Konzepte objektorientierter Programmierung
– Lecture 11 –

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Chair of Programming Methodology

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Eidgenössische Technische Hochschule Zürich
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Meeting the Requirements

Cooperating Program Parts with Well-Defined Interfaces

→ Objects (data + code)
→ Interfaces
→ Encapsulation

Classification and Specialization

→ Classification, subtyping
→ Polymorphism
→ Substitution principle

Inherently Concurrent Execution Model

→ Active objects
→ Message passing

Correctness

→ Interfaces
→ Encapsulation
→ Simple, powerful concepts

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Agenda for Today

11. Interface Specifications

11.1 Frame Properties

11.2 Invariants and Callbacks

11.3 Invariants of Object Structures

Objectives

- Understanding subtle correctness conditions

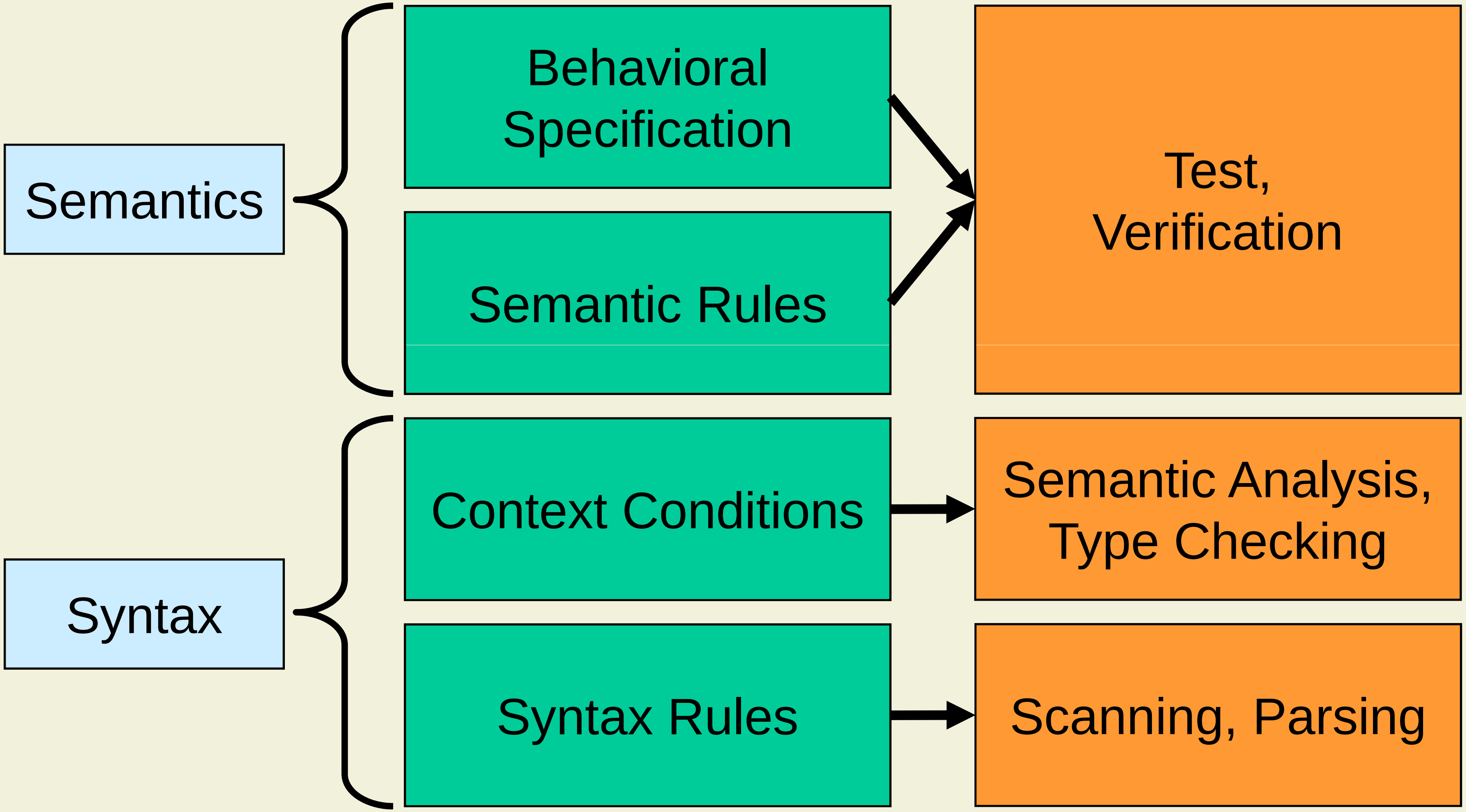
Correctness

```
class ArraySet implements Set {
  private int[ ] array;
  private int next;
  …

  public void insert( int i ) {
    for ( int j = 0; j < next; j-- )
      if array[ j ] == i then return true;
    return false;
  }
}
```

- Behavioral Specification
- Semantic Rules
- Context Conditions
- Syntax Rules

Aspects of Correctness



Test and Verification

Test

- Objective
  - Detect bugs
- Examples
  - White box test
  - Black box test
- Problems
  - Successful test does not guarantee correctness

Verification

- Objective
  - Prove correctness
- Examples
  - Formal verification based on a logic
  - Symbolic execution
- Problems
  - Expensive
  - Formal specification of behavior is required

11. Interface Specifications

11.1 Frame Properties

11.2 Invariants and Callbacks

11.3 Invariants of Object Structures

Pre-Post Specifications

```
class ArraySet implements Set {
  private int[ ] array;
  private int next;

  public boolean has( int i ) {
    for ( int j = 0; j < next; j++ )
      if ( array[ j ] == i ) return true;
    return false;
  }
  private void resize( ) {
    int[ ] tmp = new int[ array.length + 10 ];
    System.arraycopy( array, 0, tmp, 0,
      array.length );
    array = tmp;
  }
```

```
  // requires !has( i )
  // ensures has( old( i ) )
  public void insert( int i ) {
    if ( next == array.length )
      resize( );
    array[ next ] = i;
    next++;
  }

  …
}
```

Frame Properties

```
// requires !has( i )
// ensures has( old( i ) )
public void insert( int i ) {
  array[ 0 ] = i;
  next = 1;
}
```

```
Set s = new ArraySet( );
s.insert( 42 );
s.insert( 1492 );
boolean b = s.has( 42 );
```

```
// requires !has( i )
// ensures has( old( i ) )  &&
//     ∀j: old( has( j ) ) ⇒ has( j )
public void insert( int i ) { … }
```

- Methods can have side-effects
- Frame properties describe **what is left unchanged** by a method execution

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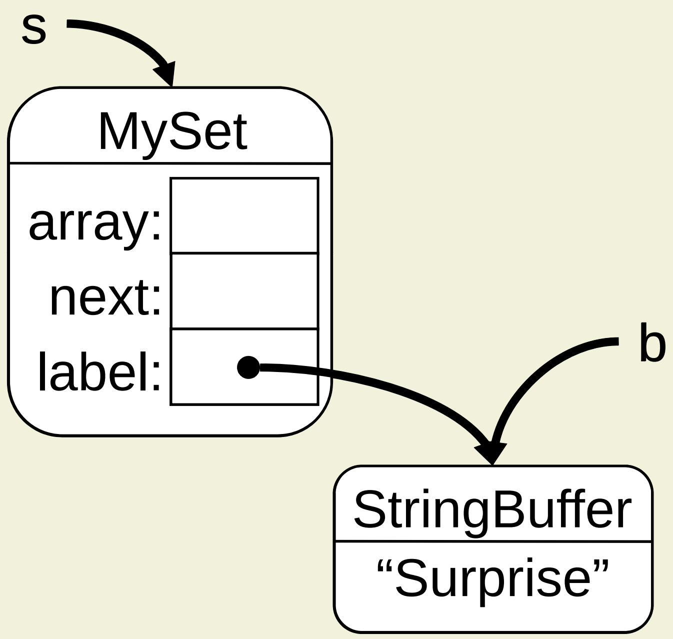
Frame Properties (cont'd)

```
// requires !has( i )
// ensures has( old( i ) )  &&
//     ∀j: old( has( j ) ) ⇒ has( j )
public void insert( int i ) { … }
```

```
void foo( Set s, StringBuffer b ) {
  b.insert( 0, "Hello" );
  s.insert( 1492 );
  System.out.println( b );
}
```

```
class MySet extends ArraySet {
  StringBuffer label;
  public void insert( int i ) {
    label.insert( 0, "Surprise" );
    super.insert( i );
  }
}
```



Modifies Clauses

- In **modular programs**, not all locations that remain unchanged are known
- **Modifies clauses** specify which locations **may be modified** by a method
- Locations **not mentioned** in the modifies clause **must remain unchanged**

```
// requires !has( i )
// ensures has( old( i ) )  &&
//    ∀j: old( has( j ) ) ⇒ has( j )
// modifies array[ next ], next,
//                    array
public void insert( int i ) {
  if ( next == array.length )
    resize( );
  array[ next ] = i;
  next++;
}
```

Example Revisited

```
// requires !has( i )
// ensures has( old( i ) )  &&
//  ∀j: old( has( j ) ) ⇒ has( j )
// modifies array[ next ], next, array
public void insert( int i ) { … }
```

```
void foo( Set s, StringBuffer b ) {
  b.insert( 0, "Hello" );
  s.insert( 1492 );
  System.out.println( b );
}
```

```
class MySet extends ArraySet {
  StringBuffer label;
  public void insert( int i ) {
    label.insert( 0, "Surprise" );
    super.insert( i );
  }
}
```

- **Behavioral subtyping:** Subtype methods have to satisfy modifies clauses of overridden supertype methods

Semantics of Modifies-Clauses

- Each method m may **modify**
  - **Locations mentioned in its modifies clause**
  - **Locations of newly allocated objects**

- All other locations have to be left unchanged
  - Temporary modifications are possible

Modifies Clauses: Example

```
// modifies array[ next ], next,
//                 array
public void insert( int i ) {
  if ( next == array.length )
    resize( );
  array[ next ] = i;
  next++;
}
```

```
// modifies array
private void resize( ) {
    int[ ] tmp = new int[ array.length + 10 ];
    System.arraycopy( array, 0, tmp, 0,
                                        array.length );
    array = tmp;
}
```

- insert modifies directly
  - this.array[this.next], this.next
- insert modifies indirectly via invocation of resize
  - this.array
  - Locations of newly allocated array

Problems of Modifies Clauses

- Enumerating modifiable locations **violates information hiding**
- Enumerating modifiable locations **does not work for interfaces**

```
class ArraySet implements Set {
  private int[ ] array;
  private int next;
  // modifies array[ next ], next, array
  public void insert( int i ) { … }
  …
}
```

```
interface Set {
  // modifies ??
  public void insert( int i );
}
```

Extended State Problem

- **Behavioral subtyping** requires subtype methods to satisfy modifies clauses of supertype methods

```
class ArraySet implements Set {
  private int[ ] array;
  private int next;

  // modifies array[ next ], next, array
  public void insert( int i ) { … }
  …
}
```

- **But:** subtype methods must have the right to modify the **extended state**

```
class MaxSet extends ArraySet {
  private int max;

  public void insert( int i ) {
    if ( i > max ) max = i;
    super.insert( i );
}
```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Abstraction: Wildcards

- Frame properties have to be specified in an **abstract** way
- Wildcard * represents **all fields of an object** (independent of the declaration class)
- Works with information hiding, interfaces, and extended state

```
class Tuple {
  private int a, b;
  // modifies this.*
  public void setFirst( int i ) { a = i; }
}
```

```
class BackupTuple extends Tuple {
  private int ba, bb;
  // modifies this.*
  public void setFirst( int i ) {
    ba = a;
    a = i;
  }
}
```

Problem: Imprecision

- **Missing precision** can be compensated (partly) by **additional postconditions**
  - Private postconditions

```
class Tuple {
  private int a, b;

  // modifies this.*
  // private ensures b == old( b )
  public void setFirst( int i ) { a = i; }
}
```

Problem: Imprecision

- **Missing precision** can be compensated (partly) by **additional postconditions**
  - Private postconditions
  - Getter methods
- Subclasses have to **strengthen inherited specification**
  - Even if method is not overridden

```
class Tuple {
  private int a, b;
  // modifies this.*
  // ensures getB( ) == old( getB( ) )
  public void setFirst( int i ) { a = i; }
}
```

```
class BackupTuple extends Tuple {
  private int ba, bb;
  // ensures bb == old( bb )
  public void setFirst( int i )
    { ba = a; a = i; }
}
```

Strengthening Postconditions

```
class Tuple {
  private int a, b;

  // modifies this.*
  // ensures b == old( b )
  public void setFirst( int i )
    { a = i; m( ); }

  // modifies this.*
  // ensures b == old( b )
  public void m( ) { }
}
```

```
class BackupTuple extends Tuple {
  private int ba, bb;


  // ensures bb == old( bb )
  public void setFirst( int i )
    { ba = a; super.setFirst( i ); }



  public void m( ) { bb = bb + 1; }
}
```

- Calling supertype methods on subtype objects may still lead to imprecise frame properties
- Further reading: K.R.M. Leino: *Data groups: Specifying the modification of extended state*

Problem: Object Structures

- **Object structures** can be handled through ownership

- Right to modify o.* includes to modify all objects owned by o

```
class ArraySet implements Set {
  private int[ ] array;
  private int next;
  // modifies array[ next ], next, array
  public void insert( int i ) { … }
  …
}
```

Problem: Object Structures

- **Object structures** can be handled through ownership
- Right to modify o.* includes to modify all objects owned by o

```
class ArraySet implements Set {
  rep private int[ ] array;
  private int next;

  // modifies this.*
  public void insert( int i ) { … }
  …
}
```

11. Interface Specifications

Object Invariants

- Object invariants describe **consistency criteria** for objects
- **Invariants** have to hold in all states, in which an object can be accessed by other objects

```
class ArraySet implements Set {
  private int[ ] array;
  private int next;

  // invariant array != null      &&
  //    0 <= next <= array.length

  public void insert( int i ) {
    if ( next == array.length )
      resize( );
    array[ next ] = i;
    next++;
  }
 …
}
```

Assuming Invariants

- Methods **assume the invariant of this** to hold in the prestate
- Methods **assume the invariants of all allocated objects** to hold in the prestate

```
  // requires !has( i )
  public void insert( int i ) {
    if ( next == array.length )
      resize( );
    array[ next ] = i;
    next++;
  }
```

```
class Client {
  ArraySet as;
  // requires !as.has( 5 )
  public void foo( ) {
    as.insert( 5 );
  }
}
```

Semantics of Invariants

- Invariants of all allocated objects have to **hold in pre- and poststates** of all method (and constructor) executions
  - but can be temporarily violated in between

```
class Redundant {
  private int a, b;
  // invariant a == b
  public void set( int v ) {
    // all invariants hold
    a = v;
    // invariant of this violated
    b = v;
    // all invariants hold
  }
}
```

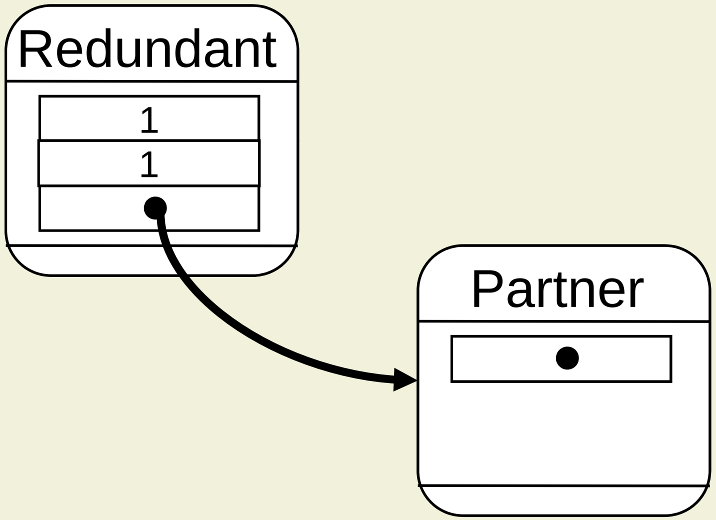
Checking Invariants

- For every method, **assume the invariants of all allocated objects in the prestate**
  - For constructors, exclude **this**
- For every method (and constructor), **prove** that all **invariants that are possibly violated** by the body hold (again) in the **poststate**
  - Vulnerable invariants depend on encapsulation
- Example: very strong encapsulation
  - Suppose invariants depend only on state of **this**
  - Suppose methods update only fields of **this**
  - Obligation: Prove invariant of **this** in poststate

Problem: Callbacks

```
class Redundant {
  private int a, b;
  private Partner p;
  // invariant a == b
  public void set( int v ) {
    a = v;
    p.foo( );
    b = v;
  }
  public int div( int v )
    { return v / ( a – b – 1 ); }
}
```

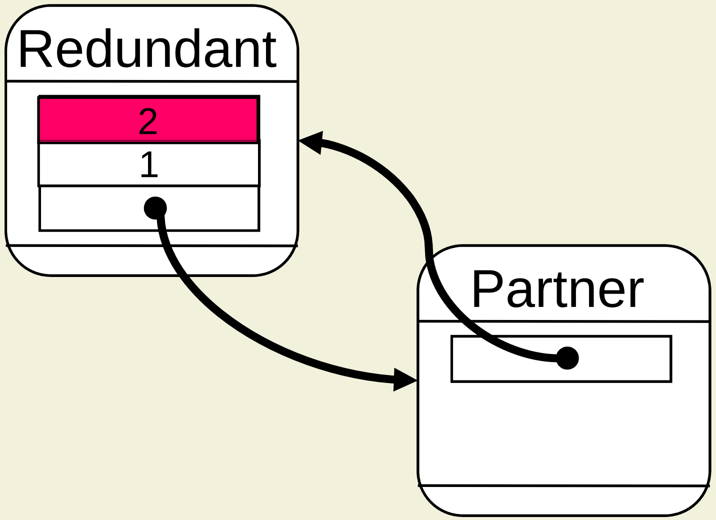
```
class Partner {

  public void foo( )
    { return 3; }
}
```



Problem: Callbacks

```
class Redundant {
  private int a, b;
  private Partner p;
  // invariant a == b
  public void set( int v ) {
    a = v;
    p.foo( );
    b = v;
  }
  public int div( int v )
    { return v / ( a – b – 1 ); }
}
```

```
class Partner {
  private Redundant r;
  public void foo( )
    { return r.div( 5 ); }
}
```



Common Variations

- Self-calls

```
class Redundant {
  private int a, b;
  // invariant a == b

  public void set( int v )
    { a = v; this.div( 5 ); b = v; }

  public int div( int v )
    { return v / ( a – b – 1 ); }
}
```

- Re-entrant monitors

```
class Redundant {
  private int a, b;
  // invariant a == b
  public synchronized
                    void set( int v )
    { a = v; this.div( 5 ); b = v; }
  public synchronized
                    int div( int v )
    { return v / ( a – b – 1 ); }
}
```

Dealing with Callbacks

- **Check invariant before** every method **call**
  - Overly restrictive: most methods do not call back (sqrt)
  - Too expensive for runtime checking
- **Detect** possible **callback** statically
  - Check invariant before call only if callback is possible
  - Difficult: requires knowledge of executed code including subclass methods
- **Specify** in each precondition which **invariants** the method actually **requires**
  - Check required invariants before method call
  - High documentation overhead

Example: Version 1

```
class Redundant {
  private int a, b;
  private Partner p;
  // invariant a == b
  public void set( int v ) {
    a = v;
    p.foo( );
    b = v;
  }
  public int div( int v )
    { return v / ( a – b – 1 ); }
}
```

Check fails

Unclear whether callback is possible

```
class Partner {

  public int foo( )
    { return 3; }
}
```

Requires no invariants

- Solution 1 reports error
  - Invariant does not hold
- Solution 2 reports error
  - Subclass of Partner might introduce callback
- Solution 3 succeeds

Example: Version 2

```
class Redundant {
  private int a, b;
  private Partner p;
  // invariant a == b
  public void set( int v ) {
    a = v;
    p.foo( );
    b = v;
  }
  public int div( int v )
    { return v / ( a – b – 1 ); }
}
```

Check fails

Callback possible

```
class Partner {
  private Redundant ;
  public void foo( )
    { return r.div( 5 ); }
}
```

Requires invariant of **this** and r

- Solution 1 reports error
  - Invariant does not hold
- Solution 2 reports error
  - Callback depends on aliasing
- Solution 3 reports error

11. Interface Specifications

Repetition: Invariants and Aliasing

```
class ArrayList {
  private int[ ] array;
  private int next;

  // invariant array != null        &&
  //    0<=next<=array.length   &&
  //    ∀i.0<=i<next: array[ i ] >= 0

  public void add( int i )    { … }
  public void addElems( int[ ] ia )
   { array = ia; next = ia.length; }

  …
}
```

```
int foo( ArrayList list ) {
  // invariant of list holds
  int[ ] ia = new int[ 3 ];
  list.addElems( ia );
  // invariant of list holds
  ia[ 0 ] = -1;
  // invariant of list violated
}
```

- Aliases can be used to by-pass invariant check
- Strong encapsulation required

Semantics of Invariants Revisited

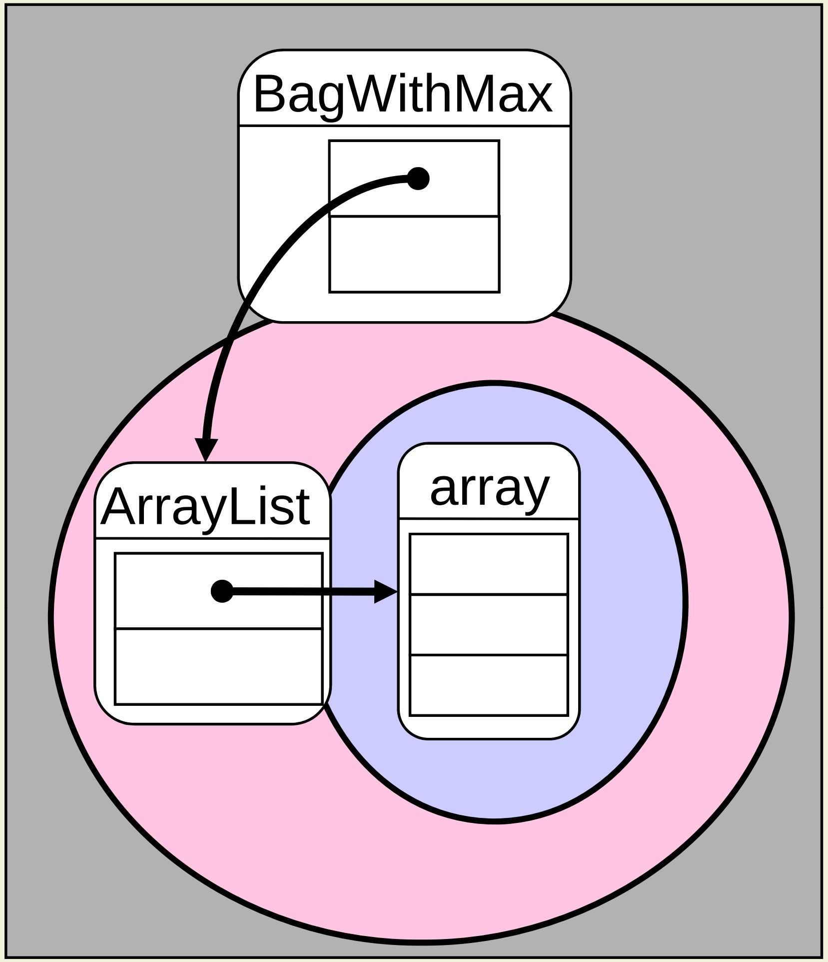
```
class ArrayList {
  // requires i>=0;
  public void add( int i ) { … }
  … }
```

- **Invariant** of BagWithMax **does not hold in** the **poststate** of call theList.add
- **Modularity problem:** BagWithMax not known when ArrayList is written

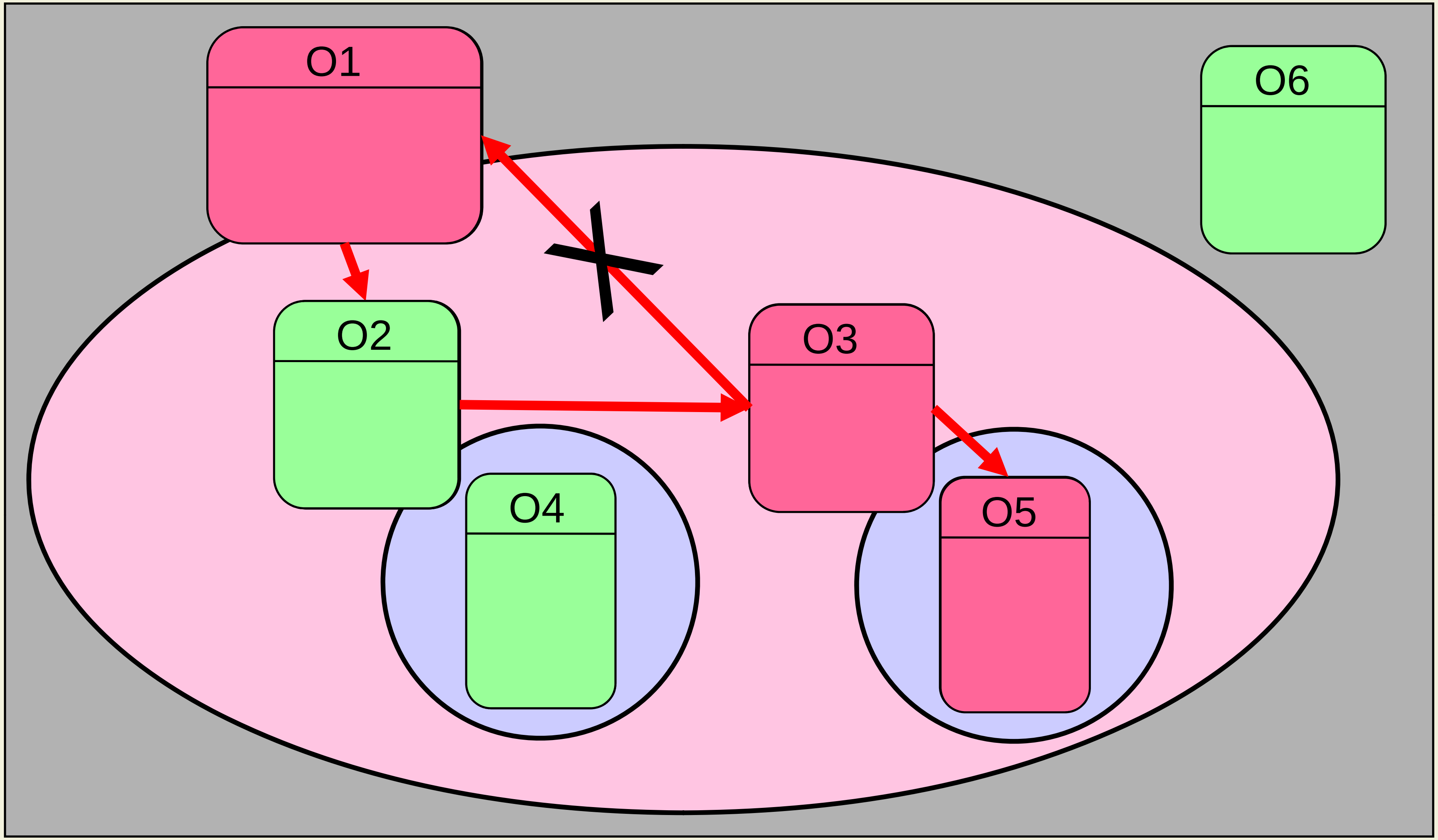
```
class BagWithMax {
  private rep ArrayList theList;
  private int maxElem;

  // invariant theList != null &&
  //       ( ∀i.0 <= i < theList.next ==>
  //       theList.array[ i ] <= maxElem )

  // requires i>=0
  public void insert( int i ) {
   theList.add( i );
   if ( i > maxElem )  maxElem = i;
  }
}
```

Refined Semantics

- Invariant may be broken while internal representation of an object is being modified
- Owned objects are part of the internal representation
- Exclude invariants of (transitive) owners from expected invariants

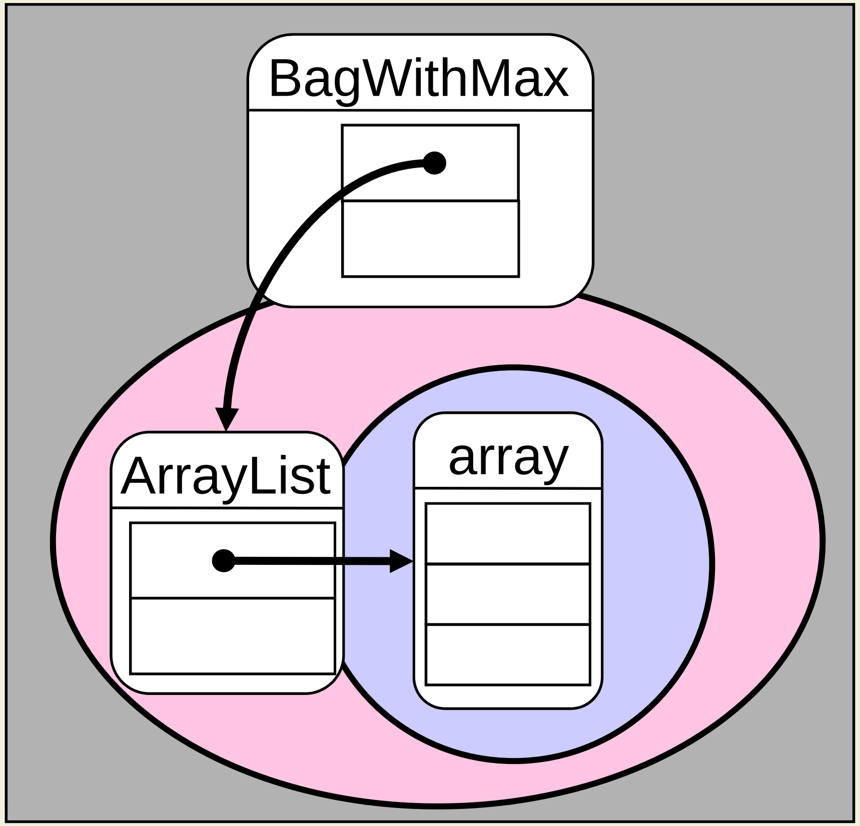


Refined Semantics: Example



Reasoning Idea

- Divide invariant check
  - A method's **implementor** is responsible for the objects in the context of the receiver
  - A method's **caller** is responsible for the objects in its context




```
class ArrayList {
  public void add( int i ) { … }
  … }
```

```
class BagWithMax {
  public void insert( int i ) {
    theList.add( i );
    if ( i > maxElem )  maxElem = i;
  }  … }
```

Checking Invariants for Object Structures

- The invariant of object X may depend on the state of X and of all objects (transitively) owned by X
- For every method, assume the invariants of **all objects transitively owned by owner of receiver** in the prestate
- For every method (and constructor), prove that all invariants that are possibly violated by the body **except for the (transitive) owners of receiver** hold (again) in the poststate **and before calls that might call back**

Example

```
class ArrayList {
  // requires i>=0;
  public void add( int i ) { … }
  … }
```

Check invariant of **this**

```
class BagWithMax {
  private rep ArrayList theList;
  private int maxElem;

  // invariant theList != null &&
  //        ( ∀i.0 <= i < theList.next ==>
  //        theList.array[ i ] <= maxElem )

  // requires i>=0
  public void insert( int i ) {
    theList.add( i );
    if ( i > maxElem )  maxElem = i;
  }
}
```

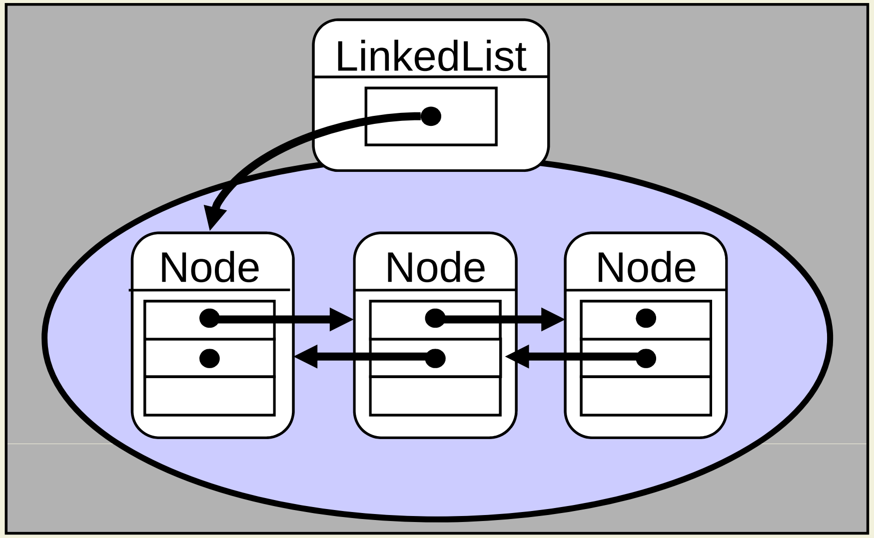
Admissible invariant

Invariant of **this** allowed to be broken

Check invariant of **this**

Limitations

- (Mutually) recursive data structures
  - No (mutual) ownership
  - Peer relationship
- Direct field access of peer objects
- Solution: check all vulnerable invariants of peer objects




```
class Node {
  peer Node next, prev;   int elem;
  // invariant next == null ||
  //               next.prev == this
  Node( int i, peer Node n ) {
    elem = i; next = n;
    if ( n != null ) n.prev = this;
  }
  ... }
```

Informal Guidelines

- Organize your system in layers
- A method execution should only modify objects in the same or underlying layers and only call methods in those layers
- The invariant of an object X should only depend on the state of objects in the layer that contains X or underlying layers

Informal Guidelines (cont‘d)

- If the invariant of an object X depends on a field f of an object in the same layer (including X itself):
  - Make sure that every method that can assign to f preserves the invariant of X before it terminates or calls a method on an object in L (including X itself)
- If the invariant of an object X in layer L depends on a field or an array element g in a deeper layer:
  - Make sure that every method execution on a receiver in layer L that modifies g is executed on receiver X and preserves the invariant of X before it terminates or calls a method on an object in L (including X itself)

Summary

- Frame properties
  - Crucial for program verification
  - Difficult to specify and prove (abstraction)
  - No good solution for runtime assertion checking
- Invariants
  - Semantics of invariants is non-trivial
  - Handling callbacks is difficult, especially for runtime assertion checking
  - Invariants of object structures require strong encapsulation