# The Java Modeling Language (Part 1)

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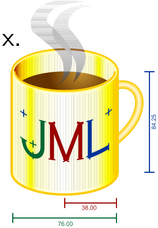
# Overview

- Since 1999 by Gary T. Leavens et al. (Iowa State University).

  www.jmlspecs.org     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.
  - `\old(x)` ... value of `x` in the pre-state (before the call).
  - `\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 derereference 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 `\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: `\old(a[i])` $\rightsquigarrow$ `\old(a[i]`$_s$`)`.
  - The memory cell is read from the pre-state store $s$.
- Incorrect: `\old(a)[\old(i)]` $\rightsquigarrow$ `\old(a)[\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`
  - $\neg P, P \wedge Q, P \vee Q, P \Rightarrow Q, Q \Rightarrow P, P \Leftrightarrow Q, \neg(P \Leftrightarrow Q)$.
- 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: `(\sum` $T$ $x$; $P$; $U$)
  - $\sum_{(x \in T) \wedge P} U$
- Product: `(\product` $T$ $x$; $P$; $U$)
  - $\prod_{(x \in T) \wedge P} U$
- Minimum: `(\min` $T$ $x$; $P$; $U$)
  - $\min\{U : x \in T \wedge P\}$
- Maximum: `(\max` $T$ $x$; $P$; $U$)
  - $\max\{U : x \in T \wedge P\}$
- Number: `(\num_of` $T$ $x$; $P$; $Q$)
  - $|\{x \in T : P \wedge Q\}|$
- Set: `new JMLObjectSet` $\{T\ x \mid P\}$
  - $\{x \in T : P\}$

# 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 `jmle`
  - 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://www.kindsoftware.com/products/opensource/escjava2
  - 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)
```

Violating condition has to be deduced from the context.

# 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) {
              ^
Account.java:27: verify: JML precondition is false
  /*@ requires amt > 0 && amt <= bal;
      ^
Balance after withdrawal: -50
```

Violated condition is explicitly reported.

# 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.

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# 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.