ECE 243S - Computer Organization
January 2020
Laboratory Exercise 1

Introduction to Assembly Language Programming
Using an ARM Cortex A9 System

The goal of this lab is to introduce you to the basic concepts of Assembly Language programming of a processor, which gives you insight into what a computer is actually doing when it executes a program. We will make use of the ARM® Cortex® A9 processor inside the *DE1-SoC Computer*. This computer system is designed for the DE1-SoC board and includes the processor, memory for holding programs and data, and various I/O ports. The ARM processor accesses each component in the system using memory-mapped I/O; the address ranges assigned to each of the various devices in the system are specified in the document called *DE1-SoC Computer System with ARM Cortex A9*, which is provided on Quercus along with Lab 1.

In this introductory exercise you will begin learning how to develop programs written in the ARM assembly language, which can be executed on the *DE1-SoC Computer*. You will need to be familiar with the ARM processor architecture and its assembly language as described in class. An overview of the ARM Cortex A9 processor can be found in the tutorial *Introduction to the ARM Processor*, which is provided with Lab 1.

Since we cannot do in-person labs at this point in the term, to develop and "execute" programs for the ARM processor you will use the *CPUlator* software-based simulation tool. It *simulates* the functional behavior of the components in the *DE1-SoC Computer*, including the ARM processor, memory, and a number of I/O devices. You will find that the CPUlator is an excellent tool for developing and debugging ARM programs on your home computer—it is easy to use and does not require a DE1-SoC board. The CPUlator is introduced in Part I, below.

Part I

In this part of the lab exercise you are to watch a short video that provides an introduction to the *CPUlator* tool. As you will see in the video, the *CPUlator* is a full-featured software development environment that allows you to compile (assemble) and debug software code for the ARM processor. As mentioned in the video, we should all feel a huge debt-of-gratitude to the author of this tool, Dr. Henry Wong, who developed, and maintains, *CPUlator* as a volunteer effort on his own personal time. Thank you Henry!!

Use the `URL` belowto access the video from Microsoft Streams, using your *UTOR* credentials. Note that the video refers to using CPUlator for the rest of the term, but that will depend on how Covid plays out this term for us, and whether we'll be able to meet in person in the labs.

`https://web.microsoftstream.com/video/15948679-3895-4c1b-91fe-07f0c34c299b`

Part II

Now, we will explore some features of the *CPUlator* by working with a simple ARM assembly language program. Consider the program given in Figure 1, which finds the largest number in a list of 32-bit integers that is stored in the memory.

Note that some sample data is included in this program. The word (4 bytes) at the label *RESULT* is reserved for storing the result, which will be the largest number found. The next word, N, specifies the number of entries in the list. The words that follow give the actual numbers in the list.

```
/* Program that finds the largest number in a list of integers   */

         .text                  // executable code follows
         .global  _start
_start:
         MOV      R4, #RESULT   // R4 points to result location
         LDR      R2, [R4, #4]  // R2 holds number of elements in the list
         MOV      R3, #NUMBERS  // R3 points to the list of integers
         LDR      R0, [R3]      // R0 holds the largest number so far

LOOP:    SUBS     R2, #1        // decrement the loop counter
         BEQ      DONE          // if result is equal to 0, branch
         ADD      R3, #4
         LDR      R1, [R3]      // get the next number
         CMP      R0, R1        // check if larger number found
         BGE      LOOP
         MOV      R0, R1        // update the largest number
         B        LOOP
DONE:    STR      R0, [R4]      // store largest number into result location

END:     B        END

RESULT:  .word    0
N:       .word    7             // number of entries in the list
NUMBERS: .word    4, 5, 3, 6    // the data
         .word    1, 8, 2

         .end
```

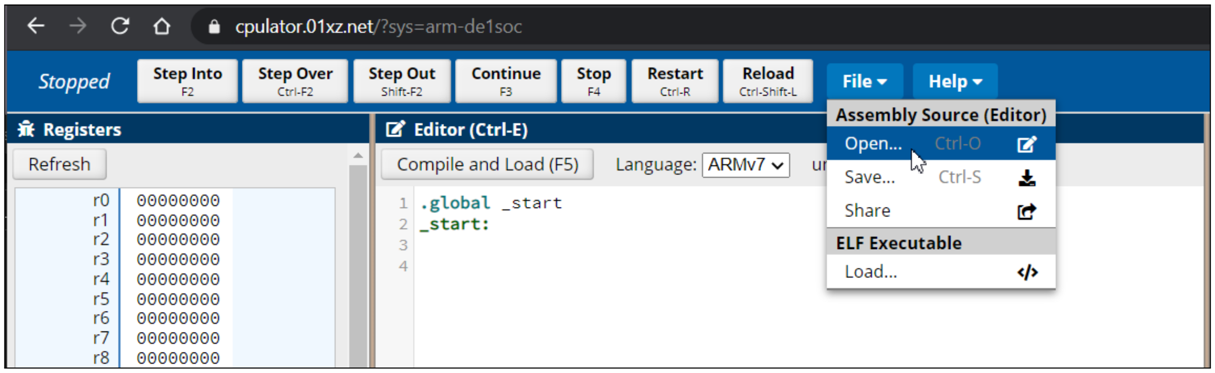
Figure 1: Assembly-language program that finds the largest number.

Make sure that you understand the program in Figure 1 and the meaning of each instruction in it. Note the extensive use of comments in the program. You should always include meaningful comments in programs that you will write!

Perform the following:

1. Create an assembly-language source-code file for the program in Figure 1, and name the file *part2.s* (this file is included in the *design files* for this lab exercise). Then, open the *CPUlator* web-site and set its system parameters to choose the `ARMv7` processor and `DE1-SoC` board (the corresponding `URL` for the *CPUlator* web page should be `https://cpulator.01xz.net/?sys=arm-de1soc`). As indicated in Figure 2, click on the `File` command near the top of the *CPUlator* window and then select `Open...`. Next, in the dialogue depicted in Figure 3, browse in your computer's file-system to choose the *part2.s* file and then click `Open`.

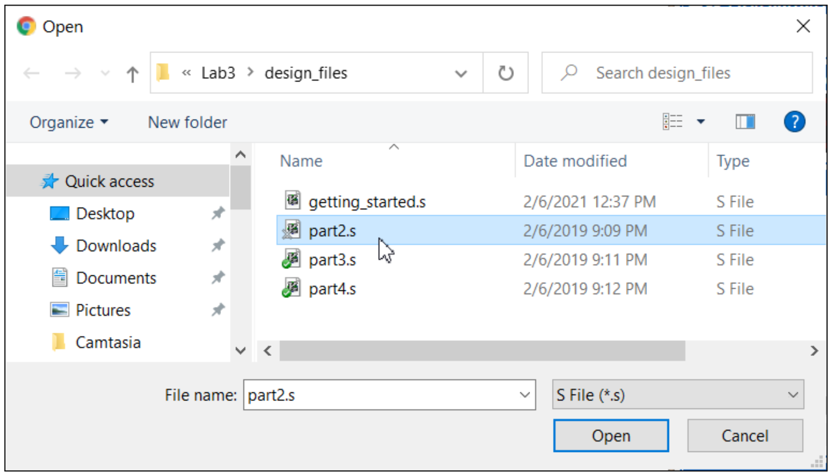
   The assembly program should be displayed in the `Editor` pane of the *CPUlator* window, as illustrated in Figure 4. You can make changes to your code in this `Editor` pane if needed by simply selecting text with your mouse and making edits using your keyboard.



```
.global _start
_start:
```

r0	00000000
r1	00000000
r2	00000000
r3	00000000
r4	00000000
r5	00000000
r6	00000000
r7	00000000
r8	00000000

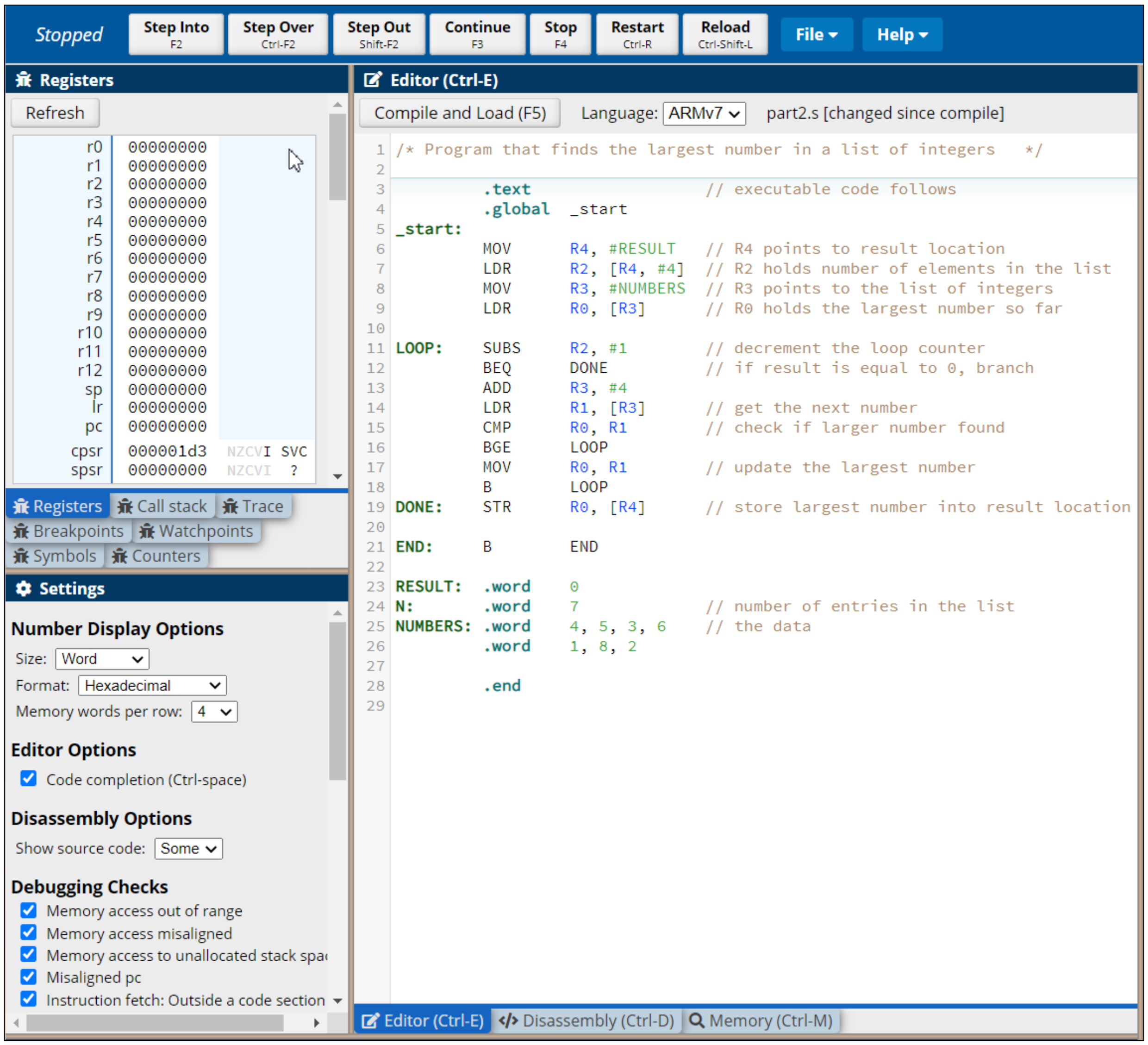
Figure 2: The `File` menu in *CPUlator*.



Name	Date modified	Type
getting_started.s	2/6/2021 12:37 PM	S File
part2.s	2/6/2019 9:09 PM	S File
part3.s	2/6/2019 9:11 PM	S File
part4.s	2/6/2019 9:12 PM	S File

File name: part2.s
S File (*.s)

Figure 3: Selecting the *part2.s* file.



Language: ARMv7   part2.s [changed since compile]

```
/* Program that finds the largest number in a list of integers   */

          .text                   // executable code follows
          .global  _start
_start:
          MOV      R4, #RESULT    // R4 points to result location
          LDR      R2, [R4, #4]   // R2 holds number of elements in the list
          MOV      R3, #NUMBERS   // R3 points to the list of integers
          LDR      R0, [R3]       // R0 holds the largest number so far

LOOP:     SUBS     R2, #1         // decrement the loop counter
          BEQ      DONE           // if result is equal to 0, branch
          ADD      R3, #4
          LDR      R1, [R3]       // get the next number
          CMP      R0, R1         // check if larger number found
          BGE      LOOP
          MOV      R0, R1         // update the largest number
          B        LOOP
DONE:     STR      R0, [R4]       // store largest number into result location

END:      B        END

RESULT:   .word    0
N:        .word    7              // number of entries in the list
NUMBERS:  .word    4, 5, 3, 6     // the data
          .word    1, 8, 2

          .end
```

```
  r0   00000000
  r1   00000000
  r2   00000000
  r3   00000000
  r4   00000000
  r5   00000000
  r6   00000000
  r7   00000000
  r8   00000000
  r9   00000000
 r10   00000000
 r11   00000000
 r12   00000000
  sp   00000000
  lr   00000000
  pc   00000000
cpsr   000001d3   NZCVI  SVC
spsr   00000000   NZCVI   ?
```

Number Display Options
Size: Word
Format: Hexadecimal
Memory words per row: 4

Editor Options
☑ Code completion (Ctrl-space)

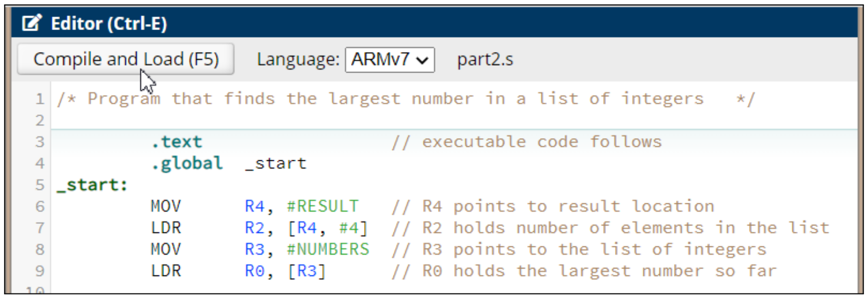
Disassembly Options
Show source code: Some

Debugging Checks
☑ Memory access out of range
☑ Memory access misaligned
☑ Memory access to unallocated stack spa
☑ Misaligned pc
☑ Instruction fetch: Outside a code section

Figure 4: The assembly-language program in the *CPUlator* `Editor` pane.

2. As indicated in Figure 5, click on the `Compile and Load` command to *assemble* your program and *load* it into the *memory* that is part of the computer system being simulated within the *CPUlator* tool. You should see the message displayed in Figure 6, in the `Messages` pane, which reports a successful compilation result. If not, then you may have inadvertently introduced an error in the program code; fix any such errors and recompile.

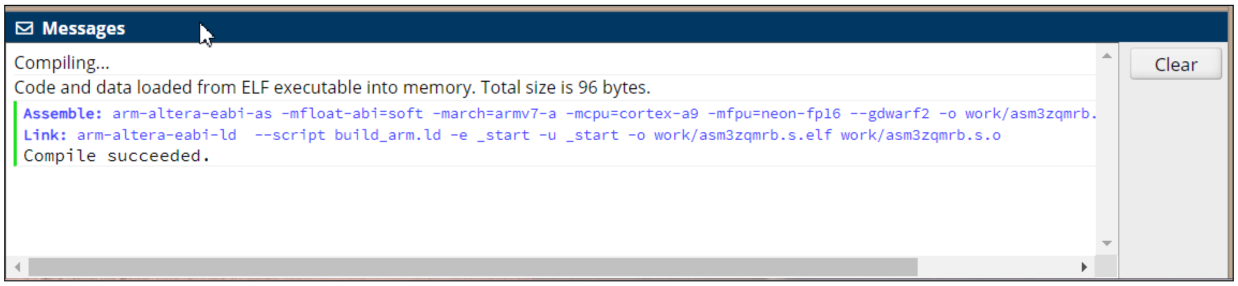
   Once the compilation is successful, the *CPUlator* window automatically displays the `Disassembly` pane, shown in Figure 7. This pane lets you see the machine code for the program and gives the address in the *memory* of each machine-code word. The `Disassembly` pane shows each instruction in the program twice: once using the original source code and a second time using the actual instruction found by *disassembling* the machine code. This is done because the *implementation* of an instruction may differ, in some cases, from the *specification* of that instruction in the source code (examples where such differences happen will be shown in class). Note: you can change the way that code is displayed in the CPUlator by using its Settings menu, which is on the left hand side of the CPUlator window (for example, changing Disassembly Options from *Some* to *None* will ensure that each instruction is displayed only once).



```
/* Program that finds the largest number in a list of integers   */

        .text                   // executable code follows
        .global  _start
_start:
        MOV     R4, #RESULT     // R4 points to result location
        LDR     R2, [R4, #4]    // R2 holds number of elements in the list
        MOV     R3, #NUMBERS    // R3 points to the list of integers
        LDR     R0, [R3]        // R0 holds the largest number so far
```

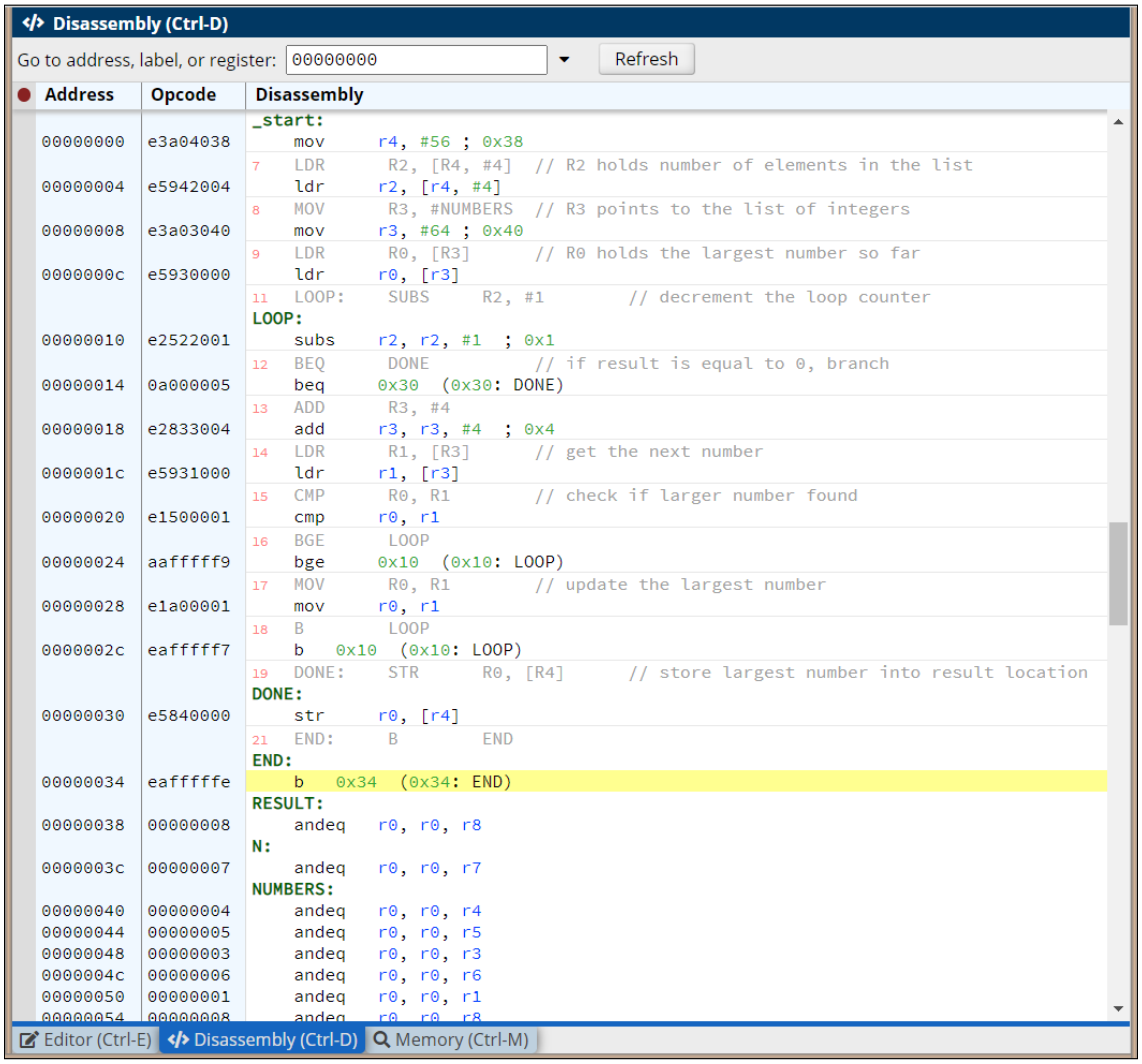
Figure 5: Compiling and loading the program.



```
Compiling...
Code and data loaded from ELF executable into memory. Total size is 96 bytes.
Assemble: arm-altera-eabi-as -mfloat-abi=soft -march=armv7-a -mcpu=cortex-a9 -mfpu=neon-fp16 --gdwarf2 -o work/asm3zqmrb.
Link: arm-altera-eabi-ld  --script build_arm.ld -e _start -u _start -o work/asm3zqmrb.s.elf work/asm3zqmrb.s.o
Compile succeeded.
```

Figure 6: The Messages pane.

3. Select the Continue command near the top of the *CPUlator* window. This command "executes" the program on the ARM processor that is part of the computer system being simulated within the *CPUlator* tool. As illustrated in Figure 7, the program runs to the line of code labeled END, at memory address 0x34, where it remains in an endless loop. Select the Stop command to halt the program's execution. Note that the largest number found in the sample list is 8 as indicated by the contents of register r0. This result is also stored in memory at the label RESULT.

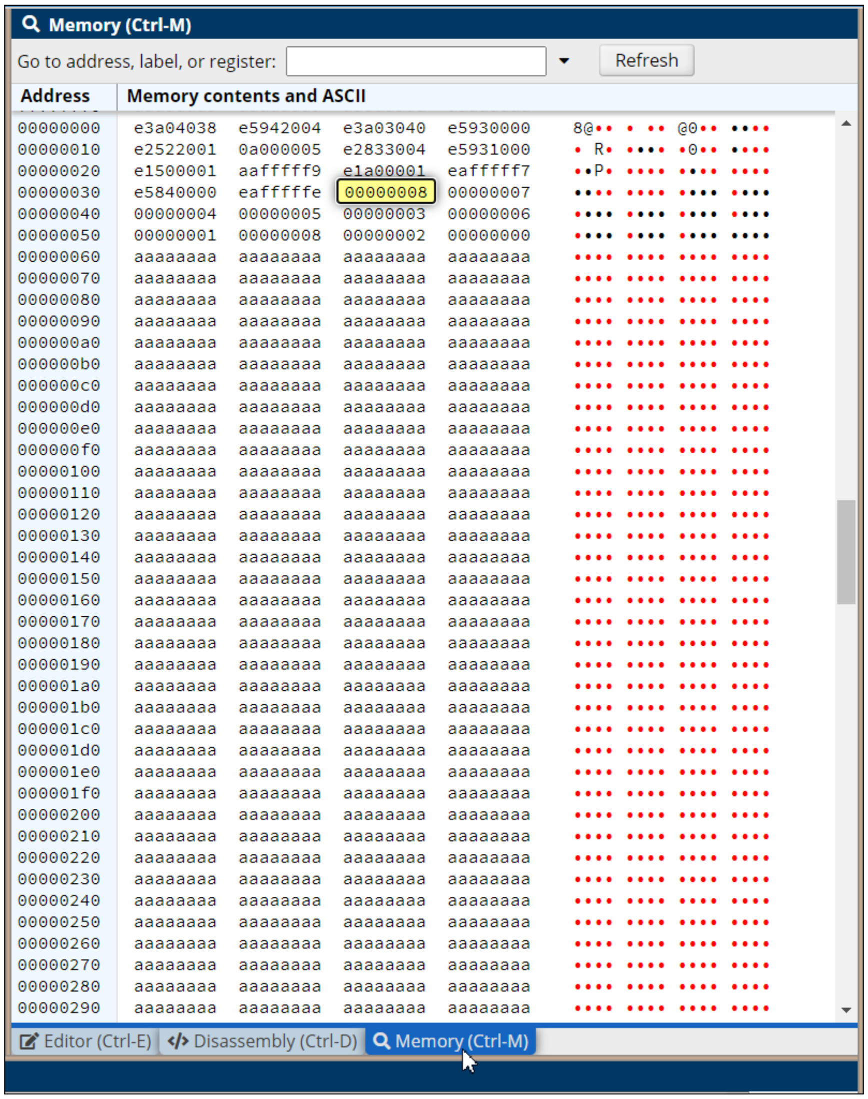


```
Address   Opcode    Disassembly
                    _start:
00000000  e3a04038      mov      r4, #56 ; 0x38
                        LDR        R2, [R4, #4]   // R2 holds number of elements in the list
00000004  e5942004      ldr      r2, [r4, #4]
                        MOV        R3, #NUMBERS   // R3 points to the list of integers
00000008  e3a03040      mov      r3, #64 ; 0x40
                        LDR        R0, [R3]       // R0 holds the largest number so far
0000000c  e5930000      ldr      r0, [r3]
                        LOOP:    SUBS      R2, #1         // decrement the loop counter
                    LOOP:
00000010  e2522001      subs     r2, r2, #1  ; 0x1
                        BEQ        DONE           // if result is equal to 0, branch
00000014  0a000005      beq      0x30  (0x30: DONE)
                        ADD        R3, #4
00000018  e2833004      add      r3, r3, #4  ; 0x4
                        LDR        R1, [R3]       // get the next number
0000001c  e5931000      ldr      r1, [r3]
                        CMP        R0, R1         // check if larger number found
00000020  e1500001      cmp      r0, r1
                        BGE        LOOP
00000024  aafffff9      bge      0x10  (0x10: LOOP)
                        MOV        R0, R1         // update the largest number
00000028  e1a00001      mov      r0, r1
                        B          LOOP
0000002c  eafffff7      b   0x10  (0x10: LOOP)
                        DONE:    STR       R0, [R4]       // store largest number into result location
                    DONE:
00000030  e5840000      str      r0, [r4]
                        END:     B         END
                    END:
00000034  eafffffe      b   0x34  (0x34: END)
                    RESULT:
00000038  00000008      andeq    r0, r0, r8
                    N:
0000003c  00000007      andeq    r0, r0, r7
                    NUMBERS:
00000040  00000004      andeq    r0, r0, r4
00000044  00000005      andeq    r0, r0, r5
00000048  00000003      andeq    r0, r0, r3
0000004c  00000006      andeq    r0, r0, r6
00000050  00000001      andeq    r0, r0, r1
00000054  00000008      andeq    r0, r0, r8
```

Figure 7: The result of executing the program.

The address of the label RESULT for this program is `0x00000038`, which can be seen near the bottom of Figure 7. Also, you may notice that the `Disassembly` pane attempts to figure out the machine code at this location, assuming that it represents a processor instruction; it does not, and so the resulting instruction displayed (`andeq`) is not meaningful.

Use the *CPUlator's* `Memory` pane, as illustrated in Figure 8, to verify that the resulting value 8 is stored in the correct location.



Memory (Ctrl-M)

Go to address, label, or register: Refresh

```
Address   Memory contents and ASCII
00000000  e3a04038 e5942004 e3a03040 e5930000   8@•• •  •• @0•• ••••
00000010  e2522001 0a000005 e2833004 e5931000   • R• •••• •0•• ••••
00000020  e1500001 aafffff9 e1a00001 eafffff7   ••P• •••• •••• ••••
00000030  e5840000 eafffffe 00000008 00000007   •••• •••• •••• ••••
00000040  00000004 00000005 00000003 00000006   •••• •••• •••• ••••
00000050  00000001 00000008 00000002 00000000   •••• •••• •••• ••••
00000060  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000070  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000080  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000090  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
000000a0  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
000000b0  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
000000c0  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
000000d0  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
000000e0  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
000000f0  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000100  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000110  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000120  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000130  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000140  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000150  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000160  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000170  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000180  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000190  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
000001a0  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
000001b0  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
000001c0  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
000001d0  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
000001e0  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
000001f0  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000200  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000210  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000220  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000230  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000240  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000250  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000260  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000270  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000280  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
00000290  aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa   •••• •••• •••• ••••
```

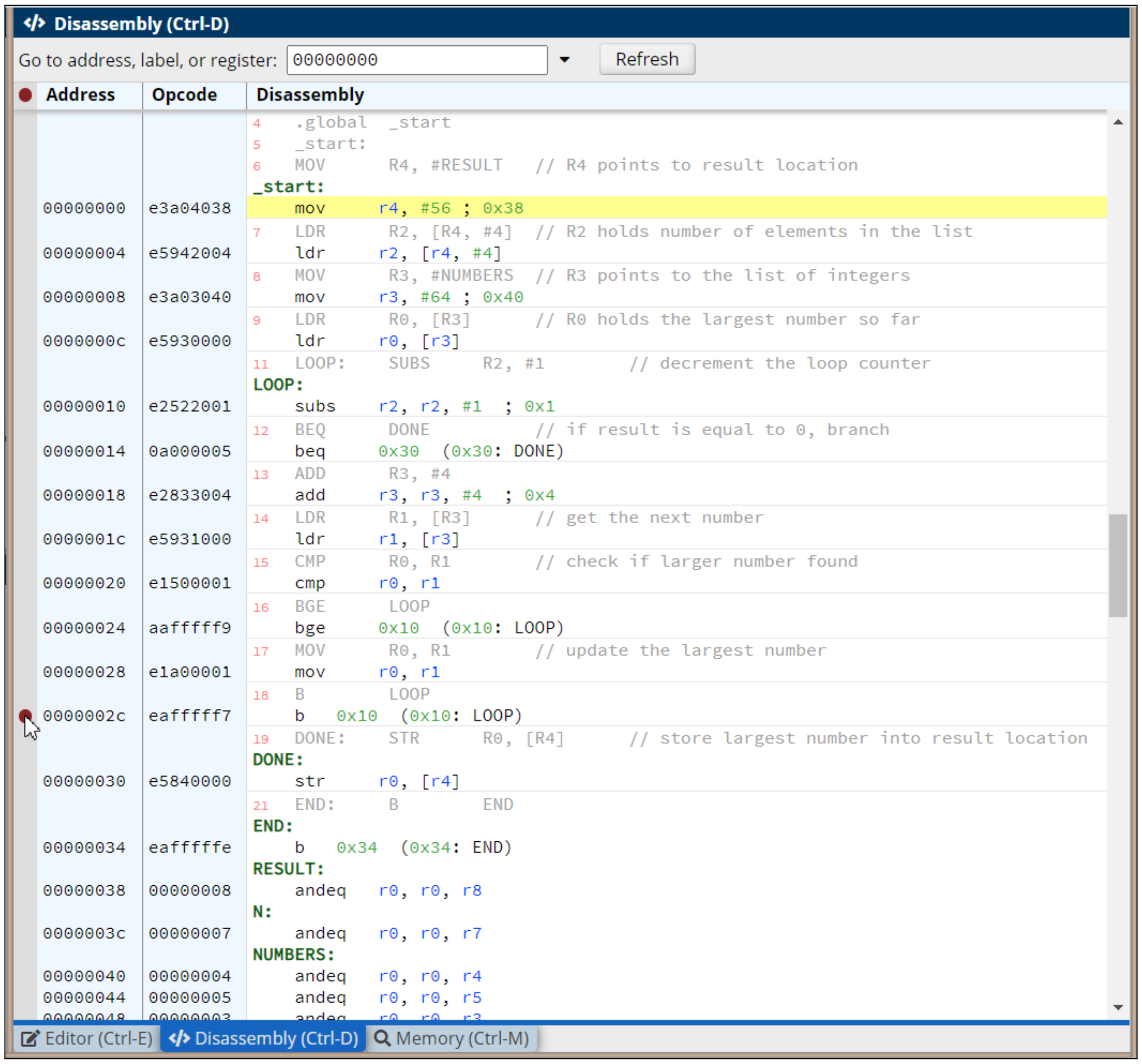
Editor (Ctrl-E) | Disassembly (Ctrl-D) | Memory (Ctrl-M)

Figure 8: The `Memory` pane.

4. You can return control of the program to the start by clicking on the `Restart` command in *CPUlator*. Do this and then *single-step* through the program by (repeatedly) selecting the `Step Into` command. Observe how each instruction that is executed affects the contents of the ARM processor's registers.

5. Double-click on the `pc` register in the *CPUlator* and then change the value of the program counter to 0. This action has the same effect as selecting the `Restart` command.

6. Now set a breakpoint at address `0x0000002C` by clicking on the gray bar to the left of this address, as illustrated in Figure 9. Select the `Continue` command to run the program again and observe the contents of register `r0` when the instruction at the breakpoint, which is `B LOOP`, is reached. Use `Continue` to repeatedly run the program, which will stop at the breakpoint in each iteration of the loop, and monitor the contents of register `r0` as the program searches for the largest number in the list.



```
Address   Opcode    Disassembly
                        .global  _start
                        _start:
                        MOV      R4, #RESULT   // R4 points to result location
                    _start:
00000000  e3a04038      mov      r4, #56 ; 0x38
                        LDR      R2, [R4, #4]  // R2 holds number of elements in the list
00000004  e5942004      ldr      r2, [r4, #4]
                        MOV      R3, #NUMBERS  // R3 points to the list of integers
00000008  e3a03040      mov      r3, #64 ; 0x40
                        LDR      R0, [R3]      // R0 holds the largest number so far
0000000c  e5930000      ldr      r0, [r3]
                        LOOP:    SUBS     R2, #1        // decrement the loop counter
                    LOOP:
00000010  e2522001      subs     r2, r2, #1  ; 0x1
                        BEQ      DONE          // if result is equal to 0, branch
00000014  0a000005      beq      0x30   (0x30: DONE)
                        ADD      R3, #4
00000018  e2833004      add      r3, r3, #4  ; 0x4
                        LDR      R1, [R3]      // get the next number
0000001c  e5931000      ldr      r1, [r3]
                        CMP      R0, R1        // check if larger number found
00000020  e1500001      cmp      r0, r1
                        BGE      LOOP
00000024  aafffff9      bge      0x10   (0x10: LOOP)
                        MOV      R0, R1        // update the largest number
00000028  e1a00001      mov      r0, r1
                        B        LOOP
0000002c  eafffff7      b    0x10   (0x10: LOOP)
                        DONE:    STR      R0, [R4]      // store largest number into result location
                    DONE:
00000030  e5840000      str      r0, [r4]
                        END:     B        END
                    END:
00000034  eafffffe      b    0x34   (0x34: END)
                    RESULT:
00000038  00000008      andeq    r0, r0, r8
                    N:
0000003c  00000007      andeq    r0, r0, r7
                    NUMBERS:
00000040  00000004      andeq    r0, r0, r4
00000044  00000005      andeq    r0, r0, r5
00000048  00000003      andeq    r0, r0, r3
```

Figure 9: Setting a breakpoint.

Be prepared to show your ability to single step and set breakpoints when you demonstrate other parts of this lab to your TA.

Part III

Implement the task in Part II by modifying the program in Figure 1 so that it uses a subroutine. The subroutine, LARGE, has to find the largest number in a list. The main program passes the number of entries and the address of the start of the list as parameters to the subroutine via registers `r0` and `r1`. The subroutine returns the value of the largest number to the calling program via register `r0`. A suitable main program is given in Figure 10.

Use the *CPUlator* tool to assemble, load, execute, and debug (as needed!) your program. Demonstrate the working program to your TA.

```
/* Program that finds the largest number in a list of integers */

            .text                   // executable code follows
            .global _start
_start:
            MOV     R4, #RESULT     // R4 points to result location
            LDR     R0, [R4, #4]    // R0 holds the number of elements in the list
            MOV     R1, #NUMBERS    // R1 points to the start of the list
            BL      LARGE
            STR     R0, [R4]        // R0 holds the subroutine return value

END:        B       END

/* Subroutine to find the largest integer in a list
 * Parameters: R0 has the number of elements in the list
 *             R1 has the address of the start of the list
 * Returns: R0 returns the largest item in the list */
LARGE:      . . .
            . . .

RESULT:     .word   0
N:          .word   7           // number of entries in the list
NUMBERS:    .word   4, 5, 3, 6  // the data
            .word   1, 8, 2

            .end
```

Figure 10: Main program for Part III.

Part IV

The program shown in Figure 11 converts a binary number into two decimal digits. The binary number is loaded from memory at the location N, and the two decimal digits that are extracted from N are stored into memory in two bytes starting at the location *Digits*. For the value $N = 76$ (`0x4c`) shown in the figure, the code sets *Digits* to `00000706`.

Make sure that you understand how the code in Figure 11 works. Then, extend the code so that it converts the binary number to four decimal digits, supporting decimal values up to 9999. You should modify the DIVIDE subroutine so that it can use any divisor, rather than only a divisor of 10. Pass the divisor to the subroutine in register `r1`.

If you run your code with the value $N = 9876$ (`0x2694`), then *Digits* should be set to `09080706`. Use the *CPUlator* tool to develop your program, and to demonstrate that it works correctly.

```
/* Program that converts a binary number to decimal */

            .text               // executable code follows
            .global _start
_start:
             MOV    R4, #N
             MOV    R5, #Digits  // R5 points to the decimal digits storage location
             LDR    R4, [R4]     // R4 holds N
             MOV    R0, R4       // parameter for DIVIDE goes in R0
             BL     DIVIDE
             STRB   R1, [R5, #1] // Tens digit is now in R1
             STRB   R0, [R5]     // Ones digit is in R0
END:         B      END

/* Subroutine to perform the integer division R0 / 10.
 * Returns: quotient in R1, and remainder in R0 */
DIVIDE:      MOV    R2, #0
CONT:        CMP    R0, #10
             BLT    DIV_END
             SUB    R0, #10
             ADD    R2, #1
             B      CONT
DIV_END:     MOV    R1, R2     // quotient in R1 (remainder in R0)
             MOV    PC, LR

N:           .word  76         // the decimal number to be converted
Digits:      .space 4          // storage space for the decimal digits

             .end
```

Figure 11: A program that converts a binary number into two decimal digits.