2.4 Subtyping, Inheritance, Extended State

Problems and Spec# approach:

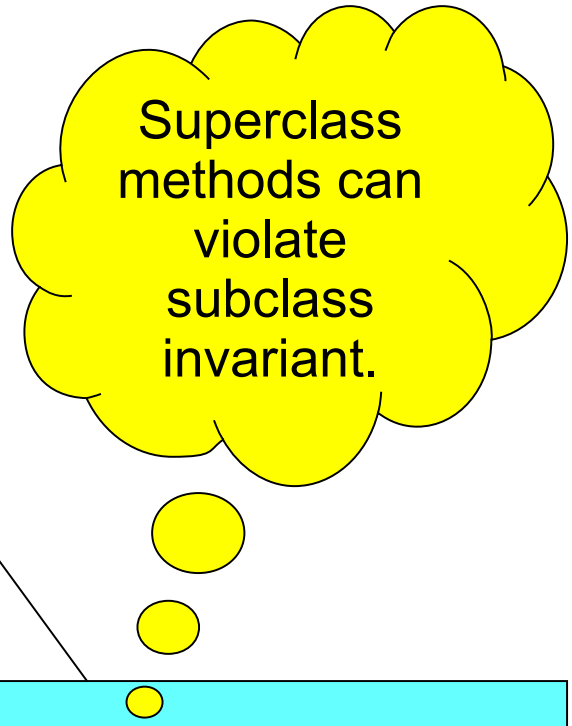
0. Subclass methods are executed in contexts where only base class is known:
   - → No refinement of preconditions in overriding methods
   - → postcond:subclass ==> postcond:base_class
1. Inherited methods could break subclass invariants:
   - → [Additive] hint to modular verifier
2. Overriding methods could break superclass invariants:
   - → Discipline to stepwise expose objects
   - → Class frames

Illustration by a “speedy” example:

```
public class  Car  {
    protected  int speed;
    invariant   0 <= speed;

    protected Car()
    {  speed = 0; }

    public  void  SetSpeed( int kmph )
      requires   0 <= kmph;
      ensures   speed == kmph;
    {
       expose (this) { speed = kmph; }
    }
}
```

1.a Inheriting class: Additive invariants

```
public class LuxuryCar : Car
{
    int  cruiseControlSetting;
    invariant   cruiseControlSetting == -1     ||
                cruiseControlSetting == speed;

    LuxuryCar()
    {  cruiseControlSettings = -1;  }
}
```



1.b Changes required in the base class:

```
public class Car {
    [Additive] protected int speed;
    invariant 0 <= speed;

    protected Car()
    { speed = 0; }

    [Additive]
    public void SetSpeed( int kmph )
      requires 0 <= kmph;
      ensures speed == kmph;
    {
       additive expose (this)
       { speed = kmph; }
    }
}
```

[Additive] annotation is needed as speed is mentioned in object invariant of LuxuryCar

Additive expose is needed as the SetSpeed method is inherited and so must expose LuxuryCar if called on a LuxuryCar Object

2.a Virtual methods

```
public class Car {
    [Additive] protected int speed;
    invariant 0 <= speed;

    protected Car()
    { speed = 0; }

    [Additive] virtual public void SetSpeed( int kmph )
      requires 0 <= kmph;
      ensures speed == kmph;
    {
      additive expose (this)
      { speed = kmph; }
    }
}
```

2.b Overriding methods:

```
public class LuxuryCar : Car  {
    int  cruiseControlSetting;
    invariant   cruiseControlSetting == -1     ||
                cruiseControlSetting == speed;

    LuxuryCar() {  cruiseControlSettings = -1;  }

    [ Additive]
    override public void SetSpeed(int kmph)
       ensures  cruiseControlSettings == kmph
             && cruiseControlSettings == speed;
   {
       additive expose (this) {
          cruiseControlSettings = kmph;
          base.SetSpeed( cruiseControlSettings );
   }  }
}
```

Exposes class frame of LuxuryCar

Exposes class frame of Car

2.5 Remarks on Further Aspects

... the course concentrated on modularity and covered only parts of Spec# --

Not treated:

- Object initialization
- Non-nullness annotations
- Purity and immutability
- Recursive dependencies among peers
- Owners per class frame

Discussion:

- Automatic modular verification technique for classes
- Main goal: detect programming errors
- Full tool support
- Data abstraction
- Specification of interface types
- Power of specification language
- Module/component concept

References / Further Reading:

Rustan Leino and Peter Müller:
Object invariants in dynamic contexts
ECOOP 2004

Mike Barnett, Robert DeLine, Manuel Fähndrich, Rustan Leino, and Wolfram Schulte:
Verification of object-oriented programs with invariants
Journal of Object Technology 2004

Peter Müller, Arnd Poetzsch-Heffter, and Gary Leavens:
Modular Invariants for Layered Object Structures
Science of Computer Programming 2006

http://www.rosemarymonahan.com/specsharp/

3. Modular Behavioural Specification (& Verification)

Component specification:

[Szyperski: Component Software, 2nd ed., p. 41 & p.78]

Definition of component:

"A software component is a unit of composition with contractually specificied interfaces and explicit context dependencies only. ..."

Discussion of component specification:

"The specification problems encountered in recursive re-entrant systems need to be solved in a modular way to cater for components. In other words, each component must be independently verifiable based on the contractual specification of the interfaces it requires and those it provides."

Central challenges:

- What is an appropriate notion of program components?
- How can we specify component behaviour in an implementation-independent way?
- How can we modularly prove implementations correct?
- How can we prove two implementations to be equivalent?
- When are specifications strong enough for compositional reasoning?

REQUIREMENTS

RATIONALE

OO-program components:

- larger than a class / smaller than a complete program
- designed by the programmer
- provide a **boundary** to component **environment**
- specifiable in an **implementation-independent** way

Components at runtime:

- have local state
- may have incoming and outgoing references
- communicate with the environment in a controlled way
- allow for callbacks
- support nesting

Overview of the following:

1. The box approach to components
2. Behavioural specifications of boxes
3. Specification of multi-access boxes

Relation to Spec# / ESC Java approach:

1. Different specification goals
2. Verification technology of Spec#/ESC Java is needed to prove implementation correctness

3.1 The Box Approach to Components

General approach:

Structure the heaps into boxes with clear boundaries s.t.:

- Implementation of a box consists of fixed set of classes
- Types of references crossing a boundary are known
- An object belongs to exactly one box (but boxes can be nested)

Relation to ownership techniques:

- ownership contexts with multiple ingoing references
- similar to ownership domains
- control of outgoing references

Different box disciplines:

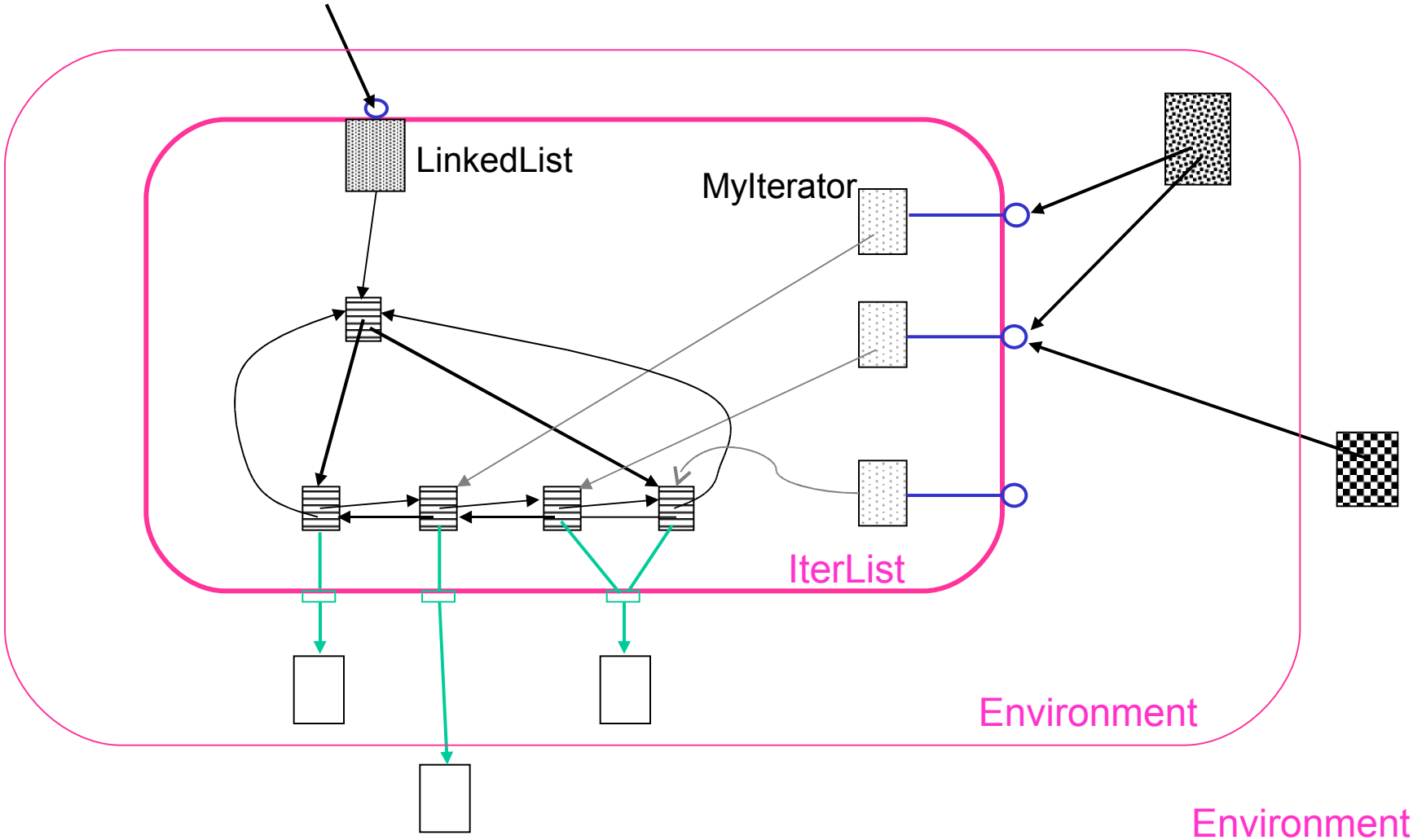
- Each module / package P defines a box:
  - box exactly contains the objects of the classes of P

- Each module / package P defines a box:
  - box contains the objects of the classes of P and objects of classes of included packages if created from objects in the box

- Programmer defined classes create boxes at runtime:
  - box contains the newly created object X and all objects directly or indirectly created by X

- others

Boxes at runtime:

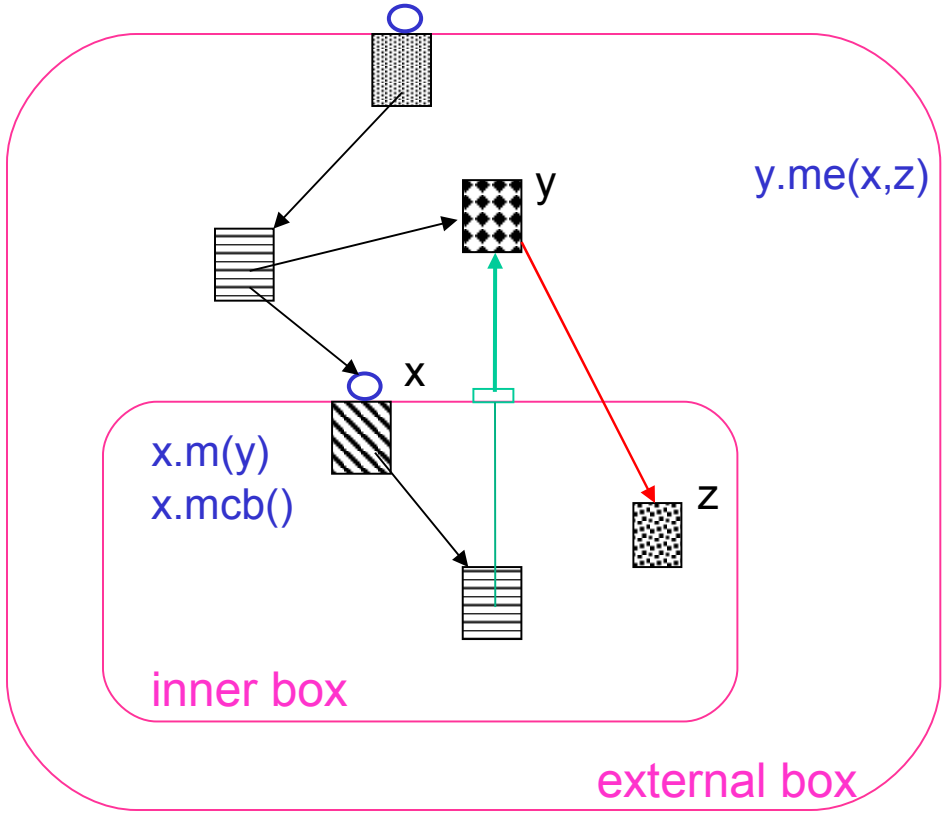


```
box decl  IterList : IList;

interface  IList  {
   Object getFirst() ;
   void add( Object o );
   Iterator iter();
}

interface  Iterator  {
   boolean hasNext() ;
   Object next();
   void remove();
}

class  Object  {
   boolean equals( Object y )
   …
}
```

```
box impl  IterList by LinkedList;

class  LinkedList  implements IList  {
     …
     Object getFirst() { … }
     void addFirst(Object o);
     Iterator  iter () {
        return new MyIterator(this);
     }
}

class  Entry  {  …  }

class MyIterator  implements Iterator {
   boolean hasNext() { .. }
   Object next(){…}
}
```

… **new** IterList(); … *creates a box instance*

Dynamic behavior at box boundaries:

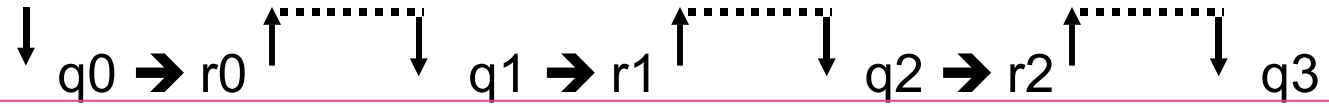


Illustrating dynamics:

- object creation
- box creation
- local state change
- boundary call
- import of references
- outgoing call
- export of references
- callbacks

3.2 Boxes: Behavioural semantics & specs

Box semantics expressed as message traces:



Hidden box state

Specification principles:

- Specify possible traces
- States are an auxiliary means to express past history
- *Normalized* object identifiers at boundary

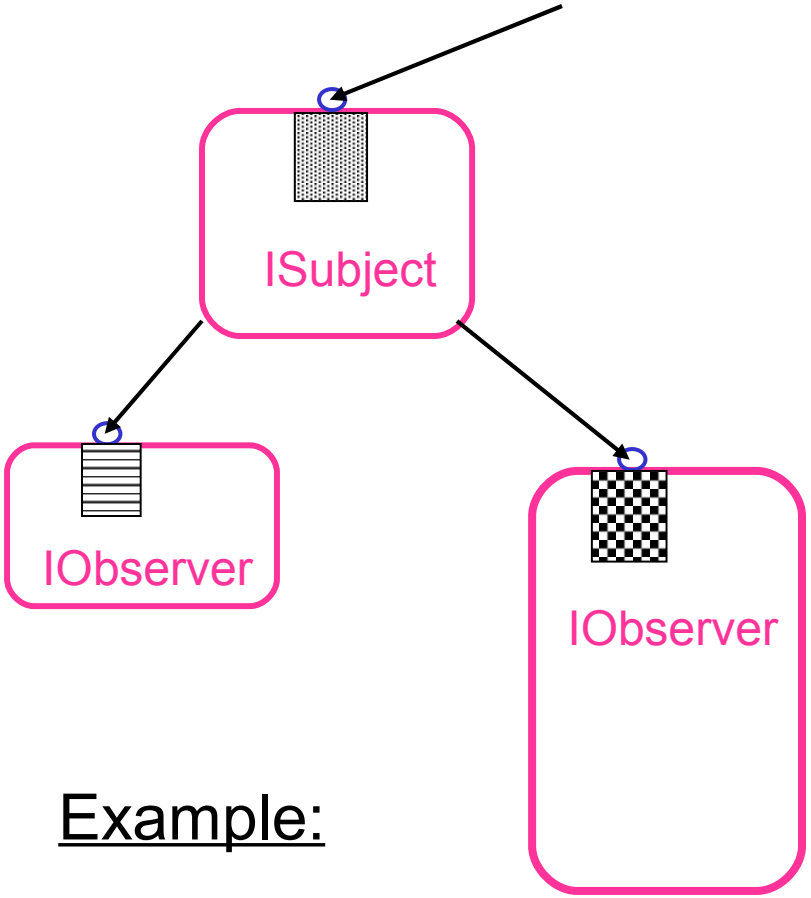
Specification technique:

- Approach:
  - Representation-independent
  - Environment-independent
  - Provides a notion of substitutability
- Constructs:
  - Model state, model programs
  - Tracking of boundary-crossing references
  - Notion of data and pure methods
- Modularity by construction:
  - Selection of box discipline (all relevant code known)
  - Well-defined boundary
  - Restriction of formulas to things controlled by box

No invariants, no frame clause for specification

Illustration of specification technique:

```
interface ISubject {
  SState getS();
  void register ( IObserver o );
  void update( SState s );
}

interface IObserver {
  void notify();
}
```



Data:

- Immutable
- Structural equality
- References are not tracked

Example:

- SState
- List<A>, Set<A>

```
box Subject implements ISubject  {
  receives Set<IObserver> obs;

  model  SState     sbs;
  model  boolean    accessible;

  Subject() {
     assert  obs.isEmtpy() && accessible;
  }

  State getS() {
     result = sbs;
  }

  void register ( IObserver o ) {
    assume   accessible ;
    obs = obs.add(o);
  }
```

Outgoing refs

Model state

Model program

```
 …
  void update( SState s )
   {
      assume  accessible;
      accessible = false;
      sbs = s;
      for( o in obs ){
        o.notify() ;
      }
      accessible = true;
} }
```

Internal data call

```
box Observer implements IObserver  {
   receives  ISubject  mySub;

   model OState  oss;

   Observer( ISubject s ) {
      s.register( this );
      assert  mySub == s;
   }

   void notify() {
      oss = oss.succState( mySub.getState() );
   }
}
```

Outgoing call in spec

Member of interface OState

Discussion:

- Specifications use only local model information and signatures of used interfaces
- Spec of Subject makes no assumption about behaviour of IObserver.notify()

  ➔ no modifies-clause for IObserver needed

- Specifications need no (mplementation) invariants
- Boundary invariants can be established during reasoning
- Specifications are restricted programs with a

  → trace semantics

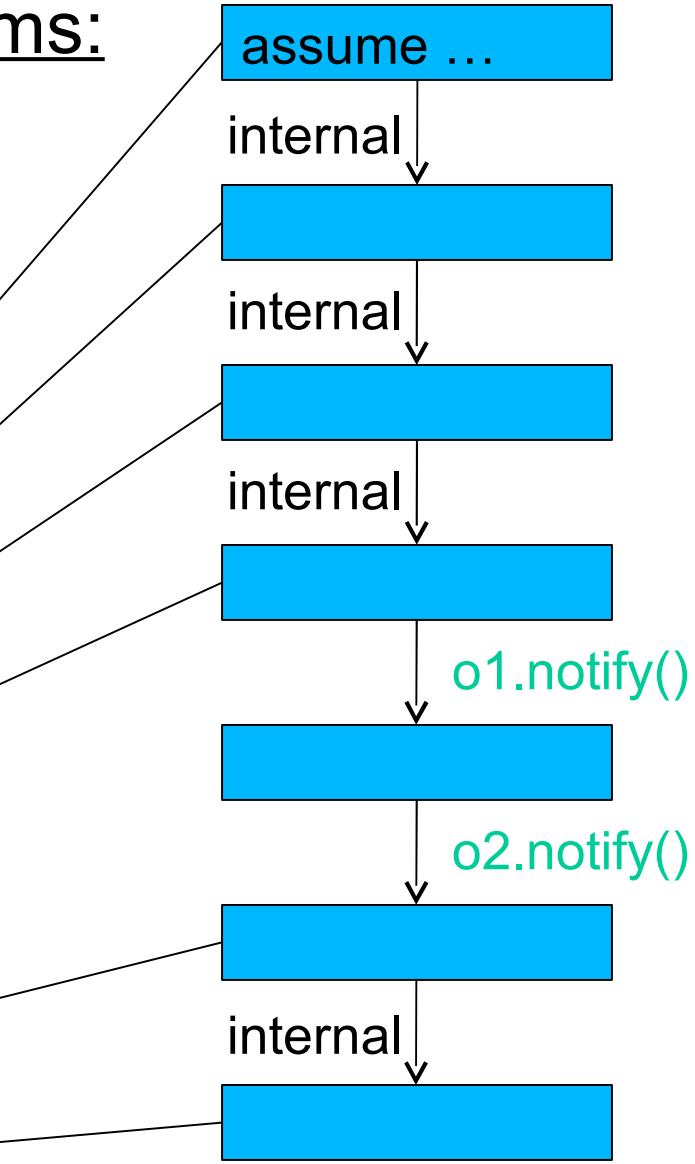
  → reference tracking

Semantics of model programs:

Trace with:

- states
- internal actions
- external calls

```
assume  accessible;
accessible = false;
sbs = s;
for( o in obs )
{
    o.notify() ;
}
accessible = true;
```



Three kinds of reasoning:

1. Deriving facts from the specification:

```
State getS()
    modifies nothing;
{
    result = sbs;
    assert  result == sbs;
}
```

```
void register ( IObserver o ) {
      assume   accessible ;
      obs = obs.add(o);
      assert  accessible  &&  obs == pre(obs).add(o)
                          &&  sbs == pre(sbs);
}
```

```
void update( State s ) {
    assume  accessible ;
    accessible = false;
    sbs = s;
    for( o in obs ){
      assert   !accessible  &&  sbs == s  &&  obs==pre(obs);
      o.notify() ;
      assume  !accessible  &&  sbs == s  &&  obs==pre(obs);
    }
    accessible = true;
    assert  accessible  &&  sbs == s  &&  obs==pre(obs) ;
}
```

Enriching the specification can essentially be done by

- classical program verification techniques and
- access restrictions (extended type states)

2. Using specifications to prove application programs:

Proof consistency after notification:

```
consistent:  OState * SState --> bool
consistent ( os.succState( sst ), sst )
```

Application program:

```
...
State s = ...
Subject sbj   =  new Subject();
Observer o1 =  new Observer(sbj);
Observer o2 =  new Observer(sbj);
sbj.update(s);
assert  consistent(o1.oss,sbj.sbs);
```

```
Subject sbj   =  new Subject();
assert   sbj.obs == {} &&  sbj.accessible ;
Observer o1 =  new Observer(sbj);
Observer o2 =  new Observer(sbj);
sbj.update(s);
assert  consistent(o1.oss,sbj.sbs);
```

```
Subject sbj   =  new Subject();
assert   sbj.obs == {} &&  sbj.accessible ;
sbj.register(o1);
assert   o1.mySub == sbj ;
Observer o2 =  new Observer(sbj);
sbj.update(s);
assert  consistent(o1.oss,sbj.sbs);
```

```
Subject sbj   =  new Subject();
assert   sbj.obs == {} &&  sbj.accessible ;
sbj.register(o1);
assert   o1.mySub == sbj  && sbj.obs == {o1}
      &&  sbj.accessible;
Observer o2 =  new Observer(sbj);
sbj.update(s);
assert  consistent(o1.oss,sbj.sbs);
```

```
Subject sbj   =  new Subject();
assert   sbj.obs == {} &&  sbj.accessible ;
sbj.register(o1);
assert   o1.mySub == sbj  && sbj.obs == {o1}
      &&  sbj.accessible;
Observer o2 =  new Observer(sbj);
assert   o1.mySub == sbj  && o2.mySub == sbj
      &&  sbj.accessible  && sbj.obs == {o1,o2};
sbj.update(s);
assert  consistent(o1.oss,sbj.sbs);
```

```
Subject sbj   =  new Subject();
assert   sbj.obs == {} &&  sbj.accessible ;
sbj.register(o1);
assert   o1.mySub == sbj  && sbj.obs == {o1}
      &&  sbj.accessible;
Observer o2 =  new Observer(sbj);
assert   o1.mySub == sbj  && o2.mySub == sbj
      &&  sbj.accessible  && sbj.obs == {o1,o2};
assume  sbj.accessible;
accessible = false;
sbs = s;
o1.notify();
o2.notify();
accesible = true;
assert  sbj.sbs == s  &&  sbj.obs=={o1,o2};
assert  consistent(o1.oss,sbj.sbs);
```

```
Subject sbj   =  new Subject();
assert   sbj.obs == {} &&  sbj.accessible ;
sbj.register(o1);
assert   o1.mySub == sbj  && sbj.obs == {o1}
      &&  sbj.accessible;
Observer o2 =  new Observer(sbj);
assert   o1.mySub == sbj  && o2.mySub == sbj
      &&  sbj.accessible  && sbj.obs == {o1,o2};
o1.notify();
assert   o1.oss == o1.oss.succState( sbj.sbs );
o2.notify();
assert  consistent(o1.oss,sbj.sbs);
```

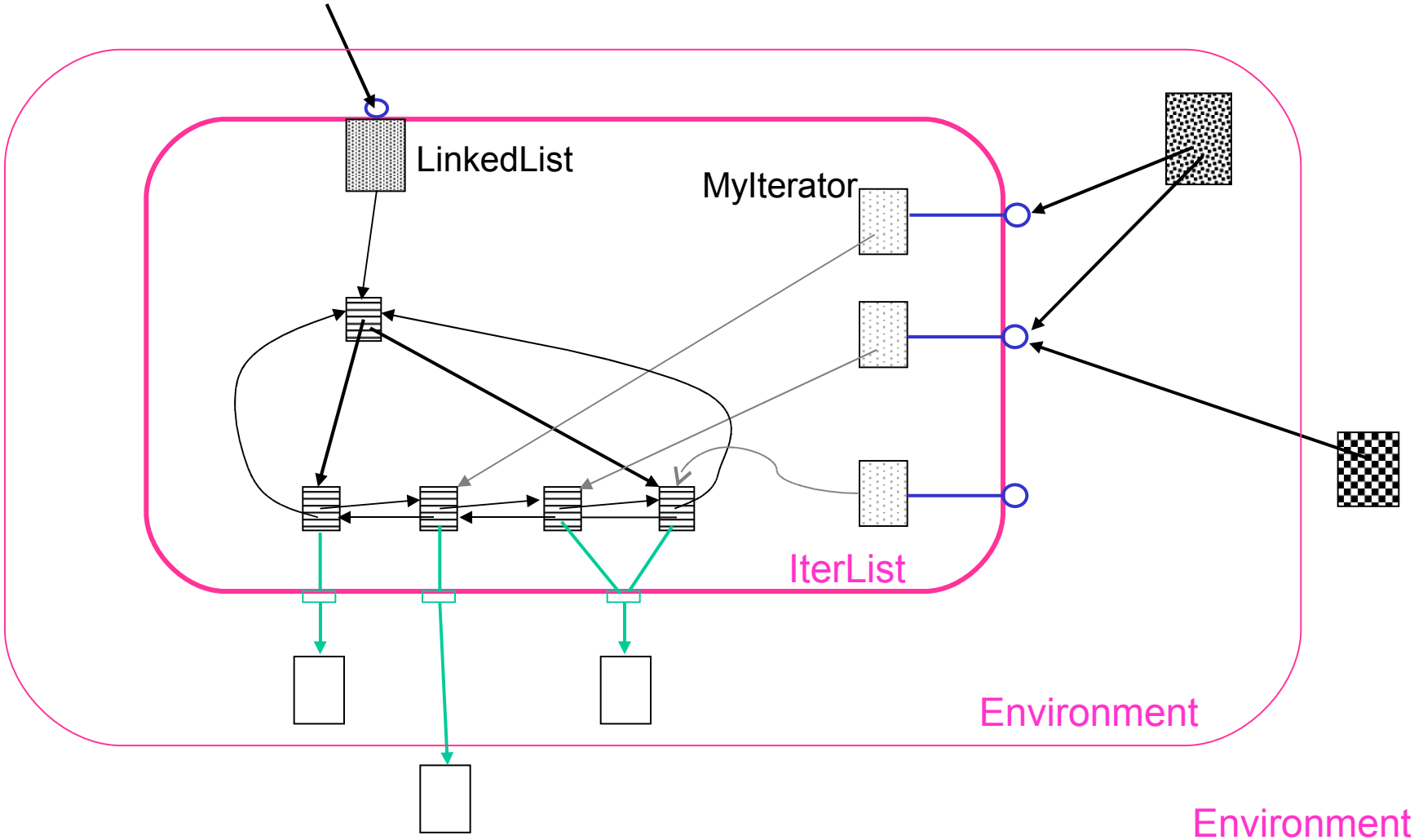
```
Subject sbj   =  new Subject();
assert   sbj.obs == {} &&  sbj.accessible ;
sbj.register(o1);
assert   o1.mySub == sbj  && sbj.obs == {o1}
      &&  sbj.accessible;
Observer o2 =  new Observer(sbj);
assert   o1.mySub == sbj  && o2.mySub == sbj
      &&  sbj.accessible  && sbj.obs == {o1,o2};
o1.notify();
o2.notify();
assert   o1.oss == o1.oss.succState( sbj.sbs );
assert  consistent(o1.oss,sbj.sbs);
```

```
Subject sbj   =  new Subject();
assert   sbj.obs == {} &&  sbj.accessible ;
sbj.register(o1);
assert   o1.mySub == sbj  && sbj.obs == {o1}
      &&  sbj.accessible;
Observer o2 =  new Observer(sbj);
assert   o1.mySub == sbj  && o2.mySub == sbj
      &&  sbj.accessible  && sbj.obs == {o1,o2};
o1.notify();
o2.notify();
assert   o1.oss == o1.oss.succState( sbj.sbs )
      &&  consistent(o1.oss.succState( sbj.sbs ), sbj.sbs );
assert  consistent(o1.oss,sbj.sbs);
```

3. Proving implementations correct:

- In general: based on refinement & simulation
- For the sketched framework: open problem

3.3 Specification of Multi-Access Boxes



The interface types:

```
interface IList {
  Object  get( int index );
  void    add( Object x );
  Object  remove( int index );
  boolean contains ( Object x );
  Iterator iter();
}

interface Iterator {
  boolean hasNext();
  Object   next();
  void     remove();
}
```

The box structure:

```
box IterList  implements IList  {
  receives  Set<Object>  elems;

  model  List<Object> list;

  //… construcors and methods of IterList

  exposes  Set<Iterator> iters {
    model  IterList myList;
    model  int pos;
    model  boolean valid;
    model  boolean hasCurrent;

  //… construcors and methods of Iterator
}
```

```
IterList() {
  assert  list.isEmpty()  &&  iters.isEmpty()
        &&  elems.isEmpty();
}

Object  get( int index ) {
  assume  0 <= index  &&  index < list.length();
  assert    result == list.nth(index);
}

void add( Object x ) {
  for( it in iters ){
    if( it.pos == list.length() ) it.valid = false;
  }
  list  = list.addLast(x);
  elems = list.toSet();
}
```

```
Object  remove( int index ) {
     assume  0 <= index  &&  index < list.length();
     for( it in iters ){
       if( it.pos >= index )  it.valid = false;
     }
     result  = list.nth(index);
     list       = list.delete(index);
     elems  = list.toSet();
   }
```

Handling tricky OO-aspects:

```
boolean contains ( Object x ) {
  if( x == null ) {
    result = list.hasElem(null);
  } else {
    result = false;
    for( y in list ) {
      if( x.equals(y) ) {
        result = true;
        break;
  } } }
}
```

Complex (?) outgoing call

Exposing references:

```
owned Iterator iter() {
  assert  !pre(iters).hasElem(result)
       &&  iters = pre(iters).add(result)
       &&  result.myList == this
       &&  result.pos == 0
       &&  result.valid == true
       &&  result.hasCurrent == false ;
}
```

Specification of Iterator with reuse:

```
boolean hasNext() {
  assume  valid;
  assert  result == (pos < myList.list.length());

Object  next() {
  assume  valid  && hasNext();
  result = myList.get(pos);
  pos++;  hasCurrent = true;
}

void  remove() {
  assume  valid && hasCurrent
  myList.remove(pos);
  hasCurrent = false;
}
```

Deriving specification invariant:

```
box IterList … {
    …
    invariant
      forall it in iters:  ( 0 <= it.pos )
                && ( it.valid ==>  it.pos <= it.myList.list.length() ) ;
}
```

Box invariants have to hold when control is outside the box.

Try to proof the invarinat by induction over the traces.

Discussion of the approach:

+ Modular programming language semantics
+ Clear relation to specification language semantics
+ Data and control abstraction
- Promising approach, but not yet validated in detail
- No programming logic so far
- No tool support so far

References / Further Reading:

Tony Hoare:
Proof of Correctness of Data Representations
Acta Informatica

Rustan Leino and Peter Müller:
A Verification Methodology for Model Fields, ESOP 2006

Arnd Poetzsch-Heffter and Jan Schäfer :
Modular Specification of Encapsulated Object-Oriented Components, FMCO 2005

Arnd Poetzsch-Heffter and Jan Schäfer :
A Representation-Independent Behavioral Semantics for Object-Oriented Components, FMOODS 2007

4. Concluding Remarks

+ Huge progress in program verification
+ Modularity meanwhile recognized as important
+ Software size and security/safety requirements
+ Nice tools
- Complexity of approaches
- Need to handle complex programs
- Not sufficient abstraction (data and control)
- Concurrency is still a construction site
- Area too challenging for research?