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.

![Graph of cities and routes]

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 next week; times and locations TBA
  • at least one in person; at least one on Zoom/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, Kristen Lamb, Eli Saracino
• 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:

    ```java
    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:

```java
public class Rectangle {
    // fields
    private int width;
    private int height;
    // methods
    ...
}
```

• Rectangle objects are built according to that blueprint:

<table>
<thead>
<tr>
<th>Width</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>55</td>
<td>72</td>
</tr>
<tr>
<td>40</td>
<td>13</td>
</tr>
</tbody>
</table>

(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:

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

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

```java
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
    ```java
    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:
    ```java
    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:
    ```java
    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:

```java
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:

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

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

  ```java
  public class ArrayBag implements Bag {
    ...
    public boolean add(Object item) {
    ...
  }
  ```
Inheritance

- We can define a class that explicitly extends another class:
  ```java
  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:

```java
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.

```java
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:

```java
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.
  
  ```java
  Bag b;
  ```

- Variables that have an interface type can hold references to objects of any class that implements the interface.
  
  ```java
  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.
  
  ```java
  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:
  ```java
  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.
  ```java
  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));
      }
  }
  ```
  ![Stack Frame Diagram]
  - 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:

```java
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:

```
values 0x23a
```

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

```
values ———> 0 0 0
```

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

```java
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;
    }
    ...
}
```

• 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.

• If the user inputs an invalid maxSize, we throw an exception.
Example: Creating Two ArrayBag Objects

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

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

```java
// 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.

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

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

```java
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:
  ```java
  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?
Adding Items

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

```
  items | numItems
    0   | null null null null
```

- After adding the first item:

```
  items | numItems
    1   | null null null null
        | "hello, world"
```

- After adding the second item:

```
  items | numItems
    2   | null null null
        | "hello, world" "howdy"
```

Adding Items (cont.)

- After adding the third item:

```
  items | numItems
    3   | null
        | "hello, world" "howdy" "bye"
```

- After adding the fourth item:

```
  items | numItems
    4   | null
        | "hello, world" "howdy" "bye" "see ya!"
```

- 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

```java
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!
        }
    }
    ...
}
```

- 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.)

```java
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.)

```java
public boolean add(Object item) {
    if (this.numItems == this.items.length) {
        expand();
    }
    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);
}
```

- `args` ...
- `message` ...
- `b` ...
- `stack` ...
- `heap` ...
- `this` ...
- `item` ...
- `numItems` ...
- `null` null null null null
- `this` ...
- `items` ...
- `null` ...
- `numItems` ...
- `0`
- `this` ...
- `items` ...
- `null` null null null
- `numItems` ...
- `1`
- `this` ...
- `items` ...
- `null` null null null
- `numItems` ...
- `1`
Example: Adding an Item (cont.)

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

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

```java
public boolean contains(Object item) {
    // Implementation...
}
```

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

```java
public boolean contains(Object item) {
    // Implementation...
}
```
Would this work instead?

```java
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;
}
```

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

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

- What's the problem with this?

Another Incorrect contains() Method

```java
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;
}
```
A Method That Takes a Bag as a Parameter

```java
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:
  ```java
  public boolean add(Object item)
  public Object grab()
  ```
- Polymorphism allows us to pass `String` objects into `add()`:
  ```java
  ArrayBag stringBag = new ArrayBag();
  stringBag.add("hello");
  stringBag.add("world");
  ```
- However, this will not work:
  ```java
  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:
  ```java
  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