Supplementing Java Bytecode with Specifications

Jędrzej Fulara
Institute of Informatics
University of Warsaw
ul. Banacha 2
02-097 Warsaw, Poland
fulara@mimuw.edu.pl

Krzysztof Jakubczyk
Institute of Informatics
University of Warsaw
ul. Banacha 2
02-097 Warsaw, Poland
kjk@mimuw.edu.pl

Aleksy Schubert
Institute of Informatics
University of Warsaw
ul. Banacha 2
02-097 Warsaw, Poland
alx@mimuw.edu.pl

ABSTRACT

Java class file is an interoperable format that can serve not only to transfer the compiled versions of Java programs, but also to embed into the files additional information which can be exploited by the execution environment of user's machine to speed up the execution of the application or to ensure certain vital properties of the code. The latter goal is specifically the aim of the proof-carrying code (PCC) techniques in which the executable code is supplied with a proof that the code obeys certain policy (e.g. the program does not store password cleartext in a file). BML (Bytecode Modelling Language) can be regarded as a part of the PCC architecture which allows to express detailed properties of bytecode programs, in particular the policies they must obey.

As most of the programming is done at the source code level, it is desirable to have a way to translate properties expressed at the source code level (in our case written in Java Modeling Language, JML) to the bytecode level. In this paper we present a *JML2BML* compiler, a tool that for a given Java source file annotated with specifications generates class files with BML.

Categories and Subject Descriptors

D.2.4 [**Software Engineering**]: Software/Program Verification

General Terms

Reliability, Verification

Keywords

Java, bytecode, JML, BML

1. INTRODUCTION

Each Java Virtual Machine is required to perform so called bytecode verification process on each class file which is loaded to be executed [12]. This verification process ensures vital properties of the loaded programs such as that all arguments on the operand stack are legal, all types of variables passed to methods are correct, all load and store operations have correct types, etc.

In certain situations, these guarantees are not sufficient. In particular, many of the current security guarantees are ensured at runtime of an application. For instance, a mobile application asks the user to acknowledge the sending of data over the mobile network. However, the user may get bored with many such prompts and disable this security property. After this, she or he may easily be made to send data to e.g. an expensive premium number. In this case, it would be more secure to give the user a load- (or download-) time guarantee that the code sends data only to expected receivers. Currently, this is partially done through digital signatures. The signatures, however, do not assure that the software is indeed secure. They only certify who takes (not so well defined) responsibility for the problems caused by the program. In fact, there were cases when many users were deceived by respected companies e.g. rootkits were installed when audio CD was inserted [2].

Another guarantee which is not secured by the traditional bytecode verification procedure is the lack of code inconsistencies typically considered to be programming errors i.e. null-pointer exceptions, array index out of range exceptions etc. In many cases, these inconsistencies can be eliminated with the help of some additional information (e.g.@NonNull annotations, suggested in [14]) which makes the checking process feasable.

The goal of the proof-carrying code (PCC) technique [19] is to give the user certain guarantees of the code to be executed at the moment of its execution. In this paradigm, the executable code (in case of Java, the bytecode) is augmented with an additional piece of information, a PCC certificate, which together with the code makes possible an automatic check that the code indeed obeys the expected policy (e.g. sends data to authorised targets only). This check is performed by the user (or by user's execution environment) right before the code is executed (see Figure 1). In fact, the usual Java bytecode verification procedure can be viewed as an example of a forerunner of thich technique. Although the certificate is in this case empty (or supplementary in case the StackMap attributes are employed), the execution environment indeed checks a vital code property before the code is executed. In more complicated cases of the proof-carrying code, one needs the additional information to make

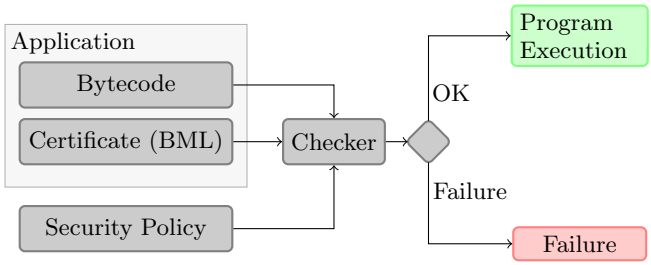

Figure 1: Proof-Carying Code architecture for bytecode.

the checking of the required property feasible or even algorithmically possible.

One of the possible ways to realise the PCC architecture is developed under the european project MOBIUS.[1] This project plans to develop both type-based and logic-based PCC program certification techniques [3]. The logic-based methods rely on specification of the object-oriented code in the fashion governed by the design-by-contract principles [18]. Bytecode Modeling Language (BML) is a specification language which realises the methodology at the bytecode level [5]. It is designed as a counterpart of the Java Modeling Language (JML), an established specification language dedicated to formally describe properties of Java programs in the design-by-contract style [16].

The use of specification formalisms such as JML or BML has another important application. Modern, high level programming languages support creating software in a modular way. Applications can be divided into smaller parts that can be developed independently. In large systems, it is a common practice to outsource some well defined subsystems to external companies. The main problem in this approach is that the pieces of software developed by different programming teams often are not fully compatible. To avoid this incompatibility and useless code that is produced, there is a need to specify precisely the desired behaviour of the components, what they require and what can we expect from them [20]. The solution is to define formally implementation contracts in languages such as JML or BML and check automatically the compliance of the code with these descriptions.

Specification languages are useful in describing the system components behaviour. They are not only helpful in dividing the problem into smaller pieces, but also focus on *what* is expected from each part, without saying about *how* should it be done. The specification languages are designed to be simple enough to be understood by programmers, so they can play the role of code documentation. Using specification language for documenting code has the advantage that it is possible to automatically verify that the source code implements the documented features [13].

The distributed development of software results in a situation where different software modules are implemented in different languages. This is facilitated by the fact that more and more languages are compiled to the same Java bytecode.

[1] See `http://mobius.inria.fr`

A few examples:

- Jython: the Python Java implementation,
- JRuby: the Ruby Java implementation,
- Jacl: the Tcl Java implementation,
- Rhino: the JavaScript Java implementation,
- Scala: a functional programming language compiled to Java bytecode.

At SugarCon 2008, Sun Microsystems President and CEO Jonathan Schwartz said "we are just going to take the 'J' off the 'JVM' and just make it a 'VM'". Therefore there will be a global trend with support of companies to use JVM with languages other than Java. This is an important reason, why it is important to be able to translate the source code specifications into lower level language specifications—in case the development is done in many languages the only common platform is the platform of the executable code. This explains the efforts concerning BML specification language.

The JML specification language exists already for several years. In the course of the time, a lot of code have been annotated with the specifications in this language (see [4] for an overview). Except for that, it is easier to understand and specify the code in the source form than in the bytecode form. In this light, it is desirable to translate these specifications from JML to BML. Moreover, the code producer in PCC scenarios, who has to produce a correctness proof, will often prefer to construct it rather in terms of the source code than in terms of the bytecode, and then compile the specification and the proof into the level of executable code.

In a broader perspective, the full infrastructure to support the use of BML annotated programs, for which complicated properties are checked at the user's end, requires the following items:

- PCC checker tools that understand BML annotations combined with PCC certificates,
- tools which enable the construction of PCC certificates,
- procedures to safely distribute the desired properties to be checked by PCC infrastructure,
- modelling languages (such as JML for Java) for other programming languages,
- compilers that compile programs to JVM bytecode along with annotation compilers,

The *JML2BML* compiler described in this paper is designed to be a part of this scheme which translates the policies and specifications to the bytecode format.

Organisation of the paper. In Section 2, we present the specification languages JML and BML. An example which illustrates the work of the compiler is presented in Section 3. Section 4 overviews the design of the *JML2BML* compiler. The most difficult problem of the specification compilation is the placement of the loop invariants. This issue is discussed in Section 5. The related work is presented in Section 6 and we conclude in Section 7.

2. SPECIFICATION LANGUAGES

2.1 JML

The Java Modelling Language (JML) is a behavioural specification language for Java prigrams [16]. It allows to write specifications according to the *design-by-contract* principles [18]. Data types and method behaviour can be precisely commented using JML annotations. They describe the invariant properties that are maintained by objects, the input method requirements (preconditions), what we can expect at the output of method (postconditions) and also some lower level properties of the code (i.e. loop invariants, loop variants etc). JML annotations are written in standard Java comments, so they do not affect the normal work of any Java compiler.

An important goal in the design of JML is that it should be easily understandable by Java programmers. It is achieved by staying as close as possible to the Java syntax and semantics. The tool support for JML is rich (see [4] for an overview). In particular, there are tools that check JML specification at runtime [6], in extended static checking fashion [9], and allow to perform software certification [17]. There are also tools that support annotation generation [8],[11].

The works on JML was started by Gary Leavens at Iowa State University. Since then it became an open project, multiple groups around the world are writing tools supporting JML and developing the language itself.

2.2 BML

The Bytecode Modelling Language (BML) is a specification language for the bytecode. It was proposed by Burdy et al. in [5]. The design of BML directly follows the fundamental concepts of JML. It inherits most constructions and keywords from the JML syntax. As the BML is developed within the MOBIUS [1] project and the main target of the project are Java-enabled mobile devices such as mobile phones, the current version of BML assumes some simplifications of the Java bytecode which are present in the J2ME platform—the Java platform for mobile devices with restricted resources.

The class files representing bytecode with BML annotations are regular Java class files, executable by all Java tools. The annotations are stored within additional attributes. The BML related attributes start with the prefix `org.bmlspecs` and according to the specification of the Java Virtual Machine they should be ignored by the Machine, since their names are not part of the original JVM specification.

Of course, following the logical structure of class files, class specifications are stored as class attributes, method specifications, as attributes of corresponding method and specifications inserted in the code are attributes of the JVM Code attribute of the given method.

The document is organized as follows. In Section 2 we describe an annotation language. In Section 3 we describe implementation of our compiler, give details on the architecture and present the main principles of the translation. Then an example of using our tool is presented. In Section 5 and 6 we describe algorithms for detecting loops in the bytecode and matching them with the source code. At the end conclusions are given and future work is discussed.

2.3 Overview of Annotations

The structure of annotations in BML and JML is very similar. We have two main types of annotations: method annotations and data type (class and interfaces) annotations.

2.3.1 Method annotations

The most important type of method annotations are *method specifications* describing the input-output behaviour of the method. This are preconditions (`requires`), defining conditions that should be fulfilled before entering the method and postconditions (`ensures`) telling what we can expect after the method finishes. One can define also which fields are modified (clause `modifies`) and which exceptions might be thrown (clause `signal`).

The other type of method annotations are specifications elements appearing in the code, like:

- Assert instructions that state some facts about fields, variables etc. that should hold at this point of program execution.
- Loop specifications that describe the loop invariants (`loop_invariant`), loop variants, like `decreases` to prove the loop's termination or `modifies` that tells which fields or variables can be changed in this loop.
- Declarations of local `ghost` variables—variables that exist only in the specification. Their values can be modified only using special `set` instructions.
- `Set` instructions are similar to Java assingments, but they operate on ghost fields and variables.

2.3.2 Data type annotations

Class (and interface) specifications describe the behaviour of a class as a whole (in the `static` version) or of objects of that class (`instance`). The most important type of *class specifications* are class invariants. They describe the property that should hold for all objects of this class in all *visible* states, i.e. after all constructors and before and after all methods. For example, having a field `Object[] list`, one can write an invariant that the list is never null and its length is 10. Class invariants can be seen as additional, implicit preconditions and postcondtitions for all methods in the class.

Other important class specifications are:

- Declarations of `ghost` fields. They are similar to local ghost variables, but are visible in the whole class scope.

- Model fields—fields present only in the specifications, representing some more complicated formulas. For example one can create a model field representing the property that a collection does not contain nulls.

More details can be found in [15] and [7].

```
1  public class List {

     private Object[] list;

5    /*@ requires list != null;
       @ ensures \result ==(\exists int i;
       @ 0 <= i && i < list.length &&
       @ \old(list[i]) == o1 && list[i] == o2);
9      @*/
     public boolean replace(Object o1, Object o2){
       /*@
         @ loop_invariant i <= list.length
13       @ && i >=0 && (\forall int k;0 <= k
         @ && k < i ==> list[k] != o1);
         @ decreases list.length - i;
         @*/
17     for (int i = 0; i < list.length; i++) {
         if (list[i] == o1) {
           list[i] = o2;
           return true;
21       }
       }
       return false;
     }
25 }
```

Figure 2: An example class `List.java` containing single method `replace`.

3. AN EXAMPLE OF USING THE COMPILER

This section provides an example demonstrating the result of launching the *JML2BML*.

3.1 Source Code

Consider the class presented on Figure 2. This is an excerpt of a class which implements a sequence of objects. We present here only one method that replaces in the `list` array the first occurence of its first parameter with the second one. True will be returned, if and only if such an element was found.

The presented code, apart from standard Java statements, contains also specifications in the JML. There is a precondition (`requires ...`) for the method `replace` defined. It requests that every time the method is invoked, the field `list` it not `null`[2]. The next three lines (starting with `ensures` constitute the method postcondition. It states that, if the precondition was fullfiled, then the method result is true if and only if there was an element in the `list` which value has been updated from `o1` to `o2`. Note that the postcondition makes use of some JML features, like `\result`, `\old` or `\exists`. This postcondition does not describe all properties of this method. For example an implementation that replaces all elements in the `list` up to the first occurence of `o1` with `o2` will fulfill this specification.

[2]In general a method can have multiple `requires-ensures` pairs. In this case the method can be invoked only in places where at least one of the conditions specified `requires` clauses holds.

In addition to specification describing input-output behaviour of the method, also the loop implementing the `replace` method is annotated. The `loop_invariant` clause contains the invariant: a formula that should hold at the beginning of the loop body at each loop iteration. In this example it states that in iteration `i` there are no occurences of `o1` in `list` on positions before `i`. The annotation `decreases` describes the loop variant. It specifies an expression (in this case `list.length - i`) which value is decreased in each loop iteration by at least one.

3.2 Bytecode

In this section we describe the result of translating the source code from Figure 2. The actual result of the compilation is a class file enriched with the attributes which contain the representation of BML specifications. This means that the binary class files are not human readable. Thus, we rely for the current presentation on its textual representation obtained from the BMLLib. The Figure 3 shows the translated `replace` method together with BML annotations inserted by our *JML2BML* compiler. The bytecode instructions labelled with 0 and 1 correspond to the initialization `i = 0`. The loop is located between lines 2 and 33. Lines 5–12 represent the `if` statement, 15–23 correspond to lines 19–20 from the source code. Loading loop condition parameters is located in lines 27–32 and 33 performs the loop condition comparison.

The `requires-enusers` pair is translated into input-output behaviour BML specifications located just before the method code. We can see that the BML code contains two places where the counterpart of the JML `requires` clause can be placed. The first one is right after the `requires` keyword and the second one is after the `precondition` keyword. In fact, both JML and BML allow one to specify many pairs of the input-output specifications. The semantics of the multiple pairs is such that for each pair where the requires formula holds at the entry to the method, the corresponding ensures formula must hold at the exit (so effectively the conjunction of all these ensures formulae must hold). However, we often want to specify that a particular method can be called only in specific context (e.g. with first parameter being non-null) and except for that it should obey the input-output behaviour described in multiple `requires-enusers` pairs. In this situation, it is more convenient to distinguish a single additional clause which should hold in all the cases instead of copying to all the pairs. In our JML code, this clause is implicit and equivalent to `true` whereas in BML this is made explicit as the formula after the `requires` keyword. This is also why the actual JML precondition is translated to the internal `precondition` statement (it is one, and in this particular instance the only one, of potentially many preconditions).

Loops specifications are located after the line labelled with 32 in the presented listing. The *JML2BML* compiler detects loops in the bytecode and inserts the annotation before the statement representing the beginning of a loop condition. In this case it is the `if_icmplt` instruction comparing `i` and `list.length`. (For more details about detecting loops see Section 5.) The modifies clause describes set of variables modified by the loop. We can see it in the listing as this clause is obligatory in BML. Currently, because of Open-

JML limitations, it is not supported by our compiler (the default value `everything` will be inserted) so we see the default value inserted at this point.

```
/*@
  @ requires true
  @  {|
  @   precondition list != null
  @   ensures \result ==
  @     (\exists int i; 0 <= i &&
  @               i < list.length &&
  @               old_list[i] == o1 &&
  @               list[i] == o2)
  @  |}
  @*/
public boolean replace(Object o1, Object o2)
0:    iconst_0
1:    istore_3
2:    goto          #27
5:    aload_0
6:    getfield      main.List.list
9:    iload_3
10:   aaload
11:   aload_1
12:   if_acmpne     #24
15:   aload_0
16:   getfield      main.List.list
19:   iload_3
20:   aload_2
21:   aastore
22:   iconst_1
23:   ireturn
24:   iinc          %3   1
/*@
  @ loop_specification
  @   modifies everything
  @   invariant i <= list.length &&
  @       i >= 0 &&
  @       (\forall int k; 0 <= k &&
  @           k < i ==> list[k] != o1)
  @   decreases list.length - i
  @*/
27:   iload_3
28:   aload_0
29:   getfield      main.List.list
32:   arraylength
33:   if_icmplt     #5
36:   iconst_0
37:   ireturn
```

Figure 3: The method `replace` in the `List.class`

4. JML2BML COMPILER DESIGN

JML2BML takes as input a Java source file with JML annotations together with the corresponding class file and outputs the class file with inserted proper BML annotations. Our compiler uses an enhanced Abstract Syntax Tree (AST) for the Java source code, taken from the OpenJML [3] compiler (a Java compiler with JML checker based upon the OpenJDK Java tool set). For different types of JML clauses, there are separate translation rules defined. At each node of the AST, all translation rules are applied. If some rule succeeds to translate this node, the result is stored in the class file, using the BMLLib library [21]. This approach makes the compiler easily extensible. It is enough to just write a new translation rule to support additional features of the JML language. Moreover, the acyclic strucure of the code should make the future maintenance more feasible and facilitate the understanding of the code mechanisms by future contributors [10].

[3]Available from `http://sourceforge.net/projects/jmlspecs`

Currently, the *JML2BML* compiler focuses on a subset of the JML called JML Level 0. Due to external libraries limitations not all desired features are translated, for example the loop `modifies` clause is not supported by OpenJML. The *JML2BML* compiler is designed to be compatible with other bytecode level tools, such as the bytecode editor *Umbra*.

4.1 Architecture Description

In this section we present the overview of the architecture of *JML2BML* compiler. The *JML2BML* compiler uses OpenJML to parse the Java source code together with the JML annotations. To insert generated BML annotations, the BMLLib library is used. The dependencies between internal packages of *JML2BML* and OpenJML and BMLLib are presented on Figure 4.

The `jml2bml.main` package provides the entry point to the application. JML annotations from given source file will be translated and inserted into corresponding class file. Functions to access some bytecode information are located in `jml2bml.bytecode` and helpers to BMLLib are collected in `jml2bml.bmllib`. The `jml2bml.rules` package contains translation rules for different aspects of JML. It should be easy to add new rules in the future. Classes for traversing the Java abstract syntax tree can be found in `jml2bml.ast`. In `jml2bml.symbols` implementation of the symbol table, which is used in the translation of JML to BML, can be found. The `jml2bml.engine` package contains the core translation mechanism.

4.2 Translation Mechanism

The full translation consists of a set of independent translation rules. Having the set of rules the AST tree of the source code with annotations is traversed. For each visited node all translation rules are applied. For most nodes translation rules do nothing—each is responsible for a few node types. The translation mechanism allows to register new rules in a very simple way. This is an important issue in case as we predict that new features will be added both to JML and BML.

4.2.1 Translation rules

The *JML2BML* compiler uses a set of translation rules. The concept of translation rule is that it should be responsible for relatively small, independent piece of translation. For example we have separate rule for translating *assert* and another one for translating *loop_invariant*. Each rule is responsible for translation of a part of the AST tree resulting from a particular non-terminal of the input grammar. Translation rule may write results of translation to the output class file (using BMLLib). It can, however, only collect some translated data that may be used by other translation rules. For example both—the *assert* and *loop_invariant* annotations contain expressions. Therefore we created an expression translation rule that makes translation of an expression but it does not write anything to output file—just returns the translated expression that will be used in other translation rules.

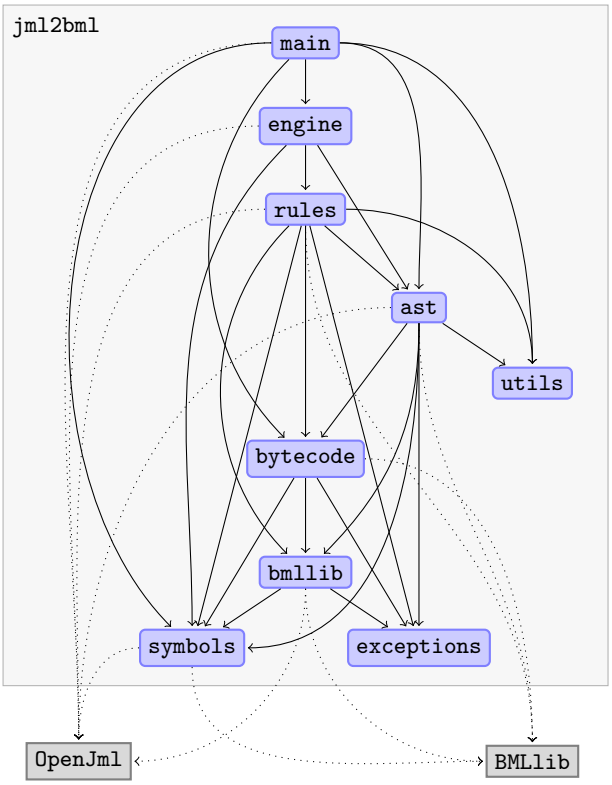

Figure 4: The dependency graph of the *JML2BML* packages. Dotted lines denote access to external libraries.

It is relatively easy to extend translation using the translation rule concept. For example if we would like to translate an annotation that was not already translated we should create a new translation rule implementation and include it in the translation mechanism by registering the rule in the translation manager. When implementing the translation rule we should first find out which AST nodes are relevant to the implemented translation operation and then override proper methods of the base skeletal class, `TranslationRule<String>`. The default methods from the skeletal class do nothing, so the methods which are not overriden will just represent identical translation for the case they represent.

Translation rule key design features are:

- the concept falls into a visitor design pattern,
- translation rule is an extension of a simple abstract class,
- translation process can be broken into smaller, independent pieces,
- extending translation is simple.

4.2.2 *Example of Translation Rule*

We present here a rule which translates a JML invariant into a BML invariant. The main non-trivial work of the rule is to combine all the JML invariants in the current class into a single invariant in the resulting BML representation (the specification in BML can conatin only one instance invariant for a single class).

The logic of the translation rule can be described in an abstract way as follows:

$$
\begin{aligned}
&\mathrm{Tr}(\mathsf{invariant\_keyword\ predicate}, \mathsf{translation\_ctxt}) = \\
&\quad \mathrm{replace}(\mathsf{translation\_ctxt}, \\
&\qquad \mathrm{getInvariant}(\mathsf{translation\_ctxt}), \\
&\qquad \mathrm{consInvariant}(\\
&\qquad\quad \mathrm{getInvExpression}(\\
&\qquad\qquad \mathrm{getInvariant}(\mathsf{translation\_ctxt})) \ \&\&^{*} \\
&\qquad\quad \mathrm{getExpression}(\mathrm{Tr}(\mathsf{predicate}, \mathsf{translation\_ctxt}))))
\end{aligned}
$$

where $\mathrm{Tr} : \mathsf{JMLAST} \times \mathsf{Ctxt} \rightarrow \mathsf{Ctxt}$ is the function which defines the translation. It takes a JML AST node and a translation context and transforms this into a new translation context which contains the result of the translation.

The replace function replaces in the given translation context the item from the second argument with the item on the third argument. In our case, it replaces the current invariant (obtained using the getInvariant function from the current context) with the newly generated one. The newly generated invariant is constructed (using consInvariant) from the conjunction of the expression obtained from the already accumulated invariant (obtained using getInvExpression) with the expression being the result of the translation of the predicate in the currently translated invariant (predicate). One remark must be made about the operation of the conjunction. In case the first argument is undefined (it happens when we translate the first invariant in the class), the operation $\&\&^{*}$ results just in its second argument.

Figure 5 contains the Java code which implements the above described translation rule. The rule directly extends the base `TranslationRule` class. It has one attribute `context`, which holds the context in which rule will be executed. Class invariants in OpenJML abstract syntax tree are represented by `JmlTypeClauseExpr` class nodes. As we use visitor pattern, we have to override method responsible for these nodes, `visitJmlTypeClauseExpr`.

Implementation of the translation method is simple. First we check if this is the node type we are interested in, line 29. We get an object representing the class which we want to add invariant to (line 30). Next, in line 32, we translate the content of invariant—the rule which translates the expression is used here. In line 38, the existing class invariant is retrieved from the class. If there is no invariant, a new one is created (line 41), otherwise we combine an old invariant formula with the new one using the `&&` logical connective (line 46). The result is fed to a new class invariant in line 48. At the end, in line 51 we set new invariant to the class.

4.3 Translating Expressions

In order to be able to translate any JML specification, one needs to translate JML expressions, so one of the most substantial tasks in writing the compiler was to write a translation rule for expressions. As BML is based on JML, the syntax of expressions is similar in both languages and includes:

- Binary arithmetic operations (+, -, *, /)

```
public class TypeClauseExprRule
  extends TranslationRule<String, Symbols> {
  /** Context object. */
  private final Context context;

  /**
   * Constructor of the rule.
   * @param context context object
   */
  public TypeClauseExprRule(Context context) {
    super();
    this.context = context;
  }

  /**
   * Main translation method. The translation
   * realises the following logic:
   * <pre>
   *    ... the abstract translation rule ...
   * </pre>
   *
   * @param node node to be translated
   * @param symb symbol table
   * @return empty string
   */
  @Override
  public String visitJmlTypeClauseExpr(
      JmlTypeClauseExpr node, Symbols symb) {
    if (node.token == JmlToken.INVARIANT) {
      BCClass clazz =
          context.get(BCClass.class);
      AbstractFormula formula =
          TranslationUtil.getFormula(
                      node.expression,
                      symb, context);

      ClassInvariant classInvariant =
          clazz.getInvariant();
      if (classInvariant == null) {
        classInvariant =
          new ClassInvariant(clazz, formula);
      } else {
        AbstractFormula newFormula =
            new Formula(Code.AND,
                classInvariant.getInvariant(),
                formula);
        classInvariant =
            new ClassInvariant(clazz,
                               newFormula);
      }
      clazz.setInvariant(classInvariant);
      return "";
    } else
      return null;
  }
}
```

Figure 5: Example implementation of translation rule for class invariants.

- Boolean operations
- Relational operators ($<$, $\leq$, $\geq$, $!=$, etc.)
- Logical formulae containing
  - special expressions such as reference to old value (`\old`), reference to the result of method (`\result`),
  - implications, conjunctions, alternatives, etc.,
  - quantifiers (with bound variables).

As in standard Java, also in JML and BML the expressions can contain local variables, references to fields (both standard and ghost), method invocations, array access etc. There can also appear constructions specific for JML and BML such as `\old` expressions. The translation of expressions is in most cases straightforward. We face a more complicated situation when identifiers are translated, because one has to distinguish between fields, ghost fields, local variables, and bound variables. All these kinds of variables are resolved in different ways at the bytecode level which makes their compilation convoluted.

5. DETECTING LOOPS IN BYTECODE

In some cases, it is crucial to use for the translation the content of the original class file, provided by the user. There is a need to link instructions from the source code with corresponding bytecode instructions from the provided class file. The most difficult and important part is to detect loops in the bytecode. To be able to compile the JML loop invariants, one should detect in the bytecode the corresponding loop. The created BML annotation should be associated with the bytecode instruction that represents the loop condition. Note that the loop condition is translated into multiple bytecode instructions. A loop can be translated in one of the ways presented on Figure 6.

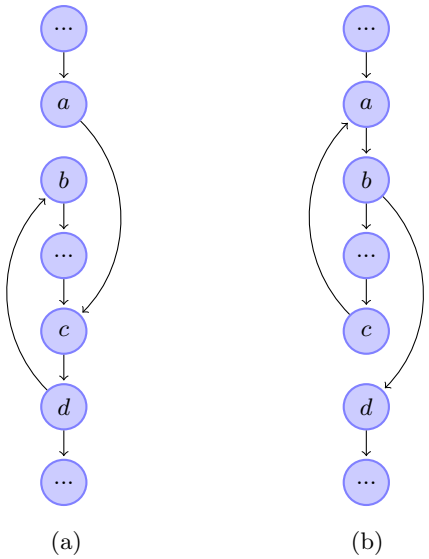

Figure 6: Two ways of compiling loops.

In the first scenario (shown on Figure 6(a)), an unconditional jump (goto) from the vertex a to the vertex c is done (vertex c denotes the start of the loop exit condition). In vertex d, the condition check is executed, and if it is fulfilled, we jump back to b. The instructions between b and c constitute the loop body. The annotation should be added to the vertex c. In the second approach (shown on Figure 6(b)), the condition is tested at the beginning (a starts the sequence of instructions which evaluates the loop condition and b represents the actual check). If the loop condition is fulfilled, we enter the loop body which starts right after c, otherwise we jump out of the loop to the vertex d. In the vertex c, an unconditional jump back to a is done to check again the loop condition after the body is executed. The BML annotation should be associated with the instruction in the vertex a.

Another difficulty is posed by `do-while` loops and loops the exit condition of which is the constant true condition which prevents the loop to finish in a normal way (i.e. the loops of the shape `while(true){...}` or `for(;;){...}` loops). The loops of this kind are usually compiled in the way presented on Figure 7.

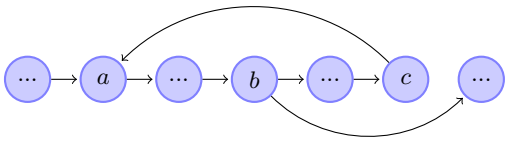

Figure 7: Compiling `do-while` loop.

Before entering the loop (between a and c), no condition is checked. There might be some `break` inside (vertex b). In these cases, the annotation should be associated with the vertex a (the start of the loop).

The *JML2BML* compiler covers all the cases described above. It tries to detect the first kind of a loop from Figure 6. If it fails then it tries to detect the second one. At the end checks, the `do-while` case is checked. In order to check if the loop of the first kind is present, the compiler uses the following algorithm. First, we retrieve the first bytecode instruction that *line number table* associates with the beginning of the loop we are interested in. We try to figure out if the this instruction can play the role of the vertex c on Figure 6(a):

- Assume that the currently tested instruction is in vertex called c. Consider all incoming edges that start in a vertex v, which is before c.
- If there are no such vertices then fail (the instruction being tested cannot be the vertex c in the loop of the first kind).
- Otherwise, take the vertex v that has the longest jump to c (other jumps are the result of some `continue` instructions inside the loop). This vertex v is assigned the role of a from Figure 6(a).
- Find the first instruction after a that has an incoming backward edge the source of which is in an vertex after c. This is our b. Find the longest backward jump of this kind. It is our vertex d.
- Check if b is connected with c.
- If it is return c.
- Otherwise fail.

Note that after the vertex c is discovered we do some additional checks which make sure that this vertex is indeed a part of a loop.

If no loop of the first kind is detected for an instruction in question then we try to detect the second kind of loop using the following algorithm:

- Assume that the currently tested instruction is in the vertex a.
- If the instruction has less than two incoming edges then fail (the instruction being tested cannot be the vertex a in the loop of the first kind).
- Find v that is after a and has the longest jump to it (other jumps are the result of some `continue` instructions inside the loop). This is c from Figure 6(b).
- Look at the next instruction d.
- Find a vertex u such that there exist an edge $(u,\ d)$ and u is between a and d, and there is no such u' that u' is between a and u and there is an edge (u',d). This is a candidate for b.
- Check that b is connected with c.
- If it is return a.
- Otherwise fail.

If both algorithms described above fail, the algorithm tries to detect the `do-while` loop. We simply check if

- There is a backward jump from the tested instruction to some a.
- If so, assuming that cases 1 and 2 failed, return a as the beginning of the loop.

5.1 Matching Bytecode Loops with Source Code Loops

Let us take any source method that has loop with JML invariant and bytecode corresponding to this method. The compiler used to generate the bytecode may have used some optimizations. Unfortunately, this causes some problems. Here are some exemples of loop optimizations:

- Loop unwinding (loop unrolling):
  In this case the invariant should be checked at every copy of the loop body. However, the unwinding may cause the need to transform the invariant formula to be checked on these copies (e.g. because there is no loop control variable any more).
- Loop interchange:
  If the internal loop invariant depends on the external loop variables then the invariant must be translated in a non-trivial way.
- Code-motion:
  Some part of the loop body may be moved before the loop. The invariant content might describe the

When we want to add BML specifications to optimised bytecode, we have to know the optimisations that were used. There are two solutions of this problem:

- Include the JML to BML compiler in an existing Java compiler application.

- Use a non-optimizing compiler.

The the first solution has the advantage that even optimized bytecode may be annotated. Unfortunately, it would have to use an existing compiler infrastructure so every change in the compiler might trigger a change in the code which translates the annotations. This would be very difficult and complicated to trace and maintain (note that the invariant transformations required for the mentioned above optimisations are very complicated). Moreover, the development environment of a potential user of the *JML2BML* compiler may be tightly connected with some other compilation technology so that switching to the one supporting *JML2BML* would be impractical.

In the second solution, the translations are more predictible and simpler compared to the optimizing compiler case. Different compiler implementations may be used e.g. Jikes or the reference Sun compiler etc. This is the approach which we took in our implementation.

In both cases, class level annotations (method pre-post conditions, class invariants) can be translated in the same way. Therefore, when we limit to only these annotations we can use the current implementation of the *JML2BML* compiler even with an optimising Java source code compiler.

For matching source loops with detected bytecode loops we use *line number table* so the source java file must be compiled with the proper flag. The *line number table* is also crucial for the translation of JML `assert` expressions. Without the knowledge how Java compiler works—how it translates every Java expression to bytecode, it would be impossible to locate proper place in bytecode where the BML `assert` should be placed. Knowing where in bytecode loops are placed and having *line number table* in input Java class file, we can detect for evely such loop the line range in source file where the loop is placed. To get the beginning line number and ending line number corresponding to a given bytecode loop in source file, we search all instructions of the loop and use the *line number table* to get line number of the instruction. When we already have source file line ranges for every bytecode loop we have to take into consideration fact, that source loop can be present in bytecode more than once. This may happen when loop is placed in `finally` block of Java `try-catch` statement—translated `finally` block can be copied to the end of both `try` and `catch` blocks. To match source loop to bytecode loops for every source code loop with `loop_invariant` present, we search for the best matching bytecode loop:

- bytecode loop line range must be in the source loop line range
- in bytecode there cannot be any other loop that has line range bigger but still in source loop line range
- there can be more than one bytecode loops matching but every all of them must have equal source line range

6. RELATED WORK

JML2BML compiler uses external libraries that are still in developement (BMLLib, OpenJML). They do not provide whole functionality needed to compile the JML Level 0. When they get more powerful, also our compiler should be enhanced to support more sophisticated specifications (and therefore get more adequate for the end user). The most urgent are the `modifies` clauses and `set` instructions. The compiler should be also provided as a Eclipse plugin.

7. CONCLUSION

We have presented *JML2BML* compiler that deals with JML annotations and translates them into BML. The resulting annotations are inserted in binary format into the class file (using the BMLLib library). The compiler is an important step in building a common verification platform for all languages compiled to the Java bytecode.

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