specification between ableC and several extensions, amounting to 11.8% of the ableC specification code base. (Section 5)
- We use reflection in conjunction with Silver's attribute grammar and parser specification features to provide a serialization / de-serialization library for arbitrary trees. This allowed 1,698 lines of hand-coded environment tree serialization/de-serialization code in the Silver compiler to be replaced with only 257 lines, removing 3.75% of the Silver code base. (Section 6)
- Use of reflection to allow a staged language evaluator to be specified as an attribute grammar and directly interpreted. (Section 7)

Silver version 0.4.1 [1] [Van Wyk et al. 2010] is the attribute grammar system used in this paper. The ableC[2] [Kaminski et al. 2017a] code and extensions to it [Kaminski et al. 2017b] are from version 0.1.3 and the Silver-ableC[3] code is from version 0.1.0. Specifications from each are shown in several figures below and can be found in `grammars` directory of the corresponding repository in the directory or file name given in caption in each figure. When indicating the number of lines of Silver code or `ableC` extension code saved by using reflection it is a comparison between these and previous versions in the corresponding repositories.

2 Background: Attribute Grammars

As this paper presents an integration of reflection into attribute grammars (AGs) we provide some background on them, and their embodiment in Silver [Van Wyk et al. 2010] here. In essence, attribute grammars provide a "semantics of context free grammars" [Knuth 1968] by associating/decorating nodes in a syntax tree with attributes that carry information (semantics) about that language construct. For example, in an AG for type checking a functional language, a nonterminal for expressions may be decorated with an attribute identifying the type of the expression and another providing a context that maps variable names to their types. Equations associated with productions are used to determine the values of the attributes.

More formally, an attribute grammar $AG = (G, A, O, \Gamma, E)$ where G is a context free grammar (NT, T, P) with a finite set of nonterminal symbols NT, a finite set of terminal symbols

[1]Available at http://melt.cs.umn.edu/silver and https://github.com/melt-umn/silver, archived at https://doi.org/10.13020/D6QX07.

[2]Available at http://melt.cs.umn.edu/ableC and https://github.com/melt-umn/ableC, archived at https://doi.org/10.13020/D6VQ25.

[3]Available at http://melt.cs.umn.edu/ and https://github.com/melt-umn/silver-ableC, archived at https://doi.org/10.13020/hbr0-9z50.

T which includes basic types for integers and strings, and P a set of grammar productions. Productions have the form

$$n :: NT_0 ::= n_1 :: X_1 ... n_n :: X_n$$

with a left-hand side nonterminal NT_0 and 0 or more right-hand side symbols in $NT \cup T$. These are labeled (n, n_i) so that tree nodes can be easily referenced. In Silver, productions are labeled as `concrete` if they are passed to the Copper [Van Wyk and Schwerdfeger 2007] scanner and parser generator bundled with Silver. Those labeled by `abstract` are not; they are used to define the abstract syntax of a language and are our primary focus here.

The set of attributes A is partitioned into synthesized attributes A_S that propagate information up the syntax tree and inherited attributes A_I that propagate information down the tree. In the example above the attribute for types is synthesized and the attribute for typing contexts is inherited. Attributes can hold various types of values beyond primitive types such as strings and integers. Vogt et al. [1989] introduced higher-order attributes in which attributes contain (yet undecorated) syntax trees. Reference [Hedin 2000] and remote [Boyland 2005] attributes that allow decorated syntax trees to be passed around as attribute values; these are sometimes thought of as references or pointers to distant nodes in the syntax tree. An occurrence-relation O indicates which attributes decorate which nonterminals and a typing context Γ tracks the types of attributes and productions for use in type checking the equations E that are used to determine the values of attributes for a specific syntax tree, perhaps as produced by a parser for the language.

Equations in E are associated with a single production $p \in P$ and typically have the form $n_i.a = e$ with n_i being a label for a symbol in p. If $i = 0$ then a is a synthesized attribute used to compute a value decorating n_0, otherwise a is an inherited attribute computing a value for a child of n_0. Equations can be written separately from their production definition in `aspect` productions.

3 Design of the Reflection System

In this section we describe the design of reflection features and how they are used in attribute grammars. The implementation is discussed later in Section 8.

We first introduce the `AST` type, a generic representation for well-sorted syntax trees. There are two operations over these: `reflect` which transforms a well-sorted syntax tree into a generic `AST`, and `reify`, which maps generic trees back into well-sorted trees.

Part of the reflection system is a Silver library that defines `AST` as a nonterminal, shown in Figure 3 on line 2. `AST` trees are constructed in the same way as other trees in Silver through the application of productions to primitive values or other trees. Each `AST` production in Figure 3 corresponds to a type (or class of types) in the Silver language: *e.g.*

```
1  grammar silver:reflection;
2  nonterminal AST;
3  abstract production nonterminalAST
4    top::AST ::=
5      prodName::String children::ASTs
6  abstract production terminalAST
7    top::AST ::=
8      terminalName::String lexeme::String
9      location::Location
10 abstract production listAST
11   top::AST ::= vals::ASTs
12 abstract production stringAST
13   top::AST ::= s::String
14 abstract production integerAST
15   top::AST ::= i::Integer
16 abstract production anyAST
17   top::AST ::= x::a
18 nonterminal ASTs;
19 abstract production consAST
20   top::ASTs ::= h::AST t::ASTs
21 abstract production nilAST
22   top::ASTs ::=
```

Figure 3. Some of the Silver nonterminals and productions used to represent abstract syntax trees. Production bodies, which contain attribute equations, are not shown. See core/reflect/AST.sv

`stringAST` to `String`, `nonterminalAST` to nonterminals (well-sorted trees), `terminalAST` to terminals (tokens returned from a scanner), `listAST` to Silver lists. Trees built by the polymorphic `anyAST` production contain values (represented by type variable `a`) that do not typically occur in abstract or concrete syntax trees and for which we cannot inspect in the same way: this includes productions, functions, and references to decorated trees. The `ASTs` nonterminal encodes a sequence of `AST` trees.

The `reflect` operation uses these productions to produce an `AST` value from any value and thus has the type `AST ::= a`. (A more familiar writing of this type might be `a -> AST`, but functions use the same type `::=` notation as productions.) For example, `reflect` will transform the Silver tree

```
integerConstant("1", false, noIntSuffix())
```

on lines 11-13 on the right of Figure 2 into the `AST` tree

```
nonterminalAST("integerConstant",
  consAST(stringAST("1"),
    consAST(booleanAST(false),
      consAST(nonterminalAST("noIntSuffix", nilAST())
        nilAST()))))
```

As with all nonterminals, attributes may be associated with the `AST` nonterminal. Aspect productions then associate new equations for the abstract productions in Figure 3. Most uses of the reflection system do this. The Silver-ableC extension discussed in Section 1 introduces a new `translation` attribute on `AST` and provides equations for this attribute on `AST` production to produce the Silver abstract syntax that is needed, as described in more detail in Section 4. Another aspect-defined attribute is `serialize`, used to print out an `AST` tree and discussed in Section 6.

In many of the applications discussed in the following sections a generic `AST` tree is converted back into a well-sorted object-language tree by the `reify` operator. This has type `Either<String a> ::= AST` and takes an `AST` and returns either a `String` error message or the well-sorted tree. Because `AST` trees can be constructed directly using the productions in Figure 3 it is possible to construct trees that do not correspond to a well-sorted tree. An attempt to reify such a tree will result in an error, returning `left(s)`, where `s` is an error message of type `String`. A successful reification wraps the tree of type `a` in the `right` constructor. The reflection system satisfies the following invariant for any tree `t`:

```
reify(reflect(t)) = right(t)
```

In practice large `AST` trees are rarely constructed directly; they usually are constructed by `reflect`.[4]. Thus ill-sorted `AST`s (and thus failures when calling `reify`) rarely occur. Even when an error does occur it is reported immediately by the call to `reify`, and we have found finding and fixing the source of such errors to be straightforward.

Despite this, during the reification process we must check that the `AST` in question actually corresponds to the inferred result type of `reify`. This requires a run-time type checking process that looks up productions and terminals to ensure they are defined and match the expected types. Since Silver supports polymorphic algebraic data types (nonterminals such as `Either<a b>`), it may not be possible to compute the final type of a sub-tree from only its arguments, so type checking also requires full Hindley-Milner type inference.

4 Reflection for Tree Construction Using Object-Language Concrete Syntax

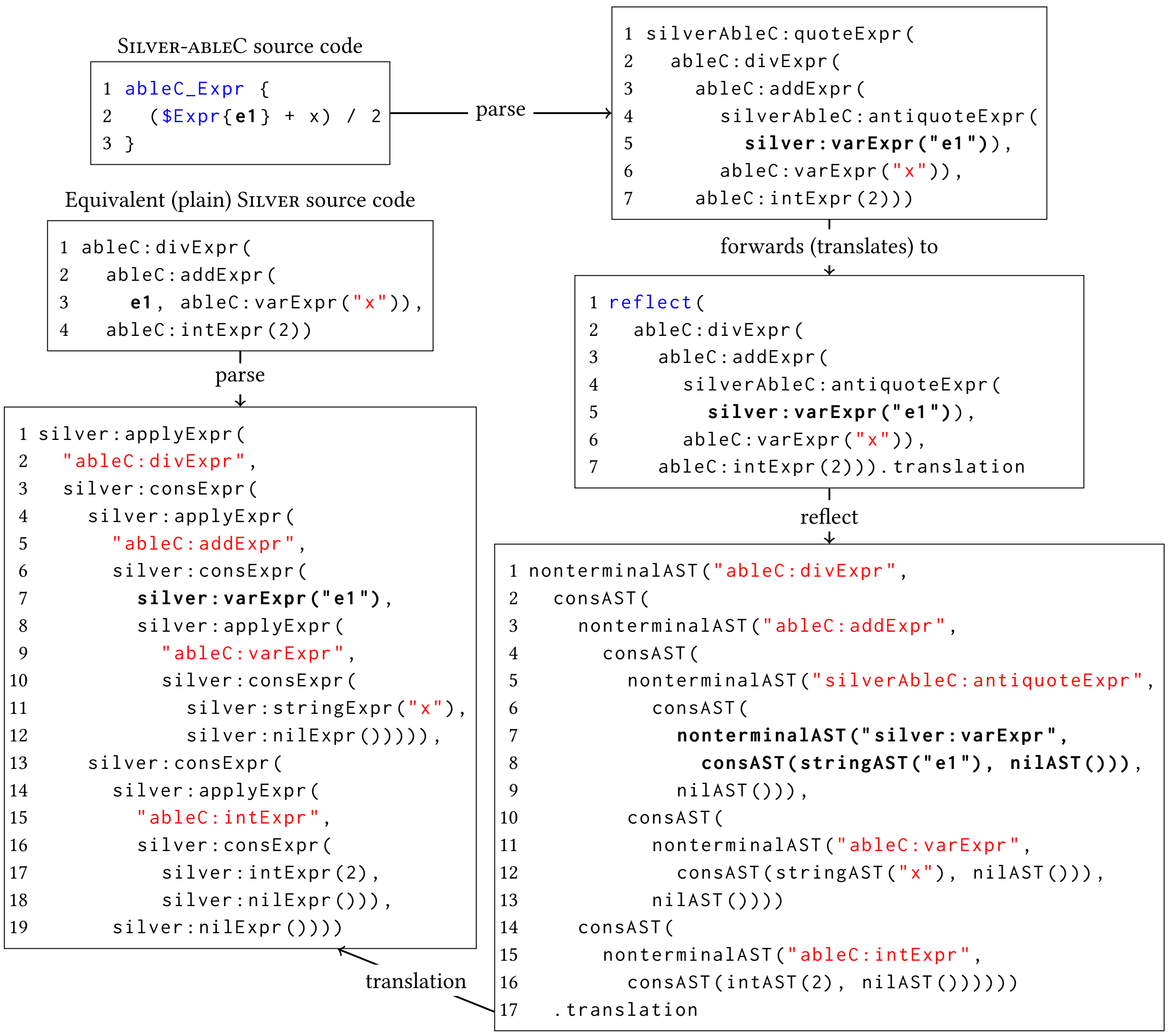
This section further describes the reflection system in Silver and demonstrates its use in an extension to Silver itself that lets language developers specifying trees in the object-language being developed using the concrete syntax of that language instead of its inconvenient abstract syntax. We demonstrate this on ableC, an extensible specification of C, defined in Silver. The extension to Silver for ableC is referred to as Silver-ableC below. Since C is a large and complex language the ability to write concrete syntax instead of abstract saves a tremendous amount of effort on the part of the language developer, and has lead to the development of ableC extensions that we may not have even undertaken without this capability. This was briefly demonstrated in Section 1 by Figure 2; the question we answer here is how reflection is used in translating the nice specification in the left of Figure 2 into the implementation on the right.

The step-by-step example use of Silver-ableC is shown in Figure 4. At the top left is a simple term written using Silver-ableC, while beneath it is an equivalent piece of code written using plain Silver (that is, without the Silver-ableC extension). Our goal is to translate the Silver-ableC code into the same abstract syntax tree as would result from parsing the plain Silver code. To keep things manageable, a simpler example than in Figure 2 is used to explain this process and the Silver-ableC extension. The antiquoted expression `e1` is written in bold and we track its translation through both processes of using and not using Silver-ableC. The name `e1` will hold an ableC tree that is to be plugged into the expression to be added to the C variable `x` and divided by 2. This is a shorter example, but qualitatively the same as on the left of Figure 2. Below this is the equivalent Silver source specification that does not use the Silver-ableC extension and requires one to write out the abstract syntax explicitly. This is a shorter example of the same thing as shown on the right of Figure 2. Both of these examples are functionally equivalent specifications and both need to translated into the same thing — a Silver abstract syntax tree.

In the plain Silver specification we see that division is represented by the ableC production `ableC:divExpr` (line 1) and the name `e1` (line 3) is the first argument to the addition production `ableC:addExpr` (line 2)[5] This is simply parsed by the Silver compiler to generate the abstract syntax representation in the lower left of Figure 4. Since Silver is bootstrapped in Silver the abstract syntax of a Silver specification implemented as a Silver attribute grammar. Thus the resulting abstract syntax is mostly applications of various Silver productions; the production `silver:applyExpr` represents the application of productions (tree creation). We see a few instances of `silver:applyExpr` production with the first argument being the name of the production in the object-language, in this case ableC, and thus the names as strings are those fully qualified names from the ableC grammar and thus the string `"ableC:divExpr"` is seen on line 2 as this use of `applyExpr` represents the application of this ableC production for division. The second `applyExpr` is the list (constructed by `silver:consExpr` and `silver:nilExpr` productions) of trees to become the children of the constructed

[4] Transformations that result in a new `AST` are less common but do occur, as will be demonstrated with substitution. But even in this case, most of the `AST` nodes are copied unchanged.

[5] In Silver, names of productions and attributes have fully-quantified forms that include the name of the grammar in which they were defined, a bit like fully qualified names in Java (but using colons instead of dots to separate names). Thus `ableC:addExpr` is the `addExpr` production in the `ableC` grammar. For reasons of brevity, we use `ableC` as the grammar name here but the actual grammar name is `edu:umn:cs:melt:ableC:abstractsyntax:host`, as can be seen in the specifications in the repository. Finally, note that when the context permits we will also refer to grammar elements using their shorter un-qualified name.



```
1 ableC_Expr {
2   ($Expr{e1} + x) / 2
3 }
```

```
1 silverAbleC:quoteExpr(
2   ableC:divExpr(
3     ableC:addExpr(
4       silverAbleC:antiquoteExpr(
5         silver:varExpr("e1")),
6       ableC:varExpr("x")),
7     ableC:intExpr(2)))
```

```
1 ableC:divExpr(
2   ableC:addExpr(
3     e1, ableC:varExpr("x")),
4   ableC:intExpr(2))
```

```
1 reflect(
2   ableC:divExpr(
3     ableC:addExpr(
4       silverAbleC:antiquoteExpr(
5         silver:varExpr("e1")),
6       ableC:varExpr("x")),
7     ableC:intExpr(2))).translation
```

```
1 silver:applyExpr(
2   "ableC:divExpr",
3   silver:consExpr(
4     silver:applyExpr(
5       "ableC:addExpr",
6       silver:consExpr(
7         silver:varExpr("e1"),
8         silver:applyExpr(
9           "ableC:varExpr",
10          silver:consExpr(
11            silver:stringExpr("x"),
12            silver:nilExpr()))))),
13    silver:consExpr(
14      silver:applyExpr(
15        "ableC:intExpr",
16        silver:consExpr(
17          silver:intExpr(2),
18          silver:nilExpr())),
19      silver:nilExpr())))
```

```
1 nonterminalAST("ableC:divExpr",
2   consAST(
3     nonterminalAST("ableC:addExpr",
4       consAST(
5         nonterminalAST("silverAbleC:antiquoteExpr",
6           consAST(
7             nonterminalAST("silver:varExpr",
8               consAST(stringAST("e1"), nilAST())),
9             nilAST())),
10        consAST(
11          nonterminalAST("ableC:varExpr",
12            consAST(stringAST("x"), nilAST())),
13          nilAST()))),
14    consAST(
15      nonterminalAST("ableC:intExpr",
16        consAST(intAST(2), nilAST())))))
17  .translation
```

Figure 4. The translation process for an ABLEC quote production. In **bold** is shown an antiquoted piece of SILVER code; note that it is the same between the original parse result (top right) and the final translation abstract syntax tree (bottom left). Production and grammar names have been shortened for clarity.

tree representing division: the first element being the representation of the addition, the second the constant 2. We see on line 7 then name e1 used as a SILVER variable reference form of expression. From an abstract syntax tree like this, the SILVER compiler will type check the specification and generate the Java code that forms the attribute grammar evaluator [Van Wyk et al. 2010].

Using reflection: We now consider the other path to this abstract syntax tree, using C concrete syntax in the SILVER-ABLEC extension and the SILVER reflection system. The first step is again parsing, but now using the SILVER-ABLEC parser. This yields a SILVER tree containing quote (line 1) and antiquote (line 4) productions in the upper right box of Figure 4. The quoteExpr on line 1 contains the ABLEC abstract syntax that was written out directly in the plain SILVER specification. The SILVER-ABLEC parser is a combination of the concrete syntax for SILVER and ABLEC with syntax for the quote and antiquote productions for different ABLEC nonterminals (such as ableC:Expr). The antiquote production, parsed from $Expr{e1}, switches back into SILVER abstract syntax. Thus line 5 here matches line 7 in the tree in the lower left.

```
1  grammar edu:umn:cs:melt:exts:silver:ableC;
2  imports silver, ableC;
3  imports silver:reflection, silver:embedding;
4
5  abstract production quoteExpr
6  top::silver:Expr ::= e::ableC:Expr
7  { forwards to reflect(new(e)).translation; }
8
9  abstract production antiquoteExpr
10 top::ableC:Expr ::= e::silver:Expr  {  }
11
12 aspect production nonterminalAST
13 top::AST ::= prodName::String children::ASTs
14 { antiquoteProds <-
15     ["ableC:antiquoteExpr",
16      "ableC:antiquoteTypeExpr", ...]; }
```

Figure 5. A sampling of Silver-ableC quote and antiquote productions, and the code to specify which productions are to be translated as antiquote productions rather than quoted ableC abstract syntax. See edu.umn.cs.melt.exts.silver.ableC/abstractsyntax

A few of the quote and antiquote productions introduced by Silver-ableC are shown in Figure 5. Quote productions such as `quoteExpr`, being extensions to the Silver language, must specify the equivalent `silver:Expr` that they translate down to. This is done via *forwarding*; the details of which are not important for understanding reflection in Silver and thus reading "`forwards to`" as "translates to" is appropriate.[6] This translation is the result of applying `reflect` to the syntax tree `e`,[7] converting the `ableC:Expr` into a tree of type `AST`. These can be seen in the lower right of Figure 4; all productions (including antiquote ones) have been expanded into their `nonterminalAST` counterparts: `ableC:divExpr` on line 2 becomes `nonterminalAST("ableC:divExpr"...)`.

From the reflected `AST`, we access the `translation` attribute (written `.translation`), seen on line 7 in the middle-right and line 17 in the lower-right of the figure. This attribute constructs the Silver abstract syntax tree in the lower left, where ableC productions have been converted into `silver:Expr` trees build by `applyExpr` as discussed above. The same is true for the contents of antiquote productions which have been reified directly into `silver:Expr`s. Note how the antiquoted Silver tree in the initial Silver-ableC abstract syntax, shown in bold, has been preserved unchanged in the final abstract syntax tree.

Some equations for `translation` are shown in Figure 6. Every kind of Silver value represented by `AST` has a straightforward transformation into a piece of Silver code, for example an integer value (`integerAST` on line 7) is translated to a Silver integer: `silver:intExpr(i)` on line 9. Here an aspect production is defining the `translation` attribute on a production defined in the `silver:reflection` grammar (line 14 of Figure 3). An attempt to translate back to Silver an `anyAST` tree (line 9) results in an error being raised as these are non-inspectable values that can be reified, but little else.

However, there is a complication introduced when dealing with antiquote productions: they contain a piece of Silver code that should be *evaluated* to obtain a tree and thus their translation should just be the wrapped piece of code. Unfortunately, this `silver:Expr` tree is no longer directly available as it has been "accidentally" reflected and turned into an `AST`. So when an antiquote production is encountered by the `translation` attribute, the child `AST` must be reified back into the `silver:Expr` that was originally specified.

When translating a `nonterminalAST`, some method of identifying whether a production is an antiquote production is required. This is done by way of a *collection production attribute* (line 17). The attribute `antiquoteProds` will contain the full names of all known antiquote productions. Extensions, such as the Silver-ableC extension which imports this grammar, can add the names of its antiquote productions to this attribute. This is done using another `aspect` production on line 14 in Figure 5 using the <- operator for injecting new elements (names) into this list; these are combined using the list append ++ operator as specified on line 18 in Figure 6. Using this, the name of a production being translated may be looked up, as can be seen in on line 21. If the name is not in the list, the `AST` is translated normally, otherwise it is reified for evaluation. Thus, the `AST` translation code forms a library for use by tree-literal Silver extensions that does not itself have any special handling for particular object-languages.

The use of antiquoting and object-language concrete syntax has been extended beyond the core implementation described above. Since many languages have notions of lists in their grammar, for example a sequence of function arguments, the Silver-ableC extension allows one to write list-like expressions in such a sequence. For example, in

```
ableC_Expr { foo( $Exprs{a}, 3, x ) }
```

the list of expressions `a`, represented by the `Exprs` nonterminal, is naturally incorporated into this enclosing list of arguments. Another useful extension lets the concrete syntax of the object-language be used in writing patterns. (Silver does pattern matching on trees much the same way that languages such as ML or Haskell do on datatypes.) Note that these useful features add some complexity to the implementation that is not shown here.

[6]Antiquote productions are effectively extensions to the object-language. To satisfy the requirements of the modular well-definedness analysis [Kaminski and Van Wyk 2012] they should forward to a translation in C. However, there is no semantic equivalent in the object-language and these will never have attributes accessed on them. Thus they forward (not shown) to a dummy value that raises an error if it is erroneously evaluated.

[7]The use of `new(e)` ensures the undecorated version of `e` is used; trees in Silver are treated as decorated when either is valid, which `reflect` would (undesirably) return wrapped in `anyAST`.

```
grammar silver:embedding;
imports silver, silver:reflection;

synthesized attribute translation<a>::a;
attribute translation<silver:Expr>
  occurs on AST;
aspect production integerAST
top::AST ::= i::Integer
{ top.translation = silver:intExpr(i); }

aspect production anyAST
top::AST ::= x::a
{ top.translation = error("anyAST␣error"); }

aspect production nonterminalAST
top::AST ::= prodName::String children::ASTs
{ collection antiquoteProds::[String]
    with ++;
  antiquoteProds := [];
  forwards to
   if ! contains(prodName, antiquoteProds)
   then silver:applyExpr(
            silver:varExpr(prodName),
            children.translation)
   else
     reify(getOnlyChildOrError(children));
}

attribute translation<[silver:Expr]>
  occurs on ASTs;
aspect production consAST
top::ASTs ::= h::AST t::ASTs
{ top.translation =
    h.translation :: t.translation; }
```

Figure 6. Some of the equations in the Silver library for computing the translation of AST to silver:Expr. See silver/hostEmbedding/Translation.sv

Discussion: Although this discussion has focused on Silver-ableC, any object-language implemented in Silver can easily benefit from the ability to write concrete syntax for constructing trees and patterns. Adapting this for another object-language amounts to specifying the concrete and abstract (Figure 5) syntax for quote and antiquote productions for the language, then importing this grammar and the concrete syntax of the object-language into another Silver instance.

In a complex language such as C, the use of concrete syntax over abstract syntax is a tremendous saver of time and effort. Trees can be specified directly and any syntax errors in the object-language concrete syntax are detected when the language specification is compiled, with error messages pointing to the precise location in the Silver specification[8]. We implemented several extensions to ableC using this new approach, including an embedding of Prolog and a supporting unification framework. These involve generating quite a bit of plain C code and we may not have attempted these without being able to use of the Silver-ableC extension to Silver. We did modify the implementation to count the number of characters that are saved by writing in the object-language concrete syntax (the left side of Figure 2) instead of the abstract (the right side). For all extensions that use Silver-ableC this saving is over 775K characters (or almost 18K lines of code based on pretty-printing the generated code with a maximum line length of 80). This is about 40% of the would-be code base size of 1.92M characters. Note that this savings came from writing new extensions that used this feature from the beginning, not from removing and replacing specifications with the concrete syntax extension.

```
template<a> a min(a x, a y) {
  if (x < y) return y  else return x;   }
min<int>(i, j)
```

```
int _template_min_int(int x, int y) {
  if (x < y) return y  else return x;   }
_template_min_int(i, j)
```

Figure 7. Instantiating an ableC C++-style template extension (top) into plain C code (bottom) by substitution.

5 Reflection for Substitutions on Trees

A common problem with processing complex tree-structured data is to update or substitute the value of a particular subtree, without introducing large amounts of boilerplate. This sort of problem may arise in a compiler when implementing a feature such as C++ templates, where we wish to replace all occurrences of a name with the tree for a particular type or expression. An example of this transformation (shown in Figure 7) comes from ableC in which a C++-style template extension (top) is instantiated to plain C code (bottom). Such a transformation may be implemented using type classes [Lämmel and Jones 2003], but in a system with a less sophisticated type system, such as Silver, it may also be expressed nicely through the use of reflection. Here we describe how reflection is useful in the ableC substitution library, but as in the previous section, this can be adopted by any object-language specified in Silver with the reflection system.

A portion of the ableC substitution library is shown in Figure 8. The substitution process works by reflecting the

[8] The source location of a tree in Silver is represented as an *annotation*. These are extra pieces of information attached to syntax tree nodes, but are omitted here for clarity as they are handled essentially the same as children. Thus location information is preserved in a reflected AST.

```
1  grammar ableC:substitution;
2  type Sub = (Maybe<AST> ::= AST);
3  inherited attribute subs::[Sub]
4    occurs on AST;
5  synthesized attribute substituted<a>::a;
6  attribute result<AST> occurs on AST;
7  aspect production nonterminalAST
8  top::AST ::= prodName::String children::ASTs
9  { top.substituted = foldl ( fromMaybe,
10     nonterminalAST(prodName, children.result),
11     map(\ s::Sub -> s(top), top.subs));
12   children.subs = top.subs;    }
13
14 aspect production stringAST
15 top::AST ::= s::String
16 { top.substituted = stringAST(s); }
17
18 function substDecl
19 Decl ::= substitutions::[Sub] base::Decl
20 { local a::AST = reflect(new(base));
21   a.subs = substitutions;
22   return case reify(a.substituted) of
23     | left(msg) -> error(msg)
24     | right(d) -> d;    }
25
26 function typeExprSubstitution
27 Sub ::= n::String sub::BaseTypeExpr
28 { return \ a::AST -> case reify(a) of
29     | right(typedefTypeExpr(n1))
30       if n == n1
31       then just(reflect(new(sub)))
32       else nothing()
33     | _ -> nothing() ;    }
```

Figure 8. A portion of the ableC substitution library. See edu.umn.cs.melt.ableC/abstractsyntax/substitution/Substituted.sv

tree to be substituted into an AST, performing the substitution on the AST to get a new AST, and finally reifying the result back to a tree of the original type. This process is driven by functions such as `substDecl` (line 18) that takes a list of substitutions and a tree on which to perform them, `base`. It reflects a copy of `base` and names this AST tree `a`. A substitution (`Sub`, line 2) is a function from AST to optional AST, a `Maybe` type. When applied to an AST, a `Substitution` returns `just(a)` if the AST matches and should be replaced by `a`, or `nothing()` if there is no match and the AST should be left unchanged. The substitution transformation on AST is driven by a pair of attributes. First an inherited attribute `subs` (line 3) that passes a list of substitutions (`[Sub]`) to perform down the tree (line 21). A synthesized attribute `substituted` of type AST (lines 5 and 6) is then reified (line 22). A failure to reify leads to an error (line 23) but otherwise the resulting `Decl` tree `d` is extracted from the `Either` value from `reify`.

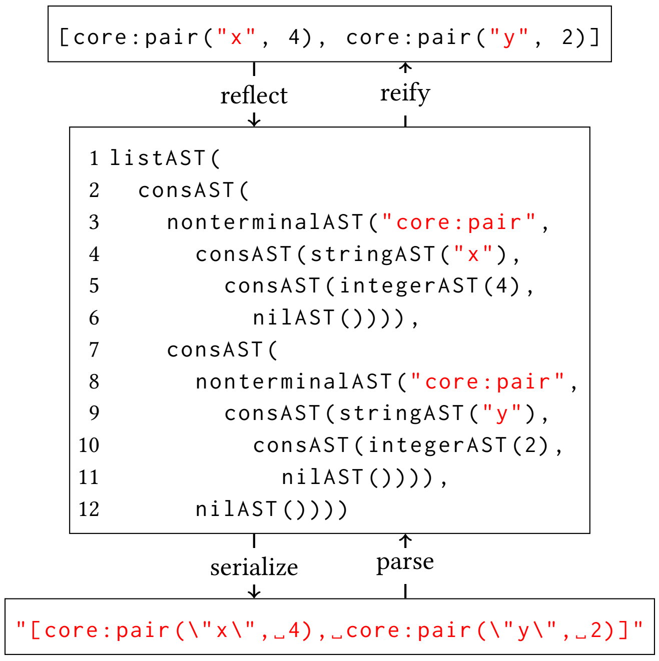
These attributes decorate AST trees, for which aspect productions are used to define the substitution behavior. On all productions aside from `nonterminalAST`, such as `stringAST` on line 14, `substituted` consists of the same production but with children that have been substituted, as it only makes sense to define substitutions for particular productions and not strings or lists. The `substituted` equation on `nonterminalAST` (line 9) first maps the substitutions in `top.subs` over itself (`top`) and `foldl` folds up the `Maybe` results using `fromMaybe` to pick the first successful substitution (which would also include substitutions applied to its children). If there are none it returns the tree with just the substituted children (line 10). The function `typeExprSubstitution` on line 26 returns a substitution (`Sub`) given a string `n` to replace with a type expression `sub`. It returns a lambda function taking an AST that reifies its input and, if successful, matches it against a pattern (line 29) to possibly return a different AST. Here if `a` is type expression for a typedef name it checks if the names are the same (line 30) and if so returns the substitution (`sub`) wrapped in `just` to indicate success.

The original implementation of the ableC substitution library defined a similar `substituted` equation for every production in the ableC abstract syntax. These all follow the same pattern and were replaced by this substitution grammar, replacing over 2,500 lines of boilerplate code in the ableC specification (11.8% of the code base), in addition to numerous similar equations on ableC extension productions.

6 Reflection for Automatic Tree Serialization and De-serialization

A significant source of boilerplate specification in the Silver specification of the Silver language is in its module for serializing and de-serializing syntax trees that represent the environment for a grammar. These environments indicate what grammar elements, such as attributes, productions, and nonterminals, are declared and certain properties of them, such as their type. The Silver compiler separately compiles grammar modules and uses the serialization of environments as interface files to avoid reading an unchanged source grammar imported by another grammar being compiled. The original implementation of serialization of environments was done by defining an attribute on all nonterminals and their productions, representing the environment as a string, and de-serialization by a parser using a custom grammar.

Using reflection and AST trees we can define a generic implementation of this, replacing 1,698 lines in the Silver compiler with 257 lines, and saving 1,441 out of 38,400 lines (3.75%) of the entire code base. This change does come at a cost, as the generic interface files are on average 215% larger than before (measured for the ableC code base), less readable by humans, and adds 2-3 seconds to builds taking around 60



```
[core:pair("x", 4), core:pair("y", 2)]
```

```
listAST(
  consAST(
    nonterminalAST("core:pair",
      consAST(stringAST("x"),
        consAST(integerAST(4),
          nilAST()))),
    consAST(
      nonterminalAST("core:pair",
        consAST(stringAST("y"),
          consAST(integerAST(2),
            nilAST()))),
      nilAST())))
```

```
"[core:pair(\"x\",␣4),␣core:pair(\"y\",␣2)]"
```

Figure 9. An example of serialization/de-serialization.

seconds. However we believe such penalties are worth the significant savings in code complexity.

A visualization of the serialization/de-serialization process is shown in Figure 9. At the top is a simplified notion of an environment consisting of a list of two pairs, mapping `x` to `4` and `y` to `2`. Serialization is done by reflecting a tree into an AST, the middle box of the figure, and accessing the `serialize` attribute on the AST, which then produces the string value at the bottom. This attribute, lines 1-3 of Figure 10, is actually of type `Either<String String>`. The reason for this is that serialization may fail if a non-printable value, such as a function, is a component of the reflected tree constructed as a `anyAST` tree (line 20). The `left` side of `Either` encodes an error message and the `right` side the successful result, as seen before in the return type of `reify`. Integer and string ASTs (lines 12 and 16) are serialized as expected, with string special characters needing to be escaped first.

Of interest is the serialization of `nonterminalAST` trees (line 8). This expression uses a monadic computation using Haskell-style `do` notation. In Silver the bind and return operation are not inferred as Silver does not have type classes and must instead be specified explicitly. Here `cSer` is the result of serializing the child nodes. If any of these fail the monadic computation passes the failure message along automatically, otherwise a string using this, the production name, and appropriate parens is constructed.

For de-serialization, we use Silver's built-in declarative parser specification features to define concrete syntax matching the serialization strings. The generated parser constructs AST trees that are then reified to recreate an environment,

```
1  synthesized attribute
2      serialize::Either<String String>
3      occurs on AST, ASTs;
4  aspect production nonterminalAST
5  top::AST ::= prodName::String
6               children::ASTs
7  { top.serialize =
8      do (bindEither, returnEither) {
9        cSer::String <- children.serialize;
10       return prodName ++ "(" ++ cSer ++ ")"
11     };  }
12 aspect production integerAST
13 top::AST ::= i::Integer
14 { top.serialize =
15     right(toString(i)); }
16 aspect production stringAST
17 top::AST ::= s::String
18 { top.serialize =
19     right("\"" ++ escapeStr(s) ++ "\""); }
20 aspect production anyAST
21 top::AST ::= x::a
22 { top.serialize =
23     left("Cannot␣serialize␣an␣anyAST"); }
```

Figure 10. Some of the Silver attribute equations for serialization. See silver/reflect/AST.sv

```
let square = fun x -> x * x
in let rec spower = fun n x ->
  if n = 0 then .<1>.
  else if n mod 2 = 0
  then .<square .~(spower (n/2) x)>.
  else .<.~x * .~(spower (n-1) x)>.
in let power7 =
  .! .<fun x -> .~(spower 7 .<x>.)>.
in power7 2
```

Figure 11. An example use of staged programming to dynamically generate an efficient power function.

as illustrated on the right of Figure 9. Together, these provide a concise and convenient mechanism for specifying serialization and de-serialization of Silver syntax trees.

7 Reflection for Implementing Evaluators for Staged Languages

In this section we provide the final example of reflection in attribute grammars to implement an evaluator for a simple staged programming language, a subset of MetaOCaml [Kiselyov 2018]. Staged programming is a programming paradigm where pieces of code may be constructed at runtime, passed around as values, and eventually run, all in a type-safe way. Examples of such languages include MetaML [Sheard 1998] and MetaOCaml. This paradigm can provide performance improvements by generating a specialized piece of code that is used more than once. The canonical example in this area is a staged power function to efficiently compute an exponent x^n by generating code specialized for a given value of n; a MetaOCaml implementation of this is shown in Figure 11. Such languages use strong typing to allow well-defined semantics when running generated code [Filinski 1999]. Calcagno et al. [2003] describes an approach to implementing staged languages by translation to a lower-level language containing constructs for reflection and term construction. One can also build a direct evaluator for a staged language, the approach we have chosen to demonstrate.

In addition to all the standard functional programming constructs, MetaOCaml has 3 new operators: quote (`.< >.`), escape (`.~`) and run (`.!`). Quote constructs a value of type `'a code`, where `'a` is the type of the quoted expression, corresponding to a fragment of code being constructed. The escape operator can be written inside of a quoted expression, indicating that the escaped expression, when evaluated, will yield a piece of code that should be plugged into the result. The run operator executes a `code` value. Static typing ensures that no run-time type errors occur in evaluating quoted code, although run-time checking is required to ensure that some corner cases involving free variables are not evaluated (e.g. `.<fun x -> .~(.! .<x>.)>.`, which is still well-typed).

The reflection system provides what is needed to elegantly implement our subset of MetaOCaml using attribute grammars [9]. The interpreter is structured using an `Expr` nonterminal in the language's abstract syntax. In addition to the usual productions for expressions, there are productions `quote`, `escape` and `run`, each of which wraps a single expression. A `Value` nonterminal has productions representing integers (`intValue :: (Value ::= Integer)`), functions (`closureValue :: (Value ::= String Expr Env)`), and code (`codeValue :: (Value ::= AST)`), among other values. An inherited attribute on `Expr` passes down the value environment, while a synthesized attribute computes the resulting value.

To evaluate a quote expression, the wrapped `Expr` is reflected, yielding an `AST` that contains reflected escape productions. A synthesized attribute on `AST` is used to find each escape production, reify the wrapped expression, evaluate the expression (using the value environment also passed down as an inherited attribute on `AST`) and replace the escape production `AST` with the `AST` from the resulting `codeValue` production. This process is somewhat similar to the previously described process of translating object-language literals or performing substitutions. Finally to evaluate a run expression, the operand is evaluated and the `AST` is extracted from the resulting `codeValue`, reified and itself evaluated.

[9]Available at http://melt.cs.umn.edu/ and https://github.com/melt-umn/meta-ocaml-lite, archived at https://doi.org/10.13020/z10a-7g60.

8 Implementing the Reflection System

This section provides a brief discussion of the implementation of the Silver reflection system. Silver is implemented by translation to Java. Basic types (such as strings and integers) all have concrete Java equivalents. The Java abstract class `Node` represents all nonterminals; every nonterminal type becomes an abstract subclass of `Node`, and every production of a nonterminal is a concrete subclass of that nonterminal's class. In this way, the Java type system encodes the syntax of the object-language being defined in Silver.

`Node` contains a number of abstract methods, such as to get the Silver name of a production or iterate over its children. Since no extra type-level information is required, `reflect` is a Silver foreign function that calls a recursive Java function to walk a `Node` and call the appropriate constructors corresponding to `AST` productions.

The implementation of `reify` is significantly more complex due to its run-time type-dependent nature; `reify` is thus a language construct in Silver (as opposed to being a foreign function as in the case of `reflect`). `reify` does run-time type checking in constructing a Silver tree to ensure that it is well-sorted. To do this, `reify` requires the run-time representation of the type of the tree it is to produce; this type is provided by Silver's type inference system. For `AST` trees representing integers or strings the reification into a Silver-value of type `Integer` or `String` is straightforward. For a `nonterminalAST`-constructed tree, `reify` gets the production name (the first child of production `nonterminalAST`) and uses Java reflection to see if that production exists, and if so, gets the Java `Class` object implementing that Silver production. On this it calls a static `reify` method (generated as a part of the class), parameterized by the expected return type it is to construct and the array of child `AST` trees yet to be reified. It checks that the appropriate number of children were provided, unifies the given expected type with the actual production left-hand-side nonterminal type, then reifies the children using the corresponding right-hand-side types. Finally, it constructs and returns a new production object with the results.

To support this, runtime type information, as an object of a new Java `TypeRep` class, is stored on each tree node. Because Silver supports parametric polymorphism, a runtime type unification process was also added, to mirror the compile-time type unification process. This is used when checking that types are compatible when constructing new trees. If not, `reify` returns an error. All Silver value classes implement a `Typeable` interface with a `getType` function returning a `TypeRep` value. Any type, *e.g.* Silver functions, or other new foreign type to be reflected into an `AST` tree, using the type-parametric `anyAST` production must implement this interface.

9 Related Work

Reflection, first introduced by Smith [1982], has been discussed in multiple contexts in computer science. Demers and Malenfant [1995] more precisely defines reflection, and distinguish between *structural reflection* where the language provides introspection of the program being executed and its abstract data types, and *behavioral reflection* where the language deals with its own semantics. A more formal view of reflection is given by Clavel and Meseguer [1996], essentially defining reflective languages as ones in which there is a mapping between certain data types in the language and a portion of the language's semantics.

Reflection is a common feature of object-oriented languages, such as Java [Kirby et al. 1998]. In such contexts reflective operations are often coupled tightly to the objects under consideration; for example, one may use reflection to get the value of a field by a string representation of its name, resulting in another object to be casted or reflected again. This differs from our notion of reflection, in which a tree composed of various nonterminals is reflected as a whole into a distinct `AST` representation, upon which further operations may be performed. In our experience this approach is a better fit for language meta-programming, as any operation on trees is primarily either "structural" (best implemented by attributes on `AST`) or "semantic" (best implemented by attributes on the nonterminals in question.)

Numerous problems related to performing generic operations on algebraic/inductive datatypes, including substitution and serialization, are described in the scrap-your-boilerplate papers by Lämmel and Jones [2003, 2004]. This is mostly achieved through advanced use of the type system (e.g. type classes), but an approach based on reflection to a generic `DataType` representation is also described; this is similar to our `AST`, (representing ADT values, lists, constants etc.) however operations on `DataType` are expressed using recursive functions and type classes rather than attributes.

The time savings of writing object-language concrete syntax in a meta-language with quote and antiquote operators has been noted previously and seen in tools such as ASF+SDF [Brand et al. 2001] and Stratego [Visser 2001, 2002]. The Stratego approach is particularly relevant; it differs from our approach in that the transformation from embedded object-language abstract syntax to meta-language abstract syntax happens incrementally through term rewriting, during which ill-sorted intermediate trees composed of meta- and object-language abstract syntax exist. Thus, ill-sorted trees can still be represented. The TypeSmart feature in Stratego [Erdweg et al. 2014] can be used to dynamically disallow ill-sorted trees; when a constructor is applied it checks that the arguments are of the required sort.

In our reflection-based approach, the dynamic checking is only needed for antiquote productions in the `reify` operation, the rest of the translation process is checked statically. This comes at the cost of the added complexity of a separate `AST` representation, not required in a rewriting approach. Instead of `reify` dynamically type-checking the `AST`, we could have the `AST` constructors check the types of their represented argument values, as done with the TypeSmart feature of Stratego. However this would require a way to access (in Silver specifications, not just in its runtime as `reify` does) the types of productions by name.

Squid quasiquotes [Parreaux et al. 2017a,b] provide concrete object-language syntax embedding for syntax tree construction in Scala. These bear some resemblance to our `AST`-based approach, most notably by allowing introspection via pattern matching of quoted `Code` values, but Squid provides stronger type safety guarantees about quoted fragments.

A definition of staged programming and the MetaML language is given by Sheard [1998]. Calcagno et al. [2003] introduces the MetaOCaml language and describes an approach to implementing staged languages by translation to a target language containing constructs for reflection and abstract syntax tree manipulation. This differs from our design, in which a meta-language supplying such constructs is used to build a direct interpreter for evaluating a staged language.

10 Discussion and Conclusion

This paper integrates a form of reflection into attribute grammars with a `reflect` construct of turning well-sorted trees into a generic representation and an inverse `reify` operation. In meta-programming systems, such as Silver, in which the type system of the the specification language enforces the well-sortedness of syntax trees, writing analyses and transformations of such trees can involve a lot of boilerplate specifications. We show how reflection lets the language developer reflect a tree into a generic form, process or analyze it in a convenient generic way, and then, in some applications, reify the tree back to the well-sorted form. In the example applications, many lines of boilerplate Silver specification were eliminated from existing applications or were avoided from the beginning. In our experience, even though well-sortedness is not guaranteed by the type system in the `AST` form we rarely found this to be problem; it is easily outweighed by the savings in lines of specifications written.

There are many additional uses of reflection in attribute grammars beyond those discussed here. Examples include writing visitor-pattern-style traversals over trees, mechanisms for (runtime) type-safe casts, and implementation of generic map and reduce operations over arbitrary trees. Reflection also opens up the possibility building a term-rewriting extension to Silver, something that is a topic of future work. Other future work includes improving the performance of the processing of Silver interface files by replacing the text-based serialization system with one that generates more compact binary representations.

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