Specification tips and pitfalls

David Cok, Joe Kiniry, and Erik Poll

Eastman Kodak Company, University College Dublin, and Radboud University Nijmegen
Specifications tips and pitfalls

1. Inherited specifications
2. Aliasing
3. Object invariants
4. Inconsistent assumptions
5. Exposed references
6. \old
7. How to write specs
#1: Specification inheritance and behavioural subtyping
Suppose \texttt{Child} extends \texttt{Parent}.

- \textbf{Behavioural subtyping} = objects from subclass \texttt{Child} “behave like” objects from superclass \texttt{Parent}

- \textbf{Principle of substitutivity} [Liskov]: code will behave “as expected” if we provide an \texttt{Child} object where a \texttt{Parent} object was expected.
Behavioural subtyping usually enforced by insisting that

- invariant in subclass is **stronger** than invariant in superclass
- for every method,
  - precondition in subclass is **weaker** (!) than precondition is superclass
  - postcondition in subclass is **stronger** than postcondition is superclass

**JML** achieves behavioural subtyping by **specification inheritance**: any child class **inherits** the specification of its parent.
Invariants are inherited in subclasses. Eg.

class Parent {
  ...
  //@ invariant invParent;
  ...
}

class Child extends Parent {
  ...
  //@ invariant invChild;
  ...
}

the invariant for Child is invChild && invParent
Specification inheritance for method specs

class Parent {
    //@ requires i >= 0;
    //@ ensures \result >= i;
    int m(int i)
    {
        ...
    }
}

class Child extends Parent {
    //@ also
    //@ requires i <= 0;
    //@ ensures \result <= i;
    int m(int i)
    {
        ...
    }
}

Keyword also indicates there are inherited specs.
Method \texttt{m} in \texttt{Child} also has to meet the spec given in \texttt{Parent} class. So the complete spec for \texttt{Child} is

\begin{verbatim}
class Child extends Parent {

    /\* @ requires i >= 0; @
    @ ensures \result >= i;
    @ also
    @ requires i <= 0
    @ ensures \result <= i;
    @*/

    int m(int i){ ... }
}
\end{verbatim}

What can result of \texttt{m(0)} be?
This spec for Child is equivalent with

```java
class Child extends Parent {

    /**
     * @requires i <= 0 || i >= 0;
     * @ensures \old(i >= 0) ==> \result >= i;
     * @ensures \old(i <= 0) ==> \result <= i;
     */
    int m(int i){ ... }
}
```
Inherited specifications: trick

Another example: two Objects that are == are always also equals. But the converse is not necessarily true. But it is true for objects whose dynamic type is Object.

```java
public class Object {
   //@ ensures (this == o) ==> \result;
   /*@ ensures typeof(this) == type(Object)
      ==> (\result == (this==o));
   */
   public boolean equals(Object o);
}
```

True for all Objects
Not necessarily true for subtypes
Inherited specifications

So

- Base class specifications apply to subclasses
  - that is, ESC/Java2 enforces *behavioral subtyping*
  - Specs from implemented *interfaces* also must hold for implementing classes

- Be thoughtful about how strict the base class specs should be

- Guard them with `typeof(this) == \type(...)` if need be

- Restrictions on exceptions such as `normal_behavior` or `signals (E e) false;` will apply to derived classes as well.
#2: Aliasing
A common but non-obvious problem that causes violated invariants is aliasing.

```java
public class Alias {
    /*@ non_null */ int[] a = new int[10];
    boolean nonneg = true;

    /*@ invariant nonneg ==>  
        (\forall int i; 0<=i && i < a.length; a[i]>=0); */

    //@ requires 0<=i && i < a.length;
    public void insert(int i, int v) {
        a[i] = v;
        if (v < 0) nonneg = false;
    }
}

produces
Alias.java:12: Warning: Possible violation of object invariant (Invariant) ...
^  
Associated declaration is "Alias.java", line 5, col 6: 
/*@ invariant nonneg ==> (\forall int i; 0<=i && i < a.length; ...
A full counterexample context (-counterexample option) produces, among lots of other information:

\[
\begin{align*}
\text{brokenObj} \neq \text{this} \\
(\text{brokenObj}) . (a@pre:2.24) &= \text{tmp0}!a:10.4 \\
\text{this} . (a@pre:2.24) &= \text{tmp0}!a:10.4
\end{align*}
\]

that is, \textbf{this} and some different object (\texttt{brokenObj}) share the same \texttt{a} object.
To fix this, declare that \texttt{a} is owned only by its parent object: (\texttt{owner} is a ghost field of \texttt{java.lang.Object})

```java
public class Alias {
    /*@ non_null */ int[] a = new int[10];
    boolean noneg = true;

    /*@ invariant noneg ==> */
    (\forall int i; 0<=i && i < a.length; a[i]>=0); */
    //@ invariant a.owner == this;

    //@ requires 0<=i && i < a.length;
    public void insert(int i, int v) {
        a[i] = v;
        if (v < 0) noneg = false;
    }

    public Alias() {
        //@ set a.owner = this;
    }
}
```
Another example. This one fails on the postcondition.

```java
public class Alias2 {
    /*@ non_null */ Inner n = new Inner();
    /*@ non_null */ Inner nn = new Inner();
    //@ invariant n.owner == this;
    //@ invariant nn.owner == this;

    //@ ensures n.i == \old(n.i + 1);
    public void add() {
        n.i++;
        nn.i++;
    }
}

Alias2();
}

class Inner {
    public int i;
    //@ ensures i == 0;
    Inner();
}
```
• The counterexample context shows

\[ \text{this.(nn:3.24) == tmp0!n:10.4} \]
\[ \text{tmp2!nn:11.4 == tmp0!n:10.4} \]

• These hint that \( n \) and \( nn \) are references to the same object.

• If we add the invariant \( //@ \text{ invariant n != nn;} \) to forbid aliasing between these two fields, then all is well.
• Aliasing is a serious difficulty in verification
• Handling aliasing is an active area of research, related to handling frame conditions
• It is all about knowing what is modified and what is not
• These owner fields or the equivalent create a form of encapsulation that can be checked by ESC/Java to control what might be modified by a given operation
• universes have now been added to JML to provide a more advanced form of alias control.
#3: Write object invariants

- Be sure that class invariants are about the object at hand.
- Statements about all objects of a class may indeed be true, but they are difficult to prove, especially for automated provers.
- For example, if a predicate $P$ is supposed to hold for objects of type $T$, then do not write
  
  ```java
  //@ invariant (\forall T t; P(t));
  ```

  Instead, write
  
  ```java
  //@ invariant P(this);
  ```

- The latter will make a more provable postcondition at the end of a constructor.
#4: Inconsistent assumptions

If you have inconsistent specifications you can prove anything:

```java
public class Inconsistent {
    public void m() {
        int a, b, c, d;
        //@ assume a == b;
        //@ assume b == c;
        //@ assume a != c;
        //@ assert a == d; // Passes, but inconsistent
        //@ assert false;  // Passes, but inconsistent
    }
}
```
Another example:

```java
public class Inconsistent2 {
    public int a,b,c,d;
    //@ invariant a == b;
    //@ invariant b == c;
    //@ invariant a != c;

    public void m() {
        //@ assert a == d; // Passes, but inconsistent
        //@ assert false;  // Passes, but inconsistent
    }
}
```

We hope to put in checks for this someday!
Problems can arise when a reference to an internal object is exported from a class:

```java
public class Exposed {
    /*@ non_null */ private int[] a = new int[10];
    //@ invariant a.length > 0 && a[0] >= 0;

    //@ ensures \result != null;
    //@ ensures \result.length > 0;
    //@ pure
    public int[] getArray() { return a; }
}

class X {
    void m(/*@ non_null */ Exposed e) {
        e.getArray()[0] = -1; // unchecked invariant violation
    }
}
```

- ESC/Java does not check that every allocated object still satisfies its invariants.
- Similar hidden problems can result if public fields are modified directly.
#6: \old
is used to indicate evaluation in the pre-state in a postcondition expression.

Consider specifying

\begin{verbatim}
public static native void arraycopy(Object[] src, int srcPos,
                                       Object[] dest, int destPos, int length);
\end{verbatim}

Try:

\begin{verbatim}
ensures (\forall \text{ int } i; 0\leq i \&\& i<\text{length}; \text{dest[destPos+i]} == \text{src[srcPos+i]})
\end{verbatim}
\texttt{\textbackslash old} is used to indicate evaluation in the pre-state in a postcondition expression.

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Wrong!
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Besides exceptions and invalid arguments, don’t forget aliasing - \textbf{dest} and \textbf{src} may be the same array:
\begin{verbatim}
ensures (\forall \text{int } i; \ 0\leq i \&\& i<\text{length};
                      dest[destPos+i] == \old(src[srcPos+i]));
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Besides exceptions and invalid arguments, don’t forget aliasing - \texttt{dest} and \texttt{src} may be the same array:

\begin{verbatim}
ensures (\forall int i; 0<=i && i<length;
         dest[destPos+i] == \texttt{\textbackslash old}(src[srcPos+i])
\end{verbatim}

And don’t forget the other elements:

\begin{verbatim}
ensures (\forall int i; (0<=i && i<destPos) ||
         (destPos+length <= i && i < destPos.length);
         dest[i] == \texttt{\textbackslash old}(dest[i])
\end{verbatim}
In postcondition
ensures (\forall int i; 0<=i \&\& i<length;
    dest[destPos+i] == \old(src[srcPos+i]);
public static native void arraycopy(Object[] src, int srcPos,
    Object[] dest, int destPos, int length);
shouldn't we write \old(length) instead of length?
In postcondition

\[\forall \text{int } i; \ 0 \leq i \land i < \text{length};\]
\[\text{dest}[\text{destPos} + i] == \text{old}(\text{src}[\text{srcPos} + i]);\]

\text{public static native void arraycopy(Object[]} src, int srcPos, 
\text{Object[]} dest, int destPos, int length);\]

shouldn’t we write \text{old}(\text{length}) instead of \text{length}?
And \text{old}(\text{dest}) [...] instead of \text{dest} [...]?
In postcondition

\[\text{ensures } (\forall \text{ int } i; 0 \leq i \land i < \text{length};
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\text{Object[] dest, int destPos, int length);}\]

shouldn’t we write \text{old}(\text{length}) instead of \text{length}?
And \text{old}(\text{dest}) \ldots \text{ instead of dest}[\text{destPos+i}]?
Strictly speaking: yes. But because this is so easy to get
forget, any mention of an argument \(x\) in postcondition
means \text{old}(x).
In postcondition

ensures (∀ int i; 0≤i && i<length;
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shouldn’t we write \old(length) instead of length?
And \old(dest)[...] instead of dest[destPos+i]?

Strictly speaking: yes. But because this is so easy to get forget, any mention of an argument \( x \) in postcondition means \old(x).

This means it’s impossible to refer to the new value of length in postcondition of arraycopy. But this value is unobservable for clients anyway.
#7: How to write specs
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Getting started

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- Add `pre-` and `post-conditions` to limit the inputs and outputs of each method.
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- Start with simple specifications; proceed to complex ones as they have value.
• Separate conjunctions to get information about which conjunct is violated. Use

\begin{verbatim}
requires A;
requires B;
not
requires A && B;
\end{verbatim}

• Use \texttt{assert} statements to find out what is going wrong.

• Use \texttt{assume} statements \textit{that you KNOW are correct} to help the prover along.
Finally

- Specification is **tricky** - getting it right is hard, even with tools
- **Try it** - a substantial research gap is experience on industrial-scale sets of code
- **Communicate** - we are willing to offer advice
- **Share** your experience - tools will get better and we will all learn better techniques for successful specification (use JML and ESC/Java mailing lists)