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
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, ...)

Erik Poll - ESC/Java2 Tutorial - June 2004 - JML – p.5/34
Pre- and post-conditions for method can be specified.

```java
/*@ 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.

```java
/*@ 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**.
Exceptional postconditions can also be specified.

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

public int debit(int amount) {
...
}
```
Exceptions are allowed by default, i.e. the default signals clause is

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

To rule them out, add an explicit

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

or use the keyword `normal_behavior`

```java
/*@ normal_behavior
  requires ...
  ensures ...
@@*/
```
Invariants (aka class invariants) are properties that must be maintained by all methods, e.g.,

```java
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!
Invariants document design decisions, e.g.,

```java
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.
```
Many invariants, pre- and postconditions are about references not being \texttt{null}. \texttt{non\_null} is a convenient short-hand for these.

```java
public class Directory {

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

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

    Directory /*@ non_null @*/ getParent() {
        ...
    }

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

```java
if (i <= 0 || j < 0) {
    ...
} else if (j < 5) {
    //@ assert i > 0 && 0 < j && j < 5;
    ...
} else {
    //@ assert i > 0 && j > 5;
    ...
}
```
JML keyword `assert` now also in Java (since Java 1.4). Still, `assert` in JML is more expressive, for example in

```java
for (n = 0; n < a.length; n++)
    if (a[n]==null) break;
/*@ assert (\forall int i; 0 <= i && i < n;
        a[i] != null);@*/
```
Frame properties limit possible side-effects of methods.

```java
/*@  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`. 

A method without side-effects is called pure.

```java
class Account {
    public /*@ pure @*/ int getBalance() { ... }
}

class Directory {
    public /*@ pure non_null @*/ getParent() { ... }
}
```

Pure method are implicitly assignable to nothing.

Only pure methods can be used in specifications.
visibility

JML supports the standard Java visibilities:

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

```java
//@ requires i <= pub;
public void pub1 (int i) { ... }
```

```java
//@ requires i <= pub && i <= priv;
private void priv1 (int i) ...
```

```java
//@ 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.:

```java
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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- 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

- parsing and typechecking
- runtime assertion checking: test for violations of assertions during execution
  jmlrac
- extended static checking: prove that contracts are never violated at compile-time
  ESC/Java2
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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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  during execution, *all* assertions are tested and any violation of an assertion produces an Error.
- **cheap & easy** to do as part of existing testing practice
- **better testing**, because **more properties** are tested, at **more places** in the code
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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

```java
/*@
... 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 all` if the domain of quantification is finite.
extended static checking

ESC/Java(2)

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- *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 (e.g., `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:

```java
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

```java
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.
To stop ESC/Java2 complaining: add a postcondition

```java
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

```java
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.
Alternative to stop ESC/Java2 complaining: add an assumption:

```java
...//@ 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