

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 (R-type format) | 001 | nand contents of regA with contents of regB, store results in destReg. |
| lw (I-type format) | 010 | load regB from memory. Memory address is formed by adding offsetField with the contents of regA. |
| sw (I-type format) | 011 | store regB into memory. Memory address is formed by adding offsetField with the contents of regA. |
| beq (I-type format) | 100 | if the contents of regA and regB are the same, then branch to the address PC+1+offsetField, where PC is the address of the beq instruction. |
| cmov (R-type) | 101 | copy the value regA into destReg if the contents of regB != 0 |
| halt (O-type format) | 110 | increment the PC (as with all instructions), then halt the machine (let the simulator notice that the machine halted). |
| noop (O-type format) | 111 | do nothing except increment PC. |

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).

R-type instructions (add, nand) instructions require 3 fields: field0 is regA, field1 is regB, and field2 is destReg.

I-type instructions (lw, sw, beq) require 3 fields: field0 is regA, field1 is regB, and field2 is either a numeric value for offsetField or a symbolic address. Numeric offsetFields can be positive or negative; symbolic addresses are discussed below.

O-type instructions (noop and halt) require no fields.

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)
(address 4): 16842749 (hex 0x100fffd)
(address 5): 29360128 (hex 0x1c00000)
(address 6): 25165824 (hex 0x1800000)
(address 7): 5 (hex 0x5)
(address 8): -1 (hex 0xffffffff)
(address 9): 2 (hex 0x2)
```

Be sure you understand how the above assembly-language program got translated to machine language.

Since your programs will always start at address 0, your program should only output the contents, not the addresses.

```
8454151
9043971
655361
16842754
16842749
29360128
25165824
5
-1
2
```

4.1. Running Your Assembler

Write your program to take two command-line arguments. The first argument is the file name where the assembly-language program is stored, and the second argument is the file name where the output (the machine-code) is written. For example, with a program name of "assemble", an assembly-language program in "program.as", the following would generate a machine-code file "program.mc":

```
assemble program.as program.mc
```

Note that the format for running the command must use command-line arguments for the file names (rather than standard input and standard output). Your program should store only the list of decimal numbers in the machine-code

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` will print the memory contents for memory locations defined in the machine-code file (addresses 0-9 in the Section 4 example).

5.1 Test Cases

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 with your simulator, and we will grade your test suite according to how thoroughly it exercises an LC3101 simulator. Each test case may execute at most 200 instructions on a correct simulator, and your test suite may contain up to 20 test cases. The goal is to how

program halts. You may assume that the two input numbers are at most 15 bits and are positive; this ensures that the (positive) result fits in an LC3101 word. See the algorithm on page 252 of the textbook for how to multiply. Remember that shifting left by one bit is the same as adding the number to itself. Given the LC3101 instruction set, it's easiest to modify the algorithm so that you avoid the right shift. Submit a version of the program that computes $(32766 * 10383)$.

Your multiplication program must be reasonably efficient--it must be at most 50 lines long and execute at most 1000 instructions for any valid numbers (this is several times longer and slower than the solution). To achieve this, you must use a loop and shift algorithm to perform the multiplication; algorithms such as successive addition (e.g. multiplying $5 * 6$ by adding 5 six times) will take too long.

7. Grading and Formatting

We will grade primarily on functionality, including error handling, correctly assembling and simulating all instructions, input and output format, method of executing your program, correctly multiplying, and comprehensiveness of the test suites.

The best way to debug your program is to generate your own test cases, figure out the correct answers, and compare your program's output to the correct answers. This is also one of the best ways to learn the concepts in the project.

The student suite of test cases for the assembler and simulator parts of this project will be graded according to how thoroughly they test an LC3101 assembler or simulator. We will judge thoroughness of the test suite by how well it exposes potentially bugs in an assembler or simulator.

For the assembler test suite, we will use each test case as input to a set of buggy assemblers. A test case exposes a buggy assembler by causing it to generate a different answer from a correct assembler. The test suite is graded based on how many of the buggy assemblers were exposed by at least one test case. This is known as "mutation testing" in the research literature on automated testing.

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(bu)-4(g)9(gy)7(s)7(im)7. The test suite is graded based on how many of the buggy sim(gy)7(s)7(im)7s were expssed by at least one test case.

8. Turning in the Project

Submit you files through blackboaim
Each part shoggybe archived in a .taimr .mp file to help with grading.

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

int readAndParse(FILE *, char *, char *, char *, char *, char *);
int isNumber(char *);

int
main(int argc, char *argv[])
{
    char *inFileString, *outFileString;
    FILE *inFilePtr, *outFilePtr;
    char label[MAXLINELENGTH], opcode[MAXLINELENGTH],
    arg0[MAXLINELENGTH],
        arg1[MAXLINELENGTH], arg2[MAXLINELENGTH];

    if (argc != 3) {
        printf("error: usage: %s <assembly-code-file> <machine-code-
file>\n",
            argv[0]);
        exit(1);
    }

    inFileString = argv[1];
    outFileString = argv[2];

    inFilePtr = fopen(inFileString, "r");
    if (inFilePtr == NULL) {
        printf("error in opening %s\n", inFileString);
        exit(1);
    }
    outFilePtr = fopen(outFileString, "w");
    if (outFilePtr == NULL) {
        printf("error in opening %s\n", outFileString);
        exit(1);
    }

    /* here is an example for how to use readAndParse to read a line from
       inFilePtr */
    if (! readAndParse(inFilePtr, label, opcode, arg0, arg1, arg2) ) {
        /* reached end of file */
    }

    /* this is how to rewind the file ptr so that you start reading from
the
       beginning of the file */
    rewind(inFilePtr);
```

```

    /* 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 ANDED with bit 31 of b, bit 30 of a ANDED 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 ORED with bit 31 of b, bit 30 of a ORED 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
```