

Formal Methods for Software Development

Java Modeling Language, Part I

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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

instead:

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

- ▶ application level \Leftrightarrow application level
- ▶ application level \Leftrightarrow library level
- ▶ library level \Leftrightarrow library level

Unit Specifications

In the object-oriented setting:

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

We start with **method** specifications.

Method specifications *potentially* refer to:

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

Specifications as Contracts

To stress different roles/obligations/responsibilities in a specification:
widely used analogy of the *specification as a contract*

“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 () { ... }  
  
}
```

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

Checks whether the pin belongs to the bank card currently inserted in the ATM. If a wrong pin is received three times in a row, the card is confiscated. After receiving the correct pin, the customer is regarded as authenticated.

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

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

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.*

1. No guarantees are given when the precondition is not satisfied.
2. Termination may or may not be guaranteed.
3. In case of termination, it may be normal or abrupt.

non-termination and abrupt termination \Rightarrow next lecture

Formal Specification

Natural language specs are very important and widely used, we focus on

Formal Specification

Describe contracts with mathematical rigour

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

JML

is

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 ( ...  
⋮
```

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

JML by Example

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

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 @.

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;
//@ ensures customerAuthenticated;
```

The easiest way to [comment out JML](#):

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

```

JML by Example

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

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

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

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

JML by Example

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

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

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

This specification case has two **preconditions** (marked by **requires**)

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

here:

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) {
    if ( ...
```

This specification case has one **postcondition** (marked by **ensures**)

▶ `customerAuthenticated`

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`'

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?

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

instead:

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

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

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

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