Formale Entwicklung objektorientierter Software

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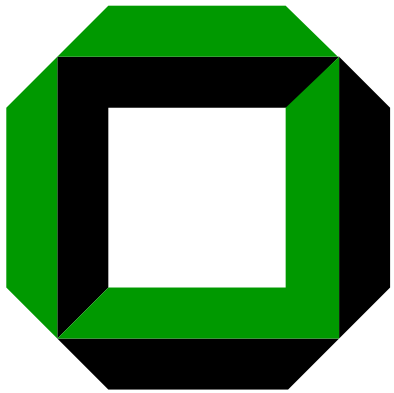

The Java Modeling Language JML

JML
By Example

A JML specification for `enterPIN`

General Structure

```
public class ATM {
  private
          BankCard insertedCard = null;
  private
          boolean  customerAuthenticated = false;


  public void enterPIN (int pin) {
    // here the implementation follows
```

A JML specification for `enterPIN`

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```
public class ATM {
  private
          BankCard insertedCard = null;
  private
          boolean  customerAuthenticated = false;
/*@ public normal_behavior // case 1 @*/
/*@ also public normal_behavior // case 2 @*/
/*@ also public normal_behavior // case 3 @*/
  public void enterPIN (int pin) {
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```

A JML specification for `enterPIN`

General Structure

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public class ATM {
  private/*@ spec_public @*/
          BankCard insertedCard = null;
  private/*@ spec_public @*/
          boolean  customerAuthenticated = false;
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  public void enterPIN (int pin) {
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A JML specification for `enterPIN`

Visibility Modifiers

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public class ATM {
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Modifiers to specification cases have no influence on their semantics.

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Specification items marked *public* cannot refer to *private* fields.

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public class ATM {
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  private /*@ spec_public @*/
          boolean  customerAuthenticated = false;

  /*@ public normal_behavior
```

Modifiers to specification cases have no influence on their semantics.

Specification items marked *public* cannot refer to *private* fields.

Private fields can be declared public for specification purposes only.

The First Specification Case

```
/*@ public normal_behavior
    requires  insertedCard != null;
    requires  !customerAuthenticated;
    requires  pin == insertedCard.correctPIN;
    assignable customerAuthenticated;
    ensures    customerAuthenticated;
 @*/
public void enterPIN (int pin) {
  // here the implementation follows
```

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    requires  insertedCard != null;
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    ensures    customerAuthenticated;
 @*/
public void enterPIN (int pin) {
  // here the implementation follows
```

The *normal_behavior* keyword specifies that the method may not throw an exception

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    requires  insertedCard != null;
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    requires  pin == insertedCard.correctPIN;
    assignable customerAuthenticated;
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public void enterPIN (int pin) {
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The conjunction of all *requires* clauses is the precondition.

The First Specification Case

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    ensures    customerAuthenticated;
 @*/
public void enterPIN (int pin) {
  // here the implementation follows
```

The conjunction of all *ensures* clauses is the postcondition.

The First Specification Case

```
/*@ public normal_behavior
    requires  insertedCard != null;
    requires  !customerAuthenticated;
    requires  pin == insertedCard.correctPIN;
    assignable customerAuthenticated;
    ensures    customerAuthenticated;
 @*/
public void enterPIN (int pin) {
  // here the implementation follows
```

The *assignable* clause list all expressions that may be assigned to.

The Second Specification Case

```
public normal_behavior
requires  insertedCard != null;
requires  !customerAuthenticated;
requires  pin != insertedCard.correctPIN;
requires  wrongPINCounter < 2;
assignable wrongPINCounter;
ensures   wrongPINCounter
                == \old(wrongPINCounter) + 1;
ensures   !customerAuthenticated;
```

The Second Specification Case

```
public normal_behavior
requires  insertedCard != null;
requires  !customerAuthenticated;
requires  pin != insertedCard.correctPIN;
requires  wrongPINCounter < 2;
assignable wrongPINCounter;
ensures   wrongPINCounter
                == \old(wrongPINCounter) + 1;
ensures   !customerAuthenticated;
```

Special JML keywords start with \

The Second Specification Case

```
public normal_behavior
requires  insertedCard != null;
requires  !customerAuthenticated;
requires  pin != insertedCard.correctPIN;
requires  wrongPINCounter < 2;
assignable wrongPINCounter;
ensures   wrongPINCounter
                == \old(wrongPINCounter) + 1;
ensures   !customerAuthenticated;
```

\old(wrongPINCounter) refers to the value of the field wrongPINCounter before method invocation.

The Third Specification Case

```
public normal_behavior
requires  insertedCard != null;
requires  !customerAuthenticated;
requires  pin != insertedCard.correctPIN;
requires  wrongPINCounter >= 2;
assignable insertedCard, wrongPINCounter,
           insertedCard.invalid;
ensures   insertedCard == null;
ensures   \old(insertedCard).invalid;
ensures   !customerAuthenticated;
```

Exceptional Behaviour

```
/*@
  @ // the contracts as defined above
  @ also public exceptional_behavior
  @   requires insertedCard==null;
  @   signals_only ATMException;
  @   signals (ATMException) !customerAuthenticated;
  @*/
public void enterPIN (int pin) {
 // here the implementation follows
```

Exceptional Behaviour

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/*@
  @ // the contracts as defined above
  @ also public exceptional_behavior
  @   requires insertedCard==null;
  @   signals_only ATMException;
  @   signals (ATMException) !customerAuthenticated;
  @*/
public void enterPIN (int pin) {
 // here the implementation follows
```

If an exception of type `ATMException` is thrown then `!customerAuthenticated` has to be true.

Exceptional Behaviour

```
/*@
  @ // the contracts as defined above
  @ also public exceptional_behavior
  @   requires insertedCard==null;
  @   signals_only ATMException;
  @   signals (ATMException) !customerAuthenticated;
  @*/
public void enterPIN (int pin) {
 // here the implementation follows
```

`signals_only` says that only exceptions of type `ATMException` may be thrown.

Pure Methods

Pure methods terminate and have no side effects.

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After declaring

```
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  return insertedCard!=null;
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After declaring

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public /*@ pure @*/ boolean cardIsInserted() {
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```

```
cardIsInserted()
```

could replace

```
insertedCard != null
```

in the above JML annotations.

A Static Invariant

```
public class BankCard {
 /*@ public static invariant
   @    (\forall BankCard p1, p2;
   @     p1!=p2;
   @     p1.cardNumber!=p2.cardNumber);
   @*/
   private /*@ spec_public @*/ int cardNumber;
   // rest of class follows}
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```

Compare to OCL version:

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   private /*@ spec_public @*/ int cardNumber;
   // rest of class follows}
```

Compare to OCL version:

```
context BankCard
inv:    BankCard::allInstances() ->  forall(p1,p2|
        p1<>p2 implies p1.cardNumber<>p2.cardNumber)
```

An Instance Invariant

```
public class BankCard {
 /*@ public instance invariant
   @    (\forall BankCard p; this!=p ==>
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   private /*@ spec_public @*/ int cardNumber;
   // rest of class follows}
```

Instance invariants must evaluate to true for all created objects of their class.

Variation on the Static Invariant

```
public class BankCard {
 /*@ public static invariant
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   @       p1!=p2;
   @       p1.cardNumber!=p2.cardNumber);
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    @              this.cardNumber!=p.cardNumber);
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    private /*@ spec_public @*/ int cardNumber;
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Another Example

OCL constraint:

```
context CentralHost
inv: validCardsCount =
     BankCard::allInstances() ->
        select(not invalid) -> size()
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```
context CentralHost
inv: validCardsCount =
     BankCard::allInstances() ->
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```

JML annotation:

```
public class CentralHost {
  /*@ public instance invariant this.validCardsCount
    @                    ==(\num_of BankCard p; !p.invalid);
    @*/}
```

JML
Expressions

Definition

Every JAVA expression according to the language specification which does not include

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is a JML expression.

Any such expression e has a natural representation in KeY's first-order logic, which we will denote by $[e]$.

Mapping from JML plus Java *to FOL*

Selected Items

JML Expression	first-order logic formula
`!e_0`	$![e_0]$
`e_0 && e_1`	$[e_0]$ & $[e_1]$
`e_0 || e_1`	$[e_0] \mid [e_1]$
`e_0 ? e_1 : e_2`	\if$[e_0]$ \then$[e_1]$ \else$[e_2]$
`e_0 != e_1`	$!([e_0] = [e_1])$
`e_0 >= e_1`	$[e_0] >= [e_1]$
`e_0 ==> e_1`	$[e_0] \rightarrow [e_1]$
`e_0 <==> e_1`	$[e_0] <\!\!\rightarrow [e_1]$
`(\forall T e; e_0; e_1)`	*forall* T e; $(![e] = \texttt{null}$ & $[e_0] \rightarrow [e_1])$
`(\exists T e; e_0; e_1)`	*exists* T e; $(![e] = \texttt{null}$ & $[e_0]$ & $[e_1])$

Quantification in JML

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JML excludes `null` from the range of quantification.

Generalised and Numerical Quantifiers

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JML
Operation Contracts

Clauses in Operation Contracts

Clause	Lightweight default	Heavyweight default
`requires`	`\not_specified`	`true`
`assignable`	`\not_specified`	`\everything`
`ensures`	`\not_specified`	`true`
`diverges`	`false`	`false`
`signals`	`\not_specified`	`(Exception)true`
`signals_only`	All exception types declared in the JAVA method declaration	

Signals Clauses

JML

```
ensures   E;
signals  (ET_1)  S_1;
   ⋮
signals  (ET_n)  S_n;
signals_only  OT_1,...,OT_m;
```

Signals Clauses

JML

$$
\begin{array}{l}
\texttt{ensures} \quad E\,; \\
\texttt{signals} \quad (ET_1) \;\; S_1\,; \\
\vdots \\
\texttt{signals} \quad (ET_n) \;\; S_n\,; \\
\texttt{signals\_only} \;\; OT_1, \ldots, OT_m\,;
\end{array}
$$

FOL Translation

$$
\begin{array}{l}
(\mathsf{e} = \texttt{null} \;\texttt{->}\; [E]) \;\&\; \\
(\mathsf{e} \neq \texttt{null} \;\texttt{->}\; ([\mathsf{ET}_1]\mathsf{::instance(e)} = \mathsf{TRUE} \;\texttt{->}\; [S_1]) \;\&\; \ldots \;\&\; \\
\qquad\qquad\qquad\quad ([\mathsf{ET}_n]\mathsf{::instance(e)} = \mathsf{TRUE} \;\texttt{->}\; [S_n])) \;\&\; \\
([\mathsf{OT}_1]\mathsf{::instance(e)} = \mathsf{TRUE} \mid \ldots \mid [\mathsf{OT}_m]\mathsf{::instance(e)} = \mathsf{TRUE})
\end{array}
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\texttt{signals\_only} \;\; OT_1, \ldots, OT_m\,;
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FOL Translation

$$
\begin{array}{ll}
(\mathsf{e} = \texttt{null} \rightarrow & [E]) \;\&\; \\
(\mathsf{e} \neq \texttt{null} \rightarrow & ([\mathsf{ET}_1]::\mathsf{instance}(\mathsf{e}) = \mathsf{TRUE} \rightarrow [S_1]) \;\&\; \ldots \;\&\; \\
& ([\mathsf{ET}_n]::\mathsf{instance}(\mathsf{e}) = \mathsf{TRUE} \rightarrow [S_n])) \;\&\; \\
([\mathsf{OT}_1]::\mathsf{instance}(\mathsf{e}) = \mathsf{TRUE} & \mid \ldots \mid [\mathsf{OT}_m]::\mathsf{instance}(\mathsf{e}) = \mathsf{TRUE})
\end{array}
$$

The variable e stores a thrown exception. If the operation terminates normally then e equals `null`.

The `diverges` *Clause*

`diverges e`

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

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is part of the operation contract for `m` then `m` must always terminate.

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If

`diverges true`

is part of the operation contract for `m` then `m` may terminate or not.

If

`diverges n == 0`

is part of the operation contract for `m` then `m` must terminate, when called in a state with `n != 0`.

De-Sugaring

```
normal_behavior
  requires R;
  assignable A;
  ensures E;
  diverges D;
```

$\Longrightarrow$

```
behavior
  requires R;
  assignable A;
  ensures E;
  diverges D;
  signals (Exception) false;
```

De-Sugaring

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normal_behavior
  requires R;
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$\Longrightarrow$

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behavior
  requires R;
  assignable A;
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  diverges D;
  signals (Exception) false;
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```
exceptional_behavior
  requires R;
  assignable A;
  diverges D;
  signals (ET) S;
  signals_only (OT);
```

$\Longrightarrow$

```
behavior
  requires R;
  assignable A;
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  diverges D;
  signals (ET) S;
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Inheritance of Specifications in JML

An invariant to a class is inherited by all its subclasses.

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An invariant to a class is inherited by all its subclasses.

An operation contract is inherited by all overridden methods.

JML
Invariants

An Instance Invariant

JML

```
public class BankCard {
  /*@ public instance invariant
    @   (\forall BankCard p; this!=p ==>
                  this.cardNumber!=p.cardNumber);
    @*/
    private /*@ spec_public @*/ int cardNumber;
    // rest of class follows}
```

An Instance Invariant

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public class BankCard {
  /*@ public instance invariant
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                  this.cardNumber!=p.cardNumber);
    @*/
    private /*@ spec_public @*/ int cardNumber;
    // rest of class follows}
```

FOL

```
\forall BankCard o; o.<created> = TRUE ->
  \forall BankCard p; p.<created> = TRUE ->
     !o = p -> !o.cardNumber = p.cardNumber
```

Visible State Semantics

According to the JML reference manual instance invariants defined in a class C must hold at any visible state for any object o of C.

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- at the beginning and end of a static method which is declared in the class of o or a superclass.

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- at the end of a constructor invocation which is initialising o,
- at the beginning and end of a non-static method invocation with o as receiver,
- at the beginning and end of a static method which is declared in the class of o or a superclass.
- when no constructor, non-static method invocation with o as receiver, or static method invocation for a method in o's class or a superclass is in progress.

Observed State Semantics

A program P is observed-state correct w.r.t. a specification S, if

1. all operations *op* fulfil all operation contracts of S for *op*,

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A program P is observed-state correct w.r.t. a specification S, if

1. all operations *op* fulfil all operation contracts of S for *op*,
2. all invariants Inv_S of S are preserved by all operations of P, and
3. all invariants are valid in the initial state of P.

Example Program

```
public class A {
  private int i = 1;
  /*@ instance invariant i>0; @*/
  public int getI() { return i; }
  /*@ requires p>0;
    @ ensures i==p; @*/
  public void setI(int p) { i=p; }
  public void m1() {setI(0);i=1; }
  public void m2() {i=0;setI(1); }
  public int m3() {i=0;i=(new B()).m5(this);}
  /*@ ensures \result>=0; @*/
  public int m4() {return 42/i;}  }
public class B {
  /*@ ensures \result>0; @*/
  public int m5(A a){if(a.getI()<=0) a.setI(1);
    return a.m4();}  }
```

Visible vs Observable States

```
public class A {
  private int i = 1;
  /*@ instance invariant i>0; */

  /*@ requires p>0;
    @ ensures i==p; @*/
  public void setI(int p) { i=p; }
  public void m1() {setI(0);
  visible, but not observable state
  i=1; }
}
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public class A {
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  i=1; }
}
```

Invariant `i > 0` not satisfied in visible state semantics.

Visible vs Observable States

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public class A {
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  /*@ instance invariant i>0; */

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  visible, but not observable state
  i=1; }
}
```

Invariant `i > 0` not satisfied in visible state semantics.

Invariant `i > 0` satisfied in observable state semantics.

A Static Invariant

```
public class CentralHost {
 /*@ public static invariant maxAccountNumber>=0; @*/
// ...
```

must hold already after the static initialisation of CentralHost is completed.

JML
Model Fields and Methods

Java Interfaces

```
public interface IBonusCard {

    public void addBonus(int newBonusPoints);

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Remember: There are no attributes in interfaces.
More precisely: Only static final fields.

Java Interfaces

Model Fields

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public interface IBonusCard {

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



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Java Interfaces

Model Fields

```
public interface IBonusCard {

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

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


    public void addBonus(int newBonusPoints);

}
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Java Interfaces

Model Fields

```
public interface IBonusCard {

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

/*@ ensures bonusPoints == \old(bonusPoints)+newBonusPoints;
  @ assignable bonusPoints;
  @ */
    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.
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Implementing Interfaces

Interface

```
public interface IBonusCard {
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Implementing Interfaces

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Implementation

```
public class BankCard implements IBonusCard{
   public int bankCardPoints;


  public void addBonus(int newBonusPoints) {
    bankCardPoints+=newBonusPoints;
  }}
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Implementing Interfaces

Interface

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public interface IBonusCard {
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Implementation

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

    public void addBonus(int newBonusPoints) {
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    }}
```

Other Representations

```
/*@ private represents bonusPoints
              <- bankCardPoints; @*/
```

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```
/*@ private represents bonusPoints
            <- bankCardPoints; @*/

/*@ private represents bonusPoints
            <- bankCardPoints * 100; @*/
```

Other Representations

```
/*@ private represents bonusPoints
            <- bankCardPoints; @*/

/*@ private represents bonusPoints
            <- bankCardPoints * 100; @*/

/*@ represents x \such_that A(x); @*/
```

Problems with Specifications Using Integers

```
/*@ requires y >= 0;
  @ ensures
  @  \result * \result <= y &&
  @ y < (abs(\result)+1) * (abs(\result)+1);
  @ */
   public static int isqrt(int y)
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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.

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The problem arises since JML uses the JAVA semantics of integers which yields

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

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1. It lives on a higher level of abstraction. A UML diagram can be annotated with OCL constraints before code is developed.
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3. OCL is an OMG standard, though one has to admit that the official standard draft still contains serious inconsistencies and many unfinished items.

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1. JML is closer to JAVA code, which encourages its use by programmers and developers. In fact, today JML specifications are much more widespread than OCL specifications.
2. JML offers a greater variety of concepts on the implementation level, like exceptional behavior, modifies (assignable) clauses and loop invariants.

THE

THE END