

Project 4: Machine Language Programming

Background

Every hardware platform is designed to execute commands in a certain machine language, expressed using agreed-upon binary codes. Writing programs directly in binary code is a possible, yet unnecessary. Instead, we can write such programs using a low-level symbolic language, called assembly, and have them translated into binary code by a program called assembler. In this project you will write some low-level assembly programs, and will be forever thankful for high-level languages like Java and Python. (Actually, assembly programming can be highly rewarding, allowing direct and complete control of the underlying machine.)

Objective

To get a taste of low-level programming in machine language, and to get acquainted with the Hack computer platform. In the process of working on this project, you will become familiar with the assembly process - translating from symbolic language to machine-language - and you will appreciate visually how native binary code executes on the target hardware platform. These lessons will be learned in the context of writing and testing two low-level programs, as follows.

Programs

Program	Description	Guidelines / Tests
Mult.asm	<p>Multiplication: in the Hack computer, the top 16 RAM words (RAM[0]...RAM[15]) are also referred to as R0...R15.</p> <p>With this terminology in mind, this program computes the value $R0 \cdot R1$ and stores the result in R2.</p> <p>The program assumes that $R0 \geq 0$, $R1 \geq 0$, and $R0 \cdot R1 < 32768$. Your program need not test these conditions, but rather assume that they hold.</p>	<p>Use a plain text editor to write your Mult.asm program using the Hack assembly language.</p> <p>Use the supplied Hack Assembler to translate your Mult.asm program, producing a Mult.hack file containing binary Hack instructions.</p> <p>Next, load the supplied Mult.tst script into the CPU Emulator. This script loads the Mult.hack program, and executes it.</p> <p>Run the script. If you get any errors, debug and edit your Mult.asm program. Then assemble the program, re-run the Mult.txt script, etc.</p>

Fill.asm	<p>I/O handling: this program illustrates low-level handling of the screen and keyboard devices, as follows.</p> <p>The program runs an infinite loop that listens to the keyboard input. When a key is pressed (any key), the program blackens the screen, i.e. writes "black" in every pixel; the screen should remain fully black as long as the key is pressed.</p> <p>When no key is pressed, the program clears the screen, i.e. writes "white" in every pixel; the screen should remain fully clear as long as no key is pressed.</p> <p>Implementation note: your program may blacken and clear the screen's pixels in any spatial/visual order, as long as pressing a key continuously for long enough results in a fully blackened screen, and not pressing any key for long enough results in a fully cleared screen.</p>	<p>Write, test, and debug your Fill.asm program by following the same guidelines given above for the Mult program.</p> <p>The supplied Fill.tst script, which comes with no compare file, is designed to do two things: (i) load the Fill.hack program, and (ii) remind you to select 'no animation', and then test the program interactively by pressing and releasing some keyboard keys.</p> <p>The supplied FillAutomatic.tst script, along with the supplied compare file FillAutomatic.cmp, are designed to test the Fill program automatically, as described by the test script documentation.</p> <p>For completeness of testing, it is recommended to test the Fill program both interactively and automatically.</p>
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Contract

Write and test the two programs described above. When executed on the supplied CPU emulator, your programs should generate the results mandated by the specified tests.

Resources

The Hack assembly language is described in detail in [Chapter 4](#).

You will need two tools: the supplied assembler - a program that translates programs written in the Hack assembly language into binary Hack code, and the supplied CPU emulator - a program that runs binary Hack code on a simulated Hack platform. Assuming that you've downloaded the Nand2Tetris Software Suite, the assembler and the CPU emulator should be available in the nand2tetris/tools folder on your computer.

Two other related and useful resources are the supplied Assembler Tutorial ([PPT](#), [PDF](#)) and CPU Emulator Tutorial ([PPT](#), [PDF](#))

We recommend going through these tutorials before starting to work on this project.

Finally, assuming that you've downloaded the Nand2Tetris Software Suite, all the project materials should be available in your nand2tetris/projects/04 folder.

Proposed Implementation

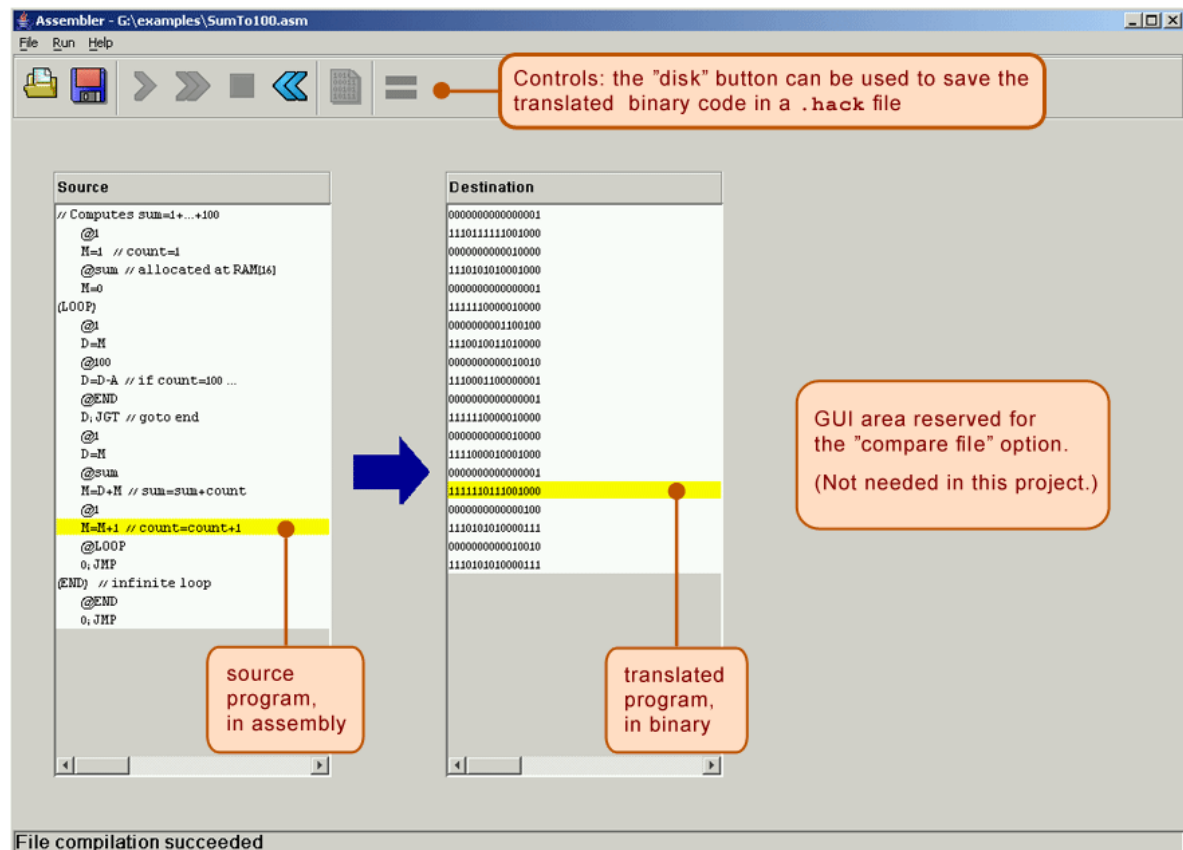
1. Use a plain text editor to write the first assembly program. Start by loading and editing the supplied projects/04/mult/Mult.asm file.
2. Use the supplied assembler (in either batch or interactive mode) to translate your program. If you get syntax errors, go to step 1; if there are no syntax errors, the assembler will generate a file named projects/04/mult/Mult.hack, containing binary instructions written in the Hack machine language.
3. Use the supplied CPU emulator to load, and then test, the translated Mult.hack code. This can be done either interactively, or batch-style, using the supplied Mult.tst script. If you get run-time errors, go to step 1.

4. Repeat stages 1-3 for the second program (Fill.asm), working in the projects/04/fill folder.

Debugging tip: The Hack language is case-sensitive. A common error occurs when one writes, say, "@foo" and "@Foo" in different parts of one's program, thinking that both labels are treated as the same symbol. In fact, the assembler treats them as two different symbols. This bug is difficult to detect, so you should be aware of it.

Tools

The supplied Hack Assembler can be used in either command mode (from the command shell), or interactively. The latter mode of operation allows observing the translation process in a visual and step-wise fashion, as shown below:



The machine language programs produced by the assembler can be tested in two different ways. First, one can run the resulting .hack program in the supplied CPU emulator. Alternatively, one can run the same program directly on the Hack hardware, using the supplied hardware simulator used in projects 1-3. To do so, one can load the Computer.hdl chip (built in project 5) into the hardware simulator, and then proceed to load the binary code (from the .hack file) into the computer's Instruction Memory (also called ROM). Since we will complete building the hardware platform and the Computer.hdl chip only in the next project, at this stage we recommend testing machine-level programs using the supplied CPU emulator.

The supplied CPU Emulator includes a ROM (also called Instruction Memory) representation, into which the binary code is loaded, and a RAM representation, which holds data. For ease of use, the emulator enables the user to view the loaded ROM-resident code in either binary mode, or in symbolic / assembly mode. In fact, the CPU emulator even allows loading symbolic code written in assembly directly into the ROM, in which case the emulator translates the loaded code into binary code on the fly. This utility seems to render the supplied assembler unnecessary, but this is not the case. First, the supplied assembler shows the translation process visually, for instructive purposes. Second, the assembler generates a persistent binary file. This file can be executed either on the CPU emulator, as we illustrate below, or directly on the hardware platform, as we'll do in the next project.

CPU Emulator (1.4b3) - G:\examples\Rect.asm

File View Run Help

Slow Fast Animate: Program flow View: Screen Format: Decimal

emulator controls

ROM Asm

0	@0
1	D=M
2	@23
3	D, J LE
4	@16
5	M=D
6	@16384
7	D=A
8	@17
9	M=D
10	@17
11	A=M
12	M=-1
13	@17
14	D=M
15	@32
16	D=D+A
17	@17
18	M=D
19	@16
20	MD=M-1
21	@10
22	D, J GT
23	@23
24	0, JMP
25	
26	
27	
28	

instruction memory

RAM

16370	0
16371	0
16372	0
16373	0
16374	0
16375	0
16376	0
16377	0
16378	0
16379	0
16380	0
16381	0
16382	0
16383	0
16384	-1
16385	0
16386	0
16387	0
16388	0
16389	0
16390	0
16391	0
16392	0
16393	0
16394	0
16395	0
16396	0
16397	0
16398	0

data memory

program's output

256 by 512 pixels simulated screen

keyboard enabler

rect.txt - Notepad

```
// Draws a rectangle 16 pixels wide and RAM[0]
// pixels long at top left corner of the screen
if RAM[0]<=0 goto end
n=RAM[0]
screen=16384 // screen base (top left)
loop: // draw 16 pixels at the screen location
RAM[screen]=-1 // -1=11...1 in binary
screen=screen+32 // proceed to next row
n=n-1
if n>0 goto loop
end:
```

pseudo code

PC 24

program counter

A 23

address register