An introduction to formal specifications and JML

Operation specification

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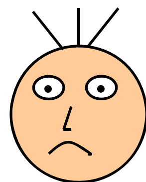
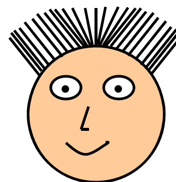
Specifying an operation

- It is often the case that operations are specified by snapshots of the states before and after the operation



Before



After

- This way of specifying operations seems rather intuitive!

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Design by Contract ™ (Bertrand Meyer)

- The specification of an operation is seen as a contract which includes two conditions:
  - The post-condition describes a condition that the operation should establish in the final state
  - The pre-condition (optional) describes under which condition the operation should establish the post-condition
- If the pre-condition is not verified, the contract is not valid, and nothing is guaranteed in the post-state.

« Design by Contract » is a registrated trademark of Eiffel Software in the USA.

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Contracts with invariants

- Invariants are implicitly added to the pre- and post-conditions.
- In the following example, the post-condition refers to « contains » which itself returns a correct result only if the invariant is true.

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Postcondition: ensures

- The postcondition uses keyword **ensures**

```
//@ ensures contains(v);
public void insert(int v){…}

//@ ensures !contains(v);
public void delete(int v){…}
```

- Here, the post-condition of **insert(v)** guarantees that **v** will be an element of the set at the end of the operation!
- Moreover, the invariant will also be true!

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Contains(v)

- **contains(v)** is a pure boolean method which checks that **v** is an element of the tree.

```
public /*@ pure @*/ boolean contains(int v){
   if (val == null) {return false;}
   else if (v == val.intValue()) {return true;}
   else if (v > val.intValue() && (rtree!= null))
            {return rtree.contains(v);}
   else if (v < val.intValue() && (ltree!= null))
            {return ltree.contains(v);}
   else {return false;}
       }
```

- It assumes that the tree is sorted, as described in the invariant.

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Incomplete post-conditions

- As will be experimented in the exercises, the specifications of **`insert`** and **`delete`** are correct but incomplete.
- Additional properties will be specified later.

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Pre-condition: requires

- Some operations cannot be applied in any initial state:
  - Because they would be unable to produce a result
  - Because they would end in an infinite loop or a run-time error.
- It is the case for **`min()`** and **`max()`** which only return a result if the set is not empty.

```
//@ requires !emptySet();
   public /*@ pure @*/ int max(){…}
```

- The pre-condition uses keyword **`requires`**

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What means a pre-condition?

- It means that the operation expects the property to be true.
- If the property is false, nothing is guaranteed!
- For example, when refueling your car, it is forbidden to:
  - Smoke
  - Let your engine run
  - Give a phone call
- If you don't obey these rules, it is not guaranteed that the refueling will proceed safely.

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Inconclusive tests

- What do we learn from a test case which calls an operation without verifying its pre-condition?
- Nothing!
- For example, if you call max() on an empty set, you will get a run-time error!
- If you compile max() with jmlc, it will not execute the code, but raises an exception inside the pre-condition

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Example of such a test

- The following test raises an EntryPrecondition error. The code of **max()** was not executed!

```
@Test
public void  testSequence_0() {
      SetAsTree s=new SetAsTree();
      int m = s.max();
}
```

```
1) testSequence_0(…)
org.jmlspecs.jmlrac.runtime.JMLEntryPreconditionError:
by method SetAsTree.max regarding specifications at
File "SetAsTree.java", line 111, character 29 when
      'this' is  null
      at SetAsTree.checkPre$max$SetAsTree(SetAsTree.java:2713)
      at SetAsTree.max(SetAsTree.java:2807)
```

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EntryPrecondition error

- Tests with an EntryPrecondition error are inconclusive, i.e. they neither reveal an error in the code nor in the specification.
- Inconclusive tests are simply useless test cases!
- For example, if you test your car under water, you will learn nothing about its conformance to its specification!

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InternalPrecondition error

- Precondition errors may also result from an erroneous use of **`max()`** in the code of another operation (e.g. **`delete`**).

```
public void delete(int v){
…
if (!ltree.emptySet()){
      int newVal = ltree.max();
      // take the largest element of the left tree
      ltree.delete(newVal);
      // remove it from the left tree
   …}
```

- If the programmer forgets to test that the ltree is not empty, this code may result in a false precondition for max().
- In this case, it corresponds to a programming fault!
- Therefore JML will return an InternalPrecondition error.

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Declarative specification

- The pre- and post-condition specify what should be done, but not how to do it.
- The code is responsible to fulfill the specification.
- Several codes are acceptable, provided that the pre/post conditions are verified.
- This allows evolutions and optimisations of the code, provided they conform to the specification.

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Towards more complete post-conditions

Incomplete post-conditions

- The current post-condition of **`insert`** and **`delete`** does only express that v is or is not in the tree.
- But it does not tell what happened to the other values in the tree!
- So the following trivial implementation of **`insert`** conforms to the specification!

```
//@ ensures contains(v);
    public void insert(int v){
     val =new Integer(v);
     ltree = null;
     rtree = null;
    }
```

An informal but more complete specification

- A more complete specification:

« The set contains v and the other elements of the set remain in the set »

- This specification expresses a property which links two states:
  - The initial state where the operation started
  - The final state where the operation ended
- The post-condition is expressed in the final state.
- We need a construct to refer to the initial state in the post-condition!

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\old(expression)

- The JML `\old` construct returns the value of its expression in the initial state.
- \old may only be used in post-conditions.

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Evolution of the number of elements (1)

- **`insert`** and **`delete`** modify the number of elements in the tree
- Let us define a **`size()`** method:

```
public /*@ pure @*/ int size(){
    int size = 1;
    if (val==null){return 0;}
    else {if (ltree != null){size+=ltree.size();};
          if (rtree != null){size+=rtree.size();};
          return size;
         }
  }
```

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Evolution of the number of elements (2)

- Inserting an element will increase the number of elements by one or leave it unchanged (if the element was already in the tree).
- We can thus express the following post-condition for **`insert`**

```
//@ ensures contains(v);
/*@ ensures size() == \old(size())+1
  @         || size() == \old(size());
  @*/
public void insert(int v){…}
```

- This condition forbids some trivial implementations of the specification.

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Evolution of the number of elements (3)

- The post-condition may even be more precise.

```
//@ ensures contains(v);
//@ ensures \old(contains(v)) ==> size() == \old(size());
//@ ensures \old(!contains(v))==> size() == \old(size())+1;
public void insert(int v){…}
```

- `A ==> B` means that A implies B, it is equivalent to `!A || B`

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Limits of the current specification

- The post-condition simply constrains the number of elements in the tree,…
- …, but not the values of these elements.

- The following specification keeps the values of old elements.

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Converting to another set…

- The following method converts the tree to a HashSet

```
public /*@ pure @*/ HashSet toHashSet(){
  HashSet hs = new HashSet();
  if (val==null){return hs;}
  else { hs.add(val) ;
         if (ltree != null){hs.addAll(ltree.toHashSet());};
         if (rtree != null){hs.addAll(rtree.toHashSet());};
         return hs;
       }
   }
```

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Post-condition based on HashSet

- The following post-condition ensures that
  - The new value is in the set
  - The old values remain in the set
  - No other value is added to the set

```
//@ ensures contains(v);
//@ ensures \old(contains(v)) ==> size() == \old(size());
//@ ensures \old(!contains(v))==> size() == \old(size())+1;
//@ ensures toHashSet().containsAll(\old(toHashSet()));
    public void insert(int v){…}
```

- This specification is complete, but relies on an equivalent data structure (HashSet).

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Computing the sum of elements

- The value of each element of the tree contributes to the sum of its elements.

```
public /*@ pure @*/ int sum(){
        if (val==null){return 0;}
        else { int s = val.intValue() ;
            if (ltree != null){s+=ltree.sum();};
            if (rtree != null){s+=rtree.sum();};
            return s;
        }
    }
```

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Postcondition based on the sum

- The following specification is not complete, but rather constraining and does not rely on an equivalent data structure.

```
//@ ensures contains(v);
//@ ensures \old(contains(v)) ==> size() == \old(size());
//@ ensures \old(!contains(v))==> size() == \old(size())+1;
//@ ensures \old(contains(v)) ==> sum() == \old(sum());
//@ ensures \old(!contains(v))==> sum() == \old(sum())+v;
public void insert(int v){…}
```

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\old and references to objects

- Take care that `\old` takes an expression as argument.
- If the expression is the name of an object, it returns the address of the object, and not its value!
- The address of the object is the same in the initial and final state: `\old(s)==s`
- If the postcondition needs to compare the value of the object, make sure you return its value, and not its address!

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Example of wrong use of \old

```
public static StringBuffer s = new StringBuffer("abc");

public static void duplicate(){
   s.append(s);
}
```

- Calling `duplicate()` changes s to « abcabc »
- Correct specification:
  `//@ ensures s.length() == \old(s.length())*2;`
- Incorrect specification:
  `//@ ensures s.length() == \old(s).length()*2;`

Exception … JMLInternalNormalPostconditionError:
by method DuplicateStringBuffer.duplicate … when
'\old(s)' is abcabc

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Specifying methods with a return value

- The post-condition specifies the final state, but also the result of a method.
- \result can be used in the post-condition to refer to the result of the method.
- For example, here is a specification of min (taking into account that min is computed recursively)

```
//@ requires !emptySet();
//@ ensures contains(\result) && \result <= val.intValue();
//@ ensures ltree != null ==> \result != val.intValue();
 public /*@ pure @*/ int min(){…}
```

- The third line forbids the trivial case where the value of the root is returned.

Some JML abbreviations

- The following notations can be used in JML assertions:

`==>`	implication
`<==`	inverse implication
`<==>`	if and only if
`<=!=>`	not if and only if

- Other keywords can be found in the JML reference manual.

Quantifiers (1)

- JML provides several quantifiers for assertions.

```
public int[] table = {1,2,3,4,5};

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

- They can be used to express a property on several objects.
- Without quantifiers, this would be expressed in the code of an iterative Java method.

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Quantifiers (2)

- A quantified expression is of the form:
- (\quantifier declaration ; boolean expr ; boolean expr)
  - The quantifier is one of (\forall, \exists, \num_of)
  - The declaration introduces the quantified variable
  - The first boolean expression constrains the range of the quantified variable
  - The second boolean expression is evaluated on all elements of the range

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Non-executable quantification

- Please note that the range expression must be of the form
  `A<i && i<B` (< may be replaced by <=)
  or `JMLCollection.has(i)`

  to be executable.
- Other boolean expressions used as range expressions are syntactically correct but will not be used by the run-time assertion checks.
- Example of non executable quantification

```
//@ public invariant (\forall int i; true; i!=0);
```

File "Quantifiers.java", line 12, character 30 warning: This quantifier is not executable.

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Other examples of quantifiers

- Existential quantifier

```
/*@ ensures
  @ (\exists int i; 0 <= i && i < table.length;
  @                   table[i] == \result);
  @*/
public int choose_one(){…}
```

- Number of elements satifying a property

```
/*@ ensures
  @ \result == (\num_of int i; 0 <= i && i < table.length;
  @                   table[i]%2 == 0);
  @*/
public int nb_even(){…}
```

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Other JML keywords

- There exist other JML keywords for boolean expressions and quantifiers.
- They will not be used in this course.

- Please refer to the JML Reference manual for a more complete information.

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Visibility of assertions and variables

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Visibility of variables and assertions

- In Java, variables and methods can be declared as **`public`**, **`protected`** or **`private`**
- JML specifications are usually public but may refer to private variables.
- Such private variables must be declared as **`/*@ spec_public @*/`**

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Private invariants

- There are not many cases where invariants should be kept private.
- The main case is
  - when there is an inheritance relation between two classes
  - Private invariants are not inherited
  - So, choose private invariants to express a property on public variables that should not be inherited.

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Example of spec_public variable

```
public class Visibility {
    private /*@ spec_public @*/ int x;
    //@ public invariant x > 0;

    //@ requires v > 0;
    //@ ensures x == v;
    public Visibility(int v){
     x = v;
    }

    //@ ensures \result == x;
    public int getX(){
     return x;
    }
```

x is declared private to restrict its access to getters and setters

x is used in the public specification of public operations. It must thus be visible in JML (spec_public)

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