Objects Analysis Threads Design

15-214

Principles of Software Construction: Objects, Design, and Concurrency

Extra Examples for OOP Basics

toad

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An Object-Oriented Set Library

- We communicate with objects by sending them messages
  - Or, equivalently, invoking their methods
- What messages should we be able to send to a set?
  - *Hint: think about mathematical set operations*

An Object-Oriented Set Library

- We communicate with objects by sending them messages
  - Or, equivalently, invoking their methods
- What messages should we be able to send to a set?
  - *Hint: think about mathematical set operations*
- Let's design an interface to a (functional) set object
  - Equivalent to header files in C
  - But now we are listing the messages understood by an object
    - Java interfaces may not have (instance) fields

```
interface IntSet {
    /** does the IntSet contain element? */
    boolean contains(int element);
    /** is the IntSet a subset of otherSet? */
    boolean isSubsetOf(IntSet otherSet);
}
```

Implementing Set

- An implementation of an interface is defined using a **class**
  - Provides method bodies for all the messages in the interface
    - It is an error if we forget one, or change its signature
  - May also define additional methods and/or data fields
  - The class is a ***subtype*** of the interfaces it implements

- Trivial example: an empty set

implements keyword specifies implemented interfaces

```
class EmptySet implements IntSet {
    /** does the IntSet contain element? */
    boolean contains(int element) {              }
}
```

Implementing Set

```
interface IntSet {
    boolean contains(int element);
    boolean isSubsetOf(IntSet otherSet);
}
class EmptySet implements IntSet { … }
```

…ed using a **class**
…s in the interface
…gnature
…data fields
…mplements

implements keyword specifies implemented interfaces

- Trivial example: an empty set

```
class EmptySet implements IntSet {
    /** does the IntSet contain element? */
    boolean contains(int element) { return false; }


}
```

error: method isSubsetOf from interface IntSet is not implemented

Implementing Set

- An implementation of an interface is defined using a **class**
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implements keyword specifies implemented interfaces

```
class EmptySet implements IntSet {
    /** does the IntSet contain element? */
    boolean contains(int element) { return false; }
    /** is the IntSet a subset of otherSet? */
    boolean isSubsetOf(IntSet otherSet) { return true; }
}
```


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Using an EmptySet

```
class EmptySet implements IntSet {
    /** does the IntSet contain element? */
    boolean contains(int element) { return false; }
    /** is the IntSet a subset of otherSet? */
    boolean isSubsetOf(IntSet otherSet) { return true; }
}
```

```
IntSet s = new EmptySet();
boolean f = s.contains(0); // false
boolean t = s.isSubsetOf(s); // true
```

Allocates memory for the EmptySet

The **receiver**, an implicit argument, called **this** inside the method

The method **name**. Identifies which method to use, of all the methods the receiver's class defines

Method **arguments**, just like function arguments

Typechecking client code

```
interface IntSet {
    boolean contains(int element);
    boolean isSubsetOf(IntSet otherSet);
}
class EmptySet implements IntSet { … }
```

2. OK to assign an EmptySet to an IntSet, because EmptySet **implements** IntSet

1. The **new** expression has type EmptySet

```
IntSet s = new EmptySet();
boolean f = s.contains(0); // false
```

5. contains() returns a **boolean**, which we can assign safely to f

3. s has type IntSet. We check that IntSet defines a contains method.

4. The contains method in IntSet accepts an **int** argument so the actual argument is OK

Typechecking: What Could Go Wrong?

```
interface IntSet {
    boolean contains(int element);
    boolean isSubsetOf(IntSet otherSet);
}
class EmptySet implements IntSet { … }
```

2. Can't assign an IntSet to an EmptySet because IntSet is not a subtype of (i.e. does not implement) EmptySet

1. Can't instantiate an interface; its methods are undefined.

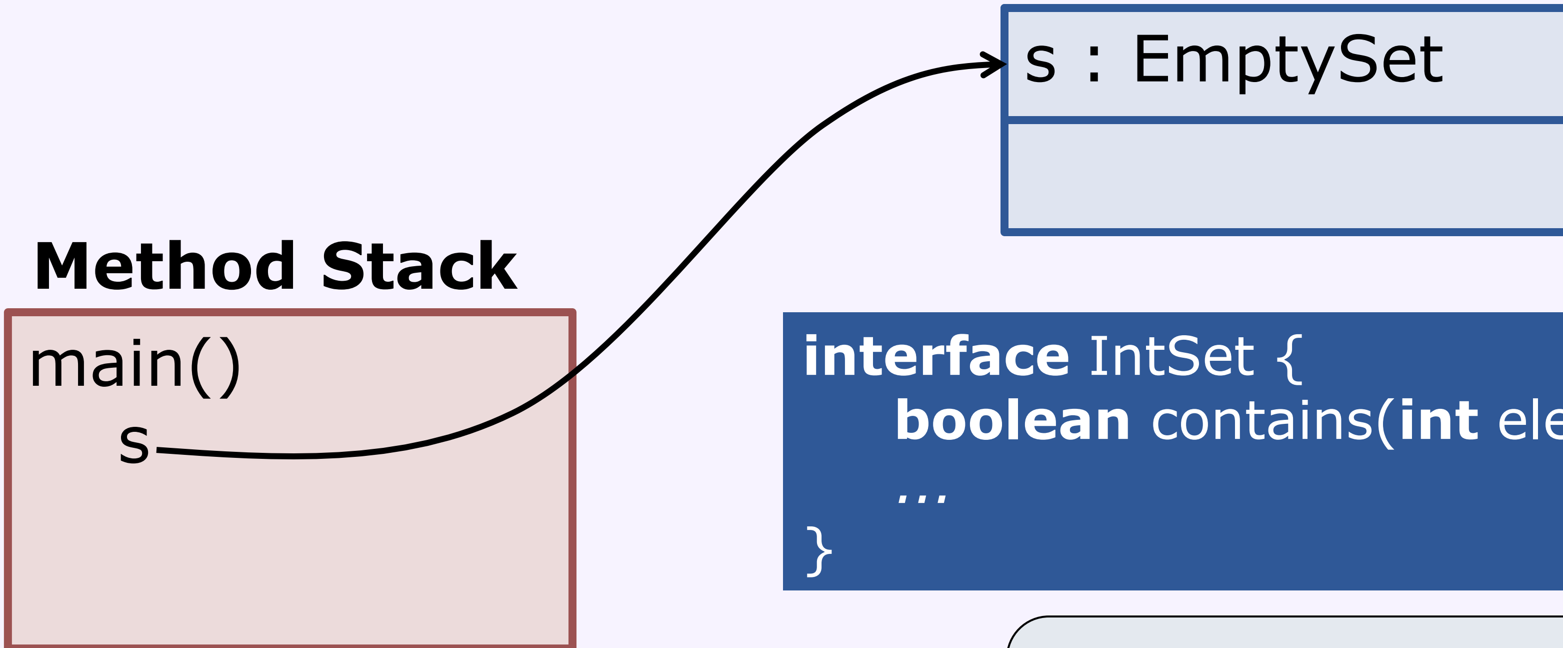
```
EmptySet s = new IntSet();

int f = s.contans("hello"); // false
```

5. contains() returns a **boolean**, which is not a subtype of **int** (unlike in C)

3. s has type EmptySet. But EmptySet does not define a contans method

4. Even if we spell contains correctly, the method takes an **int** argument, and String is not a subtype of **int**

Executing client code




```
interface IntSet {
    boolean contains(int element);
    ...
}
```

What method do we call?
s has type IntSet, which does not define contains

```
IntSet s = new EmptySet();
boolean f = s.contains(0);
boolean t = s.isSubsetOf(s); // true
```

Executing client code

Look at the object s points to. It keeps track of its class: EmptySet

s : EmptySet

Method Stack

main()

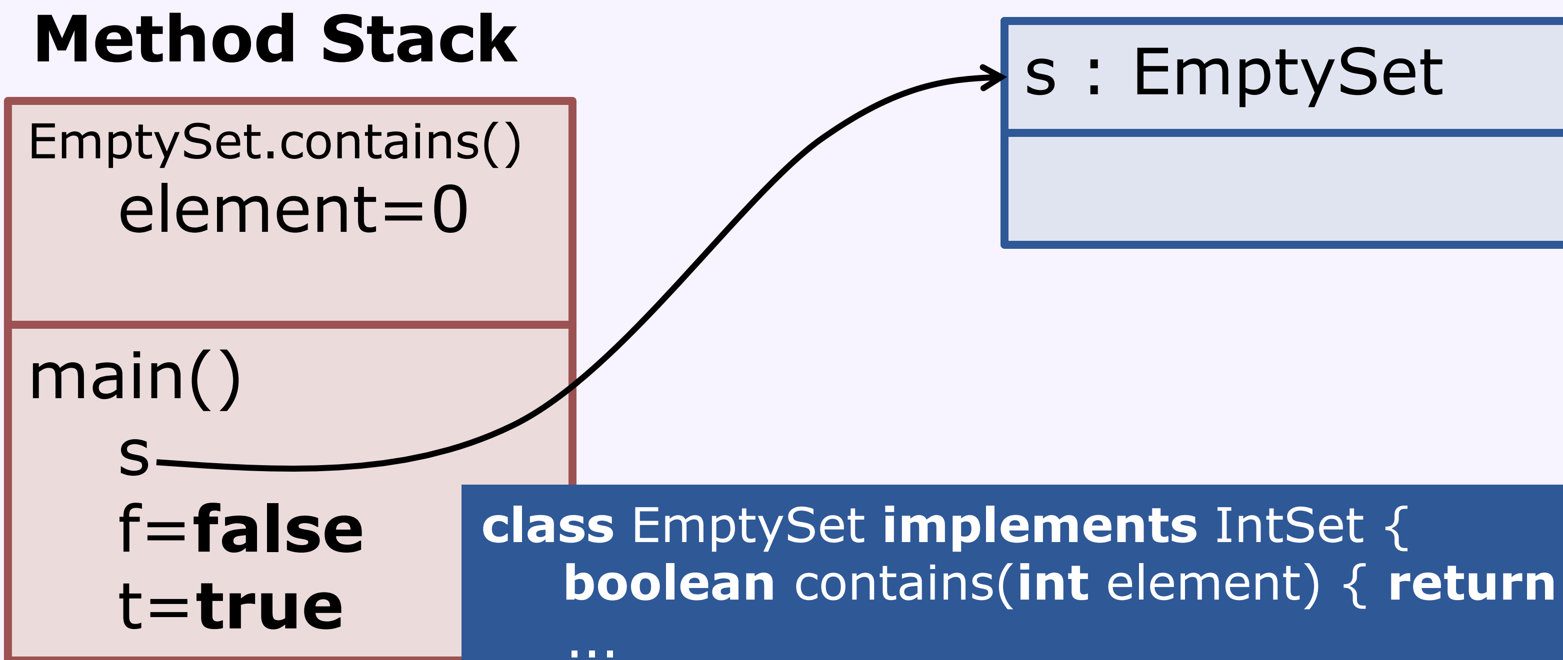
s

```
class EmptySet implements IntSet {
    boolean contains(int element) { return false; }
    ...
}
```

EmptySet defines contains(); we call this method implementation

```
IntSet s = new EmptySet();
boolean f = s.contains(0);
boolean t = s.isSubsetOf(s); // true
```

Executing client code




```
class EmptySet implements IntSet {
    boolean contains(int element) { return false; }
    …
}
```

```
IntSet s = new EmptySet();
boolean f = s.contains(0);
boolean t = s.isSubsetOf(s); // true
```

Implementing a Singleton Set

- Several classes can implement the same interface
  - Instances of these classes can all work together
  - A key strength of objects compared to alternatives such as ADTs

```
class SingletonSet implements IntSet {
    int member;

    SingletonSet(int element) { member = element; }

    boolean contains(int e) { return member == e; }
    boolean isSubsetOf(IntSet otherSet) {
        return otherSet.contains(member);
    }
}
```

A *field* stores the member of the set

A *constructor* method initializes the fields

Implicit Constructors

- If you don't define a constructor, Java generates one for you
  - It has no return type and is named after the class
    - Just like all constructors
  - It has no arguments
  - Fields (if any) are initialized to default values
    - 0 for numeric values
    - **false** for **boolean** variables
    - **null** for reference (pointer) variables

```
class EmptySet implements IntSet {
    /** This is equivalent to the auto-generated constructor */
    public EmptySet() {}
    public boolean contains(int element) { return false; }
    public boolean isSubsetOf(IntSet otherSet) {
                                              return true; }
}
```

Calling Constructors, Accessing Fields

```
class SingletonSet implements IntSet {
        int member;

        SingletonSet(int element) { member = element; }
        boolean contains(int e) { return member == e; }
        boolean isSubsetOf(IntSet otherSet) {
                return otherSet.contains(member); }
}

// client code
SingletonSet s = new SingletonSet(5);
if (s.member <= 5)
    s.member++;
```

Using the new operator invokes the constructor

- Client code can read and write the member field
  - This can make it difficult to change our code later
  - It also risks unexpected changes to the data in a functional object

Hiding Fields

```
class SingletonSet implements IntSet {
    private int member;

    public SingletonSet(int element) { member = element; }
    public boolean contains(int e) { return member == e; }
    public boolean isSubsetOf(IntSet otherSet) {
                        return otherSet.contains(member); }
```

private methods and fields can only be accessed from within the class.

public methods and fields can be accessed from anywhere

```
SingletonSet s = new SingletonSet(5);
if (s.member <= 5)
    s.member++;
```

error: cannot access **private** field member from outside class SingletonSet

Note: all methods in an **interface** are implicitly **public**

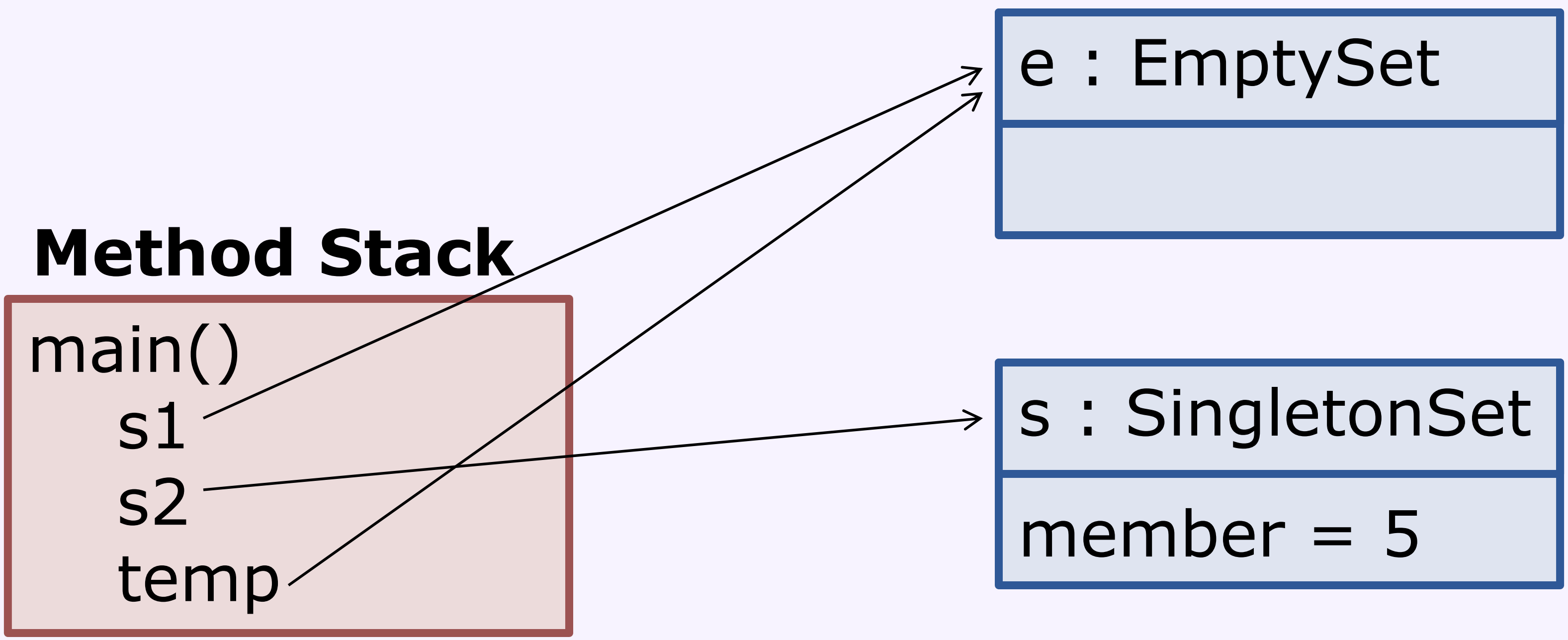
Discussion: when is it useful to have a **private** method?

Using Sets Together

```
IntSet s1 = new EmptySet();
IntSet s2 = new SingletonSet(5);
IntSet temp = s1;
s1 = s2;
s2 = temp;
System.out.println(s1.contains(5));
System.out.println(s2.contains(5));
```

What does this program print?

Using Sets Together




```
IntSet s1 = new EmptySet();
IntSet s2 = new SingletonSet(5);
IntSet temp = s1;
s1 = s2;
s2 = temp;
System.out.println(s1.contains(5));
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```
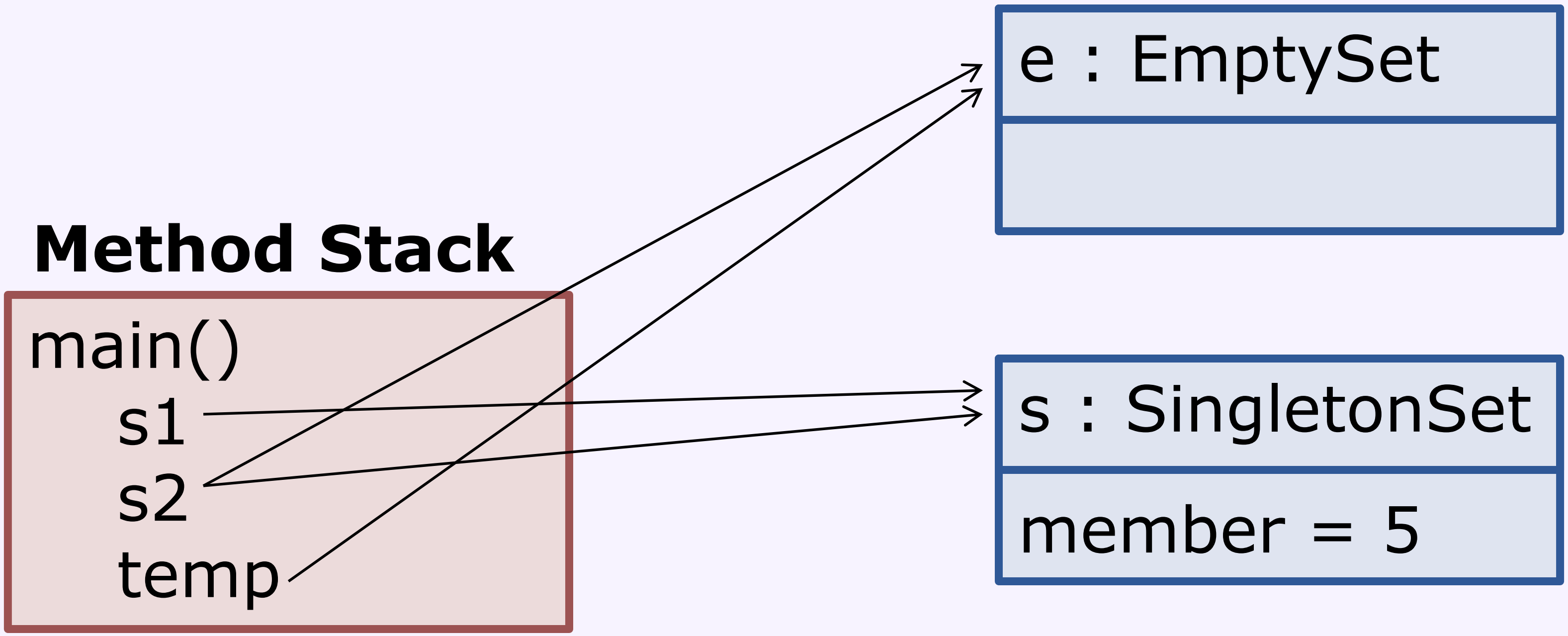

What does this program print?

Using Sets Together




```
IntSet s1 = new EmptySet();
IntSet s2 = new SingletonSet(5);
IntSet temp = s1;
s1 = s2;
s2 = temp;
System.out.println(s1.contains(5));
System.out.println(s2.contains(5));
```

What does this program print?

Using Sets Together

Dynamic Dispatch: determine which method to call based on the run-time class of the object

Polymorphism ("many forms")***:*** Sets can take two forms, and the behavior of a set depends on which form it takes.

Method Stack

main()
s1
s2
temp

s : SingletonSet
member = 5

```
IntSet s1 = new EmptySet();
IntSet s2 = new SingletonSet(5);
IntSet temp = s1;
s1 = s2;
s2 = temp;
System.out.println(s1.contains(5));
System.out.println(s2.contains(5));
```

s1 points to s.
s is of class SingletonSet.
SingletonSet.contains() is called, printing true

s2 points to e.
e is of class EmptySet.
EmptySet.contains() is called, printing false

Adding Unions

```
interface IntSet {
    boolean contains(int element);
    boolean isSubsetOf(IntSet otherSet);
    IntSet union(IntSet otherSet);
}
class UnionSet implements IntSet {
    private IntSet set1;
    private IntSet set2;
    public UnionSet(IntSet s1, IntSet s2) {
        set1 = s1; set2 = s2; }
    public boolean contains(int elem) {
        return                                  }
    public boolean isSubsetOf(IntSet otherSet) {
        return                                     }
    public IntSet union(IntSet otherSet) {
        return                          }
}
```

Adding Unions

```
interface IntSet {
    boolean contains(int element);
    boolean isSubsetOf(IntSet otherSet);
    IntSet union(IntSet otherSet);
}
class UnionSet implements IntSet {
    private IntSet set1;
    private IntSet set2;
    public UnionSet(IntSet s1, IntSet s2) {
        set1 = s1; set2 = s2; }
    public boolean contains(int elem) {
        return set1.contains(elem) || set2.contains(elem); }
    public boolean isSubsetOf(IntSet otherSet) {
        return set1.isSubsetOf(elem) && set2.isSubsetOf(elem);}
    public IntSet union(IntSet otherSet) {
        return new UnionSet(this, otherSet); }
}
```

The **this** keyword refers to the current object

Adding Unions

```
interface IntSet {
    boolean contains(int element);
    boolean isSubsetOf(IntSet otherSet);
    IntSet union(IntSet otherSet);
}
class UnionSet implements IntSet {
    private IntSet set1;
    private IntSet set2;
    public UnionSet(IntSet s1, IntSet s2) {
        this.set1 = s1; this.set2 = s2; }
    public boolean contains(int elem) {
        return set1.contains(elem) || this.set2.contains(elem); }
    public boolean isSubsetOf(IntSet otherSet) {
        return set1.isSubsetOf(elem) && set2.isSubsetOf(elem);}
    public IntSet union(IntSet otherSet) {
        return new UnionSet(this, otherSet); }
}
```

class UnionSet is a ***Composite***—an object that groups other objects, while behaving just like the objects it groups. For example, you can make a UnionSet out of UnionSets.

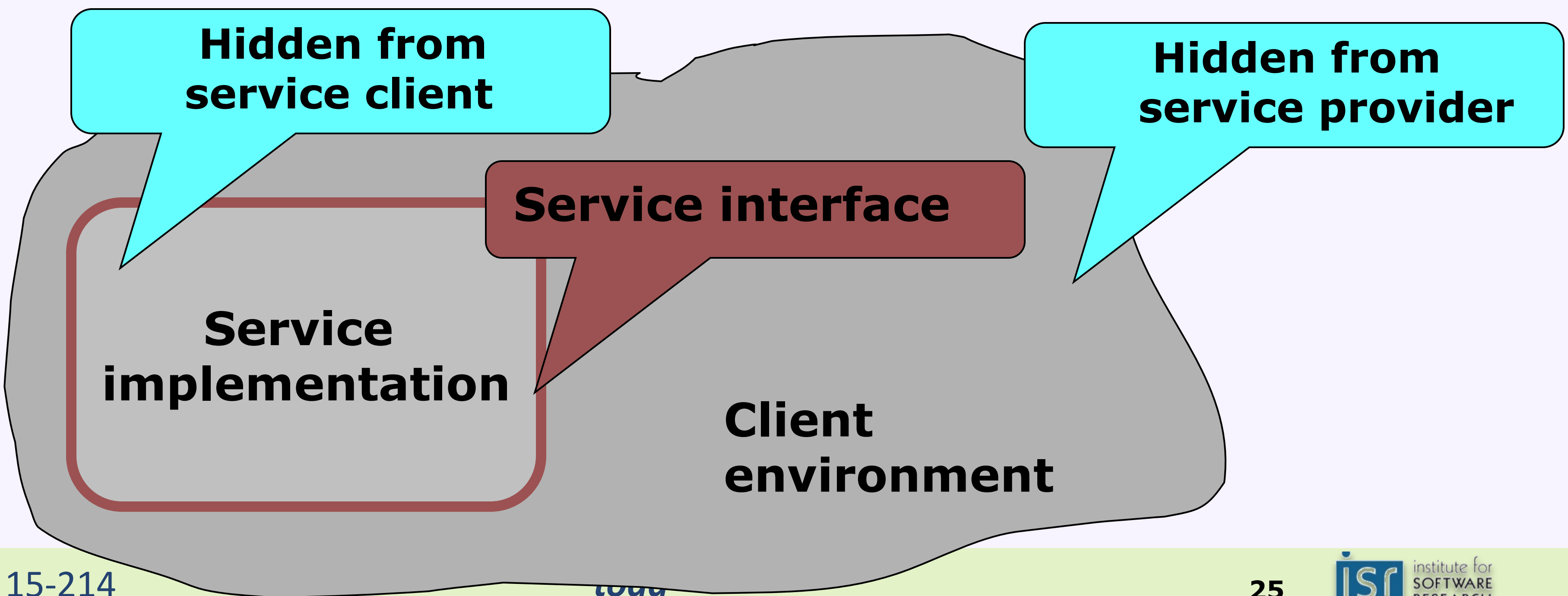
When we refer to a locally-declared field or method, we are implicitly looking in the receiver object **this**

The **this** keyword refers to the current object

Another Look at Interfaces

Contracts and Clients

- Contract of service provider and client
  - Interface specification
  - Functionality and correctness expectations
  - Performance expectations
  - Hiding of respective implementation details
  - “Focus on **concepts** rather than **operations**”



Interfaces state Expectations

```
interface IntSet {
    /** @return true if element is in this set */
    boolean contains(int element);

    /** @return true if otherSet is a subset of this set */
    boolean isSubsetOf(IntSet otherSet);

    /** @return a new set representing the union of this set
      *              and otherSet
      */
    IntSet union(IntSet otherSet);
}
```

Java **interfaces** and **classes**

Object-orientation

1. Organize program functionality around kinds of abstract "objects"
    - For each object kind, offer a specific set of operations on the objects
    - Objects are otherwise opaque
        - Details of representation are hidden
    - "Messages to the receiving object"
2. Distinguish *interface* from *class*
    - **Interface**: expectations
    - **Class**: delivery on expectations (the implementation)
3. Explicitly represent the taxonomy of object types
    - This is the "inheritance hierarchy"
        - A **square** is a **shape**

Implementation of interfaces

- Classes can *implement* one or more interfaces.

```
public class SingletonSet implements IntSet, Cloneable {…}
```

- **Semantics**
  - **Must provide code** for all methods in the interface(s)
- **Best practices**
  - Define an interface whenever there may be **multiple implementations** of a concept
  - Variables should have **interface type**, not class type

```
int sum(UnionSet set) { …      // preferably no
int sum(IntSet set) { …        // yes!
```

Classes and Interfaces

```
interface IntSet {
    boolean contains(int element);
    boolean isSubsetOf(IntSet otherSet);
}
class SingletonSet implements IntSet {
    private int member;

    public SingletonSet(int element) { member = element; }

    public boolean contains(int e) { return member == e; }
    public boolean isSubsetOf(IntSet otherSet) {
        return otherSet.contains(member);
    }

    // OK to define additional public methods in the class
    public int getMember() { return member; }
}
```

Interfaces, Types, Classes

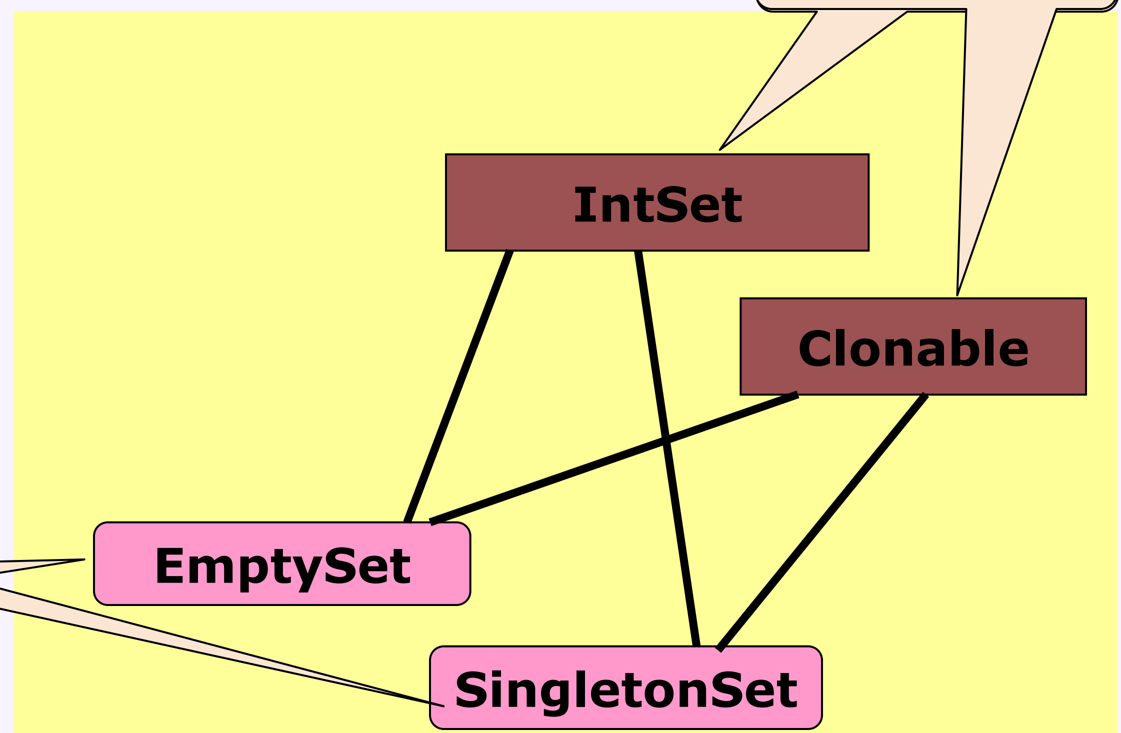
- Two ways to put a new empty list into a variable

```
IntSet s = new SingletonSet(4);
SingletonSet ss= new SingletonSet(3);
int i = ss.getMember();        // OK
int j = s.getMember();         // error: no method getMember in IntSet
```

Class

Type

Interface



Class

Object Identity & Object Equality

Object identity vs. equality

- There are two notions of equality in OO
  - The *same object.* References are the same.
  - Possibly different objects, but equivalent content
    - From the client perspective!! The actual internals might be different

```
String s1 = new String (“abc”);
String s2 = new String (“abc”);
```

  - There are two string objects, s1 and s2.
    - The strings are are equivalent, but the references are different

```
if (s1 == s2) { same object } else { different objects }

if (s1.equals(s2)) { equivalent content } else { not}
```

  - An interesting wrinkle: *literals*

Defined in the class String

```
String s3 = “abc”;
String s4 = “abc”;
```

  - These are true: s3==s4. s3.equals(s2). s2 != s3.

Encore: Polymorphism Example 2

Functional Lists of Integers

- Some operations we **expect** to see:
  - **create** a new list
    - empty, or by adding an integer to an existing list
  - return the **size** of the list
  - **get** the *i*th integer in the list
  - **concatenate** two lists into a new list

- Key questions
  - How to **implement** the lists?
    - Many options
      - Arrays, linked lists, etc
    - How to hide the details of this choice from client code?
      - Why do this?
  - How to state **expectations**?
    - A variable **v** can reference a list of integers

Interfaces – stating **expectations**

- The IntList interface

```
public interface IntList {
    int size();
    int get(int n);
    IntList concatenate(IntList otherList);
    String toString();
}
```

- The declaration for **v** ensures that any object referenced by v will have implementations of the methods **size**, **get**, **concatenate**, and **toString**

```
Intlist v = …
```

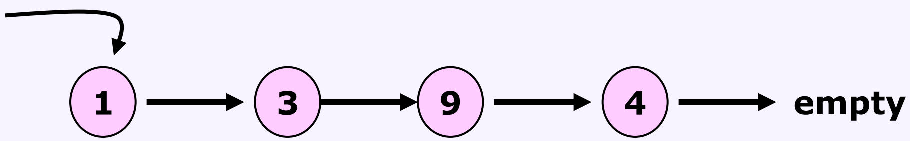
```
int len = v.size();
int third = v.get(2);
System.out.println (v.toString());
```

Implementing lists

- Two options (among many):
  - Arrays

1	3	7	5	11	13	6	42

  - Linked lists



• Operations:	Array	List
▪ **create** a new **empty** list	const	const
▪ return the **size** of the list	const	linear
▪ return the *i^th^* integer in the list	*?*	*?*
▪ **create** a list by adding to the **front**	*?*	*?*
▪ concatenate two lists into a new list	*?*	*?*

An inductive definition

- *The size of a list L is*
  - *0* *if L is the empty list*
  - *1 + size of the tail of L* *otherwise*

Implementing Size

```
public class EmptyIntList implements IntList {
      public int size() {
            return 0; }
   . . .
}
```

Base case

```
public class IntListCell implements IntList {
      public int size() {
            return 1 + next.size(); }
   . . .
}
```

Inductive case

List Representation (BROKEN!)

```
public class EmptyIntList implements IntList {
    public int size() {
        return 0;
    }
    . . .
}
```

Base case

```
public class IntListCell implements IntList {
    private int value;
    private IntListCell next;

    public int size() {
        return 1 + next.size();
    }
    . . .
}
```

Type is wrong! May be a cell or an empty list!

Inductive case

List Representation (FIXED!)

```
public class EmptyIntList implements IntList {
   public int size() {
      return 0;
   }
   . . .
}
```

Base case

```
public class IntListCell implements IntList {
   private int value;
   private IntList next;

   public int size() {
      return 1 + next.size();
   }
   . . .
}
```

Interface type provides needed flexibility.

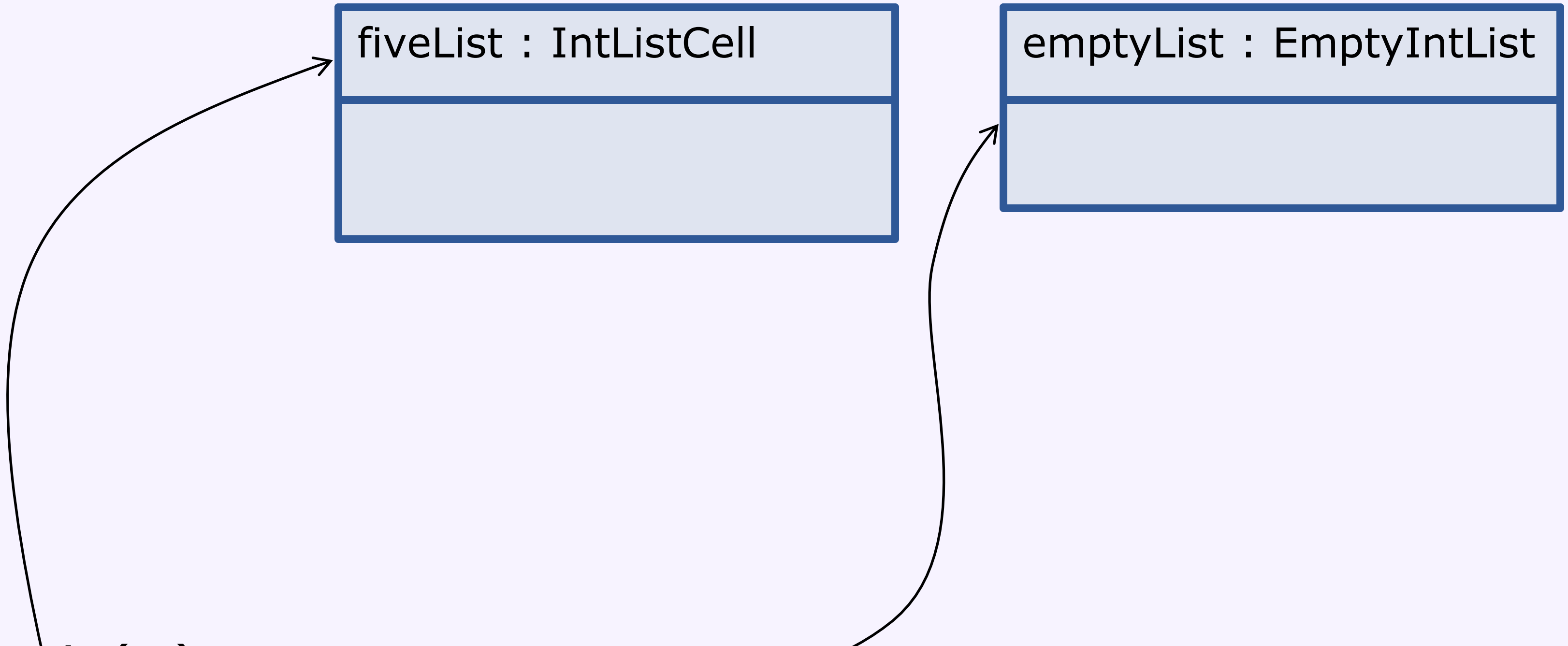
Inductive case

List Constructors

```
public class EmptyIntList implements IntList {
    public EmptyIntList() {
        // nothing to initialize
    }
    . . .
}

public class IntListCell implements IntList {
    public IntListCell(int val, IntList next) {
        this.value = val;
        this.next = next;
    }

    private int value;
    private IntList next;
    . . .
}
```

Java gives us this **default constructor** for free if we don't define any constructors.

Some Client Code

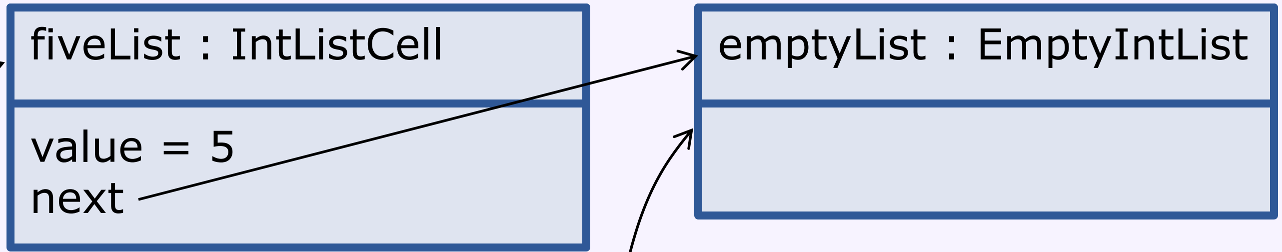


In main(…)

IntList emptyList = **new** EmptyIntList();

IntList fiveList = **new** IntListCell(5, emptyList);

Some Client Code



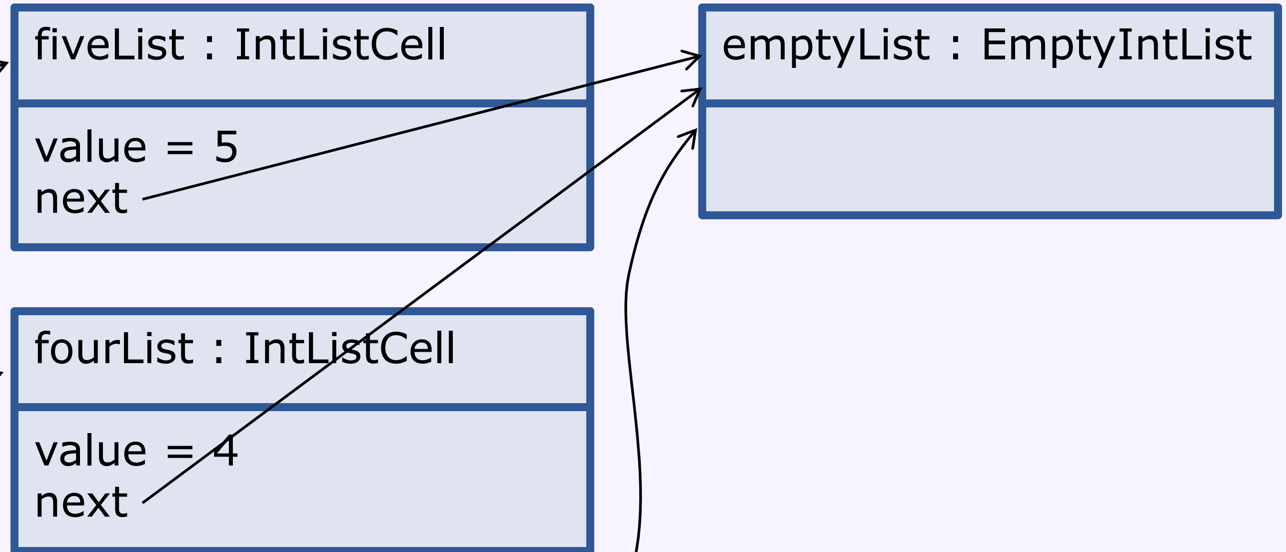

```
public IntListCell(int value, IntList next) {
      // value is 5, next is emptyList
      this.value = value; // this is fiveList
      this.next = next;
   }
```

In main(…)

IntList emptyList = **new** EmptyIntList();

IntList fiveList = **new** IntListCell(5, emptyList);

Some Client Code



In main(…)

```
IntList emptyList = new EmptyIntList();
IntList fiveList = new IntListCell(5, emptyList);
IntList fourList = new IntListCell(4, emptyList);
IntList fourFive = fourList.concatenate(fiveList); // what happens?
```

Implementing Concatenate

```
public class EmptyIntList implements IntList {
      public IntList concatenate(IntList other) {
            return other; }
   . . .
}
```

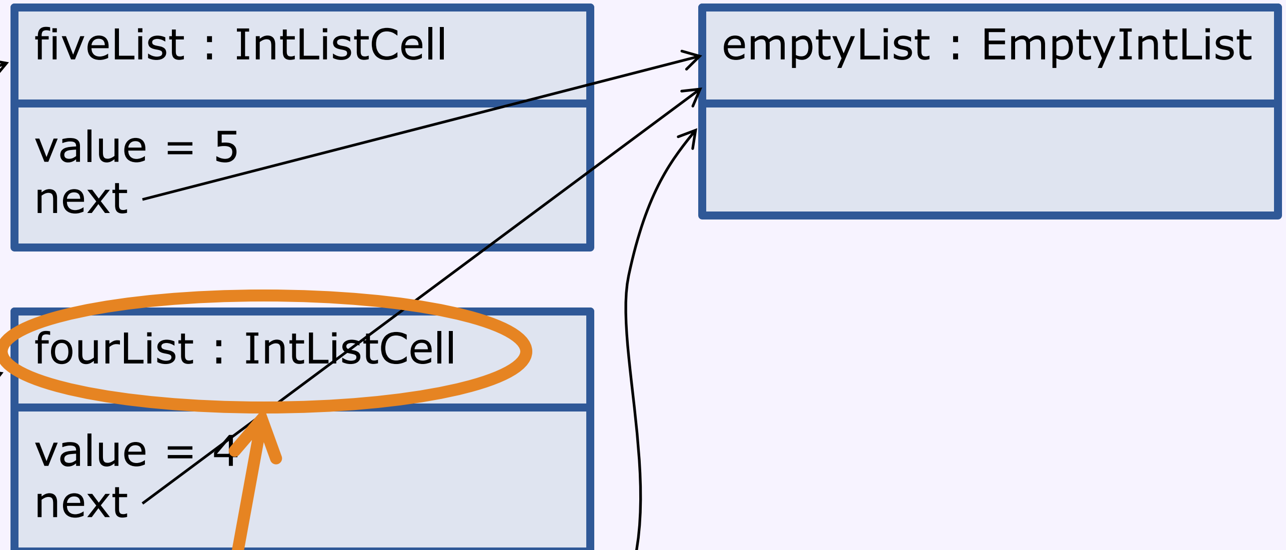
Base case

```
public class IntListCell implements IntList {
      public IntList concatenate(IntList other) {
            IntList newNext = next.concatenate(other);
            return new IntListCell(value, newNext); }
   . . .
}
```

Inductive case

Two concatenate methods – which do we use?

Some Client Code



In main(…)

```
IntList emptyList = new EmptyIntList();
IntList fiveList = new IntListCell(5, emptyList);
IntList fourList = new IntListCell(4, emptyList);
IntList fourFive = fourList.concatenate(fiveList); // what happens?
```

Method dispatch (simplified)

Example:

```
IntList fourList = new IntListCell(4, emptyList);
IntList fourFive = fourList.concatenate(fiveList);
```

- Step 1 (compile time): determine what type to look in
  - Look at the static type (IntList) of the receiver (fourList)
- Step 2 (compile time): find the method in the class with the right name
  - Find the method in the class with the right name
    - Later: there may be more than one such method

      IntList concatenate(IntList otherList);

  - Keep the method only if it is *accessible*
    - e.g. remove private methods
  - Error if there is no such method

Method dispatch (simplified)

Example:

List fourList = **new** IntListCell(4, emptyList);

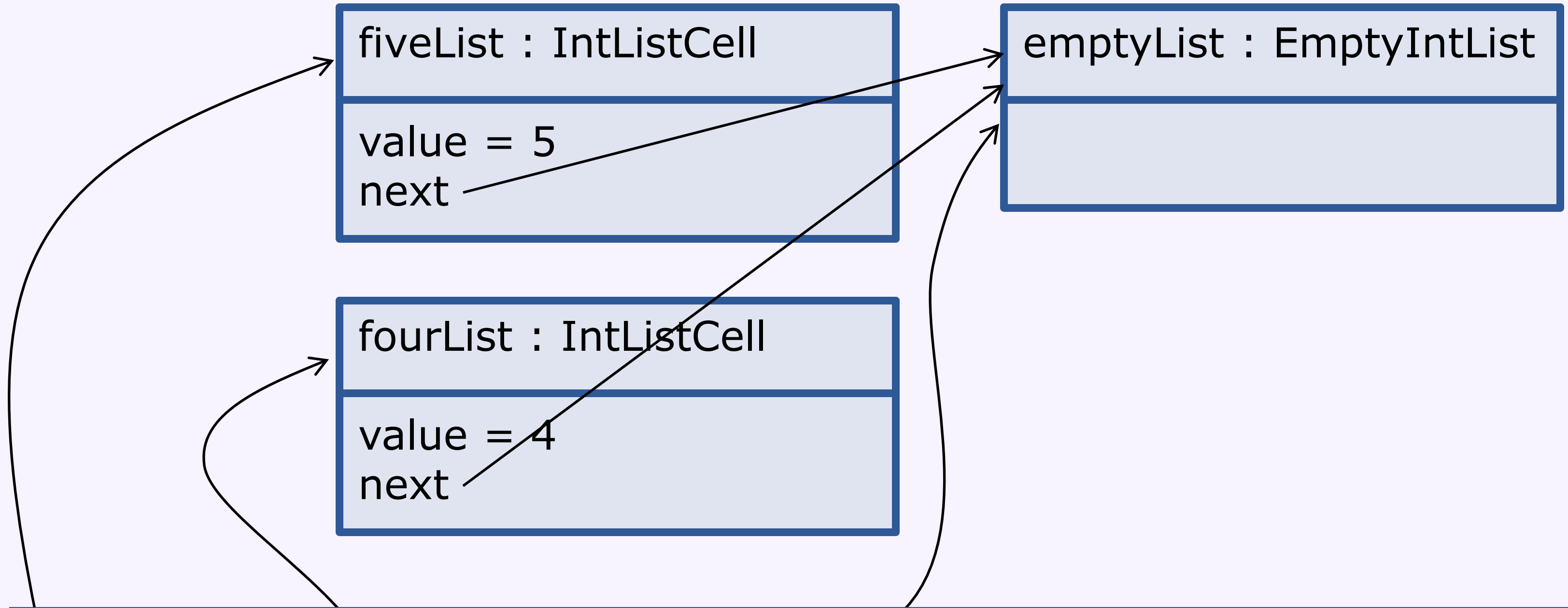
List fourFive = fourList.concatenate(fiveList);

- Step 3 (run time): Determine the run-time type of the receiver
  - Look at the object in the heap and get its class
- Step 4 (run time): Locate the method implementation to invoke
  - Look in the class for an implementation of the method we found statically (step 2)

```
public IntList concatenate(IntList other) {
        IntList newNext = next.concatenate(other);
        return new IntListCell(value, newNext); }
```

  - Invoke the method

Some Client Code

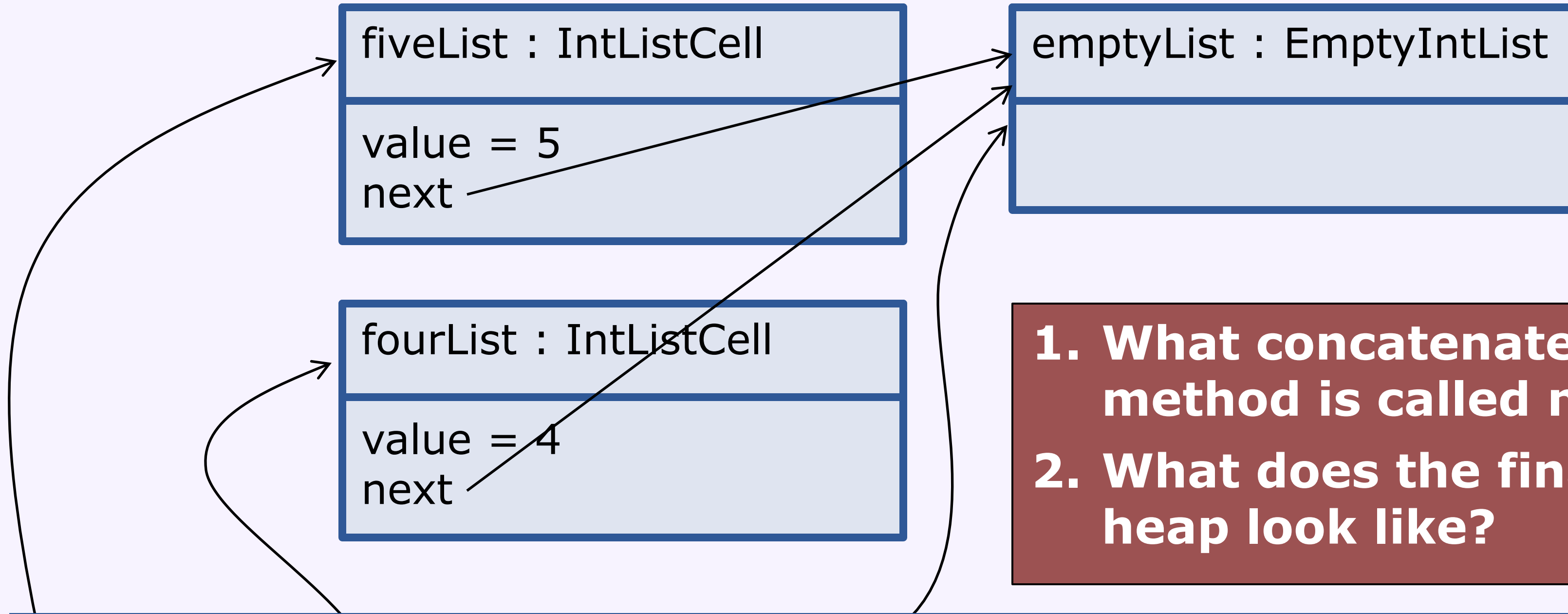



```
class IntListCell {
        public IntList concatenate(IntList other) {
                // this is fourList, other is fiveList
                IntList newNext = next.concatenate(other);
                return new IntListCell(value, newNext);
        }
```

List fourList = **new** IntListCell(4, emptyList);

List fourFive = fourList.concatenate(fiveList); ***// what happens?***

A Question for You!



1. What concatenate method is called next?

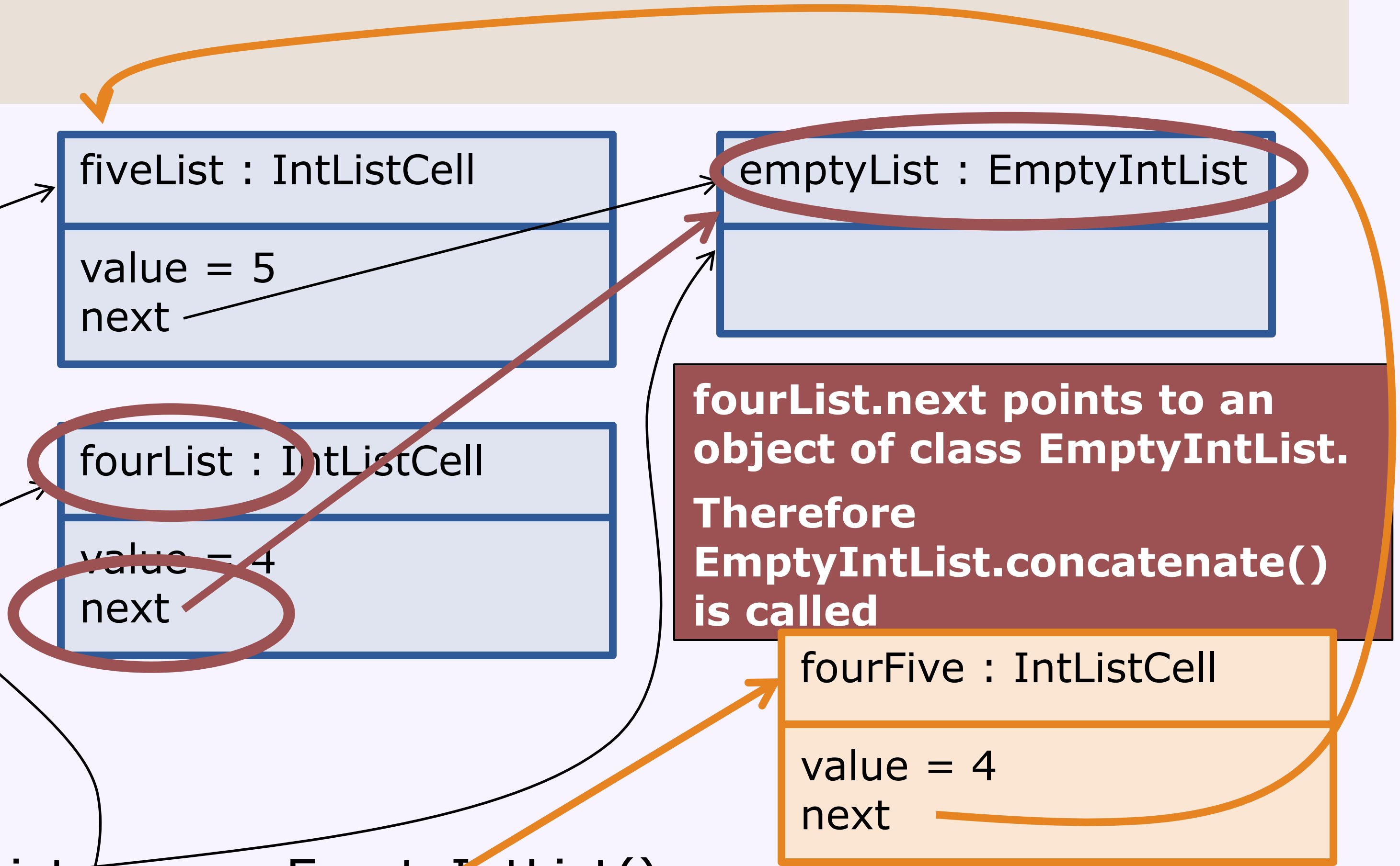
2. What does the final heap look like?

```
class IntListCell {
        public IntList concatenate(IntList other) {
                // this is fourList, other is fiveList
                IntList newNext = next.concatenate(other);
                return new IntListCell(value, newNext);
        }
```

List fourList = **new** IntListCell(4, emptyList);

List fourFive = fourList.concatenate(fiveList); ***// what happens?***

Answers



In main(…)

List emptyList = **new** EmptyIntList();

List fiveList = **new** IntListCell(5, emptyList);

List fourList = **new** IntListCell(4, emptyList);

List fourFive = fourList.concatenate(fiveList); ***// what happens?***

Toad's Take-Home Messages

- OOP – code is organized code around *kinds of things*
  - **Objects** correspond to things/concepts of interest
  - Objects embody:
    - State – held in **fields**, which hold or reference data
    - Actions – represented by **methods**, which describe operations on state
    - **Constructors** – how objects are created
  - A **class** is a family of similar objects
  - An **interface** states expectations for classes and their objects
  - Polymorphism and Encapsulation as key concepts
    - Allow different implementations behind a common interface
- Objects reside in the **heap**
  - They are accessed by **reference**, which gives the objects **identity**
  - **Dispatch** is used to choose a method implementation based on the **class** of the **receiver**
  - Equivalence (**equals**) does not mean the same object (==)