# Specifying Java Iterators using JML and Esc/Java2

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**10 November 2006**

**at**

**SAVCBS 2006**

## The Problem

- Iterators walk through a sequence of values
- May have many independent iterators for a given iterable object
- Iterators may modify the parent object
- No requirements on the sequence of values returned by an iterator

## The Problem: iteractions

- If a set of Java iterators have a common parent object, there is an interaction among them
  - an iterator may remove an object only once
  - if an iterator removes an object from the parent, all other iterators subsequently may have undefined behavior
  - if the parent object is modified, all iterators may have undefined behavior
  - Note: subclasses may define the behavior

## In this paper

- Discuss only the second issue – interactions
- Specify the interfaces, not specific instantiations
- Use JML and Esc/Java2
- Goal: determine where the specification language falls short

## The Iterable<E> interface

```
package java.lang;
public interface Iterable<E> {
        public Iterator<E> iterator();
}
```

The only functionality is to produce an Iterator.
An Iterator need not have a parent Iterable.

## The Iterator<E> interface

```
package java.lang;
public interface Iterator<E> {
        public boolean hasNext();
        public E next();
        public void remove();
}
```

# An easy piece: no duplicate remove

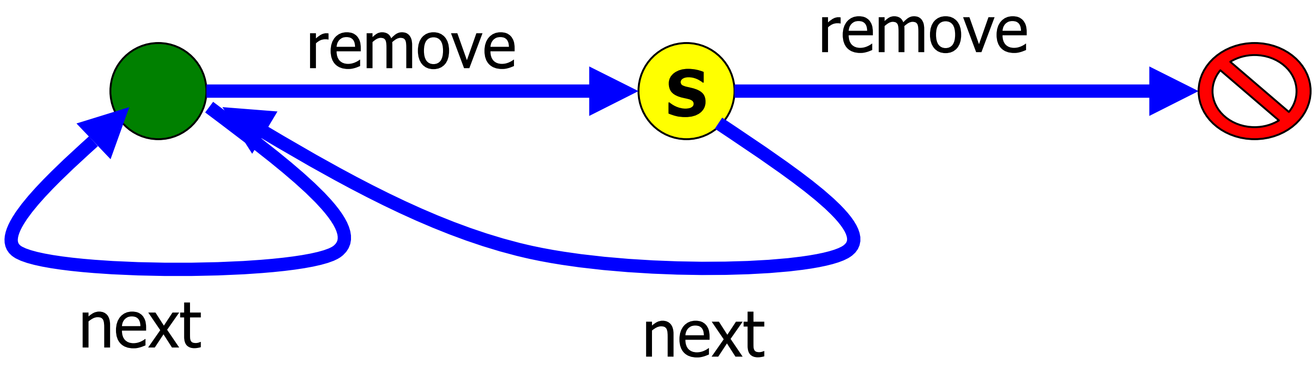
```
package java.lang;
public interface Iterator<E> {
  ...
  //@ public instance model boolean removeOK;
  //@   initially !removeOK;

 /*@    ....
          assignable removeOK;
          ensures removeOK;
  */
  public E next();

/*@
   public behavior
      requires removeOK;
      assignable removeOK;
      ensures !removeOK;
   also public exceptional_behavior
      requires !removeOK;
      signals_only IllegalStateException;
  */
  public void remove();
}
```

# A state machine!

- This actually encodes a little state machine:



- The state machine, or some equivalent, is a better specification – more obviously correct to a human.

## Other examples

- A class that requires the calling of an initialization method before any other methods
- Iterator: if hasNext() returns false, then next() is illegal

- See Cheon & Perumendla, 2005, 2006 for some initial work on this issue

# What sort of syntax?

- Regular expressions?

  ( (next)$^+$ (remove) )* is OK

  ?* (remove)(remove) is ERROR

  (remove) is ERROR

- What about nested pairs (e.g. open/close)? method arguments? return values?

## A research question

- What is the best way to specify method call sequences?
- What amount of syntax is helpful?
- How much is too much?
- Need lots of case studies and analysis of real code

# Modification interactions

- Iterators store a proxy for the state of the Iterable
- If that state changes, except by the iterator itself, the iterator becomes invalid

- (See the paper for details)
- (Actual Java implementation is similar)

# Highlights of the spec

```
package java.lang;
public interface Iterator<E> {
  //@ public instance model Iterable iterable;
  //@ public instance model int iteratorTime;
...
  /*@ public normal_behavior
      ensures iteratorTime>=iterable.lastModified;
     public pure model boolean isValid();
  */
   /*@ requires isValid() ...
    */ // No spec if !isValid() – up to subclasses
    public E next();
```

```
/*@
   public behavior
      requires isValid(); ...
      ensures iterable.lastModified >
            \old(iterable.maxIterator);
      ensures isValid();
*/
  public void remove();
}
```

# Highlights of the spec

```
package java.lang;
public interface Iterable<E> {
  /*@ public instance model int lastModified;
        public instance model int maxIterator;
        constraint lastModified >=
                              \old(lastModified);
...
/*@ ensures \result.iterable = this;
   ensures \result.isValid();
   ensures maxIterator >=
                      \result.iteratorTime;   */
   public Iterator<E> iterator();
```

```
  // Any subclass method that modifies
  // the Iterable must include specs
  // that invalidate the associated
  // Iterators, like this:

/*@
     ensures lastModified >
                     maxIterator;
*/
  public void clear();
```

## A few notes

- No object alters fields within a different object
- Iterators must be able to see the fields of the parent Iterable

- Requirement on the specifications of all methods that mutate the Iterable

## Another research topic

- How to apply specs to groups of methods?
- Would like the default to be such that forgetting to add a specification causes warnings
- history constraints impose a requirement on all methods; is there a way to impose a requirement on some methods – and how does one say which ones?:
  - by labeling with a Java annotation?
  - list method names?
  - defining a property?

```
/*@ constraint for (@Modifying)  lastModified > maxIterator; */
/*@constraint except (@NonModifying) lastModified>maxIterator;*/
```

# Ghost fields vs. model fields

- Ghost fields are additional spec-only fields
- Model fields are abstractions of the state
- Both work fine for static checking
- Both need implementations for runtime checking, inconvenient especially for classes without source
  - Ghost fields: altered through "set" statements (but one does not always have access to the implementation)
  - Model fields: need an implementation in terms of Java or ghost fields (which can be duplicative)

## Testing using Esc/Java2

- Wrote a number of Java classes that utilized these specified interfaces
- Esc/Java2 successfully warned about invalid uses and was quiet about valid uses

# Additional issue

- The validation of the *interface* specifications is through writing test cases and running a code verifier/bug finder.
- No tools to check that the specification is well-covered by the test cases (jmlc does capture some metrics)
- For *classes* there is the implementation to check, but coverage is still unchecked

## Conclusion

- JML and Esc/Java2 “worked” for this part of the iterator problem
- Two research questions:
  - Facilities are needed for specifying sequences of method calls
  - How to write specs that apply to many methods