

Introduction to JML

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First

- introduction to **JML**
- overview of tool support for JML, esp. runtime assertion checking (using **jmlrac**) and extended static checking **ESC/Java2**

Then

- **ESC/Java2: Use and Features**
- **ESC/Java2: Warnings**
- **Specification tips and pitfalls**
- **Advanced JML: more tips and pitfalls**

interspersed with demos.

JML by Gary Leavens et al.

Formal specification language for Java

- to specify behaviour of Java classes
- to record design & implementation decisions

by adding **assertions** to Java source code, eg

- **preconditions**
- **postconditions**
- **invariants**

as in Eiffel (Design by Contract), but more expressive.

The Java Modeling Language

JML

www.jmlspecs.org

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Goal: JML should be easy to use for any Java programmer.

requires, ensures

Pre- and post-conditions for method can be specified.

```
/*@ requires amount >= 0;
    ensures  balance == \old(balance-amount) &&
           \result == balance;

  @*/
public int debit(int amount) {
    ...
}
```

Here `\old(balance)` refers to the value of `balance` before execution of the method.

To make JML easy to use:

- JML assertions are added as comments in .java file, between `/*@ ... @*/`, or after `//@`,
- Properties are specified as Java boolean expressions, extended with a few operators (`\old`, `\forall`, `\result`, ...).
- using a few keywords (`requires`, `ensures`, `signals`, `assignable`, `pure`, `invariant`, `non_null`, ...)

requires, ensures

JML specs can be as strong or as weak as you want.

```
/*@ requires amount >= 0;
    ensures true;

  @*/
public int debit(int amount) {
    ...
}
```

This default postcondition “`ensures true`” can be omitted.

Design-by-Contract

signals

Pre- and postconditions define a **contract** between a class and its clients:

- Client must **ensure precondition** and may **assume postcondition**
- Method may **assume precondition** and must **ensure postcondition**

Eg, in the example specs for `debit`, it is the obligation of the client to ensure that `amount` is positive. The `requires` clause makes this **explicit**.

Exceptional postconditions can also be specified.

```
/*@ requires amount >= 0;
    ensures true;
    signals (BankException e)
        amount > balance      &&
        balance == \old(balance) &&
        e.getReason().equals("Amount too low");
*/
public int debit(int amount) throws BankException {
    ...
}
```

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signals

invariant

Exceptions mentioned in `throws` clause are allowed by default. To change this, there are three options:

- To **rule out all** exceptions, use a **normal_behavior**

```
/*@ normal_behavior
    requires ...
    ensures ...
*/
```

- To **rule out particular** exception `E`, add

```
signals (E) false;
```

- To **allow only some exceptions**, add

```
signals_only E1, ..., E2;
```

Invariants (aka *class invariants*) are properties that must be maintained by all methods, e.g.,

```
public class Wallet {
    public static final short MAX_BAL = 1000;
    private short balance;
    /*@ invariant 0 <= balance &&
        balance <= MAX_BAL;
    */
    ...
}
```

Invariants are implicitly included in all pre- and postconditions.

Invariants must *also* be preserved if exception is thrown!

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invariant

Invariants document design decisions, e.g.,

```
public class Directory {
private File[] files;
/*@ invariant
    files != null
    &&
    (\forall int i; 0 <= i && i < files.length;
        ; files[i] != null &&
        files[i].getParent() == this);
@*/
```

Making them **explicit** helps in understanding the code.

non_null

Many invariants, pre- and postconditions are about references not being null. **non_null** is a convenient short-hand for these.

```
public class Directory {

private /*@ non_null */ File[] files;

void createSubdir(/*@ non_null */ String name) {
    ...
}
/*@ non_null */ Directory getParent(){
    ...
}
```

assert

An **assert** clause specifies a property that should hold at some point in the code, e.g.,

```
if (i <= 0 || j < 0) {
    ...
} else if (j < 5) {
    /*@ assert i > 0 && 0 < j && j < 5;
    ...
} else {
    /*@ assert i > 0 && j > 5;
    ...
}
```

assert

JML keyword **assert** now also in Java (since Java 1.4). Still, **assert** in JML is more expressive, for example in

```
...
for (n = 0; n < a.length; n++)
    if (a[n]==null) break;
/*@ assert (\forall int i; 0 <= i && i < n;
    a[i] != null);
@*/
```

assignable

Frame properties limit possible side-effects of methods.

```
/*@ requires amount >= 0;
   assignable balance;
   ensures balance == \old(balance)-amount;

  @*/
public int debit(int amount) { }
...

```

E.g., debit can *only* assign to the field balance.

NB this does *not* follow from the post-condition.

Default assignable clause: assignable \everything.

pure

A method without side-effects is called pure.

```
public /*@ pure @*/ int getBalance(){...

```

```
Directory /*@ pure non_null @*/ getParent(){

```

Pure methods are implicitly assignable \nothing.

Pure methods, and only pure methods, can be used *in* specifications, eg.

```
//@ invariant 0<=getBalance() && getBalance()<=MAX_BAL

```

JML recap

The JML keywords discussed so far:

- requires
- ensures
- signals
- assignable
- normal_behavior
- invariant
- non_null
- pure
- \old, \forall, \exists, \result

This is all you need to know to get started!

Tools for JML

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- **parsing and typechecking**

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- **runtime assertion checking:**
test for violations of assertions during execution
jmlrac

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tools for JML

runtime assertion checking

- **parsing and typechecking**
- **runtime assertion checking:**
test for violations of assertions during execution
jmlrac
- **extended static checking** ie. automated program verification:
prove that contracts are never violated at compile-time
ESC/Java2
This is program verification, not just testing.

jmlrac compiler by Gary Leavens, Yoonsik Cheon, et al. at Iowa State Univ.

- translates **JML assertions** into **runtime checks:**
during execution, *all* assertions are tested and any violation of an assertion produces an Error.

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The **jmlunit** tool combines **jmlrac** and **unit testing**.

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runtime assertion checking

mlrac can generate complicated test-code for free. E.g., for

```
/*@ ...
  signals (Exception)
    balance == \old(balance);

  @*/
public int debit(int amount) { ... }
```

It will test that if `debit` throws an exception, the `balance` hasn't changed, and all invariants still hold.

mlrac even checks `\forall` if the domain of quantification is finite.

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extended static checking

ESC/Java(2)

- extended static checking = fully automated program verification, with some compromises to achieve full automation

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- but *finds lots of potential bugs quickly*

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- *tries to prove correctness of specifications, at compile-time, fully automatically*
- **not sound**: ESC/Java may miss an error that is actually present
- **not complete**: ESC/Java may warn of errors that are impossible
- but *finds lots of potential bugs quickly*
- good at proving absence of runtime exceptions (eg Null-, ArrayIndexOutOfBounds-, ClassCast-) and verifying relatively simple properties.

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ESC/Java(2) credits

- **ESC/Java** originally developed at DEC SRC – later Compaq, and now HP Research – by Rustan Leino, Cormac Flanagan, Mark Lillibridge, Greg Nelson, Raymie Stata, and James Saxe.
- **ESC/Java2**, extension that supports more of JML, developed by David Cok and Joe Kiniry.

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static checking vs runtime checking

One of the assertions below is wrong:

```
if (i <= 0 || j < 0) {
    ...
} else if (j < 5) {
    //@ assert i > 0 && 0 < j && j < 5;
    ...
} else {
    //@ assert i > 0 && j > 5;
    ...
}
```

Runtime assertion checking *may* detect this with a comprehensive test suite.

ESC/Java2 *will* detect this at compile-time.

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static checking vs runtime checking

Important differences:

- ESC/Java2 checks specs at **compile-time**, jmlrac checks specs at **run-time**
- ESC/Java2 **proves** correctness of specs, jml only **tests** correctness of specs.
Hence
 - ESC/Java2 independent of any test suite, results of runtime testing only as good as the test suite,
 - ESC/Java2 provides higher degree of confidence.

The price for this: you have to specify all pre- and postconditions of methods (incl. API methods) and invariants needed for **modular verification**

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more JML tools

Related Work

- **javadoc-style documentation: jmldoc**
- **Eclipse plugin**
- **Other full verification tools:**
 - **LOOP tool + PVS (Nijmegen)**
 - **JACK (Gemplus/INRIA)**
 - **Krakatoa tool + Coq (INRIA)**
 - **KeY (Chalmers + Germany)**

These tools also allow **interactive** verification (whereas ESC/Java2 only aims at **fully automatic** verification) and can therefore handle more complex properties.

- **runtime detection of invariants: Daikon (Michael Ernst, MIT)**
- **model-checking multi-threaded programs: Bogor (Kansas State)**

- **jContract tool for Java by Parasoft**
- **Spec# for C# by Microsoft**
- **Spark-Ada for subset of Ada by Praxis Critical Systems Ltd.**
- **OCL specification language for UML**

Acknowledgements

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- Gary Leavens leads the JML effort at Iowa St. Contributors include Albert Baker, Clyde Ruby, Curtis Clifton, Yoonsik Cheon, Anand Ganapathy, Abhay Bhorkar, Arun Raghavan, Kristina Boysen, David Behroozi. Katie Becker, Elisabeth Seagren, Brandon Shilling, Katie Becker, Ajani Thomas, and Arthur Thomas.
- The ESC project at SRC included Rustan Leino, Cormac Flanagan, Mark Lillibridge, Greg Nelson, Raymie Stata, and James Saxe.
- More people at many different places are contributing to JML

More information

These websites and mailing lists can provide more information (and have links to even more):

- JML: www.jmlspecs.org
- mailing lists: jmlspecs-interest@lists.sourceforge.net
jmlspecs-developers@lists.sourceforge.net
- ESC/Java2: <http://secure.ucd.ie/products/opensource/ESCJava2/>
- ESC/Java: <http://www.research.compaq.com/SRC/esc/>
- mailing list: jmlspecs-escjava@lists.sourceforge.net