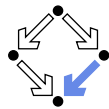


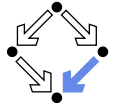
# The Java Modeling Language (Part 2)

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# JML Class Specifications



- Object invariants and history constraints.
  - `non_null`, `invariant`, `constraint`.
- Public versus private behavior.
  - `private normal_behavior`.
- Model fields and model representations.
  - `model`, `represents`.
- Data groups.
  - `in`, `maps ... \into`.
- Class refinements.
  - `refines`.

Support for programming in the large.

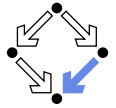
## 1. Basic Class Specifications

## 2. Classes for Modeling

## 3. Model-based Class Specifications

## 4. Rounding Things Up

# A Java Class



```
class IntStack
{
    int[] stack;
    int number;

    final int N = 10;
    IntStack()
    {
        stack = new int[N];
        number = 0;
    }

    boolean isempty()
    {
        return number == 0;
    }

    void push(int e)
    {
        if (number == stack.length)
            resize();
        stack[number] = e;
        number = number+1;
    }

    int pop()
    {
        number = number-1;
        return stack[number];
    }

    void resize()
    {
        int s[] = new int[2*stack.length+1];
        for (int i=0; i<stack.length; i++)
            s[i] = stack[i];
        stack = s;
    }
}
```

## Object Invariants



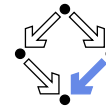
```
class IntStack
{
  /*@ non_null @*/ int[] stack;
  int number;

  /*@ invariant 0 <= number && number <= stack.length;
  ...
}
```

- A object invariant must hold **before and after** each method call.
  - Variable annotated by **non\_null** must not be null.
  - Clause **invariant** specifies a general object invariant.
  - Private **/\*@ helper @\*/** method need not maintain invariant.

Every object invariant is automatically added to the pre- and to the postcondition of every (non-helper) method.

## History Constraints

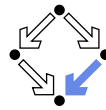


```
class IntStack
{
  ...
  // no method touches elements below the top of stack
  /*@ constraint (\forall int i; 0 <= i && i < number-1;
  @ stack[i] == \old(stack[i])); @*/
  ...
}
```

- A history constraint must hold for the pre/post-state **pair** of every method call.
  - A **constraint** condition may use **\old** to refer to the pre-state.

Every history constraint is added to the post-condition of every method.

## Light-Weight Specification



```
class IntStack // V1
{
  ...
  final int N = 10;

  /*@ ensures stack.length == N
  @ && number == 0; @*/
  IntStack()
  { stack = new int[N];
    number = 0;
  }

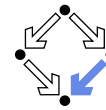
  /*@ ensures \result <==>
  @ number == 0; @*/
  boolean isempty()
  { return number == 0;
  }

  /*@ ensures number == \old(number)+1
  @ && stack[number-1] == e; @*/
  void push(int e)
  { if (number == stack.length)
    resize();
    stack[number] = e;
    number = number+1;
  }

  /*@ requires number > 0;
  @ ensures number == \old(number)-1
  @ && \result == stack[number]; @*/
  int pop()
  { number = number-1;
    return stack[number];
  }

  ...
}
```

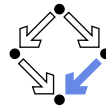
## Light-Weight Specification (Contd)



```
...
/*@ ensures stack.length > \old(stack.length)
@ && number == \old(number)
@ && (\forall int i;
  0 <= i && i < number;
  @ stack[i] == \old(stack[i])); @*/
void resize()
{ int s[] =
  new int[2*stack.length+1];
  for (int i=0; i<stack.length; i++)
    s[i] = stack[i];
  stack = s;
}
}
```

Problem: stack implementation is externally visible.

## Private Implementation vs Public Interface



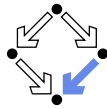
```
class IntStack
{
    private int stack[];
    private int number;
    private final int N = 10;

    public IntStack() { ... }
    public boolean isempty() { ... }
    public void push(int e) { ... }
    public int pop() { ... }

    private void resize() { ... }
}
```

Only selected methods should belong to the public interface.

## Problem with Light-Weight Specification



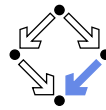
```
class IntStack
{
    private int stack[];
    private int number;
    private final int N = 10;

    /*@ ensures stack.length == N
       @ && number == 0; @*/
    public IntStack() { ... }
    ...
}
```

```
jml -Q IntStack.java
```

```
...
Field "stack" (private visibility) can not be referenced in a
specification context of "package" visibility [JML]
```

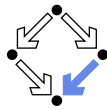
## Visibility of Specifications



- Every JML specification has a visibility level.
  - Analogous to Java visibility levels.
    - Default, private, protected, public.
  - Light-weight specifications: default visibility.
    - Similar to public but restricted to package level.
- A specification may only access fields within its visibility.
  - Only private specifications may access private fields.
  - Hack: mark private field as `/* spec_public */`.
- Heavy-weight specifications: visibility explicitly specified.
  - `public normal_behavior`, `private normal_behavior`.

Need to use heavy-weight specifications.

## Heavy-Weight Specification



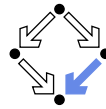
```
class IntStack // V2
{
    private /*@ non_null @*/ int[] stack;
    private int number;

    /*@ private invariant 0 <= number
       @ && number <= stack.length; @*/
    public IntStack()
    { stack = new int[N];
      number = 0;
    }

    /*@ private constraint
       @ (\forall int i;
         @ 0 <= i && i < number-1;
         @ stack[i] == \old(stack[i]));
       @*/
    private final int N = 10;

    /*@ private normal_behavior
       @ assignable stack, number;
       @ ensures stack.length == N
         @ && number == 0; @*/
    public boolean isempty()
    { return number == 0;
    }
    ...
}
```

## Heavy-Weight Specification (Contd)



```
...
/*@ private normal_behavior
  @ assignable stack, stack[*], number;
  @ ensures number == \old(number)+1
  @ && stack[number-1] == e; @*/
public void push(int e)
{ if (number == stack.length)
  resize();
  stack[number] = e;
  number = number+1;
}

/*@ private normal_behavior
  @ requires number > 0;
  @ assignable number;
  @ ensures number == \old(number)-1
  @ && \result == stack[number]; @*/
public int pop()
{ number = number-1;
  return stack[number];
}

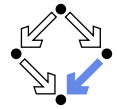
/*@ private normal_behavior
  @ assignable stack;
  @ ensures \fresh(stack)
  @ && stack.length >
  @ \old(stack.length)
  @ && number == \old(number)
  @ && (\forall int i;
  @ 0 <= i && i < number;
  @ stack[i] == \old(stack[i]));
private void resize()
{
  int s[] =
    new int[2*stack.length+1];
  for (int i=0; i<stack.length; i++)
    s[i] = stack[i];
  stack = s;
}
}
```

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## Heavy-Weight Specification: Considerations



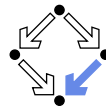
- Visibility of invariants and history constraints.
  - **private invariant**, **private constraint**.
- Explicit frame conditions recommended: assignable.
  - Default: assignable \everything.
- New predicate: **\fresh(stack)**.
  - stack is newly allocated after resize().
  - Thus assignment stack[number] == ... in push is legal.
    - Otherwise possible that stack refers after resize() to existing array.
    - Rule: assignment to location is legal in method if location appears in method assignable clause or if location is newly allocated in method.

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## Private versus Public Specifications



Let us assess the current situation.

- We have constructed a **private** specification.
  - Refers to the private variables of the class.
  - Can be used in the context of the class implementation.
  - Cannot be used as a **contract** between the user and the implementor of the class.
- For use as a contract, we need a **public** specification.
  - May refer only to public class interface.
  - But this interface may be too restricted to express the desired behavior of the class.

We need a possibility to extend the public class interface for the purpose of specifying the behavior of the class.

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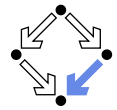
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### 1. Basic Class Specifications

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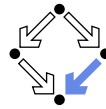


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## Model Fields

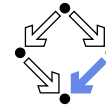


```
class C
{
  //@ model T x;
  //@ represents x <- E;
  ...
}

interface I
{
  //@ instance model T x;
  //@ represents x <- E;
  ...
}
```

- A **model** field is a **specification-only** field.
  - Considered as a normal field for the purpose of reasoning.
  - Actually not provided by the implementation.
  - In an interface, an **instance model** field, is considered a field of every class implementing the interface.
- A **represents** clause associates the model field to an implementation expression.
  - Describes how model field can be computed from actual fields.

## Example



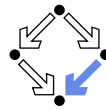
```
class IntStack
{
  private /*@ non_null @*/ int[] stack;
  private int number;

  //@ model int len;
  //@ represents len <- stack.length;

  //@ invariant 0 <= number && number <= len;

  /*@ ensures len == N && number == 0; @*/
  IntStack()
  { stack = new int[N];
    number = 0;
  }
  ...
}
```

## Class Specifications and Abstract Datatypes

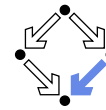


How to specify the public behavior of a class (concrete datatype)  $C$ ?

- First mathematically axiomatize an **abstract datatype**.
  - Type name  $A$  and names of operations on  $A$ .
  - Laws (“axioms”) that the operations must obey.
- Then define  $C$  and an **abstraction function**  $a : C \rightarrow A$ 
  - Maps a program object of type  $C$  to a mathematical object  $A$ .
    - Has as its inverse a **concretization relation**  $c \subseteq A \times C$ .
$$\forall x \in C : c(a(x), x) \wedge \forall y \in A : c(y, x) \Rightarrow x = a(y).$$
- Specify the methods of  $C$  in terms of the operations of  $A$ .
  - Instead of variable  $x$  of type  $C$  use term  $a(x)$  of type  $A$ .
- Thus  $C$  becomes related to the well understood  $A$ .
  - Must prove that the methods satisfy the laws of the operations of  $A$ .

**C.A.R. Hoare, 1972: Proof of Correctness of Data Representations.**

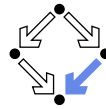
## An Abstract Datatype



The abstract datatype “integer stack”.

- Sort  $S$ .
- Operations
$$\text{empty} : S, \text{push} : \mathbb{Z} \times S \rightarrow S, \text{isempty} : S \rightarrow \mathbb{B},$$
$$\text{top} : S \rightarrow \mathbb{Z}, \text{pop} : S \rightarrow S.$$
- $\forall s, s' \in S, x, x' \in \mathbb{Z} :$ 
  - $\text{empty} \neq \text{push}(x, s);$
  - $\text{push}(x, s) = \text{push}(x', s') \Rightarrow x = x' \wedge s = s';$
  - $\text{isempty}(\text{empty}) = \text{true},$
  - $\text{isempty}(\text{push}(x, s)) = \text{false};$
  - $\text{top}(\text{push}(x, s)) = x;$
  - $\text{pop}(\text{push}(x, s)) = s.$

## A Method Specification

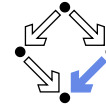


Assume concrete type `Stack` and abstraction function  $a : \text{Stack} \rightarrow S$ .

- Input  $s : \text{Stack}$ .
- Input condition:  $\text{isempty}(a(s)) = \text{false}$ .
- Output  $s' : \text{Stack}$ .
- Output condition:  $a(s') = \text{pop}(a(s))$ .

The concrete method behaves like the abstract operation *pop*.

## An Abstract Datatype in JML

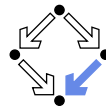


```
public /*@ pure @*/ class IntStackModel
{
    // IntStackModel() is default constructor

    /*@ public model boolean isempty();
    /*@ public model IntStackModel push(int e);
    /*@ public model int top();
    /*@ public model IntStackModel pop();

    /*@ axiom
    @ (\forall IntStackModel s, s2; s != null && s2 != null;
    @   (\forall int e, e2; ;
    @     !new IntStackModel().equals(s.push(e)) &&
    @     (s.push(e).equals(s2.push(e2)) ==> s.equals(s2) && e == e2) &&
    @     new IntStackModel().isempty() &&
    @     !s.push(e).isempty() &&
    @     e == s.push(e).top() &&
    @     s.equals(s.push(e).pop()));
    @*/
}
```

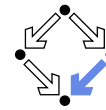
## An Abstract Datatype in JML (Contd)



- A class tagged as **pure** contains only pure methods.
  - Convenient shortcut for classes describing abstract datatypes.
- A **model** method is a **specification-only** method.
  - Just for reasoning, no implementation provided.
  - Typically pure (but need not be).
  - Behavior described by axioms (or by model programs).
- `IntStackModel` is a “class for modeling”.
  - Intended for supporting specifications.
  - May use model methods without implementations.
    - Just for reasoning, no runtime checking possible.
  - May also provide method implementations.
    - Also runtime checking possible.

The JML tool suite comes with a library of pre-defined classes for modeling (but also for executing).

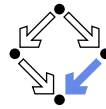
## JML Classes for Modeling



- Package **org.jmlspecs.models.\***.
    - Directory `/zvol/formal/JML/org/jmlspecs/models`.
    - Container types:
      - `JMLObjectSet`, `JMLObjectBag`, `JMLObjectSequence`, ...
    - Numerical types:
      - `JMLInfiniteIntegerClass`, `JMLFiniteIntegerClass`, ...
  - Most classes contain method implementations.
    - Useful for runtime checking.
  - Usage primarily by **model import**.
    - Not linked to classes when compiled with `javac`.
- ```
/*@ model import org.jmlspecs.models.*;
```

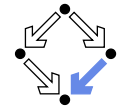
For examples, see “Leavens et al, 2004: Preliminary Design of JML”.

## JML Model Classes



```
// file "IntStackModel.jml"
/*@ public pure model class IntStackModel
@ {
@   public model IntStackModel();
@   public model boolean isempty();
@   public model IntStackModel push(int e);
@   public model int top();
@   public model IntStackModel pop();
@
@   public axiom ...
@ }
@*/
```

- A **model** class is a **specification-only** class.
  - Just for reasoning, no implementation provided.



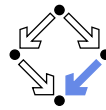
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## Specifying the Public Behavior of a Class

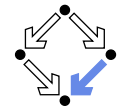


There are different styles to specify the public behavior of a class.

- Specify the public behavior in the class itself.
  - Class **adds** the public behavior to its private behavior.
- Specify the public behavior in an **abstract class**.
  - Class **inherits** from this abstract class.
- Specify the public behavior in an **interface**.
  - Class **implements** this interface.
- Specify the public behavior in an **JML specification file**.
  - Class **refines** this specification.

We will investigate these alternatives in turn.

## Public Behavior in Class



```
class IntStack // V3
{
  ... // private int[] stack, int number;

  /*@ private invariant
  @   0 <= number
  @   && number <= stack.length;
  @*/

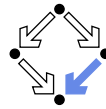
  /*@ private constraint
  @   (\forall int i;
  @     0 <= i && i < number-1;
  @     stack[i] == \old(stack[i])); @*/

  /*@ public normal_behavior
  @   assignable stackM;
  @   ensures stackM.isempty();
  @   also private normal_behavior
  @     assignable stack, number;
  @     ensures stack.length == N
  @     && number == 0;
  @*/
  public IntStack()
  {
    stack = new int[N];
    number = 0;
  } //@ nowarn Post;

  ...

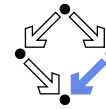
  /*@ public model
  @   non_null IntStackModel stackM;
  @   represents stackM <- toModel();
  @   public model
  @     pure IntStackModel toModel(); @*/
```

## Public Behavior in Class: Considerations



- `model pure IntstackModel toModel()`
  - Pure function to convert this object to `IntStackModel`.
  - Implementation remains unspecified (later).
- `also ...`
  - Combine public behavior and private behavior.
  - Method must satisfy each behavior.
  - Problem with assignable clause of public behavior (later).
- `nowarn Post`
  - Since implementation of `toModel` is unspecified, ESC/Java2 cannot check postcondition of public behavior.
  - Unfortunately this also prevents checking of private behavior.

## Public Behavior in Class (Contd)

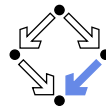


```
...
/*@ public normal_behavior
@ assignable \nothing;
@ ensures \result <==>
@   stackM.isempty();
@ also private normal_behavior
@ assignable
@   stack, stack[*], number;
@ ensures number ==
@   \old(number)+1
@   && stack[number-1] == e;
@*/
public /*@ pure @*/ boolean isempty()
{
    return number == 0;
} //@ nowarn Post;

/*@ public normal_behavior
@ assignable stackM;
@ ensures stackM ==
@   \old(stackM.push(e));
@ also private normal_behavior
@ assignable
@   stack, stack[*], number;
@ ensures number ==
@   \old(number)+1
@   && stack[number-1] == e;
@*/
public void push(int e)
{
    if (number == stack.length)
        resize();
    stack[number] = e;
    number = number+1;
} //@ nowarn Post;

...
```

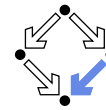
## Public Behavior in Class (Contd'2)



```
...
/*@ private normal_behavior
@ assignable stack;
@ ensures \fresh(stack)
@   && stack.length >
@   \old(stack.length)
@   && number == \old(number)
@   && (\forall int i;
@     0 <= i && i < number;
@     stack[i] ==
@     \old(stack[i])); @*/
private void resize()
{
    int s[] =
        new int[2*stack.length+1];
    for (int i=0; i<stack.length; i++)
        s[i] = stack[i];
    stack = s;
}

/*@ public normal_behavior
@ requires !stackM.isempty();
@ assignable stackM;
@ ensures
@   \result == \old(stackM.top())
@   && stackM == \old(stackM.pop());
@ also private normal_behavior
@ requires number > 0;
@ assignable number;
@ ensures number == \old(number)-1
@   && \result == stack[number];
@*/
public int pop()
{
    //@ assume number > 0;
    number = number-1;
    return stack[number];
} //@ nowarn Post;
```

## Public Behavior in Class: Considerations

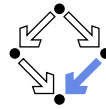


- `assume number > 0` in `pop()`
  - ESC/Java2 complains.
  - Due to the lack of the implementation of abstraction function, this cannot be deduced from the precondition of the public behavior.
- No separation of public and private behavior.
  - Both mixed in same file.

A messy solution.



## Frame Condition of Public Behavior



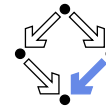
```
/*@ public normal_behavior
@ assignable stackM;
@ ensures stackM.isEmpty();
@ also private normal_behavior
@ ...
@*/
public IntStack()
{
    stack = new int[N];
    number = 0;
} //@ nowarn Post;
```

### ■ assignable stackM

- Frame condition says that only model field stackM may be changed.
- But actually concrete fields stack and number are changed.
- ESC/Java2 complains.

Need to relate model fields to concrete fields.

## Data Groups



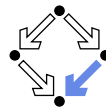
```
private /*@ non_null @*/ int[] stack; //@ in stackM;
//@ maps stack[*] \into stackM;

private int number; //@ in stackM;
```

- Declaration of field stackM also introduces a **data group** stackM.
  - A data group is a set of storage locations.
  - Initially, only the location of the declared variable is in data group.
- An **assignable** clause actually refers to data groups.
  - All storage locations in referenced data group may be changed.
- A data group may be extended.
  - **in stackM** adds declared variable to data group stackM.
  - **maps stack[\*] \into stackM** adds all elements of array stack.

By incorporation into the data group stackM, the variable stack, all elements of stack and number may change, when stackM may change.

## Implementation of Abstraction Function

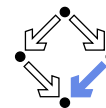


We have not yet defined the abstraction function toModel().

```
/*@ public pure model IntStackModel toModel()
@ {
@   IntStackModel m = new IntStackModel();
@   for (int i = 0; i < number; i++)
@     m = m.push(stack[i]);
@   return m;
@ } @*/
```

- Practically useful for runtime checking.
  - Any reference to model variable stackM is replaced by toModel().
  - Requires an implementation of (the methods of) IntStackModel.
- Principally useful for verification.
  - Requires a specification of toModel which uniquely determines stackM from stack and number.
  - Reasoner must be strong enough (ESC/Java2 is not).

## Specification of Abstraction Function



```
/*@ also private normal_behavior
@ ensures \result != null
@ && \result.length() == number
@ && (\forall int i; 0 <= i && i < number;
@   \result.elemAt(i) == stack[number-i-1]);
@ public pure model IntStackModel toModel()
@ {
@   IntStackModel m = new IntStackModel();
@   for (int i = 0; i < number; i++)
@     m = m.push(stack[i]);
@   return m;
@ }
@*/
```

Relates the elements of stackM to those of stack.

## Generalization of Model Type

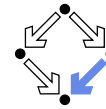


```
class IntStackModel
{
  ...
  //@ public model int length();
  //@ public model int elemAt(int i);

  /*@ public axiom
   @ (\forallall IntStackModel s; s!= null;
   @   (\forallall int e, i; ;
   @     new IntStackModel().length() == 0 &&
   @     s.push(e).length() == 1+s.length() &&
   @     s.elemAt(0) == s.top() &&
   @     s.elemAt(i+1) == s.pop().elemAt(i));
   @*/
}
```

Recursive definition of length and of elemAt.

## Public Behavior in Abstract Class



```
public abstract class IntStackBase // V4
{
  /*@ public model
   @ non_null IntStackModel stackM;
   @ represents stackM <- toModel();
   @ public model
   @ pure IntStackModel toModel();
   @*/

  /*@ public normal_behavior
   @ assignable stackM;
   @ ensures stackM.isempty();
   @*/

  /*@ public normal_behavior
   @ assignable stackM;
   @ ensures stackM.isempty();
   @*/

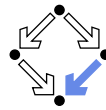
  public IntStackBase ()
  {
  } //@ nowarn Post, Invariant;
  // called by subclass constructor

  /*@ public normal_behavior
   @ ensures \result <==>
   @   stackM.isempty(); @*/
  public abstract /*@ pure @*/
  boolean isempty();

  /*@ public normal_behavior
   @ assignable stackM;
   @ ensures stackM ==
   @   \old(stackM.push(e)); @*/
  public abstract void push(int e);

  /*@ public normal_behavior
   @ requires !isempty();
   @ assignable stackM;
   @ ensures \result ==
   @   \old(stackM.top())
   @   && stackM ==
   @   \old(stackM.pop()); @*/
  public abstract int pop();
}
```

## Public Behavior in Abstract Class (Contd)



```
class IntStack extends IntStackBase
{
  private /*@ non_null @*/
  int[] stack; //@ in stackM;
  //@ maps stack[*] \into stackM;

  private int number; //@ in stackM;

  /*@ private invariant
   @ 0 <= number
   @ && number <= stack.length; @*/

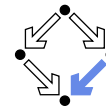
  /*@ private constraint
   @ (\forallall int i;
   @   0 <= i && i < number-1;
   @   stack[i] == \old(stack[i]));
   @*/

  private final int N = 10;

  /*@ private normal_behavior
   @ assignable stackM,
   @ stack, number;
   @ ensures stack.length == N
   @ && number == 0;
   @ also public normal_behavior
   @ assignable stackM;
   @ ensures stackM.isempty(); @*/
  public IntStack()
  { stack = new int[N];
    number = 0;
  } //@ nowarn Post, Invariant;

  ...
}
```

## Public Behavior in Abstract Class (Contd'2)



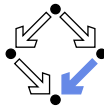
```
...
/*@ also private normal_behavior
 @ assignable \nothing;
 @ ensures \result <==> number == 0; @*/
public /*@ pure @*/ boolean isempty()
{ return number == 0;
} //@ nowarn Post, Invariant;

/*@ also private normal_behavior
 @ assignable stack, stack[*], number;
 @ ensures number ==
 @   \old(number)+1
 @ && stack[number-1] == e; @*/
public void push(int e)
{
  if (number == stack.length)
  {
    resize();
    stack[number] = e;
    number = number+1;
  } //@ nowarn Post, Invariant;

  /*@ also private normal_behavior
   @ requires number > 0;
   @ assignable number;
   @ ensures number ==
   @   \old(number)-1
   @ && \result ==
   @   stack[number];
   @*/
  public int pop()
  {
    //@ assume number > 0;
    number = number-1;
    return stack[number];
  } //@ nowarn Post, Invariant;

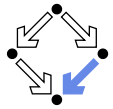
  ...
}
```

## Public Behavior in Abstract Class (Contd'3)



```
...
/*@ private normal_behavior
@ assignable stack;
@ ensures \fresh(stack)
@ \&& stack.length > \old(stack.length)
@ \&& number == \old(number)
@ \&& (\forallall int i;
@     0 <= i \&& i < number;
@     stack[i] == \old(stack[i])); @*/
private void resize()
{
    int s[] = new int[2*stack.length+1];
    for (int i=0; i<stack.length; i++)
        s[i] = stack[i];
    stack = s;
}
}
```

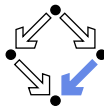
## Public Behavior in Abs.Class: Considerations



- Clear separation of behaviors.
  - Public behavior in abstract superclass.
  - Private behavior in concrete subclass.
- model stackM
  - Model field inherited by any subclass of abstract class.
- Constructor must be specified in abstract class.
  - Abstract class always has default constructor.
- also private normal\_behavior
  - Extension of public behavior by private behavior.
- assignable stackM, ... in constructor IntStack()
  - Frame condition of private behavior!
  - Constructor IntStack() calls constructor InstStackBase().

Quite clean solution.

## Public Behavior in Interface



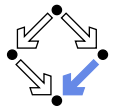
```
public interface IntStackInterface // V5
{
    /*@
    @ public instance model
    @ non_null IntStackModel stackM;
    @ represents stackM <- toModel();
    @ public model
    @ pure IntStackModel toModel();
    @*/

    /*@ public normal_behavior
    @ assignable \nothing;
    @ ensures \result <==>
    @     stackM.isempty();
    @*/
    public /*@ pure @*/ boolean isempty();

    /*@ public normal_behavior
    @ assignable stackM;
    @ ensures stackM ==
    @     \old(stackM.push(e));
    @*/
    public void push(int e);

    /*@ public normal_behavior
    @ requires !stackM.isempty();
    @ assignable stackM;
    @ ensures \result ==
    @     \old(stackM.top())
    @     \&& stackM ==
    @     \old(stackM.pop());
    @*/
    public int pop();
}
```

## Public Behavior in Interface (Contd)



```
class IntStack implements IntStackInterface
{
    private /*@ non_null @*/ int[] stack;
    /*@ in stackM;
    /*@ maps stack[*] \into stackM;

    private int number; /*@ in stackM;

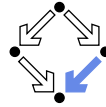
    /*@ private invariant 0 <= number
    @ \&& number <= stack.length; */

    /*@ private constraint
    @ (\forallall int i;
    @     0 <= i \&& i < number-1;
    @     stack[i] == \old(stack[i]));
    @*/

    private final int N = 10;

    /*@ private normal_behavior
    @ assignable stack, number;
    @ ensures stack.length == N
    @ \&& number == 0;
    @ also public normal_behavior
    @ assignable stackM;
    @ ensures stackM.isempty();
    @*/
    public IntStack()
    {
        stack = new int[N];
        number = 0;
    } /*@ nowarn Post, Invariant;
    ...
}
```

## Public Behavior in Interface (Contd'2)

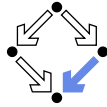


```
...
/*@ also private normal_behavior
  @ assignable \nothing;
  @ ensures \result <=> number == 0;
  @*/
public /*@ pure @*/ boolean isempty()
{ return number == 0;
} //@ nowarn Post, Invariant;

/*@ also private normal_behavior
  @ assignable stack, stack[*], number;
  @ ensures number == \old(number)+1
  @ && stack[number-1] == e; @*/
public void push(int e)
{ if (number == stack.length)2
  resize();
  stack[number] = e;
  number = number+1;
} //@ nowarn Post, Invariant;

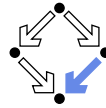
/*@ also private normal_behavior
  @ requires number > 0;
  @ assignable number;
  @ ensures number ==
    \old(number)-1
  @ && \result == stack[number];
  @*/
public int pop()
{
  //@ assume number > 0;
  number = number-1;
  return stack[number];
} //@ nowarn Post, Invariant;
...
```

## Public Behavior in Interface (Contd'3)



```
...
/*@ private normal_behavior
  @ assignable stack;
  @ ensures \fresh(stack)
  @ && stack.length > \old(stack.length)
  @ && number == \old(number)
  @ && (\forall int i;
    @ 0 <= i && i < number;
    @ stack[i] == \old(stack[i])); @*/
private void resize()
{ int s[] = new int[2*stack.length+1];
  for (int i=0; i<stack.length; i++)
    s[i] = stack[i];
  stack = s;
}
}
```

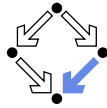
## Public Behavior in Interface: Considerations



- Clear separation of behaviors.
  - Public behavior in interface.
  - Private behavior in class.
- instance model stackM
  - Model field of any class implementing the interface.
- No constructor in interface possible.
  - Both public and private behavior of constructor specified in class.
- also private normal\_behavior
  - Extension of public behavior specified in interface by private behavior.

Rather clean solution.

## Public Behavior in JML Specification File



```
// V6, file "IntStack.jml"
public class IntStack
{
  /*@ public model
    @ non_null IntStackModel stackM;
    @ represents stackM <- toModel();
    @ public model
    @ pure IntStackModel toModel(); @*/

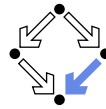
  /*@ public normal_behavior
    @ assignable stackM;
    @ ensures stackM.isempty(); @*/
  public IntStack();

  /*@ public normal_behavior
    @ assignable \nothing;
    @ ensures \result <=> stackM.isempty(); @*/
  public /*@ pure @*/ boolean isempty();

  /*@ public normal_behavior
    @ assignable stackM;
    @ ensures stackM ==
      \old(stackM.push(e)); @*/
  public void push(int e);

  /*@ public normal_behavior
    @ requires !stackM.isempty();
    @ assignable stackM;
    @ ensures \result ==
      \old(stackM.top())
    @ && stackM ==
      \old(stackM.pop()); @*/
  public int pop();
}
```

## Public Behavior in JML Spec. File (Contd)



```
/*@ refine "IntStack.jml";
class IntStack
{
  private /*@ non_null @*/
  int[] stack; /*@ in stackM;
  /*@ maps stack[*] \into stackM;

  private int number; /*@ in stackM;
  /*@ private invariant 0 <= number
  @ && number <= stack.length; @*/

  /*@ private constraint
  @ (\forall int i;
  @ 0 <= i && i < number-1;
  @ stack[i] == \old(stack[i])); @*/

  private final int N = 10;

  /*@ also private normal_behavior
  @ assignable stack, number;
  @ ensures stack.length == N
  @ && number == 0; @*/
  public IntStack()
  {
    stack = new int[N];
    number = 0;
  } /*@ nowarn Post, Invariant;

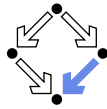
  /*@ also private normal_behavior
  @ assignable \nothing;
  @ ensures \result <==>
  @ number == 0; @*/
  public /*@ pure @*/
  boolean isempty()
  {
    return number == 0;
  } /*@ nowarn Post, Invariant;
  ...
```

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## Public Behavior in JML Spec. File (Contd'2)



```
/*@ also private normal_behavior
@ assignable stack, stack[*], number;
@ ensures number == \old(number)+1
@ && stack[number-1] == e; @*/
public void push(int e)
{ if (number == stack.length)
  resize();
  stack[number] = e;
  number = number+1;
} /*@ nowarn Post, Invariant;

/*@ also private normal_behavior
@ requires number > 0;
@ assignable number;
@ ensures number == \old(number)-1
@ && \result == stack[number]; @*/
public int pop()
{ /*@ assume number>0;
  number = number-1;
  return stack[number];
} /*@ nowarn Post, Invariant;

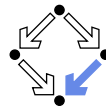
/*@ private normal_behavior
@ assignable stack;
@ ensures \fresh(stack)
@ && stack.length >
@ \old(stack.length)
@ && number == \old(number)
@ (\forall int i;
@ 0 <= i && i < number;
@ stack[i] == \old(stack[i]));
private void resize()
{
  int s[] =
  new int[2*stack.length+1];
  for (int i=0; i<stack.length; i++)
    s[i] = stack[i];
  stack = s;
}
```

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## Public Behavior in JML File: Considerations



- Clear separation of behaviors.
  - Public behavior in JML specification file.
  - Private behavior in Java implementation file.
- model stackM
  - Model field of any class refining the specification.
- Also constructor specification in JML file.
  - Only private behavior of constructor in implementation file.
- **refine "IntStack.jml"**
  - All entities specified in specification file "IntStack.jml" must be implemented in implementation file "IntStack.java".
- also private normal\_behavior
  - Extension of public behavior specified in JML file by private behavior.

Very clean solution.

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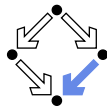
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## 1. Basic Class Specifications

## 2. Classes for Modeling

## 3. Model-based Class Specifications

## 4. Rounding Things Up

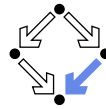


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## Desugaring Specifications

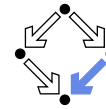


A normal\_behavior specification is translated as follows.

```
public normal_behavior      public behavior
requires P;                requires P;
assignable V;              ⇒  assignable V;
ensures Q;                 ensures Q;
                            signals (Exception e) false;
```

The method does not throw an exception.

## Desugaring Specifications (Contd)

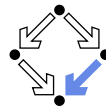


A exceptional\_behavior specification is translated as follows.

```
public exceptional_behavior  public behavior
requires P;                 requires P;
assignable V;              ⇒  assignable V;
signals (E e) Q;           ensures false;
                            signals (E e) Q;
```

The method does not return normally.

## Desugaring Specifications (Contd'2)

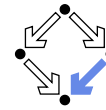


Two public behavior specifications are combined as follows.

```
public behavior            public behavior
requires P1;              requires P1 || P2;
assignable V1;            assignable V1 if P1,
ensures Q1;                V2 if P2;
signals (E1 e) R1;        ensures (\old(P1) ==> Q1)
also public behavior      && (\old(P2) ==> Q2);
requires P2;              signals (E1 e1) \old(P1) && R1;
assignable V2;            signals (E2 e2) \old(P2) && R2;
ensures Q2;
signals (E2 e) R2;
```

Basically the same for combining a public and a private behavior.

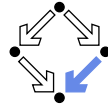
## The Meaning of a Specification



```
public behavior
requires P;
assignable V if M, ...;
ensures Q;
signals (E1 e1) R1;
...
```

- The method may be called, if  $P$  holds on the pre-state.
  - The conditions of multiple requires clauses are disjoined by  $||$ .
- The method may change  $V$ , if  $M$  holds.
  - And so on for the other variables in the assignable clause.
- If the method returns normally,  $Q$  holds on the pre/post-state pair.
  - The conditions of multiple ensures clauses are conjoined by  $\&\&$ .
- If the method throws an exception of type  $E1$ ,  $R1$  holds on the pre/post-state pair.
  - And so on for the other signals clauses.

## Specifications and Subtyping

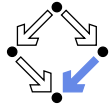


Combining specifications works also for subtyping.

- If a class  $C_2$  inherits from a class  $C_1$ ,
  - $C_2$  inherits all **non-private** entities of  $C_1$ .
- If  $C_2$  **overrides** some non-private method  $m$  of  $C_1$ ,
  - $C_2$  combines  $C_1$ 's **non-private** behavior specification of  $m$  with its own behavior specification of  $m$ .
  - This is why the new behavior specification of  $m$  in  $C_2$  must begin with `also`.
- Thus an object of type  $C_2$  behaves like an object of type  $C_1$ .
  - $C_2$  specifies a **behavioral subtype** of  $C_1$ .

Thus we can say “a  $C_2$  object is a  $C_1$  object”.

## Further Features of JML



Not covered in this course ...

- Specification shortcuts
  - `\nonnullelements`, `\not_modified`, ...
- Redundant specifications and examples.
  - `ensures_redundantly`, `invariant_redundantly`, `represents_redundantly`, `implies_that`, `for_example`, ...
- Non-functional specifications.
  - Execution time, execution space, methods invoked, ...
- Concurrency.
  - Experimental support of MultiJava.
- ...

JML is (perhaps too) large and still evolving (latest version: May 2013).