Formal Methods for Java

Lecture 5: JML and Abstract Data Types

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The Java Modelling Language (JML)

JML is a behavioral interface specification language (BISL) for Java

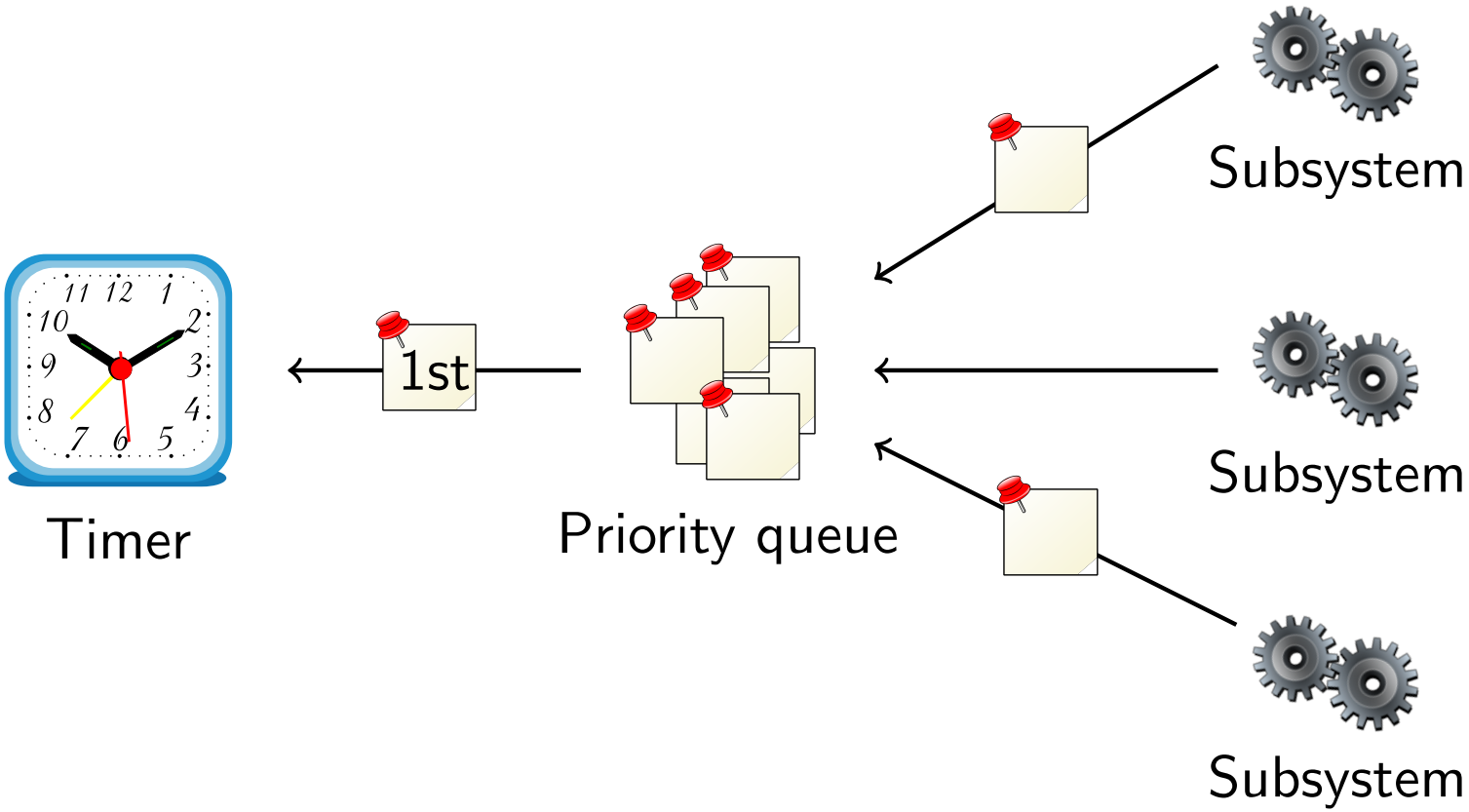
- Proposed by G. Leavens, A. Baker, C. Ruby:
  JML: A Notation for Detailed Design, 1999
- It combines ideas from two approaches:
  - Eiffel with it's built-in language for Design by Contract (DBC)
  - Larch/C++ a BISL for C++

The Roots of JML

- Ideas from Eiffel:
  - Executable pre- and post-condition (for runtime checking)
  - Uses Java syntax (with a few extensions).
  - Operator `\old` to refer to the pre-state in the post-condition.
- Ideas from Larch:
  - Describe the state transformation behavior of a method
  - Model Abstract Data Types (ADT)

JML and Abstract Data Types

Running Example: A priority queue



- Subsystems request timer events and queue them.
- First timer event is passed to the timer.
- Priority queue maintains events in its internal data structure.

Interface for Priority Queue

```
public interface PriorityQueue {

  public void enqueue(Comparable o);

  public Comparable removeFirst();

  public boolean isEmpty();

}
```

Adding (Incomplete) Specification

```
public interface PriorityQueue {

  /*@ public normal_behavior
    @  ensures !isEmpty();
    @*/
  public void enqueue(Comparable o);

  /*@ public normal_behavior
    @  requires !isEmpty();
    @*/
  public Comparable removeFirst();

  public /*@pure@*/ boolean isEmpty();

}
```

Why is Specification Incomplete?

The specification allows undesired things.

- After *removeFirst*() new value of *isEmpty*() is undefined.
- In a correct implementation, after two *enqueue*() and one *removeFirst*() list is not empty.
  Specification does not say so.
- Problem: the internal state is not visible in spec.
- There is no internal state in an interface!

Adding Model Variables

Solution: add a model variable that records the size.

```
public interface PriorityQueue {
  //@ public instance model int size;

  //@ public invariant size >= 0;

  /*@ public normal_behavior
    @  ensures size == \old(size) + 1;
    @*/
  public void enqueue(Comparable o);

  /*@ public normal_behavior
    @  requires !isEmpty();
    @  ensures size == \old(size) - 1;
    @*/
  public Comparable removeFirst();

  /*@ public normal_behavior
    @  ensures \result == (size == 0);
    @*/
  public /*@pure@*/ boolean isEmpty();
}
```

Model Variables

```
//@ public instance model int size;
```

- The keyword `instance` is the opposite of `static`.
- The keyword `model` denotes a variable that only exists in the specification.
- Public model variables can be accessed by other classes.
- Only specification can access model variables (read-only).
- If a model variable is accessed in code, the compiler complains.

Visibility in JML

```
//@ public instance model int size;
...
/*@ public normal_behavior
  @  ensures \result == (size == 0);
  @*/
public /*@pure@*/ boolean isEmpty();
```

Why is size public?

- The external interface must be public.
- The specification is part of the interface.
- To understand the specification one needs to know about *size*.
- Therefore, *size* is public.

Implementing the Specification

```
public class Heap implements PriorityQueue {
  private Comparable[] elems;
  private int numElems;

  //@ private represents size <- numElems;

  public void enqueue(Comparable o) {
    elems[numElems++] = o;
    ...
  }

  public Comparable removeFirst() {
    ...
    return elems[--numElems];
  }

  public isEmpty() {
    return numElems == 0;
  }
}
```

Representing Model variables

Every model variable in a concrete class must be represented:

```
//@ private represents size <- numElems;
```

The expression can also call pure functions:

```
//@ private represents size <- computeSize();
```

How to Model Internal Structure?

- Specification is still incomplete.
- Which values are returned by *removeFirst*()?
- We need a model variable representing the queue.
- JML defines useful types to model complex data structures.

The JML Collection Classes

JML defines its own collection classes for several reasons

- They were introduced before Java had its own collection classes.
- They are functional and have no side-effects.
- They are pure and can be used in specifications.
- They distinguish more cleanly between objects and values.

org.jmlspecs.models.JMLCollection

The base interface is *org.jmlspecs.models.JMLCollection*.

- Similar to *java.util.Collection*.
- Method *size*() returns the size of the collection.
- Method *iterator*() returns an iterator.
- Containment check is implemented by *has*().

The Collection Classes

`http://www.cs.iastate.edu/~leavens/JML-release/javadocs/org/jmlspecs/models/package-summary.html`

The collection classes are

- *JMLxxxBag*: corresponds to java.util.Collection.
- *JMLxxxSet*: corresponds to java.util.Set.
- *JMLxxxSequence*: corresponds to java.util.List.
- *JMLxxxToxxxRelation*: corresponds to java.util.Map.

The *xxx* is one of

- *Object* to denote that elements are compared with ==.
- *Equals* to denote that elements are compared with *equals*().
- *Value* to denote that elements are compared with *equals*() and are cloned before they are stored.

Running Example: Model for Internal Structure

```
//@ model import org.jmlspecs.models.JMLObjectBag;
public interface PriorityQueue {
  //@ public instance model JMLObjectBag queue;

  /*@ public normal_behavior
    @  ensures queue.equals(\old(queue).insert(o));
    @  modifies queue;
    @*/
  public void enqueue(Comparable o);

  /*@ public normal_behavior
    @  requires !isEmpty();
    @  ensures \old(queue).has(\result)
    @       && queue.equals(\old(queue).remove(\result))
    @       && (\forall java.lang.Comparable o;
    @             queue.has(o); \result.compareTo(o) <= 0);
    @  modifies queue;
    @*/
  public Comparable removeFirst();

  /*@ public normal_behavior
    @  ensures \result == (queue.isEmpty());
    @*/
  public /*@pure@*/ boolean isEmpty();
}
```

How Does It Work?

For objects, e.g., `\old(this) == this`, since `\old(this)` is the old pointer not the old content of the object.

Why does it work as expected with `\old(queue)`?

- `JMLObjectBag` is immutable
- The *insert* method is declared as
  ```
  public /*@pure@*/ JMLObjectBag insert(/*@nullable@*/ Object elem)
  ```
  Compare this to the *add* method of List:
  ```
  public void add(/*@nullable@*/ Object elem)
  ```
- *insert* returns a reference to a new larger list.
- The content of `\old(queue)` never changes, but *queue* changes.

Representing by a Pure Function

```
import org.jmlspecs.models.JMLObjectBag;
public class Heap implements PriorityQueue {
  private Comparable[] elems;  //@ in queue;
  private int numElems;        //@ in queue;

  //@ private represents queue <- computeQueue();

  private /*@pure@*/ JMLObjectBag computeQueue() {
    JMLObjectBag bag = new JMLObjectBag();
    for (int i = 0; i < numElems; i++) {
      bag = bag.insert(elems[i]);
    }
    return bag;
  }

  ...
}
```

Representing by a Ghost Variable

```
import org.jmlspecs.models.JMLObjectBag;
public class Heap implements PriorityQueue {
  private Comparable[] elems;  //@ in queue;
  private int numElems;        //@ in queue;

  //@ private ghost JMLObjectBag ghostQueue; in queue;
  //@ private represents queue <- ghostQueue;

  public void enqueue(Comparable o) {
    //@ set ghostQueue = ghostQueue.insert(o);
    ...
  }

  public Comparable removeFirst() {
    ...
    //@set ghostQueue = ghostQueue.remove(first);
    return first;
  }
```

The assignable Problem

```
//@ model import org.jmlspecs.models.JMLObjectBag;

public interface PriorityQueue {
    //@ public instance model JMLObjectBag queue;

    /*@ normal_behavior
      @  ensures queue.equals(\old(queue).insert(o));
      @*/
    public void enqueue(/*@non_null@*/ Comparable o);
    ...
```

When compiling it, it produced a warning:

```
>jmlc -Q PriorityQueue.java
File "PriorityQueue.java", line 7, character 24 caution:
A heavyweight specification case for a non-pure method
has no assignable clause [JML]
```

Lets add a assignable clause.

Adding assignable.

What does the function enqueue change?
It changes the model variable *queue* and nothing else.

```
//@ model import org.jmlspecs.models.JMLObjectBag;

public interface PriorityQueue {
    //@ public instance model JMLObjectBag queue;

    /*@ normal_behavior
      @  ensures queue.equals(\old(queue).insert(o));
      @  assignable queue;
      @*/
    public void enqueue(/*@non_null@*/ Comparable o);
    ...
```

However, when compiling Heap.java:

```
File "Heap.java", line 50, character 29 error: Field "numElems"
is not assignable by method "Heap.enqueue( java.lang.Comparable )";
only fields and fields of data groups in set "{queue}" are
assignable [JML]
```

Mapping Variables To Model Variables.

We have to tell JML that *elem* and *numElems* are the implementation of the model variable *queue*.
There is a special JML syntax:

```
import org.jmlspecs.models.JMLObjectBag;

public class Heap implements PriorityQueue {
    private Comparable[] elems; //@ in queue;
    private int numElems;     //@ in queue;

    /*@ private represents queue <- computeQueue(); @*/
    ...
```

Datagroups

- Every model variable forms a data group.
- Other variables in the class or in sub-classes can be associated with this data group.
- Functions with specification `assignable` *queue*, where *queue* is a datagroup, may modify any variable in this group.

More About Datagroups

- There is a special data group *objectState*, which should represent the object state.
- All variables should be added to this group (but they are rarely).
- Adding a datagroup to another datagroup works recursively:

```
//@ model import org.jmlspecs.models.JMLObjectBag;

public interface PriorityQueue {
    //@ public instance model JMLObjectBag queue; //@ in objectState;
```

After this change *numElems* and *elems* are also automatically contained in *objectState*.

Datagroups Group Data

Datagroups are useful to group variables.

```
class Calendar {
  //@ model JMLDataGroup datetime; in objectState;
  //@ model JMLDataGroup time, date; in datetime;
  int day,month,year; //@ in date;
  int hour,min,sec; //@ in time;
  int timezone;     //@ in objectState;
  Locale locale;    //@ in objectState;

  ...
  //@ assignable datetime;
  void setDate(Date date);

  //@ assignable timezone;
  void setTimeZone();
```

This avoids listing the variables again.

Datagroups and Visibility

Datagroups and model variables are useful for visibility issues:

```
class Tree {
  //@ public model JMLDataGroup content; in objectState

  private Node rootNode; //@ in content

  //@ assignable content;
  public void insert(Object o);
```

Using `assignable rootNode` would produce an error.