Chapter 12

Arrays

An **array** is a set of values where each value is identified by an index. You can make an array of `int`s, `double`s, or any other type, but all the values in an array have to have the same type.

Syntactically, array types look like other Java types except they are followed by `[]`. For example, `int[]` is the type "array of integers" and `double[]` is the type "array of doubles."

You can declare variables with these types in the usual ways:

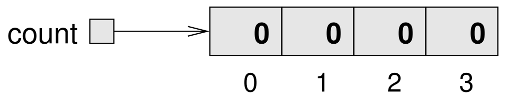
```
int[] count;
double[] values;
```

Until you initialize these variables, they are set to `null`. To create the array itself, use `new`.

```
count = new int[4];
values = new double[size];
```

The first assignment makes `count` refer to an array of 4 integers; the second makes `values` refer to an array of `double`s. The number of elements in `values` depends on `size`. You can use any integer expression as an array size.

The following figure shows how arrays are represented in state diagrams:



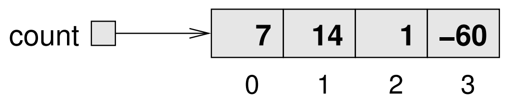
The large numbers inside the boxes are the **elements** of the array. The small numbers outside the boxes are the indices used to identify each box. When you allocate an array if `ints`, the elements are initialized to zero.

12.1 Accessing elements

To store values in the array, use the `[]` operator. For example `count[0]` refers to the "zeroeth" element of the array, and `count[1]` refers to the "oneth" element. You can use the `[]` operator anywhere in an expression:

```
count[0] = 7;
count[1] = count[0] * 2;
count[2]++;
count[3] -= 60;
```

These are all legal assignment statements. Here is the result of this code fragment:



The elements of the array are numbered from 0 to 3, which means that there is no element with the index 4. This should sound familiar, since we saw the same thing with `String` indices. Nevertheless, it is a common error to go beyond the bounds of an array, which throws an `ArrayOutOfBoundsException`.

You can use any expression as an index, as long as it has type `int`. One of the most common ways to index an array is with a loop variable. For example:

```
int i = 0;
while (i < 4) {
    System.out.println(count[i]);
    i++;
}
```

This is a standard `while` loop that counts from 0 up to 4, and when the loop variable `i` is 4, the condition fails and the loop terminates. Thus, the body of the loop is only executed when `i` is 0, 1, 2 and 3.

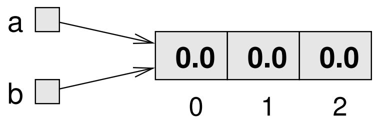
Each time through the loop we use `i` as an index into the array, printing the `i`th element. This type of array traversal is very common.

12.2 Copying arrays

When you copy an array variable, remember that you are copying a reference to the array. For example:

```
double[] a = new double [3];
double[] b = a;
```

This code creates one array of three `double`s, and sets two different variables to refer to it. This situation is a form of aliasing.



Any changes in either array will be reflected in the other. This is not usually the behavior you want; more often you want to allocate a new array and copy elements from one to the other.

```
double[] b = new double [3];

int i = 0;
while (i < 4) {
  b[i] = a[i];
  i++;
}
```

12.3 Arrays and objects

In many ways, arrays behave like objects:

- When you declare an array variable, you get a reference to an array.
- You have to use `new` to create the array itself.
- When you pass an array as an argument, you pass a reference, which means that the invoked method can change the contents of the array.

Some of the objects we looked at, like `Rectangles`, are similar to arrays in the sense that they are collections of values. This raises the question, "How is an array of 4 integers different from a Rectangle object?"

If you go back to the definition of "array" at the beginning of the chapter, you see one difference: the elements of an array are identified by indices, and the elements of an object have names.

Another difference is that the elements of an array have to be the same type. Objects can have instance variables with different types.

12.4 `for` loops

The loops we have written have a number of elements in common. All of them start by initializing a variable; they have a test, or condition, that depends on that variable; and inside the loop they do something to that variable, like increment it.

This type of loop is so common that there is another loop statement, called `for`, that expresses it more concisely. The general syntax looks like this:

```
    for (INITIALIZER; CONDITION; INCREMENTOR) {
        BODY
    }
```

This statement is equivalent to

```
    INITIALIZER;
    while (CONDITION) {
        BODY
        INCREMENTOR
    }
```

except that it is more concise and, since it puts all the loop-related statements in one place, it is easier to read. For example:

```
    for (int i = 0; i < 4; i++) {
        System.out.println(count[i]);
    }
```

is equivalent to

```
int i = 0;
while (i < 4) {
    System.out.println(count[i]);
    i++;
}
```

12.5 Array length

All arrays have one named instance variable: `length`. Not surprisingly, it contains the length of the array (number of elements). It is a good idea to use this value as the upper bound of a loop, rather than a constant value. That way, if the size of the array changes, you won't have to go through the program changing all the loops; they will work correctly for any size array.

```
for (int i = 0; i < a.length; i++) {
    b[i] = a[i];
}
```

The last time the body of the loop gets executed, `i` is `a.length - 1`, which is the index of the last element. When `i` is equal to `a.length`, the condition fails and the body is not executed, which is a good thing, since it would throw an exception. This code assumes that the array `b` contains at least as many elements as `a`.

12.6 Random numbers

Most computer programs do the same thing every time they are executed, so they are said to be **deterministic**. Usually, determinism is a good thing, since we expect the same calculation to yield the same result. But for some applications we want the computer to be unpredictable. Games are an obvious example, but there are more.

Making a program truly **nondeterministic** turns out to be not so easy, but there are ways to make it at least seem nondeterministic. One of them is to generate random numbers and use them to determine the outcome of the program. Java provides a method that generates **pseudorandom** numbers, which may not be truly random, but for our purposes, they will do.

Check out the documentation of the `random` method in the `Math` class. The return value is a `double` between 0.0 and 1.0. To be precise, it is greater than or equal to 0.0 and strictly less than 1.0. Each time you invoke `random` you get the next number in a pseudorandom sequence. To see a sample, run this loop:

```
for (int i = 0; i < 10; i++) {
    double x = Math.random();
    System.out.println(x);
}
```

To generate a random `double` between 0.0 and an upper bound like `high`, you can multiply `x` by `high`.

12.7 Array of random numbers

How would you generate a random integer between `low` and `high`? If your implementation of `randomInt` is correct, then every value in the range from `low` to `high-1` should have the same probability. If you generate a long series of numbers, every value should appear, at least approximately, the same number of times.

One way to test your method is to generate a large number of random values, store them in an array, and count the number of times each value occurs.

The following method takes a single argument, the size of the array. It allocates a new array of integers, fills it with random values, and returns a reference to the new array.

```
public static int[] randomArray(int n) {
    int[] a = new int[n];
    for (int i = 0; i<a.length; i++) {
        a[i] = randomInt(0, 100);
    }
    return a;
}
```

The return type is `int[]`, which means that this method returns an array of integers. To test this method, it is convenient to have a method that prints the contents of an array.

```
  public static void printArray(int[] a) {
      for (int i = 0; i<a.length; i++) {
          System.out.println(a[i]);
      }
  }
```

The following code generates an array and prints it:

```
    int numValues = 8;
    int[] array = randomArray(numValues);
    printArray(array);
```

On my machine the output is

```
27
6
54
62
54
2
44
81
```

which is pretty random-looking. Your results may differ.

If these were exam scores (and they would be pretty bad exam scores) the teacher might present the results to the class in the form of a **histogram**, which is a set of counters that keeps track of the number of times each value appears.

For exam scores, we might have ten counters to keep track of how many students scored in the 90s, the 80s, etc. The next few sections develop code to generate a histogram.

12.8 Counting

A good approach to problems like this is to think of simple methods that are easy to write, then combine them into a solution. This process is called **bottom-up development**. See http://en.wikipedia.org/wiki/Top-down_and_bottom-up_design.

It is not always obvious where to start, but a good approach is to look for subproblems that fit a pattern you have seen before.

In Section 8.7 we saw a loop that traversed a string and counted the number of times a given letter appeared. You can think of this program as an example of a pattern called “traverse and count.” The elements of this pattern are:

- A set or container that can be traversed, like an array or a string.
- A test that you can apply to each element in the container.
- A counter that keeps track of how many elements pass the test.

In this case, the container is an array of integers. The test is whether or not a given score falls in a given range of values.

Here is a method called `inRange` that counts the number of elements in an array that fall in a given range. The parameters are the array and two integers that specify the lower and upper bounds of the range.

```
public static int inRange(int[] a, int low, int high) {
    int count = 0;
    for (int i = 0; i < a.length; i++) {
        if (a[i] >= low && a[i] < high) count++;
    }
    return count;
}
```

I wasn’t specific about whether something equal to `low` or `high` falls in the range, but you can see from the code that `low` is in and `high` is out. That keeps us from counting any elements twice.

Now we can count the number of scores in the ranges we are interested in:

```
int[] scores = randomArray(30);
int a = inRange(scores, 90, 100);
int b = inRange(scores, 80, 90);
int c = inRange(scores, 70, 80);
int d = inRange(scores, 60, 70);
int f = inRange(scores, 0, 60);
```

12.9 The histogram

This code is repetitious, but it is acceptable as long as the number of ranges is small. But imagine that we want to keep track of the number of times each score appears, all 100 possible values. Would you want to write this?

```
int count0 = inRange(scores, 0, 1);
int count1 = inRange(scores, 1, 2);
int count2 = inRange(scores, 2, 3);
...
int count3 = inRange(scores, 99, 100);
```

I don't think so. What we really want is a way to store 100 integers, preferably so we can use an index to access each one. Hint: array.

The counting pattern is the same whether we use a single counter or an array of counters. In this case, we initialize the array outside the loop; then, inside the loop, we invoke `inRange` and store the result:

```
    int[] counts = new int[100];

    for (int i = 0; i < counts.length; i++) {
        counts[i] = inRange(scores, i, i+1);
    }
```

The only tricky thing here is that we are using the loop variable in two roles: as in index into the array, and as the parameter to `inRange`.

12.10 A single-pass solution

This code works, but it is not as efficient as it could be. Every time it invokes `inRange`, it traverses the entire array. As the number of ranges increases, that gets to be a lot of traversals.

It would be better to make a single pass through the array, and for each value, compute which range it falls in. Then we could increment the appropriate counter. In this example, that computation is trivial, because we can use the value itself as an index into the array of counters.

Here is code that traverses an array of scores once and generates a histogram.

```
int[] counts = new int[100];

for (int i = 0; i < scores.length; i++) {
    int index = scores[i];
    counts[index]++;
}
```

12.11 Glossary

array: A collection of values, where all the values have the same type, and each value is identified by an index.

element: One of the values in an array. The `[]` operator selects elements.

index: An integer variable or value used to indicate an element of an array.

deterministic: A program that does the same thing every time it is invoked.

pseudorandom: A sequence of numbers that appear to be random, but which are actually the product of a deterministic computation.

histogram: An array of integers where each integer counts the number of values that fall into a certain range.

12.12 Exercises

Exercise 12.1. Write a method called `cloneArray` that takes an array of integers as a parameter, creates a new array that is the same size, copies the elements from the first array into the new one, and then returns a reference to the new array.

Exercise 12.2. Write a method called `randomDouble` that takes two doubles, `low` and `high`, and that returns a random double x so that $low \leq x < high$.

Exercise 12.3. Write a method called `randomInt` that takes two arguments, `low` and `high`, and that returns a random integer between `low` and `high`, not including `high`.

Exercise 12.4. Encapsulate the code in Section 12.10 in a method called `makeHist` that takes an array of scores and returns a histogram of the values in the array.

Exercise 12.5. Write a method named `areFactors` that takes an integer `n` and an array of integers, and that returns `true` if the numbers in the array are all factors of `n` (which is to say that `n` is divisible by all of them). HINT: See Exercise 6.1.

Exercise 12.6. Write a method that takes an array of integers and an integer named `target` as arguments, and that returns the first index where `target` appears in the array, if it does, and -1 otherwise.

Exercise 12.7. Some programmers disagree with the general rule that variables and methods should be given meaningful names. Instead, they think variables and methods should be named after fruit.

For each of the following methods, write one sentence that describes abstractly what the method does. For each variable, identify the role it plays.

```java
public static int banana(int[] a) {
    int grape = 0;
    int i = 0;
    while (i < a.length) {
        grape = grape + a[i];
        i++;
    }
    return grape;
}

public static int apple(int[] a, int p) {
    int i = 0;
    int pear = 0;
    while (i < a.length) {
        if (a[i] == p) pear++;
        i++;
    }
    return pear;
}
```

```
public static int grapefruit(int[] a, int p) {
    for (int i = 0; i<a.length; i++) {
        if (a[i] == p) return i;
    }
    return -1;
}
```

The purpose of this exercise is to practice reading code and recognizing the computation patterns we have seen.

Exercise 12.8.

1. What is the output of the following program?
2. Draw a stack diagram that shows the state of the program just before `mus` returns.
3. Describe in a few words what `mus` does.

```
public static int[] make(int n) {
    int[] a = new int[n];

    for (int i = 0; i < n; i++) {
        a[i] = i+1;
    }
    return a;
}

public static void dub(int[] jub) {
    for (int i = 0; i < jub.length; i++) {
        jub[i] *= 2;
    }
}

public static int mus(int[] zoo) {
    int fus = 0;
    for (int i = 0; i < zoo.length; i++) {
        fus = fus + zoo[i];
    }
    return fus;
}
```

```
public static void main(String[] args) {
    int[] bob = make(5);
    dub(bob);

    System.out.println(mus(bob));
}
```

Exercise 12.9. Many of the patterns we have seen for traversing arrays can also be written recursively. It is not common to do so, but it is a useful exercise.

1. Write a method called `maxInRange` that takes an array of integers and a range of indices (`lowIndex` and `highIndex`), and that finds the maximum value in the array, considering only the elements between `lowIndex` and `highIndex`, including both ends.

   This method should be recursive. If the length of the range is 1, that is, if `lowIndex == highIndex`, we know immediately that the sole element in the range must be the maximum. So that's the base case.

   If there is more than one element in the range, we can break the array into two pieces, find the maximum in each of the pieces, and then find the maximum of the maxima.

2. Methods like `maxInRange` can be awkward to use. To find the largest element in an array, we have to provide a range that includes the entire array.

   ```
   double max = maxInRange(array, 0, a.length-1);
   ```

   Write a method called `max` that takes an array as a parameter and that uses `maxInRange` to find and return the largest value. Methods like `max` are sometimes called **wrapper methods** because they provide a layer of abstraction around an awkward method and make it easier to use. The method that actually performs the computation is called the **helper method**.

3. Write a recursive version of `find` using the wrapper-helper pattern. `find` should take an array of integers and a target integer. It should return the index of the first location where the target integer appears in the array, or -1 if it does not appear.

Exercise 12.10. One not-very-efficient way to sort the elements of an array is to find the largest element and swap it with the first element, then find the second-largest element and swap it with the second, and so on. This method is called a **selection sort** (see `http://en.wikipedia.org/wiki/Selection_sort`).

1. Write a method called `indexOfMaxInRange` that takes an array of integers, finds the largest element in the given range, and returns its *index*. You can modify your recursive version of `maxInRange` or you can write an iterative version from scratch.

2. Write a method called `swapElement` that takes an array of integers and two indices, and that swaps the elements at the given indices.

3. Write a method called `selectionSort` that takes an array of integers and that uses `indexOfMaxInRange` and `swapElement` to sort the array from largest to smallest.

Exercise 12.11. Write a method called `letterHist` that takes a String as a parameter and that returns a histogram of the letters in the String. The zeroeth element of the histogram should contain the number of a's in the String (upper and lower case); the 25th element should contain the number of z's. Your solution should only traverse the String once.

Exercise 12.12. A word is said to be a "doubloon" if every letter that appears in the word appears exactly twice. For example, the following are all the doubloons I found in my dictionary.

> Abba, Anna, appall, appearer, appeases, arraigning, beriberi, bilabial, boob, Caucasus, coco, Dada, deed, Emmett, Hannah, horseshoer, intestines, Isis, mama, Mimi, murmur, noon, Otto, papa, peep, reappear, redder, sees, Shanghaiings, Toto

Write a method called `isDoubloon` that returns `true` if the given word is a doubloon and `false` otherwise.

Exercise 12.13. Two words are anagrams if they contain the same letters (and the same number of each letter). For example, "stop" is an anagram of "pots" and "allen downey" is an anagram of "well annoyed."

Write a method that takes two Strings and returns `true` if the Strings are anagrams of each other.

Optional challenge: read the letters of the Strings only once.

Exercise 12.14. In Scrabble each player has a set of tiles with letters on them, and the object of the game is to use those letters to spell words. The scoring system is complicated, but longer words are usually worth more than shorter words.

Imagine you are given your set of tiles as a String, like `"quijibo"` and you are given another String to test, like `"jib"`. Write a method called `canSpell` that takes two Strings and returns `true` if the set of tiles can be used to spell the word. You might have more than one tile with the same letter, but you can only use each tile once.

Optional challenge: read the letters of the Strings only once.

Exercise 12.15. In real Scrabble, there are some blank tiles that can be used as wild cards; that is, a blank tile can be used to represent any letter.

Think of an algorithm for `canSpell` that deals with wild cards. Don't get bogged down in details of implementation like how to represent wild cards. Just describe the algorithm, using English, pseudocode, or Java.