

Project 1--CDA 3101 (Spring 2014)

Worth: 100 points (10% of course grade)

Assigned: Friday, Jan 24, 2014

Due: 1:25 pm, Monday, Feb 24, 2014

1. Purpose

This project is intended to help you understand the instructions of a very simple assembly language and how to assemble programs into machine language.

2. Problem

This project has three parts. In the first part, you will write a program to take an assembly-language program and produce the corresponding machine language. In the second part, you will write a behavioral simulator for the resulting machine code. In the third part, you will write a short assembly-language program to multiply two numbers.

3. LC3101 Instruction-Set Architecture

For this project, you will be developing a simulator and assembler for the LC3101 (Little Computer, used in CDA 3101). The LC3101 is very simple, but it is general enough to solve complex problems. For this project, you will only need to know the instruction set and instruction format of the LC3101.

The LC3101 is an 8-register, 32-bit computer. All addresses are word-addresses (unlike MIPS which is byte-addressed). The LC3101 has 65536 words of memory. By assembly-language convention, register 0 will always contain 0 (i.e. the machine will not enforce this, but no assembly-language program should ever change register 0 from its initial value of 0).

There are 3 instruction formats (bit 0 is the least-significant bit). Bits 31-25 are unused for all instructions, and should always be 0.

R-type instructions (add, nand):

- bits 24-22: opcode
- bits 21-19: reg A
- bits 18-16: reg B
- bits 15-3: unused (should all be 0)
- bits 2-0: destReg

I-type instructions (lw, sw, beq):

bits 24-22: opcode
bits 21-19: reg A
bits 18-16: reg B
bits 15-0: offsetField (16-bit, range of -32768 to 32767)

O-type instructions (halt, noop):
bits 24-22: opcode
bits 21-0: unused (should all be 0)

Table 1: Description of Machine Instructions

Assembly language name for instruction	Opcode in binary (bits 24, 23, 22)	Action
add (R-type format)	000	add contents of regA with contents of regB, store results in destReg.

nand (3.11 $Tm(())$ $TJETBTi((na)-4(n)Tm((na)-4(ETBT 0 0 1 119.18 25.523 Tm((na)-4())7($

4. LC3101 Assembly Language and Assembler (40%)

The first part of this project is to write a program to take an assembly-language program and translate it into machine language. You will translate assembly-language names for instructions, such as beq, into their numeric equivalent (e.g. 100), and you will translate symbolic names for addresses into numeric values. The final output will be a series of 32-bit instructions (instruction bits 31-25 are always 0).

The format for a line of assembly code is:

label instruction field0 field1 field2 comments

The leftmost field on a line is the label field. Valid labels contain a maximum of 6 characters and can consist of letters and numbers (but must start with a letter). The label is optional (the white space following the label field is required). Labels make it much easier to write assembly-language programs, since otherwise you would need to modify all address fields each time you added a line to your assembly-language program!

After the optional label is white space which consists of any number of space or tab characters. The whitespace is followed by the instruction field, where the instruction can be any of the assembly-language instruction names listed in the above table. After more white space comes a series of fields. All fields are given as decimal numbers or labels. The number of fields depends on the instruction, and unused fields should be ignored (treat them like comments).

Symbolic addresses refer to labels. For lw or sw instructions, the assembler should compute offsetField to be equal to the address of the label. This could be used with a zero base register to refer to the label, or could be used with a non-zero base register to index into an array starting at the label. For beq instructions, the assembler should translate the label into the numeric offsetField needed to branch to that label.

After the last used field comes more white space, then any comments. The comment field ends at the end of a line. Comments are vital to creating understandable assembly-language programs, because the instructions themselves are rather cryptic.

In addition to LC3101 instructions, an assembly-language program may contain directions for the assembler. The only assembler directive we will use is .fill (note the leading period). .fill tells the assembler to put a number into the place where the instruction would normally be stored. .fill instructions use one field, which can be either a numeric value or a symbolic address. For example, ".fill 32" puts the value 32 where the instruction would normally be stored. .fill with a symbolic address will store the address of the label. In the example below, ".fill start" will store the value 2, because the label "start" is at address 2.

The assembler should make two passes over the assembly-language program. In the first pass, it will calculate the address for every symbolic label. Assume that the first instruction is at address 0. In the second pass, it will generate a machine-language instruction (in decimal) for each line of assembly language. For example, here is an assembly-language program (that counts down from 5, stopping when it hits 0).

	lw	0	1	five	load reg1 with 5 (uses symbolic address)
	lw	1	2	3	load reg2 with -1 (uses numeric address)
start	add	1	2	1	decrement reg1
	beq	0	1	2	goto end of program when reg1==0
	beq	0	0	start	go back to the beginning of the loop
	noop				
done	halt				end of program
five	.fill	5			

```
negl .fill -1
stAddr .fill start          will contain the address of start (2)
```

And here is the corresponding machine language:

```
(address 0): 8454151 (hex 0x810007)
(address 1): 9043971 (hex 0x8a0003)
(address 2): 655361 (hex 0xa0001)
(address 3): 16842754 (hex 0x1010002)
```

file, one instruction per line. Any deviation from this format (e.g. extra spaces or empty lines) will render your machine-code file ungradable. Any other output that you want the program to generate (e.g. debugging output) can be printed to standard output.

4.2. Error Checking

Your assembler should catch the following errors in the assembly-language program: use of undefined labels, duplicate labels, offsetFields that don't fit in 16 bits, and unrecognized opcodes. Your assembler should exit(1) if it detects an error and exit(0) if it finishes without detecting any errors. Your assembler should NOT catch simulation-time errors, i.e. errors that would occur at the time the assembly-language program executes (e.g. branching to address -1, infinite loops, etc.).

4.3. Test Cases

An integral (and graded) part of writing your assembler will be to write a suite of test cases to validate any LC3101 assembler. This is common practice in the real world--software companies maintain a suite of test cases for their programs and use this suite to check the program's correctness after a change. Writing a comprehensive suite of test cases will deepen your understanding of the project specification and your program, and it will help you a lot as you debug your program.

The test cases for the assembler part of this project will be short assembly-language programs that serve as input to an assembler. You will submit your suite of test cases together with your assembler, and we will grade your test suite according to how thoroughly it exercises an assembler. Each test case may be at most 50 lines long, and your test suite may contain up to 20 test cases. These limits are much larger than needed for full credit (the solution test suite is composed of 5 test cases, each < 10 lines long). See Section 7 for how your test suite will be graded.

Hints: the example assembly-language program above is a good case to include in your test suite, though you'll need to write more test cases to get full credit. Remember to create some test cases that test the ability of an assembler to check for the errors in Section 4.2.

4.4. Assembler Hints

Since `offsetField` is a 2's complement number, it can only store numbers ranging from -32768 to 32767. For symbolic addresses, your assembler will compute `offsetField` so that the instruction refers to the correct label.

Remember that `offsetField` is only an 16-bit 2's complement number. Since most machines you run your assembler on have 32-bit or 64-bit integers, you will have to truncate all but the lowest 16 bits for negative values of `offsetField`.

5. Behavioral Simulator (40%)

The second part of this assignment is to write a program that can simulate any legal LC3101 machine-code program. The input for this part will be the machine-code file that you created with your assembler. With a program name of "simulate" and a machine-code file of "program.mc", your program should be run as follows:

```
simulate program.mc > output
```

This directs all print statements to the file "output".

The simulator should begin by initializing all registers and the program counter to 0. The simulator will then simulate the program until the program executes a halt.

The simulator should call `printState` (included below) before executing each instruction and once just before exiting the program. This function prints the current state of the machine (program counter, registers, memory). `printState`

As with the assembler, you will write a suite of test cases to validate the LC3101 simulator.

The test cases for the simulator part of this project will be short assembly-language programs that, after being assembled into machine code, serve as input to a simulator. You will submit your suite of test cases together

For the simulator test suite, we will correctly assemble each test case, then use it as input to a set of buggy simulators. A test case exposes a buggy simulator by causing it to generate a different answer from a correct simulator. The test suite is graded based on how many of the buggy simulators were exposed by at least one test case.

8. Turning in the Project

Submit your files through blackboard.
Each part should be archived in a .tar or .zip file to help with grading.

Here are the files you should submit for each project part:

- 1) assembler (part 1a)
 - a. C/C++ program for your assembler
 - b. suite of test cases (each test case is an assembly-language program)

You may also choose to not use this fragment.

```
/* Assembler code fragment for LC3101 */
```

```
#include <stdlib.h>
```

```
#include <stdio.h>
```

```
#include <string.h>
```

```
#define MAXLINELENGTH 1000
```

```

    /* after doing a readAndParse, you may want to do the following to
test the
        opcode */
    if (!strcmp(opcode, "add")) {
        /* do whatever you need to do for opcode "add" */
    }

    return(0);
}

/*
 * Read and parse a line of the assembly-language file. Fields are
returned
 * in label, opcode, arg0, arg1, arg2 (these strings must have memory
already
 * allocated to them).
 *
 * Return values:
 *     0 if reached end of file
 *     1 if all went well
 *
 * exit(1) if line is too long.
 */
int
readAndParse(FILE *inFilePtr, char *label, char *opcode, char *arg0,
             char *arg1, char *arg2)
{
    char line[MAXLINELENGTH];
    char *ptr = line;

    /* delete prior values */
    label[0] = opcode[0] = arg0[0] = arg1[0] = arg2[0] = '\0';

    /* read the line from the assembly-language file */
    if (fgets(line, MAXLINELENGTH, inFilePtr) == NULL) {
        /* reached end of file */
        return(0);
    }

    /* check for line too long (by looking for a \n) */
    if (strchr(line, '\n') == NULL) {
        /* line too long */
        printf("error: line too long\n");
        exit(1);
    }

    /* is there a label? */
    ptr = line;
    if (sscanf(ptr, "%[^\\t\\n ]", label)) {
        /* successfully read label; advance pointer over the label */
        ptr += strlen(label);
    }

    /*

```

```

        * Parse the rest of the line.  Would be nice to have real regular
        * expressions, but scanf will suffice.
        */
        sscanf(ptr, "%*[\t\n ]%[^\\t\\n ]%*[\t\n ]%[^\\t\\n ]%*[\t\n ]%[^\\t\\n
]%^*[\t\n ]%[^\\t\\n ]",
               opcode, arg0, arg1, arg2);
        return(1);
    }

int
isNumber(char *string)
{
    /* return 1 if string is a number */
    int i;
    return( (sscanf(string, "%d", &i)) == 1);
}

```

10. Code Fragment for Simulator

Here is some C code that may help you write the simulator. Again, you should take this merely as a hint. You may have to re-code this to make it do exactly what you want, but this should help you get started. Remember not to change stateStruct or printState.

```

/* instruction-level simulator for LC3101 */

#include <stdio.h>
#include <string.h>

#define NUMMEMORY 65536 /* maximum number of words in memory */
#define NUMREGS 8 /* number of machine registers */
#define MAXLINELENGTH 1000

typedef struct stateStruct {
    int pc;
    int mem[NUMMEMORY];
    int reg[NUMREGS];
    int numMemory;
} stateType;

void printState(stateType *);

int
main(int argc, char *argv[])
{
    char line[MAXLINELENGTH];
    stateType state;
    FILE *filePtr;

    if (argc != 2) {

```


bits. Neither a nor b are changed. E.g. $(25 \gg 2)$ is 6. Note that 25 is 11001 in binary, and 6 is 110 in binary.

3) The value of the expression $(a \ll b)$ is the number "a" shifted left by "b" bits. Neither a nor b are changed. E.g. $(25 \ll 2)$ is 100. Note that 25 is 11001 in binary, and 100 is 1100100 in binary.

4) To find the value of the expression $(a \& b)$, perform a logical AND on each bit of a and b (i.e. bit 31 of a AND'ed with bit 31 of b, bit 30 of a AND'ed with bit 30 of b, etc.). E.g. $(25 \& 11)$ is 9, since:

```
    11001 (binary)
    & 01011 (binary)
    -----
    = 01001 (binary), which is 9 decimal.
```

5) To find the value of the expression $(a | b)$, perform a logical OR on each bit of a and b (i.e. bit 31 of a OR'ed with bit 31 of b, bit 30 of a OR'ed with bit 30 of b, etc.). E.g. $(25 | 11)$ is 27, since:

```
    11001 (binary)
    | 01011 (binary)
    -----
    = 11011 (binary), which is 27 decimal.
```

6) $\sim a$ is the bit-wise complement of a (a is not changed).

Use these operations to create and manipulate machine-code. E.g. to look at bit 3 of the variable a, you might do: $(a \gg 3) \& 0x1$. To look at bits (bits 15-12) of a 16-bit word, you could do: $(a \gg 12) \& 0xF$. To put a 6 into bits 5-3 and a 3 into bits 2-1, you could do: $(6 \ll 3) | (3 \ll 1)$. If you're not sure what an operation is doing, print some intermediate results to help you debug.

12. Example Run of Simulator

```
memory[0]=8454151
memory[1]=9043971
memory[2]=655361
memory[3]=16842754
memory[4]=16842749
memory[5]=29360128
memory[6]=25165824
```

```
memory[7]=5
memory[8]=-1
memory[9]=2
```

```
@@@
```

```
state:
```

```
pc 0
```

```
memory:
```

```
mem[ 0 ] 8454151
mem[ 1 ] 9043971
mem[ 2 ] 655361
mem[ 3 ] 16842754
mem[ 4 ] 16842749
mem[ 5 ] 29360128
mem[ 6 ] 25165824
mem[ 7 ] 5
mem[ 8 ] -1
mem[ 9 ] 2
```

```
registers:
```

```
reg[ 0 ] 0
reg[ 1 ] 0
reg[ 2 ] 0
reg[ 3 ] 0
reg[ 4 ] 0
reg[ 5 ] 0
reg[ 6 ] 0
reg[ 7 ] 0
```

```
end state
```

```
@@@
```

```
state:
```

```
pc 1
```

```
memory:
```

```
mem[ 0 ] 8454151
mem[ 1 ] 9043971
mem[ 2 ] 655361
mem[ 3 ] 16842754
mem[ 4 ] 16842749
mem[ 5 ] 29360128
mem[ 6 ] 25165824
mem[ 7 ] 5
mem[ 8 ] -1
mem[ 9 ] 2
```

```
registers:
```

```
reg[ 0 ] 0
reg[ 1 ] 5
reg[ 2 ] 0
reg[ 3 ] 0
reg[ 4 ] 0
reg[ 5 ] 0
reg[ 6 ] 0
reg[ 7 ] 0
```

```
end state
```



```

@@@
state:
    pc 2
    memory:
        mem[ 0 ] 8454151
        mem[ 1 ] 9043971
        mem[ 2 ] 655361
        mem[ 3 ] 16842754
        mem[ 4 ] 16842749
        mem[ 5 ] 29360128
        mem[ 6 ] 25165824
        mem[ 7 ] 5
        mem[ 8 ] -1
        mem[ 9 ] 2
    registers:
        reg[ 0 ] 0
        reg[ 1 ] 5
        reg[ 2 ] -1
        reg[ 3 ] 0
        reg[ 4 ] 0
        reg[ 5 ] 0
        reg[ 6 ] 0
        reg[ 7 ] 0
end state

```

```

@@@
state:
    pc 3
    memory:
        mem[ 0 ] 8454151
        mem[ 1 ] 9043971
        mem[ 2 ] 655361
        mem[ 3 ] 16842754
        mem[ 4 ] 16842749
        mem[ 5 ] 29360128
        mem[ 6 ] 25165824
        mem[ 7 ] 5
        mem[ 8 ] -1
        mem[ 9 ] 2
    registers:
        reg[ 0 ] 0
        reg[ 1 ] 4
        reg[ 2 ] -1
        reg[ 3 ] 0
        reg[ 4 ] 0
        reg[ 5 ] 0
        reg[ 6 ] 0
        reg[ 7 ] 0
end state

```

```

@@@
state:
    pc 4

```

```

memory:
    mem[ 0 ] 8454151
    mem[ 1 ] 9043971
    mem[ 2 ] 655361
    mem[ 3 ] 16842754
    mem[ 4 ] 16842749
    mem[ 5 ] 29360128
    mem[ 6 ] 25165824
    mem[ 7 ] 5
    mem[ 8 ] -1
    mem[ 9 ] 2
registers:
    reg[ 0 ] 0
    reg[ 1 ] 4
    reg[ 2 ] -1
    reg[ 3 ] 0
    reg[ 4 ] 0
    reg[ 5 ] 0
    reg[ 6 ] 0
    reg[ 7 ] 0
end state

```

@@@

```

state:
    pc 2
    memory:
        mem[ 0 ] 8454151
        mem[ 1 ] 9043971
        mem[ 2 ] 655361
        mem[ 3 ] 16842754
        mem[ 4 ] 16842749
        mem[ 5 ] 29360128
        mem[ 6 ] 25165824
        mem[ 7 ] 5
        mem[ 8 ] -1
        mem[ 9 ] 2
    registers:
        reg[ 0 ] 0
        reg[ 1 ] 4
        reg[ 2 ] -1
        reg[ 3 ] 0
        reg[ 4 ] 0
        reg[ 5 ] 0
        reg[ 6 ] 0
        reg[ 7 ] 0
end state

```

@@@

```

state:
    pc 3
    memory:
        mem[ 0 ] 8454151
        mem[ 1 ] 9043971
        mem[ 2 ] 655361

```

```

        mem[ 3 ] 16842754
        mem[ 4 ] 16842749
        mem[ 5 ] 29360128
        mem[ 6 ] 25165824
        mem[ 7 ] 5
        mem[ 8 ] -1
        mem[ 9 ] 2
    registers:
        reg[ 0 ] 0
        reg[ 1 ] 3
        reg[ 2 ] -1
        reg[ 3 ] 0
        reg[ 4 ] 0
        reg[ 5 ] 0
        reg[ 6 ] 0
        reg[ 7 ] 0
end state

```

```

@@@
state:
    pc 4
    memory:
        mem[ 0 ] 8454151
        mem[ 1 ] 9043971
        mem[ 2 ] 655361
        mem[ 3 ] 16842754
        mem[ 4 ] 16842749
        mem[ 5 ] 29360128
        mem[ 6 ] 25165824
        mem[ 7 ] 5
        mem[ 8 ] -1
        mem[ 9 ] 2
    registers:
        reg[ 0 ] 0
        reg[ 1 ] 3
        reg[ 2 ] -1
        reg[ 3 ] 0
        reg[ 4 ] 0
        reg[ 5 ] 0
        reg[ 6 ] 0
        reg[ 7 ] 0
end state

```

```

@@@
state:
    pc 2
    memory:
        mem[ 0 ] 8454151
        mem[ 1 ] 9043971
        mem[ 2 ] 655361
        mem[ 3 ] 16842754
        mem[ 4 ] 16842749
        mem[ 5 ] 29360128
        mem[ 6 ] 25165824

```

```

        mem[ 7 ] 5
        mem[ 8 ] -1
        mem[ 9 ] 2
    registers:
        reg[ 0 ] 0
        reg[ 1 ] 3
        reg[ 2 ] -1
        reg[ 3 ] 0
        reg[ 4 ] 0
        reg[ 5 ] 0
        reg[ 6 ] 0
        reg[ 7 ] 0
end state

```

@@@

state:

pc 3

memory:

```

        mem[ 0 ] 8454151
        mem[ 1 ] 9043971
        mem[ 2 ] 655361
        mem[ 3 ] 16842754
        mem[ 4 ] 16842749
        mem[ 5 ] 29360128
        mem[ 6 ] 25165824
        mem[ 7 ] 5
        mem[ 8 ] -1
        mem[ 9 ] 2

```

registers:

```

        reg[ 0 ] 0
        reg[ 1 ] 2
        reg[ 2 ] -1
        reg[ 3 ] 0
        reg[ 4 ] 0
        reg[ 5 ] 0
        reg[ 6 ] 0
        reg[ 7 ] 0

```

end state

@@@

state:

pc 4

memory:

```

        mem[ 0 ] 8454151
        mem[ 1 ] 9043971
        mem[ 2 ] 655361
        mem[ 3 ] 16842754
        mem[ 4 ] 16842749
        mem[ 5 ] 29360128
        mem[ 6 ] 25165824
        mem[ 7 ] 5
        mem[ 8 ] -1
        mem[ 9 ] 2

```

registers:

```
        reg[ 0 ] 0
        reg[ 1 ] 2
        reg[ 2 ] -1
        reg[ 3 ] 0
        reg[ 4 ] 0
        reg[ 5 ] 0
        reg[ 6 ] 0
        reg[ 7 ] 0
end state
```

```
@@@
state:
    pc 2
    memory:
        mem[ 0 ] 8454151
        mem[ 1 ] 9043971
        mem[ 2 ] 655361
        mem[ 3 ] 16842754
        mem[ 4 ] 16842749
        mem[ 5 ] 29360128
        mem[ 6 ] 25165824
        mem[ 7 ] 5
        mem[ 8 ] -1
        mem[ 9 ] 2
    registers:
        reg[ 0 ] 0
        reg[ 1 ] 2
        reg[ 2 ] -1
        reg[ 3 ] 0
        reg[ 4 ] 0
        reg[ 5 ] 0
        reg[ 6 ] 0
        reg[ 7 ] 0
```

end state

```
@@@
state:
    pc 3
    memory:
        mem[ 0 ] 8454151
        mem[ 1 ] 9043971
        mem[ 2 ] 655361
        mem[ 3 ] 16842754
        mem[ 4 ] 16842749
        mem[ 5 ] 29360128
        mem[ 6 ] 25165824
        mem[ 7 ] 5
        mem[ 8 ] -1
        mem[ 9 ] 2
    registers:
        reg[ 0 ] 0
        reg[ 1 ] 1
        reg[ 2 ] -1
        reg[ 3 ] 0
```

```
        reg[ 4 ] 0
        reg[ 5 ] 0
        reg[ 6 ] 0
        reg[ 7 ] 0
end state
```

@@@

state:

pc 4

memory:

```
mem[ 0 ] 8454151
mem[ 1 ] 9043971
mem[ 2 ] 655361
mem[ 3 ] 16842754
mem[ 4 ] 16842749
mem[ 5 ] 29360128
mem[ 6 ] 25165824
mem[ 7 ] 5
mem[ 8 ] -1
mem[ 9 ] 2
```

registers:

```
reg[ 0 ] 0
reg[ 1 ] 1
reg[ 2 ] -1
reg[ 3 ] 0
reg[ 4 ] 0
reg[ 5 ] 0
reg[ 6 ] 0
reg[ 7 ] 0
```

end state

@@@

state:

pc 2

memory:

```
mem[ 0 ] 8454151
mem[ 1 ] 9043971
mem[ 2 ] 655361
mem[ 3 ] 16842754
mem[ 4 ] 16842749
mem[ 5 ] 29360128
mem[ 6 ] 25165824
mem[ 7 ] 5
mem[ 8 ] -1
mem[ 9 ] 2
```

registers:

```
reg[ 0 ] 0
reg[ 1 ] 1
reg[ 2 ] -1
reg[ 3 ] 0
reg[ 4 ] 0
reg[ 5 ] 0
reg[ 6 ] 0
reg[ 7 ] 0
```

end state

@@@

state:

pc 3

memory:

mem[0]	8454151
mem[1]	9043971
mem[2]	655361
mem[3]	16842754
mem[4]	16842749
mem[5]	29360128
mem[6]	25165824
mem[7]	5
mem[8]	-1
mem[9]	2

registers:

reg[0]	0
reg[1]	0
reg[2]	-1
reg[3]	0
reg[4]	0
reg[5]	0
reg[6]	0
reg[7]	0

end state

@@@

state:

pc 6

memory:

mem[0]	8454151
mem[1]	9043971
mem[2]	655361
mem[3]	16842754
mem[4]	16842749
mem[5]	29360128
mem[6]	25165824
mem[7]	5
mem[8]	-1
mem[9]	2

registers:

reg[0]	0
reg[1]	0
reg[2]	-1
reg[3]	0
reg[4]	0
reg[5]	0
reg[6]	0
reg[7]	0

end state

machine halted

total of 17 instructions executed

final state of machine:

```
@@@
state:
  pc 7
  memory:
    mem[ 0 ] 8454151
    mem[ 1 ] 9043971
    mem[ 2 ] 655361
    mem[ 3 ] 16842754
    mem[ 4 ] 16842749
    mem[ 5 ] 29360128
    mem[ 6 ] 25165824
    mem[ 7 ] 5
    mem[ 8 ] -1
    mem[ 9 ] 2
  registers:
    reg[ 0 ] 0
    reg[ 1 ] 0
    reg[ 2 ] -1
    reg[ 3 ] 0
    reg[ 4 ] 0
    reg[ 5 ] 0
    reg[ 6 ] 0
    reg[ 7 ] 0
end state
```