Formal Systems II: Applications

Functional Verification of Java Programs: Java Modeling Language

Bernhard Beckert · Mattias Ulbrich | SS 2017
“BISL”

short for

Behavioural Interface Specification Language

- used to describe formally input/output-behaviour of operations
- abstraction from implementation details
  - code structure, algorithms and
  - data structures
- tailored for a particular programming language

Example BISLs:

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Idea

Specifications fix a contract between caller and callee of a method (between client and implementor of a module):

If caller guarantees precondition
then callee guarantees certain outcome

- Interface documentation:
  “Behavioural Interface Specification Language”
- Contracts described in a mathematically precise language (JML)
  - higher degree of precision
  - automation of program analysis of various kinds (runtime assertion checking, static verification)
- Note: Errors in specifications are at least as common as errors in code
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Java comments with ‘@’ as first character are JML specifications
- Within a JML annotation, an ‘@’ is ignored:
  - if it is the first (non-white) character in the line
  - if it is the last character before ‘*/’.
  ⇒ The blue ‘@’s are not required, but it’s a *convention* to use them.
- JML specifications may themselves contain comments
JML Annotations

```java
/*@ public normal_behavior
@ requires pin == correctPin;
@ ensures customerAuthenticated;
@ */

public void enterPIN (int pin) {
    ...
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Visibility Modifiers

```java
public class ATM {
    private /*@ spec_public @*/ BankCard insertedCard = null;
    private /*@ spec_public @*/
        boolean customerAuthenticated = false;

    /*@ public normal_behavior ... @*/
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- Modifiers to specification cases have no influence on their semantics.
- `public` specification items cannot refer to `private` fields.
- Private fields can be declared public for specification purposes only.
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Method Contracts

/*@ requires r;
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T m(...);

Abbreviations

normal_behavior = signals(Exception e) false;
exceptional_behavior = ensures false;

keyword ‘also’ separates the contracts of a method
Method Contracts

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- can be placed anywhere in a class (or interface)
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**Pure Methods**

Pure methods terminate and have no side effects.

Hence, they can be used in JML specifications.

After declaring

```java
public /*@ pure @*/ boolean cardIsInserted() {
    return insertedCard != null;
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\[ \text{pure} \approx \text{diverges false;} + \text{assignable \ nothing;} \]
Expressions

- All Java expressions without side-effects
- $$\Rightarrow, \Leftrightarrow$$: implication, equivalence
- $$\forall$$, $$\exists$$
- $$\text{num of}, \text{sum}, \text{product}, \text{min}, \text{max}$$
- $$\text{old(...)}:$$ referring to pre-state in postconditions
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Quantification in JML

\( \forall \text{int } i; \ 0 \leq i \land i < \text{result.length}; \ \text{result}[i] > 0 \) 
equivalent to 
\( \forall \text{int } i; \ 0 \leq i \land i < \text{result.length} \Rightarrow \text{result}[i] > 0 \)

\( \exists \text{int } i; \ 0 \leq i \land i < \text{result.length}; \ \text{result}[i] > 0 \) 
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- Note that quantifiers bind two expressions, the range predicate and the body expression.
- A missing range predicate is by default true.
- JML excludes null from the range of quantification.
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equivalent to

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(\forall i; 0 \leq i < \text{result}.length; \text{result}[i] \gt 0)\quad \text{equivalent to}\quad (\forall i; 0 \leq i \land i < \text{result}.length \implies \text{result}[i] > 0)

(\exists i; 0 \leq i < \text{result}.length; \text{result}[i] > 0)\quad \text{equivalent to}\quad (\exists i; 0 \leq i \land i < \text{result}.length \land \text{result}[i] > 0)

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\(\forall i; 0 \leq i \land i < \text{result}.\text{length}; \ \text{result}[i] > 0\) equivalent to
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Generalised and Numerical Quantifiers

\( \text{\texttt{num\_of} } T \ i; \ e } \) #\(i[e]\), number of elements of type \( T \) with property \( e \)

\( \text{\texttt{sum} } T \ i; \ p; \ t } \) \( \sum [t] \)

\( \text{\texttt{product} } T \ i; \ p; \ t } \) \( \prod [t] \)

\( \text{\texttt{min} } T \ i; \ p; \ t } \) min\(\{t\}\)

\( \text{\texttt{max} } T \ i; \ p; \ t } \) max\(\{t\}\)
The assignable Clauses

Comma-separated list of:
- e. f (where f a field)

Example
C x, y;
int i;
//@ assignable x, x.i;
void m() {
  C tmp = x;
  // allowed (local variable)
  tmp.i = 27;
  // allowed (in assignable clause)
  x = y;
  // allowed (in assignable clause)
  x.i = 27;
  // forbidden (not local, not in assignable)
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The assignable Clauses

Comma-separated list of:

- e.f (where f a field)
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The assignable Clauses

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```c
C x, y; int i;
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void m() {
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    x = y;
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assignable clauses are always evaluated in the pre-state!
“Nothing” is more than you think it is

assignable $\nothing$ means that no memory location existing at method invocation must be changed.

Valid specification

```java
//@ assignable \nothing;
void n() {
    C c = new C();
    c.i = 42;
}
```

strictly pure: no memory location must be changed
weakly pure: only freshly created locations may be changed

Strict purity is too restrictive for realistic use cases. JML allows weakly pure method calls in specifications.
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The *diverges* Clause

```
diverges e;
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with a boolean JML expression $e$ specifies that the method *may* not terminate *only* when $e$ is true in the pre-state.

### Examples

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diverges false;
The method must always terminate.
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diverges true;
The method may terminate or not.
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The method must terminate, when called in a state with $n \neq 0$.
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ensures \( p; \)

signals_only \( ET_1, \ldots, ET_m; \)

signals \( (E_1 e_1) s_1; \)

\[ \ldots \]

signals \( (E_n e_n) s_n; \)

- normal termination \( \Rightarrow \) \( p \) must hold (in post-state)
- exception thrown \( \Rightarrow \) must be of type \( ET_1, \ldots, \) or \( ET_m \)
- exception of type \( E_1 \) thrown \( \Rightarrow \) \( s_1 \) must hold (in post-state)
  \[ \ldots \]
- exception of type \( E_n \) thrown \( \Rightarrow \) \( s_n \) must hold (in post-state)
The signals Clauses

\textbf{ensures} \ p;
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\ldots
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- exception of type \ E_1 \text{ thrown} \ \Rightarrow \ s_1 \text{ must hold (in post-state)}
\ldots
- exception of type \ E_n \text{ thrown} \ \Rightarrow \ s_n \text{ must hold (in post-state)}
ensures p;
signals_only ET1, ..., ETm;
signals (E1 e1) s1;
...
signals (En en) sn;

*normal termination* ⇒ p must hold (in post-state)
*exception thrown* ⇒ must be of type ET1, ..., or ETm
*exception of type E1 thrown* ⇒ s1 must hold (in post-state)
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- exception of type $E1$ thrown $\Rightarrow$ $s1$ must hold (in post-state)
  
  ... 
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public interface IBonusCard {

    public void addBonus(int newBonusPoints);

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How to add contracts to abstract methods in interfaces? Remember: There are no attributes in interfaces.
More precisely: Only static final fields.
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Model Fields

```java
public interface IBonusCard {

    /*@ public instance model int bonusPoints; */

    public void addBonus(int newBonusPoints);

}
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Remember: There are no attributes in interfaces.
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public interface IBonusCard {

/*@ public instance model int bonusPoints; @*/

/*@ ensures bonusPoints == old(bonusPoints) + newBonusPoints; @*/

public void addBonus(int newBonusPoints);

}
public interface IBonusCard {

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        assignable bonusPoints;
        @*/

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Implementing Interfaces

```java
public interface IBonusCard {
    /*@ public instance model int bonusPoints; @*/

    /*@ ... @*/
    public void addBonus(int newBonusPoints);
}

Implementation

public class BankCard implements IBonusCard{
    public int bankCardPoints;
    /*@ private represents bonusPoints = bankCardPoints; @*/

    public void addBonus(int newBonusPoints) {
        bankCardPoints += newBonusPoints;
    }
}
```
public interface IBonusCard {
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Other Representations

/*@ private represents bonusPoints = bankCardPoints; */

/*@ private represents bonusPoints = bankCardPoints * 100; */

/*@ represents x \such_that A(x); */
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Inheritance of Specifications in JML

Behavioral Subtyping, (Lizkov-Leavens Substitution Principle)

If $D$ is a subclass of $C$, then objects of type $C$ may be replaced with objects of type $D$ without altering the desirable properties of the program.

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Auxiliary Annotations

Dealing with loops

- Loops are a challenge for reasoning about programs
- Loop specifications to guide program proof systems

```c
/*@ loop_invariant linv;
   @ decreases variant;
   @ assignable A;
   @*/

while(...) { ... }
```

- Loop invariant \textit{linv} needs to hold for all iterations (each time just before the loop condition checked)
- The \textit{variant} must be decreasing non-negative integer (termination -- there is no infinite decreasing sequence)
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Other JML Features

- assertions `//@ assert e;`
- assumptions `//@ assume e;`
- data groups
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Nullity

JML has modifiers `non_null` and `nullable`

```java
private /*@spec_public non_null@*/ Object x;
⇝ implicit invariant added to class: ‘invariant x != null;’
```

```java
void m(/*@non_null@*/ Object p);
⇝ implicit precondition added to all contracts:
‘requires p != null;’
```

```java
/*@non_null@*/ Object m();
⇝ implicit postcondition added to all contracts:
‘ensures \result != null;’
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`non_null` is the default!
If something may be `null`, you have to declare it `nullable`
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Problems with Specifications Using Integers

```java
/*@
   requires y >= 0;
   ensures \result >= 0;
   ensures \result * \result <= y;
   ensures (\result+1) * (\result+1) > y;
   */

public static int isqrt(int y)
```

For $y = 1$ and $\result = 1073741821 = \frac{1}{2}(\text{MAX}_\text{INT} - 5)$ the above postcondition is true, though we do not want $1073741821$ to be a square root of $1$.

JML uses the Java semantics of integers:

\[
1073741821 \times 1073741821 = -2147483639
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The JML type \texttt{bigint} provides arbitrary precision integers.
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- **OpenJML**: tool suite, under development
- **jml**: JML syntax checker
- **jmldoc**: code documentation (like Javadoc)
- **jmlunit**: unit testing (like JUnit)
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