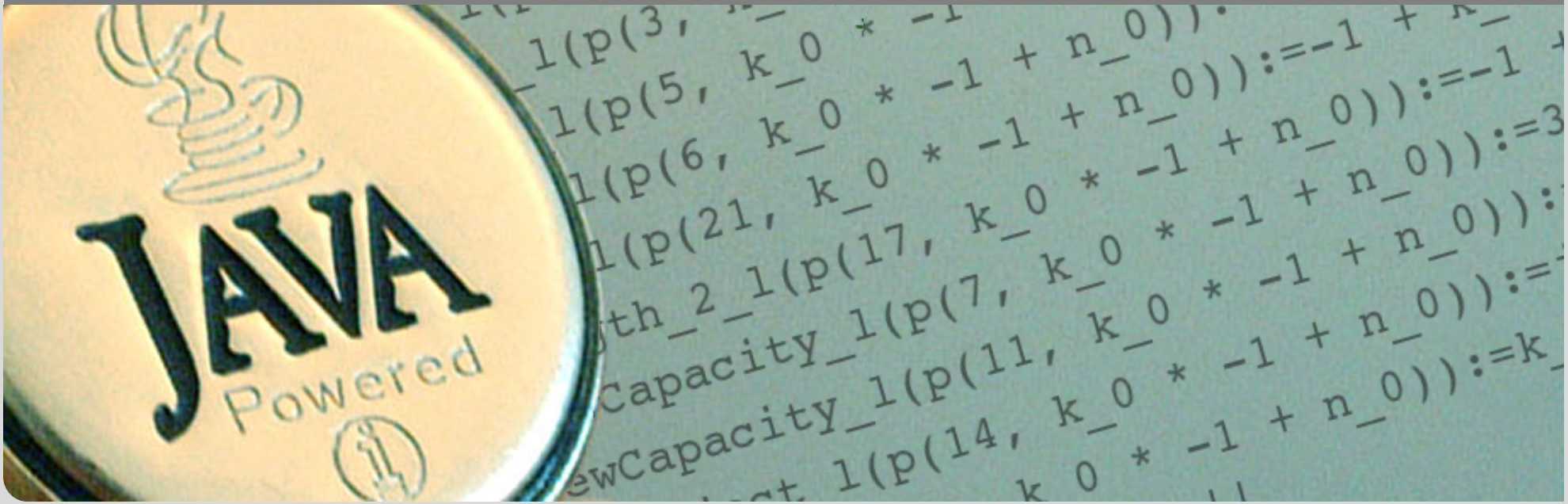
Formal Systems II: Applications

Functional Verification of Java Programs: Java Modeling Language

Bernhard Beckert · Mattias Ulbrich | SS 2017

KIT – Institut für Theoretische Informatik



“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:

Java Modeling Language	for	Java
Spec#	for	C#
ACSL	for	C (tool: Frama-C)
VCC	for	C (concurrency)
LARCH/C/C++	for	C/C++ (discontinued)
JAZZ	for	Java (discontinued)

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Design by Contract

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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JML Annotations

```
/*@ public normal_behavior
  @   requires pin == correctPin;
  @   ensures customerAuthenticated;
  @*/
public void enterPIN (int pin) {
    ...
```

- 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.
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Visibility Modifiers

```
public class ATM {
  private /*@ spec_public @*/ BankCard insertedCard = null;
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/*@ requires r;
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  @ signals(E e) s;
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T m(...);
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Abbreviations

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     normal_behavior  =  signals(Exception e) false;
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keyword '`also`' separates the contracts of a method

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- can be placed anywhere in a class (or interface)
- express global consistency properties (not specific to a particular method)
- must hold "always"
  (cf. *visible state semantics*, *observed state semantics*, *ownership, dynamic frames*)
- **`instance`** invariants *can*, **`static`** invariants *cannot* refer to **`this`**
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Pure Methods

Pure methods terminate and have no side effects.

Hence, they can be used in JML specifications.

After declaring

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public /*@ pure @*/ boolean cardIsInserted() {
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Pure Methods

$$\text{`}\texttt{pure}\text{'} \approx \text{`}\texttt{diverges false;}\text{'} + \text{`}\texttt{assignable}\ \backslash\texttt{nothing;}\text{'}$$

Expressions

- All Java expressions without side-effects
- ==>, <==>: implication, equivalence
- `\forall`, `\exists`
- `\num_of`, `\sum`, `\product`, `\min`, `\max`
- `\old`(...): referring to pre-state in postconditions
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Quantification in JML

```
(\forall int i; 0<=i && i<\result.length; \result[i]>0)
```

equivalent to

```
(\forall int i; 0<=i && i<\result.length ==> \result[i]>0)
```

```
(\exists int i; 0<=i && i<\result.length; \result[i]>0)
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equivalent to

```
(\exists int i; 0<=i && i<\result.length && \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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Generalised and Numerical Quantifiers

`(\num_of T i; e)`	$\#\{i \mid [e]\}$, number of elements of type `T` with property `e`
`(\sum T i; p; t)`	$\sum_{i:[p]} [t]$
`(\product T i; p; t)`	$\prod_{i:[p]} [t]$
`(\min T i; p; t)`	$\min_{i:[p]}\{[t]\}$
`(\max T i; p; t)`	$\max_{i:[p]}\{[t]\}$

The `assignable` Clauses

Comma-separated list of:

- `e.f` (where `f` a field)

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- **nothing**, **everything** (default)

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- `e.f` (where `f` a field)
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- `\nothing`, `\everything` (default)

Example

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C x, y; int i;
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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

```
//@ 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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with a boolean JML expression `e` specifies that the method may not terminate only when `e` is true in the pre-state.

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The method must always terminate.

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ensures p;
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signals (En en) sn;
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Model Fields

```
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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Implementing Interfaces

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public interface IBonusCard {
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Implementation

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

     public void addBonus(int newBonusPoints) {
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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

```
/*@ loop_invariant linv;
  @ decreases variant;
  @ assignable A;
  @*/
while(...) { ... }
```

- Loop invariant *linv* needs to hold for all iterations
  (each time just before the loop condition checked)
- The *variant* must be decreasing non-negative integer
  (termination – there is no infinite decreasing sequence)
- assignable, *cf.* `assignable` for methods
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Nullity

JML has modifiers **non_null** and **nullable**

```
private /*@spec_public non_null@*/ Object x;
```

⇝ implicit invariant added to class: '**invariant** x != **null**;'

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

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/*@non_null@*/ Object m();
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non_null is the default!
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Problems with Specifications Using Integers

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/*@ 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 $\backslash result = 1073741821 = \frac{1}{2}(MAX\_INT - 5)$ 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:

$$\begin{aligned} 1073741821 * 1073741821 &= -2147483639 \\ 1073741822 * 1073741822 &= 4 \end{aligned}$$

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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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Karlsruhe Institute of Technology

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- KeY: full static verification
- `OpenJML`: tool suite, under development
- `jml`: JML syntax checker
- `jmldoc`: code documentation (like Javadoc)
- `jmlunit`: unit testing (like JUnit)
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