Abstract Data Types
and Data Structures

Computer Science S-111
Harvard University
David G. Sullivan, Ph.D.

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.

```
BOSTON
  /   \
/     /
PORTLAND
/     /
CONCORD
/ 74   83/
|       |
ALBANY
|   63 134|
|     |
WORCESTER
44
|
| 42
|
| 44
|
| 49
|
| 49
|
| 54
|
PROVIDENCE

NEW YORK
```

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

```plaintext
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

```plaintext
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.

- 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

• 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:

```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

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) {
        ...
    }
}
```
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 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 with an interface type can refer to objects of any class that implements the interface:
  ```java
  Bag b = new ArrayBag();
  ```

- Using the interface as the 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 the fields are not part of the interface
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 numComparisons;
  ```

- 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.

```java
public class Foo {
    public 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.

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:
  ```java
  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.
    - a reference!
  - An object persists 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;
    }

    ...
}
```

- 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.

- 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);
    ...
}
```

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

**Stack**

```
maxSize
b2
b1
args
```

**Heap**

```
items
numItems
```

- 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:

• 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

```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

```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.numItems < this.items.length) {
        this.items[this.numItems] = item;
        this.numItems++;
        return true;
    } else {
        return false;
    }
}
```

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

Example: Adding an Item (cont.)
• 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.

• 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.

```java
            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.

    ```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;
    }
    ```

    ![Diagram showing items and numItems with values: items = "hello, world", "go BU!", "what's in the bag?", numItems = 3]

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;
}
```

- 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

```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