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Desugaring JML Method Specifications

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Abstract
JML, which stands for “Java Modeling Language,” is a behavioral interface specification language (BISL) designed to specify Java modules. JML features a great deal of syntactic sugar that is designed to make method specifications more expressive. This paper presents a desugaring process that boils down all of the syntactic sugars in JML method specifications into a much simpler form. This desugaring will help one understand the meaning of these sugars, for example for use in program verification. It may also help manipulation of JML method specifications by tools.

1 Introduction

JML [16], which stands for “Java Modeling Language,” is a behavioral interface specification language (BISL) [30] designed to specify Java [1, 11] modules. JML features a great deal of syntactic sugar that is designed to make method specifications more expressive [15].

Syntactic sugars are additions to a language that make it easier for humans to use. Syntactic sugar gives the user an easier to use notation that can be easily desugared, i.e., translated, to produce a simpler “core” syntax. Desugaring is helpful for understanding the meaning of JML method specifications, which may also be helpful in tools [5]. One tool that uses part of this desugaring process is jmldoc [5, 26]. Jmldoc is a tool that makes browsable HTML pages from JML specifications. This tool ships with the JML release [1].

In this paper we focus mainly on method specifications, i.e., on specifications that describe methods. Indeed, we only treat a subset of JML’s method specification syntax, because we leave for future work a description of how the desugarings presented here interact with JML’s redundancy features and with its refinement calculus features (model programs). JML and its tools also inherit and allow refinement of other declarations in classes and interfaces, but those are combined in a straightforward way [9, 15, 16]. Essentially a union is used to combine inherited or refined declarations, and a union, which has the semantics of a conjunction, is used for clauses with predicates, such as invariants and history constraints. Hence inheritance and refinement of these other declarations is not discussed further in this document.

After some more background about JML method specifications, we describe their desugaring in detail.

2 JML Method Specifications

This section describes method specifications, first in general terms, and then by giving their syntax. We start with basic method specifications and then describe extending specifications. The extending
specifications are considered to be syntactic sugars for basic method specifications, and their semantics is ultimately given by desugaring them into basic method specifications.

2.1 Basic Method Specifications

In JML, a basic method specification, like those in other BISLs [30], is founded on the use of pre- and postconditions [12]. A precondition in JML is introduced by the keyword requires, and a postcondition is introduced by the keyword ensures. The predicates used in pre- and postconditions are written in an extension to a subset of Java’s expression syntax, which is restricted to be side-effect free [10]. One example of an extension is that JML allows logical implication to be written as the infix operator “===>”.

Another example is that the pre-state value of an expression, \( E \), may be written as “\( \text{old}(E) \)” within a postcondition; this notation is adapted from Eiffel [24].

JML method specifications, however, include much more than just pre- and postconditions. The example given in Figure 1 illustrates the most primitive form of a JML method specification. As shown in this figure, the JML’s syntax uses annotation markers (//**, @**, and //@, see the JML Reference Manual [18], Section 4.4) to delimit text that only the JML tools (but not standard Java tools) see. Annotations look like Java comments, and so are ignored by Java. JML reads the text between the annotation markers. Furthermore, JML ignores at-signs (@) at the beginning of a line within the body of an annotation. The annotation for a method precedes the method itself.

In Figure 1, the keyword public, which precedes behavior in the specification case, means that this is a specification case intended for clients. Using public implies that the specification case may not use names that have less than public visibility. The next keyword, “behavior” indicates that this is a “heavyweight” specification case, meaning that it is intended to be complete in the sense that omitted clauses have predefined defaults as opposed to being unknown (as in the “lightweight” form of a specification case, where a behavior keyword is omitted) [10]. However, in this example, no clauses are omitted.

Following the keyword “behavior” are several clauses, each of which starts with a JML-specific keyword (forall, old, requires, etc.) and ends with a semicolon. We explain each of these in turn. The JML Reference Manual [18], gives a more detailed explanation of each clause’s semantics.

The forall clause is used to declare universally quantified logical variables that can be used throughout the specification case. In the example of Figure 1, the specification must hold for all values of the int variable i. (Note that i is only used in the ensures clause in this example.)

The second clause in Figure 1 is an old variable declaration. This is used to abbreviate specification expressions (i.e., expressions with JML extensions that are free of side-effects [18]) that can be used throughout the rest of the specification. The values of such expressions are evaluated in the pre-state of the method’s execution, which is the rationale for using the keyword “old”. That is, the variables can be thought of as initialized to the values of the corresponding expressions just after parameter passing. Like the variables declared in the forall clause, the variables declared in the old clause are logical variables, and have a scope that extends for the rest of this specification case. In the example, old.size is initialized to the old value of the instance field size (declared at the bottom of the class in the figure). Note that the old clause is distinct from JML’s \( \text{old}() \) expression; the semantic connection is that \( \text{old}() \) expressions can be given a semantics using old declarations.

As mentioned above, the requires clause gives the method’s precondition. If the precondition is not true in the pre-state, none of the rest of the specification case needs to be satisfied by the implementation. In a heavyweight specification case, an omitted requires clause defaults to one with precondition true, and hence no requirements are placed on the caller.

The diverges clause describes pre-states for which a method may go into an infinite loop, or otherwise not return to its caller. Thus the predicate in a diverges clause is interpreted in the pre-state (since, if it is satisfied, there need not be a post-state). In a heavyweight specification case, such as that shown in Figure 1, the default for this clause is false, hence this clause is normally omitted from JML method specifications. If the predicate in the diverges clause is false, as in the example, and if the specification case’s precondition is true, then the method call must finish its execution within a finite time (unless the Java virtual machine encounters a runtime error such as stack overflow or running out of memory [16]). Thus if the specification has false as its diverges clause predicate, then it is a total
public class NonNegStack {

    @public behavior
    @forall int i;
    @old int old_size = size;
    @requires 0 <= size && size < MAX_SIZE;
    @diverges false;
    @assignable size, elems[*];
    @when true;
    @working_space 0 if elem >= 0;
    @duration 20 if elem >= 0;
    @ensures \old(elem >= 0)
    @\&\& \result == size && size == old_size + 1
    @\&\& ((0 <= i && i < old_size) ==> elems[i] == \old(elems[i]))
    @\&\& elems[size-1] == elem;
    @signals_only IllegalArgumentException;
    @signals (Exception e) \old(elem < 0)
    @\&\& \not_assigned(size, elems[*]);
    @*/
    public int push(int elem) {
        if (elem >= 0) {
            elems[size++] = elem;
            return size;
        } else {
            throw new IllegalArgumentException("negative");
        }
    }

    public static final int MAX_SIZE = 10;
    private /*@ spec_public */ int size = 0;
    private /*@ non_null spec_public */ int[] elems = new int[MAX_SIZE];
}

Figure 1: An example of the core features of JML method specification cases is given in the specification of the push method, which appears just above the code for push.
correctness specification case.

The assignable clause gives a frame axiom [4] for a specification case. The frame axiom lists the locations that the method may assign to. Given a specific pre-state, only locations that are mentioned or are (perhaps indirectly) in data groups that are mentioned [19, 22], may be assigned to by the method’s execution; all other locations may not be assigned to in such an execution of the method. (Note that this does not say that the method must assign to the locations that it is permitted to assign to, only that the method may assign to them.) If omitted in a heavyweight specification case, there is no restriction on what locations the method may assign to, so it is usually important to give the frame axiom for such specification cases.

The when clause can be used in the specification of concurrency [23, 27]. It says that, assuming that the precondition holds, the method execution only proceeds to completion at some time when the given condition holds; if the condition does not hold, then the method’s execution waits for a concurrent thread to make it true, and then proceeds. (There is no guarantee that the method will proceed the first time this condition holds, so the condition may have to hold many times before the thread may proceed.) If omitted in a heavyweight specification case, its predicate defaults to true.

The working space clause specifies the space that the method call may need to have available on the heap to successfully complete its work. It gives an expression, in bytes, for the maximum additional space needed by the method’s execution, when the condition, following the keyword if, holds in the pre-state [13]. Note that the expression may depend on post-state values (including \result), so this expression is conceptually evaluated in the post-state, although it may use \old to refer to pre-state values. In the example, the method is not allowed to use extra heap space when the argument is non-negative. If omitted, there is no restriction placed on the maximum space that a method may use from the heap during its execution.

The duration clause specifies the time that the method call may use to successfully complete its work. It gives an expression, in Java Virtual Machine (JVM) machine cycles, for the maximum time available for the method’s execution, when the condition, which follows the keyword if, holds in the pre-state [13]. As with the working space, the expression giving the duration may depend on post-state values (including \result), and so is conceptually evaluated in the post-state. In the example, the method is only allowed to use 20 JVM cycles when the argument is non-negative. If omitted, there is no restriction placed on the time that a method may use during its execution.

The ensures clause gives a normal postcondition for a method. The JML semantics is that, when the method returns normally, the relationship between the pre-state and the post-state of the method must satisfy this normal postcondition. In the normal postcondition for a method with a non-void return type, the notation \result denotes the result returned by the method. In a heavyweight behavior specification case, the normal postcondition defaults to true if the ensures clause is omitted. In the example in Figure [4] the postcondition says that when the method returns normally, it must be the case that elem was not negative, and each element of the elems array that was previously defined has the same value, and the new element added is elem, and the result is the post-state value of the stack’s size. Since the argument elem must be positive for the normal postcondition to be true, the method must not return normally when elem is negative.

The signals only clause says what types of exceptions may be thrown by a method. The listed exceptions must all be subtypes of java.lang.Exception. When the precondition of the specification case holds, the method may only throw instances of types that are not subtypes of Exception (typically subtypes of java.lang.Error) or exceptions that are subtypes of those listed in the signals only clause. In other words, throwing any exception other than those listed in the signals only clause is prohibited. In a heavyweight specification case, the default list for an omitted signals only clause is the list of exceptions declared in the method’s header, or \nothing if the method’s header does not declare any exceptions. In the example, the push method is only allowed to throw an IllegalArgumentException.

The signals clause is used to say what must be true when a method’s execution throws an exception; it gives an exceptional postcondition for the method. In the exceptional postcondition, the exception result (the object thrown in the exception) is denoted by the name in the parenthesized declaration following the keyword signals. In the example in Figure [4] the exception result is named e. In a heavyweight behavior specification case, the signals clause defaults to “signals (Exception e) true;” if the signals clause is omitted; this permits the method to throw any exception permitted
by the method’s signature and the \texttt{signals\_only} clause. In the example in Figure 1, the exceptional postcondition says that when the method throws an exception, it must be the case that \texttt{elem} was negative and that both \texttt{size} and the elements of \texttt{elems} were not assigned. This implies that the method method may not throw any exception at all when the argument is non-negative.

It is important to understand that a method call may only have one four possible outcomes in the JML semantics. It may:

- terminate normally, in which case the relation between the pre-state and the post-state must satisfy the normal postcondition given by the \texttt{ensures} clause,

- throw an exception of some subtype, \texttt{ET}, of \texttt{java.lang.Exception}, in which case the relation between the pre-state and the post-state must satisfy the exceptional postcondition in each \texttt{signals} clause that names a supertype of \texttt{ET} (including those that name \texttt{ET} itself),

- not return to the caller (e.g., by looping forever or by exiting the program), in which case the \texttt{diverges} clause must have held in the pre-state, or

- encounter a Java virtual machine error. (JML considers all exceptions that are instances of \texttt{java.lang.Throwable} but not instances of \texttt{java.lang.Exception} to indicate virtual machine errors. Usually a subtype of \texttt{java.lang.Error} is used for this purpose.)

In addition to these features of basic method specifications, JML has several forms of syntactic sugar that make specifications more expressive \[15, 16\]. The aim of this paper is to explain these sugars by boiling them down to the features already described in this subsection.

### 2.2 Extending Specifications

The most interesting and subtle kind of sugar in JML has to do with support for specification inheritance and behavioral subtyping \[9, 17, 15\]. In brief, a method specification can be extended or refined by other method specifications. In JML, each subtype inherits the public and protected specifications of its supertype’s visible non-private members \[9\]; this inheritance includes method specifications. Behavioral subtyping requires that the method specifications in a subtype obey the non-private method specifications from the supertypes that the method overrides \[11, Section 8.4.6\].

Besides parts of a specification split among different types in a subtyping hierarchy, JML’s refinement constructs allow one to split a specification for a single type across several files. For example, the specifications in \texttt{SinglyLinkedList.refines-jml} can refine the specifications in \texttt{SinglyLinkedList.java}. All of the method specifications in a refinement extend the corresponding method specifications in the file being refined, without privacy restrictions.

To make it clear to the reader whether a method specification is an extension (as opposed to a specification of a new method) JML uses the keyword “\texttt{also}”. Such an \texttt{extending-specification} must be used for the specification of an overriding or refining method, regardless of whether any of the methods being overridden or refined has a specification. (Furthermore, an extending specification cannot be used when the method does not override or refine an existing method.)

### 2.3 JML Grammar

Figures \[2\] give the parts of the JML grammar that are necessary for understanding the desugarings presented below. These sections of the grammar quote a subset of the grammar from appendix A.6 of the \textit{JML Reference Manual} \[18\]. The JML grammar is defined using an extended BNF. The following conventions are used in the grammar:

- Nonterminal symbols are written in \textit{italics}.
- Terminal symbols appear in \textit{teletype} font
- Symbols within square brackets ([ ]) are optional.
method-specification ::= non-extending-specification | extending-specification

non-extending-specification ::= spec-case-seq

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

spec-case ::= lightweight-spec-case | heavyweight-spec-case

extending-specification ::= also spec-case-seq

Figure 2: Top-level Method specification syntax of JML (ignoring subclassing contracts, redundant specifications, and model programs).

lightweight-spec-case ::= generic-spec-case

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

spec-header ::= requires-clause [ requires-clause ] ...  

generic-spec-body ::= simple-spec-body | '{' generic-spec-case-seq '}'

Figure 3: Lightweight specification case syntax, which includes generic-spec-case.

• An ellipses (…) indicates that the preceding nonterminal or group of optional text can be repeated zero or more times.

Figure 2 gives the top-level syntax of method specifications in JML. Figure 3 gives the syntax of lightweight specification cases. The lightweight specification case syntax is designed to be easy to use; however, lightweight specification cases are not assumed to be complete. The lightweight-spec-case syntax is also used as part of the most general form of the heavyweight specification case syntax, given in Figure 4. A heavyweight specification case begins with one of the behavior keywords (behavior, normal_behavior, or exceptional_behavior); heavyweight specification cases, are assumed to be complete. Finally, the syntax for spec-var-decls is given in Figure 5.

3 Desugaring

This section describes the overall desugaring process, at the most abstract level for a method specification.

In the following, let $V$ stand for a visibility level, one of public, private, protected, or empty.

1. Desugar the use of non_null for argument types (see Section 3.1).
2. Desugar the use of non_null on result types (see Section 3.2).
3. Desugar the use of pure (see Section 3.3).
4. Desugar specifications that are empty to the default specification (see Section 3.4).
5. Desugar the use of nested generic-spec-case-seq, normal-spec-case-seq, and exceptional-spec-case-seq in specifications from the inside out (see Section 3.5). This eliminates nesting.
6. Desugar lightweight specifications to $V$ behavior, where $V$ is the visibility level of the method or constructor being specified. Desugar spec-cases beginning with $V$ normal_behavior and $V$ exceptional_behavior to $V$ behavior (see Section 3.6). This leaves only spec-cases that begin with $V$ behavior, for some visibility level $V$.  


heavyweight-spec-case ::= [ privacy ] behavior generic-spec-case  
| [ privacy ] exceptional_behavior exceptional-spec-case  
| [ privacy ] normal_behavior normal-spec-case

exceptional-spec-case ::= [ spec-var-decls ] spec-header [ exceptional-spec-body ]  
| [ spec-var-decls ] exceptional-spec-body
privacy ::= public | protected | private
exceptional-spec-body ::= exceptional-spec-clause [ exceptional-spec-clause ] ...  
| '{' exceptional-spec-case-seq '{'}'
exceptional-spec-clause ::= diverges-clause | assignable-clause  
| when-clause | working-space-clause | duration-clause | signals-only-clause | signals-clause
exceptional-spec-case-seq ::= exceptional-spec-case [ also exceptional-spec-case ] ...

normal-spec-case ::= [ spec-var-decls ] spec-header [ normal-spec-body ]  
| [ spec-var-decls ] normal-spec-body
normal-spec-body ::= normal-spec-clause [ normal-spec-clause ] ...  
| '{' normal-spec-case-seq '{'}'
normal-spec-clause ::= diverges-clause | assignable-clause  
| when-clause | working-space-clause | duration-clause | ensures-clause
normal-spec-case-seq ::= normal-spec-case [ also normal-spec-case ] ...

Figure 4: Behavior specification syntax, used for “heavyweight” specification cases.

spec-var-decls ::= forall-var-decls [ old-var-decls ] | old-var-decls
forall-var-decls ::= forall-var-decl [ forall-var-decl ] ...  
forall-var-decl ::= forall quantified-var-decl ;
old-var-decls ::= old-var-decl [ old-var-decl ] ...  
old-var-decl ::= old type-spec spec-variable-declarators ;

Figure 5: Specification variable declarations syntax.
7. Combine each extending-specification (in a subclass or refinement) with the inherited or refined method-specifications into a single effective method-specification (see Section 3.7).

8. Desugar each signals clause so that it refers to an exception of type Exception with a standard name (see Section 3.8).

9. Desugar the use of multiple clauses of the same kind, such as multiple requires-clauses (see Section 3.9).

10. For each visibility level, make all the assignable-clauses be the same by adding only_assigns to postconditions as needed, and make all the signals-only-clauses be the same by adding conjuncts to the exceptional postconditions as needed (see Section 3.10).

11. Desugar the also combinations within the spec-cases. (see Section 3.11).

As a way of explaining the semantics of method specifications, one should imagine the above steps as being run one after another. However, tools may wish to use this semantics differently. For example, the jmdoc tool \cite{5, 26} tries to leave specifications in their sugared form by avoiding these steps when it can. On the other hand, while the original version of JML’s runtime assertion checker \cite{3}, used an earlier version of these steps, the current version \cite{6, 7} instead factors the parts of a specification into various methods, and uses method calls to execute inherited specifications. Factoring the parts of the specification into various methods avoids the problem of renaming to avoid incorrect variable capture (see below).

### 3.1 Desugaring Non_Null for Arguments

Use of non_null for arguments of a method or constructor adds a precondition that each such argument is not null to the method or constructor’s specification. The way this desugaring is accomplished varies, depending on whether the method has any specification.

If the method has no specification, then these preconditions are added as a lightweight specification case, with a preceding also if the method overrides some other method. The translation is illustrated for methods in Figure 6. This figure shows a case where only the first and third arguments are specified as non_null; in general the translation adds a precondition for each non_null argument \(x\), of the form \(x \neq \text{null}\). (The annotation markers and at-signs in the concrete syntax are not shown in such desugarings; in the ISU JML tools they are taken out during lexical analysis.)

\[
\text{modifiers type-spec ident} \\
(\text{non_null } T_1 \ x_1, \\
T_2 \ x_2, \\
\text{non_null } T_3 \ x_3) \Rightarrow \\
\text{method-body} \\
\text{requires } x_1 \neq \text{null}; \\
\text{requires } x_3 \neq \text{null}; \\
\text{modifiers type-spec ident} \\
(T_1 \ x_1, T_2 \ x_2, T_3 \ x_3) \\
\text{method-body}
\]

Figure 6: Desugaring for arguments marked as non_null in the case where the method has no explicit specification. If this method was an override, then the desugared specification would start with also.

However, if the method or constructor has a specification already, then the desugaring is more involved. In this case, the preconditions saying that each non_null argument is not null must be added to each individual specification case, as JML’s syntax does not allow different kinds of specification cases to be combined into one spec-case-seq. So the desugaring uses the auxiliary function, addHeaders, defined in Figure 29 of Appendix A. With this auxiliary function, the desugaring for non_null arguments is shown schematically in Figure 7. This figure, shows what happens when the first and third arguments use the modifier non_null and the method-specification is not an extending-specification. If the method-specification starts with also, this also must be preserved. The desugaring for constructors is analogous.
for arguments marked as non_null, when the method has an explicit specification.

Figure 8: Example desugaring non_null arguments.
An example of this desugaring is given in Figure 8.
Note that non_null on arguments is not inherited, but only affects the specification cases written.
3.2 Desugaring Non_Null Results

The use of non_null for a result type is similar to its use for arguments, in that it adds the normal postcondition \( \text{result} \neq \text{null} \) to a method specification. The way this desugaring is accomplished is slightly different, depending on whether the method has any specification (thus far).

If the method has no specification, then this postcondition is added as the following lightweight specification case (with a preceding also if the method overrides some other method).

\[
\text{ensures } \text{result} \neq \text{null};
\]

As a consequence of the defaults for lightweight specification cases \cite{16, Appendix A}, this lightweight specification case will receive the default precondition of \not_specified.

On the other hand, if the method has a specification already (perhaps due to the use of non_null for some arguments), then adding this postcondition to the method is more tricky to deal with as a desugaring. The problem is that JML’s syntax does not provide an easy way to add a postcondition to a specification case, and adding a new specification case that does not change the method’s effective precondition or frame is also difficult to express. Thus we use the auxiliary function, addBody, described in in Figures 30 and 31 of Appendix A to add the postcondition to every existing specification case for the method.

With this auxiliary function, the desugaring for non_null arguments is shown schematically in Figure 9.

An example of this desugaring is shown in Figure 10.
3.3 Desugaring Pure

For a constructor, use of `pure` adds the clauses

\[
\text{diverges false;}
\]
\[
\text{assignable \ nothing;}
\]

\[(\text{pure}) \text{ this\_\_\_} \ast\;\]

to each specified `spec-case` for the constructor. These clauses mean that a pure constructor can assign to all instance fields of the class, including all those inherited from superclasses.

If there are no specifications given for the constructor, then the above clauses are added to the method as a lightweight specification. (Hence, if no specifications are given, the implicit precondition is `\not_specified`.)

For an instance or static method (but not for constructors), use of `pure` adds the clauses

\[
\text{diverges false;}
\]
\[
\text{assignable \ nothing;}
\]

\[(\text{pure}) \text{ \nothing}\;\]

to each given `spec-case` for the method. This is illustrated in Figure [11] which considers the method-specification is not an extending-specification. If there are no specifications given for the method, then the above clauses are added to the method as a lightweight specification.

An example of this desugaring is shown in Figure [12].

Notice that the translation leaves the modifier `pure` as a modifier on the desugared specification; this is because that modifier is needed to allow the method to be called in assertions, and because it
plays other roles in JML’s semantics. In particular, methods that override a pure method are also pure, although such overrides do not need to use the pure modifier.

Another part of JML’s semantics for pure methods and constructors is that JML adds an implicit verification condition that is not part of the method’s specification, but which must be satisfied by each implementation of a pure method or constructor, to the effect that it cannot diverge when called. That is, unless a call encounters an error, it must either return normally or throw an exception, even when such a call does not satisfy the method’s precondition. For methods, this implicit verification condition is similar to the following specification case [16, Section 2.3.1], except that one must remember that it is only a condition to be verified, and cannot be used be used in verifying even private calls to the method.

```
private behavior
  requires true;
  diverges false;
  assignable \nothing;
```

The verification condition for constructors is analogous, except that, as usual, the assignable clause used for the constructor is “assignable this.*;” instead.

### 3.4 Desugaring Empty Specifications

If at this point a method or constructor has an empty specification, then the specification defaults to one that makes minimal assumptions. For purposes of this desugaring, the specification is considered empty if it has no specification cases, even if it has examples or implications [18]. Note that a specification that uses either pure or non_null will not be empty.

The desugaring first has to deal with the special case of a completely omitted default constructor for a class. Following this, we discuss empty specifications for methods and constructors that are written in the program.

If the default (zero-argument) constructor of a class is omitted because its code is omitted, then its specification defaults to a lightweight specification consisting of an assignable clause that allows all the locations that the default (zero-argument) constructor of its superclass assigns—in essence a copy of the superclass’s default constructor’s assignable clause. Such an assignable clause makes the default constructor verify, since it will call the superclass’s default constructor. If some other frame is desired, then one has to write the specification, or at least the code, explicitly.

Otherwise, if the method or constructor whose specification is empty does not override another method, then its meaning is taken as that in which all clauses are \texttt{not_specified} [16], which is the same as the following lightweight specification.

```
requires \texttt{not_specified};
```

Tools are permitted to make their own interpretations of what \texttt{not_specified} means for various clauses; for example, ESC/Java [10] [21] [8] interprets this to be essentially the same as the lightweight specification "requires true;".

However, if the method whose specification is empty overrides some other method, then its meaning is taken to be the following lightweight specification [16].

```
also
  requires false;
```

This somewhat counter-intuitive specification is the unit for also-conjunction of specifications [20]. This specification is used so as not to change the meaning of the inherited specification.

---

2 This copying from the superclass’s constructor’s specification is not modular, but JML has no syntax for writing such a frame axiom directly.
3.5 Desugaring Nested Specifications

There are several forms of specification that allow nesting. This allows one to factor out common declarations and requires clauses. Figure 13 gives a simple example.

In general, all the clauses in the top spec-header are copied into each of the nested spec-case-seqs. For example, in Figure 13 the outer requires clause, "requires x > 0;", is copied into the nested specification cases. The only problem is that one has to be careful to avoid variable capture. To do this, first rename the specification variables declared in the nested spec-case-seq (i.e., the bound variables) so that they are not the same as any of the free variables in the outer spec-header.

In more detail, consider the schematic normal-spec-case at the top of Figure 14, which, assuming no renaming is needed to avoid capture, is desugared to the one at the bottom.

The same kind of desugaring applies to a generic-spec-case and to an exceptional-spec-case.
forall quantified-var-decl0; ... forall quantified-var-decl0;
old old-var-decl0; ... old old-var-decl0;
requires P0; ... requires P0;

\}

forall quantified-var-decl1; ... forall quantified-var-decl1;
old old-var-decl1; ... old old-var-decl1;
requires P1; ... requires P1;
normal-spec-case-body1
also ... also
forall quantified-var-declk; ... forall quantified-var-declk;
old old-var-declk; ... old old-var-declk;
requires Pk; ... requires Pk;
normal-spec-case-bodyk
\}

⇒

forall quantified-var-decl0; ... forall quantified-var-decl0;
forall quantified-var-decl1; ... forall quantified-var-decl1;
old old-var-decl0; ... old old-var-decl0;
old old-var-decl1; ... old old-var-decl1;
requires P0; ... requires P0;
requires P1; ... requires P1;
normal-spec-case-body1
also ... also
forall quantified-var-decl0; ... forall quantified-var-decl0;
forall quantified-var-declk; ... forall quantified-var-declk;
old old-var-decl0; ... old old-var-decl0;
old old-var-declk; ... old old-var-declk;
requires P0; ... requires P0;
requires Pk; ... requires Pk;
normal-spec-case-bodyk

Figure 14: Desugaring nested specifications in a normal-spec-case; note that renaming to avoid capture is needed, but not shown.
3.6 Desugaring Lightweight, Normal, and Exceptional Specifications

At this point, there are no nested spec-cases. We eliminate lightweight specification cases and normal and exceptional behavior specification cases in favor of behavior specification cases in this step.

Lightweight specifications are desugared by filling the defaults for omitted clauses [16 Appendix A] (most of which are simply “\not_specified”), and then prefixing the result with V behavior, where V is the same as the visibility of the method being specified. This desugars a lightweight specification to a behavior specification. An example of this process is given in Figure 15.

Each spec-case that starts with V normal_behavior is desugared to one that starts with V behavior by inserting a signals clause of the form “signals (Exception e) false,” which says that no exceptions can be thrown.

Similarly, spec-cases beginning with V exceptional_behavior are desugared to V behavior by inserting the clause “ensures false;”, which says that the method cannot return normally. This process leaves us with a single non-nested spec-case sequence, consisting solely of spec-cases that are heavyweight-spec-cases that use the keyword “behavior”. (It is not necessary for the desugaring to fill in the defaults for omitted clauses in such heavyweight specification cases [16 Appendix A], although this could be done as well.)

However, these spec-cases may have different visibility, and for later processing it is convenient to have the specification cases grouped by visibility level. So, combine all spec-cases with the same visibility into a single heavyweight-spec-case. For each visibility, the resulting heavyweight-spec-case has a generic-spec-body that is a generic-spec-case-seq, which contains each of the bodies of the heavyweight-spec-cases with that privacy level, separated by the “also” keyword. Although there is nesting of a sort here, it is not troublesome. This is because in each such heavyweight-spec-case the spec-var-decls and spec-header are both empty, and the generic-spec-body is either a single simple-spec-body or consists of a flat generic-spec-case-seq. This process leaves us with a spec-case-seq of up to four heavyweight-spec-cases with the form described above, one for each privacy level.

A simple example of this desugaring is shown in Figure 16.
Figure 15: An example of desugaring a lightweight specification, on the left, into a behavior specification, on the right, by filling in defaults.

Figure 16: Example desugaring of normal behavior and exceptional behavior, on the left, to behavior, on the right, and then grouping the resulting behavior specifications.
3.7 Desugaring Inheritance and Refinement

To desugar inheritance and refinement, we form an effective specification that combines the effects of inheritance and refinement; the effective specification is what one would have to write to get the same meaning without using inheritance or refinement.

Each method may refine specifications of the same name and formal argument types from the file that the current file refines. Similarly, each instance method may inherit specifications of instance methods with the same name and argument types in its supertypes (superclass and implemented interfaces). As described in the previous step, for each method, each inherited effective specification has up to four spec-cases, one for each of the four visibility levels. In the effective specification that results from combining the extending specification with these inherited specifications there are also up to four spec-cases, one for each visibility level, again joined together with “also”.

An extending specification starts with “also” and may have spec-cases with each of the four visibilities. For each visibility level, V, we combine the inherited specification with the corresponding spec-case of the extending specification, as shown in Figure 17.

The rules for combining specifications from refinements are slightly different from the rules for combining specifications that are inherited from a supertype method specification. In the case of refinements, all four visibility levels of specification are inherited by the extending specification. However, when an inherited specification comes from a supertype, the private visibility specifications are not inherited, and the package-visibility specifications are only inherited when the subtype is in the same package as the corresponding supertype. Thus, when the subtype is in a different Java package than the supertype, only the public and protected specifications are inherited.

In the process of copying inherited assertions from supertypes to subtypes, various kinds of renaming must be done, in general. For example, if a subtype shadows instance fields declared in its supertypes, then some renaming (e.g., changing \( f \) to super.\( f \)) is needed, in general, to avoid inadvertent capture of the supertype’s field names. Similarly, if the formal parameter names are different in the subtype’s overriding method, then renaming must be done on the inherited specifications to substitute that override’s formal parameter names. In a refinement, JML requires that all refining specifications for a given method use the same formal parameter names. The JML runtime assertion checker avoids these renaming problems by using method calls to evaluate the inherited parts of a method specification instead of copying predicates with renaming \([6, 7]\).
3.8 Standardizing Signals Clauses

At this point, there may be several signals-clauses in each spec-case, and each of these may describe the behavior of the method when a different exception is thrown. To standardize these signals-clauses, we make each describe the behavior when an exception of type Exception is thrown, and add a check for the originally declared exception’s type. We also use a standard, but fresh, name for all exceptions, which will allow the signals-clauses to be combined in the next step. (Although the name used must be fresh to avoid capture, we use “e” in the desugaring rules below for conciseness.) This desugaring is done as follows:

\[
\text{signals (ET } n \text{) } P; \Rightarrow \text{signals (Exception } e \text{) } (e \text{ instanceof ET}) \Rightarrow ([((ET)e)/n]P);
\]

where the notation \([((ET)e)/n]P\) means \(P\) with the cast expression \(((ET)e)\) substituted for free occurrences of \(n\).

An example of this desugaring is shown in Figure 18.

Figure 18: Example of the desugaring that standardizes signals-clauses.
assignable \( SR_{1,1}, \ldots, SR_{1,n}; \)
\[
\vdots
\]
assignable \( SR_{k,1}, \ldots, SR_{k,m}; \)
\[\Rightarrow\]
assignable \( SR_{1,1}, \ldots, SR_{1,n}, \ldots, SR_{k,1}, \ldots, SR_{k,m}; \)

Figure 19: Combining multiple assignable-clauses.

\[
\text{signals\_only Exception;}
\]
\[
\text{signals\_only StackPushException;}
\]
\[
\text{signals\_only IllegalArgumentException, StackException;}
\]
\[\Rightarrow\]
\[
\text{signals\_only StackPushException;}
\]

Figure 20: Combining multiple signals-only-clauses.

3.9 Desugaring Multiple Clauses of the Same Kind

We next desugar multiple requires-clauses and multiple simple-spec-body-clauses of the same kind to produce a specification with only one of each such clause. (See Figure 3 for definitions of these nonterminals.)

For the assignable-clauses, this process is very simple, and consists of joining together the lists from each clause with commas. The scheme describing how the assignable-clauses within a specification case are combined is shown in Figure 19.

For the signals-only-clauses, this process is also simple, but has an intersection instead of a union semantics. That is, the combination lists just those exception types, \( ET \), such that (a) \( ET \) is mentioned in some signals_only clause and (b) for each signals_only clause, the exception \( ET \) is a subtype of some type mentioned in that clause. If this results in no exception types being listed in the result, the result uses the list \( \text{nothing} \). A concrete example of how the signals-only-clauses within a specification case are combined is shown in Figure 20, assuming that StackException is a subtype of Exception, and that StackPushException is a subtype of StackException.

For working-space-clauses and duration-clauses, multiple clauses of the same kind are combined into a single such clause by first converting the if syntax into a conditional expression, and then taking the minimum of the resulting expressions, the whole expression governed by an if which is the disjunction of the original conditions.\(^3\) For example, the duration-clauses within a specification case are combined as shown in Figure 21 (Again, if the “if” and the following predicate are omitted after a spec-expression, “if true” is used as a default.)

For the other clauses, this process conjoins the predicates in each clause of the same type (within a specification case). For example, for the requires-clauses, this is shown schematically in Figure 22. Exactly the same technique is used for the when-clauses, ensures-clauses, and diverges-clauses. For the signals-clauses things are marginally more complex, because each signals clause has a bit of extra syntax. However, due to the processing in the previous step, the idea is the same, and is shown in Figure 23.

An example of this desugaring step is given in Figure 24.

After this step, each generic-spec-case in the body of each of the up to four spec-cases has only one clause of each type, and the signals-clauses all describe the behavior of an exception of type Exception with the same name.

\(^3\) Thanks to David Cok and Steve Edwards for suggesting that the entire expression be governed by this disjunction.
duration $E_1$ if $DE_1$;
duration $E_2$ if $DE_2$;
...
duration $E_{k-1}$ if $DE_{k-1}$;
duration $E_k$ if $DE_k$;
⇒
duration Long.min((DE_1 ? E_1 : Long.MAX_VALUE),
  Long.min((DE_2 ? E_2 : Long.MAX.VALUE),
  ...
  Long.min((DE_{k-1} ? E_{k-1} : Long.MAX.VALUE),
  (DE_k ? E_k : Long.MAX.VALUE)) ... ))
if ((DE_1) || (DE_2) ... || (DE_{k-1}) || (DE_k));

Figure 21: The combination of multiple duration-clauses; the combination of working-space-clauses is similar.

requires $P_1$; ... requires $P_n$; ⇒ requires ($P_1$ && ... && $P_n$);

Figure 22: Combining multiple requires-clauses; the combination of ensures-clauses, diverges-clauses, and when-clauses is similar.

signals (Exception e) $P_1$; ... signals (Exception e) $P_n$;
⇒
signals (Exception e) ($P_1$ && ... && $P_n$);

Figure 23: Combining multiple signals-clauses.
/*@ public behavior
@ assignable theElements;
@ assignable size;
@ duration 2*MC if MC>0;
@ duration 50*CT;
@ ensures \old(size >= 2);
@ ensures size() == \old(size - 2);
@ signals_only EmptyException;
@ signals_only TooSmallException;
@ (e instanceof EmptyException) => ((e instanceof EmptyException)
  \old(empty())
  \old(size == 1)
  \old(size == 1)
@)
@ signals (Exception e)
@ (e instanceof TooSmallException) ((e instanceof TooSmallException)
  \old(size == 1)
  \old(size == 1)
@)
@*/
public void popTwice()
  throws EmptyException, TooSmallException;
/*@ public behavior
@ assignable theElements, size;
@ duration Long.min(
  (MC>0 ? 2*MC, Long.MAX_VALUE),
  (true ? 50*CT, Long.MAX_VALUE))
@ if ((MC>0) || true);
@ ensures \old(size >= 2);
@ ensures size() == \old(size - 2);
@ signals_only EmptyException,
@ signals_only EmptyException,
@ TooSmallException;
@ signals (Exception e)
@ (e instanceof EmptyException)
  \old(empty())
  \old(size == 1)
  \old(size == 1)
@)
@ signals (Exception e)
@ (e instanceof TooSmallException)
  \old(size == 1)
  \old(size == 1)
@)
@*/
public void popTwice()
  throws EmptyException, TooSmallException;

Figure 24: Example of the desugaring that eliminates multiple clauses of the same kind within a specification case.
private Object push(int elem);

Figure 25: Example of making all assignable-clauses have the same frame, and all signals-only-clauses have the same list of exceptions.

3.10 Make Assignable and Signals_Only Clauses the Same

Before proceeding to the next step of combining spec-cases at each visibility level, we must have all spec-cases have the same assignable-clauses (frames) [20]. If this were not done, the semantics of the frames would not be preserved.

For very similar reasons, at this step we also make all the signals only clauses have the same list of exceptions that may be thrown.

An example of this step is given in Figure 25. Let $SR$ be the union of all the lists of store-refs in the assignable clauses of the generic-spec-cases. (In taking unions, the store-ref-list $\text{everything}$ is the universal set, and $\text{nothing}$ is the empty set.) Then each assignable clause in each generic-spec-case is replaced by “assignable $SR$.” Furthermore, for each $i$ the normal and exceptional postcondition in the $i^{th}$ generic-spec-case has $\text{only_assigned}(SR_i)$ conjoined to it. This predicate records the original intent of the frame for that specification case.

In this figure, let $ETL$ be the union of all the lists of reference-types in the generic-spec-cases. Then each signals_only clause in each generic-spec-case is replaced by “signals_only $ETL_i$.” Furthermore, for each $i$ the exceptional postcondition in the $i^{th}$ generic-spec-case has false conjoined to it if the $i^{th}$ signals-only-clause is “signals_only $\text{nothing}$;” and otherwise, if the the $i^{th}$ signals-only-clause is

\[ \text{signals_only $ETL_i$, \ldots, $ETL_j$;} \]

then the $i^{th}$ exceptional postcondition has the predicate we write as “$e \text{ instanceof } ETL_i$” conjoined to it. This predicate stands for the disjunction

\[ (e \text{ instanceof } ETL_{i,1} \lor \ldots \lor e \text{ instanceof } ETL_{i,j}) \]

This predicate records the original intent of the signals_only clause for that specification case.
\[ V \text{ behavior} \]
\[
\{ \]
\hspace{1em}forall-var-decls_1
\hspace{1em}old-var-decls_1
\hspace{1em}requires P_1;
\hspace{1em}diverges T_1;
\hspace{1em}assignable SR_1;
\hspace{1em}when W_1;
\hspace{1em}working_space WSE_1 if W_1;
\hspace{1em}duration DE_1 if D_1;
\hspace{1em}ensures Q_1;
\hspace{1em}signals_only ETL_1;
\hspace{1em}signals (Exception e) EX_1;
\] also ... also
\hspace{1em}forall-var-decls_k
\hspace{1em}old-var-decls_k
\hspace{1em}requires P_k;
\hspace{1em}diverges T_k;
\hspace{1em}assignable SR_k;
\hspace{1em}when W_k;
\hspace{1em}working_space WSE_k if W_k;
\hspace{1em}duration DE_k if D_k;
\hspace{1em}ensures Q_k;
\hspace{1em}signals_only ETL_k;
\hspace{1em}signals (Exception e) EX_k;
\}
\]
\[ \Rightarrow \]
\[ V \text{ behavior} \]
\[
\{ \]
\hspace{1em}forall-var-decls_1
\hspace{1em}old-var-decls_1
\hspace{1em}requires P_1;
\hspace{1em}diverges T_1;
\hspace{1em}assignable SR;
\hspace{1em}when W_1;
\hspace{1em}working_space WSE_1 if W_1;
\hspace{1em}duration DE_1 if D_1;
\hspace{1em}ensures \(\text{\texttt{only\_assigned}}(SR_1) \&\& (Q_1));\)
\hspace{1em}signals_only ETL;
\hspace{1em}signals (Exception e) \(\text{\texttt{only\_assigned}}(SR_1) \&\& (\text{\texttt{e instanceof}} ETL_1) \&\& (EX_1));
\] also ... also
\hspace{1em}forall-var-decls_k
\hspace{1em}old-var-decls_k
\hspace{1em}requires P_k;
\hspace{1em}diverges T_k;
\hspace{1em}assignable SR;
\hspace{1em}when W_k;
\hspace{1em}working_space WSE_k if W_k;
\hspace{1em}duration DE_k if D_k;
\hspace{1em}ensures \(\text{\texttt{only\_assigned}}(SR_k) \&\& (Q_k));\)
\hspace{1em}signals_only ETL;
\hspace{1em}signals (Exception e) \(\text{\texttt{only\_assigned}}(SR_k) \&\& (\text{\texttt{e instanceof}} ETL_k) \&\& (EX_k);\)
\}

Figure 26: Making \textit{assignable-clauses} have the same frame. Here \(SR\) is the union of \(SR_1\) through \(SR_k\) and \(ETL\) is the union of \(ETL_1\) through \(ETL_k\).
3.11 Desugaring Also Combinations

At this point, there is an effective single method specification, with at most one *spec-case* for each visibility level. Within each visibility level, the *spec-cases* in each *generic-spec-case-seq* have the same frame and same *signals_only* clause. So now, within each visibility level, we can desugar an internal *generic-spec-case-seq* to eliminate the use of “also” (and hence the vestigial nesting) as shown in Figure 27. This process disjoins the preconditions of the various specification cases within a visibility level, and uses implications between each precondition (wrapped in “\old( )” where necessary) and the corresponding predicate, so that each precondition only governs the behavior when it holds [31, 15].

There is one additional detail that needs to be mentioned about Figure 27 — when the specification variable declarations are combined, there is the possibility of variable capture. To avoid capture, one must do renaming in general.

An example of this desugaring is given in Figure 28.

4 Conclusion

We have defined a desugaring of JML’s method specification syntax into a semantically simpler form. The end point of this desugaring is suitable for further formal study.

One area for future work is to disentangle the various desugaring steps, so that tools could use them in any order. For example, one should be able to desugar multiple clauses of the same kind by using the conjunction rule illustrated in Section 3.9 at any time. Allowing different orderings brings up the possibility that applying the desugaring steps in different orders might produce different results; we should try to prove that this cannot happen.

JML also has several redundancy features [15], for example, *ensures_redundantly* clauses, and the *implies_that* and *for_example* sections in method specifications. These have no impact on most kinds of semantics for JML, and instead serve to highlight conclusions for the reader. They can, however, be used in debugging specifications [28, 29], and the conditions needed to check them also need to be formally stated (as has been done to some extent for Larch/C++ [14, 15]). More to the point, similar kinds of desugaring apply to at least the *implies_that* and *for_example* sections in method specifications, and these should be investigated more systematically.

More challenging is giving a semantics to JML’s model programs, which are derived from the refinement calculus [25, 2].

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A Definition of addHeaders and addBody

This section defines the auxiliary functions addHeaders and addBody, which are used to add preconditions and body clauses to specification cases.

The addHeaders function is fairly simple, and just has to distinguish the 4 different kinds of specification cases, as shown in Figure 29.

25
\[
V \text{ behavior} \\
\{ \\
\text{forall-var-decls}_1 \\
\text{old-var-decls}_1 \\
\text{requires } P_1; \\
\text{diverges } T_1; \\
\text{assignable } SR; \\
\text{when } W_1; \\
\text{working_space } WSE_1 \text{ if } W_1; \\
\text{duration } DE_1 \text{ if } D_1; \\
\text{ensures } Q_1; \\
\text{signals only } ETL; \\
\text{signals } (\text{Exception } e) \text{ } EX_1; \\
\text{also } ... \text{ also } \\
\text{forall-var-decls}_k \\
\text{old-var-decls}_k \\
\text{requires } P_k; \\
\text{diverges } T_k; \\
\text{assignable } SR; \\
\text{when } W_k; \\
\text{working_space } WSE_k \text{ if } W_k; \\
\text{duration } DE_k \text{ if } D_k; \\
\text{ensures } Q_k; \\
\text{signals only } ETL; \\
\text{signals } (\text{Exception } e) \text{ } EX_k; \\
\} \\
\Rightarrow \\
V \text{ behavior} \\
\text{forall-var-decls}_1 ... \text{forall-var-decls}_k \\
\text{old-var-decls}_1 ... \text{old-var-decls}_k \\
\text{requires } (P_1 || (P_2 ... || (P_k)); \\
\text{diverges } ((P_1) \Rightarrow T_1) \& \& ... \& \& ((P_k) \Rightarrow T_k); \\
\text{assignable } SR; \\
\text{when } \langle \text{old}(P_1) \Rightarrow W_1 \rangle \& \& ... \& \& \langle \text{old}(P_k) \Rightarrow W_k \rangle; \\
\text{working_space } \text{Integer.min}(\langle \text{old}(P_1 \& \& W_1) \Rightarrow WSE_1 : \text{Integer.MAX_VALUE}. \\
... \langle \text{old}(P_k \& \& W_k) \Rightarrow WSE_k : \text{Integer.MAX_VALUE} ... \rangle) \\
\text{if } ((P_1 \& \& W_1) || ... || (P_k \& \& W_k)); \\
\text{duration } \text{Long.min}(\langle \text{old}(P_1 \& \& D_1) \Rightarrow DE_1 : \text{Long.MAX_VALUE}. \\
... \langle \text{old}(P_k \& \& D_k) \Rightarrow DE_k : \text{Long.MAX_VALUE} ... \rangle) \\
\text{if } ((P_1 \& \& D_1) || ... || (P_k \& \& D_k)); \\
\text{ensures } (\langle \text{old}(P_1) \Rightarrow Q_1 \rangle \& \& ... \& \& (\text{old}(P_k) \Rightarrow Q_k)); \\
\text{signals_only } ETL; \\
\text{signals } (\text{Exception } e) (\langle \text{old}(P_1) \Rightarrow EX_1 \rangle \& \& ... \& \& (\text{old}(P_k) \Rightarrow EX_k)); \\
\}
\]

Figure 27: Desugaring also combinations
/**@ public behavior
 * {|
 *  | requires !empty();
 *  | ensures \result == theElems.header();
 *  | signals (Exception e) false;
 *  | also
 *  | requires empty();
 *  | ensures false;
 *  | signals (Exception e)
 *  |   (e instanceof EmptyException)
 *  |   ==> true;
 * |}
 */

public Object top() throws EmptyException;

Figure 28: Example of the desugaring that eliminates also.

addHeaders : spec-case × spec-header → spec-case
addHeaders(V behavior generic-spec-case, R) =
  V behavior R { | generic-spec-case | }
addHeaders(V exceptional_behavior exceptional-spec-case, R) =
  V exceptional_behavior R { | exceptional-spec-case | }
addHeaders(V normal_behavior normal-spec-case, R) =
  V normal_behavior R { | normal-spec-case | }
addHeaders(generic-spec-case, R) =
  R { | generic-spec-case | }

Figure 29: Definition of addHeaders.

The addBody function is a bit more complex, as it has to recurse into the nested structure of specification cases to find places where a simple-spec-body-clause may occur. It is defined in Figures 30 and 31.
addBody : spec-case × simple-spec-body-clause → spec-case
addBody(V behavior generic-spec-case, C) = V behavior addBody(generic-spec-case, C)
addBody(V exceptional_behavior exceptional-spec-case, C) =
    if C is an ensures-clause
        then V exceptional_behavior exceptional-spec-case
    else V exceptional_behavior addBody(exceptional-spec-case, C)
addBody(V normal_behavior normal-spec-case, C) =
    if C is a signals-clause
        then V normal_behavior normal-spec-case
    else V normal_behavior addBody(normal-spec-case, C)
addBody(generic-spec-case, C) = addBody(generic-spec-case, C)

Figure 30: First part of the definition of addBody, which is overloaded for different kinds of specification case syntax.
Figure 31: Second part of the definition of addBody.
References


