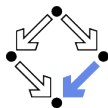


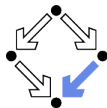
The Java Modeling Language (Part 1)

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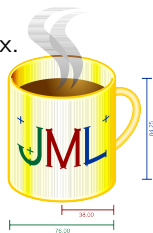


Overview



- Since 1999 by Gary T. Leavens et al. (Iowa State University).
<http://www.jmlspecs.org> <https://www.openjml.org>
- A behavioral interface specification language.
 - Syntactic interface and visible behavior of a Java module (interface/class).
 - Tradition of VDM, Eiffel, Larch/C++.
- Fully embedded into the Java language.
 - Java declaration syntax and (extended) expression syntax.
 - Java types, name spaces, privacy levels.
- JML annotations disguised as Java comments.

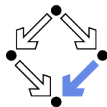
```
//@ ...            (no space between // and @)  
/*@ ...           (no space between /* and @)  
@ ... @*/
```



<https://www.cs.ucf.edu/~leavens/JML/refman/jmlrefman.pdf>

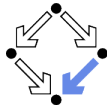
http://www.openjml.org/documentation/JML_Reference_Manual.pdf

Related Work



Related to/influenced by/derived from JML (selection).

- **C#**: Spec# (Spec Sharp).
<http://research.microsoft.com/en-us/projects/specsharp>
 - Plugin for Microsoft Visual Studio 2010.
 - Static checking (non-null types), runtime assertion checking.
 - Verification condition generator (Boogie) for various prover backends.
- **C**: VCC and ACSL (ANSI C Specification Language).
<http://research.microsoft.com/en-us/projects/vcc>
<http://frama-c.com/acsl.html>
 - Microsoft VCC with SMT solver Z3 as backend.
 - Frama-C ACSL framework with various prover backends.
- **Ada**: SPARK.
<http://www.adacore.com/sparkpro>
<https://alire.ada.dev>
 - VC generator and prover (GNATprove with cvc5, Z3, and others).



1. Basic JML

2. JML Tools

3. More Realistic JML

Basic JML



JML as required for the basic Hoare calculus.

- Assertions.

`assume`, `assert`.

- Loop assertions.

`loop_invariant`, `decreases`.

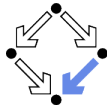
- Method contracts.

`requires`, `ensures`.

- The JML expression language.

`\forall`, `\exists`, ...

Specifying simple procedural programs.



Assertions

- Definition:

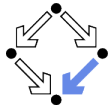
An **assertion** is a command that specifies a property which should always hold when execution reaches the assertion.

- JML: two kinds of assertions.

- `assert P`: P needs verification.
- `assume P`: P can be assumed.
 - Makes a difference for reasoning tools.
 - A runtime checker must test both kinds of assertions.

```
//@ assume n != 0;  
int i = 2*(m/n);  
//@ assert i == 2*(m/n);
```

Low-level specifications.



Loop Assertions

```
int i = n;
int s = 0;
/*@ loop_invariant i+s == n;
  *@ decreases i+1;
while (i >= 0)
{
    i = i-1;
    s = s+1;
}
```

- `loop_invariant` specifies a **loop invariant**, i.e. a property that is true before and after each iteration of the loop.
- `decreases` specifies a **termination term**, i.e. an integer term that decreases in every iteration but does not become negative.

Useful for reasoning about loops.



Assertions in Methods

```
static int isqrt(int y)
{
    //@ assume y >= 0;
    int r = (int) Math.sqrt(y);
    //@ assert r >= 0 && r*r <= y && y < (r+1)*(r+1);
    return r;
}
```

- assume specifies a condition P on the pre-state.
 - **Pre-state**: the program state before the method call.
 - The method **requires** P as the method's **precondition**.
- assert specifies a condition Q on the post-state.
 - **Post-state**: the program state after the method call.
 - The method **ensures** Q as the method's **postcondition**.

Low-level specification of a method.

Design by Contract

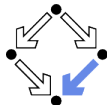


Pre- and post-condition define a **contract** between a method (i.e. its implementor) and its caller (i.e. the user).

- The method (the implementor) may **assume** the precondition and must **ensure** the postcondition.
- The caller (the user) must **ensure** the precondition and may **assume** the postcondition.
- Any method documentation must describe this contract (otherwise it is of little use).

The legal use of a method is determined by its contract (not by its implementation)!

Method Contracts

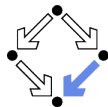


```
/*@ requires y >= 0;
   @ ensures \result >= 0
   @   && \result*\result <= y
   @   && y < (\result+1)*(\result+1); @*/
static int isqrt(int y)
{
    return (int) Math.sqrt(y);
}
```

- **requires** specifies the method **precondition**
 - May refer to method parameters.
- **ensures** specifies the method **postcondition**
 - May refer to method parameters and to result value (`\result`).

Higher-level specification of a method.

Postcondition and Pre-State

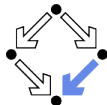


```
// swap a[i] and a[j], leave rest of array unchanged
/*@ requires
  @   a != null &&
  @   0 <= i && i < a.length && 0 <= j && j < a.length;
  @ ensures
  @   a[i] = \old(a[j]) && a[j] == \old(a[i]) &&
  @   (* all a[k] remain unchanged where k != i and k != j *) @*/
static void swap(int[] a, int i, int j)
{ int t = a[i]; a[i] = a[j]; a[j] = t; }
```

- Variable values in **postconditions**:
 - x ... value of x in the post-state (after the call).
 - Except for parameters which are always evaluated in the pre-state.
 - $\text{\old}(x)$... value of x in the pre-state (before the call).
 - $\text{\old}(E)$... value of expression E in the pre-state (in particular, the value of every variable x in E comes from the pre-state).

Variable values may change by the method call.

Data Structures in Postconditions

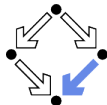


If we want to dereference in a postcondition the pre-state version of a data structure (i.e., if we want to read some element in it), we must write the **complete dereferencing expression** E in the form $\backslash\text{old}(E)$.

- **Hidden store s :** $a[i] \rightsquigarrow a[i]_s$
 - Pointer a is evaluated, some offset $i \cdot K$ is added.
 - The memory cell at the resulting address is read from store s .
- **Correct:** $\backslash\text{old}(a[i]) \rightsquigarrow \backslash\text{old}(a[i]_s)$.
 - The memory cell is read from the **pre-state store s** .
- **Incorrect:** $\backslash\text{old}(a)[\backslash\text{old}(i)] \rightsquigarrow \backslash\text{old}(a)[\backslash\text{old}(i)]_s$
 - The memory cell is read from the **post-state store s** .

We have to consider Java's "pointer semantics" of data structures (arrays and objects).

The JML Expression Language



■ Atomic Formulas

- Any Java expression of type boolean: `a+b == c`
 - Primitive operators and pure program functions (later).
- Informal property expression: `(* sum of a and b equals c *)`
 - Does not affect truth value of specification.

■ Connectives: `!P`, `P && Q`, `P || Q`, `P ==> Q`, `P <== Q`, `P <==> Q`, `P <!=> Q`

- `¬P`, `P ∧ Q`, `P ∨ Q`, `P ⇒ Q`, `Q ⇒ P`, `P ⇔ Q`, `¬(P ⇔ Q)`.

■ Universal quantification: `(\forall T x; P; Q)`

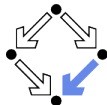
- $\forall x \in T : P \Rightarrow Q$

■ Existential quantification: `(\exists T x; P; Q)`

- $\exists x \in T : P \wedge Q$

Strongly typed first-order predicate logic with equality.

The JML Expression Language (Contd)



- **Sum:** $(\backslash\text{sum } T \ x; P; U)$
 - $\sum_{(x \in T) \wedge P} U$
- **Product:** $(\backslash\text{product } T \ x; P; U)$
 - $\prod_{(x \in T) \wedge P} U$
- **Minimum:** $(\backslash\text{min } T \ x; P; U)$
 - $\min\{U : x \in T \wedge P\}$
- **Maximum:** $(\backslash\text{max } T \ x; P; U)$
 - $\max\{U : x \in T \wedge P\}$
- **Number:** $(\backslash\text{num_of } T \ x; P; Q)$
 - $|\{x \in T : P \wedge Q\}|$
- **Set:** `new JMLObjectSet {T x | P}`
 - $\{x \in T : P\}$

Examples



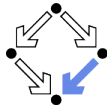
```
// sort array a in ascending order
/*@ requires a != null;
   @ ensures (* a contains the same elements as before the call *)
   @   && (\forall int i; 0 <= i && i < a.length-1; a[i] <= a[i+1]);
   @*/
static void sort(int[] a) { ... }

// return index of first occurrence of x in a, -1 if x is not in a
/*@ requires a != null;
   @ ensures
   @   (\result == -1
   @   && (\forall int i; 0 <= i && i < a.length; a[i] != x)) ||
   @   (0 <= \result && \result < a.length && a[\result] == x
   @   && (\forall int i; 0 <= i && i < \result; a[i] != x));
   @*/
static int findFirst(int[] a, int x) { ... }
```

Examples



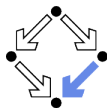
```
// swap a[i] and a[j], leave rest of array unchanged
/*@ requires
  @   a != null &&
  @   0 <= i && i < a.length && 0 <= j && j < a.length;
  @ ensures
  @   a[i] = \old(a[j]) && a[j] == \old(a[i]) &&
  @   (\forall int k; 0 <= k && k < a.length;
  @     (k != i && k != j) ==> a[k] == \old(a[k]));
  @*/
static void swap(int[] a, int i, int j) { ... }
```

1. Basic JML

2. JML Tools

3. More Realistic JML



Common JML Tools (Old)

- Static checker `jml`
 - Checks syntactic and type correctness.
- Runtime assertion checker compiler `jmlc`
 - Generates runtime assertions from (some) JML specifications.
- Executable specification compiler `jmlc`
 - Generates executable code from (some) JML specifications.
- JML skeleton specification generator `jmlspec`
 - Generates JML skeleton files from Java source files.
- Document generator `jmldoc`
 - Generates HTML documentation in the style of `javadoc`.
- Unit testing tool `junit`
 - Generates stubs for the *JUnit* testing environment using specifications as test conditions.

Not any more distributed but available in the course VM.

OpenJML (New)



> openjml ...

- **No option:** syntax and type checker.
 - Replaces jml.
- **Option -rac:** runtime assertion checker compiler.
 - Replaces jmlc.
 - Course VM: commands openjmlrac and openjmlrun.
- **Option -esc:** a program verifier (requires loop invariants).
 - Replaces escjava2 (extended static checking without invariants).
 - Course VM: command openjmlesc.

<https://www.openjml.org>

Other JML Tools



Various other tools use/support JML.

- **ESC/Java2**

- <https://github.com/GaloisInc/ESCJava2>
- An extended static checker.
- Not any more distributed but available in the course VM.

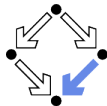
- **KeY**

- <https://www.key-project.org>
- Computer-assisted verification.
- Symbolic execution and debugging.

- ...

<http://www.jmlspecs.org/download.shtml>

Runtime Assertion Checking



```
public class Account {
    private /*@ spec_public @*/ int bal;
    ...

    //@ public invariant bal >= 0;
    /*@ requires amt > 0 && amt <= bal;
        @ assignable bal;
        @ ensures bal == \old(bal) - amt; @*/
    public void withdraw(int amt) {
        bal -= amt;
    }

    public static void main(String[] args) {
        Account acc = new Account(100);
        acc.withdraw(150);
        System.out.println("Balance after withdrawal: " + acc.balance());
    }
}
```

Runtime Assertion Checking



Common JML tools.

```
> jml -Q Account.java
> jmlc -Q Account.java
> jmlrac Account
```

```
Exception in thread "main"
```

```
    org.jmlspecs.jmlrac.runtime.JMLInternalPreconditionError:
    by method Account.withdraw
       at Account.main(Account.java:1486)
```

Violation is reported by throwing an exception.

Runtime Assertion Checking



OpenJML.

```
> openjml Account.java
> openjmlrac Account.java
> openjmlrun Account
java -cp /software/openjml/jmlruntime.jar:. Account
Account.java:48: verify: JML precondition is false
    acc.withdraw(150);
                ^
Account.java:30: verify: Associated declaration: Account.java:48:
    public void withdraw(int amt) {

Balance after withdrawal: -50
```

Violation is reported by a message without aborting the program.

Runtime Assertion Checking



OpenJML is still limited with respect to the runtime assertion checking of ensures clauses with quantified formulas.

```
> openjmlrac Swap.java
Swap.java:14: Note: Not implemented for runtime assertion checking:
  ensures clause containing quantifier variable inside
  a \old or \pre expression: k
    @ ensures (\forall int k; 2 <= k && k < a.length;
              a[k] == \old(a[k]));
```

With the Common JML tools, this clause can be runtime checked.

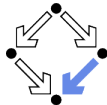
Practical Use



Recommended use with JML-annotated Java files.

- First compile with `javac`.
 - Check syntactic and type correctness of Java source.
- Then compile with `jml` (or `openjml`).
 - Check syntactic and type correctness of JML annotations.
- Then compile with `escjava2` (or `openjml -esc`).
 - Check semantic consistency of JML annotations.
 - More on ESC/Java2 later.

Errors can be made at each level.



1. Basic JML

2. JML Tools

3. More Realistic JML

More Realistic JML



JML for procedural programs with side-effects and errors.

- Side-effects
 - assignable, pure
- Exceptions
 - signals

We also have to deal with the less pleasant aspects of programs.

Side Effects

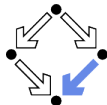


```
static int q, r, x;

/*@ requires b != 0;
    @ assignable q, r;
    @ ensures a == b*q + r && sign(r) == sign(a) &&
    @   (\forall int r0, int q0; a == b*q0+r0 && sign(r0) == sign(a);
    @     abs(r) <= abs(r0)) @*/
static void quotRem(int a, int b)
{ q = a/b; r = a%b; }
```

- assignable specifies the variables that method may change.
- Default: assignable \everything.
 - Method might change **any** visible variable.
- Possible: assignable \nothing.
 - No effect on any variable.

Pure Program Functions

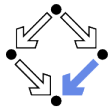


```
static /*@ pure @*/ int sign(int x)
{
  if (x == 0)
    return 0;
  else if (x > 0)
    return 1;
  else
    return -1;
}
```

```
static /*@ pure @*/ int abs(int x)
{ if (x >= 0) return x; else return -x; }
```

- Pure program functions may be used in specification expressions.
 - pure implies assignable \nothing.

JML considers pure program functions as mathematical functions.



Arrays and Side Effects

```
int[] a = new int[10];
```

- **assignable a;**

- The pointer *a* may change.

```
    a = new int[20];
```

- **assignable a[*];**

- The content of *a* may change.

```
    a[1] = 1;
```

```
// swap a[i] and a[j], leave rest of array unchanged
```

```
/*@ requires
```

```
  @ a != null &&
```

```
  @ 0 <= i && i < a.length && 0 <= j && j < a.length;
```

```
  @ assignable a[*];
```

```
  @ ensures
```

```
  @ a[i] = \old(a[j]) && a[j] == \old(a[i]) &&
```

```
  @ (\forall int k; 0 <= k && k < a.length;
```

```
  @   (k != i && k != j) ==> a[k] == \old(a[k]));
```

```
  @*/
```

```
static void swap(int[] a, int i, int j) { ... }
```

Exceptions



```
static int balance;

/*@ assignable balance;
   @ ensures \old(balance) >= amount
   @   && balance = \old(balance)-amount;
   @ signals(DepositException e) \old(balance) < amount
   @   && balance == \old(balance); @*/
static void withdraw(int amount) throws DepositException
{
    if (balance < amount) throw new DepositException();
    balance = balance-amount;
}
```

- This method has two ways to return.
 - **Normal return:** the postcondition specified by ensures holds.
 - **Exceptional return:** an exception is raised and the postcondition specified by signals holds.

Exceptions



- **Default:** `signals(Exception e) true;`
 - Instead of a normal return, method may also raise an exception without any guarantee for the post-state.
 - Even if no `throws` clause is present, runtime exceptions may be raised.
- **Consider:** `signals(Exception e) false;`
 - If method returns by an exception, `false` holds.
 - Thus the method must not raise an exception (also no runtime exception).

We also have to take care to specify the exceptional behavior of a method!

Preconditions versus Exceptions



```
/*@ requires (\exists int x; ; a == x*b);  
   @ ensures a == \result*b; @*/  
static int exactDivide1(int a, int b) { ... }
```

```
/*@ ensures (\exists int x; ; a == x*b) && a == \result*b;  
   @ signals(DivException e) !(\exists int x; ; a == x*b) @*/  
static int exactDivide2(int a, int b) throws DivException { ... }
```

- `exactDivide1` has precondition $P : \Leftrightarrow \exists x : a = x \cdot b$.
 - Method must not be called, if P is false.
 - It is the responsibility of the **caller** to take care of P .
- `exactDivide2` has precondition true.
 - Method may be also called, if P is false.
 - Method must raise `DivException`, if P is false.
 - It is the responsibility of the **method** to take care of P .

Different contracts!

Lightweight Specifications



This is the contract format we used up to now.

```
/*@ requires ...;  
   @ assignable ...;  
   @ ensures ...;  
   @ signals ...; @*/
```

- Convenient form for simple specifications.
- If some clauses are omitted, their value is *unspecified*.

So what does a (partially) unspecified contract mean?

Method Underspecification



If not specified otherwise, **client** should assume **weakest** possible contract:

- `requires false`;
 - Method should not be called at all.
- `assignable \everything`;
 - In its execution, the method may change any visible variable.
- `ensures true`;
 - If the method returns normally, it does not provide any guarantees for the post-state.
- `signals(Exception e) true`;
 - Rather than returning, the method may also throw an arbitrary exception; in this case, there are no guarantees for the post-state.

Defensive programming: for safety, client should avoid implicit assumptions.

Method Underspecification

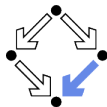


If not specified otherwise, **method** should implement **strongest** possible contract:

- `requires true;`
 - Method might be called in any pre-state.
- `assignable \nothing;`
 - In its execution, the method must not change any visible variable.
- `signals(Exception e) false;`
 - Method should not throw any exception.

Defensive programming: for safety, method should satisfy implicit client assumptions (as far as possible).

Heavyweight Specifications



```
/*@ public normal_behavior
  @ requires ...;
  @ assignable ...;
  @ ensures ...;
  @ also public exceptional_behavior
  @ requires ...;
  @ assignable ...;
  @ signals(...) ...; @*/
```

- A normal behavior and (one or multiple) exceptional behaviors.
 - Method must implement **all** behaviors.
- Each behavior has a separate precondition.
 - What must hold, such that method can exhibit this behavior.
 - If multiple hold, method may exhibit **any** corresponding behavior.
 - If none holds, method must not be called.
- For each behavior, we can specify
 - the visibility level (later), the assignable variables, the postcondition.

Heavyweight Specification Defaults

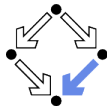


If not specified otherwise, we have the following defaults:

- `requires true`;
 - Method may be called in any state.
- `assignable \everything`;
 - In its execution, the method may change every visible variable.
- `ensures true`;
 - After normal return, no guarantees for the post-state.
- `signals(Exception e) true`;
 - Rather than returning, the method may also throw an arbitrary exception; then there are no guarantees for the post-state.

Method must not make assumptions on the pre-state, caller must not make assumptions on the method behavior and on the post-state.

Example



```
static int balance;

/*@ public normal_behavior
  @ requires balance >= amount;
  @ assignable balance;
  @ ensures balance = \old(balance)-amount;
  @ also public exceptional_behavior
  @ requires balance < amount;
  @ assignable \nothing;
  @ signals(DepositException e) true;
  @*/
static void withdraw(int amount) throws DepositException
{
  if (balance < amount) throw new DepositException();
  balance = balance-amount;
}
```

Clearer separation of normal behavior and exceptional behavior.