Formal Methods for Software Development

Java Modeling Language, Part I

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04 October 2018

Role of JML in the Course

programming/modelling language	property/specification language	verification technique
PROMELA	LTL	model checking
JAVA	JML	deductive verification

Unit Specifications

system level specifications
(requirements analysis, GUI, use cases)
important, but
not subject of this course

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unit specification – *contracts among implementers* on various levels:

- application level – application level
- application level – library level
- library level – library level

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In the object-oriented setting:

Units to be specified are interfaces, classes, and their methods

We start with method specifications.

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Method specifications *potentially* refer to:

- initial values of formal parameters
- result value
- prestate and poststate

Specifications as Contracts

To stress the different roles – obligations – responsibilities in a specification:

widely used analogy of the specification as a *contract*

"Design by Contract" methodology (Meyer, 1992, EIFFEL)

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"Design by Contract" methodology (Meyer, 1992, EIFFEL)

Contract between caller and callee (i.e., the called method)

callee guarantees certain outcome *provided* caller guarantees prerequisites

Running Example: ATM.java

```
public class ATM {

    // fields:
    private BankCard insertedCard = null;
    private int wrongPINCounter = 0;
    private boolean customerAuthenticated = false;

    // methods:
    public void insertCard (BankCard card) { ... }
    public void enterPIN (int pin) { ... }
    public int accountBalance () { ... }
    public int withdraw (int amount) { ... }
    public void ejectCard () { ... }

}
```

Informal Specification

very informal Specification of '`enterPIN (int pin)`':

> *Enter the PIN that belongs to the currently inserted bank card into the ATM. If a wrong PIN is entered three times in a row, the card is confiscated. After having entered the correct PIN, the customer is regarded as authenticated.*

Getting More Precise: Specification as Contract

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precondition	card is inserted, user not yet authenticated, `wrongPINCounter < 2` and pin is incorrect

Getting More Precise: Specification as Contract

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precondition card is inserted, user not yet authenticated,
pin is correct
postcondition user is authenticated

precondition card is inserted, user not yet authenticated,
`wrongPINCounter < 2` and pin is incorrect
postcondition `wrongPINCounter` has been increased by `1`,
user is not authenticated

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precondition card is inserted, user not yet authenticated,
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user is not authenticated

precondition card is inserted, user not yet authenticated,
`wrongPINCounter >= 2` and pin is incorrect

Getting More Precise: Specification as Contract

Contract states what is guaranteed under which conditions.

precondition card is inserted, user not yet authenticated,
pin is correct
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precondition card is inserted, user not yet authenticated,
`wrongPINCounter < 2` and pin is incorrect
postcondition `wrongPINCounter` has been increased by `1`,
user is not authenticated

precondition card is inserted, user not yet authenticated,
`wrongPINCounter >= 2` and pin is incorrect
postcondition card is confiscated
user is not authenticated

Meaning of Pre/Postcondition pairs

Definition

A **pre**/**post-condition** pair for a method `m` is **satisfied by the implementation** of `m` if:

> *When* `m` *is called in any state that satisfies the precondition then in any terminating state of* `m` *the postcondition is true.*

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2. Termination may or may not be guaranteed.
3. In case of termination, it may be normal or abrupt.

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2. Termination may or may not be guaranteed.
3. In case of termination, it may be normal or abrupt.

non-termination and abrupt termination ⇒ next lecture

Formal Specification

Natural language specs are very important and widely used

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Describe contracts with mathematical rigour

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Motivation

- High degree of precision
  - formalization often exhibits omissions/inconsistencies
  - avoid ambiguities inherent to natural language
- Potential for automation of program analysis
  - monitoring
  - test case generation
  - program verification

Java Modeling Language (JML)

JML is a specification language tailored to JAVA.

General JML Philosophy

Integrate

- specification
- implementation

in one single language.

⇒ JML is not external to JAVA

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JML
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JAVA + FO Logic + pre/postconditions, invariants + more...

JML Annotations

JML extends JAVA by annotations.

JML annotations include:

- ✔ preconditions
- ✔ postconditions
- ✔ class invariants
- ✔ additional modifiers
- ✘ 'specification-only' fields
- ✘ 'specification-only' methods
- ✔ loop invariants
- ✔ ...
- ✘ ...

✔: in this course, ✘: not in this course

JML/JAVA integration

JML annotations are attached to JAVA programs
by
writing them directly into the JAVA source code files

Ensures compatibility with standard JAVA compiler:

JML annotations live in special JAVA comments,
ignored by JAVA compiler, recognized by JML tools

JML by Example

from the file `ATM.java`

⋮

```
/*@ public normal_behavior
  @ requires !customerAuthenticated;
  @ requires pin == insertedCard.correctPIN;
  @ ensures customerAuthenticated;
  @*/
public void enterPIN (int pin) {
    if ( ...
```

⋮

JML by Example

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```

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Everything between /* and */ is invisible for JAVA.

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But:

A JAVA comment with '@' as its first character
it is *not* a comment for JML tools.

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public void enterPIN (int pin) {
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```

But:

A JAVA comment with ‘@’ as its first character
it is *not* a comment for JML tools.

JML annotations appear in JAVA comments starting with @.

JML by Example

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/*@ public normal_behavior
  @ requires !customerAuthenticated;
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But:

> A Java comment with '@' as its first character
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JML annotations appear in Java comments starting with @.

How about "//" comments?

JML by Example

```
/*@ public normal_behavior
  @ requires !customerAuthenticated;
  @ requires pin == insertedCard.correctPIN;
  @ ensures customerAuthenticated; @*/
```

equivalent to:

```
//@ public normal_behavior
//@ requires !customerAuthenticated;
//@ requires pin == insertedCard.correctPIN;
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The easiest way to comment out JML:

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/*␣@ public normal_behavior ... @*/
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The easiest way to comment out JML:

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/*␣@ public normal_behavior ... @*/
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```
//␣@ public normal_behavior
//␣@ requires !customerAuthenticated;
...
```

JML by Example

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What about the intermediate ‘@’s?

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What about the intermediate ‘@’s?

Within a JML annotation, a ‘@’ is ignored:

- if it is the first (non-white) character in the line
- if it is the last character before ‘*/’.

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What about the intermediate ‘@’s?

Within a JML annotation, a ‘@’ is ignored:

- if it is the first (non-white) character in the line
- if it is the last character before ‘*/’.

⇒ The blue ‘@’s are not *required*, but it’s a convention to use them.

JML by Example

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/*@ public normal_behavior
  @ requires !customerAuthenticated;
  @ requires pin == insertedCard.correctPIN;
  @ ensures customerAuthenticated;
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public void enterPIN (int pin) {
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```

This is a **public** specification case:

1. it is accessible from all classes and interfaces
2. it can only mention `public` fields/methods of this class

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2. Can be a problem. Solution later in the lecture.

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Each keyword ending with **behavior** opens a ‘specification case’.

normal_behavior Specification Case

The method guarantees to *not* throw any exception

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`normal_behavior` Specification Case

The method guarantees to *not* throw any exception (on the top level),

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Each keyword ending with **behavior** opens a 'specification case'.

normal_behavior Specification Case

The method guarantees to *not* throw any exception (on the top level), *if the caller guarantees all preconditions of this specification case*.

JML by Example

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  @ ensures customerAuthenticated;
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This specification case has two preconditions (marked by **requires**)

1. `!customerAuthenticated`
2. `pin == insertedCard.correctPIN`

JML by Example

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here:
preconditions are *boolean Java expressions*

JML by Example

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preconditions are *boolean JAVA expressions*

in general:
preconditions are *boolean JML expressions* (see below)

JML by Example

```
/*@ public normal_behavior
  @ requires !customerAuthenticated;
  @ requires pin == insertedCard.correctPIN;
  @ ensures customerAuthenticated;
  @*/
```

specifies only the case where both preconditions are true in prestate

the above is equivalent to:

```
/*@ public normal_behavior
  @ requires (    !customerAuthenticated
  @              && pin == insertedCard.correctPIN );
  @ ensures customerAuthenticated;
  @*/
```

JML by Example

```
/*@ public normal_behavior
  @ requires !customerAuthenticated;
  @ requires pin == insertedCard.correctPIN;
  @ ensures customerAuthenticated;
  @*/
public void enterPIN (int pin) {
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This specification case has one postcondition (marked by **ensures**)

- `customerAuthenticated`

JML by Example

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here:
postcondition is *boolean Java expressions*

in general:
postconditions are *boolean JML expressions* (see below)

JML by Example

different specification cases are connected by ‘also’.

```
/*@ public normal_behavior
  @ requires !customerAuthenticated;
  @ requires pin == insertedCard.correctPIN;
  @ ensures customerAuthenticated;
  @
  @ also
  @
  @ public normal_behavior
  @ requires !customerAuthenticated;
  @ requires pin != insertedCard.correctPIN;
  @ requires wrongPINCounter < 2;
  @ ensures wrongPINCounter == \old(wrongPINCounter) + 1;
  @*/
public void enterPIN (int pin) {
    if ( ...
```

JML by Example

```
/*@ <spec-case1> also
  @
  @ public normal_behavior
  @ requires !customerAuthenticated;
  @ requires pin != insertedCard.correctPIN;
  @ requires wrongPINCounter < 2;
  @ ensures wrongPINCounter == \old(wrongPINCounter) + 1;
  @*/
public void enterPIN (int pin) { ...
```

for the first time, JML expression not a JAVA expression

`\old(`*E*`)` means: *E* evaluated in the prestate of `enterPIN`.

E can be any (arbitrarily complex) JML expression.

JML by Example

```
/*@ <spec-case1> also <spec-case2> also
  @
  @ public normal_behavior
  @ requires insertedCard != null;
  @ requires !customerAuthenticated;
  @ requires pin != insertedCard.correctPIN;
  @ requires wrongPINCounter >= 2;
  @ ensures insertedCard == null;
  @ ensures \old(insertedCard).invalid;
  @*/
public void enterPIN (int pin) { ...
```

two postconditions state that:

‘Given the above preconditions, `enterPIN` guarantees:

`insertedCard == null` and `\old(insertedCard).invalid`’

JML by Example

Question:

could it be

```
  @ ensures \old(insertedCard.invalid);
```

instead of

```
  @ ensures \old(insertedCard).invalid;
```

??

Specification Cases Complete?

consider spec-case-1:

```
  @ public normal_behavior
  @ requires !customerAuthenticated;
  @ requires pin == insertedCard.correctPIN;
  @ ensures customerAuthenticated;
```

what does spec-case-1 *not* tell about poststate?

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recall: fields of class `ATM`:

```
insertedCard
customerAuthenticated
wrongPINCounter
```

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what does spec-case-1 *not* tell about poststate?

recall: fields of class `ATM`:

```
insertedCard
customerAuthenticated
wrongPINCounter
```

what happens with `insertCard` and `wrongPINCounter`?

Completing Specification Cases

completing spec-case-1:

```
@ public normal_behavior
@ requires !customerAuthenticated;
@ requires pin == insertedCard.correctPIN;
@ ensures customerAuthenticated;
@ ensures insertedCard == \old(insertedCard);
@ ensures wrongPINCounter == \old(wrongPINCounter);
```

Completing Specification Cases

completing spec-case-2:

```
@ public normal_behavior
@ requires !customerAuthenticated;
@ requires pin != insertedCard.correctPIN;
@ requires wrongPINCounter < 2;
@ ensures wrongPINCounter == \old(wrongPINCounter) + 1;
@ ensures insertedCard == \old(insertedCard);
@ ensures customerAuthenticated
@         == \old(customerAuthenticated);
```

Completing Specification Cases

completing spec-case-3:

```
@ public normal_behavior
@ requires insertedCard != null;
@ requires !customerAuthenticated;
@ requires pin != insertedCard.correctPIN;
@ requires wrongPINCounter >= 2;
@ ensures insertedCard == null;
@ ensures \old(insertedCard).invalid;
@ ensures customerAuthenticated
@         == \old(customerAuthenticated);
@ ensures wrongPINCounter == \old(wrongPINCounter);
```

Assignable Clause

unsatisfactory to add

```
@ ensures loc == \old(loc);
```

for all locations *loc* which *do not* change

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```
@ ensures loc == \old(loc);
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instead:
add assignable clause for all locations which *may* change

```
@ assignable loc_1,...,loc_n;
```

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@ ensures loc == \old(loc);
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for all locations *loc* which *do not* change

instead:
add assignable clause for all locations which *may* change

```
@ assignable loc1,...,locn;
```

Meaning: No location other than $loc_1, \ldots, loc_n$ can be assigned to.

Assignable Clause

unsatisfactory to add

```
@ ensures loc == \old(loc);
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for all locations *loc* which *do not* change

instead:
add assignable clause for all locations which *may* change

```
@ assignable loc_1,...,loc_n;
```

Meaning: No location other than $loc_1, \dots, loc_n$ can be assigned to.

Special cases:

No location may be changed:

```
@ assignable \nothing;
```

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@ ensures loc == \old(loc);
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Special cases:

No location may be changed:

```
@ assignable \nothing;
```

Unrestricted, method allowed to change anything:

```
@ assignable \everything;
```

Specification Cases with Assignable

completing spec-case-1:

```
@ public normal_behavior
@ requires !customerAuthenticated;
@ requires pin == insertedCard.correctPIN;
@ ensures customerAuthenticated;
@ assignable customerAuthenticated;
```

Specification Cases with Assignable

completing spec-case-2:

```
@ public normal_behavior
@ requires !customerAuthenticated;
@ requires pin != insertedCard.correctPIN;
@ requires wrongPINCounter < 2;
@ ensures wrongPINCounter == \old(wrongPINCounter) + 1;
@ assignable wrongPINCounter;
```

Specification Cases with Assignable

completing spec-case-3:

```
@ public normal_behavior
@ requires insertedCard != null;
@ requires !customerAuthenticated;
@ requires pin != insertedCard.correctPIN;
@ requires wrongPINCounter >= 2;
@ ensures insertedCard == null;
@ ensures \old(insertedCard).invalid;
@ assignable insertedCard,
@            insertedCard.invalid,
```

Assignable Groups

You can specify groups of locations as assignable, using '$*$'.

example:

```
@ assignable o.*, a[*];
```

makes all fields of object o and all positions of array a assignable.

Literature for this and the next Lecture

KeYbook *W. Ahrendt*, B. Beckert, R. Bubel, R. Hähnle, P. Schmitt, M. Ulbrich, editors.
Deductive Software Verification - The KeY Book
Vol 10001 of *LNCS*, Springer, 2016
(E-book at `link.springer.com`)

Essential reading:

JML Tutorial M. Huisman, *W. Ahrendt*, D. Grahl, M. Hentschel.
Formal Specification with the Java Modeling Language
Chapter 7 in [KeYbook]

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