Ownership Types for Object Encapsulation

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Outline

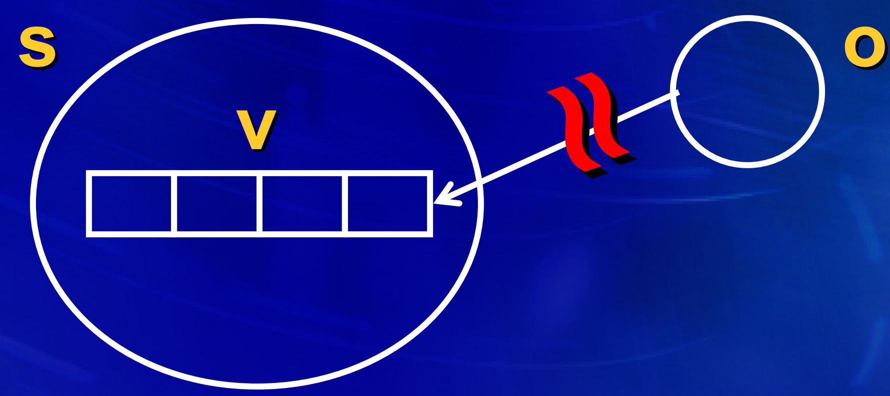
- Object Encapsulation
- Ownership Types
- Upgrades in Persistent Object Stores

Modular Reasoning

- Goal is local reasoning about correctness
  - Prove a class meets its specification, using only specifications but not code of other classes
- Crucial when dealing with large programs
- Requires no interference from code outside the class
  - Objects must be encapsulated

Object Encapsulation

- Consider a Set object s implemented using a Vector object v



- Local reasoning about s is possible
  - If objects outside s do not access v
  - That is, if v is encapsulated within s

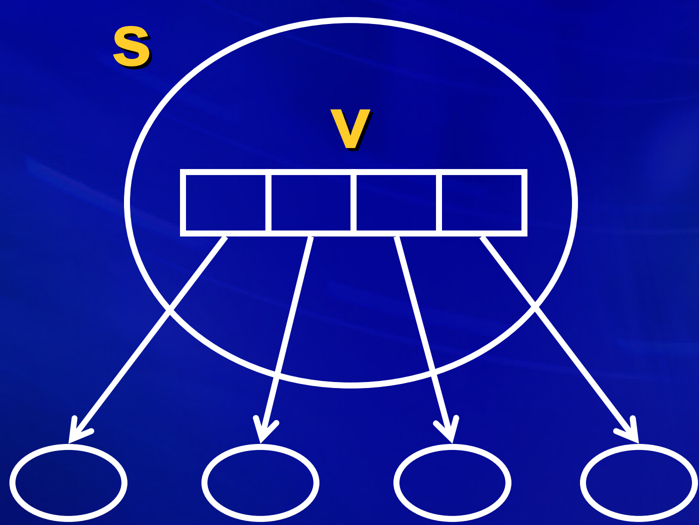
Encapsulation

- In general, all objects that s depends on must be encapsulated within s

- s depends on x if mutations of x affect behavior of s
  - Leino, Nelson (SCR ’00)
  - Detlefs, Leino, Nelson (SRC ’98)

Examples

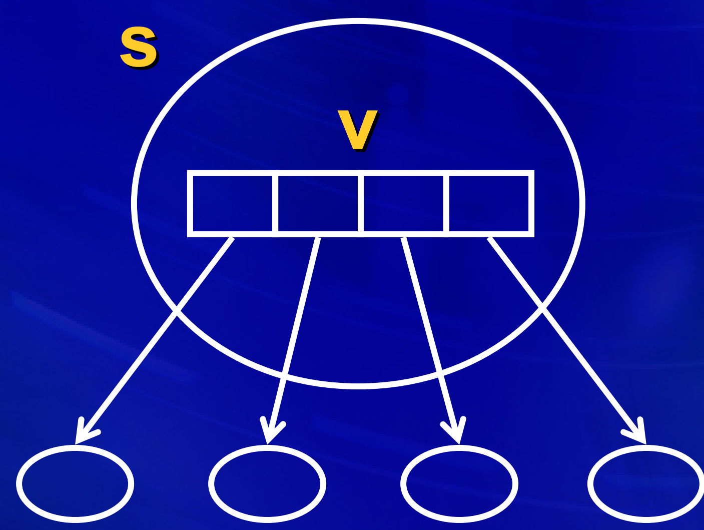
- Rep invariant for Set: no-dups
  - Then, size of vector is size of set
  - Then, remove stops at match



- Clearly, v must be inside s

Examples

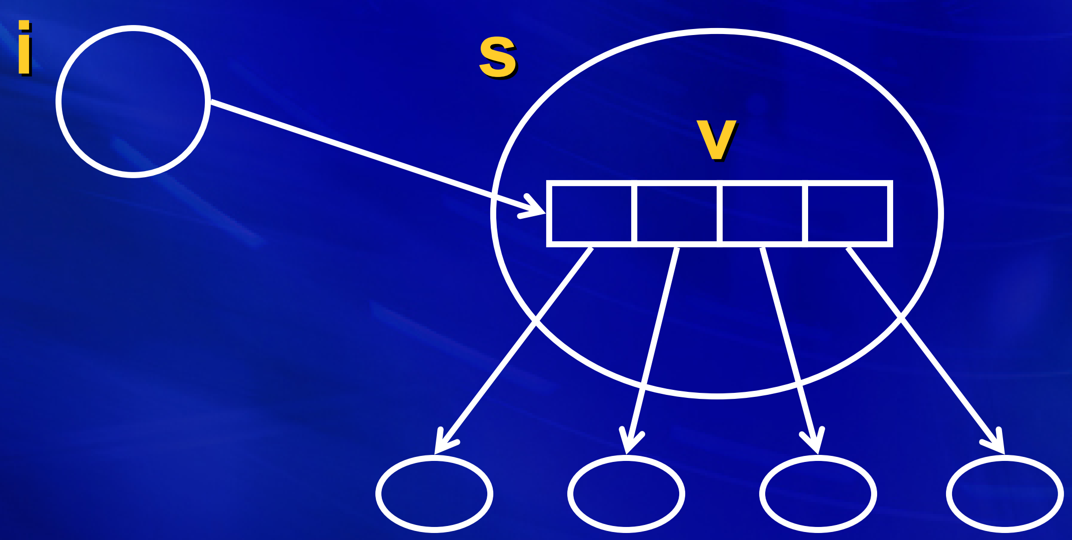
- What does no-dups mean?
  - ! e1.equals(e2), for any elements e1 & e2



- So set does not depend on elements if elements are immutable

Iterators and Encapsulation

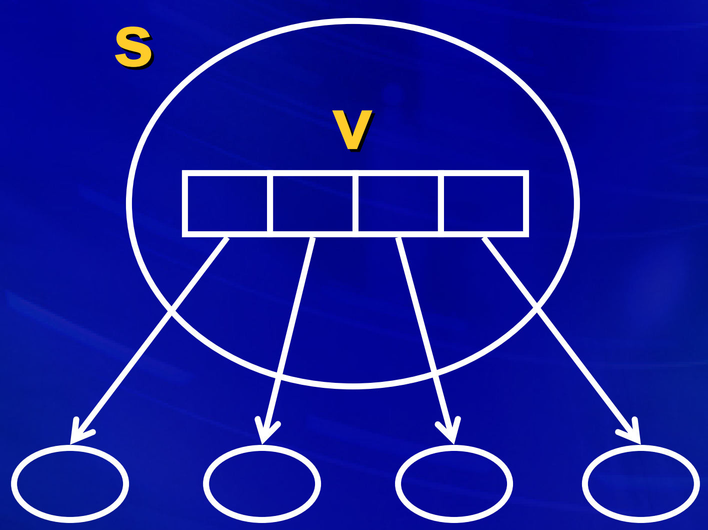
- Iterators require access to representation



- Okay if violations of encapsulation limited to the same module

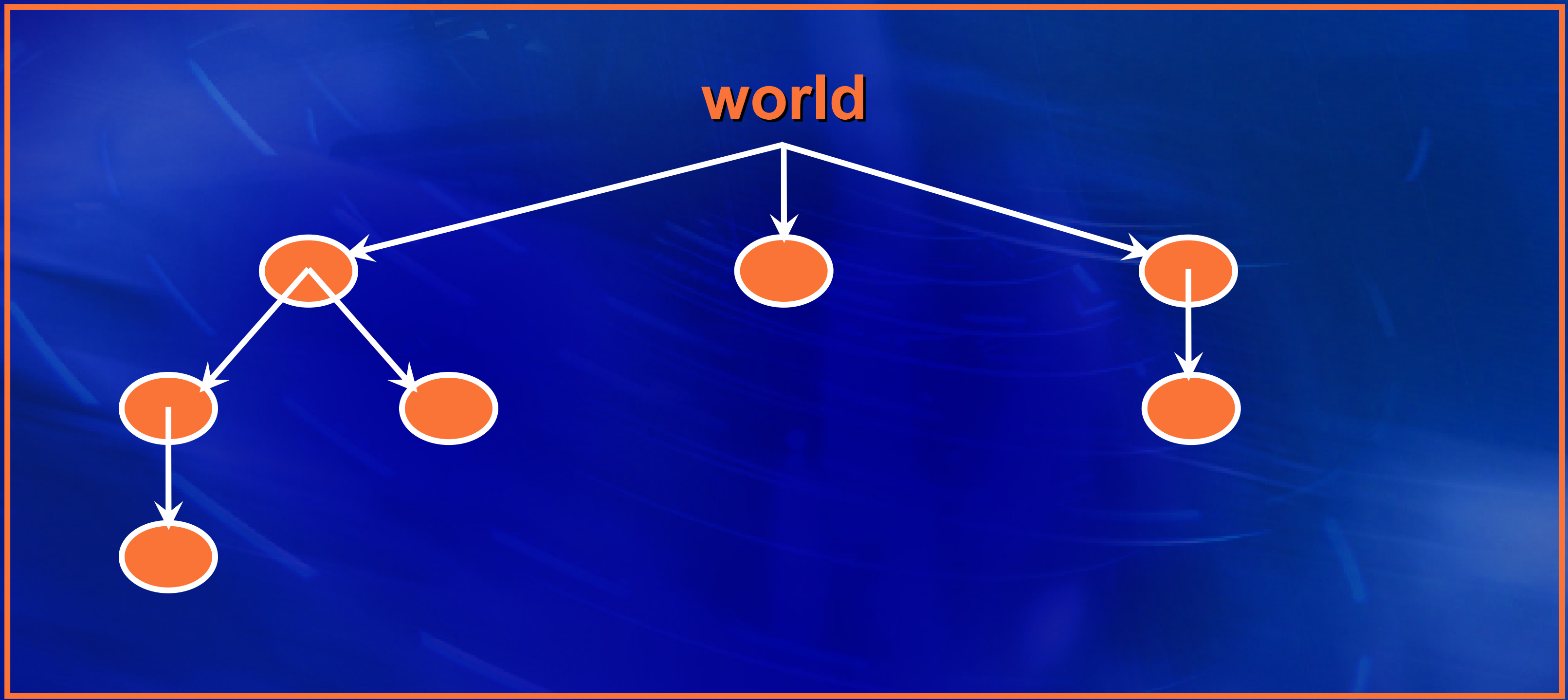
Ownership Types

- Goal is to enforce encapsulation statically



- Programmer can declare s owns v
- System ensures v is encapsulated in s

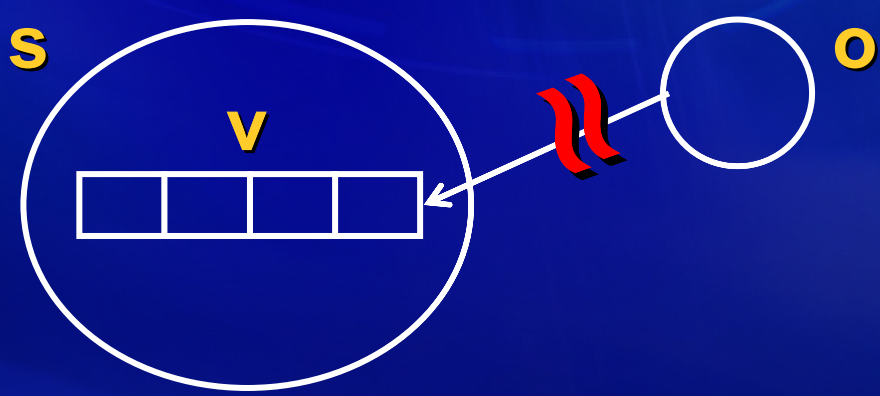
Ownership Types



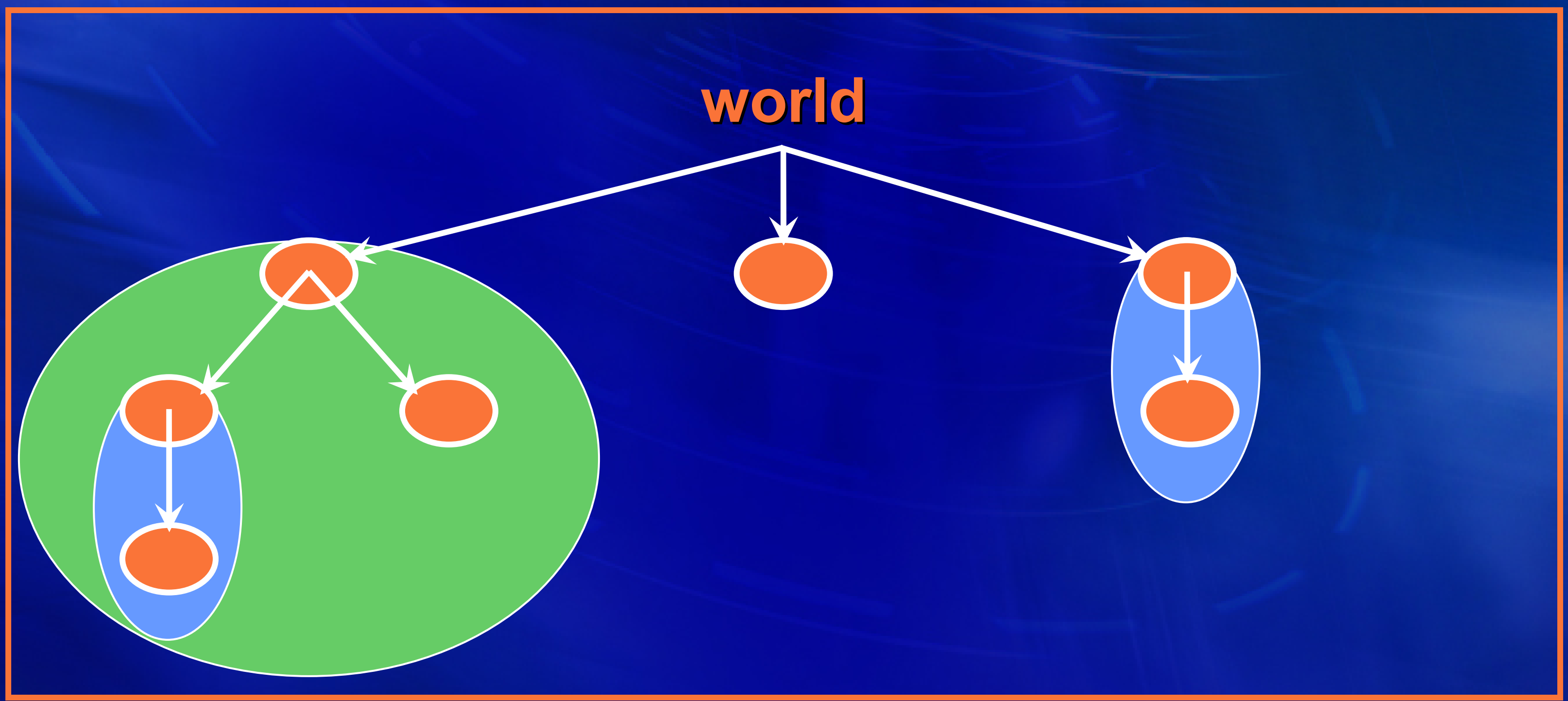
- Every object has an owner
- Owner can be another object or world
- Ownership relation forms a tree
- Owner of an object cannot change

Ownership Types for Encapsulation

- If an object owns objects it depends on
- Then type system enforces encapsulation
  - If v is inside s and o is outside
  - Then o cannot access v

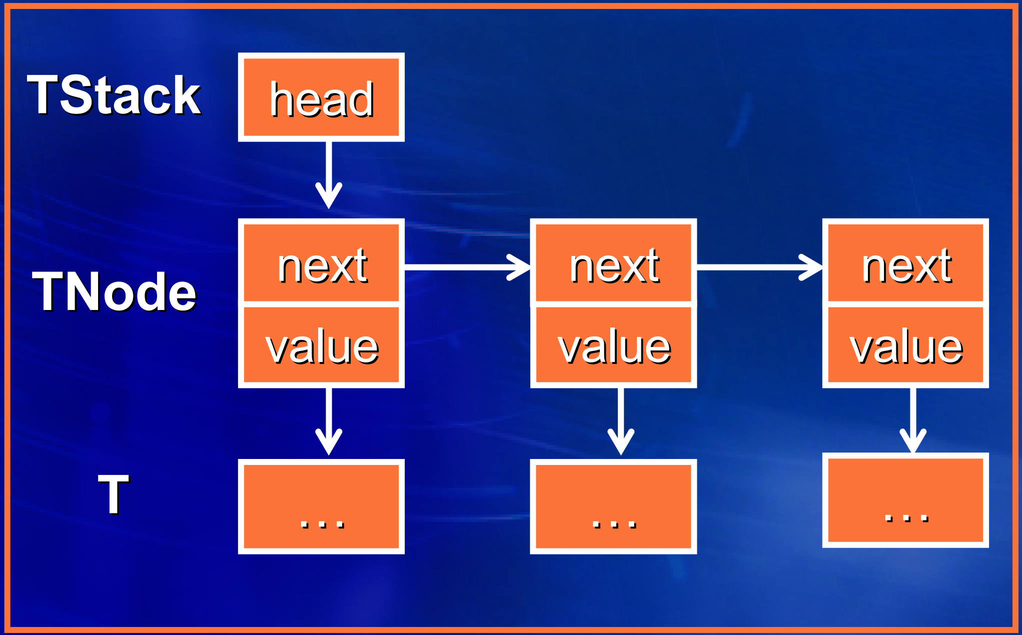


Ownership Types



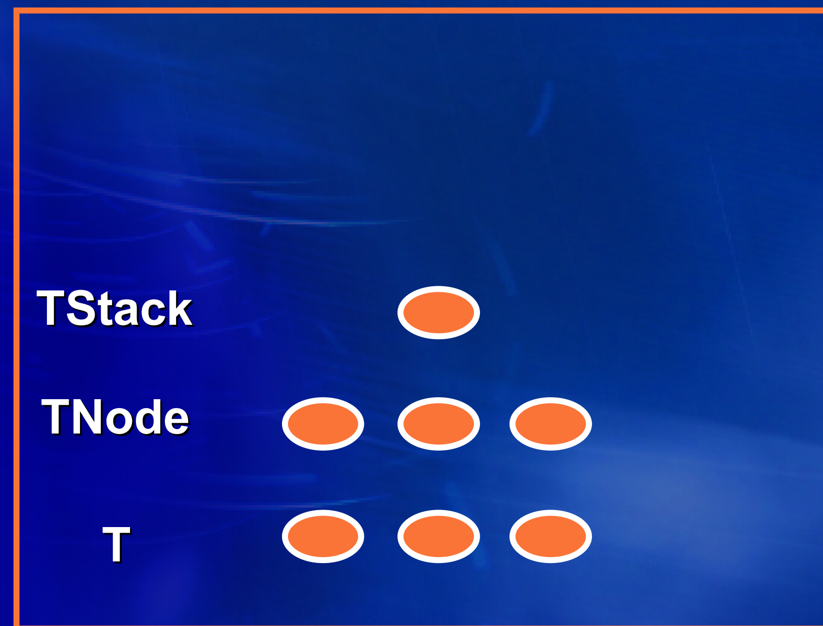
TStack Example (No Owners)

```
class TStack {
    TNode head;

    void push(T value) {…}
    T pop() {…}
}

class TNode {
    TNode next;
    T value;
    …
}

class T {…}
```



TStack Example (With Owners)

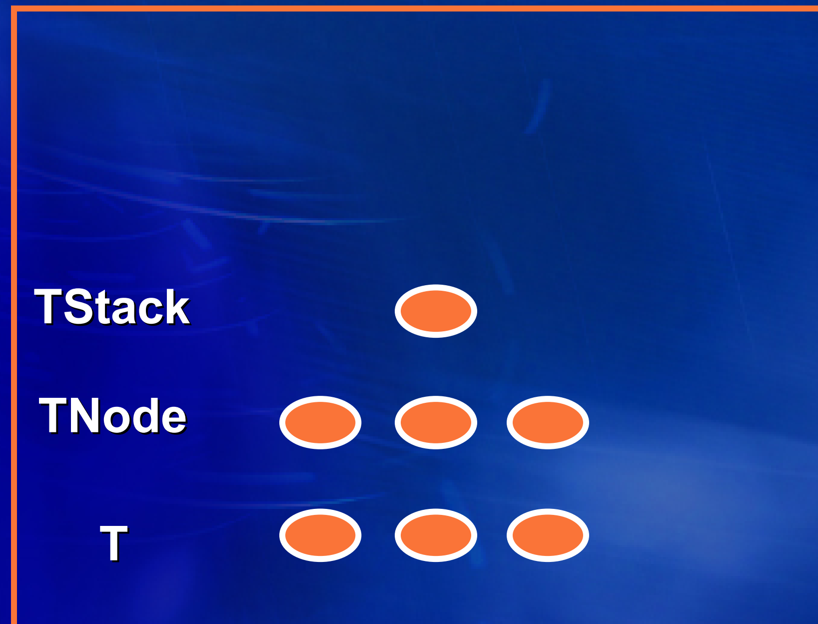
```
class TStack⟨stackOwner, TOwner⟩ {
    TNode⟨this, TOwner⟩ head;
}
class TNode⟨nodeOwner, TOwner⟩ {
    TNode⟨nodeOwner, TOwner⟩ next;
    T⟨TOwner⟩ value;
}
class T ⟨TOwner⟩ {…}
```



Classes are parameterized with owners

TStack Example

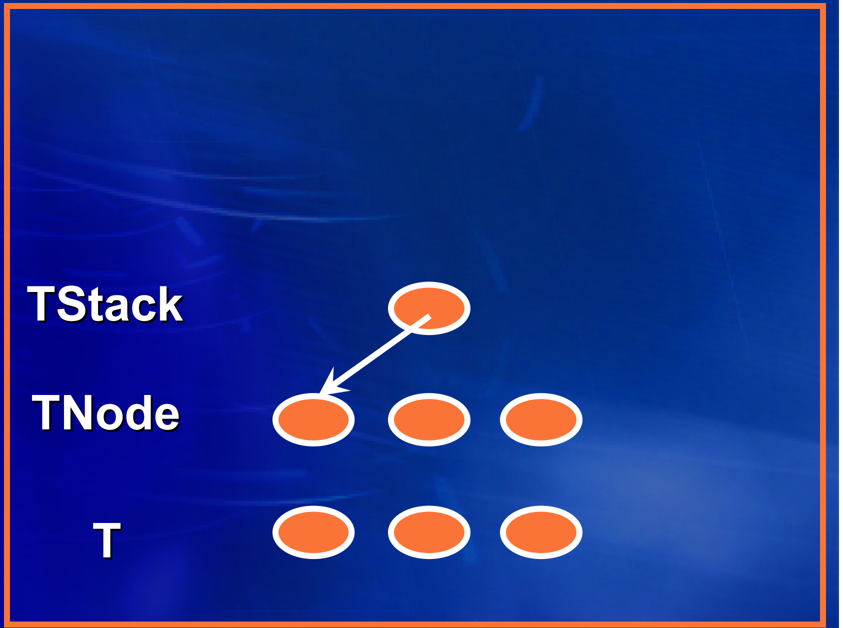
```
class TStack⟨stackOwner, TOwner⟩ {
    TNode⟨this, TOwner⟩ head;
}
class TNode⟨nodeOwner, TOwner⟩ {
    TNode⟨nodeOwner, TOwner⟩ next;
    T⟨TOwner⟩ value;
}
class T ⟨TOwner⟩ {…}
```



First owner owns the "this" object

TStack Example

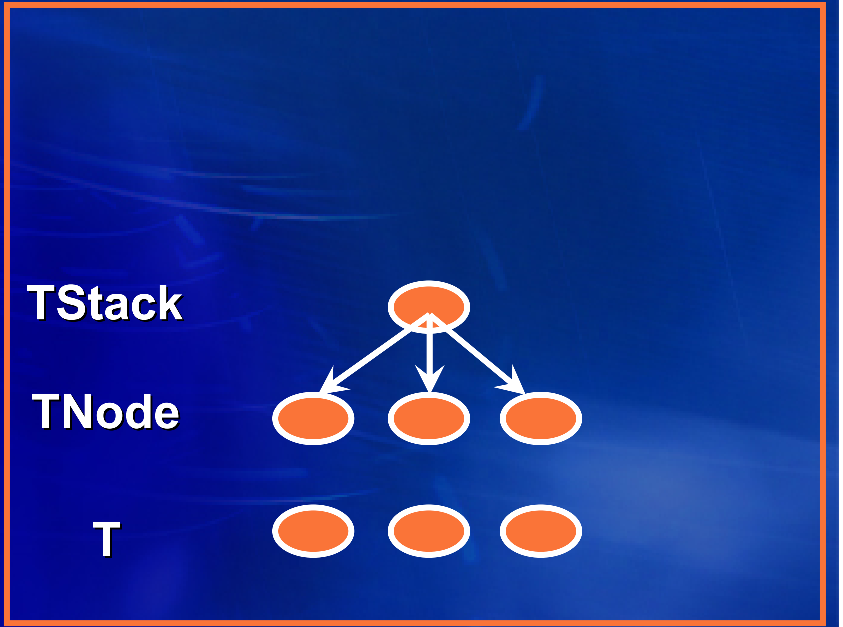
```
class TStack⟨stackOwner, TOwner⟩ {
    TNode⟨this, TOwner⟩ head;
}
class TNode⟨nodeOwner, TOwner⟩ {
    TNode⟨nodeOwner, TOwner⟩ next;
    T⟨TOwner⟩ value;
}
class T ⟨TOwner⟩ {…}
```



TStack owns the "head" TNode

TStack Example

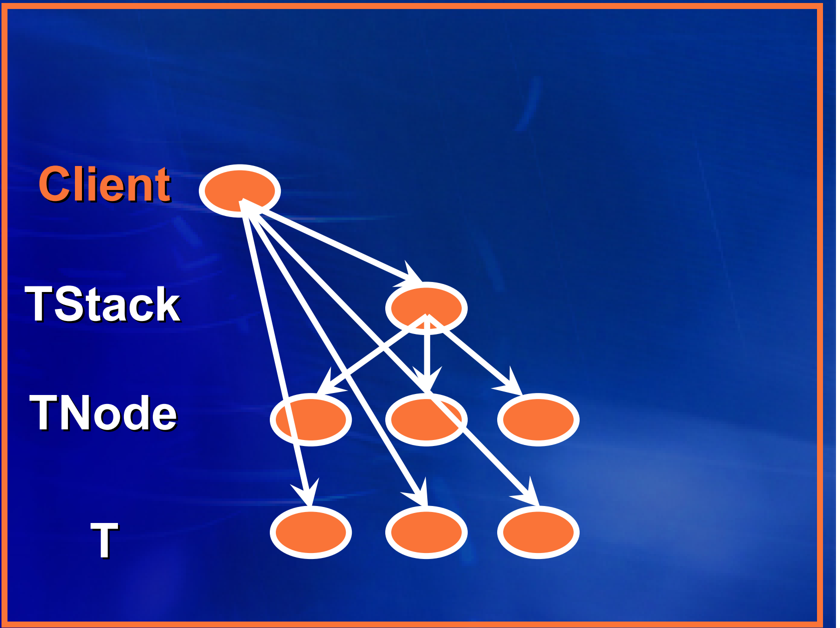
```
class TStack⟨stackOwner, TOwner⟩ {
    TNode⟨this, TOwner⟩ head;
}
class TNode⟨nodeOwner, TOwner⟩ {
    TNode⟨nodeOwner, TOwner⟩ next;
    T⟨TOwner⟩ value;
}
class T ⟨TOwner⟩ {…}
```



The "next" TNode has the same owner as the "this" TNode
All TNodes have the same owner

TStack Example

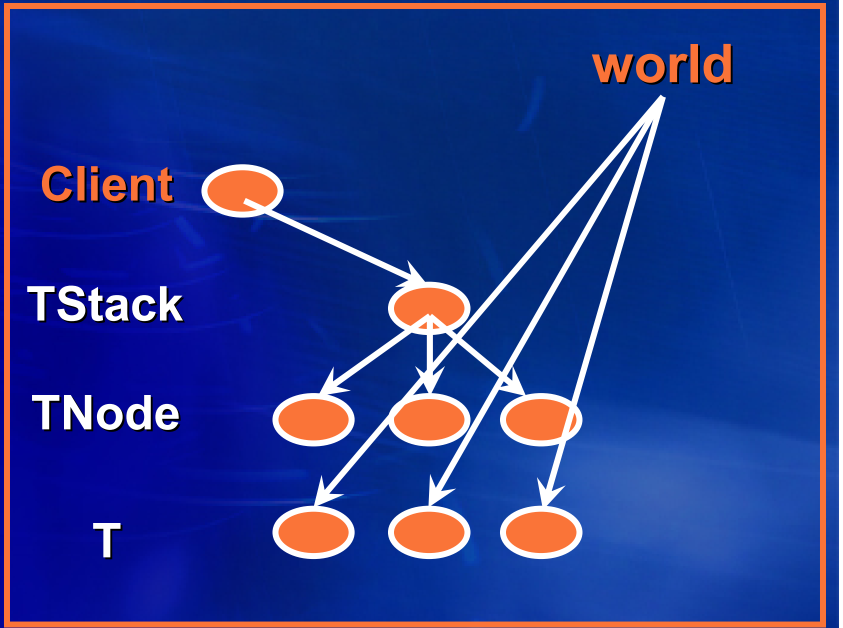
```
class TStack⟨stackOwner, TOwner⟩ {
    TNode⟨this, TOwner⟩ head;
}
class TNode⟨nodeOwner, TOwner⟩ {
    TNode⟨nodeOwner, TOwner⟩ next;
    T⟨TOwner⟩ value;
}
class Client⟨clientOwner⟩ {
    TStack⟨this,    this⟩   s1;
    TStack⟨this,    world⟩ s2;
    TStack⟨world, world⟩ s3;
}
```



s1 is an encapsulated stack with encapsulated elements

TStack Example

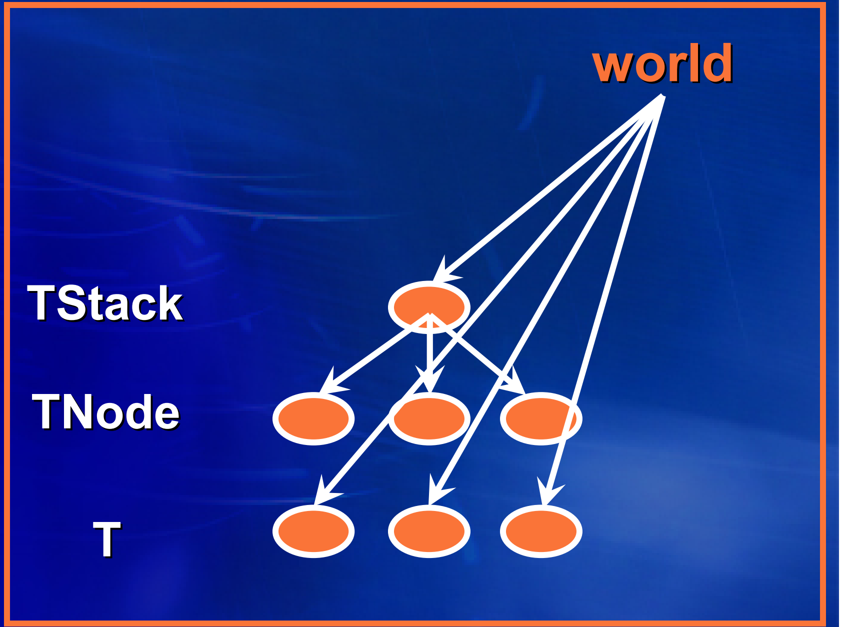
```
class TStack⟨stackOwner, TOwner⟩ {
    TNode⟨this, TOwner⟩ head;
}
class TNode⟨nodeOwner, TOwner⟩ {
    TNode⟨nodeOwner, TOwner⟩ next;
    T⟨TOwner⟩ value;
}
class Client⟨clientOwner⟩ {
    TStack⟨this,   this⟩   s1;
    TStack⟨this,   world⟩ s2;
    TStack⟨world, world⟩ s3;
}
```



s2 is an encapsulated stack with public elements

TStack Example

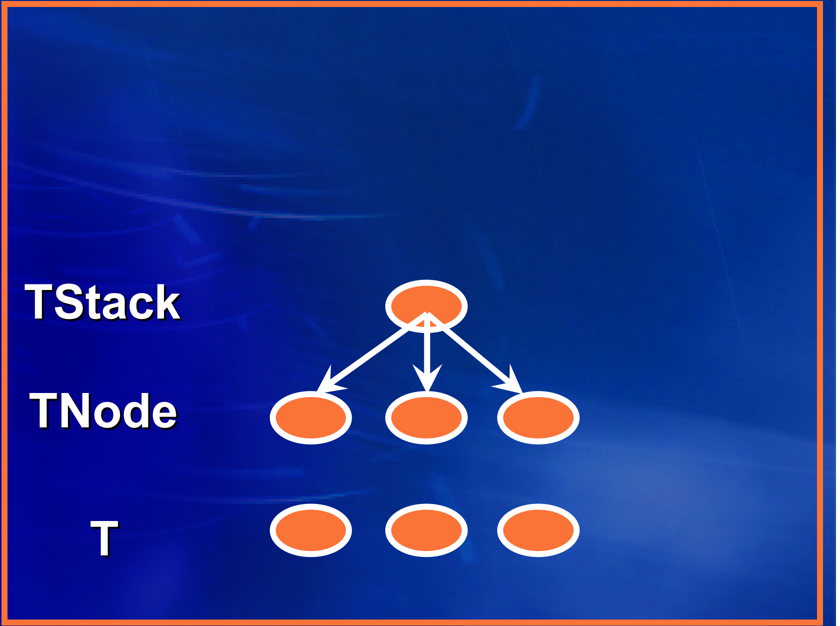
```
class TStack⟨stackOwner, TOwner⟩ {
    TNode⟨this, TOwner⟩ head;
}
class TNode⟨nodeOwner, TOwner⟩ {
    TNode⟨nodeOwner, TOwner⟩ next;
    T⟨TOwner⟩ value;
}
class Client⟨clientOwner⟩ {
    TStack⟨this,   this⟩   s1;
    TStack⟨this,   world⟩ s2;
    TStack⟨world, world⟩ s3;
}
```



s3 is a public stack with public elements

TStack Example

```
class TStack⟨stackOwner, TOwner⟩ {
    TNode⟨this, TOwner⟩ head;
}
class TNode⟨nodeOwner, TOwner⟩ {
    TNode⟨nodeOwner, TOwner⟩ next;
    T⟨TOwner⟩ value;
}
class Client⟨clientOwner⟩ {
    TStack⟨this,   this⟩   s1;
    TStack⟨this,   world⟩ s2;
    TStack⟨world, world⟩ s3;
    TStack⟨world, this⟩   s4;  // illegal
}
```



Other owners must be same as or more public than first owner [CD02]
This constraint is necessary to enforce encapsulation with subtyping

Constraints on Owners

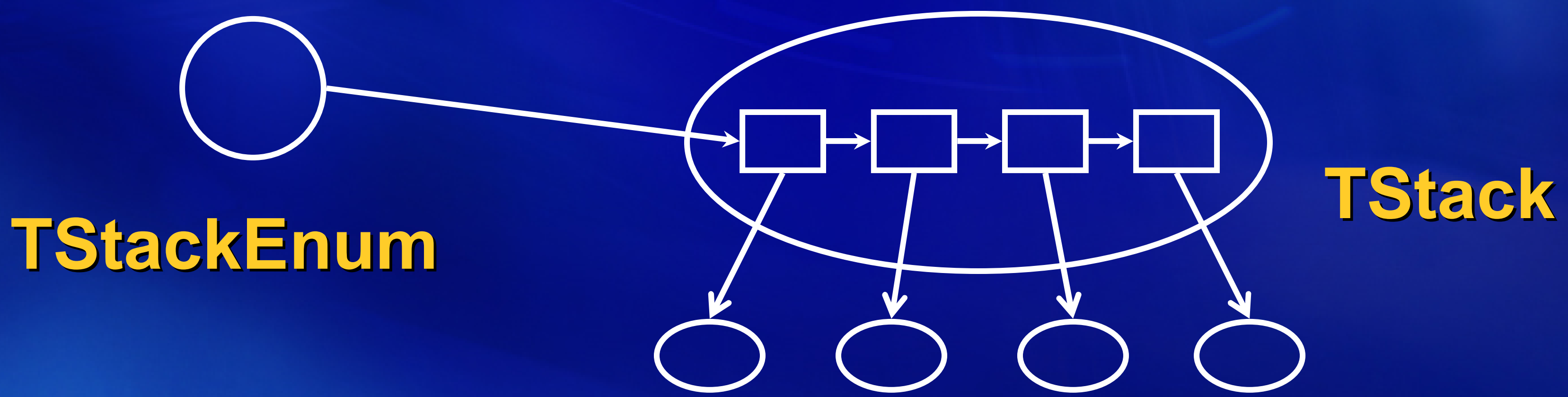
```
class Client⟨cOwner, sOwner, tOwner⟩  where (sOwner <= tOwner) {
    …
    TStack⟨sOwner, tOwner⟩ head;
}
```

This is legal only if tOwner is same as or more public than sOwner

Programmers can constrain owners using where clauses

Iterators

- Consider an Iterator i over Stack s
- If i is encapsulated within s
  - Then i cannot be used outside s
- If i is not encapsulated within s
  - Then i cannot access representation of s



Solution

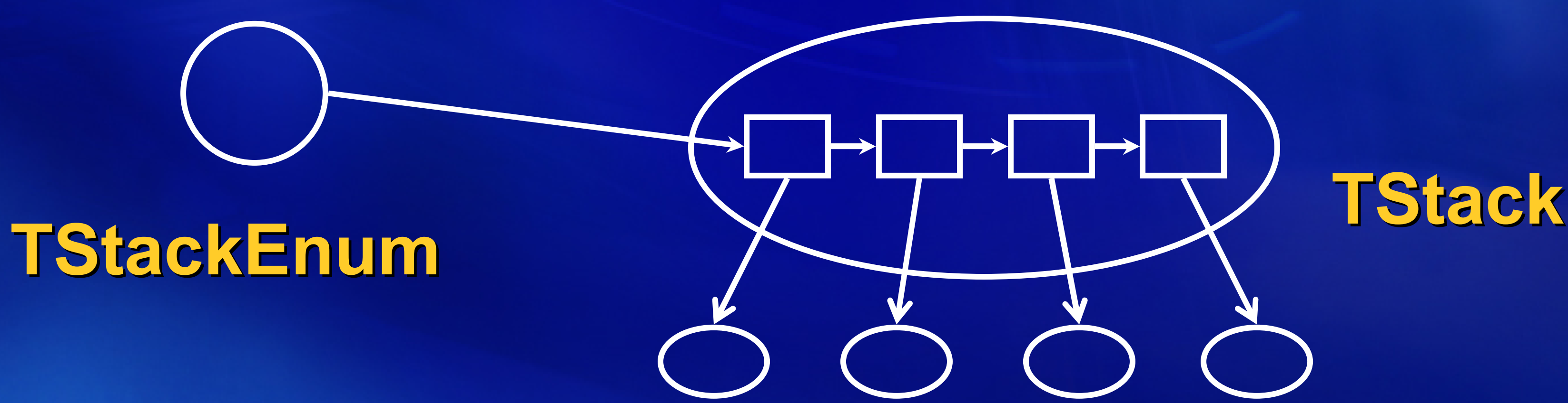
- Use inner classes

- Gives desired access to representation
- Yet, satisfies our modularity goal

Iterators

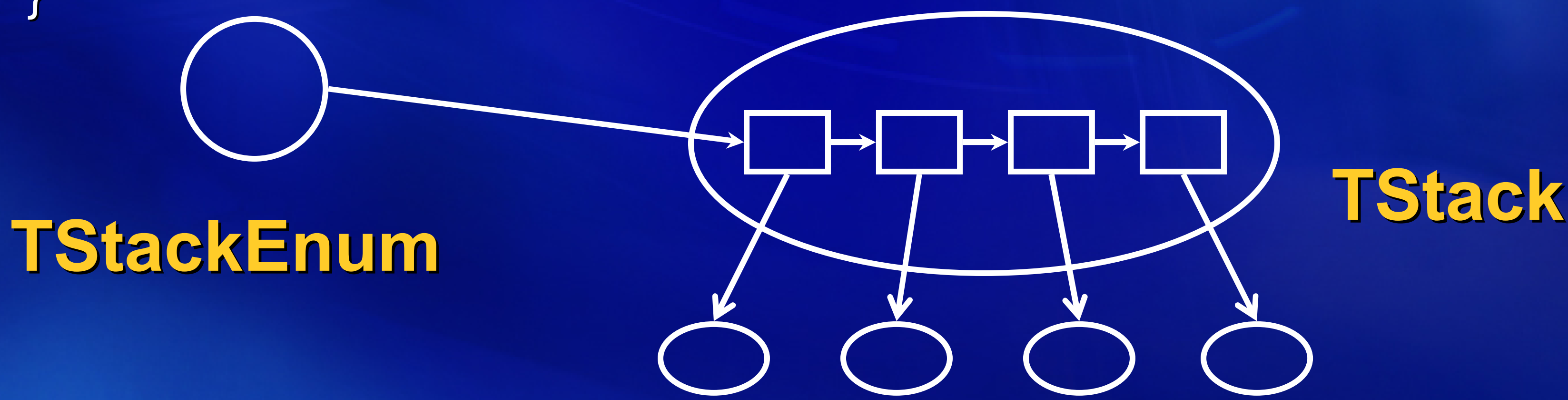
```
class TStack⟨stackOwner, TOwner⟩ {
  TNode⟨this, TOwner⟩ head;
  ….
  class TStackEnum⟨enumOwner, TOwner⟩ implements
    TEnum⟨enumOwner, TOwner⟩ {
    TNode⟨TStack.this, TOwner⟩ current = TStack.this.head;
    ….
  }
}
```

Inner class objects can access rep of outer class objects



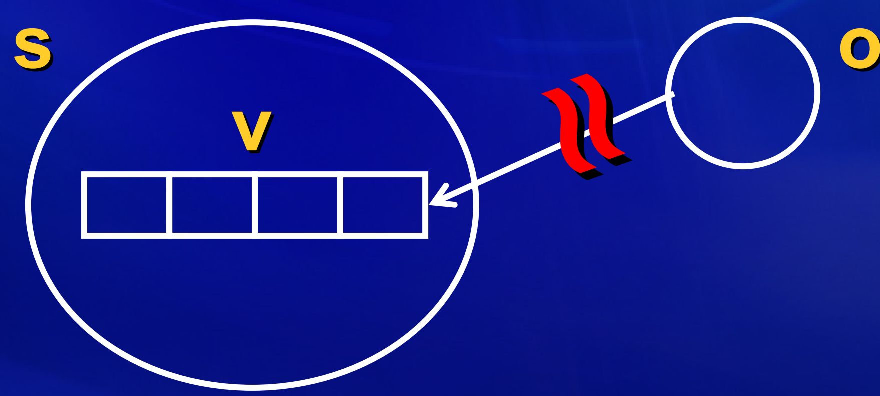
Iterators

```
class TStack⟨stackOwner, TOwner⟩ {
    TNode⟨this, TOwner⟩ head;
    ….
    class TStackEnum⟨enumOwner, TOwner⟩ implements
        TEnum⟨enumOwner, TOwner⟩ {…}

    TStackEnum ⟨enumOwner, TOwner⟩ elements ⟨enumOwner⟩ ( )
        where (enumOwner <= TOwner) {…}

}
```



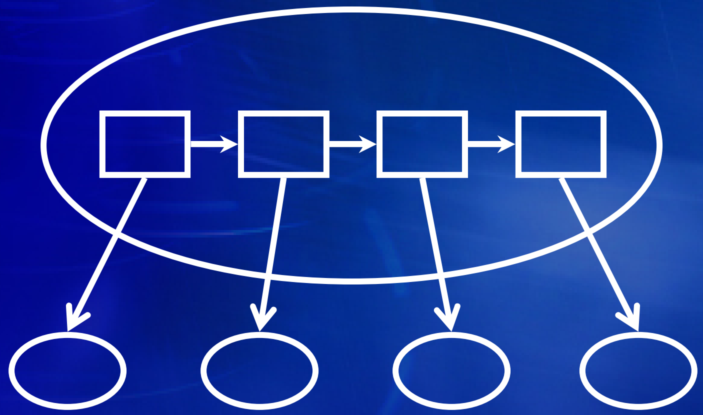
Ownership Types for Encapsulation

- If an object owns objects it depends on
- Then type system enforces encapsulation
  - If v is inside s and o is outside
  - Then o cannot access v
  - Unless o is inner class object of s



Effects Clauses

```
class TStack⟨stackOwner, TOwner⟩ {
    TNode⟨this, TOwner⟩ head;
    …
    T⟨TOwner⟩ pop() writes (this) {
        if (head == null) return null;
        T⟨TOwner⟩ value = head.value();
        head = head.next();
        return value;
    }
}
```



Methods can specify read and write effects
reads(x) means method can read x and its encapsulated objects
writes(x) means method can read/write x and its encapsulated objects

Related Work

- Types augmented with owners
  - Clarke, Potter, Noble (OOPSLA '98)
- Support for subtyping
  - Clarke, Drossopoulou (OOPSLA '02)
- Owners combined with effects clauses
  - Boyapati, Rinard (OOPSLA '01)

Summary

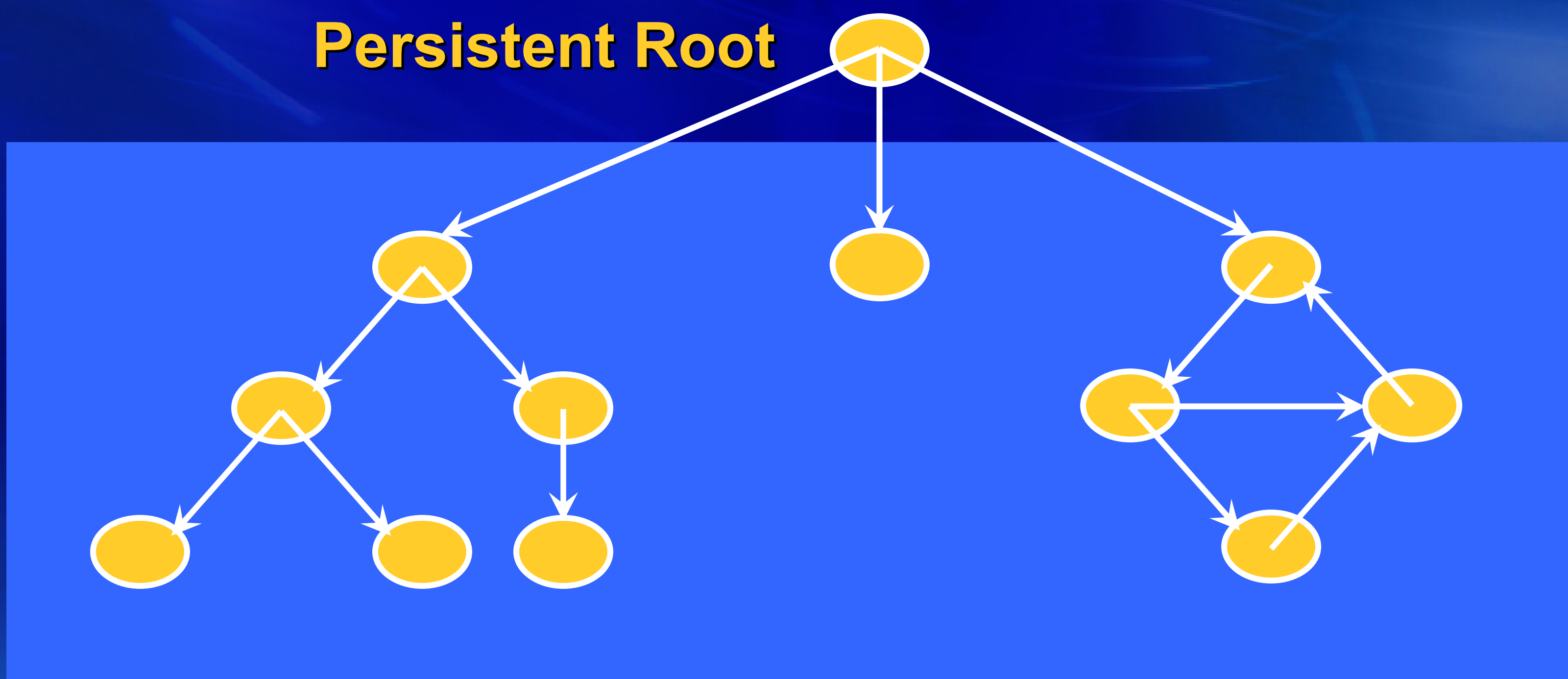
- Ownership types capture dependencies
- Extension for inner class objects allows iterators and wrappers
- Approach provides expressive power, yet ensures modular reasoning
- Effects clauses enhance modular reasoning

Applications

- Safe upgrades in persistent object stores
- Preventing data races and deadlocks
  - Boyapati, Lee, Rinard (OOPSLA '01) (OOPSLA '02)
- Safe region-based memory management
  - Boyapati, Salcianu, Beebee, Rinard (MIT '02)
- Program understanding
  - Aldrich, Kostadinov, Chambers (OOPSLA '02)

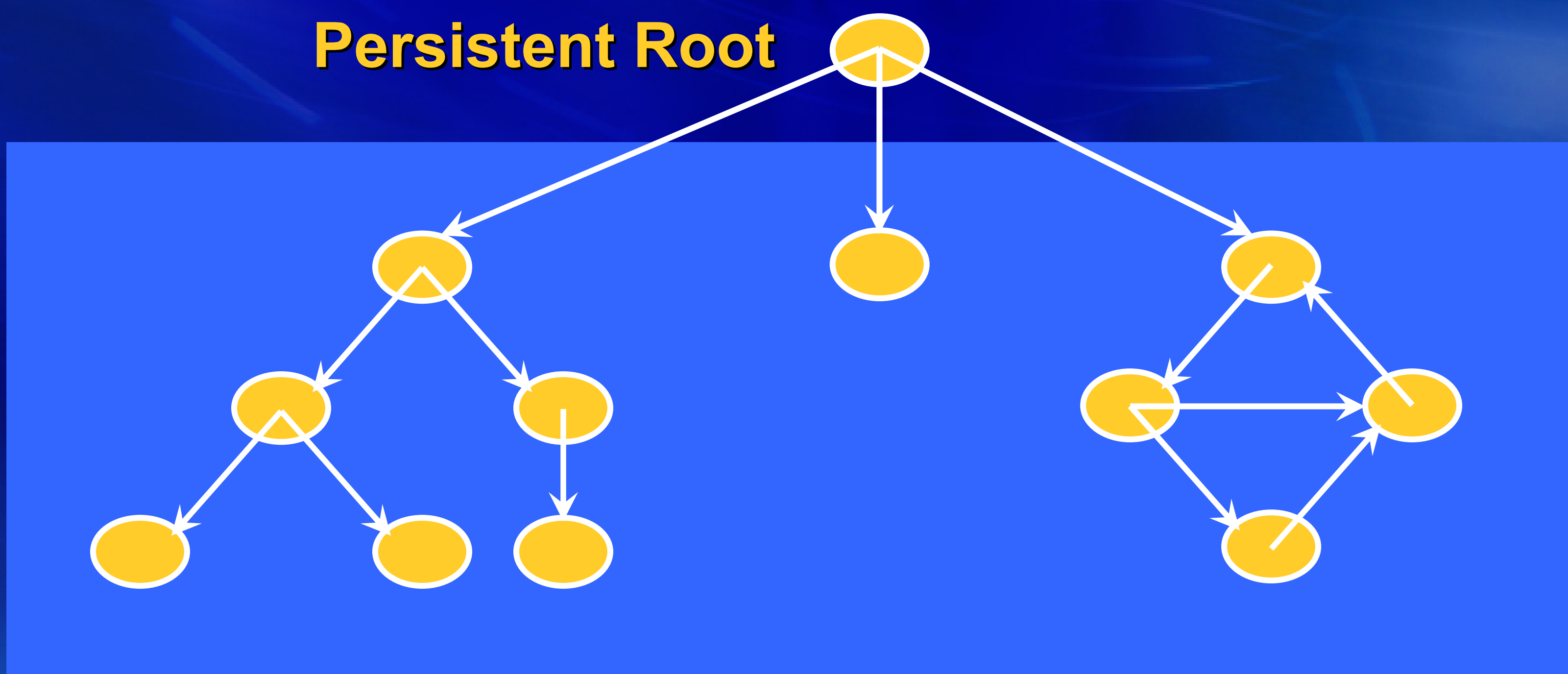
Upgrades in Persistent Object Stores

- Persistent Object Stores store objects



Upgrades in Persistent Object Stores

- Objects are accessed within transactions
  - Transactions support modular reasoning in spite of concurrency and failures



Uses of Upgrades

- Upgrades are needed to
  - Correct errors
  - Improve performance
  - Meet changing requirements
- Upgrades can be
  - Compatible or incompatible
  - Upgrades must be complete
- Encapsulation enables safe upgrades

Defining an Upgrade

- An upgrade is a set of class-upgrades
  - Upgrades must be complete
- A class upgrade is

  ⟨old-class, new-class, TF⟩
- TF: old-class $\rightarrow$ new-class
  - TF changes representation of objects
  - System preserves identity of objects

Executing an Upgrade

- Requires: transforming all old-class objects
- Goal: Don’t interfere with applications
  - Don’t stop the world
- Goal: Be efficient in space and time
  - Don’t copy the database

Solution: Lazy, Just in Time

- Applications continue to run
- Objects are transformed just before first access
- Upgrades can run in parallel

Desired Semantics

- Upgrades appear to run when installed
  - Serialized before all later application transactions

- Upgrades appear to run in upgrade order

- Within an upgrade, transforms run as if each were the first to run

Related Work

- PJama: Atkinson, Dmitriev, Hamilton (POS '00)
- Orion: Banerjee, Kim, Kim, Korth (Sigmod '87)
- O2: Deux et al (IEEE TKDE '90)
- OTGen: Lerner, Habermann (OOPSLA '90)
- Gemstone: Penney, Stein (OOPSLA '87)

How System Works

- Objects are transformed just before first access
  - Interrupt the application
  - Run earliest pending transform
  - Transform runs in its owns transaction
- Application continues after transform commits
- Transforms can be interrupted too

Example

…;U1;A1;TF1(x);A2;…

- U1 is installed
- A1 commits
- A2 accesses x and is interrupted
- TF1(x) commits
- A2 commits

Example

…;U1;A1;TF1(x);A2;…

U1 is installed

A1 commits

A2 accesses x and is interrupted

TF1(x) commits

A2 commits

Suppose A1 modifies z and TF1(x) uses z

Example

…;U1;A1;TF1(x);A2;TF1(y);A3; …

- U1 is installed
- A1 commits
- A2 accesses x and is interrupted
- TF1(x) commits
- A2 commits
- A3 accesses y and is interrupted
- TF1(y) commits
- A3 commits

Example

…;U1;A1;TF1(x);A2;TF1(y);A3; …

U1 is installed

A1 commits

A2 accesses x and is interrupted

TF1(x) commits

A2 commits

A3 accesses y and is interrupted

TF1(y) commits

A3 commits

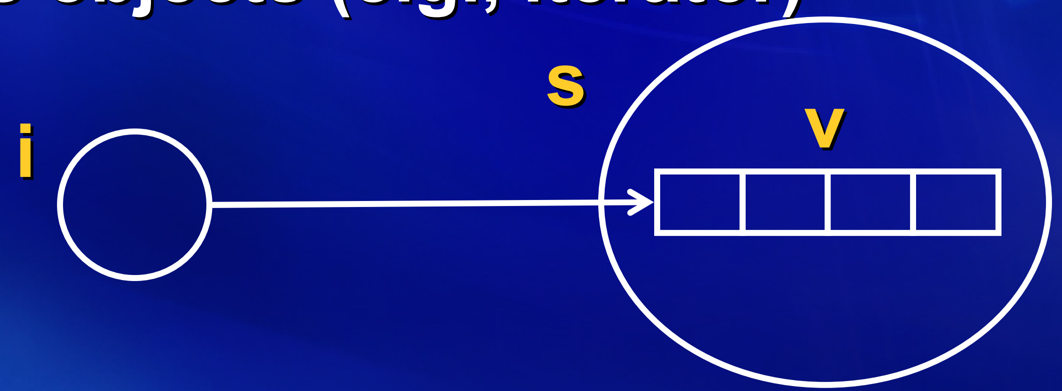
Suppose TF1(y) uses x

Insuring Correct Behavior

- S1: TF(x) only accesses objects x owns
  - Statically enforced by type system

Insuring Correct Behavior

- **S1: TF(x) only accesses objects x owns**
  - Statically enforced by type system
- **S2: x is transformed before objects x owns**
  - No access to owned objects from outside
  - Shared access to owned objects from inner class objects (e.g., iterator)



Insuring Correct Behavior

- S1: TF(x) only accesses objects x owns
- S2: x is transformed before objects x owns
- Plus basic lazy scheme

  - Applications don’t interfere with transforms
  - Transforms of unrelated objects don’t interfere
  - Transforms of related objects run in proper order (owner before owned)

Modular Reasoning

- S1: TF(x) only accesses objects x owns
- S2: x is transformed before objects x owns
- Plus basic lazy scheme

- Ensures modular reasoning: can reason about TF(x) as an extra method of x's class

Conclusions

- Modular reasoning is key
- Ownership types support modular reasoning
- Software upgrades benefit too

Ownership Types for Object Encapsulation

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Example of Local Reasoning

```
class IntVector {
   int size() reads (this) {…}  …
}
class IntStack {
   IntVector⟨this⟩ vec;
   void push(int x) writes (this) {…}  …
}
void m (IntStack s, IntVector v)  writes (s)  reads (v)
      where  !(v <= s)  !(s <= v)  {

      int n = v.size();  s.push(3);  assert( n == v.size() );
}
```

Is the condition in the assert true?

Example of Local Reasoning

```
class IntVector {
    int size() reads (this) {…}  …
}
class IntStack {
    IntVector⟨this⟩ vec;
    void push(int x) writes (this) {…}  …
}
void m (IntStack s, IntVector v)  writes (s)  reads (v)
        where  !(v <= s)  !(s <= v)  {

        int n = v.size();  s.push(3);  assert( n == v.size() );
}
```

s is not encapsulated in v, and v is not encapsulated in s

Example of Local Reasoning

```
class IntVector {
    int size() reads (this) {…}  …
}
class IntStack {
    IntVector⟨this⟩ vec;
    void push(int x) writes (this) {…}  …
}
void m (IntStack s, IntVector v)  writes (s)  reads (v)
        where  !(v <= s)  !(s <= v)  {

        int n = v.size();  s.push(3);  assert( n == v.size() );
}
```

size only reads v and its encapsulated objects
push only writes s and its encapsulated objects

Example of Local Reasoning

```
class IntVector {
   int size() reads (this) {…}  …
}
class IntStack {
   IntVector⟨this⟩ vec;
   void push(int x) writes (this) {…}  …
}
void m (IntStack s, IntVector v)  writes (s)  reads (v)
      where  !(v <= s)  !(s <= v)  {

      int n = v.size();  s.push(3);  assert( n == v.size() );
}
```

So size and push cannot interfere
So the condition in the assert must be true