Preliminary Design of JML: A Behavioral Interface Specification Language for Java

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Abstract
Gary T. Leavens, Albert L. Baker, and Clyde Ruby Abstract JML is a behavioral interface specification language tailored to Java. It also allows assertions to be intermixed with Java code, as an aid to verification and debugging. JML is designed to be used by working software engineers, and uses Eiffel-style assertion syntax combined with the model-based approach to specifications typified by VDM and Larch. However, JML supports quantifiers, specification-only variables, frame conditions, and other enhancements that make it more expressive than Eiffel. This paper discusses the goals of JML, the overall approach, and describes the basic features of the language through examples. It is intended for readers who have some familiarity with both Java and behavioral specification using pre- and postconditions.

Keywords
Behavioral interface specification, Java, JML, Eiffel, Larch, model-based specification, precondition, postcondition, frame

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Preliminary Design of JML:

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1 Introduction

Abstract

JML is a behavioral interface specification language tailored to Java. It also allows assertions to be intermixed with Java code, as an aid to verification and debugging. JML is designed to be used by working software engineers, and uses Eiffel-style assertion syntax combined with the model-based approach to specifications typified by VDM and Larch. However, JML supports quantifiers, specification-only variables, frame conditions, and other enhancements that make it more expressive than Eiffel.

This paper discusses the goals of JML, the overall approach, and describes the basic features of the language through examples. It is intended for readers who have some familiarity with both Java and behavioral specification using pre- and postconditions.

JML stands for “Java Modeling Language.” JML is a behavioral interface specification language (BISL) [Wing87] designed to specify Java [Arnold-Gosling98] [Gosling-Joy-Steele96] modules. Java modules are classes and interfaces.

The main goal our research on JML is to better understand how to make BISLs (and BISL tools) that are practical and effective for production software environments. In order to understand this goal, and the more detailed discussion of our goals for JML, it helps to define more precisely what a behavioral interface specification is. After doing this, we return to describing the goals of JML, and then give a brief overview of the tool support for JML and an outline of the rest of the paper.

1.1 Behavioral Interface Specification

As a BISL, JML describes two important aspects of a Java module:

- its interface, which consists of the names and static information found in Java declarations, and
- its behavior, which tells how the module acts when used.

Because they describe interface details for clients written in a specific programming language, BISLs are inherently language-specific [Wing87]. For example, a BISL tailored to C++, such as Larch/C++ [Leavens97c], describes how to use a module in a C++ program. A Larch/C++ specification cannot be implemented correctly in Java, and a JML specification cannot be correctly implemented in C++ (except for functions that are specified as native code).
JML specifications are designed to be annotations in Java code files [Luckham-von Henke85] [Luckham-etal87] [Rosenblum95] [Tan94] [Tan95]. To a Java compiler such annotations are comments that are ignored. This allows JML specifications, such as the specification below, to be embedded in Java code files. It is possible, however, to have specifications that are separate from code, if desired; ways of doing this will be discussed later. For the moment, consider the following simple example of a behavioral interface specification in JML, embedded in a Java code file, ‘IntMathOps.java’.

```java
public class IntMathOps {
    public static int isqrt(int y) {
        /* public_normal_behavior */
        @ requires: y >= 0;
        @ ensures: \result * \result <= y
        @ \&\& y < (\result + 1) * (\result + 1);
        @*/
        { return (int) Math.sqrt(y); }
    }
}
```

The specification above describes a Java class, `IntMathOps` that contains one static method (function member) named `isqrt`. The single-line comments to the far right (which start with `//`) give the line numbers in this specification; they are ignored by both Java and JML. Comments with an immediately following at-sign, `//@`, or, as on lines 3–7, C-style comments starting with `/*`, are annotations. Annotations, are treated as comments by a Java compiler, but the text of an annotation, the part following the `//@` or between the annotation markers `/*@` and `@*/`, but ignoring the at-signs (`@`) at the beginning of lines between them, is meaningful to JML.

In the above specification, interface information is declared in lines 1 and 2. Line 1 declares a class named `IntMathOps`, and line 2 declares a method named `isqrt`. Note that all of Java’s declaration syntax is allowed in JML, including, on lines 1 and 2, that the names declared are `public`, that the method is `static` (line 2), that its return type is `int` (line 2), and that it takes one `int` argument.

Such interface declarations must be found in a Java module that correctly implements this specification. This is automatically the case in the file ‘IntMathOps.java’ shown above, since that file also contains the implementation. In fact, when Java annotations are embedded in ‘.java’ files, the interface specification is the actual Java source code. To be correct, an implementation must have both the specified interface and the specified behavior.

In the above specification, the behavioral information is specified in the annotation text on lines 3–7. The keyword `public_normal_behavior` is used to implicitly say that the specification is
intended for clients (hence “public”), and that when the precondition is satisfied a call must return normally, without throwing an exception (hence “normal”). In such a public specification, only names with public visibility may be used.\footnote{In a protected specification, both public and protected identifiers can be used. In a specification with default (i.e., no) visibility specified, which corresponds to Java’s default visibility, public and protected identifiers can be used, as well as identifiers from the same package with default visibility. A private specification can use any identifiers that are available.} On line 4 is a precondition, which follows the keyword requires and the colon (:\). (All such colons the follow keywords are optional in JML.) On lines 5–6 is a postcondition, which follows the keyword ensures and another colon. The precondition says what must be true about the arguments (and other parts of the state); if the precondition is true, then the method must terminate normally in a state that satisfies the postcondition. This is a contract between the caller of the method and the implementor [Hoare69] [Jones90] [Jonkers91] [Guttag-Horning93] [Meyer92a] [Meyer97] [Morgan94]. The caller is obligated to make the precondition true, and gets the benefit of having the postcondition then be satisfied. The implementor gets the benefit of being able to assume the precondition, and is obligated to make the postcondition true in that case.

In general, pre- and postconditions in JML are written using an extended form of Java expressions. In this case, the only extension visible is the keyword $\text{result}$, which is used in the postcondition to denote the value returned by the method. The type of $\text{result}$ is the return type of the method; for example, the type of $\text{result}$ in $\text{isqrt}$ is int. The postcondition says that the result is an integer approximation to the square root of $y$. Note that the behavioral specification does not give an algorithm for finding the square root.

Method specifications may also be written in Java’s documentation comments. The following is an example. The part that JML sees is enclosed within the HTML "tags" $<$jml$>$ and $<$/jml$>$.$^{2}$ The use of the surrounding tags $<$pre$>$ and $<$/pre$>$ tells javadoc to ignore what JML sees, and to leave the formatting of it alone.

$^{1}$ In a protected specification, both public and protected identifiers can be used. In a specification with default (i.e., no) visibility specified, which corresponds to Java’s default visibility, public and protected identifiers can be used, as well as identifiers from the same package with default visibility. A private specification can use any identifiers that are available.

$^{2}$ Since HTML tags are not case sensitive, in this one place JML is also not case sensitive. That is, the syntax also permits the tags $<$JML$>$, $<$/JML$>$, $<$esc$>$, $<$/esc$>$, $<$ESC$>$, and $<$/ESC$>$. 
public class IntMathOps4 {
    /** Integer square root function.
     * @param int y
     * @return the positive square root of y
     */
    public int isqrt(int y) {
        return (int) Math.sqrt(y);
    }
}

Because we expect most of our users to write specifications in Java code files, most of our examples will be given as annotations in '.java' files as in the specifications above. However, it is possible to use JML to write documentation in separate, non-Java, '.jml-refined' files, such as the file 'IntMathOps2.jml-refined' below. Since these files are not Java code files, JML allows the user to omit the code for concrete methods in a class. The specification below shows how this is done, using a semicolon (;), as in a Java abstract method declaration.

public class IntMathOps2 {
    public static int isqrt(int y) {
        public_normal_behavior
        requires: y >= 0;
        ensures: result >= 0
            && result * result <= y
            && y < (result + 1) * (result + 1);
    }
}

The above specification would be implemented in the file 'IntMathOps2.java', which is shown below. This file contains a refines clause, which tells the reader of the '.java' file what is being refined and the file in which to find its specification.

//@ refine: IntMathOps2 <- "IntMathOps2.jml-refined";
public class IntMathOps2 {
    public static int isqrt(int y)
    { return (int) Math.sqrt(y); }
}
To summarize, a behavioral interface specification describes both the interface details of a module, and its behavior. The interface details are written in the syntax of the programming language; thus JML uses the Java declaration syntax. The behavioral specification uses pre- and postconditions.

1.2 Lightweight Specifications

Although we find it best to illustrate JML's features in this paper using specifications that are detailed and complete, one can use JML to write specifications at any desired level of detail. In particular, one can use JML to write "lightweight" specifications (as in ESC/Java). The syntax of JML allows one to write specifications that consist of individual clauses, so that one can say just what is desired.

For example, one might wish to specify just that $\text{isqrt}$ should be called only on positive arguments, but not want to be bothered with saying anything formal about the result. This could be done as shown below. Notice that the only specification given below is a single requires clause (with the colon omitted). Omitting public_normal_behavior in a specification technically means that the specification is intended for the same level of visibility as the method itself (thus, public is implicit in this case). Furthermore, it means that when the precondition is met, an implementation might either signal an exception or terminate normally, so this specification technically allows exceptions to be thrown. But the gain in brevity often outweighs the need for this level of precision.

```java
public class IntMathOps3 {
    public static int isqrt(int y)
    //@ requires y >= 0;
    { return (int) Math.sqrt(y); }
}
```

JML has a semantics that allows most clauses to be sensibly omitted from a specification. When the requires clause is omitted, for example, it means that no requirements are placed on the caller. When the ensures clause is omitted, it means that nothing is promised about the post-state of a method call. See Appendix A [Specification Case Defaults], page 48, for the default meanings of various other clauses.
1.3 Goals

As mentioned above, the main goal of our research is to better understand how to develop BISLs (and BISL tools) that are practical and effective. We are concerned with both technical requirements and with other factors such as training and documentation, although in the rest of this paper we will only be concerned with technical requirements for the BISL itself. The practicality and effectiveness of JML will be judged by how well it can document reusable class libraries, frameworks, and Application Programming Interfaces (APIs).

We believe that to meet the overall goal of practical and effective behavioral interface specification, JML must meet the following subsidiary goals.

- JML must be able to document the interfaces and behavior of existing software, regardless of the analysis and design methods used to create it.

  If JML were limited to only handling certain Java features or certain kinds of software, then some APIs would not be amenable to documentation using JML. Since the effort put into writing such documentation will have a proportionally larger payoff for software that is more widely reused, it is important to be able to document existing reusable software components. This is especially true since software that is implemented and debugged is more likely to be reused than software that has yet to be implemented.

- The notation used in JML should be readily understandable by Java programmers, including those with only standard mathematical training.

  A preliminary study by Finney [Finney96] indicates that graphic mathematical notations, such as those found in Z [Hayes93] [Spivey92] may make such specifications hard to read, even for programmers trained in the notation. This accords with our experience in teaching formal specification notations to programmers. Hence, our strategy for meeting this goal has been to shun most special-purpose mathematical notations in favor of Java's own expression syntax.

- The language must be capable of being given a rigorous, formal semantics, and must also be amenable to tool support.

  This goal also helps ensure that the specification language does not suffer from logical problems, which would make it less useful for static analysis, prototyping, and testing tools.

We also have in mind a long range goal of a specification compiler, that would produce prototypes from constructive specifications [Wahls-Leavens-Baker98]. Our partners at Compaq SRC and the University of Nijmegen have other goals in mind. At Compaq SRC, the goal is to make static analysis tools for Java programs that can help detect bugs. At the University of Nijmegen, the goal is to be able to do full program verification on Java programs.
As a general strategy for achieving these goals, we have tried to blend the Eiffel [Meyer92a] [Meyer92b] [Meyer97], Larch [Wing87] [Wing90a] [Guttag-Horning93] [Leavens:LarchFAQ], and refinement calculus [Back88] [Back-vonWright98] [Morgan-Vickers94] [Morgan94] approaches to specification. From Eiffel we have taken the idea that assertions can be written in a language that is based on Java expressions. We also adapt the “old” notation from Eiffel, which appears in JML as \texttt{old}, instead of the Larch-style annotation of names with state functions. However, Eiffel specifications, as written by Meyer, are typically not as detailed as model-based specifications written, for example, in Larch BISLS or VDM [Jones90]. Hence, we have combined these approaches, by using syntactic ideas from Eiffel and semantic ideas from model-based specification languages.

JML also has some other differences from Eiffel (and its cousins Sather and Sather-K). The most important is the concept of specification-only declarations. These declarations, as will be explained below, allow more abstract and exact specifications of behavior than is typically done in Eiffel; they allow one to write specifications that are similar to the spirit of VDM or Larch BISLS. A major difference is that we have extended the syntax of Java expressions with quantifiers and other constructs that are needed for logical expressiveness, but which are not always executable. Finally, we ban side-effects and other problematic features of code in assertions.

On the other hand, our experience with Larch/C++ has taught us to adapt the model-based approach in two ways, with the aim of making it more practical and easy to learn. The first adaptation is again the use of specification-only model variables. An object will thus have (in general) several such model \textit{fields}, which are used only for the purpose of describing, abstractly, the values of objects. This simplifies the use of JML, as compared with most Larch BISLS, since specifiers (and their readers) hardly ever need to know about algebraic-style specification. It also makes designing a model for a Java class or interface similar, in some respects, to designing an implementation data structure in Java. We hope that this similarity will make the specification language easier to understand. (This kind of model also has some technical advantages that will be described below.)

The second adaptation is the hiding of the details of mathematical modeling are hidden behind a facade of Java classes. In the Larch approach to behavioral interface specification [Wing87], the mathematical notation used in assertions is presented directly to the specifier. This allows the same mathematical notation to be used in many different specification languages. However, it also means that the user of such a specification language has to learn a notation for assertions that is different than their programming language’s notation for expressions. In JML we use a compromise approach, hiding these details behind Java classes. These classes are pure, in the sense that they reflect the underlying mathematics, and hence do not use side-effects (at least not in any observable way). Besides insulating the user of JML from the details of the mathematical notation, this compromise approach also insulates the design of JML from the details of the mathematical logic used for theorem proving.
We have generally taken features wholesale from the refinement calculus. Our adaptation of it consists in blending it with the idea of interface specification and adding features for object-oriented programming. However, since the refinement calculus is mostly needed for advanced specifications, in the remainder of this paper we do not discuss the JML features related to refinement, such as model programs.

1.4 Tool Support

Currently the JML release from Iowa State has some tool support for static checking of specifications, and for run-time assertion checking. Our partners at Compaq SRC are building a tool, ESC/Java, that does static analysis for Java programs, using a subset of the JML specification syntax, to can help detect bugs in Java code. At the University of Nijmegen the LOOP tool [Jacobs-etal98] is being adapted to use JML as its input language. This tool would generate verification conditions that could be checked using a theorem provers such as PVS or Isabelle/HOL. In the rest of the section we concentrate on the tool support found in the JML release from Iowa State.

Details on the running the JML checker can be found in its manual page for the release. Here we only indicate the most basic uses of the checker. Running the checker with filenames as arguments will perform type checking on all the specifications contained in the given files. For example, one could check the specifications and the file `UnboundedStack.java` by executing the following command.

```
jml UnboundedStack.java
```

To check all the relevant files in a directory and its subdirectories, one can pass the directory name to the checker, as in the following command. (In the current release, this form is more efficient, because the checker caches information about other specifications that are used in memory.)

```
jml .
```

Using the checker to do run-time checking of preconditions (the only kind of assertion checking that is currently supported) is more complicated. First one would execute the following command to generate a version of the code containing run-time precondition checks.

```
jml --assertc myProgram.java UnboundedStack.java
```
The code that is generated to do run-time precondition checking is stored in another directory. This prevents the checker from destroying your input files. The parallel directory where the generated code is stored is defined by the value of the environment variable JMLOUTDIR, which defaults to 'c:/jmlout' on Windows and '$HOME/jmlout' on Unix systems. (These defaults may be changed by the system administrator.)

After doing this, change to the appropriate directory under JMLOUTDIR, the one that corresponds to the package. For instance, if myProgram lives in the package stacktest, then on windows do something like the following.

```
cd jmlout/stacktest
```

On Unix this can be done with a command like

```
cd $HOME/jmlout/stacktest
```

Once you are in the right directory, you can use the following commands to compile and then execute the generated code.

```
jassertc myProgram.java UnboundedStack.java
jassert myProgram
```

The script jassertc calls javac on the generated code in the directory named by JMLOUTDIR, and jassert runs it.

For more details on the current state of the tools and their usage, see the ‘README.txt’ file for the release and the manual pages for these commands.

### 1.5 Outline

In the next sections we describe more about JML and its semantics. See Chapter 2 [Class and Interface Specifications], page 10, for examples that show how Java classes and interfaces are specified; this section also briefly describes the semantics of subtyping and refinement. See Chapter 3 [Extensions to Java Expressions], page 42, for a description of the expressions that can be used in specifications. See Chapter 4 [Conclusions], page 47, for conclusions from our preliminary design effort. See Appendix B [Syntax], page 49, for details on the syntax of JML.
2 Class and Interface Specifications

In this section we give some examples of JML class specifications that illustrate the basic features of JML.

2.1 Abstract Models

A simple example of an abstract class specification is the ever-popular UnboundedStack type, which is presented below. It would appear in a file named ‘UnboundedStack.java‘. In that file, the abstract values of stack objects are specified by the model data field theStack, which is declared on the fourth non-blank line. Since it is declared using the modifier model, such a field does not have to be implemented; however, for purposes of the specification we treat it exactly as any other Java field (i.e., as a variable). That is, we imagine that each instance of the class UnboundedStack has such a field.

```java
package edu.iastate.cs.jml.samples.stacks;
//@ model import edu.iastate.cs.jml.models.*;

public abstract class UnboundedStack {
    //@ public model JMLObjectSequence theStack
    @     initially: theStack != null && theStack.isEmpty();
    @*/

    //@ public invariant: theStack != null;

    public abstract void pop();
    //@ public_normal_behavior
    @     requires: !theStack.isEmpty();
    @     modifiable: theStack;
    @     ensures: theStack.equals(\old(theStack.trailer()));
    @*/

    public abstract void push(Object x);
    //@ public_normal_behavior
    @     modifiable: theStack;
    @     ensures: theStack.equals(\old(theStack.insertFront(x)));
    @*/
```
public abstract Object top();
/** @ public_normal_behavior
  * @ requires: !theStack.isEmpty();
  * @ ensures: \result == theStack.first();
  */
}

The type of the model field theStack is a pure type, JMLObjectSequence, which is a sequence of objects. It is provided by JML in the package edu.iastate.cs.jml.models,¹ which is imported in the second non-blank line of the figure. Note that this import declaration does not have to appear in the implementation, since it is modified by the keyword model. In general, any declaration form in Java can have this modifier, with the same meaning: that the declaration in question is only used for specification purposes, and does not have to appear in an implementation.

At the end of the model field’s declaration above is an initially clause. (Such clauses are adapted from RESOLVE [Ogden-etal94] and the refinement calculus [Back88] [Back-vonWright98] [Morgan-Vickers94] [Morgan94].) An initially clause attached to a field declaration permits the field to have an abstract initialization. Knowing something about the initial value of the field permits data type induction [Hoare72a] [Wing83] for abstract classes and interfaces. The initially clause must appear to be true of the field’s starting value. In each visible state (outside of the methods of UnboundedStack) all reachable objects of the type UnboundedStack must appear to have been created as empty stacks and subsequently modified using the type’s methods.

Following the model field declaration is an invariant. An invariant does not have to hold during the execution of an object’s methods, but it must hold, for each reachable object in each visible state; i.e., for each state outside of a public method’s execution, and at the beginning and end of each such execution. The figure’s invariant just says that the value of theStack should never be null.

Following the invariant are the expected specifications of the pop, push, and top methods.

The use of the modifiable clauses in the behavioral specifications of pop and push is interesting (and another difference from Eiffel). These give frame conditions [Borgida-Mylopoulos-Reiter95], which say that no fields, other than those mentioned (and those on which these fields depend, as explained below) may have their values changed.² When the modifiable clause is omitted, as it is

¹ Users can also define their own pure types, as we will show below.
² An object is modified by a method when it is allocated in both the pre- and post-states of the method, and when some of its (model or concrete) fields change their values. This means that allocating objects, using Java’s new operator, does not cause a modification.
in the specification of top, this means that no fields can have their state modified by the method’s execution. Our interpretation of this is very strict, as even benevolent side effects are disallowed if the modificable clause is omitted [Leino95] [Leino95a].

When a method can modify some fields, they may have different values in the pre-state and post-state of that method. Often the post-condition must refer to the field values in both of these states. JML uses a notation similar to Eiffel’s to refer to the pre-state value of a variable. In JML the syntax is $\texttt{old}(E)$, where $E$ is an expression. (Unlike Eiffel, we use parentheses following $\texttt{old}$ to delimit the expression to be evaluated in the pre-state explicitly.) The meaning of $\texttt{old}(E)$ is as if $E$ were evaluated in the pre-state and that value is used in place of $\texttt{old}(E)$ in the assertion. It follows that, if $E$ denotes an object with modificable fields, then an expression like $\texttt{old(myVar).theStack}$ may not mean what is desired, since access to the field $\texttt{theStack}$ of $\texttt{myVar}$ will be done in the post-state; probably what would be desired is $\texttt{old(myVar.theStack)}$. It is thus good practice to have the expression $E$ be such that its type is either the type of a primitive value, such as an int, or a pure type, such as JMLObjectSequence.

As another example, in push’s postcondition the expression $\texttt{old(theStack.trailer())}$ has type JMLObjectSequence, which is a pure type. The value of $\texttt{theStack.trailer()}$ is computed in the pre-state of the method (just after the method is called and parameters have been passed, but before execution of the body).

Note also that, since JMLObjectSequence is a reference type, one is required to use equals instead of $==$ to compare them for equality of values. (Using $==$ would be a mistake, since it would only compare them for object identity, which in combination with new would always yield false.)

The specification of push does not have a requires clause. This means that the method imposes no obligations on the caller. (The meaning of an omitted requires clause is that the method’s precondition is true, which is satisfied by all states, and hence imposes no obligations on the caller.) This seems to imply that the implementation must provide a literally unbounded stack, which is surely impossible. We avoid this problem, by following Poetzscher-Heffter [Poetzscher-Heffter97] in releasing implementations from their obligations to fulfill the postcondition when Java runs out of storage. In general, a method specified with public_normal_behavior has a correct implementation if, whenever it is called in a state that satisfies its precondition, either

- the method terminates normally in a state that satisfies its postcondition, having modified only the objects permitted by its modificable clause, or
- Java signals an error, by throwing an exception that inherits from java.lang.Error.

We discuss the specification of methods with exceptions in the next subsection.
2.2 Dependencies

In this subsection we describe how model (and concrete) fields can be related to one another, and how dependencies among them affect the meaning of the modifiable clause. We present two specifications, BoundedThing and BoundedStack, to show how this is done. Along the way we also demonstrate how to specify methods that can throw exceptions and other features of JML.

The specification in the file `BoundedThing.java`, shown below, is an interface specification with a simple abstract model. In this case, there are two model fields MAX_SIZE and size. The variable MAX_SIZE is a static model field, which is treated as a class variable, while size is treated as a normal model field, i.e., as an instance variable, because of the use of the keyword instance. This keyword tells the reader that the variable being declared is not static, but has a copy in each instance of a class that implements this interface. In specifications of interfaces that extend or classes that implement this interface, these model fields are inherited. Thus, for example, every object that has a type that is a subtype of the BoundedThing interface is thought of, abstractly, as having a field size, of type int. Similarly, every class that implements BoundedThing is thought of as having a static model field MAX_SIZE.

```java
package edu.iastate.cs.jml.samples.stacks;

public interface BoundedThing {
    //@ public model static int MAX_SIZE;
    //@ public model instance int size;
    //@ public invariant: MAX_SIZE > 0 & & 0 <= size & & size <= MAX_SIZE;
    //@ public constraint: MAX_SIZE == \old(MAX_SIZE);

    public int getSizeLimit();
    /*@ public normal_behavior
        ensures: \result == MAX_SIZE;
    */

    public boolean isEmpty();
    /*@ public_normal_behavior
        ensures: \result <=> size == 0;
    */
}
```

By default, fields declared in Java interfaces are static. Java does not allow non-static fields to be declared in interfaces, but JML allows non-static model fields in interfaces, since these are essential for defining the abstract values of the objects being specified.
public boolean isFull();
/** @ public_normal_behavior 
   * ensures: result <=> size == MAX_SIZE; 
   */

public Object clone () throws CloneNotSupportedException;
/** @ also 
   * public_behavior 
   * ensures: result instanceof BoundedThing 
   * && size == ((BoundedThing)result).size; 
   * signals: (CloneNotSupportedException) true; 
   */
}

Two pieces of class-level specification come after the abstract model in the above specification.

The first is an invariant clause. The figure’s invariant says that in every visible state, the MAX_SIZE variable has to be positive, and that every reachable object that is a BoundedThing must have a size field that has a value less than or equal to MAX_SIZE.

Following the invariant is a history constraint [Liskov-Wing94]. A history constraint is used to say how values can change between earlier and later states, such as a method’s pre-state and its post-state. This prohibits subtypes from making certain state changes, even if they implement more methods than are specified in a given class. The history constraint in the specification above says that the value of MAX_SIZE cannot change, since in every pre-state and post-state (before and after the invocation of a method), its value in the post-state, written MAX_SIZE, must equal its value in the pre-state, written old(MAX_SIZE).

Following the history constraint are the interfaces and specifications for four public methods. Notice that, if desired, the at-signs (@) may be omitted from the left sides of intermediate lines, as we do in this specification.

The use of == in the method specifications is okay, since in each case, the things being compared are primitive values, not references. The notation <=> can be read “if and only if”. It has the same meaning for Boolean values as ==, but has a lower precedence. Therefore, the expression “\result <=> size == 0” in the postcondition of the isEmpty method means the same thing as “\result == (size == 0)”.

The specification of the last method of BoundedThing, clone, is interesting. Note that it begins with the keyword also. This form is intended to tell the reader that the specification given is in addition to any specification that might have been given in the superclass Object, where clone
is declared as a protected method. A form like this must be used whenever a specification is
given for a method that overrides a method in a superclass, or that implements a method from an
implemented interface.

The specification of clone also uses public\_behavior instead of public\_normal\_behavior. In a specification that starts this way, one can describe not just the case where the execution
returns normally, but also executions where exceptions are thrown. In such a specification, the
conditions under which exceptions can be thrown can be described by the predicate in the signals
clauses\(^4\), and the conditions under which the method may return without throwing an exception
are described by the ensures clause. In this specification, the clone method may always throw
the exception, because it only needs to make the predicate “true” true to do so. When the method
returns normally, it must make the given postcondition true.

In JML, a public\_normal\_behavior specification can be thought of as a syntactic sugar for a
public\_behavior specification to which the following clause is added.

\[
\text{signals: (java.lang.Exception) false;}
\]

This formalizes the idea that a method with a public\_normal\_behavior specification may not
throw an exception when the specification’s precondition is satisfied.

JML also has a specification form public\_exceptional\_behavior, which can be used to specify
when exceptions must be thrown. A specification that uses public\_exceptional\_behavior can be
thought of as a syntactic sugar for a public\_behavior specification to which the following clause
is added.

\[
\text{ensures: false;}
\]

This formalizes the idea that a method with an public\_exceptional\_behavior specification may
not return normally when the specification’s precondition is satisfied.

Since in the specification of clone, we want to allow the implementation to make a choice
between either returning normally or throwing an exception, and we do not wish to distinguish the
preconditions under which each choice must be made, we cannot use either of the more specialized
forms public\_normal\_behavior or public\_exceptional\_behavior. Thus the specification of
clone demonstrates the somewhat unusual case when the more general form of a public\_behavior
specification is needed.

\(^4\) The keyword “ensures” can also be used in place of signals.
Finally note that in the specification of `clone`, the postcondition says that the result will be a `BoundedThing` and that its size will be the same as the model field `size`. The use of the cast in this postcondition is necessary, since the type of `result` is `Object`. (This also adheres to our goal of using Java syntax and semantics to the extent possible.) Note also that the conjunct `result instanceof BoundedThing` "protects" the next conjunct [Leavens-Wing97a] since if it is false the meaning of the cast does not matter.

The specification in the file `BoundedStackInterface.java` below gives an interface for bounded stacks that extends the interface for `BoundedThing`. In the specification below, one can refer to the static field `MAX_SIZE` from the `BoundedThing` interface, and to `size` as an inherited instance field of its objects.

```java
package edu.iastate.cs.jml.samples.stacks;
//@ model import edu.iastate.cs.jml.models.*;
public interface BoundedStackInterface extends BoundedThing {
  //@ public model instance JMLObjectSequence theStack
  // initially: theStack != null && theStack.isEmpty();
  //@
  //@ public depends: size -> theStack;
  //@ public represents: size <= theStack.length();
  //@ public invariant: theStack != null;
  //@ public invariant_redundantly: theStack.length() <= MAX_SIZE;
```
public void pop() throws BoundedStackException;
/*@  public_normal_behavior
  @  requires: !theStack.isEmpty();
  @  modifiable: size, theStack;
  @  ensures: theStack.equals(old(theStack.trailer()));
  @ also
  @  public_exceptional_behavior
  @  requires: theStack.isEmpty();
  @  signals: (BoundedStackException);
*/
public void push(Object x) throws BoundedStackException;
/*@  public_normal_behavior
  @  requires: theStack.length() < MAX_SIZE;
  @  modifiable: size, theStack;
  @  ensures: theStack.equals(old(theStack.insertFront(x)));
  @  ensures_redundantly: theStack != null && top() == x
     && theStack.length() == old(theStack.length()+1);
  @ also
  @  public_exceptional_behavior
  @  requires: theStack.length() == MAX_SIZE;
  @  signals: (BoundedStackException);
*/
public /*@ pure @*/ Object top() throws BoundedStackException;
/*@  public_normal_behavior
  @  requires: !theStack.isEmpty();
  @  ensures: result == theStack.first();
  @ also
  @  public_exceptional_behavior
  @  requires: theStack.isEmpty();
  @  signals: (BoundedStackException);
*/
}

The abstract model for BoundedStackInterface adds to the inherited model by declaring a model instance field named theStack. This field is typed as a JMLObjectSequence.

The depends and represents clauses that follow the declaration of theStack are an important feature in modeling with layers of model fields. They also play a crucial role in relating model fields to the concrete fields of objects, which can be considered to be the final layer of detail in a design. The depends clause says that size might change its value when the theStack changes, and the represents clause says how they are related. The represents clause gives additional facts that can be used in reasoning about the specification; it tells how to extract the value of size from the
value of theStack.\footnote{Of course, one could specify BoundedStack without separating out the interface BoundedThing, and in that case, this abstraction would be unnecessary. We have made this separation partly to demonstrate more advanced features of JML, and partly to fit the figures on single pages.} It serves the same purpose as an abstraction function in various proof methods for abstract data types (such as [Hoare72a]).

The depends clause is important in “loosening up” the modifiable clause, for example to permit the fields of an object that implement the abstract model to be changed [Leino95] [Leino95a]. This “loosening up” also applies to model fields that have dependencies declared. For example, since size depends on theStack, i.e., size is in some sense represented by theStack, so if size is mentioned in a modifiable clause, then theStack is implicitly allowed to be modified. Thus it is only for rhetorical purposes that we mention both size and theStack in the modifiable clauses of pop and push. Note, however, that just mentioning theStack would not permit size to be modified, because theStack does not depend on size.

The second invariant clause that follows the represents clause in the specification of fig:BoundedStackInterface above is our first example of checkable redundancy in a specification [Leavens-Baker99] [Tan94] [Tan95]. This concept is signaled in JML by the use of the suffix _redundantly on a keyword (as in ensures_redundantly). It says both that the stated property is specified to hold and that this property is believed to follow from the other properties of the specification. In this case the redundant invariant follows from given invariant, the invariant inherited from the specification of BoundedThing, and the fact stated in the represents clause. Even though this invariant is redundant, it is sometimes helpful to state such properties, to bring them to the attention of the readers of the specification.

Checking that such claimed redundancies really do follow from other information is also a good way to make sure that what is being specified is really what is intended. Such checks could be done manually, during reviews, or by an automated tool such as a theorem prover.

Following the redundant invariant of BoundedStackInterface are the specifications of the pop, push, and top methods. These are interesting for several new features that they present. Each of these has both a normal and exceptional behavior specified. The meaning of such multiple specification cases is that, when the precondition of one of them is satisfied, the rest of that specification case must be obeyed.

A specification with several specification cases is shorthand for one in which the separate specifications are combined [Dhara-Leavens96] [Leavens97c] [Wing83] [Wills94]. The desugaring can be thought of as proceeding in two steps (see [Raghavan-Leavens00] for more details). First, the public_normal_behavior and public_exceptional_behavior cases are converted into public_
behavior specifications as explained above. This would produce a specification for pop as shown below. The use of implies_that introduces a redundant specification that can be used, as is done here, to point out consequences of the specification to the user. In this case the specification in question is the one mentioned in the refine clause. Note that in the second specification case of this figure, the predicate “true” has been added for the signals clause; since this is often the predicate desired in a signals clause, JML allows it to be omitted.

```java
//@ refine: BoundedStackInterface <- "BoundedStackInterface.java";
//@ model import edu.iastate.cs.jml.models.*;
public interface BoundedStackInterface extends BoundedThing {
    public void pop() throws BoundedStackException;
    /** also
        @ implies_that
        public behavior
        @ requires: !theStack.isEmpty();
        @ modifiable: size, theStack;
        @ ensures: theStack.equals(old(theStack.trailer()));
        @ signals: (java.lang.Exception) false;
        also
        @ public behavior
        @ requires: theStack.isEmpty();
        @ ensures: false;
        @ signals: (BoundedStackException) true;
    */
}
```

The second step of the desugaring is shown below. As can be seen from this example, publicbehavior specifications that are joined together using also have a precondition that is the disjunction of the preconditions of the combined specification cases. The modifiable clause for the expanded specification is the union of all the modifiable clauses for the cases, with each modification governed by the corresponding precondition (which follows the keyword if). That is, variables are only allowed to be modified if the modification was permitted in the corresponding case, as determined by its precondition. The ensures clauses of the second desugaring step correspond to the ensures clauses for each specification case; they say that whenever the precondition for that specification case held in the pre-state, its postcondition must also hold. As can be seen in the specification below, in logic this is written using an implication between \texttt{old} wrapped around the case’s precondition and its postcondition. Having multiple ensures clauses is equivalent to writing a single ensures clause that has as its postcondition the conjunction of the given postconditions. Similarly, the signals clauses in the desugaring correspond to those in the given specification cases; as for the ensures clauses, each has a predicate that says that signaling that exception can only happen when the predicate in that case’s precondition holds.
In the file `BoundedStackInterface.refines-java` above, the precondition on `pop` reduces to `true`. However, the precondition shown is the general form of the expansion. Similar remarks apply to other predicates.

Finally, there is more redundancy in the specifications of `push` in the original specification of `BoundedStackInterface` above, which has a redundant `ensures` clause in its normal behavior. For an `ensures_redundantly` clause, what one checks is that the conjunction of the precondition, the meaning of the `modifiable` clause, and the (non-redundant) postcondition together imply the redundant postcondition. It is interesting to note that, for `push`, the specifications for stacks written in Eiffel (see page 339 of [Meyer97]) expresses just what we specify in `push`'s redundant postcondition. This conveys strictly less information than the non-redundant postcondition for `push`'s normal behavior, since it says little about the elements of the stack.\footnote{Meyer's second specification and implementation of stacks (see page 349 of [Meyer97]) is no better in this respect, although, of course, the implementation does keep track of the elements properly.}

### 2.3 Making New Pure Types

JML comes with a suite of pure types, implemented as Java classes that can be used for defining abstract models. These are found in the package `edu.iastate.cs.jml.models`, which includes
both collection and non-collection types (such as JMLInteger) and a few helper classes (such as exceptions and enumerators).

The pure collection types can hold either objects or values, and this distinction determines the notion of equality used on their elements and whether cloning is done on the elements. The object containers use $\texttt{==}$ and do not clone. Simple collection types include the set types, JMLObjectSet and JMLValueSet, and sequence types JMLObjectSequence and JMLValueSequence. The binary relation and map types can independently have objects in their domain or range. The binary relation types are named JMLObjectToObjectRelation, JMLObjectToValueRelation, and so on. The four map types are similarly named according to the scheme JML...To...Map.

Users can also create their own pure types if desired. Since these types are to be treated as purely immutable values in specifications, they must be declared with the modifier pure and pass certain conservative checks that make sure there is no possibility of observable side-effects from using such objects.

A pure interface must have a specification such that:

- all the methods in each interface it extends are pure (these may be either in pure interfaces or the methods may be explicitly specified as pure),
- all the methods it specifies must be pure in the sense described below.

We say a method or constructor is pure if it is either specified with the modifier pure or appears in the specification of a pure interface or class.

A pure method (not a constructor) must have a specification that does not allow any side-effects. That is, it must have a specification that refines (i.e., is stronger than) the following:

\begin{verbatim}
behavior
  modifiable: \nothing;
\end{verbatim}

A pure constructor must have a specification such that: it modifies only the non-static fields of the class in which it appears (including those inherited from its superclasses and model instance fields from the interfaces that implements).

Implementations of pure methods and constructors will be checked to see that they meet these conditions. In particular, a pure method or constructor implementation is prohibited from calling methods or constructors that are not pure. It must also be provably terminating.
A pure method or constructor can be declared in any class. JML will specify the intuitively pure methods and constructors in the standard Java libraries as pure.

A pure class must have a specification such that:

- it only extends other pure classes,
- all the methods in each interface it extends are pure,
- all its methods and constructors must be specified to be pure in the sense described above, and
- all its data fields must be of some primitive value type or a pure type.

Recursion is permitted, both in pure methods and in data members of pure classes. However, a pure method must be proved to terminate when its preconditions is met. When recursion is used in a specification, the proof involves the use of a measured_by clause in the specification.

Model classes should also be pure, since there is no way to use non-pure operations in an assertion. However, the modifiers model and pure are orthogonal, and thus usually one will want to list both of them when declaring a model class. In particular, one may specify a pure class that is not a model class; such a class would have to be implemented.

### 2.3.1 Money

As an example, we specify a pure interface, Money, that would be suitable for use in abstract models. Our specification is rather artificially broken up into pieces to allow each piece to have a specification that fits on a page. This organization is not necessarily something we would recommend, but it does give us a chance to illustrate more features of JML.

Consider first the interface Money specified below. The abstract model here is a single field of the primitive Java type long, which holds a number of pennies. Note that the declaration of this field, pennies, again uses the JML keyword instance.

```java
class Money
{
    //@ public model instance long pennies;
```
// @ public constraint: pennies == \old(pennies);

public long dollars();
/**
 * public_normal_behavior
 *   @ ensures: \result == pennies / 100;
 * for example
 *   @ public_normal_example
 *     @ requires: pennies == 703;
 *     @ ensures: \result == 7;
 * also
 *   @ public_normal_example
 *     @ requires: pennies == 799;
 *     @ ensures: \result == 7;
 * also
 *   @ public_normal_example
 *     @ requires: pennies == -503;
 *     @ ensures: \result == -5;
 */

public long cents();
/**
 * public_normal_behavior
 *   @ ensures: \result == pennies % 100;
 * for example
 *   @ requires: pennies == 703;
 *   @ ensures: \result == 3;
 * also
 *   @ requires: pennies == -503;
 *   @ ensures: \result == -3;
 */

public boolean equals(Object o2);
/**
 * public_normal_behavior
 *   @ ensures: \result iff o2 instanceof Money
 *            && pennies == ((Money)o2).pennies;
 */

public Object clone();
/**
 * public_normal_behavior
 *   @ ensures: \result instanceof Money
 *            && ((Money)\result).pennies == pennies;
 */
}
This interface has a history constraint, which says that the number of pennies in an object cannot change.\footnote{There is no use of \texttt{initially} in this interface, so data type induction cannot assume any particular starting value. But this is desirable, since if a particular starting value was specified, then by the history constraint, all objects would have that value.}

The interesting aspect of the operations is another kind of redundancy, examples, which following the keyword "\texttt{for\_example}". Individual examples are given by \texttt{public\_normal\_example} clauses (adapted from our previous work on Larch/C++ \cite{Leavens96b} \cite{Leavens-Baker99}). Any number of these\footnote{One may also give \texttt{public\_exceptional\_example} clauses, which are analogous to \texttt{public\_exceptional\_behavior} specifications, and \texttt{public\_example} clauses, which are analogous to \texttt{public\_behavior} specifications. There is also a lightweight form, that is similar to the \texttt{public\_example} form, except that the keyword "\texttt{public\_example}" is be omitted.} can be given in a specification. Here there are three normal examples given for \texttt{dollars} and two in the specification of \texttt{cents}. The specification in each example should be such that:

- the example's precondition implies the precondition of the expanded meaning of the specified behaviors, and
- the conjunction of the example's precondition (wrapped by \texttt{old}$\{\}$, the precondition of the expanded meaning of the specified behaviors (also wrapped by \texttt{old}$\{\}$), the modifiable clause of the expanded meaning of the specified behaviors, and the postcondition of the expanded meaning of the specified behaviors should be equivalent to the example's postcondition.

Requiring equivalence to the example's postcondition means that it can serve as a test oracle for the inputs described by the example's precondition. If there is only one specified \texttt{public\_normal\_behavior} clause and if there are no preconditions and modifiable clauses, then the example's postcondition should the equivalent to the conjunction of the example's precondition and the postcondition of the \texttt{public\_normal\_behavior} specification. Typically, examples are concrete, and serve to make various rhetorical points about the use of the specification to the reader. (Exercise: check all the examples given!)

The interface \texttt{Money} is specified to extend the interface \texttt{JMLType}. This interface is given in below. Classes that implement this interface must have \texttt{equals} and \texttt{clone} methods with the specified behavior. Most of the specifications are for methods that override methods in the class \texttt{Object}, and so they use the form of specification that begins with the keyword "\texttt{also}".
package edu.iastate.cs.jml.models;

/** Objects with a clone and equals method.
   * JMLObjectType and JMLValueType are refinements
   * for object and value containers (respectively).
   * @see JMLObjectType
   * @see JMLValueType
   */
public interface JMLType extends Cloneable, java.io.Serializable {

  /*
   * @ pure
   * @ ensures: result instanceof JMLType
   * @
   * @
   * public */
  public /*@ pure @*/ Object clone();
  /*@ also
   * @
   * public normal_behavior
   * @
   * ensures: result instanceof JMLType
   * @
   * && ((JMLType)result).equals(this);
   */

  public /*@ pure @*/ boolean equals(Object ob2);
  /*@ also
   * @
   * public normal_behavior
   * @
   * ensures: result <=>
   * @
   * ((Object)this).getClass().instanceof(ob2)
   * @
   * && (* ob2 is not distinguishable from this *);
   */
}

The specification of JMLType is noteworthy in its use of informal predicates [Leavens96b]. In this instance, the informal predicates are used as an escape from formality. The use of informal predicates avoids the delicate issues of saying formally what observable aliasing, and equality of values mean in general.\footnote{Observable aliasing is a sharing relation between objects that can be detected by a program. Such a program, might, for example modify one object and read a changed value from the shared object. Formalizing this in general is beyond the scope of this paper, and probably beyond what JML can describe.}

### 2.3.2 MoneyComparable and MoneyOps

The type Money lacks some useful operations. The extensions below provide specifications of comparison operations and arithmetic, respectively.
The specification in file 'MoneyComparable.java' is interesting because each of the specified pre-
conditions protects the postcondition from undefinedness in the postcondition [Leavens-Wing97a].
For example, if the argument m2 in the greaterThan method were null, then the expression
m2.pennies would not be defined.

package edu.iastate.cs.jml.docs.prelimdesign;

public /*@ pure @*/ interface MoneyComparable extends Money {
    public boolean greaterThan(Money m2);
    /*@ public_normal_behavior */
    @ requires: m2 != null;
    @ ensures: \result <=> pennies > m2.pennies;
    @*/

    public boolean greaterThanOrEqualTo(Money m2);
    /*@ public_normal_behavior */
    @ requires: m2 != null;
    @ ensures: \result <=> pennies >= m2.pennies;
    @*/

    public boolean lessThan(Money m2);
    /*@ public_normal_behavior */
    @ requires: m2 != null;
    @ ensures: \result <=> pennies < m2.pennies;
    @*/

    public boolean lessThanOrEqualTo(Money m2);
    /*@ public_normal_behavior */
    @ requires: m2 != null;
    @ ensures: \result <=> pennies <= m2.pennies;
    @*/
}

The interface specified in the file 'MoneyOps.java' below extends the interface specified above.
MoneyOps is interesting for the use of a pure model method, inRange. This method cannot be
invoked by Java programs; that is, it would not appear in the Java implementation. When used
in a predicate, inRange(1) is equivalent to using some correct implementation of its specification.
The specification of inRange also makes use of a local model variable declaration, which follows the
keyword "let". Such declarations allow one to abbreviate long expressions, or, to make rhetorical
points by naming constants, as is done with epsilon.

package edu.iastate.cs.jml.docs.prelimdesign;

public /*@ pure @*/ interface MoneyOps extends MoneyComparable


```java
{  
    /**
     * Model public boolean inRange(double d);
     * @public normal_behavior
     * let model double epsilon = 1.0;
     * ensures: result <= Long.MIN_VALUE + epsilon < d
     * && d < Long.MAX_VALUE - epsilon;
     */

    public USMoney plus(Money m2);
    /**
     * @public normal_behavior
     * requires: m2 != null
     * && inRange((double) pennies + m2.pennies);
     * ensures: result != null
     * && result.pennies == this.pennies + m2.pennies;
     * for_example
     */

    public USMoney minus(Money m2);
    /**
     * @public normal_behavior
     * requires: m2 != null
     * && inRange((double) pennies - m2.pennies);
     * ensures: result != null
     * && result.pennies == this.pennies - m2.pennies;
     * for_example
     */

    public USMoney scaleBy(double factor);
    /**
     * @public normal_behavior
     * requires: inRange(factor * pennies);
     * ensures: result != null
     * && result.pennies == (long)(factor * pennies);
     * for_example
     */
  }

Note also that JML uses the Java semantics for mixed-type expressions. For example in the specification of plus above, m2.pennies is coerced to a double-precision floating point number, as it would be in Java.
2.3.3 Implementation of Class and Interface Specifications

The key to proofs that an implementation of a class or interface specification is correct lies in the use of \texttt{depends} and \texttt{represents} clauses [Hoare72a] [Leino95].

2.3.4 MoneyAC

Consider, for example, the abstract class specified in the file `MoneyAC.java` below. This class is abstract and has no constructors. The class declares a concrete field \texttt{numCents}, which is related to the model instance field \texttt{pennies} by the \texttt{represents} clause. This allows relatively trivial proofs of the correctness of the \texttt{dollars} and \texttt{cents} methods, and is key to the proofs of the other methods.

```java
package edu.iastate.cs.jml.docs.prelimdesign;

public /*@ pure @*/ abstract class MoneyAC implements Money {

protected long numCents;
//@ protected depends: pennies \rightarrow numCents;
//@ protected represents: pennies \leftarrow numCents;

//@ protected constraint_redundantly: numCents == \old(numCents);

public long dollars()
{
    return numCents / 100;
}

public long cents()
{
    return numCents % 100;
}

public boolean equals(Object o2)
{
    try {
        Money m2 = (Money)o2;
        return numCents == (100 * m2.dollars() + m2.cents());
    } catch (ClassCastException e) {
        return false;
    }
}

public Object clone()
{
    return this;
}
```

2.3.5 MoneyComparableAC

The straightforward implementation of the pure abstract subclass MoneyComparableAC is given below. Besides extending the class MoneyAC, it implements the interface MoneyComparable. Note that the model and concrete fields are both inherited by this class.

```java
package edu.iastate.cs.jml.docs.prelimdesign;

public /*@ pure */ abstract class MoneyComparableAC
    extends MoneyAC implements MoneyComparable
{
    protected static long totalCents(Money m2)
    {
        long res = 100 * m2.dollars() + m2.cents();
        //@ assert: res == m2.pennies;
        return res;
    }

    public boolean greaterThan(Money m2)
    {
        return numCents > totalCents(m2);
    }

    public boolean greaterThanOrEqualTo(Money m2)
    {
        return numCents >= totalCents(m2);
    }

    public boolean lessThan(Money m2)
    {
        return numCents < totalCents(m2);
    }

    public boolean lessThanOrEqualTo(Money m2)
    {
        return numCents <= totalCents(m2);
    }
}
```

An interesting feature of the class MoneyComparableAC is the protected static method named totalCents. For this method, we give its code with an embedded assertion.
Note that the model method, `inRange` is not implemented, and does not need to be implemented to make this class correctly implement the interface `MoneyComparable`.

### 2.3.6 USMoney

Finally, a concrete class implementation is given in the file `USMoney.java` shown below. The class `USMoney` implements the interface `MoneyOps`. Note that specifications as well as code are given for the constructors.

```java
package edu.iastate.cs.jml.docs.prelimdesign;

public /*@ pure @*/ class USMoney
    extends MoneyComparableAC implements MoneyOps
{
    public USMoney(long cs)
    /*@ public_normal_behavior */
        @ modifiable: pennies;
        @ ensures: pennies == cs;
        @ implies
            @ protected_normal_behavior
                @ modifiable: numCents;
                @ ensures: numCents == cs;
        @*/
        { numCents = cs;
        }

    public USMoney(double amt)
    /*@ public_normal_behavior */
        @ modifiable: pennies;
        @ ensures: pennies == (long)(100.0 * amt);
        @ ensures_redundantly: (* pennies holds amt dollars *);
        @*/
        { numCents = (long)(100.0 * amt);
        }

    public USMoney plus(Money m2)
        { //@ assume: m2 != null;
            return new USMoney(numCents + totalCents(m2));
        }

    public USMoney minus(Money m2)
        { //@ assume: m2 != null;
            return new USMoney(numCents - totalCents(m2));
        }
```
public USMoney scaleBy(double factor)
{
    return new USMoney(numCents * factor / 100.0);
}
}

The constructors each mention the fields that they initialize in their \texttt{modifiable} clause. This because the constructor's job is to initialize these fields. One can think of a \texttt{new} expression in Java as executing in two steps: allocating an object, and then calling the constructor. Thus the specification of a constructor needs to mention the fields that it can initialize in the \texttt{modifiable} clause.

The first constructor's specification also illustrates that redundancy can also be used in a \texttt{modifiable} clause. A redundant \texttt{modifiable} clause follows if the meaning of the set of locations named is a subset of the ones given in the non-redundant clause for the same specification case. In this example the redundant \texttt{modifiable} clause follows from the given \texttt{modifiable} clause and the meaning of the \texttt{depends} clause inherited from the superclass \texttt{MoneyAC}.

The second constructor above is noteworthy in that there is a redundant \texttt{ensures} clauses that uses an informal predicate \cite{Leavens96b}. In this instance, the informal predicate is used as a comment (which could also be used). Recall that informal predicates allow an escape from formality when one does not wish to give part of a specification in formal detail.

The \texttt{plus} and \texttt{minus} methods use \texttt{assume} statements; these are like assertions, but are intended to impose obligations on the callers \cite{Back-Mikhajlova-vonWright98}.

2.4 Use of Pure Classes

Since \texttt{USMoney} is a pure class, it can be used to make models of other classes. An example is the abstract class specified in the file `Account.jml` below. The first model field in this class has the type \texttt{USMoney}, which was specified above. (Further explanation follows the specification below.)

```java
package edu.iastate.cs.jml.docs.prelimdesign;

public class Account {

    public model USMoney credit;
    public model String owner;
```
public invariant: owner != null && credit != null
&& credit.greaterThanOrEqualTo(new USMoney(0));

public constraint: owner.equals(\old(owner));

public Account(MoneyOps amt, String own);
    public_normal_behavior
    requires: own != null && amt != null
    && (new USMoney(1)).lessThanEqualTo(amt);
    modifiable: credit, owner;
    ensures: credit.equals(amt) && owner.equals(own);

public pure MoneyOps balance();
    public_normal_behavior
    ensures: \result.equals(credit);

public void payInterest(double rate);
    public_normal_behavior
    requires: 0.0 <= rate && rate <= 1.0;
    modifiable: credit;
    ensures: credit.equals(\old(credit.scaleBy(1.0 + rate)));
    for_example
    public_normal_example
    requires: rate == 0.05 && (new USMoney(4000)).equals(credit);
    ensures: credit.equals(new USMoney(4200));

public void deposit(MoneyOps amt);
    public_normal_behavior
    requires: amt != null
    && amt.greaterThanOrEqualTo(new USMoney(0));
    modifiable: credit;
    ensures: credit.equals(\old(credit.plus(amt)));
    for_example
    public_normal_example
    requires: credit.equals(new USMoney(40000))
    && amt.equals(new USMoney(1));
    ensures: credit.equals(new USMoney(40001));

public void withdraw(MoneyOps amt);
    public_normal_behavior
    requires: amt != null && (new USMoney(0)).lessThanOrEqualTo(amt)
    && amt.lessThanOrEqualTo(credit);
    modifiable: credit;
    ensures: credit.equals(\old(credit.minus(amt)));
    for_example
    public_normal_example
    requires: credit.equals(new USMoney(40001))
    && amt.equals(new USMoney(40000));
    ensures: credit.equals(new USMoney(1));
The specification of Account makes good use of examples. It also demonstrates the various ways of protecting predicates used in the specification from undefinedness [Leavens-Wing97a]. The principal concern here, as is often the case when using reference types in a model, is to protect against the model fields being null. As in Java, fields and variables of reference types can be null. In the specification of Account, the invariant states that these fields should not be null. Since method implementations must preserve the invariants, one can think of the invariant as conjoined to the precondition and postcondition of each method, and the postcondition of each constructor. Hence, for example, method pre- and postconditions do not have to state that the fields are not null. However, often other parts of the specification must be written to allow the invariant to be preserved, or established by a constructor. For example, in the specification of Account’s constructor, this is done by requiring amt and own are not null, since, if they could be null, then the invariant could not be established.

2.5 Composition for Container Classes

The following specification lead to the specification of a class Digraph (directed graph). This gives a more interesting example of how more complex models can be composed in JML from other classes. In this example we use model classes, and the pure containers provided in the package edu.iastate.cs.jml.models.

2.5.1 NodeType

The file ‘NodeType.java’ contains the specification of an abstract class NodeType. NodeType is an abstract class, as opposed to a model class, because it will require an implementation and does appear in the interface of the model class Digraph. However, we also declare this abstract class as pure, since we will also use NodeType in the specification of other classes. (And we do so appropriately, since all the methods for class NodeType are side-effect-free.) In the abstract class specification for NodeType we simply provide a model field iD, which would represent a unique identifier for nodes.

```java
package edu.iastate.cs.jml.samples.Digraph;
import edu.iastate.cs.jml.models.*;
public /*@ pure @*/ abstract class NodeType implements JMLType {
  //@ public model int iD;
```
public abstract boolean equals(Object o);
    /**< public_normal_behavior */
    { [ 
        @ requires: o instanceof NodeType;
        @ ensures: \result == (iD == ((NodeType)o).iD);
        @ also 
        @ requires: !(o instanceof NodeType);
        @ ensures: \result == false;
    ]}
    /**< */
public abstract Object clone();
    /**< public_normal_behavior */
    @ ensures: \result instanceof NodeType
    @   && ((NodeType)\result).equals(this);
    /**< */
} // end of class NodeType

The use of also in the specification of NodeType’s equals method is interesting. It separates two cases of the normal behavior for that method. This is equivalent to using two public_normal_behavior clauses, one for each case. That is, when the argument is an instance of NodeType, the method must return true just when this and o have the same iD field. And when o is not an instance of NodeType, the equals method must return false. Compare this with the specification of the equals method for the class ArcType below (see Section 2.5.2 [ArcType], page 34).

2.5.2 ArcType

ArcType is specified as a pure model class in the file ‘ArcType.jml’ shown below. It is a model class because it does not appear in the interface to Digraph, and so does not need to be implemented. We declare ArcType to be a pure class so that its methods can be used in assertions. The two model fields for ArcType, from and to, are both of type NodeType. We specify the equals method so that two references to objects of type ArcType are equal if and only if they have equal values in the from and to model fields. Thus, equals is specified using NodeType.equals. We also specify that ArcType has a public clone method, fulfilling the obligations of a type that implements JMLType. ArcType must implement JMLType so that its objects can be placed in a JMLValueSet. We use such a set for one of the model fields of DiGraph.

    package edu.iastate.cs.jml.samples.Digraph;
    
    import edu.iastate.cs.jml.models.JMLType;
    
    public pure model class ArcType implements JMLType {
public model NodeType from;
public model NodeType to;
public invariant: from != null && to != null;

public ArcType(NodeType inFrom, NodeType inTo);
public_normal_behavior
    requires: inFrom != null && inTo != null;
    modifiable: from, to;
    ensures: from.equals(inFrom) && to.equals(inTo);

public model boolean equals(Object o);
public_normal_behavior
    requires: o instanceof ArcType;
    ensures: result <=> ((ArcType)o).from.iD == from.iD
        && ((ArcType)o).to.iD == to.iD;
also
    requires: !(o instanceof ArcType);
    ensures: result == false;

public Object clone();
public_normal_behavior
    ensures: result instanceof ArcType
        && ((ArcType)result).equals(this);
}

2.5.3 Digraph

Finally, the specification of the class Digraph is given in the file ‘Digraph.jml’ shown below. This specification demonstrates how to use container classes, like JMLValueSet, combined with appropriate invariants to specify models that are compositions of other classes. Both the model fields nodes and arcs are of type JMLValueSet. However, in the first invariant clause we restrict nodes so that every object in nodes is, in fact, of type NodeType. Similarly, the next invariant clause we restrict arcs to be a set of ArcType objects. In both cases, since the type is JMLValueSet, membership is determined by the equals method for the type of the elements (rather than reference equality).

package edu.iastate.cs.jml.samples.Digraph;
model import edu.iastate.cs.jml.models.*;
public class Digraph {

    public model JMLValueSet nodes;
    public model JMLValueSet arcs;
public invariant: nodes != null
  && (∀(JMLType n)
      nodes.has(n) => n instanceof NodeType);
public invariant: arcs != null
  && (∀(JMLType a)
      arcs.has(a) => a instanceof ArcType);
public invariant: (∀(ArcType a)
    arcs.has(a) =>
    nodes.has(a.from) && nodes.has(a.to));

public Digraph();
  public_normal_behavior
  modifiable: nodes, arcs;
  ensures: nodes.isEmpty() && arcs.isEmpty();

public void addNode(NodeType n);
  public_normal_behavior
  requires: n != null;
  modifiable: nodes;
  ensures: nodes.equals(\old(nodes.insert(n)));

public void removeNode(NodeType n);
  public_normal_behavior
  requires: unconnected(n);
  modifiable: nodes;
  ensures: nodes.equals(\old(nodes.remove(n)));

public void addArc(NodeType inFrom, NodeType inTo);
  public_normal_behavior
  requires: inFrom != null && inTo != null
            && nodes.has(inFrom) && nodes.has(inTo);
  modifiable: arcs;
  ensures: arcs.equals(\old(arcs.insert(new ArcType(inFrom, inTo))));

public pure boolean isNode(NodeType n);
  public_normal_behavior
  ensures: \result == nodes.has(n);

public pure boolean isArc(NodeType inFrom, NodeType inTo);
  public_normal_behavior
  ensures: \result == arcs.has(new ArcType(inFrom, inTo));
public pure boolean isAPath(NodeType start, NodeType end);
    public_normal_behavior
    requires: nodes.has(start) && nodes.has(end);
    ensures: \result == ReachSet(new JMLValueSet(start)).has(end);  

public pure model boolean unconnected(NodeType n);
    public_normal_behavior
    ensures: \result <=>
    !\exists (ArcType a) arcs.has(a)
    && (a.from.equals(n) || a.to.equals(n));

public pure model JMLValueSet ReachSet(JMLValueSet nodeSet);
    public_normal_behavior
    requires: nodeSet != null
    && (forall (Object o) nodeSet.has(o) =>
        o instanceof NodeType && nodes.has(o));
    measured_by: nodes.size() - nodeSet.size();
    {[ 
        requires: nodeSet.equals(OneMoreStep(nodeSet));
        ensures: \result != null && \result.equals(nodeSet);
        also 
        requires: !nodeSet.equals(OneMoreStep(nodeSet));
        ensures: \result != null
        && \result.equals(ReachSet(OneMoreStep(nodeSet)));
    ]}

public pure model JMLValueSet OneMoreStep(JMLValueSet nodeSet);
    public_normal_behavior
    requires: nodeSet != null
    && (forall (Object o) nodeSet.has(o) =>
        o instanceof NodeType && nodes.has(o));
    ensures: \result != null
    && \result.equals(nodeSet.union( 
        new JMLValueSet { NodeType n | nodes.has(n)
        && (\exists (ArcType a) a != null && arcs.has(a)
            && ( nodeSet.has(a.from) && n.equals(a.to)
                || nodeSet.has(a.to) && n.equals(a.from))))});

    // end of class Digraph

An interesting use of pure model methods appears at the end of the specification of Digraph in the pure model method ReachSet. This method constructively defines the set of all nodes that are reachable from the nodes in the argument nodeSet. This specification uses a nested case analysis, between \{[ and ]\}. The meaning of this is again that each pre- and postcondition pair has to be obeyed, but by using nesting, one can avoid duplication of the requires clause that is found at the beginning of the specification. The measured_by clause is needed because this specification is recursive; the measure given allows one to describe a termination argument, and thus ensure that the specification is well-defined. This clause defines an integer-valued measure that must always be at least zero; furthermore, the measure for a call and recursive uses in the specification must strictly
decrease [Ovre-etal95]. The recursion in the specification builds up the entire set of reachable nodes by, for each recursive reference, adding the nodes that can be reached directly (via a single arc) from the nodes in nodeSet.

### 2.6 Subtyping

Following Dhara and Leavens [Dhara-Leavens96] [Leavens97c], a subtype inherits the specifications of its supertype’s public and protected members (fields and methods), as well as invariants and history constraints. This ensures that a subclass specifies a behavioral subtype of its supertypes. This inheritance can be thought of textually, by copying the public and protected specifications of the methods of a class’s ancestors and all interfaces that a class implements into the class’s specification and combining the specifications using also. (This is the reason for the use of also at the beginning of specifications in overriding methods.) By the semantics of method combination using also, these behaviors must all be satisfied by the method, in addition to any explicitly specified behaviors.

For example, consider the class PlusAccount, specified in file ‘PlusAccount.jml’ shown below. It is specified as a subclass of Account. Thus it inherits the fields of Account, and Account’s invariants, and history constraints, and public method specifications. Because it inherits the fields of its superclass, inherited method specifications of behavior are still meaningful when copied to the subclass. The trick is to always add new model fields to the subclass and relate them to the existing ones.

Note that in the represents clause below, instead of a left-facing arrow, \( \leftarrow \), the connective “\textbackslash such\_that” is used to introduce a relationship predicate. This form of the represents clause allows one to specify abstraction relations, instead of abstraction functions.

```java
package edu.iastate.cs.jml.docs.prelimdesign;

public class PlusAccount extends Account {
    public model USMoney savings, checking;

    public depends: credit \rightarrow savings, checking;
    public represents: credit \ such\_that
        credit.equals(savings.plus(checking));

    public invariant: savings != null && checking != null;
    public invariant\_redundantly: savings.plus(checking)
        .greaterThanOrEqualTo(new USMoney(0));
```
public PlusAccount(MoneyOps sav, MoneyOps chk, String own);
public_normal_behavior
  requires: sav != null && chk != null && own != null &&
             (new USMoney(1)).lessThanOrEqualTo(sav)
             && (new USMoney(1)).lessThanOrEqualTo(chk);
modifiable: credit, owner;
modifiable_redundantly: savings, checking;
ensures: savings.equals(sav) && checking.equals(chk)
        && owner.equals(own);
ensures_redundantly: credit.equals(sav.plus(chk));

public void payInterest(double rate);
public_normal_behavior
  requires: 0.0 <= rate && rate <= 1.0;
modifiable: credit, savings, checking;
ensures: checking.equals(old(checking.scaleBy(1.0 + rate)));
for_example
public_normal_example
  requires: rate == 0.05 && checking.equals(new USMoney(2000));
ensures: checking.equals(new USMoney(2100));
public void withdraw(MoneyOps amt);
also

public_normal_behavior
  requires: amt != null
    && (new USMoney(0)).lessThanOrEqualTo(amt)
    && amt.lessThanOrEqualTo(savings);
modifiable: credit, savings;
ensures: savings.equals(old(savings.minus(amt)));
ensures_redundantly: not_modified(checking);
also

public_normal_behavior
  requires: amt != null
    && (new USMoney(0)).lessThanOrEqualTo(amt)
    && amt.lessThanOrEqualTo(credit)
    && amt.greaterThan(savings);
modifiable: credit, savings, checking;
ensures: savings.equals(new USMoney(0))
    && checking.equals(
      old(checking.minus(amt.minus(savings))));
for_example

public_normal_example
  requires: savings.equals(new USMoney(40001))
    && amt.equals(new USMoney(40000));
ensures: savings.equals(new USMoney(1));
also

public_normal_example
  requires: savings.equals(new USMoney(30001))
    && checking.equals(new USMoney(10000))
    && amt.equals(new USMoney(40000));
ensures: savings.equals(new USMoney(0))
    && checking.equals(new USMoney(1));

public void deposit(MoneyOps amt);
also

public_normal_behavior
  requires: amt != null
    && amt.greaterThanOrEqualTo(new USMoney(0));
modifiable: credit, savings;
ensures: savings.equals(old(savings.plus(amt)));
ensures_redundantly: not_modified(checking);
for_example

public_normal_example
  requires: savings.equals(new USMoney(20000))
    && amt.equals(new USMoney(1));
ensures: savings.equals(new USMoney(20001));
public void depositToChecking(MoneyOps amt);
public_normal_behavior
requires: amt != null
&& amt.greaterThanOrEqualTo(new USMoney(0));
modifiable: credit, checking;
ensures: checking.equals(\old(checking.plus(amt)))
&& \not_modified(savings);
for_example
public_normal_example
requires: checking.equals(new USMoney(20000))
&& amt.equals(new USMoney(1));
enforces: checking.equals(new USMoney(20001));

public void payCheck(MoneyOps amt);
public_normal_behavior
requires: amt != null;
{[
requires: (new USMoney(0)).lessThanOrEqualTo(amt)
&& amt.lessThanOrEqualTo(checking);
modifiable: credit, checking;
ensures: checking.equals(\old(checking.minus(amt))); also
requires: (new USMoney(0)).lessThanOrEqualTo(amt)
&& amt.lessThanOrEqualTo(credit)
&& amt.greaterThan(checking);
modifiable: credit, checking, savings;
enforces: checking.equals(new USMoney(0))
&& savings.equals(\old(savings.minus(amt.minus(checking)))));
]}
for_example
public_normal_example
requires: checking.equals(new USMoney(40001))
&& amt.equals(new USMoney(40000));
enforces: checking.equals(new USMoney(1)); also
public_normal_example
requires: savings.equals(new USMoney(30001))
&& checking.equals(new USMoney(10000))
&& atm.equals(new USMoney(40000));
enforces: checking.equals(new USMoney(0))
&& savings.equals(new USMoney(1));
]}


3 Extensions to Java Expressions

JML makes extensions to the Java expression syntax for two uses. The main set of extensions are used in predicates. But there are also some extensions used in store-ref's, which are themselves used in the modifiable, accessible, depends, represents clauses.

3.1 Extensions to Java Expressions for Predicates

The expressions that can be used as predicates in JML are an extension to the side-effect free Java expressions. Since predicates are required to be side-effect free, the following Java operators are not allowed within predicates:

- assignment (=), and the various assignment operators (such as +=, -=, etc.)
- all forms of increment and decrement operators (++ and --), and
- calls to methods that are not pure.

We allow the allocation of storage (e.g., using operator new and pure constructors) in predicates, because such storage can never be referred to after the evaluation of the predicate, and because such pure constructors have no side-effects other than initializing the new objects so created.

JML adds the following new syntax to the Java expression syntax, for use in predicates:

- Informal descriptions, which look like
  (* some text describing a Boolean-valued predicate *)
  and are treated as having type boolean.
- => for logical implication; for example, the formula raining => getsWet is true if either raining is false or getsWet is true. The notation <= is used for reverse implication, and the notation <=> for logical equivalence.
- \forall and \exists, which are universal and existential quantifiers (respectively); for example,
  \( \forall \forall (\text{int } i, j) \ 0 \leq i \land i < j \land j < 10 \implies a[i] < a[j] \)
  says that a is sorted at indexes between 0 and 9. The quantifiers range over all potential values of the variables declared. Thus, when the variables declared are reference types, they may be null, or may refer to objects not constructed by the program.

There are two main syntactic forms of quantifiers. See Section B.1.10 [Predicate and Specification Expression Syntax], page 57, for details.
Set comprehensions, which can be used to succinctly define sets; for example, the following is the JMLObjectSet that is the subset of non-null Integer objects found in the set myIntSet whose values are between 0 and 10, inclusive.

\[
\text{new JMLObjectSet \{Integer i | myIntSet.has(i) \\
&& i != null && 0 <= i.getInteger() \\
&& i.getInteger() <= 10 \}}
\]

The syntax of JML (see Section B.1.10 [Predicate and Specification Expression Syntax], page 57) limits set comprehensions so that following the vertical bar (‘|’) is always an invocation of the has method of some set on the variable declared. (This restriction is used to avoid Russell’s paradox [Whitehead-Russell25].) One may often start from the sets containing the objects of primitive types found in edu.iastate.cs.jml.models.JMLModelObjectSet and (in the same package) JMLModelValueSet.

- \texttt{\textbackslash{elementtype}}, which returns the most-specific static type shared by all elements of its array argument.

- \texttt{\textbackslash{fresh}}, which asserts that objects were freshly allocated; for example, \texttt{\textbackslash{fresh}(x,y)} asserts that the objects bound to \texttt{x} and \texttt{y} were not allocated in the pre-state.

- \texttt{\textbackslash{lblneg}} and \texttt{\textbackslash{lblpos}} can be used to attach labels to expressions; these labels might be printed in various messages by support tools, for example, to identify an assertion that failed. One would only write an expression such as

\[
(\texttt{\textbackslash{lblneg} indexInBounds 0 <= index \&\& index < length})
\]

which has value that is the same as \(0 \leq index \&\& index < length\). The idea is that if this expression is used in an assertion and its value is \texttt{false} (e.g., when doing run-time checking of assertions), then a warning will be printed that includes the label \texttt{indexInBounds}. The form using \texttt{\textbackslash{lblpos}} has a similar syntax, but should be used for warnings when the value of the enclosed expression is \texttt{true}.

- \texttt{\textbackslash{lockset}}, which is the set of locks held by the current thread. It is of type \texttt{JMLObjectSet}. (This is an adaptation from ESC/Java for dealing with threads.)

- \texttt{\textbackslash{not_modif\_\_modified}}, which asserts that the values of objects (and their dependents) are the same in the post-state as in the pre-state; for example, \texttt{\textbackslash{not_modif\_\_modified}(xval,yval)} says that \texttt{xval} and \texttt{yval} have the same value in the pre- and post-states (in the sense of an \texttt{equals} method).

- \texttt{\textbackslash{old}}, which can be used to refer to values in the pre-state; e.g., \texttt{\textbackslash{old}(myPoint.x)} is the value of the \texttt{x} field of the object \texttt{myPoint} in the pre-state.

- \texttt{\textbackslash{reach}}, which returns a \texttt{JMLObjectSet} of all objects reachable from a given object or set of objects. (The object or set of objects can be specified using the syntax of a \texttt{store-ref}. See Section B.1.5 [Store Ref Syntax], page 52, for details.)

- \texttt{\textbackslash{result}}, which, in an \texttt{ensures} clause is the value or object that is being returned by a method.

- \texttt{\textbackslash{nonnulle\_\_elements}}, which can be used to assert that the elements of an array are all non-null. For example, \texttt{\textbackslash{nonnulle\_\_elements}(myArray)}, is equivalent to
myArray != null &&
(\forall i (0 <= i && i < myArray.length)
  => myArray[i] != null)

- `\texttt{typeof}`, which returns the most-specific static type of an expression. An expression of the form `\texttt{typeof}(E)` has type `\texttt{\textsc{type}}`. For example, `\texttt{typeof(true == false)}` is the type `boolean`.
- The operator `\texttt{<:}` which compares two types and returns true when the type on the left is a subtype of the type on the right. Although the notation might suggest otherwise, this operator is also reflexive; a type will compare as `\texttt{<:}` with itself.
- `\texttt{\textsc{type}}`, which can be used to mark types in expressions. For example, in `\texttt{\textsc{typeof}(myObj) <: \textsc{typeof}(PlusAccount)}`
  the use of `\texttt{\textsc{type}(PlusAccount)}` is required to introduce the type `PlusAccount` into this expression context.
- `\texttt{\textsc{type}}`, is a type standing for the type of all types.

As in Java itself, most types are reference types, and hence many expressions yield references (i.e., object identities or addresses), as opposed to primitive values. This means that `==`, except when used to compare pure values of primitive types such as `\texttt{boolean}` or `\texttt{int}`, is reference equality. As in Java, to get value equality for reference types one uses the `\texttt{equals}` method in assertions. For example, the predicate `myString == yourString`, is only true if the objects denoted by `myString` and `yourString` are the same object (i.e., if the names are aliases); to compare their values one must write `myString.equals(yourString)`.

The reference semantics makes interpreting predicates that involve the use of `\texttt{\textsc{old}}` interesting. We want to have the semantics suited for two purposes:

- execution of assertions for purposes of debugging and testing, as in Eiffel, and
- generation of mathematical assertions for static analysis and possible theorem proving (e.g., to verify program correctness).

The key to the semantics of `\texttt{\textsc{old}}` is to treat it as an abbreviation for a local definition. That is, `E` in `\texttt{\textsc{old}}(E)` can be evaluated in the pre-state, and its value bound to a locally defined name, and then the name can be used in the postcondition.

Since we are using Java expressions for predicates, there are some additional problems in mathematical modeling. We are excluding the possibility of side-effects by limiting the syntax of predicates, and by using type checking [Gifford-Lucassen86] [Lucassen87] [Lucassen-Gifford88] [Nielson-Nielson-Amtoft97] [Talpin-Jouvelot94] [Wright92] to make sure that only pure methods and constructors may be called in predicates.
Exceptions in expressions are particularly important, since they may arise in type casts. Logically, we will deal with exceptions by having the evaluation of predicates substitute an arbitrary expressible value of the normal result type when an exception is thrown during evaluation. (When the expression's result type is a reference type, an implementation would have to return null if an exception is thrown while executing such a predicate.) This corresponds to a mathematical model in which partial functions are mathematically modeled by underspecified total functions.

We will check that errors (i.e., exceptions that inherit from Error) are not explicitly thrown by pure methods. This means that they can be ignored during mathematical modeling. When executing predicates, errors will cause run-time errors.

3.2 Extensions to Java Expressions for Store-Refs

The grammatical production store-ref (see Section B.1.5 [Store Ref Syntax], page 52) is used to name locations in the modifiable, depends, represents clauses. A similar production for object-ref is used in the accessible clause. A store-ref names a location, not an object; a location is either a field of an object, or an array element. Besides the Java syntax of names and field and array references, JML supports the following syntax for store-refs. See Section B.1.4 [Behavioral Specification Syntax for Types], page 51, for more details on the syntax.

- Array ranges, of the form A[E1 .. E2], denote the locations in the array A between the value of E1 and the value of E2 (inclusive). For example, the clause
  \[
  \text{modifiable myArray[3 .. 5]}
  \]
  can be thought of an abbreviation for the following,
  \[
  \text{modifiable myArray[3], myArray[4], myArray[5]}
  \]
- One can also name all the indexes in an array A by writing, A[*], which is shorthand for A[0 .. A.length-1].
- Several notations using \fields_of allow one to refer to the fields of a set of objects, or some particular object. The \fields_of syntax is overloaded to reduce the number of keywords. There are three cases, each of which has two alternatives depending on the static type of the first argument:
  - The syntax \fields_of(x) names all the fields of the object(s) referred to by x. If x has static type edu.iastate.cs.jml.models.JMLObjectSet, then this names all the fields in all the objects in the set x, otherwise it simply names all the fields of the object x.
  - The syntax \fields_of(x, T) names all the fields of x in objects of type T. If x has static type edu.iastate.cs.jml.models.JMLObjectSet, then this names all non-static fields of all instances of type T (or a subtype) in the set x, otherwise x must have static type T (or a subtype), this store-ref names all the fields of x found in type T.
Chapter 3: Extensions to Java Expressions

Note that if \( x \) is a JMLObjectSet, it may contain objects of different types; the presence of objects of other types does not matter. Only the instances of type \( T \) participate, and there need not be any instances of type \( T \) in the set.

- The syntax \( \text{fields\_of}(x, T, f) \) names the \( f \) fields of \( x \) in objects of type \( T \). The type \( T \) must have been declared with a (non-static) field \( f \). If \( x \) has static type \texttt{edu.iastate.cs.jml.models.JMLObjectSet}, then this names the \( f \) fields in all instances of type \( T \) in the set \( x \), otherwise \( x \) must have static type \( T \), this \textit{store-ref} is the same as writing \( x.f \).

More generally, in this syntax one can use instead of \( f \), a \textit{store-ref}. For example, in

\[ \text{fields\_of}(\text{myPointSet}, \text{ColorPoint}, \text{val}[3].\text{color}) \]

if \text{myPointSet} is a JMLObjectSet, then this refers to the locations \texttt{cp.val}[3].\texttt{color} for each object \texttt{cp} of type \texttt{ColorPoint} in \texttt{myPointSet}.

In addition, \texttt{\texttt{reach}} and \texttt{\texttt{result}} can be used as \textit{store-refs}, but their meaning is unchanged from above (see Section 3.1 [Extensions to Java Expressions for Predicates], page 42). They are included in the grammar for \textit{store-ref} to allow them to be arguments to \texttt{fields\_of}. In particular, \texttt{\texttt{reach}} is useful for constructing sets for use as the first argument to \texttt{fields\_of}. 

4 Conclusions

One area of future work for JML is concurrency. The main feature currently in JML that supports concurrency is the when clause [Lerner91] [Sivaprasad95]; it says that the caller will be delayed until the condition given holds. This permits the specification of when the caller is delayed to obtain a lock, for example. While syntax for this exists in the JML parser, our exploration of this topic is still in an early stage. JML also has several primitives from ESC/Java that deal with monitors and locks.

JML is an expressive behavioral interface specification language for Java. It combines the best features of the Eiffel and Larch approaches to specification. It allows one to write specifications that are quite precise and detailed, but also allows one to write lightweight specifications. It has examples and other forms of redundancy to allow for debugging specifications and for making rhetorical points. It supports behavioral subtyping by specification inheritance.

More information on JML, including software to aid in working with JML specifications, can be obtained from ‘http://www.cs.iastate.edu/~leavens/JML.html’.

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Appendix A  Specification Case Defaults

As noted above (see Section 1.2 [Lightweight Specifications], page 5), specifications in JML do not need to be as detailed as most of the examples given in this document. If a spec-case, conjoinable-spec, or example does not use one of the behavior keywords (public_behavior, public_normal_behavior, exceptional_behavior, etc.), then it is called a lightweight specification or example.

When the various clauses of a spec-case, conjoinable-spec, or example are omitted, they have the defaults given in the table below. The table distinguishes between lightweight and non-lightweight specifications and examples. In each case the default for the lightweight form is that no assumption is made about the omitted clause. However, in a non-lightweight specification or example, the specifier is assumed to be giving a complete specification or example. Therefore, in a non-lightweight specification the meaning of an omitted clause is given a definite default. For example, the meaning of an omitted modifiable clause is that nothing can be modified. Furthermore, in a non-lightweight specification, the meaning of an omitted diverges clause is that the method may not diverge in that case. (The diverges clause is almost always omitted; it can be used to say what should be true, of the pre-state, when the specification is allowed to loop forever or signal an error.)

<table>
<thead>
<tr>
<th>Omitted clause</th>
<th>lightweight</th>
<th>non-lightweight</th>
</tr>
</thead>
<tbody>
<tr>
<td>requires:</td>
<td>not_specified</td>
<td>true</td>
</tr>
<tr>
<td>when:</td>
<td>not_specified</td>
<td>true</td>
</tr>
<tr>
<td>measured_by:</td>
<td>not_specified</td>
<td>not_specified</td>
</tr>
<tr>
<td>modifiable:</td>
<td>not_specified</td>
<td>nothing</td>
</tr>
<tr>
<td>ensures:</td>
<td>not_specified</td>
<td>true</td>
</tr>
<tr>
<td>signals:</td>
<td>(Exception) not_specified</td>
<td>(Exception) true</td>
</tr>
<tr>
<td>diverges:</td>
<td>not_specified</td>
<td>false</td>
</tr>
</tbody>
</table>

A completely omitted specification is taken to be a lightweight specification. Thus one can read off the meaning of a completely omitted specification from the lightweight column of table.

It is intended that the meaning of not_specified may vary between different uses of a JML specification. For example, consider a requires clause that is not_specified; this should be treated the same as false for purposes of refinement, but as true for specification inheritance [Porat-Fertig95].
Appendix B  Syntax

We use an extended BNF grammar to describe the syntax of JML. The extensions are as follows [Ledgard80].

- Nonterminal symbols are written as follows: nonterminal. That is, nonterminal symbols appear in an italic font (in the printed form of this document).
- Terminal symbols are written as follows: terminal. In a few cases it is also necessary to quote terminal symbols, such as when using ‘[‘ as a terminal symbol instead of a meta-symbol.
- Square brackets ([ and ]) surround optional text. Note that ‘[‘ and ‘]’ are terminals.
- The notation ‘...’ means that the preceding nonterminal or group of optional text can be repeated zero (0) or more times.

For example, the following gives a production for the nonterminal name, which is a non-empty list of ident’s separated by periods (.).

\[
name ::= \text{ident } [ \text{ . \ ident } ] \ldots
\]

To remind the reader that the notation ‘...’ means zero or more repetitions, we use ‘...’ only following optional text.

We use “//” to start a comment (to you, the reader) in the grammar.

B.1  Context-Free Syntax

B.1.1  Compilation Unit Syntax

The following is the syntax of compilation units in JML. The compilation-unit rule is the start rule for the JML grammar.

\[
\text{compilation-unit ::= [ package-definition ]} \\
\quad \text{[ refine-prefix ]} \\
\quad \text{[ import-definition ]} \ldots \\
\quad \text{[ type-definition ]} \ldots
\]

\[
\text{package-definition ::= package name ;}
\]

\[
\text{refine-prefix ::= refine [ : ] ident-list } \leftarrow \text{ string-literal ;}
\]
import-definition ::= [ model ] import name-star ;
name ::= ident [ . ident ]...
nname-star ::= ident [ . ident ]... [ . * ]

B.1.2 Type Definition Syntax

The following is the syntax of type definitions.

type-definition ::= [ doc-comment ] modifiers class-or-interface-def
| ;
class-or-interface-def ::= class-definition | interface-definition
type-spec ::= type [ dims ] | \TYPE
type ::= reference-type | builtInType
reference-type ::= name
modifiers ::= [ modifier ]...
modifier ::= private | public | protected
| static | transient | final
| abstract | native | threadsafe
| synchronized | const | volatile
| model | pure | instance
| spec_public | spec_protected | ghost
| monitored | uninitialized
class-definition ::= class ident [ extends name [ weakly ] ]
| [ implements-clause ] class-block
interface-definition ::= interface ident [ interface-extends ] class-block
interface-extends ::= extends name-weakly-list
implements-clause ::= implements name-weakly-list
name-weakly-list ::= name [ weakly ] [ , name [ weakly ] ]...
class-block ::= { [ field ] ... }

B.1.3 Field Syntax

The following gives the syntax of fields.

field ::= [ doc-comment ] ... modifiers member-decl
| [ doc-comment ] ... modifiers jml-declaration
| [ static ] compound-statement
| static_initializer method-specification
| initializer method-specification
| axiom [ : ] predicate ;
| ;
member-decl ::= variable-decls ; | method-decl
| class-definition | interface-definition
variable-decls ::= type-spec variable-declarators [ jml-var-assertion ]
variable-declarators ::= variable-declarator [ , variable-declarator ] ...
variable-declarator ::= ident [ dims ] [ = initializer ]
initializer ::= expression | array-initializer
array-initializer ::= { [ initializer-list ] }
initializer-list ::= initializer [ , initializer ] ... [ , ]
method-decl ::= [ type-spec ] method-head method-body
method-head ::= ident [ [ param-declaration-list ] ]
               [ dims ] [ throws-clause ]
method-body ::= [ method-specification ] compound-statement
               | ; [ method-specification ]
throws-clause ::= throws name [ , name ] ...
param-declaration-list ::= param-declaration [ , param-declaration ] ...
param-declaration ::= [ final ] type-spec ident [ dims ]

B.1.4 Behavioral Specification Syntax for Types

The following gives the syntax of behavioral specifications for types.

jml-var-assertion ::= initially [ : ] predicate
                      | readable_if [ : ] predicate
                      | monitored_by [ : ] spec-expression-list
jml-declaration ::= invariant | history-constraint
                      | depends-decl | represents-decl
invariant ::= invariant-keyword [ : ] predicate ;
invariant-keyword ::= invariant | invariant_redundantly
history-constraint ::= constraint-keyword [ : ] predicate
                      [ for constrained-list ] ;
constraint-keyword ::= constraint | constraint_redundantly
constrained-list ::= method-name-list | \everything
method-name-list ::= method-name [ , method-name ] ...
method-name ::= method-ref [ ( [ param-disambig-list ] ) ]
method-ref ::= method-ref-start [ . ident ] ...
               | new reference-type
method-ref-start ::= super | this | ident | \other
param-disambig-list ::= param-disambig [ , param-disambig ] ...
param-disambig ::= type-spec [ ident [ dims ] ]
depends-decl ::= depends-keyword [ : ] store-ref -> store-ref-list ;
depends-keyword ::= depends | depends_redundantly
represents-decl ::= represents-keyword [ : ]
                   store-ref <= spec-expression ;
represents-keyword ::= represents | represents_redundantly
B.1.5 Store Ref Syntax

The syntax related to the store-ref production is used in several places.

\[
\begin{align*}
store-ref-list & ::= store-ref [ , store-ref ] 
\ldots \\
store-ref & ::= store-ref-expression \\
& \mid \text{fields_of} \ (store-ref [ , reference-type [ , store-ref-expression ] ] ) \\
& \mid \text{result} \\
& \mid \text{reach} \ (store-ref) \\
& \mid \text{informal-description} \\
& \mid \text{store-ref-keyword} \\
store-ref-expression & ::= store-ref-name [ store-ref-name-suffix ] \ldots \\
store-ref-name & ::= \text{ident} \mid \text{super} \mid \text{this} \\
store-ref-name-suffix & ::= . \text{ident} \mid \text{'[ spec-array-ref-expr ']'} \\
spec-array-ref-expr & ::= \text{spec-expression} \\
& \mid \text{spec-expression} \ldots \text{spec-expression} \\
& \mid * \\
store-ref-keyword & ::= \text{nothing} \mid \text{everything} \mid \text{not_specified}
\end{align*}
\]

B.1.6 Behavioral Specification Syntax for Methods

The following gives the syntax of behavioral specifications for methods. We start with the top-level syntax that organizes these specifications.

\[
\begin{align*}
\text{method-specification} & ::= \text{specification} \mid \text{extending-specification} \\
\text{specification} & ::= \text{spec-case-seq} \\
& \mid \text{subclasc-ing-contract} \\
& \mid \text{redundant-spec} \\
\text{spec-case-seq} & ::= \text{spec-case} [ \text{also spec-case} ] \ldots \\
\text{spec-case} & ::= \text{generic-spec-case} \mid \text{behavior-spec} \mid \text{model-program} \\
\text{extending-specification} & ::= \text{also specification} \\
& \mid \text{and conjoinable-spec-seq} \\
& \mid \text{subclasc-ing-contract} \\
& \mid \text{redundant-spec} \\
\text{conjoinable-spec-seq} & ::= \text{conjoinable-spec} [ \text{and conjoinable-spec} ] \ldots \\
\text{conjoinable-spec} & ::= \text{generic-conjoinable-spec} \mid \text{behavior-conjoinable-spec} \\
\text{generic-conjoinable-spec} & ::= \text{[ model-var-decls ] simple-spec-body}
\end{align*}
\]
behavior-conjoinable-spec ::= behavior-kw
  | [ model-var-decls ]
  | simple-spec-body
  | [ model-var-decls ]
  | exceptional-behavior-kw
  | [ model-var-decls ]
  | exceptional-simple-spec-body
  | normal-behavior-kw
  | [ model-var-decls ]
  | normal-simple-spec-body
  | [ signals-clause ]...
  | [ diverges-clause ]...
  | [ signals-clause ] [ signals-clause ]...
  | [ diverges-clause ]...
  | [ signals-clause ] [ signals-clause ]...
  | [ diverges-clause ]...

exceptional-simple-spec-body ::= modifiable-clause [ modifiable-clause ]...
  | [ signals-clause ]...
  | [ diverges-clause ]...
  | [ signals-clause ] [ signals-clause ]...
  | [ diverges-clause ]...

normal-simple-spec-body ::= modifiable-clause [ modifiable-clause ]...
  | [ signals-clause ]...
  | [ diverges-clause ]...

normal-behavior-kw ::= [ model-var-decls ]

normal-simple-spec-body ::= [ signals-clause ]...
  | [ diverges-clause ]...

redundant-spec ::= implications [ examples ] | examples

implications ::= implies-that spec-case-seq

examples ::= for_example example [ also example ]...

The following is the syntax of generic specification cases. These are the least verbose and most general specification cases.

generic-spec-case ::= [ model-var-decls ] spec-header [ generic-spec-body ]
  | [ model-var-decls ] generic-spec-body

spec-header ::= requires-clause [ requires-clause ]...
  | [ when-clause ]...
  | [ measured-clause ]...
  | [ when-clause ] [ when-clause ]...
  | [ measured-clause ] [ measured-clause ]...

generic-spec-body ::= simple-spec-body

{ [ generic-spec-case-seq ] }

generic-spec-body-seq ::= generic-spec-case [ also generic-spec-case ]...

simple-spec-body ::= modifiable-clause [ modifiable-clause ]...

[ ensures-clause ]...
[ signals-clause ]...
[ diverges-clause ]...

[ ensures-clause ] [ ensures-clause ]...
[ signals-clause ]...
[ diverges-clause ]...
[ signals-clause ] [ signals-clause ]...
[ diverges-clause ]...
[ diverges-clause ] [ diverges-clause ]...
The following gives the syntax of specification cases that start with one of the `behavior` keywords.

```
behavior-spec ::= behavior-kw generic-spec-case
   | exceptional-behavior-kw exceptional-spec-case
   | normal-behavior-kw normal-spec-case
behavior-kw ::= public_behavior | protected_behavior
   | private_behavior | behavior
exceptional-behavior-kw ::= public_exceptional_behavior
   | protected_exceptional_behavior
   | private_exceptional_behavior
   | exceptional_behavior
normal-behavior-kw ::= public_normal_behavior
   | protected_normal_behavior
   | private_normal_behavior
   | normal_behavior
exceptional-spec-case ::= [ model-var-decls ] spec-header
   [ exceptional-spec-body ]
   | [ model-var-decls ] exceptional-spec-body
exceptional-spec-body ::= modifiable-clause [ modifiable-clause ]...
   [ signals-clause ]...
   [ diverges-clause ]...
   [ signals-clause [ signals-clause ]... ]
   [ diverges-clause ]...
   { [ exceptional-spec-case-seq ] }
exceptional-spec-case-seq ::= exceptional-spec-case
   [ also exceptional-spec-case ]...
normal-spec-case ::= [ model-var-decls ] spec-header
   [ normal-spec-body ]
   | [ model-var-decls ] normal-spec-body
normal-spec-body ::= modifiable-clause [ modifiable-clause ]...
   [ ensures-clause ]...
   [ diverges-clause ]...
   [ ensures-clause [ ensures-clause ]... ]
   [ diverges-clause ]...
   { [ normal-spec-case-seq ] }
normal-spec-case-seq ::= normal-spec-case [ also normal-spec-case ]...
```

The following gives the syntax of subclassing contracts.

```
subclasseing-contract ::= subclassing_contract
   accessible-clause [ accessible-clause ]...
   [ callable-clause ]...
   subclassing_contract
   callable-clause [ callable-clause ]...
accessible-clause ::= accessible-keyword [ : ] object-ref-list ;
object-ref-list ::= object-ref [ , object-ref ]...
   store-ref-keyword
```
Appendix B: Syntax

object-ref ::= store-ref-expression
   | \other [ store-ref-name-suffix ] ... 
accessible-keyword ::= accessible | accessible_redundantly 
callable-clause ::= callable-keyword [ : ] callable-methods-list ;
callable-keyword ::= callable | callable_redundantly 
callable-methods-list ::= method-name-list | store-ref-keyword

B.1.7 Model Program Syntax

The following gives the syntax of model programs, adapted from the refinement calculus [Back88] [Back-vonWright89a] [Morgan94] [Morris87].

model-program ::= model-program-kw jml-compound-statement
model-program-kw ::= public_model_program 
   | protected_model_program 
   | private_model_program 
   | model_program 
jml-compound-statement ::= { [ jml-or-java-statement ] ... }
jml-or-java-statement ::= jml-statement | statement 
jml-statement ::= nondeterministic-choice | nondeterministic-if 
   | behavior-spec | invariant 
nondeterministic-choice ::= choose alternative-statements 
alternative-statements ::= jml-compound-statement 
   | or jml-compound-statement ] ... 
nondeterministic-if ::= choose_if guarded-statements 
   | else jml-compound-statement ] 
guarded-statements ::= guarded-statement 
   | or guarded-statement ] ... 
guarded-statement ::= { 
   | assume-statement 
   | jml-or-java-statement [ jml-or-java-statement ] ... 
   }

B.1.8 Example Syntax

The following gives the syntax of examples.
example ::= [ example-kw ]
    [ model-var-decls ] [ spec-header ] simple-spec-body
    | exceptional-example-kw
    [ model-var-decls ] [ spec-header ] [ exceptional-example-body ]
    | exceptional-example-kw
    [ model-var-decls ] [ exceptionall-examle-body ]
    | normal-example-kw
    [ model-var-decls ] [ spec-header ] [ normal-example-body ]
    | normal-example-kw
    [ model-var-decls ] [ normal-example-body ]

example-kw ::= public_example | protected_example
    | private_example | example

exceptional-example-kw ::= public_exceptional_example
    | protected_exceptional_example
    | private_exceptional_example
    | exceptional_example

normal-example-kw ::= public_normal_example
    | protected_normal_example
    | private_normal_example
    | normal_example

exceptional-example-body ::= modifiable-clause [ modifiable-clause ] ...
    [ signals-clause ] ...
    | diverges-clause ] ...
    | signals-clause [ signals-clause ] ...
    [ diverges-clause ] ...

normal-example-body ::= modifiable-clause [ modifiable-clause ] ...
    [ ensures-clause ] ...
    | diverges-clause ] ...
    | ensures-clause [ ensures-clause ] ...
    [ diverges-clause ] ...

B.1.9 Method Specification Clause Syntax

The following gives the syntax of clauses that occur in method specifications.

model-var-decls ::= let model-var-decl [ model-var-decl ] ...
model-var-decl ::= model type-spec spec-variable-declarators ;
requires-clause ::= requires-keyword [ : ] pred-or-not ;
requires-keyword ::= requires | requires_redundantly
pred-or-not ::= predicate | \not_specified
when-clause ::= when-keyword [ : ] pred-or-not ;
when-keyword ::= when | when_redundantly
measured-clause ::= measured-by-keyword [ : ] not_specified ;
    | measured-by-keyword [ : ] spec-expression if predicate ] ;
measured-by-keyword ::= measured_by | measured_by_redundantly
modifiable-clause ::= modifiable-keyword [ : ] conditional-store-ref-list ;
modifiable-keyword ::= modifiable | modifiable_redundantly
Appendix B: Syntax

conditional-store-ref-list ::= conditional-store-ref
    [ , conditional-store-ref ] ...
conditional-store-ref ::= store-ref [ if predicate ]
ensures-clause ::= ensures-keyword [ : ] pred-or-not ;
ensures-keyword ::= ensures | ensures_redundantly
signals-clause ::= signals-keyword [ : ]
    ( reference-type [ ident ] ) [ pred-or-not ] ;
signals-keyword ::= signals | signals_redundantly
    | ensures | ensures_redundantly
diverges-clause ::= diverges-keyword [ : ] pred-or-not ;
diverges-keyword ::= diverges | diverges_redundantly

B.1.10 Predicate and Specification Expression Syntax

The precedence of operators in JML is similar to that in Java. The precedence levels are given in the following table.

```
  highest new () forall \exists informal-description
             [ ] , and method calls
   unary  + and - " " ! (typecast) instanceof
   * / %
   + (binary) - (binary)
  << >> >>>
   < <= > >= :
   == | !=
   &
  \~
   |
   &&
   | |
   ==> <==
   <<=>
```

lowest ?:

The following gives the syntax of predicates and specification expressions.

```
predicate ::= spec-expression
spec-expression-list ::= spec-expression [ , spec-expression ] ...
spec-expression ::= spec-conditionalexpr
spec-conditionalexpr ::= spec-equivalence-expr
    [ ? spec-conditionalexpr : spec-conditionalexpr ]
spec-equivalence-expr ::= spec-implies-expr [ <==> spec-implies-expr ] ...
spec-implies-expr ::= spec-logical-or-expr
    [ ==> spec-implies-non-backward-expr ]
spec-logical-or-expr ::= spec-logical-or-expr <= spec-logical-or-expr
    [ <= spec-logical-or-expr ] ...
```
spec-implies-non-backward-expr ::= spec-logical-or-expr
    [ ==⇒ spec-implies-non-backward-expr ]
spec-logical-or-expr ::= spec-logical-and-expr [ '||' spec-logical-and-expr ] ... 
spec-logical-and-expr ::= spec-inclusive-or-expr [ '&&' spec-inclusive-or-expr ] ... 
spec-inclusive-or-expr ::= spec-exclusive-or-expr [ '!' spec-exclusive-or-expr ] ... 
spec-exclusive-or-expr ::= spec-and-expr [ '~' spec-and-expr ] ... 
spec-and-expr ::= spec-equality-expr [ '&' spec-equality-expr ] ... 
    | spec-relational-expr [ '==' spec-relational-expr ] ... 
spec-relational-expr ::= spec-shift-expr < spec-shift-expr 
    | spec-shift-expr > spec-shift-expr 
    | spec-shift-expr <= spec-shift-expr 
    | spec-shift-expr >= spec-shift-expr 
    | spec-shift-expr <: spec-shift-expr 
spec-shift-expr ::= spec-additive-expr [ shift-op spec-additive-expr ] ... 
shift-op ::= <<= | >> | >>>
spec-additive-expr ::= spec-mult-expr [ additive-op spec-mult-expr ] ... 
additive-op ::= + | - 
spec-mult-expr ::= spec-CAST-expr [ multi-op spec-CAST-expr ] ... 
multi-op ::= * | / | %
spec-CAST-expr ::= ( type-spec ) spec-CAST-expr 
    | + spec-CAST-expr 
    | - spec-CAST-expr 
    | ^ spec-CAST-expr 
    | ! spec-CAST-expr 
    | spec-PSTFX-expr [ instanceof type-spec ]
spec-PSTFX-expr ::= spec-PRIMARY-expr [ spec-PSTFX-suffix ] ... 
spec-PRIMARY-suffix ::= . ident 
    | . this 
    | . class 
    | '[' spec-expression ']' 
    | ( [ spec-expression-list ] )
spec-PRIMARY-expr ::= ident 
    | builtInType . class 
    | spec-new-expr | constant 
    | super | this 
    | true | false | null 
    | jml-primay 
    | ( spec-expression )
jml-primary ::= \result
| \old ( spec-expression )
| \not_modified ( store-ref-list )
| \fresh ( store-ref-list )
| \reach ( store-ref )
| informal-description
| \nonnull-elements ( spec-expression )
| \typeof ( spec-expression )
| \elemtype ( spec-expression )
| \type ( type )
| \lockset
| ( \lblneg ident spec-expression )
| ( \lbldcs ident spec-expression )
| spec-quantified-exp

spec-new-exp ::= \new type spec-new-suffix
spec-new-suffix ::= ( [ spec-expression-list ] ) [ spec-init-block ]
| spec-array-decl [ spec-array-initializer ]
| set-comprehension

set-comprehension ::= \{ type-spec quantified-var-declarator
| \{ \set-comprehension-pred \}

set-comprehension-pred ::= spec-primary-expr [ . ident ] .... has ( ident )
| \&\& predicate

spec-quantified-exp ::= ( quantifier ( quantified-vars ) predicate )
| ( quantifier quantified-var-decl [ ; ] predicate )

quantifier ::= \forall | \exists
quantified-vars ::= quantified-var-decl [ ; quantified-var-decl ] ...
quantified-var-decl ::= type-spec quantified-var-declarator
| , quantified-var-declarator ...
quantified-var-declarator ::= ident [ dims ]

spec-array-decl ::= spec-dim-exprs [ dims ] | dims
spec-dim-exprs ::= \{ [ spec-expression \}', [ spec-expression \}' ] \} ...
dims ::= \{ [ spec-expression \}' | spec-array-field-or-semi \}' \} ...
spec-init-block ::= { [ spec-init-field-or-semi ] ... }
spec-init-field-or-semi ::= spec-initfield | ;
spec-initfield ::= modifiers type-spec spec-variable-declarators
| jml-var-assertion ];
spec-variable-declarators ::= spec-variable-declarator
| , spec-variable-declarator ...
spec-variable-declarator ::= ident [ dims ] [ = spec-initializer ]
spec-array-initializer ::= { [ spec-initializer
| , spec-initializer ] ... [ , ] ]
spec-initializer ::= spec-expression
| spec-array-initializer
Appendix B: Syntax

B.1.11 Statement and Annotation Statement Syntax

The following gives the syntax of statements that are standard in Java.

```
compound-statement ::= { statement [ statement ] ... }
statement ::= compound-statement
  | local-declaration ;
  | ident : statement
  | expression ;
  | if ( expression ) statement [ else statement ]
  | [ loop-invariant ] ... [ variant-function ] ... loop-stmt
  | break [ ident ] ;
  | continue [ ident ] ;
  | return [ expression ] ;
  | switch-statement
  | try-block
  | throw expression ;
  | synchronized ( expression ) statement |
  | because-statement
  | assert-statement
  | assume-statement
  | set-statement
loop-stmt ::= while ( expression ) statement
  | do statement while ( expression ) ;
  | for ( [ for-init ] ; [ expression ] ; [ expression-list ] )
for-init ::= local-declaration | expression-list
local-declaration ::= local-modifiers variable-decls
local-modifiers ::= [ local-modifier ] ...
local-modifier ::= model | final
switch-statement ::= switch ( expression ) { [ switch-body ] ... }
switch-body ::= switch-label-seq [ statement ] ...
switch-label-seq ::= switch-label [ switch-label ] ...
switch-label ::= case expression : | default :
try-block ::= try compound-statement [ handler ] ...
  | finally compound-statement ]
handler ::= catch ( param-declaration ) compound-statement
```

The following gives the syntax of JML annotations that can be used on statements. See Section B.1.7 [Model Program Syntax], page 55, for the syntax of statements that can only be used in model programs.

```
because-statement ::= because-keyword [ : ] predicate ;
because-keyword ::= because | because_redundantly
assert-statement ::= assert-keyword [ : ] predicate ;
assert-keyword ::= assert | assert_redundantly
```
assume-statement ::= assume-keyword [ : ] predicate ;
assume-keyword ::= assume | assume_redundantly
set-statement ::= set [ : ] assignment-exp ;
loop-invariant ::= maintaining-keyword [ : ] predicate ;
maintaining-keyword ::= maintaining | maintaining_redundantly

loop-invariant | loop_invariant_redundantly
variant-function ::= decreasing-keyword [ : ] spec-expression ;
decreasing-keyword ::= decreasing | decreasing_redundantly

decreasing | decreasing_redundantly

B.1.12 Java Expression Syntax

The following is the syntax of Java expressions.

expression ::= assignment-exp
expression-list ::= expression [ , expression ] ...
assignment-exp ::= conditional-exp [ assignment-opt assignment-exp ]
assignment-op ::= = | += | -= | *= | /= | %= | >>=

| >>>= | <<= | &= | = | ^= =
conditional-exp ::= logical-or-exp
logical-or-exp ::= logical-and-exp [ `||` logical-and-exp ] ...
logical-and-exp ::= inclusive-or-exp [ `&&` inclusive-or-exp ] ...
inclusive-or-exp ::= exclusive-or-exp [ `|` exclusive-or-exp ] ...
exclusive-or-exp ::= and-exp [ `^` and-exp ] ...
and-exp ::= equality-exp [ `&` equality-exp ] ...
equality-exp ::= relational-exp [ `==` relational-exp ] ...

| relational-exp [ `!=` relational-exp ] ...
relational-exp ::= shift-exp < shift-exp

| shift-exp > shift-exp
| shift-exp <= shift-exp
| shift-exp >= shift-exp
shift-exp ::= additive-exp [ shift-op additive-exp ] ...
shift-op ::= << | >> | >>>
additive-exp ::= mult-exp [ additive-op mult-exp ] ...
additive-op ::= + | -
mult-exp ::= cast-exp [ mult-op cast-exp ] ...
mult-op ::= * | / | %
cast-exp ::= ( type-spec ) cast-exp

| ++ cast-exp
| -- cast-exp
| + cast-exp
| - cast-exp
| = cast-exp
| ! cast-exp
| postfix-exp [ instanceof type-spec ]
postfix-exp ::= primary-exp [ primary-suffix ] ...
Appendix B: Syntax

B.2 Microsyntax or Lexical Grammar

Throughout the figures for the lexical grammar below, grammatical productions are to be understood lexically; that is, this grammar concerns individual characters, not tokens. Another way of thinking of this is that no white-space may intervene between the characters of a token.

The microsyntax of JML is described by the production microsyntax in the grammar below. It describes what a program looks like from the point of view of a lexical analyzer [Watt91].

The nonterminal java-literal represents Java literals which are taken without change from Java [Gosling-Joy-Steele96].

```
primary-suffix ::= . ident
| . this
| . class
| [' expression ']'
| ( [ expression-list ] )
| ++
| --

primary-expr ::= ident | builtInType . class | new-expr
| constant | super | true
| false | this | null
| ( expression )
| informal-description

builtInType ::= void | boolean | byte
| char | short | int
| long | float | double

constant ::= java-literal

new-expr ::= new type new-suffix

new-suffix ::= ( [ expression-list ] ) [ class-block ]
| array-decl [ array-initializer ]

array-decl ::= dim-exprs [ dims ]

dim-exprs ::= [' expression '][' expression '] ...

dims ::= [' '] [' '] ...

array-initializer ::= { [ initializer , initializer ] ... [ , ] }

initializer ::= expression
| array-initializer

microsyntax ::= lexeme [ lexeme ] ...
lexeme ::= white-space | comment | annotation-marker | doc-comment | token

metadata ::= ident | keyword | special-symbol | java-literal
| informal-description
```
B.2.1 White Space

Blanks, horizontal and vertical tabs, carriage returns, formfeeds, and newlines, collectively called \textit{white space}, are ignored except as they serve to separate tokens. Newlines are special in that they cannot appear in some contexts where other whitespace can appear, and are also used to end C++-style (//) comments. This is described formally below.

\[
\begin{align*}
\text{white-space} & ::= \text{non-\textit{nl}-white-space} \mid \text{end-of-line} \\
\text{non-\textit{nl}-white-space} & ::= \text{a blank, tab, or formfeed character} \\
\text{end-of-line} & ::= \text{newline} \mid \text{carriage-return} \mid \text{carriage-return newline} \\
\text{newline} & ::= \text{a newline character} \\
\text{carriage-return} & ::= \text{a carriage return character}
\end{align*}
\]

B.2.2 Comments

Both kinds of Java comments are allowed in JML: old C-style comments and new C++-style comments. However, if what looks like a comment starts with the at-sign (@) character, then it is considered to be the start of an annotation by JML, and not a comment. Furthermore, if what looks like a comment starts with an asterisk (*), then it is a documentation comment, which is parsed by JML.

\[
\begin{align*}
\text{comment} & ::= \text{C-style-comment} \mid \text{C++-style-comment} \\
\text{C-style-comment} & ::= /[* \text{C-style-body} ] \text{C-style-end} \\
\text{C-style-body} & ::= \text{non-at-star} [\text{non-star-slash} ] \ldots \\
& \quad | \text{stars-non-slash} [\text{non-star-slash} ] \ldots \\
\text{non-star-slash} & ::= \text{non-star} \\
& \quad | \text{stars-non-slash} \\
\text{stars-non-slash} & ::= * [ \ast ] \ldots \text{non-slash} \\
\text{non-at-star} & ::= \text{any character except } \text{@} \text{ or } \ast \\
\text{non-star} & ::= \text{any character except } \ast \\
\text{non-slash} & ::= \text{any character except } / \\
\text{C-style-end} & ::= [ \ast ] \ldots */ \\
\text{C++-style-comment} & ::= // \text{end-of-line} \\
& \quad | // \text{non-at-newline} [ \text{non-newline} ] \ldots \text{newline} \\
\text{non-newline} & ::= \text{any character except a newline or carriage return} \\
\text{non-at-newline} & ::= \text{any character except } \text{@} \text{ or newline or carriage return}
\end{align*}
\]
B.2.3 Annotation Markers

If what looks to Java like a comment starts with an at-sign (@) as its first character, then it is not considered a comment by JML. We refer to the tokens between //@ and the following newline, and between pairs of /*@ and @*/ as annotations.

Annotations must hold entire grammatical units of JML specifications. For example the following is illegal, because the postcondition is split over two annotations, and thus each contains a fragment instead of a complete grammatical unit.

```plaintext
//@ ensures: 0 <= x  // illegal!
//@ x < a.length;
```

Annotations look like comments to Java, and are thus ignored by it, but they are significant to JML. One way that this can be achieved is by having JML drop (i.e., ignore) the character sequences that are annotation-markers: //®, /®®, and @®®. The at-sign in @®® is optional. However, JML may recognize jml-keywords only within annotations.

Within annotations, an at-sign (@) at the beginning of a line is also ignored.

The definition of an annotation marker is given below.

```plaintext
annotation-marker ::= //@ | /®® | @®® | */
ignored-at-in-annotation ::= @
```

B.2.4 Documentation Comments

If what looks like a C-style comment starts with an asterisk (*) then it is a documentation comment. The syntax is given below.

```plaintext
doc-comment ::= /** doc-comment-body */
```

At the level of the rest of the JML grammar, a documentation comment that does not contain an embedded JML method specification is essentially described by the above, and the fact that a doc-comment-body cannot contain the two-character sequence */.

However, JML and javadoc both pay attention to the syntax inside of these documentation comments. This syntax is really best described by a context-free syntax that builds on a lexical
syntax. However, because much of the documentation is free-form, the context-free syntax has a lexical flavor to it, and is quite line-oriented. Thus it should come as no surprise that the first non-whitespace, non-asterisk (i.e., not *) character on a line determines its interpretation. In particular, this means that the jml-pre and pre-jml tokens that start and end the jml-specs portion of a documentation comment are only recognized at the beginning of a line (following any leading * and whitespace).

\[
\begin{align*}
doc-comment-body & ::= [ \text{description} ] \ldots \\
& [ \text{tagged-paragraph} ] \ldots \\
& \text{jml-specs} \\
description & ::= \text{doc-non-empty-textline} \\
tagged-paragraph & ::= \text{paragraph-tag} [ \text{doc-non-nl-ws} ] \ldots \\
& [ \text{doc-at-sign} ] \ldots [ \text{description} ] \ldots \\
jml-specs & ::= \text{pre-jml method-specification jml-pre}
\end{align*}
\]

The microsyntax or lexical grammar used within documentation comments is as follows. Note that the token doc-nl-ws can only occur at the end of a line, and is always ignored within documentation comments. Ignoring doc-nl-ws means that any asterisk at the beginning of the next line, even in the part that would be a JML method-specification, is also ignored. Otherwise the lexical syntax within a method-specification is as in the rest of JML. This method specification is attached to the following method or constructor declaration. (Currently there is no useful way to use such specifications in the documentation comments for other declarations.) Note the exception to the grammar of doc-non-empty-textline.

\[
\begin{align*}
\text{paragraph-tag} & ::= \text{@author} \mid \text{@deprecated} \mid \text{@exception} \\
& \mid \text{@param} \mid \text{@return} \mid \text{@see} \mid \text{@serial} \\
& \mid \text{@serialdata} \mid \text{@serialfield} \mid \text{@since} \\
& \mid \text{@throws} \mid \text{@version} \\
\text{doc-at-sign} & ::= \text{@} \\
\text{doc-nl-ws} & ::= \text{end-of-line} [ \text{doc-non-nl-ws} ] \ldots [ * [ \text{doc-non-nl-ws} ] \ldots ] \\
\text{doc-non-nl-ws} & ::= \text{non-nl-white-space} \\
\text{doc-non-empty-textline} & ::= \text{non-at-newline} [ \text{non-end-of-line} ] \ldots \\
\text{however, the start of the line must not match pre-jml or jml-pre} \\
\text{pre-jml} & ::= \text{pre-tag} [ \text{doc-non-nl-ws} ] \ldots \text{jml-tag} \\
\text{jml-pre} & ::= \text{end-jml-tag} [ \text{doc-non-nl-ws} ] \ldots \text{end-pre-tag} \\
\text{pre-tag} & ::= \text{<pre>} \mid \text{<PRE>} \\
\text{end-pre-tag} & ::= \text{</pre>} \mid \text{</PRE>} \\
\text{jml-tag} & ::= \text{<jml>} \mid \text{<JML>} \mid \text{<esc>} \mid \text{<ESC>} \\
\text{end-jml-tag} & ::= \text{</jml>} \mid \text{</JML>} \mid \text{</esc>} \mid \text{</ESC>}
\end{align*}
\]
B.2.5 Tokens

Character strings that are Java reserved words are made into the token for that reserved word, instead of being made into an ident token. Within an annotation this also applies to jml-keywords. The details are given below.

\[
\begin{align*}
ident & := \text{letter} [ \text{letter-or-digit} ]... \\
\text{letter} & := _, $, a \text{ through } z, \text{ or } A \text{ through } Z \\
\text{digit} & := 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 \\
\text{letter-or-digit} & := \text{letter} | \text{digit}
\end{align*}
\]

Several strings of characters are recognized as keywords or reserved words in JML. These fall into three separate categories: Java keywords, JML predicate keywords (which start with a backslash), and JML keywords. Java keywords are truly reserved words, and are recognized in all contexts. The nonterminal java-keywords represents the reserved words in Java 1.1 and 1.2. JML keywords are only recognized as such if they occur outside of a spec-expression but within either an annotation or a file that is a JML file (with suffixes '.jml', '.jml-refined', or '.refines-jml'). JML predicate keywords are, as their name implies, used within spec-expressions; they are also used in store-ref-lists and constrained-lists. The details are given below.

\[
\begin{align*}
\text{keyword} & := \text{java-keyword} \mid \text{jml-predicate-keyword} \mid \text{jml-keyword} \\
\text{jml-predicate-keyword} & := \text{\textbackslash elemtype} \mid \text{\textbackslash everything} \\
& \mid \text{\textbackslash exists} \mid \text{\textbackslash fields_of} \mid \text{\textbackslash forall} \\
& \mid \text{\textbackslash fresh} \mid \text{\textbackslash lblneg} \mid \text{\textbackslash lb spos} \\
& \mid \text{\textbackslash lockset} \mid \text{\textbackslash nonnull_elements} \mid \text{\textbackslash nothing} \\
& \mid \text{\textbackslash not_modified} \mid \text{\textbackslash not_specified} \mid \text{\textbackslash old} \\
& \mid \text{\textbackslash other} \mid \text{\textbackslash reach} \mid \text{\textbackslash result} \\
& \mid \text{\textbackslash such_that} \mid \text{\textbackslash type} \mid \text{\textbackslash typeof} \\
& \mid \text{\textbackslash TYPE}
\end{align*}
\]
Appendix B: Syntax

The following describes the special symbols used in JML. The nonterminal \texttt{java-special-symbol} is the special symbols of Java, taken without change from Java [Gosling-Joy-Steele96].

\begin{verbatim}
special-symbol ::= java-special-symbol | jml-special-symbol
jml-special-symbol ::= \texttt{\textbackslash \textendash} | \texttt{\textendash\textendash} | \texttt{\textendash\textendash\textendash} | \texttt{\textendash\textendash\textendash\textendash} | \texttt{\textendash\textendash\textendash\textendash\textendash} | \texttt{\textendash\textendash\textendash\textendash\textendash\textendash}
\end{verbatim}

An \texttt{informal-description} looks like (\* some text *). It is used in predicates. The exact syntax is given below.

\begin{verbatim}
informal-description ::= (\* non-star-close [ non-star-close ] ... * )
\end{verbatim}

\begin{verbatim}
jml-keyword ::= accessible | accessible_redundantly | also
| and | assert_redundantly | assert
| assume_redundantly | assume | axiom
| because_redundantly | because | behavior
| callable_redundantly | callable | choose_if
| choose | constraint_redundantly | constraint
| decreases_redundantly | decreases | decreasing_redundantly
| decreasing | depends_redundantly | depends
| diverges_redundantly | diverges | ensures_redundantly
| ensures | example | exceptional_behavior
| exceptional_example | ensures_redundantly | ensures
| for_example | ghost | implies_that
| initializer | initially | instance
| invariant_redundantly | invariant | let
| loop_invariant_redundantly | loop_invariant
| maintaining_redundantly | maintaining
| measured_by_redundantly | measured_by
| model_program | model | modifiable_redundantly
| modifiable | monitored_by | monitored
| normal_behavior | normal_example | or
| private_behavior | private_example
| private_exceptional_behavior | private_exceptional_example
| private_model_program | private_normal_behavior
| private_normal_example | protected_behavior | protected_example
| protected_exceptional_behavior | protected_exceptional_example
| protected_model_program | protected_normal_behavior
| protected_normal_example | public_behavior
| public_example | public_exceptional_behavior
| public_exceptional_example | public_model_program
| public_normal_behavior | public_normal_example
| pure | readable_if | refine
| represents_redundantly | represents | requires_redundantly
| requires | set | signals_redundantly
| signals | spec_protected | spec_public
| static_initializer | subclassing_contract | uninitialized
| weakly | when_redundantly | when
\end{verbatim}
non-star-close ::= non-star
  | stars-non-close
stars-non-close ::= * [ * ] ... non-close
non-close ::= any character except )
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