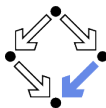


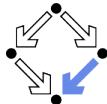
# The Java Modeling Language (Part 1)

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# Overview



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

[www.jmlspecs.org](http://www.jmlspecs.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.

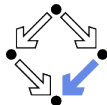
```
//@ ...
```

```
/*@ ...
```

```
@ ... @*/
```



# 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>

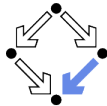
- Microsoft VCC with SMT solver Z3 as backend.
  - Frama-C ACSL framework with various prover backends.

- **Ada:** SPARK.

- <http://www.adacore.com/sparkpro>

- <https://www.adacore.com/community>

- VC generator and prover (GNATprove with CVC4, Z3, Alt-Ergo).

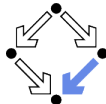


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## 1. Basic JML

## 2. JML Tools

## 3. More Realistic JML



JML as required for the basic Hoare calculus.

- Assertions.

`assume, assert.`

- Loop assertions.

`loop_invariant, decreases.`

- Method contracts.

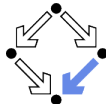
`requires, ensures.`

- 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.

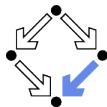
- JML: two kinds of assertions.

- `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.

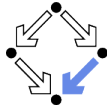
# Loop Assertions



```
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

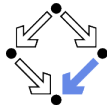
```
static int isqrt(int y)
{
    //@ assume y >= 0;
    int r = (int) Math.sqrt(y);
    //@ assert r >= 0 && r*r <= y && y < (r+1)*(r+1);
    return r;
}
```

- 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

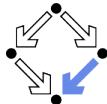


Pre- and post-condition define a **contract** between a method (i.e. its implementor) and its caller (i.e. the user).

- 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

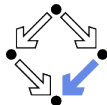


```
/*@ requires y >= 0;
   @ ensures \result >= 0
   @   && \result*\result <= y
   @   && y < (\result+1)*(\result+1); @*/
static int isqrt(int y)
{
    return (int) Math.sqrt(y);
}
```

- **requires** specifies the method **precondition**
  - May refer to method parameters.
- **ensures** specifies the method **postcondition**
  - May refer to method parameters and to result value ( $\backslash\text{result}$ ).

Higher-level specification of a method.

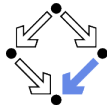
# Postcondition and Pre-State



```
// 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 post-state (after the call).
    - Except for parameters which are always evaluated in the pre-state.
  - $\text{\old}(x)$  ... value of  $x$  in pre-state (before the call).
  - $\text{\old}(E)$  ... expression  $E$  evaluated with the value of every variable  $x$  in  $E$  taken from the pre-state.

Variable values may change by the method call (more on this later).



# 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:  $( * \text{ sum of } a \text{ and } b \text{ equals } c *)$ 
  - 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: $(\backslash\text{forall } T \ x; \ P; \ Q)$

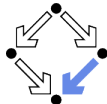
- $\forall x \in T : P \Rightarrow Q$

## ■ Existential quantification: $(\backslash\text{exists } T \ x; \ P; \ Q)$

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

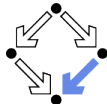
Strongly typed first-order predicate logic with equality.

# 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:**  $\text{new JMLObjectSet } \{T \ x \mid P\}$ 
  - $\{x \in T : P\}$

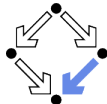
# Examples



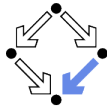
```
// sort array a in ascending order
/*@ requires a != null;
    @ ensures (* a contains the same elements as before the call *)
    @   && (\forall int i; 0 <= i && i < a.length-1; a[i] <= a[i+1]);
    @*/
static void sort(int[] a) { ... }

// 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) { ... }
```



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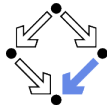
1. Basic JML

2. JML Tools

3. More Realistic JML



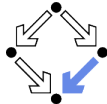
# Common JML Tools



- Type 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 `jml doc`
  - Generates HTML documentation in the style of `javadoc`.
- Unit testing tool `junit`
  - Generates stubs for the *JUnit* testing environment using specifications as test conditions.

Simple GUI launched by `jml-launcher`.

# Example

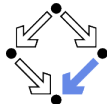


```
public class Account {
    private /*@ spec_public @*/ int bal;
    ...

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

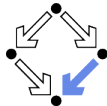
    public static void main(String[] args) {
        Account acc = new Account(100);
        acc.withdraw(200);
        System.out.println("Balance after withdrawal: " + acc.balance());
    }
}
```

# Runtime Assertion Checking



```
> 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)
```

A bit little information.

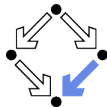


A replacement for the JML toolset (under development).

```
amir!27> openjmlrac Account.java
java -jar /software/openjml/openjml.jar -rac Account.java
Note: /software/openjml/openjml.jar(specs17/java/util/Arrays.jml)
      uses unchecked or unsafe operations.
Note: Recompile with -Xlint:unchecked for details.
amir!28> openjmlrun Account
java -cp /software/openjml/jmlruntime.jar:. Account
Account.java:48: JML precondition is false
        acc.withdraw(200);
                ^
Account.java:27: Associated declaration: Account.java:48:
    /*@ requires amt > 0 && amt <= bal;
        ^
...
Balance after withdrawal: -100
```

<http://openjml.org>.

# Other Third Party JML Tools



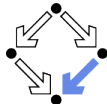
A large number of tools uses/supports JML.

- **Mobius Program Verification Environment**
  - Based on Eclipse, integrates common JML tools and ESC/Java2.
- **Sireum/Kiasan for Java**
  - Automatic verification and test case generation toolset.
- **Modern Jass**
  - Design by contract tool.
- **JMLUnitNG**
  - Test generation tool.
- **ESC/Java2**
  - Extends static checking (later).
- **KeY Verifier**
  - Computer-assisted verification (later).
- ...

Support different versions of JML/Java, for current state, see  
<http://www.jmlspecs.org/download.shtml>

# Practical Use

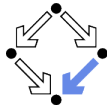
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Recommended use with JML-annotated Java files.

- 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.



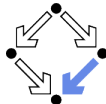
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1. Basic JML

2. JML Tools

**3. More Realistic JML**

# More Realistic JML



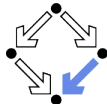
JML for procedural programs with side-effects and errors.

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

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



# Side Effects

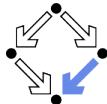


```
static int q, r, x;

/*@ 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

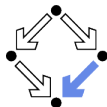


```
static /*@ pure @*/ int sign(int x)
{
    if (x == 0)
        return 0;
    else if (x > 0)
        return 1;
    else
        return -1;
}
```

```
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]) &&
```

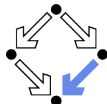
```
    @   (\forall int k; 0 <= k && k < a.length;
```

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

```
    @*/
```

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

# Exceptions

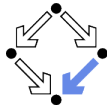


```
static int balance;

/*@ 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.

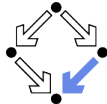
# Exceptions



- **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;
```

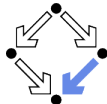
```
  @ signals(DivException e) !(\exists int x; ; a == x*b) @*/
```

```
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



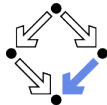
This is the contract format we used up to now.

```
/*@ 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



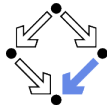
If not specified otherwise, **client** should assume **weakest** possible contract:

- `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

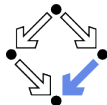


If not specified otherwise, **method** should implement **strongest** possible contract:

- `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).

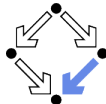
# Heavyweight Specifications



```
/*@ 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

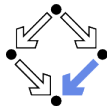


If not specified otherwise, we have the following defaults:

- `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.