The Java Modeling Language (Part 2)

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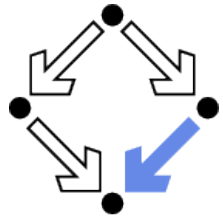
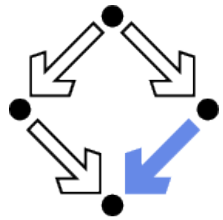
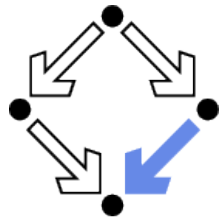


JML Class Specifications



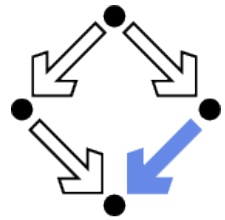
- Object invariants and history constraints.
  - `non_null`, `invariant`, `constraint`.
- Public versus private behavior.
  - `private normal_behavior`.
- Model fields and model representations.
  - `model`, `represents`.
- Data groups.
  - `in`, `maps ...\into`.
- Class refinements.
  - `refines`.

Support for programming in the large.



1. **Basic Class Specifications**
2. Classes for Modeling
3. Model-based Class Specifications
4. Rounding Things Up

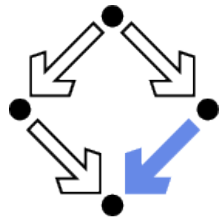
A Java Class



```
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

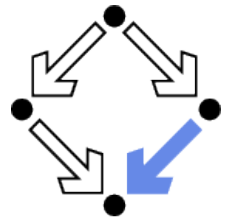


```
class IntStack
{
  /*@ non_null @*/ int[] stack;
  int number;

  //@ 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

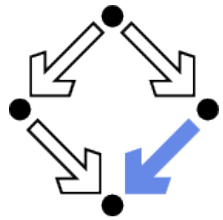


```
class IntStack
{
  ...
  // no method touches elements below the top of stack
  /*@ constraint (\forall int i; 0 <= i && i < number-1;
    @                stack[i] == \old(stack[i])); @*/
  ...
}
```

- 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.

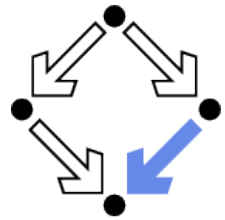
Light-Weight Specification



```
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];
  }

  ...
```

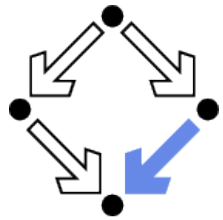
Light-Weight Specification (Contd)



```
  ...

  /*@ 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.

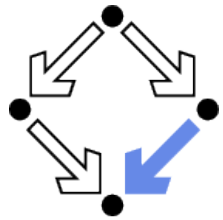
Private Implementation vs Public Interface



```
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() { ... }
}
```

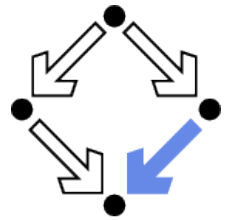
Only selected methods should belong to the public interface.

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]
```

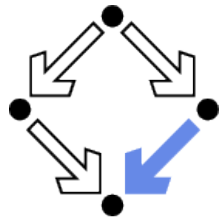
Visibility of Specifications



- 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.

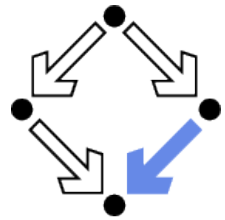
Heavy-Weight Specification



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

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

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

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

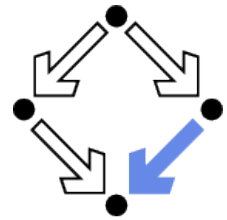
Heavy-Weight Specification (Contd)



```
...
/*@ 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];
}
```

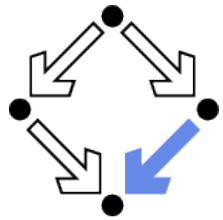
```
/*@ private normal_behavior
  @   assignable stack;
  @   ensures \fresh(stack)
  @   && stack.length >
  @        \old(stack.length)
  @   && number == \old(number)
  @   && (\forall int i;
  @        0 <= i && i < number;
  @        stack[i] == \old(stack[i]));
private void resize()
{
   int s[]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

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.

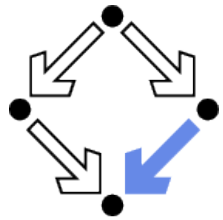
Private versus Public Specifications



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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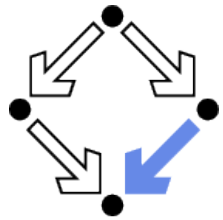
Model Fields

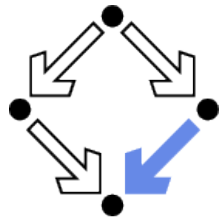


```
class C
{
   //@ model T x;
   //@ represents x <- E;
   ...
}
```

```
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



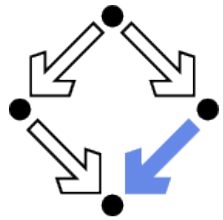
```
class IntStack
{
  private /*@ non_null @*/ int[] stack;
  private int number;

  //@ 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?

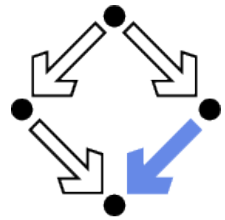
- First mathematically axiomatize an abstract datatype.
  - Type name A and names of operations on A.
  - Laws ("axioms") that the operations must obey.
- Then define C and an abstraction function $a : C \to A$
  - Maps a program object of type C to a mathematical object A.
    - Has as its inverse a 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



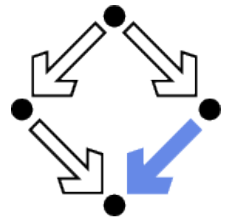
The abstract datatype "integer stack".

- Sort S.
- Operations

  $$empty : S,\ push : \mathbb{Z} \times S \to S,\ isempty : S \to \mathbb{B},$$
  $$top : S \to \mathbb{Z},\ pop : S \to S.$$

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

A Method Specification

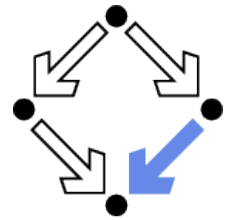


Assume concrete type Stack and abstraction function $a : \text{Stack} \to S$.

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

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

An Abstract Datatype in JML

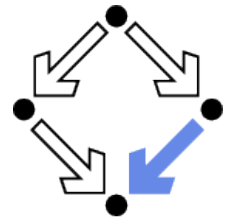


```
public /*@ pure @*/ class IntStackModel
{
  // IntStackModel() is default constructor

  //@ 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())));
    @*/
}
```

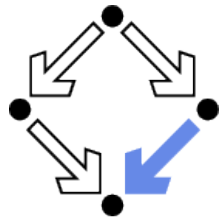
An Abstract Datatype in JML (Contd)



- 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

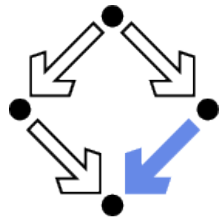


- Package `org.jmlspecs.models.*`.
  - Directory `/zvol/formal/JML/org/jmlspecs/models`.
  - Container types:
    - `JMLObjectSet`, `JMLObjectBag`, `JMLObjectSequence`, ...
  - Numerical types:
    - `JMLInfiniteIntegerClass`, `JMLFiniteIntegerClass`, ...
- Most classes contain method implementations.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

```
//@ model import org.jmlspecs.models.*;
```

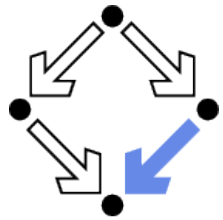
For examples, see "Leavens et al, 2004: Preliminary Design of JML".

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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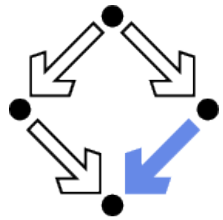
Specifying the Public Behavior of a Class

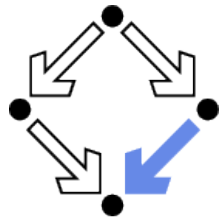


There are different styles to specify the public behavior of a class.

- 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.

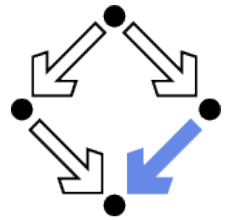
Public Behavior in Class



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

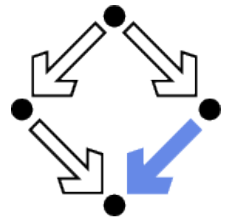
```
  /*@ public normal_behavior
    @   assignable stackM;
    @   ensures stackM.isempty();
    @ also private normal_behavior
    @   assignable stack, number;
    @   ensures stack.length == N
    @   && number == 0;
    @*/
  public IntStack()
  {
    stack = new int[N];
    number = 0;
  } //@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

  ...
```

Public 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.

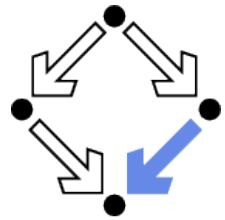
Public Behavior in Class (Contd)



```
...

/*@ public normal_behavior
  @   assignable \nothing;
  @   ensures \result <==>
  @     stackM.isempty();
  @ also private normal_behavior
  @   assignable \nothing;
  @   ensures \result <==>
  @     number == 0;
  @*/
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;

...
```

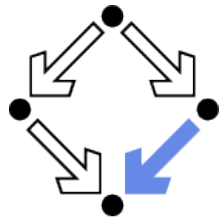
Public Behavior in Class (Contd'2)



```
...

/*@ 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;
```

```
/*@ 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;
}
}
```

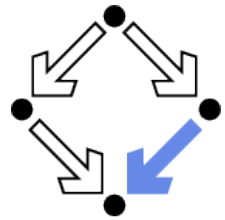
Public Behavior in Class: Considerations



- `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

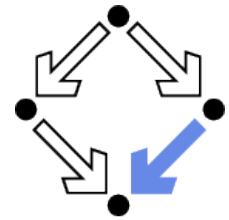


```
/*@ public normal_behavior
  @   assignable stackM;
  @   ensures stackM.isempty();
  @ also private normal_behavior
  @   ...
  @*/
public IntStack()
{
  stack = new int[N];
  number = 0;
} //@ nowarn Post;
```

- `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

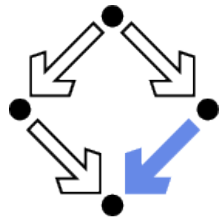


```
private /*@ non_null @*/ int[] stack; //@ in stackM;
//@ maps stack[*] \into stackM;

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

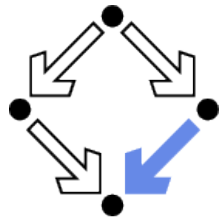


We have not yet defined the abstraction function `toModel()`.

```
/*@ 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`.
- Principially 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).

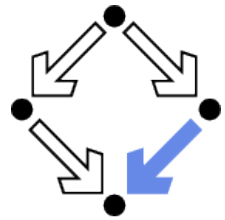
Specification of Abstraction Function



```
/*@ 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`.

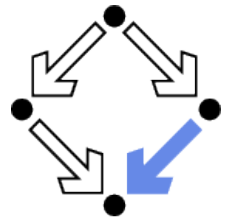
Generalization of Model Type



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

  /*@ public axiom
    @ (\forall IntStackModel s; s!= null;
    @   (\forall 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)));
    @*/
}
```

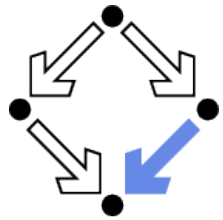
Recursive definition of `length` and of `elemAt`.

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 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();
}
```

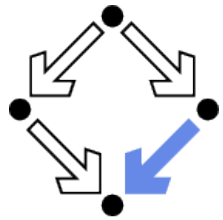
Public Behavior in Abstract Class (Contd)



```
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
    @   (\forall 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;

  ...
```

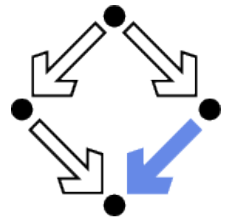
Public Behavior in Abstract Class (Contd'2)



```
...
/*@ 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;
```

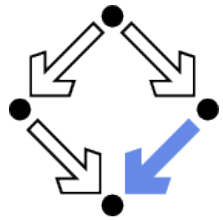
```
/*@ also private normal_behavior
  @   requires number > 0;
  @   assignable number;
  @   ensures number ==
  @     \old(number)-1
  @   && \result ==
  @       stack[number];
  @*/
public int pop()
{
  //@ assume number > 0;
  number = number-1;
  return stack[number];
} //@ nowarn Post, Invariant;

...
```

Public Behavior in Abstract Class (Contd'3)



```
  ...

  /*@ private normal_behavior
    @   assignable stack;
    @   ensures \fresh(stack)
    @   && stack.length > \old(stack.length)
    @   && number == \old(number)
    @   && (\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;
  }
}
```

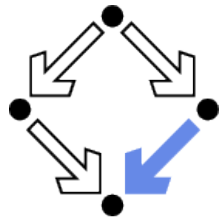
Public Behavior in Abs.Class: Considerations



- 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()`.

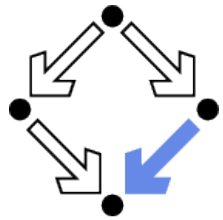
Quite clean solution.

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();
}
```

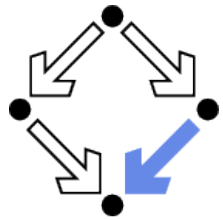
Public Behavior in Interface (Contd)



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

  ...
```

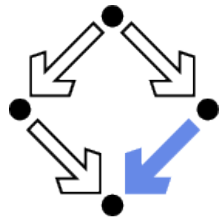
Public Behavior in Interface (Contd'2)



```
 ...

/*@ 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;
```

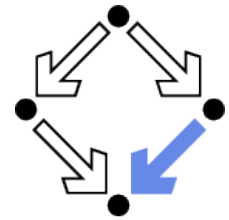
```
/*@ also private normal_behavior
  @   requires number > 0;
  @   assignable number;
  @   ensures number ==
  @      \old(number)-1
  @   && \result == stack[number];
  @*/
public int pop()
{
  //@ assume number > 0;
  number = number-1;
  return stack[number];
} //@ nowarn Post, Invariant;

...
```

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;
  }
}
```

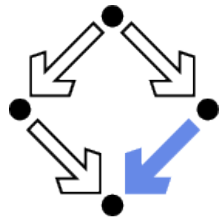
Public Behavior in Interface: Considerations



- 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.

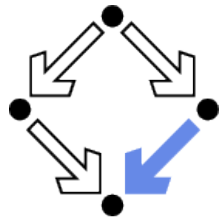
Rather clean solution.

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();
}
```

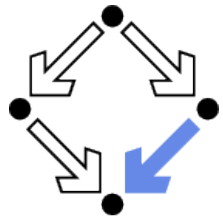
Public Behavior in JML Spec. File (Contd)



```
//@ 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;
  ...
```

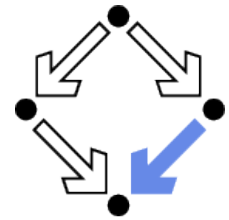
Public Behavior in JML Spec. File (Contd'2)



```
/*@ 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;
```

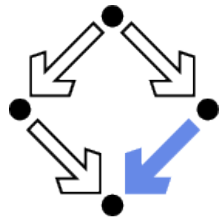
```
/*@ private normal_behavior
  @   assignable stack;
  @   ensures \fresh(stack)
  @   && stack.length >
  @        \old(stack.length)
  @   && number == \old(number)
  @   && (\forall int i;
  @        0 <= i && i < number;
  @        stack[i] == \old(stack[i]));
private void resize()
{
   int s[]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

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.



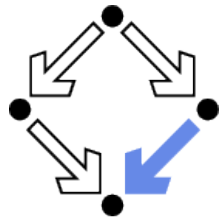
1. Basic Class Specifications

2. Classes for Modeling

3. Model-based Class Specifications

4. Rounding Things Up

Desugaring Specifications

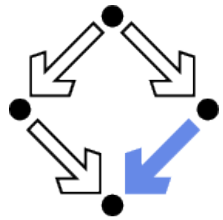


A `normal_behavior` specification is translated as follows.

```
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.

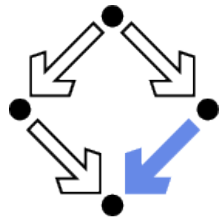
```
public exceptional_behavior
  requires P;
  assignable V;
  signals (E e) Q;
```

$\Rightarrow$

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

The method does not return normally.

Desugaring Specifications (Contd'2)

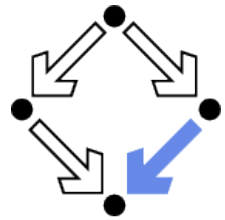


Two `public behavior` specifications are combined as follows.

```
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.

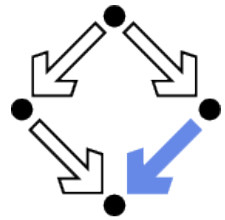
The Meaning of a Specification



```
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

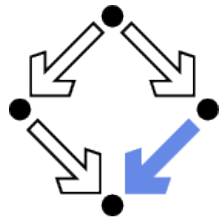


Combining specifications works also for subtyping.

- 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).