15-819M: Data, Code, Decisions

06a: Java Modeling Language

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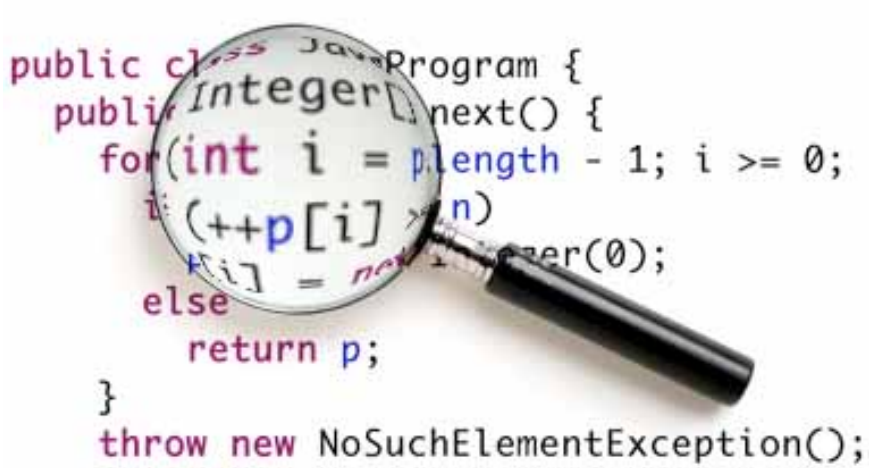

Outline

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Road-map

Deductive Verification of JAVA source code

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1. foundations: proving in first-order logic (done)

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3. proving JAVA programs correct (later)

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Deductive Verification of JAVA source code

1. foundations: proving in first-order logic (done)
2. *specifying* JAVA programs (comes now)
3. proving JAVA programs correct (later)

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What kind of Specifications

system level specifications
(requirements analysis, GUI, use cases)
important, but
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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

For object-oriented programs:

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

first focus on methods

methods specified by *potentially* referring to:

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For object-oriented programs:

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methods specified by *potentially* referring to:

- result value,
- initial values of formal parameters,
- accessible part of pre/post-state

Specifications as Contracts

Stressing different roles – obligations – responsibilities in a specification:

widely used analogy of specification = *contract*

"Design by Contract" methodology [Bertrand Meyer]

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Contract between *caller* and *callee* of 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

Contract states what is guaranteed under which conditions.

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postcondition	`wrongPINCounter` is increased by 1 user is not authenticated

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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
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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` is 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/Post-condition 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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non-termination and abrupt termination $\Rightarrow$ next lecture

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"Formal" specifications:

Describing contracts of units in a mathematically precise language.

Motivation:

- higher degree of precision
- *automation* of program analysis of various kinds:
  - static checking
  - program verification

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Java Modeling Language (JML)

JML is a specification language tailored to JAVA.

General JML Philosophy

Integrate

- specification
- implementation

in one single language.

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JML
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JAVA+ FO Logic+ pre/post-conditions, 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

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JML annotations live in in special comments,
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Neat proposed variant:

JML annotations live in Java @annotations.

JML by Example (ATM.java)

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

JML by Example (ATM.java)

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/*@ 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 (ATM.java)

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/*@ public normal_behavior
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But:

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

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JML annotations appear in JAVA comments starting with @.

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How about "//" comments?

JML by Example (ATM.java)

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

equivalent to:

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

JML by Example (ATM.java)

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/*@ public normal_behavior
  @ requires !customerAuthenticated;
  @ requires pin == insertedCard.correctPIN;
  @ ensures customerAuthenticated;
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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-blank) character in the line
- if it is the last character before '*/'.

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/*@ public normal_behavior
  @ requires !customerAuthenticated;
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What about the intermediate '@'s?

Within a JML annotation, a '@' is ignored:

- if it is the first (non-blank) 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.

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```
/*@ public normal_behavior
  @ requires !customerAuthenticated;
  @ requires pin == insertedCard.correctPIN;
  @ ensures customerAuthenticated;
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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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In this course: mostly `public` specifications.

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```
/*@ public normal_behavior
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  @ requires pin == insertedCard.correctPIN;
  @ ensures customerAuthenticated;
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public void enterPIN (int pin) {
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Each keyword ending on **behavior** opens a 'specification case'.

normal_behavior Specification Case

The method guarantees to *not* throw any exception,

JML by Example (ATM.java)

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/*@ public normal_behavior
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public void enterPIN (int pin) {
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Each keyword ending on **behavior** opens a 'specification case'.

normal_behavior Specification Case

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

JML by Example (ATM.java)

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/*@ public normal_behavior
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  @ requires pin == insertedCard.correctPIN;
  @ ensures customerAuthenticated;
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This specification case has two preconditions (marked by **requires**)

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

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/*@ public normal_behavior
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here:

preconditions are *boolean* JAVA *expressions*

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here:
preconditions are *boolean* JAVA *expressions*

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

JML by Example (ATM.java)

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

specifies only the case where both preconditions are true in pre-state

the above is equivalent to:

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

JML by Example (ATM.java)

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

- customerAuthenticated

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

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here:
postcondition is *boolean* JAVA *expressions*

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

JML by Example (ATM.java)

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 (ATM.java)

```
/*@ <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) { ...
```

Now JML expression not a JAVA expression

`\old(`*E*`)` means: *E* evaluated in the pre-state of `enterPIN`.

E can be any (arbitrarily complex) JAVA/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`'

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 post-state?

Specification Cases Complete?

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Recall: fields of class `ATM`:

- `insertedCard`
- `customerAuthenticated`
- `wrongPINCounter`

Specification Cases Complete?

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What happens with `insertCard` and `wrongPINCounter`?

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What does spec-case-1 *not* tell about post-state?

Recall: fields of class `ATM`:

- `insertedCard`
- `customerAuthenticated`
- `wrongPINCounter`

What happens with `insertCard` and `wrongPINCounter`? Frame prob.

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: Fighting Frames

Unpleasant if we have to add

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

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

Assignable Clause: Fighting Frames

Unpleasant if we have 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;
```

Assignable Clause: Fighting Frames

Unpleasant if we have 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 loc_1, ..., loc_n;
```

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

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 wrongPINCounter,
@            insertedCard,
@            insertedCard.invalid;
```

JML Modifiers

JML extends the JAVA modifiers by additional modifiers.

The most important ones are:

- `spec_public`
- `pure`

Aim: admitting more class elements to be used in JML expressions.

JML Modifiers: `spec_public`

In (`enterPIN`) example, pre/post-conditions made heavy use of class fields

But: `public` specifications can only talk about `public` fields.

No solution: make all fields public.

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One solution:

- keep the fields `private/protected`
- make those needed for specification **`spec_public`**

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One solution:

- keep the fields private/protected
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```
private /*@ spec_public @*/ BankCard insertedCard = null;
private /*@ spec_public @*/ int wrongPINCounter = 0;
private /*@ spec_public @*/ boolean customerAuthenticated
                                        = false;
```

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```

(different solution: use specification-only fields)

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

(Bug note:
in KeY1.4, spec_public fields are only visible within their class)

JML Modifiers: `pure`

It can be handy to use method calls in JML annotations.
Examples:

- `o1.equals(o2)`
- `li.contains(elem)`
- `li1.max() < li2.min()`

allowed if, and only if method is guaranteed to have no side effects

In JML, you can specify methods to be '`pure`':

```
public /*@ pure @*/ int max() { ...
```

The '`pure`' modifier puts an additional obligation on the implementer (not to cause side effects), but allows to use the method in annotations.

JML Expressions ≠ JAVA Expressions

`boolean` JML Expressions (to be completed)

- each side-effect free `boolean` JAVA expression is a `boolean` JML expression
- if `a` and `b` are `boolean` JML expressions, and `x` is a variable of type `t`, then the following are also `boolean` JML expressions:
  - `!a` ("not a")
  - `a && b` ("a and b")
  - `a || b` ("a or b")

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  - `a && b` ("a and b")
  - `a || b` ("a or b")
  - `a ==> b` ("a implies b")
  - `a <==> b` ("a is equivalent to b")
  - ...
  - ...
  - ...
  - ...

Beyond `boolean` JAVA expressions

How to express the following?

- an array `arr` only holds values ≤ 2

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Stay tuned for next lecture . . .

Outline

Literature for this Lecture

Essential reading:

in KeY Book A. Roth and Peter H. Schmitt: Formal Specification. Chapter 5 only sections 5.1,5.3, In: B. Beckert, R. Hähnle, and P. Schmitt, editors. *Verification of Object-Oriented Software: The KeY Approach*, vol 4334 of *LNCS*. Springer, 2006.

Further reading:

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 Tutorial Gary T. Leavens, Yoonsik Cheon.
Design by Contract with JML

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

`http://www.eecs.ucf.edu/~leavens/JML/`