Concepts of Object-Oriented Programming

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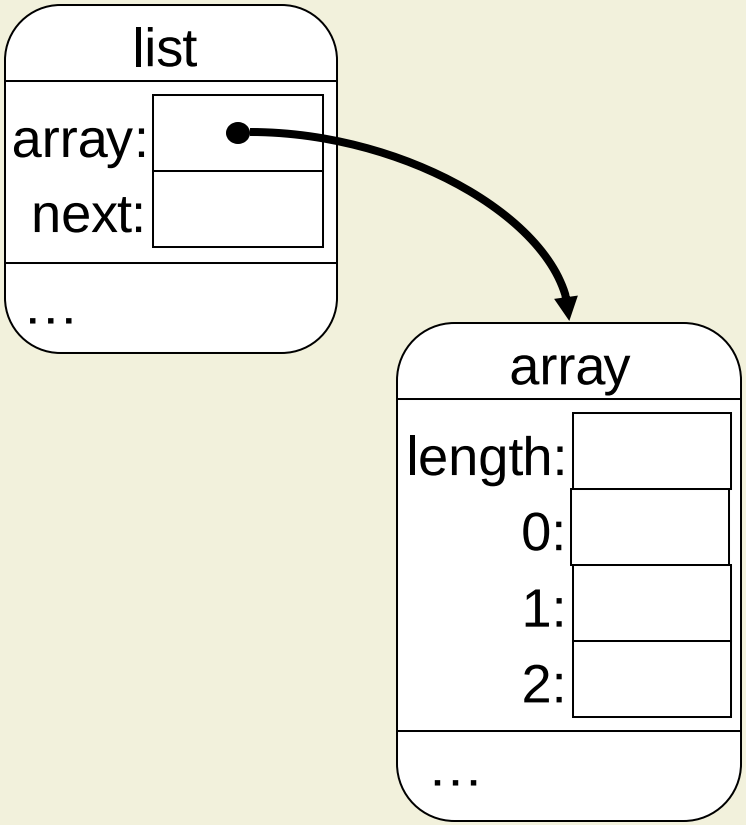
Object Structures

- Objects are the building blocks of object-oriented programming
- However, interesting abstractions are almost always provided by sets of cooperating objects

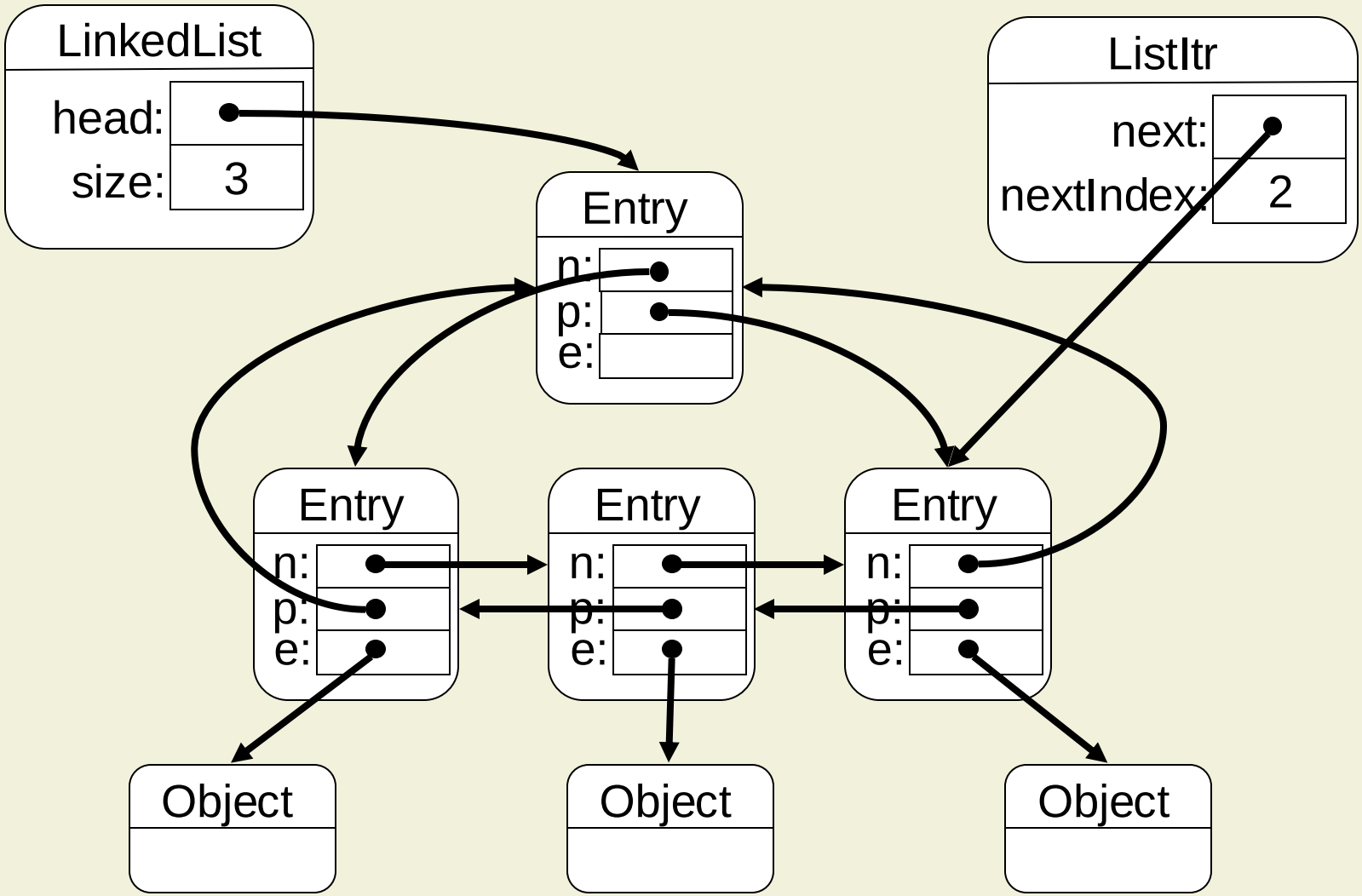
- Definition:
  An object structure is a set of objects that are connected via references

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



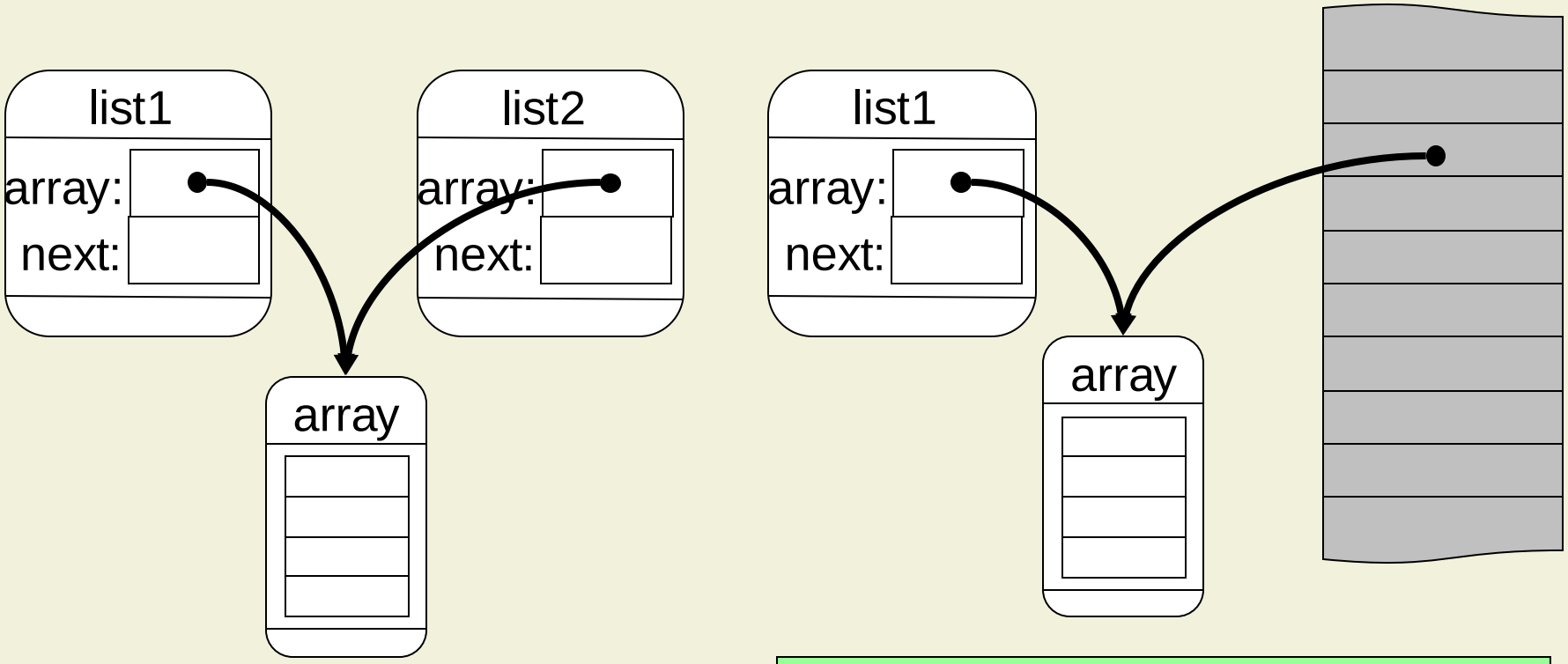
5. Object Structures and Aliasing

Aliasing

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

- 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

Aliasing from Heap and Stack Variables

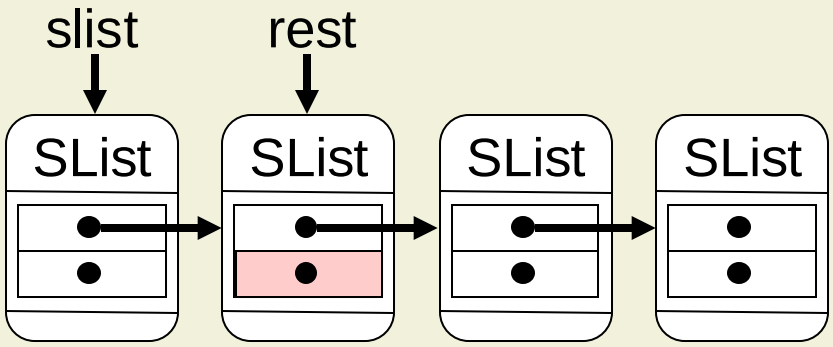



```
list1.array[ 0 ] = 1;
list2.array[ 0 ] = -1;
System.out.println( list1.array[ 0 ] );
```

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

Intended Aliasing: Efficiency

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

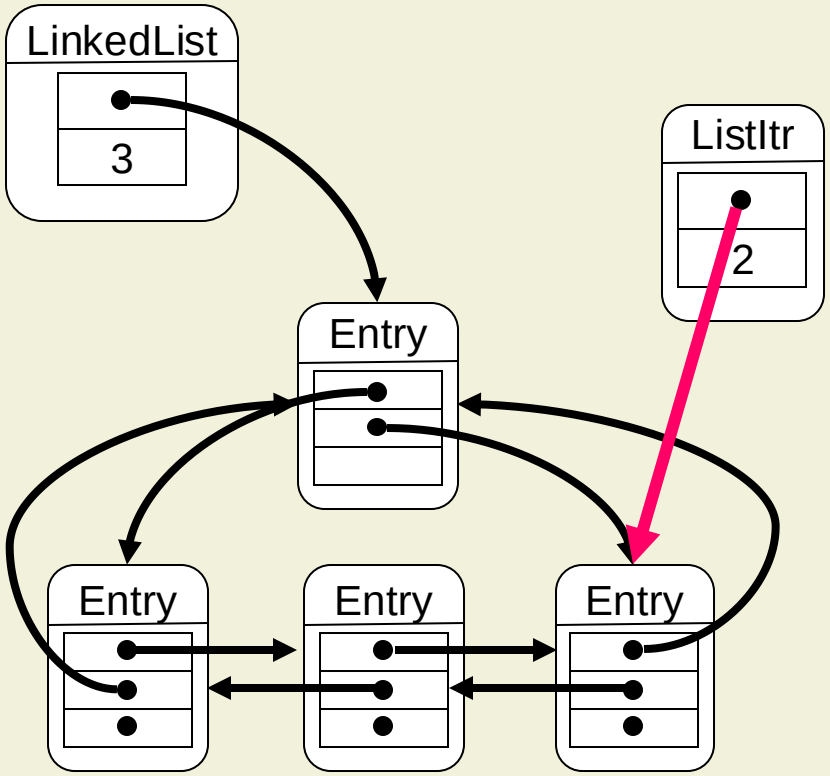



```
class SList {
  SList next;
  Object elem;
  SList rest( ) { return next; }
  void set( Object e ) { elem = e; }
}
```

```
void foo( SList slist )  {
  SList rest = slist.rest( );
  rest.set( “Hello” );     }
```

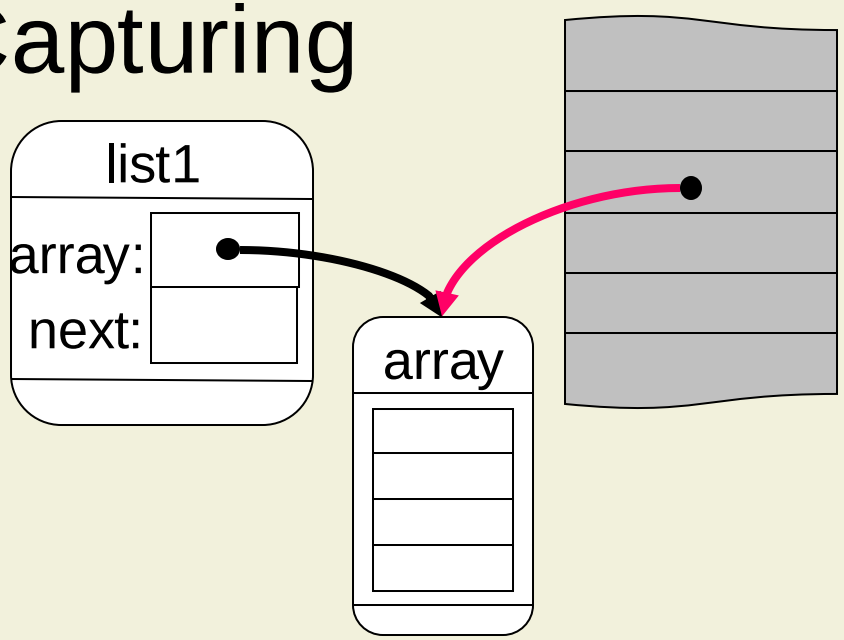
Intended Aliasing: Sharing

- 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

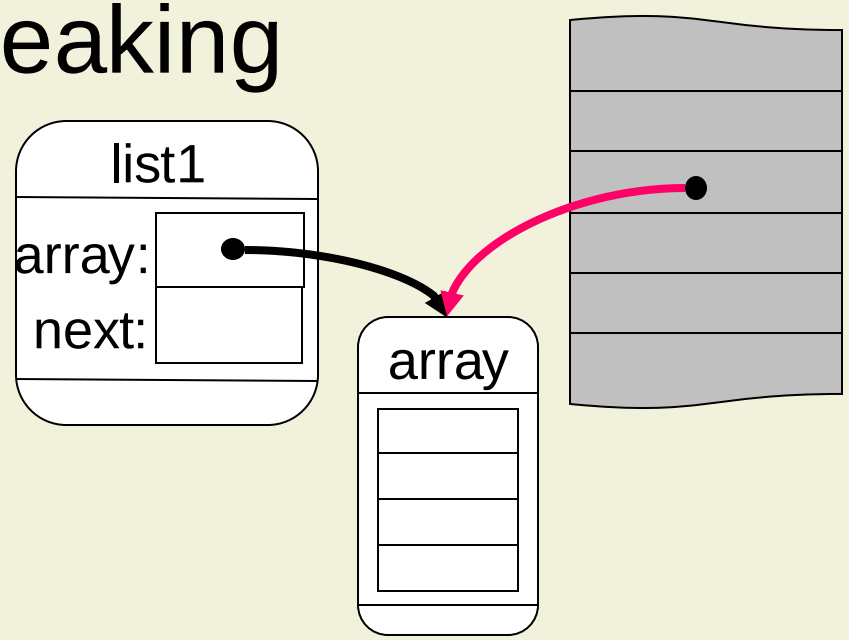
- Capturing occurs when objects are passed to a data structure and then stored by the data structure
- Capturing often occurs in constructors (e.g., streams in Java)
- Problem: Alias can be used to by-pass interface of data structure




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

Unintended Aliasing: Leaking

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




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

5. Object Structures and Aliasing

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]

Exchanging Implementations

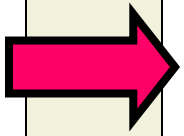
- Textbooks: information hiding enables safe changes of (hidden) implementation
- Observable behavior must be preserved
- But: beware of fragile baseclass problem

```
class Coordinate {
  private double x,y;
  …
  public double distOrigin( )
    { return Math.sqrt( x*x + y*y ); }
}
```

```
class Coordinate {
  private double radius, angle;
  …
  public double distOrigin( )
    { return radius; }
}
```

Exchanging Implementations (cont'd)

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

  // requires ia != null
  // ensures ∀i. 0<=i<ia.length:
  //                isElem( old( ia[ i ] ) )
  public void setElems( int[ ] ia )
    { array = ia; next = ia.length; }

  …
}
```

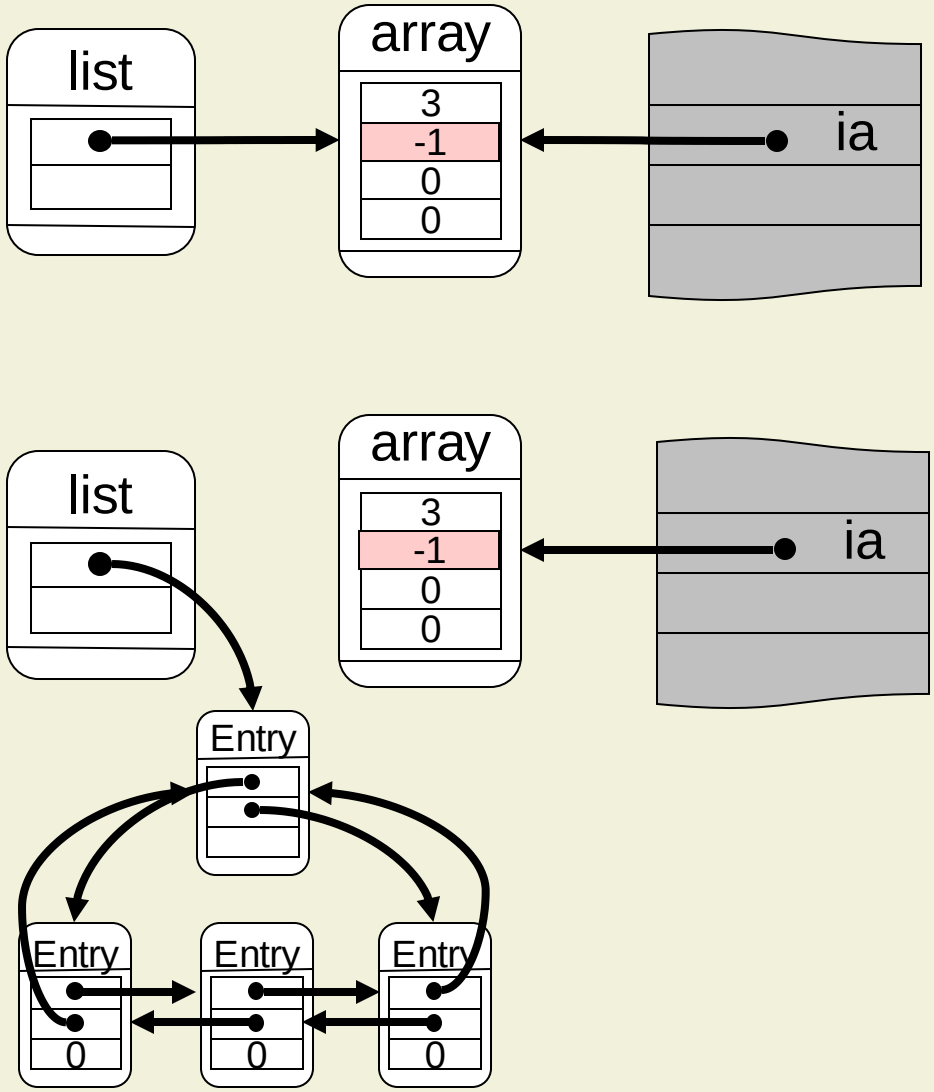


```
class List {
  private Entry head;

  // requires ia != null
  // ensures ∀i. 0<=i<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)

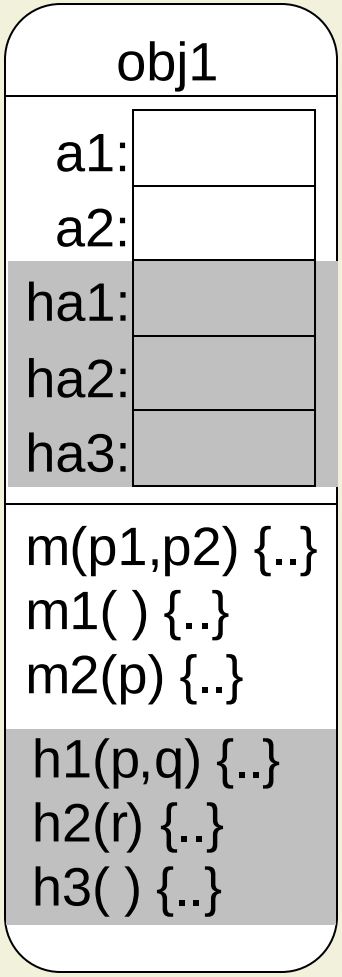
```
int foo( List list ) {
  int[ ] ia = new int[ 3 ];
  list.setElems( ia );
  ia[ 0 ] = -1;
  return list.getFirst( );
}
```



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

Consistency of Objects

- Consistency can include
  - Properties of one execution state (invariants)
  - Relations between execution states (history constraints)
- The internal representation of an object is encapsulated if it can be manipulated only by using the object's interfaces



Checks for Invariants: Textbook Solution

- Assume that all objects o are capsules
  - Only methods executed on o can modify o's state
  - The invariant of object o refers only to the encapsulated fields of o

- For each invariant, we have to show
  - That all exported methods preserve the invariants of the receiver object
  - That all constructors establish the invariants of the new object

Object Consistency in Java

- Declaring all fields **private** does not guarantee encapsulation on the level of individual objects
- Objects of same class can break the invariant
- Eiffel supports encapsulation on the object level
  - **feature** { NONE }

```
class Redundant {
  private int a, b;
  private Redundant next;
  // invariant a == b
  …
  public void set( int v ) { … }

  public void violate( ) {
    // all invariants hold
    next.a = next.b + 1;
    // invariant of next does not hold
  }
}
```

Textbook Invariants for Java

- Assumption: The invariants of object o may refer only to private fields of o

- For each invariant, we have to show
  - That all exported methods and constructors of class T preserve the invariants of all objects of T
  - That all constructors in addition establish the invariants of the new object

Consistency of Object Structures

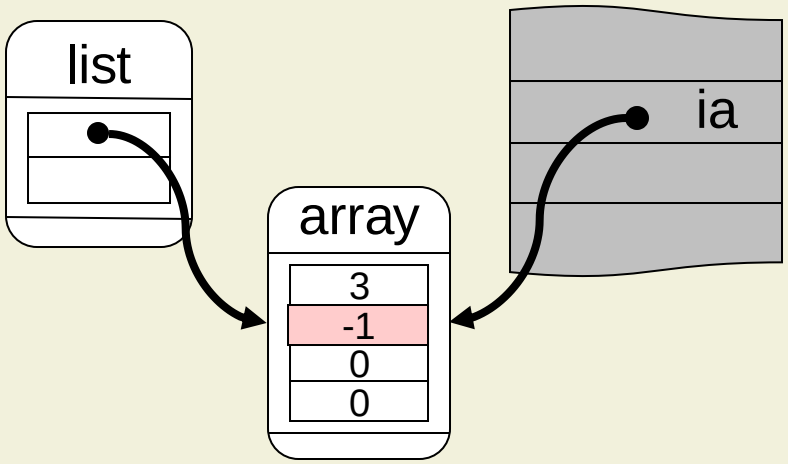
- Consistency of object structures depends on fields of several objects
- Invariants are usually specified as part of the contract of those objects that represent the interface of the object structure

```
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 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
}
```

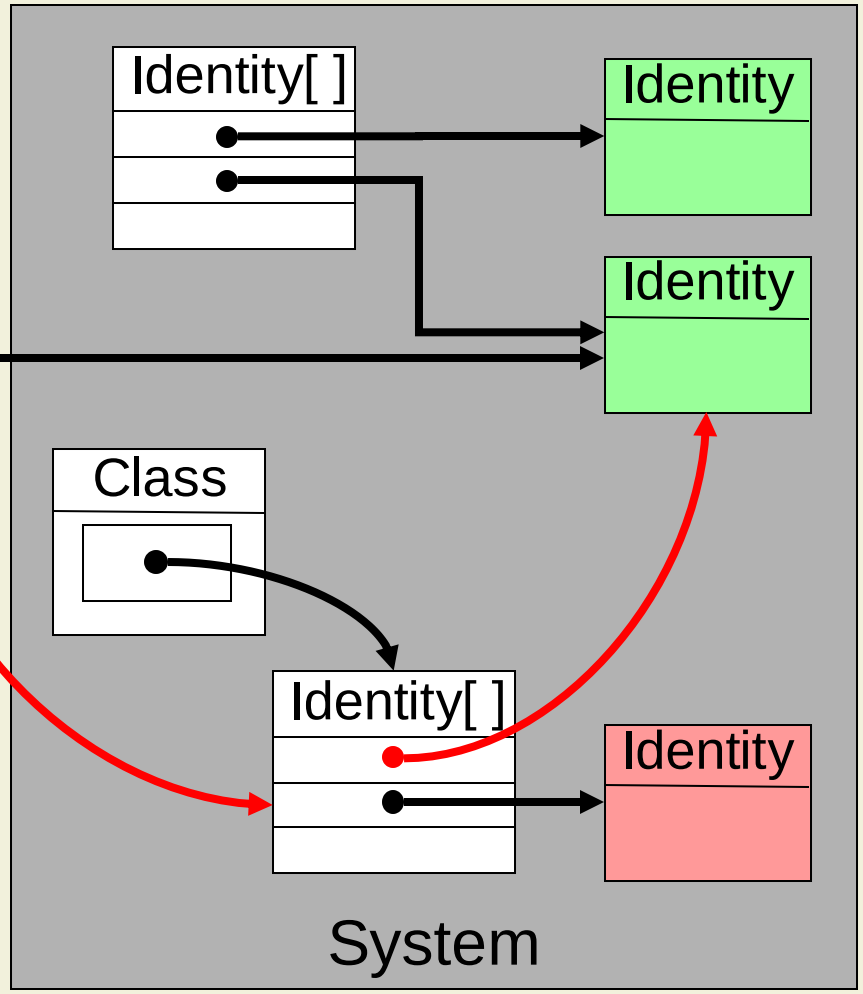
- Aliases can be used to violate invariant
- Making all fields private is not sufficient to encapsulate internal state



Security Breach in Java 1.1.1

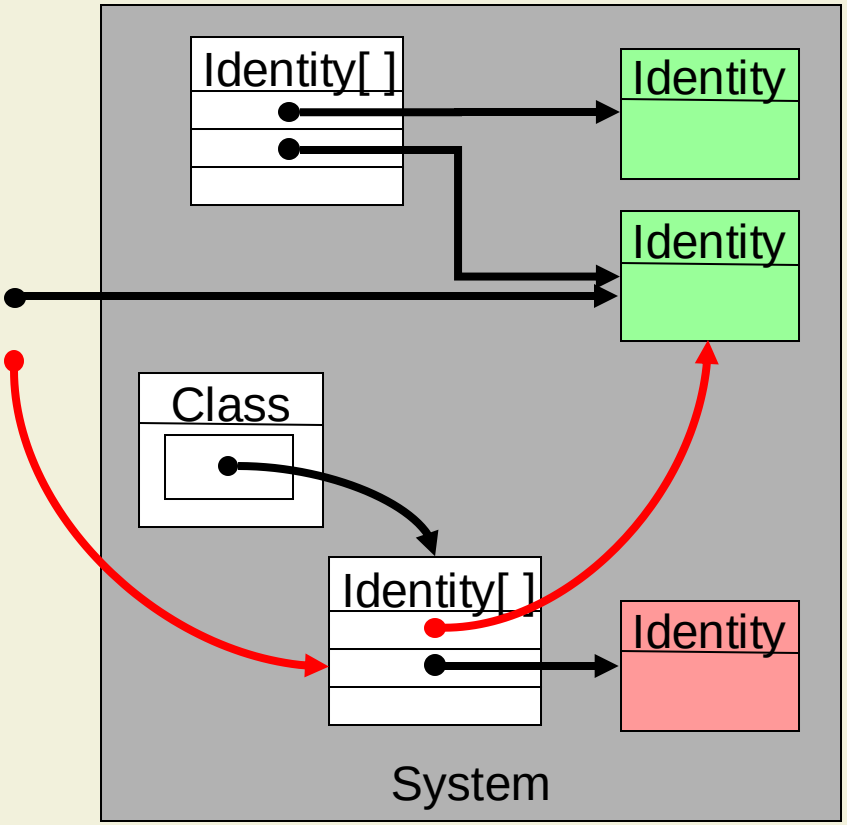
```
class Malicious  {

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

}
```

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



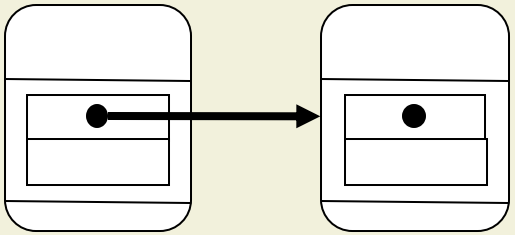
Problem Analysis

- 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

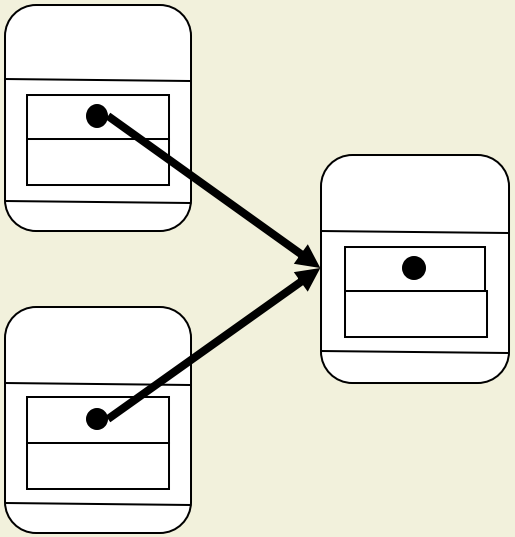


Other Problems with Aliasing

- Synchronization in concurrent programs
  - Monitor of each individual object has to be locked to ensure mutual exclusion



- Explicit memory management
  - Object may be freed only when the last reference disappears
- Optimizations
  - For instance, object inlining is not possible for aliased objects



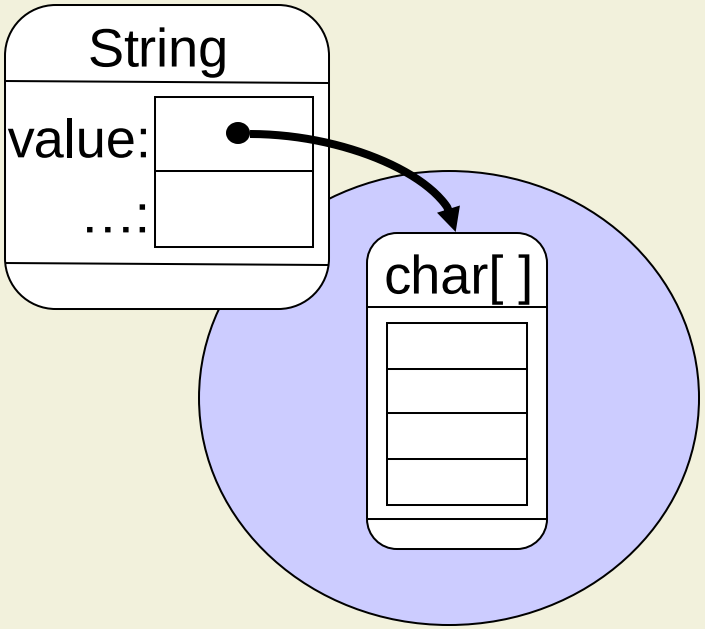
5. Object Structures and Aliasing

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
- ListItr is a private inner class of LinkedList
  - Interface ListIterator provides controlled access to ListItr-objects
  - ListItr-objects are passed out, but in a controlled fashion
  - Subclasses cannot manipulate or leak ListItr-objects
- Subclassing is severely restricted

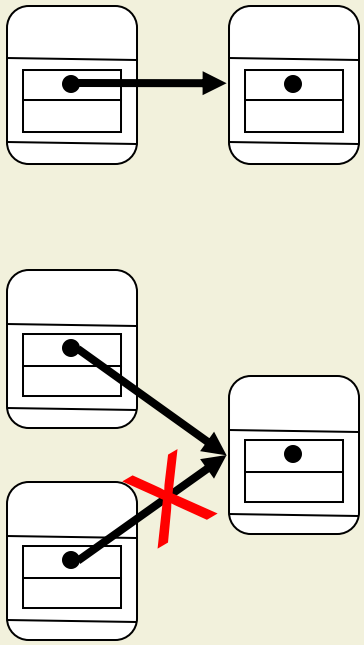
Alias Control in Java: String

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



Language Support: Unique References

- Preventing aliasing through a coding discipline is restrictive and error prone
- Language support for unique references facilitates alias control and can leverage non-aliasing guarantees to simplify memory management, thread synchronization, etc.
- A reference to an object is unique if it is the only reference to the object (the object is not aliased)



Unique Pointers in C++

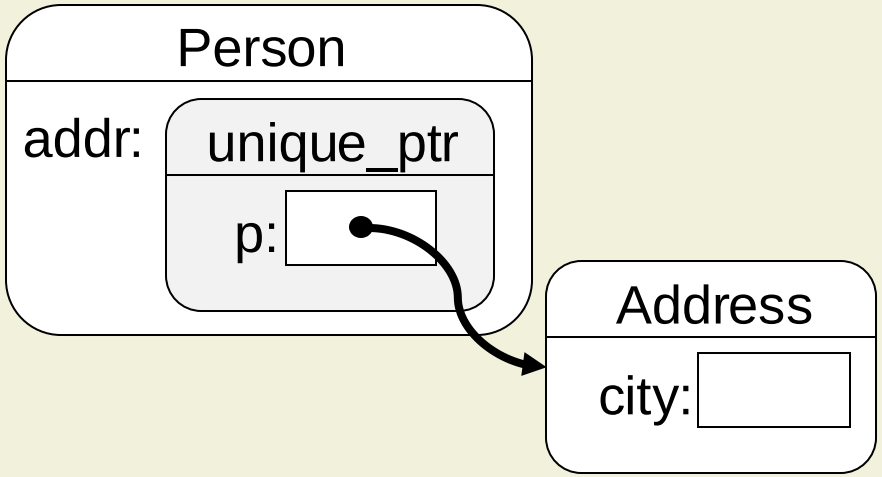
- C++ offers a library solution (as templates)

```
class Address {
  Address( string c ) { city = c; }
  …
}
```
C++

```
class Person {
  unique_ptr<Address> addr;

public:
  Person(string c) {
    addr = make_unique<Address>( c );
  }
}
```
C++

Create Address object and wrap it in unique pointer

- Unique pointers are wrappers around the underlying pointer



- They express object ownership

Protecting Uniqueness

- The pointer wrapped inside a unique_ptr struct is intended to be unique
- Direct leaking or capturing is prevented statically
- This is achieved by deleting the copy constructor and the assignment operator

```C++
class Person {
  unique_ptr<Address> addr;
}
```

```C++
unique_ptr<Address> getAddr( ) {
  return addr;
}
```

```C++
void setAddr( unique_ptr<Address> a ) {
  addr = a;
}
```

Memory Management

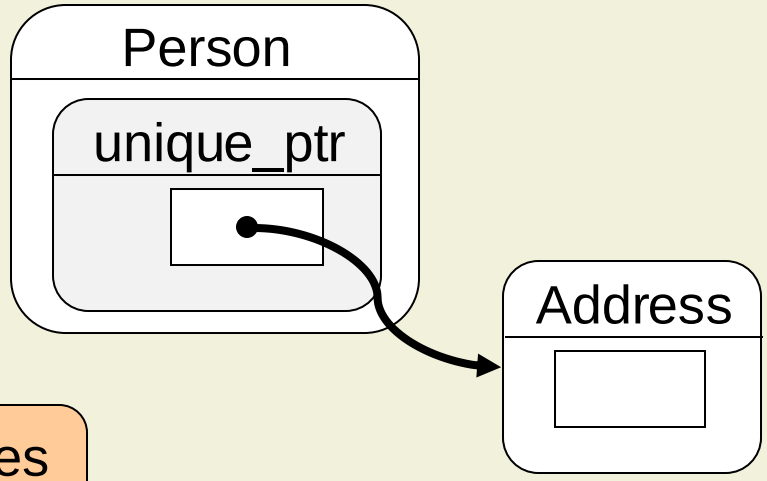
- C++ leverages uniqueness to simplify memory management

- When a unique pointer gets destroyed, it automatically de-allocates the underlying object

```
class Person {
  unique_ptr<Address> addr;
}
```

C++

```
Person* p = new Person( );
delete p;
```



Automatically de-allocates owned Address object

Ownership Transfer

- Object ownership can be transferred, for instance, to intentionally capture an object

- A move assignment transfers ownership

```
void setAddr( unique_ptr<Address> a ) {
  addr = std::move( a );
}
```
C++

- To preserve uniqueness, a move assignment sets the pointer of the origin to null (destructive read)

Temporary Ownership Transfer

- Performing operations on owned objects requires a temporary ownership transfer

```
int compare( unique_ptr<Address> a, unique_ptr<Address> b ) {
    return a->getCity( ).compare( b->getCity( ) );
}
```

C++

```
unique_ptr<Address> a = make_unique<Address>( "Zurich" );
unique_ptr<Address> b = make_unique<Address>( “Berne" );

int x = compare( std::move(a), std::move(b) );
int y = compare( std::move(a), std::move(b) );
```

Null-pointer dereferencing

After the first call, a and b contain null-pointer (destructive read)

Temporary Ownership Transfer (cont'd)

- To use parameter objects after call, ownership has to be transferred back to the caller

```
Triple compare( unique_ptr<Address> a, unique_ptr<Address> b ) {
  Triple r;    // int res;  unique_ptr<Address> a, b;
  r.res = a->getCity().compare( b->getCity() );
  r.a = std::move( a );  r.b = std::move( b );
  return r;
}
```

C++

```
unique_ptr<Address> a = make_unique<Address>( "Zurich" );
unique_ptr<Address> b = make_unique<Address>( “Berne" );

Triple r = compare( std::move(a), std::move(b) );
r = compare( std::move(r.a), std::move(r.b) );
```

C++

Parameter Passing Without Transfer

- To avoid transferring ownership back and forth, one can pass a pointer (or reference) to the unique pointer

```
int compare( unique_ptr<Address>* a, unique_ptr<Address>* b ) {
    return (*a)->getCity( ).compare( (*b)->getCity( ) );
}
```

C++

```
unique_ptr<Address> a = make_unique<Address>( "Zurich" );
unique_ptr<Address> b = make_unique<Address>( “Berne" );

int x = compare( &a, &b );
x = compare( &a, &b );
```

C++

Member Access Via Unique Pointers

- Method and field accesses on unique pointers use the familiar syntax
- unique_ptr redefines the access operator -> to yield a pointer to the owned object

```
class Person {
  unique_ptr<Address> addr;
public:
  string getCity() {
    return addr->getCity( );
  }
}
```

C++

Passing the Owned Object

- (Library) methods typically expect regular pointers

```
int compare( Address* a, Address* b ) {
    return a->getCity( ).compare( b->getCity( ) );
}
```

C++

- To use such methods, one has to call the get method of a unique pointer to obtain a regular pointer to the owned object

```
unique_ptr<Address> a = make_unique<Address>( "Zurich" );
unique_ptr<Address> b = make_unique<Address>( “Berne" );

int x = compare( a.get(), b.get() );
```

C++

No Uniqueness Guarantee

- get() creates alias to owned object
- (Library) methods are not aware that their receiver is supposed to be unique and might create an alias
- Using get() and -> is unavoidable

```
unique_ptr<Address> a;
a = make_unique<Address>("Zurich");
Address* alias = a.get();
alias->setCity("Hagen");
cout << a->getCity();
```
C++

```
static Address* cache;
class Address {
  string getCity() { cache = this; return city; }
}
```
C++

```
class Person {
  unique_ptr<Address> addr;
  string getCity() { return addr->getCity( ); }
}
```
C++

Memory Management Revisited

- Destroying a unique pointer de-allocates the underlying object, even if aliases exist

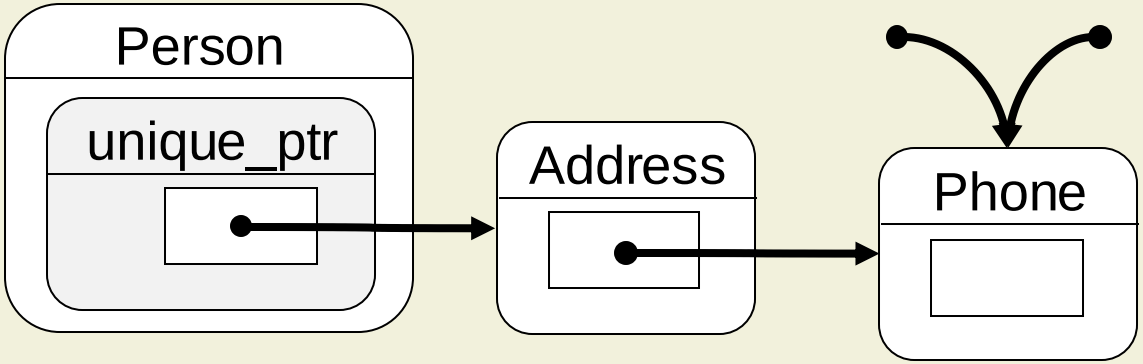
- Subsequent accesses lead to run-time errors

```
Address* returnAlias() {
    unique_ptr<Address> a;
    a = make_unique<Address>("Zurich");
    return a.get();
}
```
C++

```
Address* a = returnAlias();
cout << a->getCity();
```
C++

Shallow Ownership

- Unique pointers express ownership of the referenced object, but not its sub-objects



- Deep ownership of an entire object structure needs to be implemented explicitly by making all relevant pointers unique
  - Not possible for library classes

Unique Pointers in C++: Discussion

Pros

- Unique pointers express design intent
- Direct leaking or capturing is prevented statically
- Memory management is simplified (but requires care)

Cons

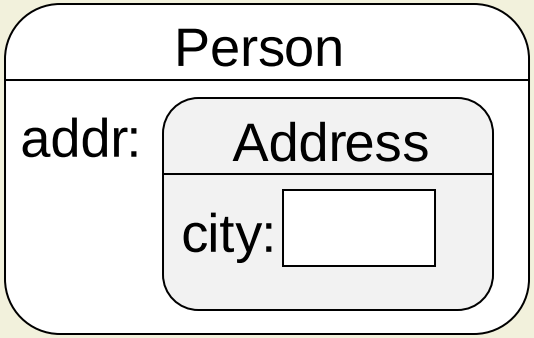
- No static guarantees
- Not effective in solving the problems caused by aliasing
- Parameter passing is awkward
- Destructive reads are error prone
- Run time overhead

Ownership in Rust

```
struct Address {
  city: String,
}
```
Rust

```
struct Person {
  addr: Address,
}
impl Person {
  fn new(c: String) -> Self {
    let a = Address { city: c };
    Self{ addr: a }
  }
}
```
Rust

- Rust supports ownership via its type system
- An expression representing a memory location (a place) of a type T owns the value in that location
- Ownership is deep

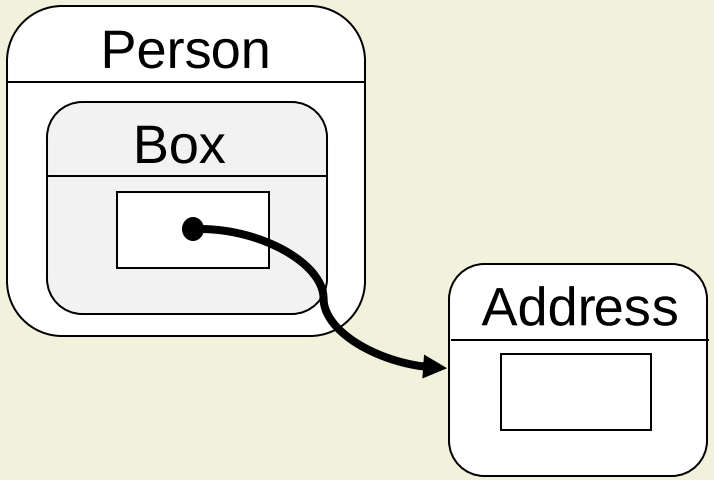


Ownership in Rust (With Pointers)

```
struct Address {
  city: String,
}
```
Rust

```
struct Person {
  addr: Box<Address>,
}
impl Person {
  fn new(c: String) -> Self {
    let a = Address { city: c };
    Self{ addr: Box::new( a ) }
  }
}
```
Rust

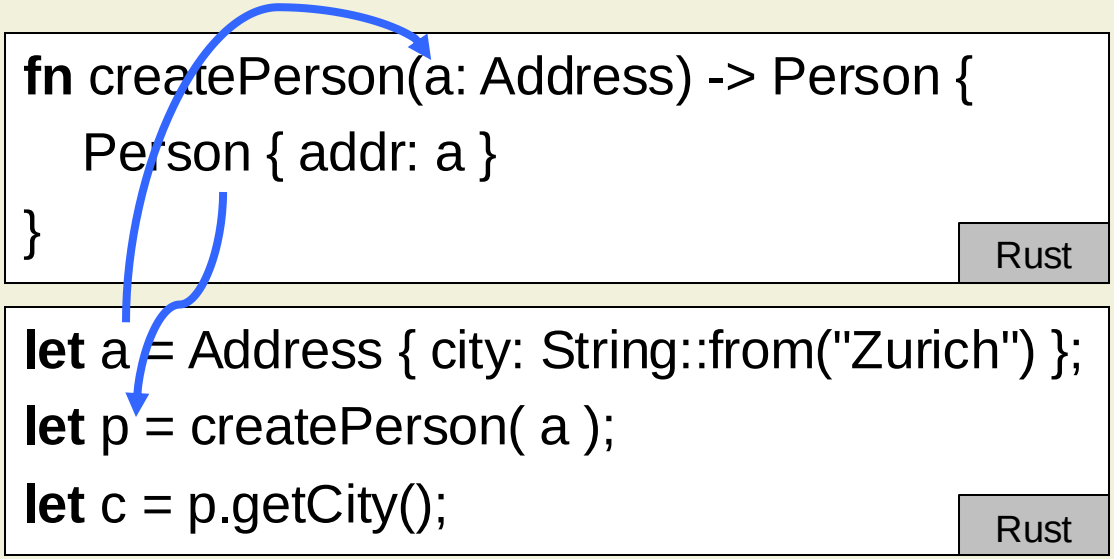
- Type Box provides owning pointers to heap-allocated values



Ownership Transfer

- When reading from a place, ownership of the owned value is transferred

- Every assignment is a move assignment



Ownership Transfer (cont'd)

- When a value is moved out of a place, the place becomes unusable until a new value is assigned

```
fn createPerson(a: Address) -> Person {
    Person { addr: a }
}
```
Rust

```
let a = Address { city: String::from("Zurich") };
let p = createPerson( a );
let q = createPerson( a );
```
Compile time error: use of a moved value

- No destructive read (in contrast to C++)
  - Whenever a place can be used, it contains a proper (non-null) value

Borrowing

- Like in C++, operations could be invoked by transferring ownership to the operation and back
- Borrowing provides temporary access to a value through a reference, without transferring ownership

```
fn compare( a: &mut Address, b: &mut Address ) -> Ordering {
    a.getCity().cmp( b.getCity() )
}
```

Rust

Reference type

```
let mut a1 = Address { city: String::fro
let mut a2 = Address { city: String::fro
let o = compare( &mut a1, &mut a2 );
let c = a1.getCity();
```

Rust

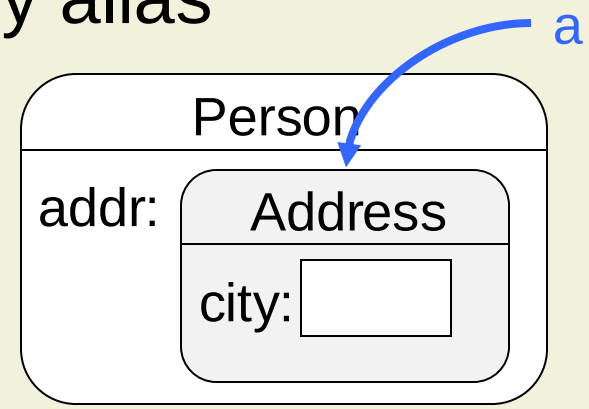
Create reference to the owned value

Value can be used after the borrow expires

More on Borrowing

- Borrowing creates a temporary alias

```
let mut p = Person::new( … );
let a = &mut p.addr;
```
Rust



- The borrowed-from place is unusable as long as the borrow exists

Compile time error: cannot use p.addr while it is borrowed

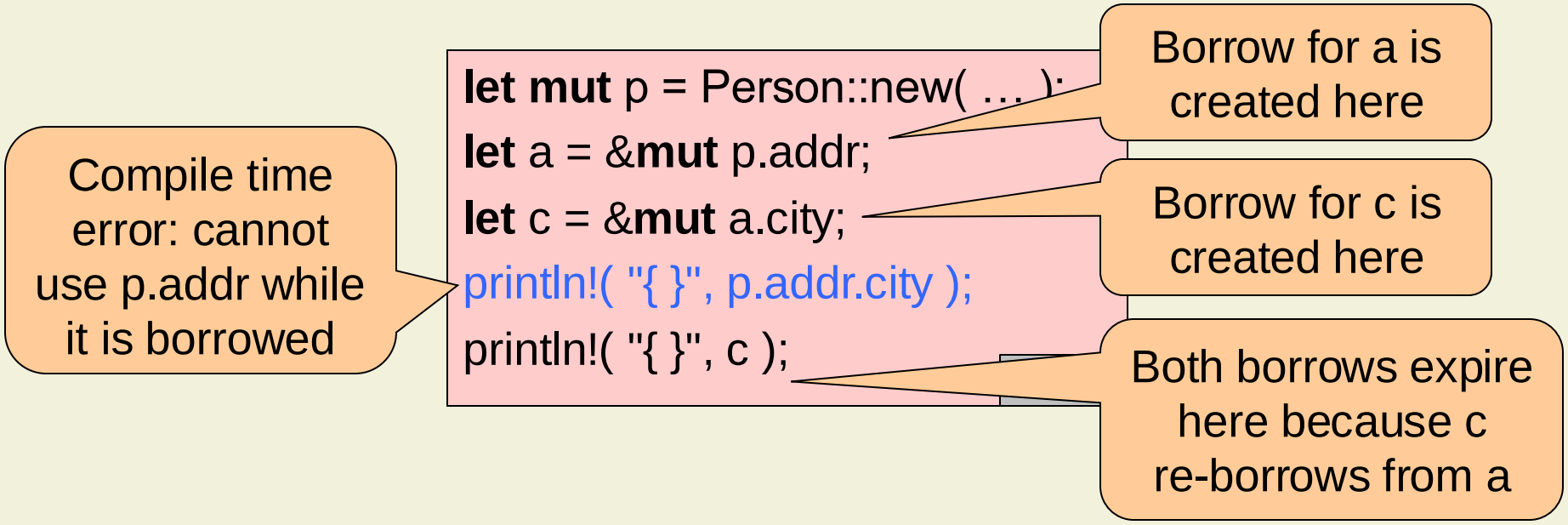
```
let mut p = Person::new( … );
let a = &mut p.addr;
println!( "{ }", p.addr.city );
println!( "{ }", a.city );
```

Borrow is created here

Borrow expires here

Borrow Checker

- The Rust compiler uses a static analysis (called borrow checker) to determine when borrows expire



- Borrow checking across functions may require annotations (lifetimes, not discussed here)

Leaking and Capturing

- Rust does not prevent (temporary) leaking through a reference

```
fn getAddr( &mut self ) -> &mut Address {
  &mut self.addr
}
```
Rust

Result is a temporary alias that cannot be captured in a value that outlives the borrow

- Capturing is safe due to ownership transfer

```
fn setAddr( &mut self, a: Address ) {
  self.addr = a
}
```
Rust

Caller can no longer use the transferred value

(Simplified) Uniqueness Guarantee

- Rust guarantees that, in each execution state, there is at most one usable place that can access a value
  - No usable aliases
  - We will make this guarantee more precise later

- Rust leverages this guarantee:
  - To ensure data race freedom
  - To perform automatic memory management (without a garbage collector)

Memory Management

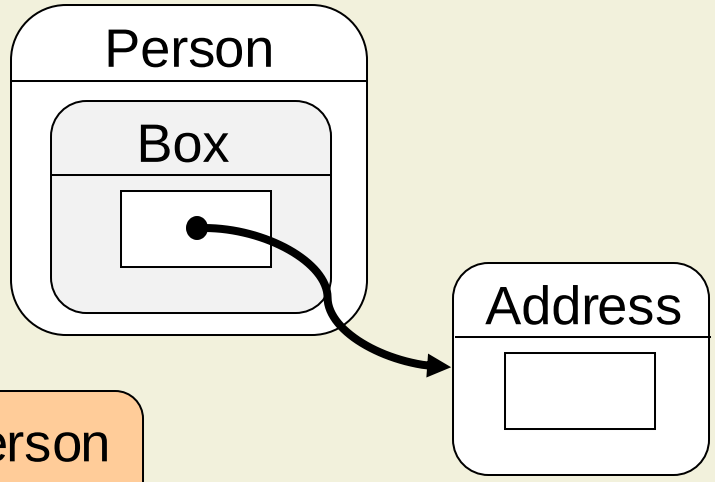
- Automatic memory management in Rust is safe
- When a place goes out of scope, all values it (transitively) owns are automatically de-allocated

```
struct Person {
  addr: Box<Address>,
}
```

Rust

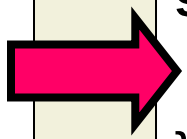
```
fn foo() {
  let p = Person::new(…);
}
```

Automatically de-allocates Person and owned Address object



Exchanging Implementations

```
struct List {
  array: Vec<i32>,
}
```
Rust



```
struct List {
  head: Box<Node>,
}
```
Rust

- Creating an alias via capturing is prevented by ownership

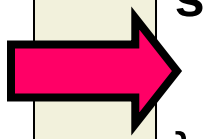
```
fn setElems(&mut self, ia: Vec<i32>) {
  self.array = ia;
}
```

Ownership transfer from caller

- Callers cannot use array after call to setElems

Exchanging Implementations (cont'd)

```
struct List {
  array: Vec<i32>,
}
```
Rust



```
struct List {
  head: Box<Node>,
}
```
Rust

- Creating an alias via leaking is still possible

```
fn getElems( &mut self )
                -> &mut Vec<i32> {
  &mut self.array
}
```
Rust

```
fn getElems( &mut self )
                        -> Vec<i32> {
  let res = Vec::new( );
  ... }
```
Rust

- Leaking and non-leaking methods typically have different result types
  - Effects on clients are unlikely (but possible)

Consistency of Object Structures

```
struct List {
  array: Vec<i32>,

  // invariant
  //    ∀i. 0 <= i < array.len():
  //                    array[ i ] >= 0
}
```
Rust

```
fn getElems( &mut self )
                  -> &mut Vec<i32> {
  &mut self.array
}
```
Rust

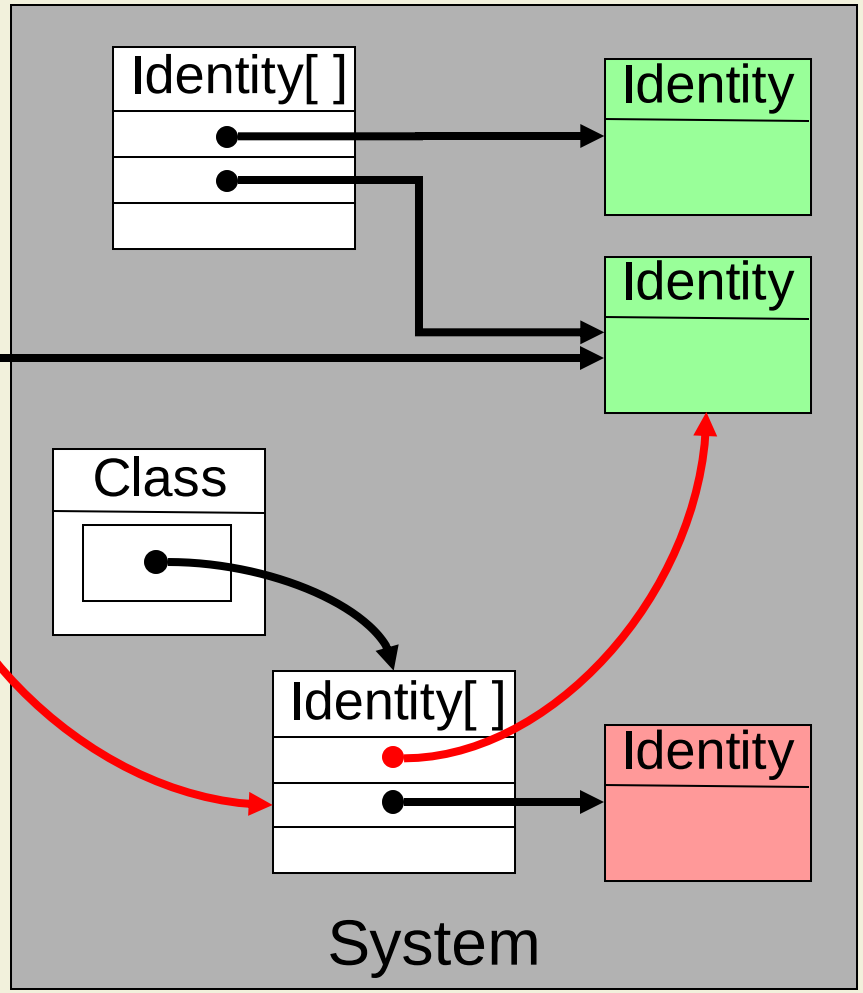
- Consistency of object structures depends on fields of several objects
- Since leaking is still possible, clients can violate invariant

```
fn violate( l: &mut List ) {
  let a = l.getElems( );
  a[ 0 ] = -1;
}
```
Rust

Security Breach in Java 1.1.1

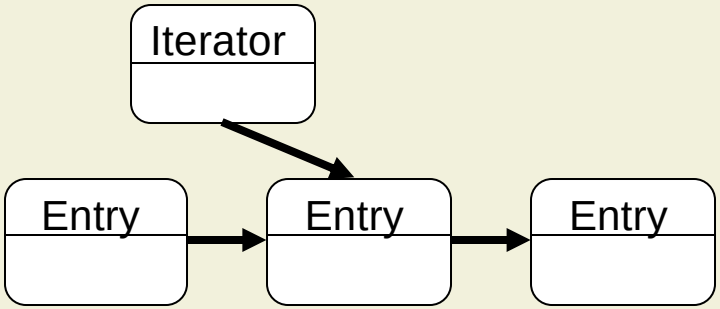
```
class Malicious  {

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

}
```

Leaking the identity array would also be possible in Rust

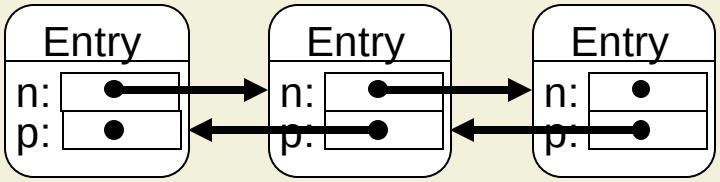


Limitations

- Rust's deep ownership and uniqueness imply that all data structures are tree-shaped



No sharing



No cyclic data structures

- Unsafe Rust provides raw pointers to work around the strict ownership and borrowing rules
  - Unsafe code should be encapsulated inside libraries
  - We assume here that only safe Rust is used

Ownership in Rust: Discussion

Pros

- Ownership guarantees effective uniqueness
- Creating aliases via capturing is prevented statically
- Uniqueness ensures safe automatic memory management and data race freedom
- No run time overhead

Cons

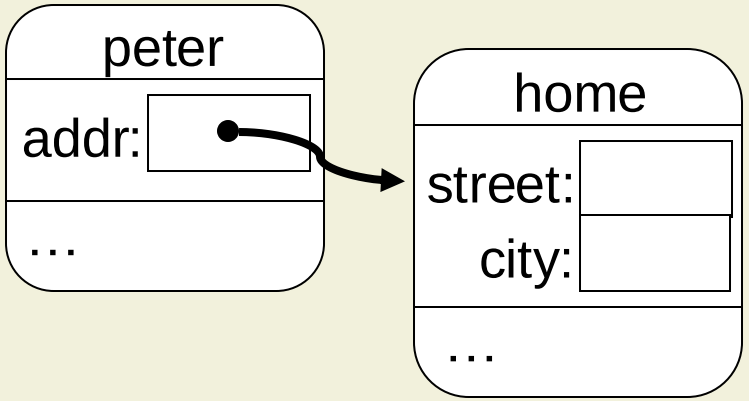
- Leaking is still possible
- Not effective in solving some of the problems caused by aliasing
- Ownership regime is sometimes too restrictive
- Guarantees may be compromised by using unsafe Rust

5. Object Structures and Aliasing

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 )
    { … }
  …
}
```

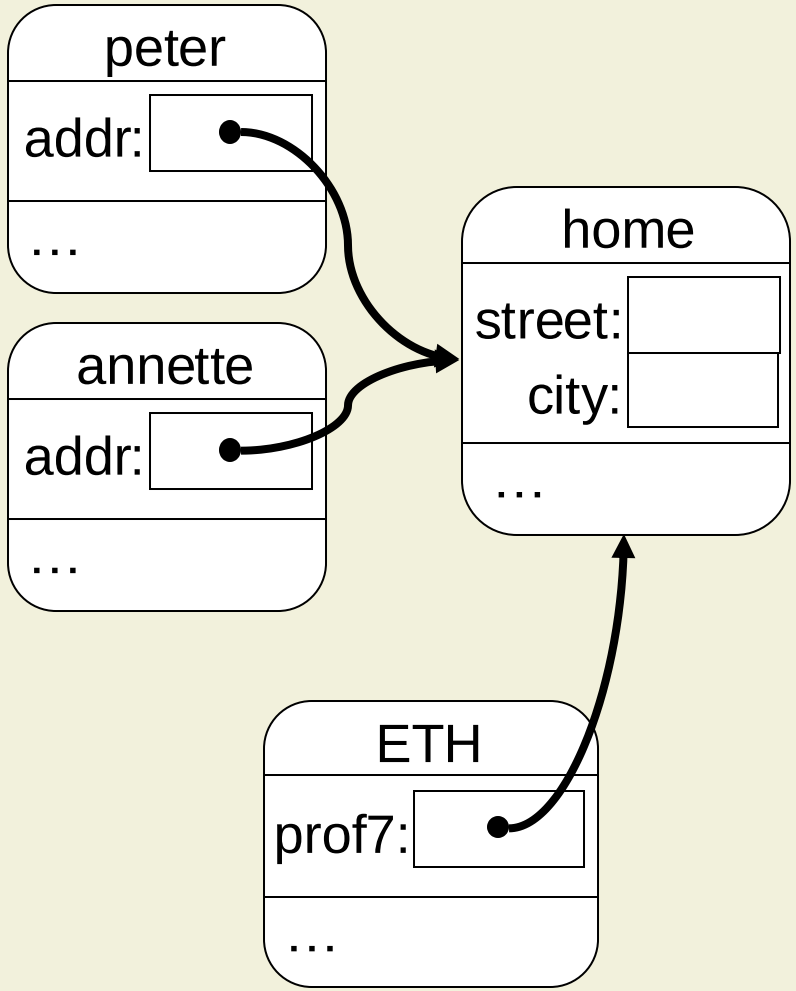
```
class Person {
  private Address addr;
  public Address getAddr(  )
    { return addr.clone( ); }
  public void setAddr( Address a )
    { addr = a.clone( ); }
  …
}
```



Drawbacks of Uniqueness

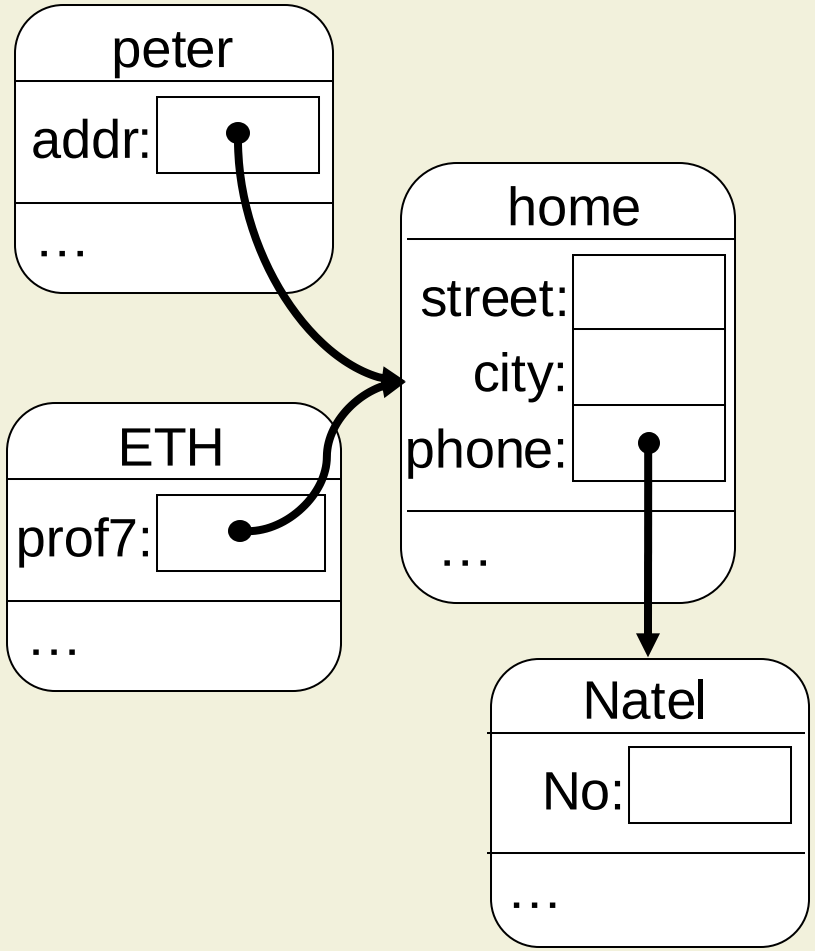
- Aliases are helpful to share side-effects
- Cloning objects is not efficient

- 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
- Effectiveness
  - Prevent unwanted modifications
- Transitivity
  - Access restrictions extend 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

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

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

- Transitivity has to be encoded explicitly
  - Requires sub-objects to implement readonly interface

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 C++: const Pointers

```
class Address {
  string city;
public:
  string getCity( )
    { 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( )  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( )  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( )  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++

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

```
class Address {
  string city;
  Phone* phone;
public:
  Phone* getPhone( ) const
    { return phone; }
…
};
```
C++

- const pointers are not transitive
  - const-ness of sub-objects has to be indicated explicitly
  - const functions must not modify sub-objects

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

Immutable References in Rust

- So far, we discussed the creation of mutable references

```
fn getAddr( &mut self ) -> &mut Address {
  &mut self.addr
}
```
Rust

- Rust also supports immutable references

```
fn getAddr( &self ) -> &Address {
  &self.addr
}
```
Rust

Shared References

- In contrast to mutable references, there can be multiple immutable references to a value

```
fn getAddr( &self ) -> &Address {
  &self.addr
}
```
Rust

```
let a1 = p.getAddr( );
let a2 = p.getAddr( );
println!( "{ }", a1.getCity() );
println!( "{ }", a2.getCity() );
```
Rust

- The value is statically guaranteed to remain immutable as long as at least one immutable borrow exists

Uniqueness Guarantee

- Rust guarantees that, in each execution state, there is either at most one usable place that can mutably access a value, or the value is immutable

- Rust refers to this guarantee as Aliasing XOR Mutability

- Rust leverages this guarantee:
  - To ensure data race freedom
  - To perform automatic memory management (without a garbage collector)

Readonly Access in Rust: Effectiveness

```
struct Address { city: String, }

impl Address {
  fn getCity( &self ) -> &String
    { &self.city }
  fn setCity( &mut self, s: String )
    { self.city = s }
}
```

Rust

```
struct Person { addr: Address, }

impl Person {
  fn getAddr( &self ) -> &Address
    { &self.addr }
  fn setAddr( &mut self, a: Address )
    { self.addr = a; /* move */ }
}
```

Rust

- Immutable references do not allow:
  - field updates
  - mutator calls

```
fn m( p: Person ) {
  let a = p.getAddr();
  a.setCity(String::from("Hagen"));
  a.city = String::from("Hagen");
}
```

Compile-time errors

Readonly Access in Rust: Reading

```rust
struct Address { city: String, }

impl Address {
  fn getCity( &self ) -> &String
    { &self.city }
  fn setCity( &mut self, s: String )
    { self.city = s }
}
```

Rust

```rust
struct Person { addr: Address, }

impl Person {
  fn getAddr( &self ) -> &Address
    { &self.addr }
  fn setAddr( &mut self, a: Address )
    { self.addr = a; /* move */ }
}
```

Rust

- Signature determines whether a function may be called on an immutable reference

```rust
fn m( p: Person ) {
  let a = p.getAddr();
  let c = a.getCity();
  …
}
```

Rust

Readonly Access in Rust: Transitivity

```
struct Phone { number: u32, };
```
Rust

```
struct Address {
  city: String,
  phone: Phone,
}

impl Address {
  fn getPhone( &self ) -> &Phone
    { &self.phone }
}
```
Rust

```
fn m( p: Person ) {
  let a = p.getAddr();
  let ph = &a.phone;
  ph.number = 2331;
}
```
Compile-time error

Rust

- Immutability guarantee is transitive
- It is not possible to obtain a mutable reference through an immutable reference

Readonly Access in Rust: Mutable Values

```
struct Address { city: String, }
```
Rust

```
struct University { prof7: &Address, }
```

```
fn m( p: Person ) {
  let mut a = Address{ city: String::from("Zurich") };
  let u = University{ prof7: &a };
  a.city = String::from("Winterthur");
  let c = &u.prof7.city;
}
```
Rust

Create immutable reference

Compile-time error: value is immutable

Immutable reference is used until here

- Value is immutable while immutable references exist

Consistency of Object Structures

```
struct List {
  array: Vec<i32>,

  // invariant
  //    ∀i. 0 <= i < array.len():
  //                    array[ i ] >= 0
}
```
Rust

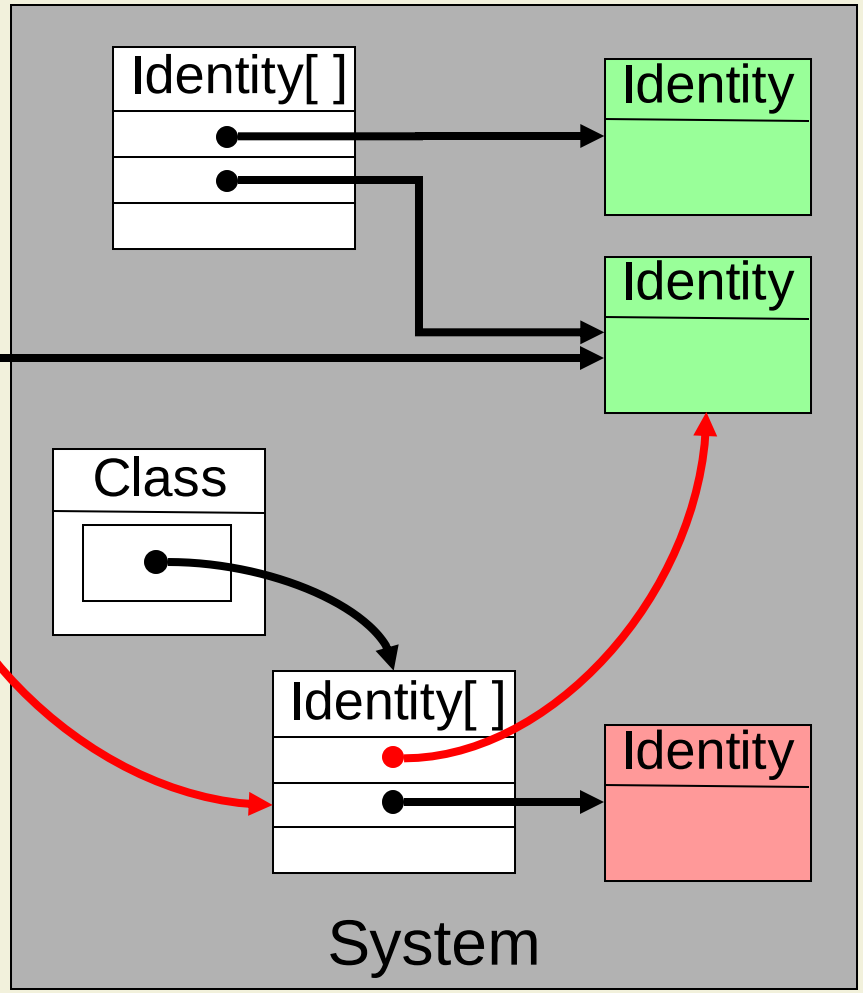
```
fn getElems( &self ) -> &Vec<i32> {
  &self.array
}
```
Rust

- Immutable references enable safe leaking
- Clients cannot use an immutable reference to violate invariant
- But leaking mutable references is also possible (**mut** keyword increases awareness)

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 */
 }

}
```

Leaking the identity array as immutable reference would be secure



Readonly Access in Rust: Discussion

- Immutable references provide temporary readonly access to mutable values
  - Work for library classes
  - Support arrays, fields, and non-public methods
- Readonly access is transitive
- Value is immutable while immutable references exist
  - Prevents, e.g., data races
  - Not suitable for all data structures

References

- Bjarne Stroustrup: *A Tour of C++.* Pearson, 2022

- Steve Klabnik and Carol Nichols: *The Rust Programming Language.* No Starch Press, 2023