Introduction: Abstract Data Types and Java Review

Computer Science E-22
Harvard Extension School

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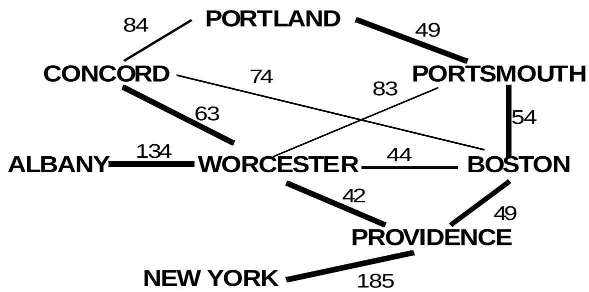
Welcome to Computer Science E-22!

- We will study fundamental *data structures.*
  - ways of imposing order on a collection of information
  - sequences: lists, stacks, and queues
  - trees
  - hash tables
  - graphs
- We will also:
  - study *algorithms* related to these data structures
  - learn how to *compare* data structures & algorithms
- Goals:
  - learn to think more intelligently about programming problems
  - acquire a set of useful tools and techniques

Sample Problem I: Finding Shortest Paths

- Given a set of routes between pairs of cities, determine the shortest path from city A to city B.



Sample Problem II: A Data "Dictionary"

- Given a large collection of data, how can we arrange it so that we can efficiently:
  - add a new item
  - search for an existing item
- Some data structures provide better performance than others for this application.
- More generally, we'll learn how to characterize the *efficiency* of different data structures and their associated algorithms.

Prerequisites

- A good working knowledge of Java
  - comfortable with object-oriented programming concepts
  - comfortable with arrays
  - some prior exposure to recursion would be helpful
  - if your skills are weak or rusty, you may want to consider first taking CSCI E-10b
- Reasonable comfort level with mathematical reasoning
  - mostly simple algebra, but need to understand the basics of logarithms (we'll review this)
  - will do some simple proofs

Requirements

- Lectures and weekly sections
  - sections: start next week; times and locations TBA
  - also available by streaming and recorded video
- Five problem sets
  - plan on 10-20 hours per week!
  - code in Java
  - must be your own work
  - grad-credit students will do extra problems
- Midterm exam
- Final exam
- Programming project
  - for grad credit only

Additional Administrivia

- Instructor: Dave Sullivan
- TAs: Alex Breen, Cody Doucette, Kylie Moses, possibly others!
- Office hours and contact info. will be available on the Web:
  http://sites.fas.harvard.edu/~cscie22
- For questions on content, homework, etc.:
  - use Piazza
  - send e-mail to cscie22@fas.harvard.edu

Review: What is an Object?

- An *object* groups together:
  - one or more data values (the object's *fields* – also known as *instance variables*)
  - a set of operations that the object can perform (the object's *methods*)
- In Java, we use a *class* to define a new type of object.
  - serves as a "blueprint" for objects of that type
  - simple example:

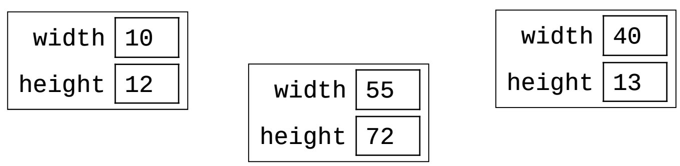
```
public class Rectangle {
    // fields
    private int width;
    private int height;

    // methods
    public int area() {
        return width * height;
    }
    …
```

Class vs. Object

- The `Rectangle` class is a blueprint:

```
public class Rectangle {
    // fields
    private int width;
    private int height;

    // methods
    ...
}
```

- `Rectangle` objects are built according to that blueprint:



(You can also think of the methods as being inside the object, but we won't show them in our diagrams.)

Creating and Using an Object

- We create an object by using the `new` operator and a special method known as a *constructor*:

```
Rectangle r1 = new Rectangle(10, 30);
```

- Once an object is created, we can call one of its methods by using *dot notation*:

```
int a1 = r1.area();
```

- The object on which the method is invoked is known as the *called object* or the *current object.*

Two Types of Methods

- Methods that belong to an object are referred to as *instance methods* or *non-static methods.*
  - they are invoked on an object

    ```
    int a1 = r1.area();
    ```
  - they have access to the fields of the called object

- *Static* methods do *not* belong to an object – they belong to the class as a whole.
  - they have the keyword static in their header:

    ```
    public static int max(int num1, int num2) {
        …
    ```
  - they do *not* have access to the fields of the class
  - outside the class, they are invoked using the class name:

    ```
    int result = Math.max(5, 10);
    ```

Abstract Data Types

- An *abstract data type* (ADT) is a model of a data structure that specifies:
  - the characteristics of the collection of data
  - the operations that can be performed on the collection

- It's *abstract* because it doesn't specify *how* the ADT will be implemented.

- A given ADT can have multiple implementations.

A Simple ADT: A Bag

- A bag is just a container for a group of data items.
  - analogy: a bag of candy
- The positions of the data items don't matter (unlike a list).
  - {3, 2, 10, 6} is equivalent to {2, 3, 6, 10}
- The items do *not* need to be unique (unlike a set).
  - {7, 2, 10, 7, 5} isn't a set, but it is a bag

A Simple ADT: A Bag (cont.)

- The operations supported by our Bag ADT:
  - `add(item)`: add `item` to the `Bag`
  - `remove(item)`: remove one occurrence of `item` (if any) from the `Bag`
  - `contains(item)`: check if `item` is in the `Bag`
  - `numItems()`: get the number of items in the `Bag`
  - `grab()`: get an item at random, without removing it
    - reflects the fact that the items don't have a position (and thus we can't say "get the 5th item in the Bag")
  - `toArray()`: get an array containing the current contents of the bag
- Note that we *don't* specify *how* the bag will be implemented.

Specifying an ADT Using an Interface

- In Java, we can use an interface to specify an ADT:

```
public interface Bag {
    boolean add(Object item);
    boolean remove(Object item);
    boolean contains(Object item);
    int numItems();
    Object grab();
    Object[] toArray();
}
```

- An interface specifies a set of methods.
  - includes only the method headers
  - *cannot* include the actual method definitions

Implementing an ADT Using a Class

- To implement an ADT, we define a class:

```
public class ArrayBag implements Bag {
    private Object[] items;
    private int numItems;
    …
    public boolean add(Object item) {
        …
}
```

- When a class header includes an `implements` clause, the class must define all of the methods in the interface.

Encapsulation

- Our implementation provides proper *encapsulation*.
  - a key principle of object-oriented programming
  - also known as *information hiding*
- We prevent direct access to the internals of an object by making its fields *private.*

```
public class ArrayBag implements Bag {
    private Object[] items;
    private int numItems;
    …
```

- We provide limited *indirect* access through methods that are labeled *public.*

```
    public boolean add(Object item) {
        …
```

All Interface Methods Are Public

- Methods specified in an interface *must* be `public`, so we don't need to use the keyword `public` in the interface definition.
- For example:

```
public interface Bag {
    boolean add(Object item);
    boolean remove(Object item);
    boolean contains(Object item);
    int numItems();
    Object grab();
    Object[] toArray();
}
```

- However, when we actually implement one of these methods in a class, we *do* need to explicitly use the keyword `public`:

```
public class ArrayBag implements Bag {
    …
    public boolean add(Object item) {
        …
```

Inheritance

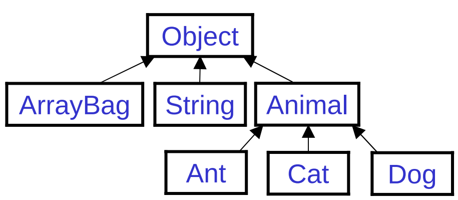
- We can define a class that explicitly *extends* another class:

```
public class Animal {
    private String name;
    …
    public String getName() {
        return name;
    }
    …
}

public class Dog extends Animal {
    …
```

- We say that `Dog` is a *subclass* of `Animal`, and `Animal` is a *superclass* of `Dog`.
- A class *inherits* the instance variables and methods of the class that it extends.

The `Object` Class

- If a class does not explicitly extend another class, it implicitly extends Java's `Object` class.
- The `Object` class includes methods that all classes must possess. For example:
  - `toString()`: returns a string representation of the object
  - `equals()`: is this object equal to another object?
- The process of extending classes forms a hierarchy of classes, with the `Object` class at the top of the hierarchy:



Polymorphism

- An object can be used wherever an object of one of its superclasses is called for.
- For example:

```
Animal a = new Dog();

Animal[] zoo = new Animal[100];
zoo[0] = new Ant();
zoo[1] = new Cat();
…
```

- The name for this capability is *polymorphism.*
  - from the Greek for "many forms"
  - the same code can be used with objects of different types

Storing Items in an `ArrayBag`

- We store the items in an array of type `Object`.

```
public class ArrayBag implements Bag {
    private Object[] items;
    private int numItems;
    …
}
```

- This allows us to store *any* type of object in the `items` array, thanks to the power of polymorphism:

```
ArrayBag bag = new ArrayBag();
bag.add("hello");
bag.add(new Double(3.1416));
```

Another Example of Polymorphism

- An interface name can be used as the type of a variable.

```
Bag b;
```

- Variables that have an interface type can hold references to objects of any class that implements the interface.

```
Bag b = new ArrayBag();
```

- Using a variable that has the interface as its type allows us to write code that works with any implementation of an ADT.

```
public void processBag(Bag b) {
    for (int i = 0; i < b.numItems(); i++) {
      …
}
```

  - the param can be an instance of *any* `Bag` implementation
  - we must use method calls to access the object's internals, because we can't know for certain what the field names are

Memory Management: Looking Under the Hood

- In order to understand the implementation of the data structures we'll cover in this course, you'll need to have a good understanding of how memory is managed.
- There are three main types of memory allocation in Java.
- They correspond to three different regions of memory.

Memory Management, Type I: Static Storage

- Static storage is used in Java for *class variables*, which are declared using the keyword `static`:

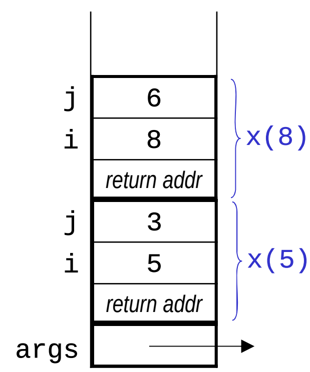
```
public static final PI = 3.1495;
public static int numCompares;
```

- There is only one copy of each class variable; it is shared by all instances (i.e., all objects) of the class.
- The Java runtime system allocates memory for class variables when the class is first encountered.
  - this memory stays fixed for the duration of the program

Memory Management, Type II: Stack Storage

- Method parameters and local variables are stored in a region of memory known as *the stack*.
- For each method call, a new *stack frame* is added to the top of the stack.

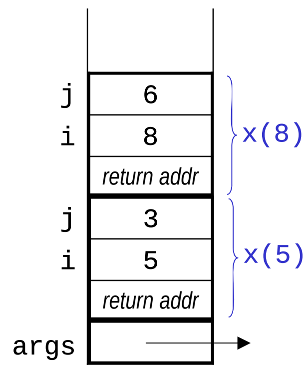
```
public class Foo {
  static void x(int i) {
      int j = i - 2;
      if (i >= 6) return;
      x(i + j);
  }
  public static void
    main(String[] args) {
      x(5);
  }
}
```



- When a method completes, its stack frame is removed. The values stored there are *not* preserved.

Stack Storage (cont.)

- Memory allocation on the stack is very efficient, because there are only two simple operations:
  - add a stack frame to the top of the stack
  - remove a stack frame from the top of the stack
- Limitations of stack storage:
  It can't be used if
  - the amount of memory needed isn't known in advance
  - we need the memory to persist after the method completes
- Because of these limitations, Java never stores arrays or objects on the stack.

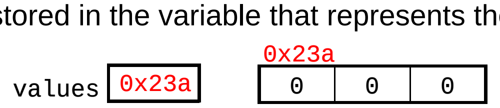


Memory Management, Type III: Heap Storage

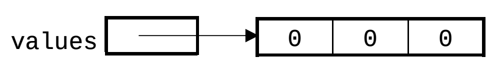
- Arrays and objects in Java are stored in a region of memory known as *the heap*.
- Memory on the heap is allocated using the `new` operator:

```
int[] values = new int[3];
ArrayBag b = new ArrayBag();
```

- `new` returns the memory address of the start of the array or object on the heap.
- This memory address – which is referred to as a *reference* in Java – is stored in the variable that represents the array/object:



- We will often use an arrow to represent a reference:



Heap Storage (cont.)

- In Java, an object or array persists until there are no remaining references to it.
- You can explicitly drop a reference by setting the variable equal to `null`. For example:

```
int[] values = {5, 23, 61, 10};
System.out.println(mean(values, 4));
values = null;
```

- Unused objects/arrays are *automatically* reclaimed by a process known as garbage collection.
  - makes their memory available for other objects or arrays

Constructors for the `ArrayBag` Class

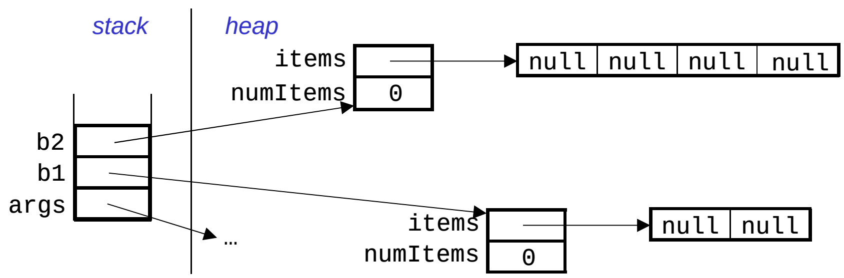
```
public class ArrayBag implements Bag {
    private Object[] items;
    private int numItems;
    public static final int DEFAULT_MAX_SIZE = 50;

    public ArrayBag() {
        items = new Object[DEFAULT_MAX_SIZE];
        numItems = 0;
    }
    public ArrayBag(int maxSize) {
        if (maxSize <= 0)
            throw new IllegalArgumentException(
              "maxSize must be > 0");
        items = new Object[maxSize];
        numItems = 0;
    }
    …
}
```

- If the user inputs an invalid value for `maxSize`, we throw an exception.

Example: Creating Two `ArrayBag` Objects

```
public static void main(String[] args) {
    ArrayBag b1 = new ArrayBag(2);
    ArrayBag b2 = new ArrayBag(4);
    …
}
```

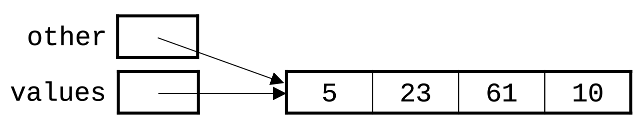
- After the objects have been created, here's what we have:



Copying References

- A variable that represents an array or object is known as a *reference variable*.
- Assigning the value of one reference variable to another reference variable copies the reference to the array or object. It does *not* copy the array or object itself.

```
int[] values = {5, 23, 61, 10};
int[] other = values;
```



- Given the lines above, what will the lines below output?

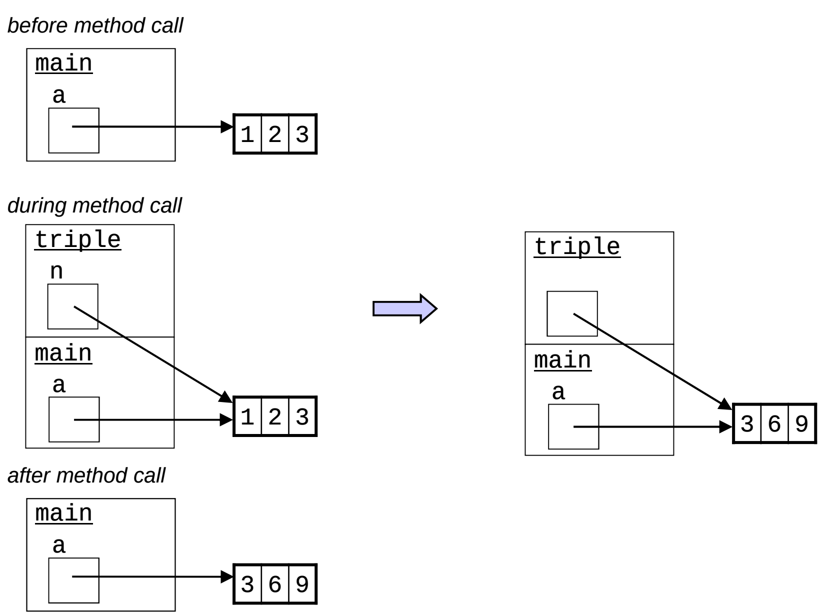
```
other[2] = 17;
System.out.println(values[2] + " " + other[2]);
```

Passing an Object/Array to a Method

- When a method is passed an object or array as a parameter, the method gets a copy of the *reference* to the object or array, *not* a copy of the object or array itself.
- Thus, any changes that the method makes to the object/array will still be there when the method returns.
- Consider the following:

```
public static void main(String[] args) {
    int[] a = {1, 2, 3};
    triple(a);
    System.out.println(Arrays.toString(a));
}

public static void triple(int[] n) {
    for (int i = 0; i < n.length; i++) {
        n[i] = n[i] * 3;
    }
}
```

Passing an Object/Array to a Method (cont.)



A Method for Adding an Item to a Bag

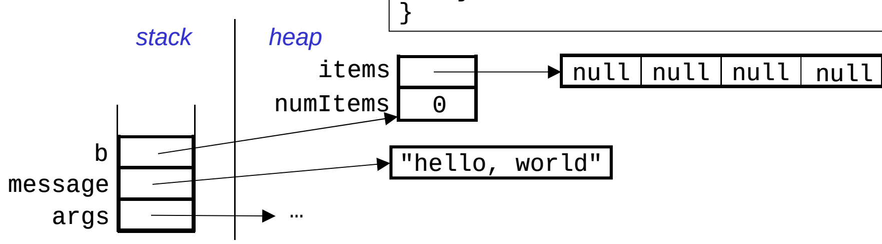
```
public class ArrayBag implements Bag {
    private Object[] items;
    private int numItems;
    …
    public boolean add(Object item) {
        if (item == null)
            throw new IllegalArgumentException();
        if (numItems == items.length)
            return false;  // no more room!
        else {
            items[numItems] = item;
            numItems++;
            return true;
        }
    }
    …
}
```

- `add()` is an instance method (a.k.a. a non-static method), so it has access to the fields of the current object.

Example: Adding an Item

```
public static void main(String[] args) {
    String message = "hello, world";
    ArrayBag b = new ArrayBag(4);
    b.add(message);
    …
}
```

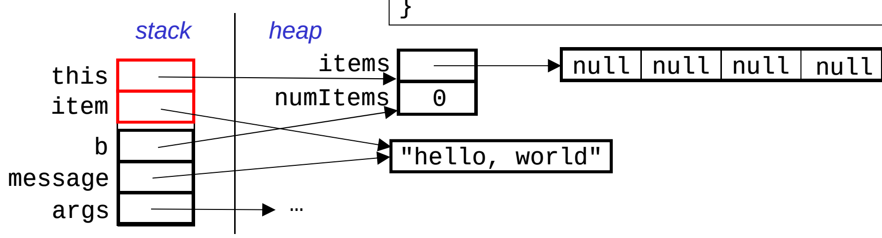
```
public boolean add(Object item) {
    …
    else {
        items[numItems] = item;
        numItems++;
        return true;
    }
}
```



Example: Adding an Item (cont.)

```
public static void main(String[] args) {
    String message = "hello, world";
    ArrayBag b = new ArrayBag(4);
    b.add(message);
    …
}
```

```
public boolean add(Object item) {
    …
    else {
        items[numItems] = item;
        numItems++;
        return true;
    }
}
```

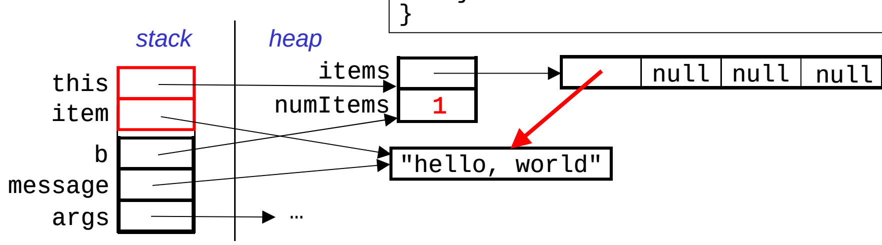


- add's stack frame includes:
  - `item`, which stores a copy of the reference passed as a param.
  - `this`, which stores a reference to the called/current object

Example: Adding an Item (cont.)

```
public static void main(String[] args) {
    String message = "hello, world";
    ArrayBag b = new ArrayBag(4);
    b.add(message);
    …
}
```

```
public boolean add(Object item) {
    …
    else {
        items[numItems] = item;
        numItems++;
        return true;
    }
}
```

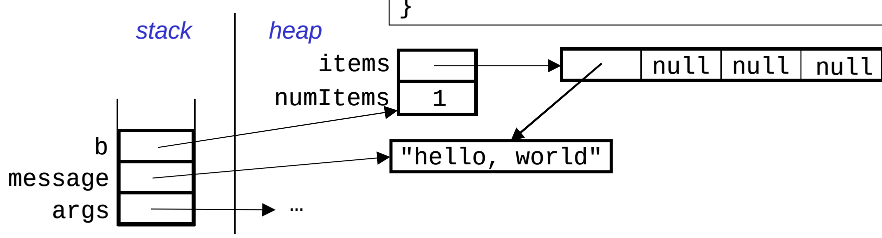


- The method modifies the `items` array and `numItems`.
  - note that the array holds a copy of the *reference* to the item, not a copy of the item itself.

Example: Adding an Item (cont.)

```
public static void main(String[] args) {
    String message = "hello, world";
    ArrayBag b = new ArrayBag(4);
    b.add(message);
    …
}
```

```
public boolean add(Object item) {
    …
    else {
        items[numItems] = item;
        numItems++;
        return true;
    }
}
```



- After the method call returns, add's stack frame is removed from the stack.

Using the Implicit Parameter

```
public class ArrayBag implements Bag {
    private Object[] items;
    private int numItems;
    …
    public boolean add(Object item) {
        if (item == null)
            throw new IllegalArgumentException();
        if (this.numItems == this.items.length)
            return false;  // no more room!
        else {
            this.items[this.numItems] = item;
            this.numItems++;
            return true;
        }
    }
    …
}
```

- We can use `this` to emphasize the fact that we're accessing fields in the current object.

Determining if a Bag Contains an Item

- Let's write the `ArrayBag contains()` method together.
- Should return `true` if an object equal to `item` is found, and `false` otherwise.

```
_________________ contains(_____________ item) {




}
```

An Incorrect `contains()` Method

```
public boolean contains(Object item) {
    for (int i = 0; i < numItems; i++) {
        if (items[i].equals(item))
            return true;
        else
            return false;
    }
    return false;
}
```

- Why won't this version of the method work in all cases?
- When would it work?

A Method That Takes a Bag as a Parameter

```
public boolean containsAll(Bag otherBag) {
    if (otherBag == null || otherBag.numItems() == 0)
        return false;

    Object[] otherItems = otherBag.toArray();
    for (int i = 0; i < otherItems.length; i++) {
        if (!contains(otherItems[i]))
            return false;
    }

    return true;
}
```

- We use `Bag` instead of `ArrayBag` as the type of the parameter.
  - allows this method to be part of the `Bag` interface
  - allows us to pass in *any* object that implements `Bag`
- Because the parameter may not be an `ArrayBag`, we can't assume it has `items` and `numItems` fields.
  - instead, we use `toArray()` and `numItems()`

A Need for Casting

- Let's say that we want to store a collection of `String` objects in an `ArrayBag`.
- `String` is a subclass of `Object`, so we can store `String` objects in the bag without doing anything special:

```
ArrayBag stringBag = new ArrayBag();
stringBag.add("hello");
stringBag.add("world");
```

- `Object` isn't a subclass of `String`, so this will <u>not</u> work:

```
String str = stringBag.grab();    // compiler error
```

- Instead, we need to use casting:

```
String str = (String)stringBag.grab();
```

Extra: Thinking About a Method's Efficiency

- For a bag with 1000 items, how many items will `contains()` look at:
  - in the best case?
  - in the worst case?
  - in the average case?
- Could we make it more efficient?
- If so, what changes would be needed to do so, and what would be the impact of those changes?

Extra: Understanding Memory Management

- Our Bag ADT has a method `toArray()`, which returns an array containing the current contents of the bag
  - allows users of the ADT to iterate over the items
- When implementing `toArray()` in our `ArrayBag` class, can we just return a reference to the `items` array? Why or why not?