Testing / Debugging: We supply five sets of test programs, test scripts, and compare files. For each test program *Xxx*.vm we recommend following these steps:

0. Use the *Xxx*VME.tst script to execute the test program *Xxx*.vm on the supplied VM emulator. This will familiarize you with the intended behavior of the test program. Inspect the simulated stack and virtual segments, and make sure that you understand what the test program is doing.
1. Use your partially implemented translator to translate the file *Xxx*.vm (test program). The result should be a text file named *Xxx*.asm, containing the Hack assembly code generated by your translator.
2. Inspect the generated *Xxx*.asm code produced by your translator. If there are visible errors, debug and fix your translator.
3. Use the supplied *Xxx*.tst and *Xxx*.cmp files to run and test your translated *Xxx*.asm program on the supplied *CPU emulator*. If there are any errors, debug and fix your translator.

When you are done with this project, be sure to save a copy of your VM translator. In the next chapter you will be asked to extend this program, adding the handling of more VM commands. If your project 8 modifications end up breaking the code developed in project 7, you'll be able to resort to your backup version.

A web-based version of project 7 is available at www.nand2tetris.org.

7.6 Perspective

In this chapter we began the process of developing a compiler for a high-level language. Following modern software engineering practices, we have chosen to base the compiler on a two-tier compilation model. In the *front-end* tier, covered in chapters 10 and 11, the high-level code is translated into an intermediate code designed to run on a virtual machine. In the *back-end* tier, covered in this and in the next chapter, the intermediate code is

translated further into the machine language of a target hardware platform (see figure 7.1).

Over the years, this two-stage compilation model has been used—implicitly and explicitly—in many compiler construction projects. In the late 1970s, IBM and Apple corporations introduced two pioneering and phenomenally successful personal computers, known as the IBM PC and the Apple II. One high-level language that became popular on these early PCs was Pascal. Alas, different Pascal compilers had to be developed, since the IBM and Apple machines used different processors, different machine languages, and different operating systems. Also, IBM and Apple were rival companies and had no interest in helping developers port their software to the other machine. As a result, software developers who wanted their Pascal apps to run on both lines of computers had to use different compilers, each designed to generate machine-specific binary code. Could there not be a better way to handle cross-platform compilation, so that programs could be written once and run everywhere?

One solution to this challenge was an early virtual machine framework called *p-code*. The basic idea was to compile Pascal programs into intermediate p-code (similar to our VM language) and then use one implementation for translating the abstract p-code into Intel's x86 instruction set, used by IBM PCs, and another implementation for translating the same p-code into Motorola's 68000 instruction set, used by Apple computers. Meanwhile, other companies developed highly optimized Pascal compilers that generated efficient p-code. The net result was that the same Pascal program could run as is on practically every machine in this nascent PC market: no matter which computer your customers used, you could ship them exactly the same p-code files, obviating the need to use multiple compilers. Of course, the whole scheme was based on the assumption that the customer's computer was equipped with a client-side p-code implementation (equivalent to our VM translator). To make this happen, the p-code implementations were distributed freely over the Internet, and customers were invited to download them to their computers. Historically, this was perhaps the first time that the notion of a cross-platform high-level language began realizing its full potential.

Following the explosive growth of the Internet and mobile devices in the mid-1990s, cross-platform compatibility became a universally vexing issue.

To address the problem, the Sun Microsystems company (later acquired by Oracle) sought to develop a new programming language whose compiled code could potentially run as is on any computer and digital device connected to the Internet. The language that emerged from this initiative—*Java*—was founded on an intermediate code execution model called the *Java Virtual Machine*, or JVM.

The JVM is a specification that describes an intermediate language called *bytecode*—the target VM language of Java compilers. Files written in bytecode are widely used for code distribution of Java programs over the Internet. In order to execute these portable programs, the client PCs, tablets, and cell phones that download them must be equipped with suitable JVM implementations, known as JREs (Java Runtime Environments). These programs are widely available for numerous processor and operating system combinations. Today, many personal computer and cell phone owners use these infrastructure programs (the JREs) routinely and implicitly, without ever noticing their existence on their devices.

The Python language, conceived in the late 1980s, is also based on a two-tier translation model, whose centerpiece is the PVM (Python Virtual Machine), which uses its own version of bytecode.

In the early 2000s, Microsoft launched its .NET Framework. The centerpiece of .NET is a virtual machine framework called *Common Language Runtime* (CLR). According to Microsoft's vision, many programming languages, like C# and C++, can be compiled into intermediate code running on the CLR. This enables code written in different languages to interoperate and share the software libraries of a common run-time environment. Of course, single-tier compilers for C and C++ are still widely used, especially in high-performance applications requiring tight and optimized code.

Indeed, one issue that was completely sidestepped in this chapter is *efficiency*. Our contract calls for developing a VM translator, without requiring that the generated assembly code be efficient. Clearly, this is a serious oversight. The VM translator is a mission-critical enabling technology, lying at the core of your PC, tablet, or cell phone: if it will generate tight and efficient low-level code, apps will run on your machine swiftly, using as little hardware resources as possible. Therefore, optimizing the VM translator is a top priority.

In general, there are numerous opportunities to optimize the VM translator. For example, assignments like `let x = y` are prevalent in high-level code; these statements are translated by the compiler into VM commands like, for example, `push local 3` followed by `pop static 1`. Clever implementations of such pairs of VM commands can generate assembly code that sidesteps the stack completely, resulting in dramatic performance gains. Of course, this is one out of many examples of possible VM optimizations. Indeed, over the years, the VM implementations of Java, Python, and C# became dramatically more powerful and sophisticated.

We note in closing that a crucial ingredient that must be added to the virtual machine model before its full potential is unleashed is a common software library. Indeed the Java Virtual Machine comes with the *standard Java class library*, and the Microsoft's .NET Framework comes with the *Framework Class Library*. These vast software libraries can be viewed as portable operating systems, providing numerous services like memory management, GUI toolkits, string functions, math functions, and so on. These extensions will be described and built in chapter 12.

8 Virtual Machine II: Control

If everything seems under control, you're just not going fast enough.
—Mario Andretti (b. 1940), race car champion

Chapter 7 introduced the notion of a *virtual machine* (VM), and project 7 began implementing our abstract virtual machine and VM language over the Hack platform. The implementation entailed developing a program that translates VM commands into Hack assembly code. Specifically, in the previous chapter we learned how to use and implement the VM's arithmetic-logical commands and push/pop commands; in this chapter we'll learn how to use and implement the VM's branching commands and function commands. As the chapter progresses, we'll extend the basic translator developed in project 7, ending with a full-scale VM translator over the Hack platform. This translator will serve as the back-end module of the compiler that we will build in chapters 10 and 11.

In any Gre at Gems in Applied Computer Science contest, stack processing will be a strong finalist. The previous chapter showed how arithmetic and Boolean expressions can be represented and evaluated by elementary operations on a stack. This chapter goes on to show how this remarkably simple data structure can also support remarkably complex tasks like nested function calling, parameter passing, recursion, and the various memory allocation and recycling tasks required to support program execution during run-time. Most programmers tend to take these services for granted, expecting the compiler and the operating system to deliver them, one way or another. We are now in a position to open up this black box and see how these fundamental programming mechanisms are actually realized.

Run-time system: Every computer system must specify a run-time model. This model answers essential questions without which programs cannot run: how to start a program's execution, what the computer should do when a program terminates, how to pass arguments from one function to another, how to allocate memory resources to running functions, how to free memory resources when they are no longer needed, and so on.

In Nand to Tetris, these issues are addressed by the *VM language* specification, along with the *standard mapping on the Hack platform* specification. If a VM translator is developed according to these guidelines, it will end up realizing an executable run-time system. In particular, the VM translator will not only translate the VM commands (`push`, `pop`, `add`, and so on) into assembly instructions—it will also generate assembly code that realizes an envelope in which the program runs. All the questions mentioned above—how to start a program, how to manage the function call-and-return behavior, and so on—will be answered by generating enabling assembly code that wraps the code proper. Let's see an example.

8.1 High-Level Magic

High-level languages allow writing programs in high-level terms. For example, an expression like $x = -b + \sqrt{b^2 - 4 \cdot a \cdot c}$ can be written as `x = -b + sqrt(power(b,2) - 4 * a * c)`, which is almost as descriptive as the real thing. Note the difference between primitive operations like + and − and functions like `sqrt` and `power`. The former are built into the basic syntax of the high-level language. The latter are extensions of the basic language.

The unlimited capacity to extend the language at will is one of the most important features of high-level programming languages. Of course, at some point, someone must implement functions like `sqrt` and `power`. However, the story of implementing these abstractions is completely separate from the story of using them. Therefore, application programmers can assume that each one of these functions will get executed—somehow—and that following its execution, control will return—somehow—to the next operation in one's code. Branching commands endow the language with additional expressive power, allowing writing conditional code like `if !(a == 0){ x = (-b + sqrt(power(b,2) - 4 * a * c)) / (2 * a) } else { x = -c/b }`. Once

again, we see that high-level code enables the expression of high-level logic —in this case the algorithm for solving quadratic equations—almost directly.

Indeed, modern programming languages are programmer-friendly, offering useful and powerful abstractions. It is a sobering thought, though, that no matter how high we allow our high-level language to be, at the end of the day it must be realized on some hardware platform that can only execute primitive machine instructions. Thus, among other things, compiler and VM architects must find low-level solutions for realizing branching and function call-and-return commands.

Functions—the bread and butter of modular programming—are standalone programming units that are allowed to call each other for their effect. For example, `solve` can call `sqrt`, and `sqrt`, in turn, can call `power`. This calling sequence can be as deep as we please, as well as recursive. Typically, the calling function (the *caller*) passes arguments to the called function (the *callee*) and suspends its execution until the latter completes *its* execution. The callee uses the passed arguments to execute or compute something and then returns a value (which may be `void`) to the caller. The caller then snaps back into action, resuming its execution.

In general then, whenever one function (the *caller*) calls a function (the *callee*), someone must take care of the following overhead:

- Save the *return address*, which is the address within the caller's code to which execution must return after the callee completes its execution;
- Save the memory resources of the caller;
- Allocate the memory resources required by the callee;
- Make the arguments passed by the caller available to the callee's code;
- Start executing the callee's code.

When the callee terminates and returns a value, someone must take care of the following overhead:

- Make the callee's *return value* available to the caller's code;
- Recycle the memory resources used by the callee;
- Reinstate the previously saved memory resources of the caller;

- Retrieve the previously saved *return address*;
- Resume executing the caller's code, from the return address onward.

Blissfully, high-level programmers don't have to ever think about all these nitty-gritty chores: the assembly code generated by the compiler handles them, stealthily and efficiently. And, in a two-tier compilation model, this housekeeping responsibility falls on the compiler's back end, which is the VM translator that we are now developing. Thus, in this chapter, we will uncover, among other things, the run-time framework that enables what is probably the most important abstraction in the art of programming: *function call-and-return*. But first, let's start with the easier challenge of handling branching commands.

8.2 Branching

The default flow of computer programs is sequential, executing one command after the other. For various reasons like embarking on a new iteration in a loop, this sequential flow can be redirected by branching commands. In low-level programming, branching is accomplished by *goto destination* commands. The destination specification can take several forms, the most primitive being the physical memory address of the instruction that should be executed next. A slightly more abstract specification is established by specifying a symbolic label (bound to a physical memory address). This variation requires that the language be equipped with a labeling directive, designed to assign symbolic labels to selected locations in the code. In our VM language, this is done using a labeling command whose syntax is label *symbol*.

With that in mind, the VM language supports two forms of branching. *Unconditional branching* is effected using a goto *symbol* command, which means: jump to execute the command just after the label *symbol* command in the code. *Conditional branching* is effected using the if-goto *symbol* command, whose semantics is: Pop the topmost value off the stack; if it's not false, jump to execute the command just after the label *symbol* command; otherwise, execute the next command in the code. This contract implies that before specifying a conditional goto command, the VM code writer (for

example, a compiler) must first specify a condition. In our VM language, this is done by pushing a Boolean expression onto the stack. For example, the compiler that we'll develop in chapters 10–11 will translate `if (n < 100) goto LOOP` into `push n, push 100, lt, if-goto LOOP`.

Example: Consider a function that receives two arguments, x and y, and returns the product $x \cdot y$. This can be done by adding x repetitively to a local variable, say `sum`, y times, and then returning `sum`'s value. A function that implements this naïve multiplication algorithm is listed in figure 8.1. This example illustrates how a typical looping logic can be expressed using the VM branching commands `goto`, `if-goto`, and `label`.

High-level code

```
// Returns x * y
int mult(int x, int y) {
   int sum = 0;
   int i = 0;
   while (i < y) {
      sum += x;
      i++;
   }
   return sum;
}
```

VM code

```
// Returns x * y
function mult(x,y)
   push 0
   pop sum
   push 0
   pop i
label WHILE_LOOP
   push i
   push y
   lt
   neg
   if-goto WHILE_END
   push sum
   push x
   add
   pop sum
   push i
   push 1
   add
   pop i
   goto WHILE_LOOP
label WHILE_END
   push sum
   return
```

Figure 8.1 Branching commands action. (The VM code on the right uses symbolic variable names instead of virtual memory segments, to make it more readable.)

Notice how the Boolean condition `!(i < y)`, implemented as `push i, push y, lt, ng`, is pushed onto the stack just before the `if-goto WHILE_END` command. In

chapter 7 we saw that VM commands can be used to express and evaluate any Boolean expression. As we see in figure 8.1, high-level control structures like if and while can be easily realized using nothing more than goto and if-goto commands. In general, any flow of control structure found in high-level programming languages can be realized using our (rather minimal set of) VM logical and branching commands.

Implementation: Most low-level machine languages, including Hack, feature means for declaring symbolic labels and for effecting conditional and unconditional "goto label" actions. Therefore, if we base the VM implementation on a program that translates VM commands into assembly instructions, implementing the VM branching commands is a relatively simple matter.

Operating system: We end this section with two side comments. First, VM programs are not written by humans. Rather, they are written by compilers. Figure 8.1 illustrates source code on the left and VM code on the right. In chapters 10–11 we'll develop a *compiler* that translates the former into the latter. Second, note that the mult implementation shown in figure 8-1 is inefficient. Later in the book we'll present optimized multiplication and division algorithms that operate at the bit level. These algorithms will be used for realizing the Math.multiply and Math.divide functions, which are part of the operating system that we will build in chapter 12.

Our OS will be written in the Jack language, and translated by a Jack compiler into the VM language. The result will be a library of eight files named Math.vm, Memory.vm, String.vm, Array.vm, Output.vm, Screen.vm, Keyboard.vm, and Sys.vm (the OS API is given in appendix 6). Each OS file features a collection of useful functions that any VM function is welcome to call for their effect. For example, whenever a VM function needs multiplication or division services, it can call the Math.multiply or Math.divide function.

8.3 Functions

Every programming language is characterized by a fixed set of built-in operations. In addition, high-level and some low-level languages offer the

great freedom of extending this fixed repertoire with an open-ended collection of programmer-defined operations. Depending on the language, these canned operations are typically called *subroutines*, *procedures*, *methods*, or *functions*. In our VM language, all these programming units are referred to as *functions*.

In well-designed languages, built-in commands and programmer-defined functions have the same look and feel. For example, to compute $x + y$ on our stack machine, we `push x`, `push y`, and `add`. In doing so, we expect the `add` implementation to pop the two top values off the stack, add them up, and push the result onto the stack. Suppose now that either we, or someone else, has written a *power* function designed to compute x^y. To use this function, we follow exactly the same routine: we `push x`, `push y`, and `call power`. This consistent calling protocol allows composing primitive commands and function calls seamlessly. For example, expressions like $(x + y)^3$ can be evaluated using `push x`, `push y`, `add`, `push 3`, `call power`.

We see that the only difference between applying a primitive operation and invoking a function is the keyword `call` preceding the latter. Everything else is exactly the same: both operations require the caller to set the stage by pushing arguments onto the stack, both operations are expected to consume their arguments, and both operations are expected to push return values onto the stack. This calling protocol has an elegant consistency which, we hope, is not lost on the reader.

Example: Figure 8.2 shows a VM program that computes the function $\sqrt{x^2 + y^2}$, also known as *hypot*. The program consists of three functions, with the following run-time behavior: `main` calls `hypot`, and then `hypot` calls `mult`, twice. There is also a call to a `sqrt` function, which we don't track, to reduce clutter.

```
 0 function main()
// Computes hypot(3,4)
 1    push 3
 2    push 4
 3    call hypot
 4    return

 5 function hypot(x,y)
// Computes sqrt(x*x + y*y)
 6    push x
 7    push x
 8    call mult
 9    push y
10    push y
11    call mult
12    add
13    call sqrt
14    return

15 function mult(x,y)
// Computes x * y (same as in figure 8.1)
16    push 0
17    pop sum
18    push 0
19    pop i
      ...
36    push sum
37    return
```

The world of function `hypot`

which has 2 arguments, and no local variables, shown during the call `hypot(3,4)`:

	stack	argument	
just after line 7 is executed:	3 3	x y	3 4
just after line 8 is executed:	9	x y	3 4
just after line 11 is executed:	9 16	x y	3 4

The world of function `mult`

which has 2 arguments and 2 local variables, shown during the call `mult(3,3)`:

	stack	argument		local	
just after line 19 is executed:	(empty)	x y	3 3	sum i	0 0
just after line 36 is executed:	9	x y	3 3	sum i	9 3

Figure 8.2 Run-time snapshots of selected stack and segment states during the execution of a three-function program. The line numbers are not part of the code and are given for reference only.

The bottom part of figure 8.2 shows that during run-time, each function sees a private world, consisting of its own working stack and memory segments. These separate worlds are connected through two "wormholes": when a function says call mult, the arguments that it pushed onto its stack prior to the call are somehow passed to the argument segment of the callee. Likewise, when a function says return, the last value that it pushed onto its stack just before returning is somehow copied onto the stack of the caller, replacing the previously pushed arguments. These hand-shaking actions are carried out by the VM implementation, as we now turn to describe.

Implementation: A computer program consists of typically several and possibly many functions. Yet at any given point during run-time, only a few of these functions are actually doing something. We use the term *calling chain* to refer, conceptually, to all the functions that are currently involved in the program's execution. When a VM program starts running, the calling chain consists of one function only, say, `main`. At some point, `main` may call another function, say, `foo`, and that function may call yet another function, say, `bar`. At this point the calling chain is `main`→`foo`→`bar`. Each function in the calling chain waits for the function that it called to return. Thus, the only function that is truly active in the calling chain is the last one, which we call the *current function*, meaning the currently executing function.

In order to carry out their work, functions normally use *local* and *argument* variables. These variables are temporary: the memory segments that represent them must be allocated when the function starts executing and can be recycled when the function returns. This memory management task is complicated by the requirement that function calling is allowed to be arbitrarily nested, as well as recursive. During run-time, each function call must be executed independently of all the other calls and maintain its own stack, local variables, and argument variables. How can we implement this unlimited nesting mechanism and the memory management tasks associated with it?

The property that makes this housekeeping task tractable is the linear nature of the call-and-return logic. Although the function calling chain may be arbitrarily deep as well as recursive, at any given point in time only one function executes at the chain's end, while all the other functions up the calling chain are waiting for it to return. This *Last-In-First-Out* processing model lends itself perfectly to the stack data structure, which is also LIFO. Let's takes a closer look.

Assume that the current function is `foo`. Suppose that `foo` has already pushed some values onto its working stack and has modified some entries in its memory segments. Suppose that at some point `foo` wants to call another function, `bar`, for its effect. At this point we have to put `foo`'s execution on hold until `bar` will terminate *its* execution. Now, putting `foo`'s working stack on hold is not a problem: because the stack grows only in one direction, the working stack of `bar` will never override previously pushed values. Therefore, saving the working stack of the caller is easy—

we get it "for free" thanks to the linear and unidirectional stack structure. But how can we save foo's memory segments? Recall that in chapter 7 we used the pointers LCL, ARG, THIS, and THAT to refer to the base RAM addresses of the local, argument, this, and that segments of the current function. If we wish to put these segments on hold, we can push their pointers onto the stack and pop them later, when we'll want to bring foo back to life. In what follows, we use the term *frame* to refer, collectively, to the set of pointer values needed for saving and reinstating the function's state.

We see that once we move from a single function setting to a multifunction setting, the humble stack begins to attain a rather formidable role in our story. Specifically, we now use the same data structure to hold both the working stacks as well as the frames of all the functions up the calling chain. To give it the respect that it deserves, from now on we'll refer to this hard-working data structure as the *global stack*. See figure 8.3 for the details.

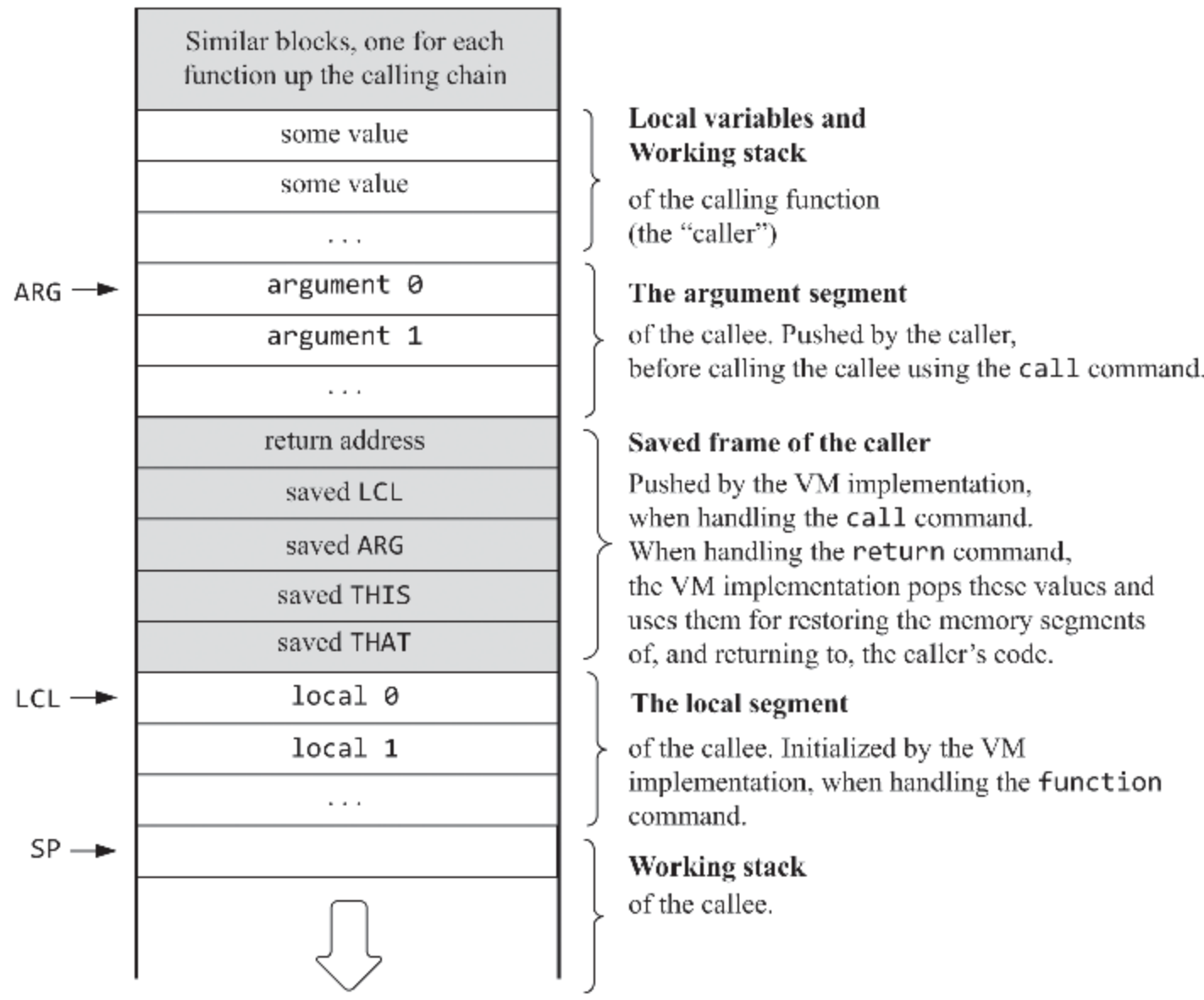


Figure 8.3 The global stack, shown when the callee is running. Before the callee terminates, it pushes a return value onto the stack (not shown). When the VM implementation handles the return command, it copies the return value onto argument 0, and sets SP to point to the address just

following it. This effectively frees the global stack area below the new value of SP. Thus, when the caller resumes its execution, it sees the return value at the top of its working stack.

As shown in figure 8.3, when handling the call *functionName* command, the VM implementation pushes the caller's frame onto the stack. At the end of this housekeeping, we are ready to jump to executing the callee's code. This mega jump is not hard to implement. As we'll see later, when handling a function *functionName* command, we use the function's name to create, and inject into the generated assembly code stream, a unique symbolic label that marks where the function starts. Thus, when handling a "function *functionName*" command, we can generate assembly code that effects a "goto *functionName*" operation. When executed, this command will effectively transfer control to the callee.

Returning from the callee to the caller when the former terminates is trickier, since the VM return command specifies no return address. Indeed, the caller's anonymity is inherent in the notion of a function call: functions like mult or sqrt are designed to serve any caller, implying that a return address cannot be specified a priori. Instead, a return command is interpreted as follows: redirect the program's execution to the memory location holding the command just following the call command that invoked the current function.

The VM implementation can realize this contract by (i) saving the return address just before control is transferred to executing the caller and (ii) retrieving the return address and jumping to it just after the callee returns. But where shall we save the return address? Once again, the resourceful stack comes to the rescue. To remind you, the VM translator advances from one VM command to the next, generating assembly code as it goes along. When we encounter a call foo command in the VM code, we know exactly which command should be executed when foo terminates: it's the assembly command just after the assembly commands that realize the call foo command. Thus, we can have the VM translator plant a label right there, in the generated assembly code stream, and push this label onto the stack. When we later encounter a return command in the VM code, we can pop the previously saved return address off the stack—let's call it *returnAddress*—and effect the operation goto *returnAddress* in assembly. This is the low-

level trick that enables the run-time magic of redirecting control back to the right place in the caller's code.

The VM implementation in action: We now turn to give a step-by-step illustration of how the VM implementation supports the function call-and-return action. We will do it in the context of executing a factorial function, designed to compute $n!$ recursively. Figure 8.4 gives the program's code, along with selected snapshots of the global stack during the execution of factorial(3). A complete run-time simulation of this computation should also include the call-and-return action of the mult function, which, in this particular run-time example, is called twice: once before factorial(2) returns, and once before factorial(3) returns.

High-level code

```
// Tests the factorial function
int main() {
    return factorial(3);
}

// Computes n!
int factorial(int n) {
    if (n==1)
       return 1;
    else
       return n * factorial(n-1);
}
```

VM code

```
// Tests the factorial function
function main
   push 3
   call factorial
   return
// Computes n!
function factorial(n)
   push n
   push 1
   eq
   if-goto BASE_CASE
   push n
   push n
   push 1
   sub
   call factorial
   call mult
   return
label BASE_CASE
   push 1
   return
```

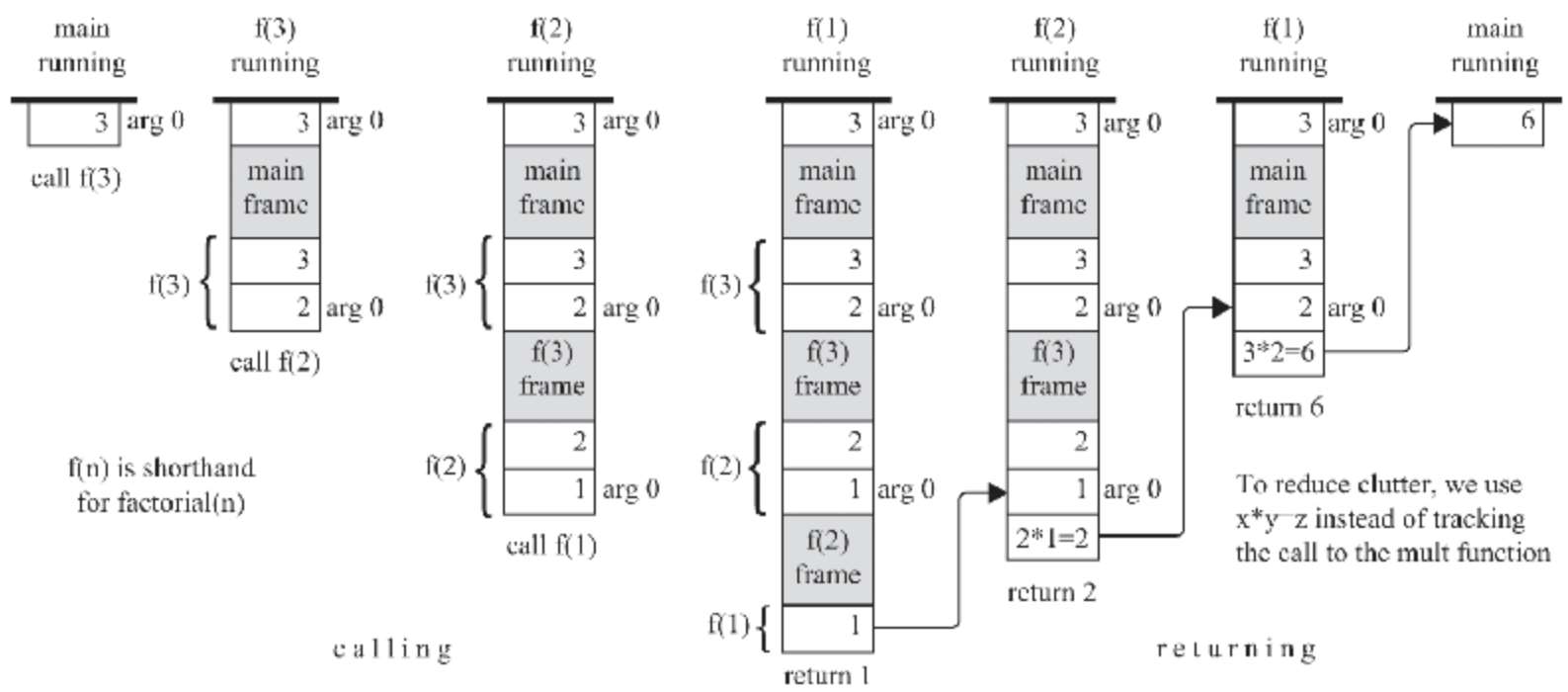


Figure 8.4 Several snapshots of the *global stack*, taken during the execution of the main function, which calls factorial to compute 3!. The running function sees only its working stack, which is the unshaded area at the tip of the global stack; the other unshaded areas in the global stack are the working stacks of functions up the calling chain, waiting for the currently running function to return. Note that the shaded areas are not "drawn to scale," since each frame consists of five words, as shown in figure 8.3.

Focusing on the leftmost and rightmost parts of the bottom of figure 8.4, here is what transpired from main's perspective: "To set the stage, I pushed the constant 3 onto the stack, and then called factorial for its effect (see the leftmost stack snapshot). At this point I was put to sleep; at some later point in time I was woken up to find out that the stack now contains 6 (see the final and rightmost stack snapshot); I have no idea how this magic

happened, and I don't really care; all I know is that I set out to compute 3!, and I got exactly what I asked for." In other words, the caller is completely oblivious of the elaborate mini-drama that was unleashed by its `call` command.

As seen in figure 8.4, the back stage on which this drama plays out is the global stack, and the choreographer who runs the show is the VM implementation: Each `call` operation is implemented by saving the frame of the caller on the stack and jumping to execute the callee. Each `return` operation is implemented by (i) using the most recently stored frame for getting the return address within the caller's code and reinstating its memory segments, (ii) copying the topmost stack value (the return value) onto the stack location associated with `argument 0`, and (iii) jumping to execute the caller's code from the return address onward. All these operations must be realized by generated assembly code.

Some readers may wonder why we have to get into all these details. There are at least three reasons why. First, we need them in order to implement the VM translator. Second, the implementation of the function call-and-return protocol is a beautiful example of low-level software engineering, so we can simply enjoy seeing it in action. Third, an intimate understanding of the virtual machine internals helps us become better and more informed high-level programmers. For example, tinkering with the stack provides an in-depth understanding of the benefits and pitfalls associated with recursion. Note that during run-time, each recursive call causes the VM implementation to add to the stack a memory block consisting of arguments, function frames, local variables, and a working stack for the callee. Therefore, unchecked use of recursion may well lead to the infamous *stack overflow* run-time debacle. This, as well as efficiency considerations, leads compiler writers to try to reexpress recursive code as sequential code, where possible. But that's a different story that will be taken up in chapter 11.

8.4 VM Specification, Part II

So far in this chapter, we have presented general VM commands without committing to exact syntax and programming conventions. We now turn to specify formally the VM *branching* commands, the VM *function* commands, and the structure of VM *programs*. This completes the specification of the VM language that we began describing in VM Specification, Part I, in chapter 7.

It's important to reiterate that, normally, VM programs are not written by humans. Rather, they are generated by compilers. Therefore, the specifications described here are aimed at compiler developers. That is, if you write a compiler that is supposed to translate programs from some high-level language into VM code, the code that your compiler generates is expected to conform to the conventions described here.

Branching Commands

- label *label*: Labels the current location in the function's code. Only labeled locations can be jumped to. The scope of the label is the function in which it is defined. The *label* is a string composed of any sequence of letters, digits, underscore (_), dot (.), and colon (:) that does not begin with a digit. The label command can be located anywhere in the function, before or after the goto commands that refer to it.
- goto *label*: Effects an unconditional goto operation, causing execution to continue from the location marked by the label. The goto command and the labeled jump destination must be located in the same function.
- if-goto *label*: Effects a conditional goto operation. The stack's topmost value is popped; if the value is not zero, execution continues from the location marked by the label; otherwise, execution continues from the next command in the program. The if-goto command and the labeled jump destination must be located in the same function.

Function Commands

- function *functionName nVars*: Marks the beginning of a function named *functionName*. The command informs that the function has *nVars* local variables.
- call *functionName nArgs*: Calls the named function. The command informs that *nArgs* arguments have been pushed onto the stack before the call.
- return: Transfers execution to the command just following the call command in the code of the function that called the current function.

VM Program

VM programs are generated from high-level programs written in languages like Jack. As we'll see in the next chapter, a high-level Jack program is loosely defined as a collection of one or more .jack class files stored in the same folder. When applied to that folder, the Jack compiler translates each class file *FileName*.jack into a corresponding file named *FileName*.vm, containing VM commands.

Following compilation, each *constructor*, *function* (*static method*), and *method* named bar in a Jack file *FileName*.jack is translated into a corresponding VM function, uniquely identified by the VM function name *FileName*.bar. The scope of VM function names is global: all the VM functions in all the .vm files in the program folder see each other and may call each other using the unique and full function name *FileName.functionName*.

Program entry point: One file in any Jack program must be named Main.jack, and one function in this file must be named main. Thus, following compilation, one file in any VM program is expected to be named Main.vm, and one VM function in this file is expected to be named Main.main, which is the application's entry point. This run-time convention is implemented as follows. When we start running a VM program, the first function that always executes is an argument-less VM function named Sys.init, which is part of the operating system. This OS function is programmed to call the entry point function in the user's program. In the case of Jack programs, Sys.init is programmed to call Main.main.

Program execution: There are several ways to execute VM programs, one of which is using the supplied *VM emulator* introduced in chapter 7. When you load a program folder containing one or more .vm files into the VM emulator, the emulator loads all the VM functions in all these files, one after the other (the order of the loaded VM functions is insignificant). The resulting code base is a sequence of all the VM functions in all the .vm files in the program folder. The notion of VM files ceases to exist, although it is implicit in the names of the loaded VM functions (*FileName.functionName*).

The Nand to Tetris VM emulator, which is a Java program, features a built-in implementation of the Jack OS, also written in Java. When the emulator detects a call to an OS function, for example, call Math.sqrt, it proceeds as follows. If it finds a corresponding function Math.sqrt command in the loaded VM code, the emulator executes the function's VM code. Otherwise, the emulator reverts to using its built-in implementation of the Math.sqrt method. This implies that as long as you use the supplied VM emulator for executing VM programs, there is no need to include OS files in your code. The VM emulator will service all the OS calls found in your code, using its built-in OS implementation.

8.5 Implementation

The previous section completed the specification of our VM language and framework. In this section we focus on implementation issues, leading up to the construction of a full-scale, VM-to-Hack translator. Section 8.5.1 proposes how to implement the function call-and-return protocol. Section 8.5.2 completes the standard mapping of the VM implementation over the Hack platform. Section 8.5.3 gives a proposed design and API for completing the VM translator that we began building in project 7.

8.5.1 Function Call and Return

The events of calling a function and returning from a function call can be viewed from two perspectives: that of the *calling function*, also referred to as *caller*, and that of the *called function*, also referred to as *callee*. Both the

caller and the callee have certain expectations, and certain responsibilities, regarding the handling of the call, function, and return commands. Fulfilling the expectations of one is the responsibility of the other. In addition, the VM implementation plays an important role in executing this contract. In what follows, the responsibilities of the VM implementation are marked by [†]:

The caller's view:	The callee's view:
• Before calling a function, I must push onto the stack as many arguments (*nArgs*) as the callee expects to get. • Next, I invoke the callee using the command call *fileName.functionName nArgs*. • After the callee returns, the argument values that I pushed before the call have disappeared from the stack, and a *return value* (that always exists) appears at the top of the stack. Except for this change, my working stack is exactly the same as it was before the call [†]. • After the callee returns, all my memory segments are exactly the same as they were before the call [†], except that the contents of my static segment may have changed, and the temp segment is undefined.	• Before I start executing, my argument segment has been initialized with the argument values passed by the caller, and my local variables segment has been allocated and initialized to zeros. My static segment has been set to the static segment of the VM file to which I belong, and my working stack is empty. The memory segments this, that, pointer, and temp are undefined upon entry [†]. • Before returning, I must push a return value onto the stack.

The VM implementation supports this contract by maintaining, and manipulating, the global stack structure described in figure 8.3. In particular, every function, call, and return command in the VM code is handled by generating assembly code that manipulates the global stack as follows: A call command generates code that saves the frame of the caller on the stack and jumps to execute the callee. A function command generates code that initializes the local variables of the callee. Finally, a return command generates code that copies the return value to the top of the caller's working

stack, reinstates the segment pointers of the caller, and jumps to execute the latter from the return address onward. See figure 8.5 for the details.

VM command	*Assembly (pseudo) code, generated by the VM translator*	

`call` *f nArgs*
(calls a function *f*, informing that *nArgs* arguments were pushed to the stack before the call)
	`push` *returnAddress*
	`push LCL`
	`push ARG`
	`push THIS`
	`push THAT`
	`ARG = SP-5-`*nArgs*
	`LCL = SP`
	`goto` *f*
	(*returnAddress*)
		// generates a label and pushes it to the stack
		// saves LCL of the caller
		// saves ARG of the caller
		// saves THIS of the caller
		// saves THAT of the caller
		// repositions ARG
		// repositions LCL
		// transfers control to the callee
		// injects the return address label into the code

`function` *f nVars*
(declares a function *f*, informing that the function has *nVars* local variables)
	(*f*)
	repeat *nVars* times:
	`push 0`
		// injects a function entry label into the code
		// *nVars* = number of local variables
		// initializes the local variables to 0

`return`
(terminates the current function and returns control to the caller)
	frame = `LCL`
	retAddr = *(*frame*-5)
	`*ARG = pop()`
	`SP = ARG+1`
	`THAT = *(`*frame*-1)
	`THIS = *(`*frame*-2)
	`ARG = *(`*frame*-3)
	`LCL = *(`*frame*-4)
	`goto` *retAddr*
		// *frame* is a temporary variable
		// puts the return address in a temporary variable
		// repositions the return value for the caller
		// repositions SP for the caller
		// restores THAT for the caller
		// restores THIS for the caller
		// restores ARG for the caller
		// restores LCL for the caller
		// go to the return address

Figure 8.5 Implementation of the function commands of the VM language. All the actions described on the right are realized by generated Hack assembly instructions.

8.5.2 Standard VM Mapping on the Hack Platform, Part II

Developers of the VM implementation on the Hack computer are advised to follow the conventions described here. These conventions complete the Standard VM Mapping on the Hack Platform, Part I, guidelines given in section 7.4.1.

The stack: On the Hack platform, RAM locations 0 to 15 are reserved for pointers and virtual registers, and RAM locations 16 to 255 are reserved for static variables. The stack is mapped on address 256 onward. To realize this mapping, the VM translator should start by generating assembly code that sets `SP` to 256. From this point onward, when the VM translator encounters

commands like pop, push, add, and so on in the source VM code, it generates assembly code that affects these operations by manipulating the address that SP points at, and modifying SP, as needed. These actions were explained in chapter 7 and implemented in project 7.

Special symbols: When translating VM commands into Hack assembly, the VM translator deals with two types of symbols. First, it manages predefined assembly-level symbols like SP, LCL, and ARG. Second, it generates and uses symbolic labels for marking return addresses and function entry points. To illustrate, let us revisit the PointDemo program presented in the introduction to part II. This program consists of two Jack class files, Main.jack (figure II.1) and Point.jack (figure II.2), stored in a folder named PointDemo. When applied to the PointDemo folder, the Jack compiler produces two VM files, named Main.vm and Point.vm. The first file contains a single VM function, Main.main, and the second file contains the VM functions Point.new, Point.getx, …, Point.print.

When the VM translator is applied to this same folder, it produces a single assembly code file, named PointDemo.asm. At the assembly code level, the function abstractions no longer exist. Instead, for each function command, the VM translator generates an entry label in assembly; for each call command, the VM translator (i) generates an assembly goto instruction, (ii) creates a return address label and pushes it onto the stack, and (iii) injects the label into the generated code. For each return command, the VM translator pops the return address off the stack and generates a goto instruction. For example:

VM code	Generated assembly code
`function Main.main`	`(Main.main)`
`…`	`…`
`call Point.new`	`goto Point.new`
`// Next VM command`	`(Main.main$ret0)`
`…`	`// Next VM command (in assembly)`
	`…`
`function Point.new`	`(Point.new)`
`…`	`…`
`return`	`goto Main.main$ret0`

Figure 8.6 specifies all the symbols that the VM translator handles and generates.

Symbol	*Usage*
`SP`	This predefined symbol points to the memory address within the host RAM just following the address containing the topmost stack value.
`LCL`, `ARG`, `THIS`, `THAT`	These predefined symbols point, respectively, to the base RAM addresses of the virtual segments `local`, `argument`, `this`, and `that` of the currently running VM function.
Xxx`.`*i* symbols (represent static variables)	Each reference to `static` *i* appearing in file *Xxx*`.vm` is translated to the assembly symbol *Xxx*`.`*i*. In the subsequent assembly process, the Hack assembler will allocate these symbolic variables to the RAM, starting at address 16.
functionName`$`*label* (destinations of `goto` commands)	Let `foo` be a function within the file *Xxx*`.vm`. The handling of each `label bar` command within `foo` generates, and injects into the assembly code stream, the symbol *Xxx*`.foo$bar`. When translating `goto bar` and `if-goto bar` commands (within `foo`) into assembly, the label *Xxx*`.foo$bar` must be used instead of `bar`.
functionName (function entry point symbols)	The handling of each `function foo` command within the file *Xxx*`.vm` generates, and injects into the assembly code stream, a symbol *Xxx*`.foo` that labels the entry-point to the function's code. In the subsequent assembly process, the assembler translates this symbol into the physical address where the function code starts.
functionName`$ret.`*i* (return address symbols)	Let `foo` be a function within the file *Xxx*`.vm`. The handling of each `call` command within `foo`'s code generates, and injects into the assembly code stream, a symbol *Xxx*`.foo$ret.`*i*, where *i* is a running integer (one such symbol is generated for each `call` command within `foo`). This symbol is used to mark the return address within the caller's code. In the subsequent assembly process, the assembler translates this symbol into the physical memory address of the command immediately following the `call` command.
`R13` - `R15`	These predefined symbols can be used for any purpose. For example, if the VM translator generates assembly code that needs to use low-level variables for temporary storage, `R13` - `R15` can come handy.

Figure 8.6 The naming conventions described above are designed to support the translation of multiple .vm files and functions into a single .asm file, ensuring that the generated assembly symbols will be unique within the file.

Bootstrap code: The standard VM mapping on the Hack platform stipulates that the stack be mapped on the host RAM from address 256 onward, and that the first VM function that should start executing is the OS function Sys.init. How can we effect these conventions on the Hack platform? Recall that when we built the Hack computer in chapter 5, we wired it in such a way that upon reset, it will fetch and execute the instruction located in ROM address 0. Thus, if we want the computer to execute a predetermined code segment when it boots up, we can put this

code in the Hack computer's instruction memory, starting at address 0. Here is the code:

```
// Bootstrap (pseudo) code, should be expressed in machine language
SP = 256
call Sys.init
```

The Sys.init function, which is part of the operating system, is then expected to call the main function of the application, and enter an infinite loop. This action will cause the translated VM program to start running. Note that the notions of *application* and *main function* vary from one high-level language to another. In the Jack language, the convention is that Sys.init should call the VM function Main.main. This is similar to the Java setting: when we instruct the JVM to execute a given Java class, say, Foo, it looks for, and executes, the Foo.main method. In general, we can effect language-specific startup routines by using different versions of the Sys.init function.

Usage: The translator accepts a single command-line argument, as follows,

```
prompt> VMTranslator source
```

where *source* is either a file name of the form *Xxx*.vm (the extension is mandatory) or the name of a folder (in which case there is no extension) containing one or more .vm files. The file/folder name may contain a file path. If no path is specified, the translator operates on the current folder. The output of the VM translator is a single assembly file, named *source*.asm. If *source* is a folder name, the single .asm file contains the translation of all the functions in all the .vm files in the folder, one after the other. The output file is created in the same folder as the input file. If there is a file by this name in the folder, it will be overwritten.

8.5.3 Design Suggestions for the VM Implementation

In project 7 we proposed building the basic VM translator using three modules: VMTranslator, Parser, and CodeWriter. We now describe how to extend this basic implementation into a full-scale VM translator. This extension can be accomplished by adding the functionality described below to the

three modules already built in project 7. There is no need to develop additional modules.

The VMTranslator

If the translator's input is a single file, say Prog.vm, the VMTranslator constructs a Parser for parsing Prog.vm and a CodeWriter that starts by creating an output file named Prog.asm. Next, the VMTranslator enters a loop that uses the Parser services for iterating through the input file and parsing each line as a VM command, barring white space. For each parsed command, the VMTranslator uses the CodeWriter for generating Hack assembly code and emitting the generated code into the output file. All this was already done in project 7.

If the translator's input is a folder, named, say, Prog, the VMTranslator constructs a Parser for handling each .vm file in the folder, and a single CodeWriter for generating Hack assembly code into the single output file Prog.asm. Each time the VMTranslator starts translating a new .vm file in the folder, it must inform the CodeWriter that a new file is now being processed. This is done by calling a CodeWriter routine named setFileName, as we now turn to describe.

The Parser

This module is identical to the Parser developed in project 7.

The CodeWriter

The CodeWriter developed in project 7 was designed to handle the VM *arithmetic-logical* and *push* / *pop* commands. Here is the API of a complete CodeWriter that handles all the commands in the VM language:

Routine	*Arguments*	*Returns*	*Function*
Constructor / initializer	Output file / stream	—	Opens an output file / stream and gets ready to write into it. Writes the assembly instructions that effect the bootstrap code that starts the program's execution. This code must be placed at the beginning of the generated output file / stream. Comment: See the *Implementation Tips* at the end of section 8.6.
`setFileName`	`fileName` (string)	—	Informs that the translation of a new VM file has started (called by the `VMTranslator`).
`writeArithmetic` (developed in project 7)	`command` (string)	—	Writes to the output file the assembly code that implements the given arithmetic-logical `command`.
`writePushPop` (developed in project 7)	`command` (`C_PUSH` or `C_POP`), `segment` (string), `index` (int)	—	Writes to the output file the assembly code that implements the given push or pop `command`.
`writeLabel`	`label` (string)	—	Writes assembly code that effects the `label` command.
`writeGoto`	`label` (string)	—	Writes assembly code that effects the `goto` command.
`writeIf`	`label` (string)	—	Writes assembly code that effects the `if-goto` command.
`writeFunction`	`functionName` (string) `nVars` (int)	—	Writes assembly code that effects the `function` command.
`writeCall`	`functionName` (string) `nArgs` (int)	—	Writes assembly code that effects the `call` command.
`writeReturn`	—	—	Writes assembly code that effects the `return` command.
`close` (developed in project 7)	—	—	Closes the output file / stream.

8.6 Project

In a nutshell, we have to extend the basic translator developed in chapter 7 with the ability to handle multiple .vm files and the ability to translate VM *branching* commands and VM *function* commands into Hack assembly code. For each parsed VM command, the VM translator has to generate assembly code that implements the command's semantics on the host Hack platform. The translation of the three *branching* commands into assembly is not difficult. The translation of the three *function* commands is more challenging and entails implementing the pseudocode listed in figure 8.5, using the symbols described in figure 8.6. We repeat the suggestion given in the previous chapter: Start by writing the required assembly code on paper. Draw RAM and global stack images, keep track of the stack pointer and the relevant memory segment pointers, and make sure that your paper-based assembly code successfully implements all the low-level actions associated with handling the call, function, and return commands.

Objective: Extend the basic VM translator built in project 7 into a full-scale VM translator, designed to handle multi-file programs written in the VM language.

This version of the VM translator assumes that the source VM code is error-free. Error checking, reporting, and handling can be added to later versions of the VM translator but are not part of project 8.

Contract: Complete the construction of a VM-to-Hack translator, conforming to VM Specification, Part II (section 8.4) and to the Standard VM Mapping on the Hack Platform, Part II (section 8.5.2). Use your translator to translate the supplied VM test programs, yielding corresponding programs written in the Hack assembly language. When executed on the supplied CPU emulator along with the supplied test scripts, the assembly programs generated by your translator should deliver the results mandated by the supplied compare files.

Resources: You will need two tools: the programming language in which you will implement your VM translator and the *CPU emulator* supplied in the Nand to Tetris software suite. Use the CPU emulator to execute and test the assembly code generated by your translator. If the generated code runs

correctly, we will assume that your VM translator performs as expected. This partial test of the translator will suffice for our purposes.

Another tool that comes in handy in this project is the supplied *VM emulator*. Use this program to execute the supplied test VM programs, and watch how the VM code effects the simulated states of the stack and the virtual memory segments. This can help understand the actions that the VM translator must eventually realize in assembly.

Since the full-scale VM translator is implemented by extending the VM translator built in project 7, you will also need the source code of the latter.

Testing and Implementation Stages

We recommend completing the implementation of the VM translator in two stages. First, implement the *branching* commands, and then the *function* commands. This will allow you to unit-test your implementation incrementally, using the supplied test programs.

Testing the Handling of the VM Commands label, if, if-goto:

- BasicLoop: Computes `1 + 2 + ··· + argument[0]`, and pushes the result onto the stack. Tests how the VM translator handles the label and if-goto commands.
- FibonacciSeries: Computes and stores in memory the first *n* elements of the Fibonacci series. A more rigorous test of handling the label, goto, and if-goto commands.

Testing the Handling of the VM Commands call, function, return:

Unlike what we did in project 7, we now expect the VM translator to handle multi-file programs. We remind the reader that by convention, the first function that starts running in a VM program is Sys.init. Normally, Sys.init is programmed to call the program's Main.main function. For the purpose of this project, though, we use the supplied Sys.init functions for setting the stage for the various tests that we wish to perform.

- SimpleFunction: Performs a simple calculation and returns the result. Tests how the VM translator handles the function and return commands. Since this test entails the handling of a single file consisting of a single function, no Sys.init test function is needed.

- FibonacciElement: This test program consists of two files: Main.vm contains a single Fibonacci function that returns recursively the n-th element of the Fibonacci series; Sys.vm contains a single Sys.init function that calls Main.fibonacci with $n = 4$ and then enters an infinite loop (recall that the VM translator generates bootstrap code that calls Sys.init). The resulting setting provides a rigorous test of the VM translator's handling of multiple .vm files, the VM function-call-and-return commands, the bootstrap code, and most of the other VM commands. Since the test program consists of two .vm files, the entire folder must be translated, producing a single FibonacciElement.asm file.
- StaticsTest: This test program consists of three files: Class1.vm and Class2.vm contain functions that set and get the values of several static variables; Sys.vm contains a single Sys.init function that calls these functions. Since the program consists of several .vm files, the entire folder must be translated, producing a single StaticsTest.asm file.

Implementation Tips

Since project 8 is based on extending the basic VM translator developed in project 7, we advise making a backup copy of the source code of the latter (if you haven't done it already).

Start by figuring out the assembly code that is necessary to realize the logic of the VM commands label, goto, and if-goto. Next, proceed to implement the methods writeLabel, writeGoto, and writeIf of the CodeWriter. Test your evolving VM translator by having it translate the supplied BasicLoop.vm and FibonacciSeries.vm programs.

Bootstrapping code: In order for any translated VM program to start running, it must include startup code that forces the VM implementation to start executing the program on the host platform. Further, for any VM code to operate properly, the VM implementation must store the base addresses of the stack and the virtual segments in the correct locations in the host RAM. The first three test programs in this project (BasicLoop, FibonaciiSeries, SimpleFunction) assume that the startup code was not yet implemented, and include test scripts that effect the necessary initializations *manually*, meaning that at this development stage you don't have to worry about it.

The last two test programs (FibonacciElement and StaticsTest) assume that the startup code is already part of the VM implementation.

With that in mind, the constructor of the CodeWriter must be developed in two stages. The first version of your constructor must not generate any bootstrapping code (that is, ignore the constructor's API guideline beginning with the text "Writes the assembly instructions …"). Use this version of your translator for unit-testing the programs BasicLoop, FibonacciSeries, and SimpleFunction. The second and final version of your CodeWriter constructor must write the bootstrapping code, as specified in the constructor's API. This version should be used for unit-testing FibonacciElement and StaticsTest.

The supplied test programs were carefully planned to test the specific features of each stage in your VM implementation. We recommend implementing your translator in the proposed order, and testing it using the appropriate test programs at each stage. Implementing a later stage before an early one may cause the test programs to fail.

A web-based version of project 8 is available at www.nand2tetris.org.

8.7 Perspective

The notions of *branching* and *function calling* are fundamental to all high-level languages. This means that somewhere down the translation path from a high-level language to binary code, someone must take care of handling the intricate housekeeping chores related to their implementation. In Java, C#, Python, and Jack, this burden falls on the virtual machine level. And if the VM architecture is *stack-based*, it lends itself nicely to the job, as we have seen throughout this chapter.

To appreciate the expressive power of our stack-based VM model, take a second look at the programs presented in this chapter. For example, figures 8.1 and 8.4 present high-level programs and their VM translations. If you do some line counting, you will note that each line of high-level code generates an average of about four lines of compiled VM code. As it turns out, this 1:4 translation ratio is quite consistent when compiling Jack programs into VM code. Even without knowing much about the art of

compilation, one can appreciate the brevity and readability of the VM code generated by the compiler. For example, as we will see when we build the compiler, a high-level statement like `let y = Math.sqrt(x)` is translated into `push x`, `call Math.sqrt`, `pop y`. The two-tier compiler can get away with so little work since it counts on the VM implementation for handling the rest of the translation. If we had to translate high-level statements like `let y = Math.sqrt(x)` directly into Hack code, without having the benefit of an intermediate VM layer, the resulting code would be far less elegant, and more cryptic.

That said, it would also be more efficient. Let us not forget that the VM code must be realized in machine language—that's what projects 7 and 8 are all about. Typically, the final machine code resulting from a two-tier translation process is longer and less efficient than that generated from direct translation. So, which is more desirable: a two-tier Java program that eventually generates one thousand machine instructions or an equivalent one-tier C++ program that generates seven hundred instructions? The pragmatic answer is that each programming language has its pros and cons, and each application has different operational requirements.

One of the great virtues of the two-tier model is that the intermediate VM code (e.g., Java's bytecode) can be *managed*, for example, by programs that test whether it contains malicious code, programs that monitor the code for business process modeling, and so on. In general, for most applications, the benefits of managed code justify the performance degradation caused by the VM level. Yet for high-performance programs like operating systems and embedded applications, the need to generate tight and efficient code typically mandates using C/C++, compiled directly to machine language.

For compiler writers, an obvious advantage of using an explicit interim VM language is that it simplifies the tasks of writing and maintaining compilers. For example, the VM implementation developed in this chapter frees the compiler from the significant tasks of handling the low-level implementation of the function call-and-return protocol. In general, the intermediate VM layer decouples the daunting challenge of building a high-level-to-low-level compiler into two far simpler challenges: building a high-level-to-VM compiler and building a VM-to-low-level translator. Since the latter translator, also called the compiler's *back end*, was already developed in projects 7 and 8, we can be content that about half of the overall

compilation challenge has already been accomplished. The other half—developing the compiler's *front end*—will be taken up in chapters 10 and 11.

We end this chapter with a general observation about the virtue of separating abstraction from implementation—an ongoing theme in Nand to Tetris and a crucial systems-building principle that goes far beyond the context of program compilation. Recall that VM functions can access their memory segments using commands like `push argument 2`, `pop local 1`, and so on while having no idea *how* these values are represented, saved, and reinstated during run-time. The VM implementation takes care of all the gory details. This complete separation of abstraction and implementation implies that developers of compilers that generate VM code don't have to worry about how the code they generate will end up running; they have enough problems of their own, as you will soon realize.

So cheer up! You are halfway through writing a two-tier compiler for a high-level, object-based, Java-like programming language. The next chapter is devoted to describing this language. This will set the stage for chapters 10 and 11, in which we'll complete the compiler's development. We begin seeing Tetris bricks falling at the end of the tunnel.

9 High-Level Language

High thoughts need a high language.
—Aristophanes (427–386 B.C.)

The assembly and VM languages presented so far in this book are low-level, meaning that they are intended for controlling machines, not for developing applications. In this chapter we present a high-level language, called Jack, designed to enable programmers to write high-level programs. Jack is a simple object-based language. It has the basic features and flavor of mainstream languages like Java and C++, with a simpler syntax and no support for inheritance. Despite this simplicity, Jack is a general-purpose language that can be used to create numerous applications. In particular, it lends itself nicely to interactive games like Tetris, Snake, Pong, Space Invaders, and similar classics.

The introduction of Jack marks the beginning of the end of our journey. In chapters 10 and 11 we will write a compiler that translates Jack programs into VM code, and in chapter 12 we will develop a simple operating system for the Jack/Hack platform. This will complete the computer's construction. With that in mind, it's important to say at the outset that the goal of this chapter is not to turn you into a Jack programmer. Neither do we claim that Jack is an important language outside the Nand to Tetris context. Rather, we view Jack as a necessary scaffold for chapters 10–12, in which we will build a compiler and an operating system that make Jack possible.

If you have any experience with a modern object-oriented programming language, you will immediately feel at home with Jack. Therefore, we begin the chapter with a few representative examples of Jack programs. All these programs can be compiled by the Jack compiler supplied in nand2tetris/tools.

The VM code produced by the compiler can then be executed as is on any VM implementation, including the supplied VM emulator. Alternatively, you can translate the compiled VM code further into machine language, using the VM translator built in chapters 7–8. The resulting assembly code can then be executed on the supplied CPU emulator or translated further into binary code and executed on the hardware platform built in chapters 1–5.

Jack is a simple language, and this simplicity has a purpose. First, you can learn (and unlearn) Jack in about one hour. Second, the Jack language was carefully designed to lend itself nicely to common compilation techniques. As a result, you can write an elegant *Jack compiler* with relative ease, as we will do in chapters 10 and 11. In other words, the deliberately simple structure of Jack is designed to help uncover the software infrastructure of modern languages like Java and C#. Rather than taking the compilers and run-time environments of these languages apart, we find it more instructive to build a compiler and a run-time environment ourselves, focusing on the most important ideas underlying their construction. This will be done later, in the last three chapters of the book. Presently, let's take Jack out of the box.

9.1 Examples

Jack is mostly self-explanatory. Therefore, we defer the language specification to the next section and start with examples. The first example is the inevitable *Hello World* program. The second example illustrates procedural programming and array processing. The third example illustrates how abstract data types can be implemented in the Jack language. The fourth example illustrates a linked list implementation using the language's object-handling capabilities.

Throughout the examples, we discuss briefly various object-oriented idioms and commonly used data structures. We assume that the reader has a basic familiarity with these subjects. If not, read on—you'll manage.

Example 1: Hello World: The program shown in figure 9.1 illustrates several basic Jack features. By convention, when we execute a compiled

Jack program, execution always starts with the Main.main function. Thus, each Jack program must include at least one class, named Main, and this class must include at least one function, named Main.main. This convention is illustrated in figure 9.1.

```
/** Prints "Hello World". File name: Main.jack */
class Main {
   function void main() {
      do Output.printString("Hello World");
      do Output.println();   // New line
      return;                // The return statement is mandatory
   }
}
```

Figure 9.1 *Hello World*, written in the Jack language.

Jack comes with a *standard class library* whose complete API is given in appendix 6. This software library, also known as the *Jack OS*, extends the basic language with various abstractions and services such as mathematical functions, string processing, memory management, graphics, and input/output functions. Two such OS functions are invoked by the Hello World program, affecting the program's output. The program also illustrates the comment formats supported by Jack.

Example 2: Procedural programming and array handling: Jack features typical statements for handling assignment and iteration. The program shown in figure 9.2 illustrates these capabilities in the context of array processing.

```
/** Inputs a sequence of integers, and computes their average. */
class Main {
   function void main() {
      var Array a;     // Jack arrays are not typed
      var int length;
      var int i, sum;
      let i = 0;
      let sum = 0;
      let length = Keyboard.readInt("How many numbers? ");
      let a = Array.new(length); // Constructs the array
      while (i < length) {
         let a[i] = Keyboard.readInt("Enter a number: ");
         let sum = sum + a[i];
         let i = i + 1;
      }
      do Output.printString("The average is: ");
      do Output.printInt(sum / length);
      do Output.println();
      return;
   }
}
```

Figure 9.2 Typical procedural programming and simple array handling. Uses the services of the OS classes Array, Keyboard, and Output.

Most high-level programming languages feature array declaration as part of the basic syntax of the language. In Jack, we have opted for treating arrays as instances of an Array class, which is part of the OS that extends the basic language. This was done for pragmatic reasons, as it simplifies the construction of Jack compilers.

Example 3: Abstract data types: Every programming language features a fixed set of primitive data types, of which Jack has three: int, char, and boolean. In object-based languages, programmers can introduce new types by creating classes that represent abstract data types as needed. For example, suppose we wish to endow Jack with the ability to handle rational numbers like 2/3 and 314159/100000 without loss of precision. This can be done by developing a standalone Jack class designed to create and manipulate fraction objects of the form *x/y*, where *x* and *y* are integers. This class can then provide a fraction abstraction to any Jack program that needs to represent and manipulate rational numbers. We now turn to describe how

a Fraction class can be used and developed. This example illustrates typical multi-class, object-based programming in Jack.

Using classes: Figure 9.3a lists a class skeleton (a set of method signatures) that specifies some of the services that one can reasonably expect to get from a fraction abstraction. Such a specification is often called an *Application Program Interface*. The client code at the bottom of the figure illustrates how this API can be used for creating and manipulating fraction objects.

```
/** Represents the Fraction type and related operations (class skeleton) */
class Fraction {

    /** Constructs a (reduced) fraction from x and y */
    constructor Fraction new(int x, int y)

    /** Returns the numerator of this fraction */
    method int getNumerator()

    /** Returns the denominator of this fraction */
    method int getDenominator()

    /** Returns the sum of this fraction and the other one */
    method Fraction plus(Fraction other)

    /** Prints this fraction in the format x/y */
    method void print()

    /** Disposes this fraction */
    method void dispose() {

    // More fraction-related methods:
    // minus, times, div, invert, etc.
}
```

```
// Computes and prints the sum of 2/3 and 1/5
class Main {
   function void main() {
      // Creates 3 fraction variables (pointers to Fraction objects)
      var Fraction a, b, c;
      let a = Fraction.new(4,6); // a = 2/3
      let b = Fraction.new(1,5); // b = 1/5

      // Adds up the two fractions, and prints the result
      let c = a.plus(b);    // c = a + b
      do c.print();         // Should print "13/15"
      return;
   }
}
```

Figure 9.3a Fraction API (top) and sample Jack class that uses it for creating and manipulating Fraction objects.

Figure 9.3a illustrates an important software engineering principle: users of an abstraction (like Fraction) don't have to know anything about its implementation. All they need is the class *interface*, also known as API. The API informs what functionality the class offers and how to use this functionality. That's all the client needs to know.

Implementing classes: So far, we have seen only the client perspective of the Fraction class—the view from which Fraction is used as a black box

abstraction. Figure 9.3b lists one possible implementation of this abstraction.

```
/** Represents the Fraction type and related operations. */
class Fraction {
   // Each Fraction object has a numerator and a denominator
   field int numerator, denominator;
   /** Constructs a (reduced) fraction from x and y */
   constructor Fraction new(int x, int y) {
      let numerator = x;
      let denominator = y;
      do reduce();     // Reduces this fraction
      return this;     // Returns a reference to the new object
   }
   // Reduces this fraction
   method void reduce() {
      var int g;
      let g = Fraction.gcd(numerator, denominator);
      if (g > 1) {
         let numerator = numerator / g;
         let denominator = denominator / g;
      }
      return;
   }
   // Computes the greatest common divisor of two given integers
   function int gcd(int a, int b) {
      // Applies Euclid's algorithm
      var int r;
      while (~(b = 0)) {
         let r = a - (b * (a / b));   // r = remainder
         let a = b;
         let b = r;
      }
      return a;
   }
   // The Fraction class declaration continues on the top right
```

```
   /** Accessors */
   method int getNumerator() {
      return numerator;
   }
   method int getDenominator() {
      return denominator;
   }
   /** Returns the sum of this fraction and the other one */
   method Fraction plus(Fraction other) {
      var int sum;
      let sum = (numerator * other.getDenominator())+
                (other.getNumerator() * denominator);
      return Fraction.new(sum, denominator *
                          other.getDenominator());
   }
   /** Prints this fraction in the format x/y */
   method void print() {
      do Output.printInt(numerator);
      do Output.printString("/");
      do Output.printInt(denominator);
      return;
   }
   /** Disposes this fraction */
   method void dispose() {
      // Frees the memory held by this object
      do Memory.deAlloc(this);
      return;
   }
   // More fraction-related methods can come here:
   // minus, times, div, invert, etc.
}  // End of the Fraction class declaration.
```

Figure 9.3b A Jack implementation of the Fraction abstraction.

The Fraction class illustrates several key features of object-based programming in Jack. *Fields* specify object properties (also called *member variables*). *Constructors* are subroutines that create new objects, and *methods* are subroutines that operate on the current object (referred to using the keyword this). *Functions* are class-level subroutines (also called *static methods*) that operate on no particular object. The Fraction class also demonstrates all the statement types available in the Jack language: let, do, if, while, and return. The Fraction class is of course just one example of the unlimited number of classes that can be created in Jack to support any conceivable programming objective.

Example 4: Linked list implementation: The data structure *list* is defined recursively as a value, followed by a list. The value null—the definition's base case—is also considered a list. Figure 9.4 shows a possible Jack implementation of a list of integers. This example illustrates how Jack can be used for realizing a major data structure, widely used in computer science.

```
/** Represents a list of integers. */
class List {
   field int data;      // A list consists of an int value,
   field List next;     // followed by a List

   /* Creates a list whose head is car and whose tail is cdr */
   // These identifiers are used in memory of the Lisp programming language
   constructor List new(int car, List cdr) {
      let data = car;
      let next = cdr;
      return this;
   }

   /* Accessors */
   method int getData() {return data;}
   method List getNext() {return next;}

   /* Prints the elements of this list */
   method void print() {
      // Initializes a pointer to the first element of this list
      var List current;
      let current = this;
      // Iterates through the list
      while (~(current = null)) {
         do Output.printInt(current.getData());
         do Output.printChar(32); // Prints a space
         let current = current.getNext();
      }
      return;
   }

   // The List class declaration continues on the top right
```

```
   /* Disposes this List */
   method void dispose() {
      // Disposes the tail of this list, recursively
      if (~(next = null)) {
         do next.dispose();
      }
      // Uses an OS routine to free the memory
      // held by this object.
      do Memory.deAlloc(this);
      return;
   }

   // More list-related methods can come here
} // End of the List class declaration.
```

```
// Client code example:

// Creates, prints, and disposes the list (2,3,5),
// which is shorthand for the list (2,(3,(5,null))).

// (This code can appear in any Jack class):
...
var List v;
let v = List.new(5,null);
let v = List.new(2,List.new(3,v));
do v.print();          // Prints 2 3 5
do v.dispose();        // Disposes the list
...
```

Figure 9.4 Linked list implementation in Jack (left and top right) and sample usage (bottom right).

The operating system: Jack programs make extensive use of the Jack operating system, which will be discussed and developed in chapter 12. For now, suffice it to say that Jack programs use the OS services abstractly, without paying attention to their underlying implementation. Jack programs can use the OS services directly—there is no need to include or import any external code.

The OS consists of eight classes, summarized in figure 9.5 and documented in appendix 6.

OS class	*Services*
`Math`	Common mathematical operations: `max(int,int)`, `sqrt(int)`, ...
`String`	Represents strings and related operations: `length()`, `charAt(int)` , ...
`Array`	Represents arrays and related operations: `new(int)`, `dispose()`
`Output`	Facilitates text output to the screen: `printString(String)`, `printInt(int)`, `println()`, ...
`Screen`	Facilitates graphics output to the screen : `setColor(boolean)`, `drawPixel(int,int)`, `drawLine(int,int,int,int)` , ...
`Keyboard`	Facilitates input from the keyboard: `readLine(String)`, `readInt(String)` , ...
`Memory`	Facilitates access to the host RAM: `peek(int)`, `poke(int,int)`, `alloc(int)`, `deAlloc(Array)`
`Sys`	Facilitates execution-related services: `halt()`, `wait(int)`, ...

Figure 9.5 Operating system services (summary). The complete OS API is given in appendix 6.

9.2 The Jack Language Specification

This section can be read once and then used as a technical reference, to be consulted as needed.

9.2.1 Syntactic Elements

A Jack program is a sequence of tokens, separated by an arbitrary amount of white space and comments. Tokens can be symbols, reserved words, constants, and identifiers, as listed in figure 9.6.

White space and comments	Space characters, newline characters, and comments are ignored.
	The following comment formats are supported:
	`//` Comment to end of line
	`/*` Comment until closing `*/`
	`/**` Aimed at software tools that extract API documentation. `*/`

Symbols	`()` Used for grouping arithmetic expressions and for enclosing argument-lists (in subroutine calls) and parameter-lists (in subroutine declarations) `[]` Used for array indexing `{}` Used for grouping program units and statements `,` Variable-list separator `;` Statement terminator `=` Assignment and comparison operator `.` Class membership `+ - * / & | ~ < >` Operators
Reserved words	`class`, `constructor`, `method`, `function` — Program components `int`, `boolean`, `char`, `void` — Primitive types `var`, `static`, `field` — Variable declarations `let`, `do`, `if`, `else`, `while`, `return` — Statements `true`, `false`, `null` — Constant values `this` — Object reference
Constants	• *Integer constants* are values in the range 0 to 32767. Negative integers are not constants but rather expressions consisting of a unary minus operator applied to an integer constant. The resulting valid range of values is –32768 to 32767 (the former can be obtained using the expression –32767–1). • *String constants* are enclosed within double quote (`"`) characters and may contain any character except newline or double quote. These characters are supplied by the OS functions `String.newLine()` and `String.doubleQuote()`. • *Boolean constants* are `true` and `false`. • The `null` constant signifies a null reference.
Identifiers	Identifiers are composed from arbitrarily long sequences of letters (`A-Z`, `a-z`), digits (`0-9`), and "`_`". The first character must be a letter or "`_`". The language is case sensitive: `x` and `X` are treated as different identifiers.

Figure 9.6 The syntax elements of the Jack language.

9.2.2 Program Structure

A Jack program is a collection of one or more classes stored in the same folder. One class must be named Main, and this class must have a function named main. The execution of a compiled Jack program always starts with the Main.main function.

The basic programming unit in Jack is a *class*. Each class *Xxx* resides in a separate file named *Xxx*.jack and is compiled separately. By convention, class names begin with an uppercase letter. The file name must be identical

to the class name, including capitalization. The class declaration has the following structure:

```
class name {
    field variable declarations     // Must precede the subroutine declarations
    static variable declarations    // Must precede the subroutine declarations
    subroutine declarations         // Constructor, method and function declarations, in any order
}
```

Each class declaration specifies a name through which the class services can be globally accessed. Next comes a sequence of zero or more field declarations and zero or more static variable declarations. Next comes a sequence of one or more subroutine declarations, each defining a *method*, a *function*, or a *constructor*.

Methods are designed to operate on the current object. *Functions* are class-level *static methods* that are not associated with any particular object. *Constructors* create and return new objects of the class type. A subroutine declaration has the following structure:

```
subroutine type name (parameter-list) {
    local variable declarations
    statements
}
```

where *subroutine* is either constructor, method, or function. Each subroutine has a *name* through which it can be accessed and a *type* specifying the data type of the value returned by the subroutine. If the subroutine is designed to return no value, its type is declared void. The *parameter-list* is a comma-separated list of <*type identifier*> pairs, for example, (int x, boolean sign, Fraction g).

If the subroutine is a *method* or a *function*, its return type can be any of the primitive data types supported by the language (int, char, or boolean), any of the class types supplied by the standard class library (String or Array), or any of the types realized by other classes in the program (e.g., Fraction or List). If the subroutine is a *constructor*, it may have an arbitrary name, but its type must be the name of the class to which it belongs. A class can have 0,

1, or more constructors. By convention, one of the constructors is named new.

Following its interface specification, the subroutine declaration contains a sequence of zero or more local variable declarations (var statements) and then a sequence of one or more statements. Each subroutine must end with the statement return *expression*. In the case of a void subroutine, when there is nothing to return, the subroutine must end with the statement return (which can be viewed as a shorthand of return void, where void is a constant representing "nothing"). Constructors must terminate with the statement return this. This action returns the memory address of the newly constructed object, denoted this (Java constructors do the same, implicitly).

9.2.3 Data Types

The data type of a variable is either *primitive* (int, char, or boolean), or *ClassName*, where *ClassName* is either String, Array, or the name of a class residing in the program folder.

Primitive types: Jack features three primitive data types:

int: two's-complement 16-bit integer

char: nonnegative, 16-bit integer

boolean: true or false

Each one of the three primitive data types int, char, and boolean is represented internally as a 16-bit value. The language is weakly typed: a value of any type can be assigned to a variable of any type without casting.

Arrays: Arrays are declared using the OS class Array. Array elements are accessed using the typical arr[*i*] notation, where the index of the first element is 0. A multidimensional array may be obtained by creating an array of arrays. The array elements are not typed, and different elements in the same array may have different types. The declaration of an array creates a reference, while the array proper is constructed by executing the constructor call Array.new (*arrayLength*). For an example of working with arrays, see figure 9.2.

Object types: A Jack class that contains at least one method defines an object type. As typical in object-oriented programming, object creation is a two-step affair. Here is an example:

```
// This client code example uses the Car and Employee classes, whose code is not shown here.
// The Car class has two fields: model (a String) and licensePlate (a String).
// The Employee class has two fields: name (a String) and car (a Car).
...
// Declares a Car object and two Employee objects (three pointer variables):
var Car c;
var Employee emp1, emp2;
...
// Constructs a new car:
let c = Car.new("Aston Martin","007"); // Sets c to the base address of a memory block
                                       // containing the new car's data.
// Constructs a new employee, and assigns a car to it:
let emp1 = Employee.new("Bond",c);
...
// Creates an alias of Bond:
let emp2 = emp1; // Only the reference (address) is copied, no new object is constructed.
// We now have two Employee pointers referring to the same object.
```

Strings: Strings are instances of the OS class String, which implements strings as arrays of char values. The Jack compiler recognizes the syntax "foo" and treats it as a String object. The contents of a String object can be accessed using charAt(*index*) and other methods documented in the String class API (see appendix 6). Here is an example:

```
var String s;   // An object variable
var char c;     // A primitive variable
...
let s = "Hello World"; // Sets s to the String object "Hello World"
let c = s.charAt(6);   // Sets c to 87, the integer character code of 'W'
```

The statement let s = "Hello World" is equivalent to the statement let s = String.new(11), followed by the eleven method calls do s.appendChar(72), …, do s.appendChar(100), where the argument of appendChar is the character's integer

code. In fact, that's exactly how the compiler handles the translation of `let s = "Hello World"`. Note that the single character idiom, for example, 'H', is not supported by the Jack language. The only way to represent a character is to use its integer character code or a `charAt` method call. The Hack character set is documented in appendix 5.

Type conversions: Jack is weakly typed: the language specification does not define what happens when a value of one type is assigned to a variable of a different type. The decisions of whether to allow such casting operations, and how to handle them, are left to specific Jack compilers. This under-specification is intentional, allowing the construction of minimal compilers that ignore typing issues. Having said that, all Jack compilers are expected to support, and automatically perform, the following assignments.

- A character value can be assigned to an integer variable, and vice versa, according to the Jack character set specification (appendix 5). Example:

```
var char c;
let c = 33; // 'A'
// Equivalently:
var String s;
let s = "A";
let c = s.charAt(0);
```

- An integer can be assigned to a reference variable (of any object type), in which case it is interpreted as a memory address. Example:

```
var Array arr;       // Creates a pointer variable
let arr = 5000;      // Sets arr to 5000
let arr[100] = 17; // Sets the contents of memory address 5100 to 17
```

- An object variable may be assigned to an `Array` variable, and vice versa. This allows accessing the object fields as array elements, and vice versa. Example:

```
// Creates the array [2,5]:
var Array arr;
let arr = Array.new(2);
let arr[0] = 2;
let arr[1] = 5;

// Creates the Fraction 2/5:
var Fraction x;
let x = arr;   // sets x to the base address of the memory block
               // representing the array [2,5]

do Output.printInt(x.getNumerator())   // prints "2"
do x.print()                           // prints "2/5"
```

9.2.4 Variables

Jack features four kinds of variables. *Static variables* are defined at the class level and can be accessed by all the class subroutines. *Field variables*, also defined at the class level, are used to represent the properties of individual objects and can be accessed by all the class constructors and methods. *Local variables* are used by subroutines for local computations, and *parameter variables* represent the arguments that were passed to the subroutine by the caller. Local and parameter values are created just before the subroutine starts executing and are recycled when the subroutine returns. Figure 9.7 gives the details. The *scope* of a variable is the region in the program in which the variable is recognized.

Kind	Description	Declared in	Scope
Class variables	`static` *type varName*1, *varName*2, ... ; One copy of each `static` variable exists, and this copy is shared by all the class subroutines (like *private static variables* in Java)	Class declaration	The class in which they are declared
Field variables	`field` *type varName*1, *varName*2, ... ; Every object (instance of the class) has a private copy of the field variables (like *member variables* in Java)	Class declaration	The class in which they are declared
Local variables	`var` *type varName*1, *varName*2, ... ; Created when the subroutine starts running and disposed when the subroutine returns.	Subroutine declaration	The subroutine in which they are declared
Parameter variables	Represent the arguments passed to the subroutine. Treated like local variables whose values are initialized by the subroutine caller.	Subroutine declaration	The subroutine in which they are declared

Figure 9.7 Variable kinds in the Jack language. Throughout the table, *subroutine* refers to either a *function*, a *method*, or a *constructor*.

Variable initialization: Static variables are not initialized, and it is up to the programmer to write code that initializes them before using them. Field variables are not initialized; it is expected that they will be initialized by the class constructor, or constructors. Local variables are not initialized, and it is up to the programmer to initialize them. Parameter variables are initialized to the values of the arguments passed by the caller.

Variable visibility: Static and field variables cannot be accessed directly from outside the class in which they are defined. They can be accessed only through accessor and mutator methods, as facilitated by the class designer.

9.2.5 Statements

The Jack language features five statements, as seen in figure 9.8.

Statement	*Syntax*	*Description*
`let`	`let` *varName* `=` *expression*`;` or: `let` *varName*`[`*expression*1`] =` *expression*2`;`	An assignment operation. The variable kind may be *static*, *local*, *field*, or *parameter*.

`if`	`if (`*expression*`) {`
	*statements*1`;`
	`} else {`
	*statements*2`;`
	`}`
		Typical *if* statement, with an optional *else* clause.
		The curly brackets are mandatory, even if *statements* is a single statement.

`while`	`while (`*expression*`) {`
	statements`;`
	`}`
		Typical *while* statement.
		The curly brackets are mandatory, even if *statements* is a single statement.

`do`	`do` *function-or-method-call*`;`	Used to call a function or a method for its effect, ignoring the returned value, if any.
`return`	`return` *expression*`;` or `return;`	Used to return a value from a subroutine. The second form must be used by `void` subroutines. Constructors must return the value `this`.

Figure 9.8 Statements in the Jack language.

9.2.6 Expressions

A Jack expression is one of the following:

- A *constant*
- A *variable name* in scope. The variable may be *static*, *field*, *local*, or *parameter*
- The this keyword, denoting the current object (cannot be used in functions)
- An *array element* using the syntax *arr*[*expression*], where *arr* is a variable name of type Array in scope
- A *subroutine call* that returns a non-void type
- An expression prefixed by one of the unary operators - or ~:

  - *expression*: arithmetic negation

  ~ *expression*: Boolean negation (bitwise for integers)
- An expression of the form *expression op expression* where *op* is one of the following binary operators:

  + - * /: integer arithmetic operators

  & |: Boolean And and Boolean Or (bitwise for integers) operators

  < > =: comparison operators
- (*expression*): an expression in parentheses

Operator priority and order of evaluation: Operator priority is *not* defined by the language, except that expressions in parentheses are evaluated first. Thus the value of the expression `2 + 3 * 4` is unpredictable, whereas `2 + (3 * 4)` is guaranteed to evaluate to 14. The Jack compiler supplied in Nand to Tetris (as well as the compiler that we'll develop in chapters 10–11) evaluates expressions left to right, so the expression `2 + 3 * 4` evaluates to 20. Once again, if you wish to get the algebraically correct result, use `2 + (3 * 4)`.

The need to use parentheses for enforcing operator priority makes Jack expressions a bit cumbersome. This lack of formal operator priority is intentional, though, as it simplifies the implementation of Jack compilers. Different Jack compilers are welcome to specify an operator priority and add it to the language documentation, if so desired.

9.2.7 Subroutine Calls

A subroutine call invokes a function, a constructor, or a method for its effect, using the general syntax *subroutineName* (*exp*$_1$, *exp*$_2$, …, *exp*$_n$), where each argument *exp* is an expression. The number and type of the arguments must match those of the subroutine's parameters, as specified in the subroutine's declaration. The parentheses must appear even if the argument list is empty.

Subroutines can be called from the class in which they are defined, or from other classes, according to the following syntax rules:

Function calls / Constructor calls:

- *className.functionName* (*exp*$_1$, *exp*$_2$, … , *exp*$_n$)
- *className.constructorName* (*exp*$_1$, *exp*$_2$, … , *exp*$_n$)

The *className* must always be specified, even if the function/constructor is in the same class as the caller.

Method calls:

- *varName.methodName* (*exp*$_1$, *exp*$_2$, … , *exp*$_n$)

  Applies the method to the object referred to by *varName*.
- *methodName* (*exp*$_1$, *exp*$_2$, … , *exp*$_n$)

  Applies the method to the *current object*. Same as this.*methodName* (*exp*$_1$, *exp*$_2$, … , *exp*$_n$).

Here are subroutine call examples:

```
class Foo {
   ...
   method void f() {
      var Bar b;          // Declares a local variable of class type Bar
      var int i;          // Declares a local variable of primitive type int
      ...
      do Foo.g()          // Calls function g of the current class
      do Bar.h()          // Calls function h of class Bar
      do m()              // Calls method m of the current class, on the this object
      do b.q()            // Calls method q of class Bar, on object b
      let i = w(b.s(), Foo.t())  // Calls method w on the this object,
                                 // Calls method s of class Bar on object b,
                                 // Calls function or constructor t of class Foo.
    }
}
```

9.2.8 Object Construction and Disposal

Object construction is done in two stages. First, a reference variable (pointer to an object) is declared. To complete the object's construction (if so desired), the program must call a constructor from the object's class. Thus, a class that implements a type (e.g., Fraction) must feature at least one constructor. Jack constructors may have arbitrary names; by convention, one of them is named new.

Objects are constructed and assigned to variables using the idiom let *varName* = *className.constructorName* (*exp*$_1$, *exp*$_2$, … , *exp*$_n$), for example, let c = Circle.new (x,y,50). Constructors typically include code that initializes the fields of the new object to the argument values passed by the caller.

When an object is no longer needed, it can be disposed, to free the memory that it occupies. For example, suppose that the object that c points at is no longer needed. The object can be deallocated from memory by calling the OS function Memory.deAlloc (c). Since Jack has no garbage collection, the best-practice advice is that every class that represents an object must feature a dispose() method that properly encapsulates this de-allocation. Figures 9.3 and 9.4 give examples. To avoid memory leaks, Jack programmers are advised to dispose objects when they are no longer needed.

9.3 Writing Jack Applications

Jack is a general-purpose language that can be implemented over different hardware platforms. In Nand to Tetris we develop a *Jack compiler over the Hack platform*, and thus it is natural to discuss Jack applications in the Hack context.

Examples: Figure 9.9 shows screenshots of four sample Jack programs. Generally speaking, the Jack/Hack platform lends itself nicely to simple interactive games like Pong, Snake, Tetris, and similar classics. Your projects/09/Square folder includes the full Jack code of a simple interactive program that allows the user to move a square image on the screen using the four keyboard arrow keys.

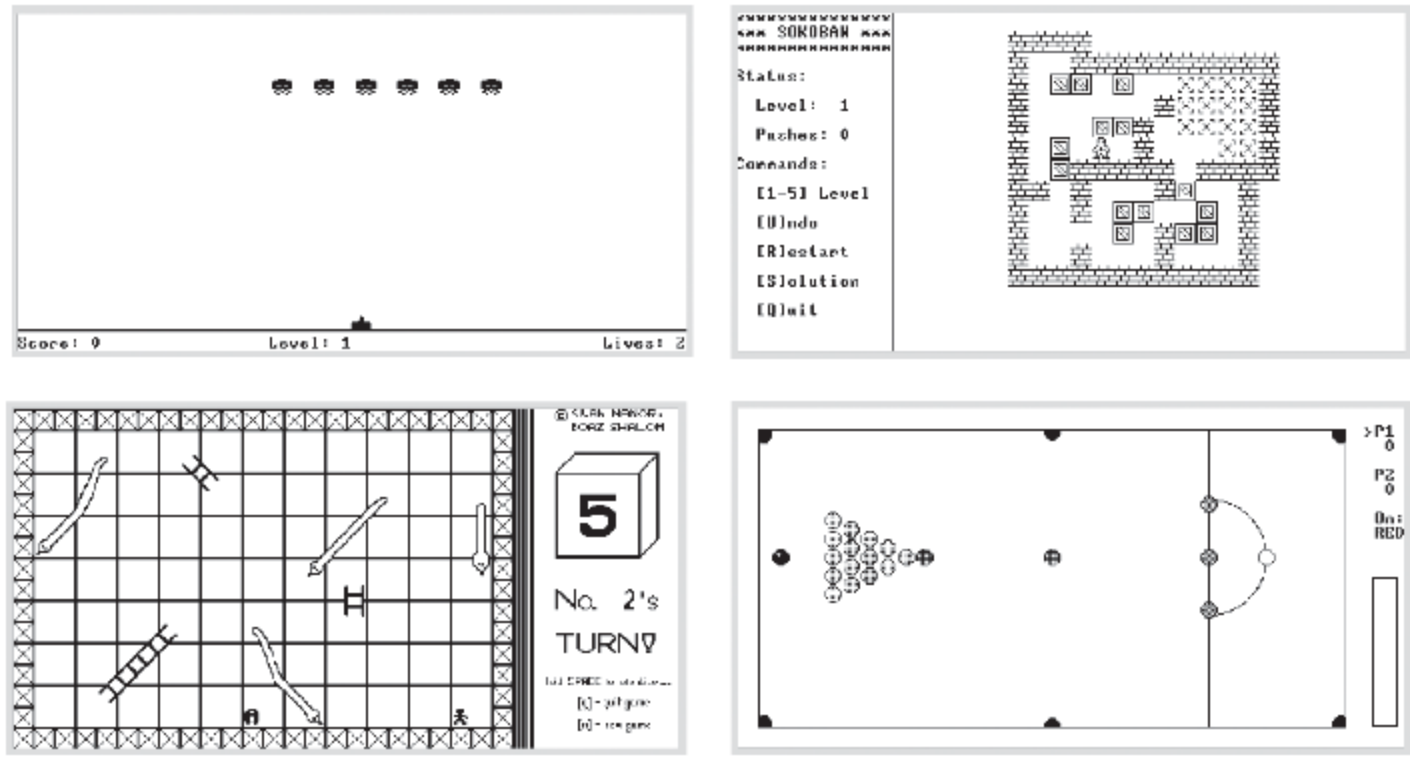


Figure 9.9 Screenshots of Jack applications running on the Hack computer.

Executing this program while reviewing its Jack source code is a good way for learning how to use Jack to write interactive graphical applications. Later in the chapter we describe how to compile and execute Jack programs using the supplied tools.

Application design and implementation: Software development should always rest on careful planning, especially when done over a spartan hardware platform like the Hack computer. First, the program designer must

consider the physical limitations of the hardware and plan accordingly. To start with, the dimensions of the computer's screen limit the size of the graphical images that the program can handle. Likewise, one must consider the language's range of input/output commands and the platform's execution speed to gain a realistic expectation of what can and cannot be done.

The design process normally starts with a conceptual description of the desired program's behavior. In the case of graphical and interactive programs, this may take the form of handwritten drawings of typical screens. Next, one normally designs an object-based architecture of the program. This entails the identification of *classes*, *fields*, and *subroutines*. For example, if the program is supposed to allow the user to create square objects and move them around the screen using the keyboard's arrow keys, it will make sense to design a Square class that encapsulates these operations using methods like moveRight, moveLeft, moveUp, and moveDown, as well as a constructor subroutine for creating squares and a disposer subroutine for disposing them. In addition, it will make sense to create a SquareGame class that carries out the user interaction and a Main class that gets things started. Once the APIs of these classes are carefully specified, one can proceed to implement, compile, and test them.

Compiling and executing Jack programs: All the .jack files comprising the program must reside in the same folder. When you apply the Jack compiler to the program folder, each source .jack file will be translated into a corresponding .vm file, stored in the same program folder.

The simplest way to execute or debug a compiled Jack program is to load the program folder into the VM emulator. The emulator will load all the VM functions in all the .vm files in the folder, one after the other. The result will be a (possibly long) stream of VM functions, listed in the VM emulator's code pane using their full *fileName.functionName* names. When you instruct the emulator to execute the program, the emulator will start executing the OS Sys.init function, which will then call the Main.main function in your Jack program.

Alternatively, you can use a VM translator (like the one built in projects 7–8) for translating the compiled VM code, as well as the eight supplied tools/OS/*.vm OS files, into a single .asm file written in the Hack machine

language. The assembly code can then be executed on the supplied CPU emulator. Or, you can use an assembler (like the one built in project 6) for translating the .asm file further into a binary code .hack file. Next, you can load a Hack computer chip (like the one built in projects 1–5) into the hardware simulator or use the built-in Computer chip, load the binary code into the ROM chip, and execute it.

The operating system: Jack programs make extensive use of the language's *standard class library*, which we also refer to as the *Operating System*. In project 12 you will develop the OS class library in Jack (like Unix is written in C) and compile it using a Jack compiler. The compilation will yield eight .vm files, comprising the OS implementation. If you put these eight .vm files in your program folder, all the OS functions will become accessible to the compiled VM code, since they belong to the same code base (by virtue of belonging to the same folder).

Presently, though, there is no need to worry about the OS implementation. The supplied VM emulator, which is a Java program, features a built-in Java implementation of the Jack OS. When the VM code loaded into the emulator calls an OS function, say Math.sqrt, one of two things happens. If the OS function is found in the loaded code base, the VM emulator executes it, just like executing any other VM function. If the OS function is not found in the loaded code base, the emulator executes its built-in implementation.

9.4 Project

Unlike the other projects in this book, this one does not require building a hardware of software module. Rather, you have to pick some application of your choice and build it in Jack over the Hack platform.

Objective: The "hidden agenda" of this project is to get acquainted with the Jack language, for two purposes: writing the Jack compiler in projects 10 and 11, and writing the Jack operating system in project 12.

Contract: Adopt or invent an application idea like a simple computer game or some interactive program. Then design and build the application.

Resources: You will need the supplied tools/JackCompiler for translating your program into a set of .vm files, and the supplied tools/VMEmulator for running and testing the compiled code.

Compiling and Running a Jack Program

0. Create a folder for your program. Let's call it the *program folder*.
1. Write your Jack program—a set of one or more Jack classes—each stored in a separate *ClassName*.jack text file. Put all these .jack files in the program folder.
2. Compile the program folder using the supplied Jack compiler. This will cause the compiler to translate all the .jack classes found in the folder into corresponding .vm files. If a compilation error is reported, debug the program and recompile until no error messages are issued.
3. At this point the program folder should contain your source .jack files along with the compiled .vm files. To test the compiled program, load the program folder into the supplied VM emulator, and run the loaded code. In case of run-time errors or undesired program behavior, fix the relevant file and go back to step 2.

Program examples: Your nand2tetris/project/09 folder includes the source code of a complete, three-class interactive Jack program (Square). It also includes the source code of the Jack programs discussed in this chapter.

Bitmap editor: If you develop a program that needs high-speed graphics, it is best to design *sprites* for rendering the key graphical elements of the program. For example, the output of the Sokoban application depicted in figure 9.9 consists of several repeating sprites. If you wish to design such sprites and write them directly into the screen memory map (bypassing the services of the OS Screen class, which may be too slow), you will find the projects/09/BitmapEditor tool useful.

A web-based version of project 9 is available at www.nand2tetris.org.

9.5 Perspective

Jack is an *object-based* language, meaning that it supports objects and classes but not inheritance. In this respect it is positioned somewhere between procedural languages like Pascal or C and object-oriented languages like Java or C++. Jack is certainly more simple-minded than any of these industrial strength programming languages. However, its basic syntax and semantics are similar to those of modern languages.

Some features of the Jack language leave much to be desired. For example, its primitive type system is, well, rather primitive. Moreover, it is a weakly typed language, meaning that type conformity in assignments and operations is not strictly enforced. Also, you may wonder why the Jack syntax includes clunky keywords like `do` and `let`, why every subroutine must end with a `return` statement, why the language does not enforce operator priority, and so on—you may add your favorite complaint to the list.

All these somewhat tedious idiosyncrasies were introduced into Jack with one purpose: allowing the development of simple and minimal Jack compilers, as we will do in the next two chapters. For example, the parsing of a statement (in any language) is significantly easier if the first token of the statement reveals which statement we're in. That's why Jack uses a `let` keyword for prefixing assignment statements. Thus, although Jack's simplicity may be a nuisance when writing Jack *applications*, you'll be grateful for this simplicity when writing the Jack *compiler*, as we'll do in the next two chapters.

Most modern languages are deployed with a set of *standard classes*, and so is Jack. Taken together, these classes can be viewed as a portable, language-oriented operating system. Yet unlike the standard libraries of industrial-strength languages, which feature numerous classes, the Jack OS provides a minimal set of services, which is nonetheless sufficient for developing simple interactive applications.

Clearly, it would be nice to extend the Jack OS to provide concurrency for supporting multi-threading, a file system for permanent storage, sockets for communications, and so on. Although all these services can be added to the OS, readers will perhaps want to hone their programming skills elsewhere. After all, we don't expect Jack to be part of your life beyond

Nand to Tetris. Therefore, it is best to view the Jack/Hack platform as a given environment and make the best out of it. That's precisely what programmers do when they write software for embedded devices and dedicated processors that operate in restricted environments. Instead of viewing the constraints imposed by the host platform as a problem, professionals view it as an opportunity to display their resourcefulness and ingenuity. That's what you are expected to do in project 9.

10 Compiler I: Syntax Analysis

Neither can embellishments of language be found without arrangement and expression of thoughts, nor can thoughts be made to shine without the light of language.

—Cicero (106–43 B.C.)

The previous chapter introduced Jack—a simple, object-based programming language with a Java-like syntax. In this chapter we start building a compiler for the Jack language. A *compiler* is a program that translates programs from a source language into a target language. The translation process, known as *compilation*, is conceptually based on two distinct tasks. First, we have to understand the syntax of the source program and, from it, uncover the program's semantics. For example, the parsing of the code can reveal that the program seeks to declare an array or manipulate an object. Once we know the semantics, we can reexpress it using the syntax of the target language. The first task, typically called *syntax analysis*, is described in this chapter; the second task—*code generation*—is taken up in the next chapter.

How can we tell that a compiler is capable of "understanding" programs? Well, as long as the code generated by the compiler is doing what it's supposed to be doing, we can optimistically assume that the compiler is operating properly. Yet in this chapter we build only the syntax analyzer module of the compiler, with no code generation capabilities. If we wish to unit-test the syntax analyzer in isolation, we have to contrive a way to demonstrate that it understands the source program. Our solution is to have the syntax analyzer output an XML file whose marked-up content reflects the syntactic structure of the source code. By inspecting the generated XML

output, we'll be able to ascertain that the analyzer is parsing input programs correctly.

Writing a compiler from the ground up is an exploit that brings to bear several fundamental topics in computer science. It requires the use of parsing and language translation techniques, application of classical data structures like trees and hash tables, and use of recursive compilation algorithms. For all these reasons, writing a compiler is also a challenging feat. However, by splitting the compiler's construction into two separate projects (actually *four*, counting chapters 7 and 8 as well) and by allowing the modular development and unit-testing of each part in isolation, we turn the compiler's development into a manageable and self-contained activity.

Why should you go through the trouble of building a compiler? Aside from the benefits of feeling competent and accomplished, a hands-on grasp of compilation internals will turn you into a better high-level programmer. Further, the same rules and grammars used for describing programming languages are also used in diverse fields like computer graphics, communications and networks, bioinformatics, machine learning, data science, and blockchain technology. And, the vibrant area of *natural language processing*—the enabling science and practice behind intelligent chatbots, robotic personal assistants, language translators, and many artificial intelligence applications—requires abilities for analyzing texts and synthesizing semantics. Thus, while most programmers don't develop compilers in their regular jobs, many programmers have to parse and manipulate texts and data sets of complex and varying structures. These tasks can be done efficiently and elegantly using the algorithms and techniques described in this chapter.

We start with a Background section that surveys the minimal set of concepts necessary for building a syntax analyzer: lexical analysis, context-free grammars, parse trees, and recursive descent parsing algorithms. This sets the stage for a Specification section that presents the Jack language grammar and the output that a Jack analyzer is expected to generate. The Implementation section proposes a software architecture for constructing a Jack analyzer, along with a suggested API. As usual, the Project section gives step-by-step instructions and test programs for building a syntax analyzer. In the next chapter, this analyzer will be extended into a full-scale compiler.

10.1 Background

Compilation consists of two main stages: *syntax analysis* and *code generation*. The syntax analysis stage is usually divided further into two substages: *tokenizing*, the grouping of input characters into language atoms called *tokens*, and *parsing*, the grouping of tokens into structured statements that have a meaning.

The tokenizing and parsing tasks are completely independent of the target language into which we seek to translate the source input. Since in this chapter we don't deal with code generation, we have chosen to have the syntax analyzer output the parsed structure of the input program as an XML file. This decision has two benefits. First, the output file can be readily inspected, demonstrating that the syntax analyzer is parsing source programs correctly. Second, the requirement to output this file explicitly forces us to write the syntax analyzer in an architecture that can be later morphed into a full-scale compiler. Indeed, as figure 10.1 shows, in the next chapter we will extend the syntax analyzer developed in this chapter into a full-scale compilation engine capable of generating executable VM code rather than passive XML code.

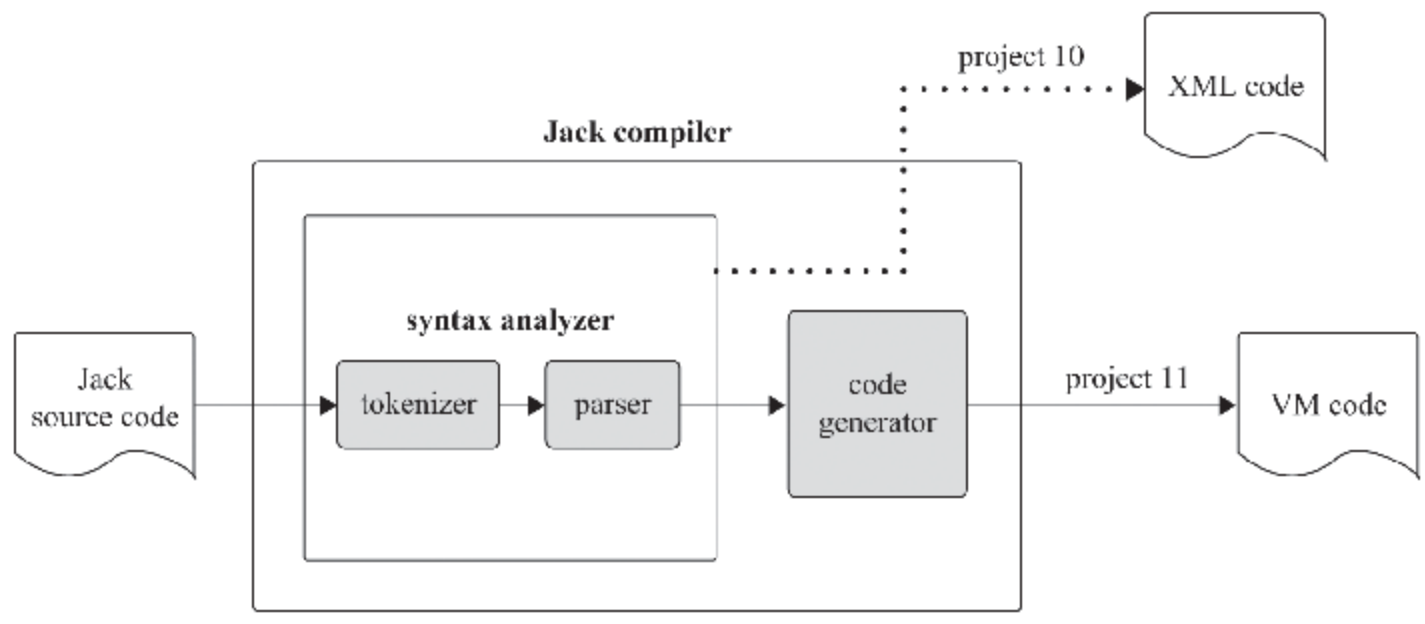


Figure 10.1 Staged development plan of the Jack compiler.

In this chapter we focus only on the syntax analyzer module of the compiler, whose job is *understanding the structure of a program*. This notion needs explanation. When humans read the source code of a computer program, they can immediately relate to the program's structure. They can

do so since they have a mental image of the language's *grammar*. In particular, they sense which program constructs are valid, and which are not. Using this grammatical insight, humans can identify where classes and methods begin and end, what are declarations, what are statements, what are expressions and how they are built, and so on. In order to recognize these language constructs, which may well be nested, humans recursively map them on the range of textual patterns accepted by the language grammar.

Syntax analyzers can be developed to perform similarly by building them according to a given *grammar*—the set of rules that define the syntax of a programming language. To understand—*parse*—a given program means to determine the exact correspondence between the program's text and the grammar's rules. To do so, we must first transform the program's text into a list of *tokens*, as we now turn to describe.

10.1.1 Lexical Analysis

Each programming language specification includes the types of *tokens*, or words, that the language recognizes. In the Jack language, tokens fall into five categories: *keywords* (like `class` and `while`), *symbols* (like `+` and `<`), *integer constants* (like `17` and `314`), *string constants* (like `"FAQ"` and `"Frequently Asked Questions"`), and *identifiers*, which are the textual labels used for naming variables, classes, and subroutines. Taken together, the tokens defined by these lexical categories can be referred to as the language *lexicon*.

In its plainest form, a computer program is a stream of characters stored in a text file. The first step in analyzing the program's syntax is grouping the characters into tokens, as defined by the language lexicon, while ignoring white space and comments. This task is called *lexical analysis*, *scanning*, or *tokenizing*—all meaning exactly the same thing.

Once a program has been tokenized, the tokens, rather than the characters, are viewed as its basic atoms. Thus, the token stream becomes the compiler's main input.

Figure 10.2 presents the Jack language lexicon and illustrates the tokenization of a typical code segment. This version of the tokenizer outputs the tokens as well as their lexical classifications.

Prog.jack (character stream)

```
...
if (x < 0) {
   // handles the sign
   let sign = "negative";
}
...
```

Tokenizing

Output (token stream)

```
...
<keyword>     if        </keyword>
<symbol>      (         </symbol>
<identifier>  x         </identifier>
<symbol>      <         </symbol>
<intConst>    0         </intConst>
<symbol>      )         </symbol>
<symbol>      {         </symbol>
<keyword>     let       </keyword>
<identifier>  sign      </identifier>
<symbol>      =         </symbol>
<stringConst> negative  </stringConst>
<symbol>      ;         </symbol>
<symbol>      }         </symbol>
...
```

keyword: 'class'|'constructor'|'function'|
'method'|'field'|'static' 'var'|
'int'|'char'|'boolean'|'void'|
'true'|'false'|'null'|'this'|'let'|
'do'|'if' 'else'|'while'|'return'

symbol: '{'|'}'|'('|')'|'['|']'|'.'|','|';'|
'+'|'-'|'*'|'/'|'&'|'|'|'<'|'>'|'='|'~'

integerConstant: a decimal integer in the range 0 ... 32767

stringConstant: '"' a sequence of characters, not including double quote or newline '"'

identifier: a sequence of letters, digits, and underscore ('_'), not starting with a digit.

Figure 10.2 Definition of the Jack lexicon, and lexical analysis of a sample input.

Tokenizing is a simple and important task. Given a language lexicon, it is not difficult to write a program that turns any given character stream into a stream of tokens. This capability provides the first stepping stone toward developing a syntax analyzer.

10.1.2 Grammars

Once we develop the ability to access a given text as a stream of tokens, or words, we can proceed to attempt grouping the words into valid sentences. For example, when we hear that "Bob got the job" we nod approvingly, while inputs like "Got job the Bob" or "Job Bob the got" sound weird. We perform these parsing tasks without thinking about them, since our brains have been trained to map sequences of words on patterns that are either accepted or rejected by the English grammar. The grammars of programming languages are much simpler than those of natural languages. See figure 10.3 for an example.

Jack grammar (subset)

statements: *statement**

statement: *letStatement* |
ifStatement |
whileStatement

letStatement: '**let**' *varName* '=' *expression* '**;**'

ifStatement: '**if**' '**(**' *expression* '**)**'
'**{**' *statements* '**}**'

whileStatement: '**while**' '**(**' *expression* '**)**'
'**{**' *statements* '**}**'

expression: *term* (*op term*)?

term: *varName* | *constant*

varName: a string not beginning with a digit

constant: a non-negative integer

op: '+' | '-' | '=' | '>' | '<'

Input examples

```
let x = 100;
```

```
let x = x + 1;
```

```
if (x = 1)
   let x = 100;
   let x = x + 1;
}
```

```
while (lim < 100) {
  if (x = 1) {
    let z = 100;
    while (z > 0) {
      let z = z - 1;
    }
  }
  let lim = lim + 10;
}
```

Figure 10.3 A subset of the Jack language grammar, and Jack code segments that are either accepted or rejected by the grammar.

A grammar is written in a *meta-language*: a language describing a language. Compilation theory is rife with formalisms for specifying, and reasoning about, grammars, languages, and meta-languages. Some of these formalisms are, well, painfully formal. Trying to keep things simple, in Nand to Tetris we view a grammar as a set of rules. Each rule consists of a left side and a right side. The left side specifies the rule's name, which is not part of the language. Rather, it is made up by the person who describes the grammar, and thus it is not terribly important. For example, if we replace a rule's name with another name throughout the grammar, the grammar will be just as valid (though it may be less readable).

The rule's right side describes the lingual pattern that the rule specifies. This pattern is a left-to-right sequence consisting of three building blocks: *terminals*, *nonterminals*, and *qualifiers*. Terminals are tokens, nonterminals are names of other rules, and qualifiers are represented by the five symbols |, *, ?, (, and). Terminal elements, like 'if', are specified in bold font and enclosed within single quotation marks; nonterminal elements, like *expression*, are specified using italic font; qualifiers are specified using

regular font. For example, the rule *ifStatement*: 'if' '(' *expression* ')' '{' *statements* '}' stipulates that every valid instance of an *ifStatement* must begin with the token if, followed by the token (, followed by a valid instance of an *expression* (defined elsewhere in the grammar), followed by the token), followed by the token {, followed by a valid instance of *statements* (defined elsewhere in the grammar), followed by the token}.

When there is more than one way to parse a pattern, we use the qualifier | to list the alternatives. For example, the rule *statement*: *letStatement* | *ifStatement* | *whileStatement* stipulates that a *statement* can be either a *letStatement*, an *ifStatement*, or a *whileStatement*.

The qualifier * is used to denote "0, 1, or more times." For example, the rule *statements*: *statement** stipulates that *statements* stands for 0, 1, or more instances of *statement*. In a similar vein, the qualifier ? is used to denote "0 or 1 times." For example, the rule *expression*: *term* (*op term)?* stipulates that *expression* is a *term* that may or may not be followed by the sequence *op term*. This implies that, for example, `x` is an *expression*, and so are `x+17`, `5*7`, and `x<y`. The qualifiers (and) are used for grouping grammar elements. For example, (*op term*) stipulates that, in the context of this rule, *op* followed by *term* should be treated as one grammatical element.

10.1.3 Parsing

Grammars are inherently recursive. Just like the sentence "Bob got the job that Alice offered" is considered valid, so is the statement `if (x<0){if(y>0){...}}`. How can we tell that this input is accepted by the grammar? After getting the first token and realizing that we have an if pattern, we focus on the rule *ifStatement*: 'if' '(' *expression* ')' '{' *statements* '}'. The rule informs that following the token if there ought to be the token (, followed by an *expression*, followed by the token). And indeed, these requirements are satisfied by the input element `(x<0)`. Back to the rule, we see that we now have to anticipate the token {, followed by *statements*, followed by the token}. Now, *statements* is defined as 0 or more instances of *statement*, and *statement*, in turn, is either a *letStatement*, an *ifStatement*, or a *whileStatement*. This expectation is met by the inner input element if `(y>0){...}`, which is an *ifStatement*.

We see that the grammar of a programming language can be used to ascertain, without ambiguity, whether given inputs are accepted or rejected.[1] As a side effect of this parsing act, the parser produces an exact correspondence between the given input, on the one hand, and the syntactic patterns admitted by the grammar rules, on the other. The correspondence can be represented by a data structure called a *parse tree*, also called a *derivation tree*, like the one shown in figure 10.4a. If such a tree can be constructed, the parser renders the input valid; otherwise, it can report that the input contains syntax errors.

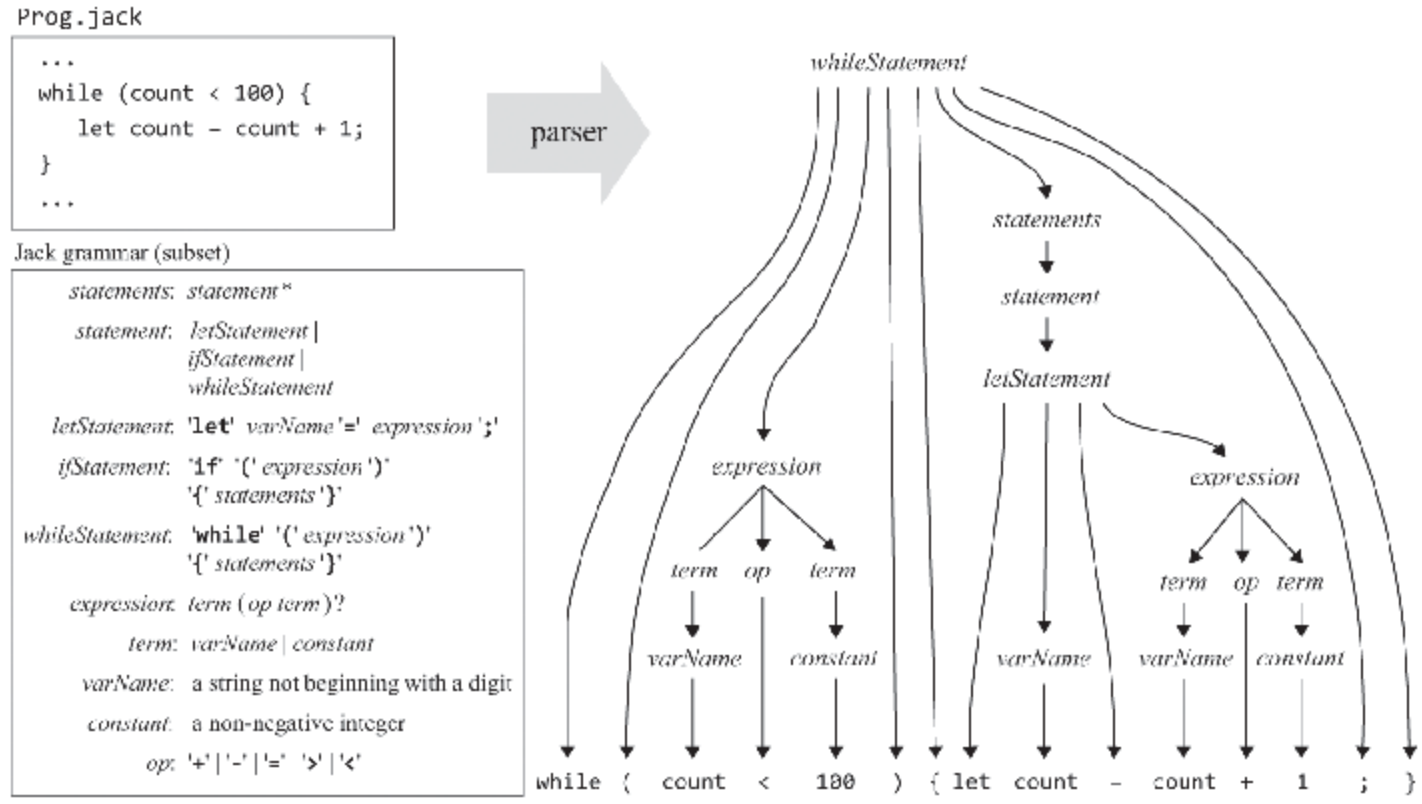


Figure 10.4a Parse tree of a typical code segment. The parsing process is driven by the grammar rules.

How can we represent parse trees textually? In Nand to Tetris, we decided to have the parser output an XML file whose marked-up format reflects the tree structure. By inspecting this XML output file, we can ascertain that the parser is parsing the input correctly. See figure 10.4b for an example.

Prog.xml

```
...
<whileStatement>
   <keyword> while </keyword>
   <symbol> ( </symbol>
   <expression>
      <term> <varName> count </varName> </term>
      <op> <symbol> < </symbol> </op>
      <term> <constant> 100 </constant> </term>
   </expression>
   <symbol> ) </symbol>
   <symbol> { </symbol>
   <statements>
      <statement> <letStatement>
         <keyword> let </keyword>
         <varName> count </varName>
         <symbol> = </symbol>
         <expression>
            <term> <varName> count </varName> </term>
            <op> <symbol> + </symbol> </op>
            <term> <constant> 1 </constant> </term>
         </expression>
         <symbol> ; </symbol>
      </letStatement> </statement>
   </statements>
   <symbol> } </symbol>
</whileStatement>
...
```

Figure 10.4b Same parse tree, in XML.

10.1.4 Parser

A parser is an agent that operates according to a given grammar. The parser accepts as input a stream of tokens and attempts to produce as output the parse tree associated with the given input. In our case, the input is expected to be structured according to the Jack grammar, and the output is written in XML. Note, though, that the parsing techniques that we now turn to describe are applicable to handling any programming language and structured file format.

There are several algorithms for constructing parse trees. The top-down approach, also known as *recursive descent parsing*, attempts to parse the tokenized input recursively, using the nested structures admitted by the language grammar. Such an algorithm can be implemented as follows. For every nontrivial rule in the grammar, we equip the parser program with a routine designed to parse the input according to that rule. For example, the grammar listed in figure 10.3 can be implemented using a set of routines named compileStatement, compileStatements, compileLet, compileIf, …, compileExpression, and so on. We use the action verb *compile* rather than *parse*, since in the next chapter we will extend this logic into a full-scale compilation engine.

The parsing logic of each compile*xxx* routine should follow the syntactic pattern specified by the right side of the *xxx* rule. For example, let us focus on the rule *whileStatement*: '**while**' '(' *expression* ')' '{' *statements* '}'. According to our scheme, this rule will be implemented by a parsing routine named compileWhile. This routine should realize the left-to-right derivation logic specified by the pattern '**while**' '(' *expression* ')' '{' *statements* '}'. Here is one way to implement this logic, using pseudocode:

```
// This routine implements the rule whileStatement:
// 'while' '('expression')' '{' statements '}'
// Should be called if the current token is 'while'.
compileWhile():
   print("<whileStatement>")
   process("while")
   process("(")
   compileExpression()
   process(")")
   process("{")
   compileStatements()
   process("}")
   print("</whileStatement>")
```

```
// A helper routine that handles
// the current token, and advances
// to get the next token.
process(str):
   if (currentToken == str)
      printXMLToken(str)
   else
      print("syntax error")
   // Gets the next token
   currentToken =
      tokenizer.advance()
```

This parsing process will continue until the *expression* and *statements* parts of the while statement have been fully parsed. Of course the *statements* part may well contain a lower-level while statement, in which case the parsing will continue recursively.

The example just shown illustrates the implementation of a relatively simple rule, whose derivation logic entails a simple case of straight-line parsing. In general, grammar rules can be more complex. For example, consider the following rule, which specifies the definition of class-level static and instance-level field variables in the Jack language:

classVarDec: ('**static**' | '**field**') *type varName* ('**,**' *varName*)* '**;**'
(where *type* and *varName* are defined elsewhere in the full Jack grammar)

Examples:
```
static int count;
static char a, b, c;
field boolean sign;
field int up, down, left, right;
```

This rule presents two parsing challenges that go beyond straight-line parsing. First, the rule admits either static or field as its first token. Second, the rule admits multiple variable declarations. To address both issues, the implementation of the corresponding compileClassVarDec routine can (i) handle the processing of the first token (static or field) directly, without calling a helper routine, and (ii) use a loop for handling all the variable declarations that the input contains. Generally speaking, different grammar rules entail slightly different parsing implementations. At the same time, they all follow the same contract: each compile*xxx* routine should get from the input, and handle, all the tokens that make up *xxx*, advance the tokenizer exactly beyond these tokens, and output the parse tree of *xxx*.

Recursive parsing algorithms are simple and elegant. If the language is simple, a single token lookahead is all that it takes to know which parsing rule to invoke next. For example, if the current token is let, we know that we have a *letStatement*; if the current token is while, we know that we have a *whileStatement*, and so on. Indeed, in the simple grammar shown in figure 10.3, looking ahead one token suffices to resolve, without ambiguity, which rule to use next. Grammars that have this lingual property are called *LL* (1). These grammars can be handled simply and elegantly by recursive descent algorithms, without backtracking.

The term *LL* comes from the observation that the grammar parses the input from *left* to right, performing *leftmost* derivation of the input. The (1)

parameter informs that looking ahead 1 token is all that it takes to know which parsing rule to invoke next. If that token does not suffice to resolve which rule to use, we can look ahead one more token. If this lookahead settles the ambiguity, the parser is said to be *LL* (2). And if not, we can look ahead yet another token, and so on. Clearly, as we need to look ahead further and further down the token stream, things become complicated, requiring a sophisticated parser.

The complete Jack language grammar, which we now turn to present, is *LL* (1), barring one exception that can be easily handled. Thus, Jack lends itself nicely to a recursive descent parser, which is the centerpiece of project 10.

10.2 Specification

This section consists of two parts. First, we specify the Jack language's grammar. Next, we specify a syntax analyzer designed to parse programs according to this grammar.

10.2.1 The Jack Language Grammar

The functional specification of the Jack language presented in chapter 9 was aimed at Jack programmers; we now give a formal specification of the Jack language, aimed at developers of Jack compilers. The language specification, or *grammar*, uses the following notation:

'xxx'	:	Represents language tokens that appear verbatim
xxx	:	Represents names of terminal and nonterminal elements
( )	:	Used for grouping
x | *y*	:	Either *x* or *y*
x y	:	*x* is followed by *y*
x ?	:	*x* appears 0 or 1 times
x *	:	*x* appears 0 or more times

With this notation in mind, the complete Jack grammar is specified in figure 10.5.

Lexical elements:	The Jack language includes five types of terminal elements (tokens):
keyword:	**'class'** | **'constructor'** | **'function'** | **'method'** | **'field'** | **'static'** | **'var'** | **'int'** | **'char'** | **'boolean'** **'void'** | **'true'** | **'false'** | **'null'** | **'this'** | **'let'** | **'do'** | **'if'** | **'else'** | **'while'** | **'return'**
symbol:	'{' '}' '(' ')' '[' | ']' | '.' | ',' | ';' | '+' | '-' | '*' | '/' | '&' | '|' | '<' | '>' | '=' | '~'
integerConstant:	A decimal integer in the range 0…32767
StringConstant:	'"' A sequence of characters not including double quote or newline '"'
identifier:	A sequence of letters, digits, and underscore ('_'), not starting with a digit
Program structure:	A Jack program is a collection of classes, each appearing in a separate file. The compilation unit is a class. A *class* is a sequence of tokens, as follows:
class:	**'class'** *className* **'{'** *classVarDec** *subroutineDec** **'}'**
classVarDec:	(**'static'** | **'field'**) *type varName* (**','** *varName*)* **';'**
type:	**'int'** | **'char'** | **'boolean'** | *className*
subroutineDec:	(**'constructor'** | **'function'** | **'method'**) (**'void'** | *type*) *subroutineName* **'('** *parameterList* **')'** *subroutineBody*
parameterList:	((*type varName*) (**','** *type varName*)*)?
subroutineBody:	**'{'** *varDec* statements* **'}'**
varDec:	**'var'** *type varName* (**','** *varName*)* **';'**
className:	*identifier*
subroutineName:	*identifier*
varName:	*identifier*
Statements:	
statements:	*statement**
statement:	*letStatement ifStatement* | *whileStatement* | *doStatement* | *returnStatement*
letStatement:	**'let'** *varName* (**'['** *expression* **']'**)? **'='** *expression* **';'**
ifStatement:	**'if'** **'('** expression **')'** **'{'** statements **'}'** (**'else'** **'{'** statements **'}'**)?
whileStatement:	**'while'** **'('** *expression* **')'** **'{'** *statements* **'}'**
doStatement:	**'do'** *subroutineCall* **';'**
returnStatement	**'return'** *expression*? **';'**
Expressions:	
expression:	*term* (*op term*)*
term:	*integerConstant* | *stringConstant* | *keywordConstant* | *varName* | *varName* **'['** *expression* **']'** | **'('** *expression* **')'** | (*unaryOp term*) | *subroutineCall*
subroutineCall:	*subroutineName* **'('** *expressionList* **')'** | (*className* | *varName*) **'.'** *subroutineName* **'('** *expressionList* **')'**
expressionList:	(*expression* (**','** *expression*) *)?
op:	**'+'** **'-'** **'*'** **'/'** **'&'** | **'|'** | **'<'** **'>'** **'='**
unaryOp:	**'-'** **'~'**
keywordConstant:	**'true'** | **'false'** | **'null'** | **'this'**

Figure 10.5 The Jack grammar.

10.2.2 A Syntax Analyzer for the Jack Language

A syntax analyzer is a program that performs both tokenizing and parsing. In Nand to Tetris, the main purpose of the syntax analyzer is to process a Jack program and understand its syntactic structure according to the Jack grammar. By *understanding* we mean that the syntax analyzer must know, at each point in the parsing process, the structural identity of the program element that it is currently handling, that is, whether it is an expression, a statement, a variable name, and so on. The syntax analyzer must possess this syntactic knowledge in a complete recursive sense. Without it, it will be

impossible to move on to code generation—the ultimate goal of the compilation process.

Usage: The syntax analyzer accepts a single command-line argument, as follows,

prompt> JackAnalyzer *source*

where *source* is either a file name of the form *Xxx*.jack (the extension is mandatory) or the name of a folder (in which case there is no extension) containing one or more .jack files. The file/folder name may contain a file path. If no path is specified, the analyzer operates on the current folder. For each *Xxx*.jack file, the parser creates an output file *Xxx*.xml and writes the parsed output into it. The output file is created in the same folder as that of the input. If there is a file by this name in the folder, it will be overwritten.

Input: An *Xxx*.jack file is a stream of characters. If the file represents a valid program, it can be tokenized into a stream of valid tokens, as specified by the Jack lexicon. The tokens may be separated by an arbitrary number of space characters, newline characters, and comments, which are ignored. There are three possible comment formats: /* comment until closing */, /** API comment until closing */, and // comment until the line's end.

Output: The syntax analyzer emits an XML description of the input file, as follows. For each terminal element (*token*) of type *xxx* appearing in the input, the syntax analyzer prints the marked-up output <*xxx*> *token* </*xxx*>, where *xxx* is one of the tags keyword, symbol, integerConstant, stringConstant, or identifier, representing one of the five token types recognized by the Jack language. Whenever a nonterminal language element *xxx* is detected, the syntax analyzer handles it using the following pseudocode:

```
print("<xxx>")
    Recursive code for handling the body of the xxx element
print("</xxx>")
```

where *xxx* is one of the following (and only the following) tags: class, classVarDec, subroutineDec, parameterList, subroutineBody, varDec, statements, letStatement, ifStatement, whileStatement, doStatement, returnStatement, expression, term, expressionList.

To simplify things, the following Jack grammar rules are not accounted for explicitly in the XML output: *type*, *className*, *subroutineName*, *varName*, *statement*, *subroutineCall*. We will explain this further in the next section, when we discuss the architecture of our compilation engine.

10.3 Implementation

The previous section specified *what* a syntax analyzer should do, with few implementation insights. This section describes *how* to build such an analyzer. Our proposed implementation is based on three modules:

- JackAnalyzer: main program that sets up and invokes the other modules
- JackTokenizer: tokenizer
- CompilationEngine: recursive top-down parser

In the next chapter we will extend this software architecture with two additional modules that handle the language's semantics: a *symbol table* and a *VM code writer*. This will complete the construction of a full-scale compiler for the Jack language. Since the main module that drives the parsing process in this project will end up driving the overall compilation process as well, we name it CompilationEngine.

The JackTokenizer

This module ignores all comments and white space in the input stream and enables accessing the input one token at a time. Also, it parses and provides the *type* of each token, as defined by the Jack grammar.

Routine	*Arguments*	*Returns*	*Function*
Constructor / initializer	Input file / stream	–	Opens the input `.jack` file / stream and gets ready to tokenize it.
`hasMoreTokens`	–	boolean	Are there more tokens in the input?
`advance`	–	–	Gets the next token from the input, and makes it the current token. This method should be called only if `hasMoreTokens` is true. Initially there is no current token.
`tokenType`	–	`KEYWORD`, `SYMBOL`, `IDENTIFIER`, `INT_CONST`, `STRING_CONST`	Returns the type of the current token, as a constant.
`keyWord`	–	`CLASS`, `METHOD`, `FUNCTION`, `CONSTRUCTOR`, `INT`, `BOOLEAN`, `CHAR`, `VOID`, `VAR`, `STATIC`, `FIELD`, `LET`, `DO`, `IF`, `ELSE`, `WHILE`, `RETURN`, `TRUE`, `FALSE`, `NULL`, `THIS`	Returns the keyword which is the current token, as a constant. This method should be called only if `tokenType` is `KEYWORD`.
`symbol`	–	char	Returns the character which is the current token. Should be called only if `tokenType` is `SYMBOL`.
`identifier`	–	string	Returns the string which is the current token. Should be called only if `tokenType` is `IDENTIFIER`.
`intVal`	–	int	Returns the integer value of the current token. Should be called only if `tokenType` is `INT_CONST`.
`stringVal`	–	string	Returns the string value of the current token, without the opening and closing double quotes. Should be called only if `tokenType` is `STRING_CONST`.

The CompilationEngine

The CompilationEngine is the backbone module of both the syntax analyzer described in this chapter and the full-scale compiler described in the next chapter. In the syntax analyzer, the compilation engine emits a structured

representation of the input source code wrapped in XML tags. In the compiler, the compilation engine will instead emit executable VM code. In both versions, the parsing logic and API presented below are exactly the same.

The compilation engine gets its input from a JackTokenizer and emits its output to an output file. The output is generated by a series of compile*xxx* routines, each designed to handle the compilation of a specific Jack language construct *xxx*. The contract between these routines is that each compile*xxx* routine should get from the input, and handle, all the tokens that make up *xxx*, advance the tokenizer exactly beyond these tokens, and output the parsing of *xxx*. As a rule, each compile*xxx* routine is called only if the current token is *xxx*.

Grammar rules that have no corresponding compile*xxx* routines: *type*, *className*, *subroutineName*, *varName*, *statement*, *subroutineCall*. We introduced these rules to make the Jack grammar more structured. As it turns out, the parsing logic of these rules is better handled by the routines that implement the rules that refer to them. For example, instead of writing a compileType routine, whenever *type* is mentioned in some rule *xxx*, the parsing of the possible types should be done directly by the compile *xxx* routine.

Token lookahead: Jack is almost an *LL*(1) language: the current token is sufficient for determining which CompilationEngine routine to call next. The only exception occurs when parsing a *term*, which occurs only when parsing an *expression*. To illustrate, consider the contrived yet valid expression `y+arr[5]-p.get(row)*count()-Math.sqrt(dist)/2`.This expression is made up of six terms: the variable y, the array element arr[5], the method call on the p object p.get (row), the method call on the this object count (), the call to the function (static method) Math.sqrt(dist), and the constant 2.

Suppose that we are parsing this expression and the current token is one of the identifiers y, arr, p, count, or Math. In each one of these cases, we know that we have a *term* that begins with an *identifier*, but we don't know which parsing possibility to follow next. That's the bad news; the good news is that a single lookahead to the next token is all that we need to settle the dilemma.

The need for this irregular lookahead operation occurs in the CompilationEngine twice: when parsing a *term*, which happens only when parsing an *expression*, and when parsing a *subroutineCall*. Now, an inspection of the Jack grammar shows that *subroutineCall* appears in two places only: either in a do *subroutineCall* statement or in a *term*.

With that in mind, we propose parsing do *subroutineCall* statements as if their syntax were do *expression*. This pragmatic recommendation obviates the need to write the irregular lookahead code twice. It also implies that the parsing of *subroutineCall* can now be handled directly by the compileTerm routine. In short, we've localized the need to write the irregular token lookahead code to one routine only, compileTerm, and we've eliminated the need for a compileSubroutineCall routine.

Routine	*Arguments*	*Returns*	*Function*
Constructor / initializer	Input file / stream Output file / stream	–	Creates a new compilation engine with the given input and output. The next routine called (by the `JackAnalyzer` module) must be `compileClass`
`compileClass`	–	–	Compiles a complete class.
`compileClassVarDec`	–	–	Compiles a static variable declaration, or a field declaration.
`compileSubroutine`	–	–	Compiles a complete method, function, or constructor.
`compileParameterList`	–	–	Compiles a (possibly empty) parameter list. Does not handle the enclosing parentheses tokens `(` and `)`.
`compileSubroutineBody`	–	–	Compiles a subroutine's body.
`compileVarDec`	–	–	Compiles a `var` declaration.
`compileStatements`	–	–	Compiles a sequence of statements. Does not handle the enclosing curly bracket tokens `{` and `}`.
`compileLet`	–	–	Compiles a `let` statement.
`compileIf`	–	–	Compiles an `if` statement, possibly with a trailing `else` clause.
`compileWhile`	–	–	Compiles a `while` statement.
`compileDo`	–	–	Compiles a `do` statement.
`compileReturn`	–	–	Compiles a `return` statement.
`compileExpression`	–	–	Compiles an expression.
`compileTerm`	–	–	Compiles a *term*. If the current token is an *identifier*, the routine must resolve it into a *variable*, an *array element*, or a *subroutine call*. A single lookahead token, which may be `[`, `(`, or `.`, suffices to distinguish between the possibilities. Any other token is not part of this term and should not be advanced over.
`compileExpressionList`	–	int	Compiles a (possibly empty) comma-separated list of expressions. Returns the number of expressions in the list.

The compileExpressionList routine: returns the number of expressions in the list. The return value is necessary for generating VM code, as we'll see when we'll complete the compiler's development in project 11. In this project we generate no VM code; therefore the returned value is not used and can be ignored by routines that call compileExpressionList.

The JackAnalyzer

This is the main program that drives the overall syntax analysis process, using the services of a JackTokenizer and a CompilationEngine. For each source *Xxx*.jack file, the analyzer

1. creates a JackTokenizer from the *Xxx*.jack input file;
2. creates an output file named *Xxx*.xml; and
3. uses the JackTokenizer and the CompilationEngine to parse the input file and write the parsed code to the output file.

We provide no API for this module, inviting you to implement it as you see fit. Remember that the first routine that must be called when compiling a .jack file is compileClass.

10.4 Project

Objective: Build a syntax analyzer that parses Jack programs according to the Jack grammar. The analyzer's output should be written in XML, as specified in section 10.2.2.

This version of the syntax analyzer assumes that the source Jack code is error-free. Error checking, reporting, and handling can be added to later versions of the analyzer but are not part of project 10.

Resources: The main tool in this project is the programming language that you will use for implementing the syntax analyzer. You will also need the supplied TextComparer utility. This program allows comparing files while ignoring white space. This will help you compare the output files generated

by your analyzer with the supplied compare files. You may also want to inspect these files using an XML viewer. Any standard web browser should do the job—just use your browser's "open file" option to open the XML file that you wish to inspect.

Contract: Write a syntax analyzer for the Jack language, and test it on the supplied test files. The XML files produced by your analyzer should be identical to the supplied compare files, ignoring white space.

Test files: We provide several .jack files for testing purposes. The projects/10/Square program is a three-class app that enables moving a black square around the screen using the keyboard's arrow keys. The projects/10/ArrayTest program is a single-class app that computes the average of a user-supplied sequence of integers using array processing. Both programs were discussed in chapter 9, so they should be familiar. Note, though, that we made some harmless changes to the original code to make sure that the syntax analyzer will be fully tested on all aspects of the Jack language. For example, we've added a static variable to projects/10/Square/Main.jack, as well as a function named more, which are never used or called. These changes allow testing how the analyzer handles language elements that don't appear in the original Square and ArrayTest files, like static variables, else, and unary operators.

Development plan: We suggest developing and unit-testing the analyzer in four stages:

- First, write and test a Jack tokenizer.
- Next, write and test a basic compilation engine that handles all the features of the Jack language, except for expressions and array-oriented statements.
- Next, extend your compilation engine to handle expressions.
- Finally, extend your compilation engine to handle array-oriented statements.

We provide input .jack files and compare .xml files for unit-testing each one of the four stages, as we now turn to describe.

10.4.1 Tokenizer

Implement the JackTokenizer module specified in section 10.3. Test your implementation by writing a basic version of the JackAnalyzer, defined as follows. The analyzer, which is the main program, is invoked using the command JackAnalyzer *source*, where *source* is either a file name of the form *Xxx*.jack (the extension is mandatory) or a folder name (in which case there is no extension). In the latter case, the folder contains one or more .jack files and, possibly, other files as well. The file/folder name may include a file path. If no path is specified, the analyzer operates on the current folder.

The analyzer handles each file separately. In particular, for each *Xxx*.jack file, the analyzer constructs a JackTokenizer for handling the input and an output file for writing the output. In this first version of the analyzer, the output file is named *Xxx*T.xml (where T stands for *tokenized output*). The analyzer then enters a loop to advance and handle all the tokens in the input file, one token at a time, using the JackTokenizer methods. Each token should be printed in a separate line, as *<tokenType> token </tokenType>*, where *tokenType* is one of five possible XML tags coding the token's type. Here is an example:

Input (e.g. Prog.jack)

```
...
// Comments and white space
// are ignored.
if (x < 0) {
   let quit = "yes";
}
...
```

JackAnalyzer *Output* (e.g. ProgT.xml)

```
<tokens>
  ...
  <keyword> if </keyword>
  <symbol> ( </symbol>
  <identifier> x </identifier>
  <symbol> &lt; </symbol>
  <integerConstant> 0 </integerConstant>
  <symbol> ) </symbol>
  <symbol> { </symbol>
  <keyword> let </keyword>
  <identifier> quit </identifier>
  <symbol> = </symbol>
  <stringConstant> yes </stringConstant>
  <symbol> ; </symbol>
  <symbol> } </symbol>
  ...
</tokens>
```

Note that in the case of *string constants*, the program ignores the double quotation marks. This requirement is by design.

The generated output has two trivial technicalities dictated by XML conventions. First, an XML file must be enclosed within some begin and end tags; this convention is satisfied by the <tokens> and </tokens> tags. Second, four of the symbols used in the Jack language (<, >, ", &) are also used for XML markup; thus they cannot appear as data in XML files. Following convention, the analyzer represents these symbols as <, >, ", and &, respectively. For example, when the parser encounters the < symbol in the input file, it outputs the line <symbol> < </symbol>. This so-called *escape sequence* is rendered by XML viewers as <symbol> < </symbol>, which is what we want.

Testing Guidelines

- Start by applying your JackAnalyzer to one of the supplied .jack files, and verify that it operates correctly on a single input file.
- Next, apply your JackAnalyzer to the Square folder, containing the files Main.jack, Square.jack, and SquareGame.jack, and to the TestArray folder, containing the file Main.jack.
- Use the supplied TextComparer utility to compare the output files generated by your JackAnalyzer to the supplied .xml compare files. For example, compare the generated file SquareT.xml to the supplied compare file SquareT.xml.
- Since the generated and compare files have the same names, we suggest putting them in separate folders.

10.4.2 Compilation Engine

The next version of your syntax analyzer should be capable of parsing every element of the Jack language, except for expressions and array-oriented commands. To that end, implement the CompilationEngine module specified in section 10.3, except for the routines that handle expressions and arrays. Test the implementation by using your Jack analyzer, as follows.

For each *Xxx*.jack file, the analyzer constructs a JackTokenizer for handling the input and an output file for writing the output, named *Xxx*.xml. The

analyzer then calls the compileClass routine of the CompilationEngine. From this point onward, the CompilationEngine routines should call each other recursively, emitting XML output similar to the one shown in figure 10.4b.

Unit-test this version of your JackAnalyzer by applying it to the folder ExpressionlessSquare. This folder contains versions of the files Square.jack, SquareGame.jack, and Main.jack, in which each expression in the original code has been replaced with a single identifier (a variable name in scope). For example:

Square folder:

```
// Square.jack
...
method void incSize() {
   if (((y + size) < 254) & ((x + size) <510)
      do erase();
      let size = size + 2;
      do draw();
   }
   return;
}
...
```

ExpressionlessSquare folder:

```
// Square.jack
...
method void incSize() {
    if (x) {
        do erase();
        let size = size;
        do draw();
   }
   return;
}
...
```

Note that the replacement of expressions with variables results in nonsensical code. This is fine, since the program semantics is irrelevant to project 10. The nonsensical code is syntactically correct, and that's all that matters for testing the parser. Note also that the original and expressionless files have the same names but are located in separate folders.

Use the supplied TextComparer utility to compare the output files generated by your JackAnalyzer with the supplied .xml compare files.

Next, complete the CompilationEngine routines that handle expressions, and test them by applying your JackAnalyzer to the Square folder. Finally, complete the routines that handle arrays, and test them by applying your JackAnalyzer to the ArrayTest folder.

A web-based version of project 10 is available at www.nand2tetris.org.

10.5 Perspective

Although it is convenient to describe the structure of computer programs using parse trees and XML files, it's important to understand that compilers don't necessarily have to maintain such data structures explicitly. For example, the parsing algorithm described in this chapter parses the input as it reads it and does not keep the entire input program in memory. There are essentially two types of strategies for doing such parsing. The simpler strategy works top-down, and that is the one presented in this chapter. The more advanced parsing algorithms, which work bottom-up, were not described here since they require elaboration of more compilation theory.

Indeed, in this chapter we have sidestepped the formal language theory studied in typical compilation courses. Also, we have chosen a simple syntax for the Jack language—a syntax that can be easily compiled using recursive descent techniques. For example, the Jack grammar does not mandate the usual operator precedence in algebraic expressions evaluation, like multiplication before addition. This enabled us to avoid parsing algorithms that are more powerful, but also more intricate, than the elegant top-down parsing techniques presented in this chapter.

Every programmer experiences the disgraceful handling of compilation errors, which is typical of many compilers. As it turns out, error diagnostics and reporting are a challenging problem. In many cases, the impact of an error is detected several or many lines of code after the error was made. Therefore, error reporting is sometimes cryptic and unfriendly. Indeed, one aspect in which compilers vary greatly is their ability to diagnose, and help debug, errors. To do so, compilers persist parts of the parse tree in memory and extend the tree with annotations that help pinpoint the source of errors and backtrack the diagnostic process, as needed. In Nand to Tetris we bypass all these extensions, assuming that the source files that the compiler handles are error-free.

Another topic that we hardly mentioned is how the syntax and semantics of programming languages are studied in computer and cognitive science. There is a rich theory of formal and natural languages that discusses properties of classes of languages, as well as meta-languages and formalisms for specifying them. This is also the place where computer science meets the study of human languages, leading to the vibrant areas of research and practice known as computational linguistics and natural language processing.

Finally, it is worth mentioning that syntax analyzers are typically not standalone programs and are rarely written from scratch. Instead, programmers usually build tokenizers and parsers using a variety of *compiler generator* tools like LEX (for *LEXical analysis*) and YACC (for *Yet Another Compiler Compiler*). These utilities receive as input a context-free grammar and produce as output syntax analysis code capable of tokenizing and parsing programs written in that grammar. The generated code can then be customized to fit the specific needs of the compiler writer. Following the "show me" spirit of Nand to Tetris, though, we have chosen not to use such black boxes in the implementation of our compiler, but rather build everything from the ground up.

---

1. And here lies a crucial difference between programming languages and natural languages. In natural languages, we can say things like "Whoever saves one life, saves the world entire." In the English language, putting the adjective after the noun is grammatically incorrect. Yet, in this particular case, it sounds perfectly acceptable. Unlike programming languages, natural languages mandate a poetic license to break grammar rules, so long as the writer knows what he or she is doing. This freedom of expression makes natural languages infinitely rich.

11 Compiler II: Code Generation

When I am working on a problem, I never think about beauty. But when I have finished, if the solution is not beautiful, I know it is wrong.

—R. Buckminster Fuller (1895–1993)

Most programmers take compilers for granted. But if you stop to think about it, the ability to translate a high-level program into binary code is almost like magic. In Nand to Tetris we devote four chapters (7–11) for demystifying this magic. Our hands-on methodology is based on developing a compiler for Jack—a simple, modern object-based language. As with Java and C#, the overall Jack compiler is based on two tiers: a virtual machine (VM) *back end* that translates VM commands into machine language and a *front end* compiler that translates Jack programs into VM code. Building a compiler is a challenging undertaking, so we divide it further into two conceptual modules: a *syntax analyzer*, developed in chapter 10, and a *code generator*—the subject of this chapter.

The syntax analyzer was built in order to develop, and demonstrate, a capability for parsing high-level programs into their underlying syntactical elements. In this chapter we'll morph the analyzer into a full-scale compiler: a program that converts the parsed elements into VM commands designed to execute on the abstract virtual machine described in chapters 7–8. This approach follows the modular analysis-synthesis paradigm that informs the construction of well-designed compilers. It also captures the very essence of translating text from one language to another: first, one uses the source language's *syntax* for analyzing the source text and figuring out its underlying *semantics*, that is, what the text seeks to say; next, one reexpresses the parsed semantics using the syntax of the target language. In

the context of this chapter, the source and the target are Jack and the VM language, respectively.

Modern high-level programming languages are rich and powerful. They allow defining and using elaborate abstractions like functions and objects, expressing algorithms using elegant statements, and building data structures of unlimited complexity. In contrast, the hardware platforms on which these programs ultimately run are spartan and minimal. Typically, they offer little more than a set of registers for storage and a set of primitive instructions for processing. Thus, the translation of programs from high level to low level is a challenging feat. If the target platform is a virtual machine and not the barebone hardware, life is somewhat easier since abstract VM commands are not as primitive as concrete machine instructions. Still, the gap between the expressiveness of a high-level language and that of a VM language is wide and challenging.

The chapter begins with a general discussion of *code generation*, divided into six sections. First, we describe how compilers use *symbol tables* for mapping symbolic variables onto virtual memory segments. Next, we present algorithms for compiling *expressions* and *strings* of characters. We then present techniques for compiling *statements* like `let`, `if`, `while`, `do`, and `return`. Taken together, the ability to compile *variables*, *expressions*, and *statements* forms a foundation for building compilers for simple, procedural, C-like languages. This sets the stage for the remainder of section 11.1, in which we discuss the compilation of *objects* and *arrays*.

Section 11.2 (Specification) provides guidelines for mapping Jack programs on the VM platform and language, and section 11.3 (Implementation) proposes a software architecture and an API for completing the compiler's development. As usual, the chapter ends with a Project section, providing step-by-step guidelines and test programs for completing the compiler's construction, and a Perspective section that comments on various things that were left out from the chapter.

So what's in it for you? Although many professionals are eager to understand how compilers work, few end up getting their hands dirty and building a compiler from the ground up. That's because the cost of this experience—at least in academia—is typically a daunting, full-semester elective course. Nand to Tetris packs the key elements of this experience into four chapters and projects, culminating in the present chapter. In the

process, we discuss and illustrate the key algorithms, data structures, and programming tricks underlying the construction of typical compilers. Seeing these clever ideas and techniques in action leads one to marvel, once again, at how human ingenuity can dress up a primitive switching machine to look like something approaching magic.

11.1 Code Generation

High-level programmers work with abstract building blocks like *variables*, *expressions*, *statements*, *subroutines*, *objects* and *arrays*. Programmers use these abstract building blocks for describing what they want the program to do. The job of the compiler is to translate this semantics into a language that a target computer understands.

In our case, the target computer is the virtual machine described in chapters 7–8. Thus, we have to figure out how to systematically translate *expressions*, *statements*, *subroutines*, and the handling of *variables*, *objects*, and *arrays* into sequences of stack-based VM commands that execute the desired semantics on the target virtual machine. We don't have to worry about the subsequent translation of VM programs into machine language, since we already took care of this royal headache in projects 7–8. Thank goodness for two-tier compilation, and for modular design.

Throughout the chapter, we present compilation examples of various parts of the Point class presented previously in the book. We repeat the class declaration in figure 11.1, which illustrates most of the features of the Jack language. We advise taking a quick look at this Jack code now to refresh your memory about the Point class functionality. You will then be ready to delve into the illuminating journey of systematically reducing this high-level functionality—and any other similar object-based program—into VM code.

```
/** Represents a two-dimensional point.
    File name: Point.jack. */
class Point {

   // The coordinates of this point:
   field int x, y

   // The number of Point objects constructed so far:
   static int pointCount;

   /** Constructs a two-dimensional point and
       initializes it with the given coordinates. */
   constructor Point new(int ax, int ay) {
        let x = ax;
        let y = ay;
        let pointCount = pointCount + 1;
        return this;
   }

   /** Returns the x coordinate of this point. */
   method int getx() { return x; }

   /** Returns the y coordinate of this point. */
   method int gety() { return y; }

   /** Returns the number of Point  constructed so far. */
   function int getPointCount() {
       return pointCount;
   }

   // Class declaration continues on top right.
```

```
   /** Returns a point which is this point plus
       the other point. */
   method Point plus(Point other) {
       return Point.new(x + other.getx(),
                        y + other.gety());
   }

   /** Returns the Euclidean distance between
       this and the other point. */
   method int distance(Point other) {
      var int dx, dy;
      let dx = x - other.getx();
      let dy = y - other.gety();
      return Math.sqrt((dx*dx) + (dy*dy));
   }

   /** Prints this point, as "(x,y)" */
   method void print() {
      do Output.printString("(");
      do Output.printInt(x);
      do Output.printString(",");
      do Output.printInt(y);
      do Output.printString(")");
      return;
   }

} // End of Point class declaration.
```

Figure 11.1 The Point class. This class features all the possible variable kinds (field, static, local, and argument) and subroutine kinds (constructor, method, and function), as well as subroutines that return primitive types, object types, and void subroutines. It also illustrates function calls, constructor calls, and method calls on the current object (this) and on other objects.

11.1.1 Handling Variables

One of the basic tasks of compilers is mapping the variables declared in the source high-level program onto the host RAM of the target platform. For example, consider Java: int variables are designed to represent 32-bit values; long variables, 64-bit values; and so on. If the host RAM happens to be 32-bit wide, the compiler will map int and long variables on one memory word and on two consecutive memory words, respectively. In Nand to Tetris there are no mapping complications: all the primitive types in Jack (int, char, and boolean) are 16-bit wide, and so are the addresses and words of the Hack RAM. Thus, every Jack variable, including pointer variables holding 16-bit address values, can be mapped on exactly one word in memory.

The second challenge faced by compilers is that variables of different *kinds* have different life cycles. Class-level static variables are shared globally by all the subroutines in the class. Therefore, a single copy of each static variable should be kept alive during the complete duration of the program's execution. Instance-level field variables are treated differently: each object (instance of the class) must have a private set of its field

variables, and, when the object is no longer needed, this memory must be freed. Subroutine-level local and argument variables are created each time a subroutine starts running and must be freed when the subroutine terminates.

That's the bad news. The good news is that we've already handled all these difficulties. In our two-tier compiler architecture, memory allocation and deallocation are delegated to the VM level. All we have to do now is map Jack *static* variables on static 0, static 1, static 2, …; *field* variables on this 0, this 1, …; *local* variables on local 0, local 1, …; and *argument* variables on argument 0, argument 1, …. The subsequent mapping of the virtual memory segments on the host RAM, as well as the intricate management of their run-time life cycles, are completely taken care of by the VM implementation.

Recall that this implementation was not achieved easily: we had to work hard to generate assembly code that dynamically maps the virtual memory segments on the host RAM as a side effect of realizing the function call-and-return protocol. Now we can reap the benefits of this effort: the only thing required from the compiler is mapping the high-level variables onto the virtual memory segments. All the subsequent gory details associated with managing these segments on the RAM will be handled by the VM implementation. That's why we sometimes refer to the latter as the compiler's *back end*.

To recap, in a two-tier compilation model, the handling of variables can be reduced to mapping high-level variables on virtual memory segments and using this mapping, as needed, throughout code generation. These tasks can be readily managed using a classical abstraction known as a *symbol table*.

Symbol table: Whenever the compiler encounters variables in a high-level statement, for example, let y = foo(x), it needs to know what the variables stand for. Is x a static variable, a field of an object, a local variable, or an argument of a subroutine? Does it represent an integer, a boolean, a char, or some class type? All these questions must be answered—for code generation—each time the variable x comes up in the source code. Of course, the variable y should be treated exactly the same way.

The variable properties can be managed conveniently using a *symbol table*. When a static, field, local, or argument variable is declared in the

source code, the compiler allocates it to the next available entry in the corresponding static, this, local, or argument VM segment and records the mapping in the symbol table. Whenever a variable is encountered elsewhere in the code, the compiler looks up its name in the symbol table, retrieves its properties, and uses them, as needed, for code generation.

An important feature of high-level languages is *separate namespaces*: the same identifier can represent different things in different regions of the program. To enable separate namespaces, each identifier is implicitly associated with a *scope*, which is the region of the program in which it is recognized. In Jack, the scope of static and field variables is the class in which they are declared, and the scope of local and argument variables is the subroutine in which they are declared. Jack compilers can realize the scope abstractions by managing two separate symbol tables, as seen in figure 11.2.

High-level (Jack) code

```
class Point {
   field int x, y;
   static int pointCount;
   ...
   method int distance(Point other) {
      var int dx, dy;
      let dx = x - other.getx();
      let dy = y - other.gety();
      return Math.sqrt((dx*dx) + (dy*dy));
   }
   ...
}
```

name	type	kind	#
x	int	field	0
y	int	field	1
pointCount	int	static	0

Class-level symbol table

name	type	kind	#
this	Point	arg	0
other	Point	arg	1
dx	int	var	0
dy	int	var	1

Subroutine-level symbol table

Figure 11.2 Symbol table examples. The this row in the subroutine-level table is discussed later in the chapter.

The scopes are nested, with inner scopes hiding outer ones. For example, when the Jack compiler encounters the expression `x + 17`, it first checks whether `x` is a subroutine-level variable (local or argument). Failing that, the compiler checks whether `x` is a static variable or a field. Some languages feature nested scoping of unlimited depth, allowing variables to be local in any block of code in which they are declared. To support unlimited nesting, the compiler can use a linked list of symbol tables, each reflecting a single scope nested within the next one in the list. When the compiler fails to find the variable in the table associated with the current scope, it looks it up in

the next table in the list, from inner scopes outward. If the variable is not found in the list, the compiler can throw an "undeclared variable" error.

In the Jack language there are only two scoping levels: the subroutine that is presently being compiled, and the class in which the subroutine is declared. Therefore, the compiler can get away with managing two symbol tables only.

Handling variable declarations: When the Jack compiler starts compiling a class declaration, it creates a class-level symbol table and a subroutine-level symbol table. When the compiler parses a static or a field variable declaration, it adds a new row to the class-level symbol table. The row records the variable's *name*, *type* (integer, boolean, char, or class name), *kind* (static or field), and *index* within the kind.

When the Jack compiler starts compiling a subroutine (constructor, method, or function) declaration, it resets the subroutine-level symbol table. If the subroutine is a method, the compiler adds the row <this, *className*, arg, 0> to the subroutine-level symbol table (this initialization detail is explained in section 11.1.5.2 and can be ignored till then). When the compiler parses a local or an argument variable declaration, it adds a new row to the subroutine-level symbol table, recording the variable's name, type (integer, boolean, char, or class name), kind (var or arg), and index within the kind. The index of each kind (var or arg) starts at 0 and is incremented by 1 after each time a new variable of that kind is added to the table.

Handling variables in statements: When the compiler encounters a variable in a statement, it looks up the variable name in the subroutine-level symbol table. If the variable is not found, the compiler looks it up in the class-level symbol table. Once the variable has been found, the compiler can complete the statement's translation. For example, consider the symbol tables shown in figure 11.2, and suppose we are compiling the high-level statement `let y = y + dy`. The compiler will translate this statement into the VM commands `push this 1`, `push local 1`, `add`, `pop this 1`. Here we assume that the compiler knows how to handle expressions and `let` statements, subjects which are taken up in the next two sections.

11.1.2 Compiling Expressions

Let's start by considering the compilation of simple expressions like `x + y – 7`. By "simple expression" we mean a sequence of *term operator term operator term* …, where each *term* is either a variable or a constant, and each *operator* is either +, −, *, or /.

In Jack, as in most high-level languages, expressions are written using *infix* notation: To add `x` and `y`, one writes `x + y`. In contrast, our compilation's target language is *postfix*: The same addition semantics is expressed in the stack-oriented VM code as `push x, push y, add`. In chapter 10 we introduced an algorithm that emits the parsed source code in infix using XML tags. Although the parsing logic of this algorithm can remain the same, the output part of the algorithm must now be modified for generating postfix commands. Figure 11.3 illustrates this dichotomy.

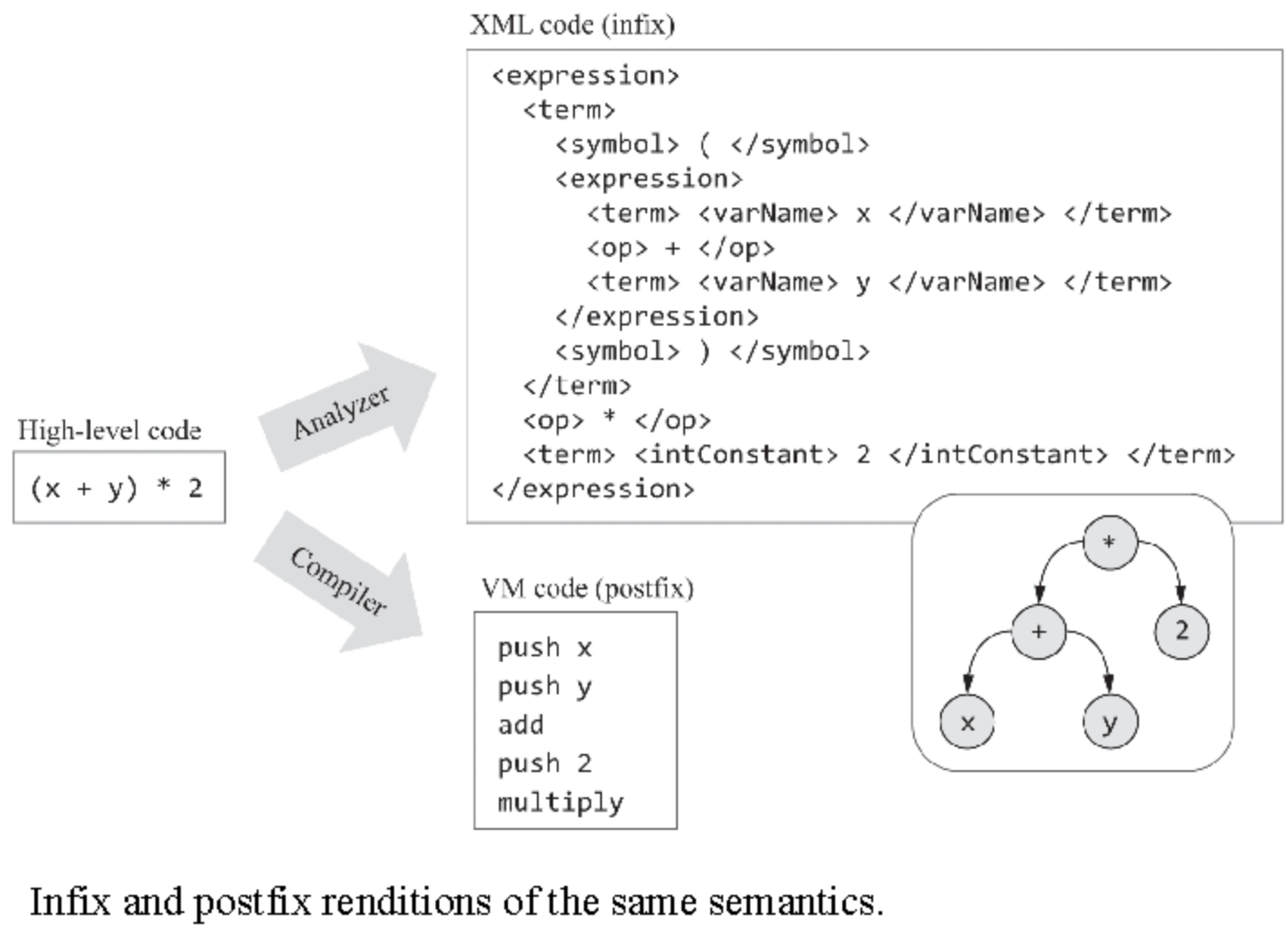


Figure 11.3 Infix and postfix renditions of the same semantics.

To recap, we need an algorithm that knows how to parse an infix expression and generate from it as output postfix code that realizes the same semantics on a stack machine. Figure 11.4 presents one such algorithm. The algorithm processes the input expression from left to right, generating VM code as it goes along. Conveniently, this algorithm also handles unary operators and function calls.

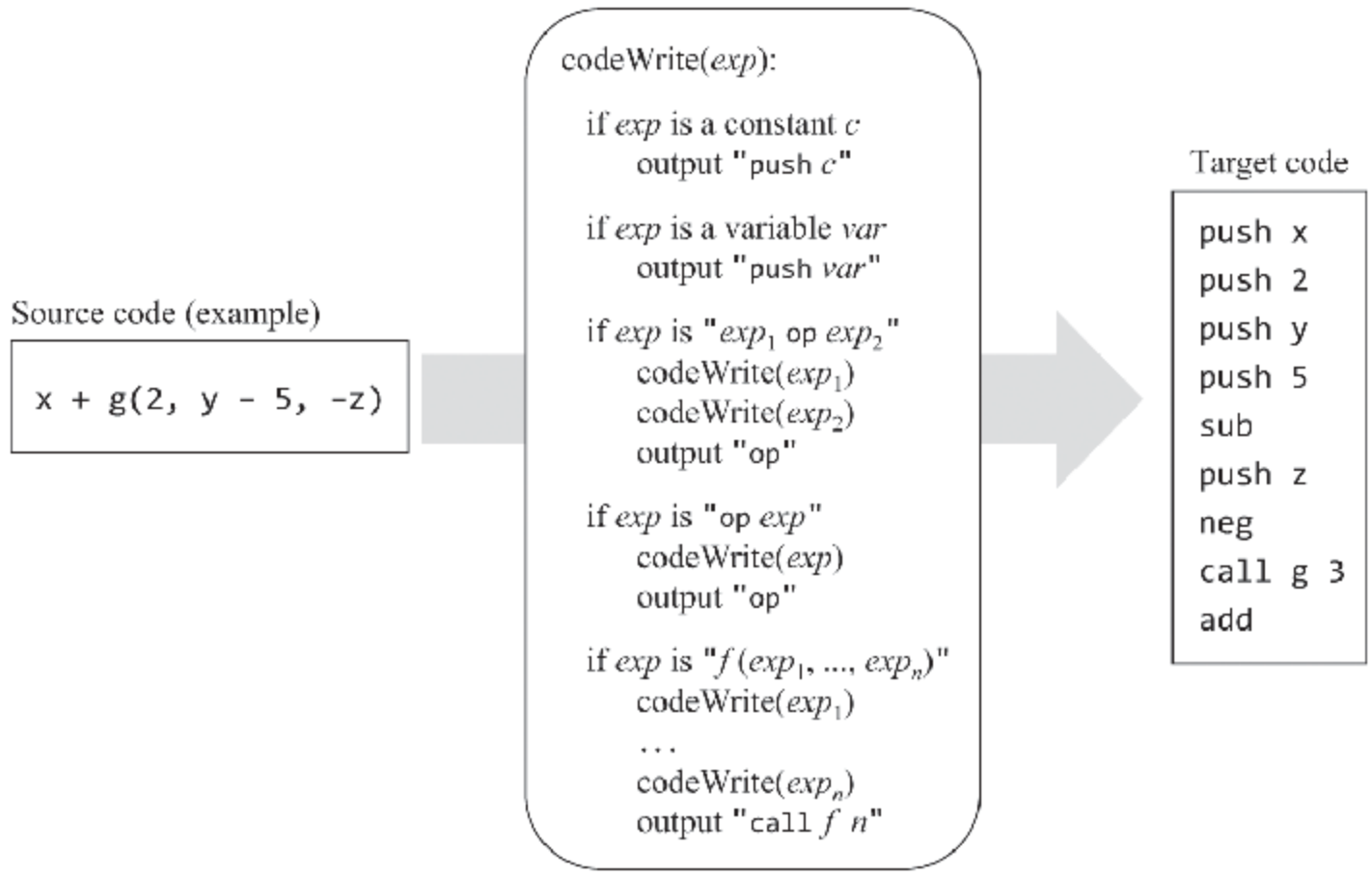


Figure 11.4 A VM code generation algorithm for expressions, and a compilation example. The algorithm assumes that the input expression is valid. The final implementation of this algorithm should replace the emitted symbolic variables with their corresponding symbol table mappings.

If we execute the stack-based VM code generated by the codeWrite algorithm (right side of figure 11.4), the execution will end up consuming all the expression's terms and putting the expression's value at the stack's top. That's exactly what's expected from the compiled code of an expression.

So far we have dealt with relatively simple expressions. Figure 11.5 gives the complete grammatical definition of Jack expressions, along with several examples of actual expressions consistent with this definition.

Definition (from the Jack grammar):

expression: *term* (*op term*) *

term: *integerConstant* | *stringConstant* | *keywordConstant* | *varName* |
varName '[' *expression* ']' | ' (' *expression* ')' | (*unaryOp term*) | *subroutineCall*

subroutineCall: *subroutineName* '(' *expressionList* ')' |
(*className* | *varName*) '.' *subroutineName* '(' *expressionList* ')'

expressionList: (*expression* (',' *expression*) *) ?

op: '+' | '-' | '*' | '/' | '&' | '|' | '<' | '>' | '='

unaryOp: '-' | '~'

keywordConstant: 'true' | 'false' | 'null' | 'this'

The definitions of *integerConstant*, *stringConstant*, *keywordConstant*, and other elements are given in the complete Jack grammar (figure 10.6), and are self-explanatory.

Examples:

```
5
x
x + 5
(-b + Math.sqrt(b*b - (4 * a * c))) / (2 * a)
arr[i] + foo(x)
foo(Math.abs(arr[x + foo(5)]))
```

Figure 11.5 Expressions in the Jack language.

The compilation of Jack expressions will be handled by a routine named compileExpression. The developer of this routine should start with the algorithm presented in figure 11.4 and extend it to handle the various possibilities specified in figure 11.5. We will have more to say about this implementation later in the chapter.

11.1.3 Compiling Strings

Strings—sequences of characters—are widely used in computer programs. Object-oriented languages typically handle strings as instances of a class named String (Jack's String class, which is part of the Jack OS, is documented in appendix 6). Each time a string constant comes up in a high-level statement or expression, the compiler generates code that calls the String constructor, which creates and returns a new String object. Next, the compiler initializes the new object with the string characters. This is done by generating a sequence of calls to the String method appendChar, one for each character listed in the high-level string constant.

This implementation of string constants can be wasteful, leading to potential memory leaks. To illustrate, consider the statement Output.printString("Loading ... please wait"). Presumably, all the high-level programmer wants is to display a message; she certainly doesn't care if the compiler creates a new object, and she may be surprised to know that the object will persist in memory until the program terminates. But that's exactly what actually happens: a new String object will be created, and this object will keep lurking in the background, doing nothing.

Java, C#, and Python use a run-time *garbage collection* process that reclaims the memory used by objects that are no longer in play (technically, objects that have no variable referring to them). In general, modern languages use a variety of optimizations and specialized string classes for promoting the efficient use of string objects. The Jack OS features only one String class and no string-related optimizations.

Operating system services: In the handling of strings, we mentioned for the first time that the compiler can use OS services as needed. Indeed, developers of Jack compilers can assume that every constructor, method, and function listed in the OS API (appendix 6) is available *as a compiled VM function*. Technically speaking, any one of these VM functions can be called by the code generated by the compiler. This configuration will be fully realized in chapter 12, in which we will implement the OS in Jack and compile it into VM code.

11.1.4 Compiling Statements

The Jack programming language features five statements: let, do, return, if, and while. We now turn to discuss how the Jack compiler generates VM code that handles the semantics of these statements.

Compiling return statements: Now that we know how to compile expressions, the compilation of return *expression* is simple. First, we call the compileExpression routine, which generates VM code designed to evaluate and put the expression's value on the stack. Next, we generate the VM command return.

Compiling let statements: Here we discuss the handling of statements of the form let *varName* = *expression*. Since parsing is a left-to-right process, we begin by remembering the *varName*. Next, we call compileExpression, which puts the expression's value on the stack. Finally, we generate the VM command pop *varName*, where *varName* is actually the symbol table mapping of *varName* (for example, local 3, static 1, and so on).

We'll discuss the compilation of statements of the form let *varName*[*expression*1] = *expression*2 later in the chapter, in a section dedicated to handling arrays.

Compiling do statements: Here we discuss the compilation of *function calls* of the form do *className.functionName* (*exp*1, *exp*2, … , *exp*n). The do abstraction is designed to call a subroutine for its effect, ignoring the return value. In chapter 10 we recommended compiling such statements as if their syntax were do *expression*. We repeat this recommendation here: to compile a do *className.functionName* (…) statement, we call compileExpression and then get rid of the topmost stack element (the expression's value) by generating a command like pop temp 0.

We'll discuss the compilation of *method calls* of the form do *varName.methodName* (…) and do *methodName* (…) later in the chapter, in a section dedicated to compiling method calls.

Compiling if and while statements: High-level programming languages feature a variety of *control flow statements* like if, while, for, and switch, of which Jack features if and while. In contrast, low-level assembly and VM languages control the flow of execution using two branching primitives: *conditional goto*, and *unconditional goto*. Therefore, one of the challenges faced by compiler developers is expressing the semantics of high-level control flow statements using nothing more than goto primitives. Figure 11.6 shows how this gap can be bridged systematically.

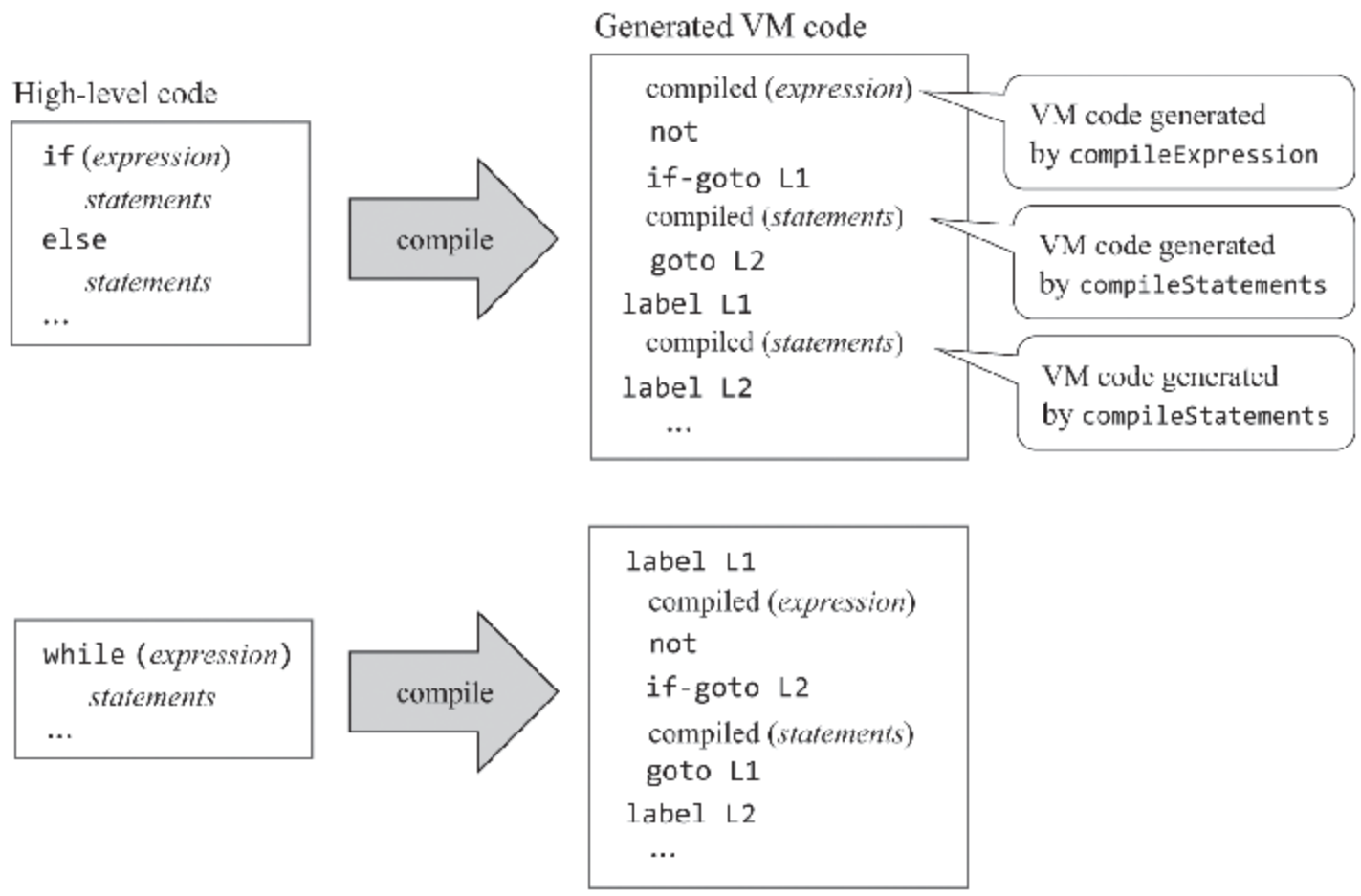


Figure 11.6 Compiling if and while statements. The L1 and L2 labels are generated by the compiler.

When the compiler detects an if keyword, it knows that it has to parse a pattern of the form if (*expression*) {*statements*} else {*statements*}. Hence, the compiler starts by calling compileExpression, which generates VM commands designed to compute and push the expression's value onto the stack. The compiler then generates the VM command not, designed to negate the expression's value. Next, the compiler creates a label, say L1, and uses it for generating the VM command if-goto L1. Next, the compiler calls compileStatements. This routine is designed to compile a sequence of the form *statement*; *statement*; ... *statement*;, where each *statement* is either a let, a do, a return, an if, or a while. The resulting VM code is referred to conceptually in figure 11.6 as "compiled (*statements*)." The rest of the compilation strategy is self-explanatory.

A high-level program normally contains multiple instances of if and while. To handle this complexity, the compiler can generate labels that are globally unique, for example, labels whose suffix is the value of a running counter. Also, control flow statements are often nested—for example, an if within a while within another while, and so on. Such nestings are taken care of implicitly since the compileStatements routine is inherently recursive.

11.1.5 Handling Objects

So far in this chapter, we described techniques for compiling *variables*, *expressions*, *strings*, and *statements*. This forms most of the know-how necessary for building a compiler for a procedural, C-like language. In Nand to Tetris, though, we aim higher: building a compiler for an object-based, Java-like language. With that in mind, we now turn to discuss the handling of *objects*.

Object-oriented languages feature means for declaring and manipulating aggregate abstractions known as *objects*. Each object is implemented physically as a memory block which can be referenced by a static, field, local, or argument variable. The reference variable, also known as an *object variable*, or *pointer*, contains the memory block's base address. The operating system realizes this model by managing a logical area in the RAM named *heap*. The *heap* is used as a memory pool from which memory blocks are carved, as needed, for representing new objects. When an object is no longer needed, its memory block can be freed and recycled back to the heap. The compiler stages these memory management actions by calling OS functions, as we'll see later.

At any given point during a program's execution, the heap can contain numerous objects. Suppose we want to apply a method, say foo, to one of these objects, say p. In an object-oriented language, this is done through the method call idiom p.foo(). Shifting our attention from the caller to the callee, we note that foo—like any other method—is designed to operate on a placeholder known as the *current object*, or this. In particular, when VM commands in foo's code make references to this 0, this 1, this 2, and so on, they should effect the fields of p, the object on which foo was called. Which begs the question: How do we align the this segment with p?

The virtual machine built in chapters 7–8 has a mechanism for realizing this alignment: the two-valued pointer segment, mapped directly onto RAM locations 3–4, also known as THIS and THAT. According to the VM specification, the pointer THIS (referred to as pointer 0) is designed to hold the base address of the memory segment this. Thus, to align the this segment with the object p, we can push p's value (which is an address) onto the stack and then pop it into pointer 0. Versions of this initialization technique are used conspicuously in the compilation of *constructors* and *methods*, as we now turn to describe.

11.1.5.1 Compiling Constructors

In object-oriented languages, objects are created by subroutines known as *constructors*. In this section we describe how to compile a constructor call (e.g., Java's `new` operator) from the *caller*'s perspective and how to compile the code of the constructor itself—the *callee*.

Compiling constructor calls: Object construction is normally a two-stage affair. First, one declares a variable of some class type, for example, `var Point p`. At a later stage, one can instantiate the object by calling a class constructor, for example, `let p = Point.new(2,3)`. Or, depending on the language used, one can declare *and* construct objects using a single high-level statement. Behind the scenes, though, this action is always broken into two separate stages: declaration followed by construction.

Let's take a close look at the statement `let p = Point.new(2,3)`. This abstraction can be described as "have the `Point.new` constructor allocate a two-word memory block for representing a new `Point` instance, initialize the two words of this block to 2 and 3, and have `p` refer to the base address of this block." Implicit in this semantics are two assumptions: First, the constructor knows how to allocate a memory block of the required size. Second, when the constructor—being a subroutine—terminates its execution, it returns to the caller the base address of the allocated memory block. Figure 11.7 shows how this abstraction can be realized.

High-level code

```
// Can appear in any class:
...
// Declares three local variables:
var Point p1, p2;
var int d;
...
// Constructs two objects:
let p1 = Point.new(2,3);
let p2 = Point.new(5,7);
...
```

compile

Generated VM code

```
...
// var Point p1, p2;
// var int d;
// The compilation engine adds p1, p2, and d to the
// subroutine's symbol table; no code is generated.
...
// let p1 = Point.new(2,3);
// To handle the right-hand side, the compilation engine calls
// compileExpression. This results in putting 2 and 3 at the
// stack's top and generating the command call Point.new 2
// The compilation engine generates the command:
pop local 0
// let p2 = Point.new(5,7);
// Similar.
...
```

name	type	kind	#
p1	Point	local	0
p2	Point	local	1
d	int	local	2

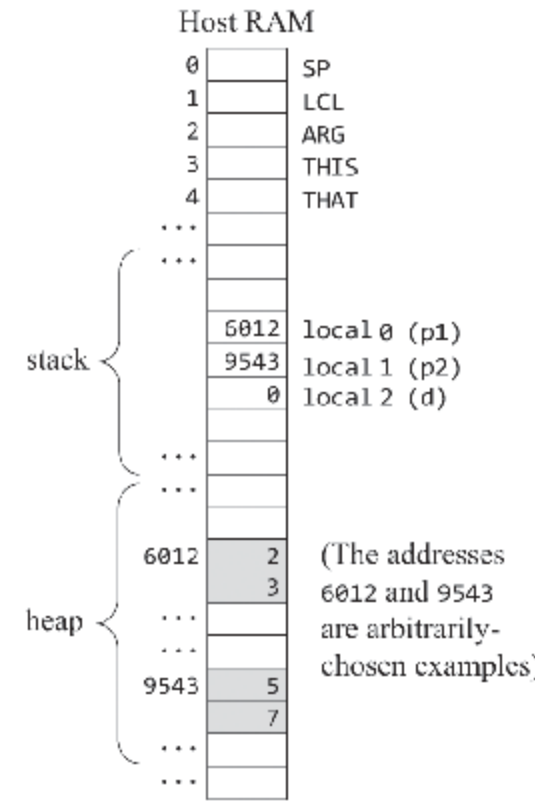


Figure 11.7 Object construction from the caller's perspective. In this example, the caller declares two object variables and then calls a class constructor for constructing the two objects. The constructor works its magic, allocating memory blocks for representing the two objects. The calling code then makes the two object variables refer to these memory blocks.

Three observations about figure 11.7 are in order. First, note that there is nothing special about compiling statements like `let p = Point.new(2,3)` and `let p = Point.new(5,7)`. We already discussed how to compile `let` statements and subroutine calls. The only thing that makes these calls special is the hocus-pocus assumption that—somehow—two objects will be constructed. The implementation of this magic is entirely delegated to the compilation of the *callee*—the constructor. As a result of this magic, the constructor creates the two objects seen in the RAM diagram in figure 11.7. This leads to the second observation: The physical addresses 6012 and 9543 are irrelevant; the high-level code as well as the compiled VM code have no idea where the objects are stored in memory; the references to these objects are strictly symbolic, via `p1` and `p2` in the high-level code and `local 0` and `local 1` in the compiled code. (As a side comment, this makes the program relocatable and safer.) Third, and stating the obvious, nothing of substance actually happens until the generated VM code is executed. In particular, during *compile-time*,

the symbol table is updated, low-level code is generated, and that's it. The objects will be constructed and bound to the variables only during *run-time*, that is, if and when the compiled code will be executed.

Compiling constructors: So far, we have treated constructors as black box abstractions: we assume that they create objects, *somehow*. Figure 11.8 unravels this magic. Before inspecting the figure, note that a constructor is, first and foremost, a *subroutine*. It can have arguments, local variables, and a body of statements; thus the compiler treats it as such. What makes the compilation of a constructor special is that in addition to treating it as a regular subroutine, the compiler must also generate code that (i) creates a new object and (ii) makes the new object the *current object* (also known as this), that is, the object on which the constructor's code is to operate.

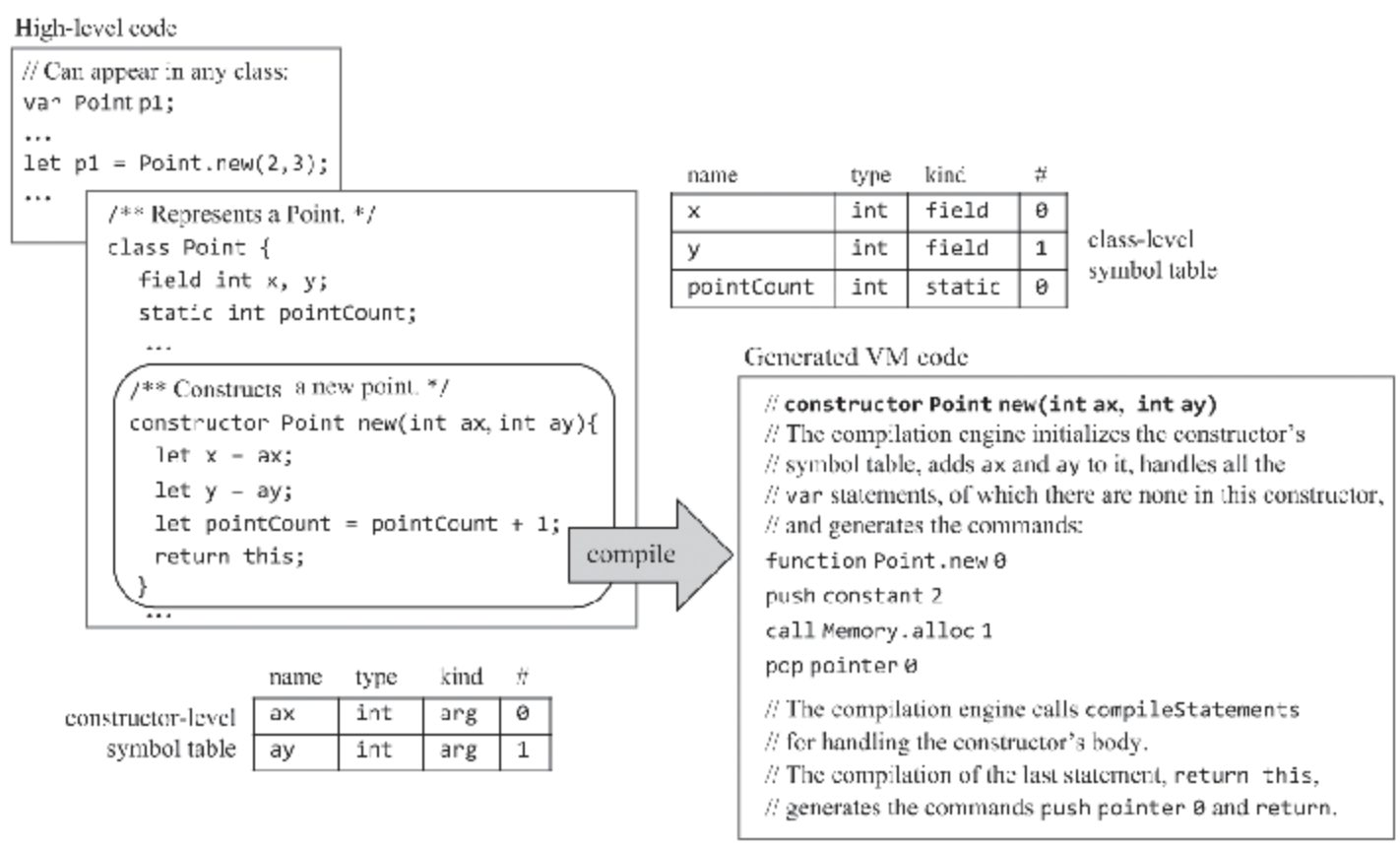


Figure 11.8 Object construction: the constructor's perspective.

The creation of a new object requires finding a free RAM block sufficiently large to accommodate the new object's data and marking the block as used. These tasks are delegated to the host operating system. According to the OS API listed in appendix 6, the OS function Memory.alloc (*size*) knows how to find an available RAM block of a given *size* (number of 16-bit words) and return the block's base address.

Memory.alloc and its sister function Memory.deAlloc use clever algorithms for allocating and freeing RAM resources efficiently. These algorithms will be presented and implemented in chapter 12, when we'll build the operating system. For now, suffice it to say that compilers generate low-level code that uses alloc (in constructors) and deAlloc (in destructors), abstractly.

Before calling Memory.alloc, the compiler determines the size of the required memory block. This can be readily computed from the class-level symbol table. For example, the symbol table of the Point class specifies that each Point object is characterized by two int values (the point's x and y coordinates). Thus, the compiler generates the commands push constant 2 and call Memory.alloc 1, effecting the function call Memory.alloc(2). The OS function alloc goes to work, finds an available RAM block of size 2, and pushes its base address onto the stack—the VM equivalent of returning a value. The next generated VM statement—pop pointer 0—sets THIS to the base address returned by alloc. From this point onward, the constructor's this segment will be aligned with the RAM block that was allocated for representing the newly constructed object.

Once the this segment is properly aligned, we can proceed to generate code easily. For example, when the compileLet routine is called to handle the statement let x = ax, it searches the symbol tables, resolving x to this 0 and ax to argument 0. Thus, compileLet generates the commands push argument 0, followed by pop this 0. The latter command rests on the assumption that the this segment is properly aligned with the base address of the new object, as indeed was done when we had set pointer 0 (actually, THIS) to the base address returned by alloc. This one-time initialization ensures that all the subsequent push / pop this *i* commands will end up hitting the right targets in the RAM (more accurately, in the *heap*). We hope that the intricate beauty of this contract is not lost on the reader.

According to the Jack language specification, every constructor must end with a return this statement. This convention forces the compiler to end the constructor's compiled version with push pointer 0 and return. These commands push onto the stack the value of THIS, the base address of the constructed object. In some languages, like Java, constructors don't have to end with an explicit return this statement. Nonetheless, the compiled code of Java constructors performs exactly the same action at the VM level, since

that's what constructors are expected to do: create an object and return its handle to the caller.

Recall that the elaborate low-level drama just described was unleashed by the caller-side statement let *varName* = *className.constructorName* (...). We now see that, by design, when the constructor terminates, *varName* ends up storing the base address of the new object. When we say "by design," we mean by the syntax of the high-level object construction idiom and by the hard work that the compiler, the operating system, the VM translator, and the assembler have to do in order to realize this abstraction. The net result is that high-level programmers are spared from all the gory details of object construction and are able to create objects easily and transparently.

11.1.5.2 Compiling Methods

As we did with constructors, we'll describe how to compile method calls and then how to compile the methods themselves.

Compiling method calls: Suppose we wish to compute the Euclidean distance between two points in a plane, p1 and p2. In C-style procedural programming, this could have been implemented using a function call like distance(p1,p2), where p1 and p2 represent composite data types. In object-oriented programming, though, p1 and p2 will be implemented as instances of some Point class, and the same computation will be done using a method call like p1.distance(p2). Unlike functions, *methods* are subroutines that always operate on a given object, and it's the caller's responsibility to specify this object. (The fact that the distance method takes another Point object as an argument is a coincidence. In general, while a method is always designed to operate on an object, the method can have 0, 1, or more arguments, of any type).

Observe that distance can be described as a *procedure* for computing the distance from a given point to another, and p1 can be described as the *data* on which the procedure operates. Also, note that both idioms distance(p1,p2) and p1.distance(p2) are designed to compute and return the same value. Yet while the C-style syntax puts the focus on distance, in the object-oriented syntax, the object comes first, literally speaking. That's why C-like languages are sometimes called *procedural*, and object-oriented languages

are said to be *data-driven*. Among other things, the object-oriented programming style is based on the assumption that objects know how to take care of themselves. For example, a Point object knows how to compute the distance between it and another Point object. Said otherwise, the distance operation is *encapsulated* within the definition of being a Point.

The agent responsible for bringing all these fancy abstractions down to earth is, as usual, the hard-working compiler. Because the target VM language has no concept of objects or methods, the compiler handles object-oriented method calls like p1.distance (p2) as if they were procedural calls like distance (p1,p2). Specifically, it translates p1.distance (p2) into push p1, push p2, call distance. Let us generalize: Jack features two kinds of method calls:

// Applies a method to the object referred to by *varName*:
varName.*methodName*(*exp*$_1$, *exp*$_2$, ..., *exp*$_n$)

// Applies a method to the *current object*:
methodName(*exp*$_1$, *exp*$_2$, ..., *exp*$_n$) // Same as `this.` *methodName*(*exp*$_1$, *exp*$_2$, ..., *exp*$_n$)

To compile the method call *varName.methodName*(*exp*$_1$, *exp*$_2$, ..., *exp*$_n$), we start by generating the command push *varName*, where *varName* is the symbol table mapping of *varName*. If the method call mentions no *varName*, we push the symbol table mapping of this. Next, we call compileExpressionList. This routine calls compileExpression n times, once for each expression in the parentheses. Finally, we generate the command call *className.methodName* $n+1$, informing that $n+1$ arguments were pushed onto the stack. The special case of calling an argument-less method is translated into call *className.methodName* 1. Note that *className* is the symbol table *type* of the *varName* identifier. See figure 11.9 for an example.

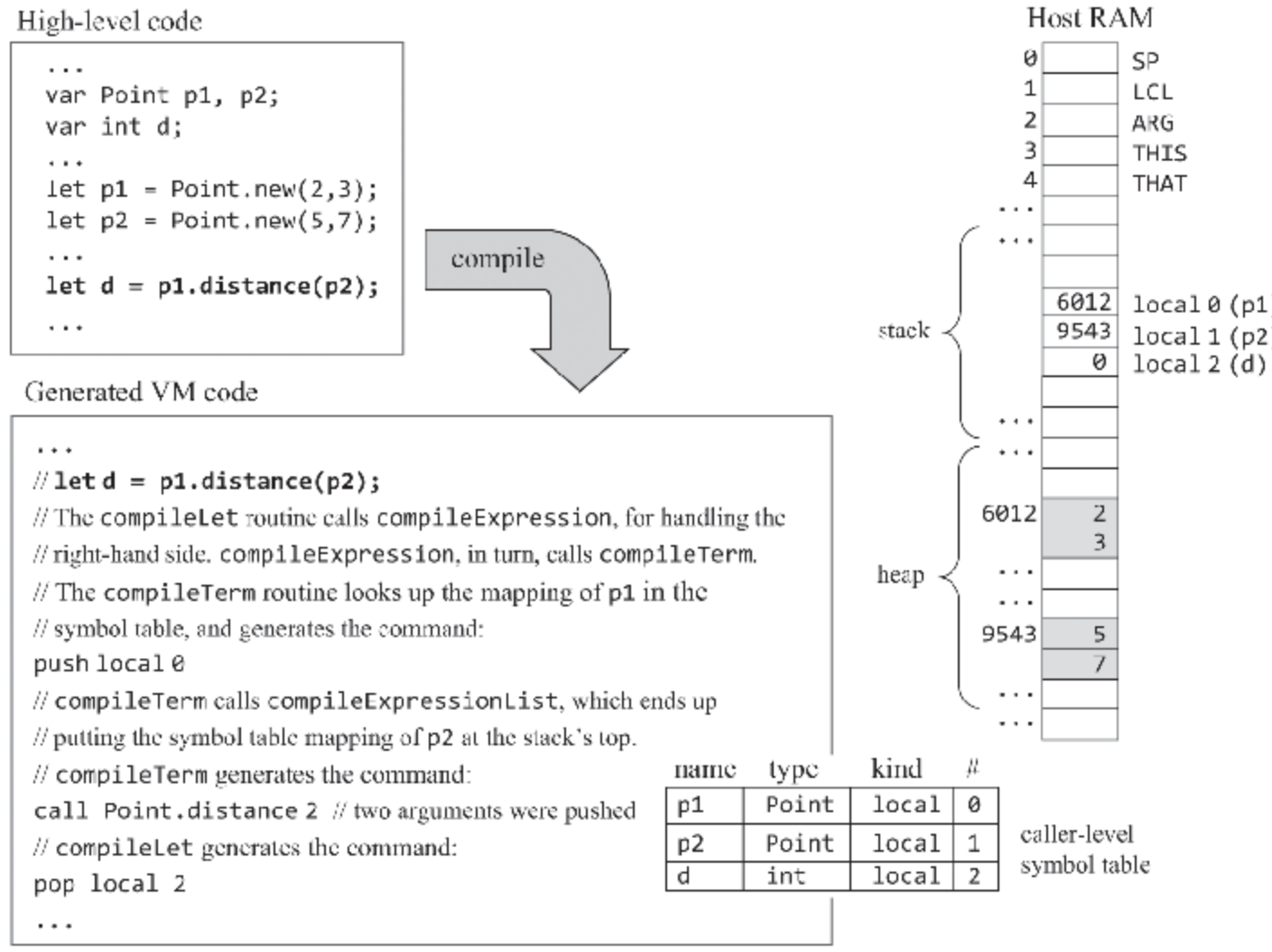


Figure 11.9 Compiling method calls: the caller's perspective.

Compiling methods: So far we discussed the distance method abstractly, from the caller's perspective. Consider how this method could be implemented, say, in Java:

```
/** A Point class method: returns the distance between this Point and the other one. */
int distance(Point other) {
   int dx, dy;
   dx = x - other.x;
   dy = y - other.x;
   return Math.sqrt((dx*dx) + (dy*dy));
}
```

Like any method, distance is designed to operate on the *current object*, represented in Java (and in Jack) by the built-in identifier this. As the above example illustrates, though, one can write an entire method without ever mentioning this. That's because the friendly Java compiler handles statements like `dx=x-other.x` as if they were `dx=this.x-other.x`. This convention makes high-level code more readable and easier to write.

We note in passing, though, that in the Jack language, the idiom *object.field* is not supported. Therefore, fields of objects other than the current object can be manipulated only using accessor and mutator methods. For example, expressions like `x – other.x` are implemented in Jack as `x – other.getx()`, where `getx` is an accessor method in the `Point` class.

So how does the Jack compiler handle expressions like `x – other.getx()`? Like the Java compiler, it looks up `x` in the symbol tables and finds that it represents the first field in the current object. But *which* object in the pool of so many objects out there does the *current object* represent? Well, according to the method call contract, it must be the first argument that was passed by the method's caller. Therefore, from the callee's perspective, the current object must be the object whose base address is the value of argument `0`. This, in a nutshell, is the low-level compilation trick that makes the ubiquitous abstraction "apply a method to an object" possible in languages like Java, Python, and, of course, Jack. See figure 11.10 for the details.

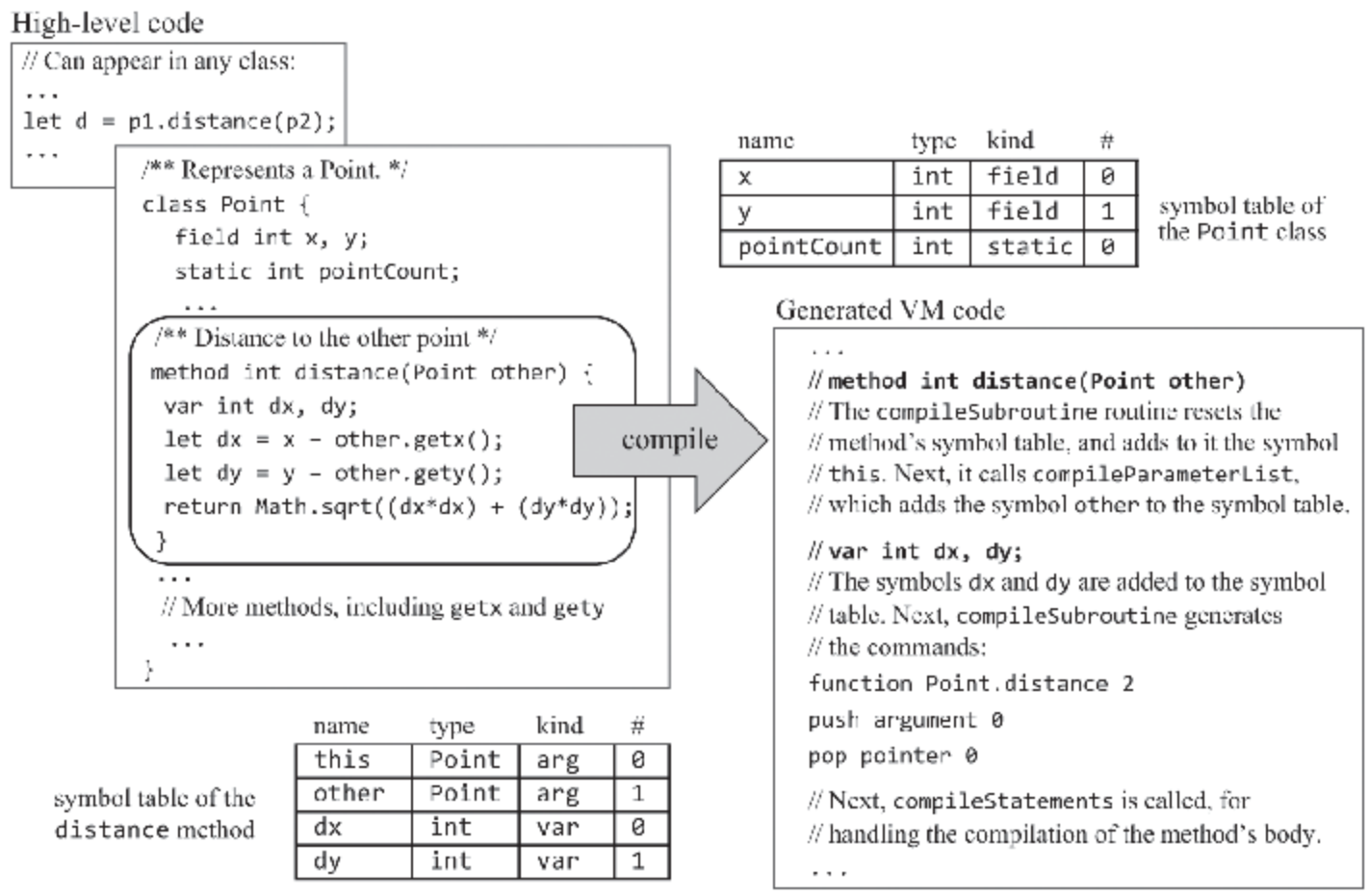


Figure 11.10 Compiling methods: the callee's perspective.

The example starts at the top left of figure 11.10, where the caller's code makes the method call `p1.distance(p2)`. Turning our attention to the compiled version of the callee, note that the code proper starts with `push argument 0`, followed by `pop pointer 0`. These commands set the method's `THIS` pointer to

the value of argument 0, which, by virtue of the method calling contract, contains the base address of the object on which the method was called to operate. Thus, from this point onward, the method's this segment is properly aligned with the base address of the target object, making every push / pop this *i* command properly aligned as well. For example, the expression x—other.getx () will be compiled into push this 0, push argument 1, call Point.getx 1, sub. Since we started the compiled method code by setting THIS to the base address of the called object, we are guaranteed that this 0 (and any other reference this *i*) will hit the mark, targeting the right field of the right object.

11.1.6 Compiling Arrays

Arrays are similar to objects. In Jack, arrays are implemented as instances of an Array class, which is part of the operating system. Thus, arrays and objects are declared, implemented, and stored exactly the same way; in fact, arrays *are* objects, with the difference that the array abstraction allows accessing array elements using an index, for example, let arr[3]=17. The agent that makes this useful abstraction concrete is the compiler, as we now turn to describe.

Using pointer notation, observe that arr[i] can be written as *(arr+i), that is, memory address arr+i. This insight holds the key for compiling statements like let x=arr[i]. To compute the physical address of arr[i], we execute push arr, push i, add, which results in pushing the target address onto the stack. Next, we execute pop pointer 1. According to the VM specification, this action stores the target address in the method's THAT pointer (RAM[4]), which has the effect of aligning the base address of the virtual segment that with the target address. Thus we can now execute push that 0 and pop x, completing the low-level translation of let x=arr[i]. See figure 11.11 for the details.

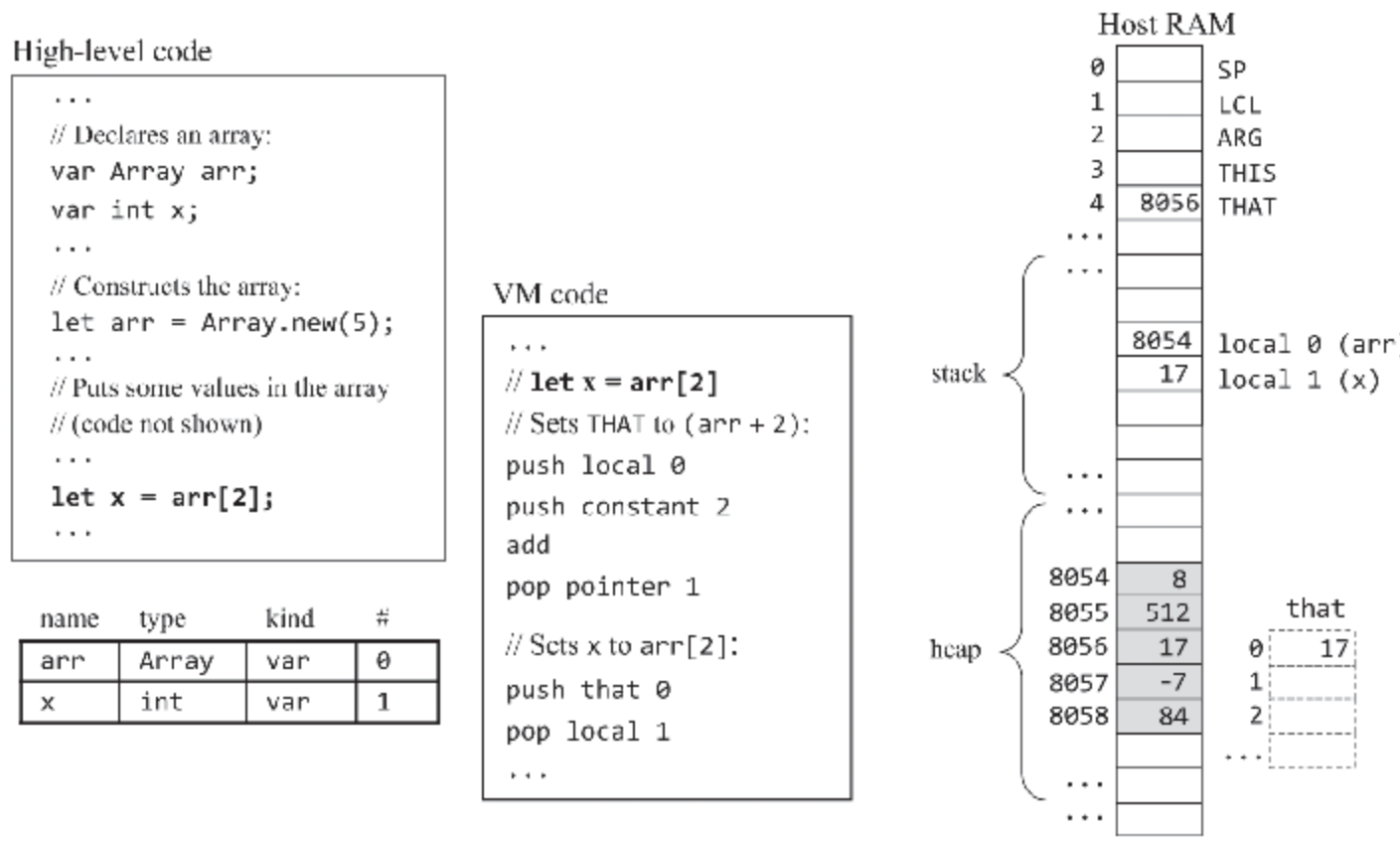


Figure 11.11 Array access using VM commands.

This nice compilation strategy has only one problem: it doesn't work. More accurately, it works with statements like `let a=b[j]` but fails with statements in which the left-hand side of the assignment is indexed, as in `let a[i]=b[j]`. See figure 11.12.

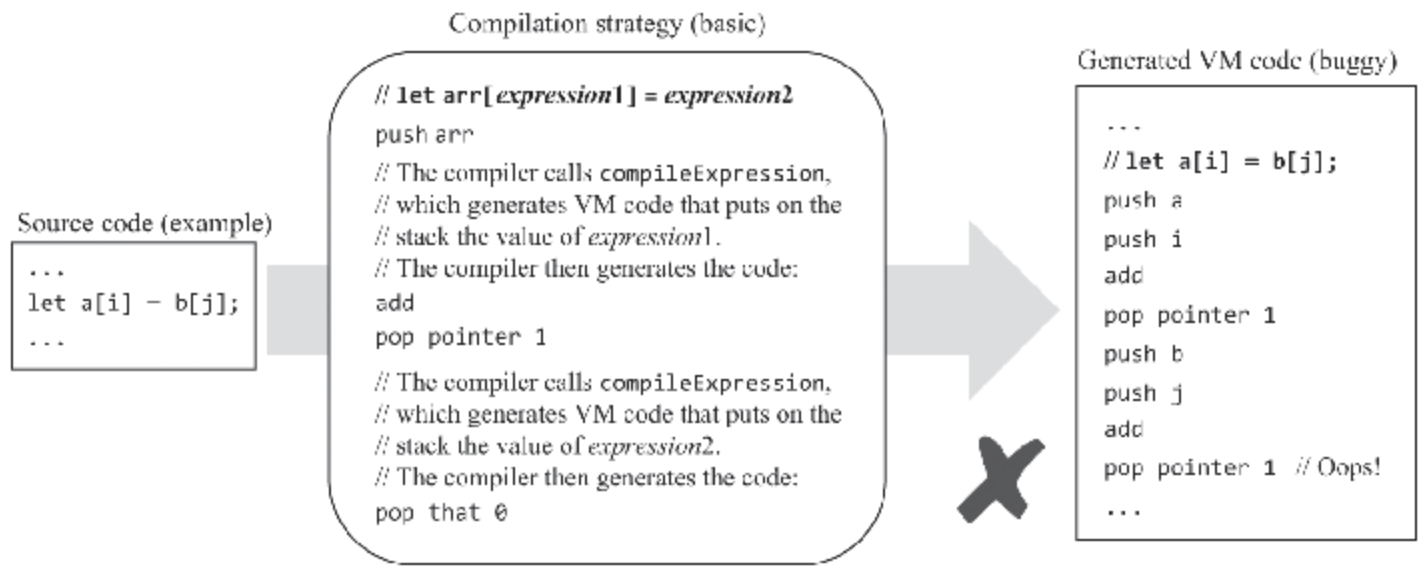


Figure 11.12 Basic compilation strategy for arrays, and an example of the bugs that it can generate. In this particular case, the value stored in pointer 1 is overridden, and the address of a[i] is lost.

The good news is that this flawed compilation strategy can be easily fixed to compile correctly any instance of let arr[*expression*1] = *expression*2. As before, we start by generating the command push arr, calling compileExpression, and generating the command add. This sequence puts the target address (arr + *expression*1) at the stack's top. Next, we call

compileExpression, which will end up putting at the stack's top the value of *expression*2. At this point we save this value—we can do it using pop temp 0. This operation has the nice side effect of making (arr + *expression*1) the top stack element. Thus we can now pop pointer 1, push temp 0, and pop that 0. This little fix, along with the recursive nature of the compileExpression routine, makes this compilation strategy capable of handling let arr[*expression*1] = *expression*2 statements of any recursive complexity, such as, say, let a[b[i]+a[j+b[a[3]]]]=b[b[j]+2].

In closing, several things make the compilation of Jack arrays relatively simple. First, Jack arrays are not typed; rather, they are designed to store 16-bit values, with no restrictions. Second, all primitive data types in Jack are 16-bit wide, all addresses are 16-bit wide, and so is the RAM's word width. In strongly typed programming languages, and in languages where this one-to-one correspondence cannot be guaranteed, the compilation of arrays requires more work.

11.2 Specification

The compilation challenges and solutions that we have described so far can be generalized to support the compilation of any object-based programming language. We now turn from the general to the specific: from here to the end of the chapter, we describe the *Jack compiler*. The Jack compiler is a program that gets a Jack program as input and generates executable VM code as output. The VM code realizes the program's semantics on the virtual machine specified in chapters 7–8.

Usage: The compiler accepts a single command-line argument, as follows,

prompt> JackCompiler *source*

where *source* is either a file name of the form *Xxx*.jack (the extension is mandatory) or the name of a folder (in which case there is no extension) containing one or more .jack files. The file/folder name may contain a file path. If no path is specified, the compiler operates on the current folder. For each *Xxx*.jack file, the compiler creates an output file *Xxx*.vm and writes the

VM commands into it. The output file is created in the same folder as the input file. If there is a file by this name in the folder, it will be overwritten.

11.3 Implementation

We now turn to provide guidelines, implementation tips, and a proposed API for extending the syntax analyzer built in chapter 10 into a full-scale Jack compiler.

11.3.1 Standard Mapping over the Virtual Machine

Jack compilers can be developed for different target platforms. This section provides guidelines on how to map various constructs of the Jack language on one specific platform: the virtual machine specified in chapters 7–8.

Naming Files and Functions

- A Jack class file *Xxx*.jack is compiled into a VM class file named *Xxx*.vm
- A Jack subroutine *yyy* in file *Xxx*.jack is compiled into a VM function named *Xxx.yyy*

Mapping Variables

- The first, second, third, … *static* variable declared in a class declaration is mapped on the virtual segment entry static 0, static 1, static 2, …
- The first, second, third, … *field* variable declared in a class declaration is mapped on this 0, this 1, this 2, …
- The first, second, third, … *local* variable declared in the var statements of a subroutine is mapped on local 0, local 1, local 2, …
- The first, second, third, … *argument* variable declared in the parameter list of a *function* or a *constructor* (but not a *method*) is mapped on argument 0, argument 1, argument 2, …
- The first, second, third, … *argument* variable declared in the parameter list of a *method* is mapped on argument 1, argument 2, argument 3, …

Mapping Object Fields

To align the virtual segment this with the object passed by the caller of a *method*, use the VM commands push argument 0, pop pointer 0.

Mapping Array Elements

The high-level reference arr[*expression*] is compiled by setting pointer 1 to (arr + *expression*) and accessing that 0.

Mapping Constants

- References to the Jack constants null and false are compiled into push constant 0.
- References to the Jack constant true are compiled into push constant 1, neg. This sequence pushes the value −1 onto the stack.
- References to the Jack constant this are compiled into push pointer 0. This command pushes the base address of the current object onto the stack.

11.3.2 Implementation Guidelines

Throughout this chapter we have seen many conceptual compilation examples. We now give a concise and formal summary of all these compilation techniques.

Handling Identifiers

The identifiers used for naming variables can be handled using symbol tables. During the compilation of valid Jack code, any identifier not found in the symbol tables may be assumed to be either a subroutine name or a class name. Since the Jack syntax rules suffice for distinguishing between these two possibilities, and since the Jack compiler performs no "linking," there is no need to keep these identifiers in a symbol table.

Compiling Expressions

The compileExpression routine should process the input as the sequence *term op term op term* .... To do so, compileExpression should implement the codeWrite algorithm (figure 11.4), extended to handle all the possible *terms* specified in the Jack grammar (figure 11.5). Indeed, an inspection of the grammar rules reveals that most of the action in compiling *expressions* occurs in the compilation of their underlying *terms*. This is especially true following our recommendation that the compilation of subroutine calls be handled directly by the compilation of *terms* (implementation notes following the CompilationEngine API, section 10.3).

The *expression* grammar and thus the corresponding compileExpression routine are inherently recursive. For example, when compileExpression detects a left parenthesis, it should recursively call compileExpression to handle the inner expression. This recursive descent ensures that the inner expression will be evaluated first. Except for this priority rule, the Jack language supports *no operator priority*. Handling operator priority is of course possible, but in Nand to Tetris we consider it an optional compiler-specific extension, not a standard feature of the Jack language.

The expression x * y is compiled into push x, push y, call Math.multiply 2. The expression x / y is compiled into push x, push y, call Math.divide 2. The Math class is part of the OS, documented in appendix 6. This class will be developed in chapter 12.

Compiling Strings

Each string constant "*ccc* ... *c*" is handled by (i) pushing the string length onto the stack and calling the String.new constructor, and (ii) pushing the character code of *c* on the stack and calling the String method appendChar, once for each character *c* in the string (the Jack character set is documented in appendix 5). As documented in the String class API in appendix 6, both the new constructor and the appendChar method return the string as the return value (i.e., they push the string object onto the stack). This simplifies compilation, avoiding the need to re-push the string each time appendChar is called.

Compiling Function Calls and Constructor Calls

The compiled version of calling a function or calling a constructor that has *n* arguments must (i) call compileExpressionList, which will call compileExpression *n* times, and (ii) make the call informing that *n* arguments were pushed onto the stack before the call.

Compiling Method Calls

The compiled version of calling a method that has *n* arguments must (i) push a reference to the object on which the method is called to operate, (ii) call compileExpressionList, which will call compileExpression *n* times, and (iii) make the call, informing that $n+1$ arguments were pushed onto the stack before the call.

Compiling do Statements

We recommend compiling do *subroutineCall* statements as if they were do *expression* statements, and then yanking the topmost stack value using pop temp 0.

Compiling Classes

When starting to compile a class, the compiler creates a class-level symbol table and adds to it all the *field* and *static* variables declared in the class declaration. The compiler also creates an empty subroutine-level symbol table. No code is generated.

Compiling Subroutines

- When starting to compile a subroutine (*constructor*, *function*, or *method*), the compiler initializes the subroutine's symbol table. If the subroutine is a *method*, the compiler adds to the symbol table the mapping <this, *className*, arg, 0>.
- Next, the compiler adds to the symbol table all the parameters, if any, declared in the subroutine's parameter list. Next, the compiler handles all the var declarations, if any, by adding to the symbol table all the subroutine's local variables.

- At this stage the compiler starts generating code, beginning with the command function *className.subroutineName nVars*, where *nVars* is the number of local variables in the subroutine.
- If the subroutine is a *method*, the compiler generates the code push argument 0, pop pointer 0. This sequence aligns the virtual memory segment this with the base address of the object on which the method was called.

Compiling Constructors

- First, the compiler performs all the actions described in the previous section, ending with the generation of the command function *className.constructorName nVars*.
- Next, the compiler generates the code push constant *nFields*, call Memory.alloc 1, pop pointer 0, where *nFields* is the number of fields in the compiled class. This results in allocating a memory block of *nFields* 16-bit words and aligning the virtual memory segment this with the base address of the newly allocated block.
- The compiled constructor must end with push pointer 0, return. This sequence returns to the caller the base address of the new object created by the constructor.

Compiling Void Methods and Void Functions

Every VM function is expected to push a value onto the stack before returning. When compiling a void Jack method or function, the convention is to end the generated code with push constant 0, return.

Compiling Arrays

Statements of the form let arr[*expression*1] = *expression*2 are compiled using the technique described at the end of section 11.1.6. *Implementation tip*: When handling arrays, there is never a need to use that entries whose index is greater than 0.

The Operating System

Consider the high-level expression `Math.sqrt((dx*dx)+(dy*dy))`.. The compiler compiles it into the VM commands `push` *dx*, `push` *dx*, `call Math.multiply 2`, `push` *dy*, `push` *dy*, `call Math.multiply 2`, `add`, `call Math.sqrt 1`, where *dx* and *dy* are the symbol table mappings of `dx` and `dy`. This example illustrates the two ways in which operating system services come into play during compilation. First, some high-level abstractions, like the expression `x * y`, are compiled by generating code that calls OS subroutines like `Math.multiply`. Second, when a Jack expression includes a high-level call to an OS routine, for example, `Math.sqrt(x)`, the compiler generates VM code that makes exactly the same call using VM postfix syntax.

The OS features eight classes, documented in appendix 6. Nand to Tetris provides two different implementations of this OS—*native* and *emulated*.

Native OS Implementation

In project 12 you will develop the OS class library in Jack and compile it using a Jack compiler. The compilation will yield eight `.vm` files, comprising the native OS implementation. If you put these eight `.vm` files in the same folder that stores the `.vm` files resulting from the compilation of *any* Jack program, all the OS functions will become accessible to the compiled VM code since they belong to the same code base.

Emulated OS Implementation

The supplied VM emulator, which is a Java program, features a Java-based implementation of the Jack OS. Whenever the VM code loaded into the emulator calls an OS function, the emulator checks whether a VM function by that name exists in the loaded code base. If so, it executes the VM function. Otherwise, it calls the built-in implementation of this OS function. The bottom line is this: If you use the supplied VM emulator for executing the VM code generated by your compiler, as we do in project 11, you need not worry about the OS configuration; the emulator will service all the OS calls without further ado.

11.3.3 Software Architecture

The proposed compiler architecture builds upon the syntax analyzer described in chapter 10. Specifically, we propose to gradually evolve the syntax analyzer into a full-scale compiler, using the following modules:

- JackCompiler: main program, sets up and invokes the other modules
- JackTokenizer: tokenizer for the Jack language
- SymbolTable: keeps track of all the variables found in the Jack code
- VMWriter: writes VM code
- CompilationEngine: recursive top-down compilation engine

The JackCompiler

This module drives the compilation process. It operates on either a file name of the form *Xxx*.jack or on a folder name containing one or more such files. For each source *Xxx*.jack file, the program

1. creates a JackTokenizer from the *Xxx*.jack input file;
2. creates an output file named *Xxx*.vm; and
3. uses a CompilationEngine, a SymbolTable, and a VMWriter for parsing the input file and emitting the translated VM code into the output file.

We provide no API for this module, inviting you to implement it as you see fit. Remember that the first routine that must be called when compiling a .jack file is compileClass.

The JackTokenizer

This module is identical to the tokenizer built in project 10. See the API in section 10.3.

The SymbolTable

This module provides services for building, populating, and using symbol tables that keep track of the symbol properties *name*, *type*, *kind*, and a running *index* for each kind. See figure 11.2 for an example.

Routine	*Arguments*	*Returns*	*Function*
Constructor / initializer	—	—	Creates a new symbol table.
`reset`	—	—	Empties the symbol table, and resets the four indexes to 0. Should be called when starting to compile a subroutine declaration.
`define`	`name` (string) `type` (string) `kind` (`STATIC`, `FIELD`, `ARG`, or `VAR`)	—	Defines (adds to the table) a new variable of the given `name`, `type`, and `kind`. Assigns to it the index value of that `kind`, and adds 1 to the index.
`varCount`	`kind` (`STATIC`, `FIELD`, `ARG`, or `VAR`)	int	Returns the number of variables of the given `kind` already defined in the table.
`kindOf`	`name` (string)	(`STATIC`, `FIELD`, `ARG`, `VAR`, `NONE`)	Returns the `kind` of the named identifier. If the identifier is not found, returns `NONE`.
`typeOf`	`name` (string)	string	Returns the `type` of the named variable.
`indexOf`	`name` (string)	int	Returns the `index` of the named variable.

Implementation note: During the compilation of a Jack class file, the Jack compiler uses two instances of SymbolTable.

The VMWriter

This module features a set of simple routines for writing VM commands into the output file.

Routine	*Arguments*	*Returns*	*Function*
Constructor / initializer	Output file / stream	—	Creates a new output `.vm` file / stream, and prepares it for writing.
`writePush`	`segment` (`CONSTANT`, `ARGUMENT`, `LOCAL`, `STATIC`, `THIS`, `THAT`, `POINTER`, `TEMP`) `index` (int)	—	Writes a VM `push` command.
`writePop`	`segment` (`ARGUMENT`, `LOCAL`, `STATIC`, `THIS`, `THAT`, `POINTER`, `TEMP`) `index` (int)	—	Writes a VM `pop` command.
`writeArithmetic`	`command` (`ADD`, `SUB`, `NEG`, `EQ`, `GT`, `LT`, `AND`, `OR`, `NOT`)	—	Writes a VM arithmetic-logical command.
`writeLabel`	`label` (string)	—	Writes a VM `label` command.
`writeGoto`	`label` (string)	—	Writes a VM `goto` command.
`writeIf`	`label` (string)		Writes a VM `if-goto` command.
`writeCall`	`name` (string) `nArgs` (int)	—	Writes a VM `call` command.
`writeFunction`	`name` (string) `nVars` (int)	—	Writes a VM `function` command.
`writeReturn`	—	—	Writes a VM `return` command.
`close`	—	—	Closes the output file / stream.

The CompilationEngine

This module runs the compilation process. Although the CompilationEngine API is almost identical the API presented in chapter 10, we repeat it here for ease of reference.

The CompilationEngine gets its input from a JackTokenizer and uses a VMWriter for writing the VM code output (instead of the XML produced in project 10). The output is generated by a series of compile*xxx* routines, each designed to handle the compilation of a specific Jack language construct *xxx* (for example, compileWhile generates the VM code that realizes while statements). The contract between these routines is as follows: Each

compile*xxx* routine gets from the input and handles all the tokens that make up *xxx*, advances the tokenizer exactly beyond these tokens, and emits to the output VM code effecting the semantics of *xxx*. If *xxx* is a part of an expression, and thus has a value, the emitted VM code should compute this value and leave it at the top of the stack. As a rule, each compile*xxx* routine is called only if the current token is *xxx*. Since the first token in a valid .jack file must be the keyword class, the compilation process starts by calling the routine compileClass.

Routine	*Arguments*	*Returns*	*Function*
Constructor / initializer	Input file / stream Output file / stream	–	Creates a new compilation engine with the given input and output. The next routine called must be `compileClass`.
`compileClass`	–	–	Compiles a complete class.
`compileClassVarDec`	–	–	Compiles a static variable declaration, or a field declaration.
`compileSubroutine`	–	–	Compiles a complete method, function, or constructor.
`compileParameterList`	–	–	Compiles a (possibly empty) parameter list. Does not handle the enclosing parenthesis tokens `(` and `)`.
`compileSubroutineBody`	–	–	Compiles a subroutine's body.
`compileVarDec`	–	–	Compiles a `var` declaration.
`compileStatements`	–	–	Compiles a sequence of statements. Does not handle the enclosing curly bracket tokens `{` and `}`.
`compileLet`	–	–	Compiles a `let` statement.
`compileIf`	–	–	Compiles an `if` statement, possibly with a trailing `else` clause.
`compileWhile`	–	–	Compiles a `while` statement.
`compileDo`	–	–	Compiles a `do` statement.
`compileReturn`	–	–	Compiles a `return` statement.
`compileExpression`	–	–	Compiles an expression.
`compileTerm`	–	–	Compiles a *term*. If the current token is an *identifier*, the routine must resolve it into a *variable*, an *array element*, or a *subroutine call*. A single lookahead token, which may be `[`, `(`, or `.`, suffices to distinguish between the possibilities. Any other token is not part of this term and should not be advanced over.
`compileExpressionList`	–	int	Compiles a (possibly empty) comma-separated list of expressions. Returns the number of expressions in the list.

Note: The following Jack grammar rules have no corresponding compile xxx routines in the CompilationEngine: *type*, *className*, *subroutineName*, *varName*, *statement*, *subroutineCall*.

The parsing logic of these rules should be handled by the routines that implement the rules that refer to them. The Jack language grammar is presented in section 10.2.1.

Token lookahead: The need for token lookahead, and the proposed solution for handling it, are discussed in section 10.3, just after the CompilationEngine API.

11.4 Project

Objective: Extend the syntax analyzer built in chapter 10 into a full-scale Jack compiler. Apply your compiler to all the test programs described below. Execute each translated program, and make sure that it operates according to its given documentation.

This version of the compiler assumes that the source Jack code is error-free. Error checking, reporting, and handling can be added to later versions of the compiler but are not part of project 11.

Resources: The main tool that you need is the programming language in which you will implement the compiler. You will also need the supplied VM emulator for testing the VM code generated by your compiler. Since the compiler is implemented by extending the syntax analyzer built in project 10, you will also need the analyzer's source code.

Implementation Stages

We propose morphing the syntax analyzer built in project 10 into the final compiler. In particular, we propose to gradually replace the routines that generate passive XML output with routines that generate executable VM code. This can be done in two main development stages.

(Stage 0: Make a backup copy of the syntax analyzer code developed in project 10.)

Stage 1: Symbol table: Start by building the compiler's SymbolTable module, and use it for extending the syntax analyzer built in Project 10, as follows. Presently, whenever an identifier is encountered in the source code, say foo, the syntax analyzer outputs the XML line <identifier> foo </identifier>. Instead, extend your syntax analyzer to output the following information about each identifier:

- *name*
- *category* (field, static, var, arg, class, subroutine)
- *index*: if the identifier's category is field, static, var, or arg, the running index assigned to the identifier by the symbol table
- *usage*: whether the identifier is presently being *declared* (for example, the identifier appears in a static / field / var Jack variable declaration) or *used* (for example, the identifier appears in a Jack expression)

Have your syntax analyzer output this information as part of its XML output, using markup tags of your choice.

Test your new SymbolTable module and the new functionality just described by running your extended syntax analyzer on the test Jack programs supplied in project 10. If your extended syntax analyzer outputs the information described above correctly it means that you've developed a complete executable capability to understand the semantics of Jack programs. At this stage you can make the switch to developing the full-scale compiler and start generating VM code instead of XML output. This can be done gradually, as we now turn to describe.

(Stage 1.5: Make a backup copy of the extended syntax analyzer code).

Stage 2: Code generation: We provide six application programs, designed to gradually unit-test the code generation capabilities of your Jack compiler. We advise developing, and testing, your evolving compiler on the test programs in the given order. This way, you will be implicitly guided to

build the compiler's code generation capabilities in sensible stages, according to the demands presented by each test program.

Normally, when one compiles a high-level program and runs into difficulties, one concludes that the program is screwed up. In this project the setting is exactly the opposite. All the supplied test programs are error-free. Therefore, if their compilation yields any errors, it's the compiler that you have to fix, not the programs. Specifically, for each test program, we recommend going through the following routine:

1. Compile the program folder using the compiler that you are developing. This action should generate one .vm file for each source .jack file in the given folder.
2. Inspect the generated VM files. If there are visible problems, fix your compiler and go to step 1. Remember: All the supplied test programs are error-free.
3. Load the program folder into the VM emulator, and run the loaded code. Note that each one of the six supplied test programs contains specific execution guidelines; test the compiled program (translated VM code) according to these guidelines.
4. If the program behaves unexpectedly, or if an error message is displayed by the VM emulator, fix your compiler and go to step 1.

Test Programs

Seven: Tests how the compiler handles a simple program containing an arithmetic expression with integer constants, a `do` statement, and a `return` statement. Specifically, the program computes the expression `1+(2*3)` and prints its value at the top left of the screen. To test whether your compiler has translated the program correctly, run the translated code in the VM emulator, and verify that it displays `7` correctly.

ConvertToBin: Tests how the compiler handles all the procedural elements of the Jack language: expressions (without arrays or method calls), functions, and the statements `if`, `while`, `do`, `let`, and `return`. The program does not test the handling of methods, constructors, arrays, strings, static variables, and field variables. Specifically, the program gets a 16-bit decimal value from

RAM[8000], converts it to binary, and stores the individual bits in RAM[8001…8016] (each location will contain 0 or 1). Before the conversion starts, the program initializes RAM[8001…8016] to –1. To test whether your compiler has translated the program correctly, load the translated code into the VM emulator, and proceed as follows:

- Put (interactively, using the emulator's GUI) some decimal value in RAM[8000].
- Run the program for a few seconds, then stop its execution.
- Check (by visual inspection) that memory locations RAM[8001…8016] contain the correct bits and that none of them contains –1.

Square: Tests how the compiler handles the object-based features of the Jack language: constructors, methods, fields, and expressions that include method calls. Does not test the handling of static variables. Specifically, this multiclass program stages a simple interactive game that enables moving a black square around the screen using the keyboard's four arrow keys.

While moving, the size of the square can be increased and decreased by pressing the z and x keys, respectively. To quit the game, press the q key. To test whether your compiler has translated the program correctly, run the translated code in the VM emulator, and verify that the game works as expected.

Average: Tests how the compiler handles arrays and strings. This is done by computing the average of a user-supplied sequence of integers. To test whether your compiler has translated the program correctly, run the translated code in the VM emulator, and follow the instructions displayed on the screen.

Pong: A complete test of how the compiler handles an object-based application, including the handling of objects and static variables. In the classical Pong game, a ball is moving randomly, bouncing off the edges of the screen. The user tries to hit the ball with a small paddle that can be moved by pressing the keyboard's left and right arrow keys. Each time the paddle hits the ball, the user scores a point and the paddle shrinks a little, making the game increasingly more challenging. If the user misses and the

ball hits the bottom the game is over. To test whether your compiler has translated this program correctly, run the translated code in the VM emulator and play the game. Make sure to score some points to test the part of the program that displays the score on the screen.

ComplexArrays: Tests how the compiler handles complex array references and expressions. To that end, the program performs five complex calculations using arrays. For each such calculation, the program prints on the screen the expected result along with the result computed by the compiled program. To test whether your compiler has translated the program correctly, run the translated code in the VM emulator, and make sure that the expected and actual results are identical.

A web-based version of project 11 is available at www.nand2tetris.org.

11.5 Perspective

Jack is a general-purpose, object-based programming language. By design, it was made to be a relatively simple language. This simplicity allowed us to sidestep several thorny compilation issues. For example, while Jack looks like a typed language, that is hardly the case: all of Jack's data types —`int`, `char`, and `boolean`—are 16 bits wide, allowing Jack compilers to ignore almost all type information. In particular, when compiling and evaluating expressions, Jack compilers need not determine their types. The only exception is the compilation of method calls of the form `x.m()`, which requires determining the class type of `x`. Another aspect of the Jack type simplicity is that array elements are not typed.

Unlike Jack, most programming languages feature rich type systems, which place additional demands on their compilers: different amounts of memory must be allocated for different types of variables; conversion from one type into another requires implicit and explicit casting operations; the compilation of a simple expression like `x+y` depends strongly on the types of `x` and `y`; and so on.

Another significant simplification is that the Jack language does not support *inheritance*. In languages that support inheritance, the handling of

method calls like x.m() depends on the class membership of the object x, which can be determined only during run-time. Therefore, compilers of object-oriented languages that feature inheritance must treat all methods as virtual and resolve their class memberships according to the run-time type of the object on which the method is applied. Since Jack does not support inheritance, all method calls can be compiled statically during compile time.

Another common feature of object-oriented languages not supported by Jack is the distinction between private and public class members. In Jack, all static and field variables are private (recognized only within the class in which they are declared), and all subroutines are public (can be called from any class).

The lack of real typing, inheritance, and public fields allows a truly independent compilation of classes: a Jack class can be compiled without accessing the code of any other class. The fields of other classes are never referred to directly, and all linking to methods of other classes is "late" and done just by name.

Many other simplifications of the Jack language are not significant and can be relaxed with little effort. For example, one can easily extend the language with for and switch statements. Likewise, one can add the capability to assign character constants like 'c' to char type variables, which is presently not supported by the language.

Finally, our code generation strategies paid no attention to optimization. Consider the high-level statement c++. A naïve compiler will translate it into the series of low-level VM operations push c, push 1, add, pop c. Next, the VM translator will translate each one of these VM commands further into several machine-level instructions, resulting in a considerable chunk of code. At the same time, an optimized compiler will notice that we are dealing with a simple increment and translate it into, say, the two machine instructions @c followed by M=M+1. Of course, this is only one example of the finesse expected from industrial-strength compilers. In general, compiler writers invest much effort and ingenuity to ensure that the generated code is time- and space-efficient.

In Nand to Tetris, efficiency is rarely an issue, with one major exception: the operating system. The Jack OS is based on efficient algorithms and optimized data structures, as we'll elaborate in the next chapter.

12 Operating System

Civilization progresses by extending the number of operations that we can perform without thinking about them.

—Alfred North Whitehead, *Introduction to Mathematics* (1911)

In chapters 1–6 we described and built a general-purpose hardware architecture. In chapters 7–11 we developed a software hierarchy that makes the hardware usable, culminating in the construction of a modern, object-based language. Other high-level programming languages can be specified and implemented on top of the hardware platform, each requiring its own compiler.

The last major piece missing in this puzzle is an *operating system*. The OS is designed to close gaps between the computer's hardware and software, making the computer system more accessible to programmers, compilers, and users. For example, to display the text `Hello World` on the screen, several hundred pixels must be drawn at specific screen locations. This can be done by consulting the hardware specification and writing code that turns bits on and off in selected RAM locations. Clearly, high-level programmers expect a better interface. They want to write `print ("Hello World")` and let someone else worry about the details. That's where the operating system enters the picture.

Throughout this chapter, the term *operating system* is used rather loosely. Our OS is minimal, aiming at (i) encapsulating low-level hardware-specific services in high-level programmer-friendly software services and (ii) extending high-level languages with commonly used functions and abstract data types. The dividing line between an *operating system* in this sense and a *standard class library* is not clear. Indeed, modern programming

languages pack many standard operating system services like graphics, memory management, multitasking, and numerous other extensions into what is known as the language's *standard class library*. Following this model, the Jack OS is packaged as a collection of supporting classes, each providing a set of related services via Jack subroutine calls. The complete OS API is given in appendix 6.

High-level programmers expect the OS to deliver its services through well-designed interfaces that hide the gory hardware details from their application programs. To do so, the OS code must operate close to the hardware, manipulating memory, input/output, and processing devices almost directly. Further, because the OS supports the execution of every program that runs on the computer, it must be highly efficient. For example, application programs create and dispose objects and arrays all the time. Therefore, we better do it quickly and economically. Any gain in the time- and space-efficiency of an enabling OS service can impact dramatically the performance of all the application programs that depend on it.

Operating systems are usually written in a high-level language and compiled into binary form. Our OS is no exception—it is written in Jack, just like Unix was written in C. Like the C language, Jack was designed with sufficient "lowness" in it, permitting an intimate closeness to the hardware when needed.

The chapter starts with a relatively long Background section that presents key algorithms normally used is OS implementations. These include mathematical operations, string manipulations, memory management, text and graphics output, and keyboard input. This algorithmic introduction is followed by a Specification section describing the Jack OS, and an Implementation section that offers guidance on how to build the OS using the algorithms presented. As usual, the Project section provides the necessary guidelines and materials for gradually constructing and unit-testing the entire OS.

The chapter embeds key lessons in system-oriented software engineering and in computer science. On the one hand, we describe programming techniques for developing low-level system services, as well as "programming at the large" techniques for integrating and streamlining the OS services. On the other hand, we present a set of elegant and highly efficient algorithms, each being a computer science gem.

12.1 Background

Computers are typically connected to a variety of input/output devices such as a keyboard, screen, mouse, mass storage, network interface card, microphone, speakers, and more. Each of these I/O devices has its own electromechanical idiosyncrasies; thus, reading and writing data on them involves many technical details. High-level languages abstract away these details by offering high-level abstractions like `let n = Keyboard.readInt("Enter a number:")`. Let's delve into what should be done in order to realize this seemingly simple data-entry operation.

First, we engage the user by displaying the prompt `Enter a number:`. This entails creating a `String` object and initializing it to the array of `char` values `'E'`, `'n'`, `'t'`, …, and so on. Next, we have to render this string on the screen, one character at a time, while updating the *cursor* position for keeping track of where the next character should be physically displayed. After displaying the `Enter a number:` prompt, we have to stage a loop that waits until the user will oblige to press some keys on the keyboard—hopefully keys that represent digits. This requires knowing how to (i) capture a keystroke, (ii) get a single character input, (iii) append these characters to a string, and (iv) convert the string into an integer value.

If what has been elaborated so far sounds arduous, the reader should know that we were actually quite gentle, sweeping many gory details under the rug. For example, what exactly is meant by "creating a string object," "displaying a character on the screen," and "getting a multicharacter input"?

Let's start with "creating a string object." String objects don't pop out of thin air, fully formed. Each time we want to create an object, we must find available space for representing the object in the RAM, mark this space as used, and remember to free it when the object is no longer needed. Proceeding to the "display a character" abstraction, note that characters cannot be displayed. The only things that can be physically displayed are individual pixels. Thus, we have to figure out what is the character's *font*, compute where the bits that represent the font image can be found in the screen memory map, and then turn these bits on and off as needed. Finally, to "get a multicharacter input," we have to enter a loop that not only listens to the keyboard and accumulates characters as they come along but also

allows the user to backspace, delete, and retype characters, not to mention the need to echo each of these actions on the screen for visual feedback.

The agent that takes care of this elaborate behind-the-scenes work is the operating system. The execution of the statement `let n = Keyboard.readInt("Enter a number:")` entails many OS function calls, dealing with diverse issues like memory allocation, input driving, output driving, and string processing. Compilers use the OS services abstractly by injecting OS function calls into the compiled code, as we saw in the previous chapter. In this chapter we explore *how these functions are actually realized*. Of course, what we have surveyed so far is just a small subset of the OS responsibilities. For example, we didn't mention mathematical operations, graphical output, and other commonly needed services. The good news is that a well-written OS can integrate these diverse and seemingly unrelated tasks in an elegant and efficient way, using cool algorithms and data structures. That's what this chapter is all about.

12.1.1 Mathematical Operations

The four arithmetic operations *addition*, *subtraction*, *multiplication*, and *division* lie at the core of almost every computer program. If a loop that executes a million times contains expressions that use some of these operations, they'd better be implemented efficiently.

Normally, addition is implemented in hardware, at the ALU level, and subtraction is gained freely, courtesy of the two's complement method. Other arithmetic operations can be handled either by hardware or by software, depending on cost/performance considerations. We now turn to present efficient algorithms for computing multiplication, division, and square roots. These algorithms lend themselves to both software and hardware implementations.

Efficiency First

Mathematical algorithms are made to operate on n-bit values, n typically being 16, 32, or 64 bits, depending on the operands' data types. As a rule, we seek algorithms whose running time is a polynomial function of this

word size n. Algorithms whose running time depends on the *values* of n-bit numbers are unacceptable, since these values are exponential in n. For example, suppose we implement the multiplication operation $x \times y$ naïvely, using the repeated addition algorithm `for i = 1 … y {sum = sum + x}`. If y is 64-bit wide, its value may well be greater than 9,000,000,000,000,000,000, implying that the loop may run for billions of years before terminating.

In sharp contrast, the running times of the multiplication, division, and square root algorithms that we present below depend not to the n-bit *values* on which they are called to operate, which may be as large as 2^n, but rather on n, the number of their bits. When it comes to efficiency of arithmetic operations, that's the best that we can possibly hope for.

We will use the *Big-O* notation, $O(n)$, to describe a running time which is "in the order of magnitude of n." The running time of all the arithmetic algorithms that we present in this chapter is $O(n)$, where n is the bit width of the inputs.

Multiplication

Consider the standard multiplication method taught in elementary school. To compute 356 times 73, we line up the two numbers one on top of the other, right-justified. Next, we multiply 356 by 3. Next, we shift 356 to the left one position, and multiply 3560 by 7 (which is the same as multiplying 356 by 70). Finally, we sum up the columns and obtain the result. This procedure is based on the insight that $356 \times 73 = 356 \times 70 + 356 \times 3$. The binary version of this procedure is illustrated in figure 12.1, using another example.

$x = 27 =$	... 0 0 0 0 **1 1 0 1 1**	
$y = 9 =$	... 0 0 0 0 0 **1 0 0 1**	i-th bit of y
	... 0 0 0 0 1 1 0 1 1	1
	... 0 0 0 1 1 0 1 1 0	0
	... 0 0 1 1 0 1 1 0 0	0
	... 0 1 1 0 1 1 0 0 0	1
$x * y = 243 =$	... 0 **1 1 1 1 0 0 1 1**	sum

```
// Returns x * y, where x, y ≥ 0.
multiply(x, y):
  sum = 0
  shiftedx = x
  for i = 0 ... n – 1 do
      if ((i-th bit of y) == 1)
          sum = sum + shiftedx
      shiftedx = 2 * shiftedx
  return sum
```

Figure 12.1 Multiplication algorithm.

Notation note: The algorithms presented in this chapter are written in a self-explanatory pseudocode syntax. We use indentation to mark blocks of code, obviating the need for curly brackets or begin/end keywords. For example, in figure 12.1, $sum = sum + shiftedx$ belongs to the single-statement body of the if logic, and $shiftedx = 2 * shiftedx$ ends the two-statement body of the for logic.

Let's inspect the multiplication procedure illustrated at the left of figure 12.1. For each i-th bit of y, we shift x i times to the left (same as multiplying x by 2^i). Next, we look at the i-th bit of y: If it is 1, we add the shifted x to an accumulator; otherwise, we do nothing. The algorithm shown on the right formalizes this procedure. Note that 2 * *shiftedx* can be computed efficiently either by left-shifting the bitwise representation of *shiftedx* or by adding *shiftedx* to itself. Either operation lends itself to primitive hardware operations.

Running time: The multiplication algorithm performs n iterations, where n is the bit width of the y input. In each iteration, the algorithm performs a few addition and comparison operations. It follows that the total running time of the algorithm is $a + b \cdot n$, where a is the time it takes to initialize a few variables, and b is the time it takes to perform a few addition and comparison operations. Formally, the algorithm's running time is $O(n)$, where n is the bit width of the inputs.

To reiterate, the running time of this $x \times y$ algorithm does not depend on the *values* of the x and y inputs; rather, it depends on the *bit width* of the inputs. In computers, the bit width is normally a small fixed constant like 16 (short), 32 (int), or 64 (long), depending on the data types of the inputs. In the Hack platform, the bit width of all data types is 16. If we assume that each iteration of the multiplication algorithm entails about ten Hack machine instructions, it follows that each multiplication operation will require at most 160 clock cycles, irrespective of the size of the inputs. In contrast, algorithms whose running time is proportional not to the bit width but rather to the values of the inputs will require $10 \cdot 2^{16} = 655{,}360$ clock cycles.

Division

The naïve way to compute the division of two n-bit numbers x / y is to count how many times y can be subtracted from x until the remainder becomes less than y. The running time of this algorithm is proportional to the value of the dividend x and thus is unacceptably exponential in the number of bits n.

To speed things up, we can try to subtract large chunks of y's from x in each iteration. For example, suppose we have to divide 175 by 3. We start by asking: What is the largest number, $x = (90, 80, 70, \ldots, 20, 10)$, so that $3 \cdot x \leq 175$? The answer is 50. In other words, we managed to subtract fifty 3's from 175, shaving fifty iterations from the naïve approach. This accelerated subtraction leaves a remainder of $175 - 3 \cdot 50 = 25$. Moving along, we now ask: What is the largest number, $x = (9, 8, 7, \ldots 2, 1)$, so that $3 \cdot x \leq 25$? The answer is 8, so we managed to make eight additional subtractions of 3, and the answer, so far, is $50 + 8 = 58$.The remainder is $25 - 3 \cdot 8 = 1$, which is less than 3, so we stop the process and announce that $175/3 = 58$ with a remainder of 1.

This technique is the rationale behind the dreaded school procedure known as *long division*. The binary version of this algorithm is identical, except that instead of accelerating the subtraction using powers of 10 we use powers of 2. The algorithm performs n iterations, n being the number of digits in the dividend, and each iteration entails a few multiplication (actually, shifting), comparison, and subtraction operations. Once again, we have an x/yalgorithm whose running time does not depend on the values of x and y. Rather, the running time is $O(n)$, where n is the bit width of the inputs.

Writing down this algorithm as we have done for multiplication is an easy exercise. To make things interesting, figure 12.2 presents another division algorithm which is as efficient, but more elegant and easier to implement.

```
// Returns the integer division x / y,
// where x ≥ 0 and y > 0.
divide(x, y):
    if (y > x) return 0
    q = divide (x, 2 * y)
    if ((x – 2 * q * y) < y)
        return 2 * q
    else
        return 2 * q + 1
```

Figure 12.2 Division algorithm.

Suppose we have to divide 480 by 17. The algorithm shown in figure 12.2 is based on the insight $480/17 = 2 \cdot (240/17) = 2 \cdot (2 \cdot (120/17)) = 2 \cdot (2 \cdot (2 \cdot (60/17))) = \cdots$, and so on. The depth of this recursion is bounded by the number of times y can be multiplied by 2 before reaching x. This also happens to be, at most, the number of bits required to represent x. Thus, the running time of this algorithm is $O(n)$, where n is the bit width of the inputs.

One snag in this algorithm is that each multiplication operation also requires $O(n)$ operations. However, an inspection of the algorithm's logic reveals that the value of the expression $(2 * q * y)$ can be computed without multiplication. Instead, it can be obtained from its value in the previous recursion level, using addition.

Square Root

Square roots can be computed efficiently in a number of different ways, for example, using the Newton-Raphson method or a Taylor series expansion. For our purpose, though, a simpler algorithm will suffice. The square root function $y = \sqrt{x}$ has two attractive properties. First, it is monotonically increasing. Second, its inverse function, $y = x^2$, is a function that we already know how to compute efficiently—multiplication. Taken together, these properties imply that we have all we need to compute square roots efficiently, using a form of *binary search*. Figure 12.3 gives the details.

```
// Computes the integer part of y = √x
// Strategy: finds an integey such that y^2 ≤ x < (y+1)^2  (for 0 ≤ x < 2^n)
// by performing binary search in the range 0 ... 2^(n/2) – 1
sqrt(x):
   y = 0
   for  j = (n/2 – 1) ... 0  do
      if (y+2^j)^2 ≤ x then y = y+2^j
   return y
```

Figure 12.3 Square root algorithm.

Since the number of iterations in the binary search that the algorithm performs is bound by $n / 2$ where n is the number of bits in x, the algorithm's running time is $O(n)$.

To sum up this section about mathematical operations, we presented algorithms for computing multiplication, division, and square root. The running time of each of the algorithms is $O(n)$, where n is the bit width of the inputs. We also observed that in computers, n is a small constant like 16, 32, or 64. Therefore, every addition, subtraction, multiplication, and division operation can be carried out swiftly, in a predictable time that is unaffected by the magnitude of the inputs.

12.1.2 Strings

In addition to primitive data types, most programming languages feature a *string* type designed to represent sequences of characters like "Loading game …" and "QUIT". Typically, the string abstraction is supplied by a String class that is part of the standard class library that supports the language. This is also the approach taken by Jack.

All the string constants that appear in Jack programs are implemented as String objects. The String class, whose API is documented in appendix 6, features various string processing methods like appending a character to the string, deleting the last character, and so on. These services are not difficult to implement, as we'll describe later in the chapter. The more challenging String methods are those that convert integer values to strings and strings of digit characters to integer values. We now turn to discuss algorithms that carry out these operations.

String representation of numbers: Computers represent numbers internally using binary codes. Yet humans are used to dealing with numbers that are written in decimal notation. Thus, when humans have to read or input numbers, *and only then*, a conversion to or from decimal notation must be performed. When such numbers are captured from an input device like a keyboard, or rendered on an output device like a screen, they are cast as strings of characters, each representing one of the digits 0 to 9. The subset of relevant characters is:

Character:	'0'	'1'	'2'	'3'	'4'	'5'	'6'	'7'	'8'	'9'
Character code:	48	49	50	51	52	53	54	55	56	57

(The complete Hack character set is given in appendix 5). We see that digit characters can be easily converted into the integers that they represent, and vice versa. The integer value of character c, where $48 \le c \le 57$, is $c - 48$. Conversely, the character code of the integer x, where $0 \le x \le 9$, is $x + 48$.

Once we know how to handle single-digit characters, we can develop algorithms for converting any integer into a string and any string of digit characters into the corresponding integer. These conversion algorithms can be based on either iterative or recursive logic, so figure 12.4 presents one of each.

int to string:

```
// Returns the string representation of
// a nonnegative integer.
int2String(val):
   lastDigit = val % 10
   c = character representing lastDigit
   if (val < 10)
     return  c  (as a string)
   else
     return  int2String(val / 10).appendChar(c)
```

string to int:

```
// Returns the integer value of a string
// of digit characters, assuming that str[0]
// represents the most significant digit.
string2Int(str):
    val = 0
    for ( i = 0 . . . str.length() ) do
        d = integer value of str.charAt(i)
        val = val * 10 + d
    return  val
```

Figure 12.4 String-integer conversions. (appendChar, length, and charAt are String class methods.)

It is easy to infer from figure 12.4 that the running times of the int2String and string2Int algorithms are $O(n)$, where n is the number of the digit-characters in the input.

12.1.3 Memory Management

Each time a program creates a new array or a new object, a memory block of a certain size must be allocated for representing the new array or object. And when the array or object is no longer needed, its RAM space may be recycled. These chores are done by two classical OS functions called alloc and deAlloc. These functions are used by compilers when generating low-level code for handling constructors and destructors, as well as by high-level programmers, as needed.

The memory blocks for representing arrays and objects are carved from, and recycled back into, a designated RAM area called a *heap*. The agent responsible for managing this resource is the operating system. When the OS starts running, it initializes a pointer named heapBase, containing the heap's base address in the RAM (in Jack, the heap starts just after the stack's end, with heapBase=2048). We'll present two heap management algorithms: basic and improved.

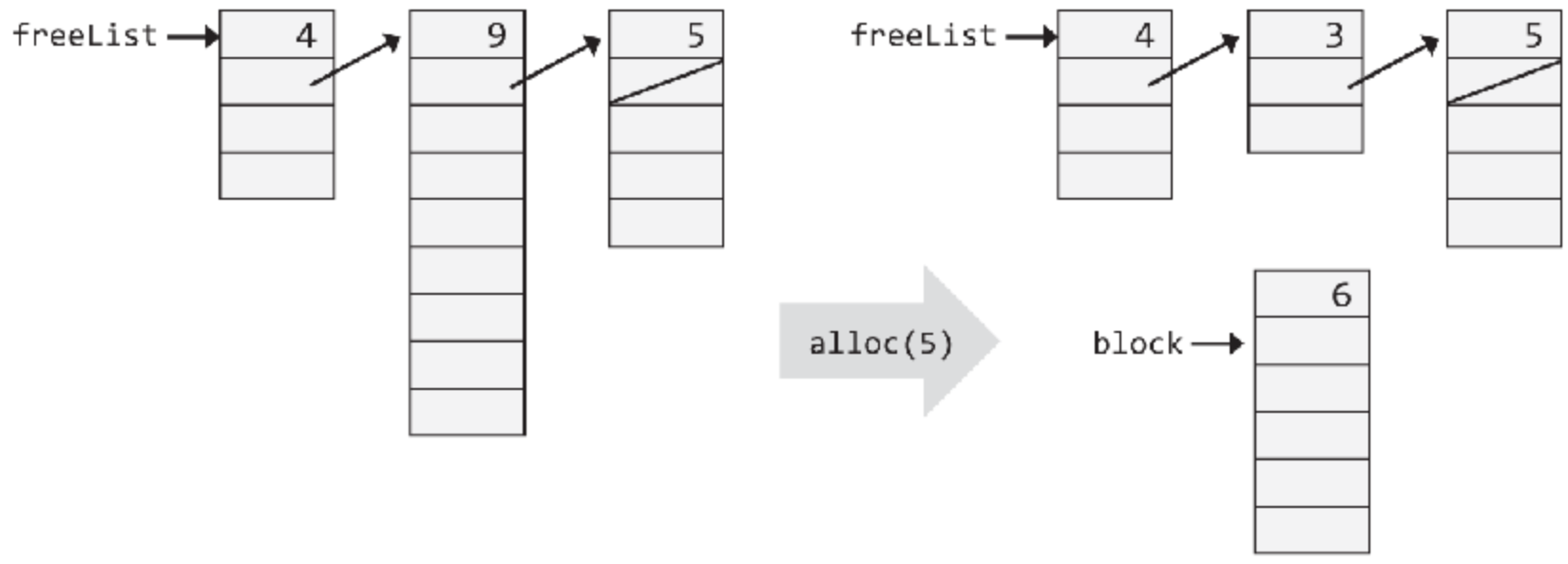
Memory allocation algorithm (basic): The data structure that this algorithm manages is a single pointer, named free, which points to the beginning of the heap segment that was not yet allocated. See figure 12.5a for the details.

```
init():
    free = heapBase

// Allocates a memory block of size words.
alloc(size):
    block = free
    free = free + size
    return block

// Frees the memory space of the given object.
deAlloc(object):
    do nothing
```

Figure 12.5a Memory allocation algorithm (basic).

The basic heap management scheme is clearly wasteful, as it never reclaims any memory space. But, if your application programs use only a few small objects and arrays, and not too many strings, you may get away with it.

Memory allocation algorithm (improved): This algorithm manages a linked list of available memory segments, called freeList (see figure 12.5b). Each segment in the list begins with two housekeeping fields: the segment's *length* and a pointer to the *next* segment in the list.




```
init():
    freeList = heapBase
    freeList.size = heapSize
    freeList.next = 0

// Allocates a memory block of size words.
alloc(size):
    search freeList using best-fit or first-fit heuristics
        to obtain a segment with segment.size ≥ size + 2
    if no such segment is found, return failure
        (or attempt defragmentation)
    block = base address of the found space
    update the freeList and the fields of block
        to account for the allocation
    return block

// Frees the memory space of the given object.
deAlloc(object):
    append object to the end of the freeList
```

Figure 12.5b Memory allocation algorithm (improved).

When asked to allocate a memory block of a given size, the algorithm has to search the freeList for a suitable segment. There are two heuristics for doing this search. *Best-fit* finds the shortest segment that is long enough for representing the required size, while *first-fit* finds the first segment that is long enough. Once a suitable segment has been found, the required memory block is carved from it (the location just before the beginning of the returned block, block[−1], is reserved to hold its length, to be used during deallocation).

Next, the *length* of this segment is updated in the freeList, reflecting the length of the part that remained after the allocation. If no memory was left

in the segment, or if the remaining part is practically too small, the entire segment is eliminated from the freeList.

When asked to reclaim the memory block of an unused object, the algorithm appends the deallocated block to the end of the freeList.

Dynamic memory allocation algorithms like the one shown in figure 12.5b may create block fragmentation problems. Hence, a *defragmentation* operation should be considered, that is, merging memory areas that are physically adjacent in memory but logically split into different segments in the freeList. The defragmentation can be done each time an object is deallocated, when alloc() fails to find a block of the requested size, or according to some other, periodical ad hoc condition.

Peek and poke: We end the discussion of memory management with two simple OS functions that have nothing to do with resource allocation. Memory.peek(*addr*) returns the value of the RAM at address *addr*, and Memory.poke(*addr*,*value*) sets the word in RAM address *addr* to *value*. These functions play a role in various OS services that manipulate the memory, including graphics routines, as we now turn to discuss.

12.1.4 Graphical Output

Modern computers render graphical output like animation and video on high-resolution color screens, using optimized graphics drivers and dedicated graphical processing units (GPUs). In Nand to Tetris we abstract away most of this complexity, focusing instead on fundamental graphics-drawing algorithms and techniques.

We assume that the computer is connected to a physical black-and-white screen arranged as a grid of rows and columns, and at the intersection of each lies a pixel. By convention, the columns are numbered from left to right and the rows are numbered from top to bottom. Thus pixel (0,0) is located at the screen's top-left corner.

We assume that the screen is connected to the computer system through a *memory map*—a dedicated RAM area in which each pixel is represented by one bit. The screen is refreshed from this memory map many times per second by a process that is external to the computer. Programs that simulate the computer's operations are expected to emulate this refresh process.

The most basic operation that can be performed on the screen is drawing an individual pixel specified by (*x*,*y*) coordinates. This is done by turning the corresponding bit in the memory map on or off. Other operations like drawing a line and drawing a circle are built on top of this basic operation. The graphics package maintains a *current color* that can be set to *black* or *white*. All the drawing operations use the current color.

Pixel drawing (drawPixel): Drawing a selected pixel in screen location (*x*,*y*) is achieved by locating the corresponding bit in the memory map and setting it to the current color. Since the RAM is an *n*-bit device, this operation requires reading and writing an *n*-bit value. See figure 12.6.

```
// Sets pixel (x,y) to the current color.
drawPixel(x,y):
    Using x and y, compute the RAM address where
        the pixel is represented;
    Using Memory.peek, get the 16-bit value of
        this address;
    Using some bitwise operation, set (only) the bit
        that corresponds to the pixel to the current color;
    Using Memory.poke, write the modified 16-bit
        value "back" to the RAM address.
```

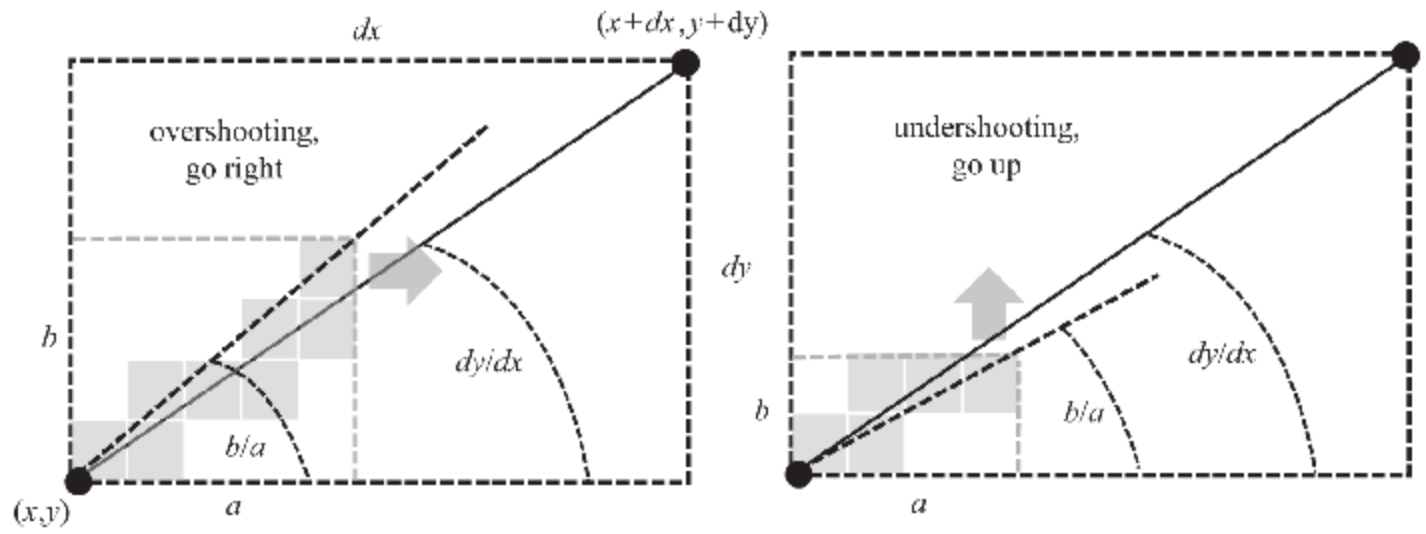
Figure 12.6 Drawing a pixel.

The memory map interface of the Hack screen is specified in section 5.2.4. This mapping should be used in order to realize the drawPixel algorithm.

Line drawing (drawLine): When asked to render a continuous "line" between two "points" on a grid made of discrete pixels, the best that we can possibly do is approximate the line by drawing a series of pixels along the imaginary line connecting the two points. The "pen" that we use for drawing the line can move in four directions only: up, down, left, and right.

Thus, the drawn line is bound to be jagged, and the only way to make it look good is to use a high-resolution screen with the tiniest possible pixels. Note, though, that the human eye, being yet another machine, also has a limited image-capturing capacity, determined by the number and type of receptor cells in the retina. Thus, high-resolution screens can fool the human brain to believe that the lines made of pixels are visibly smooth. In fact they are always jagged.

The procedure for drawing a line from ($x1$,$y1$) to ($x2$,$y2$) starts by drawing the ($x1$,$y1$) pixel and then zigzagging in the direction of ($x2$,$y2$) until that pixel is reached. See figure 12.7.




```
// Draws a line between two given points.
drawLine(x1, y1, x2, y2):
    set x to x1, y to y1, compute dx and dy.
    // a and b track how many times we
    // went right, and up, so far.
    a = 0, b = 0
    while ((a ≤ dx) and (b ≤ dy))
        drawPixel (x + a, y + b)
        // Goes right, or up:
        if (b/a > dy/dx)   { a=a+1 }
        else               { b=b+1 }
```

```
// Draws a line between two points (improved).
drawLine(x1, y1, x2, y2):
    set x to x1, y to y1, compute dx and dy.
    // a and b track how many times we
    // went right, and up, so far.
    a = 0, b = 0
    diff = 0
    while ((a < dx) and (b < dy))
        drawPixel (x + a, y + b)
        // Goes right, or up:
        if (diff < 0)  { a=a+1, diff = diff − dy }
        else           { b=b+1, diff = diff − dx }
```

involves only addition and subtraction operations

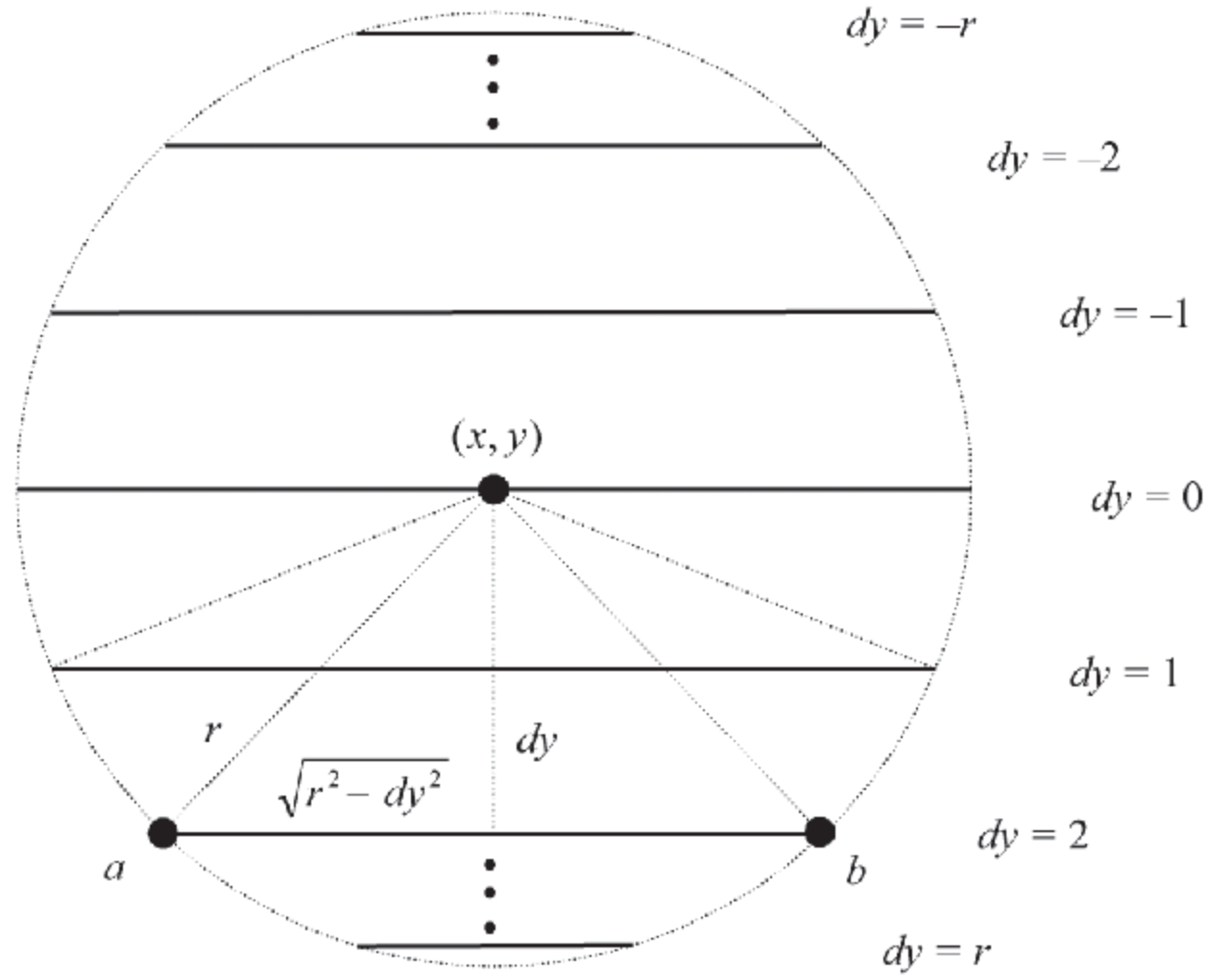
Figure 12.7 Line-drawing algorithm: basic version (bottom, left) and improved version (bottom, right).

The use of two division operations in each loop iteration makes this algorithm neither efficient nor accurate. The first obvious improvement is replacing the $b / a > dy / dx$ condition with the equivalent $a \cdot dy < b \cdot dx$, which requires only integer multiplication. Careful inspection of the latter condition reveals that it may be checked without any multiplication. As shown in the improved algorithm in figure 12.7, this may be done

efficiently by maintaining a variable that updates the value of $(a \cdot dy - b \cdot dx)$ each time a or b is incremented.

The running time of this line-drawing algorithm is $O(n)$, where n is the number of pixels along the drawn line. The algorithm uses only addition and subtraction operations and can be implemented efficiently in either software or hardware.

Circle drawing (drawCircle): Figure 12.8 presents an algorithm that uses three routines that we've already implemented: multiplication, square root, and line drawing.



point $a = (x - \sqrt{r^2 - dy^2}, y + dy)$ point $b = (x + \sqrt{r^2 - dy^2}, y + dy)$

```
// Draws a filled circle of radius r, centered at (x,y).
drawCircle(x, y, r):
    for each dy = -r to r do:
        drawLine((x - √(r² - dy²), y + dy), (x + √(r² - dy²), y + dy))
```

Figure 12.8 Circle-drawing algorithm.

The algorithm is based on drawing a sequence of horizontal lines (like the typical line *ab* in the figure), one for each row in the range $y-r$ to $y+r$. Since r is specified in pixels, the algorithm ends up drawing a line in every row along the circle's north-south diameter, resulting in a completely filled circle. A simple tweak can cause this algorithm to draw only the circle's outline, if so desired.

12.1.5 Character Output

To develop a capability for displaying characters, we first turn our physical, pixel-oriented screen into a logical, character-oriented screen suitable for rendering fixed, bitmapped images that represent characters. For example, consider a physical screen that features 256 rows of 512 pixels each. If we allocate a grid of 11 rows by 8 columns for drawing a single character, then our screen can display 23 lines of 64 characters each, with 3 extra rows of pixels left unused.

Fonts: The character sets that computers use are divided into *printable* and *non-printable* subsets. For each printable character in the Hack character set (see appendix 5), an 11-row-by-8-column bitmap image was designed, to the best of our limited artistic abilities. Taken together, these images are called a *font*. Figure 12.9 shows how our font renders the uppercase letter N. To handle character spacing, each character image includes at least a 1-pixel space before the next character in the row and at least a 1-pixel space between adjacent rows (the exact spacing varies with the size and squiggles of individual characters). The Hack font consists of ninety-five such bitmap images, one for each printable character in the Hack character set.

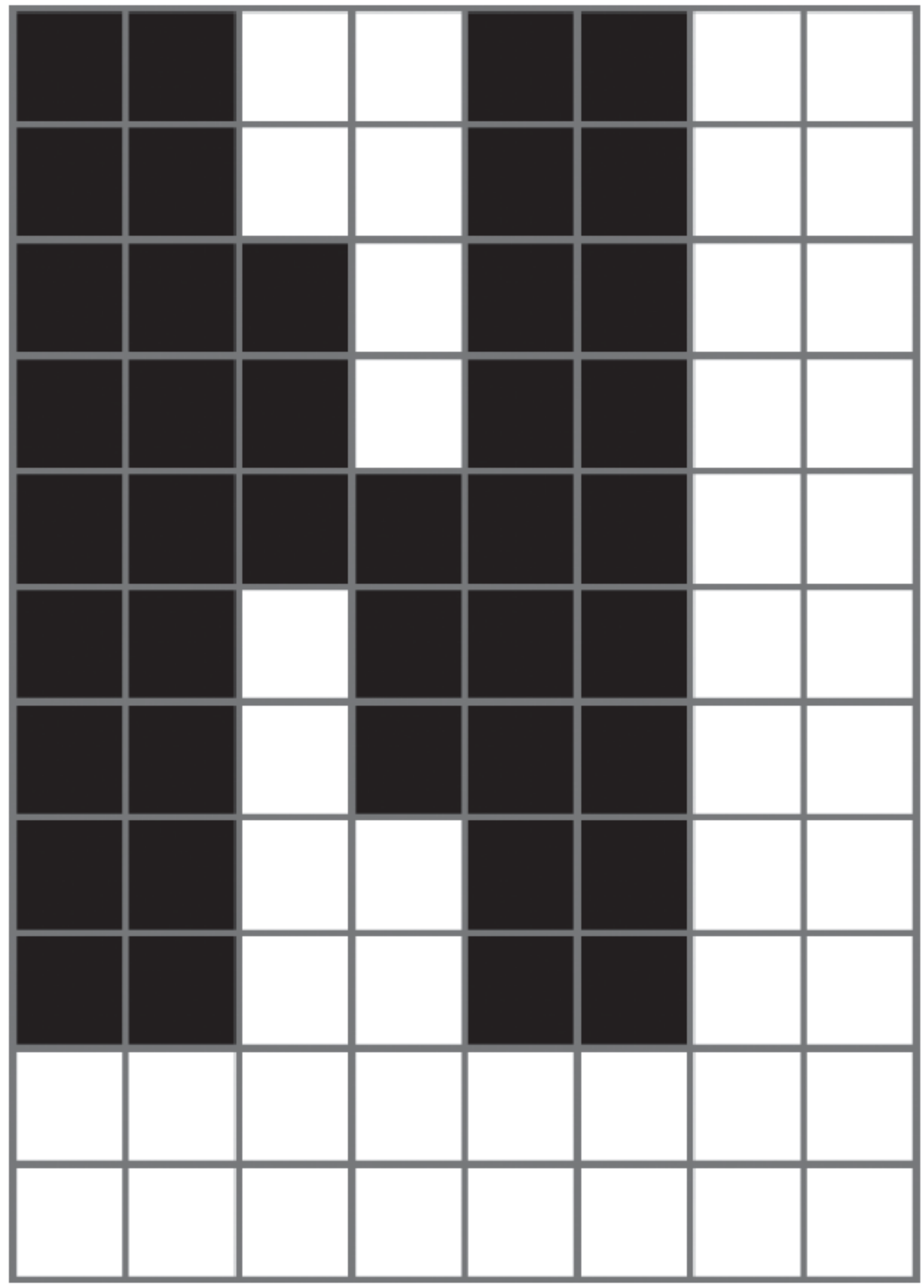


Figure 12.9 Example of a character bitmap.

Font design is an ancient yet vibrant art. The oldest fonts are as old as the art of writing, and new ones are routinely introduced by type designers who wish to make an artistic statement or solve a technical or functional objective. In our case, the small physical screen, on the one hand, and the wish to display a reasonable number of characters in each row, on the other, led to the pragmatic choice of a frugal image area of 11×8 pixels. This economy forced us to design a crude font, which nonetheless serves its purpose well.

Cursor: Characters are usually displayed one after the other, from left to right, until the end of the line is reached. For example, consider a program in which the statement print("a") is followed (perhaps not immediately) by the statement print ("b"). This implies that the program wants to display ab on the screen. To effect this continuity, the character-writing package maintains a global *cursor* that keeps track of the screen location where the next character should be drawn. The cursor information consists of column and row counts, say, cursor.col and cursor.row. After a character has been displayed, we do cursor.col++. At the end of the row we do cursor.row++ and cursor.col = 0. When the bottom of the screen is reached, there is a question of what to do next. Two possible actions are effecting a scrolling operation or clearing the screen and starting over by setting the cursor to (0,0).

To recap, we described a scheme for writing individual characters on the screen. Writing other types of data follows naturally from this basic capability: strings are written character by character, and numbers are first converted to strings and then written as strings.

12.1.6 Keyboard Input

Capturing inputs that come from the keyboard is more intricate than meets the eye. For example, consider the statement let name = Keyboard.readLine("enter your name:"). By definition, the execution of the readLine function depends on the dexterity and collaboration of an unpredictable entity: a human user. The function will not terminate until the user has pressed some keys on the keyboard, ending with an ENTER. The problem is that humans press and release keyboard keys for variable and unpredictable durations of time, and often take a coffee break in the middle. Also, humans are fond of backspacing, deleting, and retyping characters. The implementation of the readLine function must handle all these irregularities.

This section describes how keyboard input is managed, in three levels of abstraction: (i) detecting which key is currently pressed on the keyboard, (ii) capturing a single-character input, and (iii) capturing a multicharacter input.

Detecting keyboard input (keyPressed): Detecting which key is presently pressed is a hardware-specific operation that depends on the keyboard

interface. In the Hack computer, the keyboard continuously refreshes a 16-bit memory register whose address is kept in a pointer named KBD. The interaction contract is as follows: If a key is currently pressed on the keyboard, that address contains the key's character code (the Hack character set is given in appendix 5); otherwise, it contains 0. This contract is used for implementing the keyPressed function shown in figure 12.10.

Listens to the keyboard

```
// Returns the character code of the
// currently pressed key on the keyboard,
// or 0 if no key is pressed.
keyPressed():
  // uses Memory.peek
```

Gets a character

```
// Waits until a key is pressed and released;
// echoes the character on the screen, advances
// the cursor, and returns the character code.
readChar():
   display the cursor
   // waits until a key is pressed:
   while (keyPressed() = 0)
      do nothing
   c = code of the currently pressed key
   // waits until the key is released:
   while (keyPressed() ≠ 0)
      do nothing
   display c at the current cursor location
   advance the cursor
   return c
```

Gets a string

```
// Displays the message on the screen, gets the next
// line (until a newLine character) from the keyboard,
// and returns its value, as a string.
readLine(message):
   display the message
   str = empty string
   repeat
      c = readChar()
      if (c == newLine):
         display newLine
         return str
      else if (c == backSpace):
            remove the last character from str
            move the cursor back
         else
            str.appendChar(c)
   return str
```

Figure 12.10 Handling input from the keyboard.

Reading a single character (readChar): The elapsed time between the *key pressed* and the subsequent *key released* events is unpredictable. Hence, we have to write code that neutralizes this uncertainty. Also, when users press keys on the keyboard, we want to give feedback as to which keys have been pressed (something that you have probably grown to take for granted). Typically, we want to display some graphical cursor at the screen location where the next input goes, and, after some key has been pressed, we want to echo the inputted character by displaying its bitmap on the screen at the cursor location. All these actions are implemented by the readChar function.

Reading a string (readLine): A multicharacter input typed by the user is considered final after the ENTER key has been pressed, yielding the newLine character. Until the ENTER key is pressed, the user should be allowed to

backspace, delete, and retype previously typed characters. All these actions are accommodated by the readLine function.

As usual, our input-handling solutions are based on a cascading series of abstractions: The high-level program relies on the readLine abstraction, which relies on the readChar abstraction, which relies on the keyPressed abstraction, which relies on the Memory.peek abstraction, which relies on the hardware.

12.2 The Jack OS Specification

The previous section presented algorithms that address various classical operating system tasks. In this section we turn to formally specify one particular operating system—the Jack OS. The Jack operating system is organized in eight classes:

- Math: provides mathematical operations
- String: implements the String type
- Array: implements the Array type
- Memory: handles memory operations
- Screen: handles graphics output to the screen
- Output: handles character output to the screen
- Keyboard: handles input from the keyboard
- Sys: provides execution-related services

The complete OS API is given in appendix 6. This API can be viewed as the OS specification. The next section describes how this API can be implemented using the algorithms presented in the previous section.

12.3 Implementation

Each OS class is a collection of subroutines (constructors, functions, and methods). Most of the OS subroutines are simple to implement and are not discussed here. The remaining OS subroutines are based on the algorithms

presented in section 12.2. The implementation of these subroutines can benefit from some tips and guidelines, which we now turn to present.

Init **functions**: Some OS classes use data structures that support the implementation of some of their subroutines. For each such *OSClass*, these data structures can be declared statically at the class level and initialized by a fucntion which, by convention, we call *OSClass*.init. The init functions are for internal purposes and are not documented in the OS API.

Math

multiply: In each iteration *i* of the *multiplication* algorithm (see figure 12.1), the *i*-th bit of the second multiplicand is extracted. We suggest encapsulating this operation in a helper function bit (x,i) that returns true if the i-th bit of the integer x is 1, and false otherwise. The bit(x,i) function can be easily implemented using shifting operations. Alas, Jack does not support shifting. Instead, it may be convenient to define a fixed static array of length 16, say twoToThe, and set each element *i* to 2 raised to the power of *i*. The array can then be used to support the implementation of bit (x,i). The twoToThe array can be built by the Math.init function.

divide: The *multiplication* and *division* algorithms presented in figures 12.1 and 12.2 are designed to operate on nonnegative integers. Signed numbers can be handled by applying the algorithms to absolute values and setting the sign of the return values appropriately. For the multiplication algorithm, this is not needed: since the multiplicands are given in two's complement, their product will be correct with no further ado.

In the *division* algorithm, y is multiplied by a factor of 2, until $y > x$. Thus y can overflow. The overflow can be detected by checking when y becomes negative.

sqrt: In the *square root* algorithm (figure 12.3), the calculation of $(y+2^j)^2$ can overflow, resulting in an abnormally negative result. This problem can be addressed by changing efficiently the algorithm's if logic to: if $(y+2^j)^2 \le x$ and $(y+2^j)^2 > 0$ then $y = y+2^j$.

String

All the string constants that appear in a Jack program are realized as objects of the String class, whose API is documented in appendix 6. Specifically, each string is implemented as an object consisting of an array of char values, a maxLength property that holds the maximum length of the string, and a length property that holds the actual length of the string.

For example, consider the statement `let str="scooby"`. When the compiler handles this statement, it calls the String constructor, which creates a char array with `maxLength=6` and `Length=6`. If we later call the String method str.eraseLastChar(), the length of the array will become 5, and the string will effectively become "scoob". In general, then, array elements beyond length are not considered part of the string.

What should happen when an attempt is made to add a character to a string whose length equals maxLength? This issue is not defined by the OS specification: the String class may act gracefully and resize the array—or not; this is left to the discretion of individual OS implementations.

intValue, setInt: These subroutines can be implemented using the algorithms presented in figure 12.4. Note that neither algorithm handles negative numbers—a detail that must be handled by the implementation.

newLine, backSpace, doubleQuote: As seen in appendix 5, the codes of these characters are 128, 129, and 34.

The remaining String methods can be implemented straightforwardly by operating on the char array and on the length field that characterizes each String object.

Array

new: In spite of its name, this subroutine is not a constructor but rather a function. Therefore, the implementation of this function must allocate memory space for the new array by explicitly calling the OS function Memory.alloc.

dispose: This void method is called by statements like do arr.dispose(). The dispose implementation deallocates the array by calling the OS function Memory.deAlloc.

Memory

peek, poke: These functions provide direct access to the host memory. How can this low-level access be accomplished using the Jack high-level language? As it turns out, the Jack language includes a trapdoor that enables gaining complete control of the host computer's memory. This trapdoor can be exploited for implementing Memory.peek and Memory.poke using plain Jack programming.

The trick is based on an anomalous use of a reference variable (pointer). Jack is a weakly typed language; among other quirks, it does not prevent the programmer from assigning a constant to a reference variable. This constant can then be treated as an absolute memory address. When the reference variable happens to be an array, this scheme provides indexed access to every word in the host RAM. See figure 12.11.

```
// Creates a Jack-level "proxy" of the RAM:
var Array memory;
let memory = 0;    // No problem . . .
...
// Gets the value of the RAM at address i:
let x = memory[i];
...
// Sets the value of the RAM at address i:
let memory[i] = 17;
...
```

Figure 12.11 A trapdoor enabling complete control of the host RAM from Jack.

Following the first two lines of code, the base of the memory array points to the first address in the computer's RAM (address 0). To get or set the value of the RAM location whose physical address is *i*, all we have to do is

manipulate the array element memory[*i*]. This will cause the compiler to manipulate the RAM location whose address is $0+i$, which is what we want.

Jack arrays are not allocated space on the heap at compile-time but rather at run-time, if and when the array's new function is called. Note that if new were a constructor and not a function, the compiler and the OS would have allocated the new array to some obscure address in the RAM that we cannot control. Like many classical hacks, this trick works because we use the array variable without initializing it properly, as is normally done when using arrays.

The memory array can be declared at the class level and initialized by the Memory.init function. Once this hack is done, the implementation of Memory.peek and Memory.poke becomes trivial.

alloc, deAlloc: These functions can be implemented by either one of the algorithms shown in figures 12.5a and 12.5b. Either *best-fit* or *first-fit* can be used for implementing Memory.deAlloc.

The standard VM mapping on the Hack platform (see section 7.4.1) specifies that the *stack* be mapped on RAM addresses 256 to 2047. Thus the *heap* can start at address 2048.

In order to realize the freeList linked list, the Memory class can declare and maintain a static variable, freeList, as seen in figure 12.12. Although freeList is initialized to the value of heapBase (2048), it is possible that following several alloc and deAlloc operations freeList will become some other address in memory, as illustrated in the figure.

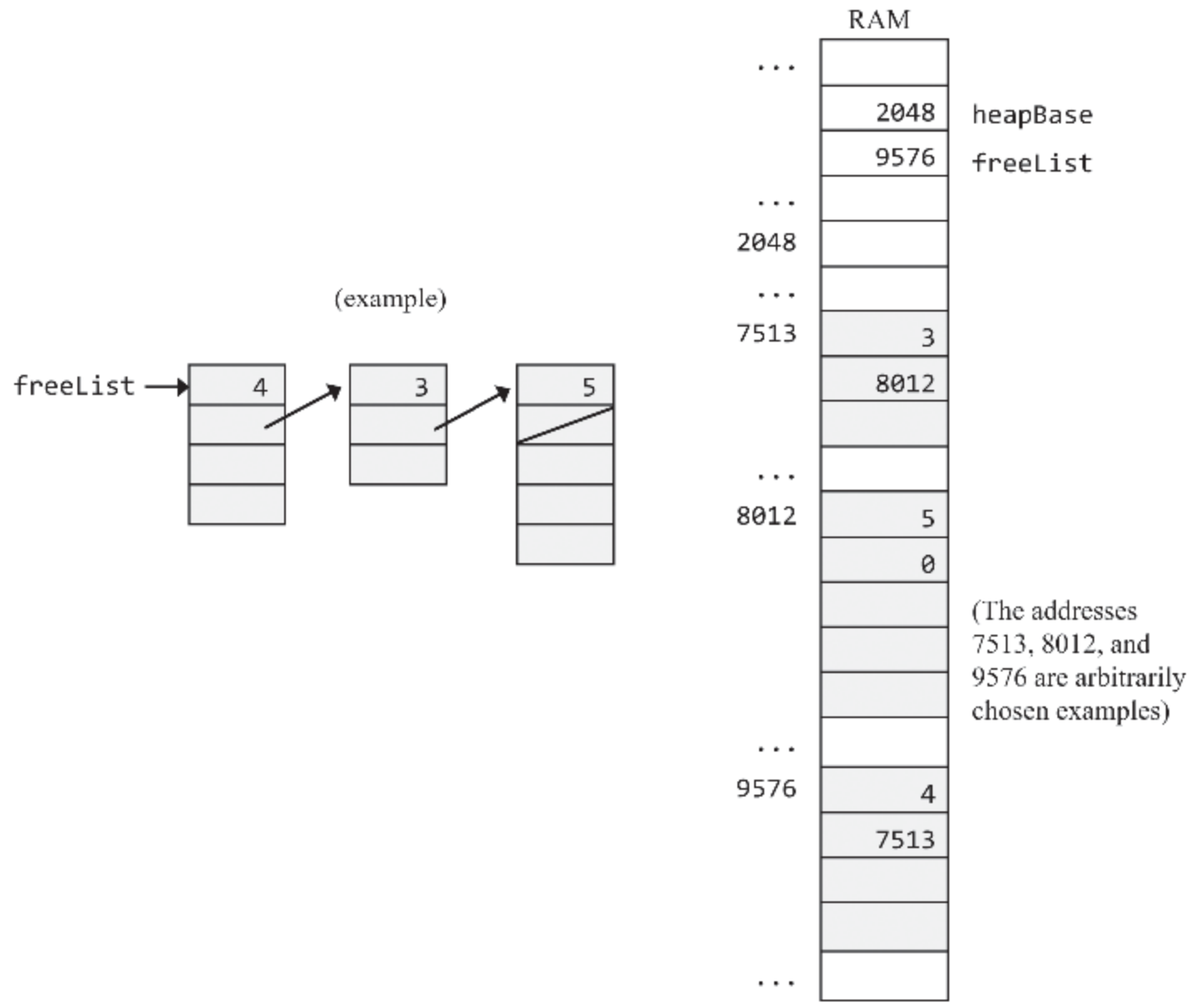


Figure 12.12 Logical view (left) and physical implementation (right) of a linked list that supports dynamic memory allocation.

For efficiency's sake, it is recommended to write Jack code that manages the freeList linked list directly in the RAM, as seen in figure 12.12. The linked list can be initialized by the Memory.init function.

Screen

The Screen class maintains a *current color* that is used by all the drawing functions of the class. The current color can be represented by a static Boolean variable.

drawPixel: Drawing a pixel on the screen can be done using Memory.peek and Memory.poke. The screen memory map of the Hack platform specifies that the pixel at column *col* and row *row* $(0 \le col \le 511, 0 \le row \le 255)$ is mapped to the *col* % 16 bit of memory location $16384 + row \cdot 32 + col/16$. Drawing a single pixel requires changing a single bit in the accessed word (and that bit only).

drawLine: The basic algorithm in figure 12.7 can potentially lead to overflow. However, the algorithm's improved version eliminates the problem.

Some aspects of the algorithm should be generalized for drawing lines that extend to four possible directions. Be reminded that the screen origin (coordinates (0,0)) is at the top-left corner. Therefore, some of the directions and plus/minus operations specified in the algorithm should be modified by your drawLine implementation.

The special yet frequent cases of drawing straight lines, that is, when $dx = 0$ or $dy = 0$,should not be handled by this algorithm. Rather, they should benefit from a separate and optimized implementation.

drawCircle: The algorithm shown in figure 12.8 can potentially lead to overflow. Limiting circle radii to be at most 181 is a reasonable solution.

Output

The Output class is a library of functions for displaying characters. The class assumes a character-oriented screen consisting of 23 rows (indexed 0 … 22, top to bottom) of 64 characters each (indexed 0 … 63, left to right). The top-left character location on the screen is indexed (0,0). A visible cursor, implemented as a small filled square, indicates where the next character will be displayed. Each character is displayed by rendering on the screen a rectangular image, 11 pixels high and 8 pixels wide (which includes margins for character spacing and line spacing). The collection of all the character images is called a *font*.

Font implementation: The design and implementation of a font for the Hack character set (appendix 5) is a drudgery, combining artistic judgment and rote implementation work. The resulting font is a collection of ninety-five rectangular bitmap images, each representing a printable character.

Fonts are normally stored in external files that are loaded and used by the character-drawing package, as needed. In Nand to Tetris, the font is embedded in the OS Output class. For each printable character, we define an array that holds the character's bitmap. The array consists of 11 elements, each corresponding to a row of 8 pixels. Specifically, we set the value of

each array entry *j* to an integer value whose binary representation (bits) codes the 8 pixels appearing in the *j*-th row of the character's bitmap. We also define a static array of size 127, whose index values 32 … 126 correspond to the codes of the printable characters in the Hack character set (entries 0 … 31 are not used). We then set each array entry *i* of that array to the 11-entry array that represents the bitmap image of the character whose character code is *i* (did we mention drudgery?).

The project 12 materials include a skeletal Output class containing Jack code that carries out all the implementation work described above. The given code implements the ninety-five-character font, except for one character, whose design and implementation is left as an exercise. This code can be activated by the Output.init function, which can also initialize the cursor.

printChar: Displays the character at the cursor location and advances the cursor one column forward. To display a character at location (*row*,*col*), where $0 \le row \le 22$ and $0 \le col \le 63$, we write the character's bitmap onto the box of pixels ranging from $11 \cdot row$ to $11 \cdot row + 10$ and from $8 \cdot col$ to $8 \cdot col + 7$.

printString: Can be implemented using a sequence of printChar calls.

printInt: Can be implemented by converting the integer to a string and then printing the string.

Keyboard

The Hack computer memory organization (see section 5.2.6) specifies that the *keyboard memory map* is a single 16-bit memory register located at address 24576.

keyPressed: Can be implemented easily using Memory.peek ().

readChar, readString: Can be implemented by following the algorithms in figure 12.10.

readInt: Can be implemented by reading a string and converting it into an int value using a String method.

Sys

wait: This function is supposed to wait a given number of milliseconds and return. It can be implemented by writing a loop that runs approximately duration milliseconds before terminating. You will have to time your specific computer to obtain a one millisecond wait, as this constant varies from one CPU to another. As a result, your Sys.wait() function will not be portable. The function can be made portable by running yet another configuration function that sets various constants reflecting the hardware specifications of the host platform, but for Nand to Tetris this is not needed.

halt: Can be implemented by entering an infinite loop.

init: According to the Jack language specification (see section 9.2.2), a Jack program is a set of one or more classes. One class must be named Main, and this class must include a function named main. To start running a program, the Main.main function should be called.

The operating system is also a collection of compiled Jack classes. When the computer boots up, we want to start running the operating system and have *it* start running the main program. This chain of command is implemented as follows. According to the Standard VM Mapping on the Hack Platform (section 8.5.2), the VM translator writes bootstrap code (in machine language) that calls the OS function Sys.init. This bootstrap code is stored in the ROM, starting at address 0. When we reset the computer, the program counter is set to 0, the bootstrap code starts running, and the Sys.init function is called.

With that in mind, Sys.init should do two things: call all the init functions of the other OS classes, and then call Main.main.

From this point onward the user is at the mercy of the application program, and the Nand to Tetris journey has come to an end. We hope that you enjoyed the ride!

12.4 Project

Objective: Implement the operating system described in the chapter.

Contract: Implement the operating system in Jack, and test it using the programs and testing scenarios described below. Each test program uses a subset of OS services. Each of the OS classes can be implemented and unit-tested in isolation, in any order.

Resources: The main required tool is Jack—the language in which you will develop the OS. You will also need the supplied Jack compiler for compiling your OS implementation, as well as the supplied test programs, also written in Jack. Finally, you'll need the supplied VM emulator, which is the platform on which the tests will be executed.

Your projects/12 folder includes eight skeletal OS class files named Math.jack, String.jack, Array.jack, Memory.jack, Screen.jack, Output.jack, Keyboard.jack, and Sys.jack. Each file contains the signatures of all the class subroutines. Your task is completing the missing implementations.

The VM emulator: Operating system developers often face the following chicken-and-egg dilemma: How can we possibly test an OS class in isolation, if the class uses the services of other OS classes not yet developed? As it turns out, the VM emulator is perfectly positioned to support unit-testing the OS, one class at a time.

Specifically, the VM emulator features an executable version of the OS, written in Java. When a VM command call foo is found in the loaded VM code, the emulator proceeds as follows. If a VM function named foo exists in the loaded code base, the emulator executes its VM code. Otherwise, the emulator checks whether foo is one of the built-on OS functions. If so, it executes foo's built-in implementation. This convention is ideally suited for supporting the testing strategy that we now turn to describe.

Testing Plan

Your projects/12 folder includes eight test folders, named MathTest, MemoryTest, …, for testing each one the eight OS classes Math, Memory, …. Each folder contains a Jack program, designed to test (by using) the services of the corresponding OS class. Some folders contain test scripts and compare

files, and some contain only a .jack file or files. To test your implementation of the OS class *Xxx*.jack, you may proceed as follows:

- Inspect the supplied *Xxx*Test/*.jack code of the test program. Understand which OS services are tested and how they are tested.
- Put the OS class *Xxx*.jack that you developed in the *Xxx*Test folder.
- Compile the folder using the supplied Jack compiler. This will result in translating both your OS class file and the .jack file or files of the test program into corresponding .vm files, stored in the same folder.
- If the folder includes a .tst test script, load the script into the VM emulator; otherwise, load the folder into the VM emulator.
- Follow the specific testing guidelines given below for each OS class.

Memory, Array, Math: The three folders that test these classes include test scripts and compare files. Each test script begins with the command load. This command loads all the .vm files in the current folder into the VM emulator. The next two commands in each test script create an output file and load the supplied compare file. Next, the test script proceeds to execute several tests, comparing the test results to those listed in the compare file. Your job is making sure that these comparisons end successfully.

Note that the supplied test programs don't comprise a full test of Memory.alloc and Memory.deAlloc. A complete test of these memory management functions requires inspecting internal implementation details not visible in user-level testing. If you want to do so, you can test these functions by using step-by-step debugging and by inspecting the state of the host RAM.

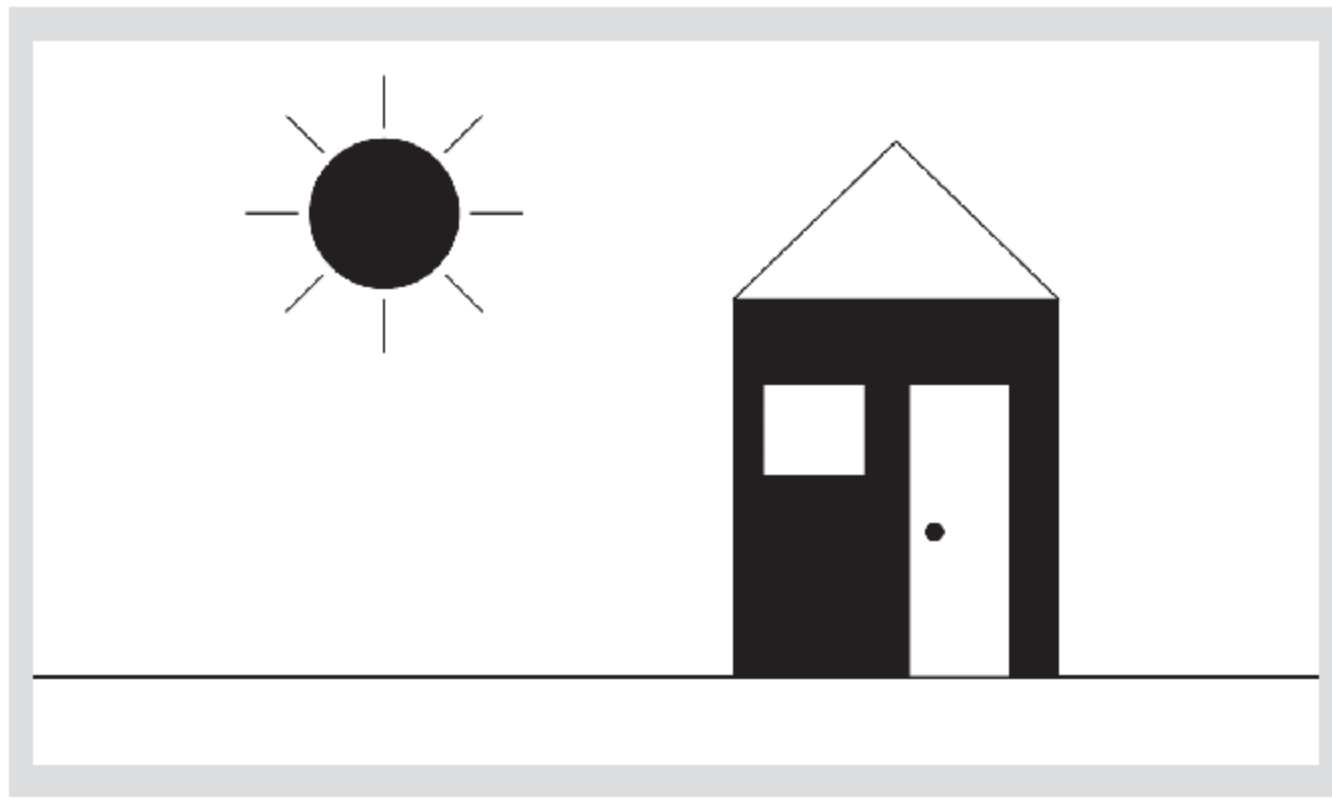
String: Execution of the supplied test program should yield the following output:

```
new,appendChar: abcde
setInt: 12345
setInt: -32767
length: 5
charAt[2]: 99
setCharAt(2,'-'): ab-de
eraseLastChar: ab-d
intValue: 456
intValue: -32123
backSpace: 129
doubleQuote: 34
newLine: 128
```

Output: Execution of the supplied test program should yield the following output:

```
A                                                                    B

0123456789
ABCDEFGHIJKLMNOPQRSTUVWXYZ abcdefghijklmnopqrstuvwxyz
!#$%&'()*+,-./:;<=>?@[]^_`{|}~"
-12346789




C                                                                    D
```

Screen: Execution of the supplied test program should yield the following output:



Keyboard: This OS class is tested by a test program that effects user-program interaction. For each function in the Keyboard class (keyPressed, readChar, readLine, readInt) the program prompts the user to press some keys. If the OS function is implemented correctly and the requested keys are pressed, the program prints ok and proceeds to test the next OS function. Otherwise, the program repeats the request. If all requests end successfully, the program prints Test ended successfully. At this point the screen should show the following output:

```
keyPressed test:
Please press the 'Page Down' key
ok
readChar test:
(Verify that the pressed character is echoed to the screen)
Please press the number '3': 3
ok
readLine test:
(Verify echo and usage of 'backspace')
Please type 'JACK' and press enter: JACK
ok
readInt test:
(Verify echo and usage of 'backspace')
Please type '-32123' and press enter: -32123
ok

Test completed successfully
```

Sys

The supplied .jack file tests the Sys.wait function. The program requests the user to press a key (any key) and waits two seconds, using a call to Sys.wait. It then prints a message on the screen. Make sure that the time that elapses between your release of the key and the appearance of the printed message is about two seconds.

The Sys.init function is not tested explicitly. However, recall that it performs all the necessary OS initializations and then calls the Main.main function of each test program. Therefore, we can assume that nothing will work properly unless Sys.init is implemented correctly.

Complete Test

After testing successfully each OS class in isolation, test your entire OS implementation using the Pong game introduced earlier in the book. The source code of Pong is available in projects/11/Pong. Put your eight OS .jack files in the Pong folder, and compile the folder using the supplied Jack compiler. Next, load the Pong folder into the VM emulator, execute the game, and ensure that it works as expected.

12.5 Perspective

This chapter presented a subset of basic services that can be found in most operating systems. For example, managing memory, driving I/O devices, supplying mathematical operations not implemented in hardware, and implementing abstract data types like the string abstraction. We have chosen to call this standard software library an *operating system* to reflect its two main functions: encapsulating the gory hardware details, omissions, and idiosyncrasies in transparent software services, and enabling compilers and application programs to use these services via clean interfaces. However, the gap between what we have called an OS and industrial-strength operating systems remains wide.

For starters, our OS lacks some of the basic services most closely associated with operating systems. For example, our OS supports neither multi-threading nor multiprocessing; in contrast, the kernel of most

operating systems is devoted to exactly that. Our OS supports no mass storage devices; in contrast, the main data store handled by operating systems is a file system abstraction. Our OS features neither a command-line interface (as in a Unix shell) nor a graphical interface consisting of windows and menus. In contrast, this is the operating system interface that users expect to see and interact with. Numerous other services commonly found in operating systems are not present in our OS, like security, communication, and more.

Another notable difference lies in the liberal way in which our OS operations are invoked. Some OS operations, for example, `peek` and `poke`, give the programmer complete access to the host computer resources. Clearly, inadvertent or malicious use of such functions can cause havoc. Therefore, many OS services are considered privileged, and accessing them requires a security mechanism that is more elaborate than a simple function call. In contrast, in the Hack platform, there is no difference between OS code and user code, and operating system services run in the same user mode as that of application programs.

In terms of efficiency, the algorithms that we presented for multiplication and division were standard. These algorithms, or variants thereof, are typically implemented in hardware rather than in software. The running time of these algorithms is $O(n)$ addition operations. Since adding two n-bit numbers requires $O(n)$ bit operations (gates in hardware), these algorithms end up requiring $O(n2)$ bit operations. There exist multiplication and division algorithms whose running time is asymptotically significantly faster than $O(n2)$, and for a large number of bits these algorithms are more efficient. In a similar fashion, optimized versions of the geometric operations that we presented, like line drawing and circle drawing, are often implemented in special graphics-acceleration hardware.

Like every hardware and software system developed in Nand to Tetris, our goal is not to provide a complete solution that addresses all wants and needs. Rather, we strive to build a working implementation and a solid understanding of the system's *foundation*, and then propose ways to extend it further. Some of these optional extension projects are mentioned in the next and final chapter in the book.

13 More Fun to Go

We shall not cease from exploration, and at the end we will arrive where we started, and know the place for the first time.

—T. S. Eliot (1888–1965)

Congratulations! We've finished the construction of a complete computing system, starting from first principles. We hope that you enjoyed this journey. Let us, the authors of this book, share a secret with you: We suspect that we enjoyed writing the book even more. After all, we got to design this computing system, and design is often the "funnest" part of every project. We are sure that some of you, adventurous learners, would like to get in on that design action. Maybe you would like to improve the architecture; maybe you have ideas for adding new features here and there; maybe you envision a wider system. And then, maybe, you want to be in the navigator's seat and decide where to go, not just how to get there.

Almost every aspect of the Jack/Hack system can be improved, optimized, or extended. For example, the assembly language, the Jack language, and the operating system can be modified and extended by rewriting portions of your respective assembler, compiler, and OS implementations. Other changes would likely require modifying the supplied software tools as well. For example, if you change the hardware specification or the VM specification, then you would likely want to modify the respective emulators. Or, if you want to add more input or output devices to the Hack computer, you would probably need to model them by writing new built-in chips.

In order to allow complete flexibility of modification and extension, we made the source code of all the supplied tools publicly available. All our

code is 100 percent Java, except for some of the batch files used for starting the software on some platforms. The software and its documentation are available at www.nand2tetris.org. You are welcome to modify and extend all our tools as you deem desirable for your latest idea—and then share them with others, if you want. We hope that our code is written and documented well enough to make modifications a satisfying experience. In particular, we wish to mention that the supplied hardware simulator has a simple and well-documented interface for adding new built-in chips. This interface can be used for extending the simulated hardware platform with, say, mass storage or communications devices.

While we cannot even start to imagine what your design improvements may be, we can briefly sketch some of the ones we were thinking of.

Hardware Realizations

The hardware modules presented in the book were implemented either in HDL or as supplied executable software modules. This, in fact, is how hardware is actually designed. However, at some point, the HDL designs are typically committed to silicon, becoming "real" computers. Wouldn't it be nice to make Hack or Jack run on a real hardware platform made of atoms rather than bits?

Several different approaches may be taken toward this goal. On one extreme, you can attempt to implement the Hack platform on an FPGA board. This would require rewriting all the chip definitions using a mainstream Hardware Description Language and then dealing with implementation issues related to realizing the RAM, the ROM, and the I/O devices on the host board. One such step-by-step optional project, developed by Michael Schröder, is referred to in the www.nand2tetris.org website. Another extreme approach may be to attempt emulating Hack, the VM, or even the Jack platform on an existing hardware device like a cell phone. It seems that any such project would want to reduce the size of the Hack screen to keep the cost of the hardware resources reasonable.

Hardware Improvements

Although Hack is a *stored program* computer, the program that it runs must be prestored in its ROM device. In the present Hack architecture, there is no way of loading another program into the computer, except for simulating the replacement of the entire physical ROM chip.

Adding a *load program* capability in a balanced way would likely involve changes at several levels of the hierarchy. The Hack hardware should be modified to allow loaded programs to reside in the writable RAM rather than in the existing ROM. Some type of permanent storage, like a built-in mass storage chip, should probably be added to the hardware to allow storage of programs. The operating system should be extended to handle this permanent storage device, as well as new logic for loading and running programs. At this point an OS user interface *shell* would come in handy, providing file and program management commands.

High-Level Languages

Like all professionals, programmers have strong feelings about their tools—programming languages—and like to personalize them. And indeed, the Jack language, which leaves much to be desired, can be significantly improved. Some changes are simple, some are more involved, and some—like adding inheritance—would likely require modifying the VM specification as well.

Another option is realizing more high-level languages over the Hack platform. For example, how about implementing Scheme?

Optimization

Our Nand to Tetris journey has almost completely sidestepped optimization issues (except for the operating system, which introduced some efficiency measures). Optimization is a great playfield for hackers. You can start with local optimizations in the hardware, or in the compiler, but the best bang for the buck will come from optimizing the VM translator. For example, you may want to reduce the size of the generated assembly code, and make it

more efficient. Ambitious optimizations on a more global scale will involve changing the specifications of the machine language or the VM language.

Communications

Wouldn't it be nice to connect the Hack computer to the Internet? This could be done by adding a built-in communication chip to the hardware and writing an OS class for dealing with it and for handling higher-level communication protocols. Some other programs would need to talk with the built-in communication chip, providing an interface to the Internet. For example, an HTTP-speaking web browser in Jack seems like a feasible and worthy project.

These are some of our design itches—what are yours?

Appendix 1: Boolean Function Synthesis

By logic we prove, by intuition we discover.

—Henri Poincaré (1854–1912)

In chapter 1 we made the following claims, without proof:

- Given a truth table representation of a Boolean function, we can synthesize from it a Boolean expression that realizes the function.
- Any Boolean function can be expressed using only And, Or, and Not operators.
- Any Boolean function can be expressed using only Nand operators.

This appendix provides proofs for these claims, and shows that they are interrelated. In addition, the appendix illustrates the process by which Boolean expressions can be simplified using Boolean algebra.

A1.1 Boolean Algebra

The Boolean operators And, Or, and Not have useful algebraic properties. We present some of these properties briefly, noting that their proofs can be easily derived from the relevant truth tables listed in figure 1.1 of chapter 1.

Commutative laws: x And $y = y$ And x

x Or $y = y$ Or x

Associative laws: x And (y And z) = (x And y) And z

x Or (y Or z) = (x Or y) Or z

Distributive laws: x And (y Or z) = (x And y) Or (x And z)

x Or (y And z) = (x Or y) And (x Or z)

De Morgan laws: Not(x And y) = Not(x) Or Not(y)

Not(x Or y) = Not(x) And Not(y)

Idempotent laws: x And $x = x$

x Or $x = x$

These algebraic laws can be used to simplify Boolean functions. For example, consider the function Not (Not (x) And Not (x Or y)). Can we reduce it to a simpler form? Let's try and see what we can come up with:

Not(Not(x) And Not(x Or y)) = // by De Morgan law:

Not(Not(x) And (Not(x) And Not(y))) = // by the associative law:

Not((Not(x) And Not(x)) And Not(y)) = // by the idempotent law:

Not(Not(x) And Not(y)) = // by De Morgan law:

Not(Not(x)) Or Not(Not(y)) = // by double negation:

x Or y

Boolean simplifications like the one just illustrated have significant practical implications. For example, the original Boolean expression Not (Not (x) And Not (x Or y)) can be implemented in hardware using five logic gates, whereas the simplified expression x Or y can be implemented using a single logic gate. Both expressions deliver the same functionality, but the latter is five times more efficient in terms of cost, energy, and speed of computation.

Reducing a Boolean expression into a simpler one is an art requiring experience and insight. Various reduction tools and techniques are available, but the problem remains challenging. In general, reducing a Boolean expression into its simplest form is an *NP-hard* problem.

A1.2 Synthesizing Boolean Functions

Given a truth table of a Boolean function, how can we construct, or synthesize, a Boolean expression that represents this function? And, come to think of it, are we *guaranteed* that every Boolean function represented by a truth table can also be represented by a Boolean expression?

These questions have very satisfying answers. First, yes: every Boolean function can be represented by a Boolean expression. Moreover, there is a constructive algorithm for doing just that. To illustrate, refer to figure A1.1, and focus on its leftmost four columns. These columns specify a truth table definition of some three-variable function $f(x,y,z)$. Our goal is to synthesize from these data a Boolean expression that represents this function.

x	y	z	$f(x,y,z)$	$f_3(x,y,z)$	$f_5(x,y,z)$	$f_7(x,y,z)$
0	0	0	0	0	0	0
0	0	1	0	0	0	0
0	1	0	1	1	0	0
0	1	1	0	0	0	0
1	0	0	1	0	1	0
1	0	1	0	0	0	0
1	1	0	1	0	0	1
1	1	1	0	0	0	0

$f_3(x,y,z) = \text{Not}(x)\ \text{And}\ y\ \text{And}\ \text{Not}(z)$
$f_5(x,y,z) = x\ \text{And}\ \text{Not}(y)\ \text{And}\ \text{Not}(z)$
$f_7(x,y,z) = x\ \text{And}\ y\ \text{And}\ \text{Not}(z)$
$f(x,y,z) = f_3(x,y,z)\ \text{Or}\ f_5(x,y,z)\ \text{Or}\ f_7(x,y,z)$

Figure A1.1 Synthesizing a Boolean function from a truth table (example).

We'll describe the synthesis algorithm by following its steps in this particular example. We start by focusing only on the truth table's rows in which the function's value is 1. In the function shown in figure A1.1, this happens in rows 3, 5, and 7. For each such row i, we define a Boolean

function f_i that returns 0 for all the variable values except for the variable values in row i, for which the function returns 1. The truth table in figure A1.1 yields three such functions, whose truth table definitions are listed in the three rightmost columns in the table. Each of these functions f_i can be represented by a conjunction (And-ing) of three terms, one term for each variable x, y, and z, each being either the variable or its negation, depending on whether the value of this variable is 1 or 0 in row i. This construction yields the three functions f_3, f_5, and f_7, listed at the bottom of the table. Since these functions describe the only cases in which the Boolean function f evaluates to 1, we conclude that f can be represented by the Boolean expression $f(x, y, z) = f_3(x, y, z)$ Or $f_5(x, y, z)$ Or $f_7(x, y, z)$. Spelling it out: $f(x, y, z)$ =(Not (x) And y And Not (z)) Or (x And Not (y) And Not (z)) Or (x And y And Not (z)).

Avoiding tedious formality, this example suggests that any Boolean function can be systematically represented by a Boolean expression that has a very specific structure: it is the disjunction (Or-ing) of all the conjunctive (And-ing) functions f_i whose construction was just described. This expression, which is the Boolean version of a sum of products, is sometimes referred to as the function's *disjunctive normal form* (DNF).

Note that if the function has many variables, and thus the truth table has exponentially many rows, the resulting DNF may be long and cumbersome. At this point, Boolean algebra and various reduction techniques can help transform the expression into a more efficient and workable representation.

A1.3 The Expressive Power of Nand

As our *Nand to Tetris* title suggests, every computer can be built using nothing more than Nand gates. There are two ways to support this claim. One is to actually build a computer from Nand gates only, which is exactly what we do in part I of the book. Another way is to provide a formal proof, which is what we'll do next.

Lemma 1: Any Boolean function can be represented by a Boolean expression containing only And, Or, and Not operators.

Proof: Any Boolean function can be used to generate a corresponding truth table. And, as we've just shown, any truth table can be used for synthesizing a DNF, which is an Or-ing of And-ings of variables and their negations. It follows that any Boolean function can be represented by a Boolean expression containing only And, Or, and And operators.

In order to appreciate the significance of this result, consider the infinite number of functions that can be defined over *integer numbers* (rather than binary numbers). It would have been nice if every such function could be represented by an algebraic expression involving only addition, multiplication, and negation. As it turns out, the vast majority of integer functions, for example, $f(x) = 2x$ for $x \neq 7$ and $f(7) = 312$, cannot be expressed using a close algebraic form. In the world of *binary numbers*, though, due to the finite number of values that each variable can assume (0 or 1), we do have this attractive property that every Boolean function *can* be expressed using nothing more than And, Or, and Not operators. The practical implication is immense: any computer can be built from nothing more than And, Or, and Not gates.

But, can we do better than this?

Lemma 2: Any Boolean function can be represented by a Boolean expression containing only Not and And operators.

Proof: According to De Morgan law, the Or operator can be expressed using the Not and And operators. Combining this result with Lemma 1, we get the proof.

Pushing our luck further, can we do better than this?

Theorem: Any Boolean function can be represented by a Boolean expression containing only Nand operators.

Proof: An inspection of the Nand truth table (the second-to-last row in figure 1.2 in chapter 1) reveals the following two properties:

- Not (x) = Nand (x, x)

  In words: If you set both the x and y variables of the Nand function to the same value (0 or 1), the function evaluates to the negation of that

value.

- And (x, y) = Not (Nand (x, y))

  It is easy to show that the truth tables of both sides of the equation are identical. And, we've just shown that Not can be expressed using Nand.

Combining these two results with Lemma 2, we get that any Boolean function can be represented by a Boolean expression containing only Nand operators.

This remarkable result, which may well be called the fundamental theorem of logic design, stipulates that computers can be built from one atom only: a logic gate that realizes the Nand function. In other words, if we have as many Nand gates as we want, we can wire them in patterns of activation that implement any given Boolean function: all we have to do is figure out the right wiring.

Indeed, most computers today are based on hardware infrastructures consisting of billions of Nand gates (or Nor gates, which have similar generative properties). In practice, though, we don't have to limit ourselves to Nand gates only. If electrical engineers and physicists can come up with efficient and low-cost physical implementations of other elementary logic gates, we will happily use them directly as primitive building blocks. This pragmatic observation does not take away anything from the theorem's importance.

Appendix 2: Hardware Description Language

Intelligence is the faculty of making artificial objects, especially tools to make tools.
—Henry Bergson (1859–1941)

This appendix has two main parts. Sections A2.1–A2.5 describe the HDL language used in the book and in the projects. Section A2.6, named HDL Survival Guide, provides a set of essential tips for completing the hardware projects successfully.

A Hardware Description Language (HDL) is a formalism for defining *chips*: objects whose *interfaces* consist of input and output *pins* that carry binary signals, and whose *implementations* are connected arrangements of other, lower-level chips. This appendix describes the HDL that we use in Nand to Tetris. Chapter 1 (in particular, section 1.3) provides essential background that is a prerequisite to this appendix.

A2.1 HDL Basics

The HDL used in Nand to Tetris is a simple language, and the best way to learn it is to play with HDL programs using the supplied hardware simulator. We recommend starting to experiment as soon as you can, beginning with the following example.

Example: Suppose we have to check whether three 1-bit variables a, b, c have the same value. One way to check this three-way equality is to evaluate the Boolean function $\neg((a \neq b) \vee (b \neq c))$. Noting that the binary

operator *not-equal* can be realized using a Xor gate, we can implement this function using the HDL program shown in figure A2.1.

interface / implementation

```
/** If the three given bits are equal, sets out to 1; else sets out to 0. */
CHIP Eq3 {
    IN  a, b, c;
    OUT out;
    PARTS:
    Xor(a=a, b=b, out=neq1);          // Xor(a,b) → neq1
    Xor(a=b, b=c, out=neq2);          // Xor(b,c) → neq2
    Or (a=neq1, b=neq2, out=outOr); // Or(neq1,neq2) → outOr
    Not(in=outOr, out=out);           // Not(outOr) → out
}
```

Figure A2.1 HDL program example.

The Eq3.hdl implementation uses four *chip-parts*: two Xor gates, one Or gate, and one Not gate. To realize the logic expressed by $\neg((a \neq b) \vee (b \neq c))$, the HDL programmer connects the chip-parts by creating, and naming, three *internal pins*: neq1, neq2, and outOr.

Unlike internal pins, which can be created and named at will, the HDL programmer has no control over the names of the input and output pins. These are normally supplied by the chips' architects and documented in given APIs. For example, in Nand to Tetris, we provide *stub files* for all the chips that you have to implement. Each stub file contains the chip interface, with a missing implementation. The contract is as follows: You are allowed to do whatever you want *under* the PARTS statement; you are not allowed to change anything *above* the PARTS statement.

In the Eq3 example, it so happens that the first two inputs of the Eq3 chip and the two inputs of the Xor and Or chip-parts have the same names (a and b). Likewise, the output of the Eq3 chip and that of the Not chip-part happen to have the same name (out). This leads to bindings like a=a, b=b, and out=out. Such bindings may look peculiar, but they occur frequently in HDL programs, and one gets used to them. Later in the appendix we'll give a simple rule that clarifies the meaning of these bindings.

Importantly, the programmer need not worry about how chip-parts are implemented. The chip-parts are used like black box abstractions, allowing the programmer to focus only on how to arrange them judiciously in order

to realize the chip function. Thanks to this modularity, HDL programs can be kept short, readable, and amenable to unit testing.

HDL-based chips like Eq3.hdl can be tested by a computer program called *hardware simulator*. When we instruct the simulator to evaluate a given chip, the simulator evaluates all the chip-parts specified in its PARTS section. This, in turn, requires evaluating *their* lower-level chip-parts, and so on. This recursive descent can result in a huge hierarchy of downward-expanding chip-parts, all the way down to the terminal Nand gates from which all chips are made. This expensive drill-down can be averted using *built-in chips*, as we'll explain shortly.

HDL is a declarative language: HDL programs can be viewed as textual specifications of chip diagrams. For each chip *chipName* that appears in the diagram, the programmer writes a *chipName* (...) statement in the HDL program's PARTS section. Since the language is designed to describe *connections* rather than *processes*, the order of the PARTS statements is insignificant: as long as the chip-parts are connected correctly, the chip will function as stated. The fact that HDL statements can be reordered without affecting the chip's behavior may look odd to readers who are used to conventional programming. Remember: HDL is not a programming language; it's a specification language.

White space, comments, case conventions: HDL is case-sensitive: foo and Foo represent two different things. HDL keywords are written in uppercase letters. Space characters, newline characters, and comments are ignored. The following comment formats are supported:

```
//  Comment to end of line
/*  Comment until closing */
/** API documentation comment */
```

Pins: HDL programs feature three types of *pins*: input pins, output pins, and internal pins. The latter pins serve to connect outputs of chip-parts to inputs of other chip-parts. Pins are assumed by default to be single-bit, carrying 0 or 1 values. Multi-bit *bus* pins can also be declared and used, as described later in this appendix.

Names of chips and pins may be any sequence of letters and digits not starting with a digit (some hardware simulators disallow using hyphens). By convention, chip and pin names start with a capital letter and a lowercase letter, respectively. For readability, names can include uppercase letters, for example, xorResult. HDL programs are stored in .hdl files. The name of the chip declared in the HDL statement CHIP *Xxx* must be identical to the prefix of the file name *Xxx*.hdl.

Program structure: An HDL program consists of an *interface* and an *implementation*. The interface consists of the chip's API documentation, chip name, and names of its input and output pins. The implementation consists of the statements below the PARTS keyword. The overall program structure is as follows:

```
/** API documentation: what the chip does. */
CHIP ChipName {
     IN inputPin1, inputPin2, ... ;
     OUT outputPin1, outputPin2, ... ;

PARTS:
    // Here comes the implementation.
}
```

Parts: The chip implementation is an unordered sequence of chip-part statements, as follows:

```
PARTS:
chipPart(connection, ... , connection);
chipPart(connection, ... , connection);
...
```

Each *connection* is specified using the binding *pin*1 = *pin*2, where *pin*1 and *pin*2 are input, output, or internal pin names. These connections can be visualized as "wires" that the HDL programmer creates and names, as needed. For each "wire" connecting *chipPart*1 and *chipPart*2 there is an internal pin that appears twice in the HDL program: once as a *sink* in some

*chipPart*1(…) statement, and once as a *source* in some other *chipPart*2 (…) statement. For example, consider the following statements:

```
chipPart1(..., out = v,...);          // out of chipPart1 feeds the internal pin v
chipPart2(..., in = v, ...);          // in of chipPart2 is fed from v
chipPart3(..., in1 = v, ..., in2 = v,...);   // in1 and in2 of chipPart3 are also fed from v
```

Pins have fan-in 1 and unlimited fan-out. This means that a pin can be fed from a single source only, yet it can feed (through multiple connections) one or more pins in one or more chip-parts. In the above example, the internal pin `v` simultaneously feeds three inputs. This is the HDL equivalent of *forks* in chip diagrams.

The meaning of a = a: Many chips in the Hack platform use the same pin names. As shown in figure A2.1, this leads to statements like `Xor(a=a, b=b, out=neq1)`. The first two connections feed the `a` and `b` inputs of the implemented chip (`Eq3`) into the `a` and `b` inputs of the `Xor` chip-part. The third connection feeds the `out` output of the `Xor` chip-part to the internal pin `neq1`. Here is a simple rule that helps sort things out: In every chip-part statement, the left side of each = binding always denotes an input or output pin *of the chip-part*, and the right side always denotes an input, output, or internal pin *of the implemented chip*.

A2.2 Multi-Bit Buses

Each input, output, or internal pin in an HDL program may be either a single-bit value, which is the default, or a multi-bit value, referred to as a *bus*.

Bit numbering and bus syntax: Bits are numbered from right to left, starting with 0. For example, `sel=110`, implies that `sel[2]=1`, `sel[1]=1`, and `sel[0]=0`.

Input and output bus pins: The bit widths of these pins are specified when they are declared in the chip's IN and OUT statements. The syntax is x[*n*], where x and *n* declare the pin's name and bit width, respectively.

Internal bus pins: The bit widths of internal pins are deduced implicitly from the bindings in which they are declared, as follows,

```
chipPart1(…, x[i] = u, …);
chipPart2(…, x[i..j] = v, …);
```

where x is an input or output pin of the chip-part. The first binding defines u to be a single-bit internal pin and sets its value to x[*i*]. The second binding defines v to be an internal bus-pin of width $j-i+1$ bits and sets its value to the bits indexed *i* to *j* (inclusive) of bus-pin x.

Unlike input and output pins, internal pins (like u and v) may not be subscripted. For example, u[*i*] is not allowed.

True/false buses: The constants true (1) and false (0) may also be used to define buses. For example, suppose that x is an 8-bit bus-pin, and consider this statement:

```
chipPart(…, x[0..2] = true, …, x[6..7] = true, …);
```

This statement sets x to the value 11000111. Note that unaffected bits are set by default to false (0). Figure A2.2 gives another example.

```
// Sets out = Not(in), bitwise
CHIP Not8 {
    IN  in[8];
    OUT out[8];
    ...
}
```

```
CHIP Foo {
    ...
    PARTS
    ...
    Not8(in[0..1]  = true,
         in[3..5]  = six,
         in[7]     = true,
         out[3..7] = out1,
         ...              );
    ...
}
```

Assumption: `six` is an internal pin, containing the value `110`.

`out1` is an internal pin, created by the `Not8` chip-part statement.

Below: the resulting contents of the `in` input of `Not8`, and of `out1`.

	7	6	5	4	3	2	1	0
in:	1	0	1	1	0	0	1	1

	4	3	2	1	0
out1:	0	1	0	0	1

Figure A2.2 Buses in action (example).

A2.3 Built-In Chips

Chips can have either a *native* implementation, written in HDL, or a *built-in* implementation, supplied by an executable module written in a high-level programming language. Since the Nand to Tetris hardware simulator was written in Java, it was convenient to realize the built-in chips as Java classes. Thus, before building, say, a Mux chip in HDL, the user can load a built-in Mux chip into the hardware simulator and experiment with it. The behavior of the built-in Mux chip is supplied by a Java class file named Mux.class, which is part of the simulator's software.

The Hack computer is made from about thirty generic chips, listed in appendix 4. Two of these chips, Nand and DFF, are considered *given*, or *primitive*, akin to axioms in logic. The hardware simulator realizes given chips by invoking their built-in implementations. Therefore, in Nand to Tetris, Nand and DFF can be used without building them in HDL.

Projects 1, 2, 3, and 5 evolve around building HDL implementations of the remaining chips listed in appendix 4. All these chips, except for the CPU and Computer chips, also have built-in implementations. This was done in order to facilitate behavioral simulation, as explained in chapter 1.

The built-in chips—a library of about thirty *chipName*.class files—are supplied in the nand2tetris/tools/builtInChips folder in your computer. Built-in chips have HDL interfaces identical to those of regular HDL chips.

Therefore, each .class file is accompanied by a corresponding .hdl file that provides the built-in chip interface. Figure A2.3 shows a typical HDL definition of a built-in chip.

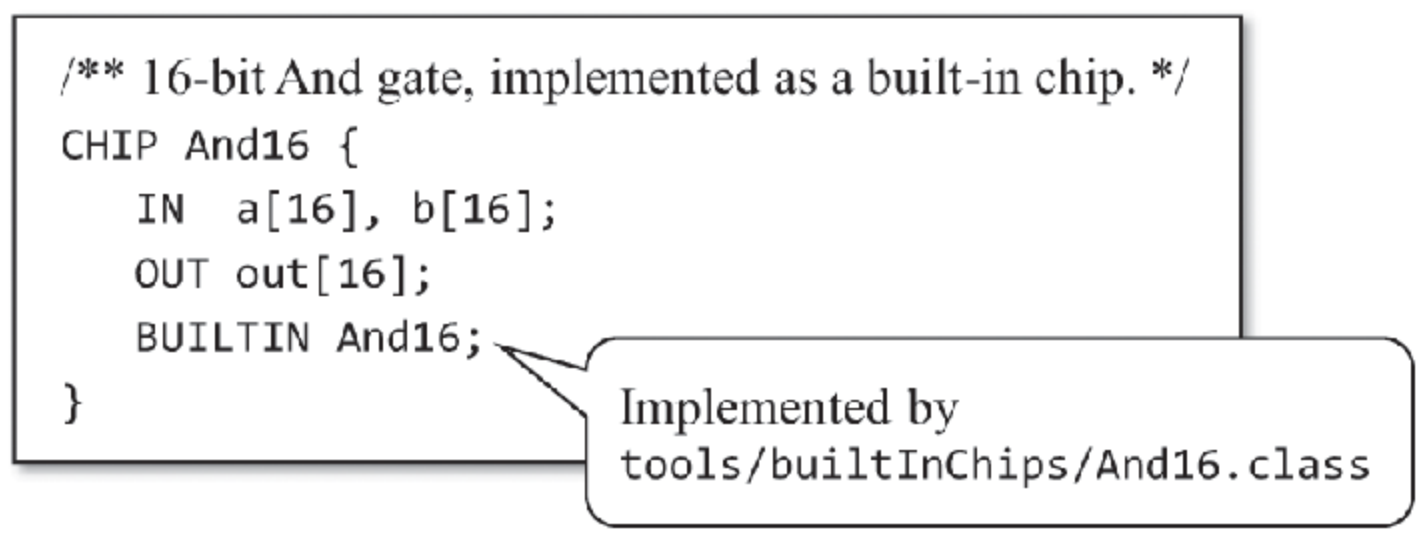


Figure A2.3 Built-in chip definition example.

It's important to remember that the supplied hardware simulator is a general-purpose tool, whereas the Hack computer built in Nand to Tetris is a specific hardware platform. The hardware simulator can be used for building gates, chips, and platforms that have nothing to do with Hack. Therefore, when discussing the notion of built-in chips, it helps to broaden our perspective and describe their general utility for supporting any possible hardware construction project. In general, then, built-in chips provide the following services:

Foundation: Built-in chips can provide supplied implementations of chips that are considered *given*, or *primitive*. For example, in the Hack computer, Nand and DFF are given.

Efficiency: Some chips, like RAM units, consist of numerous lower-level chips. When we use such chips as chip-parts, the hardware simulator has to evaluate them. This is done by evaluating, recursively, all the lower-level chips from which they are made. This results in slow and inefficient simulation. The use of built-in chip-parts instead of regular, HDL-based chips speeds up the simulation considerably.

Unit testing: HDL programs use chip-parts abstractly, without paying attention to their implementation. Therefore, when building a new chip, it is

always recommended to use built-in chip-parts. This practice improves efficiency and minimizes errors.

Visualization: If the designer wants to allow users to "see" how chips work, and perhaps change the internal state of the simulated chip interactively, he or she can supply a built-in chip implementation that features a graphical user interface. This GUI will be displayed whenever the built-in chip is loaded into the simulator or invoked as a chip-part. Except for these visual side effects, GUI-empowered chips behave, and can be used, just like any other chip. Section A2.5 provides more details about GUI-empowered chips.

Extension: If you wish to implement a new input/output device or create a new hardware platform altogether (other than Hack), you can support these constructions with built-in chips. For more information about developing additional or new functionality, see chapter 13.

A2.4 Sequential Chips

Chips can be either *combinational* or *sequential*. Combinational chips are time independent: they respond to changes in their inputs instantaneously. Sequential chips are time dependent, also called *clocked*: when a user or a test script changes the inputs of a sequential chip, the chip outputs may change only at the beginning of the next *time unit*, also called a *cycle*. The hardware simulator effects the progression of time using a simulated clock.

The clock: The simulator's two-phase clock emits an infinite sequence of values denoted `0, 0+, 1, 1+, 2, 2+, 3, 3+,` and so on. The progression of this discrete time series is controlled by two simulator commands called tick and tock. A tick moves the clock value from t to $t+$, and a tock from $t+$ to $t+1$, bringing upon the next time unit. The *real time* that elapsed during this period is irrelevant for simulation purposes, since the simulated time is controlled by the user, or by a test script, as follows.

First, whenever a sequential chip is loaded into the simulator, the GUI enables a clock-shaped button (dimmed when simulating combinational

chips). One click on this button (a tick) ends the first phase of the clock cycle, and a subsequent click (a tock) ends the second phase of the cycle, bringing on the first phase of the next cycle, and so on.

Alternatively, one can run the clock from a test script. For example, the sequence of scripting commands repeat *n* {tick, tock, output} instructs the simulator to advance the clock *n* time units and to print some values in the process. Appendix 3 documents the *Test Description Language* (TDL) that features these commands.

The two-phased time units generated by the clock regulate the operations of all the sequential chip-parts in the implemented chip. During the first phase of the time unit (tick), the inputs of each sequential chip-part affect the chip's internal state, according to the chip logic. During the second phase of the time unit (tock), the chip outputs are set to the new values. Hence, if we look at a sequential chip "from the outside," we see that its output pins stabilize to new values only at tock—at the point of transition between two consecutive time units.

We reiterate that combinational chips are completely oblivious to the clock. In Nand to Tetris, all the logic gates and chips built in chapters 1–2, up to and including the ALU, are combinational. All the registers and memory units built in chapter 3 are sequential. By default, chips are combinational; a chip can become *sequential* explicitly or implicitly, as follows.

Sequential, built-in chips: A *built-in chip* can declare its dependence on the clock explicitly, using the statement,

CLOCKED *pin*, *pin*, ..., *pin*;

where each *pin* is one of the chip's input or output pins. The inclusion of an input pin *x* in the CLOCKED list stipulates that changes to *x* should affect the chip's outputs only at the beginning of the next time unit. The inclusion of an output pin *x* in the CLOCKED list stipulates that changes in any of the chip's inputs should affect *x* only at the beginning of the next time unit. Figure A2.4 presents the definition of the most basic, built-in, sequential chip in the Hack platform—the DFF.

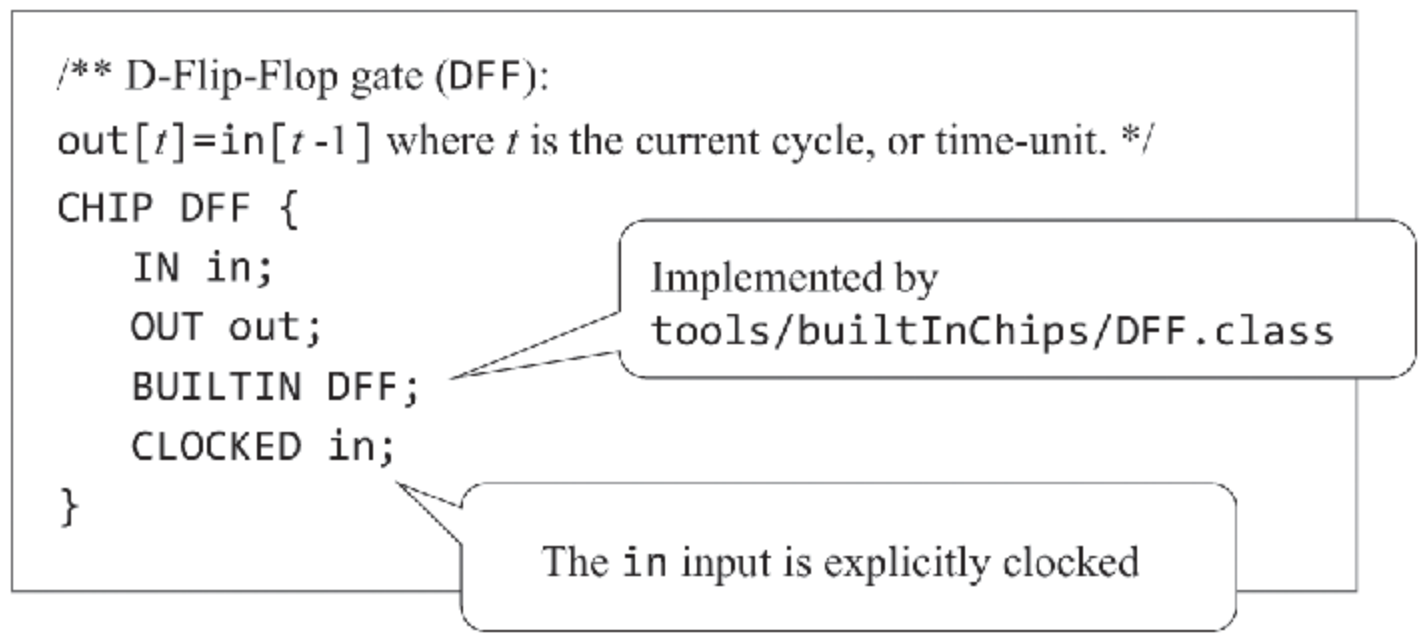


Figure A2.4 DFF definition.

It is possible that only some of the input or output pins of a chip are declared as clocked. In that case, changes in the non-clocked input pins affect the non-clocked output pins instantaneously. That's how the address pins are implemented in RAM units: the addressing logic is combinational and independent of the clock.

It is also possible to declare the CLOCKED keyword with an empty list of pins. This statement stipulates that the chip may change its internal state depending on the clock, but its input-output behavior will be combinational, independent of the clock.

Sequential, composite chips: The CLOCKED property can be defined explicitly only in built-in chips. How, then, does the simulator know that a given chip-part is sequential? If the chip is not built-in, then it is said to be clocked when one or more of its chip-parts is clocked. The clocked property is checked recursively, all the way down the chip hierarchy, where a built-in chip may be explicitly clocked. If such a chip is found, it renders every chip that depends on it (up the hierarchy) "clocked." Therefore, in the Hack computer, all the chips that include one or more DFF chip-parts, either directly or indirectly, are clocked.

We see that if a chip is not built-in, there is no way to tell from its HDL code whether it is sequential or not. *Best-practice advice*: The chip architect should provide this information in the chip API documentation.

Feedback loops: If the input of a chip feeds from one of the chip's outputs, either directly or through a (possibly long) path of dependencies, we say

that the chip contains a *feedback loop*. For example, consider the following two chip-part statements:

```
Not (in=loop1, out=loop1) // Invalid feedback loop
DFF (in=loop2, out=loop2) // Valid feedback loop
```

In both examples, an internal pin (loop1 or loop2) attempts to feed the chip's input from its output, creating a feedback loop. The difference between the two examples is that Not is a combinational chip, whereas DFF is sequential. In the Not example, loop1 creates an instantaneous and uncontrolled dependency between in and out, sometimes called a *data race*. In contrast, in the DFF case, the in-out dependency created by loop2 is delayed by the clock, since the in input of the DFF is declared clocked. Therefore, out(t) is not a function of in(t) but rather of in(t - 1).

When the simulator evaluates a chip, it checks recursively whether its various connections entail feedback loops. For each loop, the simulator checks whether the loop goes through a clocked pin somewhere along the way. If so, the loop is allowed. Otherwise, the simulator stops processing and issues an error message. This is done to prevent uncontrolled data races.

A2.5 Visualizing Chips

Built-in chips may be *GUI empowered*. These chips feature visual side effects designed to animate some of the chip operations. When the simulator evaluates a GUI-empowered chip-part, it displays a graphical image on the screen. Using this image, which may include interactive elements, the user can inspect the chip's current state or change it. The permissible GUI-empowered actions are determined, and made possible, by the developer of the built-in chip implementation.

The present version of the hardware simulator features the following GUI-empowered, built-in chips:

ALU: Displays the Hack ALU's inputs, output, and the presently computed function.

Registers (ARegister, DRegister, PC): Displays the register's contents, which may be modified by the user.

RAM chips: Displays a scrollable, array-like image that shows the contents of all the memory locations, which may be modified by the user. If the contents of a memory location change during the simulation, the respective entry in the GUI changes as well.

ROM chip (ROM32K): Same array-like image as that of RAM chips, plus an icon that enables loading a machine language program from an external text file. (The ROM32K chip serves as the instruction memory of the Hack computer.)

Screen chip: Displays a 256-rows-by-512-columns window that simulates the physical screen. If, during a simulation, one or more bits in the RAM-resident *screen memory map* change, the respective pixels in the screen GUI change as well. This continuous refresh loop is embedded in the simulator implementation.

Keyboard chip: Displays a keyboard icon. Clicking this icon connects the real keyboard of your computer to the simulated chip. From this point on, every key pressed on the real keyboard is intercepted by the simulated chip, and its binary code appears in the RAM-resident *keyboard memory map*. If the user moves the mouse focus to another area in the simulator GUI, the control of the keyboard is restored to the real computer.

Figure A2.5 presents a chip that uses three GUI empowered chip-parts. Figure A2.6 shows how the simulator handles this chip. The GUIDemo chip logic feeds its in input into two destinations: register number address in the RAM16K chip-part, and register number address in the Screen chip-part. In addition, the chip logic feeds the out values of its three chip-parts to the "dead-end" internal pins a, b, and c. These meaningless connections are designed for one purpose only: illustrating how the simulator deals with built-in, GUI-empowered chip-parts.

```
// Demo of GUI-empowered chips.
// The logic of this chip is meaningless, and is used merely to force
// the simulator to display the GUI effects of its built-in chip-parts.
CHIP GUIDemo {
   IN  in[16], load, address[15];
   OUT out[16];
   PARTS:
   RAM16K(in=in, load=load, address=address[0..13], out=a);
   Screen(in=in, load=load, address=address[0..12], out=b);
   Keyboard(out=c);
}
```

Figure A2.5 A chip that activates GUI-empowered chip-parts.

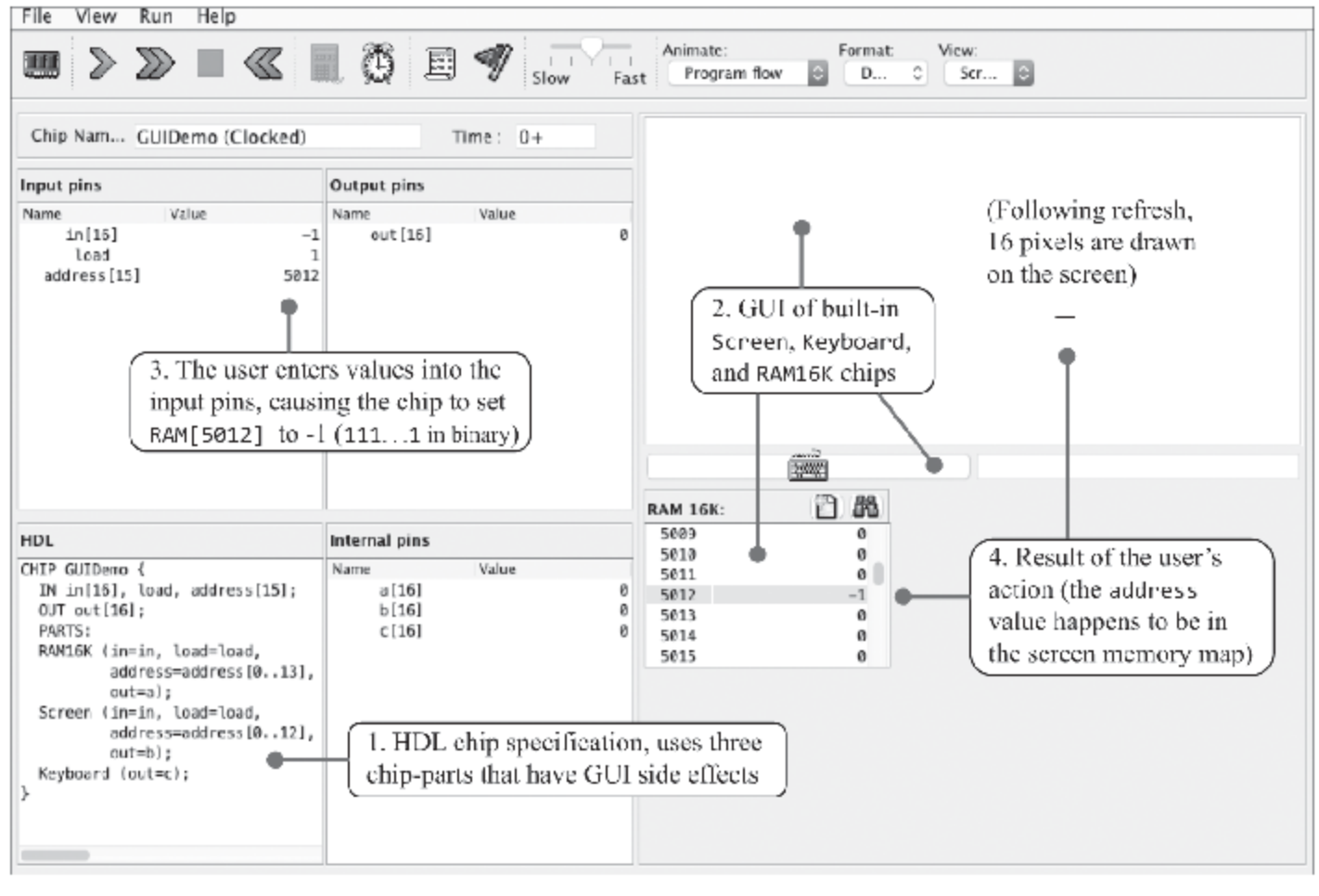


Figure A2.6 GUI-empowered chips demo. Since the loaded HDL program uses GUI-empowered chip-parts (step 1), the simulator renders their respective GUI images (step 2). When the user changes the values of the chip input pins (step 3), the simulator reflects these changes in the respective GUIs (step 4).

Note how the changes effected by the user (step 3) impact the screen (step 4). The circled horizontal line shown on the screen is the visual side effect of storing –1 in memory location 5012. Since the 16-bit two's complement binary code of –1 is 1111111111111111, the computer draws 16 pixels starting at column 320 of row 156, which happen to be the screen

coordinates associated with RAM address 5012. The mapping of memory *addresses* on (*row*, *column*) screen coordinates is specified in chapter 4 (section 4.2.5).

A2.6 HDL Survival Guide

This section provides practical tips about how to develop chips in HDL using the supplied hardware simulator. The tips are listed in no particular order. We recommend reading this section once, beginning to end, and then consulting it as needed.

Chip: Your nand2tetris/projects folder includes thirteen subfolders, named 01, 02, …, 13 (corresponding to the relevant chapter numbers). The hardware project folders are 01, 02, 03, and 05. Each hardware project folder contains a set of supplied HDL *stub files*, one for each chip that you have to build. The supplied HDL files contain no implementations; building these implementations is what the project is all about. If you do not build these chips in the order in which they are described in the book, you may run into difficulties. For example, suppose that you start project 1 by building the Xor chip. If your Xor.hdl implementation includes, say, And and Or chip-parts, and you have not yet implemented And.hdl and Or.hdl, your Xor.hdl program will not work even if its implementation is perfectly correct.

Note, however, that if the project folder included no And.hdl and Or.hdl files, your Xor.hdl program will work properly. The hardware simulator, which is a Java program, features built-in implementations of all the chips necessary to build the Hack computer (with the exception of the CPU and Computer chips). When the simulator evaluates a chip-part, say And, it looks for an And.hdl file in the current folder. At this point there are three possibilities:

- No HDL file is found. In this case, the built-in implementation of the chip kicks in, covering for the missing HDL implementation.
- A stub HDL file is found. The simulator tries to execute it. Failing to find an implementation, the execution fails.

- An HDL file is found, with an HDL implementation. The simulator executes it, reporting errors, if any, to the best of its ability.

Best-practice advice: You can do one of two things. Try to implement the chips in the order presented in the book and in the project descriptions. Since the chips are discussed bottom-up, from basic chips to more complex ones, you will encounter no chip order implementation troubles—provided, of course, that you complete each chip implementation correctly before moving on to implement the next one.

A recommended alternative is to create a subfolder named, say, stubs, and move all the supplied .hdl stub files into it. You can then move each stub file that you want to work on into your working folder, one by one. When you are done implementing a chip successfully, move it into, say, a completed subfolder. This practice forces the simulator to always use built-in chips, since the working folder includes only the .hdl file that you are working on (as well as the supplied .tst and .cmp files).

HDL files and test scripts: The .hdl file that you are working on and its associated .tst test script file must be located in the same folder. Each supplied test script starts with a load command that loads the .hdl file that it is supposed to test. The simulator always looks for this file in the current folder.

In principle, the simulator's File menu allows the user to load, interactively, both an .hdl file and a .tst script file. This can create potential problems. For example, you can load the .hdl file that you are working on into the simulator, and then load a test script from another folder. When you execute the test script, it may well load a different version of the HDL program into the simulator (possibly, a stub file). When in doubt, inspect the pane named HDL in the simulator GUI to check which HDL code is presently loaded. *Best-practice advice*: Use the simulator's File menu to load either an .hdl file or a .tst file, but not both.

Testing chips in isolation: At some point you may become convinced that your chip is correct, even though it is still failing the test. Indeed, it is possible that the chip is perfectly implemented, but one of its chip-parts is not. Also, a chip that passed its test successfully may fail when used as a

chip-part by another chip. One of the biggest inherent limitations of hardware design is that test scripts—especially those that test complex chips—cannot guarantee that the tested chip will operate perfectly in all circumstances.

The good news is that you can always diagnose which chip-part is causing the problem. Create a test subfolder and copy into it only the three .hdl, .tst, and .out files related to the chip that you are presently building. If your chip implementation passes its test in this subfolder as is (letting the simulator use the default built-in chip-parts), there must be a problem with one of your chip-part implementations, that is, with one of the chips that you built earlier in this project. Copy the other chips into this test folder, one by one, and repeat the test until you find the problematic chip.

HDL syntax errors: The hardware simulator displays errors on the bottom status bar. On computers with small screens, these messages are sometimes off the bottom of the screen, not visible. If you load an HDL program and nothing shows up in the HDL pane, but no error message is seen, this may be the problem. Your computer should have a way to move the window, using the keyboard. For example, on Windows use Alt+Space, M, and the arrow keys.

Unconnected pins: The hardware simulator does not consider unconnected pins to be errors. By default, it sets any unconnected input or output pin to false (binary value 0). This can cause mysterious errors in your chip implementations.

If an output pin of your chip is always 0, make sure that it is properly connected to another pin in your program. In particular, double-check the names of the internal pins ("wires") that feed this pin, either directly or indirectly. Typographic errors are particularly hazardous here, since the simulator doesn't throw errors on disconnected wires. For example, consider the statement Foo(..., sum=sun), where the sum output of Foo is supposed to pipe its value to an internal pin. Indeed, the simulator will happily create an internal pin named sun. Now, if sum's value was supposed to feed the output pin of the implemented chip, or the input pin of another chip-part, this pin will in fact be 0, *always*, since nothing will be piped from Foo onward.

To recap, if an output pin is always 0, or if one of the chip-parts does not appear to be working correctly, check the spelling of all the relevant pin names, and verify that all the input pins of the chip-part are connected.

Customized testing: For every *chip*.hdl file that you have to complete your project folder also includes a supplied test script, named *chip*.tst, and a compare file, named *chip*.cmp. Once your chip starts generating outputs, your folder will also include an output file named *chip*.out. If your chip fails the test script, don't forget to consult the .out file. Inspect the listed output values, and seek clues to the failure. If for some reason you can't see the output file in the simulator GUI, you can always inspect it using a text editor.

If you want, you can run tests of your own. Copy the supplied test script to, say, *MyTestChip*.tst, and modify the script commands to gain more insight into your chip's behavior. Start by changing the name of the output file in the output-file line and deleting the compare-to line. This will cause the test to always run to completion (by default, the simulation stops when an output line disagrees with the corresponding line in the compare file). Consider modifying the output-list line to show the outputs of your internal pins.

Appendix 3 documents the Test Description Language (TDL) that features all these commands.

Sub-busing (indexing) internal pins: This is not permitted. The only bus-pins that can be indexed are the input and output pins of the implemented chip or the input and output pins of its chip-parts. However, there is a workaround for sub-busing internal bus-pins. To motivate the work-around, here is an example that doesn't work:

```
CHIP Foo {
     IN  in[16];
     OUT out;
     PARTS:
     Not16  (in=in, out=notIn);
     Or8Way (in=notIn[4..11], out=out);   // Error: internal bus cannot be indexed.
 }
```

Possible fix, using the work-around:

```
Not16 (in=in, out[4..11]=notIn);
Or8Way (in=notIn, out=out); // Works!
```

Multiple outputs: Sometimes you need to split the multi-bit value of a bus-pin into two buses. This can be done by using multiple out= bindings.

For example:

```
CHIP Foo {
     IN  in[16];
     OUT out[8];
     PARTS:
     Not16 (in=in, out[0..7]=low8, out[8..15]=high8);   // Splitting the out value
     Bar8Bit (a=low8, b=high8, out=out);
 }
```

Sometimes you may want to output a value and also use it for further computations. This can be done as follows:

```
CHIP Foo {
    IN a, b, c;
    OUT out1, out2;
    PARTS:
    Bar (a=a, b=b, out=x, out=out1); // Bar's output feeds the out1 output of Foo
    Baz (a=x, b=c, out=out2);        // A copy of Bar's output also feeds Baz's a input
}
```

Chip-parts "auto complete" (sort of): The signatures of all the chips mentioned in this book are listed in appendix 4, which also has a web-based version (at www.nand2tetris.org). To use a chip-part in a chip implementation, copy-paste the chip signature from the online document into your HDL program, then fill in the missing bindings. This practice saves time and minimizes typing errors.

Appendix 3: Test Description Language

Mistakes are the portals of discovery.

—James Joyce (1882–1941)

Testing is a critically important element of systems development, and one that typically gets insufficient attention in computer science education. In Nand to Tetris we take testing very seriously. We believe that before one sets out to develop a new hardware or software module P, one must first develop a module T designed to test it. Further, T should be part of P's development's contract. Therefore, for every chip or software system specified in this book, we supply official test programs, written by us. Although you are welcome to test your work in any way you see fit, the contract is such that, ultimately, your implementation must pass *our* tests.

In order to streamline the definition and execution of the numerous tests scattered all over the book projects, we designed a uniform test description language. This language works almost the same across all the relevant tools supplied in Nand to Tetris: the *hardware simulator* used for simulating and testing chips written in HDL, the *CPU emulator* used for simulating and testing machine language programs, and the *VM emulator* used for simulating and testing programs written in the VM language, which are typically compiled Jack programs.

Every one of these simulators features a GUI that enables testing the loaded chip or program interactively, or batch-style, using a test script. A test script is a sequence of commands that load a hardware or software module into the relevant simulator and subject the module to a series of preplanned testing scenarios. In addition, the test scripts feature commands

for printing the test results and comparing them to desired results, as defined in supplied compare files. In sum, a test script enables a systematic, replicable, and documented testing of the underlying code—an invaluable requirement in any hardware or software development project.

In Nand to Tetris, we don't expect learners to write test scripts. All the test scripts necessary to test all the hardware and software modules mentioned in the book are supplied with the project materials. Thus, the purpose of this appendix is not to teach you how to write test scripts but rather to help you understand the syntax and logic of the supplied test scripts. Of course, you are welcome to customize the supplied scripts and create new ones, as you please.

A3.1 General Guidelines

The following usage guidelines are applicable to all the software tools and test scripts.

File format and usage: The act of testing a hardware or software module involves four types of files. Although not required, we recommend that all four files have the same prefix (file name):

Xxx.yyy: where *Xxx* is the name of the tested module and *yyy* is either hdl, hack, asm, or vm, standing, respectively, for a chip definition written in HDL, a program written in the Hack machine language, a program written in the Hack assembly language, or a program written in the VM virtual machine language

Xxx.tst: a test script that walks the simulator through a series of steps designed to test the code stored in *Xxx*

Xxx.out: an optional output file to which the script commands can write current values of selected variables during the simulation

Xxx.cmp: an optional compare file containing the *desired* values of selected variables, that is, the values that the simulation *should* generate if the module is implemented correctly

All these files should be kept in the same folder, which can be conveniently named *Xxx*. In the documentation and descriptions of all the simulators, the term "current folder" refers to the folder from which the last file has been opened in the simulator environment.

White space: Space characters, newline characters, and comments in test scripts (*Xxx*.tst files) are ignored. The following comment formats can appear in test scripts:

```
//  Comment to end of line
/*  Comment until closing */
/** API documentation comment */
```

Test scripts are not case-sensitive, except for file and folder names.

Usage: For each hardware or software module *Xxx* in Nand to Tetris we supply a script file *Xxx*.tst and a compare file *Xxx*.cmp. These files are designed to test your implementation of *Xxx*. In some cases, we also supply a skeletal version of *Xxx*, for example, an HDL interface with a missing implementation. All the files in all the projects are plain text files that should be viewed and edited using plain text editors.

Typically, you will start a simulation session by loading the supplied *Xxx*.tst script file into the relevant simulator. The first command in the script typically loads the code stored in the tested module *Xxx*. Next, optionally, come commands that initialize an output file and specify a compare file. The remaining commands in the script run the actual tests.

Simulation controls: Each one of the supplied simulators features a set of menus and icons for controlling the simulation.

File menu: Allows loading into the simulator either a relevant program (.hdl file, .hack file, .asm file, .vm file, or a folder name) or a test script (.tst file). If the user does not load a test script, the simulator loads a default test script (described below).

Play icon: Instructs the simulator to execute the next simulation step, as specified in the currently loaded test script.

Pause icon: Instructs the simulator to pause the execution of the currently loaded test script. Useful for inspecting various elements of the simulated environment.

Fast-forward icon: Instructs the simulator to execute all the commands in the currently loaded test script.

Stop icon: Instructs the simulator to stop the execution of the currently loaded test script.

Rewind icon: Instructs the simulator to reset the execution of the currently loaded test script, that is, be ready to start executing the test script from its first command onward.

Note that the simulator's icons listed above don't "run the code." Rather, they run the test script, which runs the code.

A3.2 Testing Chips on the Hardware Simulator

The supplied hardware simulator is designed for testing and simulating chip definitions written in the Hardware Description Language (HDL) described in appendix 2. Chapter 1 provides essential background on chip development and testing; thus, we recommend reading it first.

Example: Figure A2.1 in appendix 2 presents an `Eq3` chip, designed to check whether three 1-bit inputs are equal. Figure A3.1 presents `Eq3.tst`, a script designed to test the chip, and `Eq3.cmp`, a compare file containing the expected output of this test.

/* Eq3.tst: Tests the Eq3.hdl program. The Eq3 chip sets out to 1 if its three 1-bit inputs have the same values, or 0 otherwise. */

```
load Eq3.hdl,              // Loads the HDL program into the simulator.
output-file Eq3.out,       // Writes the script outputs to this file.
compare-to Eq3.cmp,        // Compares the script outputs to this file.
output-list a b c out;     // Each subsequent output command will
                           // write the values of variables a, b, c and
                           // out to the output file.
set a 0, set b 0, set c 0, eval, output;
set a 1, set b 1, set c 1, eval, output;
set a 1, set b 0, set c 0, eval, output;
set a 0, set b 1, set c 0, eval, output;
set a 1, set b 0, set c 1, eval, output;
```

Eq3.cmp

```
| a | b | c |out|
| 0 | 0 | 0 | 1 |
| 1 | 1 | 1 | 1 |
| 1 | 0 | 0 | 0 |
| 0 | 1 | 0 | 0 |
| 1 | 0 | 1 | 0 |
```

Figure A3.1 Test script and compare file (example).

A test script normally starts with some setup commands, followed by a series of simulation steps, each ending with a semicolon. A simulation step typically instructs the simulator to bind the chip's input pins to test values, evaluate the chip logic, and write selected variable values into a designated output file.

The Eq3 chip has three 1-bit inputs; thus, an exhaustive test would require eight testing scenarios. The size of an exhaustive test grows exponentially with the input size. Therefore, most test scripts test only a subset of representative input values, as shown in the figure.

Data types and variables: Test scripts support two data types: *integers* and *strings*. Integer constants can be expressed in decimal (%D prefix) format, which is the default, binary (%B prefix) format, or hexadecimal (%X prefix) format. These values are always translated into their equivalent two's complement binary values. For example, consider the following commands:

```
set a1 %B1111111111111111
set a2 %XFFFF
set a3 %D-1
set a4 -1
```

All four variables are set to the same value: 1111111111111111 in binary, which happens to be the binary, two's complement representation of –1 in decimal.

String values are specified using a `%S` prefix and must be enclosed by double quotation marks. Strings are used strictly for printing purposes and cannot be assigned to variables.

The hardware simulator's two-phase clock (used only in testing sequential chips) emits a series of values denoted `0, 0+, 1, 1+, 2, 2+, 3, 3+,` and so on. The progression of these *clock cycles* (also called *time units*) can be controlled by two script commands named tick and tock. A tick moves the clock value from t to $t+$, and a tock from $t+$ to $t+1$,bringing upon the next time unit. The current time unit is stored in a system variable named time, which is read-only.

Script commands can access three types of variables: pins, variables of built-in chips, and the system variable time.

Pins: input, output, and internal pins of the simulated chip (for example, the command set in `0` sets the value of the pin whose name is in to `0`)

Variables of built-in chips: exposed by the chip's external implementation (see figure A3.2.)

Chip name	Exposed variables	Data type / range	Methods
`Register`	`Register[]`	16-bit (-32768…32767)	
`ARegister`	`ARegister[]`	16-bit	
`DRegister`	`DRegister[]`	16-bit	
`PC` (prog. counter)	`PC[]`	15-bit (0…32767)	
`RAM8`	`RAM8[0...7]`	each entry is 16-bit	
`RAM64`	`RAM64[0...63]`	each entry is 16-bit	
`RAM512`	`RAM512[0...511]`	each entry is 16-bit	
`RAM4K`	`RAM4K[0...4095]`	each entry is 16-bit	
`RAM16K`	`RAM16K[0...16383]`	each entry is 16-bit	
`ROM32K`	`ROM32K[0...32767]`	each entry is 16-bit	`load` *Xxx*`.hack` / *Xxx*`.asm`
`Screen`	`Screen[0...16383]`	each entry is 16-bit	
`Keyboard`	`Keyboard[]`	16-bit, read-only	

Figure A3.2 Variables and methods of key built-in chips in Nand to Tetris.

time: the number of time-units that elapsed since the simulation started (a read-only variable)

Script commands: A script is a sequence of commands. Each command is terminated by a comma, a semicolon, or an exclamation mark. These terminators have the following semantics:

Comma (,): Terminates a script command.

Semicolon (;): Terminates a script command and a simulation step. A *simulation step* consists of one or more script commands. When the user instructs the simulator to *single-step* using the simulator's menu or play icon, the simulator executes the script from the current command until a semicolon is reached, at which point the simulation is paused.

Exclamation mark (!): Terminates a script command and stops the script execution. The user can later resume the script execution from that point onward. Typically used for debugging purposes.

Below we group the script commands in two conceptual sections: *setup commands*, used for loading files and initializing settings, and *simulation commands*, used for walking the simulator through the actual tests.

Setup Commands

load *Xxx*.hdl: Loads the HDL program stored in *Xxx*.hdl into the simulator. The file name must include the .hdl extension and must not include a path specification. The simulator will try to load the file from the current folder and, failing that, from the tools/builtInChips folder.

output-file *Xxx*.out: Instructs the simulator to write the results of the output commands in the named file, which must include an .out extension. The output file will be created in the current folder.

output-list *v*1, *v*2, …: Specifies what to write to the output file when the output command is encountered in the script (until the next output-list command, if any). Each value in the list is a variable name followed by a formatting specification. The command also produces a single header line, consisting of the variable names, which is written to the output file. Each item *v* in the output-list has the syntax *varName format padL.len.padR* (without any spaces). This directive instructs the simulator to write *padL* space characters, then the current value of the variable *varName*, using the

specified *format* and *len* columns, then *padR* spaces, and finally the divider symbol |. The *format* can be either %B (binary), %X (hexa), %D (decimal), or %S (string). The default format is %B1.1.1.

For example, the CPU.hdl chip of the Hack platform has an input pin named reset, an output pin named pc (among others), and a chip-part named DRegister (among others). If we want to track the values of these entities during the simulation, we can use something like the following command:

```
Output-list time%S1.5.1      // The system variable time
            reset%B2.1.2     // One of the chip's input pins
            pc%D2.3.1        // One of the chip's output pins
            DRegister[]%X3.4.4  // The internal state of this chip-part
```

(State variables of built-in chips are explained below). This output-list command may end up producing the following output, after two subsequent output commands:

```
| time  |reset|   pc |DRegister[]|
|   20+ |  0  |   21 |   FFFF    |
|   21  |  0  |   22 |   FFFF    |
```

compare-to *Xxx*.cmp: Specifies that the output line generated by each subsequent output command should be compared to its corresponding line in the specified compare file (which must include the .cmp extension). If any two lines are not the same, the simulator displays an error message and halts the script execution. The compare file is assumed to be present in the current folder.

Simulation Commands

set *varName value*: Assigns the value to the variable. The variable is either a pin or an internal variable of the simulated chip or one of its chip-parts. The bit widths of the value and the variable must be compatible.

eval: Instructs the simulator to apply the chip logic to the current values of the input pins and compute the resulting output values.

output: Causes the simulator to go through the following logic:

1. Get the current values of all the variables listed in the last output-list command.
2. Create an output line using the format specified in the last output-list command.
3. Write the output line to the output file.
4. (If a compare file has been previously declared using a compare-to command): If the output line differs from the compare file's current line, display an error message and stop the script's execution.
5. Advance the line cursors of the output file and the compare file.

tick: Ends the first phase of the current time unit (clock cycle).

tock: Ends the second phase of the current time unit and embarks on the first phase of the next time unit.

repeat ***n*** **{*commands*}**: Instructs the simulator to repeat the commands enclosed in the curly brackets *n* times. If *n* is omitted, the simulator repeats the commands until the simulation has been stopped for some reason (for example, when the user clicks the Stop icon).

while ***booleanCondition*** **{*commands*}**: Instructs the simulator to repeat the commands enclosed in the curly brackets as long as the *booleanCondition* is true. The condition is of the form *x op y* where *x* and *y* are either constants or variable names and *op* is =, >, <, >=, <=, or < >. If *x* and *y* are strings, *op* can be either = or < >.

echo ***text***: Displays the *text* in the simulator status line. The text must be enclosed in double quotation marks.

clear-echo: Clears the simulator's status line.

breakpoint ***varName value***: Starts comparing the current value of the specified variable to the specified *value* following the execution of each subsequent script command. If the variable contains the specified *value*, the execution halts and a message is displayed. Otherwise, the execution continues normally. Useful for debugging purposes.

clear-breakpoints: Clears all the previously defined breakpoints.

builtInChipName method argument (s): Executes the specified method of the specified built-in chip-part using the supplied arguments. The designer of a built-in chip can provide methods that allow the user (or a test script) to manipulate the simulated chip. See figure A3.2.

Variables of built-in chips: Chips can be implemented either by HDL programs or by externally supplied executable modules. In the latter case, the chip is said to be *built-in*. built-in chips can facilitate access to the chip's state using the syntax *chipName*[*varName*], where *varName* is an implementation-specific variable that should be documented in the chip API. See figure A3.2.

For example, consider the script command set RAM16K[1017] 15. If RAM16K is the currently simulated chip, or a chip-part of the currently simulated chip, this command sets its memory location number 1017 to 15. And, since the built-in RAM16K chip happens to have GUI side effects, the new value will also be reflected in the chip's visual image.

If a built-in chip maintains a single-valued internal state, the current value of the state can be accessed through the notation *chipName*[]. If the internal state is a vector, the notation *chipName*[*i*] is used. For example, when simulating the built-in Register chip, one can write script commands like set Register[] 135. This command sets the internal state of the chip to 135; in the next time unit, the Register chip will commit to this value, and its output pin will start emitting it.

Methods of built-in chips: Built-in chips can also expose *methods* that can be used by scripting commands. For example, in the Hack computer, programs reside in an instruction memory unit implemented by the built-in chip ROM32K. Before running a machine language program on the Hack

computer, the program must be loaded into this chip. To facilitate this service, the built-in implementation of ROM32K features a load method that enables loading a text file containing machine language instructions. This method can be accessed using a script command like ROM32K load *fileName*.hack.

Ending example: We end this section with a relatively complex test script designed to test the topmost Computer chip of the Hack computer.

One way to test the Computer chip is to load a machine language program into it and monitor selected values as the computer executes the program, one instruction at a time. For example, we wrote a machine language program that computes the maximum of RAM[0] and RAM[1] and writes the result in RAM[2]. The program is stored in a file named Max.hack.

Note that at the low level in which we are operating, if such a program does not run properly it may be either because the program is buggy or because the hardware is buggy (or, perhaps, the test script is buggy, or the hardware simulator is buggy). For simplicity, let us assume that everything is error-free, except for, possibly, the simulated Computer chip.

To test the Computer chip using the Max.hack program, we wrote a test script called ComputerMax.tst. This script loads Computer.hdl into the hardware simulator and then loads the Max.hack program into its ROM32K chip-part. A reasonable way to check whether the chip works properly is as follows: Put some values in RAM[0] and RAM[1], reset the computer, run the clock enough cycles, and inspect RAM[2]. This, in a nutshell, is what the script in figure A3.3 is designed to do.

```
/* ComputerMax.tst script.
Uses a Max.hack  program that sets
RAM[2] to max(RAM[0], RAM[1]). */

// Loads Computer and sets up for the simulation:
load Computer.hdl,
output-file ComputerMax.out,
compare-to ComputerMax.cmp,
output-list RAM16K[0] RAM16K[1] RAM16K[2];

// Loads Max.hack into the ROM32K chip-part:
ROM32K load Max.hack,

// Sets the first 2 cells of the RAM16K chip-part
// to test values:
set RAM16K[0] 3,
set RAM16K[1] 5,
output;

// Runs enough clock cycles to complete the
// program's execution:
repeat 14 {
    tick, tock,
    output;
}

// (Script continues on the right)
```

```
// Sets up for another test, using other values.

// Resets the Computer: Done by setting
// reset to 1, and running the clock
// in order to commit the Program Counter
// (PC, a sequential chip) to the new reset value:
set reset 1,
tick,
tock,
output;

// Sets reset to 0, loads new test values, and
// runs enough clock cycles to complete the
// program's execution:
set reset 0,
set RAM16K[0] 23456,
set RAM16K[1] 12345,
output;
repeat 14 {
    tick, tock,
    output;
}
```

Figure A3.3 Testing the topmost Computer chip.

How can we tell that fourteen clock cycles are sufficient for executing this program? This can be found by trial and error, by starting with a large value and watching the computer's outputs stabilizing after a while, or by analyzing the run-time behavior of the loaded program.

Default test script: Each Nand to Tetris simulator features a default test script. If the user does not load a test script into the simulator, the default test script is used. The default test script of the hardware simulator is defined as follows:

```
// Default test script of the hardware simulator:
repeat {
    tick,
    tock;
}
```

A3.3 Testing Machine Language Programs on the CPU Emulator

Unlike the *hardware simulator*, which is a general-purpose program designed to support the construction of any hardware platform, the supplied

CPU emulator is a single-purpose tool, designed to simulate the execution of machine language programs on a specific platform: the Hack computer. The programs can be written either in the symbolic or in the binary Hack machine language described in chapter 4.

As usual, the simulation involves four files: the tested program (*Xxx*.asm or *Xxx*.hack), a test script (*Xxx*.tst), an optional output file (*Xxx*.out), and an optional compare file (*Xxx*.cmp). All these files reside in the same folder, normally named *Xxx*.

Example: Consider the multiplication program Mult.hack, designed to effect `RAM[2]=RAM[0]*RAM[1]`. Suppose we want to test this program in the CPU emulator. A reasonable way to do it is to put some values in `RAM[0]` and `RAM[1]`, run the program, and inspect `RAM[2]`. This logic is carried out by the test script shown in figure A3.4.

```
// Loads the program and sets up for the simulation:
load Mult.hack,
output-file Mult.out,
compare-to Mult.cmp,
output-list RAM[2]%D2.6.2;

// Sets the first 2 RAM cells to test values:
set RAM[0] 2,
set RAM[1] 5;

// Runs enough clock cycles to complete the program's execution:
repeat 20 {
  ticktock;
}
output;

// Re-runs the program, with different test values:
set PC 0,
set RAM[0] 8,
set RAM[1] 7;

// Mult.hack is based on a naïve repetitive addition algorithm,
// so greater multiplicands require more clock cycles:
repeat 50 {
  ticktock;
}
output;
```

Figure A3.4 Testing a machine language program on the CPU emulator.

Variables: Scripting commands running on the CPU emulator can access the following elements of the Hack computer:

`A`:	Current value of the address register (unsigned 15-bit)
`D`:	Current value of the data register (16-bit)
`PC`:	Current value of the Program Counter (unsigned 15-bit)
`RAM[`*i*`]`:	Current value of RAM location *i* (16-bit)
`time`:	Number of *time units* (also called *clock cycles*, or *ticktocks*) that elapsed since the simulation started (a read-only system variable)

Commands: The CPU emulator supports all the commands described in section A3.2, except for the following changes:

load *progName*: Where *progName* is either *Xxx*.asm or *Xxx*.hack. This command loads a machine language program (to be tested) into the simulated instruction memory. If the program is written in assembly, the simulator translates it into binary, on the fly, as part of executing the load *programName* command.

eval: Not applicable in the CPU emulator.

builtInChipName method argument (*s*): Not applicable in the CPU emulator.

tickTock: This command is used instead of tick and tock. Each ticktock advances the clock one time unit (cycle).

Default Test Script

```
// Default test script of the CPU emulator:
repeat {
    ticktock;
}
```

A3.4 Testing VM Programs on the VM Emulator

The supplied *VM emulator* is a Java implementation of the virtual machine specified in chapters 7–8. It can be used for simulating the execution of VM programs, visualizing their operations, and displaying the states of the effected virtual memory segments.

A VM program consists of one or more .vm files. Thus, the simulation of a VM program involves the tested program (a single *Xxx*.vm file or an *Xxx* folder containing one or more .vm files) and, optionally, a test script (*Xxx*.tst), a compare file (*Xxx*.cmp), and an output file (*Xxx*.out). All these files reside in the same folder, normally named *Xxx*.

Virtual memory segments: The VM commands push and pop are designed to manipulate *virtual memory segments* (argument, local, and so on). These

segments must be allocated to the host RAM—a task that the VM emulator carries out as a side effect of simulating the execution of the VM commands call, function, and return.

Startup code: When the VM translator translates a VM program, it generates machine language code that sets the stack pointer to 256 and then calls the Sys.init function, which then initializes the OS classes and calls Main.main. In a similar fashion, when the VM emulator is instructed to execute a VM program (a collection of one or more VM functions), it is programmed to start running the function Sys.init. If such a function is not found in the loaded VM code, the emulator is programmed to start executing the first command in the loaded VM code.

The latter convention was added to the VM emulator to support unit testing of the VM translator, which spans two book chapters and projects. In project 7, we build a basic VM translator that handles only push, pop, and arithmetic commands without handling function calling commands. If we want to execute such programs, we must somehow anchor the virtual memory segments in the host RAM—at least those segments mentioned in the simulated VM code. Conveniently, this initialization can be accomplished by script commands that manipulate the pointers controlling the base RAM addresses of the virtual segments. Using these script commands, we can anchor the virtual segments anywhere we want in the host RAM.

Example: The FibonacciSeries.vm file contains a sequence of VM commands that compute the first *n* elements of the Fibonacci series. The code is designed to operate on two arguments: *n* and the starting memory address in which the computed elements should be stored. The test script listed in figure A3.5 tests this program using the arguments 6 and 4000.

```
/* The FibonacciSeries.vm program computes the first n Fibonacci numbers.
In this test n = 6, and the numbers will be written to RAM addresses 4000 to 4005. */

load FibonacciSeries.vm,
output-file FibonacciSeries.out,
compare-to FibonacciSeries.cmp,
output-list RAM[4000]%D1.6.2 RAM[4001]%D1.6.2 RAM[4002]%D1.6.2
            RAM[4003]%D1.6.2 RAM[4004]%D1.6.2 RAM[4005]%D1.6.2;

// The program's code contains no function/call/return commands.
// Therefore, the script initializes the stack, local and argument segments explicitly:

set SP 256,
set local 300,
set argument 400;

// Sets the first argument to n = 6, the second argument to the address where the series
// will be written, and runs enough VM steps for completing the program's execution:

set argument[0] 6,
set argument[1] 4000;
repeat 140 {
  vmstep;
}
output;
```

Figure A3.5 Testing a VM program on the VM emulator.

Variables: Scripting commands running on the VM emulator can access the following elements of the virtual machine:

Contents of VM segments:

`local[`*i*`]`:	Value of the *i*-th element of the `local` segment
`argument[`*i*`]`:	Value of the *i*-th element of the `argument` segment
`this[`*i*`]`:	Value of the *i*-th element of the `this` segment
`that[`*i*`]`:	Value of the *i*-th element of the `that` segment
`temp[`*i*`]`:	Value of the *i*-th element of the `temp` segment

Pointers of VM segments:

`local`:	Base address of the `local` segment in the RAM
`argument`:	Base address of the `argument` segment in the RAM
`this`:	Base address of the `this` segment in the RAM
`that`:	Base address of the `that` segment in the RAM

Implementation-specific variables:

`RAM[`*i*`]`:	Value of the *i*-th location of the host RAM
`SP`:	Value of the stack pointer
`currentFunction`:	Name of the currently executing function (read-only)
`line`:	Contains a string of the form *currentFunctionName*`.`*lineIndexInFunction* (read-only). For example, when execution reaches the third line of the function `Sys.init`, the `line` variable contains the value `Sys.init.3`. Can be used for setting breakpoints in selected locations in the loaded VM program.

Commands: The VM emulator supports all the commands described in Section A3.2, except for the following changes:

load *source*: Where the optional *source* parameter is either *Xxx*.vm, a file containing VM code, or *Xxx*, the name of a folder containing one or more .vm files (in which case all of them are loaded, one after the other). If the .vm files are located in the current folder, the source argument can be omitted.

tick / tock: Not applicable.

vmstep: Simulates the execution of a single VM command and advances to the next command in the code.

Default Script

// Default script of the VM emulator:

```
repeat {
    vmStep;
}
```

Appendix 4: The Hack Chip Set

The chips are sorted alphabetically by name. In the online version of this document, available in www.nand2tetris.org, this API format comes in handy: To use a chip-part, copy-paste the chip signature into your HDL program, then fill in the missing bindings (also called *connections*).

```
Add16(a= ,b= ,out= ) /* Adds up two 16-bit two's complement values */
ALU(x= ,y= ,zx= ,nx= ,zy= ,ny= ,f= ,no= ,out= ,zr= ,ng= ) /* Hack ALU */
And(a= ,b= ,out= ) /* And gate */
And16(a= ,b= ,out= ) /* 16-bit And */
ARegister(in= ,load= ,out= ) /* Address register (built-in) */
Bit(in= ,load= ,out= ) /* 1-bit register */
CPU(inM= ,instruction= ,reset= ,outM= ,writeM= ,addressM= ,pc= ) /* Hack CPU */
DFF(in= ,out= ) /* Data flip-flop gate (built-in) */
DMux(in= ,sel= ,a= ,b= ) /* Routes the input to one out of two outputs */
DMux4Way(in= ,sel= ,a= ,b= ,c= ,d= ) /* Routes the input to one out of four outputs */
DMux8Way(in= ,sel= ,a= ,b= ,c= ,d= ,e= ,f= ,g= ,h= ) /* Routes the input to one out of 8 outputs */
DRegister(in= ,load= ,out= ) /* Data register (built-in) */
HalfAdder(a= ,b= ,sum= , carry= ) /* Adds up two bits */
FullAdder(a= ,b= ,c= ,sum= ,carry= ) /* Adds up three bits */
Inc16(in= ,out= ) /* Sets out to in + 1 */
Keyboard(out= ) /* Keyboard memory map (built-in) */
Memory(in= ,load= ,address= ,out= ) /* Data memory of the Hack platform (RAM) */
Mux(a= ,b= ,sel= ,out= ) /* Selects between two inputs */
Mux16(a= ,b= ,sel= ,out= ) /* Selects between two 16-bit inputs */
Mux4Way16(a= ,b= ,c= ,d= ,sel= ,out= ) /* Selects between four 16-bit inputs */
Mux8Way16(a= ,b= ,c= ,d= ,e= ,f= ,g= ,h= ,sel= ,out= ) /* Selects between eight 16-bit inputs */
Nand(a= ,b= ,out= ) /* Nand gate (built-in) */
Not(in= ,out= ) /* Not gate */
Not16(in= ,out= ) /* 16-bit Not */
Or(a= ,b= ,out= ) /* Or gate */
Or16(a= ,b= ,out= ) /* 16-bit Or */
Or8Way(in= ,out= ) /* 8-way Or */
PC(in= ,load= ,inc= ,reset= ,out= ) /* Program Counter */
RAM8(in= ,load= ,address= ,out= ) /* 8-word RAM */
RAM64(in= ,load= ,address= ,out= ) /* 64-word RAM */
RAM512(in= ,load= ,address= ,out= ) /* 512-word RAM */
RAM4K(in= ,load= ,address= ,out= ) /* 4K RAM */
RAM16K(in= ,load= ,address= ,out= ) /* 16K RAM */
Register(in= ,load= ,out= ) /* 16-bit register */
ROM32K(address= ,out= ) /* Instruction memory of the Hack platform (ROM, built-in) */
Screen(in= ,load= ,address= ,out= ) /* Screen memory map (built-in) */
Xor(a= ,b= ,out= ) /* Xor gate */
```

Appendix 5: The Hack Character Set

32:	space	56:	8	80:	P	104:	h	127:	DEL
33:	!	57:	9	81:	Q	105:	i	128:	newLine
34:	"	58:	:	82:	R	106:	j	129:	backSpace
35:	#	59:	;	83:	S	107:	k	130:	leftArrow
36:	$	60:	<	84:	T	108:	l	131:	upArrow
37:	%	61:	=	85:	U	109:	m	132:	rightArrow
38:	&	62:	>	86:	V	110:	n	133:	downArrow
39:	'	63:	?	87:	W	111:	o	134:	home
40:	(	64:	@	88:	X	112:	p	135:	end
41:	)	65:	A	89:	Y	113:	q	136:	pageUp
42:	*	66:	B	90:	Z	114:	r	137:	pageDown
43:	+	67:	C	91:	[	115:	s	138:	insert
44:	,	68:	D	92:	/	116:	t	139:	delete
45:	-	69:	E	93:	]	117:	u	140:	esc
46:	.	70:	F	94:	^	118:	v	141:	f1
47:	/	71:	G	95:	_	119:	w	142:	f2
48:	0	72:	H	96:	`	120:	x	143:	f3
49:	1	73:	I	97:	a	121:	y	144:	f4
50:	2	74:	J	98:	b	122:	z	145:	f5
51:	3	75:	K	99:	c	123:	{	146:	f6
52:	4	76:	L	100:	d	124:	|	147:	f7
53:	5	77:	M	101:	e	125:	}	148:	f8
54:	6	78:	N	102:	f	126:	~	149:	f9
55:	7	79:	O	103:	g			150:	f10
								151:	f11
								152:	f12

Appendix 6: The Jack OS API

The Jack language is supported by eight standard classes that provide basic OS services like memory allocation, mathematical functions, input capturing, and output rendering. This appendix documents the API of these classes.

Math

This class provides commonly needed mathematical functions.

function int multiply(int x, int y): Returns the product of x and y. When a Jack compiler detects the multiplication operator * in the program's code, it handles it by invoking this function. Thus the Jack expressions x * y and the function call Math.multiply(x,y) return the same value.

function int divide(int x, int y): Returns the integer part of x / y. When a Jack compiler detects the division operator / in the program's code, it handles it by invoking this function. Thus the Jack expressions x / y and the function call Math.divide(x,y) return the same value.

function int min(int x, int y): Returns the minimum of x and y.

function int max(int x, int y): Returns the maximum of x and y.

function int sqrt(int x): Returns the integer part of the square root of x.

String

This class represents strings of char values and provides commonly needed string processing services.

constructor String new(int maxLength): Constructs a new empty string with a maximum length of maxLength and initial length of 0.

method void dispose(): Disposes this string.

method int length(): Returns the number of characters in this string.

method char charAt(int i): Returns the character at the i-th location of this string.

method void setCharAt(int i, char c): Sets the character at the i-th location of this string to c.

method String appendChar(char c): Appends c to this string's end and returns this string.

method void eraseLastChar(): Erases the last character from this string.

method int intValue(): Returns the integer value of this string until a non-digit character is detected.

method void setInt(int val): Sets this string to hold a representation of the given value.

function char backSpace(): Returns the backspace character.

function char doubleQuote(): Returns the double quote character.

function char newLine(): Returns the newline character.

Array

In the Jack language, arrays are implemented as instances of the OS class Array. Once declared, the array elements can be accessed using the syntax arr[i]. Jack arrays are not typed: each array element can hold a primitive data type or an object type, and different elements in the same array can have different types.

function Array new(int size): Constructs a new array of the given size.

method void dispose(): Disposes this array.

Output

This class provides functions for displaying characters. It assumes a character-oriented screen consisting of 23 rows (indexed 0…22, top to bottom) of 64 characters each (indexed 0…63, left to right). The top-left character location on the screen is indexed (0,0). Each character is displayed by rendering on the screen a rectangular image 11 pixels high and 8 pixels wide (which includes margins for character spacing and line spacing). If needed, the bitmap images ("font") of all the characters can be found by inspecting the given code of the Output class. A visible cursor, implemented as a small filled square, indicates where the next character will be displayed.

function void moveCursor(int i, int j): Moves the cursor to the j-th column of the i-th row and overrides the character displayed there.

function void printChar(char c): Displays the character at the cursor location and advances the cursor one column forward.

function void printString(String s): Displays the string starting at the cursor location and advances the cursor appropriately.

function void printInt(int i): Displays the integer starting at the cursor location and advances the cursor appropriately.

function void println(): Advances the cursor to the beginning of the next line.

function void backSpace(): Moves the cursor one column back.

Screen

This class provides functions for displaying graphical shapes on the screen. The Hack physical screen consists of 256 rows (indexed 0…255, top to bottom) of 512 pixels each (indexed 0…511, left to right). The top-left pixel on the screen is indexed (0,0).

function void clearScreen(): Erases the entire screen.

function void setColor(boolean b): Sets the current color. This color will be used in all the subsequent draw*Xxx* function calls. Black is represented by true,

white by false.

function void drawPixel(int x, int y): Draws the (x,y) pixel using the current color.

function void drawLine(int x1, int y1, int x2, int y2): Draws a line from pixel (x1,y1) to pixel (x2,y2) using the current color.

function void drawRectangle(int x1, int y1, int x2, int y2): Draws a filled rectangle whose top-left corner is (x1,y1) and bottom-right corner is (x2,y2) using the current color.

function void drawCircle(int x, int y, int r): Draws a filled circle of radius $r \leq 181$ around (x,y) using the current color.

Keyboard

This class provides functions for reading inputs from a standard keyboard.

function char keyPressed(): Returns the character of the currently pressed key on the keyboard; if no key is currently pressed, returns 0. Recognizes all the values in the Hack character set (see appendix 5). These include the characters newLine (128, return value of String.newLine()), backSpace (129, return value of String.backSpace ()), leftArrow (130), upArrow (131), rightArrow (132), downArrow (133), home (134), end (135), pageUp (136), pageDown (137), insert (138), delete (139), esc (140), and f1–f12 (141–152).

function char readChar(): Waits until a keyboard key is pressed and released, then displays the corresponding character on the screen and returns the character.

function String readLine(String message): Displays the message, reads from the keyboard the entered string of characters until a newLine character is detected, displays the string, and returns the string. Also handles user backspaces.

function int readInt(String message): Displays the message, reads from the keyboard the entered string of characters until a newLine character is detected, displays the string on the screen, and returns its integer value until the first non-digit character in the entered string is detected. Also handles user backspaces.

Memory

This class provides memory management services. The Hack RAM consists of 32,768 words, each holding a 16-bit binary number.

function int peek(int address): Returns the value of RAM[address].

function void poke(int address, int value): Sets RAM[address] to the given value.

function Array alloc(int size): Finds an available RAM block of the given size and returns its base address.

function void deAlloc(Array o): Deallocates the given object, which is cast as an array. In other words, makes the RAM block that starts in this address available for future memory allocations.

Sys

This class provides basic program execution services.

function void halt(): Halts the program execution.

function void error(int errorCode): Displays the error code, using the format ERR<errorCode>, and halts the program's execution.

function void wait(int duration): Waits approximately duration milliseconds and returns.

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