# Konzepte objektorientierter Programmierung
# – Lecture 7 –

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Software Component Technology

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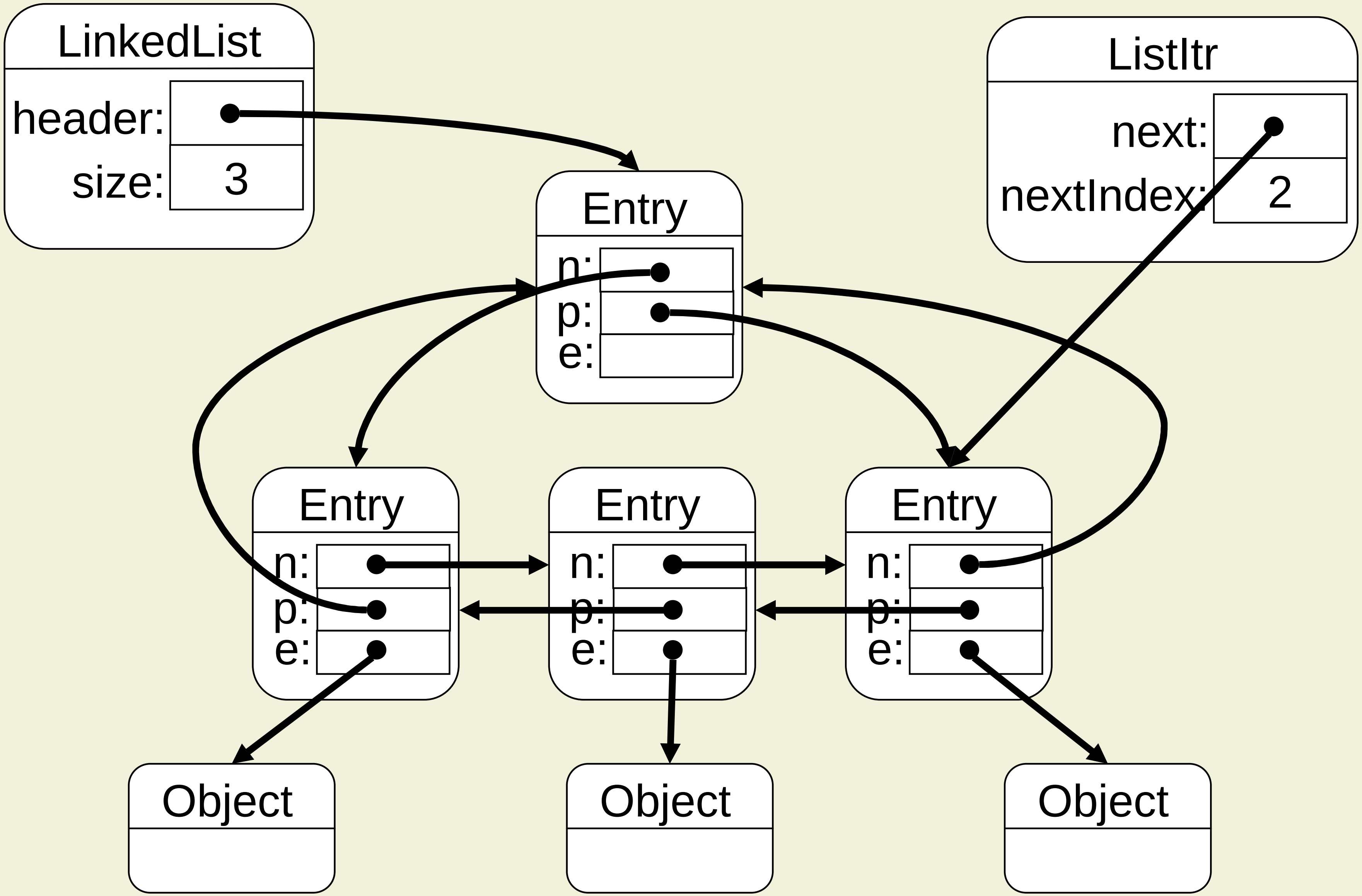
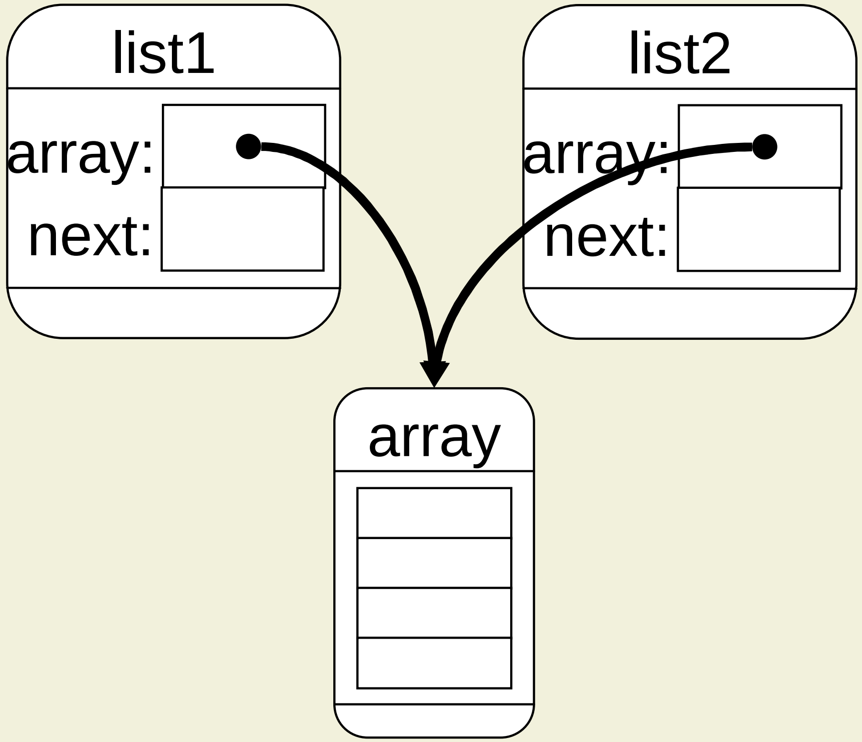
# Example 2: Doubly-Linked Lists



# Aliasing




```
list1.array[ 0 ] = 1;
list2.array[ 0 ] = -1;
System.out.println( list1.array[ 0 ] );
```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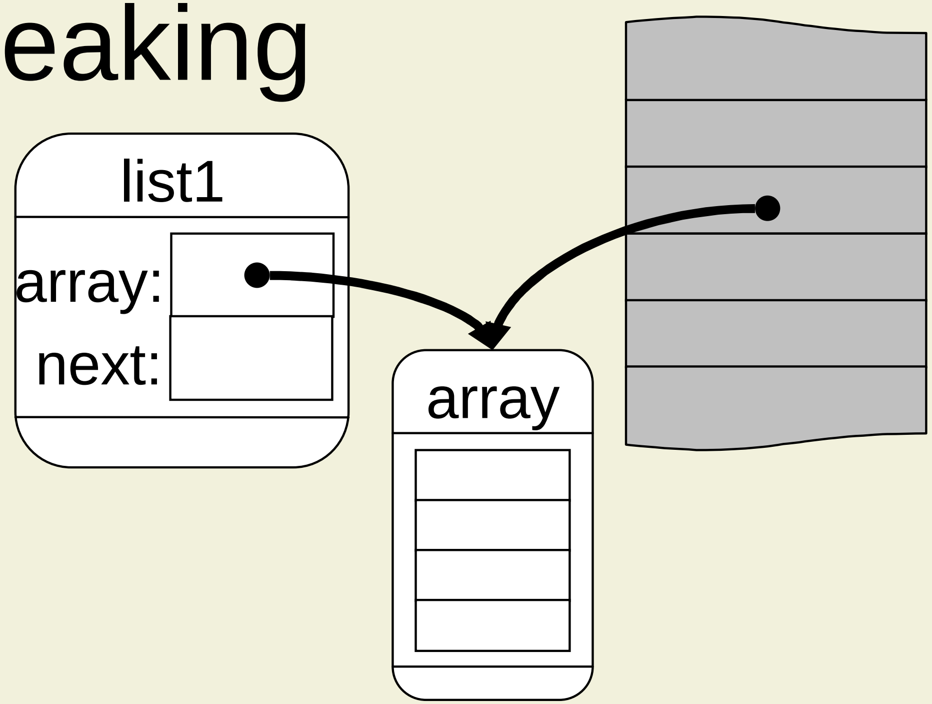
# Unintended Aliasing: Leaking

- Leaking occurs when data structure **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; }
  …
}
```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# Agenda for Today

## 7. Static Safety and Extended Typing

### 7.1 Type Systems

### 7.2 Readonly Types

### 7.3 Ownership Types

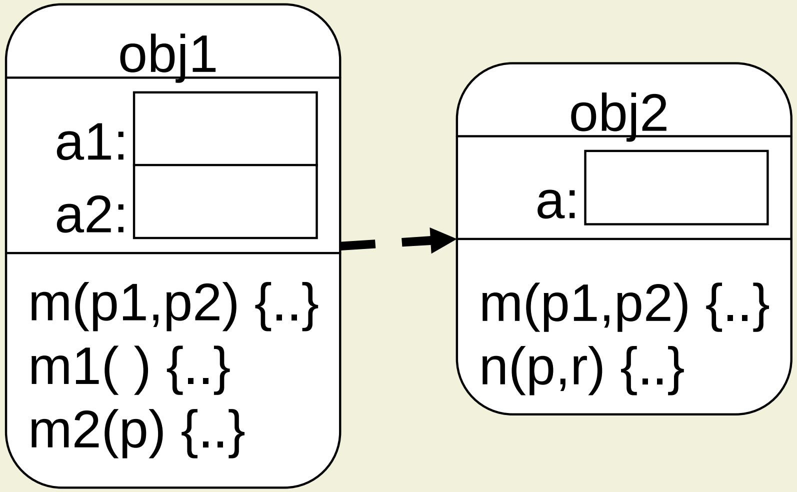
## Objectives

- Type safety
- Static checking by type systems

# 7. Static Safety and Extended Typing

# Static Safety

- Objects access attributes and methods of other objects
- If the receiver object does not have the requested attribute or method, a **runtime error** occurs
- **Type systems** can be used to **detect such errors statically**




```
…
r = obj2.m( 0, 1 );
s = obj2.a;
```

```
r = obj2.m( );
r = obj2.anotherMethod( 0, 1 );
s = obj2.anotherField;
```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# Type Systems

- Definition:
  *A type system is a tractable syntactic method for proving absence of certain program behaviors by classifying phrases according to the kinds of values they compute.*

  [B.C. Pierce, 2002]

- *Syntactic*: Rules can be checked by a compiler
- *Phrases*: Expressions, methods, etc. of a program
- *Kinds of values*: Types


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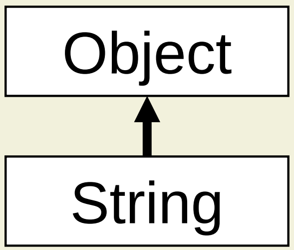
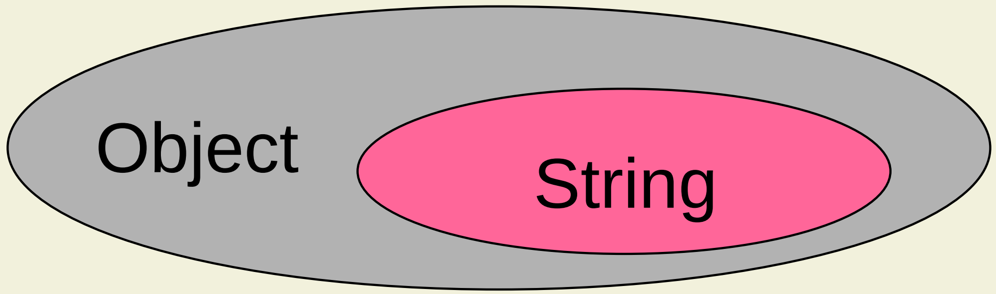
# Types

- Definition:
  *A type is a set of values sharing some properties. A value v has type T if v is an element of T.*
- *Properties*: Available methods, attributes, etc.
- The **subtype relation** corresponds to the **subset relation**




- Usually, each class or interface of a program defines a type

# Type Checking

- **Each expression** of a program **has a type**
- **Types** of variables and methods are **declared explicitly**
- Types of expressions can be derived from the types of their constituents
- **Type rules** are used to check whether a program is **correctly typed**

```
"A String"
5+7
```

```
int a;
boolean equals( Object o )
```

```
a + 7
"A Number: " + 7
"A String".equals( null )
```

# Type Rules: Assignment

- The assignment

```
v = exp;
```

  is correctly typed if
  - exp is correctly typed and
  - The type of exp is a subtype of the declared type of v

```
Object v;
v = new String( );
return v.equals( “Hello” );
```

```
String v;
v = new Object( );
v = v.concat( “Hello” );
```

# Type Rules: Result Types

- If S is a subtype of T and S has a method m that overrides a method in T then the result type of m in S must be a subtype of the result type of m in T

```
class T {  Object m( ) { … }  }
```

```
class S extends T {
  String m( ) { … }
}
```

```
Object v;
T t = new S( );
v = t.m( );
return v.equals( “Hello” );
```

```
class T {  String m( ) { … }  }
```

```
class S extends T {
  Object m( ) { … }
}
```

```
String v;
T t = new S( );
v = t.m( );
v = v.concat( “Hello” );
```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# Static Type Safety

- Definition:
  *A programming language is called type-safe if its design prevents type errors.*

- Type-safe object-oriented languages guarantee the following type invariant:
  *In every execution state, the type of the value held by variable v is a subtype of the declared type of v*

- Type safety guarantees the absence of certain runtime errors

# Dynamic Type Checking

- Some OO-languages support **type conversions by casts**
- Casts **cannot be type-checked statically**
- **Runtime checks** throw an exception in case of a type error
- **instanceof** can be used to avoid runtime errors

```
Object[ ] oa = new Object[ 10 ];
String s = “A String”;

oa[ 0 ] = s;


…
if ( oa[ 0 ] instanceof String )
  s = (String) oa[ 0 ];

s = s.concat( “Another String” );
```



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# Discussion

- Advantages of static type checking
  - Robustness: **Elimination of type errors**
  - Readability: Types are **excellent documentation**
  - Efficiency: Type information allows **optimizations**

- Limitations of **static** type checking
  - Does only work if all clients of a class are **recompiled after changes** are made
  - Does not work if code can be obtained at runtime in **executable format** (dynamic class loading, mobile code)
  - Strong static typing is sometimes **not flexible** enough


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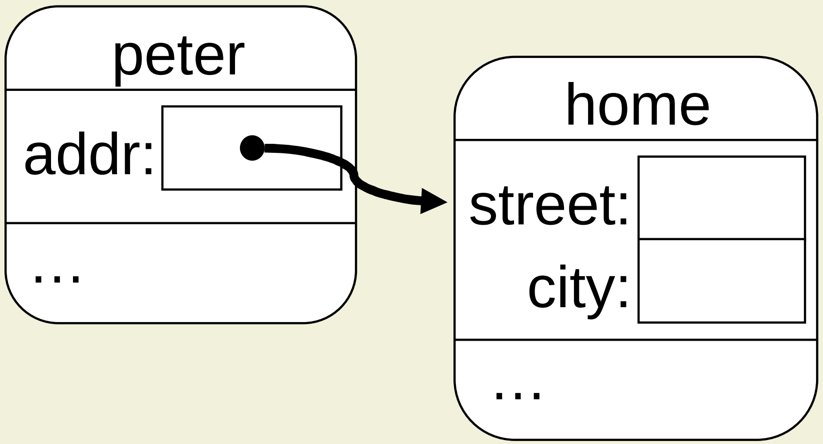
# 7. Static Safety and Extended Typing

# Object Structures Revisited

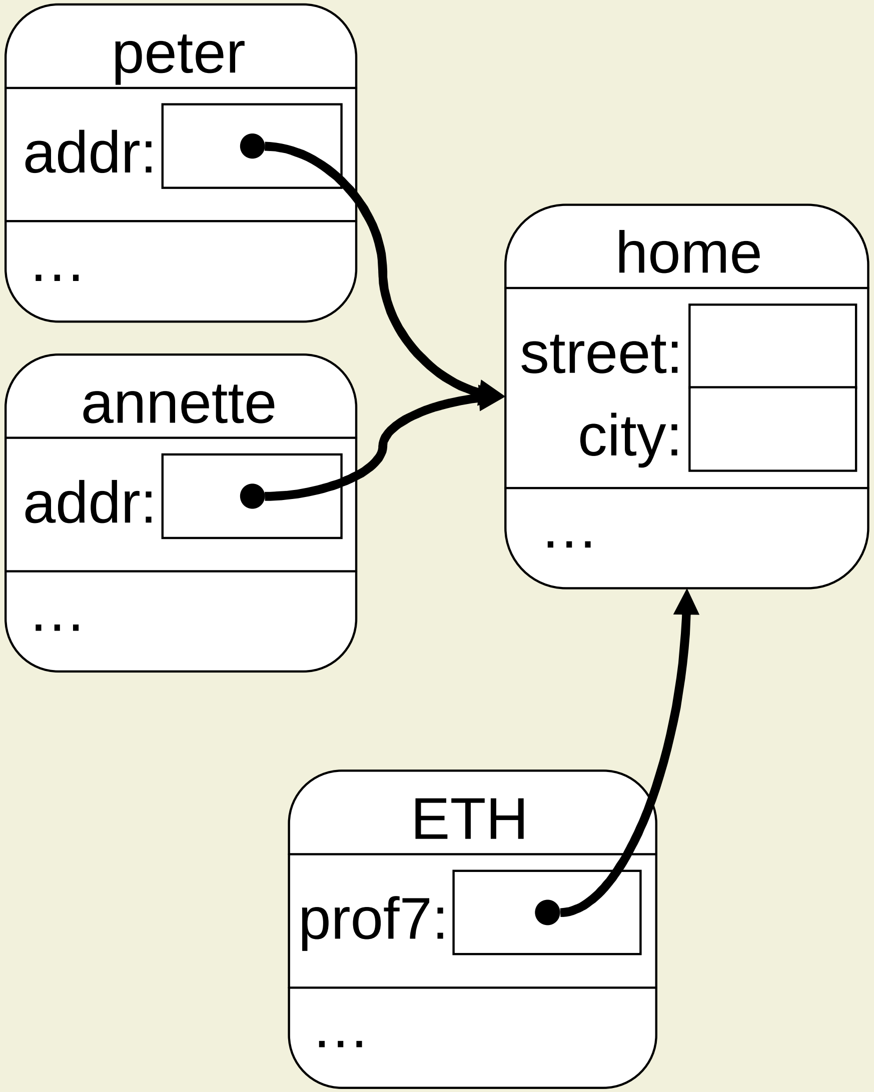
```
class Address {
  private String street;
  private String city;

  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 Control

- Aliases are helpful to **share side-effects**
- Cloning objects is not efficient
- In many cases, it would suffice to **restrict access** to shared objects



# Readonly Access in Java

```
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( ); }
  …
}
```

- Address objects are returned as ReadonlyAddress
- Clients use only the methods in this interface



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# Problems of Java Solution

- Solution does not work for
  - Reused library classes that do not implement a readonly interface
  - Arrays, fields, non-public methods
- Solution is not safe
  - Readwrite aliases can occur, e.g., by capturing
  - Clients can use casts to get full access

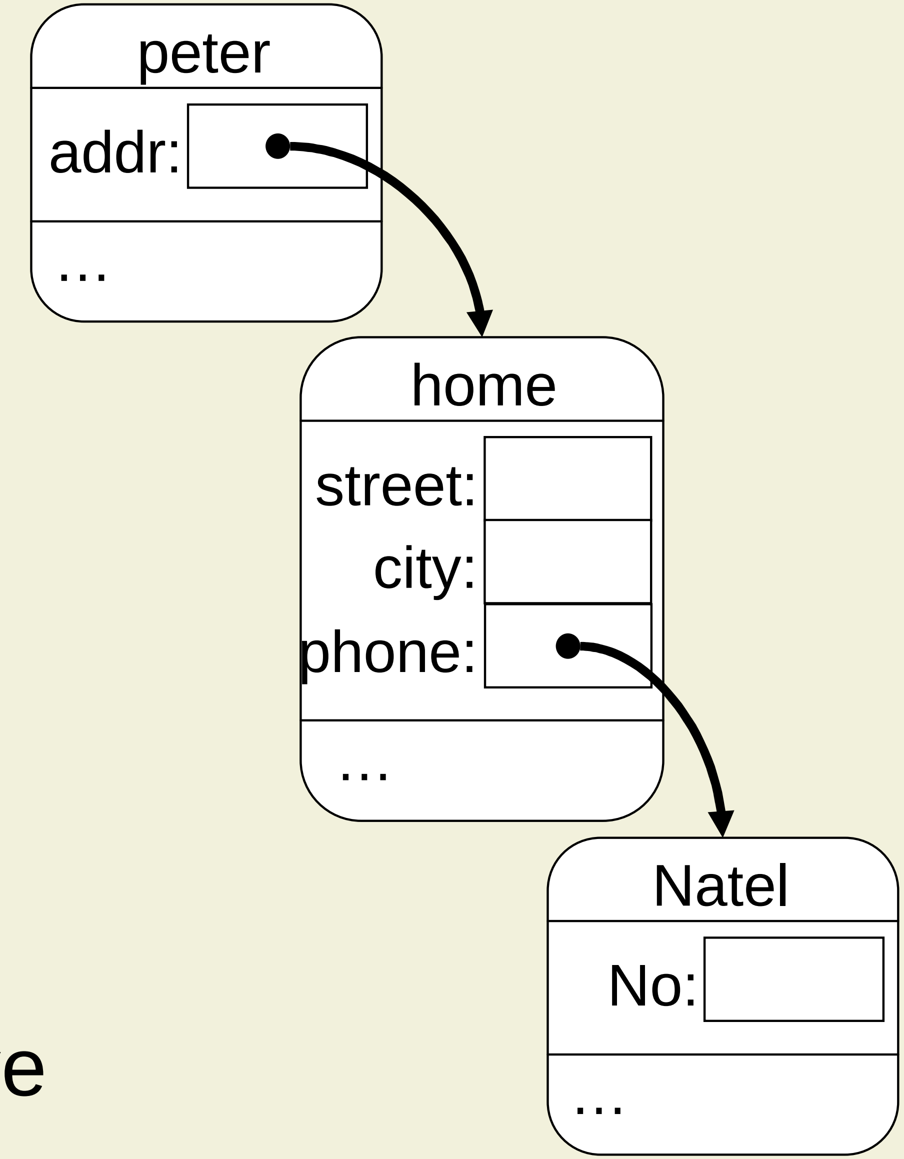
```
class Person {
  private Address addr;
  public ReadonlyAddress
     getAddr( )    { return addr; }
  public void setAddr( Address a )
   { addr = a.clone( ); }
  … }
```

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

# Transitive Readonly Access

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

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




- Problem: objects structures
- **const** in C++ is not transitive

# Pure Methods

- Tag side-effect free methods as **pure**
- Pure methods
  - Must not contain writing attribute access
  - 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**
- **Peer type** *peer(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 peer and readonly types is **defined as in Java**
  - S extends or implements T ⇒ *peer(S)* < *peer(T)*
  - S extends or implements T ⇒ *ro(S)* < ro*(T)*
- **peer types** are **subtypes of** corresponding **readonly types**
  - *peer(T)* < *ro(T)*

```
class T { … }
```

```
class S extends T { … }
```

```
S peerS = …
T peerT  = …
readonly S roS = …
readonly T roT = …
```

```
peerT      = peerS;
roT        = roS ;
roT        = peerT;
```

```
peerT  = 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
  - An attribute access
  - An array access
  - A method invocation

  expression is determined by the type combinator function *

| * | *peer(T)* | *ro(T)* |
|---|---|---|
| *peer(S)* | *peer(T)* | *ro(T)* |
| *ro(S)* | *ro(T)* | *ro(T)* |

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

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

*ro(Address)* * *peer( int[ ] )*

*ro( int[ ] )*

# Type Rules: Transitive Readonly (cont’d)

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

  expression is determined by the type combinator function *

| * | *peer(T)* | *ro(T)* |
|---|---|---|
| *peer(S)* | *peer(T)* | *ro(T)* |
| *ro(S)* | *ro(T)* | *ro(T)* |

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

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

$$\underbrace{\mathit{ro(Address)} * \mathit{peer(\ int[\ ]\ )}}_{\mathit{ro(\ int[\ ]\ )}}$$



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# Type Rules: Readonly Access

- Expressions of readonly types must not occur
  - As target of an **writing attribute access**
  - As target of a **writing array access**
  - As target of an **invocation** of a **non-pure method**
- Readonly types must not be **cast to peer types**

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

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



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# Discussion

- Readonly types enable **safe sharing of objects**
- All rules for pure methods and readonly types can be **checked statically by a compiler**
- Readonly types solve problems of interface solution
  - Reused library classes
  - Arrays, attributes, and non-public methods
  - Casts
- Readwrite aliases can still occur, e.g., by capturing


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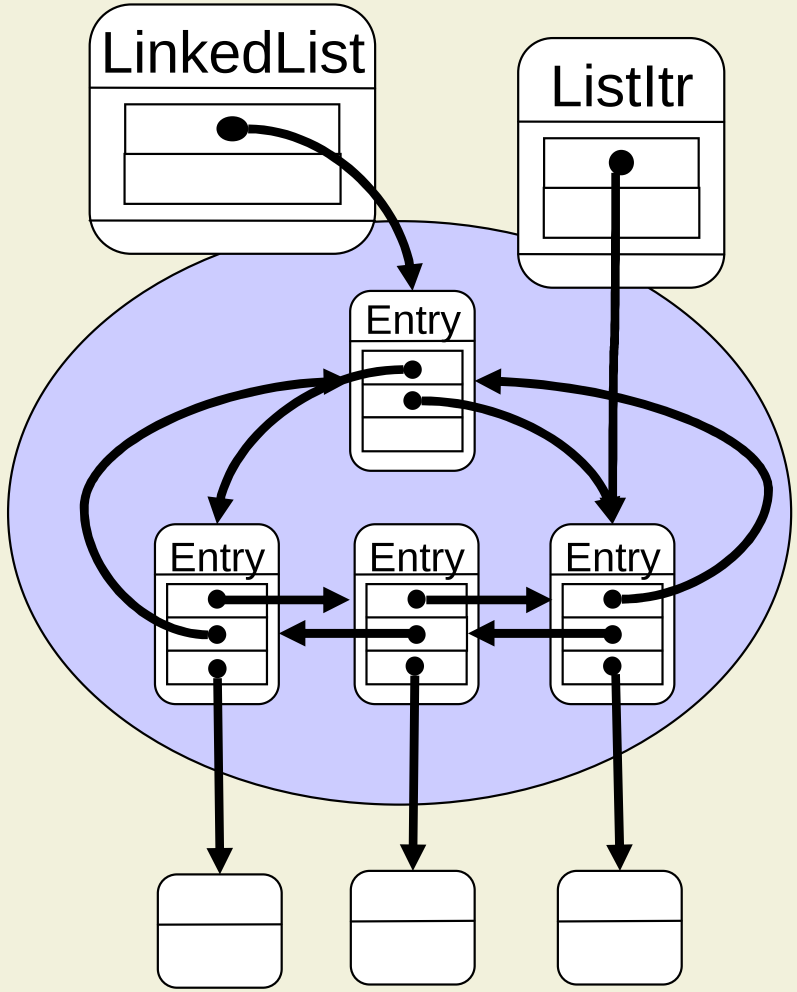
# 7. Static Safety and Extended Typing

# Roles in Object Structures

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



# (Simplified) Programming Discipline

- **Rule 1: No Role Confusion**
  - Expression with one alias mode must not be assigned to variables with another mode
- **Rule 2: No Representation Exposure**
  - rep-mode must not occur in an object's interface
  - Methods must not take or return rep-objects
  - Fields with rep-mode may only be accessed on **this**
- **Rule 3: No Argument Dependence**
  - Implementations must not depend on the state of argument objects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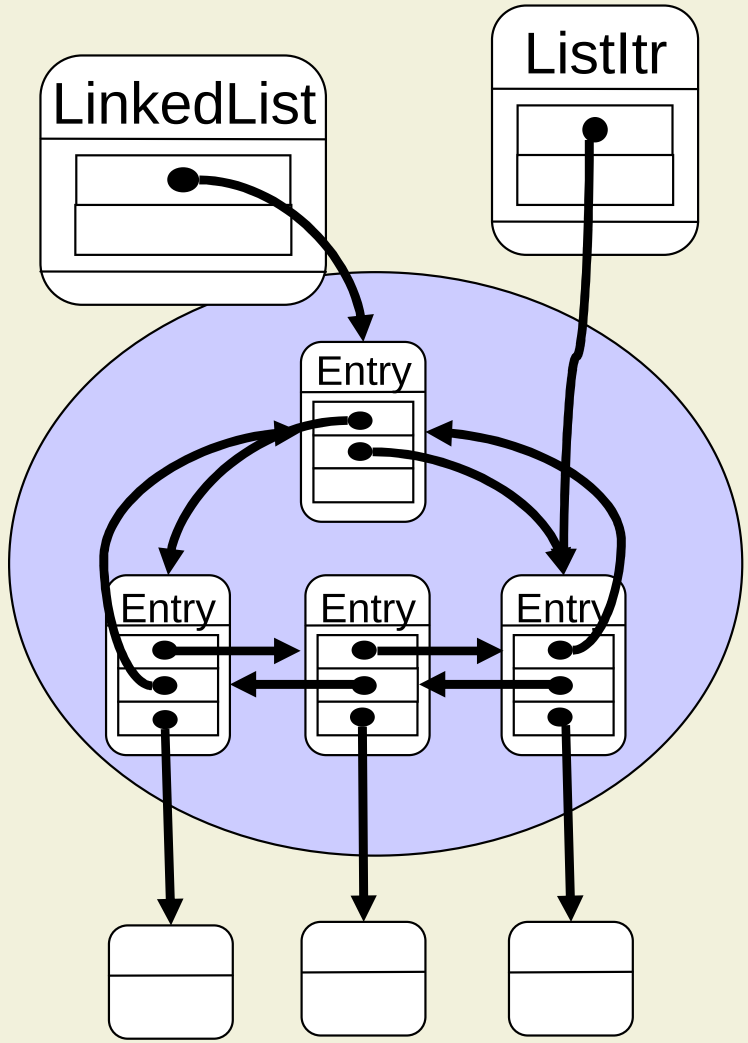
# Ownership Model

- The **object store** is partitioned into **contexts**
- Each object **belongs to exactly one context**
- Each context has at most one **owner object**
  - The owner does not belong to the context it owns
- Contexts are **hierarchical**





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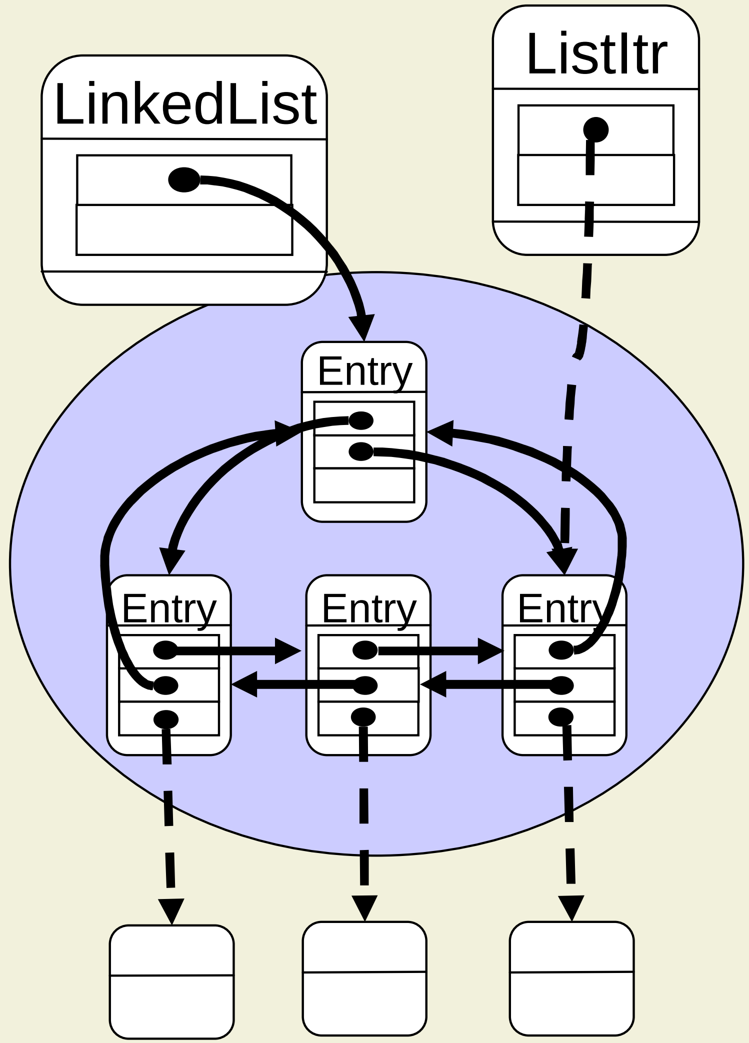
# Ownership Invariant

- The owner is the only object outside a context that can have a readwrite reference to objects inside
- Objects inside a context cannot have readwrite references to objects outside



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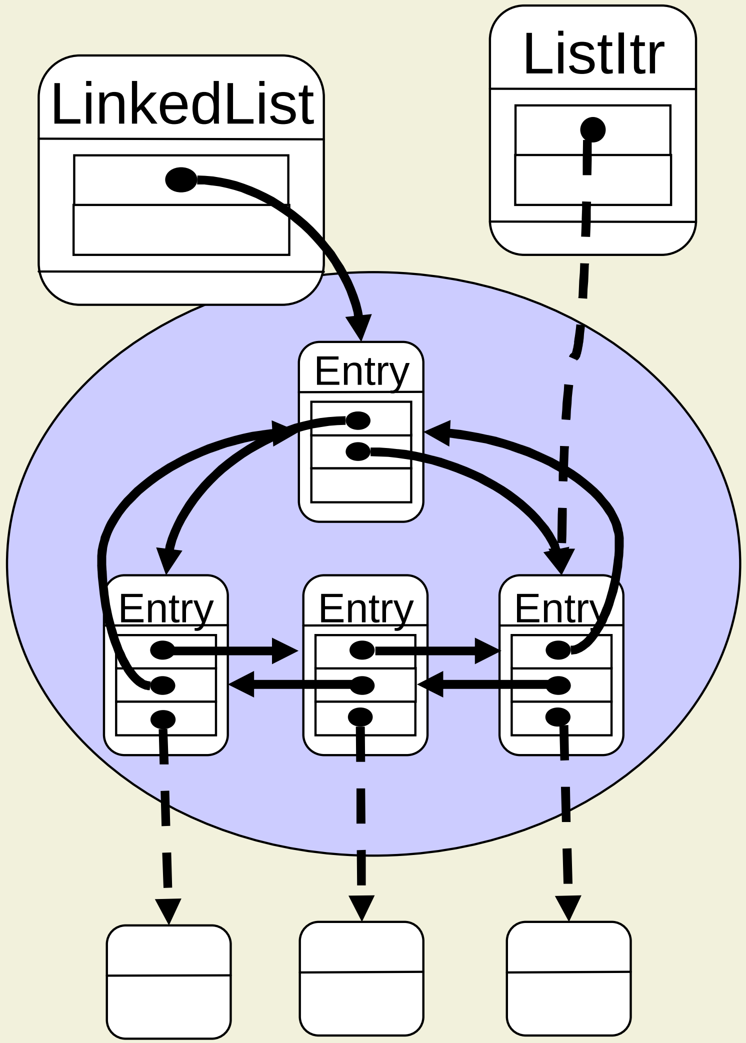
# Alias Control by Extended Typing

- We introduce different types for the different roles of objects
  - peer types for objects in the **same context as this** (interface objects)
  - Rep types for representation objects in the **context owned by this**
  - Readonly types for argument objects **in any context**
- Type rules replace the programming discipline



# Types

- Each class or interface T introduces **three types**
- Peer and readonly types
- **Rep type** *rep(T)*
  - Denoted by **rep** T in programs

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

```
class Entry {
  private readonly Object element;
  private Entry previous, next;
  public Entry( readonly Object o,
                            Entry p, Entry n ) { … }
}
```

# Subtype Relation

- **Subtyping** among rep types is **defined as in Java**
  - S extends or implements T ⇒ *rep(S)* < rep*(T)*
- **Rep types** are **subtypes of** corresponding **readonly types**
  - *rep(T) < ro(T)*
- **No subtype** relation between **peer** and **rep types**

```
class T { … }
```

```
class S extends T { … }
```

```
T peerT  = …
readonly T roT = …
rep S repS = …
rep T repT = …
```

```
repT     = repS;
roT      = repT ;
```

```
repT     = peerT;
peerT    = repT ;
repT     = roT;
```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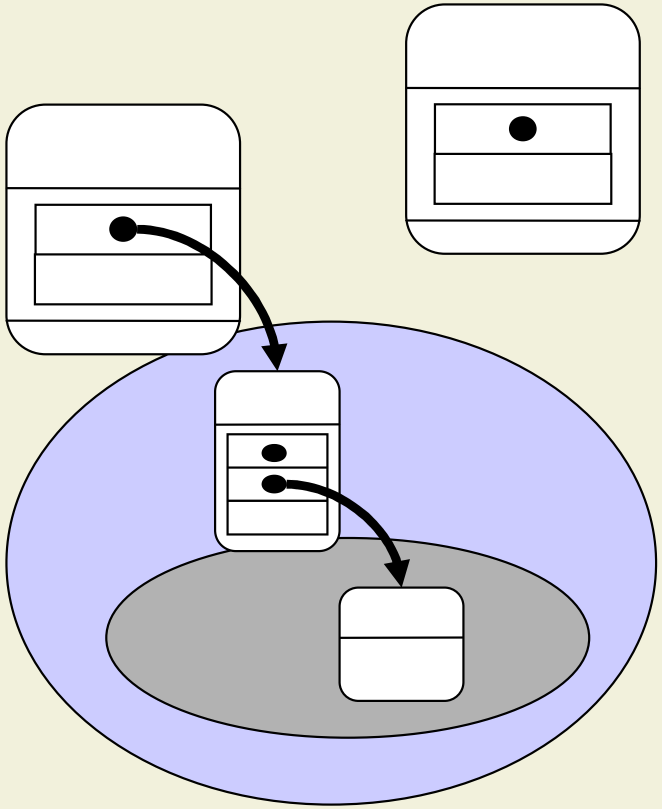
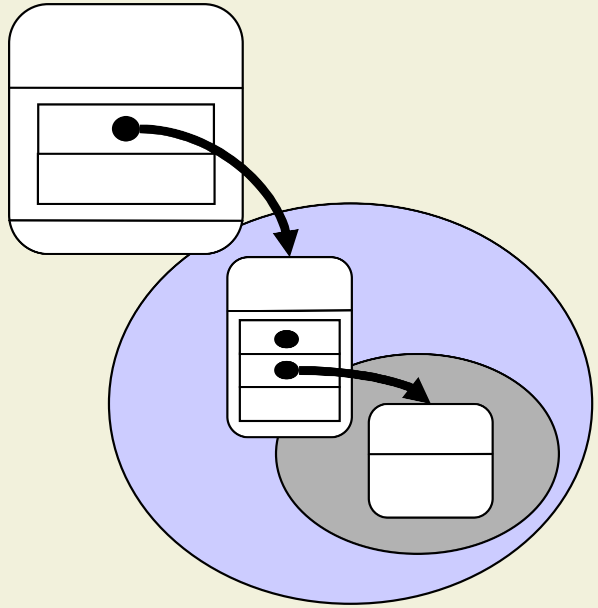
# Type Rules: The Type Combinator

| * | *peer(T)* | *rep(T)* | *ro(T)* |
|---|---|---|---|
| *peer(S)* | *peer(T)* | *rep(T)* | *ro(T)* |
| *rep(S)* | *rep(T)* | ***illegal*** | *ro(T)* |
| *ro(S)* | *ro(T)* | *ro(T)* | *ro(T)* |

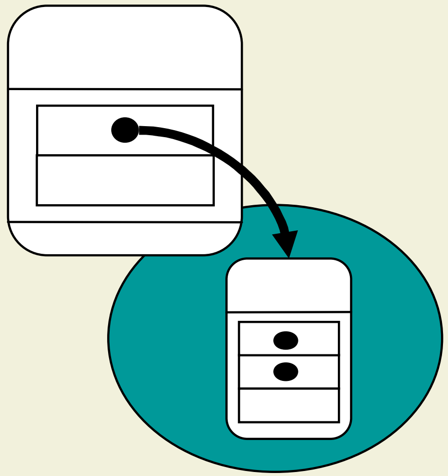


# Types Rules: Access to Contexts

- Objects in different **contexts must not be confused**



- A rep type indicates that an object is owned by **this**
- Attributes of **rep types** and methods that have rep types as parameter or result types can **safely be accessed**
  - On **readonly targets**
  - On target **this**





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# Type Rules: Attribute Access

- The attribute access

  ```
  v = exp.f;
  ```

  is correctly typed if
  - exp is correctly typed
  - $\tau(exp) * \tau(f) \leq \tau(v)$
  - $\tau(f)$ is rep $\Rightarrow$ $\tau(exp)$ is readonly

- The attribute access

  ```
  v = this.f;
  ```

  is correctly typed if
  - $\tau(\mathbf{this}) * \tau(f) \leq \tau(v)$

- Analogous rules are used for method invocations


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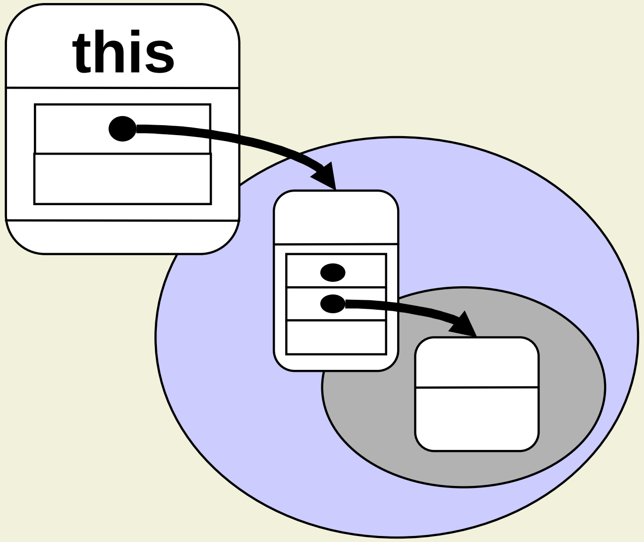
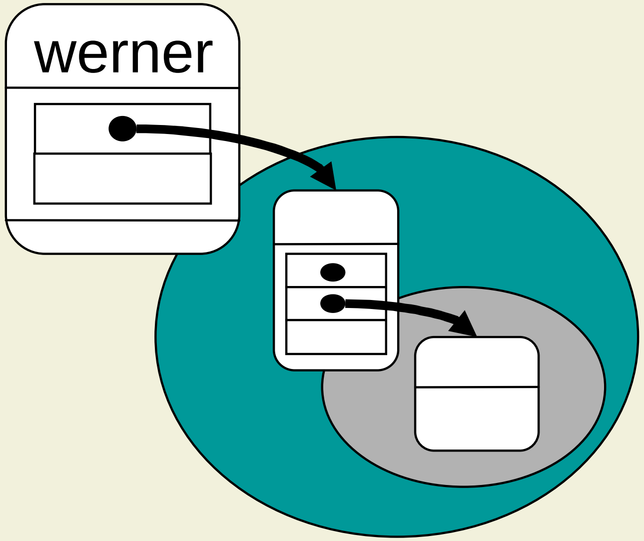
# Examples: Attribute Access




**class** Person {
  **public rep** Address addr;
  … }

**class** Address {
  **public rep int**[ ] phone;
  … }




**rep** Address a = **this**.addr;
**readonly** Person row = werner;
**readonly** Address roa = row.addr;

**rep int**[ ] no = **this**.addr.phone;
**rep** Address a = werner.addr;



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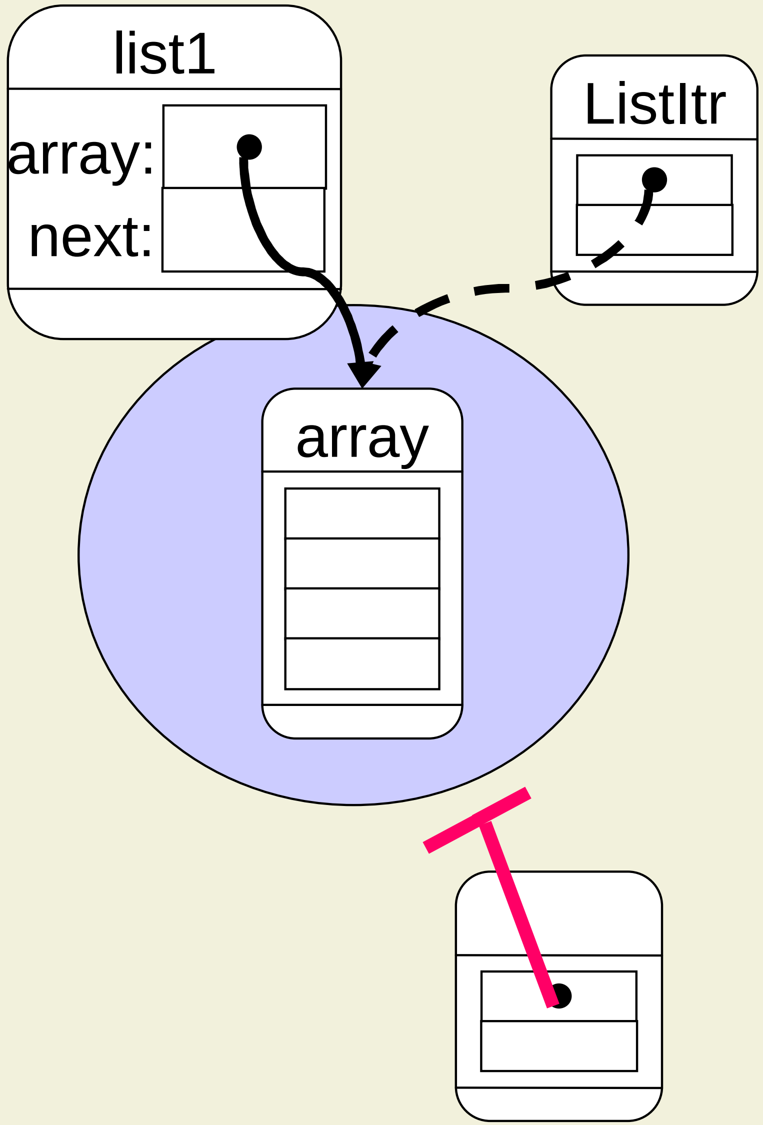
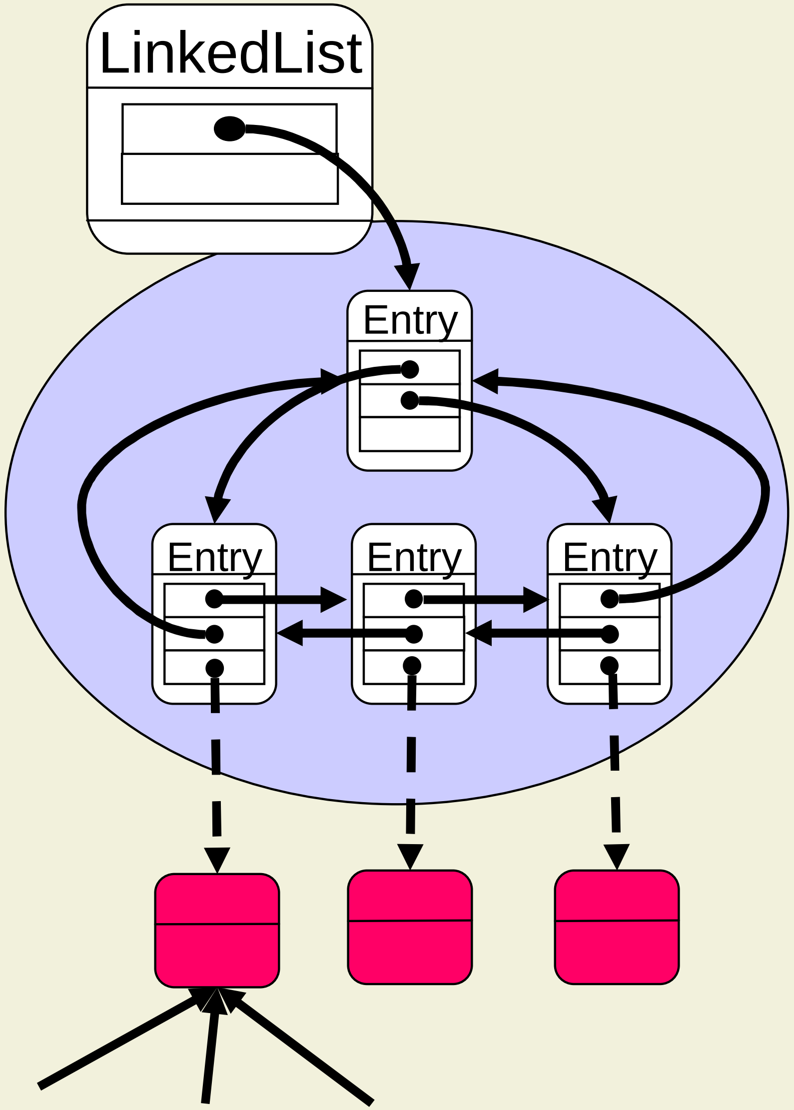
# No Representation Exposure

- Capturing or leaking **cannot lead to rep exposure**
  - Interface objects and representation objects have different types
- **Representations** of different interface objects **cannot be confused**
  - Rep fields and methods can only be accessed on **this** and readonly targets



# No Argument Dependence

- Argument objects have **readonly types**
- Argument objects may be **freely aliased**
- Invariants **must not depend** on fields of objects referenced through readonly types




```
private readonly T v, w;
// invariant v != w        -- legal
// invariant v.f != w.f    -- illegal
```

# Dynamic Types

- At compile time, each class or interface T introduces three types
  - *peer(T), rep(T), ro(T)*
- At runtime, the dynamic type of an object consists of its class and its context
  - rep and readonly are only used to classify references
- Information about dynamic types can be used to cast readonly types with dynamic checks

```
readonly Address roa = …;
Address a = ( Address ) roa;     /* dynamic check whether this and roa
                                    belong to the same context */
```

# Achievements

- Rep and readonly 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 int[ ] leak( ) {
    return array;
  }
}
```

# Open Problems

- Ownership types are an area of current research activities
- Open issues
  - **Several owners** sharing a common representation, e.g., a list header and iterators
  - **Transfer** of objects from one context to another, e.g., for capturing
  - **Application** of ownership types to all areas where aliasing leads to problems, e.g., thread synchronization

# Diplom- und Semesterarbeiten

- The Software Component Technology Group has developed the **Universe Type System** to control aliasing and dependencies
- **Areas for student projects** include
  - Extending the implementation of the type checker
  - Performing case studies
  - Extending the type system
  - Working on a type safety proof
- If interested, please contact **Werner Dietl** or **Peter Müller**
- Next semester, we offer a seminar on aliasing



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