Arrays

We will now explore different ways to organize and access data. Let’s begin with arrays. An array is a collection of variables of the same type. An array of integers named x is declared as follows:

```java
int[] x;
```

The set of square brackets identifies x as an integer array, as opposed to a simple integer variable. However, this statement does not set aside space for the array. Space is allocated as follows:

```java
x = new int[6];
```

The two statements above are often combined:

```java
int[] x = new int[6];
```

The reserved word "new" is familiar territory, as it precedes calls to constructor methods. The number "6" above is the number of elements in the array. The effect of the statement is to declare x as an integer array containing six elements. Each element is automatically initialized with the value 0. To place a different value in an element of the array, a statement such as the following may be used:

```java
x[0] = 500;
```

This statement places the integer value 500 in the 0th element of the array. The number "0", above, is an array index, also called an array subscript.

With this introduction, let’s proceed to an example. The program DemoArray uses an array to store and output the squares of integers from 0 to 5 (see Figure 1).

```java
public class DemoArray {
    public static void main(String[] args) {
        int[] numbers = new int[6];
        numbers[0] = 0;
        numbers[1] = 1;
        numbers[2] = 4;
        numbers[3] = 9;
        numbers[4] = 16;
        numbers[5] = 25;
        for (int i = 0; i < 6; i++)
            System.out.println(i + " " + numbers[i]);
    }
}
```

Figure 1. DemoArray.java

This program generates the following output:
A six-element integer array named `numbers` is declared in line 5. Lines 6 through 11 initialize `numbers` with the squares of integers 0 through 5. Lines 12-13 output the contents of the array to the standard output. The loop control variable, `i`, is used within the `for` loop as an index into the array to retrieve elements in the array.

The memory assignments for `numbers` at two critical places in the program are shown in Figure 2. Just after line 5, each element in the array contains 0 as a default value, as shown in Figure 2a. Over the next six lines, each element is re-assigned a new value. The final state of the array, just after line 11, is shown in Figure 2b.

![Memory assignments in DemoArray](image)

Figure 2. Memory assignments in DemoArray (a) after line 5 (b) after line 11

The figure shows the array elements in boxes and the array indices to the left of the boxes.

One of the most common errors in working with arrays is attempting to access a non-existing element. For example, let's assume the following line is added just after line 11 in DemoArray:

```java
numbers[6] = 36;
```

The modified program will compile without errors. However, when it is executed, a run-time error occurs and the following message appears at the standard error stream (the host system's CRT display):

```
Exception in thread "main" java.lang.ArrayIndexOutOfBoundsException
at DemoArray.main(Compiled Code)
```

Ouch! The critical term above is "ArrayIndexOutOfBoundsException". An attempt was made to assign a value to an array element that did not exist. The array `numbers` contains six elements, but the indices range from 0 to 5. The index 6 is out of bounds.

**The length Field**

Knowing the length of an array is so critical that a public data field is available for any array. The name of the field is `length`. The length of the `numbers` array in DemoArray, for example, is
numbers.length

It equals 6 because the numbers array has 6 elements. An excellent use of length is in setting up a for loop. Line 12 in DemoArray could be replaced with

```java
for (int i = 0; i < numbers.length; i++)
```

Instead of explicitly entering the constant "6", the length is specified using the length field of the array. This is much safer, since changes to the size of the array in the source program are automatically accommodated when the program is re-compiled and executed. Note that the for loop does not execute for \(i = 6\). The expression \(i < numbers.length\) ensures that the loop only executes up to \(i = 5\).

Here's an important caution. Don't confuse length — the length of an array — with the length() method of the String class. They perform similar operations, but they work with different entities in the language. For example, if line 12 in DemoArray is replaced with

```java
for (int i = 0; i < numbers.length(); i++)  // Wrong!
```
you will be greeted by the following message when the program is compiled:

```
DemoArray.java:24: Method length() not found in class java.lang.Object.
    for (int i = 0; i < numbers.length(); i++)  // Wrong!
^ 1 error
```

This is very definitely a syntax error, as the length() method of the String class cannot be used with an array object. The error is caught by the compiler.

**Initialization Lists**

It is possible to initialize array elements without the step-by-step series of assignments in DemoArray. Instead, an initialization list can be used. For example, lines 5-11 in DemoArray could be replaced with the following single statement:

```java
int[] numbers = { 0, 1, 4, 9, 16, 25 };
```

The effect is to declare numbers as an integer array and initialize it with the values enclosed in braces. Note that a comma follows each value except the last and that the closing brace is followed by a semicolon.

In previous demo programs, we used both variables and constants. Variables change as a program executes, constants do not. When an initialization list is used, it is often the case that the array holds constants. Strictly speaking, such arrays should be declared "final" as with other variable constants, thus ensuring elements are not inadvertently changed during program execution. Let's illustrate this with a simple demo program using an initialization list. The program CubeIt prompts the user for an integer from 1 to 10 and then outputs the cube of the integer (see Figure 3).
Arrays of Other Data Types

Thus far, we have discussed only integer arrays. Of course, arrays are a legitimate data structure for any of Java’s eight primitive data types, as well as for objects. (We will discuss arrays of objects shortly.) All issues discussed above for the int data type apply in the same manner for
the char, byte, short, long, float, double, and boolean data types. The only difference is in the default values in the event an array is declared but not initialized. For integer or floating point arrays (byte, short, int, long, float, and double), the array elements are initialized with zero. For boolean arrays and for char arrays, the array elements are initialized with false and with null characters, respectively.

An example of a character array follows:

```java
char[] greeting = { 'h', 'e', 'l', 'l', 'o' };
```

A boolean array might be useful, for example, to hold the status of spaces on a game board. The Tic Tac Toe game has nine spaces that are empty when a game begins. As a game progresses, the spaces are gradually filled with X's or O's. An array holding the status of the spaces could be declared as follows:

```java
boolean[] spaceOccupied = new boolean[9];
```

All nine elements of the array `spaceOccupied` are initialized by default with `false`. As the game progresses, elements can be assigned `true` as spaces are selected.

**Arrays of Objects**

Java supports arrays of objects in a manner consistent with that for primitive data types. If a class existed for `Widget` objects, then an array named `fasteners` holding 100 such objects could be declared as follows:

```java
Widget[] fasteners = new Widget[100];
```

In the preceding section, we identified the default values for array elements when an array is declared but is not explicitly initialized. When the declaration is for an array of objects, the default value is a null reference. So the statement above allocates memory for 100 references to `Widget` objects and each reference is initialized with `null`.

Let's recast the above in terms of the objects most familiar to us: strings. The following declares an array of `String` objects named `sea` of size 4:

```java
String[] sea = new String[4];
```

This array initially contains four null references. We can initialize the array as follows:

```java
sea[0] = "Mediterranean";
sea[1] = "Black";
sea[2] = "North";
sea[3] = "Red";
```

Or, the five preceding statements can be combined using an initialization list:

```java
String[] sea = { "Mediterranean", "Black", "North", "Red" };
```

The memory assignments after the above statement executes are shown in Figure 4. Strictly speaking, the array `sea` holds an array of references, not objects. (The objects are somewhere else.) Nevertheless, it is customary to refer to such an array as "an array of objects", with the understanding that the memory assignments are as shown in Figure 4.
The elements of the array could be printed as follows:

```java
for (int i = 0; i < sea.length; i++)
    System.out.println(sea[i]);
```

Here is a reminder of the difference between `length` and `length()`. Note that `sea.length` is the length of the array (in this case, 4), whereas `sea[3].length()` is the length of the 4th string in the array (in this case, 3). Either of the alternate expressions `sea.length()` or `sea[3].length()` is invalid and will cause a compile error.

Let's put these ideas to work in a demo program. The program `DemoStringArray` counts and outputs some of Java's reserved words (see Figure 5).

```java
public class DemoStringArray {
    private static final String[] RESERVED_WORDS = {
        "abstract", "boolean", "break", "byte", "byvalue", "case",
        "cast", "catch", "char", "class", "const", "continue",
        "default", "do", "double", "else", "extends", "false",
        "final", "finally", "float", "for", "future", "generic",
        "goto", "if", "implements", "import", "inner", "instanceof",
        "int", "interface", "long", "native", "new", "null",
        "operator", "outer", "package", "private", "protected",
        "public", "rest", "return", "short", "static", "super",
        "switch", "synchronized", "this", "throw", "throws",
        "transient", "true", "try", "var", "void", "volatile", "while"
    };

    public static void main(String[] args) {
        int n = RESERVED_WORDS.length;
        System.out.println("Java has "+ n + " reserved words");
        System.out.println("The reserved words beginning with 's' are");
        for (int i = 0; i < n; i++)
            if (RESERVED_WORDS[i].charAt(0) == 's')
                System.out.println(RESERVE...
Java has 59 reserved words
The reserved words beginning with 's' are
short
static
super
switch
synchronized

Since Java's list of reserved words is fixed, the array RESERVED_WORDS is declared as
"final" outside the main() method. Within the main() method, the first statement retrieves
the length of the array and assigns it to the int variable n (see line 18). In line 19, the number of
reserved words is printed. (Java has 59 reserved words.) Then we proceed to print the reserved
words (lines 21-23); however, we only print words beginning with 's'. The if statement in line
22 uses the following expression:

RESERVED_WORDS[i].charAt(0) == 's'

This is a relational expression that yields true or false. If it is true, the word at index i in
the array is printed, otherwise we proceed to check the next word. Since RESERVED_WORDS is
a array of String objects, the term RESERVED_WORDS[i] can be used anywhere a String
variable can be used — such as preceding a String method using dot notation. The method
charAt() is an instance method of the String class. With 0 as an argument, it returns the
character at index 0 in the string. In this case, it returns the first character in the current word.
Connecting this to the constant 's' with a test for equality (==) achieves the desired effect of
determining if the current word in the array begins with the letter 's'. If so, it is printed.

Arrays of Button and AudioClip Objects
Lest we get too comfortable working mostly with String objects, let's explore arrays of other
objects. The demo program DemoSound is an applet that plays a sound when an on-screen
button was selected with a mouse click. Let's extend this idea with an applet that displays ten
buttons and plays a different sound for each button. The applet DemoSoundArray includes an
array of ten Button objects and ten AudioClip objects (see Figure 6).
```java
import java.awt.*;
import java.awt.event.*;
import java.applet.*;

public class DemoSoundArray extends Applet implements ActionListener
{
    private static final int MAX = 10;
    private AudioClip[] tone = new AudioClip[MAX];
    private Button[] beep = new Button[MAX];

    public void init()
    {
        for (int i = 0; i < MAX; i++)
        {
            String soundFile = "sounds\\" + i + ".au";
            tone[i] = getAudioClip(getDocumentBase(), soundFile);
            beep[i] = new Button("Beep " + i);
            beep[i].addActionListener(this);
            add(beep[i]);
        }
    }

    public void actionPerformed(ActionEvent ae)
    {
        for (int i = 0; i < MAX; i++)
        {
            if (ae.getSource() == beep[i])
                tone[i].play();
        }
    }
}
```

Figure 6. DemoSoundArray.java

When this applet executes (using appletviewer or a web browser), the arrangement of buttons shown in Figure 7 appears in the applet window.

![Applet Viewer](image)

Figure 7. Graphic window from DemoSoundArray applet

When a button is selected with a mouse click, a beep is heard.

Once again, we must defer a detailed discussion of some aspects of this program to later chapters. (The implementation of action listeners is presented later.) We are mainly concerned with this applet's use of arrays of objects. Two arrays are declared. In line 9 an array of AudioClip
objects named tone is declared, and in line 10 an array of Button objects named beep is declared. The arrays are initialized in lines 16-17.

The `getAudioClip()` method of the Applet class gets an audio clip and returns a reference to it. The reference is stored in the tone array. Two arguments are required and together they identify the location of the audio clip. The first argument is a URL (Uniform Resource Locator) specifying the location of the document in which the applet is embedded. This is provided by the `getDocumentBase()` method of the Applet class. It provides a URL, or a path, to the applet on the host system. The second argument is a string representing the name and location of the audio clip, relative to the URL. In the example, the string is initialized in the preceding line with the expression

```
"sounds\\" + i + ".au"
```

The first time through the loop, i equals 0, so the expression equals sounds\0.au. The ten audio clips are stored in files named 0.au, 1.au, etc. up to 9.au in a subdirectory named sounds. (Note that \\" is the escape sequence representing the backslash character.)

The Button array is initialized using the `Button()` constructor. The argument is the button's label represented as a string. As with the audio clip filenames, the button labels are created on the fly using string concatenation. The effect is readily seen in the button labels in Figure 7.

The link between mouse clicks and buttons is established in line 18 by adding an action listener for each button. The buttons are added to the applet window in line 19. At this point, everything is setup and ready to go. Note that the `actionPerformed()` method is not explicitly called in the `init()` method. It is called automatically when a mouse click occurs in a button while the applet is running. Lines 25-27 scan through the beep array to determine which button the click is associated with. When a match is found, the tone for that button is played (line 27).

**Command Line Arguments**

Although this chapter marks our formal introduction to arrays, every Java application seen thus far included an array specification. It appeared in the `main()` method signature:

```
public static void main(String[] args)
```

The specification of arguments passed to `main()` appears within parentheses. Although we have already seen numerous examples of method arguments, this is our first example of an array argument. The signature above identifies args as an array of String objects. The String objects contained in args represent the command-line arguments entered when the Java program was launched. This is a very simple but powerful feature. Let's see how it works. The program DemoCommandLineArgs prints out a count of its command-line arguments as well as the individual arguments (see Figure 8).

---

1 In fact, AudioClip is an interface (not a class), but for this discussion it can be thought of as a class. An interface is a collection of constants and abstract methods. The methods of the AudioClip interface (e.g., play()) are implemented in the Applet class.
public class DemoCommandLineArgs
{
    public static void main(String[] args)
    {
        System.out.println(args.length + " command-line argument(s)");
        for (int i = 0; i < args.length; i++)
            System.out.println(args[i]);
    }
}

Figure 8. DemoCommandLineArgs.java

A sample dialogue with this program follows:

PROMPT> java DemoCommandLineArgs Have a nice day!
4 command-line argument(s)
Have
a
nice
day!

Four arguments were entered, as shown above. Note that the command itself is not considered a command-line argument. The number of command-line arguments is retrieved within the program using args.length. This value is printed in line 5. It is also used in line 6 to setup the for loop that prints the arguments on separate lines. The arguments are retrieved and printed in line 7 as expected: args[0] is the first command-line argument, args[1] is the second command-line argument, and so on.

Space and tab characters ('\t') serve as delimiters for the arguments. The arguments can contain any combination of letters, digits, or punctuation characters, with the exception of a double quote. Multiple words are treated as one argument if they are enclosed in double quotes:

PROMPT> java DemoCommandLineArgs Canada "United States"
2 command-line argument(s)
Canada
United States

The examples above show how command-line arguments work. However, they don't shed light on how command-line arguments can contribute to a Java program. In fact, command-line arguments are an extremely useful mechanism to get extra information into a program without coding it in the source file. The extra information usually modifies the default operation of the program in some manner. For example, at the DOS prompt the following command

dir /os

displays a directory listing sorted by increasing file size. The string "/os" is a command-line argument. Within the dir program, this argument, if present, is used to control the format of the directory listing. (For a listing of all options for the dir command, enter dir /?.)

Some programs may "require" extra information. For example, the DOS type command outputs the content of a file to the standard output. If the command is invoked without specifying a file (i.e., the number of arguments is zero), the message "Required parameter missing" is printed.
Let's demonstrate the use of command-line arguments to control a program's behaviour. The program FindString reads text from the standard input and echoes tokens to the standard output — but only if they contain a string specified in the command line (see Figure 9).

```java
import java.io.*;
import java.util.*;

public class FindString {
    public static void main(String[] args) throws IOException {
        // precisely one command-line argument required
        if (args.length != 1) {
            System.out.println("usage: java FindString \"string\" ");
            return;
        }

        // prepare keyboard for input
        BufferedReader stdin =
            new BufferedReader(new InputStreamReader(System.in), 1);

        // process lines until 'null' (no more input)
        String line;
        while ((line = stdin.readLine()) != null) {
            // prepare to tokenize line
            StringTokenizer st = new StringTokenizer(line);

            // process tokens in line
            while (st.hasMoreTokens()) {
                String s = st.nextToken();
                if (s.indexOf(args[0]) >= 0)
                    System.out.println(s);
            }
        }
    }
}
```

Figure 9. FindString.java

A sample dialogue with this program follows: (Input is read from a test file named testdata.txt.)

```
PROMPT> java FindString "te" < testdata.txt
Microsystems,
redistribute
intended
maintenance
redistribute
```

Only five words in the test data file contain the string "te". The program follows the same general framework as EchoAlphaWords in Chapter 4. Lines 9-13 ensure that precisely one command-line argument was entered. If args.length does not equal 1, the program is terminated early with the following message:
usage: java FindString "string"

Note that input is read from the standard input; so, a reference to the input redirection syntax is not warranted in the usage message. The double quotes are removed from the string stored in the array passed on to the main() method.

Line 30 contains the critical step. The indexOf() method in the String class returns an integer representing the position of a substring in a string. The substring is the command-line argument args[0], and the string is a token in the input stream. If the substring is not in the string, -1 is returned. Any return value equal or greater than zero means the substring was found. If so, the string is printed.

As another example of command-line arguments, the program RandomGen outputs a series of random floating-point numbers based on three arguments provided on the command line. The arguments specify the number of random numbers to generate and the minimum and maximum of the range for the numbers (see Figure 10).

```java
public class RandomGen {
    public static void main(String[] args) {
        // exactly three arguments required
        if (args.length != 3) {
            System.out.println("Usage: java RandomGen n min max");
            return;
        }

        // convert command-line arguments
        int n = Integer.parseInt(args[0]);
        double min = Double.parseDouble(args[1]);
        double max = Double.parseDouble(args[2]);

        // generate the random numbers
        for (int i = 0; i < n; i++) {
            double r = Math.random() * (max - min) + min;
            System.out.println(r);
        }
    }
}
```

Figure 10. RandomGen.java

As sample dialogue with this program follows:
We'll use RandomGen later to generate test data for other programs. For the moment, let's just examine how command-line arguments are used to control the program's behaviour. In the sample dialogue, three arguments appear: 10 (the number of random floating-point numbers to generate) and 5.5 and 7.0 (the range for the numbers). The output clearly shows ten numbers lying in this range.

The program requires exactly three command-line arguments. If args.length is not three, the program terminates early with a usage message. The three arguments are converted, as appropriate, in lines 13-15 and assigned to the variables n, min, and max respectively. The numbers are generated in a for loop that executes n times. Within the loop a random double is generated in line 20 using the expression

$$\text{Math.random()} \ast (\text{max} - \text{min}) + \text{min}$$

Since the random() method generates a random double in the range 0.0 to 1.0, multiplying by max - min and then adding min effectively scales the result into the desired range. The number is printed in line 21.

Finally, let's combine command-line arguments with our discussion of file streams in Chapter 4. The program JavaType mimics the DOS TYPE command (see Figure 11).
Figure 11. JavaType.java

This program requires one command-line argument specifying the name of a file to "type" to the standard output. If the number of command-line arguments is less than one, the message "Required parameter missing" is output (lines 7-11). If the number of command-line arguments is greater than one, the message "Too many parameters" is output (lines 12-16). If precisely one argument was entered, yet no corresponding file exists, the message "File not found - filename" is output, where filename is the command-line argument (lines 18-23). If we get past these three checks, we're in the clear. The file is opened as a BufferedReader object named inputFile in lines 26-27, its contents are read and sent to the standard output in lines 30-32, then the file is closed in line 35.

Working With Arrays

The term "number crunching" is computer-talk for the sorts of operations we do on large volumes of data. The data are usually stored in disk files and are read into a program for "crunching" — for analysis in various ways. Let's see how arrays are used for typical number crunching operations. The program NumberStats reads data into an array, then calculates some summary statistics on the data (see Figure 12).
import java.io.*;
import java.util.*;

public class NumberStats
{
    private static final int MAX = 100; // maximum number of numbers
    public static void main(String[] args) throws IOException
    {
        BufferedReader stdin =
            new BufferedReader(new InputStreamReader(System.in), 1);
        double[] numbers = new double[MAX];
        int size = 0;

        // input data and put into array
        String line;
        while ((line = stdin.readLine()) != null)
        {
            // prepare to tokenize line
            StringTokenizer st = new StringTokenizer(line, " , 	");

            // process tokens in line
            while (st.hasMoreTokens())
            {
                String s = st.nextToken();
                numbers[size] = Double.parseDouble(s);
                size++;
            }
        }

        // output some statistics on the data
        System.out.println("N = " + size);
        System.out.println("Minimum = " + min(numbers, size));
        System.out.println("Maximum = " + max(numbers, size));
        System.out.println("Mean = " + mean(numbers, size));
        System.out.println("Standard deviation = " + sd(numbers, size));
    }

    // find the minimum value in an array
    public static double min(double[] n, int length)
    {
        double min = n[0];
        for (int j = 1; j < length; j++)
        {
            if (n[j] < min)
            {
                min = n[j];
            }
        }
        return min;
    }

    // find the maximum value in an array
    public static double max(double[] n, int length)
    {
        double max = n[0];
        for (int j = 1; j < length; j++)
        {
            if (n[j] > max)
            {
                max = n[j];
            }
        }
        return max;
    }

    // calculate the mean of the values in an array
    public static double mean(double n[], int length)
    {
63     double mean = 0.0;
64     for (int j = 0; j < length; j++)
65         mean += n[j];
66     return mean / length;
67 
68     // calculate the standard deviation of values in an array
69     public static double sd(double[] n, int length)
70     {
71         double m = mean(n, length);
72         double t = 0.0;
73         for (int j = 0; j < length; j++)
74             t += (m - n[j]) * (m - n[j]);
75         return Math.sqrt(t / (length - 1.0));
76     }
77 
78 
79 

Figure 12. NumberStats.java

Although the program works fine with keyboard entry, let's show it in action with data read from a file. For this, a sample file was created with stock market trading data for the euro — the currency in Europe introduced at the beginning of 1999. Each entry is the euro's value in US dollars, with a sample recorded every hour for 24 hours, beginning 6:00 p.m. Eastern Standard Time on January 3, 1999, just after the euro's introduction. The content of the file is shown in Figure 13.

1.175, 1.176, 1.179, 1.182, 1.188, 1.185, 1.187, 1.188,
1.186, 1.184, 1.180, 1.180, 1.179, 1.180, 1.178, 1.180,
1.180, 1.180, 1.181, 1.182, 1.182, 1.183, 1.183

Figure 13. Content of euro.dat sample data file (source: Globe and Mail)

Although we could easily design NumberStats to read data from a file specified on the command, the program is setup to read from the standard input. The following is a sample dialog of the program inputting data from euro.dat using input redirection:

PROMPT> java NumberStats < euro.dat
N = 24
Minimum = 1.175
Maximum = 1.188
Mean = 1.1816666666666664
Standard deviation = 0.0034220089023169176

During the 24 hour period observed, the euro's value in US dollars ranged from $1.175 to $1.188, with a mean of $1.182 and a standard deviation of $0.003422 (n = 24).

The program includes four methods in addition to main():

- min()      find the minimum value in an array (lines 41-48)
- max()      find the maximum value in an array (lines 51-58)
- mean()     calculate the mean of the values in an array (lines 61-67)
- sd()       calculate the standard deviation of the values in an array (lines 70-77)

The min() and max() methods are straight forward. The mean() and sd() methods are based on formulas found in any statistics book:
\[
\text{mean} = \bar{X} = \frac{\sum x_i}{n} \quad \text{and} \quad sd = \sqrt{\frac{\sum (X - x_i)^2}{n - 1}}
\]

So, the mean is calculated by summing all the array elements, then dividing by the number of elements. The standard deviation is calculated by subtracting each element from the mean, squaring the result, repeating this for each element in the array, summing the results over all elements in the array, dividing the result by "one less than" the number elements, and then taking the positive square root of the result. Now, if you re-read the preceding sentence, it might actually make sense to you. But, perhaps you should just compare the formula above and with lines 70-77 in NumberStats. With our understanding of loops, methods, and arrays, it is apparent that the \text{sd()} method calculates the standard deviation of elements in an array.

In the \text{main()} method we see how the statistics methods are put to use. The data for this program originate external to the program, and the number of items of data to be processed is not known. This creates a problem. Once an array is declared in Java, its size is fixed. Individual elements can change, but the size cannot. For this reason, a Java array is called a \text{static data structure.} (The term "static", in this sense, has no connection the formal use of the same term in the Java language.) \text{Dynamic data structures} are supported through the \text{Vector} class, and we'll see examples of these shortly.

To get around the "fixed-size" problem, an approach is taken in NumberStats that is not particularly elegant. But it works. A final constant named \text{MAX} is defined in line 6 and set to 100. This program can process up to 100 data items. To process more data, we must change the source code and recompile. A \text{double} array named \text{numbers} is declared in line 13. Its size is 100 elements. So, the expression \text{numbers.length} is an integer equal to 100. This isn't much use in this program, because we aren't reading 100 numbers. We have no option but to declare and maintain a local variable that represents the "actual" number of elements placed in the array. The variable \text{size} serves this purpose. It is declared and initialized to zero in line 14. As data are read, \text{size} is incremented (line 28). Anywhere the "length" of the array is required for subsequent operations, it is imperative that \text{size} is used, not \text{numbers.length}. In fact, all the statistical methods were defined to receive an integer length as an argument. This is cumbersome, but we really have no option. If the methods used the ".length" field of the array argument, the results would be wrong because portions of the array never initialized would be included in the statistics.

The data in \text{euro.dat} are formatted in three lines with eight values per line. The values are followed by a comma and a space character, and by a newline at the end of each line. This format is convenient, but it is not "required". If the data were organized one item per line, or in six lines of four, they could just as easily be read by NumberStats. This added flexibility is supported by combining string tokenization with \text{readLine()}. Of course, we have used the \text{StringTokenizer} class before, but this is our first example of reading numeric data. Note that the \text{StringTokenizer} constructor receives two arguments. (In our previous examples, only one argument was used — the string to be tokenized.) The second argument is a delimiter string to replace the default delimiter string. We've added the comma (,) as a possible delimiter for the tokens. The other allowable delimiters are spaces and tabs. Note that the newline character is also a delimiter, but it is effectively handled (i.e., removed) by \text{readLine()}.  

The process of reading a token, converting it to a double, and placing it in the array (lines 26-27) is straightforward. Once the array is filled with data, we just sit back and watch the statistics methods do their job. Lines 33-37 call the methods in turn and print the results.
Graphing Data in an Applet

If you believe a picture is worth a thousand words, then you'll like the next example. The program GraphData embeds the data from euro.dat in an applet and graphs the progress of the euro's stock market trading value (see Figure 14).
import java.awt.*;
import java.applet.*;

public class GraphData extends Applet {
    private static final double[] EURO = {
        1.175, 1.176, 1.179, 1.182, 1.188, 1.185, 1.187, 1.188,
        1.186, 1.184, 1.180, 1.179, 1.180, 1.178, 1.180,
        1.180, 1.180, 1.182, 1.181, 1.182, 1.182, 1.183, 1.183
    };
    private static final int XSIZE = 500;
    private static final int YSIZE = 250;
    private static final int GAP = 50;
    private static final int WIDTH = XSIZE - 2 * GAP;
    private static final int HEIGHT = YSIZE - 2 * GAP;

    public void paint(Graphics g) {
        // draw rectangle around graphics window
        g.drawRect(0, 0, XSIZE - 1, YSIZE - 1);

        // set new origin to bottom-left of graph
        g.translate(GAP, GAP + HEIGHT);

        // draw axes
        g.drawLine(0, 0, WIDTH, 0);    // x axis
        g.drawLine(0, 0, 0, -HEIGHT);  // y axis

        // find minimum and maximum values in array
        double yMin = min(EURO, EURO.length);
        double yMax = max(EURO, EURO.length);

        // label graph
        g.setFont(new Font("Helvetica", Font.PLAIN, 14));
        g.drawString("Euro value (US$) over 24 hr. Jan 3-4, 1999", 75, 16);

        // label y axis with minimum and maximum values
        g.setFont(new Font("Helvetica", Font.PLAIN, 12));
        g.drawString("" + yMax, -34, -HEIGHT + 8);
        g.drawString("" + yMin, -34, 0);

        // find first point of first line to draw
        int x2 = 0;
        int y2 = -(int)((EURO[0] - yMin) / (yMax - yMin) * HEIGHT);

        // draw graph (a series of connected lines)
        for (int i = 1; i < EURO.length; i++) {
            int x1 = x2;
            int y1 = y2;
            x2 = (int)((i / (EURO.length - 1.0)) * WIDTH);
            y2 = -(int)((EURO[i] - yMin) / (yMax - yMin) * HEIGHT);
            g.drawLine(x1, y1, x2, y2);
        }

        // find the minimum value in a array
        public static double min(double[] n, int length) {
            double min = n[0];
            for (int j = 1; j < length; j++)
                if (n[j] < min)
                    min = n[j];
            return min;
        }
    }
}

// find the minimum value in a array
public static double min(double[] n, int length) {
    double min = n[0];
    for (int j = 1; j < length; j++)
        if (n[j] < min)
            min = n[j];
    return min;
}
When the applet is run, the graph in Figure 15 appears.

As noted in earlier, applets are distinctly different from Java applications. Applets are small programs embedded in web pages. They are executed through an html document from a browser or using appletviewer. There is no "standard input", per se. To get around this, the data in euro.dat are embedded in the source code in GraphData (see lines 6-10).

Our most important task is "planning". It is one thing to draw a series of connected lines, it is quite another to organize and plan how the graph is laid out — keeping in mind the need to change the data, or to re-size the graph. For this purpose, three defined constants are critical: XSIZE, YSIZE, and GAP (see lines 11-13). XSIZE and YSIZE are the dimensions of the graphics window, and GAP is the space allocated around the inner edge of the window. From these, the additional constants WIDTH and HEIGHT are defined (lines 14-15) to set the dimensions of the graph. The role of these constants is depicted in Figure 16.
The area marked-off by the dotted line in Figure 16 is where the graph is placed. To keep it simple, the gap is the same around all four sides of the graph, thus positioning the graph in the centre of the graphics window.

Before proceeding, we must understand the coordinate system in Java's graphics windows. By default, the origin is point (0, 0) at the top-left corner of the window, as shown in Figure 16. The units are pixels, so all coordinates must be integers. Positive $x$ values are to the right of the origin, and positive $y$ values are below the origin. This is fine for $x$, but it's not quite what we want for $y$. It is customary to plot data with positive $y$ values "above" the origin. Simple "negation" of $y$ values will adjust for this. As well, we'd like to work with "our origin", not the graphics window's origin. Once again, there is a simple fix. The translate() method in the Graphics class allows us to change the origin. Our preferred origin is labeled "New origin" in Figure 16.

Let's walk through the tasks in plotting the euro's trading value. First, a box is drawn around the graphics window (line 20) using the default coordinates. The arguments to the drawRect() method are rectangle's $x$ coordinate, $y$ coordinate, width, and height, respectively. Then, a new origin is set that is well-suited to the chosen layout (line 23). The arguments to the translate() method are the $x$ and $y$ coordinate of the new origin. Subsequent drawing operations are relative to this point. The axes are drawn in lines 26-27. The drawLine() method of the Graphics class requires four arguments: the $x$-$y$ coordinate of the beginning of the line and the $x$-$y$ coordinate at the end of the line, respectively. Note that the coordinates are simple and intuitive, given the new origin.

Then, the axes are labeled (lines 34-40). The $y$ axis shows only the minimum and maximum values, and these are obtained in lines 30-31 using the min() and max() methods from the NumberStats program presented earlier (see Figure 14).

The data are plotted in a for loop that draws a series of lines. Each line begins where the previous line finishes. This explains why $x1$ and $y1$ are assigned $x2$ and $y2$, respectively, in
each new iteration (lines 49-50). With \( n \) points, it is only necessary to draw \( n - 1 \) lines; so, the loop control variable, \( i \), is initialized at 1 (instead of 0). The coordinates of the first point of the first line are established before the loop begins (lines 43-44).

Although we have a new origin that suits our layout, the raw data must be transformed into \( x \)-\( y \) pixel coordinates. The \( x \) coordinate is implicit: Each point is the value of the euro “one hour after” the previous value. The \( y \) coordinate is the US dollar value of the euro at that point in time. So, in our graph the \( x \) axis is “time” and the \( y \) axis is “US dollars”. The \( x \) coordinate of the first point in the first line is 0 (line 43). Subsequent \( x \) coordinates are computed in line 51 using the expression

\[
\text{(int)}\left(\frac{i}{\text{EURO.length} - 1.0}\right) \times \text{WIDTH}
\]

This expression uses the loop control variable, \( i \), to set each new \( x \) coordinate. By dividing \( i \) by \( \text{EURO.length} - 1.0 \) and multiplying by \( \text{WIDTH} \), the \( x \) coordinates are evenly spaced along the \( x \) axis, given the width of the graph and the number of points plotted.

Transforming the \( y \) coordinates is tricky. For this, we need the statistics \( y_{\text{Min}} \) and \( y_{\text{Max}} \), calculated earlier (lines 30-31). The \( y \) coordinates are computed in line 52 using the following expression:

\[
-(\text{int})\left(\frac{\text{EURO}[i] - y_{\text{Min}}}{y_{\text{Max}} - y_{\text{Min}}} \times \text{HEIGHT}\right)
\]

The effect is to transform euro dollar values such that when \( \text{EURO}[i] = y_{\text{Min}} \), the result is 0, and when \( \text{EURO}[i] = y_{\text{Max}} \) the result is \(-\text{HEIGHT}\). All other values are evenly distributed between these limits. The \( y \) coordinate of the first point in the first line is calculated in line 44 using the same expression, except with \( i \) equal to 0. The unary negation operator (\(-\)) precedes the expression to ensure that positive values are “above” the origin, for reasons noted earlier.

Note in lines 43-54 in \texttt{GraphData} that numeric literals are not used (except 0 and 1). There is a great "pay off" in the planning invested in working with pre-defined constants. The \texttt{GraphData} applet can be re-sized easily by changing \( \text{XSIZE} \) and \( \text{YSIZE} \), and the amount of space around the graph is configurable by altering \( \text{GAP} \). Furthermore, new data can be substituted for the \texttt{EURO} array. The new data can have any range and there can be any number of points. The "planning" in \texttt{GraphData} is sufficiently flexible that all the pieces fall into place when the program is re-compiled. Of course, there are limits. With \( \text{XSIZE} = 250 \) and \( \text{GAP} = 50 \), we're left with 150 pixels along the \( x \) axis for the graph. Clearly, we cannot use \texttt{GraphData} in its present form to plot an array containing one thousand elements. More sophisticated techniques must be devised.

The other main deficiency in \texttt{GraphData} is in the text labels. As seen in lines 34-40, numeric literals are used to "nudge" the text to reasonable positions relative to the axes. Although the effect is pleasing, this approach is bad news if the graph is re-sized or if new text is substituted. Unfortunately, fonts do not scale easily and it is difficult to determine the "pixel" length of a text string; so, a more flexible approach is not possible, given the tools at hand. In the program's present form, changes in the labels require brute-force tuning using a trial and error approach.

**Multi-Dimensional Arrays**

Multi-dimensional arrays are a useful and powerful extension to simple one-dimensional arrays. In essence, a multi-dimensional array is an "array of arrays". We noted earlier that a \texttt{boolean} array could store the status of spaces on a game board. For example, the status of the nine spaces in a Tic Tac Toe game could be represented as
boolean[] spaceOccupied = new boolean[9];

Since a game board is a two-dimensional space, it may be better to use a data structure that more-closely matches the layout of the board. A two-dimensional array seems particularly applicable in this case:

boolean[][] spaceOccupied = new boolean[3][3];

A row is identified as an index in the first set of brackets, and a column by as an index in the second set. With the declaration above, the array is initialized with false for each element. If the first move of the game were to select and 'X' in the middle of the game board, the array is updated as follows:

spaceOccupied[1][1] = true;

This may be followed by selecting an 'O' in the bottom-right corner:

spaceOccupied[2][2] = true;

Figure 17 illustrates the state of the status array and of the game after these two moves.

![Figure 17](image)

Figure 17. A two-dimensional boolean array for the status of a Tic Tac Toe game. Status after two moves for (a) array (b) game

The spaceOccupied array could assist in determining if a space selected by the user — identified by its row and column indices — is available:

```java
if (spaceOccupied[row][col])
    System.out.println("Sorry, try again!");
```

Of course, multi-dimensional arrays are legitimate data structures for any of Java's primitive data types as well as for objects. As with one-dimensional arrays, an initialization list may be used if the values are known in advance. The syntax is a reasonable extension of that noted earlier for one-dimensional arrays:

```java
int[][] abc = {
    { 1, 2, 3 },
    { 4, 5, 6 },
    { 7, 8, 9 },
    { 10, 11, 12 },
};
```

The array `abc` above is a two-dimensional array with four rows and three columns. Indices may vary from 0 to 3 for the rows and from 0 to 2 for the columns. So, `abc[3][2]` equals 12, but `abc[2][3]` generates an "index out of bounds" exception. The expression `abc.length` equals 4 (the number of rows in the array), whereas the expression `abc[3].length` equals 3 (the number of elements in the last row).
Multi-dimensional arrays needn't be rectangular. The following array declaration is permissible:

```java
int[][] triangle = {
    { 1 },
    { 2, 3 },
    { 4, 5, 6 },
    { 7, 8, 9, 10 },
};
```

The expression `test[n].length` equals the length of the `n`th row; and so, varies from 1 to 4 as `n` varies from 0 to 3.

**Rotating a Graphic Object**

A rectangular array is often called a *matrix*. Matrix algebra is an important branch of mathematics, as many common and interesting problems are well expressed and developed using matrices. Let's explore one such example in the field of computer graphics. Figure 18 illustrates a simple house drawn in a graphics window. The house is shown to the right and above the origin. The y coordinates are negative as consistent with Java's graphics coordinate system. The house could be drawn using the `drawLine()` method of Java's `Graphics` class, as shown in previous programs. Five calls to `drawLine()` are required, each specifying the end points of one of the lines.

![Figure 18. A house displayed in a graphics window](image)

An alternate way to draw the house is to store the points in arrays and use the `drawPolygon()` method:

```java
int[] houseX = { 30, 30, 50, 70, 70};
int[] houseY = { -40, -60, -70, -60, -40};
g.drawPolygon(houseX, houseY, houseX.length);
```

The `drawPolygon()` method requires three arguments: an array of x points, an array of y points, and the number of points. So far, so good. If we want to transform our basic house in
some simple yet consistent manner, then we must confront a mathematical problem that is well-suited to matrix algebra, and, hence, multi-dimensional arrays. In computer graphics, there are three basic transformations collectively known as affine transformations:

- **Translating** moving an object left, right, up, or down
- **Scaling** enlarging or shrinking an object
- **Rotation** rotating an object about a point

The task of translating, scaling, or rotating our simple graphics house requires transforming each point into a new point such that the new set of points is true to the original set, except transformed in the desired manner. For translating, we simply add a displacement to each \( x \) and \( y \) coordinate:

\[
x' = x + d_x \quad y' = y + d_y
\]

For scaling, we simply multiply each \( x \) and \( y \) coordinate by a scaling factor:

\[
x' = x \cdot s_x \quad y' = y \cdot s_y
\]

For rotating, we transform each point as follows:

\[
x' = x \cdot \cos\theta - y \cdot \sin\theta \quad y' = x \cdot \sin\theta + y \cdot \cos\theta
\]

where \( \theta \) is the angle of rotation in degrees. Rotating is a bit tricky, so let's explain with a figure. Figure 19 shows a point \( x, y \), and the same point, \( x', y' \), rotated about the origin by \( \theta \) degrees. Since rotation is about the origin, the distance from the origin to each point is the same. This is shown as \( z \) in the figure.

![Figure 19. Rotating a point about the origin](image)

Our task is to calculate \( x' \) and \( y' \) in terms of \( x, y \), and the angle of rotation, \( \theta \). From basic trigonometry, we know that

\[
x = z \cdot \cos\phi
\]

\[
y = z \cdot \sin\phi
\]

In terms of the new point, \( x', y' \), we have
\[ x' = z \cdot \cos(\theta + \phi) = z \cdot \cos \phi \cdot \cos \theta - z \cdot \sin \phi \cdot \sin \theta \]  
\[ y' = z \cdot \sin(\theta + \phi) = z \cdot \cos \phi \cdot \sin \theta + z \cdot \sin \phi \cdot \cos \theta \]  

Substituting equations 4 and 5 into equations 6 and 7 yields the equations for \( x' \) and \( y' \) (equation 3).

So, what does the above discussion have to do with multi-dimensional arrays or matrix algebra? A lot. As it turns out, the three affine transformations, and some variations on these, can all be implemented using the same operation — multiplying a vector by a transformation matrix. The arithmetic is simple, but as you may unfamiliar with vector and matrix algebra, a brief review is in order.

A vector is another term for an array, and a matrix is another term for a two-dimensional array.² A vector multiplied by another vector yields a single value as a result, for example

\[
\begin{pmatrix}
6 & 5 & 4
\end{pmatrix}
\begin{pmatrix}
9 \\
8 \\
7
\end{pmatrix}
= 6 \times 9 + 5 \times 8 + 4 \times 7 = 54 + 40 + 28 = 122
\]  

A vector multiplied by matrix yields a vector result, for example

\[
\begin{pmatrix}
1 \\
2 \\
3
\end{pmatrix}
\begin{pmatrix}
4 & 5 & 6 \\
3 & 2 & 1 \\
7 & 6 & 5
\end{pmatrix}
= \begin{pmatrix}
1 \times 4 + 2 \times 5 + 3 \times 6 \\
1 \times 3 + 2 \times 2 + 3 \times 1 \\
1 \times 7 + 2 \times 6 + 3 \times 5
\end{pmatrix}
= \begin{pmatrix}
4 + 10 + 18 \\
3 + 4 + 3 \\
7 + 12 + 15
\end{pmatrix}
= \begin{pmatrix}
32 \\
10 \\
34
\end{pmatrix}
\]  

We'll put the operation above to use in our next Java program, so have another look if you're not convinced of the arithmetic. For our purpose, the vector represents a point to transform:

\[
P = \begin{pmatrix}
x \\
y \\
1
\end{pmatrix}
\]  

The matrix used to transform this point will differ depending on whether we are interested in translating (T), scaling (S), or rotating (R):

\[
T = \begin{pmatrix}
1 & 0 & d_x \\
0 & 1 & d_y \\
0 & 0 & 1
\end{pmatrix}
\quad
S = \begin{pmatrix}
x_x & 0 & 0 \\
0 & s_y & 0 \\
0 & 0 & 1
\end{pmatrix}
\quad
R = \begin{pmatrix}
\cos \theta & -\sin \theta & 0 \\
\sin \theta & \cos \theta & 0 \\
0 & 0 & 1
\end{pmatrix}
\]  

So, if we are interested in translating an object, we take each point, \( P \), and transform it into \( P' \) using

\[ P' = P \cdot T \]  

---

² The term "vector", as it is used here, is unrelated to Java's Vector class, discussed in the next section.
If we want to scale our object, each point, \( P \), is transformed into \( P' \) using

\[
P' = P \cdot S
\]  

(13)

and for rotating, each point, \( P \), is transformed into \( P' \) using

\[
P' = P \cdot R
\]  

(14)

The third value in the point vector is of no use to us, so it is discarded after the transformation.

As an example, let's convince ourselves that equation 12 performs translation:

\[
\begin{bmatrix}
  x \\
  y \\
  1
\end{bmatrix}
\begin{bmatrix}
  1 & 0 & d_x \\
  0 & 1 & d_y \\
  0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  x \times 1 + y \times 0 + 1 \times d_x \\
  x \times 0 + y \times 1 + 1 \times d_y \\
  x \times 0 + y \times 0 + 1 \times 1
\end{bmatrix}
= \begin{bmatrix}
  x + d_x \\
  y + d_y \\
  1
\end{bmatrix}
= P'
\]  

(15)

The result above shows the translated point with new coordinates \( x + d_x \) and \( y + d_y \). This is the effect of translating, as expressed in equation 1 at the beginning of this section.

The transformations above are powerful tools for computer graphics. Let's demonstrate this using an example program. The program `DemoRotate` is a Java applet that draws the simple house shown earlier and then draws it again rotated 45° about the origin (see Figure 20).
import java.awt.*;
import java.applet.*;

public class DemoRotate extends Applet {
  private static final int SIZE = 200;
  private static final double ROTATE = 45.0; // degrees cw

  public void paint(Graphics g) {
    // points for the house polygon
    int[] houseX = {30, 30, 50, 70, 70};
    int[] houseY = {-40, -60, -70, -60, -40};

    // compute rotation angle in radians
    double theta = Math.toRadians(ROTATE);

    // transformation matrix for rotation
    double[][] r = {
      {Math.cos(theta), -Math.sin(theta), 0.0},
      {Math.sin(theta), Math.cos(theta), 0.0},
      {0.0, 0.0, 1.0}
    };

    // draw a rectangle around the graphics window
    g.drawRect(0, 0, SIZE - 1, SIZE - 1);

    // set a new origin in the middle of the graphics window
    g.translate(SIZE / 2, SIZE / 2);

    // draw outline of the original house (in black)
    g.setColor(Color.black);
    g.drawPolygon(houseX, houseY, houseX.length);

    // transform points (use 'rotate' matrix)
    double[] p = new double[3];
    for (int i = 0; i < houseX.length; i++) {
      p[0] = houseX[i];
      p[1] = houseY[i];
      p[2] = 1.0;
      p = vmProduct(p, r);
      houseX[i] = (int)Math.round(p[0]);
      houseY[i] = (int)Math.round(p[1]);
    }

    // draw the transformed house
    g.drawPolygon(houseX, houseY, houseX.length);

    // calculate product of vector 'v' and matrix 'm' (return a new vector)
    public static double[] vmProduct(double[] v, double[][][] m) {
      double[] temp = new double[v.length];
      for (int i = 0; i < v.length; i++)
        temp[i] = v[0] * m[i][0] + v[1] * m[i][1] + v[2] * m[i][2];
      return temp;
    }
  }
}
This program generates the following output:

The techniques to draw the original house were covered earlier. The interesting part in this program is the implementation of the affine transformation for rotation using matrix algebra. The transformation matrix is initialized in lines 19-23 as a two-dimensional double array named \( r \) (for "rotate"). The values in the array are consistent with the transformation matrix for rotation presented earlier (see equation 11). The amount of rotation is declared in the final constant \( \text{ROTATE} \) in line 7 as 45°. Since Java's \( \sin() \) and \( \cos() \) methods expect an angle in radians, the \( \text{toRadians}() \) method (line 16) transforms the angle before it is passed on to these methods.

After the original object is drawn, the affine transformation is applied to the array of points (lines 41-50). In turn, each point is read from the original array \( \text{houseX} \) and \( \text{houseY} \) and assigned to a temporary point array named \( p \) (lines 44-46). This point and the transformation matrix \( r \) are passed as arguments to the \( \text{vmProduct}() \) method in line 47. The \( \text{vmProduct}() \) method multiplies the vector (\( p \)) by the matrix (\( r \)) and returns a new vector in \( p \). The first two values in \( p \) are placed back into the \( \text{houseX} \) and \( \text{houseY} \) array as the newly transformed points (lines 48-49).

The vector-matrix multiplication in the \( \text{vmProduct}() \) method is a straightforward implementation of the arithmetic shown earlier in equation 9. After the transformation the rotated house is drawn (line 53).

See Chapter 5 of Foley et al's *Computer graphics: Principles and practice* for more details on 2D transformations for computer graphics.