Introduction: Abstract Data Types and Java Review

Computer Science E-22
Harvard Extension School

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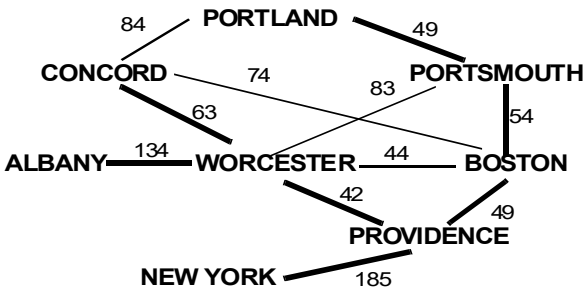
Welcome to Computer Science E-22!

- 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
- Sections
  - optional but highly recommended
  - start this week; times and locations TBA
  - all on Zoom; one section will be recorded
- Five problem sets
  - plan on 10-20 hours per week!
  - code in Java
  - must be your own work
    - see syllabus or website for the collaboration policy
  - grad-credit students will do extra problems
- Midterm exam
- Final exam

Additional Administrivia

- Instructor: Dave Sullivan
- TAs: Alex Breen, Libby James, Eli Saracino, Michael Yue
- Office hours and contact info. will be available on the Web:
  https://cscie22.sites.fas.harvard.edu
- For questions on content, homework, etc.:
  - use Ed Discussion on Canvas
  - send e-mail to cscie22-staff@lists.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 this.width * this.height;
    }
    …
```

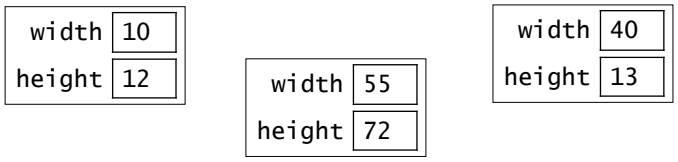
Class vs. Object

- 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.
  - does *not* commit to any low-level details
- 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 we want a `Bag` to support:
  - `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
- We want the bag to be able to store objects of any type.

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
  - does *not* typically include the full method definitions
- Like a class, it must go in a file with an appropriate name.
  - in this case: `Bag.java`

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.
  - if the class doesn't define them, it won't compile

Encapsulation

- Our implementation provides proper *encapsulation*.
  - a key principle of object-oriented programming
- 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 use the keyword `public` in the definition:

```
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 the methods in a class, we *do* need to use `public`:

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

Inheritance

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

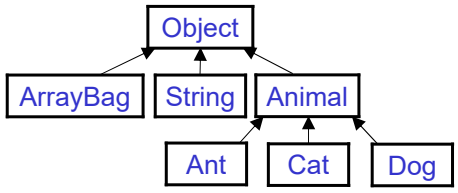
```
public class Animal {
    private String name;
    …
    public String getName() {
        return this.name;
    }
    …
}

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

- To understand how data structures are implemented, you need to understand 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 for *class variables*, which are declared *outside any method* using the keyword `static`:

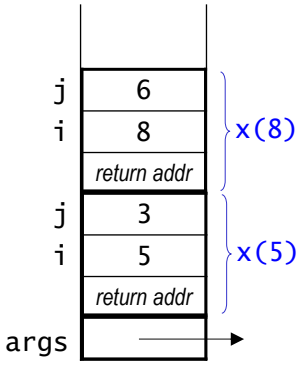
```
public class MyMethods {
    public static int numCompares;
    public static final double PI = 3.14159;
```

- There is only one copy of each class variable.
  - shared by all objects of the class
  - Java's version of a global variable
- The Java runtime 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 {
  public static int x(int i) {
      int j = i - 2;
      if (i >= 6) {
          return i;
      }
      return x(i + j);
  }
  public static void
    main(String[] args) {
      System.out.println(x(5));
  }
}
```



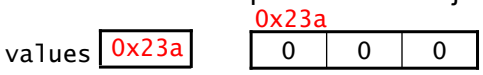
- When a method completes, its stack frame is removed.

Memory Management, Type III: Heap Storage

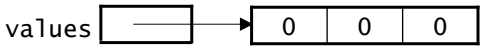
- Objects (including arrays) are stored in a region of memory known as *the heap*.
- Memory on the heap is allocated using the `new` operator:

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

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



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



Heap Storage (cont.)

- An object remains on the heap until there are no remaining references to it.
- Unused objects are automatically reclaimed by a process known as *garbage collection*.
  - makes their memory available for other objects

Two 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() {
        this.items = new Object[DEFAULT_MAX_SIZE];
        this.numItems = 0;
    }
    public ArrayBag(int maxSize) {
    ...
}
```

- A class can have multiple constructors.
  - the parameters must differ in some way
- The first one is useful for small bags.
  - creates an array with room for 50 items.
- The second one allows the client to specify the max # of items.

Two Constructors for the ArrayBag Class

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

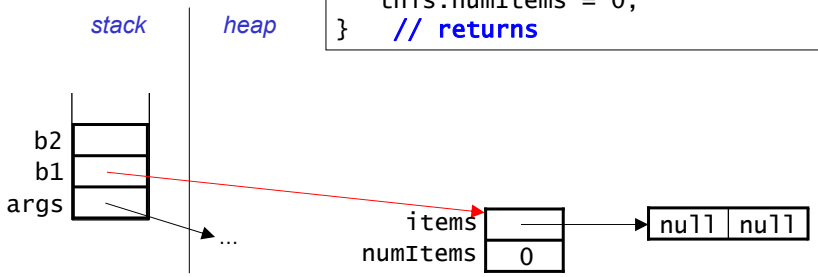
    public ArrayBag() {
        this.items = new Object[DEFAULT_MAX_SIZE];
        this.numItems = 0;
    }
    public ArrayBag(int maxSize) {
        if (maxSize <= 0) {
            throw new IllegalArgumentException(
              "maxSize must be > 0");
        }
        this.items = new Object[maxSize];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

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

Example: Creating Two `ArrayBag` Objects

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

```
// constructor
public ArrayBag(int maxSize) {
   ...  // error-checking
   this.items = new Object[maxSize];
   this.numItems = 0;
}   // returns
```



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    ArrayBag b1 = new ArrayBag(2);
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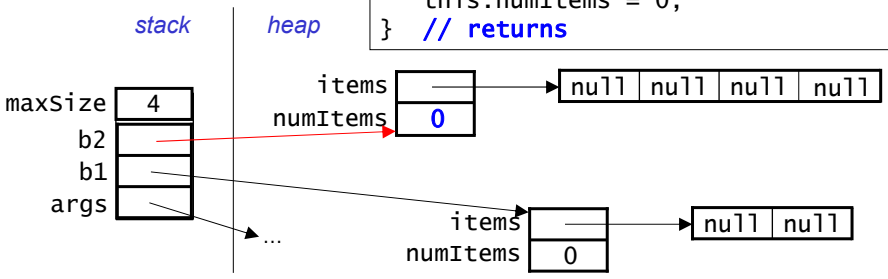
    …
}
```

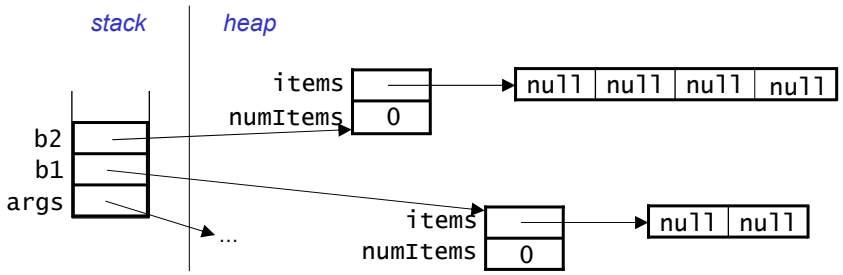
```
// constructor
public ArrayBag(int maxSize) {
   ...  // error-checking
   this.items = new Object[maxSize];
   this.numItems = 0;
}  // returns
```



Example: Creating Two `ArrayBag` Objects

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

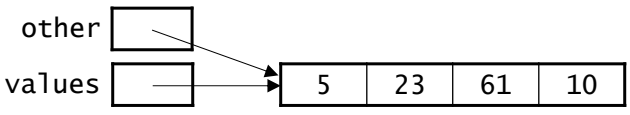
- After the objects have been created, here's what we have:



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:

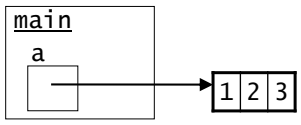
```
public static void main(String[] args) {
    int[] a = {1, 2, 3};
    triple(a);
    System.out.println(Arrays.toString(a));
}

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

What is the output?

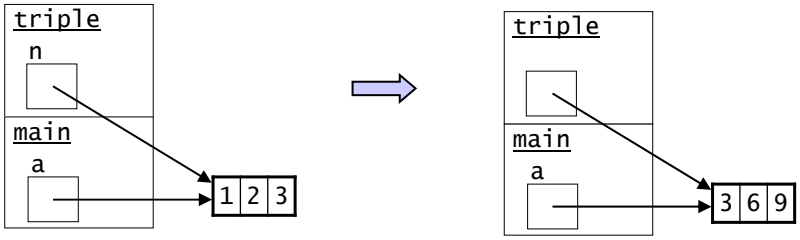
Passing an Object/Array to a Method (cont.)

before method call

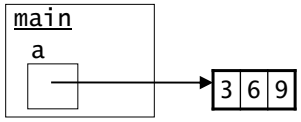



```
public static void main(String[] args) {
    int[] a = {1, 2, 3};
    triple(a);
    System.out.println(...);
}
```

during method call

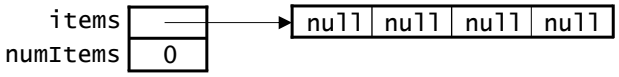


after method call

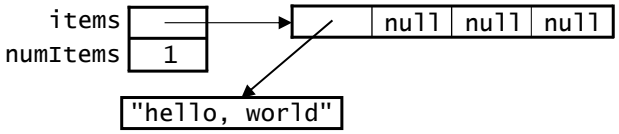


Adding Items

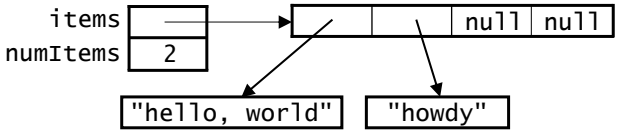
- We fill the array from left to right. Here's an empty bag:



- After adding the first item:

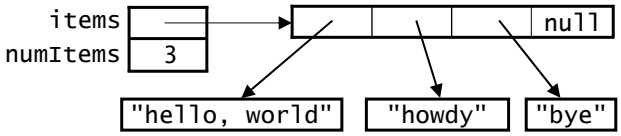


- After adding the second item:

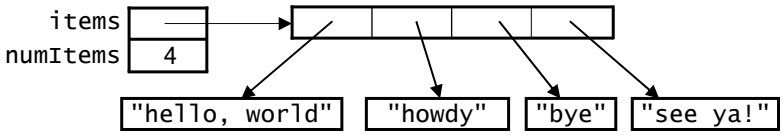


Adding Items (cont.)

- After adding the third item:



- After adding the fourth item:



- At this point, the `ArrayBag` is full!
  - it's non-trivial to "grow" an array, so we don't!
  - additional items cannot be added until one is removed

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("no nulls");
        } else if (this.numItems == this.items.length) {
            return false;   // no more room!
        } else {
            this.items[this.numItems] = item;
            this.numItems++;
            return true;    // success!
        }
    }
    ...
}
```

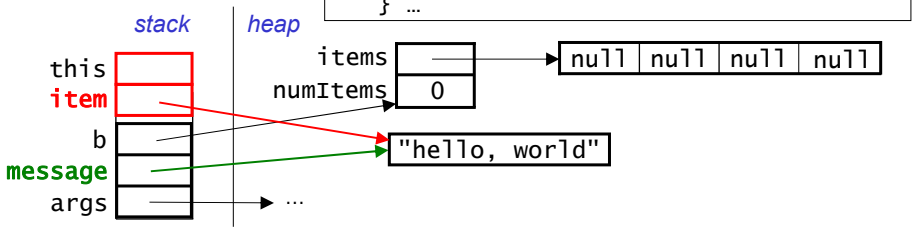
- takes an object of any type!
- returns a `boolean` to indicate if the operation succeeded

- Initially, `this.numItems` is 0, so the first item goes in position 0.
- We increase `this.numItems` because we now have 1 more item.
  - and so the *next* item added will go in the correct position!

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 {
        this.items[this.numItems] = item;
        this.numItems++;
        return true;
    } …
```

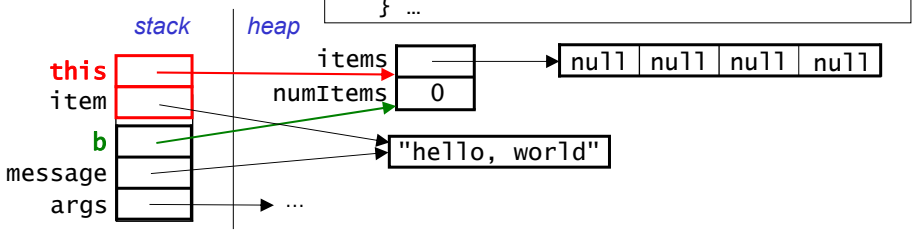


- add's stack frame includes:
  - `item`, which stores a copy of the reference passed as a param.

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 {
        this.items[this.numItems] = item;
        this.numItems++;
        return true;
    } …
```

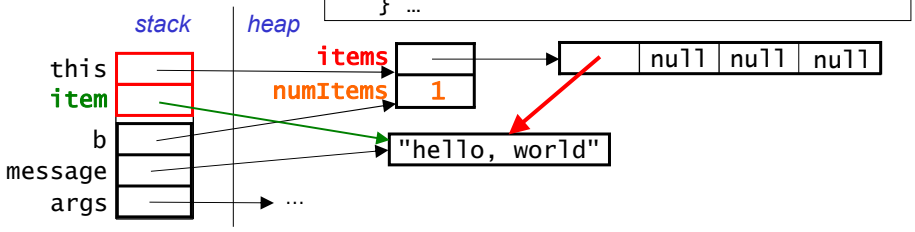


- add's stack frame includes:
  - `item`, which stores a copy of the reference passed as a param.
  - `this`, which stores a reference to the called `ArrayBag` object

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 {
        this.items[this.numItems] = item;
        this.numItems++;
        return true;
    } …
```

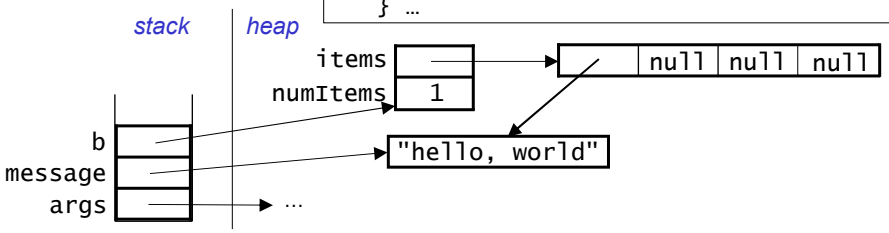


- The method modifies the `items` array and `numItems`.
  - note that the array holds a copy of the *reference* to the item, not a copy of the item itself.

Example: Adding an Item (cont.)

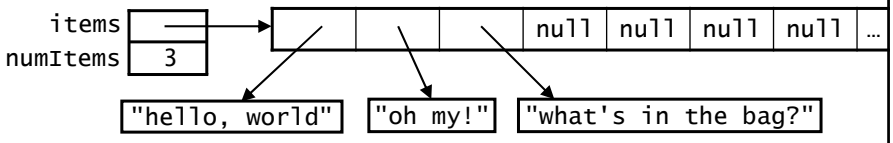
```
public static void main(String[] args) {
    String message = "hello, world";
    ArrayBag b = new ArrayBag(4);
    b.add(message);
    …
}
```

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



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

Extra Practice: Determining if a Bag Contains an Item



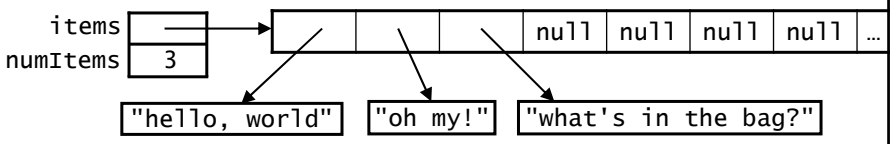
- Let's write the `ArrayBag` `contains()` method together.
  - should return `true` if an object equal to `item` is found, and `false` otherwise.

```
_____________________ contains(_____________ item) {




}
```

Would this work instead?



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

```
public boolean contains(Object item) {
    for (int i = 0; i < this.items.length; i++) {
        if (this.items[i].equals(item)) { // not ==
            return true;
        }
    }
    return false;
}
```

Another Incorrect `contains()` Method

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

- What's the problem with this?

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 (! this.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`
- We must use methods in the interface to manipulate `otherBag`.
  - we can't use the fields, because they're not in the interface

A Type Mismatch

- Here are the headers of two `ArrayBag` methods:

```
public boolean add(Object item)
public Object grab()
```

- Polymorphism allows us to pass `String` objects into `add()`:

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

- However, this will not work:

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

  - the return type of `grab()` is `Object`
  - `Object` isn't a subclass of `String`, so polymorphism doesn't help!
- Instead, we need to use a *type cast*:

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

  - this cast doesn't actually change the value being assigned
  - it just reassures the compiler that the assignment is okay