Formal Specification and Verification

Java Modeling Language

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Based on a lecture by Wolfgang Ahrendt and Reiner Hähnle at Chalmers University, Göteborg

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)

What kind of Specifications

system level specifications

(requirements analysis, GUI, use cases)

important, but

not subject of this course

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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

in the object-oriented setting:

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

first focus on methods

methods specified by *potentially* referring to:

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- pre-state and post-state

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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

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

widely used analogy of the specification as a *contract*

"Design by Contract" methodology

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"Design by Contract" methodology

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 is 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
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

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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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Describing contracts of units in a mathematically precise language.

Motivation:

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

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
is
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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to not confuse JAVA compiler:

JML annotations live in in special comments,
ignored by JAVA, recognized by JML.

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

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

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

JML by Example

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/*@ public normal_behavior
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But:

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

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JML annotations appear in Java comments starting with @.

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But:

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How about "//" comments?

JML by Example

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

equivalent to:

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

JML by Example

```
/*@ public normal_behavior
  @ requires !customerAuthenticated;
  @ requires pin == insertedCard.correctPIN;
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What about the intermediate ‘`@`’s?

JML by Example

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/*@ public normal_behavior
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public void enterPIN (int pin) {
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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 '`*/`'.

JML by Example

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

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

In this course: mostly `public` specifications.

JML by Example

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

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/*@ public normal_behavior
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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

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

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

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here:
preconditions are *boolean* JAVA *expressions*

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2. `pin == insertedCard.correctPIN`

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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 pre-state

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;
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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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- `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 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?

consider spec-case-1:

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recall: fields of class `ATM`:

```
insertedCard
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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`?

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

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 loc1,...,locn;
```

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 $loc_1, \ldots, loc_n$ 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.

Not desired: make all fields public.

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

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one solution:

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

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

JML Modifiers: spec_public

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

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Not desired: make all fields public.

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(different solution: use specification-only fields)

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one solution:

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

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

(Bug note:
in KeY 1.4, `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 $\neq$ 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` ("not a")
  - `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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First-order Logic in JML Expressions

JML `boolean` expressions extend JAVA `boolean` expressions by:

- implication
- equivalence

First-order Logic in JML Expressions

JML `boolean` expressions extend JAVA `boolean` expressions by:

- implication
- equivalence
- quantification

boolean JML Expressions

boolean JML expressions are defined recursively:

boolean JML Expressions

- 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")
  - `a ==> b` ("a implies b")
  - `a <==> b` ("a is equivalent to b")
  - `(\forall t x; a)` ("for all `x` of type `t`, `a` is true")
  - `(\exists t x; a)` ("there exists `x` of type `t` such that `a`")

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  - `(\exists t x; a)` ("there exists `x` of type `t` such that a")
  - `(\forall t x; a; b)` ("for all `x` of type `t` fulfilling a, b is true")
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JML Quantifiers

in

`(\forall t x; a; b)`

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a called "range predicate"

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those forms are redundant:

`(\forall t x; a; b)`
equivalent to
`(\forall t x; a ==> b)`

`(\exists t x; a; b)`
equivalent to
`(\exists t x; a && b)`

Pragmatics of Range Predicates

`(\forall t x; a; b)` and `(\exists t x; a; b)`

widely used

pragmatics of range predicate:

`a` used to restrict range of `x` further than `t`

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example: "`arr` is sorted at indexes between 0 and 9":

```
(\forall int i,j; 0<=i && i<j && j<10;
```

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example: "`arr` is sorted at indexes between 0 and 9":

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(\forall int i,j; 0<=i && i<j && j<10; arr[i] <= arr[j])
```

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(\forall int i; 0<=i && i<arr.length; m >= arr[i])
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Using Quantified JML expressions

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(\exists int i; 0<=i && i<arr.length; m == arr[i])
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Using Quantified JML expressions

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(\forall int i; 0<=i && i<arr.length; m >= arr[i])
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```
arr.length>0 ==>
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Using Quantified JML expressions

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(\forall int i; 0<=i && i<maxAccountNumber;
                accountProxies[i].accountNumber == i )
```

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How to express:

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How to express:

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```
(\forall BankCard p1, p2;
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- JML quantifiers range also over non-created objects

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note:

- JML quantifiers range also over non-created objects
- same for quantifiers in KeY!
- in JML, restrict to created objects with `\created`
- in KeY? ($\Rightarrow$ coming lecture)

Example: Specifying `LimitedIntegerSet`

```
public class LimitedIntegerSet {
  public final int limit;
  private int arr[];
  private 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 boolean contains(int elem) {/*...*/}

  // other methods
}
```

Prerequisites: Adding Specification Modifiers

```
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) {/*...*/}

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public /*@ pure @*/ boolean contains(int elem)  {/*...*/}
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how to specify result value?

Result Values in Postcondition

In postconditions,
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In postconditions,
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```
/*@ public normal_behavior
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public /*@ pure @*/ boolean contains(int elem) {/*...*/}
```

Specifying add() (spec-case1)

```
/*@ 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)

```
/*@ 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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- 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 LimitedSortedIntegerSet

```
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 Implementations

method `contains`

- can employ binary search (logarithmic complexity)

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method `add`

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- thereby tries to establish sortedness in post-state
- why is that sufficient?
- it assumes sortedness in pre-state

method `remove`

- (accordingly)

Specifying Sortedness with JML

recall class fields:

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

sortedness as JML expression:

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

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sortedness as JML expression:

```
(\forall int i; 0 < i && i < size;
                arr[i-1] <= arr[i])
```

(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 pre-state

Specifying Sorted `contains()`

can assume sortedness of pre-state

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

`contains()` is *pure*

⇒ sortedness of post-state trivially ensured

Specifying Sorted `remove()`

can assume sortedness of pre-state

must ensure sortedness of post-state

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

Specifying Sorted `add()` (spec-case1)

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  @ ensures size == \old(size) + 1;
  @ 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)

```
/*@ 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);
  @ ensures \result == false;
  @ ensures (\forall int e;
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  @ ensures (\forall int i; 0 < i && i < size;
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  @*/
public boolean add(int elem) {/*...*/}
```

Factor out Sortedness

so far: 'sortedness' has swamped our specification

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JML Class Invariant

construct for specifying data constraints centrally

Factor out Sortedness

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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;

  /*@ public 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/post-conditions
}
```

JML Class Invariant

- JML class invariant can be places 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 '`self`', like '`self.size`')

JML syntax: **`instance invariant`**

Instance vs. Static Invariants

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both

can refer to

– static fields

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

instance is default

if **`instance`** or **`static`** is omitted $\Rightarrow$ instance invariant!

Static JML Invariant Example

```
public class BankCard {

  /*@ public static invariant
    @  (\forall BankCard p1, p2;
    @     \created(p1) && \created(p2);
    @     p1!=p2 ==> p1.cardNumber!=p2.cardNumber)
    @*/

  private /*@ spec_public @*/ int cardNumber;

  // rest of class follows

}
```

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) { ...
```

Recall Specification of enterPIN()

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private /*@ spec_public @*/ BankCard insertedCard = null;
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  @*/
public void enterPIN (int pin) { ...
```

last lecture:
all 3 *spec-cases* were **normal_behavior**

Specifying Exceptional Behavior of Methods

`normal_behavior` specification case, with preconditions P,
forbids method to throw exceptions if pre-state satisfies P

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keyword **`signals`** specifies *post-state*, depending on thrown exception

Specifying Exceptional Behavior of Methods

normal_behavior specification case, with preconditions P,
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exceptional_behavior specification case, with preconditions P,
requires method to throw exceptions if pre-state satisfies P

keyword **signals** specifies *post-state*, 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()

```
/*@ <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

- an exception *must* be thrown (‘`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

```
signals_only (E1,..., En);
```

where `E1,..., En` are exception types

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where `E1,..., En` are exception types

Meaning:

if an exception is thrown, it is of type `E1` or ... or `En`

signals Clause: General Case

an exceptional specification case can have several clauses of the form

```
signals (E) b;
```

where `E` is exception type, `b` is boolean expression

signals Clause: General Case

an exceptional specification case can have several clauses of the form

```
signals (E) b;
```

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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diverges true;
```

Allowing Non-Termination

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- **`exceptional_behavior`**

specification cases enforce termination

in each specification case, termination can be permitted via the clause

`diverges true;`

Meaning:

given the precondition of the specification case holds in pre-state,
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

`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` 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/post-conditions 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:

LinkedList: non_null or nullable?

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

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 Remark on `non_null` and `nullable`

`non_null` as default in JML is fairly new.

$\Rightarrow$ Not yet well reflected in literature and tools.

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 () { ...
```

Tools

Many tools support JML (see `www.eecs.ucf.edu/~leavens/JML/`).
Most basic tool set:

- `jml`, a syntax and type checker
- `jmlc`, JML/Java compiler. Compile runtime assertion checks into the code.
- `jmldoc`, like `javadoc` for Java + JML
- `jmlunit`, unit testing based on JML

For the lab, we do not require using the tools, but we recommend to use `jml` to check the syntax.

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. (e-version via Chalmers Library)

further reading, all available at
`www.eecs.ucf.edu/~leavens/JML/documentation.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 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