Software Engineering using Formal Methods

Java Modeling Language, Part II

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Recap: Specifying LimitedIntegerSet

```
public class LimitedIntegerSet {
  public final int limit;
  private /*@ spec_public @*/ int arr[];
  private /*@ spec_public @*/ int size = 0;

  public LimitedIntegerSet(int limit) {
    this.limit = limit;
    this.arr = new int[limit];
  }
  public boolean add(int elem) {/*...*/}

  public void remove(int elem) {/*...*/}

  public /*@ pure @*/ boolean contains(int elem) {/*...*/}

  // other methods
}
```

Result Values in Postcondition

```
/*@ public normal_behavior
  @ ensures \result == (\exists int i;
  @                              0 <= i && i < size;
  @                              arr[i] == elem);
  @*/
public /*@ pure @*/ boolean contains(int elem) {/*...*/}
```

Specifying add() (spec-case1) – new element can be added

```
/*@ public normal_behavior
  @ requires size < limit && !contains(elem);
  @ ensures \result == true;
  @ ensures contains(elem);
  @ ensures (\forall int e;
  @                  e != elem;
  @                  contains(e) <==> \old(contains(e)));
  @ ensures size == \old(size) + 1;
  @
  @ also
  @
  @ <spec-case2>
  @*/
public boolean add(int elem) {/*...*/}
```

Specifying add() (spec-case2) – new element cannot be added

```
/*@ public normal_behavior
  @
  @ <spec-case1>
  @
  @ also
  @
  @ public normal_behavior
  @ requires (size == limit) || contains(elem);
  @ ensures \result == false;
  @ ensures (\forall int e;
  @                 contains(e) <==> \old(contains(e)));
  @ ensures size == \old(size);
  @*/
public boolean add(int elem) {/*...*/}
```

Specifying remove()

```
/*@ public normal_behavior
  @ ensures !contains(elem);
  @ ensures (\forall int e;
  @                  e != elem;
  @                  contains(e) <==> \old(contains(e)));
  @ ensures \old(contains(elem))
  @         ==> size == \old(size) - 1;
  @ ensures !\old(contains(elem))
  @         ==> size == \old(size);
  @*/
public void remove(int elem) {/*...*/}
```

Specifying Data Constraints

So far:
JML used to specify method specifics.

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- consistency of redundant data representations (like indexing)
- restrictions for efficiency (like sortedness)

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JML used to specify method specifics.

How to specify constraints on class data, e.g.:

- consistency of redundant data representations (like indexing)
- restrictions for efficiency (like sortedness)

Data constraints are global: all methods must preserve them

Consider LimitedSorted IntegerSet

```
public class LimitedSortedIntegerSet {
  public final int limit;
  private int arr[];
  private int size = 0;

  public LimitedSortedIntegerSet(int limit) {
    this.limit = limit;
    this.arr = new int[limit];
  }
  public boolean add(int elem) {/*...*/}

  public void remove(int elem) {/*...*/}

  public boolean contains(int elem) {/*...*/}

  // other methods
}
```

Consequence of Sortedness for Implementer

method `contains`

- Can employ binary search (logarithmic complexity)

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method `add`

- Search first index with bigger element, insert just before that
- Thereby try to establish sortedness in poststate
- Why is that sufficient?
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method `remove`

- (accordingly)

Specifying Sortedness with JML

Recall class fields:

```
public final int limit;
private int arr[];
private int size = 0;
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(What's the value of this if `size < 2`?)

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Sortedness as JML expression:

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(\forall int i; 0 < i && i < size;
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```

(What's the value of this if `size < 2`?)

But where in the specification does the red expression go?

Specifying Sorted `contains()`

Can assume sortedness of prestate

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```
/*@ public normal_behavior
  @ requires (\forall int i; 0 < i && i < size;
  @                                arr[i-1] <= arr[i]);
  @ ensures \result == (\exists int i;
  @                                  0 <= i && i < size;
  @                                  arr[i] == elem);
  @*/
public /*@ pure @*/ boolean contains(int elem) {/*...*/}
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Specifying Sorted `contains()`

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  @                              0 <= i && i < size;
  @                              arr[i] == elem);
  @*/
public /*@ pure @*/ boolean contains(int elem) {/*...*/}
```

`contains()` is *pure*

⇒ sortedness of poststate trivially ensured

Specifying Sorted `remove()`

Can assume sortedness of prestate

Must ensure sortedness of poststate

```
/*@ public normal_behavior
  @ requires (\forall int i; 0 < i && i < size;
  @                          arr[i-1] <= arr[i]);
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  @ ensures (\forall int e;
  @                  e != elem;
  @                  contains(e) <==> \old(contains(e)));
  @ ensures \old(contains(elem))
  @         ==> size == \old(size) - 1;
  @ ensures !\old(contains(elem))
  @         ==> size == \old(size);
  @ ensures (\forall int i; 0 < i && i < size;
  @                         arr[i-1] <= arr[i]);
  @*/
public void remove(int elem) {/*...*/}
```

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  @ ensures (\forall int i; 0 < i && i < size;
  @                             arr[i-1] <= arr[i]);
  @
  @ also <spec-case2>
  @*/
public boolean add(int elem) {/*...*/}
```

Specifying Sorted add() (spec-case2) – cannot add

```
/*@ public normal_behavior
  @
  @ <spec-case1> also
  @
  @ public normal_behavior
  @ requires (\forall int i; 0 < i && i < size;
  @                              arr[i-1] <= arr[i]);
  @ requires (size == limit) || contains(elem);
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JML Class Invariant

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We can do better, using

JML Class Invariant

construct for specifying data constraints centrally

1. delete blue and red parts from previous slides
2. add 'sortedness' as JML class invariant instead

JML Class Invariant

```
public class LimitedSortedIntegerSet {

  public final int limit;

  /*@ private invariant (\forall int i;
    @                               0 < i && i < size;
    @                               arr[i-1] <= arr[i]);
    @*/

  private /*@ spec_public @*/ int arr[];
  private /*@ spec_public @*/ int size = 0;

  // constructor and methods,
  // without sortedness in pre/postconditions
}
```

JML Class Invariant

- JML class invariant can be placed anywhere in class
- (Contrast: method contract must be in front of its method)
- Custom to place class invariant in front of fields it talks about

Instance vs. Static Invariants

instance invariants

Can refer to instance fields of `this` object
(unqualified, like '`size`', or qualified with '**`this`**', like '**`this`**`.size`')

JML syntax: **`instance invariant`**

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Can refer to

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Can refer to

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– instance fields via explicit reference, like '`o.size`'

In classes, **instance is default**. In interfaces, **static is default**.

If **`instance`** or **`static`** is omitted for invariants

⇒ instance invariant in classes, static invariant in interfaces

Static JML Invariant Example

```
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

}
```

Class Invariants: Intuition, Notions & Scope

Class invariants must be

- established by
  - constructors (instance invariants)
  - static initialisation (static invariants)

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- preserved by all (non-helper) methods
  - assumed in prestate (implicit preconditions)
  - ensured in poststate (implicit postconditions)
  - can be violated during method execution

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Scope of invariant

- not limmited to it's class/interface
- depends on visibility (`private` vs. `public`) of local state

⇒ An invariant must not be violated by any code in any class

The JML modifier: `helper`

JML helper methods

```
T /*@ helper @*/ m(T p1, ..., T pn)
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Neither assumes nor ensures any invariant by default.

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Pragmatics & Usage examples of helper methods

- Helper methods are usually **`private`**.
- Used for structuring implementation of public methods
  (e.g. factoring out reoccurring steps)
- Used in constructors
  (where invariants have not yet been established)

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Additional purpose in KeY context

Normal form, used when translating JML to Dynamic Logic. (See later lecture)

Referring to Invariants

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- **\invariant_for**(o) is `true` in a state where all invariants of `o` are `true`, otherwise `false`

Pragmatics:

- Use **\invariant_for(this)** when local invariant is intended but *not* implicitly given, e.g., in specification of **helper** methods.

Referring to Invariants

Aim: refer to invariants of arbitrary objects in JML expressions.

- **`\invariant_for`**`(o)` is a `boolean` JML expression
- **`\invariant_for`**`(o)` is `true` in a state where all invariants of `o` are `true`, otherwise `false`

Pragmatics:

- Use **`\invariant_for(this)`** when local invariant is intended but *not* implicitly given, e.g., in specification of **`helper`** methods.
- Put **`\invariant_for(o)`**, where **`o`** $\neq$ `this`, into local **`requires`**/**`ensures`** clause or **`invariant`** to assume/guarantee or maintain invariant of **`o`** locally

Examples of Referring to Invariants

```
public class Database {
  ...
  /*@ public normal_behavior
    @ requires ...;
    @ ensures  ...;
    @*/
  public void add (Set newItems) {
    ... <rough adding at first> ...;
    cleanUp();
  }
  ...
```

Examples of Referring to Invariants

```
public class Database {
  ...
  /*@ public normal_behavior
    @ requires ...;
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    @*/
  public void add (Set newItems) {
    ... <rough adding at first> ...;
    cleanUp();
  }
  ...
  /*@ private normal_behavior
    @ ensures \invariant_for(this);
    @*/
  private /*@ helper @*/ void cleanUp() { ... }
  ...
```

Examples of Referring to Invariants

Example

If all (non-helper) methods of `ATM` shall maintain invariant of object stored in `insertedCard`:

```
public class ATM {
  ...
/*@ private invariant
  @ insertedCard != null ==> \invariant_for(insertedCard);
  @*/
  private BankCard insertedCard;
  ...
```

Examples of Referring to Invariants

Alternatively more fine grained:

Example

If method withdraw of ATM relies on invariant of insertedCard:

```
public class ATM {
  ...
  private BankCard insertedCard;
  ...
  /*@ public normal_behavior
    @ requires \invariant_for(insertedCard);
    @ requires <other preconditions>;
    @ ensures <postcondition>;
    @*/
  public int withdraw (int amount) { ... }
  ...
```

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- For non-helper methods, **\invariant_for(this)** implicitly added to pre- and postconditions!

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- **`\invariant_for`**`(expr)` returns true iff `expr` satisfies the invariant of its static type:
  - Given `class B extends A`
  - After executing initialiser `A o = new B();`
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- For non-helper methods, **`\invariant_for(this)`** implicitly added to pre- and postconditions!
- **`\invariant_for`**`(expr)` returns true iff `expr` satisfies the invariant of its static type:
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    `\invariant_for(o)` is true when `o` satisfies invariants of `A` ,
    `\invariant_for((B)o)` is true when `o` satisfies invariants of `B`.
- If `o` and `this` have different types, `\invariant_for(o)` only covers **`public`** invariants of `o`'s type.
  E.g., `\invariant_for(insertedCard)` refers to **`public`** invariants of `BankCard`.

Recall Specification of `enterPIN()`

```
private /*@ spec_public @*/ BankCard insertedCard = null;
private /*@ spec_public @*/ int wrongPINCounter = 0;
private /*@ spec_public @*/ boolean customerAuthenticated
                                    = false;

/*@ <spec-case1> also <spec-case2> also <spec-case3>
  @*/
public void enterPIN (int pin) { ...
```

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/*@ <spec-case1> also <spec-case2> also <spec-case3>
  @*/
public void enterPIN (int pin) { ...
```

last lecture:

all 3 *spec-cases* were **normal_behavior**

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normal_behavior specification case, with preconditions P,
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Keyword **`signals`** specifies *poststate*, depending on thrown exception

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`exceptional_behavior` specification case, with preconditions P,
requires method to throw exceptions if prestate satisfies P

Keyword **`signals`** specifies *poststate*, depending on thrown exception

Keyword **`signals_only`** limits types of thrown exception

Completing Specification of enterPIN()

```
/*@ <spec-case1> also <spec-case2> also <spec-case3> also
  @
  @ public exceptional_behavior
  @ requires insertedCard==null;
  @ signals_only ATMException;
  @ signals (ATMException) !customerAuthenticated;
  @*/
public void enterPIN (int pin) { ...
```

Completing Specification of enterPIN()

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/*@ <spec-case1> also <spec-case2> also <spec-case3> also
  @
  @ public exceptional_behavior
  @ requires insertedCard==null;
  @ signals_only ATMException;
  @ signals (ATMException) !customerAuthenticated;
  @*/
public void enterPIN (int pin) { ...
```

In case `insertedCard==null` in **pre**state:

- enterPIN *must* an exception ('**exceptional_behavior**')
- it can only be an `ATMException` ('**signals_only**')
- method must then ensure `!customerAuthenticated` in **post**state ('**signals**')

`signals_only` Clause: General Case

An exceptional specification case can have one clause of the form

$$\texttt{\textbf{signals\_only}}\ \texttt{E}_1\texttt{,...,E}_n\texttt{;}$$

where $\texttt{E}_1\texttt{,...,E}_n$ are exception types

`signals_only` Clause: General Case

An exceptional specification case can have one clause of the form

```
signals_only E1,...,En;
```

where $E_1, \ldots, E_n$ are exception types

Meaning:

If an exception is thrown, it is of type E_1 or ... or E_n

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signals (E) b;
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signals (E) b;
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where `E` is exception type, `b` is boolean expression

Meaning:

If an exception of type `E` is thrown, `b` holds in post condition

Allowing Non-Termination

By default, both:

- **`normal_behavior`**
- **`exceptional_behavior`**

specification cases enforce termination

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In each specification case, non-termination can be permitted via the clause

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diverges true;
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specification cases enforce termination

In each specification case, non-termination can be permitted via the clause

`diverges true;`

Meaning:

Given the precondition of the specification case holds in prestate, the method may or may not terminate

Further Modifiers: `non_null` and `nullable`

JML extends the JAVA modifiers by further modifiers:

- class fields
- method parameters
- method return types

can be declared as

- **`nullable`**: may or may not be **`null`**
- **`non_null`**: must not be **`null`**

non_null: Examples

```
private /*@ spec_public non_null @*/ String name;
```

Implicit invariant '`public invariant name != null;`'
added to class

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```
public void insertCard(/*@ non_null @*/ BankCard card) {..
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Implicit precondition '`requires card != null;`'
added to each specification case of `insertCard`

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private /*@ spec_public non_null @*/ String name;
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```
public void insertCard(/*@ non_null @*/ BankCard card) {..
```

Implicit precondition '`requires card != null;`'
added to each specification case of `insertCard`

```
public /*@ non_null @*/ String toString()
```

Implicit postcondition '`ensures \result != null;`'
added to each specification case of `toString`

non_null Default

non_null is default in JML!

⇒ same effect even without explicit '**non_null**'s

`private /*@ spec_public @*/ String name;`

Implicit invariant '`public invariant name != null;`'
added to class

`public void insertCard(BankCard card) {..`

Implicit precondition '`requires card != null;`'
added to each specification case of `insertCard`

`public String toString()`

Implicit postcondition '`ensures \result != null;`'
added to each specification case of `toString`

`nullable`: Examples

To prevent such pre/postconditions and invariants: '**`nullable`**'

```
private /*@ spec_public nullable @*/ String name;
```

No implicit invariant added

```
public void insertCard(/*@ nullable @*/ BankCard card) {..
```

No implicit precondition added

```
public /*@ nullable @*/ String toString()
```

No implicit postcondition added to specification cases of `toString`

LinkedList: non_null or nullable?

```
public class LinkedList {
    private Object elem;
    private LinkedList next;
    ....
```

In JML this means:

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public class LinkedList {
    private Object elem;
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In JML this means:

- All elements in the list are **non_null**

LinkedList: non_null or nullable?

```
public class LinkedList {
    private Object elem;
    private LinkedList next;
    ....
```

In JML this means:

- All elements in the list are **non_null**
- The list is cyclic, or infinite!

LinkedList: non_null or nullable?

Repair:

```
public class LinkedList {
    private Object elem;
    private /*@ nullable @*/ LinkedList next;
    ....
```

⇒ Now, the list is allowed to end somewhere!

Final Remarks on `non_null` and `nullable`

`non_null` as default in JML only since some years.

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is not the same as:

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/*@ nullable @*/ Object[] a; //@ invariant a != null;
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```
/*@ non_null @*/ Object[] a;
```

is not the same as:

```
/*@ nullable @*/ Object[] a; //@ invariant a != null;
```

because the first one also implicitly adds

```
(\forall int i; i >= 0 && i < a.length; a[i] != null)
```

I.e. extends **`non_null`** also to the elements of the array!

JML and Inheritance

All JML contracts, i.e.

- specification cases
- class invariants

are inherited down from superclasses to subclasses.

A class has to fulfill all contracts of its superclasses.

In addition, the subclass may add further specification cases, *starting with* **also**:

```
/*@ also
  @
  @ <subclass-specific-spec-cases>
  @*/
public void method () { ...
```

General Behaviour Specification Case

Complete Behavior Specification Case

```
behavior
  forall T1 x1; ...  forall Tn xn;
  old U1 y1 = F1; ...  old Uk yk = Fk;
  requires P;
  measured_by Mbe if Mbp;
  diverges D;
  when W;
  accessible R;
  assignable A;
  callable p1(...), ..., pl(...);
  captures Z;
  ensures Q;
  signals_only E1, ..., Eo;
  signals (E e) S;
  working_space Wse if Wsp;
  duration De if Dp;
```

gray not in this course

green in this course

General Behaviour Specification Case

Meaning of a behavior specification case in JML

An implementation of a method *m* satisfying its behavior spec. case must ensure: If property *P* holds in the method's prestate, then one of the following must hold

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 requires P;
 diverges D;
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- *D* holds in the prestate and method *m* does not terminate (default: D=`false`)
- ...

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         E1,...,Eo;
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```

- ...
- in the reached (normal or abrupt) poststate: All of the following items must hold
  - only heap locations (static/instance fields, array elements) that did not exist in the prestate or are listed in *A* (assignable) may have been changed

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- ...
- in the reached (normal or abrupt) poststate: All of the following items must hold
  - only heap locations ...
  - if *m* terminated normally, then in its poststate property *Q* holds (default: Q=`true`)

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          E1,...,Eo;
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```

- ...
- in the reached (normal or abrupt) poststate: All of the following items must hold
  - only heap locations ...
  - if *m* terminated normally then ...
  - if *m* terminated abruptly then
    - with an exception listed in **`signals_only`** (default: all exceptions of *m*'s throws declaration + `RuntimeException` and `Error`) and
    - for matching **`signals`** clause, the exceptional postcondition *S* holds

General Behaviour Specification Case

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        E1,...,Eo;
 signals (E e) S;
```

- ...
- in the reached (normal or abrupt) poststate: All of the following items must hold
  - ...
  - `\invariant_for(this)` must be maintained (in normal or abrupt termination) by non-`helper` methods

Desugaring: Normal Behavior and Exceptional Behavior

Both **`normal_behavior`** and **`exceptional_behavior`** cases are expressible as general **`behavior`** cases:

Normal Behavior Case

- defaults to '`signals (Throwable e) false;`'
- forbids overwriting of `signals` and `signals_only`

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- defaults to '`ensures false`'
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Normal Behavior and Exceptional Behavior

Both **`normal_behavior`** and **`exceptional_behavior`** cases are expressible as general **`behavior`** cases:

Normal Behavior Case

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- forbids overwriting of `signals` and `signals_only`

Exceptional Behavior Case

- defaults to ‘`ensures false`’
- forbids overwriting of `ensures`

Both default to ‘`diverge false`’, but allow it to be overwritten.

Tools

Several tools support JML
(see `www.eecs.ucf.edu/~leavens/JML//index.shtml`).

On the course website:
web interface, implemented by Bart van Delft, to OpenJML.

Many thanks to Bart!

Literature for this Lecture

Essential reading:

New JML Tutorial M. Huisman, W. Ahrendt, D. Grahl, M. Hentschel.
Formal Specification with the Java Modeling Language
to appear in the new KeY Book, end 2016
(available via Google group or personal request)

Further reading, all available at
`www.eecs.ucf.edu/~leavens/JML//index.shtml`

JML Reference Manual Gary T. Leavens, Erik Poll, Curtis Clifton, Yoonsik Cheon, Clyde Ruby, David Cok, Peter Müller, and Joseph Kiniry.
JML Reference Manual

JML Overview Gary T. Leavens, Albert L. Baker, and Clyde Ruby.
JML: A Notation for Detailed Design