

Concepts of Object-Oriented Programming

Peter Müller

Chair of Programming Methodology

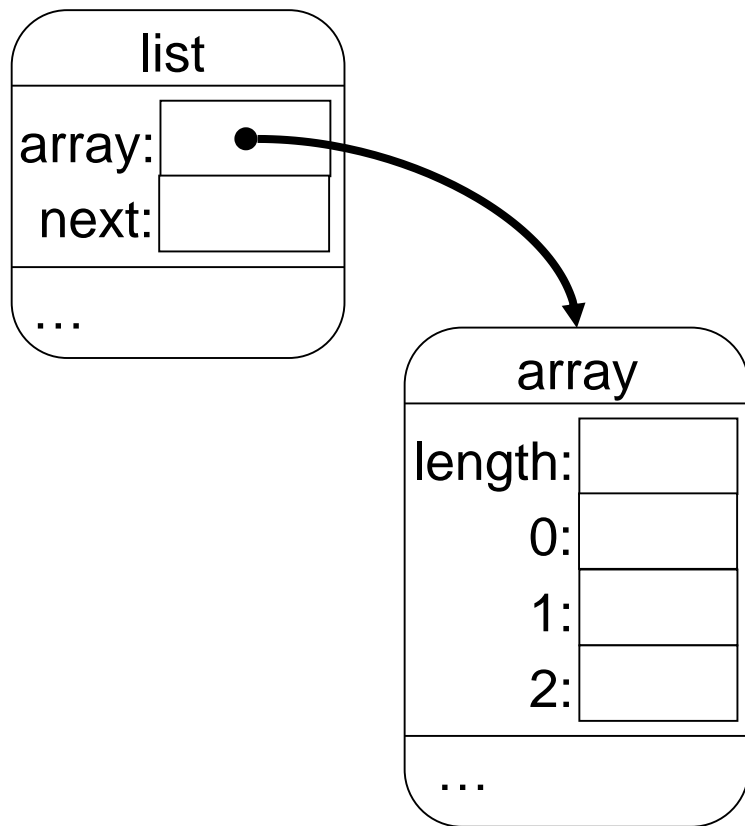
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ETH zürich

Object Structures

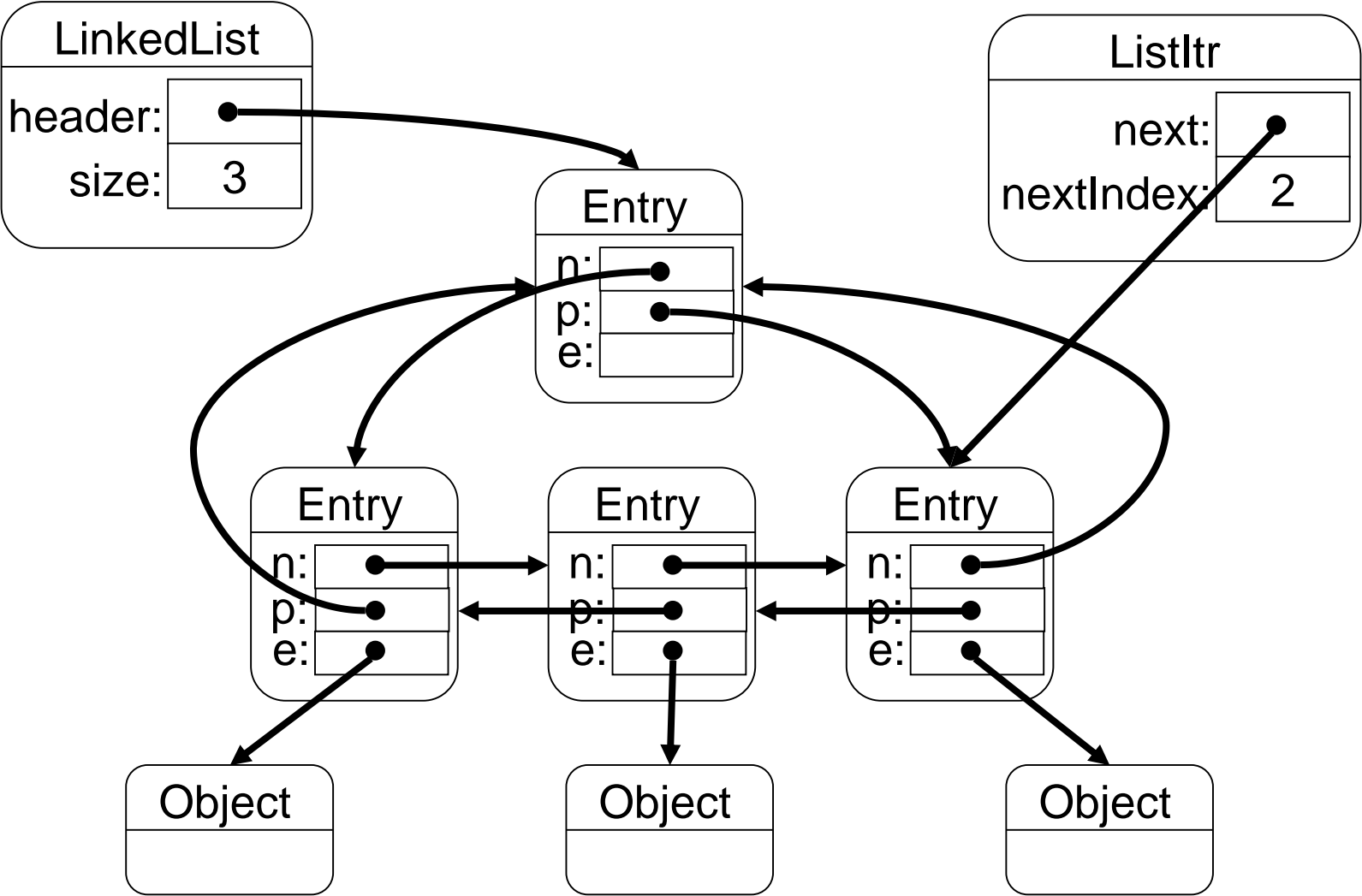
- Objects are the building blocks of object-oriented programming
- However, interesting abstractions are almost always provided by sets of cooperating objects
- Definition:
An object structure is a set of objects that are connected via references

Example 1: Array-Based Lists



```
class ArrayList {  
    private int[ ] array;  
    private int next;  
  
    public void add( int i ) {  
        if (next==array.length) resize( );  
        array[ next ] = i;  
        next++;  
    }  
  
    public void setElems( int[ ] ia )  
        { ... }  
  
    ...  
}
```

Example 2: Doubly-Linked Lists



6. Object Structures and Aliasing

6.1 Aliasing

6.2 Problems of Aliasing

6.3 Readonly Types

6.4 Ownership Types

Alias

- Definition:

A name that has been assumed temporarily

[WordNet, Princeton University]

Aliasing in Procedural Programming

```
program aliasTest
procedure assign( var p: int, var q: int );
begin

    p := 25;

end;
begin
    var x: int := 1;
    assign( x, x );

end
end.
```

Aliasing in Procedural Programming

- var-parameters are passed **by reference** (call by name)
- Modification of a var-parameter is observable by caller

```
program aliasTest
procedure assign( var p: int, var q: int );
begin

    p := 25;

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```
program aliasTest
procedure assign( var p: int, var q: int );
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end;
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end.
```

Aliasing in Procedural Programming

- var-parameters are passed **by reference** (call by name)
- Modification of a var-parameter is observable by caller
- Aliasing: **Several variables** (here: p, q) refer to **same memory location**
- Aliasing can lead to **unexpected side-effects**

```
program aliasTest
procedure assign( var p: int, var q: int );
begin

    p := 25;

end;
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Aliasing in Procedural Programming

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```
program aliasTest
  procedure assign( var p: int, var q: int );
  begin
    { p = 1  $\wedge$  q = 1 }
    p := 25;
    { p = 25  $\wedge$  q = 25 }
  end;
  begin
    var x: int := 1;
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```

Aliasing in Object-Oriented Programming

- Definition:

An object o is aliased if two or more variables hold references to o .

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- Variables can be

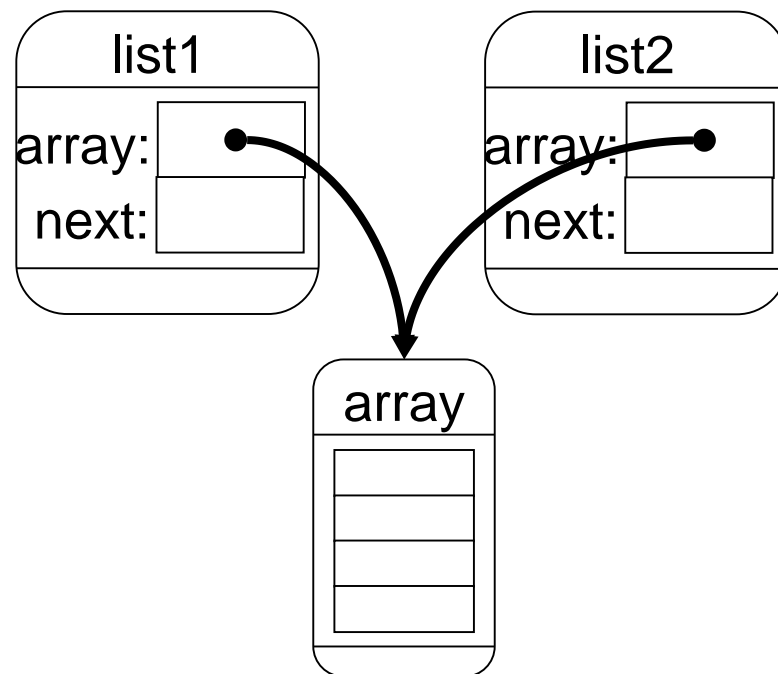
- Fields of objects (instance variables)
- Static fields (global variables)
- Local variables of method executions, including **this**
- Formal parameters of method executions
- Results of method invocations or other expressions

Static Aliasing

- Definition:

An alias is static if all involved variables are fields of objects or static fields.

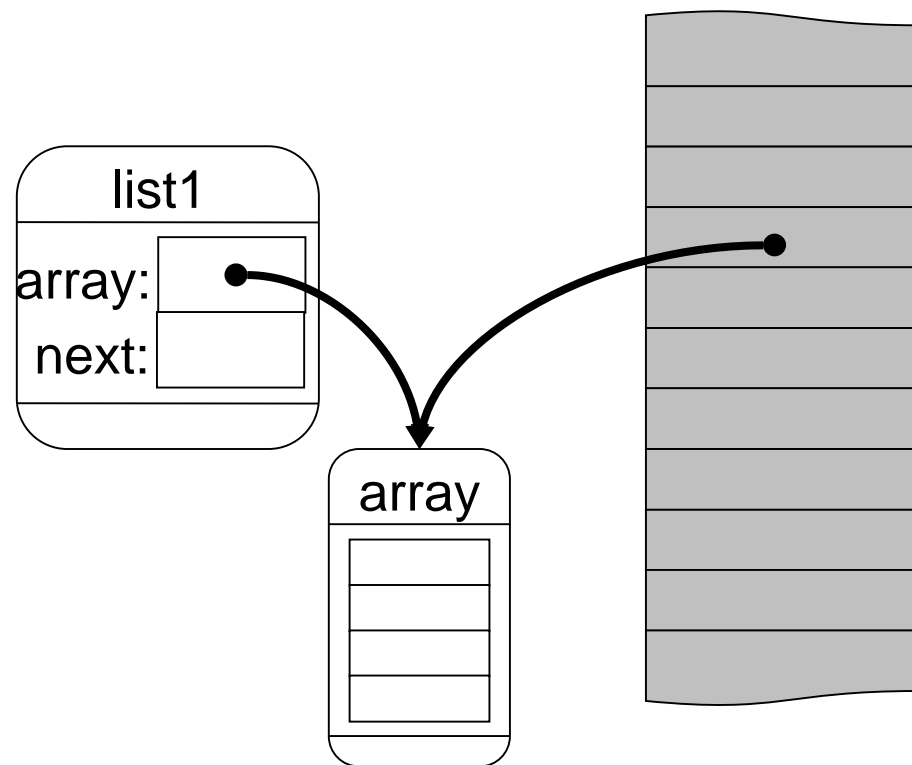
- Static aliasing occurs in the heap memory



```
list1.array[ 0 ] = 1;  
list2.array[ 0 ] = -1;  
System.out.println( list1.array[ 0 ] );
```

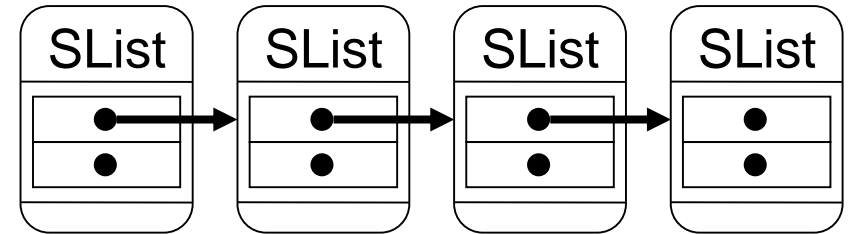
Dynamic Aliasing

- Definition:
An alias is dynamic if it is not static.
- Dynamic aliasing involves stack-allocated variables



```
int[ ] ia = list1.array;  
list1.array[ 0 ] = 1;  
ia[ 0 ] = -1;  
System.out.println( list1.array[ 0 ] );
```

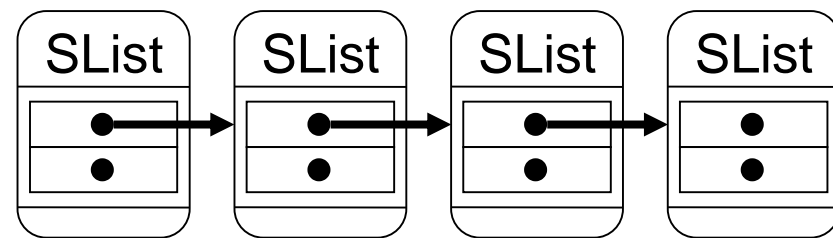
Intended Aliasing: Efficiency



```
class SList {  
    SList next;  
    Object elem;  
    SList rest( ) { return next; }  
    void set( Object e ) { elem = e; }  
}
```


Intended Aliasing: Efficiency

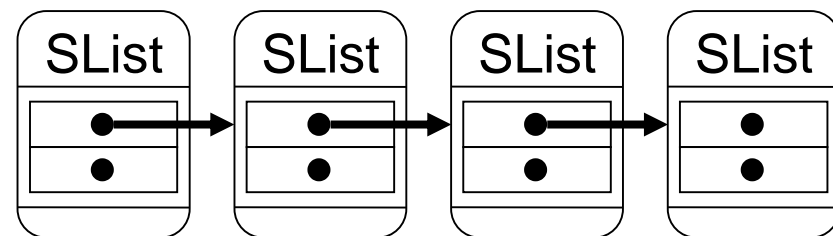
- In OO-programming, data structures are usually **not copied** when passed or modified
- Aliasing and **destructive updates** make OO-programming efficient



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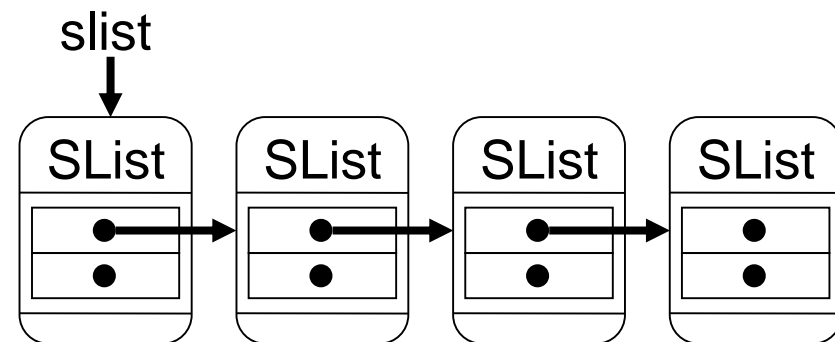


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```
void foo( SList slist ) {  
    SList rest = slist.rest( );  
    rest.set( "Hello" );  
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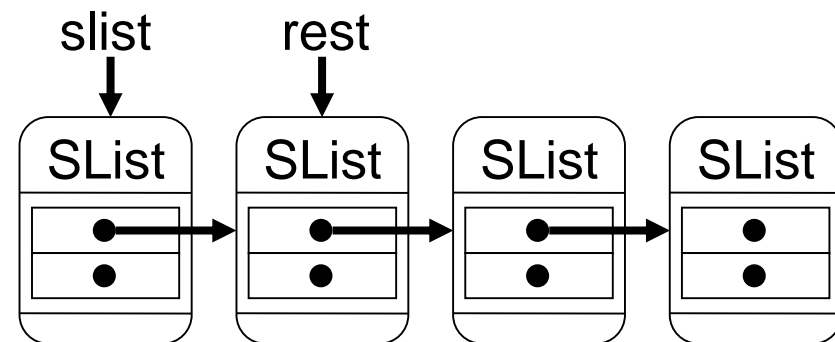


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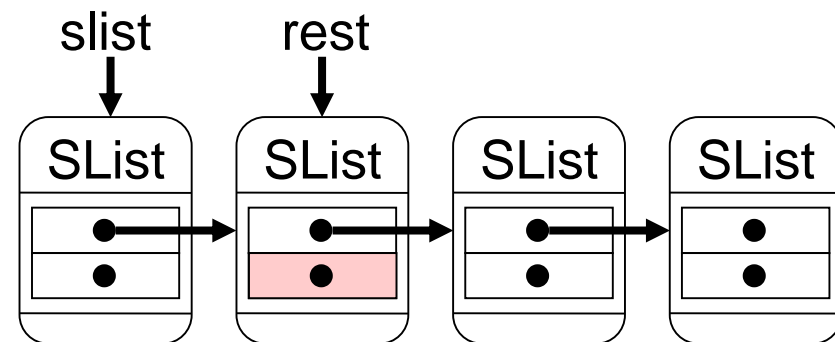
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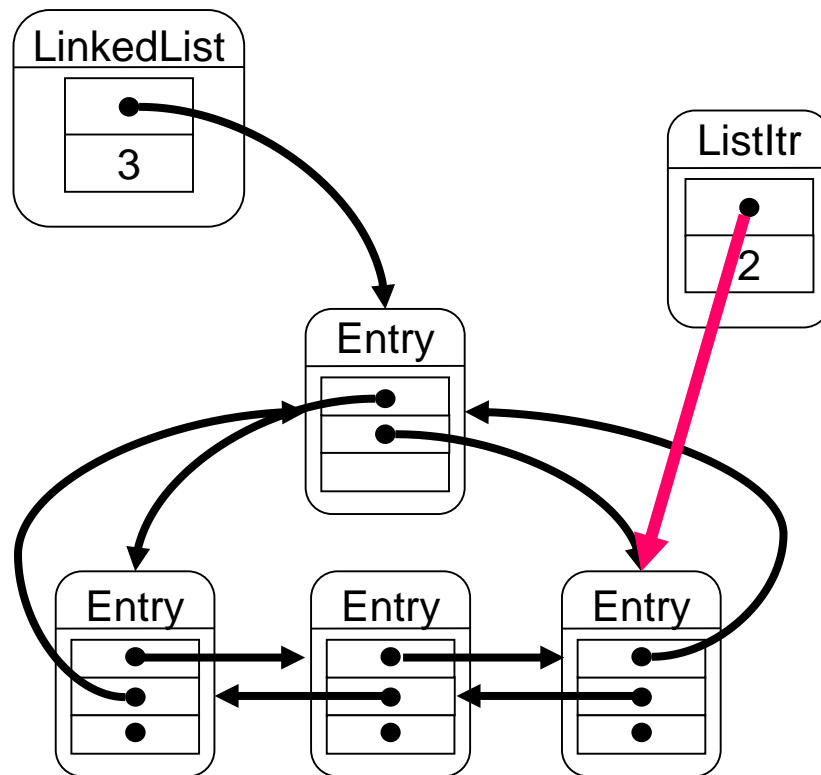


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```

Intended Aliasing: Sharing

- Aliasing is a direct **consequence of object identity**
- Objects have **state** that can be modified
- Objects have to be **shared** to make modifications of state effective



Unintended Aliasing: 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

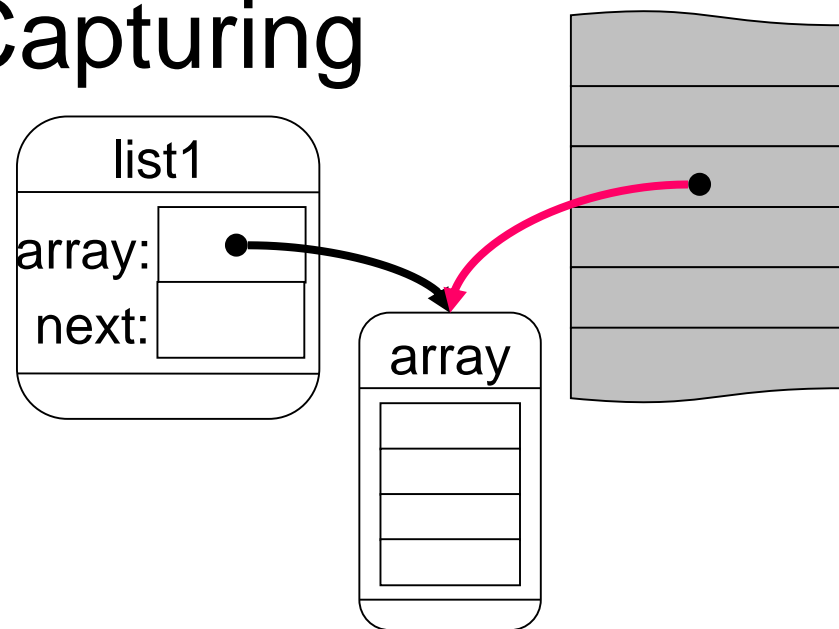
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```
class ArrayList {  
    private int[ ] array;  
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    public void setElems( int[ ] ia )  
        { array = ia; next = ia.length; }  
    ...  
}
```


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Unintended Aliasing: Leaking

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- Leaking **often** happens **by mistake**
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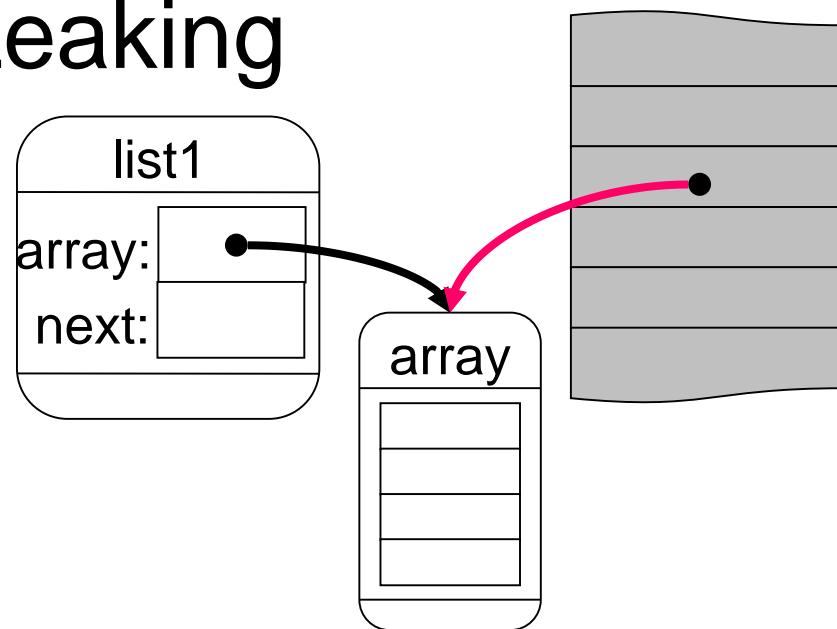
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```
class ArrayList {  
    private int[ ] array;  
    private int next;  
    public int[ ] getElems( )  
        { return array; }  
    ...  
}
```

Unintended Aliasing: Leaking

- Leaking occurs when data structure **pass a reference** to an object, which is **supposed to be internal** to the outside
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6. Object Structures and Aliasing

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6.3 Readonly Types

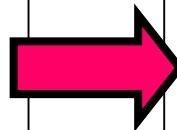
6.4 Ownership Types

Observation

- Many **well-established techniques** of object-oriented programming work for individual objects, but **not for object structures in the presence of aliasing**
- “*The big lie of object-oriented programming is that objects provide encapsulation*” [Hogg, 1991]
- Examples
 - Information hiding and exchanging implementations
 - Encapsulation and consistency

Exchanging Implementations

```
class ArrayList {  
  private int[ ] array;  
  private int next;  
  
  // requires ia != null  
  // ensures  $\forall i. 0 \leq i < \text{ia.length}:$   
  //           isElem( old( ia[ i ] ) )  
  public void setElems( int[ ] ia )  
    { array = ia; next = ia.length; }  
  
  ...  
}
```



```
class ArrayList {  
  private Entry header;  
  
  // requires ia != null  
  // ensures  $\forall i. 0 \leq i < \text{ia.length}:$   
  //           isElem( old( ia[ i ] ) )  
  public void setElems( int[ ] ia )  
    { ... /* create Entry for each  
              element */ }  
  
  ...  
}
```

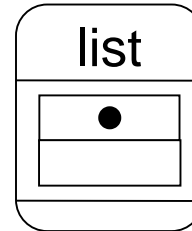
- Interface including contract remains unchanged

Exchanging Implementations (cont'd)

```
int foo( ArrayList list ) {  
    int[ ] ia = new int[ 3 ];  
    list.setElems( ia );  
    ia[ 0 ] = -1;  
    return list.getFirst( );  
}
```

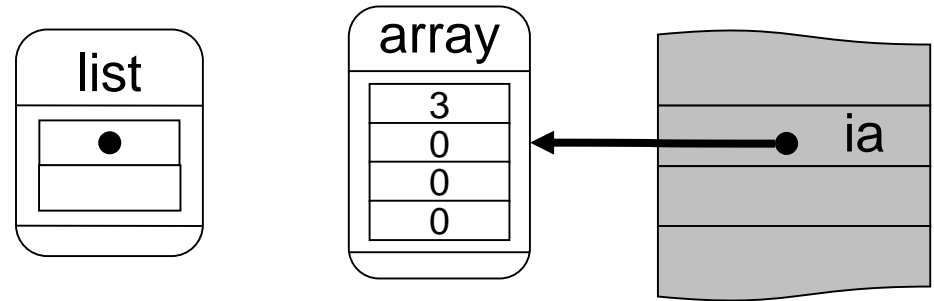

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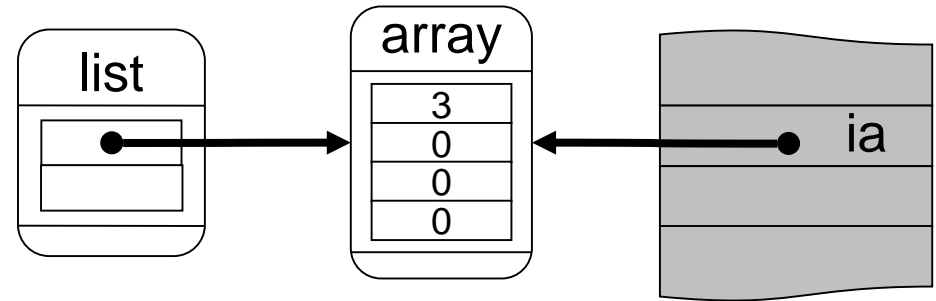
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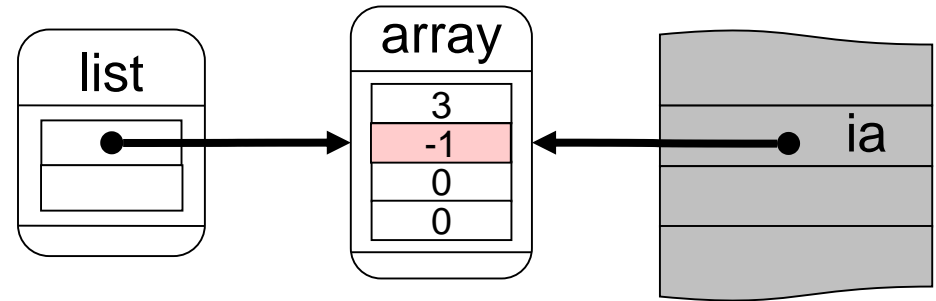
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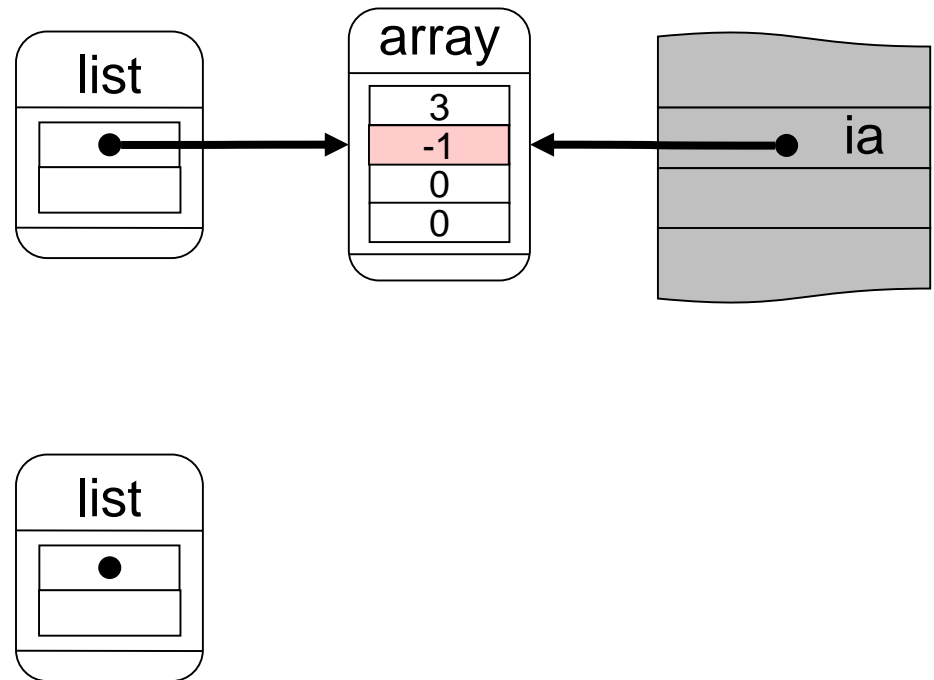
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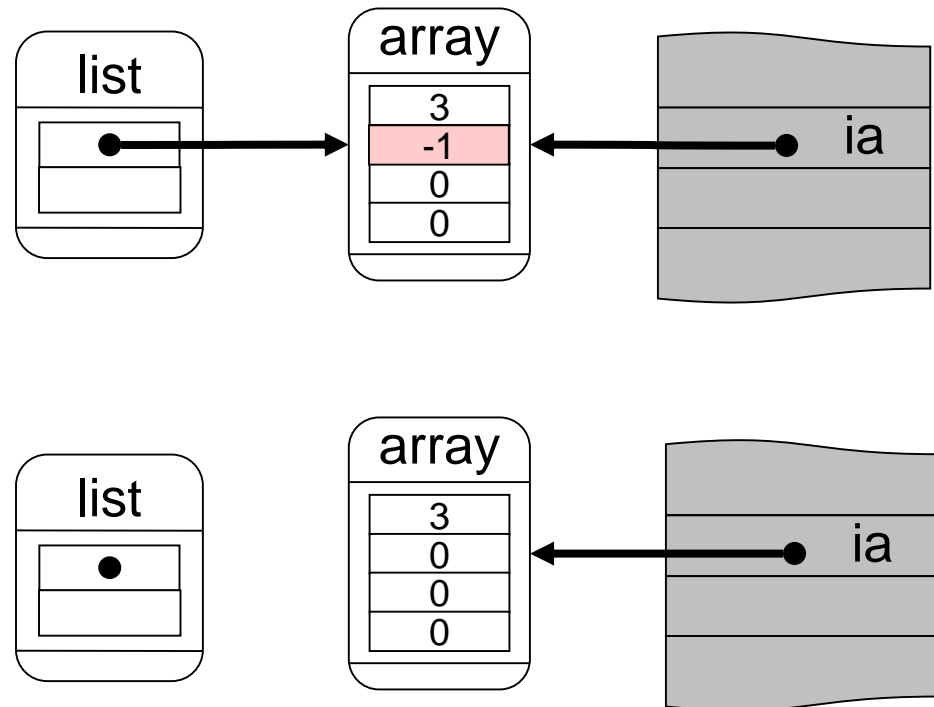
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Exchanging Implementations (cont'd)

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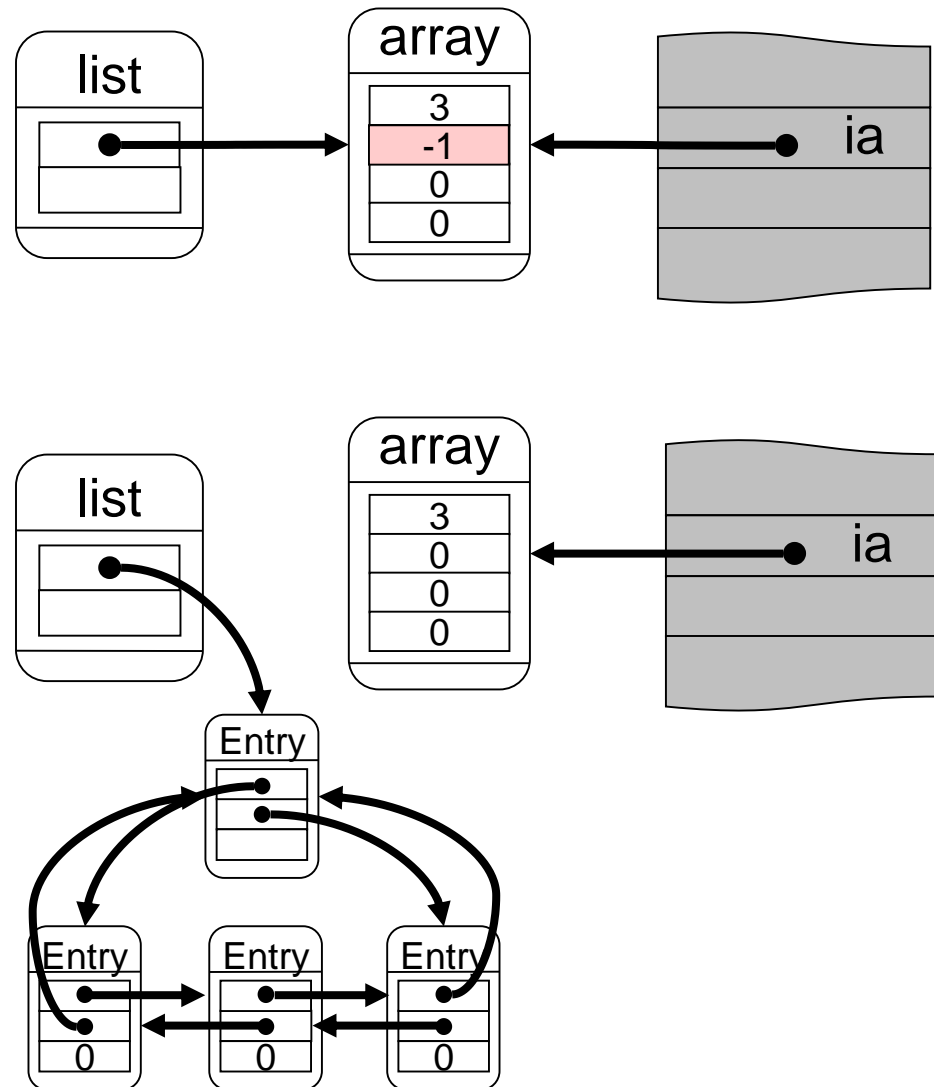


Exchanging Implementations (cont'd)

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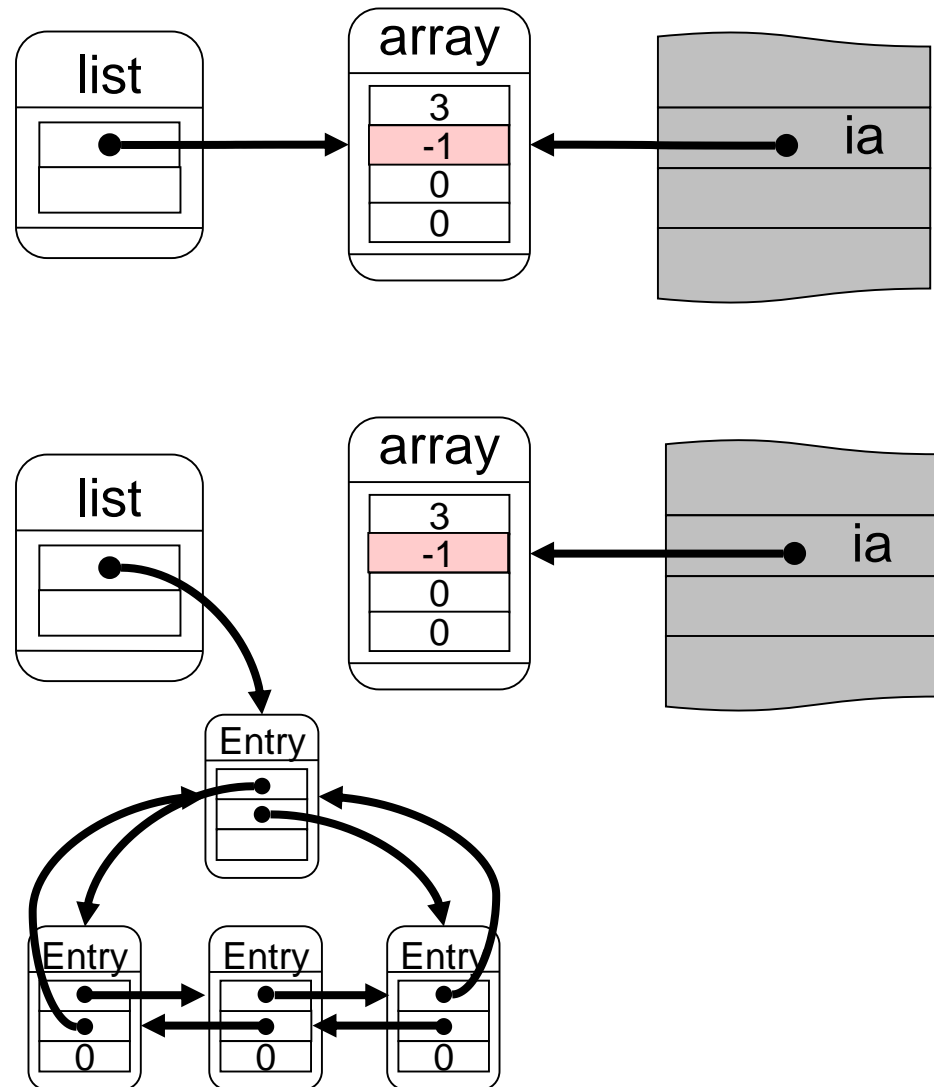


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    int[ ] ia = new int[ 3 ];
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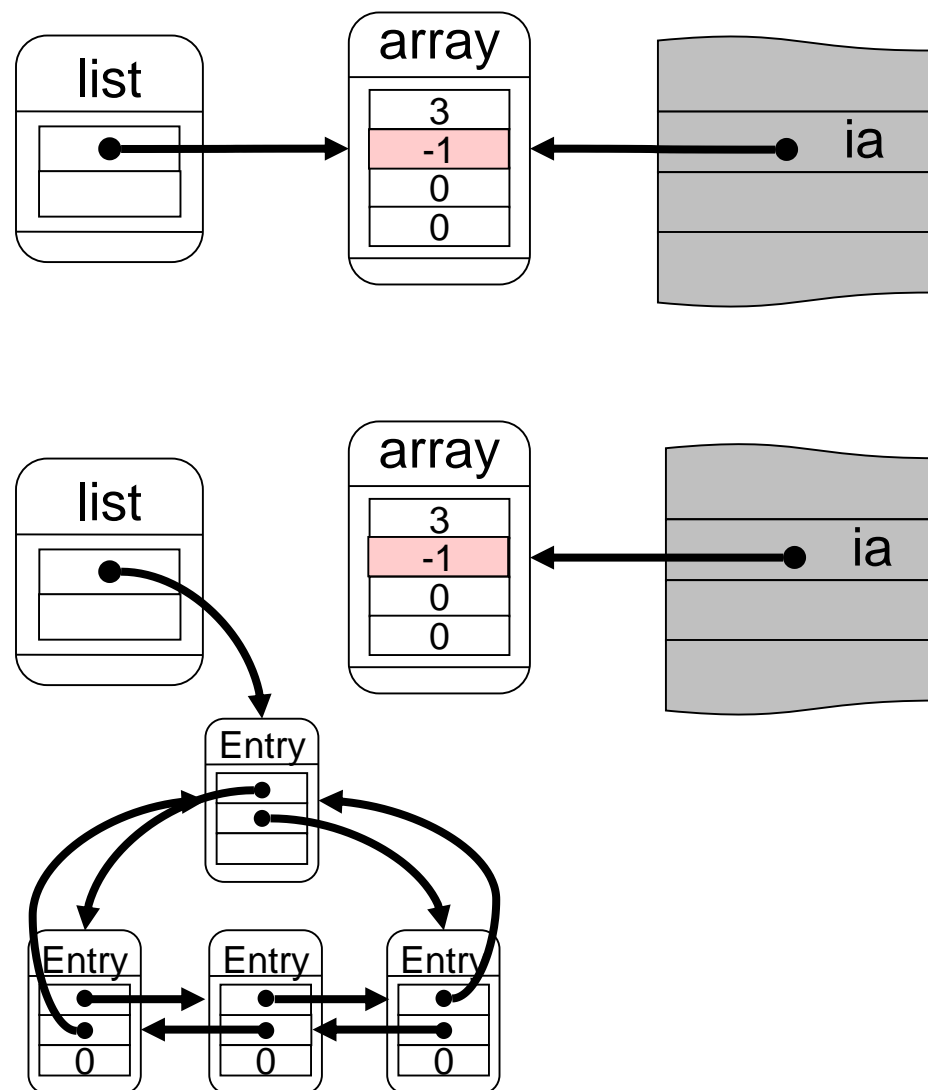
Exchanging Implementations (cont'd)

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int foo( ArrayList list ) {
    int[ ] ia = new int[ 3 ];
    list.setElems( ia );
    ia[ 0 ] = -1;
    return list.getFirst( );
}

```

- Aliases can be used to by-pass interface
- **Observable behavior is changed!**



Consistency of Object Structures

- Consistency of object structures depends on **fields of several objects**
- **Invariants** are usually specified as part of the contract **of those objects** that represent the **interface of the object structure**

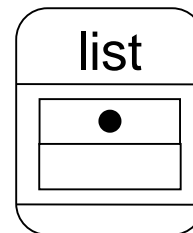
```
class ArrayList {  
    private int[ ] array;  
    private int next;  
  
    // invariant array != null    &&  
    //  0<=next<=array.length  &&  
    //   $\forall i. 0 \leq i < \text{next}: \text{array}[i] \geq 0$   
  
    public void add( int i )    { ... }  
    public void setElems( int[ ] ia )  
        { ... }  
  
    ...  
}
```

Consistency of Object Structures (cont'd)

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

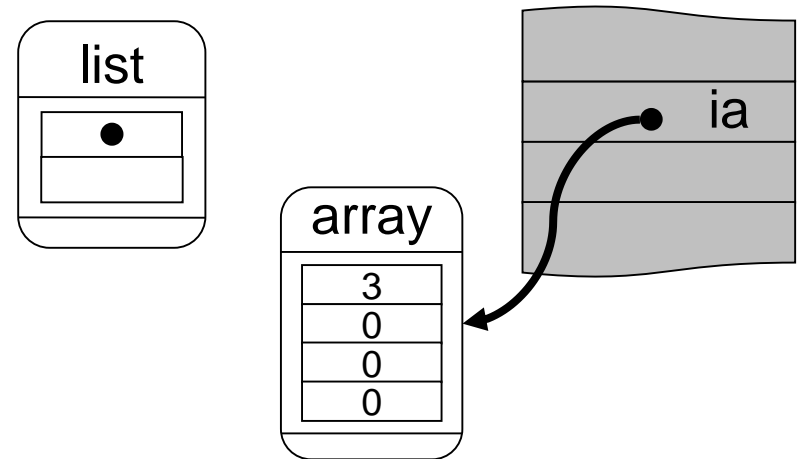
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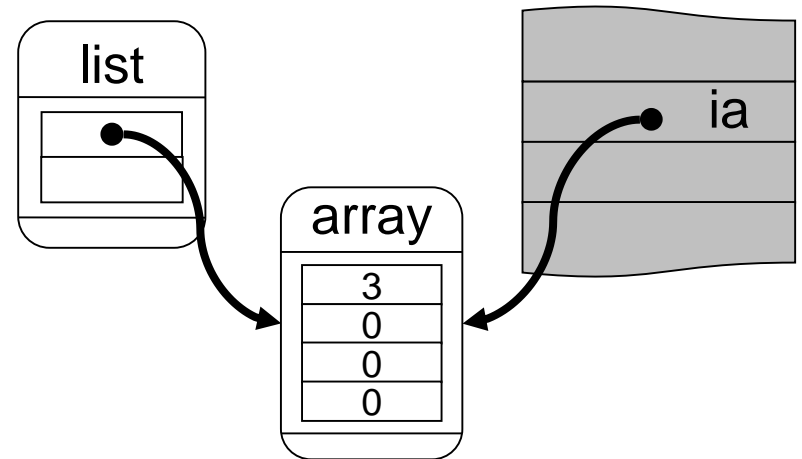
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```



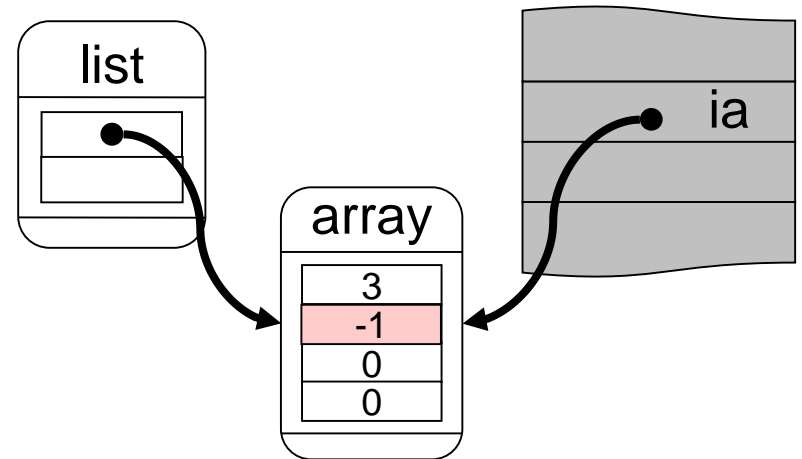
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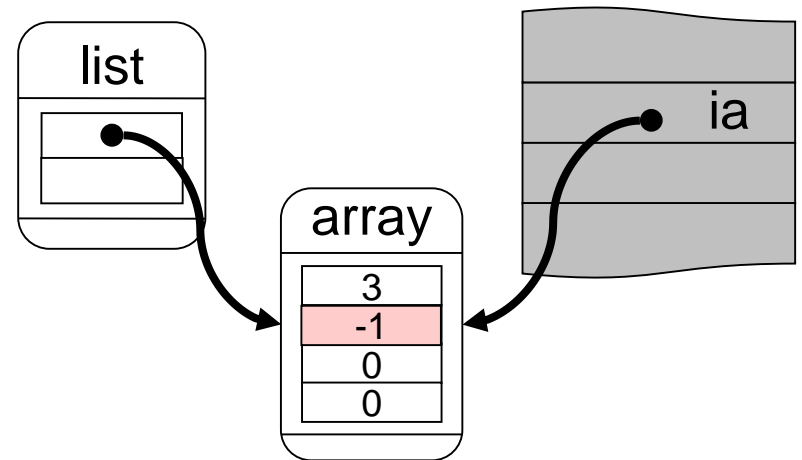
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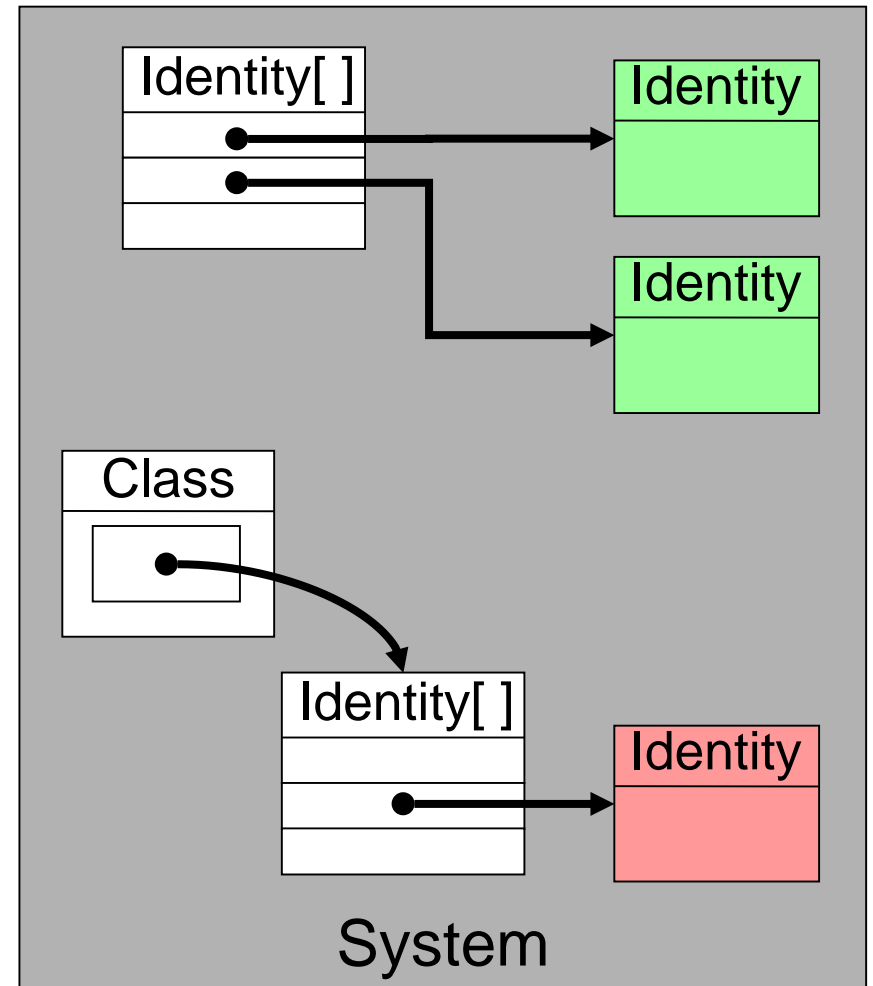
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```

- Aliases can be used to violate invariant
- Making all fields private is not sufficient to encapsulate internal state

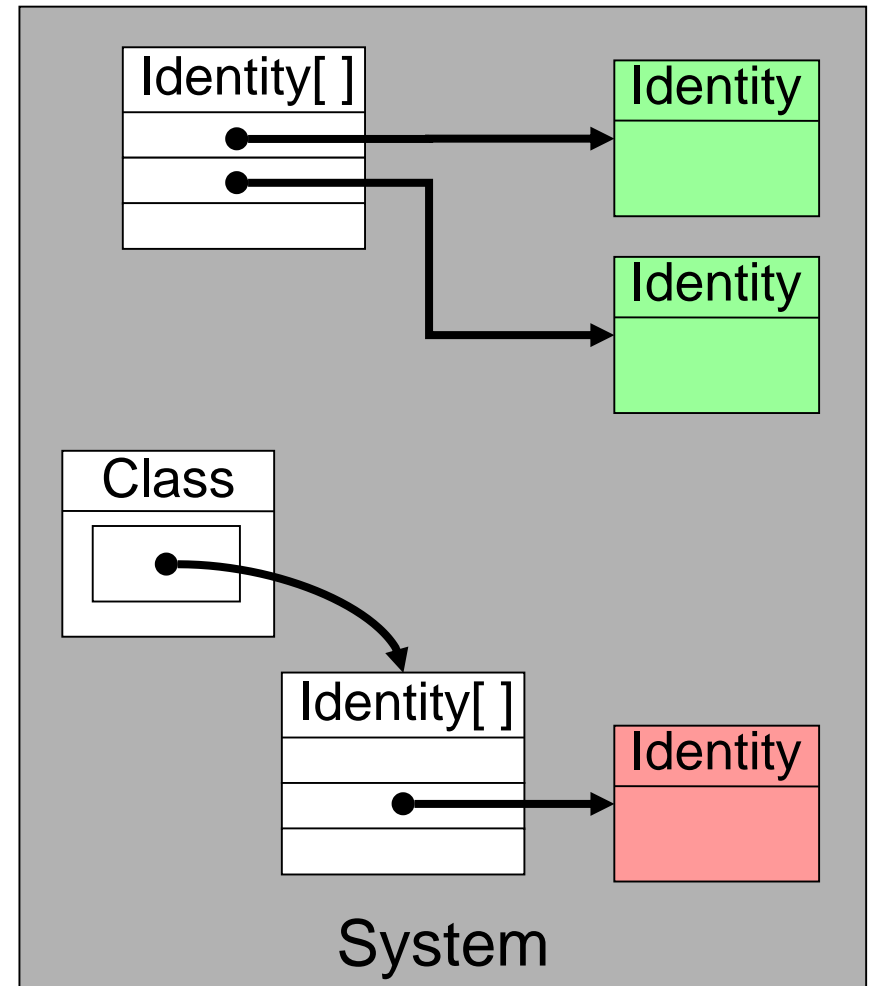


Security Breach in Java 1.1.1



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```
class Malicious {  
  
    void bad( ) {  
        Identity[ ] s;  
        Identity trusted = java.Security...;  
        s = Malicious.class.getSigners( );  
        s[ 0 ] = trusted;  
        /* abuse privilege */  
    }  
}
```



Security Breach in Java 1.1.1

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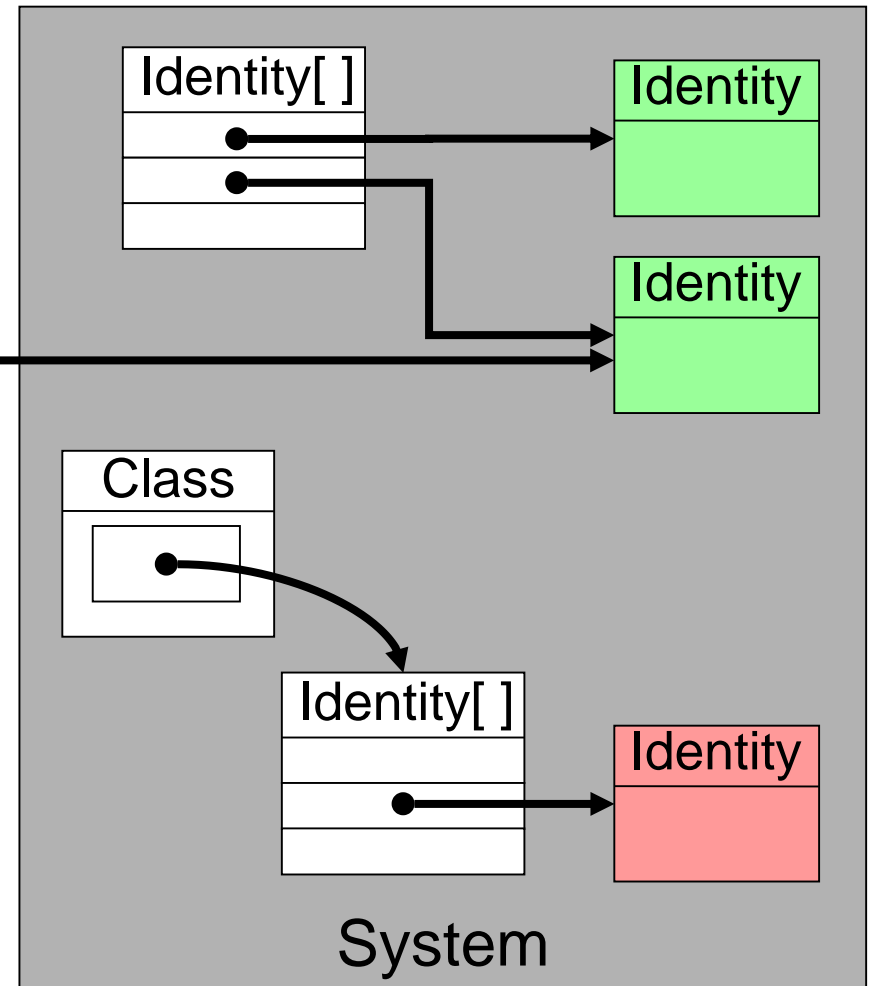
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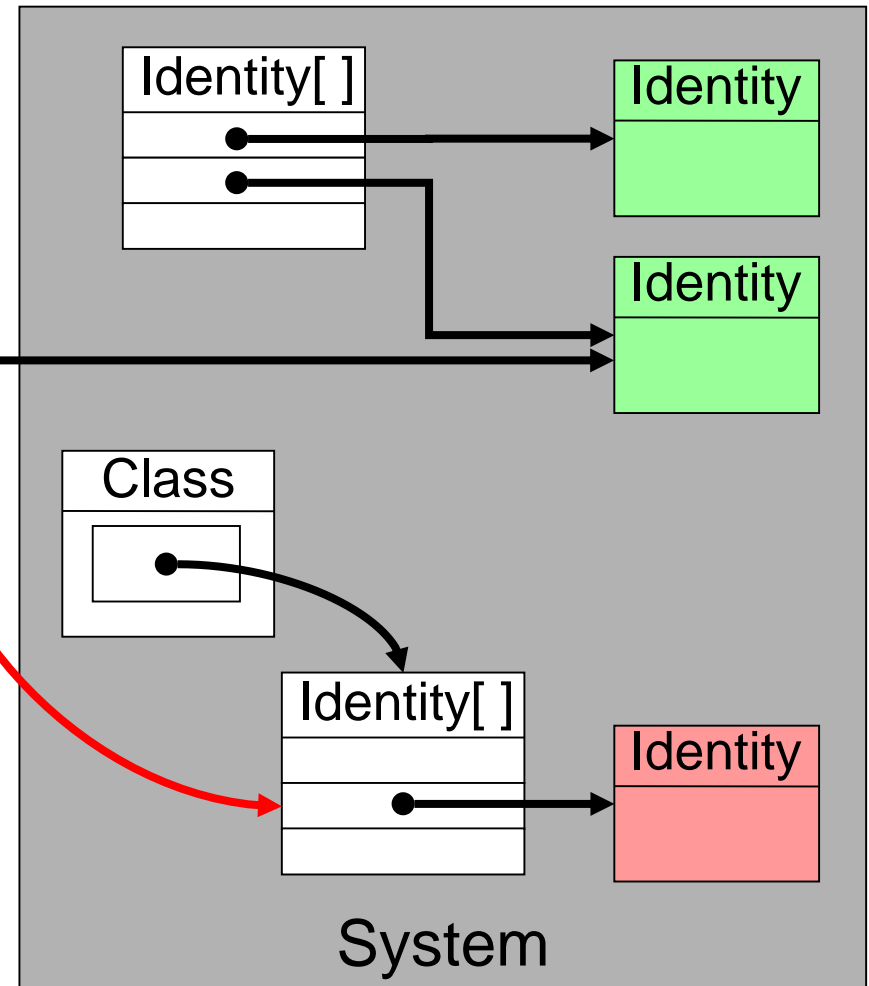
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}
```

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}
```

Identity[] getSigners()
{ **return** signers; }



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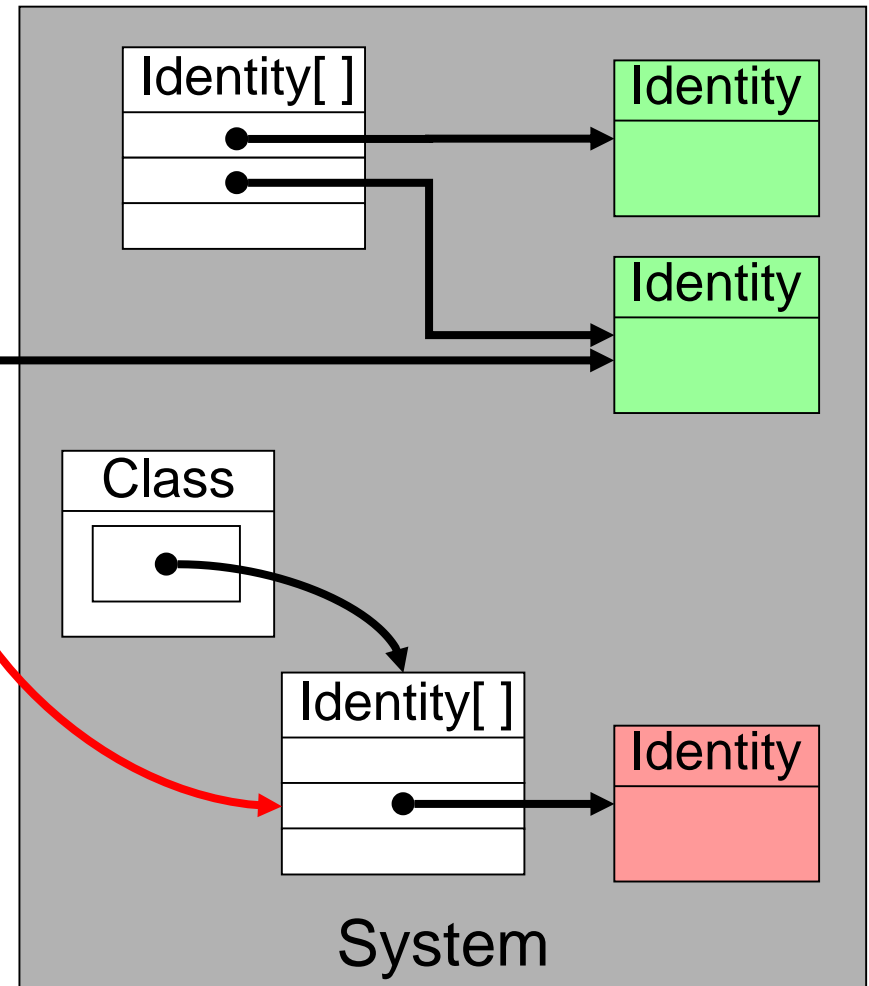
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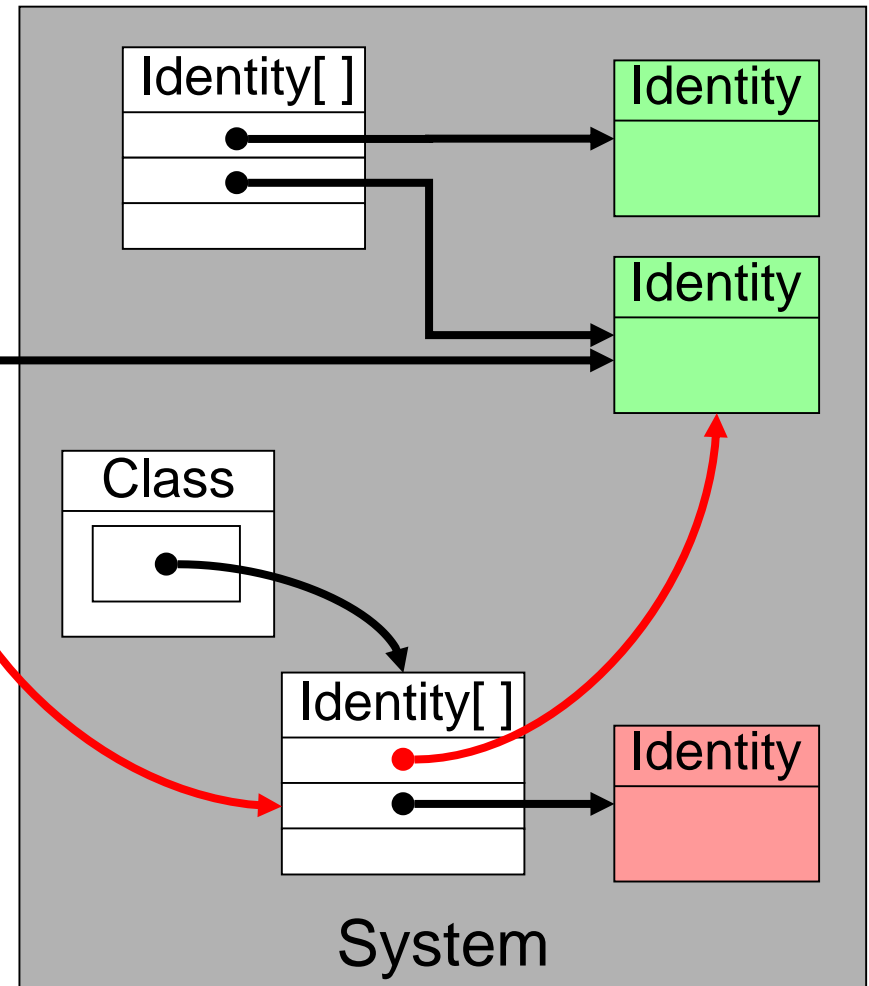
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```

```
    Identity[ ] s;
```

```
    Identity trusted = java.Security...;
```

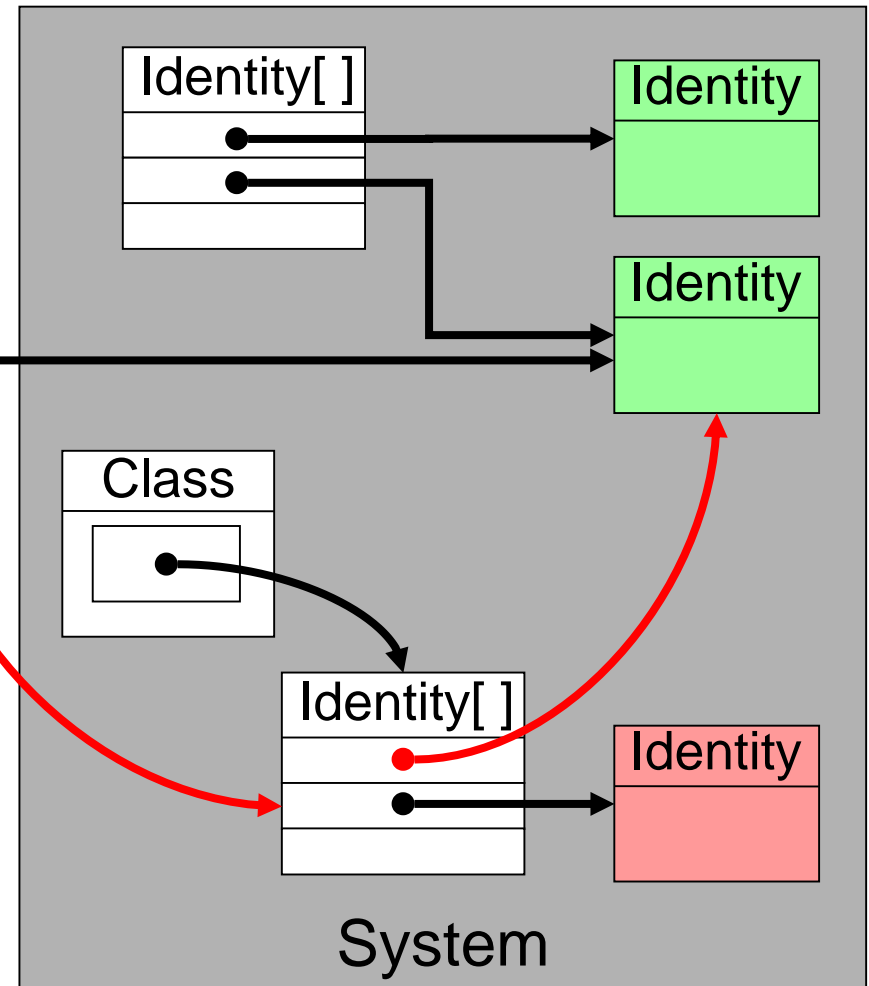
```
    s = Malicious.class.getSigners( );
```

```
    s[ 0 ] = trusted;
```

```
    /* abuse privilege */
```

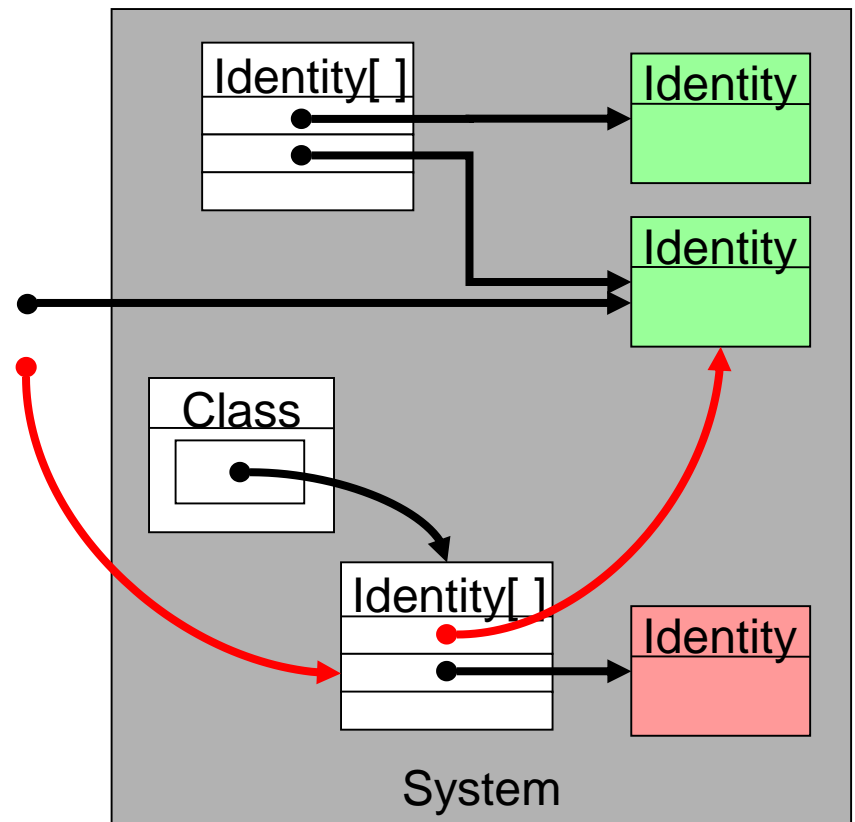
```
  }
```

```
}
```



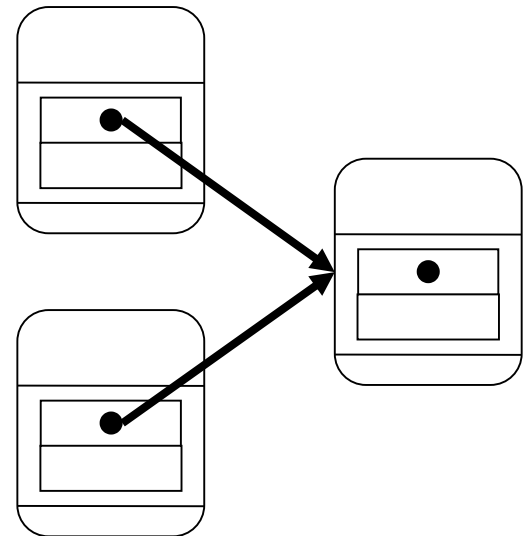
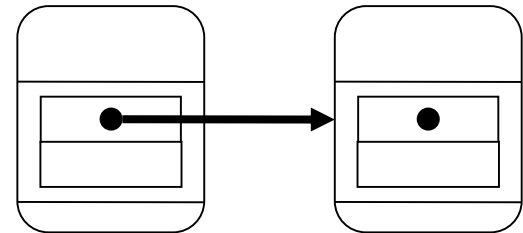
Problem Analysis

- Breach caused by unwanted alias
 - Leaking of reference
- Difficult to prevent
 - Information hiding: not applicable to arrays
 - Restriction of Identity objects: not effective
 - Secure information flow: read access permitted
 - Run-time checks: too expensive



Other Problems with Aliasing

- Synchronization in concurrent programs
 - Monitor of each individual object has to be locked to ensure mutual exclusion
- Distributed programming
 - For instance, parameter passing for remote method invocation
- Optimizations
 - For instance, object inlining is not possible for aliased objects

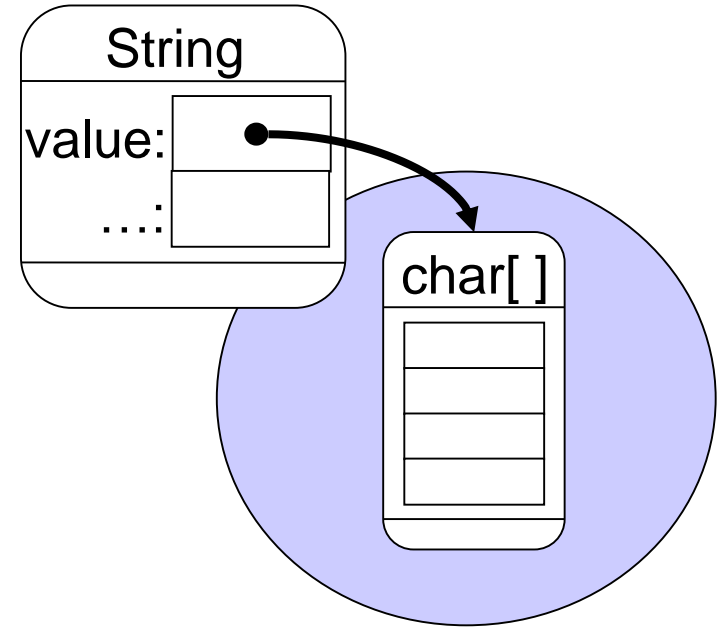


Alias Control in Java: LinkedList

- All **fields** are **private**
- Entry is a **private inner class** of LinkedList
 - References are not passed out
 - Subclasses cannot manipulate or leak Entry-objects
- Listltr is a **private inner class** of LinkedList
 - Interface Listlterator provides controlled access to Listltr-objects
 - Listltr-objects are passed out, but in a controlled fashion
 - Subclasses cannot manipulate or leak Listltr-objects
- **Subclassing is severely restricted**

Alias Control in Java: String

- All **fields** are **private**
- References to internal character-array are not passed out
- **Subclassing is prohibited** (final)



6. Object Structures and Aliasing

6.1 Aliasing

6.2 Problems of Aliasing

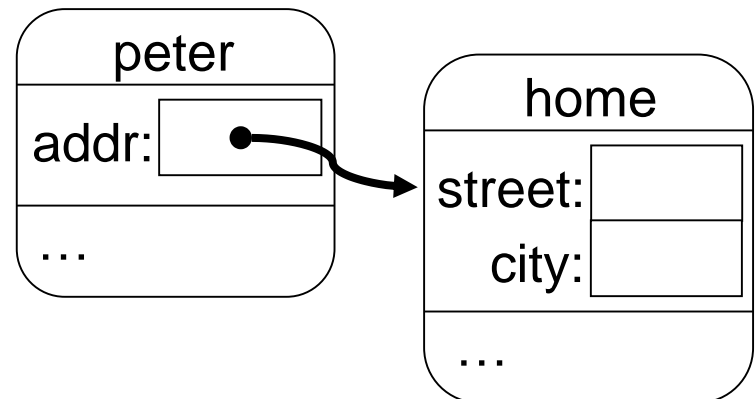
6.3 Readonly Types

6.4 Ownership Types

Object Structures Revisited

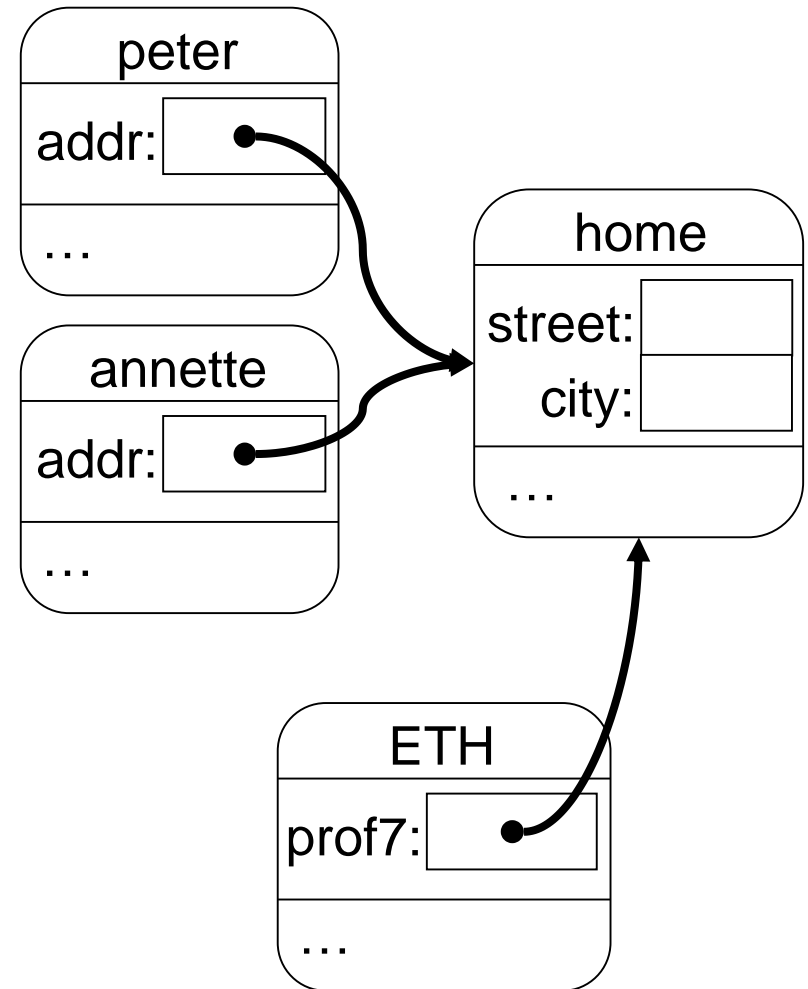
```
class Address ... {  
    private String street;  
    private String city;  
  
    public String getStreet( ) { ... }  
    public void setStreet( String s )  
        { ... }  
  
    public String getCity( ){ ... }  
    public void setCity( String s )  
        { ... }  
    ...  
}
```

```
class Person {  
    private Address addr;  
    public Address getAddr( )  
        { return addr.clone( ); }  
    public void setAddr( Address a )  
        { addr = a.clone( ); }  
    ...  
}
```



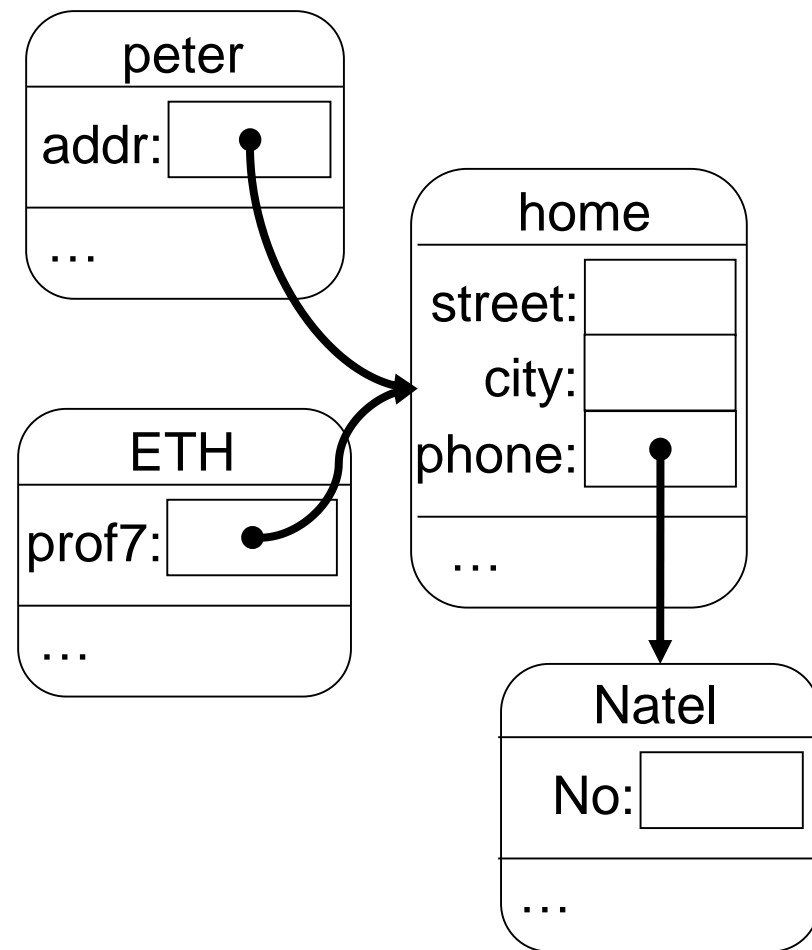
Drawbacks of Alias Prevention

- Aliases are helpful to share side-effects
- Cloning objects is not efficient
- In many cases, it suffices to restrict access to shared objects
- Common situation: grant read access only



Requirements for Readonly Access

- Mutable objects
 - Some clients can mutate the object, but others cannot
 - Access restrictions apply to references, not whole objects
- Prevent field updates
- Prevent calls of mutating methods
- Transitivity
 - Access restrictions extend to references to sub-objects



Readonly Access via Supertypes

```
interface ReadonlyAddress {  
    public String getStreet( );  
    public String getCity( );  
}
```

```
class Address  
    implements ReadonlyAddress ... {  
    ... /* as before */ }
```


Readonly Access via Supertypes

```
interface ReadonlyAddress {  
    public String getStreet( );  
    public String getCity( );  
}
```

```
class Address  
    implements ReadonlyAddress ... {  
    ... /* as before */ }
```

```
class Person {  
    private Address addr;  
    public ReadonlyAddress  
        getAddr( )  
        { return addr; }  
    public void setAddr( Address a )  
        { addr = a.clone( ); }  
    ... }
```

Readonly Access via Supertypes

```
interface ReadonlyAddress {  
    public String getStreet( );  
    public String getCity( );  
}
```

```
class Address  
    implements ReadonlyAddress ... {  
    ... /* as before */ }
```

```
class Person {  
    private Address addr;  
    public ReadonlyAddress  
        getAddr( )  
        { return addr; }  
    public void setAddr( Address a )  
        { addr = a.clone( ); }  
    ... }
```

- Clients use only the methods in the interface
 - Object remains mutable
 - No field updates
 - No mutating method in the interface

Limitations of Supertype Solution

- Reused classes might not implement a readonly interface
 - See discussion of structural subtyping

Limitations of Supertype Solution

- Reused classes might not implement a readonly interface
 - See discussion of structural subtyping
- Interfaces do not support arrays, fields, and non-public methods

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- Reused classes might not implement a readonly interface
 - See discussion of structural subtyping
- Interfaces do not support arrays, fields, and non-public methods
- Transitivity has to be encoded explicitly
 - Requires sub-objects to implement readonly interface

```
class Address
    implements ReadonlyAddress ... {
    ...
    private PhoneNo phone;
    public PhoneNo getPhone( )
    { return phone; } }
```

```
interface ReadonlyAddress {
    ...
    public PhoneNo getPhone( );
}
```

Limitations of Supertype Solution

- Reused classes might not implement a readonly interface
 - See discussion of structural subtyping
- Interfaces do not support arrays, fields, and non-public methods
- Transitivity has to be encoded explicitly
 - Requires sub-objects to implement readonly interface

```
class Address
    implements ReadonlyAddress ... {
    ...
    private PhoneNo phone;
    public PhoneNo getPhone( )
    { return phone; } }
```

```
interface ReadonlyAddress {
    ...
    public ReadonlyPhoneNo getPhone( );
}
```

Supertype Solution is not Safe

- No checks that methods in readonly interface are **actually side-effect free**

Supertype Solution is not Safe

- No checks that methods in readonly interface are **actually side-effect free**
- **Readwrite aliases** can occur, e.g., through capturing

```
class Person {  
    private Address addr;  
    public ReadonlyAddress getAddr( )  
        { return addr; }  
    public void setAddr( Address a )  
        { addr = a.clone( ); }  
    ...  
}
```


Supertype Solution is not Safe

- No checks that methods in readonly interface are **actually side-effect free**
- **Readwrite aliases** can occur, e.g., through capturing
- Clients can use **casts** to get full access

```
class Person {  
    private Address addr;  
    public ReadonlyAddress getAddr( )  
        { return addr; }  
    public void setAddr( Address a )  
        { addr = a.clone( ); }  
    ...  
}
```

```
void m( Person p ) {  
    ReadonlyAddress ra = p.getAddr( );  
    Address a = (Address) ra;  
    a.setCity( "Hagen" );  
}
```

Readonly Access in Eiffel

- Better support for fields
 - Readonly supertype can contain getters
 - Field updates only on “this” object
- Command-query separation
 - Distinction between mutating and inspector methods
 - But **queries** are **not checked to be side-effect free**
- Other problems as before
 - Reused classes, transitivity, arrays, aliasing, downcasts

Readonly Access in C++: const Pointers

```
class Address {  
    string city;  
public:  
    string getCity( void )  
        { return city; }  
    void setCity( string s )  
        { city = s; }  
};
```

C++

```
class Person {  
    Address* addr;  
public:  
    const Address* getAddr( )  
        { return addr; }  
    void setAddr( Address a )  
        { /* clone */ }  
};
```

C++

- C++ supports readonly pointers
 - No field updates
 - No mutator calls

Readonly Access in C++: const Pointers

```
class Address {  
    string city;  
public:  
    string getCity( void )  
        { return city; }  
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        { city = s; }  
};
```

C++

```
class Person {  
    Address* addr;  
public:  
    const Address* getAddr( )  
        { return addr; }  
    void setAddr( Address a )  
        { /* clone */ }  
};
```

C++

- C++ supports readonly pointers
 - No field updates
 - No mutator calls

```
void m( Person* p ) {  
    const Address* a = p->getAddr( );  
    a->setCity( "Hagen" );  
    cout << a->getCity( );  
}
```

C++

Readonly Access in C++: const Pointers

```
class Address {
    string city;
public:
    string getCity( void )
        { return city; }
    void setCity( string s )
        { city = s; }
};
```

C++

```
class Person {
    Address* addr;
public:
    const Address* getAddr( )
        { return addr; }
    void setAddr( Address a )
        { /* clone */ }
};
```

C++

- C++ supports readonly pointers
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```
void m( Person* p ) {
    const Address* a = p->getAddr( );
    a->setCity( "Hagen" );
    cout << a->getCity( );
}
```

Compile-time
error

Readonly Access in C++: const Pointers

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class Address {  
    string city;  
public:  
    string getCity( void )  
        { return city; }  
    void setCity( string s )  
        { city = s; }  
};
```

C++

```
class Person {  
    Address* addr;  
public:  
    const Address* getAddr( )  
        { return addr; }  
    void setAddr( Address a )  
        { /* clone */ }  
};
```

C++

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 - No field updates
 - No mutator calls

```
void m( Person* p ) {  
    const Address* a = p->getAddr( );  
    a->setCity( "Hagen" );  
    cout << a->getCity( );  
}
```

Compile-time
errors

Readonly Access in C++: const Functions

```
class Address {  
    string city;  
public:  
    string getCity( void ) const  
        { return city; }  
    void setCity( string s )  
        { city = s; }  
};
```

C++

```
class Person {  
    Address* addr;  
public:  
    const Address* getAddr( )  
        { return addr; }  
    void setAddr( Address a )  
        { /* clone */ }  
};
```

C++

- const functions must not modify their receiver object

Readonly Access in C++: const Functions

```
class Address {  
    string city;  
public:  
    string getCity( void ) const  
        { return city; }  
    void setCity( string s )  
        { city = s; }  
};
```

C++

```
class Person {  
    Address* addr;  
public:  
    const Address* getAddr( )  
        { return addr; }  
    void setAddr( Address a )  
        { /* clone */ }  
};
```

C++

- const functions must not modify their receiver object

```
void m( Person* p ) {  
    const Address* a = p->getAddr( );  
    a->setCity( "Hagen" );  
    cout << a->getCity( );  
}
```

C++

Readonly Access in C++: const Functions

```
class Address {  
    string city;  
public:  
    string getCity( void ) const  
        { return city; }  
    void setCity( string s )  
        { city = s; }  
};
```

C++

```
class Person {  
    Address* addr;  
public:  
    const Address* getAddr( )  
        { return addr; }  
    void setAddr( Address a )  
        { /* clone */ }  
};
```

C++

- const functions must not modify their receiver object

```
void m( Person* p ) {  
    const Address* a = p->getAddr( );  
    a->setCity( "Hagen" );  
    cout << a->getCity( );  
}
```

Compile-time
error

Readonly Access in C++: const Functions

```

class Address {
    string city;
public:
    string getCity( void ) const
        { return city; }
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        { city = s; }
};
  
```

C++

```

class Person {
    Address* addr;
public:
    const Address* getAddr( )
        { return addr; }
    void setAddr( Address a )
        { /* clone */ }
};
  
```

C++

- const functions must not modify their receiver object

```

void m( Person* p ) {
    const Address* a = p->getAddr( );
    a->setCity( "Hagen" );
    cout << a->getCity( );
}
  
```

Call of const
function allowed

Compile-time
error

It wouldn't be C++ ...

```
class Address {  
    string city;  
public:  
    string getCity( void ) const  
        { return city; }  
    void setCity( string s ) const {  
        Address* me = ( Address* ) this;  
        me->city = s;  
    } };
```

C++

```
class Person {  
    Address* addr;  
public:  
    const Address* getAddr( )  
        { return addr; }  
    void setAddr( Address a )  
        { /* clone */ }  
};
```

C++

- const-ness can be cast away
 - No run-time check

It wouldn't be C++ ...

```

class Address {
    string city;
public:
    string getCity( void ) const
        { return city; }
    void setCity( string s ) const {
        Address* me = ( Address* ) this;
        me->city = s;
    } };
  
```

C++

```

class Person {
    Address* addr;
public:
    const Address* getAddr( )
        { return addr; }
    void setAddr( Address a )
        { /* clone */ }
};
  
```

C++

- const-ness can be cast away
 - No run-time check

```

void m( Person* p ) {
    const Address* a = p->getAddr( );
    a->setCity( "Hagen" );
}
  
```

Call of const
function allowed

It wouldn't be C++ ... (cont'd)

```
class Address {
    string city;
public:
    string getCity( void ) const
        { return city; }
    void setCity( string s )
        { city = s; }
};
```

C++

```
class Person {
    Address* addr;
public:
    const Address* getAddr( )
        { return addr; }
    void setAddr( Address a )
        { /* clone */ }
};
```

C++

- const-ness can be cast away
 - No run-time check

```
void m( Person* p ) {
    const Address* a = p->getAddr( );
    Address* ma = ( Address* ) a;
    ma->setCity( "Hagen" );
}
```

C++

Readonly Access in C++: Transitivity

```
class Phone {  
  public:  
    int number;  
};
```

C++

```
class Address {  
  string city;  
  Phone* phone;  
  public:  
    Phone* getPhone( void ) const  
    { return phone; }  
  ...  
};
```

C++

Readonly Access in C++: Transitivity

```
class Phone {  
public:  
    int number;  
};
```

C++

```
class Address {  
    string city;  
    Phone* phone;  
public:  
    Phone* getPhone( void ) const  
        { return phone; }  
    ...  
};
```

C++

```
void m( Person* p ) {  
    const Address* a = p->getAddr( );  
    Phone* p = a->getPhone( );  
    p->number = 2331...;  
}
```

C++

- **const** pointers are not transitive
- **const**-ness of sub-objects has to be indicated explicitly

Transitivity (cont'd)

```
class Address {  
    string city;  
    Phone* phone;  
public:  
    const Phone* getPhone( void ) const {  
        phone->number = 2331 ...;  
        return phone;  
    }  
    ...  
};
```

C++

Transitivity (cont'd)

```
class Address {  
    string city;  
    Phone* phone;  
public:  
    const Phone* getPhone( void ) const {  
        phone->number = 2331 ...;  
        return phone;  
    }  
    ...  
};
```

const functions may
modify objects other
than the receiver

C++

Readonly Access in C++: Discussion

Pros

Cons

Readonly Access in C++: Discussion

Pros

- const pointers provide readonly pointers to **mutable objects**
 - Prevent field updates
 - Prevent calls of non-const functions

Cons

Readonly Access in C++: Discussion

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 - Prevent calls of non-const functions
- Work for **library classes**

Cons

Readonly Access in C++: Discussion

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- const pointers provide readonly pointers to **mutable objects**
 - Prevent field updates
 - Prevent calls of non-const functions
- Work for **library classes**
- Support arrays, fields, and non-public methods

Cons

Readonly Access in C++: Discussion

Pros

- const pointers provide readonly pointers to **mutable objects**
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 - Prevent calls of non-const functions
- Work for **library classes**
- Support arrays, fields, and non-public methods

Cons

- const-ness is **not transitive**

Readonly Access in C++: Discussion

Pros

- const pointers provide readonly pointers to **mutable objects**
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 - Prevent calls of non-const functions
- Work for **library classes**
- Support arrays, fields, and non-public methods

Cons

- const-ness is **not transitive**
- const pointers are **unsafe**
 - Explicit casts

Readonly Access in C++: Discussion

Pros

- const pointers provide readonly pointers to **mutable objects**
 - Prevent field updates
 - Prevent calls of non-const functions
- Work for **library classes**
- Support arrays, fields, and non-public methods

Cons

- const-ness is **not transitive**
- const pointers are **unsafe**
 - Explicit casts
- **Readwrite aliases** can occur

Pure Methods

- Tag side-effect free methods as **pure**
- Pure methods
 - Must not contain field update
 - Must not invoke non-pure methods
 - Must not create objects
 - Can be overridden only by pure methods

```
class Address {  
    private String street;  
    private String city;  
    public pure String getStreet( )  
        { ... }  
    public void setStreet( String s )  
        { ... }  
    public pure String getCity( )  
        { ... }  
    public void setCity( String s )  
        { ... }  
    ...  
}
```

Types

- Each class or interface T introduces two types
 - Readwrite type $rw\ T$
 - Denoted by T in programs
 - Readonly type $ro\ T$
 - Denoted by **readonly** T in programs

Types

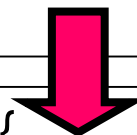
- Each class or interface T introduces two types
 - Denoted by T in programs
- Readwrite type $rw\ T$
 - Denoted by **readonly** T in programs

```
class Person {  
    private Address addr;  
    public ReadonlyAddress  
        getAddr( ) { return addr; }  
    public void setAddr( Address a )  
        { addr = a.clone( ); }  
    ... }
```

Types

- Each class or interface T introduces two types
 - Denoted by T in programs
- Readwrite type $rw\ T$
 - Denoted by T in programs
- Readonly type $ro\ T$
 - Denoted by **readonly** T in programs

```
class Person {  
    private Address addr;  
    public ReadonlyAddress  
        getAddr( ) { return addr; }  
    public void setAddr( Address a )  
        { addr = a.clone( ); }  
    ... }  
}
```



```
class Person {  
    private Address addr;  
    public readonly Address  
        getAddr( ) { ... }  
    ...  
}
```

Subtype Relation

- **Subtyping** among readwrite and readonly types is defined as in Java
 - S extends or implements T \Rightarrow
 $rw\ S <: rw\ T$
 - S extends or implements T \Rightarrow
 $ro\ S <: ro\ T$

Subtype Relation

- **Subtyping** among readwrite and readonly types is **defined as in Java**
 - S extends or implements $T \Rightarrow$
 $rw\ S <: rw\ T$
 - S extends or implements $T \Rightarrow$
 $ro\ S <: ro\ T$
- **Readwrite types** are **subtypes of** corresponding **readonly types**
 - $rw\ T <: ro\ T$

Subtype Relation

- **Subtyping** among readwrite and readonly types is defined as in Java
 - S extends or implements $T \Rightarrow rw\ S <: rw\ T$
 - S extends or implements $T \Rightarrow ro\ S <: ro\ T$
- **Readwrite types** are subtypes of corresponding readonly types
 - $rw\ T <: ro\ T$

```
class T { ... }
```

```
class S extends T { ... }
```

```
S rwS = ...
```

```
T rwT = ...
```

```
readonly S roS = ...
```

```
readonly T roT = ...
```

```
rwT = rwS;
```

```
roT = roS;
```

```
roT = rwT;
```

```
rwT = roT;
```

Type Rules: Transitive Readonly

```
class Address {  
    ...  
    private int[ ] phone;  
    public int[ ] getPhone( ) { ... }  
}
```

```
class Person {  
    private Address addr;  
    public readonly Address  
        getAddr( ) { return addr; }  
    ...  
}
```


Type Rules: Transitive Readonly

```
class Address {  
    ...  
    private int[ ] phone;  
    public int[ ] getPhone( ) { ... }  
}
```

```
class Person {  
    private Address addr;  
    public readonly Address  
        getAddr( ) { return addr; }  
    ...  
}
```

```
Person p = ...  
readonly Address a;  
a = p.getAddr( );  
  
int[ ] ph = a.getPhone( );
```

Type Rules: Transitive Readonly

```
class Address {  
    ...  
    private int[ ] phone;  
    public int[ ] getPhone( ) { ... }  
}
```

```
class Person {  
    private Address addr;  
    public readonly Address  
        getAddr( ) { return addr; }  
    ...  
}
```

- Accessing a value **of a readonly type** or **through a readonly type** should yield a readonly value

```
Person p = ...  
readonly Address a;  
a = p.getAddr( );  
int[ ] ph = a.getPhone( );
```

Type Rules: Transitive Readonly (cont'd)

- The type of
 - A field access
 - An array access
 - A method invocationis determined by the type combinator ►

►	<i>rw T</i>	<i>ro T</i>
<i>rw S</i>	<i>rw T</i>	<i>ro T</i>
<i>ro S</i>	<i>ro T</i>	<i>ro T</i>

Type Rules: Transitive Readonly (cont'd)

- The type of
 - A field access
 - An array access
 - A method invocation
 is determined by the type combinator ►

Person p = ...

readonly Address a;

a = p.getAddr();

int[] ph = a.getPhone();

►	<i>rw T</i>	<i>ro T</i>
<i>rw S</i>	<i>rw T</i>	<i>ro T</i>
<i>ro S</i>	<i>ro T</i>	<i>ro T</i>

Type Rules: Transitive Readonly (cont'd)

- The type of
 - A field access
 - An array access
 - A method invocation
 is determined by the type combinator ►

Person p = ...

readonly Address a;

a = p.getAddr();

int[] ph = a.getPhone();

ro Address

►	<i>rw T</i>	<i>ro T</i>
<i>rw S</i>	<i>rw T</i>	<i>ro T</i>
<i>ro S</i>	<i>ro T</i>	<i>ro T</i>

Type Rules: Transitive Readonly (cont'd)

- The type of
 - A field access
 - An array access
 - A method invocation
 is determined by the type combinator ►

```

Person p = ...
readonly Address a;
a = p.getAddr( );

int[ ] ph = a.getPhone( );
  
```

ro Address

rw int[]

►	<i>rw T</i>	<i>ro T</i>
<i>rw S</i>	<i>rw T</i>	<i>ro T</i>
<i>ro S</i>	<i>ro T</i>	<i>ro T</i>

Type Rules: Transitive Readonly (cont'd)

- The type of
 - A field access
 - An array access
 - A method invocation
 is determined by the type combinator ►

```

Person p = ...
readonly Address a;
a = p.getAddr( );

int[ ] ph = a.getPhone( );
  
```

ro Address



rw int[]

►	<i>rw T</i>	<i>ro T</i>
<i>rw S</i>	<i>rw T</i>	<i>ro T</i>
<i>ro S</i>	<i>ro T</i>	<i>ro T</i>

Type Rules: Transitive Readonly (cont'd)

- The type of
 - A field access
 - An array access
 - A method invocation
 is determined by the type combinator ►

►	<i>rw T</i>	<i>ro T</i>
<i>rw S</i>	<i>rw T</i>	<i>ro T</i>
<i>ro S</i>	<i>ro T</i>	<i>ro T</i>

Person p = ...

readonly Address a;

a = p.getAddr();

int[] ph = a.getPhone();

ro Address

rw int[]

ro int[]

Type Rules: Transitive Readonly (cont'd)

- The type of
 - A field access
 - An array access
 - A method invocation
 is determined by the type combinator ►

►	<i>rw T</i>	<i>ro T</i>
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<i>ro S</i>	<i>ro T</i>	<i>ro T</i>

Person p = ...

readonly Address a;

a = p.getAddr();

readonly int[] ph = a.getPhone();

ro Address

rw int[]

ro int[]

Type Rules: Readonly Access

- Expressions of readonly types must not occur as receiver of
 - a **field update**
 - an **array update**
 - an **invocation** of a **non-pure method**
- Readonly types must not be **cast to readwrite types**

```
readonly Address roa;  
roa.street = "Rämistrasse";  
roa.phone[ 0 ] = 41;  
roa.setCity( "Hagen" );
```

```
readonly Address roa;  
Address a = ( Address ) roa;
```

Discussion

- Readonly types enable **safe sharing of objects**
- Very similar to const pointers in C++, but:
 - Transitive
 - No casts to readwrite types
 - Stricter definition of pure methods
- All rules for pure methods and readonly types can be **checked statically by a compiler**
- Readwrite aliases can still occur, e.g., by capturing

6. Object Structures and Aliasing

6.1 Aliasing

6.2 Problems of Aliasing

6.3 Readonly Types

6.4 Ownership Types

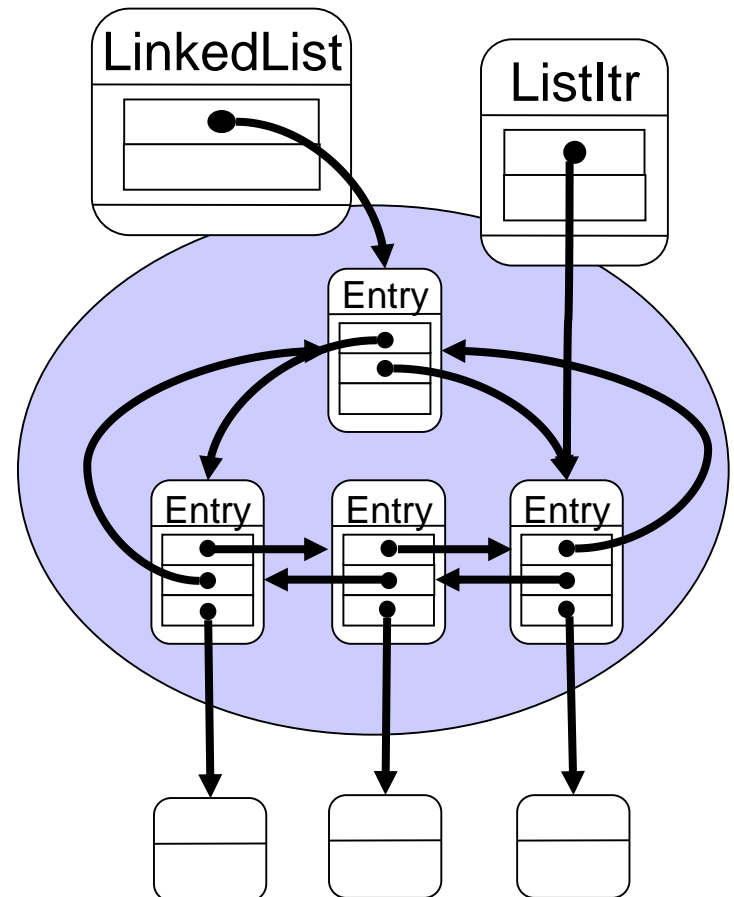
Object Topologies

- Read-write aliases can still occur, e.g., by capturing or leaking
- We need to distinguish “internal” references from other references

```
class Person {  
    private Address addr;  
    private Company employer;  
    public readonly Address getAddr( )  
        { return addr; }  
    public void setAddr( Address a )  
        { addr = a.clone( ); }  
  
    public Company getEmployer( )  
        { return employer; }  
    public void setEmployer( Company c )  
        { employer = c; }  
  
    ...  
}
```

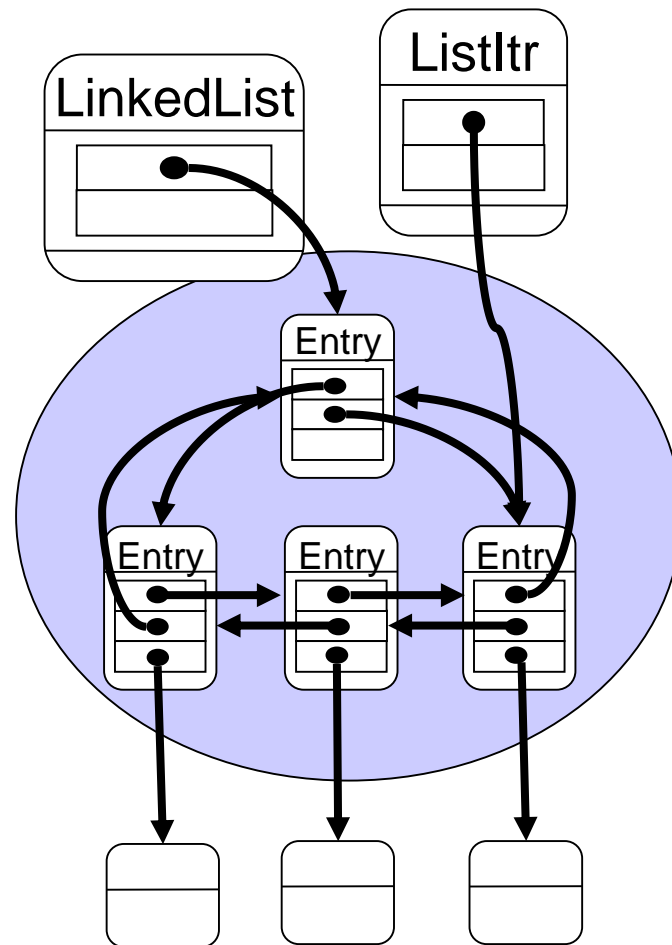
Roles in Object Structures

- **Interface objects** that are used to access the structure
- **Internal representation** of the object structure
 - Must not be exposed to clients
- **Arguments** of the object structure
 - Must not be modified



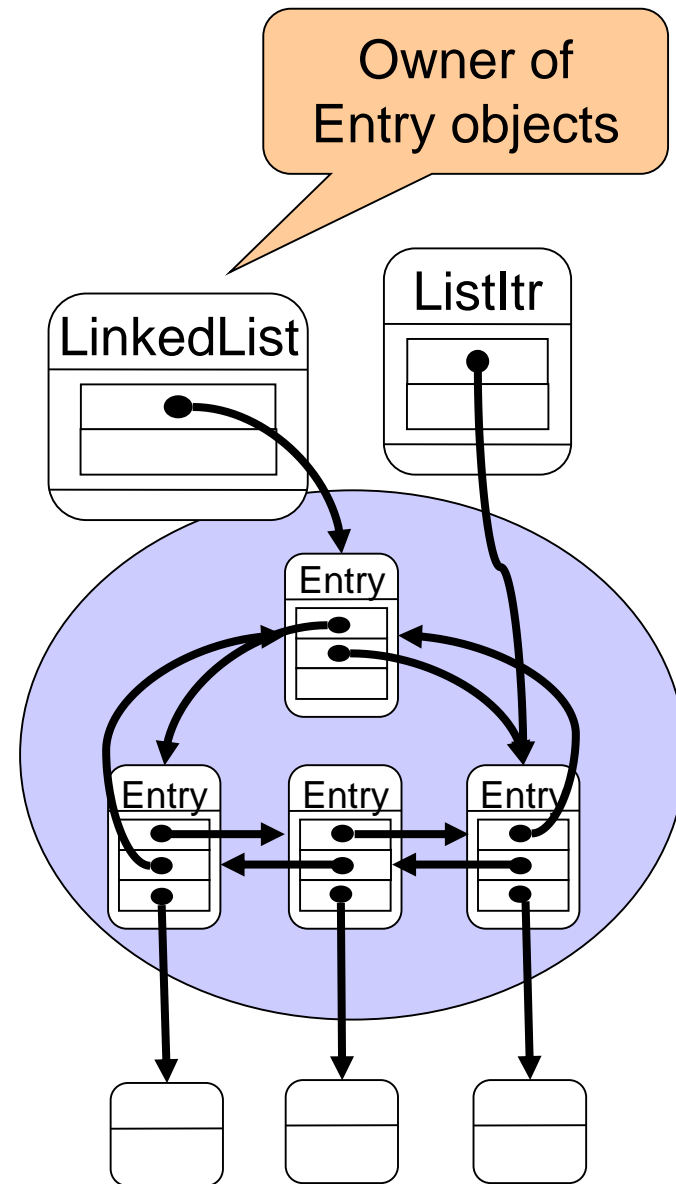
Ownership Model

- Each object has **zero or one owner objects**
- The set of objects with the same owner is called a **context**
- The ownership relation is **acyclic**
- The heap is structured into a forest of **ownership trees**



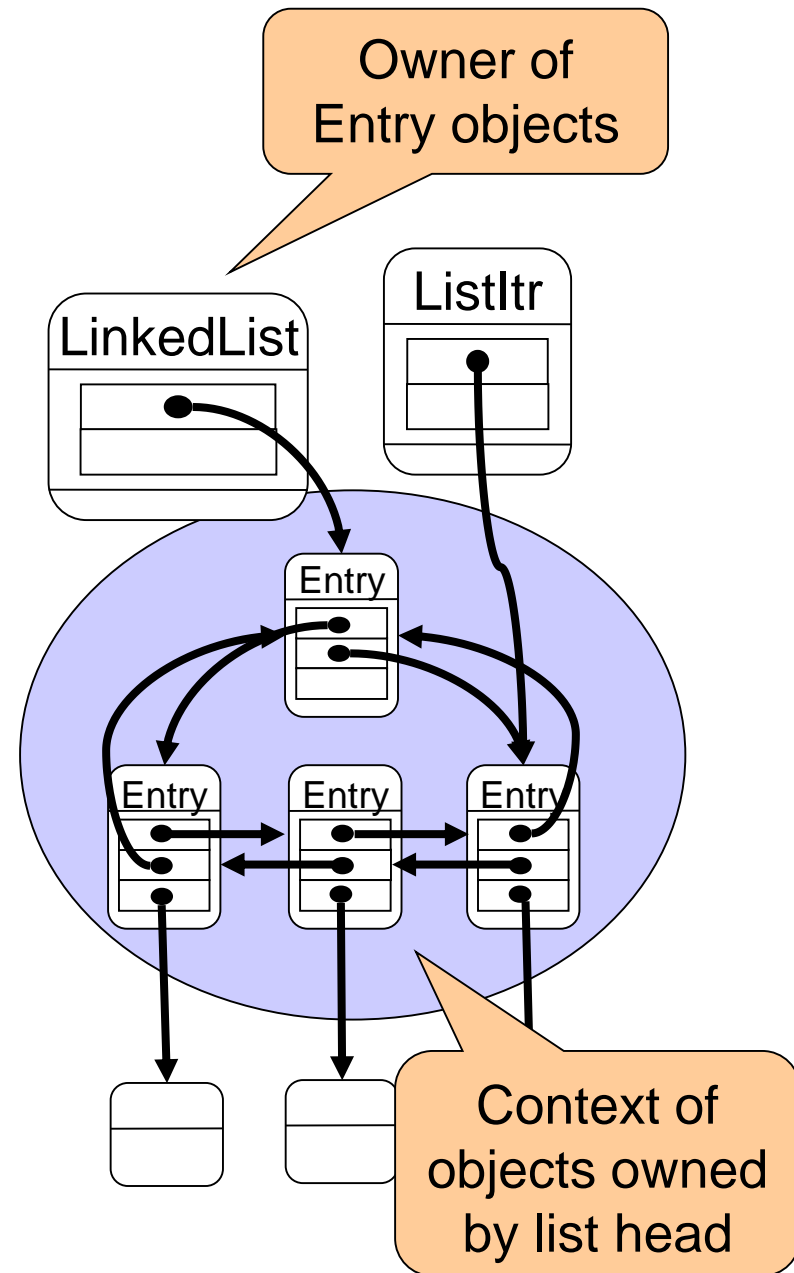
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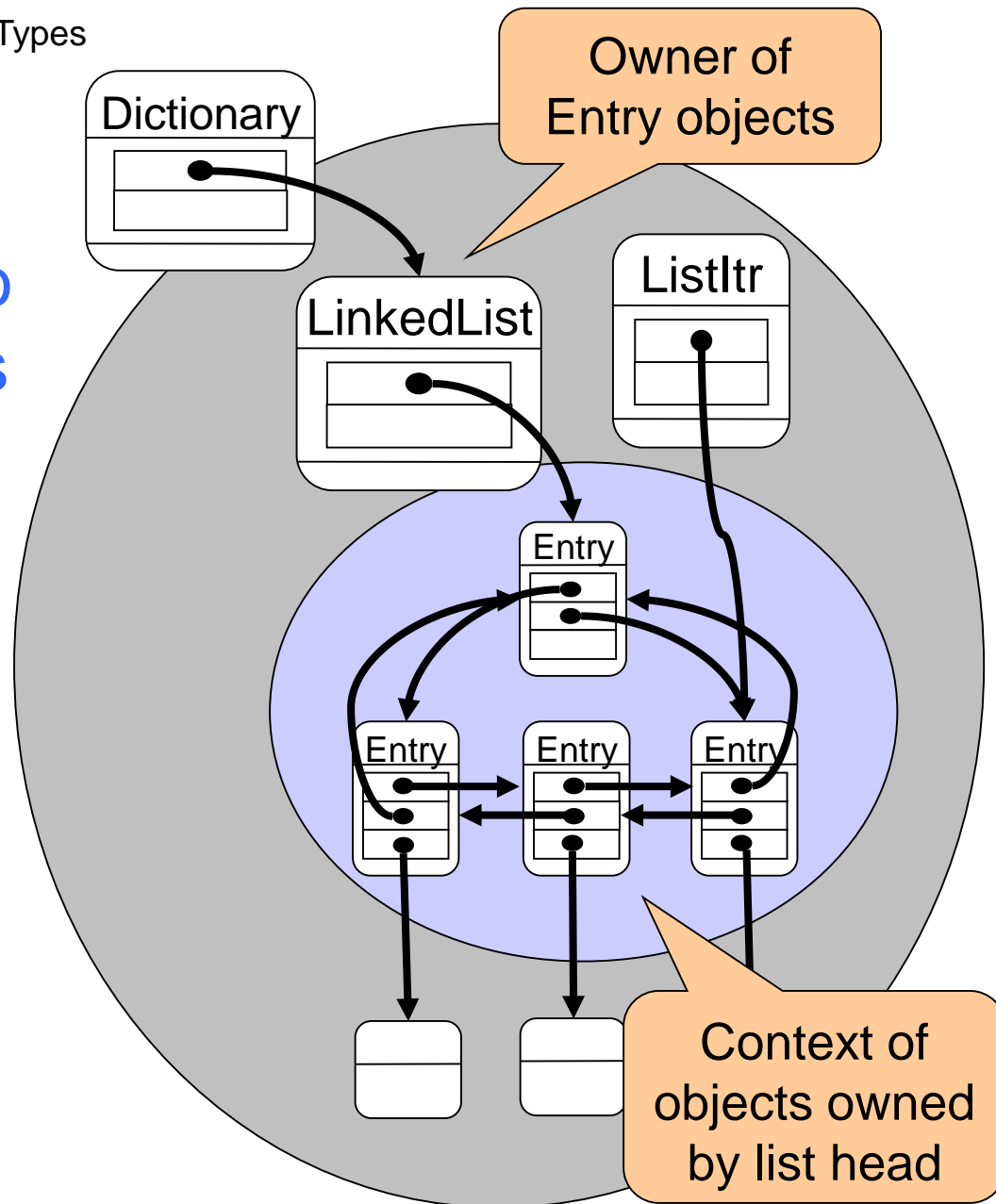
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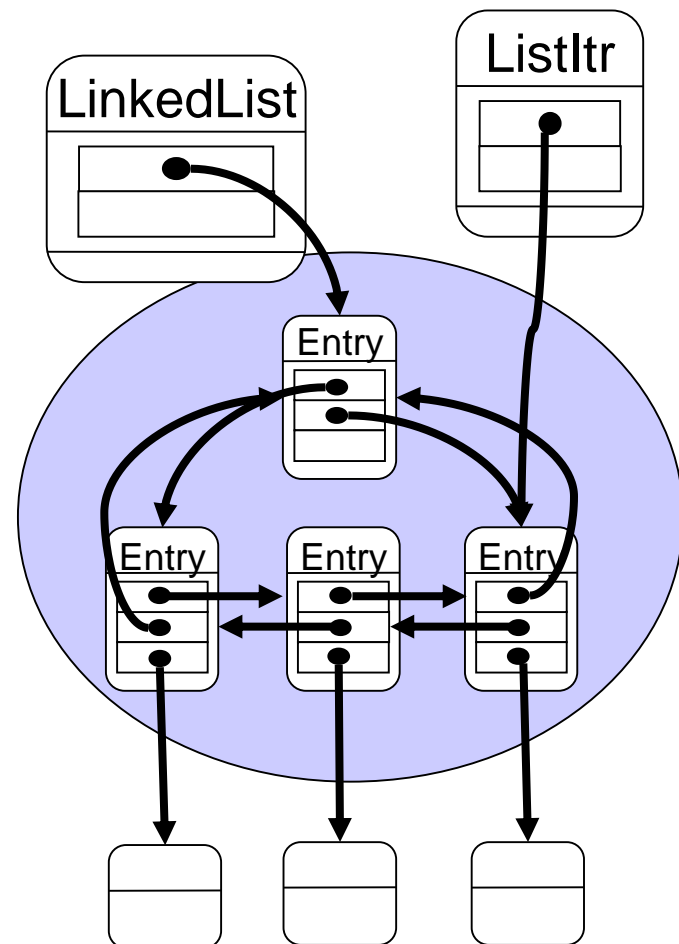
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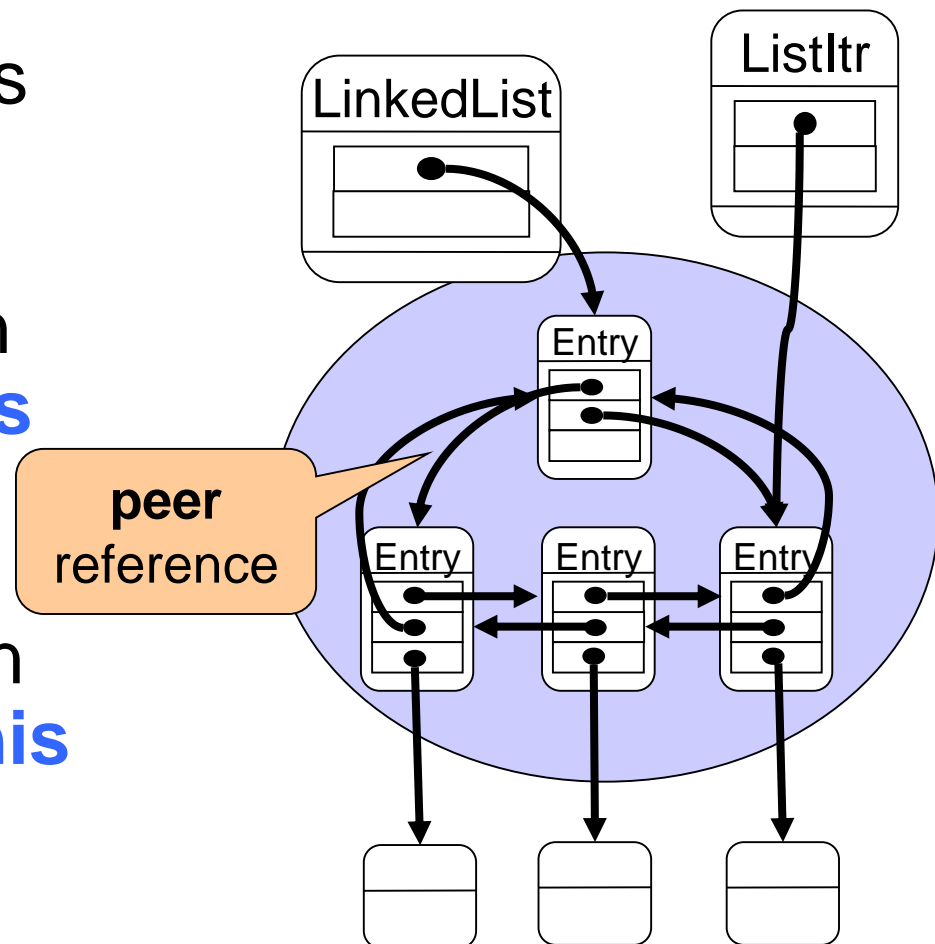
OwnershipTypes

- We use types to express ownership information
- **peer** types for objects in the **same context as this**
- **rep** types for representation objects in the **context owned by this**
- **any** types for argument objects **in any context**



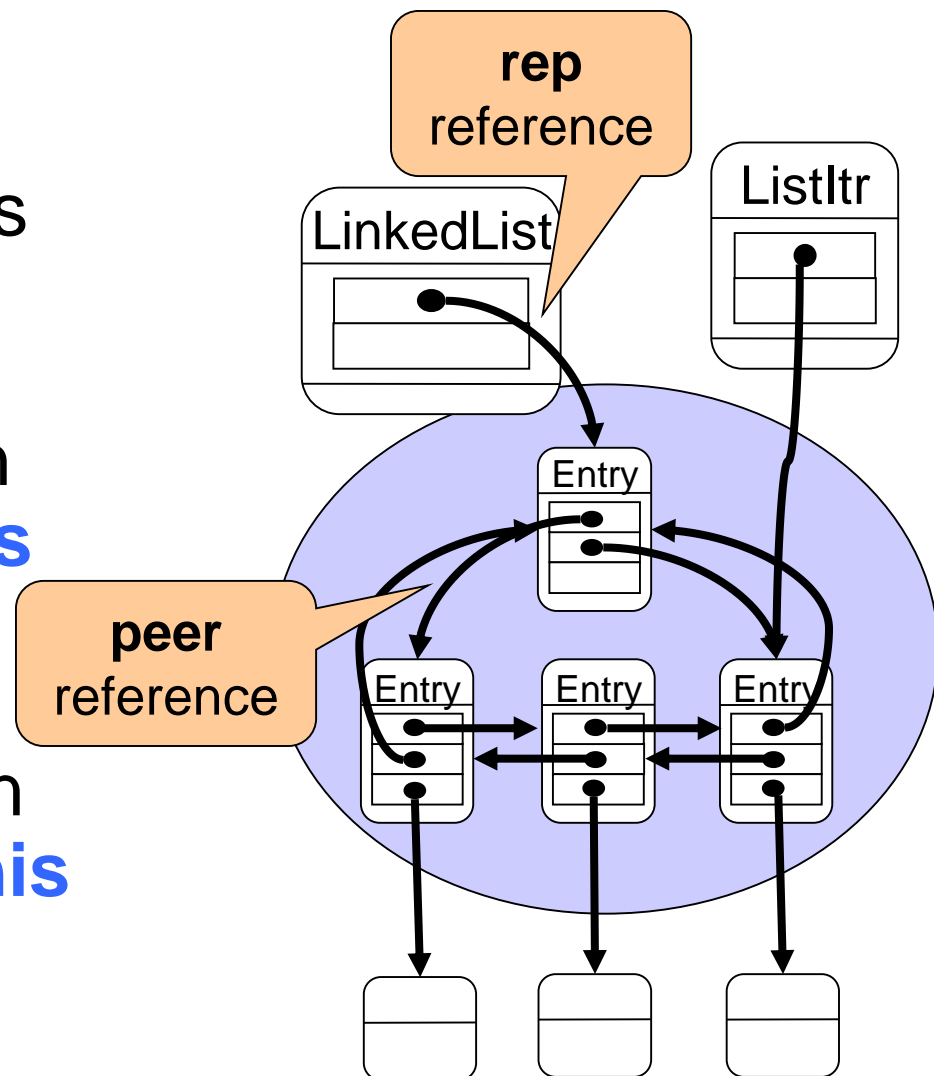
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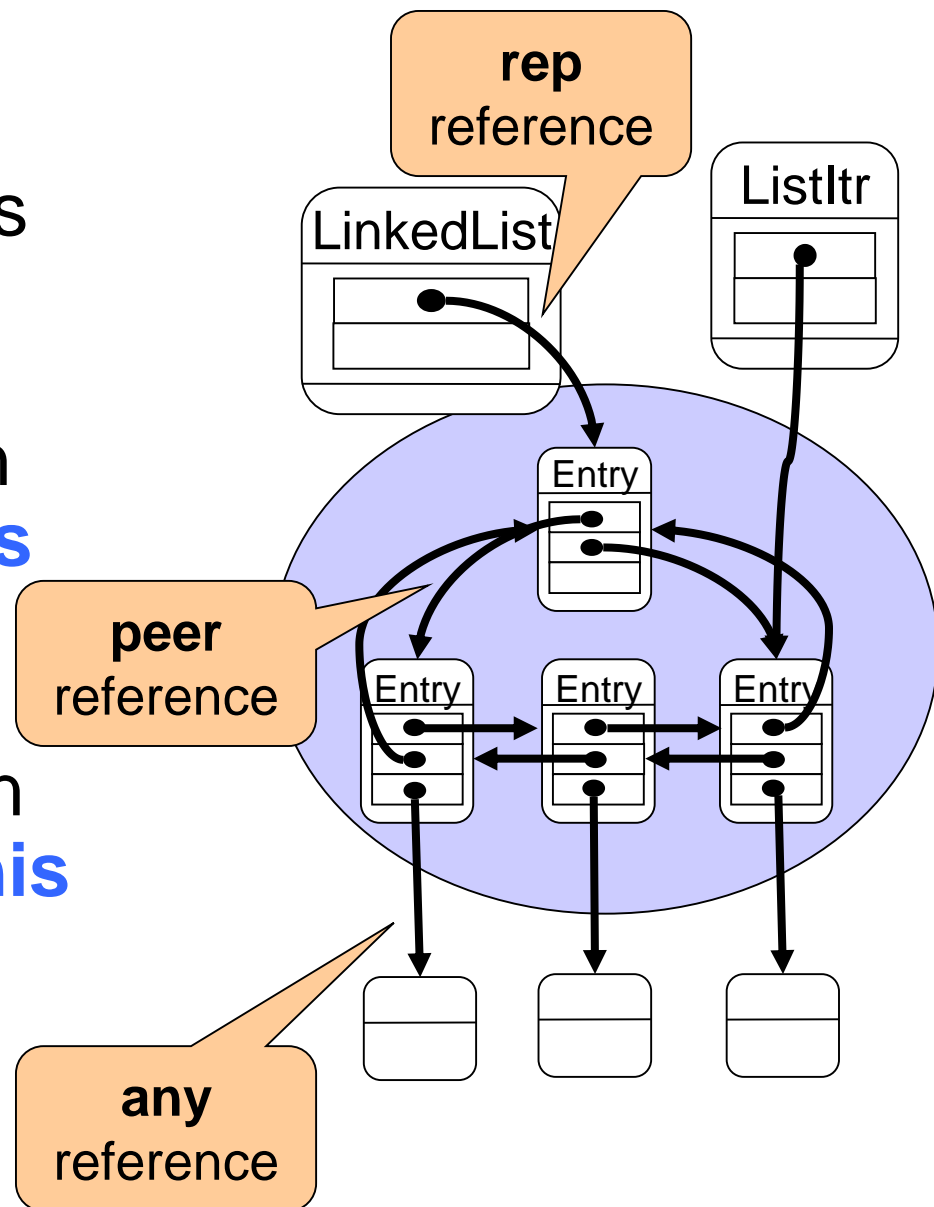
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- We use types to express ownership information
- **peer** types for objects in the **same context as this**
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Example

```
class LinkedList {  
  private rep Entry header;  
  ...  
}
```

```
class Entry {  
  private any Object element;  
  private peer Entry previous, next;  
  ...  
}
```

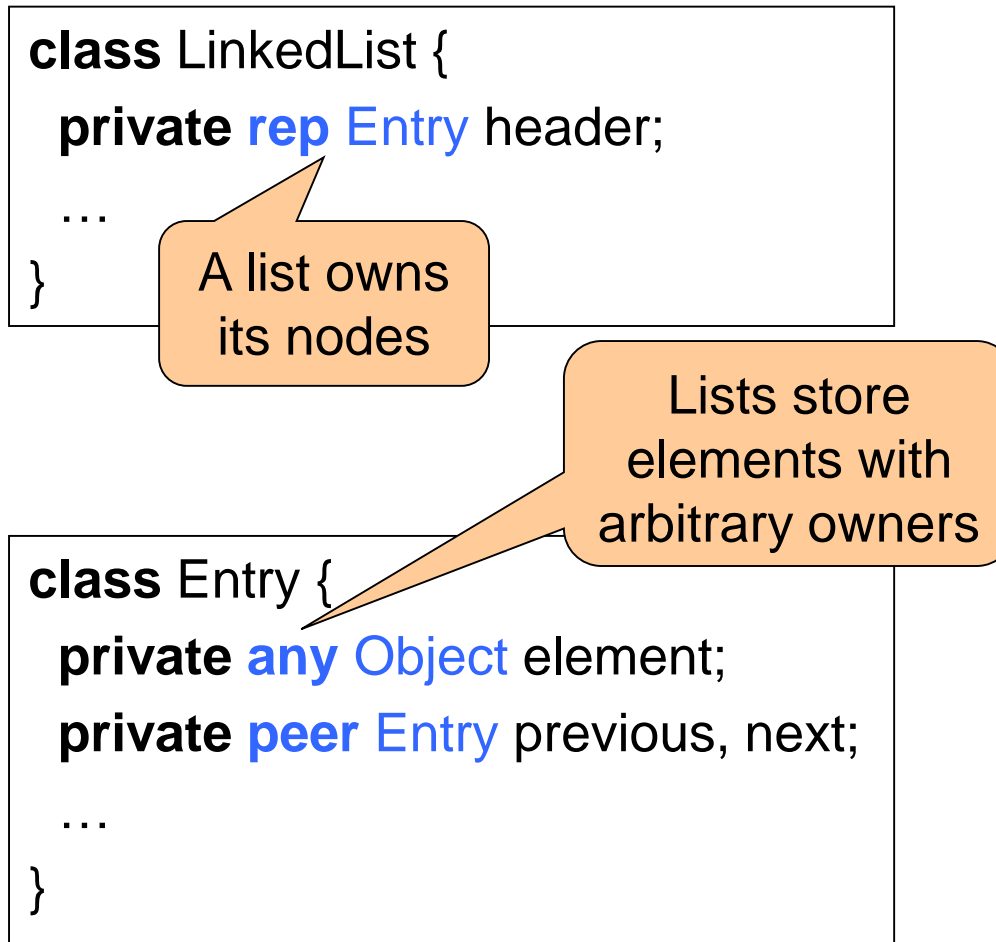
Example

```
class LinkedList {  
  private rep Entry header;  
  ...  
}
```

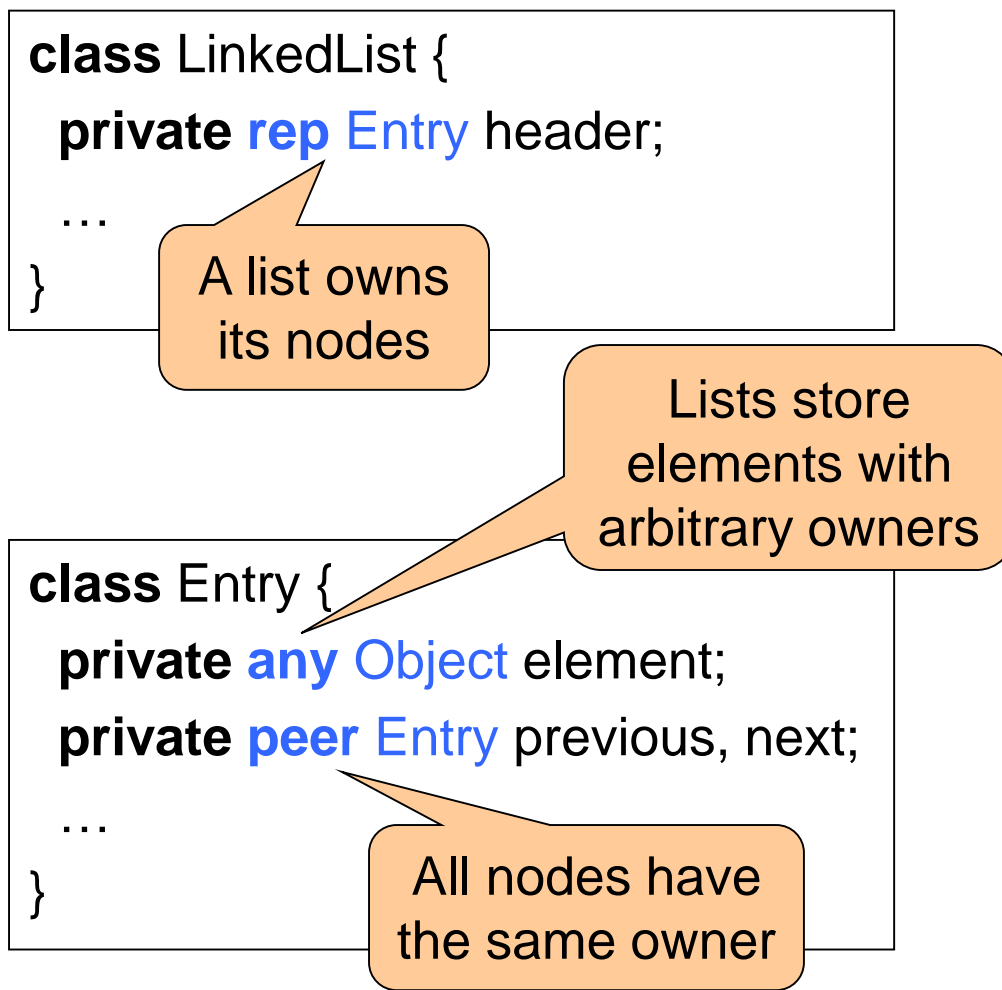
A list owns
its nodes

```
class Entry {  
  private any Object element;  
  private peer Entry previous, next;  
  ...  
}
```


Example



Example



Type Safety

- Run-time type information consists of
 - The class of each object
 - The **owner** of each object
- Type invariant: the **static ownership information** of an expression e **reflects the run-time owner** of the object o referenced by e 's value
 - If e has type ***rep* T** then o 's owner is **this**
 - If e has type ***peer* T** then o 's owner is the **owner of this**
 - If e has type ***any* T** then o 's owner is **arbitrary**

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 - If e has type **any** T then o 's owner is **arbitrary**



An existential
type

Subtyping and Casts

- For types with identical ownership modifier, subtyping is defined as in Java
 - *rep S* <: *rep T*
 - *peer S* <: *peer T*
 - *any S* <: *any T*

```
class T { ... }
```

```
class S extends T { ... }
```

Subtyping and Casts

- For types with identical ownership modifier, subtyping is defined as in Java
 - $rep\ S <: rep\ T$
 - $peer\ S <: peer\ T$
 - $any\ S <: any\ T$
- **rep types** and **peer types** are **subtypes of** corresponding **any types**
 - $rep\ T <: any\ T$
 - $peer\ T <: any\ T$

```
class T { ... }
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```
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Subtyping and Casts

- For types with identical ownership modifier, subtyping is defined as in Java
 - $\text{rep } S <: \text{rep } T$
 - $\text{peer } S <: \text{peer } T$
 - $\text{any } S <: \text{any } T$
- rep types** and **peer types** are **subtypes of** corresponding **any types**
 - $\text{rep } T <: \text{any } T$
 - $\text{peer } T <: \text{any } T$

```
class T { ... }
```

```
class S extends T { ... }
```

```
peer T peerT = ...
```

```
any T anyT = ...
```

```
rep S repS = ...
```

```
rep T repT = ...
```

```
repT      = repS;
```

```
anyT      = repT;
```

```
peerT     = ( peer T ) anyT;
```

```
repT      = ( rep T ) anyT;
```

```
repT      = peerT;
```

```
peerT     = repT;
```

```
repT      = anyT;
```

Subtyping and Casts

- For types with identical ownership modifier, subtyping is defined as in Java
 - $\text{rep } S <: \text{rep } T$
 - $\text{peer } S <: \text{peer } T$
 - $\text{any } S <: \text{any } T$
- rep types** and **peer types** are subtypes of corresponding **any types**
 - $\text{rep } T <: \text{any } T$
 - $\text{peer } T <: \text{any } T$

```
class T { ... }
```

```
class S extends T { ... }
```

```
peer T peerT = ...
```

```
any T anyT = ...
```

```
rep S repS = ...
```

```
rep T repT = ...
```

```
repT      = repS;
```

```
anyT      = repT;
```

```
peerT     = ( peer T ) anyT;
```

```
repT      = ( rep T ) anyT;
```

Run-time
checks

```
repT      = peerT;
```

```
peerT     = repT;
```

```
repT      = anyT;
```


Example (cont'd)

```
class LinkedList {  
  private rep Entry header;  
  public void add( any Object o ) {  
    rep Entry newE = new rep Entry( o, header, header.previous );  
    ...  
  }  
}
```

```
class Entry {  
  private any Object element;  
  private peer Entry previous, next;  
  public Entry( any Object o, peer Entry p, peer Entry n ) { ... }  
}
```

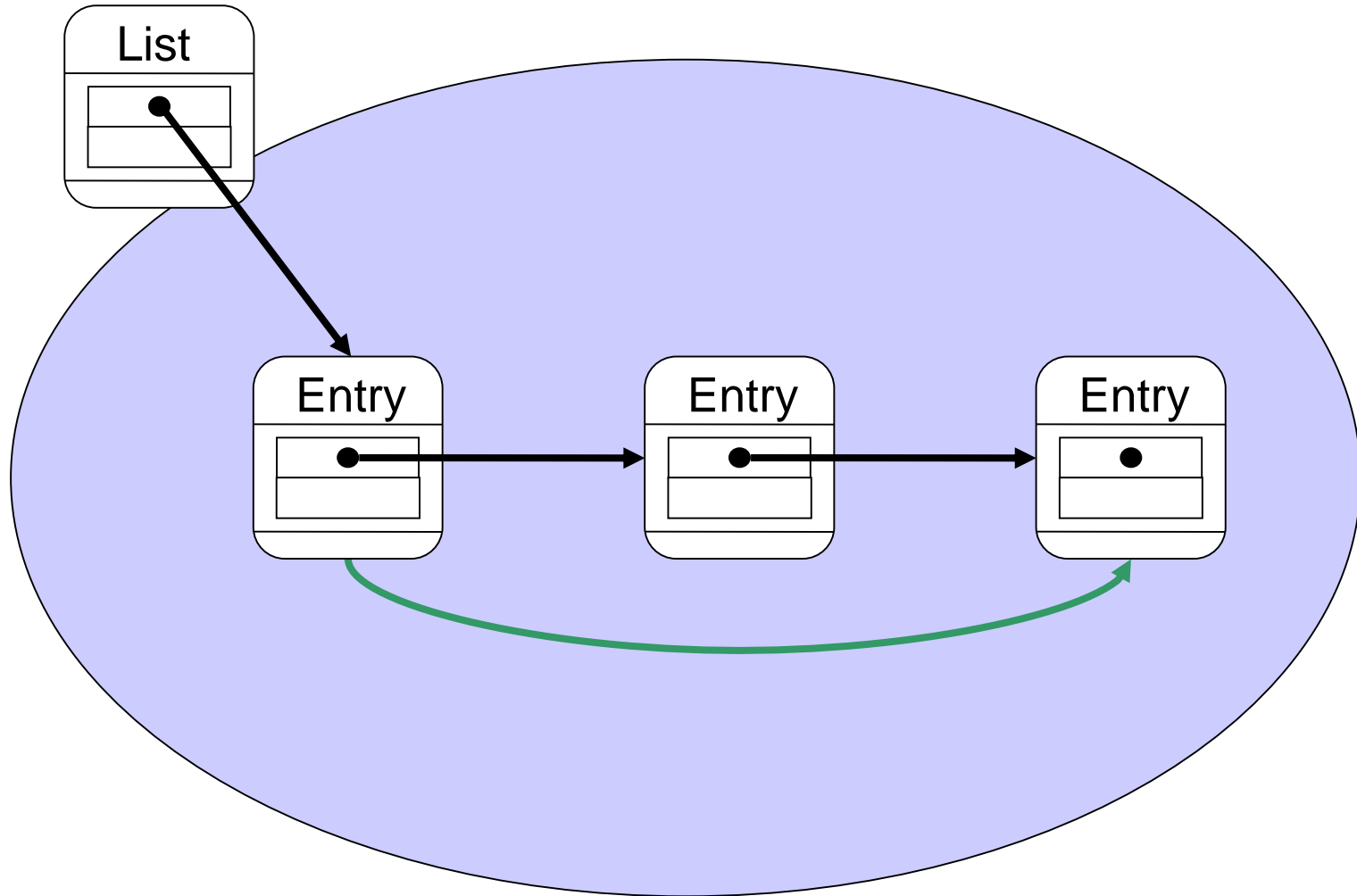
Example (cont'd)

```
class LinkedList {  
  private rep Entry header;  
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    ...  
  }  
}
```

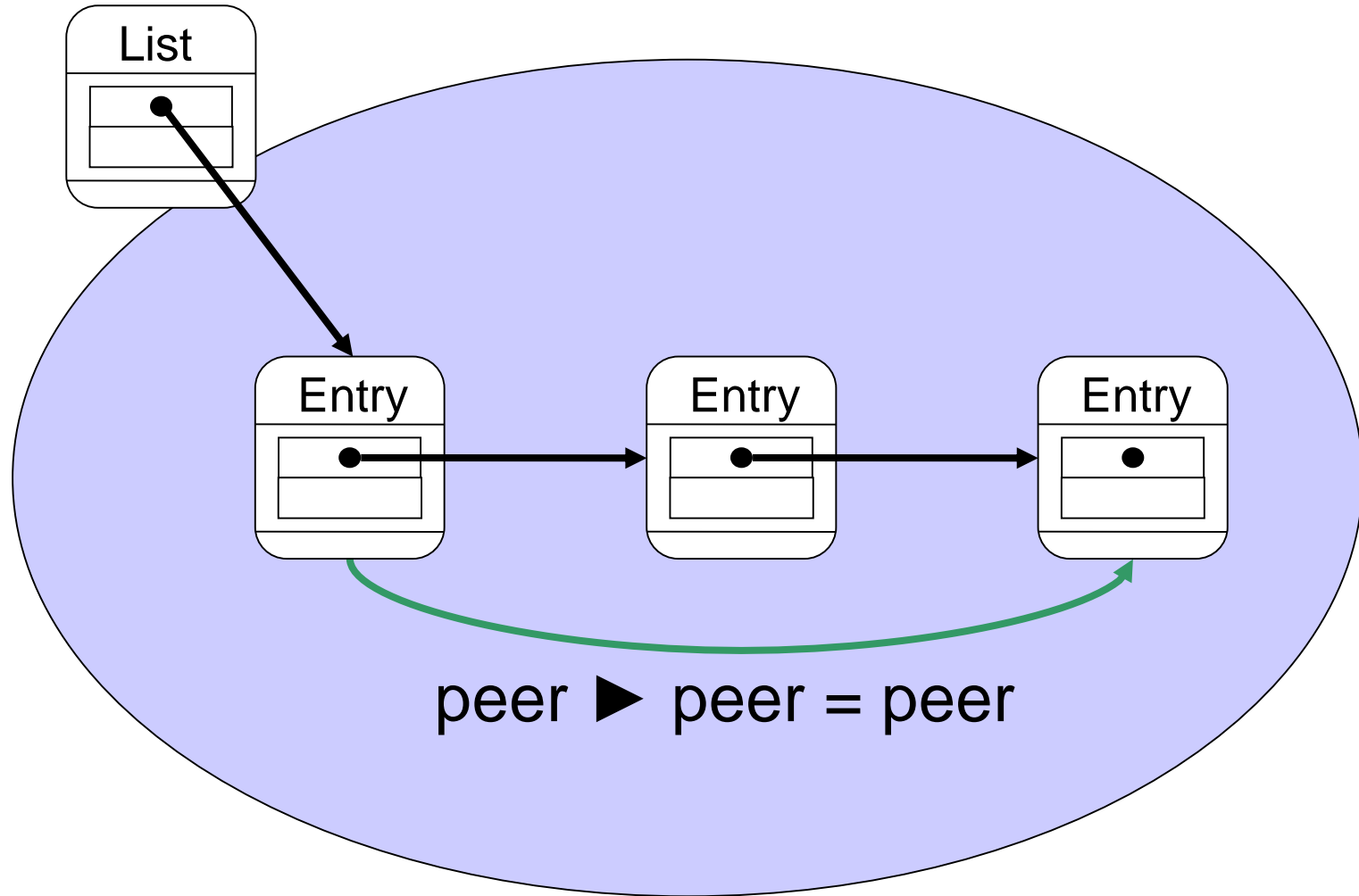
Ownership information
is relative to **this**
reference (viewpoint)

```
class Entry {  
  private any Object element;  
  private peer Entry previous, next;  
  public Entry( any Object o, peer Entry p, peer Entry n ) { ... }  
}
```

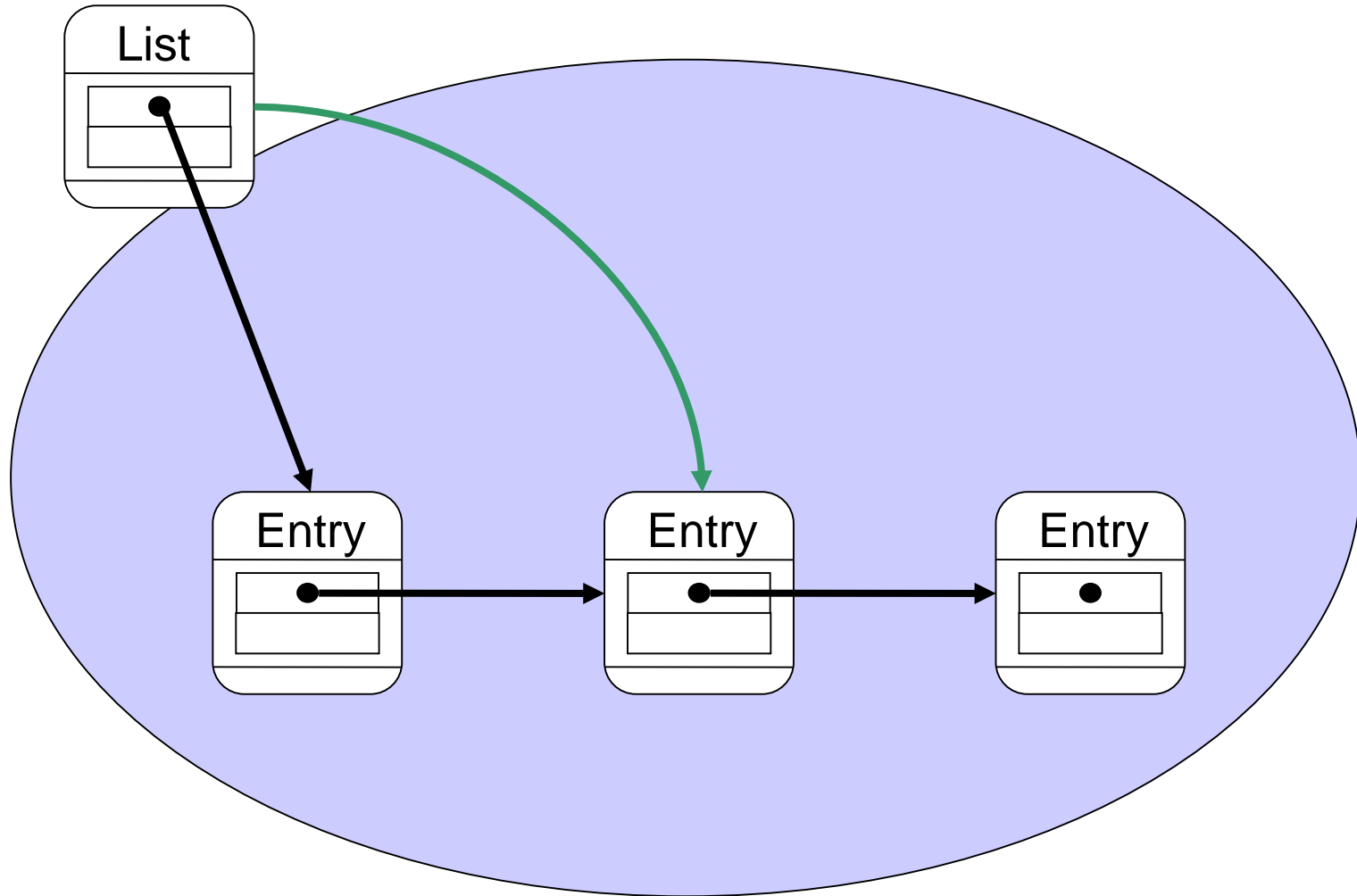
Viewpoint Adaptation: Example 1



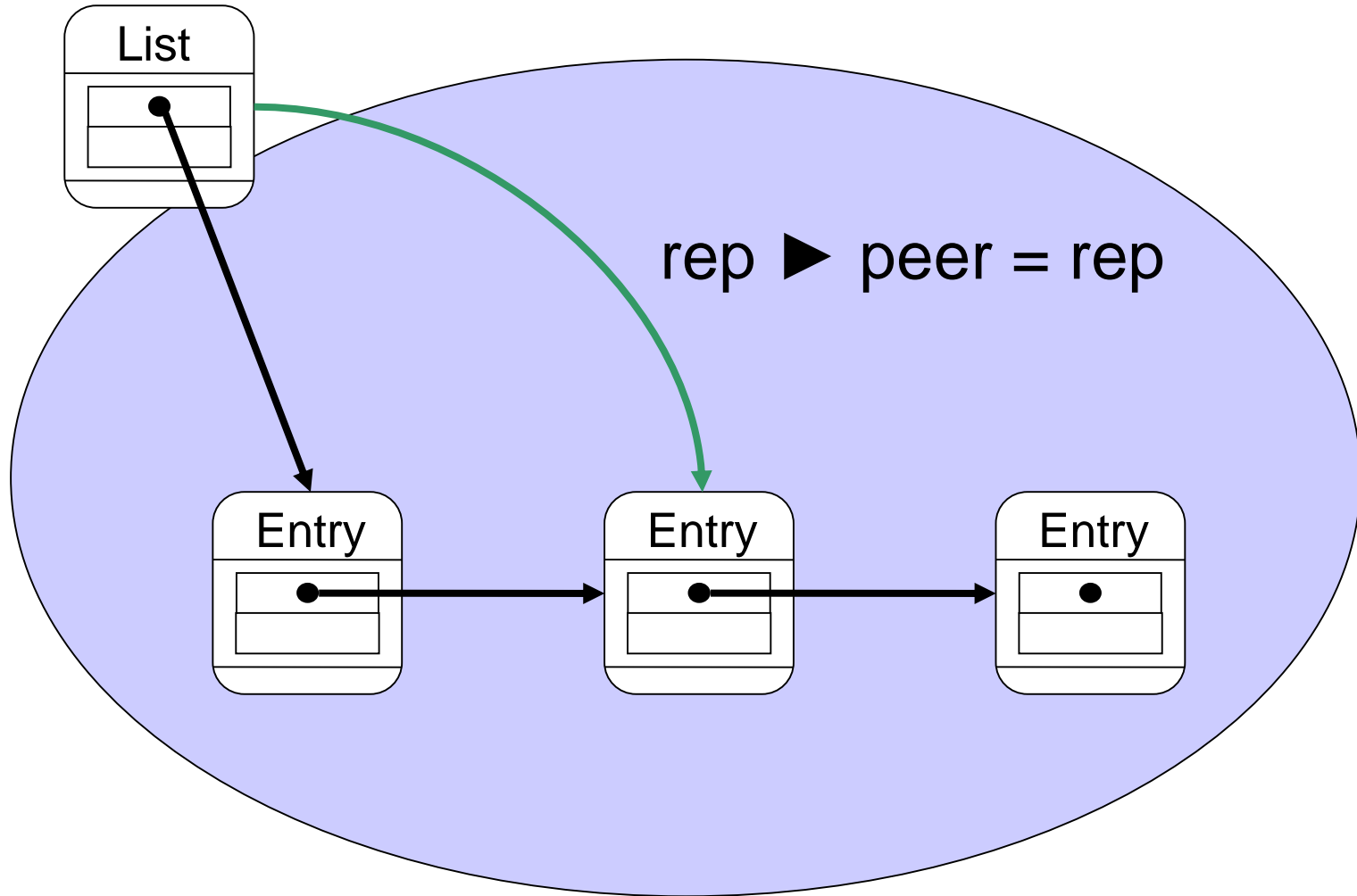
Viewpoint Adaptation: Example 1



Viewpoint Adaptation: Example 2



Viewpoint Adaptation: Example 2



Viewpoint Adaptation

►	<i>peer T</i>	<i>rep T</i>	<i>any T</i>
<i>peer S</i>	<i>peer T</i>	?	<i>any T</i>
<i>rep S</i>	<i>rep T</i>	?	<i>any T</i>
<i>any S</i>	?	?	<i>any T</i>

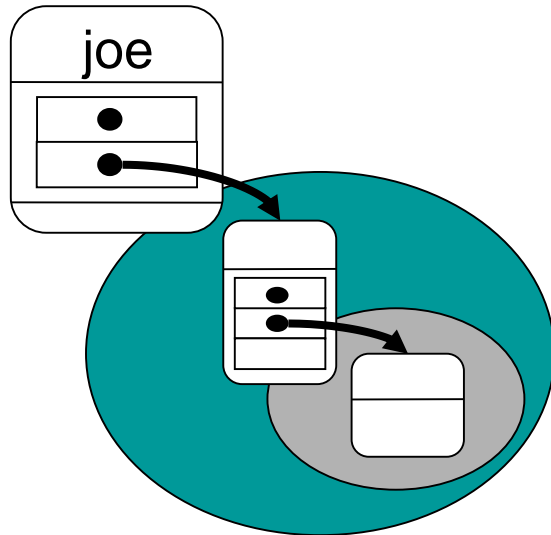
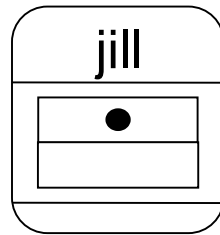
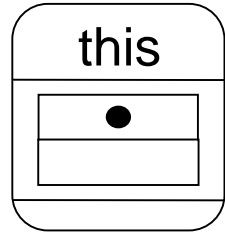
v = e.f;

$$\tau(e) \blacktriangleright \tau(f) \leq \tau(v)$$

e.f = v;

$$\tau(v) \leq \tau(e) \blacktriangleright \tau(f)$$

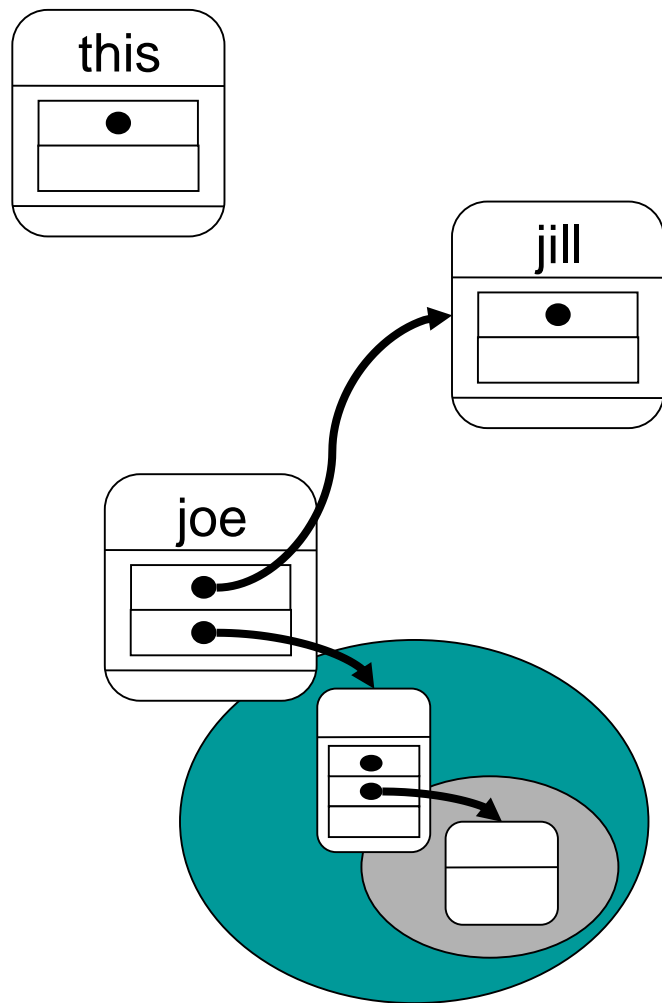
Read vs. Write Access



```
class Person {  
  public rep Address addr;  
  public peer Person spouse;  
  ...  
}
```

```
peer Person joe, jill;
```


Read vs. Write Access

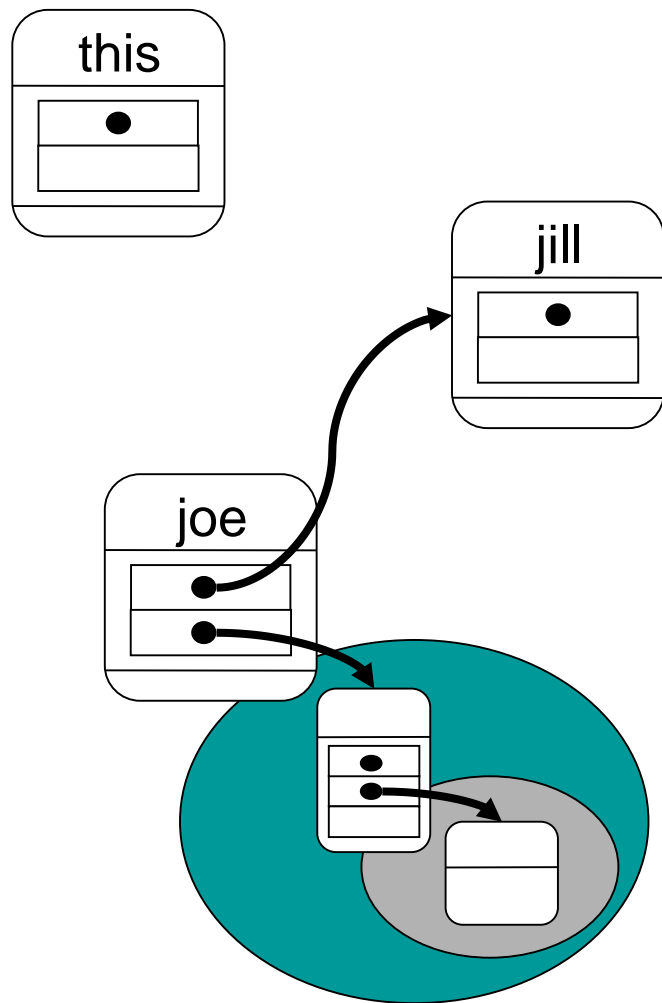


```
class Person {  
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peer Person joe, jill;
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```
joe.spouse = jill;
```

Read vs. Write Access



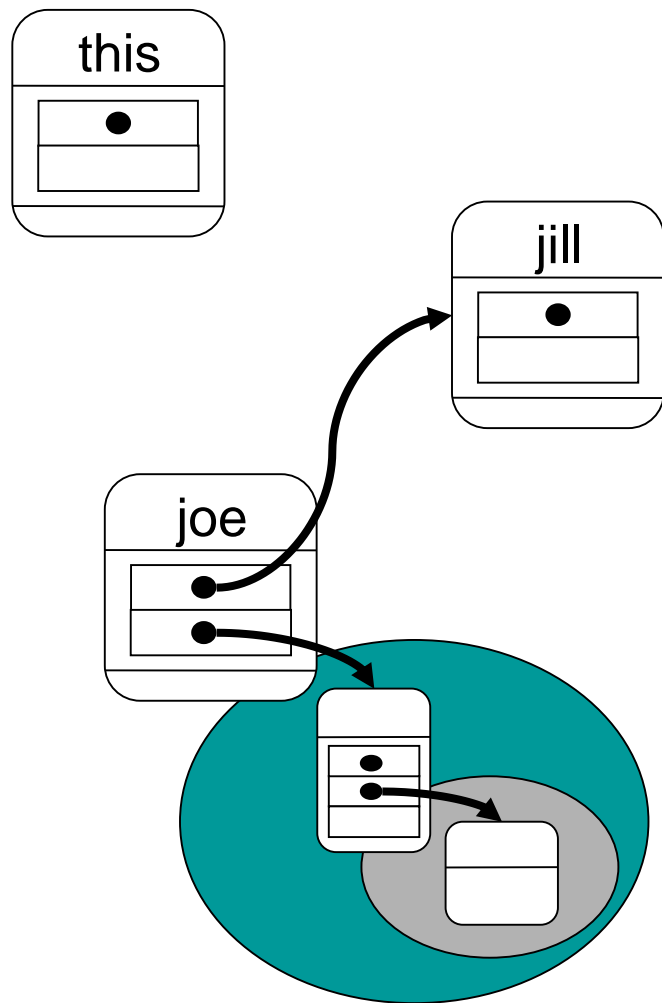
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class Person {  
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  ...  
}
```

```
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```

```
joe.spouse = jill;
```

```
any Address a = joe.addr;
```

Read vs. Write Access



```
class Person {  
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    ...  
}
```

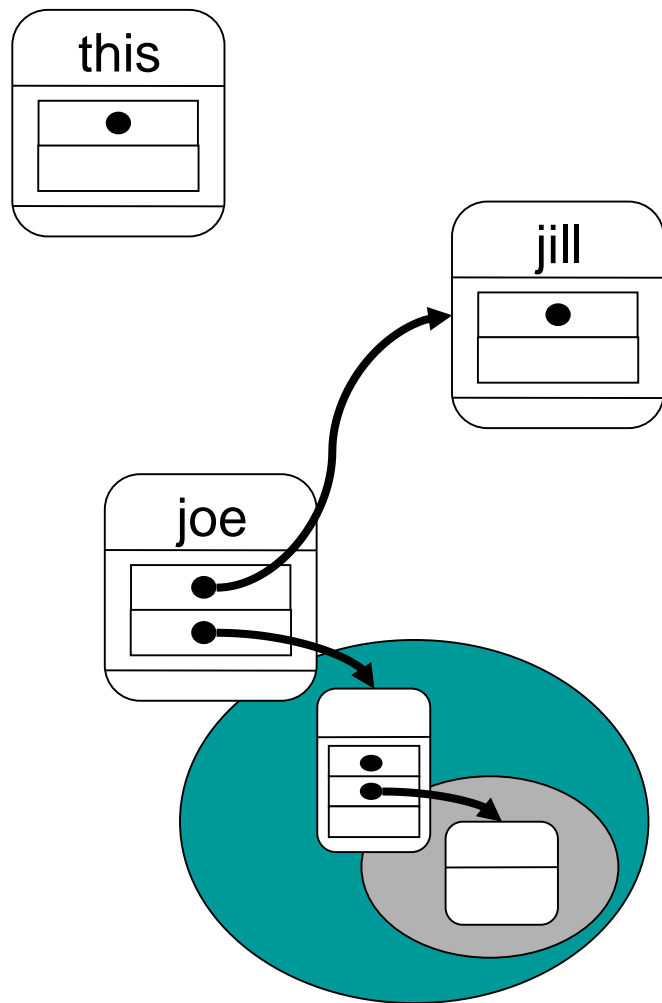
```
peer Person joe, jill;
```

```
joe.spouse = jill;
```

```
any Address a = joe.addr;
```

```
joe.addr = new rep Address( );
```

Read vs. Write Access



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class Person {  
    public rep Address addr;  
    public peer Person spouse;  
    ...  
}
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The lost Modifier

- Some ownership relations **cannot be expressed** in the type system
- Internal modifier **lost** for fixed, but unknown owner

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lost Address

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- Reading locations with lost ownership is allowed

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- Some ownership relations **cannot be expressed** in the type system
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- Updating locations with lost ownership is unsafe

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joe.spouse = jill;
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lost Address

The lost Modifier: Details

►	<i>peer T</i>	<i>rep T</i>	<i>any T</i>
<i>peer S</i>	<i>peer T</i>	<i>lost T</i>	<i>any T</i>
<i>rep S</i>	<i>rep T</i>	<i>lost T</i>	<i>any T</i>
<i>any S</i>	<i>lost T</i>	<i>lost T</i>	<i>any T</i>
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Another
existential type

The lost Modifier: Details

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<i>any S</i>	<i>lost T</i>	<i>lost T</i>	<i>any T</i>
<i>lost S</i>	<i>lost T</i>	<i>lost T</i>	<i>any T</i>

Another
existential type

■ Subtyping

- $\text{rep } T <: \text{lost } T$
- $\text{peer } T <: \text{lost } T$
- $\text{lost } T <: \text{any } T$

Type Rules: Field Access

- The field read

$$v = e.f;$$

is correctly typed if

- e is correctly typed
- $\tau(e) \blacktriangleright \tau(f) \leq \tau(v)$

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- The field write

$e.f = v;$

is correctly typed if

- e is correctly typed
- $\tau(v) <: \tau(e) \blacktriangleright \tau(f)$
- $\tau(e) \blacktriangleright \tau(f)$ does not have **lost** modifier

Type Rules: Field Access

- The field read

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$$e.f = v;$$

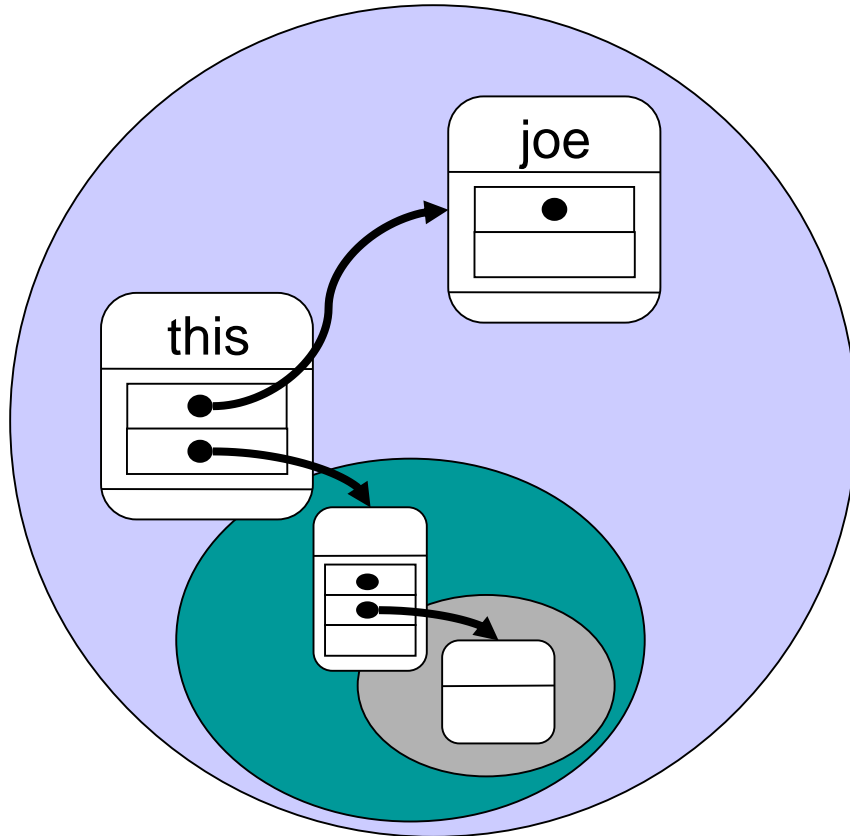
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- e is correctly typed
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- Analogous rules for method invocations

- Argument passing is analogous to field write
- Result passing is analogous to field read

The self Modifier



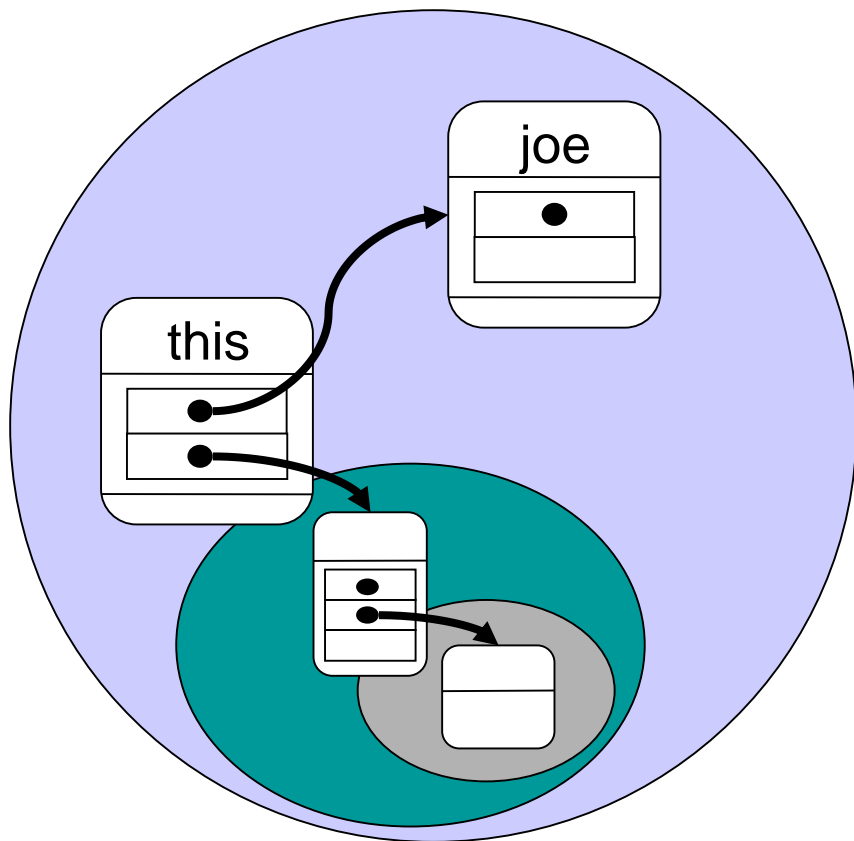
```
class Person {  
    public rep Address addr;  
    public peer Person spouse;  
    ...  
}
```

```
peer Person joe;
```

```
joe.addr = new rep Address( );
```

```
this.addr = new rep Address( );
```


The self Modifier



```
class Person {  
    public rep Address addr;  
    public peer Person spouse;  
    ...  
}
```

```
peer Person joe;
```

```
joe.addr = new rep Address( );
```

```
this.addr = new rep Address( );
```

- Internal modifier **self** only for the **this** literal

The self Modifier: Details

►	<i>peer T</i>	<i>rep T</i>	<i>any T</i>
<i>peer S</i>	<i>peer T</i>	<i>lost T</i>	<i>any T</i>
<i>rep S</i>	<i>rep T</i>	<i>lost T</i>	<i>any T</i>
<i>any S</i>	<i>lost T</i>	<i>lost T</i>	<i>any T</i>
<i>lost S</i>	<i>lost T</i>	<i>lost T</i>	<i>any T</i>
<i>self S</i>	<i>peer T</i>	<i>rep T</i>	<i>any T</i>

v = e.f;

$$\tau(e) \blacktriangleright \tau(f) <: \tau(v)$$

e.f = v;

$$\tau(v) <: \tau(e) \blacktriangleright \tau(f)$$

$\tau(e) \blacktriangleright \tau(f)$ does not have **lost** modifier

The self Modifier: Details

►	<i>peer T</i>	<i>rep T</i>	<i>any T</i>
<i>peer S</i>	<i>peer T</i>	<i>lost T</i>	<i>any T</i>
<i>rep S</i>	<i>rep T</i>	<i>lost T</i>	<i>any T</i>
<i>any S</i>	<i>lost T</i>	<i>lost T</i>	<i>any T</i>
<i>lost S</i>	<i>lost T</i>	<i>lost T</i>	<i>any T</i>
<i>self S</i>	<i>peer T</i>	<i>rep T</i>	<i>any T</i>

- Subtyping

- $\text{self } T <: \text{peer } T$

$v = e.f;$

 $\tau(e) \blacktriangleright \tau(f) <: \tau(v)$

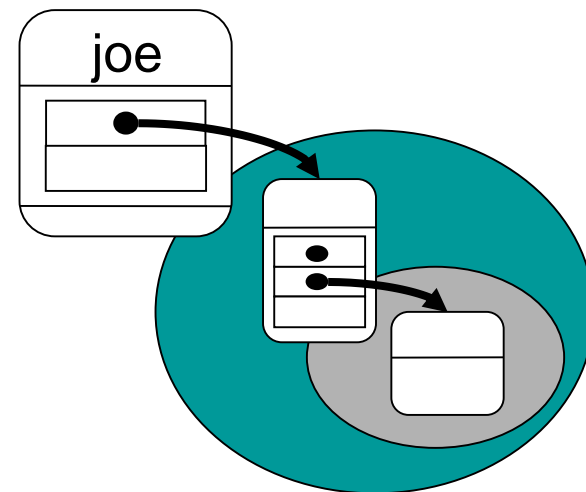
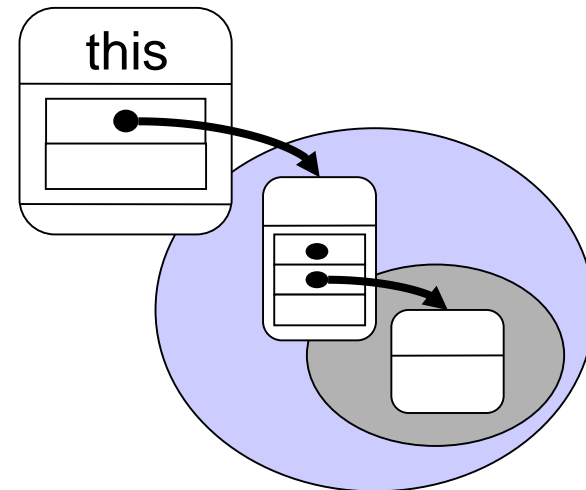
$e.f = v;$

 $\tau(v) <: \tau(e) \blacktriangleright \tau(f)$
 $\tau(e) \blacktriangleright \tau(f)$ does not have **lost** modifier

Example: Sharing

```
class Person {  
  public rep Address addr;  
  ...  
}
```

- Different Person objects have different Address objects
 - No unwanted sharing



Example: Internal vs. External Objects

```
class Person {  
    private rep Address addr;  
  
    public rep Address getAddr( ) {  
        return addr;  
    }  
  
    public void setAddr( rep Address a ) {  
        addr = a;  
    }  
  
    public void setAddr( any Address a ) {  
        addr = new rep Address( a );  
    }  
}
```

Example: Internal vs. External Objects

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class Person {  
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  public rep Address getAddr( ) {  
    return addr;  
  }  
  
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  public void setAddr( any Address a ) {  
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```

Address is part of
Person's internal
representations

Example: Internal vs. External Objects

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Address is part of
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Clients receive a
lost-reference

Example: Internal vs. External Objects

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Address is part of
Person's internal
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Clients receive a
lost-reference

Cannot be called
by clients

Example: Internal vs. External Objects

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    addr = new rep Address( a );  
  }  
}
```

Address is part of
Person's internal
representations

Clients receive a
lost-reference

Cannot be called
by clients

Cloning
necessary

Internal vs. External Objects (cont'd)

```
class Person {  
    private any Company employer;  
  
    public any Company getEmployer( ) {  
        return employer;  
    }  
  
    public void setEmployer( any Company c ) {  
        employer = c;  
    }  
}
```

Internal vs. External Objects (cont'd)

```
class Person {  
  private any Company employer;  
  
  public any Company getEmployer( ) {  
    return employer;  
  }  
  
  public void setEmployer( any Company c ) {  
    employer = c;  
  }  
}
```

Company is shared
between many
Person objects

Internal vs. External Objects (cont'd)

```
class Person {  
  private any Company employer;  
  
  public any Company getEmployer( ) {  
    return employer;  
  }  
  
  public void setEmployer( any Company c ) {  
    employer = c;  
  }  
}
```

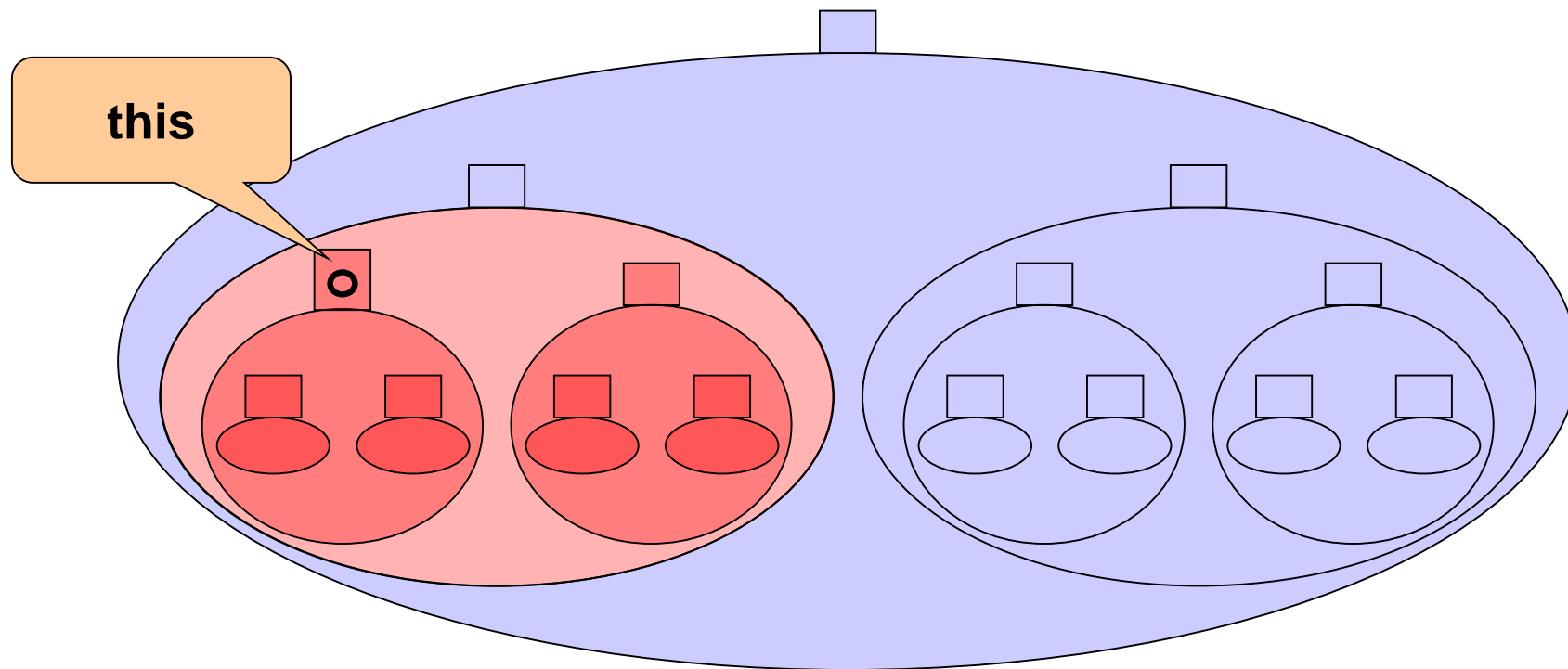
Company is shared
between many
Person objects

Can be called
by clients

Owner-as-Modifier Discipline

- Based on the ownership type system we can strengthen encapsulation with extra restrictions
 - Prevent modifications of internal objects
 - Treat **any** and **lost** as readonly types
 - Treat **self**, **peer**, and **rep** as readwrite types
- Additional rules enforce owner-as-modifier
 - Field write $e.f = v$ is valid only if $\tau(e)$ is **self**, **peer**, or **rep**
 - Method call $e.m(\dots)$ is valid only if $\tau(e)$ is **self**, **peer**, or **rep**, or called method is **pure**

Owner-as-Modifier Discipline (cont'd)



- A method may modify only objects directly or indirectly owned by the owner of the current **this** object

Internal vs. External Objects Revisited

```
class Person {  
  private rep Address addr;  
  private any Company employer;  
  
  public rep Address getAddr( ) { return addr; }  
  
  public void setAddr( any Address a ) {  
    addr = new rep Address( a );  
  }  
  
  public any Company getEmployer( ) { return employer; }  
  
  public void setEmployer( any Company c ) { employer = c; }  
}
```

Internal vs. External Objects Revisited

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class Person {  
  private rep Address addr;  
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  public rep Address getAddr( ) { return addr; }  
  
  public void setAddr( any Address a ) {  
    addr = new rep Address( a );  
  }  
  
  public any Company getEmployer( ) { return employer; }  
  
  public void setEmployer( any Company c ) { employer = c; }  
}
```

Company is shared;
cannot be modified

Internal vs. External Objects Revisited

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  public rep Address getAddr( ) { return addr; }  
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    addr = new rep Address( a );  
  }  
  
  public any Company getEmployer( ) { return employer; }  
  public void setEmployer( any Company c ) { employer = c; }  
}
```

Company is shared;
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Clients receive
(transitive)
readonly reference

Internal vs. External Objects Revisited

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class Person {  
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  public rep Address getAddr( ) { return addr; }  
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    addr = new rep Address( a );  
  }  
  
  public any Company getEmployer( ) { return employer; }  
  public void setEmployer( any Company c ) { employer = c; }  
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Accidental capturing
is prevented

Achievements

- **rep** and **any** types enable encapsulation of whole object structures

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- **rep** and **any** types enable encapsulation of whole object structures
- Encapsulation cannot be violated by subclasses, via casts, etc.

```
class ArrayList {  
    protected rep int[ ] array;  
    private int next;  
  
    ...  
}
```

```
class MyList extends ArrayList {  
    public peer int[ ] leak( ) {  
        return array;  
    }  
}
```

Achievements

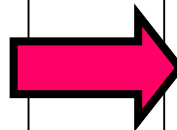
- **rep** and **any** types enable **encapsulation of whole object structures**
- Encapsulation **cannot be violated** by subclasses, via casts, etc.
- The technique **fully supports subclassing**
 - In contrast to solutions with private inner or final classes, etc.

```
class ArrayList {  
    protected rep int[ ] array;  
    private int next;  
  
    ...  
}
```

```
class MyList extends ArrayList {  
    public peer int[ ] leak( ) {  
        return array;  
    }  
}
```

Exchanging Implementations

```
class ArrayList {  
  private int[ ] array;  
  private int next;  
  
  // requires ia != null  
  // ensures  $\forall i. 0 \leq i < \text{ia.length}:$   
  //           isElem( old( ia[ i ] ) )  
  public void setElems( int[ ] ia )  
    { array = ia; next = ia.length; }  
  
  ...  
}
```



```
class ArrayList {  
  private Entry header;  
  
  // requires ia != null  
  // ensures  $\forall i. 0 \leq i < \text{ia.length}:$   
  //           isElem( old( ia[ i ] ) )  
  public void setElems( int[ ] ia )  
    { ... /* create Entry for each  
          element */ }  
  
  ...  
}
```

- Interface including contract remains unchanged

Exchanging Implementations (cont'd)

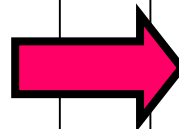
```

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

  // requires ia != null
  // ensures  $\forall i. 0 \leq i < \text{ia.length}:$ 
  //           isElem( old( ia[ i ] ) )
  public void
  setElems( any int[ ] ia )
  { System.arraycopy(...);
    next = ia.length; }

  ...
}

```



```

class ArrayList {
  private rep Entry header;

  // requires ia != null
  // ensures  $\forall i. 0 \leq i < \text{ia.length}:$ 
  //           isElem( old( ia[ i ] ) )
  public void
  setElems( any int[ ] ia )
  { ... /* create Entry for each
        element */ }

  ...
}

```

Exchanging Implementations (cont'd)

```

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

  // requires ia != null
  // ensures  $\forall i. 0 \leq i < \text{ia.length}:$ 
  //           isElem( old( ia[ i ] ) )
  public void
  setElems( any int[ ] ia )
  { System.arraycopy(...);
    next = ia.length; }

  ...
}

```

Accidental capturing
is prevented

```

class ArrayList {
  private rep Entry header;

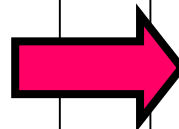
  // requires ia != null
  // ensures  $\forall i. 0 \leq i < \text{ia.length}:$ 
  //           isElem( old( ia[ i ] ) )
  public void
  setElems( any int[ ] ia )
  { ... /* create Entry for each
        element */ }

  ...
}

```


Exchanging Implementations (cont'd)

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

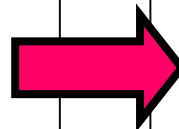


```
class ArrayList {  
  private rep Entry header;  
  
  public void any int[ ] getElems( )  
    { /* create new array */ }  
  ...  
}
```

Exchanging Implementations (cont'd)

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

Leaking is still
possible



```
class ArrayList {  
  private rep Entry header;  
  
  public void any int[ ] getElems( )  
  { /* create new array */ }  
  ...  
}
```

Exchanging Implementations (cont'd)

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

  public any int[ ] getElems( )
  { return array; }
  ...
}
```

Leaking is still possible

```
class ArrayList {
  private rep Entry header;

  public void any int[ ] getElems( )
  { /* create new array */ }
  ...
}
```

```
peer ArrayList list = new peer ArrayList( );
list.prepend( 0 );
any int[ ] ia = list.getElems( );
list.prepend( 1 );
assert ia[ 0 ] == 1;
```

Exchanging Implementations (cont'd)

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

  public any int[ ] getElems( )
  { return array; }

  ...
}
```

Leaking is still possible

```
class ArrayList {
  private rep Entry header;

  public void any int[ ] getElems( )
  { /* create new array */ }

  ...
}
```

```
peer ArrayList list = new peer ArrayList( );
list.prepend( 0 );
any int[ ] ia = list.getElems( );
list.prepend( 1 );
assert ia[ 0 ] == 1;
```

- Observable behavior is changed

Consistency of Object Structures

- Consistency of object structures depends on fields of several objects
- Invariants are usually specified as part of the contract of those objects that represent the interface of the object structure

```
class ArrayList {  
    private int[ ] array;  
    private int next;  
  
    // invariant array != null    &&  
    //  0<=next<=array.length  &&  
    //   $\forall i. 0 \leq i < \text{next}: \text{array}[i] \geq 0$   
  
    public void add( int i )    { ... }  
    public void setElems( int[ ] ia )  
        { ... }  
  
    ...  
}
```

Invariants for Object Structures

- The invariant of object *o* **may depend on**
 - Encapsulated fields of *o*
 - Fields of objects (transitively) owned by *o*
- Interface objects have **full control** over their rep-objects

```
class ArrayList {  
    private rep int[ ] array;  
    private int next;  
  
    // invariant array != null    &&  
    //  0<=next<=array.length    &&  
    //   $\forall i. 0 \leq i < \text{next}: \text{array}[i] \geq 0$   
  
    public void add( int i )    { ... }  
    public void setElems  
        ( any int[ ] ia )    { ... }  
  
    ...  
}
```

Security Breach in Java 1.1.1

```
class Malicious {
```

```
  void bad( ) {
```

```
    Identity[ ] s;
```

```
    Identity trusted = java.Security...;
```

```
    s = Malicious.class.getSigners( );
```

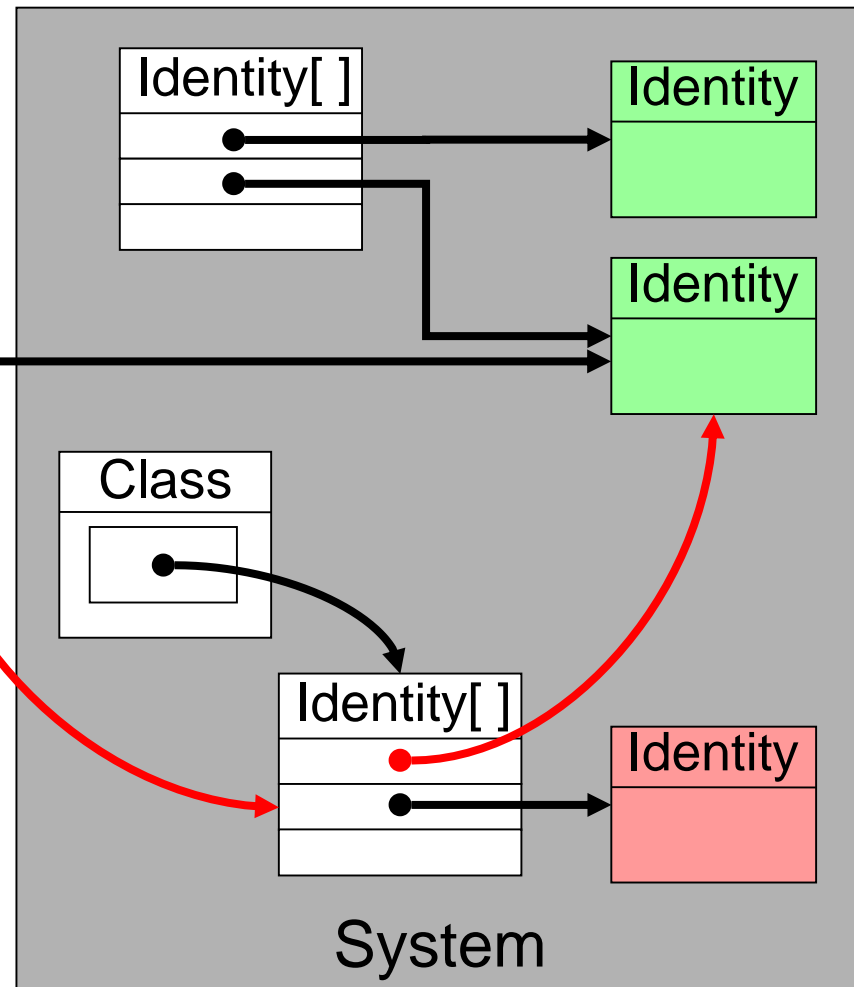
```
    s[ 0 ] = trusted;
```

```
    /* abuse privilege */
```

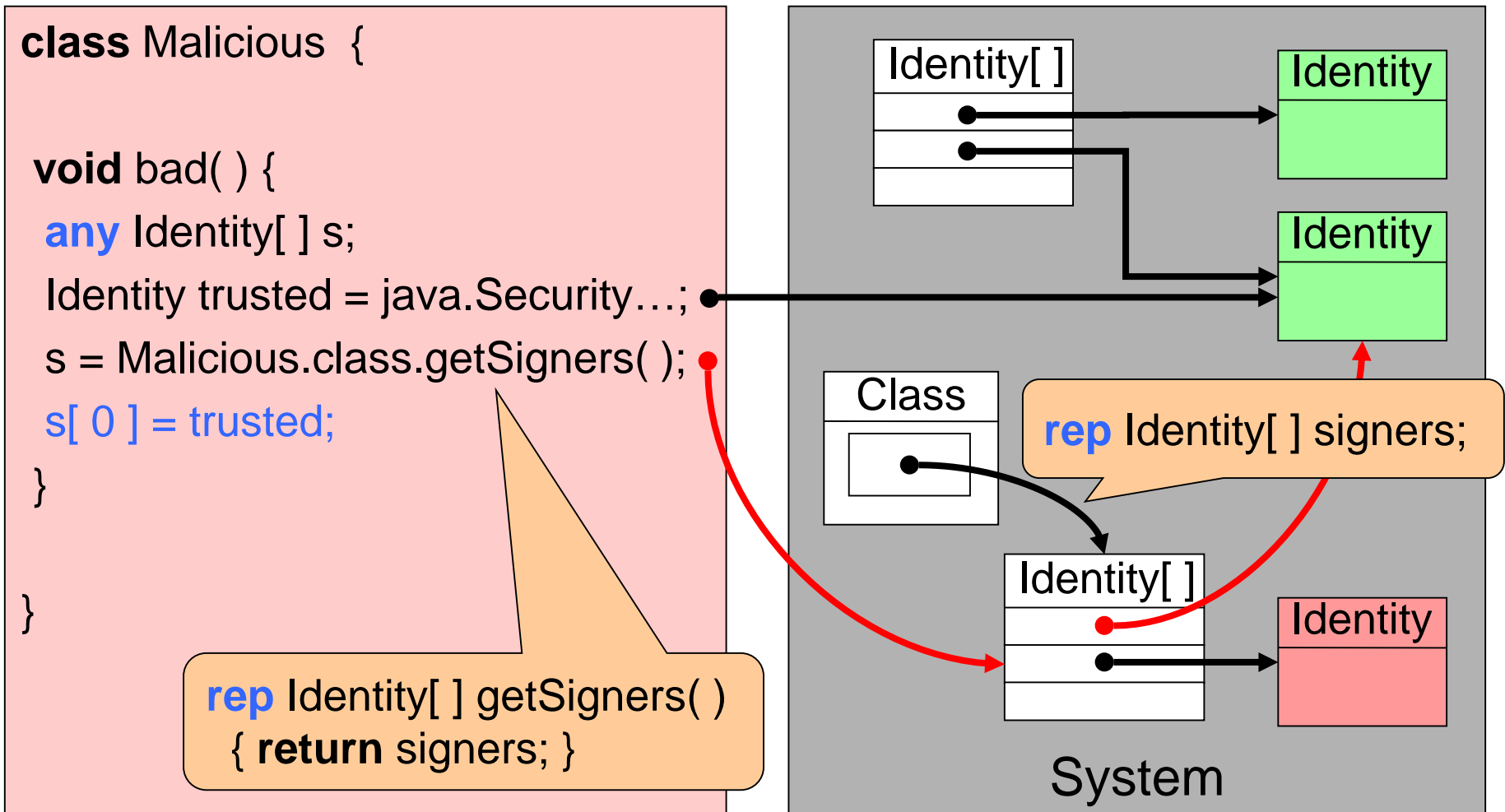
```
  }
```

```
}
```

Identity[] getSigners()
{ **return** signers; }



Security Breach in Java 1.1.1 (cont'd)



Ownership Types: Discussion

- Ownership types express **heap topologies** and enforce **encapsulation**
- Owner-as-modifier is helpful to **control side effects**
 - Maintain object invariants
 - Prevent unwanted modifications
- Other applications also need **restrictions of read access**
 - Exchange of implementations
 - Thread synchronization

References

- Werner Dietl and Peter Müller: *Universes: Lightweight Ownership for JML*. Journal of Object Technology, 2005
- Werner Dietl, Sophia Drossopoulou, and Peter Müller: *Separating Ownership Topology and Encapsulation with Generic Universe Types*. ACM Trans. Program. Lang. Syst., 2011