Specification tips and pitfalls

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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

Behavioural subtyping

Suppose `Child extends Parent`.

- **Behavioural subtyping** = objects from subclass `Child` "behave like" objects from superclass `Parent`
- **Principle of substitutivity** [Liskov]:
  code will behave "as expected" if we provide an `Child` object where a `Parent` object was expected.

Behavioural subtyping

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.

Specification inheritance for invariants

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.

Specification inheritance for method specs

Method `m` in `Child` also has to meet the spec given in `Parent` class. So the complete spec for `Child` is

```
class Child extends Parent {

  /*@   requires i >= 0;
    @   ensures  \result >= i;
    @ also
    @   requires i <= 0
    @   ensures  \result <= i;
    @*/
  int m(int i){ ... }
}
```

What can result of `m(0)` be?

Specification inheritance for method specs

This spec for `Child` is equivalent with

```
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.

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

Not necessarily true for subtypes

True for all Objects

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.

```
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); */

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

produces

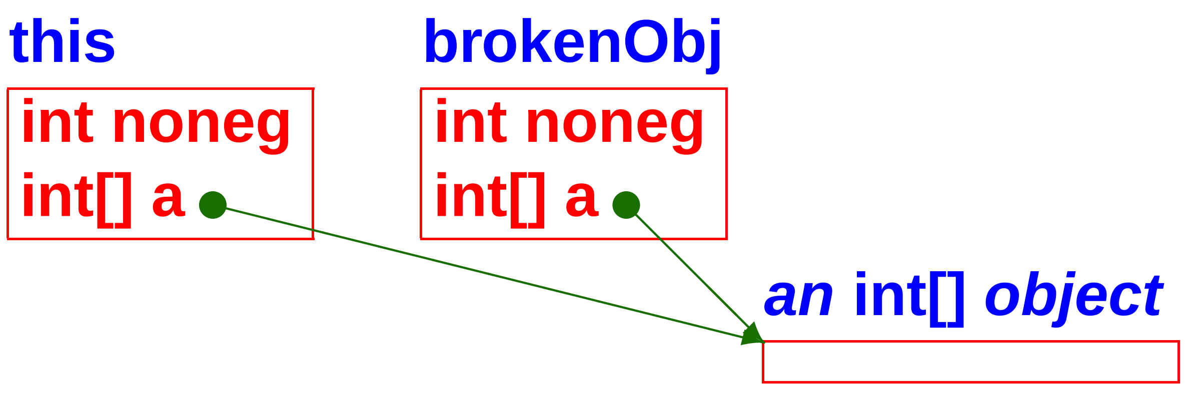
```
Alias.java:12: Warning: Possible violation of object invariant (Invariant)
  }
  ^
Associated declaration is "Alias.java", line 5, col 6:
  /*@ invariant noneg ==> (\forall int i; 0<=i && i < a.length; ...
```

Aliasing

A full counterexample context (-counterexample option) produces, among lots of other information:

```
brokenObj%0 != this
(brokenObj%0).(a@pre:2.24) == tmp0!a:10.4
this.(a@pre:2.24) == tmp0!a:10.4
```

that is, this and some different object (brokenObj) share the same a object.



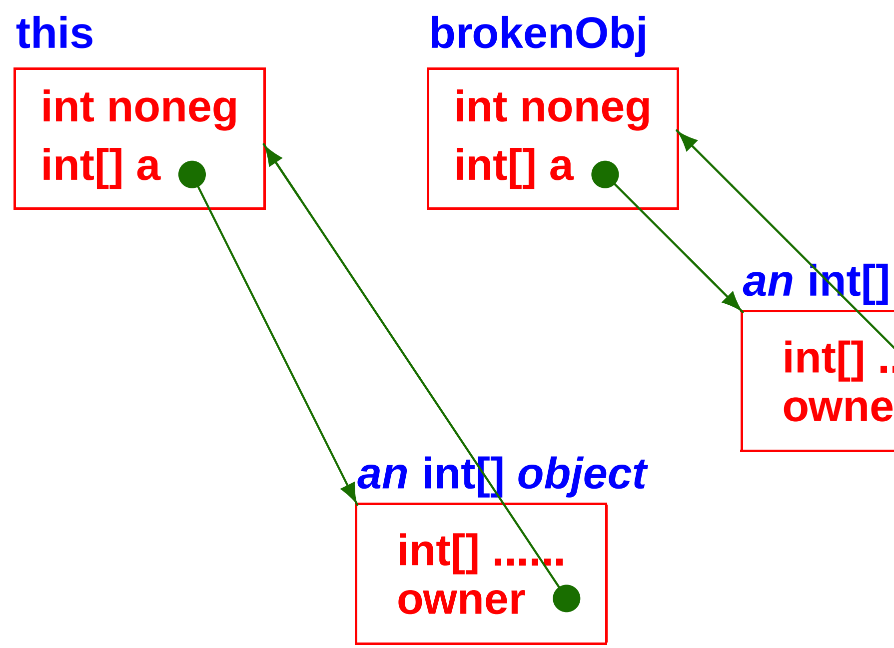
To fix this, declare that a is owned only by its parent object:
(owner is a ghost field of java.lang.Object)

```
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.

```
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**

```
this.(nn:3.24) == tmp0!n:10.4
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 *//@ invariant n != nn;* to forbid aliasing between these two fields, then all is well.**

Aliasing

- 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**

```
//@ invariant (\forall T t; P(t));
```

- **Instead, write**

```
//@ 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:

```
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
  }
}
```

#4: Inconsistent assumptions

Another example:

```
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!

#5: Exposed references

Problems can arise when a reference to an internal object is exported from a class:

```
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

\old is used to indicate evaluation in the pre-state in a postcondition expression.

Consider specifying

```
public static native void arraycopy(Object[] src, int srcPos,
                                    Object[] dest, int destPos, int length
```

Try:

```
ensures (\forall int i; 0<=i && i<length; dest[destPos+i] == src[srcPos+i]
```

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Besides exceptions and invalid arguments, don't forget aliasing - dest and src may be the same array:

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ensures (\forall int i; 0<=i && i<length;
                            dest[destPos+i] == \old(src[srcPos+i]);
```

And don't forget the other elements:

```
ensures (\forall int i; (0<=i && i<destPos) ||
                              (destPos+length <= i && i < destPos.length);
                            dest[i] == \old(dest[i]);
```

\old

In postcondition

```
ensures (\forall int i; 0<=i && i<length;
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```

shouldn't we write `\old(length)` instead of `length`?

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

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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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- For each class: what invariant expresses the self-consistency of the internal data?
- Add pre- and post-conditions to limit the inputs and outputs of each method.
- Add possible unchecked exceptions to throws clauses.
- Start with simple specifications; proceed to complex ones as they have value.

Getting started

- **Separate conjunctions to get information about which conjunct is violated. Use**

  ```
  requires A;
  requires B;
  ```

  not

  ```
  requires A && B;
  ```

- **Use assert statements to find out what is going wrong.**
- **Use assume statements *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)