Assorted Materials on Java

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Chapter 1

Java Overview

Different people have different ways of learning programming languages. Your author likes to read reference manuals (believe it or not)—at least if they are reasonably complete—on the grounds that this is the most efficient way to absorb a language quickly. Unfortunately, it is an approach that only works when one knows what to expect from a programming language, and has the necessary mental cubbyholes already constructed and ready for filing away specific details. Less grizzled programmers usually benefit from some kind of tutorial introduction, in which we look at examples of programs and program fragments. That's the purpose of this chapter. After reading it, the succeeding chapters of this book ought to be somewhat more digestible.

1.1 Compilation, Execution, and Program Structure

Let's start with the traditional simplest program:

```
/* Sample Program #1 */
public class Hello {
  public static void main (String[] arguments) {
    System.out.println ("Hello, world!");  // Message + newline
  }
}
```

This example illustrates a number of things about Java:

Java programs are collections of definitions. In this case, we have definitions of a *class* named `Hello`, and a *function* (or *method*) named `main`.

Definitions are grouped into classes. Java programs may contain definitions of functions, variables, and a few other things. Every such definition is contained in (*is a member of*) some class.

Dots indicate some kind of containment. In the example above, `System` is a class and `out` is a variable defined in that class. We can think of that variable, in turn, as referring to an object that has parts (*members*), one of which is the `println` method. So in general, you can read $X.Y$ as "the Y that is (or whose definition is) contained in X." We sometimes call '.' the *selection operator.*

The syntax "*method-name*(*expressions*)" denotes a *method call.* (Also called *function call* and *method (or function) invocation.*) The program first evaluates the expressions, which are called *actual parameters.* In our example, there is only one (more would be separated by commas), and its value is a *string* of characters. Next, the value(s) of any actual parameters are handed off to (*passed*) to the indicated method, which then does whatever it does (unsurprisingly, `System.out.println` prints the string that you pass it, followed by an end-of-line.)

Executing a complete program means calling a method named `main`. (Not just any method called `main`, but we'll get to that detail later). Appropriately enough, the method called is often referred to as the *main program.* You won't always have to write a `main` method. For example, when you write a Java *applet* (a program intended to be run by a Web browser when one clicks on the appropriate thing) the browser will supply a standard `main`, and your applet provides one of the methods it calls. But for *standalone* programs (also called *application* programs), `main` is where things start.

Comments are surrounded by `/* */` or by `//` and the end of the line. Only humans read comments; they have no effect on the program.

Precise details on how to prepare and run this program differ from one implementation of Java to another. Here is a typical sequence.

- Put the program in one or more files. It generally makes things easier for the Java system if each class is placed in a file named after the class—for our example, `Hello.java`. One can put several classes into a file or name the file arbitrarily, but the Java system will then sometimes be unable to find what it needs.

- *Compile* the file with a Java *compiler.* A compiler is a translation program that converts a *source program* (our little sample program is a source program) into some form that is more easily executed. Java compilers typically translate each class into a *class file.* For example, if we use Sun Microsystems's software, the command line

  ```
  javac Hello.java
  ```

  will translate class Hello into the file `Hello.class`.

- *Execute* the program by invoking a Java *interpreter.* An interpreter is a program that executes programs. In the case of Sun's software, the command

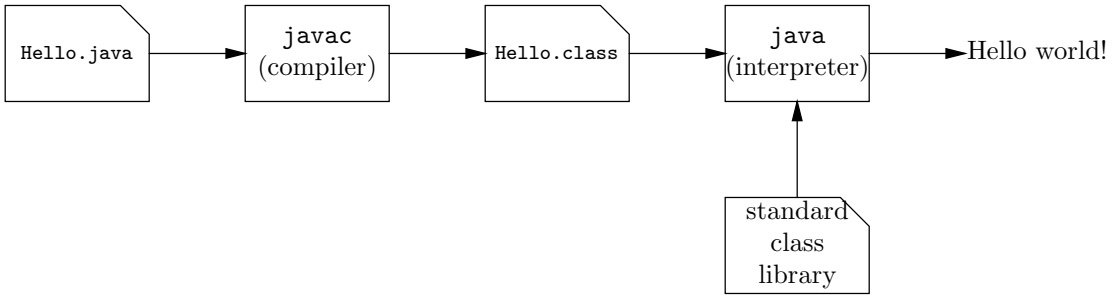


Figure 1.1: From program to execution. Our sample program is first processed by a compiler to create a class file, which can then be executed by an interpreter to finally print a message. In this tiny program, pre-supplied programs from the standard class library actually do most of the work.

```
java Hello
```

runs our program, producing the output line

```
Hello, world!
```

The argument to the `java` program is the name of the class containing the desired `main` method. The interpreter finds out what it is supposed to do by reading the file `Hello.class`, together with a library of other class files that implement standard, pre-defined parts of Java (like the `System` class mentioned above).

A note on printing. It isn't theoretically central to the topic of programming, but the printing or other display of results is obviously rather important. Many introductory Java texts get rather hung up on the use of various GUI (Graphical User Interface) tools for displaying and inputting text, commands, or other communications. I'd rather keep it simple, so we'll start with straightforward interaction with a textual display and keyboard. For output purposes, we use `System.out.println` as you've seen, which comes with a couple of useful variants. Here is an equivalent to the `main` method above:

```
public static void main (String[] args) {
  System.out.print ("Hello,");
  System.out.print (" world!");
  System.out.println ();
}
```

By comparing the two versions, you can probably deduce that the difference between `print` and `println` is that `println` ends the line immediately after printing, whereas `print` does not. You'll use `print` to break the printing of a complex line of output into pieces.

1.2 Simple Values and Expressions

You can think of a program as a set of instructions for creating *values* and moving them around, eventually sending them to something that does something visible with them, like displaying them, or moving some physical control. Values may either be *primitive*—in Java, these are various kinds of numbers, characters (as from an alphabet), and booleans (true/false)—or they may *structured* into compound values. A programming language construct that produces a value is called an *expression.*

1.2.1 Writing Numbers

Something that denotes a number is known as a *numeral,* or, especially in programming languages, as a numeric *literal.* Java has both *integral* and *floating-point* literals (the difference being that the latter can have fractional parts). Here are some examples, which are mostly self-explanatory:

```
class Numerals {
  public static void main (String[] args) {
     // A. All print 42
     System.out.println (42);    // Base 10
     System.out.println (052);   // Base 8 (starts with 0)
     System.out.println (0x2a);  // Base 16 (a=10, b=11, ..., f=15)
     // B. All print 31.45
     System.out.println (31.45);
     System.out.println (3.145e1);  // en or En means ×10^n
     System.out.println (3145e-2);
     // C. Prints 12345678901
     System.out.println (12345678901L);
  }
}
```

Technically, what we think of as negative numbers, such as `-3`, are actually positive literals operated on by the negation operator (`-`).

Example C indirectly illustrates a common feature of "production" programming languages such as C, C++, Java, Fortran, Pascal, Basic, and so on. For reasons having to do with fast and efficient execution, the "integers" in these programming languages comprise a tiny, finite portion of the mathematical integers. Ordinary integers in Java, for example, are all in the range -2^{31} to $2^{31}-1$, or about ± 2 billion. To get somewhat larger integers, you must use a distinct *type* of value, known as a `long`, whose literals have a trailing '`L`' on them. These give you a range of -2^{63} to $2^{63}-1$. To go even further requires one of the built-in library classes (appropriately called `java.math.BigInteger`), for which there aren't any built-in literals.

1.2.2 Arithmetic

Java expressions include the familiar algebraic notation, which you can play with easily enough by putting examples into a `main` function:

```
class Arith {
   public static void main (String[] args) {
      // A. Prints 3
      System.out.println ((3 + 7 + 10) * (1000 - 8)
                          / 992 - 17);
      // B. Prints 2.7166666666666663
      System.out.println (2.0 + 1.0/2 + 1.0/6 + 1.0/24 + 1.0/120);
      // C. Prints 2
      System.out.println (2 + 1/2 + 1/6 + 1/24 + 1/120);
      // D. Prints -3
      System.out.println (1 - 2 - 2);
      // E. Prints 17
      System.out.println (117 % 20);
      // F. Prints Infinity
      System.out.println (1.0 / 0.0);
      // G. Prints -2147483648
      System.out.println (2147483647 + 1);
      // H. Prints NaN
      System.out.println (0.0 / 0.0);
      // I. Halts the program with an exception
      System.out.println (1/0);
   }
}
```

As you can see, these examples look pretty much like what you might write by hand, and illustrate a few more points:

- '`*`' denotes multiplication and '`%`' denotes remainder.
- **Operators have precedences.** Example B illustrates *grouping:* the subexpression `2.0 + 1.0/2` is interpreted as $2.0+(1.0/2)$, not $(2.0+1.0)/2$, because the division operator *groups more tightly* (or *has higher precedence* than the addition operator. Example A uses parentheses to control grouping.
- **Operators associate.** Example D illustrates grouping when the operators have the same precedence. It is interpreted as $(1-2)-2$, not $1-(2-2)$, because subtraction (like most operators) *associates left* with operators of the same precedence.

Integer quantities and floating-point quantities are distinct. In mathematics, the quantity written '1' can be interpreted as either an integer or a real number, and the expression 1/2 always means the same as 0.5. In Java (as in most programming languages), a number written without a decimal point (an *integral quantity*) is of a different type from one written with a decimal point (a *floating-point quantity*), and the rules of arithmetic differ markedly. Division of two integers throws away the fractional part of the answer to yield an integer, whereas division

of floating-point numbers behaves more like regular mathematics. Thus `1/2` yields 0, while `1.0/2.0` yields 0.5. When the two types are mixed, Java first converts the integer quantities to floating point.

Floating-point arithmetic approximates real arithmetic. If you work out the mathematical value you'd normally expect from example B, you'll see it differs slightly from the one printed, which appears to be off by about 3.7×10^{-16}. Floating-point arithmetic is a compromise between computational speed and mathematical truth. The results of each operation are computed, correctly rounded, to a certain number of binary digits (in this case, 52).

Arithmetic has limited range. Example G illustrates that when an integer value becomes too large, the result "wraps around" to the smallest number. There are special values (which print as `Infinity` and `-Infinity` to represent numbers that are too large in floating point, which are also used when non-zero floating-point numbers are divided by 0 (Example F).

Arithmetic nonsense has predictable effects. Example H shows that a floating-point operation with an undefined value (there's no sensible definition one can give to 0/0) yields a strange special value called NaN (for "Not A Number"). The analogous integer operation causes an error (what Java calls an *exception*), since for various reasons, there is no available integer to use as NaN.

1.2.3 Comparisons and Logical Operations

Comparison operators and logical operators produce the two boolean values `true` and `false`:

```
class Compare {
   public static void main (String[] args) {
      // A. All print true
      System.out.println (true);
      System.out.println (3 < 4);
      System.out.println (3 <= 4); System.out.println (3 <= 3);
      System.out.println (4 > 3);
      System.out.println (4 >= 3); System.out.println (3 >= 3);
      System.out.println (4 != 3); System.out.println (3 == 3);
      // B. All print false
      System.out.println (false);
      System.out.println (3 < 3); System.out.println (3 != 3);
      // C. All print true
      System.out.println (3 < 4 && 4 < 5);
      System.out.println (3 > 4 || 4 < 5);
      System.out.println (! (3 < 4 && 4 < 3));
      // D. All print true
```

```
        System.out.println (3 < 4 || 1/0 == 0);
        System.out.println (! (3 > 4 && 1/0 == 0));
    }
}
```

Again, this is all pretty easy to figure out, once you see the transliterations Java uses for common notations:

$\leq$	$\Longrightarrow$	`<=`	$\geq$	$\Longrightarrow$	`>=`
$=$	$\Longrightarrow$	`==`	$\neq$	$\Longrightarrow$	`!=`
and	$\Longrightarrow$	`&&`	or	$\Longrightarrow$	`||`
not	$\Longrightarrow$	`!`			

All of the operators demonstrated have precedences below those of arithmetic operators, with the logical operators having the lowest precedences, *except* that logical not (`!`) has a precedence equal to that of the negation operator (`-3`). If that strikes you as potentially confusing, welcome to the club. Java has a large collection of operators at 15 different levels of precedence, which quickly become difficult to remember. As a stylistic matter, therefore, feel free to use parentheses even when operator-precedence rules make them redundant, if that makes your program clearer.

Example D illustrates that `&&` and `||` are "short-circuit" operators. Even though the second operand in both these cases would cause an exception, no such thing happens because the `||` only evaluates its right operand if needed. Upon evaluating its left operand, and finding it true, it skips evaluation of the right operand, while the `&&` doesn't bother to evaluate its right operand if the left evaluates to false. This is an important property of these two operators; the first operand acts as a kind of *guard* on the second. All the other arithmetic and comparison operators, as well as method calls, always evaluate all their operands.

1.2.4 Strings

In programming-language jargon, a *string* is a sequence of *characters*. We write strings in double quotes, using a backslash where needed to indicate special characters, including double quotes and backslashes:

```
System.out.println ("Simple string.");
System.out.println ("");   // An empty string
System.out.println ("Say \"Hello.\"");  // \" is double quote
System.out.println ("Name:\tJohn");     // \t is tab
System.out.println ("\\FOO\\BAR");
System.out.println ("One thing\nThe other thing");
```

These statements print (on Unix systems):

```
Simple string.

Say "Hello."
Name:   John
\FOO\BAR
One thing
The other thing
```

The newline character (notated `\n`) denotes the end-of-line on Unix systems. This is not, unfortunately, universal, which is why I've used `println` rather than `\n` to put things on separate lines (`println` "does the right thing" at the end of a line for whatever system you use).

Characters, the components of strings, have their own literals, which are enclosed in single quotes, with the same back-slashing notation:

```
'A'    '\t'   '\''    '"'   '\n'
```

The `+` operator works on strings, but in that case means "concatenate", as in

```
System.out.println ("The value of" +
                    " 17+25 is " + (17+25) + ".");
```

which prints

```
The value of 17+25 is 42
```

You might well protest at this point that `(17+25)` yields an integer, not a string. This is correct; conveniently, though, the `+` operator is smart enough that when one of its operands is a string, and the other isn't, it converts the other operand to a string. In fact, underneath the hood, the `println` method ultimately prints strings, and the variations that work on other types first perform this same conversion.

There are quite a few other operations on strings, of which some of the more important are these:

`("19-character string").length ()`	$\Longrightarrow$	19	length of string
`("abcd").charAt (3)`	$\Longrightarrow$	`'d'`	get a character (number from 0)
`("abcd").equals ("abcd")`	$\Longrightarrow$	`true`	compare contents
`("Hello, world!").substring (7, 12)`	$\Longrightarrow$	`"world"`	substring between start and end positions
`("Hello, world!").substring (7)`	$\Longrightarrow$	`"world!"`	substring starting at given position

The `.equals` method here is interesting. You might think that `==` would work, but for reasons we'll see later, that is not a reliable way to compare strings.

1.2.5 Static Methods: Abstracting Computation

Method (function) definition is the most basic *abstraction mechanism* in a typical programming language. It enables you to "define a new verb" for later use in your program, making it unnecessary to write, remember, or even know the details of how to perform some action.

In Java, there are *static* methods (also called *class methods*) and *non-static* (or *instance*) methods. We'll look at instance methods later. Static methods correspond to plain, ordinary functions, subprograms, or procedures in other programming languages (such as C, Pascal, Fortran, Scheme, or Basic). We've already seen examples of static method definition (of the `main` method).

The basic syntax is relatively easy:

A `static` T_r N `(`T_1 N_1`,` T_2 N_2`, ...) {`
  B
`}`

where

- T_r, T_1, etc., denote *types* of values. T_r is the type of value returned (produced, yielded) by the method, and the other T_i are the *formal-parameter types,* the types of values that may be passed to the method. In Java, unlike dynamically typed languages such as Scheme or the scripting languages Python and Perl, one must be specific about the types of most quantities. You can indicate that a method does stuff (printing, for example), but does not return a value, by using the special "type" **void** for T_r.

- *A* is one of the keywords **public**, **private**, **protected**, or it is simply missing (the default). It indicates the *access* of the method—what other parts of the program may call it. The **public** modifier, as you might guess, means that the method may be called from anywhere. The **private** modifier restricts access to the same class. (See §1.13)

- N is the name by which the method is known. A method definition always occurs inside a class definition. The full name of a static method N defined in a class C is $C.N$ (dot means "that is defined in"). However, the simple name N works within the same class.

- N_1, etc., are the *formal parameters.* These are names by which the body of the method (*B*) can refer to the values passed to it.

- `{` *B* `}` is the *body* of the method. *B* is a sequence of statements that perform whatever computation the method is supposed to perform (*B* may be empty if the method does nothing).

- The *header* of the method definition—everything except the body—defines its *signature,* which consists of its name, return type, and formal-parameter types.

So far, the only statements we've seen are method calls (to `println`). We'll see more later, but there's one particularly important ones for methods that return values: the statement

`return` *E*`;`

means "end this call to the method, causing it to yield the value *E* (an expression)." Here are two examples:

```
/** The square of X. */
public static double square (double x) {
  return x*x;
}

/** The distance between points (X0, Y0) and (X1, Y1). */
public static double dist (double x0, double y0, double x1, double y1) {
  return Math.sqrt (square (x1 - x0) + square (y1 - y0));
  // NOTE: Math.sqrt is a standard square-root function */
}
```

These two examples also illustrate some *documentation conventions* that I'll be using throughout. Comments beginning with '`/**`' are, by convention, called *documentation comments.* They are to be used before definitions of things to describe what those things do or are for. In the case of methods, I refer to the parameter names by writing them in upper case (the idea being that this is a way to set them off from the rest of the text of the comment in a way that does not depend on fancy fonts, colors, or the like). At least one tool (called `javadoc`) recognizes these comments and can process them into on-line documentation.

1.3 Conditional Execution

To do anything very interesting, programs eventually have to make decisions—to perform different calculations depending on the data. There are several constructs to represent this in Java. Here, we'll consider the simplest.

1.3.1 If statements

An *if-statement* has one of the forms

`if (`*condition*`)` *then-part*
`  // or`
`if (`*condition*`)` *then-part* `else` *else-part*

(Normally, though, we lay these statements out on separate lines, as you'll see). The *condition* is a boolean expression. If it evaluates to **true**, the program executes the *then-part* (a statement), and otherwise the *else-part,* which simply defaults to the empty statement if absent.

We'll often need to have *then-part* or *else-part* contain more than one statement. The trick used for this purpose (and for other constructs that have a "statement" part that needs to be several statements) is to use a kind of statement called a *block*. A block consists of any number of statements (including zero) enclosed in curly braces (`{ }`). Unlike other statements you've seen, it does not end in a semicolon. For example:

```
if (3 > 4) {
   System.out.println ("3 > 4.");
   System.out.println ("Looks like we're in trouble.");
} else
   System.out.println ("OK");
```

1.3.2 Conditional Expressions

The expression C`?`E_t`:`E_f yields either the value of E_t or E_f, depending on whether C evaluates to true or false. That is, '`?`' means roughly "then" and '`:`' means "otherwise", with an invisible "if" in front. This peculiar-looking ternary operator is not commonly used in C, C++, or Java, perhaps because it, well, looks peculiar. It is only your author's desire for balance that prompts its inclusion here. Here are some examples:

```
System.out.println (3 < 4 ? "Less" : "More");  // Prints Less
System.out.println (4 < 3 ? "Less" : "More");  // Prints More
// The next two mean the same, and print 3.1
System.out.println (1 < 0 ? 1.1 : 1 > 2 ? 2.1 : 3.1);
System.out.println (1 < 0 ? 1.1 : (1 > 2 ? 2.1 : 3.1));
```

The expressions after '`?`' and '`:`' must be the same type of thing; `3<4 ? 1 : "Hello"` is erroneous.

1.4 Arrays I: The Command Line

Before finally turning to an example, we'll need one other little piece of syntax to allow simple communication from the outside world to our program. I said earlier that the main program looks like this:

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

This notation means that the formal parameter, `args`, is an *array* of strings[1]. For our immediate purposes, this means that it references a sequence of string values, called `args[0]`, `args[1]`, etc., up to `args[args.length - 1]`. That is, `args.length` is the number of strings in `args`. When you start your program with

```
java MainClassName foo bar baz
```

[1]The name `args` is arbitrary, and you are free to choose another.

the method `main` is called with `"foo"` as `args[0]`, `"bar"` as `args[1]`, and `"baz"` as `args[2]`.

You have to be careful to remember that the arguments to `main` are strings. The following main program won't work:

```
class Remainder {
  public static void main (String[] operands) {
    System.out.println (operands[0] % operands[1]);
  }
}
```

You might think that you could run this with

```
java Remainder 1003 12
```

and have it print 7. However, until told otherwise, the Java system will not assume that a string is to be treated as a number just because all its characters happen to be digits. The operation of converting a string of characters into a number requires specific action in Java:

```
class Remainder {
  public static void main (String[] operands) {
    System.out.println (Integer.parseInt (operands[0])
                        % Integer.parseInt (operands[1]));
  }
}
```

That is, the `Integer.parseInt` method converts a string of decimal digits to an integer. (There's a similar method `Double.parseDouble` for floating-point numbers).

1.4.1 Case analysis and the Switch Statement

From time to time, you'll find yourself in a situation where you need to break some subproblem down into cases. This is something to avoid if possible, but not all problems lend themselves to simple, unconditional formulae. You can always get by with multiple uses of the **if** statement, like this mathy example:

```
if (x < -10.0)
  y = 0.0;
else if (x < 0.0)
  y = 1.0 / f(-x);
else if (x < 10.0)
  y = f(x);
else
  y = Double.POSITIVE_INFINITY;
```

This compound **if** statement is so common that we customarily format as you see above, instead of indenting the entire **else** part of the first **if**, etc., like this:

```
// Example of how NOT to format your program
if (x < -10.0)
  y = 0.0;
else
  if (x < 0.0)
    y = 1.0 / f(-x);
  else
    if (x < 10.0)
      y = f(x);
    else
      y = Double.POSITIVE_INFINITY;
```

From time to time, you'll encounter programs where first, there are *lots* of cases, and second, each test is of the form

`if (`*E* `=` *some integral constant*`)`

where *E* is the same each time. For this purpose, there is a special construct, introduced with the keyword **switch**. For example, consider this fragment:

```
if (action == PICK_UP)
  acquireObject ();
else if (action == DROP)
  releaseObject ();
else if (action == ENTER || action == EXIT)
  changeRooms (action);
else if (action == QUIT) {
  cleanUp ();
  return;
} else if (action == CLIMB)
  ...
else
  ERROR ();
```

Here, `action` is some integral variable (this might include character constants as well, but not strings), and the upper-case names are all defined in a class somewhere as *symbolic constants* standing for integers. (The typical way to do this is

```
static final int  // 'final' means 'constant'
  QUIT = 0,
  PICK_UP = 1,
  DROP = 2,
  ENTER = 3,
  EXIT = 4,
  CLIMB = 5,
  etc.
```

As a matter of style, whenever you represent some set of possible values with arbitrary integers like this, always introduce meaningful symbols like these—avoid sprinkling your program with "mystery constants.")

An arguably clearer way to write the **if** statement above is with **switch**, as follows:

```
switch (action) {
case PICK_UP:
  acquireObject ();
  break;
case DROP:
  releaseObject ();
  break;
case ENTER: case EXIT:
  changeRooms (action);
  break;
case QUIT:
  cleanUp ();
  return;
case CLIMB:
  ...
default:
  ERROR ();
}
```

Here, the **break** statements mean "leave this **switch** statement."

1.5 Example: Finding Primes

You've now seen a great deal of the *expression language* of Java, enough in fact to write quite elaborate programs in the *functional* style. Let's start with a simple program to find prime numbers. A prime number is an integer larger than 1 whose only positive divisors are itself and 1[2]. Suppose that we want a program that, when given a number, will print all primes less than or equal to that number, perhaps in groups of 10 like this:

You type: `java primes 101`
It types:
```
2 3 5 7 11 13 17 19 23 29
31 37 41 43 47 53 59 61 67 71
73 79 83 89 97 101
```

1.5.1 Starting from the top

There are many ways to attack a simple problem like this. We may proceed *top-down,* starting with a sort of overall outline or skeleton, which we subsequently fill

[2]Depending on whom you read, there can be negative primes as well, but for us, this would be an unnecessary complication, so we stick to positive primes.

in, or *bottom-up,* building pieces we know we'll need and assembling them into a whole. Finally, we might use a little of both, as we'll do here. For example, the description above suggests the following program, with comments in place of stuff we haven't written yet:

```
class primes {
  /** Print all primes up to ARGS[0] (interpreted as an
   *  integer), 10 to a line. */
  public static void main (String[] args) {
    printPrimes (Integer.parseInt (args[0]));
  }

  /** Print all primes up to and including LIMIT, 10 to
   *  a line. */
  private static void printPrimes (int limit) {
    // do the work
  }
}
```

This is a simple example of the classic "put off until tomorrow," top-down school of programming, in which we simplify our task in stages by assuming the existence of methods that do well-defined pieces of it (writing down their definitions, not including their bodies, but including comments that will remind us what they're supposed to do). Then we handle each incomplete piece (sometimes called an *obligation*) by the same process until there are no more incomplete pieces

1.5.2 Starting from the bottom

Our problem involves prime numbers, so it might well occur to you that it would be useful to have a method that tests to see if a number is prime. Let's proceed, bottom-up now, to define one, hoping to tie it in later to program we've started building from the top.

```
/** True iff X is a prime number. */
private static boolean isPrime (int x) {
  return /*( X is prime )*/;
}
```

I've introduced a piece of pseudo-Java here to help in developing our program: the notation

`/*(` *description of a value* `)*/`

is intended to denote an obligation to produce some expression (as yet undetermined) that yields a value fitting the given description. The description "`X` is prime" is a true/false sentence, so in this example, `isPrime` yields true iff `X` is prime[3]:

[3]The notation *iff* used here and elsewhere is mathematician's shorthand for "if and only if."

One general technique is to work backward from possible answers to the conditions under which those answers work. For example, we know immediately that a number is *not* prime—that we should return **false**—if it is ≤ 1, so we can replace the dummy comment as follows:

```
if (x <= 1)
  return false;
else
  return /*( True iff X is prime, given that X>1 )*/;
```

I'll call this the *method of guarded commands:* the "guards" here are the conditions in the **if** statements, and the "commands" are the statements that get executed when a condition is true.

For larger numbers, the obvious brute-force approach is to try dividing x by all positive numbers ≥ 2 and $< x$. If there are none, then x must be prime, and if any of them divides x, then x must be composite (non-prime). Let's put this task off until tomorrow, giving us our finished `isPrime` method:

```
private static boolean isPrime (int x) {
  if (x <= 1)
    return false;
  else
    return ! isDivisible (x, 2);
}

/** True iff X is divisible by any positive number >=K and < X,
 *  given K > 1. */
private static boolean isDivisible (int x, int k) {
  /*{ return true iff x is divisible by some integer j, k ≤ j <
x; }*/
}
```

Here, I am using another piece of pseudo-Java: the comment

`/*{` *description of an action* `}*/`

is intended to denote an obligation to produce one or more statements that perform the described action.

By the way, we saw conditional expressions in §1.3. They allow an alternative implementation of `isPrime`:

```
private static boolean isPrime (int x) {
  return (x <= 1) ? false : ! isDivisible (x, 2);
}
```

To tackle this new obligation, we can again use guarded commands. For one thing, we know that `isDivisble` should return **false**, according to its comment, if $k \geq x$, since in that case, there aren't any numbers $\geq k$ and $< x$:

```
if (k >= x)
  return false;
else
  /*{ return true iff x is divisible by some integer j,
      where k ≤ j < x, assuming that k<x; }*/
```

Now, if we assume that $k < x$, then (always following the documentation comment) we know that one case where we should return **true** is where k divides x:

```
if (k >= x)
  return false;
else if (x % k == 0)
  return true;
else
  /*{ return true iff x is divisible by some integer j, k ≤ j <
x,
      assuming k<x, and x is not divisible by k; }*/
```

Here, I've used the remainder operator to test for divisibility.

Well, if k itself does not divide x, then for x to be divisible by some number $\geq k$ and $< x$, x must be divisible by a number $\geq k + 1$ and $< x$. How do we test for that? By a curious coincidence, we just happen to have a method, `isDivisible`, whose comment says that if given two parameters, x and k, it returns "True iff x is divisible by any positive number $\geq k$ and $< x$, given $k > 1$." So our final answer is

```
/** True iff X is divisible by any positive number >=K and < X,
 *  given K > 1. */
private static boolean isDivisible (int x, int k) {
  if (k >= x)
    return false;
  else if (x % k == 0)
    return true;
  else
    return isDivisible (x, k+1);
}
```

Now you might object that there's something circular about this development: to finish the definition of `isDivisible`, we used `isDivisible`. But in fact, the reasoning used is impeccable: *assuming* that `isDivisible` does what its comment says, the body we've developed can only return a correct result. The only hole through which an error could crawl is the question of whether `isDivisble` ever gets around to returning a result at all, or instead keeps calling itself, forever putting off until tomorrow the production of a result.

However, you can easily convince yourself there is no problem here. Each time `isDivisible` gets called, it is called on a problem that is "smaller" in some sense. Specifically, the difference $x - k$ gets strictly smaller with each call, and (because of the guard $k >= x$) must stop getting smaller once $x - k \leq 0$. (Formally, we use

the term *variant* for a quantity like $x - k$, which shrinks (or grows) with every call but cannot pass some fixed, finite limit.) We have established that `isDivisible` is not circular, but is a proper *recursive* definition.

1.5.3 Meeting in the middle

We are left with one final obligation, the `printPrimes` procedure:

```
/** Print all primes up to and including LIMIT, 10 to a line. */
private static void printPrimes (int limit) {
  /*{ do the work }*/
}
```

Let's make the reasonable assumption that we'll be printing prime numbers one at a time by looking at each number up to the limit, and figuring out whether to print it. What do we need to know at any given time in order to figure out what to do next? First, clearly, we need to know how far we've gotten so far—what the next number to be considered is. Second, we need to know what the limit is, so as to know when to stop. Finally, we need to know how many primes we've already printed, so that we can tell whether to start a new line. This all suggests the following refinement:

```
private static void printPrimes (int limit) {
  printPrimes (2, limit, 0);
  System.out.println ();
}

/** Print all primes from L to U, inclusive, 10 to a line, given
 *  that there are initially M primes printed on the current
 *  line. */
private static void printPrimes (int L, int U, int M) {
  ...
}
```

This illustrates a small point I hadn't previously mentioned: it's perfectly legal to have several methods with the same name, as long as the number and types of the arguments distinguish which you intend to call. We say that the name `printPrimes` here is *overloaded*.

To implement this new method, we once again employ guarded commands. We can easily distinguish four situations:

A. $L > U$, in which case there's nothing to do;

B. $L \leq U$ and L is not prime, in which case we consider the next possible prime;

C. $L \leq U$ and L is prime and M is less than 10, in which case we print L and go on to the next prime); and

D. $L \leq U$ and L is prime and M is divisible by 10, which is like the previous case, but first we go to the next line of output and adjust M).

A completely straightforward transliteration of all this is:

```
if (L > U)                                  // (A)
  ;
if (L <= U && ! isPrime (L))                // (B)
  printPrimes (L+1, U, M);
if (L <= U && isPrime (L) && M != 10) {     // (C)
  System.out.print (L + " ");
  printPrimes (L+1, U, M+1);
}
if (L <= U && isPrime (L) && M == 10) {     // (D)
  System.out.println ();
  System.out.print (L + " ");
  printPrimes (L+1, U, 1);
}
```

Well, this is a little wordy, isn't it? First of all, the conditions in the **if** statements are mutually exclusive, so we can write this sequence more economically as:

```
if (L > U)                                  // (A)
  ;
else if (! isPrime (L))                     // (B)
  printPrimes (L+1, U, M);
else if (M != 10) {                         // (C)
  System.out.print (L + " ");
  printPrimes (L+1, U, M+1);
} else {                                    // (D)
  System.out.println ();
  System.out.print (L + " ");
  printPrimes (L+1, U, 1);
}
```

Step (A) looks kind of odd. We often write things like this as

```
if (L > U)
  return;
```

to make it clearer that we're done at this point, or we can *factor* the condition like this:

```
if (L <= U) {
  if (! isPrime (L))                          // (B)
    printPrimes (L+1, U, M);
  else if (M != 10) {                         // (C)
    System.out.print (L + " ");
    printPrimes (L+1, U, M+1);
  } else {                                    // (D)
```

```
      System.out.println ();
      System.out.print (L + " ");
      printPrimes (L+1, U, 1);
    }
  }
```

I use the term "factor" here in a sort of arithmetical sense. Just as we can rewrite $ab+ac+ad$ as $a(b+c+d)$, so also we can "factor out" the implicit `!(L <= U)` from all the other conditions and just drop the `L > U` case.

Finally, using a little knowledge about how remainders work and doing a little more factoring of a different kind, we can do this:

```
if (L <= U) {
  if (! isPrime (L))                          // (B)
    printPrimes (L+1, U, M);
  else {
    if (M == 10)
      System.out.println ();
    System.out.print (L + " ");
    printPrimes (L+1, U, (M+1) % 10);
  }
}
```

1.6 Example: Pig Latin

We'd like to write a program (never mind why) that translates into "Pig Latin." There are numerous dialects of Pig Latin; we'll use the simple rule that one translates into Pig Latin by moving any initial consonants to the end of the word, in their original order, and then appending "ay." So,

You type: `java pig all gaul is divided into three parts`
It types: `allay aulgay isay ividedday intoay eethray artspay`

We'll simplify our life further by agreeing that 'y' is a consonant.

1.6.1 Vowels

This time, let's start from the bottom. Presumably, we'll need to know whether a letter is a consonant. Here's a brute-force way:

```
static boolean isVowel (char x) {
  return x == 'a' || x == 'e' || x == 'i' || x == 'o' || x == 'u';
}
```

(This method has *default access;* I haven't labeled it specifically **private** or **public**. Most of the time, in fact, this is fine, although it is often good discipline (that is, leads to cleaner programs) to keep things as private as possible.)

Aside: Tedious programs. When you find yourself writing a particularly tedious expression, it's often a hint to look around for some shortcut (you will probably spend longer looking for the shortcut than you would grinding through the tedium, but you are likely to learn something that you can use to relieve later tedium). For example, if you browse through the detailed documentation for the `String` type (see, for example, §5.2), you'll find the useful function `indexOf`, which returns the first point in a string where a given character appears, or -1 if it doesn't appear at all. Then the `return` statement above is simply

```
return ("aeiou").indexOf (x) >= 0;
```

1.6.2 Translation

Now let's turn to the problem of actually re-arranging a string. We've already seen all the parts: `substring` will extract a piece of a string, and '`+`' will concatenate strings. So, if we just knew how many consonants there were at the beginning of a word, `w`, the translation would just be

```
w.substring (k) + w.substring (0, k) + "ay"
```

where `k` is the number of consonants at the beginning of `w`. This expression works for any value of `k` between 0 and the length of `w`, inclusive. But which value to choose? Again, we put that off until tomorrow:

```
/** Translation of W (a single word) into Pig Latin. */
static String toPig (String w) {
  return w.substring (consonants (w)) + w.substring (0, consonants (w)) + "ay";
}

/** The number of consonants at the beginning of W (a single word). */
static int consonants (String w) {
  /*{ return the number of consonants at start of W }*/;
}
```

1.6.3 Counting Consonants

Assume now that tomorrow has arrived, let's consider how to implement `consonants`, again using a guarded command approach. Look for easy (or "base") cases. Clearly, we return 0 if `w` is empty:

```
if (w.length () == 0)
  return 0;
else
  /*{ return the number of consonants at start of W,
       assuming W is not empty }*/;
```

Likewise, in the remaining case, we should return 0 if `w` starts with a vowel:

```
if (w.length () == 0)
  return 0;
else if (isVowel (w.charAt (0)))
  return 0;
else
  /*{ return the number of consonants at start of W,
       assuming W starts with a consonant }*/;
```

Finally, a word that starts with a consonant clearly has one more consonant at the beginning than the "tail" of that word (the word with its first letter removed):

```
if (w.length () == 0)
  return 0;
else if (isVowel (w.charAt (0)))
  return 0;
else
  return 1 + consonants (w.substring (1));
```

and there's nothing left to do. Optionally, we can condense things a bit, if desired:

```
if (w.length () == 0 || isVowel (w.charAt (0)))
  return 0;
else
  return 1 + consonants (w.substring (1));
```

Again, this program exemplifies a typical feature of the functional programming style: we've assembled a method from a collection of *facts* about the problem:

- An empty string has no consonants at the beginning.
- A string that starts with a vowel has no consonants at the beginning.
- A string that isn't empty and doesn't start with a vowel has one more consonant at the beginning than its tail does.

We could actually have written these independently and in any order and with redundant guards; for example:

```
if (w.length () > 0 && !isVowel (w.charAt (0)))
  return 1 + consonants (w.substring (1));
else if (w.length () > 0 && isVowel (w.charAt (0)))
  return 0;
else if (w.length () == 0)
  return 0;
// Should never get here.
```

(Java compilers, being none too bright, will complain that we might not execute a **return**, but we know the cases are exhaustive.) However, we usually take advantage of the cases we've already eliminated at each step to shorten the tests.

Cutting expenses. As it happens, the `substring` method in Java is considerably more expensive than `charAt`. So we might consider ways to use the latter exclusively. For example,

```
/** The number of consonants at the beginning of W (a single word). */
static int consonants (String w) {
  return consonants (w, 0);
}

/** The number of consonants at the beginning of the substring of W
 *  that starts at position K. */
static int consonants (String w, int k) {
  /*{ return the number of consonants immediately at and
       after position k start of w }*/;
}
```

For the body of this second `consonants` method, we can use the the same facts as before, expressed slightly differently:

```
  if (w.length () <= k || isVowel (w.charAt (k)))
    return 0;
  else
    return 1 + consonants (w, k+1);
```

This new `consonants` method is a *generalization* of the original; it can count consonants anywhere in a word, not just at the front. As a result, the resulting function is arguably smaller and cleaner than our first version. Generalization often has this effect (and just as often makes things more complex than they have to be—programming will always require judgment).

1.6.4 To the top

Finally, we want to apply `toPig` to each of the command-line arguments and print the results. With what you've seen so far, an approach rather like the last version of `consonants` seems reasonable:

```
class pig {
  public static void main (String[] words) {
    translate (words, 0);
    System.out.println ();
  }

  /** Print the translations of SENT[K], SENT[K+1], ..., all on one line */
  static void translate (String[] sent, int k) {
    ...
  }
```

In this case, `translate` doesn't have to do anything if `k` is already off the end of the array `sent` (for "sentence"). Otherwise, it has to print the translation of word `#k`, followed by the translations of the following words. So,

```
if (k < sent.length) {
  System.out.print (toPig (sent[k]) + " ");
  translate (sent, k+1);
}
```

which completes the program.

1.7 Variables and Assignment

Method signatures and documentation comments are abstractions of actions. When you write `translate` in the main program of §1.6, you should be thinking of "translation into Pig Latin," and not the details of this procedure, because *any* method that correctly translates a word into Pig Latin would serve the main program, not just the one you've happened to write. Likewise, the formal parameters of methods are abstractions of values. For example, `k` in the `translate` method of the last section refers to "the index of the first word to translate," rather than any particular value.

Formal parameters are a particular kind of *variable.* Although in some ways similar to mathematical variables, they aren't quite the same thing: whereas in mathematics, a variable denotes *values,* in computer languages they denote *containers of values.* The difference is that computer languages provide an *assignment operation,* which in Java is written `=` (a choice inherited from Fortran, and requiring the use of `==` for equality). The expression

```
x = 43
```

has 43 as its value, but also has the *side effect* of placing the value 43 in the container `x`. Until this value is replaced by another assignment, any use of `x` yields the value 43. An expression such as

```
x = x + 2;
```

first finds the value (contents) of `x`, adds 2, and then places the result back in `x`. This particular sort of statement is so common that there is a shorthand[4]:

```
x += 2
```

as well as `-=`, `*=`, etc.

This last example demonstrates something confusing about variables: depending on where it is used, `x` can either mean "the container named `x`" or "the value contained in the container named `x`". It has the first meaning in what are called

[4]You'll find that most C, C++, and Java programmers also use another shorthand, `x++` or `++x`, to increment `x` by one. You won't see me use it, since I consider it a superfluous and ugly language misfeature.

left-hand side contexts (like the left-hand side of an assignment operator) and the second in *right-hand side* or *value* contexts.

You can introduce new variables as temporary quantities in a method by using a *local-variable declaration,* with one of the following forms:

Type variable-name;
Type variable-name = *initial-value*;

For example,

```
int x;
String[] y;
double pi = 3.1415926535897932383;
double pi2 = pi * pi;
```

A declaration with initialization is just like a declaration of a variable followed by an assignment. With either of these forms, you can save some typing by re-using the *Type* part:

```
int x, y;
int a = 1, b = 2, c;
```

Be careful with this power to abbreviate; compactness does not necessarily lead to readability.

If you're used to typical scripting languages (like Perl or Python), or to Lisp dialects (such as Scheme), you may find it odd to have to say what type of value a variable contains. However, this requirement is common to most "production" languages these days. The original purpose of such *static typing* was to make it easier for compilers to produce fast programs. Although some authors praise the "radical" and "liberating" alternative of having no restrictive variable types (*dynamic typing*), experience suggests that static typing provides both useful internal consistency checking and documentation that is of increasing value as programs start to become large.

With the program features we've seen so far, local variables and the assignment statement are theoretically unnecessary. When we look at iterative statements in the next section, you'll see places where local variables and assignment become necessary. Still, they can provide shorthand to avoid repeating expressions, such as in this rewrite of a previous example

```
static String toPig (String w) {
  int numCon = consonants (w);
  return w.substring (numCon) + w.substring (0, numCon) + "ay";
}
```

or this example, involving an **if** statement:

Version 1:

```
if (x % k == 0)
  System.out.println (x + " is divisible by " + k);
else
  System.out.println (x + " is not divisible by " + k);
```

Version 2:

```
String sense;
if (x % k == 0)
  sense = " ";
else
  sense = " not ";
System.out.println (x + " is" + sense + "divisible by " + k);
```

They may also be used for breaking up huge, unreadable expressions into bite-sized pieces:

Version 1:

```
tanh = u / (1.0 + u*u / (3.0 + u*u / (5.0 + u*u / 7.0)));
```

Version 2:

```
double u2 = u*u, tanh;
tanh = 7.0;
tanh = 5.0 + u2/tanh;
tanh = 3.0 + u2/tanh;
tanh = 1.0 + u2/tanh;
tanh = u / tanh;
```

This example also shows another use of a variable (`u2`) to represent a repeated expression.

1.8 Repetition

In the Scheme language, a *tail recursive* method (one in which the recursive call is the last operation in the method, like `printPrimes` in §1.5.3) is always implemented in such a way that the recursive calls can go on indefinitely (to any *depth*)—in Scheme, `printPrimes` would consume the same amount of computer memory for all values of its arguments. The typical imperative "production" languages in use today (including Java) do not put this requirement on their compilers, so that it is possible for the original Java version of `printPrimes` to fail for large values of `limit`. To a large extent, this difference is historical. Defining a function in the early algebraic languages (from which Java, C, and C++ descend) was a much less casual occurrence than in current practice and functions tended to be larger. Programmers relied on other methods to get repetitive execution. That tendency has survived, although the culture has changed so that programmers are more willing to introduce function definitions.

As a result, most commonly used languages include constructs for expressing repetition (or *iteration*). These come in two flavors: those where the (maximum) number of repetitions is explicit (*definite iteration*) and those in which repetition terminates when some general condition is met and the number of repetitions is not directly expressed (*indefinite iteration*).

1.8.1 Indefinite iteration

Consider the problem of computing the gcd (greatest common divisor) of two non-negative integers—the largest integer that divides both. Recursively, this is easy using the method of guarded commands. First, we notice that if one of the numbers is 0, then (since every positive integer divides 0), the other number must be the gcd:

```
/** The greatest common divisor of A, and B, where A,B >= 0 */
static int gcd (int a, int b)
{
  if (b == 0)
    return a;
  else
    return /*( the gcd of a and b, given that b != 0 )*/;
}
```

Next, we use the fact that if $a = r \bmod b$ for the remainder $0 \leq r < b$, then the gcd of a and r is the same as the gcd of a and b:

```
/** The greatest common divisor of A, and B, where A,B >= 0 */
static int gcd (int a, int b)
{
  if (b == 0)
    return a;
  else
    return gcd (b, a % b);
}
```

[Why does this terminate? What is the variant here?]

Were you to do this on a small slate (with limited space), you might end up re-using the same space for each new set of values for a and b. You would then be treating a and b as local variables and you would think of the process as something like "keep repeating this calculation, changing a and b until $b = 0$." In Java, we might write this:

```
static int gcd (int a, int b) {
  while (b != 0) {
    int b1 = a % b;
    a = b; b = b1;
  } // Now b == 0
  return a;
}
```

This last program's relationship to the preceding recursive version might be a little clearer if we re-write the former like this:

```
static int gcd (int a, int b)
{
  if (b != 0)
    return gcd (b, a % b);

  return a;
}
```

A statement of the form

`while (`*condition*`)` *statement*

means "if *condition* evaluates to false, do nothing ("exit the loop"); otherwise execute *statement* (called the *loop body*) and then repeat the entire process." Another way to say the same thing is that the **while** loop is equivalent to

```
if (condition) {
  statement
  while (condition) statement
}
```

This is a recursive definition, with the inner **while** loop functioning as the recursive "call."

The **while** loop tests whether to terminate before each iteration. It is sometimes desirable to test *after* each iteration, so that the loop body is always executed at least once. For example, in a program that communicates with its users using a simple text-based interface, you'll often want to prompt for a response, read the response, and repeat the process until the response is legal. For this purpose, there is a **do-while** loop:

```
String response;
do {
  System.out.print ("Proceed? [y/n] ");
  response = readWord ();
} while (! (response.equals ("y") || response.equals ("n")));
```

(Assume that `readWord` reads the next whitespace-delimited word typed as input.) This loop corresponds to the following recursive function:

```
static String getResponse () {
  System.out.print ("Proceed? [y/n] ");
  String response = readWord ();
  if (response.equals ("y") || response.equals ("n"))
    return response;
  else
    return getResponse ();
}
```

Many loops fall into neither of these categories. Instead, one discovers whether to stop only in the middle of a computation. For this purpose, Java has a general-purpose exiting construct, **break**, which in its simplest form ends execution of the enclosing loop. For example, suppose that we want to prompt for and read a sequence of words from some input source and print their Pig Latin translations, one per line, until we get to a single period. We could write

```
String word;
System.out.print ("> ");
word = readWord ();
while (! word.equals (".")) {
  System.out.println (word + " => " + toPig (word));
  System.out.print ("> ");
  word = readWord ();
}
```

but the repetition of the statements for prompting and reading is a little annoying. With **break**, we can use a "loop and a half," like this:

```
while (true) {
  System.out.print ("> ");
  word = readWord ();
  if (word.equals ("."))
    break;
  System.out.println (word + " => " + toPig (word));
}
```

The "`while (true)`" statement loops indefinitely, since its condition is, of course, never false. It is only stopped by the `break` statement in the middle of the loop body.

Question: What do these two loops do?

```
while (false) {
   System.out.println ("Hello!");
}
```

```
do {
   System.out.println ("Hello!")
} while (false);
```

1.8.2 Definite Iteration

Consider the computation of $N!$, the factorial function, which for non-negative integers is defined by the recurrence

$$\begin{aligned} 0! &= 1 \\ (N+1)! &= (N+1) \cdot N! \end{aligned}$$

or to write it out explicitly[5],

$$N! = 1 \cdot 2 \cdots N = \prod_{1 \le k \le N} k.$$

The recurrence suggests a recursive definition[6]:

```
/** N!, for N >= 0. */
static long factorial (long N) {
  if (N <= 0)
    return 1;
  else
    return N * factorial (N-1);
}
```

I've chosen to use type `long` because the factorial function grows quickly, and `long` is an integer type that accommodates values up to $2^{63} - 1$ (slightly less than 10^{19}).

Now this last function is not tail-recursive; it multiplies by `N` after the recursive call. A simple trick makes it tail recursive—we compute a *running product* as an extra parameter:

```
static long factorial (long N) {
  return factorial (N, 1);
}

/** N! * P, assuming N >= 0. */
static long factorial (long N, long p) {
  if (N <= 0)
    return p;
  else return factorial (N-1, p*N);
}
```

This function is now amenable to being converted to a loop directly:

```
static long factorial (long N0) {
  long p, N;
  N = N0; p = 1;
  while (N > 0) {
    p *= N;     // Means p = p*N
    N -= 1;     // Means N = N-1
  }
  return p;
}
```

[5]The symbol $\prod$ means "product of" just as $\sum$ means "sum of." When N is 0, so that you have an empty product, mathematical convention makes the value of that product 1, the multiplicative identity. By the same token, an empty sum is 0 by convention, the additive identity.

[6]This function yields 1 if given a negative argument. Since negative arguments are illegal (says the comment), the function may yield any result—or even fail to terminate—and still conform to the "letter of the specification." Therefore, substituting $\le$ for $=$ in the test is perfectly correct.

The call `factorial(N,1)` corresponds to initializing `p` to 1. This is a typical example of a *reduction loop* used to perform a certain binary operation on a sequence of values. The variable `p` serves as the *accumulator.*

This loop fits a very common pattern: one variable (here, `N`) is first initialized, and then incremented or decremented each time through a loop until it reaches some limit. The loop therefore has a predictable maximum number of iterations each time it is started. Numerous programming languages (FORTRAN, Algol, Pascal, and Ada, to name just a few) have special *definite iteration* constructs for just such combinations of actions. The Ada version, for example is

```
p := 1;
for N in reverse 1 .. N0 loop
  p := p*N;
end loop;
```

Here, `N` is a *loop control variable,* which is modified only by the loop statement and may not be assigned to.

Instead of having a restricted definite iteration like other languages, Java (as in C and C++) has a more general form, in which we explicitly write the initialization, bounds test, and increment in one statement:

```
long p, N;
p = 1;
for (N = N0; N > 0; N -= 1)
  p *= N;
return p;
```

This **for** statement is little more than a compact shorthand for a **while** loop with some initial stuff at the beginning. In general,

```
for (S0; C; S1)
  B
```

$\Longleftrightarrow$

```
{ S0;
  while (C) {
    B
    S1
  } }
```

If you take this equivalence literally, you'll see that it's also legal to write

```
long p;
p = 1;
for (long N = N0; N > 0; N -= 1)
  p *= N;
```

declaring the loop-control variable in the loop itself.

In this case, since multiplication is commutative, we can also write

```
long p;
p = 1;
for (long N = 1; N <= N0; N += 1)
  p *= N;
```

and get the same effect. For whatever reason, incrementing loops like this tend to be more common than decrementing loops.

The three parts of a **for** statement all have defaults: the test is **true** if omitted, and the other two parts default to the null statement, which does nothing. Thus, you will find that many programmers write an infinite loop (`while (true)...`) as

```
for (;;) ...
```

1.8.3 Example: Iterative Prime-Finding

Let's look at what happens when we replace the recursive methods in §1.5 with iterative constructs. First, let's start with the original prime-testing methods from that section, re-arranged slightly to make the conversion clear:

```
private static boolean isPrime (int x) {
  if (x <= 1)
    return false;
  else
    return ! isDivisible (x, 2);
}

private static boolean isDivisible (int x, int k) {
  if (k < x) {
    if (x % k == 0)
      return true;
    else
      return isDivisible (x, k+1);
  }
  return false;
}
```

Using essentially the same techniques we used for factorial, we get the following iterative version for `isDivisible`:

```
private static boolean isDivisible (int x, int k) {
  while (k < x) {
    if (x % k == 0)
      return true;
    k += 1;
  }
  return false;
}
```

which we may also code as a **for** loop with a null initialization clause:

```
  for (; k < x; k += 1)
    if (x % k == 0)
      return true;
  return false;
```

Now we can actually get rid of the `isDivisible` method altogether by integrating it into `isPrime`:

```
private static boolean isPrime (int x) {
  if (x <= 1)
    return false;
  for (int k = 2; k < x; k += 1)
    if (x % k == 0)
      return false;
  return true;
}
```

Since `isPrime` evaluates `! isDivisible(x, 2)`, we had to be careful also to reverse the sense of some of the return values.

Similar manipulations allow us also to convert `printPrimes`:

```
/** Print all primes up to and including LIMIT, 10 to a line. */
private static void printPrimes (int limit) {
  int n;
  n = 0;
  for (int L = 2; L <= U; L += 1) {
    if (isPrime (L)) {
      if (n != 0 && n % 10 == 0)
        System.out.println ();
      System.out.print (L + " ");
      n += 1;
    }
  }
  System.out.println ();
}
```

(The full syntax of **for** actually allows us to make this even shorter by replacing the first three lines of the body with

```
  for (int L = 2, n = 0; L <= U; L += 1) {
```

but I am not sure that this is any clearer.)

1.8.4 Example: Counting

The consonant-counting method in the Pig Latin translator (§1.6.3) looked like this:

```
/** The number of consonants at the beginning of W (a single word). */
static int consonants (String w) {
  return consonants (w, 0);
}

static int consonants (String w, int k) {
```

```
  if (w.length () <= k || isVowel (w.charAt (k)))
    return 0;
  else
    return 1 + consonants (w, k+1);
}
```

This looks like a reduction loop, as introduced in §1.8.2, except that we stop prematurely at the first vowel. Indeed, we can use the same structure:

```
static int consonants (String w) {
  int n;
  n = 0;
  for (int k = 0; k < w.length () && ! isVowel (w.charAt (k)); k += 1)
    n += 1;
  return n;
}
```

1.9 More on Arrays

You saw arrays in §1.4, where they were used as the argument to the main program. Array types are the most basic type used to hold sequences of items. If T is any type (so far, we've seen `int`, `long`, `char`, `double`, `boolean`, and `String`), then 'T`[]`' denotes the type "array of T." This definition is completely recursive, so that 'T`[][]`' is "array of array of T."

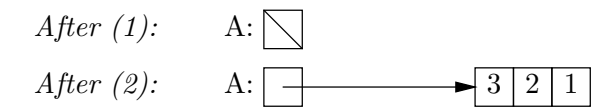
The array types are examples of what are called *reference types* in Java. This means that a declaration such as

```
int[] A;   // (1)
```

tells us that at any given time, `A` contains either a *reference* (or *pointer*) to an array of `int`s, or it contains something called the *null pointer,* which points at nothing (not even at an array containing 0 `int`s). For example, `A` declared above initially contains a null pointer, and after

```
A = new int[] { 3, 2, 1 };  // (2)
```

it contains a pointer to an array containing 3 `int`s: `A[0]==3`, `A[1]==2`, `A[2]==1`. You should keep pictures like this in your mind:



As illustrated in statement (2) above, one creates a new array for `A` to point to with the **new** operator. More commonly, you'll simply want to create an array of a given size first, and fill in its contents later. So you'll often see statements or declarations like these:

```
A = new int[100];
int[] B = new int[A.length];
```

which make `A` and `B` point at 100-element arrays, initially containing all 0's.

The syntax in (2) is convenient when using arrays to contain constant *tables* of values. For this purpose, Java (following C) allows a slightly condensed syntax when (and only when) you combine array declaration with creation. The following declaration, for example, is equivalent to (2):

```
int[] A = { 3, 2, 1 };
```

1.9.1 Example: Linear Interpolation

Interpolation is a procedure for approximating the value of a function at some point where its value is unknown from its (known) values at surrounding, known points. If the function is reasonably well-behaved (that is, continuous, and with a sufficiently small second derivative), one can *linearly interpolate* $y = f(x)$, given $y_i = f(x_i)$ and $y_{i+1} = f(x_{i+1})$, with $x_i \leq x \leq x_{i+1}$ and $x_i \neq x_{i+1}$ as

$$y \approx y_i + (y_{i+1} - y_i) \cdot \frac{x - x_i}{x_{i+1} - x_i} \tag{1.1}$$

We'd typically have an ascending sequence of x_i and would choose the two that bracketed our desired x.

Suppose we'd like to write a program to carry out linear interpolation. Actually, with such a common, useful, and well-defined procedure as interpolation, we'd probably be best advised to cast it as a general-purpose method, rather than a main program. This method would take as its arguments an ordered array of x_i values, an array of corresponding y_i (that is $f(x_i)$) values, and a value x. The output would be our approximation to $f(x)$:

```
public class Interpolate {

  /** Given XI in strictly ascending order, YI with
   *  0 < XI.length = YI.length, and X with
   *  XI[0] <= X <= XI[XI.length-1], a linear approximation
   *  to a function whose value at each XI[i] is YI[i]. */

  public static double eval (double x, double[] xi, double[] yi)
  {
     For some i such that x >= xi[i] and x <= xi[i+1],
      return
        yi[i] + (yi[i+1] - yi[i]) * ((x - xi[i]) / (xi[i+1] - xi[i]));
  }
}
```

You should be able to see that the **return** expression is just a transcription of formula (1.1).

To find `i`, an obvious approach is to work our way along `xi` until we find an adjacent pair of values that bracket `x`. We can use a **for** loop, like this:

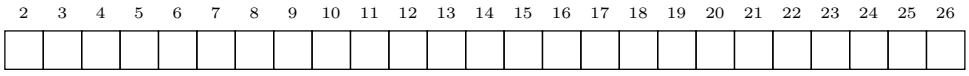
```
for (int i = 0; ; i += 1)
  if (xi[i] <= x && x <= xi[i+1])
    return ···;
```

The **return** statement has the effect of exiting the loop as well as returning a value. Since the documentation on this method requires that there be some `i` satisfying the **if** statement, we know that the function must eventually execute the **return**, if it is called properly.

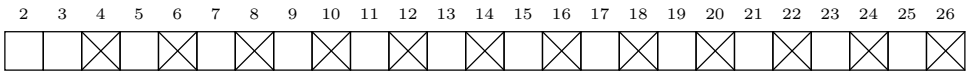
This raises a more general, and very important, engineering issue: what to do when a caller violates the "contract" established by a documentation comment. In this case, Java will catch such violations indirectly. If there is no value of `i` that works properly, or if the length of `yi` is shorter than that of `xi`, a call to this method will eventually cause an *exception* when the program tries to perform an array indexing operation with an index that's "off the end" of the array. We'll talk about these more in §1.14. For now it suffices to say that causing (in Java terminology, *throwing*) an exception halts the program with a somewhat informative message.

1.9.2 Example: The Sieve of Eratosthenes

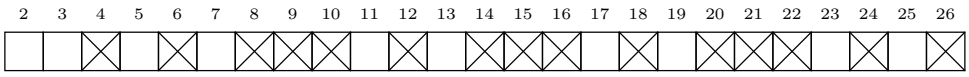
We've considered one way to find all primes by using a function that determines whether any particular integer is prime. There are ways to do compute primes "by the batch," one of the simplest of which is the *sieve of Eratosthenes.* The idea behind this algorithm is to find primes one at time, and for each prime found, to immediately eliminate all multiples of the prime from any further consideration. Conceptually, we start with a sequence of integers, like this:



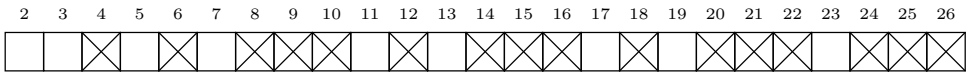
Starting at the left, we find the next empty box. Since it is marked '2', we cross off every second box, starting from $2^2 = 4$, giving



The process now repeats. The next empty box is marked '3', so we cross off each third box, starting from $3^2 = 9$, giving



Now cross off every fifth box starting from $5^2 = 25$, giving



No further work is needed (since 7^2 is off the end of our sequence), and the boxes that remain empty correspond to primes.

Why does this work? Basically, it is set up in such a way that we cross off every number that is divisible by some smaller prime. Since the primes are not divisible by smaller primes, they are never crossed off. We can start crossing starting off at the square because we know that if a prime p divides a composite number $q < p^2$, then q will already have been crossed off. This is because q/p is a factor of q and $q/p < p$ if $q < p^2$. So we crossed off q either when we processed q/p (if it is prime) or when we processed one of its (smaller) prime factors.

Java has no direct notion of "boxes that can be crossed off," so we must find a way to *represent* these with the constructs we do have. A convenient possibility is to use an array of **boolean** values, with, say **true** meaning "not crossed off" (possibly prime) and **false** meaning "crossed off" (definitely composite). Here is one possible implementation:

```
/** Returns an array, p, of size N+1 such that p[k] is true iff
 *  k is a prime. */
public static boolean[] primes (int n)
{
  boolean[] sieve = new boolean[n+1];
  /* Set all entries to true, except for 0 and 1. */
  for (int i = 2; i <= n; i += 1)
    sieve[i] = true;

  for (int k = 2; k*k <= n; k += 1) {
    /* If k is prime (has not been crossed off), then */
    if (sieve[k]) {
      /* Cross of every k'th number, starting from k*k */
      for (int j = k*k; j <= n; j += k)
        sieve[j] = false;
    }
  }

  return sieve;
}
```

To use this function in `printPrimes` (page 39):

```
private static void printPrimes (int limit) {
  boolean[] isPrime = primes (limit);
  int n;
```

```
    n = 0;
    for (int L = 2; L <= U; L += 1) {
      if (isPrime[L]) {
        if (n != 0 && n % 10 == 0)
          System.out.println ();
        System.out.print (L + " ");
        n += 1;
      }
    }
  }
```

1.9.3 Multi-dimensional Arrays

As the illustrations suggest, an array is naturally thought of as a one-dimensional sequence of things. Suppose, though, that we want to represent some sort of two-dimensional table of values—something like a matrix in linear algebra. One possibility is to make creative use of a one-dimensional array. For example, represent the matrix

$$A = \begin{pmatrix} 1 & 3 & 5 & 7 \\ 2 & 5 & 8 & 11 \\ 3 & 7 & 11 & 15 \end{pmatrix}$$

with the array

```
int[] A = { 1, 3, 5, 7, 2, 5, 8, 11, 3, 7, 11, 15 };
```

The problem is one of inconvenience for the programmer. Instead of typical mathematical notation such as $A_{i,j}$ for the element at row i and column j, one is forced to write `A[i * 4 + j]` instead (assuming rows and columns numbered from 0). Therefore, programming languages devoted to scientific computation (where you do this sort of thing a lot) usually have some notation specifically for multi-dimensional arrays as well.

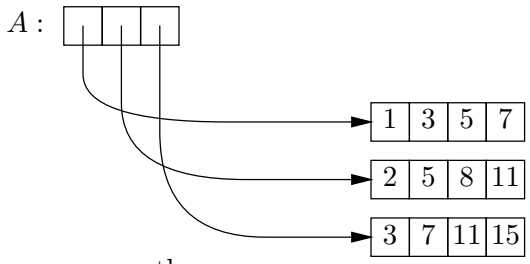
In Java, though, we can simply rely on the fact that arrays can be arrays of any type of value, including arrays. So, our 3×4 matrix, above, may be represented as an array of 3 4-element integer arrays:

```
int[][] A;
A = new int[][] { new int [] { 1, 3, 5, 7 },
                  new int [] { 2, 5, 8, 11 },
                  new int [] { 3, 7, 11, 15 } };
```

or, since this is very tedious to write, we can put everything into the declaration of `A`, in which case we are allowed a little abbreviation:

```
int[][] A = { { 1, 3, 5, 7 }, { 2, 5, 8, 11 }, { 3, 7, 11, 15 } };
```

Diagrammatically,



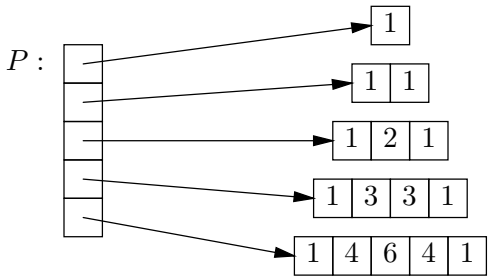
Now `A[i]` gives us the entire i^{th} row and `A[i][j]` gives us A_{ij}.

As for one-dimensional arrays, we also have the option of creating a "blank" array, and later filling it in, as in this program to create a Hilbert matrix, which is

$$\begin{pmatrix} 1 & 1/2 & 1/3 & 1/4\cdots \\ 1/2 & 1/3 & 1/4 & 1/5\cdots \\ 1/3 & 1/4 & 1/5 & 1/6\cdots \\ 1/4 & 1/5 & 1/6 & 1/7\cdots \\ \vdots & \vdots & \vdots & \vdots \end{pmatrix}$$

```
public static double[][] Hilbert (int N) {
  double[][] result = new double[N][N];
  for (int i = 0; i < N; i += 1)
    for (int j = 0; j < N; j += 1)
      result[i][j] = 1.0 / (i + j + 1);
  return result;
}
```

Although nice rectangular arrays such as these are the most common, the rows are all quite independent of each other, and nothing keeps us from creating more irregular structures, such as this version of Pascal's triangle (in which each square contains either 1 or the sum of the two squares above it):



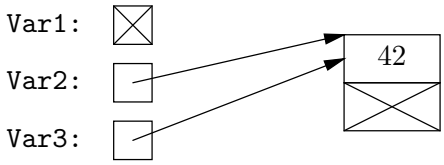
Here's a possible program for this purpose:

```
public static int[][] Pascal (int N) {
  // Create array of N initially null rows.
  int[][] result = new int[N][];
  for (int i = 0; i < N; i += 1) {
    // Set row #i to a row of i+1 0's.
```

```
      result[i] = new int[i+1];
      // The ends of the row are 1.
      result[i][0] = result[i][i] = 1;
      for (int j = 1; j < i-1; j += 1)
        result[i][j] = result[i-1][j-1] + result[i-1][j];
    }
    return result;
  }
```

1.10 Introduction to Objects

In §1.9, I mentioned that array types are examples of *reference types,* types in which the values are pointers to things (*objects*) that themselves can contain variables. The type `String` is another example. A simple variable of a reference type conceptually looks like one of the pictures below:



The variable `Var1` doesn't point at anything; it contains a *null pointer,* appropriately denoted **null** in Java. The variables `Var2` and `Var3` both contain pointers to the same object.

This particular object contains two variables, one an integer, and one a (null) pointer. You've already seen how to get at these variables (*instance variables*) in the case of an array: for an array pointed to by `A`, they are referred to `A.length` and `A[`i`]` for non-negative $i <$ `A.length` (the latter are usually called the *elements* of `A`). Arrays, however, are a special case. Let's look at some more typical objects.

1.10.1 Simple Object Type Definition and Creation

So far, we've used class declarations simply to contain static methods. They actually have another use: each class definition introduces a new type of object. For example, let's start with this simple declaration:

```
/** A point in 2-dimensional Euclidean space */
class Point {
  double x, y;
  other definitions
}
```

This tells us that `Point` is a type of object that contains two instance variables. A variable declaration such as

```
Point A, B;
```

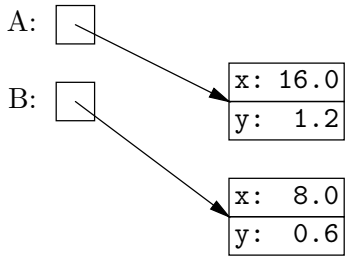
tells us that `A` and `B` can contain pointers to `Point` objects. Initially, however, `A` and `B` contain null pointers. The expression `new Point()` has as its value a new (i.e., never-before-seen) pointer to a `Point` object, so that after

```
A = new Point ();
B = new Point ();
```

`A` and `B` do point to `Point` objects. The instance variables are now available as `A.x` and `A.y`, so that after

```
A.x = 16.0; A.y = 1.2;
B.x = A.x / 2.0; B.y = A.y / 2.0;
```

we have



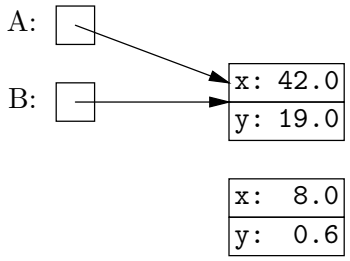
It's probably not too early to emphasize that `A` and `B` contain *pointers*, not `Point` objects. To see why this distinction matters, consider the result of

```
B = A;
B.x = 42.0; B.y = 19.0;
System.out.println ("A.x = " + A.x + ", A.y = " + A.y);
```

Here's what gets printed:

```
A.x = 42.0, A.y = 19.0
```

despite the fact that we never explicitly assigned to `A.x` or `A.y`. Here's the final situation pictorially:



As you can see, the object originally pointed to by `B` has not been changed (despite the assignment `B = A`), only `B` (the pointer variable) has changed so that it now contains the same contents (arrow) as does `A`. *The values of* `A` *and* `B` *are pointers, not objects.*

1.10.2 Instance Methods

The centrality of classes in the syntax of Java reflects an underlying philosophy of program construction, *object-based programming,* characterized by having programs organized by types of object. That is, the actual executable code is collected into methods that are themselves grouped by class (object type). From the programmer's point of view, a type of object is characterized by the operations that may be performed on it. We've seen one kind of operation: *selection* of fields (like `x` and `y` above) using '.' syntax. More generally, we'd like to be able to introduce arbitrarily complex operations; for this purpose we use methods.

So far, we've looked only at static methods, which correspond to ordinary subprograms such as are found in all programming languages. Like other object-based languages, Java provides an additional kind of method—an *instance method*—that is intended to be used on objects of a class. For example, suppose that we'd like to know how far a particular `Point` is from the origin. We might first try expanding the class as follows:

```
class Point {
  double x, y;

  /** Distance from P to the origin. */
  static double dist (Point p) {
    return Math.sqrt (p.x * p.x + p.y * p.y);
  }
}
```

And now, given a point `Q`, we write `Point.dist(Q)` to get its length. However, most Java programmers would write `dist` differently:

```
/** Distance of THIS from the origin. */
double dist () {
  return Math.sqrt (this.x * this.x + this.y * this.y);
}
```

Since we don't say **static**, this version of `dist` is an *instance method*. To use it on `Q`, we write `Q.dist()`.

The change is largely "syntactic sugar." In effect, an instance method, f, that is defined in a class named C

- Has an implicit first parameter that is not listed in the parameter list. The formal type of the parameter is C and its name is **this**;
- Is called using the syntax $E.f\ (\cdots)$, where E evaluates to a (non-null) C. E becomes the value of **this**, the implicit first parameter.

That is, the instance-method version of `dist` corresponds roughly to a static method declared:

```
static double dist (Point this) { ... }
```

and `Q.dist()` corresponds to `Point.dist(Q)` (however, **this** is reserved and you may not use it explicitly as a parameter name)[7].

As an additional shorthand, inside the methods of `Point`, the names of instance methods and variables are automatically prefixed with '`this.`' if they appear bare. So for example, we could write

```
class Point {
  double x, y;

  double dist () {
    return x*x + y*y;
  }
}
```

and the occurrences of `x` and `y` in `dist` are equivalent to `this.x` and `this.y`

1.10.3 Constructors

One particularly useful kind of method takes control at the time a new object is created. These are called constructors, and have their own special syntax; for our running example:

```
class Point {
  double x, y;

  /** A point whose coordinates are (x,y) */
  public Point (double x, double y) {
    this.x = x; this.y = y;
  }

  ...
}
```

The constructor is distinguished by having the same name as the class and no return type[8]. With this addition to `Point`, we may rewrite some previous initializations like this:

```
A = new Point (16.0, 1.2);
B = new Point (A.x / 2.0, A.y / 2.0);
```

In the absence of any explicit constructor, Java defines one with no parameters for you (which does nothing). However, now that we've defined a `Point` constructor,

[7] At this point, you may wonder why the designers of Java (and many previous object-based languages such as C++) chose such an annoyingly different syntax for instance methods. Your author wonders the same thing. This "worship of the first parameter" appears to be an historical accident resulting from somebody's bright idea unfortunately taking root. What can I say? It happens.

[8] Again, your author finds the introduction of new syntax for this purpose to be completely unjustified. This particular piece of gratuitous irregularity is inherited from C++.

Java doesn't automatically supply one and we can no longer write `new Point()`. If we still need to do so, we can introduce another definition:

```
/** A point whose coordinates are (x,y) */
public Point (double x, double y) {
  this.x = x; this.y = y;
}

/** The point (0,0) */
public Point () { }
```

This is an example of *overloading*—the use of the same name (in this case, the same constructor name) for two different functions, distinguished by how we call them.

1.10.4 Example: A Prime-Number Class

In §1.9.2, we saw how to compute batches of prime numbers, using an array as the data structure. Let's look at a typically object-based way of packaging the prime number sieve.

The main philosophical idea behind this design is that from the point of view of someone who needs to use prime numbers, the sieve is a set of prime numbers and the most important operation is a membership test: Is x in the set of prime numbers? This suggests a class that looks like this:

```
/** A finite set of prime numbers */
public class PrimeSieve {
  /** The set of prime numbers <= N. */
  public PrimeSieve (int N) { ... }

  /** A number, N, such that THIS contains exactly the primes <= N.
   *  (This was the number supplied to the constructor.) */
  public int limit () { ... }

  /** Returns true iff X is in THIS. */
  public boolean contains (int x) { ... }

  ...
}
```

I have been a bit more careful than usual, and used **public** to indicate that the class, its constructor, and the `limit` and `contains` methods are intended to be used anywhere in the program.

To complete the implementation of `PrimeSieve`, we copy in the pieces from §1.9.2 to give the result in Figure 1.2. This time, the actual sieve representation (the array) is declared to be **private**, and therefore not directly available outside of `PrimeSieve`. Since the only code that can touch the instance variable `sieve` is what's written here, we can be sure that as long as the program text in `PrimeSieve` works, these methods will give the answers their comments call for.

Finally, here's how we modify `printPrimes` to use this new class:

```
private static void printPrimes (int limit) {
  PrimeSieve primes = new PrimeSieve (limit);
  int n;
  n = 0;
  for (int L = 2; L <= U; L += 1) {
    if (primes.contains (L)) {
      if (n != 0 && n % 10 == 0)
        System.out.println ();
      System.out.print (L + " ");
      n += 1;
    }
  }
}
```

1.11 Interfaces

Let's break up the `printPrimes` method in §1.10.4 into a piece that knows about primes and one that knows about printing (on page 51):

```
private static void printPrimes (int limit) {
  printSet (new PrimeSieve (limit));
}

static void printSet (PrimeSieve set) {
  int n;
  n = 0;
  for (int L = 0; L <= set.limit (); L += 1) {
    if (set.contains (L)) {
      if (n != 0 && n % 10 == 0)
        System.out.println ();
      System.out.print (L + " ");
      n += 1;
    }
  }
}
```

I've modified the **for** loop in `printSet` so that it no longer assumes that the smallest prime is 2. As a result, the body of `printSet` would correctly display any set of non-negative numbers that provided `limit` and `contains` methods.

Java allows us to capture this fact by defining an *interface* that describes simple sets of non-negative integers:

```
/** A finite set of prime numbers */
public class PrimeSieve {
  /** The set of prime numbers <= N.  Requires N >= 0. */
  public PrimeSieve (int N) {
    sieve = new boolean[N+1];
    for (int i = 2; i <= n; i += 1)
      sieve[i] = true;
    for (int k = 2; k*k <= n; k += 1) {
      if (sieve[k]) {
        for (int j = k*k; j <= n; j += k)
          sieve[j] = false;
      }
    }
  }

  /** A number, N, such that THIS contains exactly the primes <= N.
   *  (This was the number supplied to the constructor.) */
  public int limit () { return sieve.length - 1; }

  /** Returns true iff X is in THIS. */
  public boolean contains (int x) {
    if (x < 0 || x >= sieve.length)
      return false;
    return sieve[x];
  }

  private boolean[] sieve;
}
```

Figure 1.2: The Sieve of Eratosthenes as a Java class.

```
/** A bounded set of natural numbers. */
public interface FiniteNaturalSet {
 /** A number, N, such that all numbers in THIS are <= N. */
 int limit ();

 /** Returns true iff X is in THIS. */
 boolean contains (int x);
}
```

There are no bodies for these methods: `FiniteNaturalSet` defines only what operations are available, not how they are to be done. Likewise, there is no constructor because this interface does not define a particular kind of set, with a particular representation, and there is no universal set of fields and initializations of those fields that must be used by all possible objects that supply these two methods. With this interface, we may now write

```
static void printSet (FiniteNaturalSet set) {
  ...
  for (int L = 0; L <= set.limit (); L += 1) {
    if (set.contains (L)) {
       ...
    }
  }
}
```

This will work for any `FiniteNaturalSet`, but to make it work again for our original application, we have to indicate that a `PrimeSieve` *is a* kind of `FiniteNaturalSet`, which we do like this:

```
public class PrimeSieve implements FiniteNaturalSet {
  The rest of PrimeSieve is as before
}
```

(We also say that `PrimeSieve` is a *subtype* of `FiniteNaturalSet`.) So basically, we're back where we were before except that should we need to print other sets of natural numbers, we will not have to write new versions of `printSet`. Instead, `printSet` will, in effect, adapt itself to any variety of `FiniteNaturalSet` object we pass to it, calling the `contains` and `limit` functions that were defined for that kind of set.

For example, here's a class that defines a set consisting of all perfect squares within some range[9]:

```
public class SquareSet implements FiniteNaturalSet {
  /** The set consisting of { LOW^2, (LOW+1)^2, ..., HIGH^2 },
   *  where 0 <= LOW, HIGH < square root of 2^31 */
  public SquareSet (int low, int high) {
```

[9]You might have to puzzle over how `contains` works here. Go ahead; it'll be good for you.

```
    this.low = low; this.high = high;
  }

  public int limit () { return high*high; }

  public boolean contains (int x) {
    if (x < low*low || x > high*high)
      return false;
    // Note: (int) E, where E is a double, truncates E (rounds toward
    // 0) to an integer value.
    int approx_root = (int) Math.sqrt (x);
    return (approx_root*approx_root == x ||
            (approx_root+1)*(approx_root+1) == x);
  }

  private int low, high;
}
```

so that now,

```
printSet (new SquareSet (1, 100))
```

prints all the squares up to 100^2. As you can see `SquareSet` is very different from `PrimeSieve`, even though both are `FiniteNaturalSets`. In particular, `SquareSet` does not compute all the squares in its constructor, but tests each argument to `contains` separately. All of this detail is irrelevant to `printSet`, and is hidden behind the interface.

1.12 Inheritance

As it happens, interfaces are just special cases of classes, which actually provide a more powerful facility. Specifically, interfaces are restricted not to contain instance variables or implementations of methods. We could instead have written

```
public abstract class FiniteNaturalSet {
 /** A number, N, such that all numbers in THIS are <= N. */
 public abstract int limit ();

 /** Returns true iff X is in THIS. */
 public abstract boolean contains (int x);
}
```

and then

```
public class PrimeSieve extends FiniteNaturalSet { ... }
```

(note the different keyword). As was the case for **implements**, a `PrimeSieve` is a `FiniteNaturalSet` by virtue of its declaration.

The keyword **abstract** roughly means "not completely implemented here." An unimplemented method may not be called, and to enforce this, an object of an abstract class may not be created (i.e., with **new**). This particular class must be abstract because it contains abstract (bodiless) methods. In effect, the **interface** keyword made all methods implicitly abstract and public. Unfortunately, it is not quite that simple: one can *implement* any number of interfaces, but can *extend* only one class.

Let's consider another example. Suppose that you were writing a program that dealt with geometrical figures in a plane—triangles, rhombi, circles, and the like. We anticipate that we'll need things like lists or sets that can contain any kind of figure, so we'll first need a general type that encompasses all figures. Its methods should be things that make sense for any figure. The class shown in Figure 1.3 (page 56) is one possibility. I've crammed quite a few features into it, so it warrants a bit of close study.

First, we see that there are two constructors, each of which constructs a `Figure` at a specific reference point. Constructor (2) simply creates a new reference `Point` and passes it to constructor (1); that's the meaning of `this(...)` in the first line of its body—"the other constructor whose only argument is a single `Point`."

Next we see that some of the methods—`type`, `location`, `translate`, and one `contains` method (4)—do have implementations. That's because we can write a sensible implementation for them that applies to all `Figures`. On the other hand, we have no general way to compute the area or extent of a `Figure`, based on the information given, so `area`, and one `contains` method are abstract. Once we know how to compute `contains(x,y)`, however, we can easily compute `contains(p)`, so the latter method *is* implemented. But how can it work if it calls an unimplemented method? Wait and see.

Now let's define a particular kind of `Figure`: a rectangle.

```
public class Rectangle extends Figure {
  /** A Rectangle with sides parallel to the axes, width W,
   *  height H, and lower-left corner X0, Y0. */
  public Rectangle (double x0, double y0, double w, double h) {  // (7)
    super (x0, y0);
    this.w = w; this.h = h;
  }

  public String type () {                        // (8)
    return "rectangle";
  }

  /** The area enclosed by THIS. */
  public double area () {                        // (9)
    return w * h;
  }
```

```
/** A closed figure in the plane.  Every Figure has a "reference
 *  point" within it, which serves as the location of the Figure. */
public abstract class Figure {
  /** A Figure with reference point P0. */
  public Figure (Point p0) {                    // (1)
    this.p0 = p0;
  }

  public Figure (double x0, double y0) {        // (2)
    this (new Point (x0, y0));
  }

  /** The generic name for THIS's type of figure
   *  (e.g., "circle").  This is the default implementation. */
  public String type () {                       // (3)
    return "2d figure";
  }

  /** The area enclosed by THIS. */
  public abstract double area ();

  /** True iff (X,Y) is inside THIS. */
  public abstract boolean contains (double x, double y);

  /** True iff P is inside THIS. */
  public boolean contains (Point p) {           // (4)
    return contains (p.x, p.y);
  }

  /** The reference point for THIS. */
  public Point location () { return p0; }       // (5)

  /** Translate (move) THIS by DX in the x direction and DY in the
   *  y direction. */
  public void translate (double dx, double dy) {// (6)
    p0.x += dx; p0.y += dy;
  }

  /** A rough printable description of THIS. */
  public String toString () {
    return type () + " at (" + p0.x + ", " + p0.y + ")";
  }

  private Point p0;
}
```

Figure 1.3: The abstract class representing all `Figures`. Its constructors deal only with its location.

```
  /* Continuation of Rectangle */

  /** True iff (X,Y) is inside THIS. */
  public boolean contains (double x, double y) {// (10)
    Point p = location ();
    return x >= p.x && x <= p.x+w
           && y >= p.y && y <= p.y+h;
  }

  private double w, h;
}
```

This class is not abstract—all its methods are implemented. Because it extends `Figure`, it *inherits* all the fields and methods that `Figure` has. That is, the implementations of methods (4), (5), and (6) are effectively carried over into `Rectangle` (so if `R` is declared

```
Rectangle R = new Rectangle (1.0, 2.0, 4.0, 3.0);
```

then `R.location ()` gives its location, the point (1.0,2.0)).

Since a `Rectangle` is a `Figure`, the constructor (7) must first call the constructor for `Figure`, which is the meaning of the "call" to `super` as the first line of its body. Next, the `Rectangle` constructor initializes the instance variables that are specific to it: `w` and `h`.

The `Rectangle` class provides implementations for `area` and the two-argument `contains` method. The call `R.contains(p)` (on method (4)) will call the `contains` method (10). A call on `R.toString ()` will return the result

```
rectangle at (1.0, 2.0)
```

That is, even though `toString` is defined in `Figure` at (3), this call will use the `type` function that is defined in `Rectangle` at (8). We say that definition (8) *overrides* definition (3). (Likewise, (9) and (10) override the matching definitions in `Figure`, but since the latter don't have bodies, there is nothing terribly surprising in that fact.)

What this all illustrates is that

> A call on an instance (i.e., non-static) method $A.f(\cdots)$ chooses which matching definition of f to use depending on the *current value* of A.

So if A's value is a pointer to a `Rectangle`, then the definition of f in the `Rectangle` class prevails (if there is no such method, we use the inherited definition).

Question: To test that you understand this rule, suppose we added the following method to the `Figure` class:

```
static void prt (Figure f) {
  System.out.println (f.toString ());
}
```

If we now execute the call

```
Figure.prt (new Rectangle (1.0, 2.0, 4.0, 3.0));
```

what happens?

Answer: Despite the fact that `prt` is defined in `Figure` and despite the fact that its formal parameter, `f`, is declared to be a `Figure`, this call prints

```
rectangle at (1.0, 2.0)
```

just as before. It is the *value* of `f` (a pointer to a rectangle) that matters, not its declared type. Yes, `f` points to a `Figure`, but it is a particular kind of `Figure`—specifically a `Rectangle`.

1.13 Packages and Access Control

The keywords **public**, **private**, and **protected** are features of the Java language that support what parts of your program have access to what instance variables, classes, and methods. They add no programming power, but are intended instead to support common notions of disciplined program design. The underlying idea is simple. The designer of a particular class in effect makes a "contract" with the users (*clients*) of the class that guarantees the behavior of particular methods. The clients, for their part, must supply legal arguments to these methods, and must keep their hands off the internals (methods and variables not mentioned in the contract).

The **public** keyword is a syntactic marker indicating classes and members that are part of the contract. The other possible keywords (and the absence of a keyword) indicate classes and members that are not part of the contract. Unfortunately, there are various degrees of "confidentiality," requiring more than one possible non-public access level. The obvious kind is indicated by the keyword **private**: a private member is accessible only within the actual text of a class definition; no other class knows about such members. When possible, make your non-public members private. Sometimes, however, more than one class must participate in implementing a feature, and perfect privacy is impractical.

For this purpose, Java allows us to group classes into *packages,* and to restrict some information to the package. The standard Java library contains quite a few packages. One of them, called `java.lang`, contains classes that are basic to the language (like `String`). The declaration

```
package numbers;

public class PrimeSieve extends FiniteNaturalSet { ...
```

as the first statement in our previous example tells us that `PrimeSieve` is in the package `numbers`, so that its full name (when referenced from outside the package) is `numbers.PrimeSieve`. Many programs tend to have no package declaration, which simply puts them in the *anonymous package.*

To look at a more generic case:

```
package demo;

public class A {              // (0)
  public A (int x) { ... }    // (1)
  A () { ... }                // (2)
  void f () { ... }           // (3)
  protected g () { ... }      // (4)
  private h () { ... }        // (5)
}

class B {                     // (6)
  ...
}
```

This tells us that declarations (2), (3), and (6) are *package private:* they may be used only in package `demo`. As a result, in package `demo`, one can write `new A()`, but outside one can only write `new A(3)`. The restrictions on protected declaration (4) are a little looser, classes that extend `demo.A` may also call `g`, even if those classes are not in package `demo`.

You will find it annoying to denote classes by their full *qualified* names all the time. This is especially true of the Java standard library classes—`java.util.Map` is not a particularly enlightening elaboration of `Map`, for example. There are four useful devices to alleviate this annoyance and let you use an unqualified or *simple* name instead of the fully qualified name:

- The declaration

  ```
  import java.util.Map;
  ```

  at the beginning of a program (after any **package** declaration, and before any class declaration) means that the simple name `Map` may be substituted for `java.util.Map` in this file.

- The declaration

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

  in effect imports all the classes in the package `java.util`.

- Finally, all programs have an implicit `import java.lang.*;` at the beginning. Therefore, you can always write `String` rather than `java.lang.String` and `Object` rather than `java.lang.Object`.

- Within the text of a definition in a package, names of other classes and interfaces in the package don't have to be qualified.

1.14 Handling Exceptional Cases

A sad fact of software life is that inordinate amounts of programmers' time is spent writing program text whose sole purpose is to detect erroneous conditions. This fact is reflected in many modern programming languages, in the form of features that are intended to detect erroneous uses of the language, and to report such errors or refer them to parts of the program that can deal with them. In Java, this reporting device is called *throwing an exception.*

1.14.1 Built-in Exceptions

There are any number of things that one's program is Not Supposed to Do. For example, the following is wrong:

```
class Bad {
  static void blowUp () {
    String s = null;
    if (s.equals (""))          // (??)
      System.out.println ("Oops!");
  }

  public static void main (String[] args) {
    blowUp ();
  }
}
```

The problem is that you have tried to call the `equals` method (an instance method) on a "non-instance"—the null pointer doesn't point at anything. Java responds by throwing an exception when the condition at (??) is evaluated. Assuming you are not expecting it, what probably happens is that your entire program grinds to a halt with a message such as this:

```
Exception in thread "main" java.lang.NullPointerException
        at Bad.blowUp(Bad.java:4)
        at Bad.main(Bad.java:9)
```

which tells us where the error occurred (in the method `Bad.blowUp` in file `Bad.java` at line 4) and how we got to that point (we were called from `Bad.main` at line 9 of the same file). This message (called a *back trace* or *stack trace*) also gives us the *exception type:* `NullPointerException`, which is suggestively named to tell us what we did wrong.

You'll get any number of similar messages for other programming errors, such as attempting to use an array index that is out of bounds, or attempting to do an integer division by 0.

1.14.2 What Exactly is an Exception?

It is typical in object-oriented programming that nouns used informally to describe the important concepts or entities in one's program are turned into classes of object.

Accordingly, "exception" in Java is actually a class of object known as `Throwable` (full name `java.lang.Throwable`, see §1.13), which has numerous subtypes that extend it, each one representing a particular kind of exceptional condition. These exceptions are organized into three broad categories under three of the subtypes: `Error` intended for calamitous program-stopping problems such as running out of memory; `RuntimeException` for exceptions caused by built-in operations (e.g., `NullPointerException`) or other programmer errors; and `Exception` for conditions that are not necessarily programmer errors (for example, that may be caused by I/O errors or other conditions that arise outside the program).

1.14.3 Throwing Exceptions Explicitly

The **throw** statement throws an exception. Here's a simple extension to one of our previous examples:

```
/** True iff X is divisible by any positive number >=K and < X,
 *  given K > 1. */
private static boolean isDivisible (int x, int k) {
  if (k <= 1)
    throw new IllegalArgumentException ();
  ...
}
```

`IllegalArgumentException` is conveniently supplied as part of the Java library to allow one to signal, well, illegal arguments. As you can see, the **throw** command takes a single operand, a pointer to some kind of `Throwable` object, which in this case (as is usually done, in fact) we create on the spot with `new`.

1.14.4 Catching Exceptions

Sometimes, you expect to receive an exception—for example many input/output operations carry the possibility of an externally caused error. Robust programs are prepared for such events. Java provides a way to say "I know that exceptions of type X can occur during the execution of statements S. If one does, perform statements E." For example, to starting read a file Java, one often does something like this:

```
Reader openFile (String fileName) {
  try {
    return new FileReader (fileName);
  } catch (FileNotFoundException e) {
    System.err.println ("Could not open file " + fileName);
    return null;
  }
}
```

to indicate that the program should print an error message if the desired file cannot be found.

Chapter 2

Describing a Programming Language

A *programming language* is a notation for describing computations or processes. The term "language" here is technically correct, but a little misleading. A programming language is enormously simpler than any human (or *natural*) language, for the simple reason that for it to be useful, somebody has to write a program that converts programs written in that language into something that runs on a computer. The more complex the language, the harder this task. So, programming "languages" are sufficiently simple that, in contrast to English, one can actually write down complete and precise descriptions of them (at least in principle).

2.1 Dynamic and Static Properties

Over the years, we've developed standard ways to describe programming languages, using a combination of formal notations for some parts and semi-formal prose descriptions for other parts. A typical language description consists of a *core*—the general rules that determine what the legal (or *well-formed*) programs are and what they do—plus *libraries* of definitions for standard, useful program components. The description of the core, in turn, typically divides into *static* and *dynamic* properties.

Static properties. In computer science, we use the term *static* in several senses. A static language property is purely a property of the *text* of a program, independent of any particular set of *data* that might be input to that program. Together, the static properties determine which programs are *well-formed;* we only bother to define the effects of well-formed programs. Traditionally, we divide static properties into *lexical structure, (context-free) syntax,* and *static semantics.*

- *Lexical Structure* refers to the alphabet from which a program may be formed and to the smallest "words" that it is convenient to define (which are called *tokens, terminals,* or *lexemes.)* I put "word" in quotes because tokens can be far more varied than what we usually call words. Thus, numerals, identifiers, punctuation marks, and quoted strings are usually identified as tokens.

Rules about what comments look like, where spaces are needed, and what significance ends of lines have are also considered lexical concerns.

- *Context-free Syntax* (or *grammar*) refers roughly to how tokens may be put together, ignoring their meanings. We call a "sentence" such as "The a; walk bird" syntactically incorrect or ungrammatical. On the other hand, the sentence "Colorless green ideas sleep furiously" is grammatical, although meaningless[1].

- *Static Semantics* refers to other rules that determine the meaningfulness of a program ("semantics" means "meaning"). For example, the rule in Java that all identifiers used in a program must have a definition is a static semantic rule.

The boundaries between these three may seem unclear, and with good reason: they are rather arbitrary. We distinguish them simply because there happen to be convenient notations for describing lexical structure and context-free syntax. There is considerable overlap between the categories, and sometimes it is a matter of taste which notation one uses for a particular part of a programming language's description.

Dynamic Properties. The *dynamic semantics* of a program refers to its meaning as a computation—what it does when it is executed (assuming, of course, that the rules governing static properties of the programming language tell us that it is well-formed). For example, the fact that `x+y` fetches the current values of variables `x` and `y` and yields their sum is part of the dynamic semantics of that expression. In general, the term *dynamic* in the context of programming languages refers to properties that change (or are only determined) during the execution of a program. For example, the fact that the expression `x>y` yields a boolean (true/false) value is a static property of the expression, while the actual value of the expression during a particular evaluation is a dynamic property. As usual, the boundaries between static and dynamic can be unclear. For example, the evaluation of `3>4` follows the same rules for '`>`' as does the evaluation of `x>y`, but its value is always the same (**false**). Should we call the value of `3>4` a static or dynamic property? We'll generally follow the sensible course of simply ignoring such questions.

Libraries. In one sense, a program consists of a set of definitions, all building on one another, one of which may be identified as the "main program." There have to be some primitive definitions with which to start. The core defines some of these primitive definitions, and others come from *libraries* of definitions. Typically, there will be set of libraries—referred to as the *standard (runtime) library* or sometimes as the *standard prologue*—that "comes with" the programming language, and is present in every implementation. One could consider it part of the core, except that it is typically described as a set of declarations of the sort that any program could contain.

[1] This sentence is a famous example due to Noam Chomsky.

2.2 Describing Lexical Structure and Syntax

The original description of the Algol 60 language[2] is the model on which many other "official" descriptions of programming languages have been based. It introduced a novel notation (adapted, really, from linguistics) for describing the (context-free) syntax of a language that came to be known as Backus-Naur Form or Backus Normal Form after its inventors (the usual abbreviation, *BNF,* works for both)[3]. In this book, we'll use a somewhat extended version of BNF notation.

The basic idea is simple. A BNF description is a sequence of definitions of what are called *syntactic variables,* or *nonterminals.* Each such variable stands for a set of possible phrases. One distinguished variable (the *start symbol*) stands for the set of all grammatical phrases in the language we are trying to describe. For example[4]:

Sentence: NounPhrase VerbPhrase
NounPhrase: Adjective NounPhrase
NounPhrase: Adjective PluralNoun
VerbPhrase: PluralVerb $Adverb_{opt}$
Adjective: `laughing`
Adjective: `little`
SingularNoun: `boys`
SingularNoun: `girls`
SingularVerb: `ran`
Adverb: `quickly`

Read the first definition, for example as "A *Sentence* may be formed from a *NounPhrase* followed by a *VerbPhrase*." We read ':' as "may be" as opposed to "is," because as you can see, there can be several ways to form certain kinds of phrase. The second definition illustrates *recursion:* a *NounPhrase* may be formed from an *Adjective* followed by a (smaller) *NounPhrase.* The recursion stops when we use the second definition of *NounPhrase.* The definition of *VerbPhrase* illustrates a useful piece of notation: the subscript '*opt*' to indicate an optional part of the definition. Equivalently, we could have written

VerbPhrase: PluralVerb Adverb
VerbPhrase: PluralVerb

Each of the terms that does not appear to the left of a ':' is a *terminal symbol.* Our convention will be that non-italicized terminals "stand for themselves"—thus, "laughing little boys ran" is a phrase generated by this grammar. As you can see,

[2]P. Nauer, ed., "Report on the Algorithmic Language Algol 60," *Comm ACM*, 6(1), 1963, pp. 1–17.

[3]In notations where the same thing can be written in many different ways, a *normal form* for some expression is supposed to be a particular choice among these different ways that is somehow unique. For example, the expressions $x-3$, $x+(-3)$, $-3+x$, and $1\cdot x-5+2$ all refer to the same value for any x. A normal form might be "$a\cdot x+b$, where a and b are constants." There is only one way to write the expression that way: $1\cdot x+(-3)$. BNF does *not* have this property, so of the two names, I prefer Backus-Naur Form.

[4]This example is adapted from Hopcroft and Ullman, *Formal Languages and Their Relation to Automata,* Addison-Wesley, 1969.

we don't mention *lexical* details such as blanks when giving grammar rules; we'll deal with those details separately.

There are several pieces of notational trickery we'll use to shorten definitions a bit. Multiple definitions of the same nonterminal may be collected together and written either like this:

NounPhrase: Adjective NounPhrase | *Adjective PluralNoun*

(that is, read '|' as "or"). With longer definitions, we'll usually use the following style:

NounPhrase:
    Adjective NounPhrase
    Adjective PluralNoun

The effect of our definition of *NounPhrase* is to define it to be a sequence of one or more *Adjectives* followed by a *PluralNoun.* We'll sometimes use a traditional shorthand for this and write its definition as simply

NounPhrase: Adjective^{+} *PluralNoun*

The raised '+' means "one or more." Similarly, there is a related notation that we might use to define another kind of *NounPhrase* in which the *Adjectives* are optional:

SimpleNounPhrase: Adjective* *PluralNoun*

The asterisk here (called the *Kleene star*) means "zero or more."

Two other common cases are the "list of one or more Xs separated by Ys" and the "list of one or more Xs separated by Ys," which one can write as in these examples:

ExpressionList: Expression | *ExpressionList* **,** *Expression*
ParameterList: ExpressionList$_{opt}$

Rather than defining new nonterminals, however, we'll allow a shorthand that replaces *ExpressionList* and *ParameterList* with

Expression$^{+}_{\textbf{,}}$
Expression$^{*}_{\textbf{,}}$

respectively.

Continuing lines. Sometimes a definition gets too long for a line. Our convention here is to indent continuation lines to indicate that they are *not* alternatives. For example, this is one continued alternative, not two:

BasicClassDeclaration:
    class *SimpleName Extends*$_{opt}$ *Implements*$_{opt}$
        `{` *ClassBodyDeclaration** `}`

Chapter 3

Values, Types, and Containers

A programming language is a notation for describing the manipulation of some set of conceptual entities: numbers, strings, variables, and functions, among others. A description of this set of entities—of what we call the *semantic domain* of the language—is therefore central to the description of a programming language. To experienced programmers, the notation itself—the syntax of the language—is largely a convenient veneer; the semantic domain is what they are really talking about. They think "behind the syntax" to the effects of their programs on the denizens of the semantic domains, or as the Cornell computer scientist David Gries puts it, they program *into* a programming language rather than *in* it.

To set the stage for what is to come, this chapter is devoted to developing a model for Java's semantic domain, one that is actually applicable to a large range of programming languages. Our model consists of the following components:

Values are "what data are made of." They include, among other things, integers, characters, booleans (true and false), and pointers. Values, as I use the term, are *immutable;* they never change.

Containers contain values and other containers. Their contents (or *state*) can vary over time as a result of the execution of a program. Among other things, I use the term to include what are elsewhere called *objects.* Containers may be *simple,* meaning that they contain a single value, or *structured,* meaning that they contain other containers, which are identified by names or indices. A container is *named* if there is some label or identifier a program can use to refer to it; otherwise it is *anonymous.* In Java, for example, local variables, parameters, and fields are named, while objects created by **new** are anonymous.

Types are, in effect, tags that are stuck on values and containers like Post-it$^{\text{tm}}$ notes. Every value has such a type, and in Java, so does every container. Types on containers determine the types of values they may contain.

Environments are special containers used by the programming language for its local and global named variables.

3.1 Values and Containers

One of the first things you'll find in an official specification of a programming language is a description of the primitive values supported by that language. In Java, for example, you'll find seven kinds of number (types **byte**, **char**, **short**, **int**, **long**, **float**, and **double**), true/false values (type **boolean**), and pointers. In C and C++, you will also find functions (there are functions in Java, too, but the language doesn't treat them as it does other values), and in Scheme, you will find rational numbers and symbols.

The common features of all values in our model are that they have types (see §3.2) and they are *immutable;* that is, they are changeless quantities. We may loosely speak of "changing the value of `x`" when we do an assignment such as '`x = 42`' (or '`(set! x 42)`') but under our model what really happens here is that `x` denotes a *container,* and these assignments remove the previous value from the container and deposit a new one. At first, this may seem to be a confusing, pedantic distinction, but you should come to see its importance, especially when dealing with pointers.

3.1.1 Containers and Names

A *container* is something that can contain values and other containers. Any container may either be *labeled* (or *named*)—that is, have some kind of name or label attached to it—or *anonymous*. A container may be simple or structured. A *simple container,* represented in my diagrams as a plain rectangular box, contains a single value. A *structured container* contains other containers, each with some kind of label; it is represented in diagrams by nested boxes, with various abbreviations. The full diagrammatic form of a structured container consists of a large container box containing zero or more smaller containers[1], each with a *label* or *name,* as in Figure 3.1a. Figures 3.1b–e show various alternative depictions that I'll also use. The inner containers are known as *components, elements* (chiefly in arrays), *fields,* or *members.*

An *array* is a kind of container in which the labels on the elements are themselves values in the programming language—typically integers or tuples of integers. Figure 3.2 shows various alternative depictions of a sample array whose elements are labeled by integers and whose elements contain numbers.

3.1.2 Pointers

A *pointer* (also known as a *reference*[2]) is a value that designates a container. When I draw diagrams of data structures, I will use rectangular boxes to represent containers

[1]The case of a structured container with no containers inside it is a bit unusual, I admit, but it does occur.

[2]For some reason, numerous Java enthusiasts are under the impression that there is some well-defined distinction between "references" and "pointers" and actually attempt to write helpful explanations for newcomers in which they assume that sentences like "Java has *references,* not *pointers*" actually convey some useful meaning. They don't. The terms are synonyms.

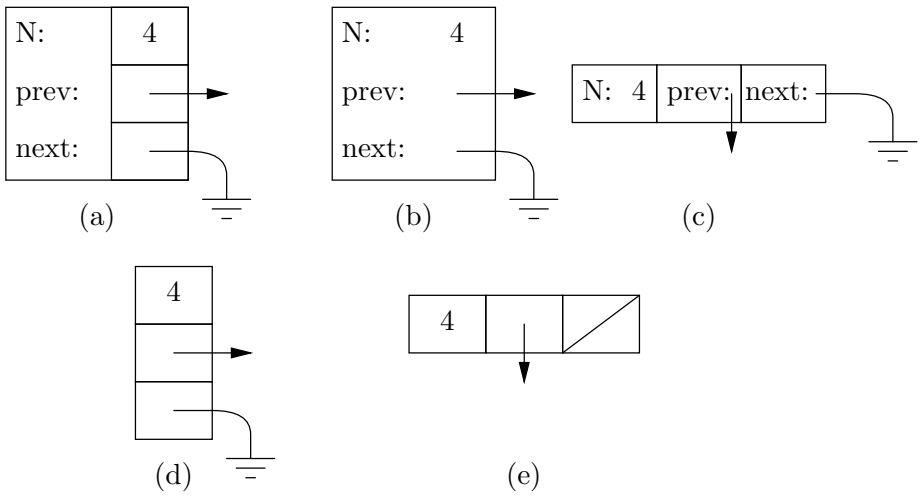


Figure 3.1: A structured container, depicted in several different ways. Diagrams (d) and (e) assume that the labels are known from context.

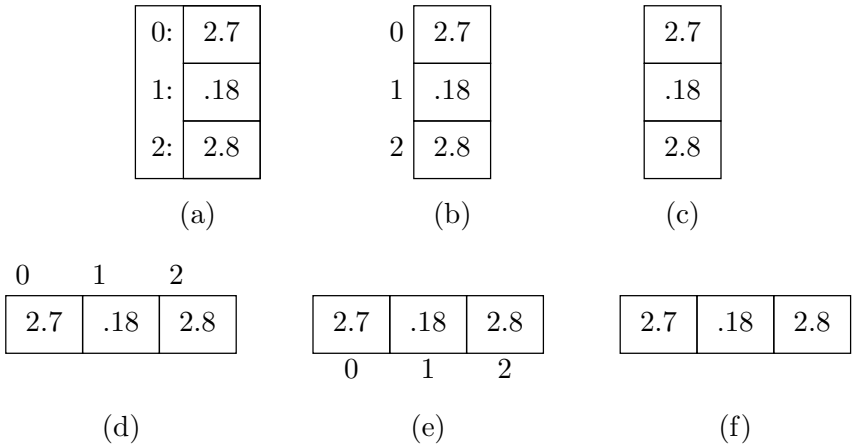
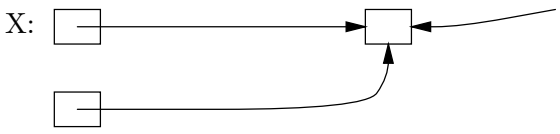
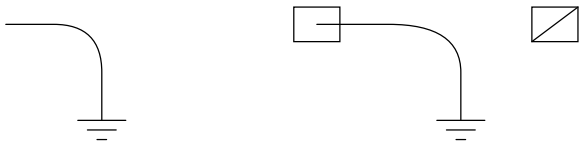


Figure 3.2: Various depictions of one-dimensional array objects. The full diagram, (a), is included for completeness; it is generally not used for arrays. The diagrams without indices, (c) and (f), assume that the indices are known from context or are unimportant.



(a) All pointers here are equal.



(b) Null pointers.

Figure 3.3: Diagrammatic representations of pointers.

and arrows to represent pointers. Two pointer values are the same if they point to the same container. For example, all of the arrows in Figure 3.3a represent equal pointer values. As shown there, we indicate that a container contains a certain pointer value by drawing the pointer's tail inside the container. The operation of following a pointer value to the container at its head (i.e., its point) in order to extract or store a value is called *dereferencing* the pointer, and the pointed-to container is the *referent* of the pointer.

Certain pointer values are known as *null pointers*, and point at nothing. In diagrams, I will represent them with the electrical symbol for ground, or use a box with a diagonal line through it to indicate a container whose value is a null pointer. Figure 3.3b illustrates these conventions with a "free-floating" null pointer value and two containers with a null pointer value. Null pointers have no referents; dereferencing null pointers is undefined, and generally erroneous.

Value or Object? Sometimes, it is not entirely clear how best to apply the model to a certain programming language. For example, we model a pair in Scheme as an object containing two components (`car` and `cdr`). The components of the pair have values, but does the pair *as a whole* have a value? Likewise, can we talk about the value in the arrays in Figure 3.2, or only about the values in the individual elements? The answer is a firm "that depends." We are free to say that the container in Figure 3.2a has the value `<2.7, 0.18, 2.8>`, and that assigning, say, 0 to the first element of the array replaces its *entire* contents with the value `<0, 0.18, 2.8>`. In a programming language with a lot of functions that deal with entire arrays, this would be useful. To describe Java, however, we don't happen to need the concept of "the value of an array object."

3.2 Types

The term "type" has numerous meanings. One may say that a type is a set of values (e.g., "the type **int** is the set of all values between -2^{31} and $2^{31} - 1$, inclusive.").

Or we may say that a type is a programming language construct that defines a set of values and the operations on them. For the purposes of this model, however, I'm just going to assume that a type is a sort of *tag* that is attached to values and (possibly) containers. Every value has a unique type. This model does *not* necessarily reflect reality directly. For example, in typical Java implementations, the value representing the character `'A'` is indistinguishable from the integer value 65 of type **short**. These implementations actually use other means to distinguish the two than putting some kind of marker on the values. For us programmers, however, this is usually an invisible detail.

Any given programming language provides some particular set of these type tags. Most provide a way for the programmer to introduce new ones. Few programming languages, however, provide a direct way to look at the tag on a value (for various reasons, among them the fact that it might not really be there!).

3.2.1 Static vs. dynamic types

When *containers* have tags (they don't have to; in Scheme, for example, they generally don't), these tags generally determine the possible values that may be contained. In the simplest case, a container labeled with type T may only contain values of type T. In Java (and C, C++, FORTRAN, and numerous other languages), this is the case for all the numeric types. If you want to store a value of type **short** into a container of type **int**, then you must first *coerce* (a technical term, meaning *convert*) the **short** into an **int**. As it happens, that particular operation is often merely notional; it doesn't require any machine instructions to perform, but we can still talk that way.

In more complex cases, the type tag on a container may indicate that the values it contains can have one of a whole set of possible types. In this case, we say that the allowable types on values are *subtypes* of the container's type. In Java, for example, if the definition of class `Q` contains the clause "**extends** `P`" or "**implements** `P`," then `Q` is a subtype of `P`; a container tagged to contain pointers to objects of type `P` may contain pointers to objects of type `Q`. The subtype relation is transitive: any subtype of `Q` is also a subtype of `P`. As a special case, any type is a subtype of itself; we say that one type is a *proper subtype* of another to mean that it is an unequal subtype.

If type C is a subtype of type P, and V is a value whose type tag is C, we say that "V *is a* P" or "V *is an instance of* P." Unfortunately, this terminology makes it a little difficult to say that V "really is a" P and not one of its proper subtypes, so in this class I'll say that "the type of V *is exactly* P" when I want to say that.

In Java, all objects created by **new** are anonymous. If `P` is a class, then the declaration

```
P x;
```

does *not* mean that "`x` contains objects of type `P`," but rather that "`x` contains *pointers to* objects of type `P` (or null)." If `Q` is a subtype of `P`, furthermore, then the type "pointer to `Q`" is a subtype of "pointer to `P`." However, because it is extremely

burdensome always to be saying "`x` contains a pointer to `P`," the universal practice is just to say "`x` is a `P`." After this section, I'll do that, too, but until it becomes automatic, I suggest that you consciously translate all such shorthand phrases into their full equivalents.

All this discussion should make it clear that the tag on a value can differ from the tag on a container that holds that value. This possibility causes endless confusion, because of the rather loose terminology that arose in the days before object-oriented programming (it is object-oriented programming that gives rise to cases where the confusion occurs). For example, the following Java program fragment introduces a variable (container) called `x`; says that the container's type is (pointer to) `P`; and directs that a value of type (pointer to) `Q` be placed in `x`:

```
P x = new Q ();
```

Programmers are accustomed to speak of "the type of `x`." But what does this mean: the type of the value contained in `x` (i.e., pointer to `Q`), or the type of the container itself (i.e., pointer to `P`)?

We will use the phrase "the *static type* of `x`" to mean the type of the container (in the example above, this type is "pointer to `P`"), and the phrase "the *dynamic type* of `x`" to mean the type of the value contained in `x` (in the example above, "pointer to `Q`"). This is an extremely important distinction! Object-oriented programming in Java or C++ will be a source of unending confusion to you until you understand it completely.

3.2.2 Type denotations in Java

A *type denotation* is a piece of syntax that names a type.

Syntax.

Type: *PrimitiveType* | *ReferenceType*
PrimitiveType:
    boolean
    byte | **char** | **short** | **int** | **long**
    float | **double**
ReferenceType:
    ClassOrInterfaceType | *ArrayType*
ClassOrInterfaceType: *Name* $TypeArguments_{opt}$
ClassType: *Name* $TypeArguments_{opt}$
InterfaceType: *Name* $TypeArguments_{opt}$
ArrayType: *Type* `[ ]`
TypeArguments: `<` $ActualTypeArgument^{+}_{,}$ `>`
ActualTypeArgument:
    ReferenceType
    Wildcard
Wildcard: `?` $WildcardBounds_{opt}$

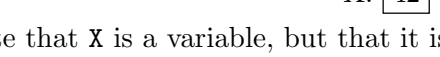
WildcardBounds:
extends *ReferenceType*
super *ReferenceType*

As the names suggest, the *Name* in a *ClassOrInterfaceType* must be the name of a class or interface, the name of a class in a *ClassType*, and of an interface in an *InterfaceType*. We've already seen examples of defining simple classes and interfaces. See §6 for the significance of *TypeArguments*.

3.3 Environments

In order to direct a computer to manipulate something, you have to be able to mention that thing in your program. Programming languages therefore provide various ways to *denote* values (literal constants, such as `42` or `'Q'`) and to denote (or *name*) containers. Within our model, we can imagine that at any given time, there is a set of containers, which I will call the *current environment,* that allows the program to get at anything it is supposed to be able to reach. In Java (and in most other languages as well) the current environment cannot itself be named or manipulated directly by a program; it's just used whenever the program mentions the name of something that is supposed to be a container. The containers in this set are called *frames*. The named component containers inside them are what we usually call local variables, parameters, and so forth. You have already seen this concept in CS 61A, and might want to review the material from that course.

When we have to talk about environments, I'll just use the same container notation used in previous sections. Occasionally, I will make use of "free-floating" labeled containers, such as



to indicate that `X` is a variable, but that it is not important to the discussion what frame it sits in.

3.4 Applying the model to Java

As modern languages in the Algol family go, Java is fairly simple[3]. Nevertheless, there is quite a bit to explain. Here is a summary of how Java looks, as described in the terminology of our model. We'll get into the details of what it all means in a later note.

- All simple containers contain either numeric values, booleans, or pointers (known as *references* in Java). (There are also functions, but the manipulation of function-valued containers is highly restricted, and not entirely accessible to programmers. We say no more about them here.)

[3] Algol 60 (ALGOrithmic Language) was the first widely used language with the kind free-format syntax familiar to C, C++, and Java users. It has, in fact, been called "a marked improvement on its successors."

- All simple containers are named and only simple containers are named. The names are either identifiers (for variables, parameters, or fields) or non-negative integers (for array elements).
- All simple containers have well-defined initial values: 0 for numerics, **false** for booleans, and **null** for pointers.
- The referents of pointers are always anonymous structured containers (called *objects* in Java).
- Aside from environments, objects are created by means of the **new** expression, which returns a pointer (initially the only one) to a new object.
- Each container has a static type, restricting the values it may contain. A container's type may be *primitive*—which in Java terminology means that it may one of the numeric types or **boolean**—or it may be a *reference type,* meaning that it contains pointers to objects (including arrays). If a container's static type is primitive, it is the same as its dynamic type (that is, the type of the container equals the type of the value). If a container has a reference type, then its dynamic type is a subtype of the container's type.
- Named containers comprise local variables, parameters, instance variables, and class variables. Every function call creates a *subprogram frame,* (or *procedure frame,* or *call frame*), which contains parameters and local variables. The **new** operator creates *class objects* and *array objects,* which contain instance variables (also called *fields* in the case of class objects and *elements* in the case of arrays). The type of a class object is called, appropriately enough, a *class.* Each class has associated with it a frame that (for lack of a standard term) I will call a *class frame,* which contains the class variables (also called *static variables*) of the class.

Chapter 4

Numbers

4.1 Integers and Characters

The Scheme language has a notion of integer data type that is particularly convenient for the programmer: Scheme integers correspond directly to mathematical integers and there are standard functions that correspond to the standard arithmetic operations on mathematical integers. While convenient for the programmer, this causes headaches for those who have to implement the language. Computer hardware has no built-in data type that corresponds directly to the mathematical integers, and the language implementor must build such a type out of more primitive components. That is easy enough, but making the resulting arithmetic operations fast is not easy.

Historically, therefore, most "traditional" programming languages don't provide full mathematical integers either, but instead give programmers something that corresponds to the hardware's built-in data types. As a result, what passes for integer arithmetic in these languages is at least quite fast. What I call "traditional" languages include FORTRAN, the Algol dialects, Pascal, C, C++, Java, Basic, and many others. The integer types provided by Java are in many ways typical.

4.1.1 Integral values and their literals

Syntax

IntegerLiteral: *IntegerNumeral* $IntegerTypeSuffix_{opt}$
IntegerNumeral: `0`
    PositiveDigit $DecimalDigit^{+}$
    `0` $OctalDigit^{+}$
    `0x` $HexDigit^{+}$
    `0X` $HexDigit^{+}$
PositiveOctalDigit: `1` | `2` | `3` | `4` | `5` | `6` | `7`
OctalDigit: `0` | *PositiveOctalDigit*
PositiveDigit: *PositiveOctalDigit* | `8` | `9`
DecimalDigit: `0` | *PositiveDigit*

Type	Modulus	Minimum	Maximum
`long`	2^{64}	-2^{63} (-9223372036854775808)	$2^{63}-1$ (9223372036854775807)
`int`	2^{32}	-2^{31} (-2147483648)	$2^{31}-1$ (2147483647)
`short`	2^{16}	-2^{15} (-32768)	$2^{15}-1$ (32767)
`byte`	2^{8}	-2^{7} (-128)	$2^{7}-1$ (127)
`char`	2^{16}	0 0	$2^{16}-1$ (65535)

Table 4.1: Ranges of values of Java integral types. Values of a type represented with n bits are computed modulo 2^n (the "Modulus" column).

HexDigit:
    DecimalDigit
    `a` | `b` | `c` | `d` | `e` | `f`
    `A` | `B` | `C` | `D` | `E` | `F`
IntegerTypeSuffix: `l` | `L`

An integer literal is an atomic element of the syntax (or *token*); it may not contain whitespace, and must be separated from other tokens that can contain letters and digits by whitespace or punctuation.

Semantics. The integral values in Java differ from the ordinary mathematical integers in that they come from a finite set (or *domain*). Specifically, the five integer types have the ranges shown in Table 4.1. As we will see in §4.1.2, arithmetic on Java integers is also different from familiar arithmetic; Java uses *modular arithmetic:* when a computation would "overflow" the range of values for a type, the value yielded is a *remainder* of division by some *modulus.*

Only types **char**, **int**, and **long** specifically have literals; to get values of other types, one can use *casts.* The cast notation '`(`T`)` V' means "V converted to type T". Thus,

```
(short) 15  // is a short value
(byte) 15   // is a byte value.
```

The *IntegerLiterals* above denote values of type **long** if suffixed with a lower- or upper-case letter '`L`', and otherwise denote values of type **int**. You have your choice of decimal, octal (base 8), and hexadecimal (base 16) numerals. The digits for the extra six values needed for base 16 are denoted by the letters a–f in either upper or lower case.

One odd thing about the syntax is that there is no provision for negative numbers. Instead, negative literals are treated as negated expressions elsewhere in the grammar, so that, for example, `-1` is treated as two tokens, a minus sign followed by an integer literal. For your purposes, the effect is just about the same. Unfortunately, because of this particular treatment, the language designers felt obliged to introduce a small kludge. The legal decimal literals range from 0 to 2147483647 and from 0L to 9223372036854775807L, since those are the ranges of possible positive values for the types **int** and **long**. However, as you can see from Table 4.1, this limit would not allow you to write the most negative numbers easily, so as a special case, the two decimal literals 2147483648 and 92233720368547758O8L are allowed *as long as* they are the operands of a unary minus. This leads to the really obscure and useless fact that:

```
x = -2147483648;   // is legal, but
x = 0-2147483648;   // is not!
```

And as if this weren't enough, the range of octal and hexadecimal numerals is bigger than that of decimal numerals. The maximum decimal numerals are $2^{31} - 1$ and $2^{63} - 1$, while the maximum octal and hexadecimal numerals have maximum values of $2^{32} - 1$ and $2^{64} - 1$. The values beyond the decimal range represent negative values, as we'll see in §4.1.2. The reason for this puzzling discrepancy is the assumption that decimal numerals are intended to represent integers used *as* mathematical integers, whereas octal and hexadecimal values tend to be used for other purposes, including as sequences of bits.

Characters

Character values (type **char**) are non-negative integers, a fact that causes considerable confusion. Specifically, the integer values 0–65535 represent the characters specified by the Unicode character set, version 2.0. While you could, therefore, refer to character values in your program by their integer equivalents, it is generally considered much better (in particular, more readable) style to use *character literals,* which make clear what character you are referring to:

`if (c == 'a')` *is preferable to* `if (c == 97)`

Syntax.

CharacterLiteral: `'` *SingleCharacter* `'`
`'` *EscapeSequence* `'`
SingleCharacter: Any Unicode character except CR, LF, `'` or `\`
EscapeSequence:
`\b` | `\t` | `\n` | `\f` | `\r` | `\"` | `\'` | `\\`
OctalEscape
OctalEscape: *ZeroToThree* $OctalDigit_{opt}$ $OctalDigit_{opt}$
ZeroToThree: `0` | `1` | `2` | `3`

Escape	Unicode	Meaning	Escape	Unicode	Meaning
`\b`	`\u0008`	Backspace (BS)	`\r`	`\u000d`	Carriage return (CR)
`\t`	`\u0009`	Horizontal tab (HT)	`\"`	`\u0022`	Double quote
`\n`	`\u000a`	linefeed (LF)	`\'`	`\u0027`	Single quote
`\f`	`\u000c`	Form feed (FF)	`\\`	`\u005c`	Backslash

Table 4.2: Escape sequences for use in character and string literals, with equivalent Unicode escape sequences where they are legal. The carriage return, newline, backslash, and single quote characters are illegal in character literals, as are their Unicode escapes. Likewise, return, newline, backslash, and double quote characters are illegal in string literals.

Here, 'LF' and 'CR' refer to the characters "linefeed" (also referred to as *newline*) and "carriage return."

The escape sequences are intended to give somewhat mnemonic but still concise representations for control characters (things that don't show up as printed characters) and for a few other values beyond the limits of the ASCII character set (that is, the subset of Unicode in which almost all Java code is written). They also allow you to insert characters that are not allowed by the *SingleCharacter* syntax: carriage returns, linefeeds, single quotes, and backslashes.

An *OctalEscape* represents a numeric value represented as an octal (base-8) numeral. It differs from an octal *IntegerNumeral* only in that it yields a value of type **char** rather than **int**. Octal escapes are considered moderately passé in Java; `\u` or the other escape sequences are officially preferred. The other escape sequences denote the characters indicated in Table 4.2.

Examples.

```
'a'          // Lower-case a
'A'          // Upper-case A
' '          // Blank
'\t'         // (Horizontal) tab character
'\011'       // Another version of horizontal tab
'\u03b4'     // Greek lower-case delta
'δ'          // Another way to write delta (if your
             // compiler supports it)
'c' - 'a'    // The value 2 ('c' is 99, 'a' is 97).
'\377'       // Character value 255 (largest octal escape)
'\u00FF'     // Another way to write '\377'
'ÿ'          // Another way to write '\377' (if your
             // compiler supports it)
```

4.1.2 Modular integer arithmetic

The integral arithmetic operators in Java are addition (`x+y`), subtraction (`x-y`), unary negation (`-x`), unary plus (`+x`), multiplication (`x*y`), integer division (`x/y`),

and integer remainder (`x%y`).

Syntax.

UnaryExpression: UnaryAdditiveOperator Operand
UnaryAdditiveOperator: `+` | `-`
BinaryExpression: Operand BinaryOperator Operand
BinaryOperator: `+` | `-` | `*` | `/` | `%`

Semantics. The integer division and remainder operations yield integer results. Division rounds toward 0 (i.e., throwing away any fractional part), so that `3/2` is equal to `1` and both `(-3)/2` and `3/(-2)` are equal to `-1`. Division and remainder are related by the formula

```
(x / y) * y + (x % y) ≡ x
```

so that

```
x % y ≡ x - ((x / y) * y)
```

Working out a few examples:

```
5 % 3 ≡ 5 - ((5 / 3) * 3) ≡ 5 - (1*3) ≡ 2
-5 % 3 ≡ (-5) - (((-5) / 3) * 3) ≡ (-5) - ((-1)*3) ≡ -2
5 % (-3) ≡ 5 - ((5 / (-3)) * (-3)) ≡ 5 - ((-1)*(-3)) ≡ 2
(-5) % (-3) ≡ (-5) - (((-5) / (-3)) * (-3))
            ≡ (-5) - (1*(-3))
            ≡ -2
```

Division or remaindering by 0 throws an `ArithmeticException` (see 1.14).

On integers, all of these operations first convert (*promote*) their operands to either the type **int** or (if at least one argument is **long**) the type **long**. After this promotion, the result of the operation is the same as that of the converted operands. Thus, even if `x` and `y` are both of type **byte**, `x+y` and `-x` are **int**s. To be more specific:

> To compute $x \oplus y$, where $\oplus$ is any of the Java operations `+`, `-`, `*`, `/`, or `%`, and x and y are integer quantities (of type `long`, `int`, `short`, `char`, or `byte`),
>
> - If either operand has type `long`, compute the mathematical result converted to type `long`.
> - Otherwise, compute the mathematical result converted to type `int`.

By "mathematical result," I mean the result as in normal arithmetic, where '/' is understood to throw away any remainder. Depending on the operands, of course, the result of any of these operations (aside from unary plus, which essentially does nothing but convert its operand to type **int** or **long**), may lie outside the domain of type **int** or **long**. This happens, for example, with `100000*100000`.

The computer hardware will produce a variety of results for such operations, and as a result, traditional languages prior to Java tended to finesse the question of what result to yield, saying that operations producing an out-of-range result were "erroneous," or had "undefined" or "implementation-dependent" results. In fact, they also tended to finesse the question of the range of various integer types; in standard C, for example, the type `int` has *at least* the range of Java's type `short`, but may have more. To do otherwise than this could make programs slower on some machines than they would be if the language allowed compilers more choice in what results to produce. The designers of Java, however, decided to ignore any possible speed penalty in order to avoid the substantial hassles caused by differences in the behavior of integers from one machine to another.

Java integer arithmetic is *modular:* the rule is that the actual result of any integer arithmetic operation (including conversion between integer types) is equivalent to the mathematical result "modulo the modulus of the result type," where the modulus is that given in Table 4.1. In mathematics, we say that two numbers are identical "modulo N" if they differ by a multiple of N:

$$a \equiv b \bmod N \text{ iff there is an integer, } k, \text{ such that } a - b = kN.$$

The numeric types in Java are all computed modulo some power of 2. Thus, the type `byte` is computed modulo 256 (2^8). Any attempt to convert an integral value, x, to type `byte` gives a value that is equal to x modulo 256. There is an infinity of such values; the one chosen is the one that lies between -2^7 (-128) and $2^7 - 1$ (127), inclusive. For example, converting the values 127, 0, and -128 to type `byte` simply gives 127, 0, and -128, while converting 128 to type `byte` gives -128 (because $128-(-128) = 2^8 = 256$) and converting 513 to type `byte` gives 1 (because $1 - 513 = -2 \cdot 2^8$). The result of `100000*100000`, being of type **int**, is computed modulo 2^{32} in the range -2^{31} to $2^{31} - 1$, giving 1410065408, because

$$100000^2 - 1410065408 = 8589934592 = 2 \cdot 2^{32}.$$

For addition, subtraction, and multiplication, it doesn't matter at what point you perform a conversion to the type of result you are after. This is an extremely important property of modular arithmetic. For example, consider the computation `527 * 1000 + 600`, where the final result is supposed to be a `byte`. Doing the conversion at the last moment gives

$$527 \cdot 1000 + 600 = 527600 \equiv -16 \bmod 256;$$

or we can first convert all the numerals to `byte`s:

$$15 \cdot -24 + 88 = -272 \equiv -16 \bmod 256;$$

or we can convert the result of the multiplication first:

$$527000 + 600 \equiv 152 + 600 = 752 \equiv -16 \bmod 256.$$

We always get the same result in the end.

Unfortunately, this happy property breaks down for division. For example, the result of converting 256/7 to a `byte` (36) is not the same as that of converting 0/7 to a `byte` (0), even though both 256 and 0 are equivalent as `byte`s (i.e., modulo 256). Therefore, the precise points at which conversions happen during the computation of an expression involving integer quantities are important. For example, consider

```
short x = 32767;
byte y = (byte) (x * x * x / 15);
```

A conversion of integers, like other operations on integers, produces a result of type T that is equivalent to the mathematical value of V modulo the modulus of T. So, according to the rules, `y` above is computed as

```
short x = 32767;
byte y = (byte) ((int) ((int) (x*x) * x) / 15);
```

The computation proceeds:

```
x*x --> 1073676289
(int) 1073676289 --> 1073676289
1073676289 * x --> 35181150961663
(int) 35181150961663 --> 1073840127
1073840127 / 15 --> 71589341
(byte) 71589341 --> -35
```

If instead I had written

```
byte y = (byte) ((long) x * x * x / 15);
```

it would have been evaluated as

```
byte y = (byte) ((long) ((long) ((long) x * x) * x) / 15);
```

which would proceed:

```
(long) x --> 32767
32767L * x --> 1073676289
(long) 1073676289L --> 1073676289
1073676289L * x --> 35181150961663
(long) 35181150961663L --> 35181150961663
35181150961663L / 15 --> 2345410064110
(byte) 2345410064110L --> -18
```

Why this way? All these remainders seem rather tedious to us humans, but because of the way our machines represent integer quantities, they are quite easy for the hardware. Let's take the type `byte` as an example. Typical hardware represents a byte x as a number in the range 0–255 that is equivalent to x modulo 256, encoded as an 8-digit number in the binary number system (whose digits—called *bits*—are 0 and 1). Thus,

```
0    --> 00000000₂
1    --> 00000001₂
2    --> 00000010₂
5    --> 00000101₂
127  --> 01111111₂
-128 --> 10000000₂   (≡ 128 mod 256)
-1   --> 11111111₂   (≡ 255 mod 256)
```

As you can see, all the numbers whose top bit (representing 128) is 1 represent negative numbers; this bit is therefore called the *sign bit*. As it turns out, with this representation, taking the remainder modulo 256 is extremely easy. The largest number representable with eight bits is 255. The ninth bit position (100000000_2) represents 256 itself, and all higher bit positions represent multiples of 256. That is, every multiple of 256 has the form

$$b_0 \cdots b_n \underbrace{00000000}_{8},$$

which means that to compute a result modulo 256 in binary, one simply throws away all but the last eight bits.

Be careful in this notation about converting to a number format that has more bits. This may seem odd advice, since when converting (say) `byte`s (eight bits) to `int`s (32 bits), the value does not change. However, the `byte` representation of -3 is 253, or in binary 11111101_2, whereas the `int` representation of -3 is

$$11111111111111111111111111111101_2 = 4294967293.$$

In converting from a `byte` to an `int`, therefore, we duplicate the sign bit to fill in the extra bit positions (a process called *sign extension*). Why is this the right thing to do? Well, the negative quantity $-x$ as a `byte` is represented by $2^8 - x$, since $2^8 - x \equiv -x \bmod 2^8$. As an `int`, it is represented by $2^{32} - x$, and

$$2^{32} - x = (2^{32} - 2^8) + (2^8 - x) = 11111111111111111111111100000000_2 + (2^8 - x).$$

4.1.3 Manipulating bits

Syntax.

UnaryExpression: `~` *Operand*
BinaryExpression: Operand BinaryOperator Operand
BinaryOperator: `&` | `^` | `|` | `<<` | `>>` | `>>>`

Semantics. One can look at a number as a bunch of bits, as shown in the preceding section. Java (like C and C++) provides operators for treating numbers as bits. The *bitwise operators*—`&`, `|`, `^`, and `~`—all operate by lining up their operands (after binary promotion) and then performing some operation on each bit or pair of corresponding bits, according to the following tables:

Operation	*Operand Bits (L,R)* (0,0)	(0,1)	(1,0)	(1,1)
`&` (and)	0	0	0	1
`|` (or)	0	1	1	1
`^` (xor)	0	1	1	1

Operation	*Operand Bit* 0	1
`~` (not)	1	0

The "xor" (exclusive or) operation also serves the purpose of a "not equal" operation: it is 1 if and only if its operands are not equal.

In addition, the operation x`<<N` produces the result of multiplying `x` by 2^N (or shifting N 0's in on the right). `x>>>N` produces the result of shifting N 0's in on the left, throwing away bits on the right. Finally, `x>>N` shifts N copies of the sign bit in on the left, throwing away bits on the right. This has the effect of dividing by 2^N and rounding down (toward $-\infty$). The left operand of the shift operand is promoted to **int** or **long**, and the result is the same as this promoted type. The right operand is taken modulo 32 for **int** results and modulo 64 for **long** results, so that `5<<32`, for example, simply yields `5`.

For example,

```
                int x = 42;   // == 0...0101010 base 2
                int y = 7;    // == 0...0000111

x & y == 2   // 0...0000010 | x << 2 == 168   // 0...10101000
x | y == 47  // 0...0101111 | x >> 2 == 10    // 0...00001010
x ^ y == 45  // 0...0101101 | ~y << 2 == -32  // 1...11100000
~y    == -8  // 11...111000 | ~y >> 2 == -2   // 1...11111110
                           | ~y >>> 2 == 2^30 - 2
                           |                  // 00111...1110
                           | (-y) >> 1 == -4
```

As you can see, even though these operators manipulate bits, whereas `int`s are supposed to be numbers, no conversions are necessary to "turn `int`s into bits." This isn't surprising, given that the internal representation of an `int` actually *is* a collection of bits, and always has been; these are operations that have been carried over from the world of machine-language programming into higher-level languages. They have numerous uses; some examples follow.

Masking

One common use for the bitwise-and operator is to *mask off* (set to 0) selected bits in the representation of a number. For example, to zero out all but the least significant 4 bits of `x`, one can write

```
x = x & 0xf;  // or  x &= 0xf;
```

To turn off the sign bit (if `x` is an `int`):

```
x &= 0x7fffffff;
```

To turn off all *but* the sign bit:

```
x &= 0x80000000;
```

In general, if the expression `x&~N` masks off exactly the bits that `x&N` does not.

If $n \geq 0$ is less than the *word length* of an integer type (32 for `int`, 64 for `long`), then the operation of masking off all but the least-significant n bits of a number of that type is (as we've seen), the same as computing an equivalent number modulo 2^n that is in the range 0 to $2^n - 1$. One way to form the mask for this purpose is with an expression like this:

```
/** Mask for the N least-significant bits, 0<=N<32. */
int MASK = (1<<n) - 1;
```

[Why does this work?] With the same value of `MASK`, the statement

```
xt = x & ~MASK;
```

has the interesting effect of *truncating* `x` to the next smaller multiple of 2^n [Why?], while

```
xr = (x + ((1 << n) >>> 1)) & ~MASK;
// or
xr = (x + ((~MASK>1) & MASK)) & ~MASK;
// or, if n > 0, just:
xr = (x + (1 << (n-1))) & ~MASK;
```

rounds `x` to the nearest multiple of 2^n [Why?]

Packing

Sometimes one wants to save space by packing several small numbers into a single `int`. For example, I might know that `w`, `x`, and `y` are each between 0 and $2^9 - 1$. I can *pack* them into a single `int` with

```
z = (w<<18) + (x<<9) + y;
```

or

```
z = (w<<18) | (x<<9) | y;
```

From this `z`, I can extract `w`, `x`, and `y` with

```
w = z >>> 18; x = (z >>> 9) & 0x1ff; y = z & 0x1ff;
```

(In this case, the `>>` operator would work just as well.) The hexadecimal value `0x1ff` (or 111111111_2 in binary) is used here as a *mask*; it suppresses (masks out) bits other than the nine that interest us. Alternatively, you can perform the masking operation first, extracting `x` with

```
x = (z & 0x3fe00) >>> 9;
```

In order to change just one of the three values packed into `z`, we essentially have to take it apart and reconstruct it. So, to set the `x` part of `z` to 42, we could use the following assignment:

```
z = (z & ~0x3fe00) | (42 << 9);
```

The mask `~0x3fe00` is the complement of the mask that extracts the value of `x`; therefore `z&~0x3fe00` extracts everything *but* `x` from `z` and leaves the `x` part 0. The right operand is simply the new value, 42, shifted over into the correct position for the `x` component (I could have written 378 instead, but the explicit shift is clearer and less prone to error, and compilers will generally do the computation for you so that it does not have to be re-computed when the program runs). Likewise, to add 1 to the value of `x`, if we know the result won't overflow 9 bits, we could perform the following assignment:

```
z = (z & ~0x3fe00) | ((((z & 0x3fe00) >>> 9) + 1) << 9);
```

Actually, in this particular case, I could also just write

```
z += 1 << 9;
```

[Why?]

4.2 Floating-Point Numbers

Syntax.

UnaryExpression: UnaryAdditiveOperator Operand
UnaryAdditiveOperator: `+` | `-`
BinaryExpression: Operand BinaryOperator Operand
BinaryOperator: `+` | `-` | `*` | `/` | `%`

Semantics. Just as it provides general integers, Scheme also provides rational numbers—quotients of two integers. Just as the manipulation of arbitrarily large integers has performance problems, so too does the manipulation of what are essentially pairs of arbitrarily large integers. It isn't necessary, furthermore, to have large rational numbers to have large integer numerators and denominators. For example, $(8/7)^{30}$ is a number approximately equal to 55, but its numerator has 28 digits and its denominator has 27. For most of the results we are after, on the other hand, we need considerably fewer significant digits, and the precision afforded by large numerators and denominators is largely wasted, and comes at great cost in computational speed.

Therefore, standard computer systems provide a form of limited-precision rational arithmetic known as *floating-point arithmetic.* This may be provided either directly by the hardware (as on Pentiums, for example), or by means of standard software (as on the older 8086 processors, for example).

Java has adopted what is called IEEE Standard Binary Floating-Point Arithmetic. The basic idea behind a floating-point type is to represent only numbers having the form

$$\pm b_0.b_1 \cdots b_{n-1} \times 2^e,$$

where n is a fixed number, e is an integer in some fixed range (the *exponent*), and the b_i are binary digits (0 or 1), so that $b_0.b_1 \cdots b_{n-1}$ is a fractional binary number (the *significand*) There are two floating-point types:

- **float**: $n = 24$ and $-127 < e < 128$;
- **double**: $n = 53$ and $-1023 < e < 1024$.

In addition to ordinary numbers, these types also contain several special values:

- $\pm\infty$, which represent the results of dividing non-zero numbers by 0, or in general numbers that are beyond the range of representable values;
- -0, which is essentially the same as 0 (they are `==`, for example) with some extra information. The difference shows up in the fact that `1/-0.0` is negative infinity. Used properly, it turns out to be a convenient "trick" for giving functions desired values at discontinuities. Take a course in numerical analysis if you are curious.
- `NaN`, or *Not A Number,* standing for the results of invalid operations, such as `0/0`, or subtraction of equal infinities.

To test `x` to see if it is infinite, use `Double.isInfinite(x)`. One checks a value `x` to see if it is not a number with `Double.isNaN(x)` (you can't use `==` for this test because a NaN has the odd property that it is not equal, greater than, or less than any other value, including itself!) Because of these `NaN` values, every floating-point expression can be given a reasonable value.

4.2.1 Floating-Point Literals

Syntax

RealLiteral:
DecimalDigit$^+$ `.` *DecimalDigit** *Exponent*$_{opt}$ *FloatType*$_{opt}$
`.` *DecimalDigit*$^+$ *Exponent*$_{opt}$ *FloatType*$_{opt}$
DecimalDigit$^+$ *Exponent* *FloatType*$_{opt}$
DecimalDigit$^+$ *Exponent*$_{opt}$ *FloatType*
Exponent:
`e` *Sign*$_{opt}$ *DecimalDigit*$^+$
`E` *Sign*$_{opt}$ *DecimalDigit*$^+$
Sign: `+` | `-`
FloatType: `f` | `F` | `d` | `D`

As for integer literals, no embedded whitespace is allowed. Upper- and lower-case versions of *FloatType* and of the 'e' in *Exponents* are equivalent. Literals that end in `f` or `F` are of type **float**, and all others are of type **double**. There are no negative literals, since the unary minus operator does the trick, as for integer literals.

An *Exponent* of the form '`E`$\pm N$' means $\times 10^{\pm N}$, and otherwise these literals are interpreted as ordinary numbers with decimal points. For example, `1.004e-2` means 0.01004. However, since the floating-point types do not include all values that one can write this way, the number you write is first *rounded* to the nearest representable value. For example, there is no exact 24-bit binary representation for 0.2; its binary representation is 0.00110011.... Therefore, when you write `0.2f`, you get instead 0.20000000298....

Floating-point literals other than zero must be in the range

`1.40239846e-45f` *to* `3.40282347e+38f (float)`
`4.94065645841246544e-324` *to* `1.79769313486231570e+308 (double)`

The classes `java.lang.Float` and `java.lang.Double` in the standard library contain definitions of some useful constants.

Double.MAX_VALUE, Float.MAX_VALUE The largest possible values of type **double** and **float**.

Double.MIN_VALUE, Float.MIN_VALUE The smallest possible values of type **double** and **float**.

Double.POSITIVE_INFINITY, Float.POSITIVE_INFINITY $+\infty$ for types **double** and **float**.

Double.NEGATIVE_INFINITY, Float.NEGATIVE_INFINITY $-\infty$ of type **double** and **float**.

Double.NaN, Float.NaN A Not-A-Number of type **double** and **float**.

4.2.2 Floating-point arithmetic

In what follows, I am going to talk only about the type `double`. This is the default type for floating-point literals, and in the type commonly used for computation. The type `float` is entirely analogous, but since it is not as often used, I will avoid redundancy and not mention it further. The type `float` is useful in places where space is at a premium and the necessary precision is not too high.

The floating-point arithmetic operators in Java are addition (`x+y`), subtraction (`x-y`), unary negation (`-x`), unary plus (`+x`), multiplication (`x*y`), division (`x/y`), and remainder (`x%y`). The remainder operation obeys the same law as for integers:

`(x / y) * y + (x % y)` $\equiv$ `x`

except that division is floating-point division rather than integer division; it doesn't discard the fraction.

The result of any arithmetic operation involving ordinary floating-point quantities is rounded to the nearest representable floating-point number (or to $\pm\infty$ if out of range). In case of ties, where the unrounded result is exactly halfway between two floating-point numbers, one chooses the one that has a last binary digit of 0 (the rule of *round to even.*) The only exception to this rule is that conversions of floating-point to integer types, using a cast such as `(int) x`, always *truncate*—that is, round to the number nearest to 0, throwing the fractional part away[1].

The justifications for the round-to-even rule are subtle. In computations involving many floating-point operations, it can help avoid biasing the arithmetic error in any particular direction. It also has the very interesting property of preventing drift in certain computations. Suppose, for example, that a certain loop has the effect of computing

```
x = (x + y) - y;
```

on each of many iterations (you wouldn't do this explicitly, of course, but it may happen to one of your variables for certain particular values of the input data). The round-to-even rule guarantees that the value of `x` here will change at most once, and then drift no further (a remarkably hard thing to prove, I'm told, but feel free to try).

So far, we've discussed only the usual cases. Operations involving the extra values require a few more rules. Division of a positive or negative quantity by zero yields an infinity, and -0 reverses the sign of the result. Dividing ± 0 by ± 0 yields a `NaN`, as does subtraction of equal infinities, division of two infinite quantities, or any arithmetic operation involving `NaN` as one of the operands.

In principle, I've now said all that needs to be said. However, there are many subtle consequences of these rules. You'll have to take a course in numerical analysis to learn all of them, but for now, here are a few important points to remember.

Binary vs. decimal

Computers use binary arithmetic because it leads to simple hardware (i.e., cheaper than using decimal arithmetic). There is, however, a cost to our intuitions to doing this: although any fractional binary number can be represented as a decimal fraction, the reverse is not true. For example, the nearest `double` value to the decimal fraction 0.1 is

$$0.1000000000000000055511151231257827021181583404541015625$$

so when you write the literal `0.1`, or when you compute `1.0/10.0`, you actually get the number above. You'll see this sometimes when you print things out with a little too much precision. For example, the nearest `double` number to 0.123 is

$$0.122999999999999999822364316\ldots$$

[1]The handling of rounding to integer types is *not* the IEEE convention; Java inherited it from C and C++.

so that if you print this number with the `%24.17e` format from our library, you'll see that bunch of 9s. Fortunately, less precision will get rounded to something reasonable.

Round-off

For two reasons, the loop

```
double x; int k
for (x = 0.1, k = 1; x <= N; x += 0.1, k += 1)
{ ... }
```

(where $10N < 2^{31}$) will not necessarily execute $10N$ times. For example, when `N` is 2, 3, 4, or 20, the loop executes $10N - 1$ times, whereas it executes $10N$ times for other values in the range 1–20. The first reason is the one mentioned above: 0.1 is only approximately representable. The second is that each addition of this approximation of 0.1 to `x` may round. The rounding is sometimes up and sometimes down, but eventually the combined effects of these two sources of error will cause `x` to drift away from the mathematical value of $0.1k$ that the loop naively suggests. To get the effect that was probably intended for the loop above, you need something like this:

```
for (int kx = 1; kx <= 10*N; k += 1) {
    double x = kx * 0.1;
    // or double x = (double) kx / 10.0;
```

(The division is more accurate, but slower). With this loop, the values of `x` involve only one or two rounding errors, rather than an ever-increasing number. Still, IEEE arithmetic can be surprisingly robust; for example, computing 20*0.1 rounds to exactly 2 (a single multiplication is more accurate than repeated additions).

On the other hand, since integers up to $2^{53} - 1$ (about 9×10^{15}) *are* represented exactly, the loop

```
for (x = 1.0, k = 1; x <= N; x += 1.0, k += 1) { ... }
```

will execute exactly N times (if $N < 2^{53}$) and `x` and `k` will always have the same mathematical value. In general, operations on integers in this range (except, of course, division) give exact results. If you were doing a computation involving integers having 10–15 decimal digits, and you were trying to squeeze seconds, floating-point might be the way to go, since for operations like multiplication and division, it can be faster than integer arithmetic on `long` values.

In fact, with care, you might even use floating-point for financial computations, computed to the penny (it has been done). I say "with care," since 0.01 is not exactly representable in binary. Nevertheless, if you represent quantities in pennies instead of in dollars, you can be sure of the results of additions, subtractions, and (integer) multiplications, at least up to $9,999,999,999,999.99.

When the exponents of results exceed the largest one representable (*overflow*), the results are approximated by the appropriate infinity. When the exponents get

too small to represent at all (*underflow*), the result will be 0. In IEEE (and Java) arithmetic, there is an intermediate stage called *gradual underflow*, which occurs when the exponent (e in the formula above) is at its minimum, and the first significand bit (b_0) is 0.

We often describe the rounding properties of IEEE floating-point by saying that results are correct "to 1/2 unit in the last place (ulp)," because rounding off changes the result by at most that much. Another, looser characterization is to talk about *relative error*. The relative-error bound is pessimistic, but has intuitive advantages. If `x` and `y` are two `double` quantities, then (in the absence of overflow or any kind of underflow) the computed result, `x*y`, is related to the mathematical result, $\texttt{x} \cdot \texttt{y}$, by

$$\texttt{x*y} = \texttt{x} \cdot \texttt{y} \cdot (1 + \epsilon), \text{ where } |\epsilon| \leq 2^{-53}.$$

and we say that ϵ is the relative error (it's bound is a little larger than 10^{-16}, so you often hear it said that double-precision floating point gives you something over 15 significant digits). Division has essentially the same rule.

Addition and subtraction also obey the same form of relative-error rule, but with an interesting twist: adding two numbers with opposite signs and similar magnitudes (meaning within a factor of 2 of each other) always gives an *exact* answer. For example, in the expression `0.1-0.09`, the subtraction itself does not cause any round-off error (why?), but since the two operands are themselves rounded off, the result is not exactly equal to 0.01. The subtraction of nearly equal quantities tends to leave behind just the "noise" in the operands (but it gets that noise absolutely right!).

Spacing

Unlike integers, floating-point numbers are not evenly spaced throughout their range. Figure 4.1 illustrates the spacing of simple floating-point numbers near 0 in which the significand has 3 bits rather than Java's 24 or 53. Because the numbers get farther apart as their magnitude increases, the absolute value of any round-off error also increases.

There are numerous pitfalls associated with this fact. For example, many numerical algorithms require that we repeat some computation until our result is "close enough" to some desired result. For example, we can compute the square root of a real number y by the recurrence

$$x_{i+1} = x_i + \frac{y - x_i^2}{2x_i}$$

where x_i is the i^{th} approximation to $\sqrt{y}$. We could decide to stop when the error $|y - x_i^2|$ become small enough[2]. If we decided that "small enough" meant, say, "within 0.001," then for values of y less than 1 we would get very few significant digits of precision and for values of y greater than 10^{13}, we'll never stop. This is one

[2]In actual practice, by the way, this convergence test isn't necessary, since the error in x_i^2 as a function of i is easily predictable for this particular formula.

Figure 4.1: Non-negative 3-bit floating-point numbers near 0, showing how the spacing expands as the numbers get bigger. Each tick mark represents a floating-point number. Assume that the minimum exponent is -4, so that the most closely spaced tick marks are $2^{-6} = 1/64$ apart.

reason relative error, introduced in the last section, is useful; no matter where you are on the floating-point scale, round off always produces the same relative error.

Comment on floating-point equality.

Some textbooks incorrectly tell you never to compare floating-point numbers for equality, but rather to check to see whether they are "close" to each other. This is highly misleading advice (that's more diplomatic than "wrong," isn't it?). It is true that naive uses of `==` can get you into trouble; for example, you should not expect that after setting `x` to `0.0001`, `x*10000==1.0`, since `x` will not be exactly equal to 1/10000. That simply follows from the behavior of round off, as we've discussed.

However, one doesn't have to be naive. First, we've seen that (up to a point) `double` integers work like `ints` or `longs`. Second, IEEE standard arithmetic is designed to behave very well around many singularities in one's formulas. For example, suppose that $f(x)$ approaches 0 as x approaches 1—for concreteness, suppose that $f(x)$ approximates $\ln x$—and that we want to compute $f(x)/(1-x)$, giving it the value 1 when $x = 1$. We can write the following computation in Java:

```
if (x == 1.0)
   return 1.0;
else
   return f(x) / (1.0 - x);
```

and it will return a normal number (neither NaN nor infinity) whenever `x` is close to 1.0. Despite rounding errors, IEEE arithmetic guarantees that `1.0-x` will evaluate to 0 if and only if `x==1.0`.

Chapter 5

Strings, Streams, and Patterns

In olden times (that is, until the early 1980's), essentially all communication with ordinary application programs was in the form of *text:* that is, strings (sequences) of characters, sometimes presented as broken into lines and pages. The situation is much more varied these days—what with bit-mapped displays, point-and-click, voice communication, multi-media, and the like—and, of course, computer-controlled machinery (industrial robots, on-board flight-control systems) is an exception that has been with us nearly since the beginning. Nevertheless, the manipulation of text still has an important place, and your author's somewhat antique position is that text is often a distinct improvement over some more "modern" interfaces that have displaced it.

Java provides a number of library classes that deal with plain textual data. The primitive type `char` represents single characters in the Unicode character set. Most commonly, these crop up in your programs when you extract them from `String`s, using the `charAt` method. Corresponding to this primitive type, the Java library contains the wrapper class `Character`, which defines a number of useful functions for manipulating individual characters. The class you're likely to deal with most is `String`, which, as we've seen, gives us sequences of characters, suitable for reading from a terminal or file or for printing. This class allows you to compare strings and extract pieces of them, and thus to *parse* written notation (that is, to resolve it into its grammatical constituents and determine its meaning). However, complex analysis of text is quite tedious with the primitive tools provided by `String` and recent versions of Java have added a new class, `Pattern` (in package `java.util.regex`), which as its name suggests, provides a language for describing sets of `Strings`. Together with another new type, `java.util.Scanner` (§5.6), you can describe the format of textual input. On the other side of the coin, the construction of `String`s generally involves the concatenation of individual pieces, some of which are constants and some of which are created dynamically. Here, too, Java 2, version 1.5 has introduced a set of convenient formatting methods, adapted from C, for complex `String` construction (§5.2.1).

Input and output by a program requires additional abstractions (§5.4). Again, these involve sequences of characters or other symbols (such as bits or bytes). However, there is a very strong bias towards producing output and consuming input

incrementally, so that the program need never have the complete sequence of inputs or outputs on hand simultaneously. Historically, this was for reasons of efficiency and capacity (if you are processing billions of characters using a computer with mere kilobytes of memory, you have little choice).

5.1 Bytes and Characters

It is often said that the business of computers is "processing symbols." Ultimately, this means that the atomic constituents of a computer's data come from some *finite alphabet* and these constituents' only characteristic is that they are all distinct from one another. So, you often hear that "computers deal with 1's and 0's"—that the basic alphabet consists of the set of bits: $\{0, 1\}$. While this is true, our programs usually deal with data in somewhat larger pieces—clumps of bits, if you will. These days, the smallest of these is typically the *byte,* 8 bits, represented directly in Java as the type **byte**.

However, the fact our basic alphabet consists of numbers is misleading. The whole purpose of symbols is to *stand for* things. In the case of computers, we use numbers to stand for everything. In particular, we use them to stand for printed characters. The Java type **char**, which we think of as being a set of printed characters, is an integer type, whose members can be added and multiplied. If we want to use **char**s to represent characters (as we usually do), this becomes evident by *how we use them.* So, if the computer sends the number 113 to a printing device in a particular way, it will cause the lower-case letter 'q' to be printed. Thus, we humans will think of the computer as dealing with letters, whereas internally it is dealing with numbers.

5.1.1 ASCII and Unicode

Most programs today are written using an alphabet (or, as we computer people often say, *character set*) that goes by the name *ASCII,* standing for *American Standard Code for Information Interchange.* The same standard character set suffices for most of the textual input and output by programs. This standard defines both a set of characters and a computer-friendly encoding that maps each character to an integer in the range 0–127, as detailed in Table 5.1. This set contains ordinary, printable characters (upper- and lower-case letters, digits, punctuation marks, and blanks), and an assortment of non-printing *control characters* (so called because in the old days, they used to be used to control teletypes or other communication devices). Among the control characters, there are several *format effectors* whose effect is to control spacing and line breaks—things like horizontal and vertical tabs, line feed, carriage return, form feed (which skips to a new page), and backspace. See §4.1.1 for a further discussion.

Needless to say, there are both technical and political consequences to having a character set that is called "American" and that only has room for 127 characters. To accommodate an international clientele, a group called the Unicode Consortium has developed a much more extensive character set (generally called *Unicode*) with

65536 (2^{16}) possible codes that incorporates many of the world's alphabets. Its first 127 characters are a copy of ASCII (so a program written entirely in ASCII is also written in Unicode). The other characters may appear in Java programs, just like ordinary ASCII characters. That is, those that are letters or digits (in any alphabet) are perfectly legal in identifiers, and all the extra characters are legal as character or string literals (§5.2, S4.1.1) and in comments.

Unfortunately, most of our compilers, editors, and so forth are geared to the ASCII character set. Therefore, Java defines a convention whereby any Unicode character may be written with ASCII characters. Before they do anything else to your program, Java translators will convert notation `\u`*abcd* (where the four italic letters are hexadecimal digits) into the Unicode character whose encoding is $abcd_{16}$. The notation actually allows you to insert any number of '`u`', as in `\uuu0273`. In principle, you could write the program fragment

```
x= 3;
y=2;
```

as

```
\u0078\u003d\u0020\u0033\u003b\u000a\u0079\u003d\u0032\u003b
```

but who would want to? The intention is to use Unicode for cases where you need non-ASCII letters. For example, if you wanted to write

```
double δ = Ψ_1 - Ψ_0;
```

you could write

```
double \u03b4 = \u03a8_1 - \u03a8_0;
```

and the compiler would be perfectly happy. Alas, getting this printed with real Greek letters is a different story, requiring the right editors and other programming tools. That topic is somewhat beyond our scope here.

Most of the early work in computers was done in the United States and Western Europe. In the United States, the ASCII character set (requiring codes 0–127) suffices for most text, and the addition of what are called the Latin-1 symbols (codes 128-255) take care of most of Europe's needs (they include characters such as 'é' and 'ö'). Therefore, characters in those parts of the world fit into 8 bits, and there has been a tendency to use the terms "byte" and "character" as if they were synonymous. This confusion remains in Java to some extent, although to a lesser extent than predecessors such as C. For example, as you will see in §5.4, files are treated as streams of bytes, but the methods we programmers apply to read or write generally deal in **char**s. There is some internal translation that the Java library performs between the two (which in the United States usually consists in throwing away half of each **char** on output and filling in half of each **char** with 0 on input) so that we don't usually have to think about the discrepancy.

	d_1															
d_0	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0	^@	^A	^B	^C	^D	^E	^F	^G	^H	^I	^J	^K	^L	^M	^N	^O
1	^P	^Q	^R	^S	^T	^U	^V	^W	^X	^Y	^Z	^[	^\	^]	^^	^_
2	␣	!	"	#	$	%	&	’	(	)	*	+	,	-	.	/
3	0	1	2	3	4	5	6	7	8	9	:	;	<	=	>	?
4	@	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
5	P	Q	R	S	T	U	V	W	X	Y	Z	[		]	^	_
6	‘	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o
7	p	q	r	s	t	u	v	w	x	y	z	{	|	}	~	*DEL*

Table 5.1: ASCII codes (equivalent to the first 128 Unicode characters). The code for the character at line d_0 and column d_1 is 0xd_0d_1. The characters preceded by carats ^ are control characters, further described in Table 5.2; the notation means that the character ^c can be produced on a typical computer keyboard by holding down the control-shift key while typing c.

Table of Control Characters

Name	Ctrl	Meaning	Name	Ctrl	Meaning
NUL	^@	Null	DLE	^p	Data link escape
SOH	^a	Start of heading	DC1	^q	Device control 1
STX	^b	Start of text	DC2	^r	Device control 2
ETX	^c	End of text	DC3	^s	Device control 3
EOT	^d	End of transmission	DC4	^t	Device control 4
ENQ	^e	Enquiry	NAK	^u	Negative acknowledge
ACK	^f	Acknowledge	SYN	^v	Synchronize
BEL	^g	Bell	ETC	^w	End transmitted block
BS	^h	Backspace	CAN	^x	Cancel
HT	^i	Horizontal tab	EM	^y	End of medium
LF	^j	Line feed	SUB	^z	Substitute
VT	^k	Vertical tab	ESC	^[	Escape
FF	^l	Form feed	FS	^\	File separator
CR	^m	Carriage return	GS	^]	Group separator
SO	^n	Shift out	RS	^^	Record separator
SI	^o	Shift in	US	^_	Unit separator
			DEL	^?	Delete or rubout

Table 5.2: ASCII control characters and their original meanings.

5.1.2 The class Character

Besides its use as a wrapper for primitive characters (see §6.5), the class `Character` is stuffed with useful methods for handling **char**s. The ones most likely to be of interest first are the ones that distinguish types of characters:

`Character.isWhitespace(`*c*`)` is true iff **char** *c* is "whitespace"—that is, a blank, tab, newline (end-of-line in Unix), carriage return, form feed (new page), or one of a few other esoteric control characters.

`Character.isDigit(`*c*`), Character.isLetter(`*c*`), Character.isLetterOrDigit(`*c*`)` test whether *c* is a digit ('0'–'9'), letter ('a'–'z' and 'A'–'Z'). Actually, the complete set of letters and digits is much larger, comprising most of the world's major alphabets.

`Character.isUpperCase(`*c*`), Character.isLowerCase(`*c*`)` test for upper- and lowercase letters.

As a stylistic matter, it is always better to use these than to test "by hand:"

```
/* Good */                    /* Bad */                /* REALLY Bad */
if (Character.isDigit(x))     if (x>='0' && x<='9')    if (x>=48 && x<=57)
```

A few other routines are sometimes useful for text manipulation:

`Character.toLowerCase(`*c*`), Character.toUpperCase(`*c*`)` return the lower- or uppercase equivalent of *c*, if it's a letter, and otherwise just *c*.

`Character.digit(`*c*`, `*r*`)` returns the integer equivalent of *c* as a radix-*r* digit, or -1 if *c* isn't such a digit. So `digit('3', 10) == 3`, `digit('A', 16) == 10`, `digit('9', 8) == -1`.

`Character.forDigit (`*n*`, `*r*`)` converts numbers back into digits. So `forDigit(5, 10) == '5'`, `forDigit(11,16) == 'b'`.

If you happen to have a method where you use these a lot, you'll soon get tired of writing `Character.`. Fortunately, placing

```
import static java.lang.Character.*;
```

among the **import** statements at the beginning of a program file will make it unnecessary to write the qualifier.

5.2 Strings

Pages 99–101 list the headers of the extensive set of operations available on `Strings`. In addition, the core Java language provides some useful shorthand syntax for using some of these operations, as described in §5.2

Objects of type `String` are *immutable:* that is, the contents of the object pointed to by a particular reference value never changes. It is not possible to "set the fifth character of string `y` to *c*." Instead, you set `y` to an entirely new string, so that after

```
y = "The bat in the hat is back.";
x = y;
y = y.substring (0, 4) + 'c' + y.substring (5);
```

the variable `y` now points to the string

```
The cat in the hat is back.
```

while `x` (containing `y`'s original value) still points to

```
The bat in the hat is back.
```

This property of `String`s makes certain uses of them a bit clumsy or slow, so there is another class, `StringBuffer`, whose individual characters *can* be changed (see §5.3).

5.2.1 Constructing Strings

You will almost never have to construct `String`s using **new** `String(···)`, so I have not bothered to show any in Figure 5.1. String literals (like `""` or `"Hello!"`) handle most constant strings.

The `valueOf` methods allow you to form `String`s from primitive values. For example,

```
String.valueOf (130+3)   is "133"
String.valueOf (true)    is "true"
String.valueOf (1.0/3.0) is "0.3333333333333333"
```

Normally, you don't need these routines, because the concatenation operator (`+`) on `String` uses `valueOf` to convert non-string arguments. For example,

```
"The answer is " (130 + 3)  is "The answer is 133"
"" + (130 + 3)              is "133"
```

When applied to `Objects` (reference-type values), `valueOf` (and therefore `String` concatenation) becomes particularly interesting. For non-null reference values, it uses the `toString` operator to convert the object to a `String`. Now, this function is defined in class `Object`, and therefore can be overridden in *any* user-defined type. You can therefore control how types you create are printed—a very pretty example of object-oriented function dispatching. For example, suppose I define

```
/** A point in 2-space. */
class Point {
  public double x, y;
  ...
  public String toString () {
    return "(" + x + "," + y + ")";
  }
}
```

```
package java.lang;
public final class String
  implements java.io.Serializable, Comparable<String>, CharSequence
{
   /* Unless otherwise noted, the following routines will throw a
    * NullPointerException if given a null argument and
    * IndexOutOfBoundsException if a non-existent portion of a
    * String is referenced. */

   /** A Comparator for which
    *      compare(s0, s1) == s0.compareToIgnoreCase (s1)
    *  for Strings s0 and s1 (used for specifying the order of
    *  Strings in sorted lists and the like). */
   public static final java.util.Comparator<String> CASE_INSENSITIVE_ORDER;

        /* Conversions and translations */
   /** The following 6 functions all return a printable
    *  representation of their argument. */
   public static String valueOf(char x);
   public static String valueOf(double x);
   public static String valueOf(float x);
   public static String valueOf(int x);
   public static String valueOf(long x);
   public static String valueOf(boolean x);
   /** If OBJ == NULL, then the string "null".  Otherwise,
    *  same as OBJ.toString (). */
   public static String valueOf(Object obj);

   /** A String that is formed by converting the trailing arguments
    *  (0 or more Objects) into Strings according to the pattern given
    *  in FORMAT.   See §5.2.1 for details. */
   public String format (String format, Object ... args);

        /* Accessors */
   /** The length of this. */
   public int length();
   /** Character #K of this (numbering starts at 0). */
   public char charAt(int k);
   /** The String whose characters are charAt(b)..charAt(e-1). */
   public String substring(int b, int e);
   /** Same as substring(b, length()). */
   public String substring(int b);
```

Continues...

Figure 5.1: Excerpts from class `String`, part 1. Excludes bodies.

Class String, continued.

```
     /* Predicates */
/** Compare this String to STR lexicographically.  Returns a
 *  value less than 0 if this String compares less than STR,
 *  greater than 0 if this String is greater than STR, and 0
 *  if they are equal. */
public int compareTo(String str);
/** Same as compareTo ((String) obj).  Thus, throws a
 *  ClassCastException if OBJ is not a String. */
public int compareTo(Object obj);
/** As for compareTo(STR), but ignores the distinction between
 *  upper- and lower-case letters. */
public int compareToIgnoreCase(String str);
/** If FOLD is false, equivalent to
 *    substring(K0,K0+LEN).compareTo(S.substring(K1,K1+LEN)) == 0,
 *  and otherwise (if FOLD is true) equivalent to
 *    0 == substring(K0, K0+LEN)
 *              .compareToIgnoreCase (S.substring(K1, K1+LEN))
 *  except that it returns false if either substring operation
 *  would cause an exception. */
public boolean regionMatches(boolean fold, int k0,
                             String S, int k1, int len);
/** Same as regionMatches (false, K0, S, K1, LEN) */
public boolean regionMatches(int k0, String S, int k1, int len);
/** Same as
 *    OBJ instanceof String && compareTo ((String) OBJ) == 0.  */
public boolean equals(Object obj);
/** Same as compareToIgnoreCase (STR) == 0.  */
public boolean equalsIgnoreCase(String str);
/** Same as regionMatches (K0, STR, 0, STR.length ()) */
public boolean startsWith(String str, int k0);
/** Same as startsWith (0, STR) */
public boolean startsWith(String str);
/** Same as startsWith (length () - STR.length (), STR). */
public boolean endsWith(String str);

     /* Conversions and translations */
/** The following four routines return lower- or upper-case
 *  versions of this String.  The LOCALE argument, if present,
 *  modifies the result in the case of Turkish. */
public String toLowerCase();
public String toUpperCase();
```

Continues...

Figure 5.1, continued: The class `String`, part 2.

Class String, continued.

```
     /* Non-destructive modifications */
  /** Returns a new string consisting of this string concatenated
   *  with S. */
  public String concat(String S);
  /** A string copied from this, but with all instances of C0
   *  replaced by C1. */
  public String replace(char c0, char c1);
  /** The string resulting from trimming all characters that are
   *  <= ' ' (space) from both ends of this.  Thus, trims blanks,
   *  tabs, form-feeds, and in fact, all ASCII control
   *  characters. */
  public String trim();

     /* Searches */
  /** The smallest (first) k>=S such that C == charAt(k), or -1
   *  if there is no such k.  */
  public int indexOf(int c, int s);
  /** Same as indexOf (C, 0). */
  public int indexOf(int c);
  /** The largest (last) k<=S such that C == charAt(k), or -1
   *  if there is no such k.  */
  public int lastIndexOf(int c, int s);
  /** Same as lastIndexOf (C, length ()-1). */
  public int lastIndexOf(int c);

  /** The smallest (first) k>=S such that startsWith (TARGET, S),
   *  or -1 if there is none. */
  public int indexOf(String target, int s);
  /** Same as indexOf (TARGET, 0) */
  public int indexOf(String target);
  /** The largest (last) k<=S such that startsWith (TARGET, S), or
   *  -1 if there is none.  The last occurrence of the empty
   *  string, "", is at length (). */
  public int lastIndexOf(String target, int s);
  /** Same as lastIndexOf (TARGET, length ()) */
  public int lastIndexOf(String target);

     /* Miscellaneous. */
  /** Returns this string. */
  public String toString();
  /** Returns an integer hash code for this string.  The actual
   *  code returned is the Java int equal to
   *     s_0 31^{n-1} + s_1 31^{n-2} + ... + s_{n-1} mod 2^32 */
  public int hashCode();
  /** A String .equal to this and having the property that
   *     s0.equals (s1) iff s0.intern () == s1.intern (). */
  public String intern();
}
```

Figure 5.1, continued: The class `String`, part 3.

Now if in a program I write something like

```
Point start = ...;
...
System.out.println ("Starting point: " + start);
// same as "Starting point: " + String.valueOf (start)
```

I could see printed

```
Starting point: (1.1,-2.3)
```

There is a default `toString` that works for all objects. On `String`, it is simply the identity function.

To construct more complicated `String`s, you will generally use A`.concat(`B`)`, more often written conveniently as A `+` B, or the extremely powerful method `format`, a welcome addition to Java that came in with Java 2, version 1.5.

To understand the idea behind `format`, it's best to look at an example. Suppose that I am trying to create a `String` of the form

```
"Average of 1000 inputs: 29.65, standard deviation: 4.81."
```

where the numbers come from variables `N`, `mean`, and `sigma`. I can use concatenation and write this as

```
"Average of " + N + " inputs: " + mean + ", standard deviation: " + sigma;
```

This works, but has the slight problem that `mean` and `sigma` get printed with however many decimal places it takes to represent their value unambiguously, whereas we were content with two places. You might also object that it looks a tad messy. Now, there is another way to produce the `String` we want:

```
String.format ("Average of %d inputs: %.2f, standard deviation: %.2f",
               N, mean, sigma);
```

which inserts the values of `N`, `mean`, and `sigma` at the places indicated by the *format specifiers* `%d` (which means, "format as a decimal integer"), and `%.2f` (which means "format as a decimal numeral rounded to two places to the right of the decimal point"). C programmers will recognize the format specifiers from the `printf` series of functions in the C library. The first argument to `format` is called the *format string,* and the rest are simply additional arguments, which we index from 1 (so `N` is argument 1, and `sigma` is argument 3).

Java has an extensive set of format specifiers, including a whole set (not found in C) that handles dates and times. You'll find a full description in the on-line documentation for `java.util.Formatter`. Here, we'll just do a quick summary of some useful ones.

Most format specifiers have the general form

`%[`K`$][*flags*][$W$][`.`P]C

where square brackets ('`[`$\cdots$`]`') here indicate optional parts:

C specifies the *conversion* to be applied to the argument to make it into a `String`. In most cases, it is a single character.

K is an optional integer index, indicating which of the arguments is to be converted. By default, `format` will take the arguments in order, so that our format-string example above is equivalent to

```
"Average of %1$d inputs: %2$.2f, standard deviation: %3$.2f",
```

W is an optional non-negative integer width, giving the minimum size of the converted string.

P is an optional non-negative integer precision, that restricts the number of characters in some way, depending on *C*.

flags are characters that modify the meaning of *C*.

Table 5.3 shows some of the most useful values of *C*. The categories in that table refer to possible types of arguments:

integral the integer numeric types **int**, **short**, **long**, and **byte** (or more accurately, the corresponding "boxed" types `Integer`, `Short`, `Long`, and `Byte`: see §6.5), plus `java.math.BigInteger` (a class that represents all the integers, or at least those that fit in memory).

general any type.

floating point the numeric types **float** and **double** (again, more accurately `Float` and `Double`), plus `java.math.BigDecimal` (a class that represents all rational numbers expressible in finite decimal notation).

none doesn't use an argument.

The flag characters generally have different meanings for different types, as detailed above. However, the '-' flag always means "left justify within the specified width (*W*)". So,

`String.format ("|%-5d|%5d|", 13, 13)` *produces* `"|13   |   13|"`

5.2.2 Aside: Variable-Length Parameter Lists

I sort of snuck a new feature past in the discussion of `format`. As shown in Figure 5.1, its definition begins

```
public String format (String format, Object ... args)
```

Those dots are actually written as shown, and mean "any number of parameters may follow here, each of which must be an `Object`." You may actually write something like this as the last parameter in any method definition. The type need not be `Object`. Although it looks like a major new mechanism, it's actually a pretty simple shorthand for something you could write otherwise. Let's take a full example with an actual implementation:

Conversion	Category	Description
'd'	integral	format as a decimal integer. With the '0' flag, pad on the left with 0s if necessary to get width W.
'o'	integral	format as an octal (base 8) integer. With the '#' flag, always start with 0 digit. The '0' flag works as for 'd'.
'x', 'X'	integral	format as a hexadecimal (base 16) integer. With 'X', use upper-case letters. The '0' flag works as for 'd'. With the '#' flag, always start with '0x' or '0X'.
'f'	floating point	format as a number with decimal point without an (*fixed point,* as in 186000). If present, P gives the number of decimal places.
'e', 'E'	floating point	format in scientific notation (as in 1.86e5). If present, P is the number of digits after the decimal point. With 'E', uses upper-case 'E' (1.86E5).
'g', 'G'	floating point	format in 'f' or 'e' ('E' in the case of 'G') format, depending on size. If present, P is the number of significant figures.
's', 'S'	general	convert to `String`, usually using `toString`. With 'S', convert to upper case first. If present, P is the maximum number of characters (any extra characters are dropped). It's possible for a type to provide even more control over its '%s' format by implementing the `Formattable` interface. See the full documentation.
'n'	none	an end of line on output.
'%'	none	a percent sign (so, to output "`33%`", you'd use the format specifiers "`%d%%`").

Table 5.3: Common format conversion characters and their meanings. See the text for the meaning of "category."

```
/** A String consisting of the concatenation of the items in ARGS,
 *  separated by SEPARATOR. */
public static String makeList (String separator, String ... args) {
  String result;
  result = "";
  for (int i = 0; i < args.length; i += 1) {
     if (i > 0)
        result += separator;
     result += args[i];
  }
  return result;
}
```

Now with this definition, we can write:

```
makeList (" ", "The", "quick", "brown", "fox")
  produces "The quick brown fox"
```

Also,

```
String[] words = { "The", "quick", "brown", "fox" };
makeList (" ", words) produces "The quick brown fox"
```

has the same result. What is happening here is simply that the definition of the parameter with the ellipses (. . .), also known as a *varargs parameter*, is actually an array, as if the definition had been written

```
public static String makeList (String separator, String[] args) {
```

except that when the Java compiler sees that you have not given it an array (as in the first call to `makeList` above), it creates one for you, so that

```
makeList (" ", "The", "quick", "brown", "fox")
  is implicitly re-written to
makeList (" ", new String[] {"The", "quick", "brown", "fox"} )
```

The Scheme and Common Lisp languages have a similar feature.

In the case of `format`, something else is apparently also going on, because (as in some of our examples) we can supply arguments of type **int** or **double**, which are not `Objects`. We'll see how that works in §6.5.

5.2.3 String Accessors

The accessors let you get at individual characters or substrings of a `String`. Characters are numbers from 0, so that the last is at index `length()-1`. Substrings are specified by giving the index of the first character of the substring and the index just beyond that of the last character, which seems a little odd, but has its advantages. An attempt to fetch non-existent characters raises the exception `IndexOutOfBoundsException`.

Example: Squeeze out selected character.

```
/** Return S with all occurrences of C removed. */
static String squeeze (String S, char c) {
  String S2;
  S2 = "";
  for (int i = 0; i < S.length; i += 1)
    if (S.charAt (i) != c)
      S2 += S.charAt (i);
  return S2;
}
```

Here is another method, using substring:

```
/** Return S with all occurrences of C removed. */
static String squeeze (String S, char c) {
  int i;
  i = 0;
  while (i < S.length) {
    if (S.charAt (i) != c)
      i += 1;
    else
      S = S.substring (0, i) + S.substring (i+1);
  }
  return S;
}
```

The original string object is *not* changed in either of these (indeed, it is impossible to do so).

5.2.4 String Comparisons, Tests, and Searches

One very common pitfall (sometimes even for experienced programmer) is that the equality operator (`==`) does *not* test equality of the *contents* in `Strings`. When applied to `Strings`, it has its usual meaning: pointer equality. Within a given class, all character-by-character identical string literals and constant String expressions refer to the same `String` object; however, every application of **new** creates a new object, so that

```
String x = "Foo";
x == new String (x)                // false
new String (x) == new String (x)   // false
x == x                             // true
x == "Foo"                         // true (in same class)
x.equals (new String (x))          // true
```

The `intern` function on strings in effect chooses a single `String` object amongst all those that are equal (contain the same character sequence). However, I suggest that

you generally avoid such tricks except where speed is needed, and use the `equals` and `compareTo` methods (and their ilk) for comparing strings.

5.2.5 String Hashing

The `hashCode` function is a hashing function that facilitates the creation of search structures for strings. Because it depends only on the characters in the string, it has the necessary property for all hash functions, that

S_0`.hashCode()==`S_1`.hashCode()` *if* S_0`.equals(`S_1`)`

for strings S_0 and S_1. You might think that the function described in the documentation comment is slow to compute, but because $31 = 2^5 - 1$, the following fairly inexpensive function computes the same value:

```
/** Compute S.hashCode () */
public static int hashCode (String s) {
  int r;
  r = 0;
  for (int i = 0; i < s.length (); i += 1)
    r = (r<<5) - r + s.charAt (i);
  return r;
}
```

5.3 StringBuffers

You can think of a `StringBuffer` as a *mutable* (modifiable) `String`. Use them to build up strings quickly (that is, without having to create a new object each time you add a character). In fact, the Java system itself uses `StringBuffers` behind the scenes to implement the '+' operator on `Strings`.

For example, suppose you wanted to take an array of integers and create a `String` consisting of those integers separated from each other by slashes ('/'). That is, you'd like

`join (new int[] { 42, -128, 70, 0 })` *to produce* `"42/-128/70/0"`

Here's one approach:

```
public static String join (int[] A) {
  StringBuffer result = new StringBuffer ();
  for (int i = 0; i < A.length; i += 1) {
    if (i > 0)
       result.append ('/');
    result.append (A[i]);
  }
  return result.toString ();
}
```

```
package java.lang;
public final class StringBuffer
       implements java.io.Serializable, CharSequence {
  /* Unless otherwise noted, the following routines will throw a
   * NullPointerException if given a null argument and
   * IndexOutOfBoundsException if a non-existent portion of a String
   * or StringBuffer is referenced. */

        /* Constructors */
   /** An empty (length() == 0) StringBuffer. */
   public StringBuffer();
   /** A new StringBuffer whose initial contents are INIT */
   public StringBuffer(String init);

        /* Accessors */
   /** The current length of this. */
   public int length();
   /** Character #K of this (numbering starts at 0). */
   public char charAt(int k);
   /** The String whose characters are charAt(b)..charAt(e-1). */
   public String substring(int b, int e);
   /** Same as substring(b, length()). */
   public String substring(int b);

   /** Sets DEST[D0] to charAt(B0), DEST[D0+1] to charAt(B0+1), ...
    *  up but not including charAt(END0).  Exception if DEST is
    *  null or not big enough. */
   public void getChars(int b0, int end0, char[] dest, int d0);

   /** The contents of this as a String. (Further changes to this
    *  StringBuffer don't affect the String.) */
   public String toString();
```

Continues...

Figure 5.2: The class `StringBuffer`, part 1. Excludes bodies and deprecated (obsolete) functions.

```
    /* Modifiers */
/** Insert X into this StringBuffer, putting its first character
 *  at position K (0 <= K <= length()).  Move the original
 *  characters starting at K to the right to make room, and
 *  increase the length as needed. */
public StringBuffer insert(int k, String x);

/** Each remaining insert operation, insert(k, ARGS), is
 *  equivalent to insert(k, String.valueOf(ARGS)). */
public StringBuffer insert(int k, char x);
public StringBuffer insert(int k, double x);
public StringBuffer insert(int k, float x);
public StringBuffer insert(int k, int x);
public StringBuffer insert(int k, long x);
public StringBuffer insert(int k, boolean x);
public StringBuffer insert(int k, Object obj);
public StringBuffer insert(int k, char[] C, int k0, int len);
public StringBuffer insert(int k, char[] C);

/** The operations append(ARGS) are all equivalent to
 *     insert(length(), ARGS) */
public StringBuffer append(char x);
public StringBuffer append(double x);
public StringBuffer append(float x);
public StringBuffer append(int x);
public StringBuffer append(long x);
public StringBuffer append(boolean x);
public StringBuffer append(Object x);
public StringBuffer append(String x);
public StringBuffer append(char[] C, int k0, int len);
public StringBuffer append(char[] C);
```

Continues...

Figure 5.2, continued: The class `StringBuffer`, part 2.

```
    /** Remove the characters at positions START..END-1 from this
     *  StringBuffer, moving the following characters over and
     *  decrementing the length appropriately.  Return this. */
    public StringBuffer delete(int start, int end);
    /** Same as delete(k, k+1) */
    public StringBuffer deleteCharAt(int k);

    /** Same as delete(START, END).insert(START, X) */
    public StringBuffer replace(int start, int end, String x);
    /** Reverse the sequence of characters in this; return this. */
    public StringBuffer reverse();
    /** Causes charAt(K) to be C.  Exception if charAt(K) would cause
     *  an exception */
    public void setCharAt(int k, char c);
    /** Causes length() to be LEN.  If len0 is the previous length,
     *  then charAt(k) is unchanged for 0 <= k < len0, and
     *  charAt(k)==0 for len0 <= k < LEN. */
    public void setLength(int len);
}
```

Figure 5.2, continued: The class `StringBuffer`, part 3.

5.4 Readers, Writers, Streams, and Files

At some point, useful programs communicate with the outside world. While graphical user interfaces can be useful for interaction, there is a great deal of communication that can be described simply as the transmission of a sequence of characters, bytes, bits, or generally symbols from some finite alphabet. When your browser requests a Web page, for example, what actually happens under the hood is that it codes its request as a stream of characters and receives in return a stream of characters, which it then interprets as fancily formatted page. To the programs that manipulate them, everything from Java source programs to Microsoft Word documents to error messages written on your screen look like streams of characters. So it's not surprising to find that the Java library contains numerous classes and interfaces dedicated to several forms of the abstract notion of "a stream of symbols."

This area is an instance of where object-oriented programming languages can be useful. The problem is that their are many potential sources and destinations for streams of characters, but the programs that deal with those characters (interpret or produce them) are indifferent to their source, and might be useful for streams of many different origins. As with other situations of this sort, we react by defining an abstraction that captures just those universal characteristics of a "stream of characters" that programs need and expressing this abstraction within our programming language as some kind of interface.

An obvious question to ask is why a "stream of characters" should be anything other than an "array of characters" or "list of characters." What justification is there for a new concept? There are a couple of reasons:

- There is not necessarily a way to know the *length* of a stream of characters. Indeed, it need not have any finite length *a priori.*

- It is the nature of an array or list that one always has access to its entirety. There is no notion of "finishing with" element k of a list; if you accessed it once, your program is perfectly entitled to access it again. The implementation is required to keep all data in the an array or list available, so that the size of a program becomes proportional to the amount of data it processes. Needless to say, this is a problem in the case of input to a program that runs indefinitely. However, it is also an efficiency issue for programs that access data *sequentially,* and don't need to go back to element k after they've finished with it.

In Java, the situation is rather complicated, because the language and its library have been through a number of major revisions, each one of which seems to have taken a different approach to the problem. The result is that the current library contains *all* the solutions of its prior versions, leading to quite a bit of redundancy and confusion. We'll try to sort this out by picking and choosing our topics and concentrating on how to do useful things.

5.4.1 Input

The classes handling input in Java are loosely organized as follows:

- The abstract class `java.io.InputStream` represents a stream of **byte**s.
- A large number of concrete classes implement `InputStream`. In particular, these include `java.io.FileInputStream`, which produces the contents of a file as a stream of bytes. The *standard input* (which by default is the stream of data you type at the terminal) is presented to your program as an `InputStream` (called `System.in`), although the language is silent as to which concrete implementation it is.
- The abstract class `java.io.Reader` represents a stream of **char**s.
- There are large number of concrete implementations of `Reader`, including:

  `java.io.InputStreamReader` takes an `InputStream` and presents it as a `Reader`.

  `java.io.StringReader` takes a `String` and presents its characters as a `Reader`.

  `java.io.BufferedReader` is an implementation of `Reader` that takes any kind of `Reader` and makes it into a more efficient one by reading large segments at a time.

  `java.util.Scanner` is a class that takes a `Reader` or an `InputStream` and delivers its characters clumped into useful *tokens* (see §5.6).

For example, a program that reads words from the standard input might set things up as follows:

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

class WordReader {
   public static void main (String[] args) {
      Scanner input = new Scanner (System.in);
      processWords (input);
   }
   ...
```

after which, the `next` method in `input` will deliver words from the input, one at a time, as described in §5.6.

Sometimes, you'll instead want to fetch the input from a named file. For example, you might want to run your program like this:

```
java DoMyTaxes tax-2004.dat
```

and have it mean that your program is to read its input from the file named `tax-2004.dat`. To get this effect, you could write:

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

public class DoMyTaxes {
   public static void main (String[] args) {
      try {
         Scanner input = new Scanner (new FileInputStream (args[0]));
         processTaxes (input);
      } catch (FileNotFoundException e) {
         System.err.println ("Could not open file " + args[0]);
         System.exit (1);
      }
   }
   ...
```

Many programs allow you to take input either way, so that plain

```
java DoMyTaxes
```

reads input from the terminal. For this, we put the two cases above together:

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

public class DoMyTaxes {
   public static void main (String[] args) {
      try {
         Scanner input;
         if (args.length == 0)
           input = new Scanner (System.in);
         else
           input = new Scanner (new FileInputStream (args[0]));
         processTaxes (input);
      } catch (FileNotFoundException e) {
         System.err.println ("Could not open file " + args[0]);
         System.exit (1);
      }
   }
   ...
```

Finally, some programs allow you the option of putting the input directly onto the command line, so that `args[0]` isn't just the name of the input; it *is* is the input:

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

```
public class DoCommands {
   public static void main (String[] args) {
       Scanner input = new Scanner (new StringReader (args[0]));
       processCommands (input);
   }
   ...
```

5.4.2 Readers and InputStreams

The classes `Reader` and `InputStream` are abstract. They do not, in and of themselves, define any particular source of input. In the examples above, think of `FileInputStream` and `StringReader` as types of vacuum cleaners. A `Scanner` is an attachment that one can place on either of these. The types `Reader` and `InputStream` are like standard nozzle shapes: you can attach a `Scanner` to any kind of nozzle that conforms to `Reader` or `InputStream`.

Thus, `InputStream` describes a family of classes that support the following methods (among others):

`read()` Return the next byte of input (as an **int** in the range 0–255) or -1 if at the end.

`read(`b, k, len`)` where b is an array of **bytes**, reads at most len bytes into b`[`k`]`, b`[`k`+1], ...` and returns the number read. This method is here for efficiency; it is often faster to read many bytes at once.

`close()` shuts down the stream. Such an operation is often necessary to tell the system when input is no longer needed, since it may otherwise have to consume time or space keeping input available.

`mark(`n`) and reset()` respectively make a note of the program's current place in the input and "rewind" the input to the last mark (assuming that no more than n characters have been read since). Depending on the kind of `InputStream`, they do not always work. So...

`markSupported()` is true iff an `InputStream` allows marking.

The `Reader` class is almost the same, but deals in **char**s rather than `bytes`.

It might occur to you that it would probably be rather clumsy to have to write your program using just `read`. Quite true: you will normally attach something more useful (typically a `Scanner` in this class) to your `Reader`s or `InputStream`s, rather than using them directly. On the other hand, you do have to be familiar with these classes if you wish to create a new kind of input source and want it to be "plug-to-plug compatible" with existing classes that attach to `Reader`s and `InputStream`s.

5.4.3 Output

The classes handling output in Java are roughly analogous to those for input, but with data going in the "opposite direction:"

- The abstract class `java.io.OutputStream` absorbs a stream of **byte**s.
- Numerous concrete classes implement `OutputStream`, notably:

  `java.io.FileOutputStream` writes its stream of bytes into a file.

  `java.io.BufferedOutputStream` collects its stream of bytes and feeds it to another `OutputStream` in chunks, for efficiency.

  java.io.PrintStream adds methods to `OutputStream` that make it easy to write things such as strings and numbers in their printed forms. The standard output and standard error output streams of a program are both `PrintStream`s. Generally, `PrintStream`s are set up to send their streams of bytes to another `OutputStream` (such as a `FileOutputStream`).

- The abstract class `java.io.Writer` absorbs a stream of **char**s.
- Concrete implementations of `Writer` include:

  `java.io.OutputStreamWriter` converts its stream of **char**s that it receives into a stream of bytes and gives it to an `OutputStream`.

  `java.io.StringWriter` collects its stream of **char**s into a `String` that you can extract at any time with `toString`.

  `java.io.BufferedWriter` is analogous to `BufferedOutputStream`, but connects to another `Writer` and deals in **char**s.

  `java.io.PrintWriter` is analogous to `PrintStream`.

5.4.4 PrintStreams and PrintWriters

Especially when creating output intended for human consumption, writing things one character at a time is rather clumsy. The `PrintStream` and `PrintWriter` classes in `java.io` are intended to make this more convenient. Both of these have a set of `print` and `println` methods that convert their argument to a `String` and then write its characters. In `println` method, furthermore, additionally appends an end-of-line sequence, so that the next output starts on a new line. Together with `String` concatenation (‘`+`’), they allow you to write just about anything. For example:

```
System.out.println ("Average of " + N + " inputs: " + mean
                    + ", standard deviation: " + sigma);
```

With Java 2, version 1.5, you have the alternative of using the powerful `format` methods as well:

```
System.out.format ("Average of %d inputs: %.2f, standard deviation: %.2f%n",
                   N, mean, sigma);
```

which has the same effect as

```
System.out.print
  (String.format ("Average of %d inputs: %.2f, standard deviation: %.2f%n",
                  N, mean, sigma));
```

5.5 Regular Expressions and the Pattern Class

So far, all the means we've seen for breaking up a string or other stream of characters have been quite primitive, which can lead to some rather involved programs to do simple things. Consider the problem of interpreting the command-line arguments to a program. A certain program might allow the following parameters

`--output-file=`*FILE* `--output=`*FILE*
`--verbose`
`--charset=unicode` `--charset=ascii`
`--mode=`*N*

where *FILE* is any non-empty sequence of characters and *N* is an integer. That is, a user might start this program with commands like

```
java MyProgram --output-file=result.txt --charset=unicode
java MyProgram --verbose
```

Suppose we want to write a function to test whether a given string has one of these formats. Here's a brute-force approach:

```
/** Return true iff OPTION is a valid command argument. */
public static boolean validArgument (String arg) {
  return (arg.startsWith ("--output-file=") && arg.length () > 14)
      || (arg.startsWith ("--output=") && arg.length () > 9)
      || arg.equals ("--verbose")
      || arg.equals ("--charset=unicode")
      || arg.equals ("--charset=ascii")
      || (arg.startsWith ("--mode=") && isInteger (arg));
}

static boolean isInteger (String numeral) {
  for (int i = 0; i < numeral.length (); i += 1)
    if (! Character.isDigit (numeral.charAt (i)))
      return false;
  return true;
}
```

Clearly, it would be nice not to have to write so much. In fact, we can write the body of `validArgument` much more succinctly like this:

```
final static String argumentPattern =
     "--output(-file)?=.+|--verbose|--charset=(unicode|ascii)"
   + "|--mode=\\d+";

public static boolean validArgument (String arg) {
  return (arg.matches (argumentPattern));
}
```

(Here, we used a separate constant declaration for the pattern string and used '+' to break it across lines for better readability. We could have dispensed with the definition of `argumentPattern` and simply written the pattern string into the **return** statement.)

Here, `matches` method on `String`s treats `argumentPattern` as a *regular expression,* which is a description of a set of strings. To *match* a regular expression is to be a member of this set. For a complete description of regular expressions as they are realized in Java, see the documentation for the classes `Pattern` and `Matcher` in the package `java.util.regex`. For now, we'll just look at some of the most common constructs, summarized in Table 5.4.

The most basic regular expressions contain no special characters, and denote simply a literal match. For example, the two expressions

```
s.equals ("--verbose")     s.matches ("--verbose")
```

have the same value. In set language, we say that the regular expression `--verbose` denotes the set containing the single string `"--verbose"`.

Other forms of regular expression exist to create sets that contain more than one string. For example, to see if a one-character string, `s`, consists of a single vowel (other than 'y'), you could write either

```
s.matches ("a|e|i|o|u")    or   s.matches ("[aeiou]")
```

while to check for a (lower-case) consonant, you'll need

```
s.matches ("[b-df-hj-np-tv-z]")
```

To test for a word starting with single consonant followed by one or more vowels, you would write

```
s.matches ("[b-df-hj-np-tv-z][aeiou]+")
```

Finally, to check that `s` consists of a series of zero or more such words, each one followed by any amount of whitespace, you could write

```
s.matches ("([b-df-hj-np-tv-z][aeiou]+\\s+)*")
```

Here, I had to write two backslashes to create a '`\s`' because in Java string literals, a single backslash is written as a double backslash.

So far, I have been writing strings and calling them regular expressions. The whole truth is somewhat more complicated. The Java library defines two classes: `Pattern` and `Matcher`, both of which are in the package `java.util.regex`. The relationship is suggested in the following program fragment:

```
/* String representing a regular expression */
String R = "[b-df-hj-np-tv-z][aeiou]+";
String s = "To be or not to be";
/* A Pattern representing the same regular expression */
Pattern P = Pattern.compile (R);
```

Regular Expression	**Matches**
x	x, if x is any character not described below
`[`$c_1c_2\cdots$`]`	Any one of the characters c_1, c_2, ... Any of the c_i may also have the form x`-`y, meaning "any single character $\geq x$ and $\leq y$."
`[^`$c_1c_2\cdots$`]`	Any single character *other than* c_1, c_2, ... Here, too, you can use x`-`y as short for all characters $\geq x$ and $\leq y$.
.	Any character except (normally) line terminators (newline characters or other character sequences that mark the end of a line).
`\s`	Any whitespace character (blank, tab, newline, etc.).
`\S`	Any non-whitespace character.
`\d`	Any digit.
`^`	Matches zero characters, but only at the beginning of a line or string.
`$`	Matches zero characters, but only at the end of a line or string.
(R)	Matches the same thing as R. Parentheses serve as grouping operators, just as they do in arithmetic expressions.
R`*`	Any string that can be broken into zero or more pieces, each of which matches R. This is called the *closure* of R.
R`+`	Same as $RR*$. That is, it matches any string that can be broken into one or more pieces, each of which matches R.
R_0R_1	Any string that consists of something that matches R_0 immediately followed by something that matches R_1.
R_0`|`R_1	Any string that matches *either* R_0 or R_1.

Table 5.4: Common regular expressions. Lower-case italic letters denote single characters. R, R_0, R_1, etc. are regular expressions (the definitions are recursive). As with arithmetic expressions, operators have precedences, and are listed here in decreasing order of precedence. Thus, '`ab|xy*`' matches the same strings as '`(ab)|(x(y*))`' rather than '`a(b|x)(y*)`' or '`((ab)|(xy))*`'.

```
/* An object that represents the places where P matches s or
   parts of it. */
Matcher M = P.matcher (s);
if (M.matches ())
   System.out.format ("P matches all of '%s'%n", s);
if (M.lookingAt ())
   System.out.format ("P matches the beginning of '%s'%n", s);
if (M.find ())
   /* M.group () is the piece of s that was matched by the last
      matches, lookingAt, or find on M. */
   System.out.format ("P first matches '%s' in '%s'%n", M.group (), s);
if (M.find ())
   System.out.format ("P next matches '%s' in '%s'%n", M.group (), s);
if (M.find ())
   System.out.format ("P next matches '%s' in '%s'%n", M.group (), s);
```

which, for the given value of `s`, would print:

```
P first matches 'be' in 'To be or not to be'
P next matches 'no' in 'To be or not to be'
P next matches 'to' in 'To be or not to be'
```

A `Pattern` is a "compiled" regular expression, and a `Matcher` is something that finds matches for a given `Pattern` inside a given `String`. The reason for wanting to compile a regular expression into a `Pattern` is mostly one of efficiency: it takes time to interpret the language of regular expressions and to convert it into a form that is easy to apply quickly to a string. The reason to have a `Matcher` class (rather than just writing something like `P.find (s)` is that you will often want to look for multiple matches for a pattern in `s`, and to see just what part of `s` was matched. Therefore, you need something that keeps track of both a regular expression, a string, and the last match within that string. The expression we used previously,

```
s.matches ("([b-df-hj-np-tv-z][aeiou]+\\s+)*")
```

where `s` is a `String`, is equivalent to

```
Pattern.compile ("([b-df-hj-np-tv-z][aeiou]+\\s+)*").matcher (s).matches ()
```

We can use complex regular expressions to do some limited *parsing*—breaking a string into parts. For example, suppose that we want to divide a time and date in the form "mm/dd/yy hh:mm:ss" (as in "3/7/02 12:36:12") into its constituent parts. The means to do so is illustrated here:

```
Pattern daytime = Pattern.compile ("(\\d+)/(\\d+)/(\\d+)\s+(\\d+):(\\d+):(\\d+)");
Matcher m = daytime.matcher ("It is now 3/7/02 12:36:12.");
if (m.find ()) {
    System.out.println ("Year: " + m.group(3));
    System.out.println ("Month: " + m.group(1));
```

```
        System.out.println ("Day: " + m.group(2));
        System.out.println ("Hour: " + m.group(4));
        System.out.println ("Minute: " + m.group(5));
        System.out.println ("Second: " + m.group(6));
    }
```

That is, after any kind of matching operation (in this case, `find`), `m.group(`n`)` returns whatever was matched by the regular expression in the n^{th} pair of parentheses (counting from 1), or `null` if nothing matched that group.

Regular expressions and `Matchers` provide many more features than we have room for here. For example, you can control much more closely how many repetitions of a subpattern match a given string. You can not only find matches for patterns, but also conveniently replace those matches with substitute strings. The intent of this section was merely to suggest what you'll find in the on-line documentation for the Java library.

5.6 Scanner

One application for text pattern matchers is in reading text input. A `Scanner`, found in package `java.util`, is a kind of all-purpose input reader, similar to a `Matcher`. In effect, you attach a `Scanner` to a source of characters—which can be a file, the standard input stream, or a string, among other things—and it acts as a kind of "nozzle" that spits out chunks of the stream as `Strings`. You get to select what constitutes a "chunk." For example, suppose that the standard input consists of words alternating with integers, like this:

```
axolotl 12   aardvark 50
bison
16
cougar 6
panther 2 gazelle 100
```

and you want to read in these data and, let's say, print them out in a standard form and find the total number of animals. Here's one way you might do so, using a default `Scanner`:

```
import java.util.*;

class Wildlife {

  public static void main (String[] args) {
    int total;
    Scanner input = new Scanner (System.in);
    total = 0;
    while (input.hasNext ()) {
       String animal = input.next ();
       int count = input.nextInt ();
       total += count;
       System.out.format ("%-15s %4d%n", animal, count);
    }
    System.out.format ("%-15s %4d%n", "Total", total);
  }

}
```

This program first creates a `Scanner` out of the standard input (`System.in`). Each call to the `next` first skips any *delimiter* that happens to be there, and then returns the next *token* from the input: all characters up to and not including the next delimiter or the end of the input. Each call to `nextInt` is the same, but converts its token into an `int` first (and causes an error if the next token is not an `int`). Finally, `hasNext` returns true iff there is another token before the end of the input. For the given input, the program above prints

```
axolotl          12
aardvark         50
bison            16
cougar            6
panther           2
gazelle         100
Total           186
```

By default, the delimiter used is "any span of whitespace," which is defined as one or more characters for which the method `Character.isWhitespace` returns true. You can change this. For example, to allow comments in the input file above, like this:

```
# Counts from sector #17
axolotl 12   aardvark 50
bison
16
cougar 6  # NOTE: count uncertain
panther 2 gazelle 100
```

insert the following line immediately after the definition of `input`:

```
input.useDelimiter (Pattern.compile ("(
s|#.*)+"));
```

Just as with a `Matcher`, you can set a `Scanner` loose looking for a token that matches a particular pattern (rather than looking for whitespace that matches). So, for example, to skip to the next point in the input file that reads "Chapter N," where N is an integer, you could write

```
if (input.findWithinHorizon ("Chapter \\d+", 0) != null) {
   /* What to do if you find a new chapter */
}
```

The second argument limits the number of characters searched; 0 means that there is no limit. This method returns the next match to the pattern string, or null if there is none.

Again, this section merely suggests what `Scanners` can do. The on-line documentation for the Java library contains the details.

Chapter 6

Generic Programming

Inheritance gives us one way to re-use the contents of a class, method, or interface by allowing it to mold itself to a variety of different kinds of objects having similar properties. However, it doesn't give us everything we might want.

For example, the Java library has a selection of useful classes that, like arrays, represent indexed sequences of values, but are expandable (unlike an array), and provide, in addition, a variety of useful methods. They are all various implementations of the interface `List`. One of these classes is `ArrayList`, which you might use as shown in the example here. Suppose we have a class called `Person`, designed to hold information such as name, Social-Security Number, and salary:

```
public class Person {
  public Person (String name, String SSN, double salary) {
    this.name = name; this.SSN = SSN; this.salary = salary;
  }

  public double salary;
  public String name, SSN;
}
```

We can create a list of `Person`s using a program along the following lines:

```
ArrayList people = new ArrayList ();
while (/*( there are more people to add )*/) {
   Person p = /*( the next person )*/;
   people.add (p);
}
```

That is, `.add` expands the list `people` by one object (which goes on the end). Then we could compute the total payroll like this:

```
double total;
total = 0.0;
for (int i = 0; i < people.size (); i += 1) {
    total += ((Person) people.get (i)).salary;
}
```

That is, `people.get(i)` is sort of like `A[i]` on arrays. But there's an odd awkwardness here: if `people` were an array, we'd write `people[i].salary`. What's with the `(Person)` in front? It is an example of a *cast,* a conversion, which we've seen in other contexts. For reference types, a cast `(`C`)` E means "I assert that the value of E is a C, and if it isn't, throw an exception."

To understand why we need this cast, we have to look at the definition of `ArrayList`, which (effectively) contains definitions like this[1]:

```
public class ArrayList implements List {
   /** The number of elements in THIS. */
   public int size () { ... }
   /** The Ith element of THIS. */
   public Object get (int i) { ... }
   /** Append X as the last element in THIS.  (Always returns true). */
   public boolean add (Object x) { ... }
   ...
```

In order to make the class work on all kinds of objects, the type returned by `get` and taken by `add` is `Object`, the supertype of all reference types. Unfortunately, the Java compiler insists on knowing, for an expression such as `someone.salary`, that `someone` is actually going to have a `salary`. If all it knows is that `people.get (i)` is an `Object`, then it has no idea whether it is a kind of `Object` with a `salary`. Hence the need for the cast to `Person`. When you write

```
((Person) people.get (i)).salary
```

you are saying "I claim that the result of `people.get (i)` is a `Person`" and as a result, the Java system will check that the value returned by `get` really is a `Person` before attempting to take its `salary`. Furthermore, the compiler will proceed under the assumption that the value is a `Person`, and so must indeed have a `salary` field.

6.1 Simple Type Parameters

From your point of view, supplying this extra cast to `Person`, while not terribly burdensome, is redundant, adds to "code clutter," and also delays the detection of certain mistakes until the program executes. The only obvious way around it is unsatisfactory: creating new versions of `ArrayList` for every possible kind of element. Inheritance is no help, as it does not change the signatures (argument and return types) of methods. With Java 2, version 1.5, however, there is a way to say what you mean here—that `people` is a list of `Person`s—using *generic programming:*

[1]The return value of `add` indicates whether the operation changed the list, and is therefore useless in lists, where the `add` operation *always* changes the list. It's there because `List` is just one subtype of an even larger family of types in which the `add` method sometimes does *not* change the target object.

```
ArrayList<Person> people = new ArrayList<Person> ();
while (/*( there are more people to add )*/) {
   Person p = /*( the next person )*/;
   people.add (p);
}
...
double total;
total = 0.0;
for (int i = 0; i < people.size (); i += 1) {
    total += people.get (i).salary;
}
```

To make this work, the definition of `ArrayList` actually reads:

```
public class ArrayList<Item> implements List<Item> {
   /** The number of elements in THIS. */
   public int size () { ... }
   /** The Ith element of THIS. */
   public Item get (int i) { ... }
   /** Append X as the last element in THIS.  (Always returns true). */
   public boolean add (Item x) { ... }
   ...
}
```

The identifier `Item` here is a *type variable,* meaning that it ranges over reference types (interfaces, classes, and array types). The clause "`class ArrayList<Item>`" declares `Item` as a *formal type parameter* to the class `ArrayList`. Finally, `ArrayList<Person>` is a *parameterized type* in which `Person` is an *actual type parameter*. As you can see, you can use `ArrayList<Person>` just as you would an ordinary type—in declarations, **implements** or **extends** clauses, and with **new**, for example.

As another example, the Java library also defines the type `java.util.HashMap`, one of a variety of classes implementing `java.util.Map`, which is intended as a kind of dictionary type. Here is an example in which we take our array of `Person`s from above and arrange to be able to retrieve any `Person` record by name:

```
Map<String, Person> dataBase = new HashMap<String, Person> ();
for (int i = 0; i < people.size (); i += 1) {
  Person someone = people.get (i);
  dataBase.put (someone.name, someone);
}
```

Having set up `dataBase` in this fashion, we can now write little programs like this to retrieve employee records:

```
/** Read name queries from INPUT and respond by printing associated
 *  information from DATA.  Each query is a name (a string). The
 *  end of INPUT or a single period (.) signals the end. */
public static void doQueries (Scanner input, Map<String, Person> data)
{
  while (input.hasNext ()) {
     String name = input.next ();
     if (name.equals ("."))
        break;
     Person info = data.get (name);
     System.out.format ("Name: %s, SSN: %s, salary: $%6.2f%n",
                        name, info.SSN, info.salary);
  }
}
```

The definition of `HashMap` needed to get this effect might look like this[2]:

```
public class HashMap<Key, Value> implements Map<Key, Value> {
  ...
  /** The value mapped to by K, or null if there is none. */
  public Value get (Object k) { ... }
  /** Cause get(K) to become V, returning the previous value of
   *  get(K).  Values for all other keys are unchanged. */
  public Value put (Key k, Value v) { ... }
}
```

The difference from the `ArrayList` example is that we have more than one type parameter.

6.2 Type Parameters on Methods

Suppose that you'd like to generalize the following method:

```
/** Set all the items in A to X. */
public void set (String[] A, String x)
{
  for (int i = 0; i < A.length; i += 1)
    A[i] = x;
}
```

This works for arrays of `String`s, but nothing else. The rules of Java allow you to write

[2]You might wonder why the argument to `get` can be any `Object`. Since the argument to `put`, which is what allows you to add things to the map, is `Key`, `get(x)` will return **null** whenever `x` does not have type `Key`. This is harmless, however, and the designers, I guess, decided to be lenient.

```
/** Set all the items in A to X. */
public static void set2 (Object[] A, Object x)
{
  for (int i = 0; i < A.length; i += 1)
    A[i] = x;
}
```

because all arrays are subtypes of `Object[]`. However you won't find out until execution time if you have supplied an argument for `x` that doesn't have a matching type. With type parameters, however, you can write

```
/** Set all the items in A to X. */
public static <AType> void set3 (AType[] A, AType x)
{
  for (int i = 0; i < A.length; i += 1)
    A[i] = x;
}
```

Here `AType` is a formal type parameter of the *method*, which you can now call with any kind of array. The compiler will insure that you have supplied the right kind of value for `x`.

6.3 Restricting Type Parameters

The useful class `java.util.Collections` contains a number of methods that work on lists, among them one for sorting a list. With what you saw in the last section, you might think that this would suffice to sort any kind of list:

```
public static <T> void sort(List<T> list) {
  ...
}
```

Unfortunately, not quite. In order to sort anything, you have to know what it means for one item to be less than another, and there is no general method for determining such a thing. That is, somewhere in the body of `sort`, there will presumably have to be some statement like

```
if (list.get (i).lessThan (list.get (j))) etc.
```

but there is no such general `lessThan` method that works on all types.

By convention, Java classes can define an ordering upon themselves by implementing the `java.lang.Comparable` interface, which looks like this:

```
public interface Comparable<T> {
  /** Returns a value < 0 if THIS is ``less than'' Y, > 0 if THIS is
   *  greater than Y, and 0 if equal.  */
  int compareTo(T y);
}
```

So we really want to say that `sort` accepts a type parameter `T`, but only if `T` implements the `Comparable` interface. Here's one way to write it:

```
public static <T extends Comparable<T>> void sort(List<T> list) {
  ...
}
```

we call the "`extends Comparable<T>`" clause a *type bound*.

6.4 Wildcards

Sometimes, it really doesn't matter *what* kind of items are stored in your `List`. For example, because `toString` is a method that works on all objects, if you want a method to print them all in a numbered list,

```
public static <T> void printAll (List<T> list) {
   for (int n = 1; n <= list.size (); i += 1)
      System.out.println (n + ". " + list.get (i));
}
```

(The '`+`' operation on `String`s allows you to concatenate any `Object` to a `String`; it does so by calling the `toString` on that `Object`.) However, you never really use the name `T` for anything. Therefore, you can use this shorthand instead:

```
public static void printAll (List<?> list) {
   for (int n = 1; n <= list.size (); i += 1)
      System.out.println (n + ". " + list.get (i));
}
```

You can restrict this *wildcard type variable,* just as you can named type variables:

```
public static void printAllNames (List<? extends Person> list) {
   for (int n = 1; n <= list.size (); i += 1)
      System.out.println (n + ". " + list.get (i).name);
}
```

6.5 Generic Programming and Primitive Types

One possibly unfortunate characteristic of Java is that primitive types (**boolean**, **long**, **int**, **short**, **byte**, **char**, **float**, and **double**) are completely distinct from reference types. Everything other than a primitive value is an `Object` (that is, all reference types are subtypes of `Object`).

Alas, all the examples of useful classes from the Java library that we've seen deal with `Object`s: you can have lists of `Object`s and maps from `Object`s to `Object`s, but you can't use the same classes to get lists of **int**s. The language is not set up to provide such a thing without essentially copying of these classes from the library

and making changes to them by hand—one for each primitive type. The designers thought this was not a great idea and came up with a compromise instead.

Package `java.lang` of the Java library contains a set of *wrapper classes* in `java.lang` corresponding to each of the primitive types:

Primitive	⟹	*Wrapper*	*Primitive*	⟹	*Wrapper*
long	⟹	`Long`	**char**	⟹	`Character`
int	⟹	`Integer`	**boolean**	⟹	`Boolean`
short	⟹	`Short`	**float**	⟹	`Float`
byte	⟹	`Byte`	**double**	⟹	`Double`

The wrapper classes turned out to be a convenient dumping ground for a variety of static methods and constants associated with the primitive types. For example, there are constants `MAX_VALUE` and `MIN_VALUE` defined in the wrappers for numeric types, so that `Integer.MAX_VALUE` is the largest possible **int** value. There are also methods for parsing `String` values containing numeric literals back and forth to primitive types.

The original reason for introducing these classes, however, was so that their instances could contain a value of the corresponding primitive type (commonly called *wrapping* or *boxing* the value.) That is,

```
Integer I = new Integer (42);
int i = I.intValue ();  // i now has the value 42.
```

There is no way to change the `intValue` of a given `Integer` object once it is created; `Integer`s are *immutable* just like primitive values. Since `Integer` is a reference type, however, we can store its instances in an `ArrayList`, for example:

```
/** A list of the prime numbers between L and U. */
public List<Integer> primes (int L, int U)
{
  ArrayList<Integer> primes = new ArrayList<Integer>;
  for (int x = L; x < U; x += 1)
    if (isPrime (x))
        primes.add (new Integer (x));
  return primes;
}
```

These wrappers let us use the library classes for primitive types, but the syntax is clumsy, especially if we want to perform primitive operations such as arithmetic:

```
/** Add X to each item in L. */
public void increment (List<Integer> L, int x)
{
  for (int i = 0; i < L.size (); i += 1)
    L.set (i, new Integer (L.get (i).intValue () + x));
}
```

So in version 1.5 of Java 2, the designers introduced *automatic boxing and unboxing* of primitive values. Basically, the idea is that a primitive value will be implicitly converted (*coerced*) to a corresponding wrapper value when needed, and vice-versa. For example:

```
Integer x = 42;  // is equivalent to Integer x = new Integer (42)
int y = x;       // is equivalent to int y = x.intValue ();
```

Now we can write

```
/** Add X to each item in L. */
public void increment (List<Integer> L, int x)
{
  for (int i = 0; i < L.size (); i += 1)
    L.set (i, L.get (i) + x);
}
```

So now it at least *looks like* we can write classes that deal with all types of value, primitive and reference. Nothing, alas, is free. The boxing coercion especially uses up both space and time. For large and intensively used collections of values, it may still be necessary to tune one's program by building specialized versions of such general-purpose classes.

6.6 Caveats

Let's face it, inheritance and type parameterization in Java are both complicated. I've tried to finesse some of the complexity (for example, there are still a number of generic-programming features that I haven't discussed at all.) Here are a few particular pitfalls it might be helpful to beware of.

Type hierarchy. A very common mistake is to think that, for example, because `String` is a subtype of `Object`, that therefore `ArrayList<String>` must be a subtype of `ArrayList<Object>`. In fact, this is not the case. Actually, it's not difficult to see why. In Java, if C is a subtype of P, then anything you can do to a P you can also do to a C. If `L` is an `ArrayList<Object>`, then you can write

```
Person someone = ...;
L.add (someone);
```

But clearly, you *cannot* do that to an `ArrayList<String>`; therefore you'd better not be allowed to have `L` point to an `ArrayList<String>`, which means that `ArrayList<String>` had better *not* be a subtype of `ArrayList<Object>` (nor vice-versa).

Consequences of the implementation. You might be tempted to think that `ArrayList<Person>` is a just new copy of `ArrayList` with `Person` substituted for `Item` throughout. For a number of reasons, partly historical[3], it's really just a plain `ArrayList`s under the hood and all varieties of `ArrayList<`T`>` for all T actually run exactly the same code. During translation, however, the compiler enforces the extra requirement that an `ArrayList<Person>` may only contain `Person`s. There are a couple of noticeable consequences of this design that are frankly annoying. If T is a type parameter, then

- You cannot use `new` T. For example, inside the definition of `ArrayList`, you can't write "`new Item[...]`."
- You cannot write `X instanceof` T.
- You cannot use T as the type of a static field.

[**Advanced Question:** See if you can figure out why these restrictions might exist.]

The restriction against using a type parameter in a **new** is bothersome. Suppose you'd like to write:

```
class MyThing<T> {
  private T[] stuff;

  MyThing (int N) {
     stuff = new T[N];
  }

  T get (int i) { return stuff[i]; }
}
```

It makes perfect sense, but doesn't work, because you're not allowed to use `T` with **new**. Instead, write the following:

```
  MyThing (int N) {
     stuff = (T[]) new Object[N];
  }
```

This is a terrible kludge, really, justified only by necessity. Your author feels dirty just mentioning it. The code above would not work, for example, if you substituted a real type, like `String` for the type variable `T`; at execution time, you would get an error on the conversion to `String[]`, because an array of `Object` is not an array of `String`. The code above works only because the Java compiler "really" substitutes `Object` for `T` inside the body of `MyThing`, and then inserts additional conversions where needed. Perhaps it is advisable for the time being *not* to think about this unfortunate glitch too much and hope the designers eventually come up with a better solution!

[3]These generic programming features were designed under stringent constraints. Backward compatibility, in particular, was an important goal. Old versions of `ArrayList` and other functions in the Java library had no parameters, and Java's designers did not want to have to force programmers to rewrite all their existing Java programs.

Chapter 7

Multiple Threads of Control

Sometimes, we need programs that behave like several separate programs, running simultaneously and occasionally communicating. Familiar examples come from the world of graphical user interfaces (GUIs) where we have, for example, a chess program in which one part that "thinks" about its move while another part waits for its user to resize the board or push the "Resign" button. In Java, such miniprograms-within-programs are called *threads*. The term is short for "thread of control." Java provides a means of creating threads and indicating what code they are to execute, and a means for threads to communicate data to each other without causing the sort of chaos that would result from multiple programs attempting to make modifications to the same variables simultaneously. The use of more than one thread in a program is often called *multi-threading;* however, we also use the terms *concurrent programming,* and *parallel programming,* especially when there are multiple processors each of which can be dedicated to running a thread.

Java programs may be executed on machines with multiple processors, in which case two active threads may actually execute instructions simultaneously. However, the language makes no guarantees about this. That's a good thing, since it would be a rather hard effect to create on a machine with only one processor (as most have). The Java language specification also countenances implementations of Java that

- Allow one thread to execute until it wants to stop, and only then choose another to execute, or
- Allow one thread to execute for a certain period of time and then give another thread a turn (*time-slicing*), or
- Repeatedly execute one instruction from each thread in turn (*interleaving*).

This ambiguity suggests that threads are not intended simply as a way to get parallelism. In fact, the thread is a useful *program structuring tool* that allows sequences of related instructions to be written together as a single, coherent unit, even when they can't actually be executed that way.

```
package java.lang;

public interface Runnable {
    /** Execute the body of a thread. */
    void run();
}


public class Thread implements Runnable {
    /** Minimum, maximum, and default thread priorities. */
    public static final int
        MIN_PRIORITY, NORM_PRIORITY, MAX_PRIORITY;

    /** A new Thread with name NAME that will run
     *  the code in BODY.run() when started. */
    public Thread(Runnable body, String name);
    /** Same as Thread (BODY, some generated name) */
    public Thread(Runnable body);
    /** Same as Thread (null, NAME) */
    public Thread(String name);
    /** Same as Thread (this, some generated name) [that is,
     *  the Thread supplies its own run() routine.] */
    public Thread();

    /** Begin independent execution of the body of this
     *  Thread.  Throws exception if this Thread has already
     *  started. */
    public void start();

    /** Inherited from Runnable. If this Thread provides
     *  its own body, this executes it. */
    public void run();

    /** The Thread that is executing the caller. */
    public static native Thread currentThread();
    /** Fetch (set) the name of this Thread. */
    public final String getName();
    public final void setName(String newName);
    /** The (set) the current priority of this Thread. */
    public final int getPriority();
    public final void setPriority(int newPriority);
```

Continued on page 135.

Figure 7.1: The interface `java.lang.Runnable` and class `java.lang.Thread`. See also §7.1.

Class `Thread` *continued from page 134.*

```
    /** Current interrupt state of this Thread. */
    public boolean isInterrupted();
    /** Causes this.isInterrupted() to become true. */
    public void interrupt();
    /** Resets this.isInterrupted() to false, and returns its
     *  prior value. */
    public static boolean interrupted();

    /** Causes CURRENT to wait until CURRENT.isInterrupted()
     *  or this thread terminates, or 10^-3 · MILLIS + 10^-9 · NANOS
     *  seconds have passed.  */
    public final void join(long millis, int nanos)
        throws InterruptedException;
    /** Same as join (MILLIS, 0); join(0) waits forever. */
    public final void join(long millis)
        throws InterruptedException;
    /** Same as join(0) */
    public final void join() throws InterruptedException;

    /** Causes CURRENT to wait until CURRENT.isInterrupted()
     *  or 10^-3 · MILLIS + 10^-9 · NANOS seconds have passed.  */
    public static void sleep(long millis, int nanos)
        throws InterruptedException;
    /** Same as sleep(MILLIS, 0). */
    public static void sleep(long millis)
        throws InterruptedException;
}
```

Figure 7.2: Class`java.lang.Thread`, continued.

7.1 Creating and Starting Threads

Java provides the built-in type `Thread` (in package `java.lang`) to allow a program a way to create and control threads. Figures 7.1–7.2 describe this class and the `Runnable` interface as the programmer sees them. In the figure, `CURRENT` refers to the `Thread` executing the call, also called `Thread.currentThread()`.

There are essentially two ways to use it to create a new thread. Suppose that our main program discovers that it needs to have a certain task carried out—let's say washing the dishes—while it continues with its work—let's say playing chess. We can use either of the following two forms to bring this about:

```
class Dishwasher implements Runnable {
   Fields needed for dishwashing.
   public void run () { wash the dishes }
}

class MainProgram {
   public static void main (String[] args) {
      ...
      if (dishes are dirty) {
        Dishwasher washInfo = new Dishwasher ();
        Thread washer = new Thread (washInfo);
        washer.start ();
      }
      play chess
   }
}
```

Here, we first create a data object (`washInfo`) to contain all data needed for dishwashing. It implements the standard interface `java.lang.Runnable`, which requires defining a function `run` that describes a computation to be performed. We then create a `Thread` object `washer` to give us a handle by which to control a new thread of control, and tell it to use `washInfo` to tell it what this thread should execute. Calling `.start` on this `Thread` starts the thread that it represents, and causes it to call `washInfo.run ()`. The main program now continues normally to play chess, while thread `washer` does the dishes. When the `run` method called by `washer` returns, the thread is terminated and (in this case) simply vanishes quietly.

In this example, I created two variables with which to name the `Thread` and the data object from which the thread gets its marching orders. Actually, neither variable is necessary; I could have written instead

```
if (dishes are dirty)
   (new Thread (new Dishwasher ())).start ();
```

Java provides another way to express the same thing. Which you use depends on taste and circumstance. Here's the alternative formulation:

```
class Dishwasher extends Thread {
   Fields needed for dishwashing.
   public void run () { wash the dishes }
}

class MainProgram {
   public static void main (String[] args) {
      ...
      if (dishes are dirty) {
        Thread washer = new Dishwasher ();
        washer.start ();
        // or just (new Dishwasher ()).start ();
      }
      play chess
   }
}
```

Here, the data needed for dishwashing are folded into the `Thread` object (actually, an extension of `Thread`) that represents the dishwashing thread.

When you execute a Java application (as opposed to an embedded Java program, such as an applet), the system creates an anonymous *main thread* that simply calls the appropriate `main` procedure. When the `main` procedure terminates, this main thread terminates and the system then typically waits for any other threads you have created to terminate as well.

7.2 A question of terminology

The fact that Java's `Thread` class has the name it does may tempt you into making the equation "thread = `Thread`." Unfortunately, this is not correct. When I write "thread" (uncapitalized in normal text font), I mean "thread of control"—an independently executing instruction sequence. When I write "`Thread`" (capitalized in typewriter font), I mean "a Java object of type `java.lang.Thread`." The relationship is that a `Thread` is an object visible to a program by which one can manipulate a thread—a sort of handle on a thread. Each `Thread` object is associated with a thread, which itself has no name, and which becomes active when some other thread executes the `start` method of the `Thread` object.

A `Thread` object is otherwise just an ordinary Java object. The thread associated with it has no special access to the associated `Thread` object. Consider a slight extension of the `Dishwasher` class above:

```
class SelfstartingDishwasher extends Dishwasher {
  SelfstartingDishwasher () {
    start ();
  }
}

class MainProgram {
   public static void main (String[] args) {
      ...
      if (dishes are dirty) {
        Thread washer = new SelfstartingDishwasher ();
        // actually, we could just use
        //    new SelfstartingDishwasher ();
        // and get an anonymous dishwasher, since we don't
        // refer to 'washer' again.
      }
      play chess
   }
}
```

Initially, the anonymous main thread executes the code in `MainProgram`. The main thread creates a `Thread` (actually a `SelfstartingDishwasher`), pointed to by `washer`, and then executes the statements in its constructor. That's right: the *main thread* executes the code in the `SelfstartingDishwasher` constructor, just as it would for any object. While executing this constructor, the main thread executes `start()`, which is short for `this.start()`, with the value `this` being that of `washer`. That activates the thread (lower case) associated with `washer`, and that thread executes the `run` method for `washer` (inherited, in this case, from `Dishwasher`). If we were to define additional procedures in `SelfstartingDishwasher`, they could be executed either by the main thread or by the thread associated with `washer`. The only magic about the type `Thread` is that among other things, it allows you to start up a new thread; otherwise `Threads` are ordinary objects.

Just to cement these distinctions in your mind, I suggest that you examine the following (rather perverse) program fragment, and make sure that you understand why its effect is to print '`true`' a number of times. It makes use of the static (class) method `Thread.currentThread`, which returns the `Thread` associated with the thread that calls it. Since `Foo` extends `Thread`, this method is inherited by `Foo`.

```
// Why does the following program print nothing but 'true'?
class Foo extends Thread {
   public void run () {
     System.out.println (Main.mainThread != currentThread());
   }

   public void printStuff () {
     Thread mainThr = Main.mainThread;
```

```
      System.out.println (mainThr == Thread.currentThread ());
      System.out.println (mainThr == Foo.currentThread ());
      System.out.println (mainThr == this.currentThread ());
      System.out.println (mainThr == currentThread ());
   }
}

class Main {
   static Thread mainThread;
   public static void main (String[] args) {
      mainThread = Thread.currentThread ();
      Thread aFoo = new Foo ();
      aFoo.start ();
      System.out.println (mainThread == Foo.currentThread ());
      System.out.println (mainThread == aFoo.currentThread ());
      aFoo.printStuff ();
   }
}
```

7.3 Synchronization

Two threads can communicate simply by setting variables that they both have access to. This sounds simple, but it is fraught with peril. Consider the following class, intended as a place for threads to leave String-valued messages for each other.

```
class Mailbox { // Version I. (Non-working)
   volatile String msg;

   Mailbox () { msg = null; }

   void send (String msg0) {
      msg = msg0;
   }

   String receive () {
      String result = msg;
      msg = null;
      return result;
   }
}
```

Here, I am assuming that there are, in general, several threads using a `Mailbox` to send messages and several using it to receive, and that we don't really care which thread receives any given message as long as each message gets received by exactly one thread.

This first solution has a number of problems:

1. If two threads call `send` with no intervening call to `receive`, one of their messages will be lost (a *write-write conflict*).

2. If two threads call `receive` simultaneously, they can both get the same message (one example of a *read-write conflict* because we wanted one of the threads to *write* null into `result` before the other thread *read* it.

3. If there is no message, then `receive` will return `null` rather than a message.

Items (1) and (2) are both known as *race conditions*—so called because two threads are racing to read or write a shared variable, and the result depends (unpredictably) on which wins. We'd like instead for any thread that calls `send` to wait for any existing message to be received first before preceding; likewise for any thread that calls `receive` to wait for a message to be present; and in all cases for multiple senders and receivers to wait their respective turns before proceeding.

7.3.1 Mutual exclusion

We could try the following re-writes of `send` and `receive`:

```
class Mailbox { Version II. (Still has problems)
   volatile String msg;

   Mailbox () { msg = null; }

   void send (String msg0) {
     while (msg != null)
        ; /* Do nothing */
     msg = msg0;
   }

   String receive () {
     while (msg == null)
       ; /* Do nothing */
     String result = msg;
     msg = null;
     return result;
   }
}
```

The **while** loops with empty bodies indulge in what is known as *busy waiting.* A thread will not get by the loop in `send` until `this.msg` becomes null (as a result of action by some other thread), indicating that no message is present. A thread will not get by the loop in `receive` until `this.msg` becomes non-null, indicating that a message is present. (For an explanation of the keyword **volatile**, see §7.3.3.)

Unfortunately, we still have a serious problem: it is still possible for two threads to call `send`, simultaneously find `this.msg` to be null, and then both set it, losing one message (similarly for `receive`). We want to make the section of code in each procedure from testing `this.msg` for null through the assignment to `this.msg` to be effectively *atomic*—that is, to be executed as an indivisible unit by each thread.

Java provides a construct that allows us to *lock* an object, and to set up regions of code in which threads *mutually exclude* each other if operating on the same object.

Syntax.

SynchronizeStatement:
synchronized `(` *Expression* `)` *Block*

The *Expression* must yield a non-null reference value.

Semantics. We can use this construct in the code above as follows:

```
class Mailbox { // Version III.  (Starvation-prone)
   String msg;

   Mailbox () { msg = null; }

   void send (String msg0) {
     while (true)
        synchronized (this) {
           if (msg == null) {
              msg = msg0;
              return;
           }
        }
   }

   String receive () {
     while (true)
        synchronized (this) {
           if (msg != null) {
              String result = msg;
              msg = null;
              return result;
           }
        }
   }
}
```

The two **synchronized** blocks above are said to *lock* the object referenced by their argument, `this`.

When a given thread, call it t, executes the statement

synchronized (X) `{` S `}`

the effect is as follows:

- If some thread other than t has one or more *locks* on the object pointed to by X, t stops executing until these locks are removed. t then places a lock on the object pointed to by X (the usual terminology is that it *acquires* a lock on X). It's OK if t already has such a lock; it then gets another. These operations, which together are known as *acquiring a lock on (the object pointed to by)* X are carried out in such a way that only one thread can lock an object at a time.
- S is executed.
- No matter how S exits—whether by **return** or **break** or exception or reaching its last statement or whatever—the lock that was placed on the object is then removed.

As a result, if every function that touches the object pointed to by X is careful to synchronize on it first, only one thread at a time will modify that object, and many of the problems alluded to earlier go away. We call S a *critical region* for the object referenced by X. In our Mailbox example, putting accesses to the `msg` field in critical regions guarantees that two threads can't both read the `msg` field of a Mailbox, find it null, and then both stick messages into it (one overwriting the other).

We're still not done, unfortunately. Java makes no guarantees about which of several threads that are waiting to acquire a lock will 'win'. In particular, one cannot assume a first-come-first-served policy. For example, if one thread is looping around in `receive` waiting for the `msg` field to become non-null, it can permanently prevent another thread that is executing `send` from ever acquiring the lock! The 'receiving' thread can start executing its critical region, causing the 'sending' thread to wait. The receiving thread can then release its lock, loop around, and re-acquire its lock even though the sending thread was waiting for it. We say that the sender can *starve.* There are various technical reasons for Java's being so loose and chaotic about who gets locks, which we won't go into here. We need a way for a thread to wait for something to happen without starving the very threads that could make it happen, and without monopolizing the processor with useless thumb-twiddling.

7.3.2 Wait and notify

The solution is to use the routines `wait`, `notify`, and `notifyAll` to temporarily remove locks until something interesting happens. These methods are defined on all `Object`s. If thread T calls X`.wait()`, then T must have a lock on the object pointed to by X (there is an exception thrown otherwise). The effect is that T temporarily removes all locks it has on that object and then *waits on* X. (Confusingly, this is *not* the same as waiting to acquire a lock on the object; that's why I used the phrase "stops executing" above instead.) Other threads can now acquire locks on

the object. If a thread that has a lock on X executes `notifyAll`, then all threads waiting on X at that time stop waiting and each tries to re-acquire all its locks on X and continue (as usual, only one succeeds; the rest continue to contend for a lock on the object). The `notify` method is the same, but wakes up only one thread (choosing arbitrarily). With these methods, we can re-code `Mailbox` as follows:

```
// Version IV. (Mostly working)
void send (String msg0) {
  synchronized (this) {
    while (msg != null)
      try {
        this.wait ();
      } catch (InterruptedException e) { }

    msg = msg0;
    this.notifyAll ();
  }
}

String receive () {
  synchronized (this) {
    while (this.msg == null)
      try {
        this.wait ();
      } catch (InterruptedException e) { }

    String result = msg;
    this.notifyAll ();   // Unorthodox placement.  See below.
    msg = null;
    return result;
  }
}
```

In the code above, the `send` method first locks the `Mailbox` and then checks to see if all messages that were previously sent have been received yet. If there is still an unreceived message, the thread releases its locks and waits. Some other thread, calling `receive`, will pick up the message, and notify the would-be senders, causing them to wake up. The senders cannot immediately acquire the lock since the receiving thread has not left `receive` yet. Hence, the placement of `notifyAll` in the `receive` method is not critical, and to make this point, I have put it in a rather non-intuitive place (normally, I'd put it just before the return as a stylistic matter). When the receiving thread leaves, the senders may again acquire their locks. Because several senders may be waiting, all but one of them will typically lose out; that's why the `wait` statements are in a loop.

This pattern—a function whose body synchronizes on `this`—is so common that there is a shorthand (whose meaning is nevertheless identical):

```
synchronized void send (String msg0) {
  while (msg != null)
    try {
      this.wait ();
    } catch (InterruptedException e) { }

  msg = msg0;
  this.notifyAll ();
}

synchronized String receive () {
  while (this.msg == null)
    try {
      this.wait ();
    } catch (InterruptedException e) { }

  String result = msg;
  this.notifyAll ();
  msg = null;
  return result;
}
```

There are still times when one wants to lock some arbitrary existing object (such as a shared `Vector` of information), and the **synchronized** statement I showed first is still useful.

It may have occurred to you that waking up all threads that are waiting only to have most of them go back to waiting is a bit inefficient. This is true, and in fact, so loose are Java's rules about the order in which threads get control, that it is still possible with our solution for one thread to be starved of any chance to get work done, due to a constant stream of fellow sending or receiving threads. At least in this case, *some* thread gets useful work done, so we have indeed improved matters. A more elaborate solution, involving more objects, will fix the remaining starvation possibility, but for our modest purposes, it is not likely to be a problem.

7.3.3 Volatile storage

You probably noticed the mysterious qualifier **volatile** in the busy-waiting example. Without this qualifier on a field, a Java implementation is entitled to pretend that no thread will change the contents of a field after another thread has read those contents until that second thread has acquired or released a lock, or executed a `wait`, `notify`, or `notifyAll`. For example, a Java implementation can treat the following two pieces of code as identical, and translate the one on the left into the one on the right:

```
                                tmp = X.z;
while (X.z < 100) {             while (tmp < 100) {
```

```
    X.z += 1;                    tmp += 1;
}                              }
                               X.z = tmp;
```

But of course, the effects of these two pieces of code are *not* identical if another thread is also modifying `X.z` at the same time. If we declare `z` to be volatile, on the other hand, then Java must use the code on the left.

By default, fields are not considered volatile because it is potentially expensive (that is, slow) not to be able to keep things in temporary variables (which may often be fast registers). It's not common in most programs, with the exception of what I'll call the *shared, one-way flag idiom.* Suppose that you have a simple variable of some type other than `long` or `double`[1] and that some threads only read from this variable and others only write to it. A typical use: one thread is doing some lengthy computation that might turn out to be superfluous, depending on what other threads do. So we set up a boolean field in some object that is shared by all these threads:

```
volatile boolean abortComputation;
```

Every now and then (say at the top of some main loop), the computing thread checks the value of `abortComputation`. The other threads can tell it to stop by setting `abortComputation` to **`true`**. Making this field volatile in this case has exactly the same effect as putting every attempt to read or write the field in a `synchronized` statement, but is considerably cheaper.

7.4 Interrupts

Amongst programmers, the traditional definition of an *interrupt* is an "asynchronous transfer of control" to some pre-arranged location in response to some event[2]. That is, one's program is innocently tooling along when, between one instruction and the next, the system inserts what amounts to a kind of procedure call to a subprogram called an *interrupt handler.* In its most primitive form, an interrupt handler is not a separate thread of control; rather it usurps the thread that is running your program. The purpose of interrupts is to allow a program to handle a given situation when

[1]The reason for this restriction is technical. The Java specification requires that assigning to or reading from a variable of a type other than `long` and `double`, is *atomic,* which means that any value read from a variable is one of the values that was assigned to the variable. You might think that always has to be so. However, many machines have to treat variables of type `long` and `double` internally as if they were actually two smaller variables, so that assigning to them is actually *two* operations. If a thread reads from such a variable *during* an assignment (by another thread), it can therefore get a weird value that consists partly of what was previously in the variable, and partly what the assignment is storing into the variable. Of course, a Java implementation could "do the right thing" in such cases by quietly performing the equivalent of a **synchronized** statement whenever reading or writing such "big" variables, but that is expensive, and it was deemed better simply to let bad things happen and to warn programmers to be careful.

[2]Actually, 'interrupt' is also used to refer to the precipitating event itself; the terminology is a bit loose.

it occurs, without having to check constantly (or *poll,* to use the technical term) to see if the situation has occurred while in the midst of other work.

For example, from your program's point of view, an interrupt occurs when you type a `Ctrl-C` on your keyboard. The operating system you are using handles numerous interrupts even as your program runs; one of its jobs is to make these invisible to your program.

Without further restrictions, interrupts are extremely difficult to use safely. The problem is that if one really can't control at all where an interrupt might occur, one's program can all too easily be caught with its proverbial pants down. Consider, for example, what happens with a situation like this:

```
// Regular program          |  // Interrupt handler
theBox.send (myMessage);    |  theBox.send (specialMessage);
```

where the interrupt handlers gets called in the middle of the regular program's `send` routine. Since the interrupt handler acts like a procedure that is called during the sending of `myMessage`, we now have all the problems with simultaneous sends that we discussed before. If you tried to fix this problem by declaring that the interrupt handler must wait to acquire a lock on `theBox` (i.e., changing the normal rule that a thread may hold any number of locks on an object), you'd have an even bigger problem. The handler would then have to wait for the regular program, but the regular program would not be running—the handler would be!

Because of these potential problems, Java's "interrupts" are greatly constrained; in fact, they are really not asynchronous at all. One cannot, in fact, interrupt a thread's execution at an arbitrary point, nor arrange to execute an arbitrary handler. If `T` points to an active `Thread` (one that has been started, and has not yet terminated), then the call `T.interrupt()` puts the thread associated with `T` in *interrupted status*. When that thread subsequently performs a `wait`—or if it is waiting at the time it is interrupted—two things happen in sequence:

- The thread re-acquires all its locks on the object on which it executed the `wait` call in the usual way (that is, it waits for any other thread to release its locks on the object).
- The thread then throws the exception `InterruptedException` (from package `java.lang`). This is a checked exception, so your program must have the necessary `catch` clause or `throws` clause to account for this exception. At this point, the thread is no longer in interrupted status (so if it chooses to wait again, it won't be immediately re-awakened).

In Figures 7.1–7.2, methods that are declared to throw `InterruptedException` do so when the current thread (the one executing the call, not necessarily the `Thread` whose method is being executed) becomes interrupted (or was at the time of the call). When that happens `CURRENT.isInterrupted()` reset to false.

You've probably noticed that being interrupted requires the coöperation of the interrupted thread. This discipline allows the programmers to insure that interrupts occur only where they are non- disruptive, but it makes it impossible to achieve

effects such as stopping a renegade thread "against its will." In the current state of the Java library, it appears that this is, in fact, impossible. That is, there is no general way, short of executing `System.exit` and shutting down the entire program, to reliably stop a runaway thread. While poking around in the Java library, you may run across the methods `stop, suspend, resume,` and `destroy` in class `Thread`. All of these methods are either *deprecated,* meaning that they are present for historical reasons and the language designers think you shouldn't use them, or (in the case of `destroy`) unimplemented. I suggest that you join in the spirit of deprecation and avoid these methods entirely. First, it is very tricky to use them safely. For example, if you manage to `suspend` a thread while it has a lock on some object, that lock is not released. Second, because of the peculiarities of Java's implementation, they won't actually do what you want. Specifically, the `stop` method does not stop a thread immediately, but only at certain (unspecified) points in the program. Threads that are in an infinite loop doing nothing but computation may never reach such a point.

Chapter 8

Types Object, Class, and System

This chapter contains excerpts from a few miscellaneous classes that often come up, but didn't fit anywhere else.

8.1 Objects

The class `java.lang.Object` is the root of the hierarchy of all Java classes. That is, every reference type (including the array types) is a direct or indirect extension of `Object`, so that all the methods in `Object` are defined for all reference types. A class that does not explicitly extend another class extends `Object`. All interfaces implicitly include the methods defined for `Object`[1]. This universal definition is extremely convenient in the definition of other Java classes. For example, all Java objects can be printed, thanks to `toString`, and all can be included in hash tables, thanks to `hashCode`.

The non-final methods are specifically intended to be extended by individual classes, so that, for example, when you define a new class, you can define what its values look like as `Strings` by overriding `toString`. Therefore, the documentation comments on them simply describe their default behavior.

The thread-related methods (`wait`, `notify`, and `notifyAll`) are described in more detail in Chapter 7.

8.2 Class

Some languages provide ways to "look at themselves:" some of their values represent constructs in the language. The property of providing such values is called *reflection.* Java provides quite a bit of this in the package `java.lang.reflect`, which provides classes such as `Field` and `Method` to represent the corresponding pieces of Java programs. Usually, you'll have no need for the features in that package. One

[1]This works because a value whose static type is an interface type always points at an object whose class directly or indirectly extends `Object`.

```
package java.lang;
public class Object {
   /* Constructor */
   public Object();

   /* True iff this is "equal to" OBJ.  The definition provided here
    * here is equivalent to this == OBJ (pointer equality). */
   public boolean equals(Object obj);
   /** The Class object that represents the class of this. */
   public final native Class<?> getClass();
   /** A String representing this.  Default implementation returns
    *    getClass().getName()+'@'+Integer.toHexString(hashCode()) */
   public String toString();
   /** Some integer value.  This should always have the property
    *  that if x.equals(y), then x.hashCode() == y.hashCode(). It
    *  is desirable that the reverse be true "as much as possible".
    *  Nothing is said about the default implementation, except
    *  that there is one. */
   public native int hashCode();

   /** A "copy" of this, which should not be the same object (i.e.,
    *  the result!=this).  A class wishing to provide the ability
    *  to produce clones should override the method with a public
    *  method.  All array types do so.  The default implementation is
    *  to create a new object of the same dynamic type as THIS, all of
    *  whose instance variables are copied (as by =) from those of THIS.
    *  This default implementation works only on classes that
    *  implement the marker interface java.lang.Cloneable, and throws
    *  CloneNotSupportedException otherwise. */
   protected Object clone() throws CloneNotSupportedException;

   /** An action to take when this object is about to be
    *  destroyed as a result of garbage collection. */
   protected void finalize() throws Throwable;
```

Continued on next page.

Figure 8.1: The class Object.

Continued from page 150.

```
        /* Thread-related. */

   /* These methods all throw IllegalMonitorStateException if
    * the thread that executes them does not hold a lock on this. */

   /** Cause some thread that is waiting on this (as a result of
    *  executing one of the wait functions) to be released from
    *  the waiting state.  */
   public final native void notify();
   /** Cause all threads that are waiting on this (as a result of
    *  executing one of the wait functions) to be released from
    *  the waiting state.  */
   public final native void notifyAll();
   /** Put the current thread in a waiting state for this object and
    *  release all locks.  When notified or interrupted, re-acquire
    *  all locks and continue.  If TIMEOUT or TIMEOUTNANOS is >0,
    *  also continue after approximately TIMEOUT + 10^-6 *
TIMEOUTNANOS
    *  milliseconds.  Throws InterruptedException if awakened by an
    *  interrupt. IllegalArgumentException if TIMEOUT <0 or
    *  TIMEOUTNANOS not between 0 and 999999. */
   public final void wait(long timeout, int timeoutnanos)
       throws InterruptedException;
   /** Same as wait (TIMEOUT, 0) */
   public final void wait(long timeout) throws InterruptedException;
   /** Same as wait (0,0) */
   public final void wait() throws InterruptedException;
}
```

Figure 8.1, continued: Class `Object`, continued

particular reflective class from outside that package, however, is hard to avoid: `java.lang.Class`, which as its name implies represents Java classes.

There is no public constructor for `Class`. For every Java class in a program, there is a value of type `Class` that provides information about that class, as indicated in Figure 8.2. If T is a class or interface type, then T`.class` is the `Class` value that represents it. Given the name of a class (as a `String`), the `forName` method will fetch the `Class` value for the class with that name. About the only thing you'll usually use `Class` for is for getting at the name of a certain object's type for diagnostic messages and the like, as in

```
System.err.format ("Encountered error on %s (of type %s)%n",
                   x, x.getClass ());
```

In particular, do *not* write things like

```
if (x.getClass () == Foo.class) { ... }
```

since (in the rare case that you really do need to test a value's type explicitly) it is much more direct to write

```
if (x instanceof Foo) { ... }
```

One important use for this class is in *dynamic class loading* Java allows one to load classes into a running program "on the fly" after finding out their name, perhaps as a result of user input or computation. One can then create new objects of these types, using the `newInstance` method. This is a rather advanced subject, and we won't go into it further here.

8.3 System

The class `java.lang.System` contains a hodgepodge of definitions with no common theme except that they don't belong anywhere else. Figure 8.3 lists a few of the ones that you'll find particularly useful.

I/O streams. The three I/O-related variables `in`, `out`, and `err` give access to three standard streams (one input and two output). These initially take or deliver their data to whatever your system's notion of the *standard input, standard output,* and *standard error,* streams might be. There are methods in For programs initiated from a command line, for example, these tend to be input from and output to the same terminal and screen at which you type commands. `System` for *re-directing* these, generally to other files. The two output streams are differentiated for the benefit of systems that can separate the two streams of output. By convention, you send error or warning messages to the standard error, and "normal" output to the standard output.

```
package java.lang;
import java.lang.reflect.*;

public final class Class<T>
   implements java.io.Serializable, GenericDeclaration,
              Type, AnnotatedElement
{
   /** If it is not already loaded, load the class NAME using the
    *  LOADER to do so.  If uninitialized, initialize the class
    *  (i.e., initialize class variables and run the static
    *  initializers) iff INIT. */
   public static Class<?> forName(String name, boolean init,
                                  ClassLoader loader)
      throws ClassNotFoundException;
   /** Same as forName(NAME, true, MYLOADER), where MYLOADER denotes
    *  the class loader for the calling class. */
   public static Class<?> forName(String name)
      throws ClassNotFoundException;
   /** The fully qualified name of this class.  Arrays have special
    *  names; see the full documentation. */
   public native String getName();
   /** Returns a string of the form "class F" or "interface F",
    *  where F is what is returned by getName (), or the primitive
    *  type name if this Class represents a primitive type. */
   public String toString();
   /** Create a new instance of the class represented by this, using
    *  the default constructor (as in new Foo()).  */
   public Object newInstance()
        throws InstantiationException, IllegalAccessException;

   ...
   /* See the full documentation for other definitions.*/
}
```

Figure 8.2: The class `java.lang.Class`, with comments for a few commonly used methods only.

System properties. Java is supposed to be portable, and portability sometimes requires that a program be able to adjust to certain characteristics of the environment it is running in. Therefore, Java makes available some properties that you may fetch by means of the `System.getProperty` methods. Each property has a name: a `String` by which it may be looked up. The full documentation contains a complete list of standard keys that are always present. There are few you might find particularly useful:

file.separator File separator between directory names (`"/"` on UNIX).

line.separator Line separator (`"\n"` on UNIX).

user.name User's account name.

user.home User's home directory.

user.dir User's current working directory

So `System.getProperty ("user.name")` gets the current user's account name.

```
package java.lang;

public final class System {
    /** The stream of bytes from the standard input. */
    public static final java.io.InputStream in,
    /** A printable stream to the standard output. */
    public static final java.io.PrintStream out;
    /** A printable stream to the standard error-message
     *  output. */
    public static final java.io.PrintStream err;

    /** Set new values of in, out, or err, if legal.  */
    public static void setErr(java.io.PrintStream str);
    public static void setIn(java.io.InputStream str);
    public static void setOut(java.io.PrintStream str);

    /** Copy LEN elements from SRC[SRCPOS .. SRCPOS+LEN-1]
     *  to DST[DSTPOS .. DSTPOS+LEN-1]. Throws exception if
     *  SRC and DST aren't arrays or have type mismatches. */
    public static void
        arraycopy(Object src, int srcPos, Object dst,
                  int dstPos, int len);
    /** Milliseconds since midnight, 1 Jan 1970, UTC. */
    public static long currentTimeMillis();
    /** Terminate the program; return CODE as the return
     *  status to the operating system. */
    public static void exit(int code);

    /** The value of the system property named KEY, or
     *  DEFLT if there is no such property. */
    public static String getProperty(String key, String deflt);
    /** Same as getProperty (KEY, null) */
    public static String getProperty(String key);

    /** The standard .hash function defined in Object
     *  for OBJ (before overriding). */
    public static int identityHashCode(Object obj);
    ...
}
```

Figure 8.3: Part of the class `java.lang.System`.

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