

Introduction to JML

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Outline of this talk

What this set of slides aims to do

- **introduction to JML**
- **provide overview of tool support for JML (jmlrac, jmlunit, escjava)**
- **explain idea of extended static checking and difference with runtime assertion checking**
- **some more ESC/Java2 tips**

The Java Modeling Language

JML

`www.jmlspecs.org`

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.

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

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

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.

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

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**.

signals

Exceptional postconditions can also be specified.

```
/*@ requires amount >= 0;
   ensures true;
   signals (ISOException e)
           amount > balance      &&
           balance == \old(balance) &&
           e.getReason() == AMOUNT_TOO_BIG;

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

signals

Exceptions are allowed by default, i.e. the default signals clause is

```
signals (Exception) true;
```

To rule them out, add an explicit

```
signals (Exception) false;
```

or use the keyword `normal_behavior`

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

invariant

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!

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){  
        ...  
    Directory /*@ non_null */ 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`.

Only pure methods can be used *in* specifications.

visibility

JML supports the standard Java visibilities:

```
public int pub;   private int priv;
```

```
//@ requires i <= pub;
```

```
public void pub1 (int i) { ... }
```

```
//@ requires i <= pub && i <= priv;
```

```
private void priv1 (int i) ...
```

```
//@ requires i <= pub && i <= priv; // WRONG !!
```

```
public void pub2(int i) { ... }
```

Specs of **public** methods may not refer to **private** fields.

visibility: spec_public

Keyword `spec_public` loosens visibility for specs.
Private `spec_public` fields are allowed in public specs,
e.g.:

```
public int pub;
```

```
private /*@ spec_public @*/ int priv;
```

```
//@ requires i <= pub && i <= priv; // OK
```

```
public void pub2(int i) { ... }
```

Exposing private details is ugly, of course. A nicer, but more advanced alternative in JML is to use public `model` fields to represent (abstract away from) private implementation details.

Tools for JML

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

runtime assertion checking

jmlrac compiler by Gary Leavens 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**.

runtime assertion checking

jmlrac 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.

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

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ESC/Java(2)

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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.

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.

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.

modular reasoning (1)

ESC/Java2 reasons about every method individually. So in

```
class A{  
    byte[] b;  
    public void n() { b = new byte[20]; }  
    public void m() { n();  
                    b[0] = 2;  
                    ... }  
}
```

ESC/Java2 warns that `b[0]` may be a null dereference here, even though you can see that it won't be.

modular reasoning (1)

To stop ESC/Java2 complaining: add a postcondition

```
class A{
  byte[] b;
  //@ ensures b != null && b.length = 20;
  public void n() { a = new byte[20]; }
  public void m() { n();
                   b[0] = 2;
                   ... }
}
```

So: property of method that is relied on has to be made explicit.

And: subclasses that override methods have to preserve these.

modular reasoning (2)

Similarly, ESC/Java will complain about `b[0] = 2` in

```
class A{
  byte[] b;
  public void A() { b = new byte[20]; }
  public void m() { b[0] = 2;
                  ... }
}
```

Maybe you can see that this is a spurious warning, though this will be harder than in the previous example: you'll have to inspect *all* constructors and *all* methods.

modular reasoning (2)

To stop ESC/Java2 complaining here: add an invariant

```
class A{
  byte[] b;
  //@ invariant b != null && b.length == 20;
  // or weaker property for b.length ?
  public void A() { b = new byte[20]; }
  public void m() { b[0] = 2;
                  ... }
}
```

So again: properties you rely on have to be made explicit.

And again: subclasses have to preserve these properties.

assume

Alternative to stop ESC/Java2 complaining: add an assumption:

```
...  
//@ assume b != null && b.length > 0;  
b[0] = 2;  
...
```

Especially useful during development, when you're still trying to discover hidden assumptions, or when ESC/Java2's reasoning power is too weak.

(requires can be understood as a form of assume.)

more JML tools

- javadoc-style documentation: **jmlDoc**
- Other red **verification** tools:
 - **LOOP tool + PVS** (Nijmegen)
 - **JACK** (Gemplus/INRIA)
 - **Krakatoa tool + Coq** (INRIA)

These tools (also) aim at **interactive** verification of complex properties, whereas ESC/Java2 aims at **automatic** verification of relatively simple properties.

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

See www.jmlspecs.org

Acknowledgements

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- **David Cok is a primary contributor to JML and ESC/Java2.**

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: www.cs.kun.nl/sos/research/escjava**
- **ESC/Java: www.research.compaq.com/SRC/esc/**
- **mailing list: jmlspecs-escjava@lists.sourceforge.net**