5. Specification and Checking

Overview:

- Motivation and problems
- Specifying classes
  - Invariants
  - Pre- and post-conditions
  - Frame properties
  - Model-based specification
- Behavioral subtyping
  - Relation between specification & implementation
  - Concrete pre-post specifications
  - Abstract pre-post specifications
  - Treatment of invariants
  - Treatment of frame properties
  - Using the techniques together

Learning objectives:

- Specification and checking of properties
- Application of specification and checking techniques
- Understanding behavior
- Basis for behavioral subtyping and substitutability

5.1 Motivation and Problems

Motivation of specification:

- Documenting implementation aspects (e.g. data structure invariants):

  → How does an object behave internally?

- As *Contract* between user and provider of code:

  → How does an object interact with the environment?

- Formulating the relevant behavior, in particular:

  → When can an object be substituted by another object?

Specification with assertions:

a. Simple property:

```
...
C cobj = new C(...);
assert cobj.x != null ;
```

b. Loop invariant (Schleifeninvariante):

```
public static int isqrt( int y ){
  int count = 0, sum = 1;
  while (sum <= y) {
    count++;
    sum += 2 * count + 1;
    assert  count*count <= y
         && sum==(count+1)*(count+1);
  }
  return count;
}
```

c. More complex property for an AWT-fragment:

```
...
Container c;
Button b;
...
c.remove(b);
assert !EX Container cex: EX int i:
    cex.getComponents()[i] == b;
```

Pre-post specifications for methods:

```
public class IntMathOps {

  /*@ public normal_behavior
    @  requires    y >= 0
    @  modifiable \nothing
    @  ensures     \result*\result <= y
    @       &&  y < (Math.abs(\result)+1)
    @                 *(Math.abs(\result)+1);
    @*/
  public static int isqrt(int y){ ... }
}
```

Class invariants:

```
public class List {
  int length;
  ListElems le;
  //@ invariant length == le.leng();
  ...
}
```

Further kinds of functional properties:

- Event specifications:
  - occurrence of exceptions
  - modifications of variables
  - invocation of methods
- Termination
- History constraints:
  - relations between state pairs (S1,S2), where S1 happens before S2
- Temporal properties:
  - Is something true until an event happens?
  - Will something eventually happen?

Typical non-functional properties of programs:

- Resource consumption:
  - execution time
  - memory
  - I/O, network resources
- Dependency on the environment (e.g. file system)
- Robustness

Specification problems/challenges:

Examples: (Specification problems)

1. Information hiding: How can behavior based on private attributes be specified?

```
public class WhatCouldBeMySpec {
   private int a = 0;
   public void set( int p ) {  a = p; }
   public int get() { return a; }
}
```

2. How are effects to the environment specified?

```
public class EnvironmentalEffects {
   public void localonly( Object mo ) {
      do_something_good();
      if( mo instanceof Atmosphere )
           ((Atmosphere) mo).pollute();
   }
}
```

3. Behavioral conformance/substitutability:

```
public class Superclass
{   public int a = 0;
    public void dincrA() { a++; }
}

public class Subclass extends Superclass
{   public void dincrA() { a--; }
}
```

Approaches to formulate specifications:

- Specification using informal language
- Specification using the means of the programming language (e.g. assert statements)
- Specification using an annotation language that is executable (we illustrate the use of JML)
- Specification with more abstract declarative language constructs

Questions:

- Which terms/functions/etc. can be used to formulate properties?
- Information hiding: Private and protected parts should not appear in public specification.
- What is the meaning of specification constructs that go beyond the programming languages?

5.2 Specifying Classes

Overview:

We consider specifications written in the Java Modeling Language (JML):

- Lightweight specifications
- Direct specifications
- Specifications with abstraction

5.2.1 Lightweight specifications

Explanation: (lightweight specification)

Lightweight (*leichte)* specifications describe certain properties of objects and methods without aiming to provide all details or a complete description of the method/class behavior.

Example: (lightweight specification)

1. Lightweight specifications help in documenting properties that cannot be expressed by the type system.

```
public class Bag {

  //@ requires input != null;
  public Bag(int[] input) {
    n = input.length;
    a = new int[n];
    System.arraycopy(input, 0, a, 0, n);
  }
  ...
}
```

2. Lightweight specifications can be used for annotating private program elements. This can increase readability and checkability of programs:

```
public final
class String implements ... {
    /** Used for character storage */
    //@ private invariant value != null ;
    private char value[];

    /** First index of the storage used */
    //@ private invariant offset >= 0
    private int offset;

    /** Number of characters in String */
    //@ private invariant count >= 0 ;
    private int count;

    /*@ private invariant
      @   offset + count <= value.length ;
      @*/
    ...
}
```

5.2.2 Direct specifications of objects

Assumptions:

- Specification only depends on the state of one object.
- Relevant attributes are visible to users.
- Methods only modify the target object of the invocation.
- No subtyping, no inheritance.

Specify:

- the possible states of an object X by invariants formulated over the attribute values of X;
- the method behavior by describing
  - → the result value
  - → the modification of the attribute values
- environmental properties by guaranteeing that attribute values of other objects are not modified.

Specification techniques are explained along with the following running example:

```
public class Point {
   /** Koordinaten */
   /*@ spec_public @*/ private float x, y;

   private float dist;
   ...
}
```

Invariants

Invariants specify range constraints of attributes and relations between attribute values:

Example: (Invariants)

```
public class Point {
   ...
   //@ public invariant x >= 0.0 && y >= 0.0;

   /*@ private invariant
     @   dist == Math.sqrt(x*x+y*y) ;
     @*/
   ...
}
```

Meaning:

Invariants have to hold:

- in the initial state of the program
- in pre- and poststates of methods for all allocated objects (notice: the set of allocated objects may be different in pre- and poststate)
- in prestates of constructors for all allocated objects except for the newly created one;
  in poststates for all allocated objects

Behavior of constructors and methods:

Constructors have to establish the invariants.
Methods must maintain the invariants.

The precondition for their application as well as the caused changes and the result are specified by *requires* and *ensures clauses.*

A complete specification should address exceptional behavior as well.

Example: (Constructor/method specs.)

```
public class Point {
  ...

  /** Creation of a Point */
  /*@  public normal_behavior
    @   requires x >= 0.0 && y >= 0.0 ;
    @   ensures  this.x == x && this.y == y;
    @ also
    @  public exceptional_behavior
    @   requires x < 0.0 || y < 0.0 ;
    @   signals (IllegalArgumentException)
    @*/
  public Point ( float x, float y ) { ... }


  /*@  public normal_behavior
    @   ensures \result == this.x ;
    @*/
  public float getX() { ... }


  /** distance from origin */
  /*@  public normal_behavior
    @   ensures \result == Math.sqrt(x*x+y*y);
    @*/
  public float distance() { ... }

...
```

```
  ...

  /** move this Point */
  /*@  public normal_behavior
    @   requires x+dx >= 0.0 && y+dy >= 0.0 ;
    @   ensures    x == \old(x)+dx
    @          && y == \old(y)+dy ;
    @ also
    @  public exceptional_behavior
    @   requires x+dx < 0.0 || y+dy < 0.0 ;
    @   signals (IllegalArgumentException)
    @*/
  public void move( float dx, float dy ){ ...}
}
```

Remark:

- The specification above does not give a complete account of what is modified, i.e., it is incomplete (e.g. w.r.t. attribute `dist` and method `move`).
- It does not specify what is left unchanged.
- It has no implementation that satisfies the JML specification (see below).

Specification of frame properties:

Frame specifications list the variables to which a method may assign values. This way, they specify which variables remain unchanged.

Reason for this indirect description technique:

- The number of assignable variables is smaller.
- Frame specification should as well apply to variables that are not visible or known at a method declaration.

Properties that do not *depend* on assignable variables remain unchanged. Such properties of the environment of a method execution are called ***frame properties***.

Specification construct:

Modifies/assignable clause (*Veränderungsklausel*):

`assignable` <list of conditional variable expressions>

(The keyword `modifies` is also used.)

Example: (Assignable clause)

```
assignable  x, this.a, p.a.b

assignable  x, this.a if(this==p)
```

Meaning:

Methods and constructors may only assign to instance and class variables that

- are listed in the assignable clause such that the given condition (if any) is satisfied in the prestate or
- are allocated during execution of constructor or method.

If no assignable clause is given, the meaning is the same as with an empty variable list.

Example:

```
public class Point {
  ...
  /*@  public normal_behavior
    @    requires    x >= 0.0 && y >= 0.0 ;
    @    assignable this.x, this.y ;
    @    ensures     this.x == x && this.y == y;
    @ also
    @  private normal_behavior
    @    requires    x >= 0.0 && y >= 0.0 ;
    @    assignable dist ;
    @ also
    @  public exceptional_behavior
    @    requires x < 0.0 || y < 0.0 ;
    @    signals (IllegalArgumentException)
    @*/
  public Point ( float x, float y ) { ...}
```

```
  ...
  /*@  public normal_behavior
    @   ensures \result == this.x ;
    @*/
  public float getX() { ... }
  ...
  /*@  public normal_behavior
    @   requires   x+dx >= 0.0 && y+dy >= 0.0;
    @   assignable x, y ;
    @   ensures     x == \old(x)+dx
    @           && y == \old(y)+dy ;
    @ also
    @  private normal_behavior
    @   requires   x+dx >= 0.0 && y+dy >= 0.0;
    @   assignable dist ;
    @ also
    @  public exceptional_behavior
    @   requires x+dx < 0.0 || y+dy < 0.0 ;
    @   signals (IllegalArgumentException)
    @*/
  public void move( float dx, float dy ){ ...}
}
```

Remark:

Private assignable clauses can be used for internal checks.

5.2.3 Specification with abstraction

Specification frameworks should provide the possibility to express properties *without referring to the implementation*.

Implementation-independent properties can be expressed by referring to a *model* of the system.

We consider ***abstract/model*** variables. They are for example needed, if

- concrete attributes are not declared (interfaces) or
- access rules do not allow to refer to concrete attributes in specifications (e.g. private attributes)
- implementation independency should be achieved, e.g. to support modifications in implementations.

Syntax in JML:

Abstract/model variables/attributes are declared in JML like concrete attributes prefixed with the keyword `model` as modifier.
In JML, model variables are of a Java-type.

Example: (Model attributes)

```
public class Point {
  /** Koordinaten */
  //@ public model float x, y;
  //@ public invariant x>=0.0 && y>=0.0;

  private double dist, angle ;
  /*@ private invariant dist >= 0.0
    @   && 0.0<=angle && angle<=Math.PI/2;
    @*/

  //@ private depends x <- dist, angle ;
  //@ private depends y <- dist, angle ;

  /*@ private represents x
    @          <- Math.cos(angle)*dist ;
    @*/
  /*@ private represents y
    @          <- Math.sin(angle)*dist ;
    @*/
  ...
}
```

Meaning:

Model attributes *can depend* on concrete attributes or other model attributes.

The dependency has to be specified in a *depends clause* (*Abhängigkeitsklausel*).

The value of a model attribute may only depend on the values of attributes for which a dependency is declared.

A *representation clause* (*Repräsentationsklausel)* may define how the abstract value is computed. It links abstract specification and implementation.

Remark:

- Abstract descriptions are a fundamental issue in specification and a prerequisite for scalability.
- If specification A is more abstract than B, we also say that B *refines* or *specializes* A (is a *refinement/specialization* of A).
- Different kinds of abstraction:
  - w.r.t. level of implementation detail and non-determinism (vs. *refinement*)
  - w.r.t. provided functionality (vs. *specialization*)

Model attributes and frame properties:

If a model attribute *a* appears in the assignable clause of method *m*, *m* may assign to all attributes on which *a* depends.

Example: (Assignable model attributes)

The constructor Point may modify *dist* and *angle*:

```
public class Point {
  ...
  /*@  public normal_behavior
    @   requires    x >= 0.0 && y >= 0.0 ;
    @   assignable this.x, this.y ;
    @   ensures     this.x == x && this.y == y;
    @ also
    @  public exceptional_behavior
    @   requires x < 0.0 || y < 0.0 ;
    @   signals (IllegalArgumentException)
    @*/
  public Point ( float x, float y ) { ...}

  /*@  public normal_behavior
    @   ensures \result == this.x ;
    @*/
  public float getX() { ... }
  ...
```

```
  ...
  /*@  public normal_behavior
    @    requires    x+dx >= 0.0 && y+dy >= 0.0;
    @    assignable x, y ;
    @    ensures     x == \old(x)+dx
    @             && y == \old(y)+dy ;
    @ also
    @  public exceptional_behavior
    @    requires x+dx < 0.0 || y+dy < 0.0 ;
    @    signals (IllegalArgumentException)
    @*/
  public void move( float dx, float dy ){ ...}
}
```

Remark:

- The specification that *dist* may be modified is not necessary, because *x* and *y* depend on *dist*.
- Requiring equality within the ensures clause is problematic if floats are involved.

The following example demonstrates an abstract specification of a type `UnboundedStack` for which no attributes are declared.

The specification is based on a side-effect free type `JMLObjectSequence` that is predefined in JML:

„Most specifications need existing knowledge!“

Example: (Specifying types that have no concrete attributes)

```
package org.jmlspecs.models;

public /*@ pure @*/ class JMLObjectSequence
    implements JMLCollection
{
    public /*@ pure @*/
    boolean equals(Object obj) { ... }

    public /*@ pure @*/
    boolean isEmpty() { ... }

    public /*@ pure @*/
    Object first()
       throws JMLSequenceException { ... }

    public /*@ pure @*/
    /*@ non_null @*/ JMLObjectSequence
   insertFront(Object item)
          throws IllegalStateException { ... }
    ...
}
```

Pure methods must not have side-effects (assignable \nothing).

Pure constructors may only modify the attributes of the created object.

Class- and interface types are *pure*, if they only contain pure methods and constructors.

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

public abstract class UnboundedStack {
 /*@ public model JMLObjectSequence theStack
   @        initially theStack != null
   @                  && theStack.isEmpty();
   @*/
  //@ public invariant theStack != null;

 /*@ public normal_behavior
   @   requires   !theStack.isEmpty();
   @   assignable theStack;
   @   ensures    theStack.equals(
                   \old(theStack.trailer()));
   @*/
  public abstract void pop( );

 /*@ public normal_behavior
   @   assignable theStack;
   @   ensures    theStack.equals(
                \old(theStack.insertFront(x)));
   @*/
  public abstract void push(Object x);

 /*@ public normal_behavior
   @   requires !theStack.isEmpty();
   @   ensures \result == theStack.first();
   @*/
  public abstract Object top( );
}
```

Summarizing remarks:

- Specifications can build on implementation parts. They can be used for documentation and checking code.

- Specification techniques can support implementation independent formulations:
  - Enables to exchange implementation without change of specification
  - Allows design contract prior to implementation
  - Needs other types to express properties.

- Well-understood specification techniques for object-based programs:
  - class invariant
  - requires/ensures specifications
  - modifies clauses: Specify what is not modified by describing what is allowed to be modified

Are these techniques applicable and sufficient to master all aspects of object-oriented programs?

5.3 Behavioral Subtyping

Subtyping of programming languages enforces that

- no type errors occur, and
- there is a method implementation for each method invocation.

It does not guarantee that subtype objects **behave** like supertype objects.

Example: (no specialization)

D-objects do not behave similar to C-objects:

```
class C {
  int a;
  int getA(){ return a; }
  void incr() { a++; }
}

class D extends C {
  int getA(){ return a+2; }
  void incr() {
    throw new NullPointerException();
  }
}
```

Problem:

What does it mean that

- a subtype behaves *like* the supertype or
- is a specialization of the supertype?

In particular, how do we handle

- abstract types/classes?
- extensions of the state space?

The operational semantics provides a bad basis for defining behavioral subtyping (why?).

Approach:

Define the behavioral subtype relation based on **specified** properties:

→ Each subtype object has to satisfy the specification of the supertype.

For pre- and post-specifications this means:

- pre[Supertype] => pre[Subtype]
- post[Subtype] => post[Supertype]

Explanation: (Behavioral subtyping)

A subtype S is called a *behavioral* subtype of T iff S-objects behave according to the specification of T (auf Deutsch: S ist ein *konformer* Subtyp von T).

Remark:

- Behavioral subtyping depends on the **specification**.
- Main goal is to understand the relation between sub- and supertypes.
- The described techniques should be applied to informal specifications/documentation as well.

Kinds of Specialization:

- Refining implementation
- Refining nondeterminism
- Adding methods and extending state

Overview:

- Relation between specifications & implementations
- Pre-post specifications without abstract variables and without abstraction (*concrete specs*)
- Pre-post specifications with abstract variables and with abstraction (*abstract specs*)
- Treatment of invariants
- Treatment of frame properties
- Illustrating example

Relation between specification & implementation

Instead of relating an implementation of class D to the specifications of all its supertypes, we check that:

- the specification of D, spec(D), is a behavioral subtype of its direct supertype,
- the implementation of D, impl(D), satisfies spec(D).

Illustration:

```
class C {
  pre  PMC(this,p)
  post QMC(this,p,result)
  R m( T p ){ .../* impl(m,C) */ }
}

class D extends C {
  pre  PMD(this,p)
  post QMD(this,p,result)
  R m( T p ){ .../* impl(m,D) */ }
}
```

Check:

a) { PMD(this,p) } impl(m,D) { QMD(this,p,result) }

b) PMC(this,p) => PMD(this,p)

c) QMD(this,p,result) => QMC(this,p,result)

Remark:

Specification languages usually support ***specification inheritance*** in a form that establish (b) and (c) or refined versions of it automatically.

Example: (Spec. inheritance in JML)

```
class C {
  /*@  public normal_behavior
    @    requires PREMC
    @    ensures  POSTMC ; @*/
 R m( T p ){ ... }
}

class D extends C {
  /*@  also
    @    public normal_behavior
    @      requires PREMD
    @      ensures  POSTMD ;  @*/
 R m( T p ){ ... }
}
```

The specification of D is an abbreviation for:

```
class D extends C {  // not JML
 /*@ public normal_behavior
   @   requires PREMC || PREMD
   @   ensures  ( \old(PREMC) => POSTMC )
   @         && ( \old(PREMD) => POSTMD );
   @*/
 R m( T p ){ ... }
}
```

Concrete pre-post specifications

Pre- and postconditions of methods in supertypes are valid pre-/postconditions for subtype methods:

-> Inheritance of specification

Subtypes without additional attributes:

Inherited method:

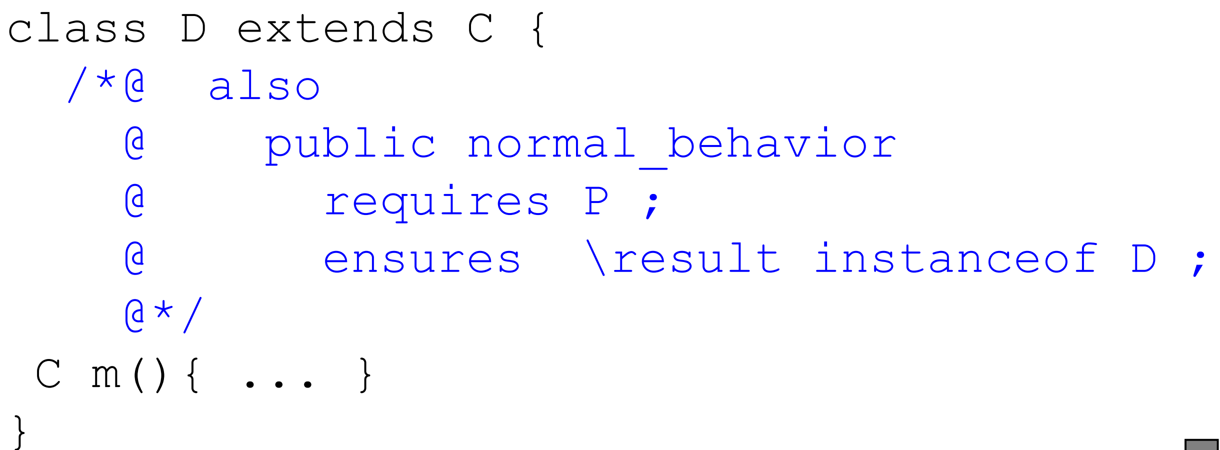
- Specification is inherited without change.

Overriding method:

- Precondition inherited or new weaker precondition
- Postcondition inherited and possibly strengthened by additional properties

Example:

```
class C {
  /*@  public normal_behavior
    @     requires P ;
    @     ensures  Q ;
    @*/
 C m(){ ... }
}
```



```
class D extends C {
  /*@  also
    @    public normal_behavior
    @      requires P ;
    @      ensures  \result instanceof D ;
    @*/
 C m(){ ... }
}
```

Additional method:

- no constraints (but see about invariants).

Remark:

Similar restrictions have to be applied to the specification of exceptional behavior.

Subtypes with extended state:

If the state space is *extended* in the subtype,
it can be necessary to strengthen the precondition
of overriding methods w.r.t. properties concerning
the additional attributes. However, this would violate:

pre[Supertype]   => pre[Subtype]

Solution:

Use abstraction with model variables.

Abstract pre-post-specifications

The basic idea is to write specifications in terms of
abstract states and to provide abstraction functions:

- from concrete objects to their abstract states
- from abstract states of subtype objects to abstract
  states of supertype objects.

The abstraction functions in particular provide the
flexiblity to handle extended state.

Here, we only consider an example:

Example:

```
class C {
  //@  public model boolean valid;
  //@  public model AS state;

 /*@  public normal_behavior
    @     requires valid && r(state) ;
    @     ensures  q(state)   ;
    @*/
 void m(){ ... }
}

class D extends C {
  private BD d;

  //@ private depends valid <- d;
  //@ private represents valid <- CD.pd(d) ;

  //@ private depends state <- d;
  //@ private represents state <- CD.f(d) ;
  ...
}

class E extends C {
  private BE e;

  //@ private depends valid <- e;
  //@ private represents valid <- CE.pe(e) ;

  //@ private depends state <- e;
  //@ private represents state <- CE.g(e) ;

  ...
}
```

- `pd` is a predicate expressing when attribute d has a valid state.
- `f` is an abstraction function mapping values of concrete type `BD` to the abstract type `AS`.

The definitions of `pd` and `f` can be tailored to the needs of class `D`. The same holds for `pe`, `g` and class `E`.

Remarks:

- Often one assumes an explicit abstraction function that maps values of subtype objects into the state space of the supertype.
- Abstract/model variables enable two kinds of state extensions:
  - overriding the representation function
  - additional abstract variables
- The variations in the subtypes can be captured by representation functions.

Treatment of Invariants

In principle, invariants can be expressed by pre- and post-conditions. However, as a specification construct they allow to express

- restrictions on subtype behavior in supertypes:

→ Invariants of supertypes have to be satisfied by additional subtype methods.

Example:

```
class C {
  public int a = 0;
  //@  public invariant a >= 0;
  ...
  // no declaration of m
}

class D extends C {
  ...
  void m(){ a = -1; } // violates invariant
  ...
}
```

General Approach:

Invariants of supertypes have to be satisfied by all subtype methods. This can be formulated as:

inv[Subtype] => inv[Supertype]

This can be achieved by invariant inheritance:

=> The subtype invariant is the conjunction of the supertype invariant and additional invariant clauses specified in the subtype.

Questions:

- What is the precise meaning of an invariant? When should invariants hold?
- How is subtyping and dynamic binding handled for invariants?

There is no well-established answer to these questions. We discuss existing answers.

Semantical variation:

1. Invariants have to hold in *visible* states:

JML: „Invariants have to hold in each state outside of a public method‘s execution and at the beginning and end of such execution.“

2. Transformation into pre- and postconditions:

Invariants have to hold in poststates of constructors. If they hold in the prestate of a method, they have to hold in the poststate as well.

For verification, both alternatives are problematic:

Let S be a subtype of T, m be a method in T and *x* a variable of type T holding an S-object:

... x.m(...) ...

For the verification we need inv[S] as precondition. But: S may not be known at the invocation site.

Example:

```
class C {
  public int a = 0;
  //@  public invariant a >= 0;
  ...
  void m(){
  ... // maintains invariant
  }
}

class Foo {
  void mfoo( C x ) {
    ... x.m() ...
  }
}
```

```
class D extends C {
  public int b = 0;
  //@  public invariant a > 1;
  //@  public invariant b >= 0;
  ...
  void m(){
    b = 4 / a ;
  ... // maintains both invariants
  }
}
```

Problem: What has to be shown for the prestate of a method invocation `x.m()`?

Classical solution:

- Make sure that invariants can only be broken by methods of the object. Thus:
  - if they are established in the post-state of each call of a constructor and method of the class,
  - then they hold in the pre-state of each call.
- Solution has problems with recursion.

Other solutions:

- Specify the invariants based on abstractions
- Allow the programmer to define where invariants should hold and reflect this in the meaning of invariants (solution of Spec#)
- Use a more sophisticated meaning of invariants

Treatment of frame properties

The specification of frame properties has to cope with two problems:

- Information hiding: not all assignable variables can be named in the specification.
- Extended state: The supertype specification cannot capture the state of additional attributes in subtypes.

Example:

```
class C {
  public  int a = 0;
  private int b = 0;
  public static int c = 123;
  ...

  /*@ public normal_behavior
    @   assignable a;
    @*/
  public void m(){ a++; b++ }
}

class Foo {
  void mfoo( C x ) {
    ... x.m() ...
  }
}
```

```
class D extends C {
  public int d = 0;
  ...
  public void m(){
    super.m();
    d = 87;
    C.c = 4 ;
  ...
  }
}
```

Possible solution:

→ Use abstract attributes/variables, depends- and representation clauses.

→ Information hiding: Abstract attributes can depend on non-accessible attributes.

→ Extended state: Depends relation can be extended in subtypes.

(Example is given in the following subsection)

Using the techniques together

Specification techniques for OO-programs have two goals:

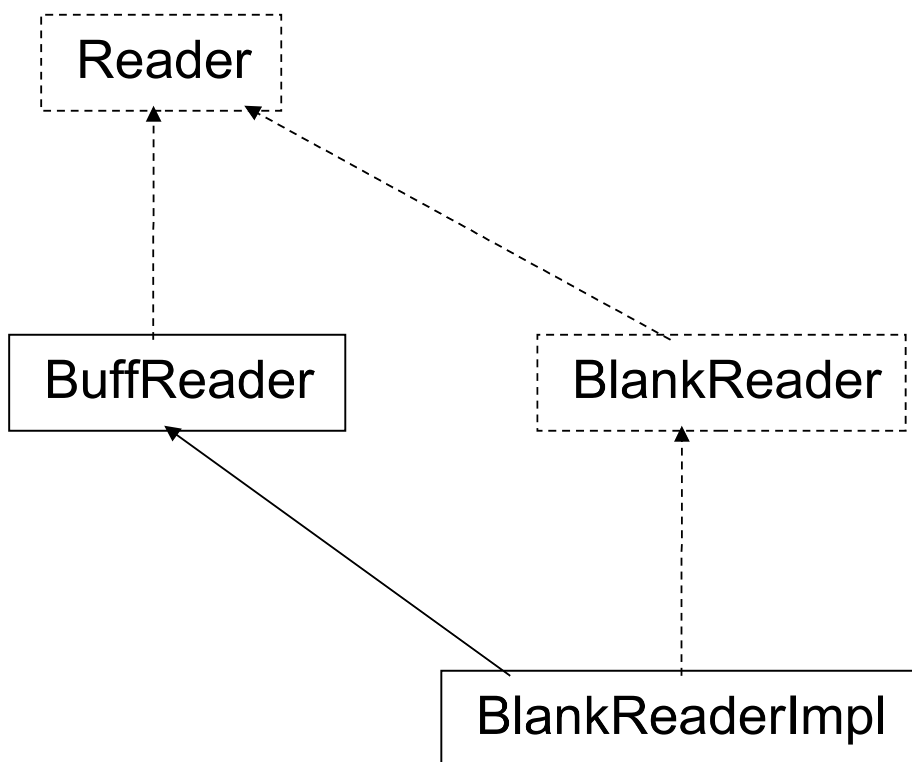
- Specification of properties by annotating programs.
- Complete specification of types as basis for behavioral subtyping.

We illustrate this by a larger example.

Example:

The following example is a Java-version of the central example given in:

K. R. M. Leino, G. Nelson: Data abstraction and information hiding, Transactions on Programming Languages and Systems 24(5): 491-553 (2002).



The example demonstrates:

- state extensions
- behavioral subtyping

```
public interface Reader {
  //@ public model instance boolean valid;
  //@ public model instance Object  state;

  /*@ public normal_behavior
    @   requires    valid;
    @   assignable  state;
    @   ensures     -1 <= \result
    @               && \result < 65535 ;
    @*/
  public int getChar();

  /*@ public normal_behavior
    @   requires    valid;
    @   assignable  valid, state;
    @*/
  public void close();

}
```

```
public abstract
class BuffReader implements Reader {

 protected /*@ spec_public @*/ int lo, cur, hi;
 protected /*@ spec_public @*/ char[] buff;

 //@ public model boolean svalid;

 /*@ public represents valid <-
   @  0 <= lo  &&  lo <= cur  &&  cur <= hi  &&
   @  buff != null  &&  hi-lo <= buff.length &&
   @  svalid ;
   @*/
 public int getChar() {
   if( cur == hi ) refill();
   if( cur == hi ) return -1;
   cur++;
   return buff[cur-lo-1];
 }

 /*@ public normal_behavior
   @   requires    valid;
   @   assignable  state;
   @   ensures     cur == \old(cur) ;
   @*/
 public abstract void refill();

 //@ depends valid <- lo,cur,hi, buff, svalid;
 //@ depends state <- lo,cur,hi, buff, buff[*];
 //@ depends svalid <-lo, hi, buff;
}
```

```
public interface BlankReader extends Reader {

  /*@ public normal_behavior
    @   requires    0 <= n;
    @   assignable  valid, state;
    @   ensures     valid  && \result == this ;
    @*/
   public BlankReader init( int n );
}
```

A non-trivial application of `BlankReader` and `BlankReaderImpl` (s. next slide):

```
public class  ReaderTest {

  public static void main( String[] args ) {
    BlankReader br = new BlankReaderImpl();
    br.init(1000000);

    int count = 0;
    int chr;
    do {
      chr = br.getChar();
      count++;
    } while( chr != -1 );
    br.close();
    System.out.println(count);
  }
}
```

```
public class BlankReaderImpl
                extends BuffReader
                implements BlankReader
{
  private int num;
  //@ private represents svalid <- hi <= num ;

  public BlankReader init( int n ) {
    num  = n;
    buff = new byte[ Math.min(n,8192) ];
    lo   = 0;
    cur  = 0;
    hi   = buff.length;
    for( int i = 0; i < hi; i++ ) {
      buff[i] = 32;
    }
    return this;
  }

  public void refill() {
    lo = cur;
    hi = Math.min( lo+buff.length, num );
  }

  public void close() {}

  //@ private depends state  <- num ;
  //@ private depends svalid <- num ;

  //  representation of state not
  //  considered
}
```