4. Object Structures, Aliasing, and Encapsulation

Collaboration remark:

The following slides are partly taken from the lecture „Konzepte objektorientierter Programmierung“ by Prof. Peter Müller (ETH Zürich).

Overview:

- Object Structures and Aliasing
- Immutability
- Alias Control and Encapsulation

Motivation:

- Understand the possible collaborations of objects
- Object systems need structure and control

„Unless objects are conceptually allowed to contain other objects in their entirety, there is little hope to master complexity in a pure object-oriented approach. ... It is, therefore, and quite paradoxically, nontrivial to introduce the notion of components into object systems."

[David Luckham et al.]

4.1 Object Structures and Aliasing

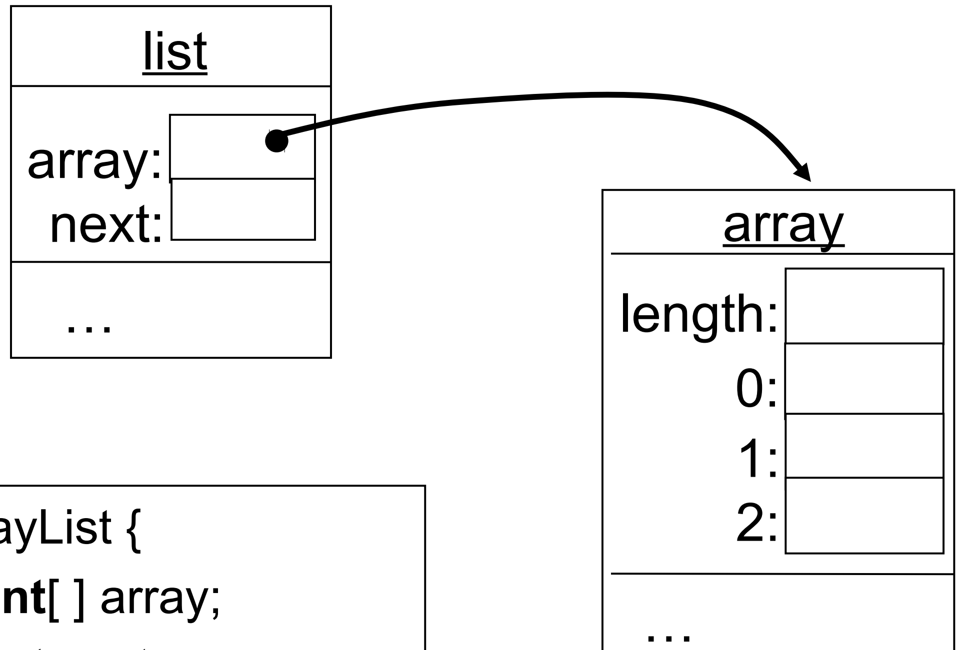
- Objects are the basic building blocks of object-oriented programming.
- However, interesting system components and program abstractions are almost always provided by sets of cooperating objects.

Explanation: (Object structure)

An ***object structure*** (*Objektgeflecht*) is a set of objects that are connected via references.

Examples: (Object structures)

1. A very simple structure consisting of 2 objects:




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

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

  public void addElems(...)
    { … }
  …
}
```

2. A simple structure of several objects:

:LinkedList
header:
size: 3

: Entry
element:
next:
previous:

: Entry
element:
next:
previous:

: Entry
element:
next:
previous:

: Entry
element:
next:
previous:

... ...

3. More interesting object structures can e.g. be found in graphical user interfaces.

Problems:

- Structural integrity (→ structural invariants)
- Behavior and state of an object tightly depends on other objects.
- „Multiple references“ to one object (→ aliasing)

Explanation: (Aliasing in OO programming)

An object X is ***aliased*** if two or more variables hold references to X. A variable can be

- an instance variable
- a class or static variable (global variable)
- a local variable of a method incarnation, including the implicit parameter **this**
- a formal parameter
- the result of a method invocation or her intermediate expression results

Often such a variable is called an ***alias*** of X.

Aliasing is called ***static*** if all involved variables are instance or static variables, i.e. belong to the heap. Otherwise, it is called ***dynamic***.

Desirable Aspects of Aliasing:

- Consistent view to shared objects
- Multiple cursors/iterators into object structures
- Time and space efficiency

Examples: (Desirable aliasing)

1. Address objects that capture the address of a person or institution:
   - Several objects may reference an address *A*.
   - If *A* is modified, the referencing objects keep a consistent and up-to-date view.
2. Consider a complex tree or graph structure:
   - The structure can be traversed by several iterators.
   - Cursors can point to nodes of current interest.
3. Data structures can share objects (e.g. singly linked lists):
   - avoids to copy data structures when they are enlarged or reduced in size;
   - saves a lot of memory space.

Undesirable Aspects of Aliasing:

1. Side-effects may become difficult to understand and control
2. Inconsistent access to objects
3. Aliases allow to by-pass interface operations
4. Optimizations and formal techniques become more complex

Examples: (Undesirable aliasing)

1. Violation of invariants through aliases:
   - A set class uses a list class to implement the collection. Invariant: no duplicates.
   - Alias to the list can lead to invariant violation.

2. Inconsistent access:
   - An algorithm reads in different steps the attributes of an address object *X* (name, street, town).
   - Someone else modifies *X* while the algorithm reads its information.

3. By-passing interfaces:

Security breach in Java JDK 1.1.1:

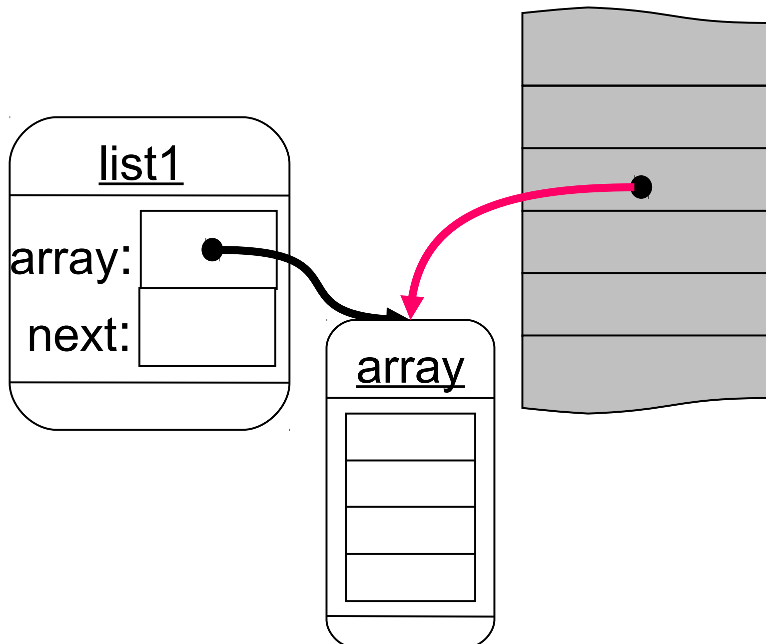
- Each Class-object stores array of signers
- Only trusted signers get extended access rights to the host system
- Through *leaking* of the array of signers, a malicious applet can modify the list of signers to get extended rights
- Again, access modifiers cannot prevent the problem, because arrays are mutable

```
private Identity[ ] signers;
…
public Identity[ ]
getSigners( ) {
    return signers;
}
```

Forms of Alias Creation:

Capturing:

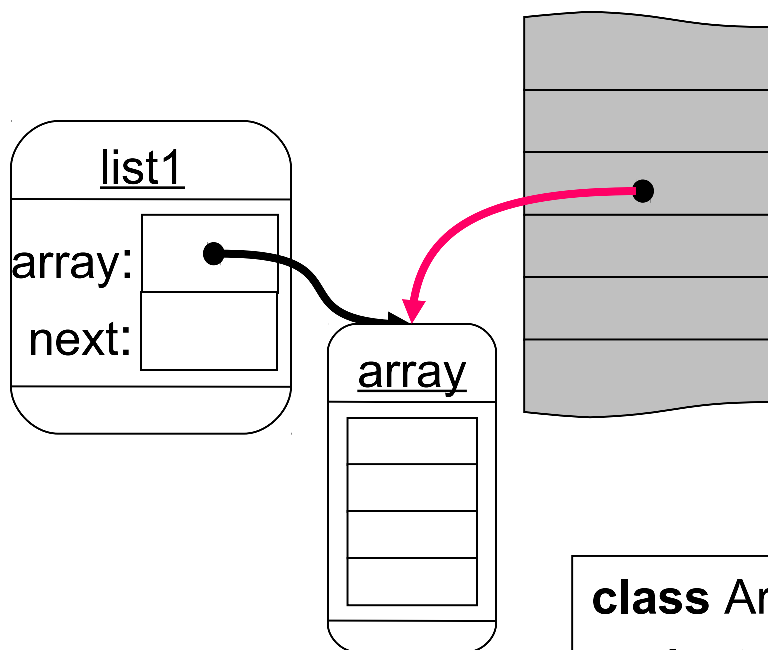
- Capturing occurs when objects are **passed to a data structure and then stored** by the data structure.
- Capturing often occurs **in constructors** (e.g., streams in Java).
- Problem: Alias can be used to **by-pass interface** of data structure.




```
class ArrayList {
  private int[ ] array;
  private int next;
  public void addElems( int[ ] ia )
    { array = ia; next = ia.length; }
  …
}
```

Leaking:

- Leaking occurs when data structure **passes a reference** to an object which is **supposed to be internal** to the outside
- Leaking **often** happens **by mistake.**
- Problem: Alias can be used to **by-pass interface** of data structure.




```
class ArrayList {
  private int[ ] array;
  private int next;
  public int[ ] getElems( )
    { return array; }
  …
}
```

General approaches to solve alias problems:

- Support aliasing, but disable modifications (avoids undesirable aspects (1.), (2.) and (4.) from above)
- Control aliasing and access

4.2 Immutability

Referential transparency means that the holder of an object reference *R*

- does not have to care about aliases of *R*,
- in particular, cannot observe whether aliases of *R* exist (by using *R*).

Techniques to achieve referential transparency:

- immutability
- uniqueness

Assumption:

To keep the following definitions simpler, we assume that reading and writing to instance variables of an object *X* can only be done by methods of *X*'s class (possibly inherited methods).

That is, objects can only be observed by method invocation.

Explanation: (Immutability)

We assume that equality for the primitive types is defined by „==“ and for reference types by some reasonably defined method `equals`.

An object *X* is called *(observationally)* ***immutable*** if after termination of its constructor call any two invocations

X.m(p1,...,pn) and *X.m(q1,...,qn)*

with *pi* equals *qi* $(1 \leq i \leq n)$ either

- yield equal results or
- throw equal exceptions or
- both do not terminate.

A *class* C is called *immutable* if all instances of C in any program execution are immutable.

Remark:

- Immutability is usually defined by prohibiting state changes and dependency of „external“ state.
- About 660 concrete classes in Java‘s standard library are immutable (about 20%)

Examples: (Immutability)

1. Immutable class:

```
class ImmutableList {
  private int head;
  private ImmutableList tail;

  boolean isempty(){ return tail == null; }

  int head(){
    if( isempty() )
       throw new NoSuchElementException();
    return head;
  }
  ImmutableList tail(){
    if( isempty() )
      throw new NoSuchElementException();
    return tail;
  }
  ImmutableList cons( int i ) {
    ImmutableList aux = new ImmutableList();
    aux.head = i;
    aux.tail = this;
    return aux;
  }
  boolean equals( Object that ) {
    ...
  }
}
```

Objects of class ImmutableList are immutable for an appropriate method `equals`.

```
class ImmutableList {  // continued
  ...
  boolean equals( Object that ) {
    if( that == null ||
        !(that instanceof ImmutableList )
      return false;
    ImmutableList tl = (ImmutableList) that;
    if( isempty() ) {
      return that.isempty();
    } else if( that.isempty() ) {
      return false;
    } else {
      return ( this.head == that.head )
           &&  tail().equals( that.tail() );
    }
  }
}
```

2. Immutability and inheritance:

   There may be scenarios in which objects *of type* ImmutableList are not immutable:

```
...
static boolean somemethod( ImmutableList il )
{
   if( !il.isempty() ) {
      return il.head() == il.head();
   } else return true;
}
```

```
class NotImmutableList extends ImmutableList
{
   private boolean flag;

   boolean isempty(){ return false; }

   int head(){
      flag = !flag;
      if( flag ){
         return 7;
      } else return 9;
   }

   ImmutableList cons( int i ) {
      return new NotImmutableList();
   }
}

...
ImmutableList il = new NotImmutableList();
il.cons(7).cons(9);
System.out.println( somemethod(il) );
...
```

The example demonstrates that

→ subclasses can breach immutability.

3. Immutable objects must not depend on global variables:

```
class Global {
   public static int a = 5;
   public static int getA(){
      return a;
   }
}

class Immutable2 {
   public int alwaysTheSame() {
      return Global.getA();
   }
}
```

Immutable2-objects are not immutable!

The example demonstrates that

→ mutability can depend on global state.

4. Immutable objects with varying I/O-behavior:

```
final class Immutable3 {
    private int state;
    public int alwaysTheSame() {
        System.out.println(state++);
        return 47;
    }
}
```

5. Immutable objects where state changes can make sense:

   Typical example: Initialization of instance variables on demand, i.e., not by the constructor, but prior to first use.

Techniques for Realizing Immutability:

Immutability is implemented using different techniques:

- Access and inheritance restrictions
- Immutable state (local and reachable state)
- Prohibition of access to global state (direct or via methods)

Sufficient criteria for immutability of an object *X*:

- Instance variables of *X* cannot be modified after termination of its constructor.
- X is not exposed during construction.
- Objects referenced by *X* are immutable according to these criteria.
- Constructors can only take immutable objects as parameters.
- Methods do not depend on global variables, i.e.,
  - They do not access global variables.
  - They do not invoke methods that depend on global variables.
- Methods do not create new objects.

Remarks:

- The above criteria are still difficult to check:
  - It is difficult to show that no modifications can occur.
  - Inheritance has to be controlled.
- Classes like String are (almost) immutable, although they modify the state and do not satisfy the above criteria.
- Restricted forms of immutability can be checked by tools.

4.3 Alias Control and Encapsulation

Explanation: (Alias control, encapsulation)

Techniques for ***alias control*** avoid or alleviate alias problems by preventing certain forms of aliasing and by guaranteeing structural invariants.

Implementation techniques for alias control are:

- Alias modes
- Access restrictions
- Read-only references/methods
- Encapsulation

Encapsulation techniques structure the state space of executing programs in a way that allows

- to guarantee data and structural consistency by
- establishing *boundaries*/*capsules* with well-defined

interfaces.

Alias control and encapsulation techniques are another approach to reduce aliasing problems:

1. Side-effects are simpler to control.
2. Consistent access to objects can be achieved.
3. By-passing of interface operations can be avoided

Overview:

- Notions of alias control
- Type-based encapsulation

4.3.1 Notions of Alias Control

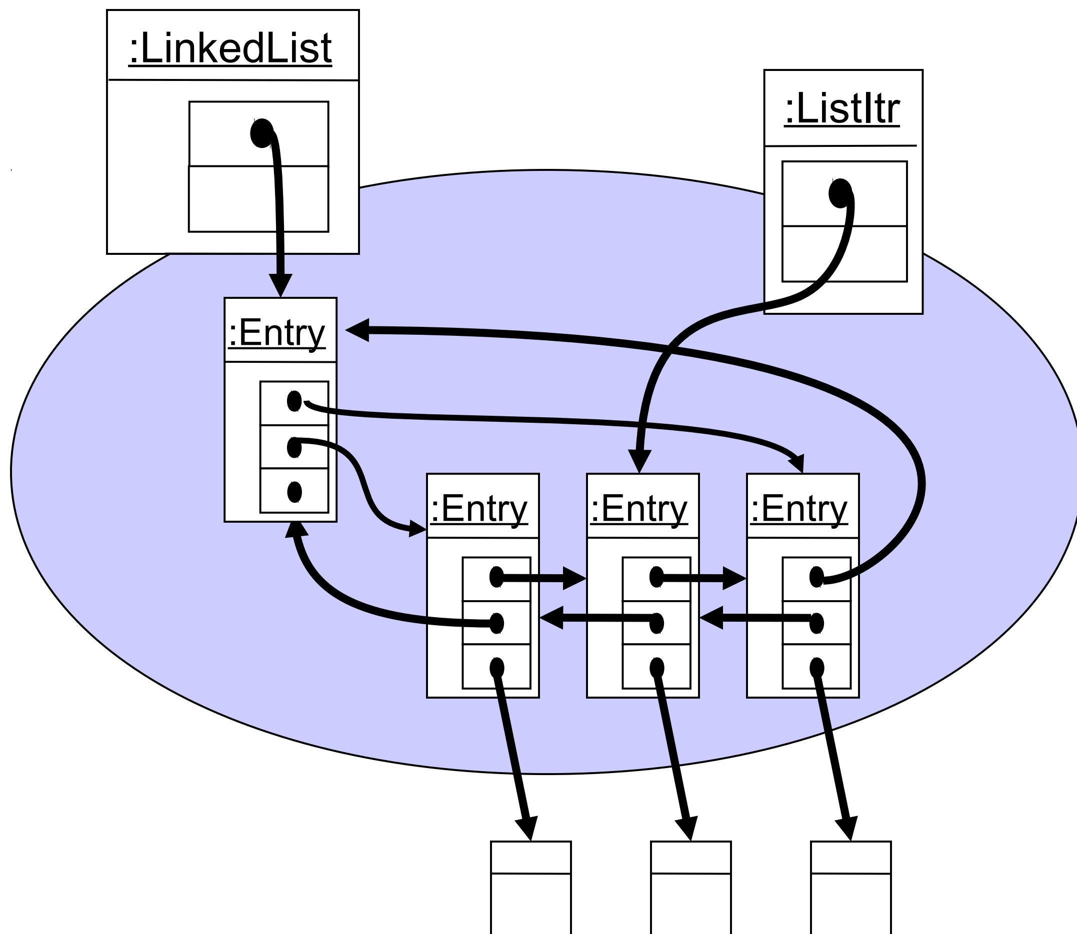
We need **better control** over the objects in an object structure to avoid aliasing problems.

Approach: ***Alias modes***:

- Define **roles** of objects in object structures
- Assign a tag (**alias mode**) to every expression to indicate the role of the referenced object
- Impose **programming rules** to guarantee that objects are only used according to their alias modes

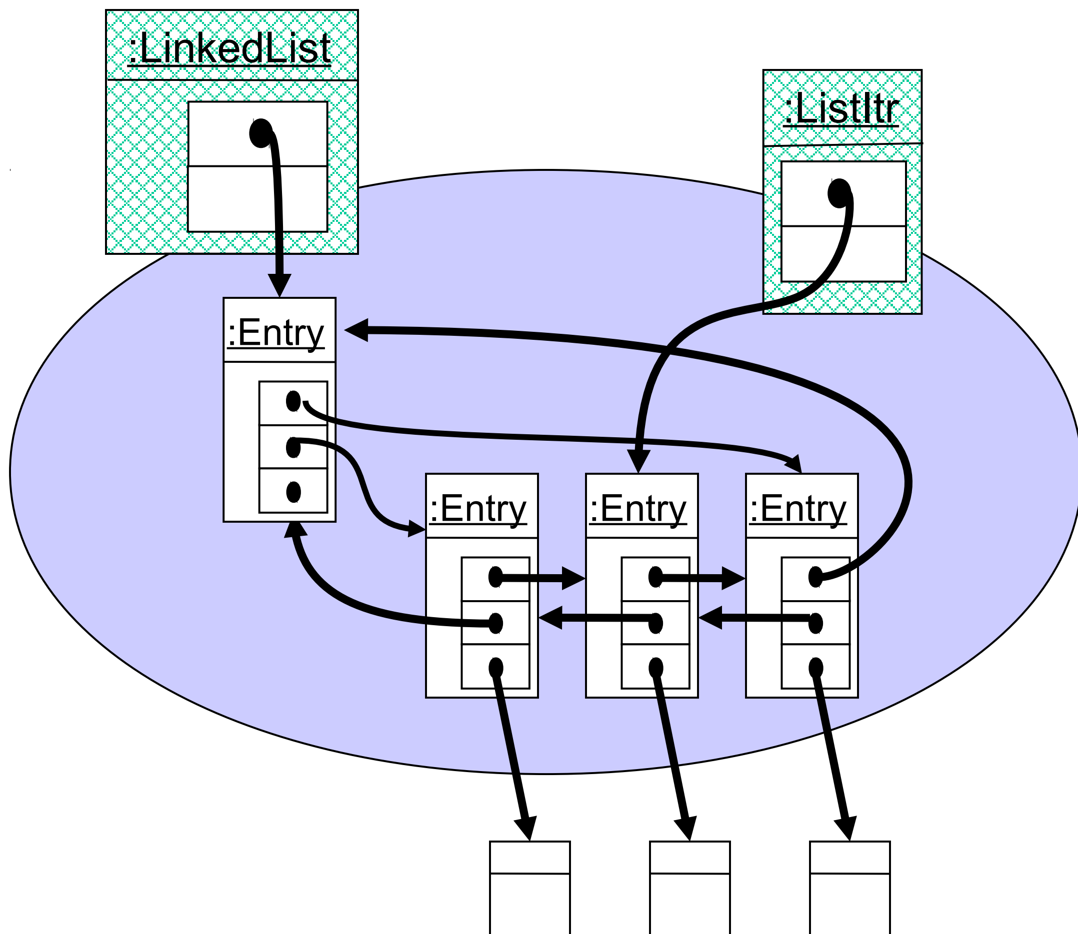
Roles in Object Structures:

- **Interface objects** that are used to access the structure
- Internal **representation** of the object structure
- **Arguments** of the object structure



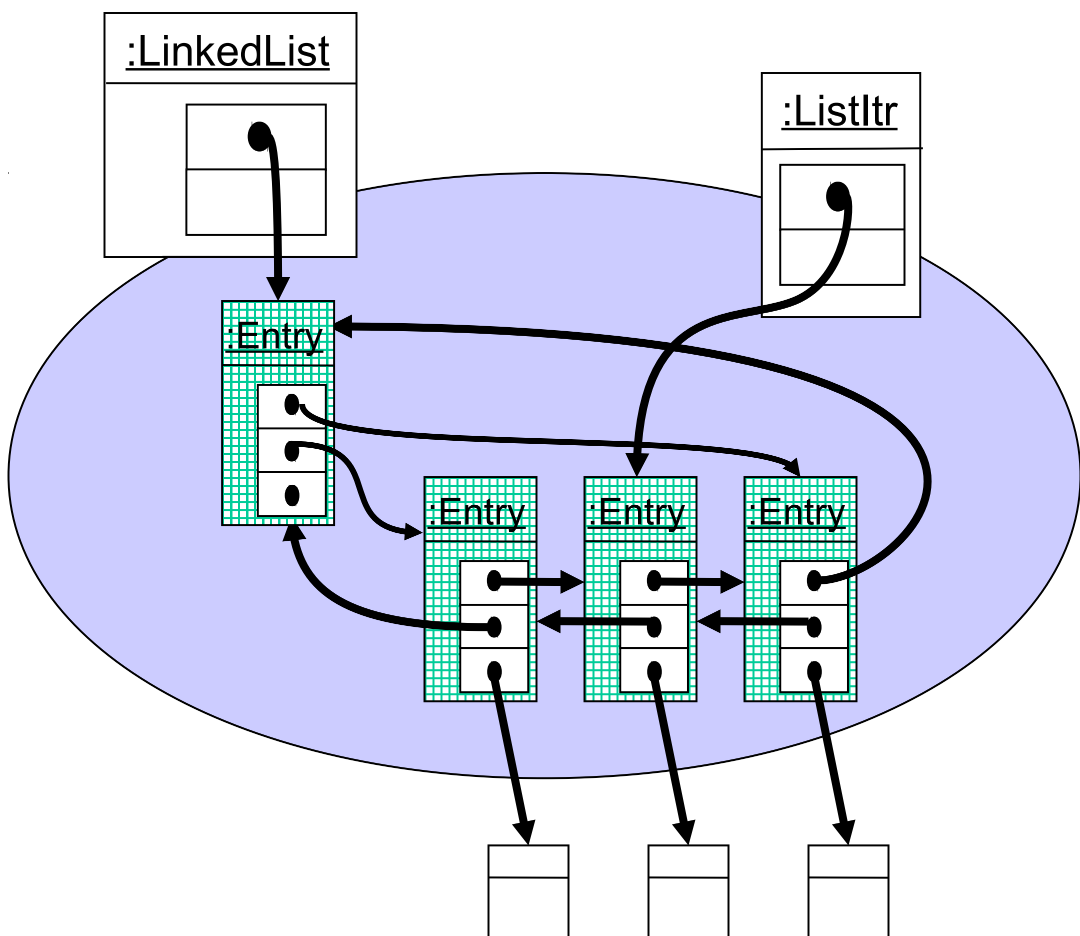
1. Interface objects (default mode):

- Interface objects are used to **access the structure**
- Interface objects can be **used in any way** objects are usually used (passed around, changed, etc.)



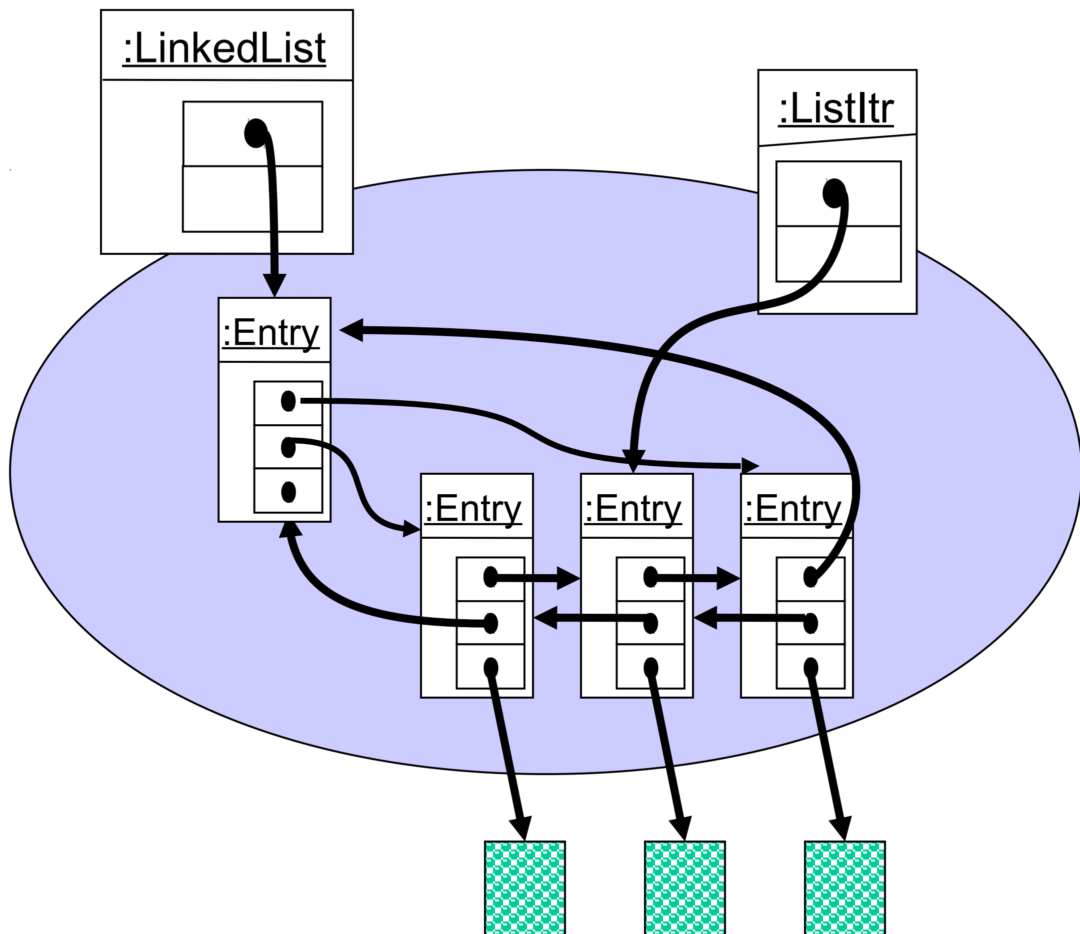
2. Representations (rep mode):

- Expressions with mode “rep” hold references to the **representation** of the object structure
- Objects referenced by rep-expressions can **be changed**
- Rep-objects **must not be exported** from the object structure



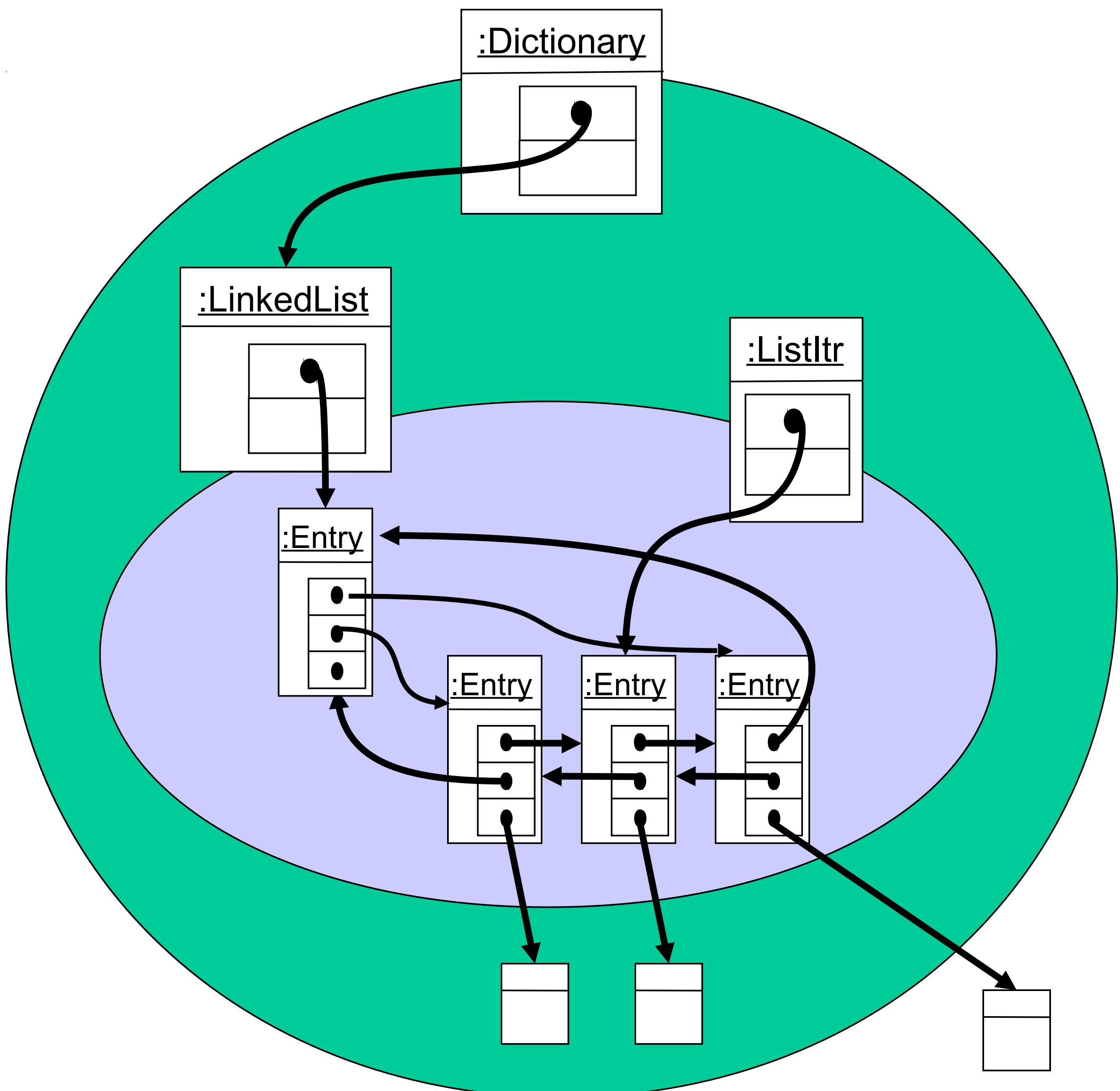
3. Arguments (arg mode):

- Expressions with mode “arg” hold references to **arguments** of the object structure.
- Objects **must not be changed** through arg-references.
- Arg-objects can be **passed around** and aliased freely.



Meaning of alias modes:

- Alias modes describe the role of an object relative to an interface object
- Informally: references with
  - **default mode** stay in the same bubble
  - **rep-mode** go from an interface object into its bubble
  - **arg-mode** may go to any bubble.



Example: (Alias modes as annotations)

In programs, alias modes can be expressed by comments/annotations tagging types:

```
class LinkedList {
  private /* rep */ Entry header;
  private int size;

  public void add( /* arg */ Object o ) {
    /* rep */ Entry newE  =
          new /* rep */ Entry( o, header, header.previous );
    … }
}
```

```
class Entry {
  private /* arg */ Object element;
  private Entry previous, next;

  public Entry( /* arg */ Object o, Entry p, Entry n ) { … }
}
```

Programming Discipline (simplified):

Rule 1: No role confusion

- Expressions with one alias mode must not be assigned to variables with another mode

Rule 2: No representation exposure

- rep-mode must not occur in an object's interface
- Methods must not take or return rep-objects
- Fields with rep-mode may only be accessed on **this**

Rule 3: No argument dependence

- Implementations must not depend on the state of argument objects

The following examples illustrate these rules.

Example: (Role confusion)

- Array is **internal representation** of the list
- Method addElems **confuses alias modes**

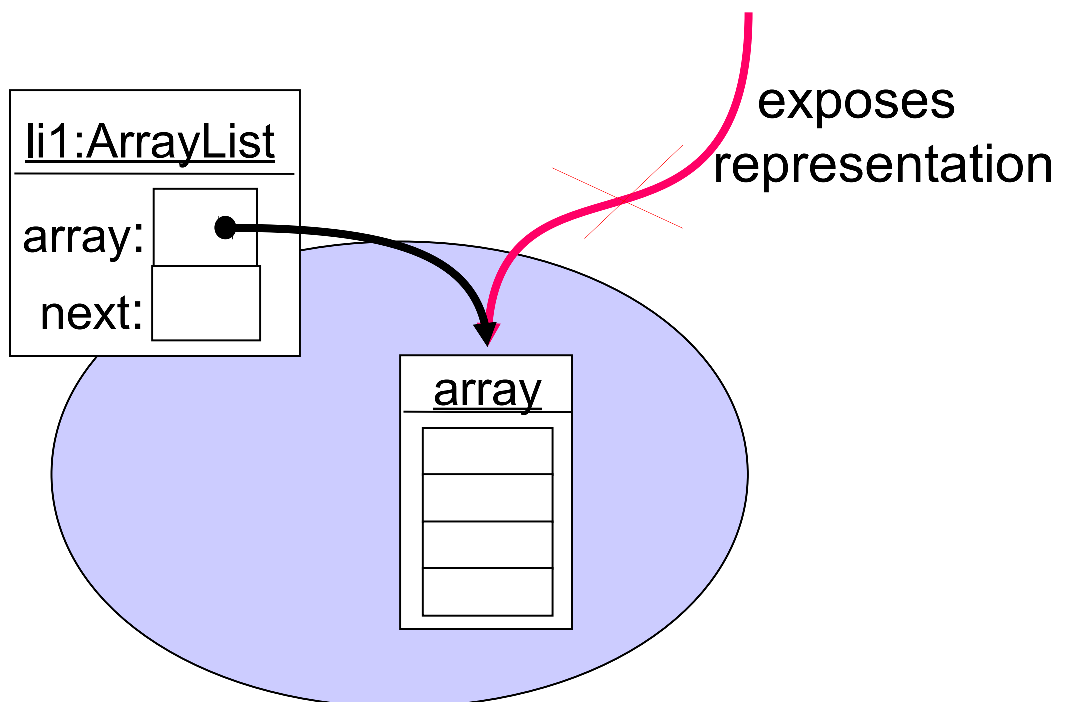
```
class ArrayList {
  private /* rep */ int[ ] array;
  private int next;

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

Clean solution requires **array copy:**

```
 public void addElems( int[ ] ia ) {
    array = new /* rep */ int[ ia.length ];
    System.arraycopy (ia, 0, array, 0, ia.length );
    next = ia.length;
  }
```

Example: (Representation exposure)

- Rep-objects can only be referenced
  - by their interface objects
  - by other rep-objects of the same object structure
- Rep-objects can only be modified
  - by methods executed on their interface objects
  - by methods executed on rep-objects of the same object structure
- Rep-objects are **encapsulated** inside the **object structure**



Example: (Argument dependencies)

```
class Task {
   int prio;
   ...
}

class PriorityQueue {

  Vector tasks = new Vector();

  /*@ invariant
    @  (\forall int i,j;
    @     0<=i && i<j && j<tasks.size();
    @       tasks.get(i).prio <=
    @            tasks.get(j).prio     );
    @*/

  void insertTask(/*arg*/ Task t ){...}

  Task nextTask(){
     return
      (Task) tasks.get(tasks.size()-1);
} }
```

`PriorityQueue` depends on the `prio`-attribute of the `Task`-arguments.

Modifying the attribute could violate the invariant of priority queues and cause malfunction of `nextTask`.

4.3.2 Type-based Encapsulation

Type systems can be used to guarantee encapsulation invariants:

- Encapsulation at the package level: *confined types*
- Further structuring techniques

Encapsulation at the Package Level:

Goal:

Guarantee that objects of particular type can only be accessed and manipulated by the classes of one package.

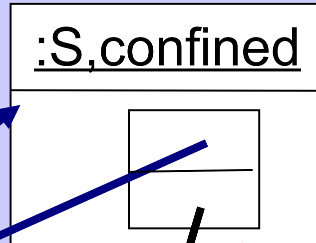
Approach:

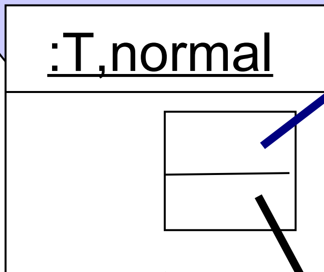
1. Consider a package P as a capsule containing the objects of the classes in P. The capsules are disjoint.
2. Mark a type T (interface/class) of P as *confined* if objects of type T should only be manipulated by program code in P. We say as well that these objects are confined.
3. Define rules guaranteeing that references of confined objects of P are only stored in instance variables, parameters and local variables of objects of P.

outside P

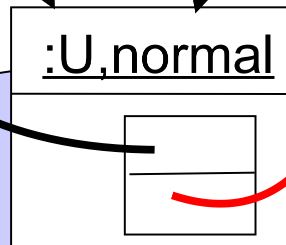
package P

inside P





encapsulation error



package Q

Connection with type systems:

- Each variable gets as extended type information:
  - the package to which it belongs (implicit)

- Each object gets as extended type information:
  - the package to which it belongs (implicit)
  - information whether confined or normal

- Encapsulation errors (analogous to type errors) occur if a variable *v* of package *P* references a confined object *X* of a package *Q* different from *P*. Invariant:

If *v* references some confined *X*, then *v* and *X* belong to the same package.

- Encapsulation errors are excluded by statically checkable rules (analogous to type conditions/rules).

We consider an extension to Java by confined types:

J. Vitek, B. Bokowski: Confined types in Java.
Software: Practice & Experience, 31(6):507-532, 2001.

Remark:

The study of the encapsulation rules is of general interest for the development of OO-programs.

Scenarios in which references are exported (1-6):

```
package inside;

public class C extends outside.B {

      public void putReferences() {
        C c = new C();
/*1*/   outside.B.c1 = c;
/*2*/   outside.B.storeReference(c);
/*3*/   outside.B.c3s = new C[]{c};
/*4*/   calledByConfined();
/*5*/   implementedInSubclass();
/*6*/   throw new E();
      }

      public void implementedInSubclass(){}
/*7*/ public static C f = new C();
/*8*/ public static C m(){ return new C();}

/*9*/ public static C[] fs
                        = new C[]{new C()};

/*10*/ public C() { }
}

public class E extends RuntimeException{}
```

Scenarios in which references are imported (7-10):

```
package outside;

public class B {
/*1*/ public static inside.C c1;
/*2*/ public static void storeReference(
                              inside.C c2){
           // store c2
       }
/*3*/  public static inside.C[] c3s;
/*4*/  public void calledByConfined(){
            // store this
       }
       static void getReferences() {
/*7*/    inside.C c7 = inside.C.f;
/*8*/    inside.C c8 = inside.C.m();
/*9*/    inside.C[] c9s = inside.C.fs;
/*10*/   inside.C c10 = new inside.C();
         D d = new D();
         try {
             d.putReferences();
/*6*/    } catch (inside.E ex) {
            // store ex
         }
      }
}
class D extends inside.C {
/*5*/ public void implementedInSubclass(){
         // store this
}     }
```

Explanation: (confined, anonymous)

A type is called ***confined***

- if it is declared with the keyword `confined` or
- if it is an array type with a confined component type.

A set of methods and constructors can be declared as ***anonymous*** if the following properties hold:

A1: The reference `this` can only be used for accessing fields and calling anonymous methods of the current instance or for object reference comparison.

A2: Anonymity of methods and constructors must be preserved when overriding methods.

A3: Constructors called from an anonymous constructor must be anonymous.

A4: Native methods may not be declared anonymous.

Remark:

- The behavior of anonymous methods only depends on the actual parameters and the values of the instance variables of the implicit parameter.

- Anonymous methods cannot introduce new aliases to the current receiver object.

- Anonymous methods allow confined types to use methods inherited from normal supertypes.

Static Encapsulation Rules:

The following rules **guarantee** the encapsulation:

Confinement in declarations:

C1: A confined class or interface must not be declared public and must not belong to the unnamed global package.

C2: Subtypes of a confined type must be confined.

Preventing widening:

C3: Widening of references from a confined type to an unconfined type is forbidden in assignments, method call arguments, return statements, and explicit casts.

C4: Methods invoked on a confined object must either be non-native methods defined in a confined class or be anonymous methods.

C5: Constructors called from the constructors of a confined class must either be defined by a confined class or be anonymous constructors.

Preventing transfer from the inside and outside:

C6: Subtypes of java.lang.Throwable and java.lang.Thread must not be confined.

C7: The declared type of public and protected fields in unconfined types must not be confined.

C8: The return type of public and protected methods in unconfined types must not be confined.

Further Structuring Techniques:

Different structuring techniques have been discussed in the literature in the last years.
Often cited techniques:

- Balloon types:

  P. S. Almeida: Balloon Types: Controlling Sharing of State in Data Types. ECOOP ’97.

- Ownership:

  D. G. Clarke, J. M. Potter, J. Noble: Ownership Types for Flexible Alias Protection. OOPSLA ’98.

  Simple Ownership Types for Object Containment. ECOOP ’01.

  P. Müller, A. Poetzsch-Heffter: A Type System for Controlling Representation Exposure in Java. Formal Techniques for Java Programs ‘00.

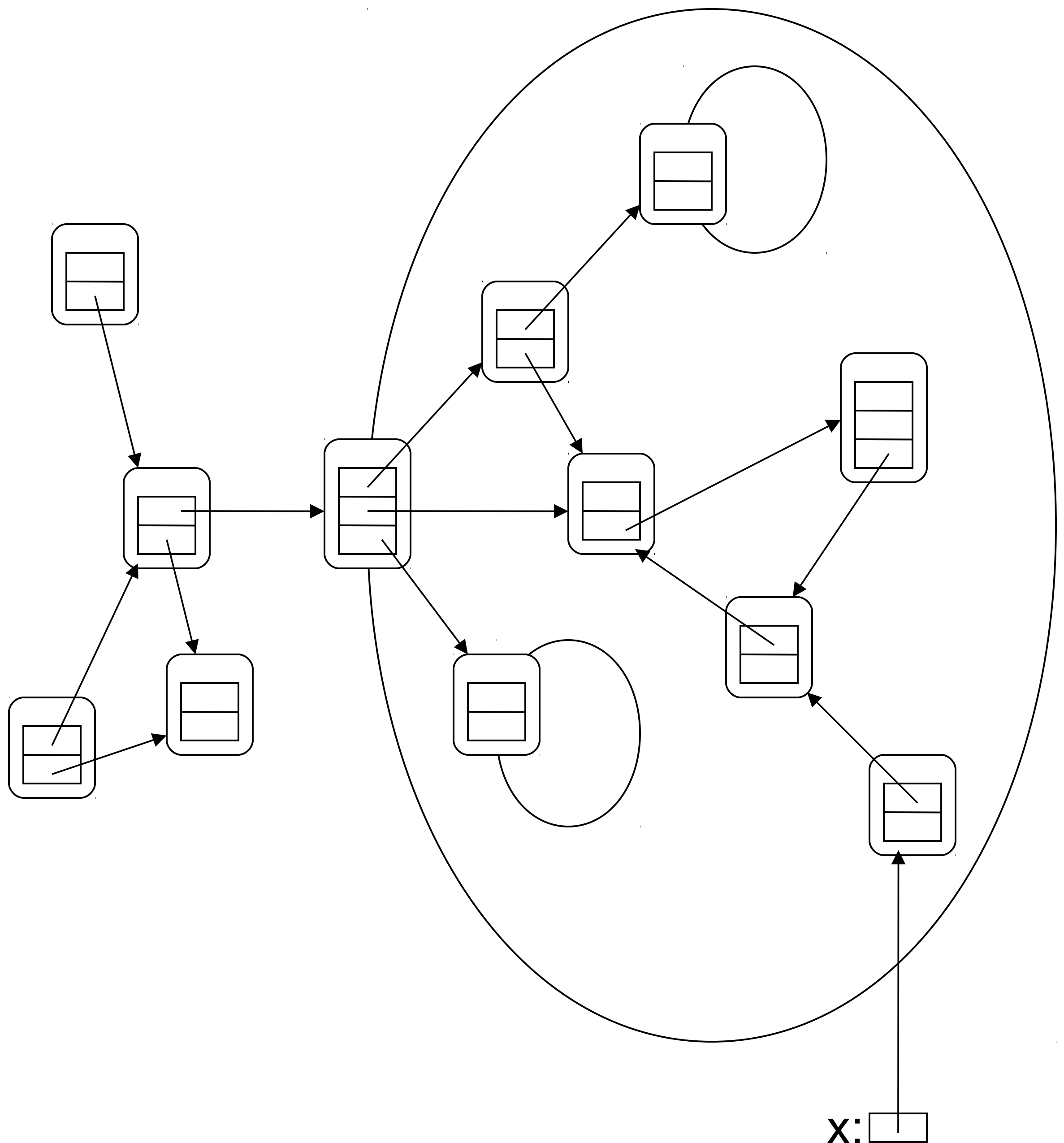
Other approaches are:

- Preventing aliasing
- Write protection and readonly modes

Balloon types:

A type can be marked as balloon type.
Objects of balloon types are called b*alloon objects*.

Idea:



Cluster:

Let G be the undirected graph with

- all objects as nodes and
- all references between non-balloon objects and from balloon objects to non-balloon objects as edges.

A ***cluster*** is a connected subgraph of G which is not contained in a larger connected subgraph.

Internal objects:

An object O is said to be *internal* to a balloon object B if and only if:

- O is a non-balloon object in the same cluster as B or
- O is a balloon object referenced by B or by some non-balloon object in the same cluster as B or
- there exists a balloon object B‘ internal to B and O is internal to B‘.

External objects:

An object is said to be *external* to a balloon object B iff it is neither B nor internal to B.

Balloon invariant:

If B is an object of a ballon type then:

- B is referenced by at most one instance variable.
- If such a stored reference exists it is from an object external to B.
- No object internal to B is referenced by any object external to B.

Remark:

- The invariant allows that objects referenced only by dynamic aliases reference internal objects. Such objects are internal to the balloon.

  That is why a balloon B can contain more objects than just the set of all objects reachable from B.

- To guarantee the balloon invariant, Almeida uses the following techniques:
  - Assignment of references to instance variables of balloon objects is not always allowed.
  - Data flow analysis

Ownership:

Idea:

- Introduce an ownership relation between objects:
  object X owns object Y.

- Define encapsulation based on ownership:

  Only the owner may directly access his objects.

- Declare the ownership relation as extended type information.

Example: (Ownership annotations)

```
class Engine {
  void start() { ... }
  void stop() { ... }
}

class Driver { ... }

class Car {
  rep Engine engine;  // belongs to representation
  Driver driver;      // not part of representation
  Car() {
    engine = new rep Engine();
    driver = null;
  }
```

```
  rep Engine getEngine() { return engine; }
  void setEngine( rep Engine e){ engine=e; }
  void go () {
    if(driver!=null) engine.start();
  }
}

class Main  {
  void  main() {
    Driver bob = new Driver();   // root owner
    Car car = new Car();         // root owner
    car.driver = bob;
    car.go();

    car.engine.stop();           // fails
    car.getEngine().stop();      // fails

    rep Engine e = new rep Engine();
    car.setEngine(e);            // fails
  }
}
```

The ***ownership relation*** is a binary relation between objects where objects are either normal objects or the special owner `root`.

The owner of an object X is determined when X is created:

- If X is created by new T(), then `root` is the owner.
- If X is created by new rep T(), then the current receiver object will be the owner of X.

<u>Ownership invariant:</u>

All reference paths from a global object, that is, an object owned by root, to some object X with owner B go through B.

<u>Remark</u>:

- Ownership invariant is more general than the balloon invariant. It allows references to leave the set of owned objects.

- The ownership relation in the described form is still quite restrictive, as it only allows one owner.

- Recently, a number of different ownership models have been developed and investigated.