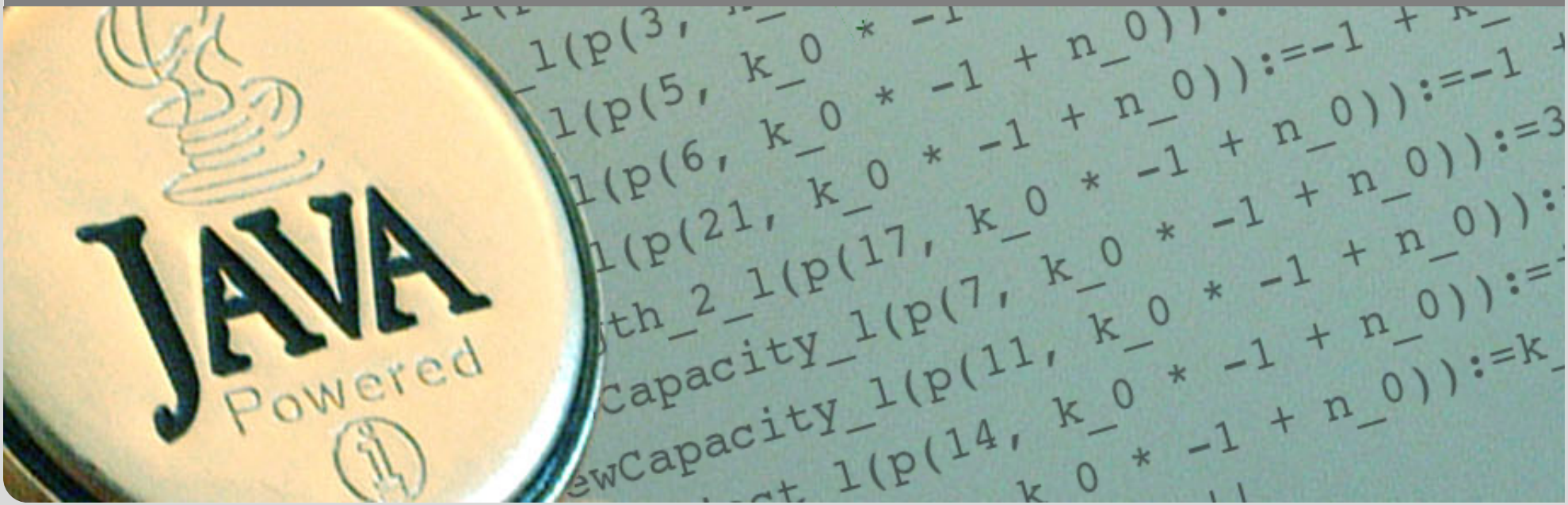
Karlsruhe Institute of Technology

Applications of Formal Verification

Functional Verification of Java Programs: Java Modelling Language

Prof. Dr. Bernhard Beckert · Dr. Vladimir Klebanov | SS 2012

KIT – Institut für Theoretische Informatik



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
- Contracts described in a mathematically precise language (JML)
  - higher degree of precision
  - *automation* of program analysis of various kinds (runtime assertion checking, static verification)
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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 '*/'.

  $\Rightarrow$ The blue '@'s are not required, but it's a *convention* to use them.
- JML specifications may themselves contain comments

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public void enterPIN (int pin) {
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Visibility Modifiers

```
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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```
/*@ requires r;
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  @ signals_only E1,...,En;
  @ signals(E e) s;
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T m(...);
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Abbreviations

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

keyword '`also`' separates the contracts of a method

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/*@ requires r;      //what is the caller's obligation?
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```
//@ invariant i;
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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*)
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Pure Methods

Pure methods terminate and have no side effects.

After declaring

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

‘`pure`’ $\approx$ ‘`diverges false;`’ + ‘`assignable \nothing;`’

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)
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equivalent to

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

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(\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)`	$\#\{i\|[e]\}$, 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)`	$\underset{i:[p]}{min}\{[t]\}$
`(\max T i; p; t)`	$\underset{i:[p]}{max}\{[t]\}$

The `assignable` Clauses

Comma-separated list of:

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

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Example

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C x, y; int i;
//@ assignable x, x.i;
void m() {




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```
C x, y; int i;
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//@ assignable x, x.i;
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```
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)
}
```

The `assignable` Clauses

Comma-separated list of:

- `e.f` (where `f` a field)
- `a[*]`, `a[x..y]` (where `a` an array expression)
- **`\nothing`**, **`\everything`** (default)

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}
```

`assignable` clauses are always evaluated in the pre-state!

The `diverges` Clause

```
diverges e;
```

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

Examples

```
diverges false;
```

The method must always terminate.

```
diverges true;
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The method may terminate or not.

```
diverges n == 0;
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The method must terminate, when called in a state with `n!=0`.

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The `signals` Clauses

```
ensures p;
signals_only ET1, ..., ETm;
signals (E1 e1) s1;
...
signals (En en) sn;
```

- normal termination $\Rightarrow$ `p` must hold (in post-state)
- exception thrown $\Rightarrow$ must be of type `ET1`, ..., or `ETm`
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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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  @ assignable bonusPoints;
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Implementing Interfaces

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

    /*@ ... @*/
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Implementation

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

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

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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

```
/*@ 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:

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

The JML type `\bigint` provides arbitrary precision integers.

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JML Tools

Many tools support JML (see JML homepage). Among them:

- `jml`: JML syntax checker
- `jmldoc`: code documentation (like Javadoc)
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- ESC/Java2: leightweight static verification
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