Concepts of Object-Oriented Programming

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Chair of Programming Methodology

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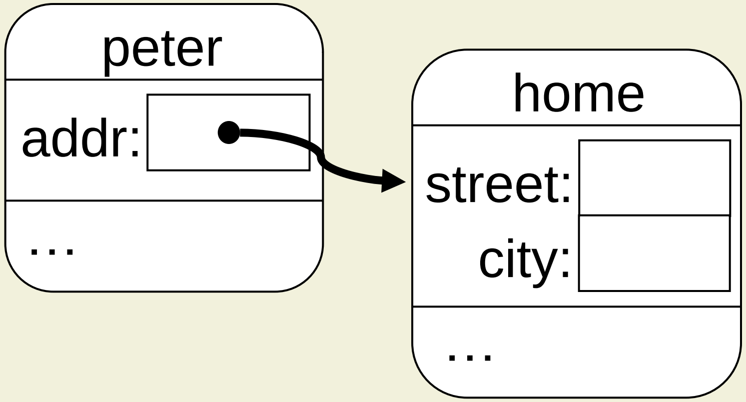
7. Ownership Types

Object Structures Revisited

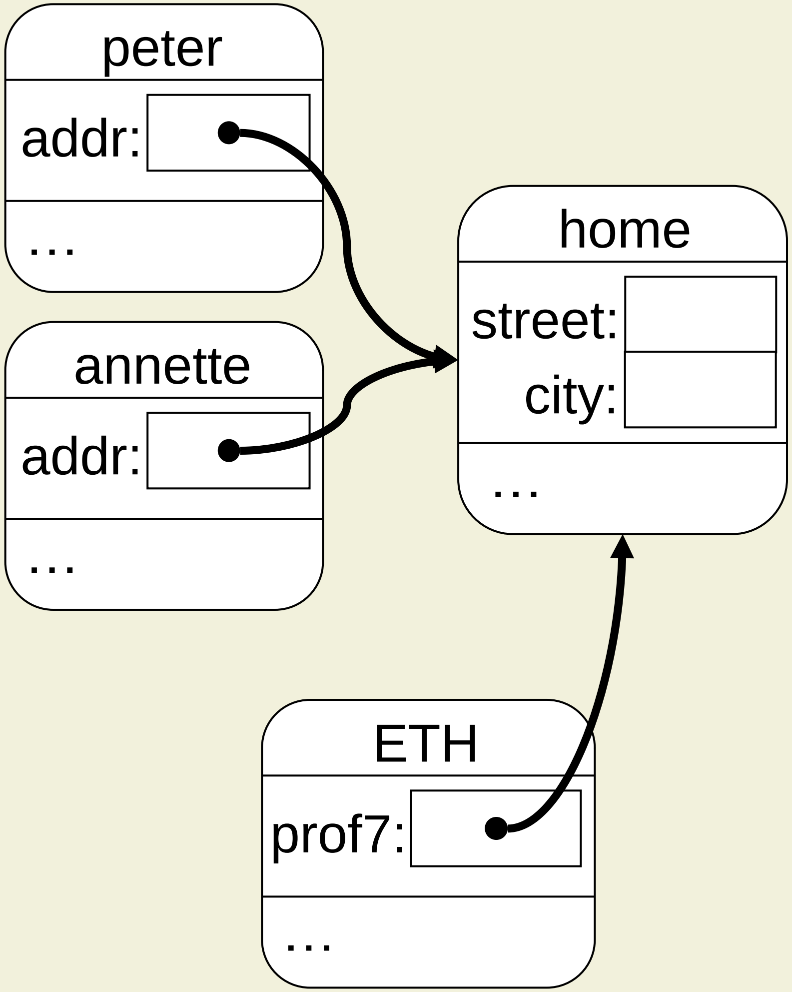
```
class Address {
  private String street;
  private String city;

  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( ); }
  …
}
```



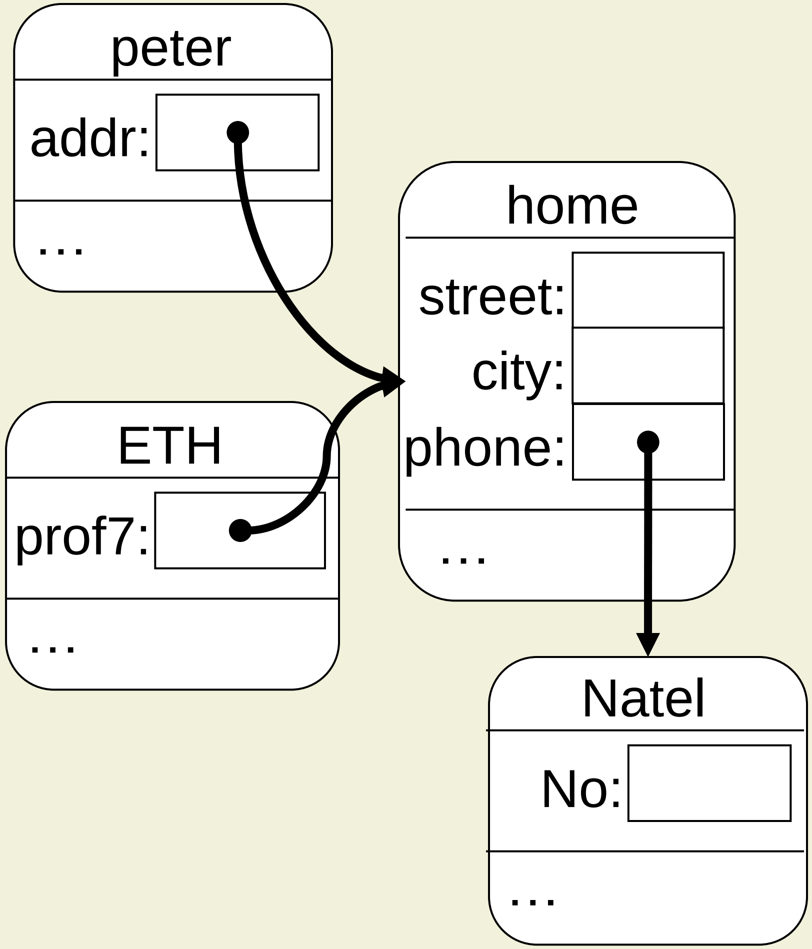
Drawbacks of Alias Prevention

- 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 */ }
```

```
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
- 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
- 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

```
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

```
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

```
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++

```
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++

const functions may modify objects other than the receiver

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 for 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 only be overridden 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

```
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*
- 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; }
  …
}
```

- 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 invocation

  is determined by the type combinator ►

►	*rw T*	*ro T*
rw S	*rw T*	*ro T*
ro S	*ro T*	*ro T*

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

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

ro Address ► *rw int[ ]*

ro int[ ]

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Type Rules: Transitive Readonly (cont'd)

- The type of
  - A field access
  - An array access
  - A method invocation

  is determined by the type combinator ▶

▶	*rw T*	*ro T*
rw S	*rw T*	*ro T*
ro S	*ro T*	*ro T*

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

- Readonly types must not be cast to readwrite types

```
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
- All rules for pure methods and readonly types can be checked statically by a compiler
- Readwrite aliases can still occur, e.g., by capturing

7. Ownership Types

Object Topologies

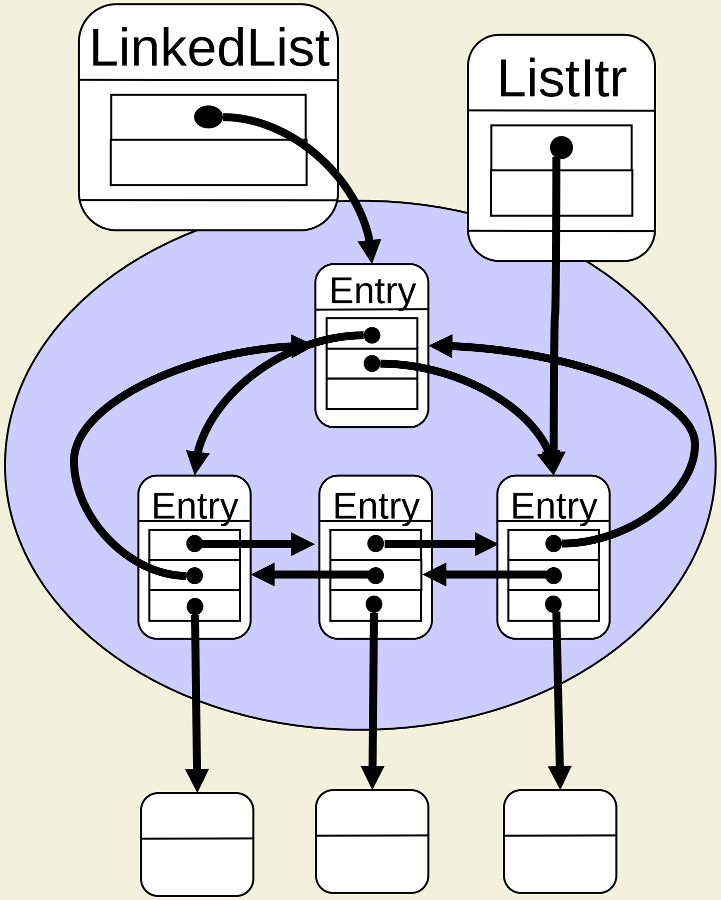
- Read-write aliases can still occur, e.g., by capturing or leaking
- We need to distinguish “internal” references from other references

```
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; }
  …
}
```

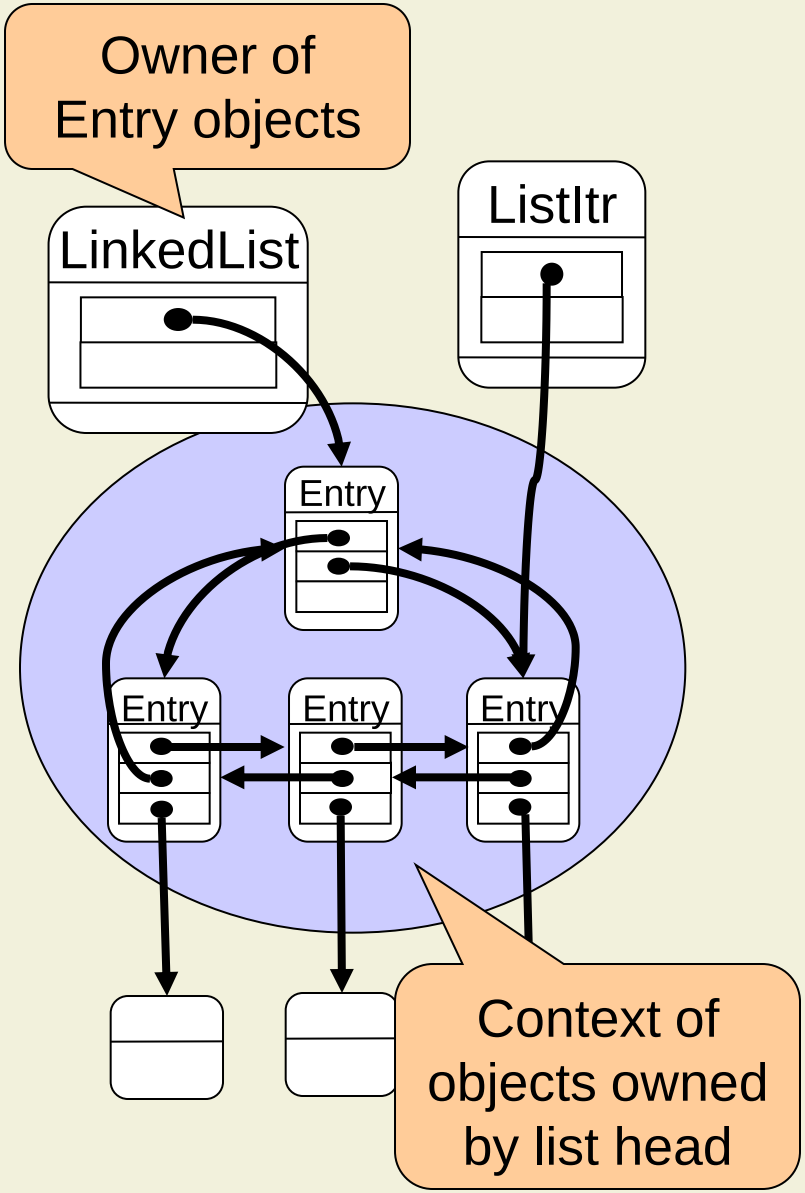
Roles in Object Structures

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



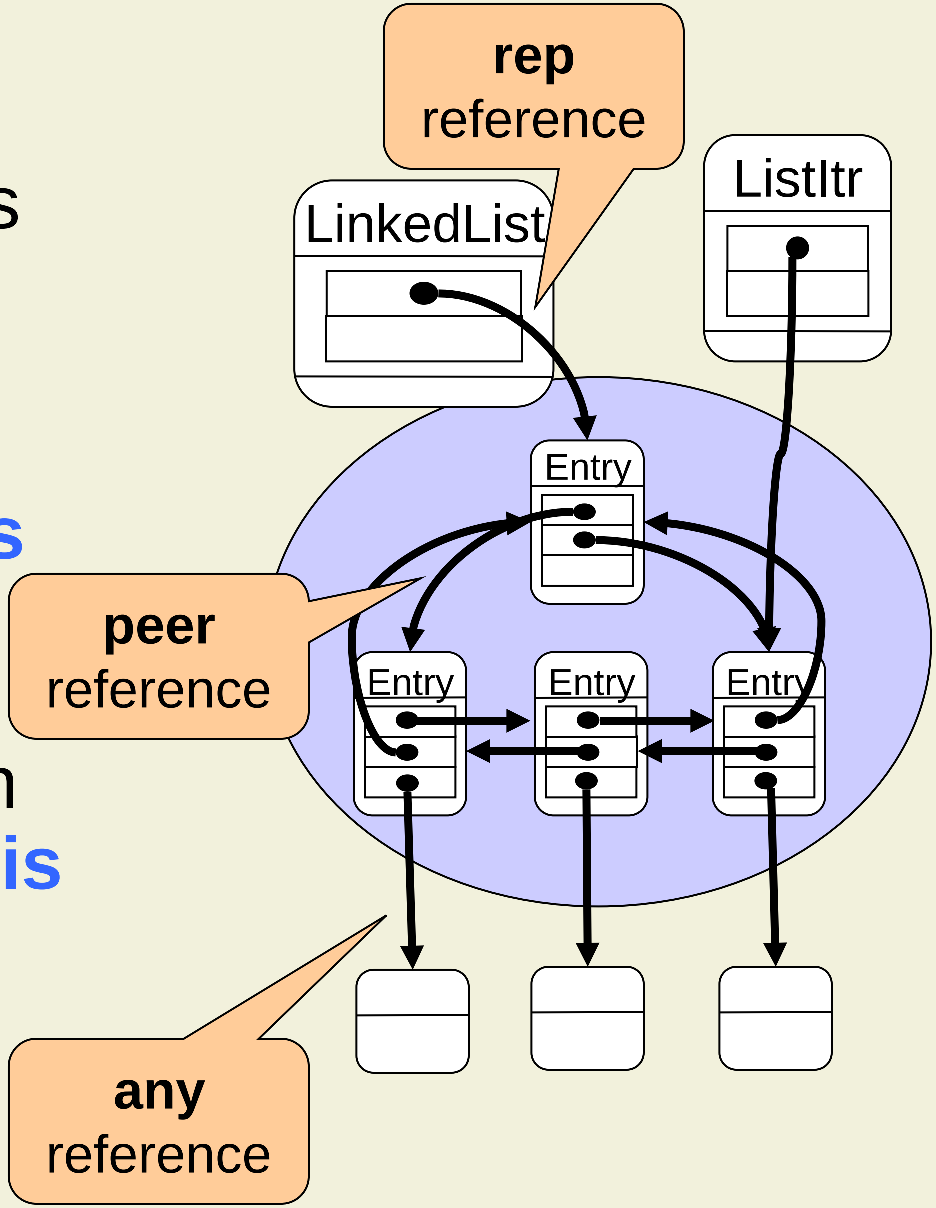
Ownership Model

- 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



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



Example

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

A list owns its nodes

Lists store elements with arbitrary owners

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

All nodes have the same owner

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

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*
- **rep** types and **peer** types are subtypes of corresponding **any** types
  - *rep T <: any T*
  - *peer T <: 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;
```

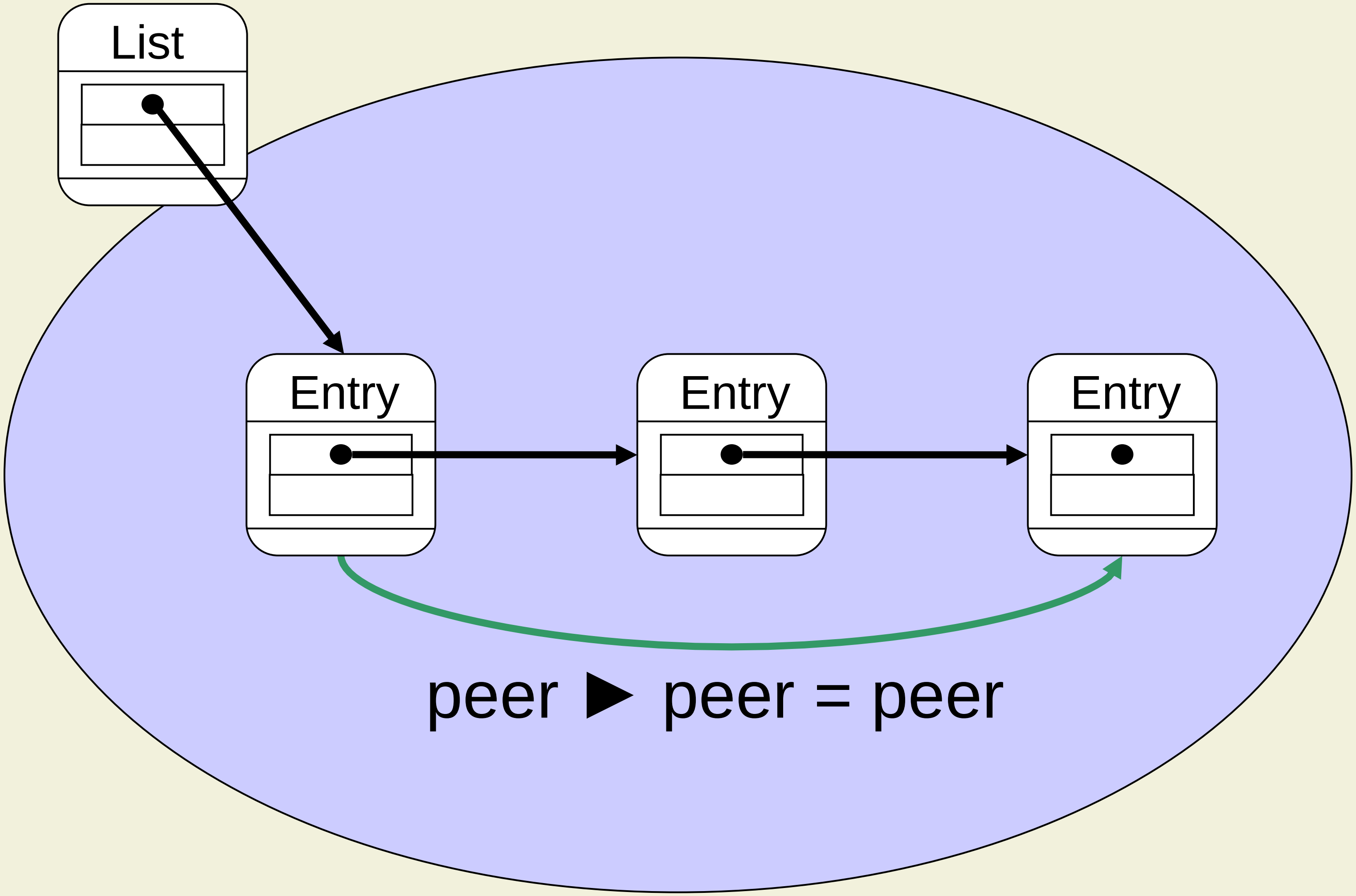
Example (cont'd)

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

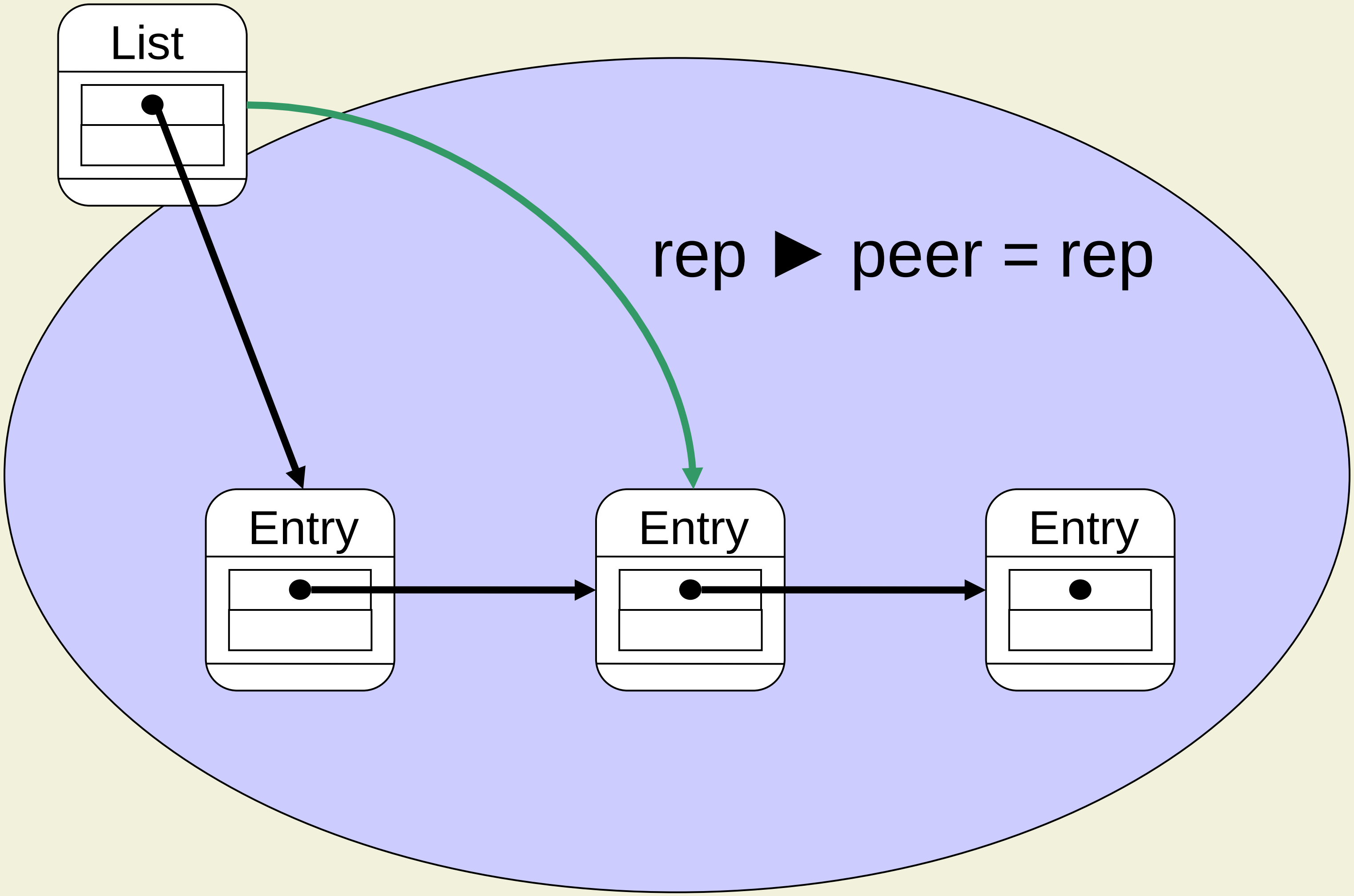
Ownership information is relative to **this** reference (viewpoint)

```
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 2



Viewpoint Adaptation

▶	*peer T*	*rep T*	*any T*
peer S	*peer T*	*?*	*any T*
rep S	*rep T*	*?*	*any T*
any S	*?*	*?*	*any T*

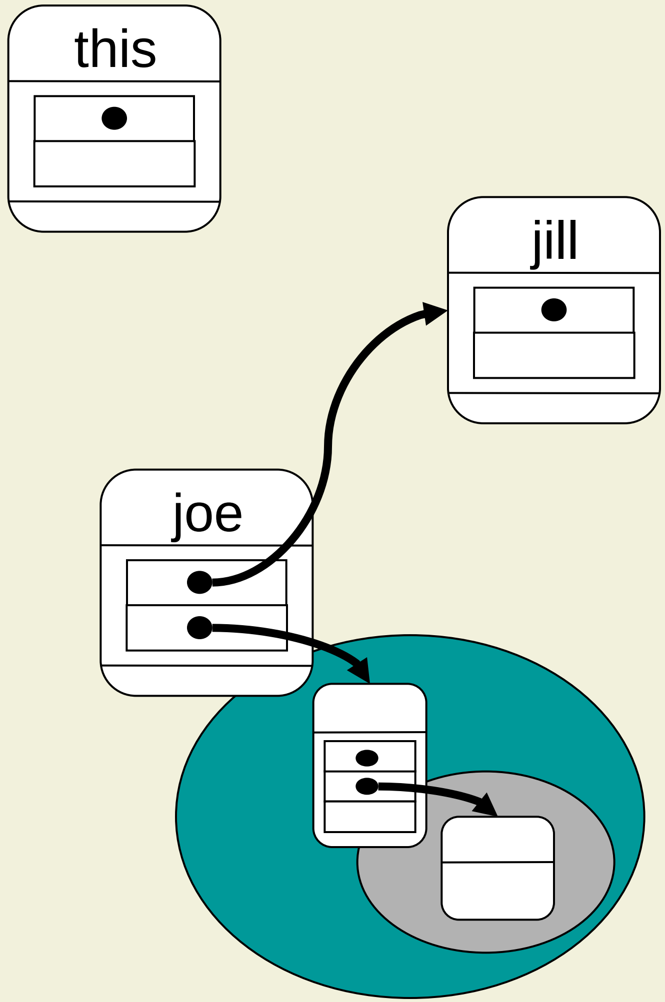
$$\boxed{v = e.f;}$$

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

$$\boxed{e.f = v;}$$

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

Read vs. Write Access




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

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

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

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

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

The lost Modifier

- Some ownership relations cannot be expressed in the type system
- Internal modifier **lost** for fixed, but unknown owner
- Reading locations with lost ownership is allowed
- Updating locations with lost ownership is unsafe

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

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

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

lost Address

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

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

lost Address

The lost Modifier: Details

▶	*peer T*	*rep T*	*any T*
peer S	*peer T*	*lost T*	*any T*
rep S	*rep T*	*lost T*	*any T*
any S	*lost T*	*lost T*	*any T*
lost S	*lost T*	*lost T*	*any T*

Another existential type

- Subtyping
  - *rep T <: lost T*
  - *peer T <: lost T*
  - *lost T <: any T*

Type Rules: Field Access

- The field read

  `v = e.f;`

  is correctly typed if
  - e is correctly typed
  - $\tau(\, e\,) \blacktriangleright \tau(\, f\,) <: \tau(\, v\,)$

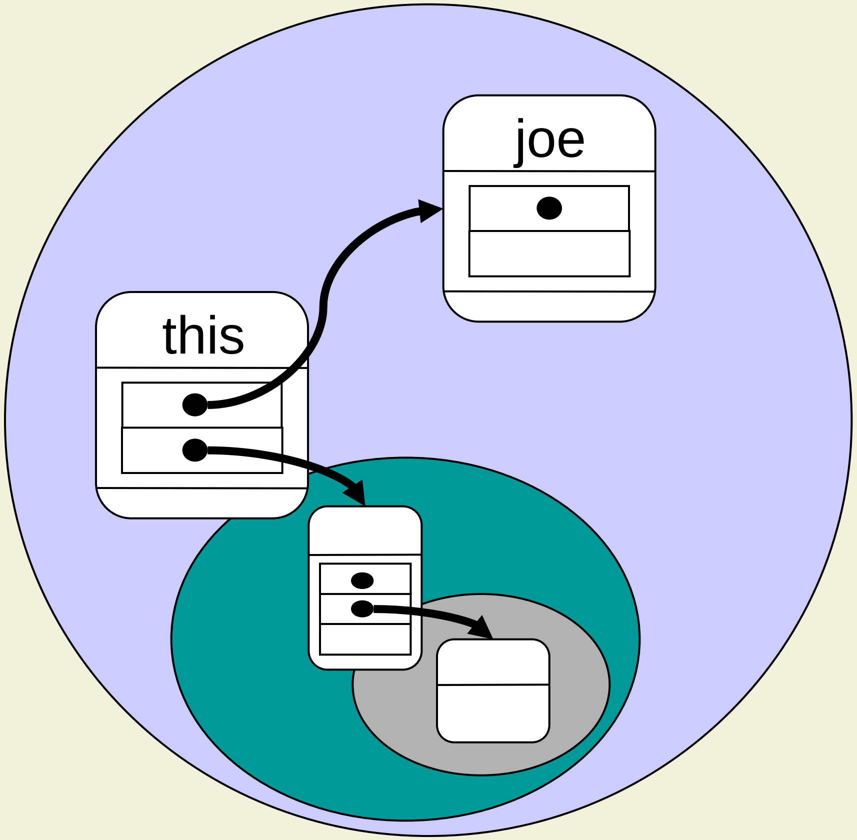
- The field write

  `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

- 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( );
```

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

The self Modifier: Details

▶	*peer T*	*rep T*	*any T*
peer S	*peer T*	*lost T*	*any T*
rep S	*rep T*	*lost T*	*any T*
any S	*lost T*	*lost T*	*any T*
lost S	*lost T*	*lost T*	*any T*
self S	*peer T*	*rep T*	*any T*

$\boxed{v = e.f;}$

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

$\boxed{e.f = v;}$

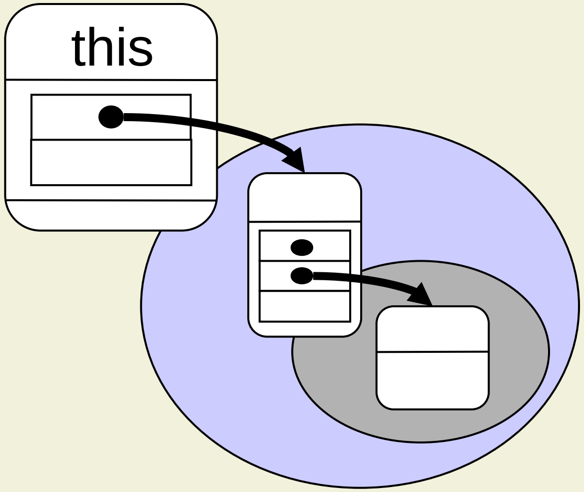
$\tau(v) <: \tau(e) \blacktriangleright \tau(f)$

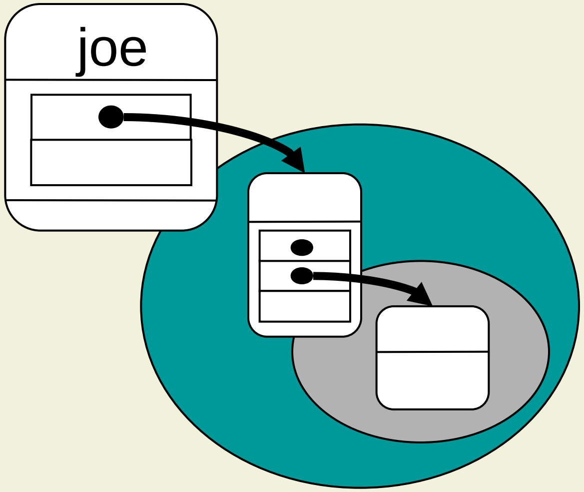
$\tau(e) \blacktriangleright \tau(f)$ does not have **lost** modifier

- Subtyping
  - *self T <: peer T*

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 );
  }
}
```

Address is part of Person's internal represenations

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;
  }
}
```

Company is shared between many Person objects

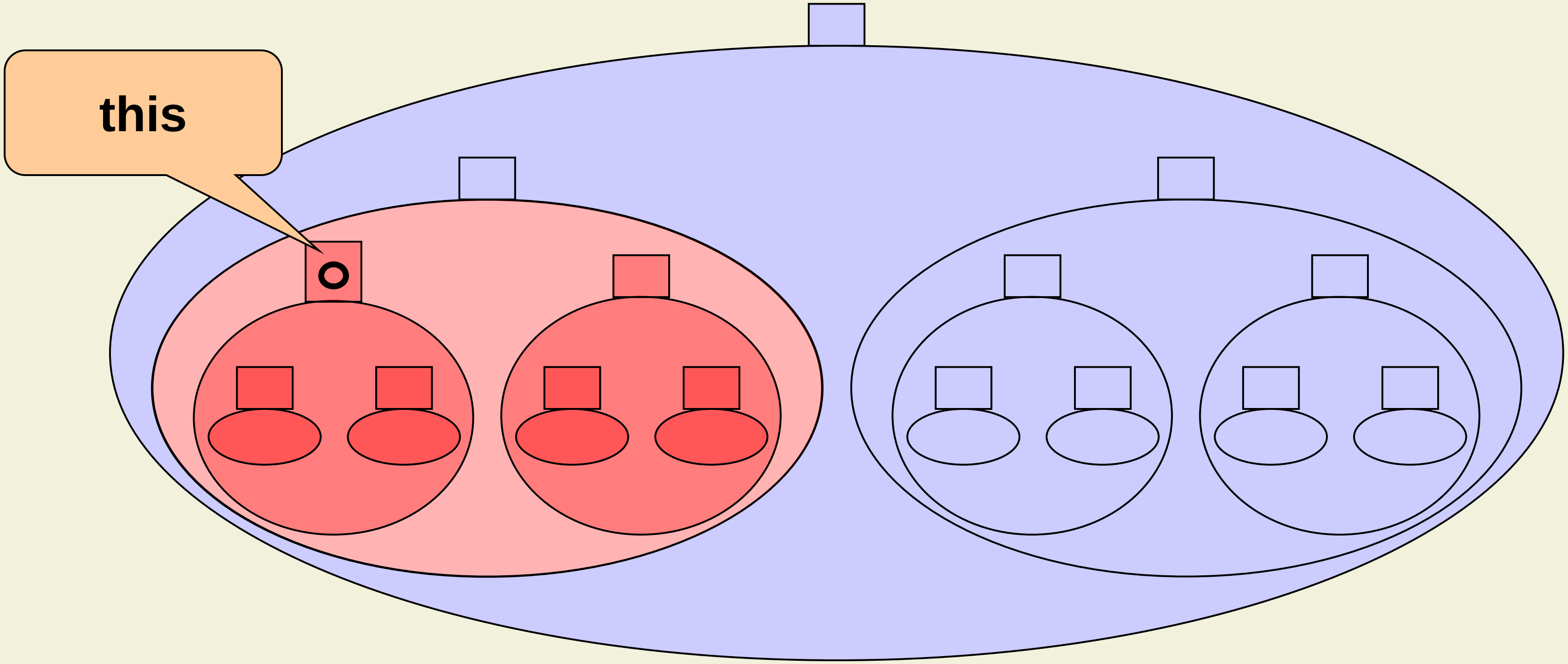
Can be called by clients

Owner-as-Modifier Discipline

- Based on the topological 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 τ(e) is **self**, **peer**, or **rep**
  - Method call e.m(…) is valid only if τ(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; }
}
```

Company is shared; cannot be modified

Clients receive (transitive) readonly reference

Accidental capturing is prevented

(Simplified) Programming Discipline

- Rule 1: No Role Confusion
  - Expression with one alias mode must not be a variables with another mode, except to an arg variable

> Different types for different roles

- Rule 2: No Representation Exposure
  - rep-mode must not occur in an object's interfa
  - Methods must not take or return rep-objects
  - Fields with rep-mode may only be accessed on **this**

> Viewpoint adaptation for **rep** types

- Rule 3: No Argument Dependence
  - Implementations must not depend on the sta argument objects

> Like with programming discipline

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 final, private inner 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 ∀i. 0<=i<ia.length:
  //            isElem( old( ia[ i ] ) )
  public void addElems( int[ ] ia )
    { array = ia; next = ia.length; }

  …
}
```

```
class ArrayList {
  private Entry header;


  // requires ia != null
  // ensures ∀i. 0<=i<ia.length:
  //            isElem( old( ia[ i ] ) )
  public void addElems( 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 ∀i. 0<=i<ia.length:
  //              isElem( old( ia[ i ] ) )
  public void
  addElems( any int[ ] ia )
   { System.arraycopy(…);
     next = ia.length; }
  …
}
```

```
class ArrayList {
  private rep Entry header;


  // requires ia != null
  // ensures ∀i. 0<=i<ia.length:
  //              isElem( old( ia[ i ] ) )
  public void
  addElems( any int[ ] ia )
   { … /* create Entry for each
           element */ }
  …
}
```

Accidental capturing is prevented

Exchanging Implementations (cont'd)

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

  public any int[ ] getElems( )
    { return ia; }
  …
}
```

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   &&
  //    ∀i.0<=i<next: array[ i ] >= 0

  public void add( int i )    { … }
  public void addElems( 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   &&
  //   ∀i.0<=i<next: array[ i ] >= 0

  public void add( int i )   { … }
  public void addElems
       ( any int[ ] ia )   { … }

  …
}
```

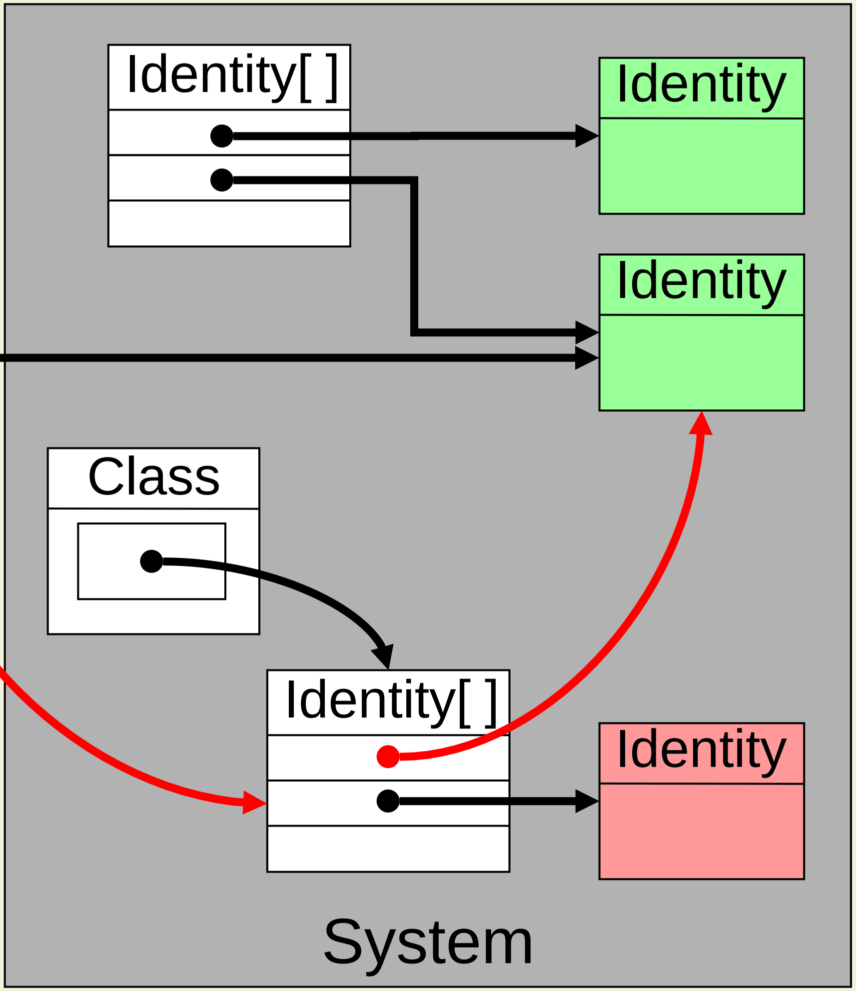
Security Breach in Java 1.1.1

```
class Malicious {

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

}
```

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



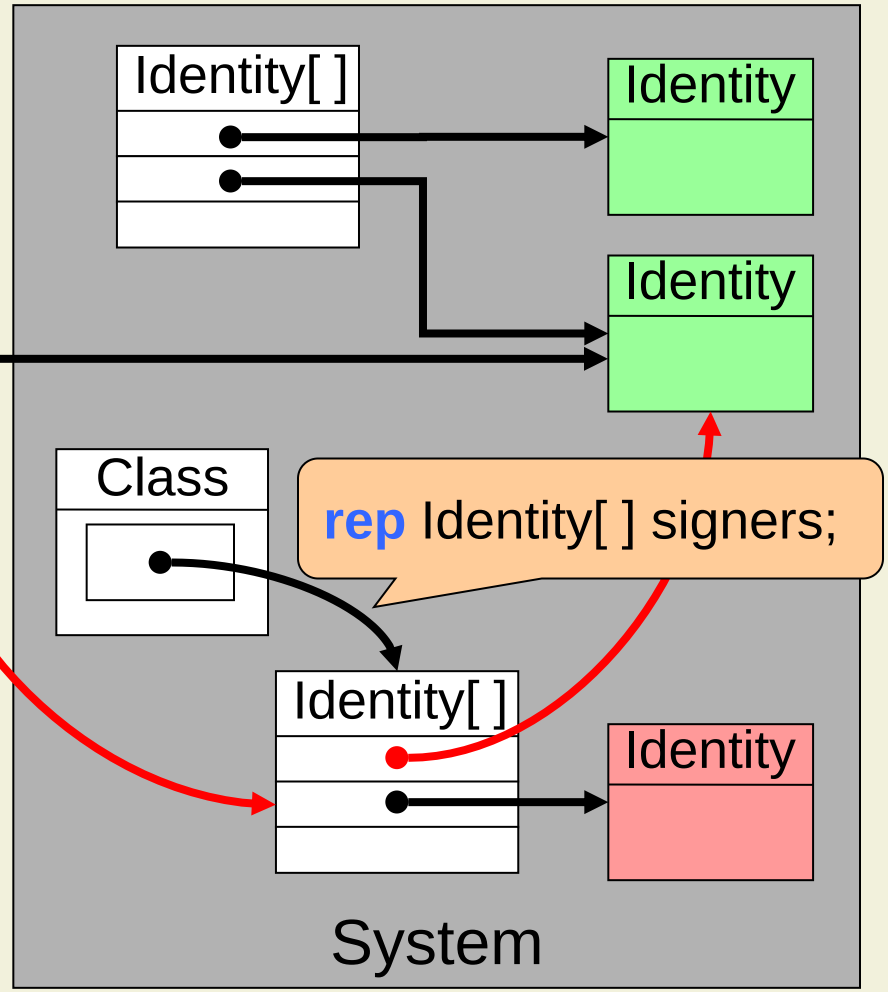
Security Breach in Java 1.1.1 (cont’d)

```
class Malicious {

 void bad( ) {
  any Identity[ ] s;
  Identity trusted = java.Security…;
  s = Malicious.class.getSigners( );
  s[ 0 ] = trusted;
 }

}
```

```
rep Identity[ ] getSigners( )
  { return signers; }
```



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
- Ownership types are an area of current research