Formal Methods for Java

Lecture 4: 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++

Semantics of Specification

```
/*@ requires x >= 0;
  @ ensures \result <= Math.sqrt(x) && Math.sqrt(x) < \result + 1;
  @*/
public static int isqrt(int x) {
  body
}
```

Whenever the method is called with values that satisfy the requires-formula and the method terminates normally then the ensures-formula holds.
For all executions of the method,

$$(Norm, heap, lcl) \xrightarrow{body} (Ret, heap', lcl'),$$

if $lcl(x) >= 0$ then the formula

$$lcl'(\backslash result) <= Math.sqrt(lcl(x)) < lcl'(\backslash result) + 1$$

holds.

What About Exceptions?

```
/*@ requires true;
  @ ensures \result <= Math.sqrt(x) && Math.sqrt(x) < \result + 1;
  @ signals (IllegalArgumentException) x < 0;
  @ signals_only IllegalArgumentException;
  @*/
public static int isqrt(int x) {
  body
}
```

For all transitions

$$(Norm, heap, lcl) \xrightarrow{body} (Exc(v), heap', lcl')$$

where *lcl* satisfies the precondition and v is an Exception, v must be of type IllegalArgumentException. Furthermore, *lcl* must satisfy $x < 0$.
The code is still allowed to throw an Error like a OutOfMemoryError or a ClassNotFoundError.
If no signals_only clause is specified, JML assumes a sane default value: The method may throw only exceptions it declares with the `throws` keyword (in this case none).

Side-Effects

A method can change the heap in an unpredictable way.
The assignable clause restricts changes:

```
/*@ requires x >= 0;
  @ assignable \nothing;
  @ ensures \result <= Math.sqrt(x) && Math.sqrt(x) < \result + 1;
  @*/
public static int isqrt(int x) {
  body
}
```

For all executions of the method,

$$(Norm, heap, lcl) \xrightarrow{body} (Ret, heap', lcl'),$$

if $lcl(x) >= 0$ then the formula

$$lcl'(\backslash result) <= Math.sqrt(lcl(x)) < lcl'(\backslash result + 1)$$

holds and $heap = heap'$.

Lightweight vs. Heavyweight Specifications

A lightweight specification

```
/*@ requires P;
  @ assignable X;
  @ ensures Q;
  @*/
public void foo() throws IOException;
```

is an abbreviation for the heavyweight specification

```
/*@ public behavior
  @   requires P;
  @   diverges false;
  @   assignable X;
  @   ensures Q;
  @   signals_only IOException
  @*/
public void foo() throws IOException;
```

Making Exceptions Explicit

```
/*@ public normal_behavior
  @   requires x >= 0;
  @   assignable \nothing;
  @   ensures \result <= Math.sqrt(x) && Math.sqrt(x) < \result + 1;
  @ also
  @ public exceptional_behavior
  @   requires x < 0;
  @   assignable \nothing;
  @   signals (IllegalArgumentException) true;
  @*/
public static int isqrt(int x) throws IllegalArgumentException {
  if (x < 0)
     throw new IllegalArgumentException();
  body
}
```

Making Exceptions Explicit (2)

- If several specification are given with also, the method must fulfill all specifications.
- A specification with normal_behavior implicitly has the clause

```
signals (java.lang.Exception) false
```

  so the method may not throw an exception.
- A specification with exceptional_behavior implicitly has the clause

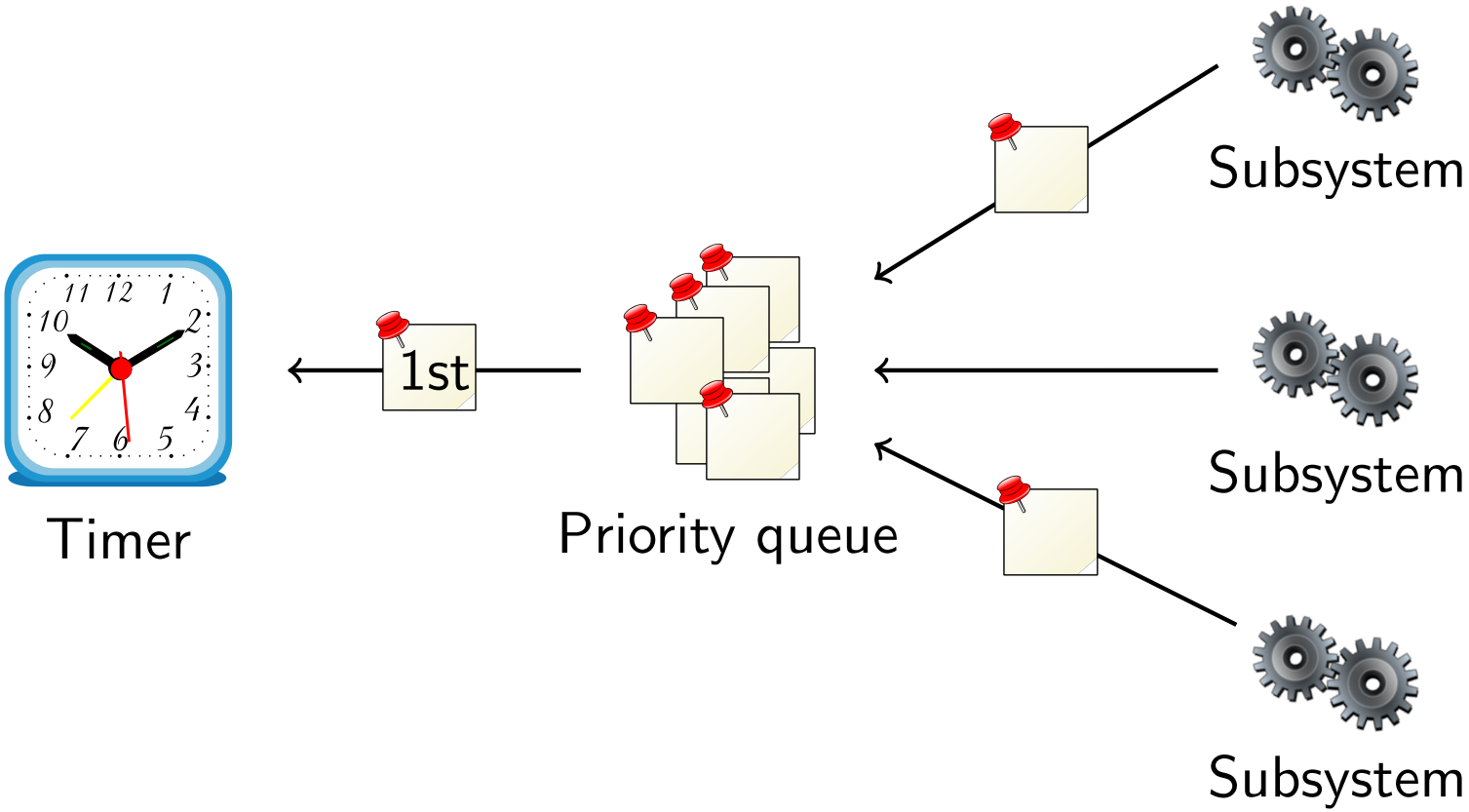
```
ensures false
```

  so the method may not terminate normally.

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)

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.

Priority Queue Interface

```
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 not even 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;
```

- Model variables 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.

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();
}
```

What is JMLObjectBag?

- `org.jmlspecs.models.JMLObjectBag` is a pure class.
  It has pure function and no references to non-pure classes.
- Therefore, it can be used in specifications.
- There are lot of other classes:
  `http://www.cs.iastate.edu/~leavens/JML-release/javadocs/org/jmlspecs/models/package-summary.html`