The Java Modeling language

JML

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JML

- formal specification language for sequential Java
  by Gary Leavens et. al.
  - to specify behaviour of Java classes & interfaces
  - to record detailed design decisions

  by adding annotations to Java source code in Design-By-Contract style, using eg. pre/postconditions and invariants

- Design goal: meant to be usable by any Java programmer

Lots of info on http://www.jmlspecs.org

to make JML easy to use

- JML annotations added as special Java comments, between `/*@ .. @*/` or after `//@`
- JML specs can be in .java files, or in separate .jml files
- Properties specified using Java syntax, extended with some operators

  `\old( ), \result, \forall, \exists, ==>` ,..

  and some keywords

  `requires, ensures, invariant, ....`

JML example

```
public class ePurse{
 private int balance;
 //@ invariant 0 <= balance && balance < 500;

 //@ requires amount >= 0;
 //@ ensures  balance <= \old(balance);
  public debit(int amount) {
    if (amount > balance) {
          throw (new BankException("No way"));}
    balance = balance - amount;
 }
```

What can you do with this?

- documentation/specification
  - record detailed design decisions & document assumptions (and hence obligations!)
  - precise, unambiguous documentation
    - parsed & type checked
- use tools for
  - runtime assertion checking
    - eg when testing code
  - compile time (static) analyses
    - up to full formal program verification

LOTS of freedom in specifying

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

  Eg for `debit(int amount)`

  ```
  //@ ensures balance == \old(balance)-amount;
  //@ ensures balance <= \old(balance);
  //@ ensures true;
  ```

  Good bottom-line spec to start: give minimal specs (**`requires`**, **`invariants`**) necessary to rule out (Runtime)Exceptions

- JML specs can be low(er) level

  ```
  //@ invariant f != null;
  ```

  or high(er) level

  ```
  //@ invariant child.parent == this;
  ```

Rest of this talk

- A bit more JML
- Tools, possibilities, related work, etc

exceptional postconditions: signals

```
/*@ requires amount >= 0;
  @  ensures balance <= \old(balance);
  @  signals (BankException) balance == \old(balance);
  @*/
 public debit(int amount) throws BankException {
   if (amount > balance) {
         throw (new BankException("No way"));}
   balance = balance - amount;
}
```

Often specs (should) concentrate on *ruling out* exceptional behaviour

ruling out exceptions

```
/*@ normal_behavior
  @  requires amount >= 0 && amount <= balance;
  @  ensures balance <= \old(balance);
  @*/
 public debit(int amount) throws BankException{
   if (amount > balance) {
         throw (new BankException("No way"));}
   balance = balance - amount;
}
```

Or omit "`throws BankException`"

assert and loop_invariant

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

/*@ loop_invariant 0 <= i && i < a.length &
                   (\forall int j; 0<= j & j < i;
                       a[i] != null );
        decreasing   a.length-i;
  @*/
while (a[i] != null) {...}
```

non_null

- Lots of invariants and preconditions are about references not being null, eg

```
int[] a; //@ invariant a != null;
```

- Therefore there is a shorthand

```
/*@ non_null @*/ int[] a;
```

- But, as most references are non-null, JML adopted this as default. So only *nullable* fields, arguments and return types need to be annotated, eg

```
/*@ nullable @*/ int[] b;
```

- JML will move to adopting JSR308 Java tags for this

```
@Nullable int[] b;
```

pure

Methods without side-effects that are guaranteed to terminate can be declared as pure

```
/*@ pure @*/ int getBalance (){
    return balance;
};
```

Pure methods can be used in JML annotations

```
//@ requires amount < getBalance();
public debit (int amount)
```

assignable (aka modifies)

For non-pure methods, frame properties can be specified using assignable clauses, eg

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

says **debit** is *only* allowed to modify the **balance** field

- NB this does *not* follow from the postcondition
- Assignable clauses are needed for modular verification
- Fields can be grouped in Datagroups, so that spec does not have to list concrete fields

resource usage

Syntax for specifying resource usage

```
/*@ measured_by len;          // max recursion depth
  @ working_space (len*4); // max heap space used
  @ duration len*24;         // max execution time
  @ ensures \fresh(\result); // freshly allocated
  @*/
public List(int len) {...
}
```

model state

```
interface Connection{
//@ model boolean opened; // spec-only field

//@ ensures !opened;
public Connection(...);

//@ requires !opened;
//@ ensures   opened;
public void open ();

//@ requires  opened;
//@ ensures  !opened;
public void close ();
```

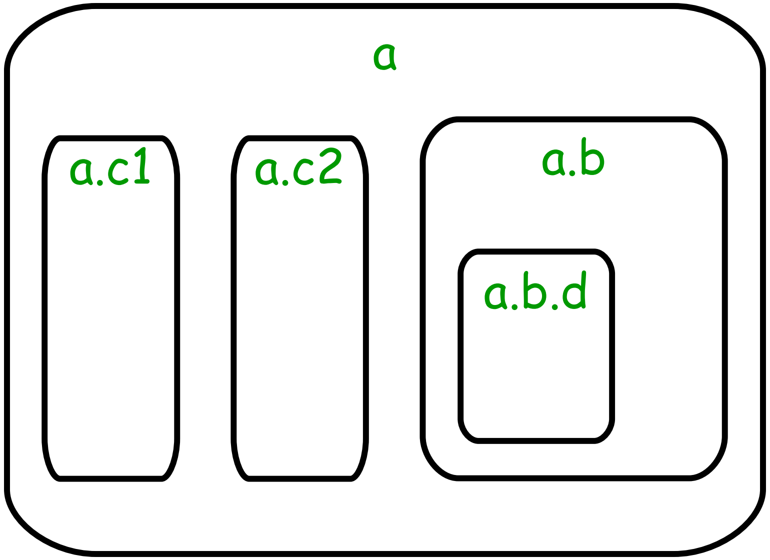
pointer trouble

References are the main source of trouble, also in verification

Universes are a type system to control aliasing

```
class A {
  //@ invariant invA;
  /*@ rep @*/ C c1, c2;
  /*@ rep @*/ B b;
}

class B {
   //@ invariant invB;
   /*@ rep @*/ D d;
}
```



tools, related work, ...

tool support: runtime assertion checking

- implemented in JMLrac, with JMLunit extension
- annotations provide the test oracle:
  - any annotation violation is an error,

  except if it is the initial precondition

- Pros
  - Lots of tests for free
  - Complicated test code for free, eg for

    ```
    signals (Exception) balance ==\old(balance);
    ```

  - More precise feedback about root causes
    - eg "Invariant X violated in line 200" after 10 sec instead of "Nullpointer exception in line 600" after 100 sec

tool support: compile time checking

- extended static checking
  automated checking of simple specs
  - ESC/Java(2)

- formal program verification tools
  interactive checking of arbitrarily complex specs
  - **KeY**, Krakatoa, Freeboogie, JMLDirectVCGen....

There is a trade-off between usability & qualifability.
In practice, each tool support its own subset of JML.

testing vs verification

- verification gives *complete* coverage
  - *all* paths, *all* possible inputs
- if testing fails, you get a counterexample (trace);

  if verification fails, you typically don't....
- verification can be done *before* code is complete
- verification *requires many more specs*
  - as verification is done on a per method basis
  - incl API specs

related work

- OCL for UML

  pro: not tied to a specific programming language

  con: idem

  less expressive, and semantics less clear

- Spec# for C#

  by Rustan Leino & co at Microsoft Research

- SparkAda for Ada

  by Praxis High Integrity System

  Commercially used

tools and tool status

- For Java 1.4
  - JML2 jmlrac
  - ESC/Java2
  - KeY

- For newer Java versions - under construction
  - OpenJML

    based on openjdk

    front end for runtime checking (and ESC)

program verification state-of-the-art

- JML verification tools can cope with typical Java Card code
  - small API, only 100's loc

- Microsoft hypervisor verification Hyper-V using VCC
  - 60 kloc of C code

some ideas...

- Coping with concurrency
  Track thread-ownership of objects
  marking objects are thread-local or shared,
  to make guarantees about memory-separation between threads.
  Largely supported by type system

- Traceability could maybe be supported by naming JML annotations

```
//@ invariant  propertyXyz: .... ;
```

questions?

Exercise: JML specification for arraycopy

```
/*@ requires ... ;
      ensures ... ;
  @*/
static void arraycopy (int[] src,  int srcPos,
                       int[] dest, int destPos,
                       int len)
 throws NullPointerException,
        ArrayIndexOutOfBoundsException;
```

Copies an array from the specified source array, beginning at the specified position, to the specified position of the destination array.

Exercise: JML specification for arraycopy

```
/*@ requires src != null && dest != null &&
             0 <= srcPos && srcPos + len < src.length &&
             0 <= destPos && srcPos + len < dest.length;

    ensures (\forall int i; 0 <= i && i < len;
                 dest[dstPos+i] == src[srcPos+i] ) &&
              (* rest unchanged *)
   @*/
 static void arraycopy (int[] src,  int srcPos,
                        int[] dest, int destPos,
                        int len);
```

Exercise: JML specification for arraycopy

```
/*@ requires src != null && dest != null &&
             0 <= srcPos && srcPos + len < src.length &&
             0 <= destPos && srcPos + len < dest.length;

    ensures (\forall int i; 0 <= i && i < len;
                 dest[dstPos+i] == \old(src[srcPos+i])) &&
              (* rest unchanged *)
  @*/
 static void arraycopy (int[] src,  int srcPos,
                        int[] dest, int destPos,
                        int len);
```

Exercise: JML specification for arraycopy

```
/*@ requires ...

     ensures (\forall int i; 0 <= i && i < len;
                 dest[dstPos+i] == \old(src[srcPos+i])) &&
               (* rest unchanged *)
   @*/
 static void arraycopy (int[] src,  int srcPos,
                        int[] dest, int destPos,
                        int len);
```

We don't have to write `\old(len)` and `\old(dest)[\old(dstPos)+1]` in the postcondition, because all parameters are implicily \old() in JML postconditions

Defaults and conjoining specs

- Default pre- and postconditions
  ```
  //@ requires true;
  //@ ensures true;
  ```
  can be omitted

- ```
  //@ requires P
  //@ requires Q
  ```
  means the same as
  ```
  //@ requires P && Q;
  ```
  ```

Default signals clause?

```
//@ requires amount >= 0;
//@ ensures balance <= \old(balance);
public debit(int amount) throws BankException
```

- Can debit throw a BankException, if precondition holds?
  YES
- Can debit throw a NullPointerException, if the precondition holds?
  NO. Unlike Java, JML *only* allows method to throw unchecked exceptions explicitly mentioned in throws-clauses!
- Methods *are* always allowed to throw Errors

Default signals clause?

- For a method

```
//@ public void m throws E1, ... En { ... }
```

the default is

```
//@ signals (E1) true;
     ...
//@ signals (En) true;
//@ signals_only E1, ... En;
```

- Here

```
//@ signals_only E1, ... En;
```

is shorthand for

```
/*@ signals (Exception e)
       \typeof(e) <: E1 || ... || \typeof(e) <: En;
  @*/
```

Specifying exceptional behaviour is tricky!

- Beware of the difference between
  1. if P holds then exception E *must* be thrown
  2. if P holds then exception E *may* be thrown
  3. if exception of type E is thrown then P will hold (in the poststate)

  This is what **`signals`** specifies

- Most often we just want to rule out exceptions
  - and come up with preconditions and invariants to do this

- Ruling out exceptions also helps with certified analyses for PCC, as it rules out many execution paths

requiring & ruling out exceptions

```
/*@  requires amount <= balance;
      ensures ...;
      signals (Exception) false;
   also
     requires amount > balance;
      ensures false;
      signals (BankException) ...;
  @*/

public debit(int amount) throws BankException
```

requiring & ruling out exceptions

```
/*@ normal_behavior
      requires amount <= balance;
      ensures ...;
   also
    exceptional_behavior
     requires amount > balance;
      signals (BankException) ...;
  @*/
 public debit(int amount) throws BankException
```

requiring & ruling out exceptions

```
/*@ normal_behavior
      requires amount <= balance;
      ensures ...;
   also
    exceptional_behavior
     requires amount > balance;
      signals (BankException) ...;
  @*/
 public debit(int amount) throws BankException
```

requiring & ruling out exceptions

or simply

```
/*@ requires amount <= balance;
     ensures ...;
   @*/
  public debit(int amount) // throws BankException
```

Effectively a `normal_behavior`, since there is no throws clause

Ruling out exceptions, esp. RuntimeExceptions, as much as possible is the natural thing to do – and a good bottom line specification

Visibility and spec_public

The standard Java visibility modifiers (public, protected, private) can be used on invariants and method specs, eg

```
//@ private invariant 0 <= balance;
```

Visibility of fields can be loosened using the keyword spec_public, eg

```
public class ePurse{
   private /*@ spec_public @*/ int balance;

   //@ ensures balance <= \old(balance);
   public debit(int amount)
```

allows private field to be used in (public) spec of **debit**

Of course, this exposes implementation details, which is not nice...

Dealing with undefinedness

- Using Java syntax in JML annotations has a drawback
  - what is the meaning of

    `//@ requires !(a[3] < 0);`

  if `a.length == 2` ?
- How to cope with Java expressions that throw exceptions?
  - runtime assertion checker can report the exception
  - program verifier can treat `a[3]` as unspecified integer

- Moral: write protective specifications, eg

  `//@ requires a.length > 4 && !(a[3] < 0);`

pure

Methods without side-effects that are guaranteed to terminate can be declared as pure

```
/*@ pure @*/ int getBalance (){
    return balance;
};
```

Pure methods can be used in JML annotations

```
//@ requires amount < getBalance();
public debit(int amount)
```

assignable

The default assignable clause is

```
//@ assignable \everything;
```

Pure methods are

```
//@ assignable \nothing;
```

Pure constructors are

```
//@ assignable this.*;
```

Reasoning in presence of late binding

Late binding (aka dynamic dispatch) introduces a complication in reasoning:

which method specification do we use to reason about

....; x.m(); ....

if we don't know the dynamic type of x?

Solutions:

1. do a case distinction over all possible dynamic types of x,
   - ie. x's static type A and all its subclasses

Obviously not modular!

1. insist on behavioural subtyping:
   - use spec for m in class A and require that specs for m in subclasses are stronger or identical

Behavioural subtyping & substitutivity

- The aim of behavioural subtyping aims to ensure the principle of subsitutivity:

  "substituting a subclass object for a parent object will not cause any surprises"

- Well-typed OO languages already ensure this in a weak form, as soundness of subtyping:

  "substituting a subclass object for a parent object will not result in 'Method not found' errors at runtime"

behavioural subtyping

Two ways to achieve behavioural subtyping

1. For any method spec in a subclass, prove that it is implies the spec for that method in the parent class
   - ie prove that the precondition is *weaker* !

   and the postcondition is stronger
1. Implicitly conjoin method spec in a subclass with method specs in the parent class
   - called specification inheritance, which is what JML uses
   - this guarantees that resulting precondition is weaker, and the resulting postcondition is stronger

Specification inheritance for method specs

Method specs are inherited in subclasses, and required keyword **also** warns that this is the case

```
class Parent {
    //@ requires i >=0;
    //@ ensures  \result >= i;
    int m(int i) {...}
}
class Child extends Parent {
    //@ also
    //@  requires i <= 0;
    //@  ensures  \result <= i;
    int m(int i) {...}
}
```

Effective spec of **m** in Child:

```
requires true;
ensures
  (i>=0 ==> result>=i)
&&
  (i<=0 ==> result<=i);
```

Specification inheritance for invariants

Invariants are inherited in subclasses, eg in

```
class Parent {
    //@ invariant invParent;
    ...
}

class Child extends Parent {
    //@ invariant invChild;
    ...
}
```

the invariant for the Child is **`invChild && invParent`**

JML
invariants

The semantics of invariants

- Basic idea:
  - Invariants have to hold on method entry and exit
  - but may be broken temporarily during a method

- NB invariants also have to hold if an exception is thrown!

- But there's more to it than that...

The callback problem

```
class A {
  int i;
  int[] a;
  B b;
  //@ invariant 0<=i && i< a.length;

  void inc() {a[i]++; }

  void break() {
    int oldi = i; i = -1;
    b.m(); i = oldi;
  }
```

```
class B {
  A a;

  void m() {
    a.inc(); // possible callback
  }

}
```

invariant temporarily broken

What if b.m() does a callback on **inc** of that *same* A object, while its invariant is broken...

The semantics of invariants

- An invariant can be temporarily broken during a method, but – because of the possible callbacks - it has to hold when any other method is invoked.
- Worse still, one object could break another object's invariant...
- visible state semantics

  all invariants of *all* objects have to hold in *all* visible states, ie. entry and exit points of methods

Problems with invariants

- The visible state semantics is *very* restrictive
  - eg, a constructor cannot call out to other methods before it has established the invariant

  It can be loosened in an ad-hoc manner by declaring methods as **`helper`** methods
  - **`helper`** methods don't require or ensure invariants
  - effectively, you can think of them as in-lined

- The more general problem: how to cope with invariants that involve multiple (or aggregate) objects
  - still an active research area...
  - one solution is to use some notion of object ownership

universes & relevant invariant semantics

Current JML approach to weakening visible state semantics for invariants

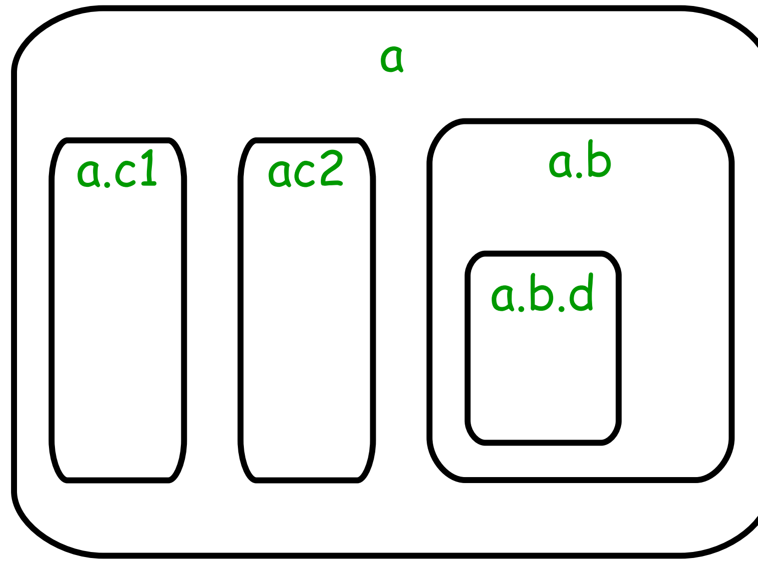
- universe type system
  - enforces hierachical nesting of objects

- relevant invariant semantics
  - invariant of outer objects may be broken when calling methods in inner objects

universes for alias control

```
class A {
  //@ invariant invA;
  /*@ rep @*/ C c1, c2;
  /*@ rep @*/ B b;
}

class B {
   //@ invariant invB;
   /*@ rep @*/ D d;
}
```



- invariants should only depend on owned state
- an object's invariant may be broken when it invokes methods on sub-objects