UTA

JML

- Introduction
- Fundamental Concepts
- JML Specifications
- Summary

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What is JML?

- A behavioral interface specification language for Java
  - The syntactic interface specifies the signature of a method
  - The behavior interface specifies what should happen at runtime
- Combines the practicality of DBC languages and the formality of model-based specification language

Type Specification

- JML can be used to specify an abstract data type
  - Abstract fields can be specified using model or ghost fields
  - The behavior of each method can be specified using method specifications
  - Invariants and constraints can be specified to further refine the behavior of an ADT

Method Specification

- A method specification consists of three components
  - Precondition – a logic assertion that specifies the states in which a method can be called
  - Frame Axiom – the set of locations that can be updated
  - Normal post-condition – a logic assertion that specifies the states that may result from normal return
  - Exceptional post-condition – a logic assertion that specify the states that may result when an exception occurs

An Example

```
package org.jmlspecs.samples.jmlrefman;              // line 1
                                                     // line 2
public abstract class IntHeap {                      // line 3
                                                     // line 4
   //@ public model non_null int [] elements;        // line 5
                                                     // line 6
   /*@ public normal_behavior                        // line 7
      @   requires elements.length >= 1;             // line 8
      @   assignable \nothing;                       // line 9
      @   ensures \result                            // line 10
      @       == (\max int j;                        // line 11
      @             0 <= j && j < elements.length;   // line 12
      @             elements[j]);                    // line 13
      @*/                                            // line 14
   public abstract /*@ pure @*/ int largest();       // line 15
                                                     // line 16
   //@ ensures \result == elements.length;           // line 17
   public abstract /*@ pure @*/ int size();          // line 18
};                                                   // line 19
```


Why JML?

- Supports the powerful concept of design by contract
  - Record details of method responsibilities
  - Help to assign blames
  - Avoids inefficient defensive checks
  - Supports modular reasoning
  - Enables automatic tool support
  - Can be used to document detailed designs

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Defensive Checks

Suppose that you are writing a method to implement binary search. Can you think of any requirement that must be satisfied before calling this method?

```
/*@ requires a != null
  @           && (\forall int i;
  @                  0 < i && i < a.length;
  @                  a[i-1] <= a[i]);
  @ */
int binarySearch (int[] a, int x) {
}
```


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Why not just code?

Code contains all the information. So, why additional specification?

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Tool Support

- jmlc – JML Compiler which can compile annotated Java programs into bytecode. The compiled code includes runtime assertion checking.
- jmlunit – A unit testing tool that combines JML and JUnit. The tool uses code generated by jmlc to check the test results.
- jmldoc – Generate documentation for annotated programs.
- escjava – Check JML annotations statically for potential bugs such as null pointer and out of array bounds.
- jml – A faster substitute of jmlc. It checks JML annotations but does not generate code.

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Model and Ghost

- A feature declared with model is only present for the purpose of specification
  - A model field is an abstraction of one or more concrete Java fields
  - Model methods and types are used to help specification
  - A model field is connected to one or more concrete fields, whereas model methods and types are simply imaginary
- A ghost field is also only present for the purpose of specification
  - Unlike a model field, a ghost field has no connection to concrete fields.

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Lightweight vs Heavyweight

- JML allows both heavyweight and lightweight specs
  - A lightweight spec. only specifies important aspects that are of interest,
  - A heavyweight spec. can only omit parts of a specification when the default behavior is believed appropriate
- A specification is heavyweight if it starts with the following keywords: normal_behavior, exception_behavior, or behavior

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Visibility (1)

- The context of an annotation is the smallest grammatical unit that has an attached visibility and that contains the annotation
  - For instance, the annotation context of a pre-/post-condition is the method
- An annotation cannot refer to names that are more hidden than the visibility of the annotation context
  - For instance, public clients should be able to see all the names in publicly visible annotations

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Visibility (2)

- An expression in a public annotation context can refer to x only if x is declared as public.
- An expression in a protected annotation context can refer to x only if x is declared as public or protected, and x must be visible according to Java's rules
- An expression in a default visibility annotation context can refer to x only if x is declared as public, protected, or with default visibility, and x must be visible according to Java's rules
- An expression in a private visibility annotation context can refer to x only if x is visible according to Java's rule.

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Visibility (3)

```
public class PrivacyDemoLegalAndIllegal {
    public int pub;
    protected int prot;
    int def;
    private int priv;

    //@ public invariant pub > 0;
    //@ public invariant prot > 0;
    //@ public invariant def > 0;
    //@ public invariant priv < 0;

    //@ protected invariant pub > 1;
    //@ protected invariant prot > 1;
    //@ protected invariant def > 1;
    //@ protected invariant priv < 1;

    //@ invariant pub > 1;
    //@ invariant prot > 1;
    //@ invariant def > 1;
    //@ invariant priv < 1;

    //@ private invariant pub > 1;
    //@ private invariant prot > 1;
    //@ private invariant def > 1;
    //@ private invariant priv < 1;
}
```


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Visible State

- A visible state for an object is one that occurs at one of the following moments:
  - At the end of a non-helper constructor invocation
  - At the beginning of a non-helper finalizer invocation
  - At the beginning or end of a non-helper non-static non-finalizer method invocation
  - At the beginning or end of a non-helper static method invocation
  - When no constructor, destructor, non-static or static method invocation is in progress
- A visible state for a type T if it occurs after static initialization is complete and it is a visible state for some object of type T

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Invariant

- Properties that must hold in all visible states
  - A method or constructor assumes an invariant if the invariant must hold in its pre-state.
  - A method or constructor establishes an invariant if the invariant must hold in its post-state.
  - A method or constructor preserves an invariant if the invariant is both assumed and established.

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Static vs Instance Invariants

- Invariants can be declared static or instance
  - A static invariant cannot refer to the current object or any instance field or any non-static method
  - Instance variants must be established by the constructor of an object and must be preserved by all non-helper instance methods
  - Static invariants must be established by the static initialization of a class, and must be preserved by all non-helper constructors and methods

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Checking Invariants

- Invariants can be checked as follows:
  - Each non-helper constructor of a class C must preserve the static invariants of C and must establish the instance invariant of the object under construction.
  - Each non-helper, non-static, non-finalizer method of a class C must preserve the static invariants of C, and must preserve the instance invariants of the receiver object.
  - Each non-helper static method of a class C must preserve the static invariant of C

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Example

```
package org.jmlspecs.samples.jmlrefman;
public abstract class Invariant {
   boolean [] b;
   //@ invariant b != null && b.length == 6
   //@ assignable b;
   Invariant () {
      b = new boolean [6];
   }
}
```


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Invariants and Exceptions

- Invariant should be preserved in the case of both normal termination and abrupt termination
- If it is expected for an invariant to be violated in case of an exception, then it is suggested either to strengthen the precondition of the method or weaken the invariant.
- If a method has no side effects when it throws an exception, then it automatically preserves all invariants.

Invariants and Inheritance

- A class inherits all the instance invariants specified in its super classes and super interfaces

History Constraints

- History constraints or constraints are restrictions that must hold between a combination of two visible states.

- A method respects a constraint if and only if its pre-state and post-state satisfy the constraint.
  - A constraint declaration may optionally list the methods that must respect the constraint
  - otherwise, the constraint must be respected by all the non-helper methods

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Example

```
package org.jmlspecs.samples.jmlrefman;

public abstract class Constraint {

    int a;
    //@ constraint a == \old(a);

    boolean[] b;

    //@ invariant b != null;
    //@ constraint b.length == \old(b.length) ;

    boolean[] c;

    //@ invariant c != null;
    //@ constraint c.length >= \old(c.length) ;

    //@ requires bLength >= 0 && cLength >= 0;
    Constraint(int bLength, int cLength) {
      b = new boolean[bLength];
      c = new boolean[cLength];
    }
}
```


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Invariants vs Constraints

What are the differences between invariants and constraints?

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A few points ….

- Static constraints should be respected by all constructors and methods, and instance constraints must be respected by all instance methods.
- Constraints should be respected at both normal and abrupt termination.
- Constraints in a class are inherited by its subclasses.
- A method only has to respect a constraint only if its preconditions are satisfied.

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Method Specification

- A method specification consists of three major components:
  - Pre-conditions, Post-conditions (normal and abrupt termination), and Frame conditions
- It can either be heavyweight or lightweight

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Accessibility

- A heavyweight specification may be declared with an explicit modifier
  - The access modifier of a heavyweight specification case cannot allow more access than the method being specified
  - For instance, a public method may have a private specification, but a private method may not have a public specification
- A lightweight specification has the same accessibility as the method being specified

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Example - LWS

```
package org.jmlspecs.samples.jmlrefman;

public abstract class Lightweight {

    protected boolean P, Q, R;
    protected int X;

    /*@ requires P;
      @  assignable X;
      @  ensures Q;
      @  signals (Exception) R;
      @*/
    protected abstract int m() throws Exception;
}
```

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Example - HWS

```
package org.jmlspecs.samples.jmlrefman;

public abstract class Heavyweight {

   protected boolean P, Q, R;
   protected int X;

   /*@ protected behavior
     @   requires P;
     @   diverges \not_specified;
     @   assignable X;
     @   when \not_specified;
     @   working_space \not_specified;
     @   duration \not_specified;
     @   ensures Q;
     @   signals (Exception) R;
     @*/
   protected abstract int m() throws Exception;
}
```


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Behavior Spec. (1)

```
behavior
  requires P;
  diverges D;
  assignable A;
  when W;
  ensures Q;
  signals (E1 e1) R1;
  ...
  signals (En en) Rn;
also
code_contract
  accessible C
  callable p ()
```

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Behavior Spec. (2)

If a non-helper method is invoked in a pre-state that satisfies P and all applicable invariants, then one of the following is true:

- JVM throws an error
- The method does not terminate and the predicate D holds in the pre-state
- The method terminates normally or abnormally
  - Only locations that either did not exist in the pre-state, that are local to the method, or that are either named by A or are dependents of such locations, can be assigned
  - In case of a normal return, Q holds and so do all applicable invariants and constraints
  - In case of an exception of type Ei, Ri holds and so do all applicable invariants and constraints
  - Only locations named in C can be directly accessed by the method
  - Only methods named in p are directly called by the method

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Behavior Spec. (3)

The semantics for a specification case of a helper method is the same as that for a non-helper method, except that:

- The instance invariants for the current object and the static invariants for the current class are not assumed to hold in the pre-state, and do not have to be established in the post-state
- The instance constraints for the current object and the static constraints for the current class do not have to be established in the post-state

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Normal Behavior Spec.

- ❑ A normal behavior spec. is just a behavior spec with an implicit signal clause: signals (java.lang.Exception) false;
  - A normal spec. is indicated by the keyword normal_behavior and cannot have any signals clause
  - Has the same semantics as the behavior spec. with the false signal clause

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Exceptional Behavior Spec.

- ❑A exceptional behavior spec. is just a behavior spec with an implicit ensures clause: ensures false;
  - An exceptional behavior spec. is indicated by the keyword exceptional_behavior and cannot have any ensures clause
  - Has the same semantics as the behavior spec. with the false ensures clause

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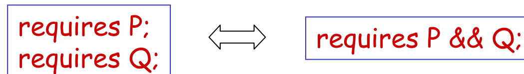
Requires Clause

- A requires clause specifies a precondition of method or constructor
- If there is no requires clause, then the default precondition is \not_specified for a lightweight spec., and is true for a heavyweight spec.



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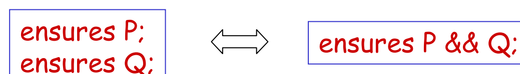
Ensures Clause

- An ensures clause specifies a normal postcondition of a method or constructor
- An ensures clause may contain expressions of form \old(e), which is evaluated at the pre-state
- If there is no ensures clause, then the default precondition is \not_specified for a lightweight spec., and is true for a heavyweight spec.



Signals Clause

- A signals clause specifies a abnormal postcondition of a method or constructor
- A signals clause may contain expressions of form \old(e), which is evaluated at the pre-state
- There can be multiple signal clauses, one for each possible exception
- A signal clause specifies when an exception may be thrown, not when a certain exception must be thrown.

```
signals (E e) P;
```


Diverges Clause (1)

- A diverges clause specified when a method may loop forever or otherwise not return to its caller
- When a diverges clause is omitted, the default diverges condition is \not_specified for a lightweight spec., and false for a heavyweight spec..
- The partial correctness of a method can be reasoned by setting the diverges condition to true.

Diverges Clause (2)

```
package org.jmlspecs.samples.jmlrefman;

public abstract class Diverges {

   /*@ public behavior
     @    diverges true;
     @    assignable \nothing;
     @    ensures false;
     @    signals (Exception) false;
     @*/
   public static void abort();

}
```


Assignable Clauses

- An assignable clause specifies that, from the client's point of view, only the locations named can be assigned by the method
  - Local locations and locations that are created by the method can always be assigned.
- For a lightweight spec., the default list is \not_specified; for a heavyweight spec., the default list is \everything.
- A pure method has an implicit assignable clause: assignable \nothing.

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When Clause

- A when clause specifies when a caller of a method will be delayed until the when condition holds.
- For a lightweight spec., the default when condition is \not_specified; for a heavyweight spec., the default when condition is true.
- A when clause is used to specify the concurrency aspects of a method. Currently, JML provides primitive support for concurrency.

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Built-in Operators (1)

- \result – the return value, can only be used in an ensures clause of a non-void method
- \old(e) – the value obtained by evaluating e at the pre-state
- \not_assigned (x, y, …) – asserts that a list of locations as well as their dependent locations are not assigned
- \not_modified (x, y, …) – asserts that a list of locations are not assigned
- \fresh (x, y, ..) – asserts that objects are newly created, i.e., they do not exist in the pre-state

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Built-in Operators (2)

❑ \nonnullelements – asserts that an array and its elements are all non-null

```
\nonnullelements(myArray)
```

```
myArray != null &&
(\forall int i; 0 <= i && i < myArray.length;
        myArray[i] != null)
```


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Built-in Operators (3)

❑ \typeof – returns the most-specific dynamic type of an expression

❑ \elemtype – returns the most-specific static type shared by all the elements of an array

❑ \type – introduces the literals of type T: \type(PlusAccount) returns PlusAccount

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Built-in Operators (4)

- \forall – the universal quantifier
- \exists – the existential quantifier

```
(\forall int i, j; 0 <= i && i < j && j < 10; a[i] < a[j])
```


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Built-in Operators (5)

- \max – returns the maximum of a range of values
- \min – returns the minimum of a range of values
- \product – returns the product of a range of values
- \sum – returns the sum of a range of values
- \num_of – counts the number of the values that satisfy a certain condition

Built-in Operators (6)

```
(\sum int i; 0 <= i && i < 5; i) == ?
(\product int i; 0 <= i && i < 5; i) == ?
(\max int i; 0 <= i && i < 5; i) == ?
(\min int i; 0 <= i && i < 5; i) == ?
(\num_of in i; <= i && i < 5; i < 3) == ?
```


Statements

- An assert statement states that a condition must be true when the control flow reaches the statement.
- A set statement assigns a value to a ghost variable within annotations
- A unreachable statement asserts that the control flow shall never reach a point
- A debug statement helps debugging by allowing to execute an arbitrary Java expression within an annotation.

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Example

```
//@ assert x > 0;
//@ set i = 0;
//@ set collection.elementType = \type(int);
if (true) {…} else { //@ unreachable; }
//@ debug System.out.println(x);
//@ debug x = x + 1;
```


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Summary

- What is JML? Why JML?
- What is a behavioral interface specification?
- How to specify the behavior of a type in JML?
- How to specify the behavior of a method in JML?
- What is a model field? And a ghost field? How do they differ?
- What is an invariant? And constraints? How do they differ?
- What is a lightweight spec.? And a heavyweight spec.? How do they differ?
- How to specify a normal behavior? How to specify an exceptional behavior?