Unit 6, Part 1

Abstract Data Types and Data Structures

Computer Science S-111
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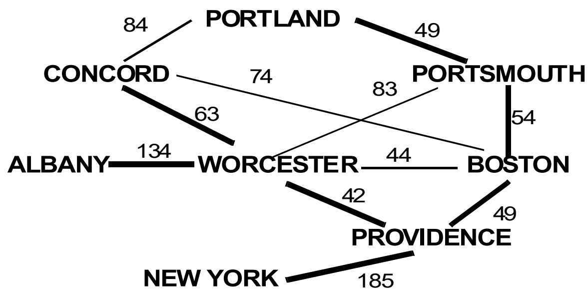
Congrats on completing the first half!

- In the second half, 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.

Example of Comparing Algorithms

- Consider the problem of finding a phone number in a phonebook.
- Let's informally compare the time efficiency of two algorithms for this problem.

Algorithm 1 for Finding a Phone Number

```
findNumber(person) {
    for (p = number of first page; p <= number of the last page; p++) {
        if person is found on page p {
            return the person's phone number
        }
    }
    return NOT_FOUND
}
```

- If there were 1,000 pages in the phonebook, how many pages would this look at in the worst case?
- What if there were 1,000,000 pages?

Algorithm 2 for Finding a Phone Number

```
findNumber(person) {
    min = the number of the first page
    max = the number of the last page
    while (min <= max) {
        mid = (min + max) / 2       // page number of the middle page
        if person is found on page mid {
            return the person's number
        } else if the person's name comes earlier in the book {
            max = mid – 1
        } else {
            min = mid + 1
        }
    }
    return NOT_FOUND
}
```

- If there were 1,000 pages in the phonebook, how many pages would this look at in the worst case?
- What if there were 1,000,000 pages?

Searching a Collection of Data

- The phonebook problem is one example of a common task: searching for an item in a collection of data.
  - another example: searching for a record in a database
- Algorithm 1 is known as *sequential search*.
  - also called *linear search*
- Algorithm 2 is known as *binary search*.
  - only works if the items in the data collection are sorted

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 {
    …
    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

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) {
        …
```

One Possible Bag Implementation

- One way to store the items in the bag is to use an array:

```
public class ArrayBag {

    private _____________[] items;

    ...
}
```

- What type should the array be?

- 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 Rectangle(20, 30));
```

- How could we keep track of how many items are in a bag?

Another Example of Polymorphism

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

```
Bag b;
```

- Variables with an interface type can refer to objects of any class that implements the interface:

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

- Using the interface as the 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 the fields are not part of the interface

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`:

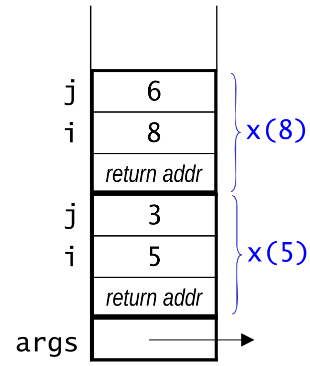
```
public class MyMethods {
    public static int numCompares;
    public static final double PI = 3.14159;
```

- 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 are stored in a memory region 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 on the heap.
  - a reference!
- An object stays 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) {
    ...
}
```

- As we've seen before, we 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

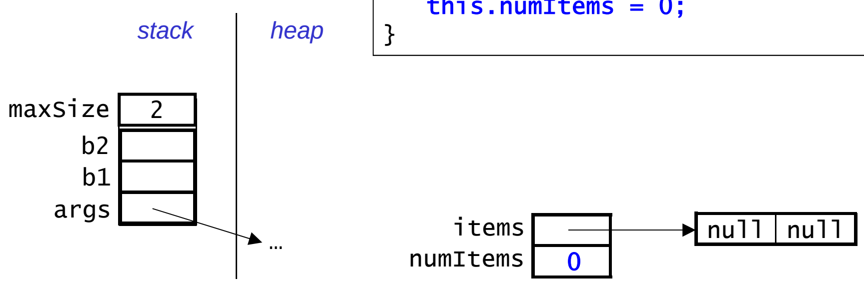
```
public class ArrayBag implements Bag {
    private Object[] items;
    private int numItems;
    public static final int DEFAULT_MAX_SIZE = 50;

    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);
    …
}
```

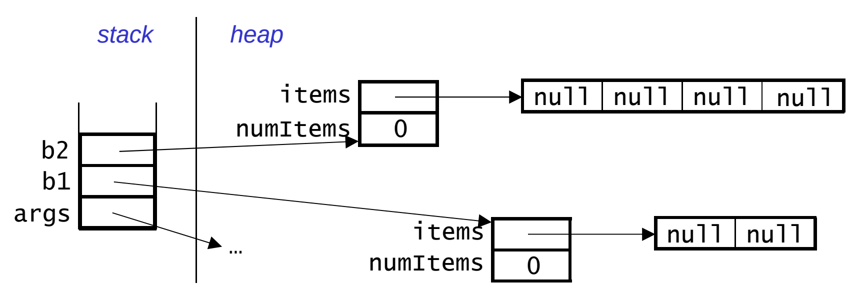
```
// constructor
public ArrayBag(int maxSize) {
   ...  // error-checking
   this.items = new Object[maxSize];
   this.numItems = 0;
}
```



Example: Creating Two `ArrayBag` Objects

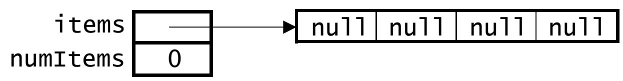
```
// client
public static void main(String[] args) {
    ArrayBag b1 = new ArrayBag(2);
    ArrayBag b2 = new ArrayBag(4);
    …
}
```

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

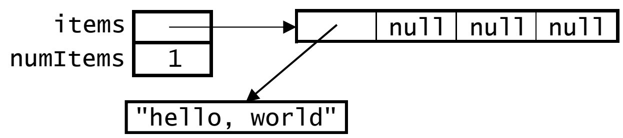


Adding Items

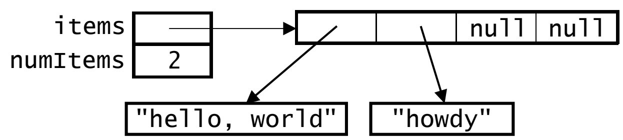
- We fill the array from left to right. Here's an empty bag:



- After adding the first item:

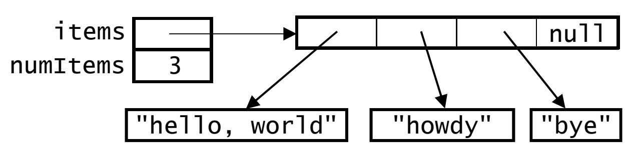


- After adding the second item:

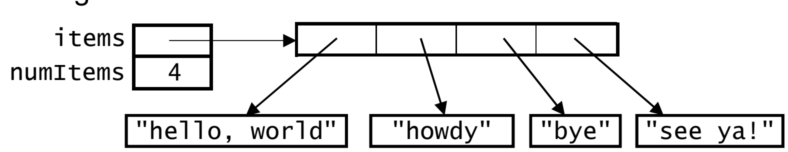


Adding Items (cont.)

- After adding the third item:



- After adding the fourth item:

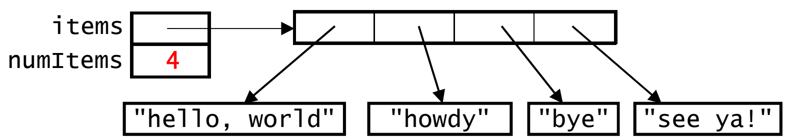


- At this point, the `ArrayBag` is full!
  - it's non-trivial to "grow" an array, so we don't!
  - additional items cannot be added until one is removed

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



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!
        }
    }
    ...
}
```

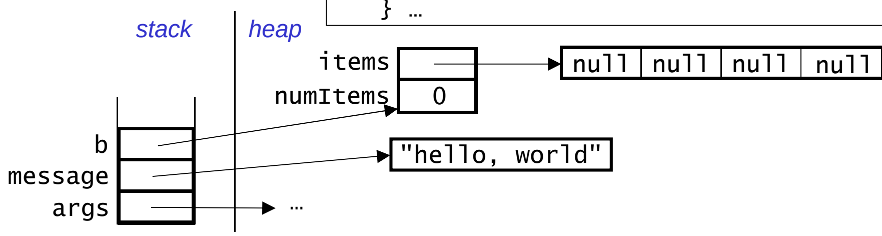
- takes an object of any type!
- returns a `boolean` to indicate if the operation succeeded

- 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

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

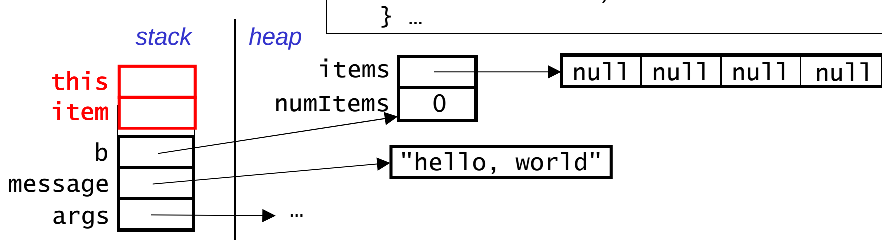
```
public boolean add(Object item) {
   …
   else {
       this.items[this.numItems] = item;
       this.numItems++;
       return true;
   } …
```



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;
   } …
```

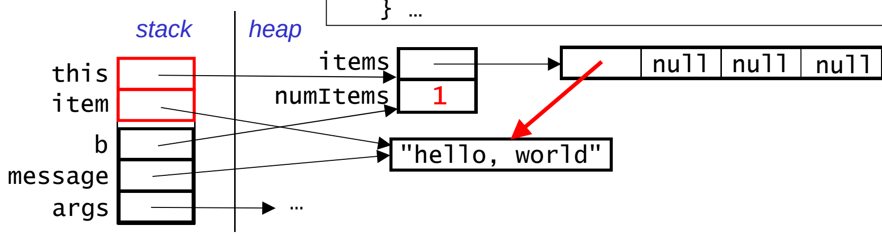


- add's stack frame includes:
  - `item`, which stores…
  - `this`, which stores…

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;
   } …
```

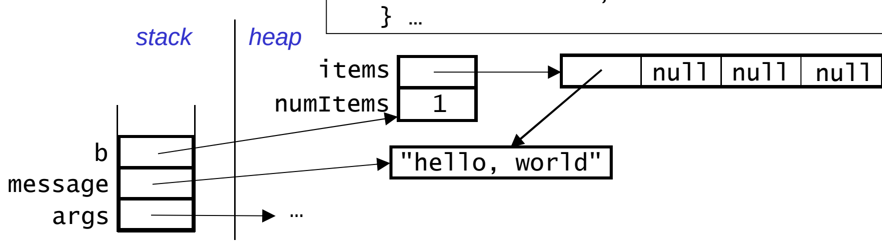


- The method modifies the `items` array and `numItems`.
  - note that the array holds a copy of the *reference* to the item, not a copy of the item itself.

Example: Adding an Item (cont.)

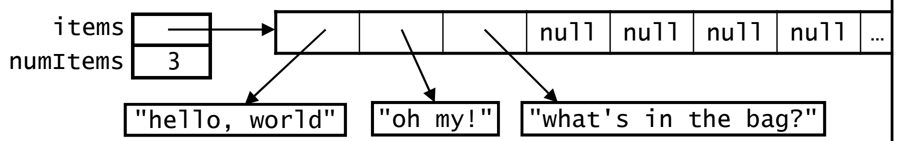
```
public static void main(String[] args) {
    String message = "hello, world";
    ArrayBag b = new ArrayBag(4);
    b.add(message);
    …
}
```

```
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.

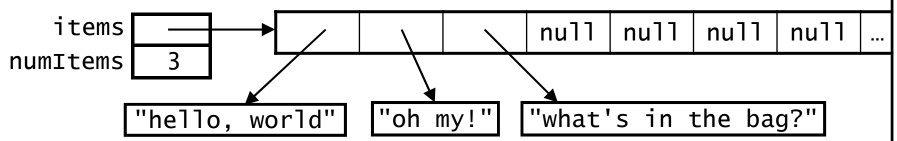
Extra Practice: Determining if a Bag Contains an Item



- 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 <u>not</u> 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