Question 1 (10 points) For each of the following, either fill in the correct answer or answer **True** or **False** as appropriate:

1. Name of the basic circuit we have learned that is used to store 1-bit of information. Any pulse controlled latch

2. The unique number associated with each word in memory is called by this name. __Address______

3. The addressability of LC-3 is 2 bytes. (True/False) ___True________

4. Write the size of the address space of LC-3's memory. ___32768_______

5. The Gated D-Latch is a sequential logic circuit. (True/False) ___False_______

6. Finite State Machines are implemented using Combinational Logic Circuits. (True/False) ___False_______

7. The Finite State Machine of LC-3 is an asynchronous Finite State Machine ___False_______

8. Flip-Flops help to synchronize with the system clock. (True/False) ___True_______

9. What is another name for the Program Counter (or PC). Instruction Pointer

10. What is the word length of the LC-3 ALU? ___16 bits_____

Question 2 (15 points) Write short answers to each of the following.
Part A: In LC-3 what are **MAR** and **MDR**? What are they used for? How many bits are there in the **MAR** and **MDR**?

MAR = Memory Address Register

MDR = Memory Data Register

While reading from memory, the address of the location to be read is first placed in the MAR. Then, the data from that memory location appears in the MDR.

While writing, the data to be stored is first placed in the MDR. Then the adddress where it is to be stored is placed in the MAR.

Part B: In LC-3 what are the condition code registers? How are they used?

N, Z, and P are the three condition codes in LC-3.

Every time a data is moved some place (registers or memory), or an operation is performed, the condition codes are set depending on the value.

Part C: In LC-3 what is the purpose of the **Instruction Register**?

Contains the fetched instruction from the memory location pointed to by the PC. This is the instruction to be decoded and executed.

Question 3 (10 points)

Part A: The LC-3 has 15 opcodes that define the instructions in its ISA. However, the instruction set charts of LC-3 (see page 2) lists 19 instructions. Explain.

Because instructions like ADD and AND use two different addressing modes. Also, there are two Jump instructions that use the same opcode. These four variations make up 15+4 = 19 instructions.

Part B: For each of the following categories, name all the LC-3 instructions that fall in that category (Select from: **ADD**, **AND**, **Branch**, **Jump**, **Load**, **NOT**, **Store**, **HALT**):

Operate Instructions	ADD, AND, NOT
Data Movement Instructions	Load, Store
Control Instructions	Branch, Jump, HALT

Question 4 (20 points) For each of the following, decode each instruction by listing the following: the opcode, all operands, the addressing mode used, and the task it performs using symbolic names (e.g. **Load**, **ADD**, **R3**, **R2**, **#11**, **R2 = R2 + 3**, etc.)):

A.

0	0	0	0	0	0	1	1	1	1	1	1	1	0	1	1

Opcode: __0000 (BR)__________ Operands: ___#-5_______________

Addressing Mode: __PC Relative mode__ Task: _if P then PC = PC - 5_______

B.

0	0	0	1	1	1	0	1	1	0	0	0	0	1	1	0

Opcode: ___0001 (ADD)________ Operands: __R6, R6, R6________

Addressing Mode: __Register mode_____ Task: __R6 = R6 + R6_________

C.

0	0	0	1	1	1	0	1	1	0	1	0	0	1	1	0

Opcode: ___0001 (ADD)________ Operands: __R6, R6, #6_________

Addressing Mode: Register+Immediate mode Task: ___R6 = R6 + 6___________

D.

1	1	0	1	1	0	1	1	0	1	0	0	0	1	1	0

Opcode: ___1101 (Reserved)__ Operands: _____N/A____________

Addressing Mode: ___N/A_______________ Task: _Not an instruction_________

E.

0	0	1	0	1	1	1	0	0	0	0	0	1	0	0	1

Opcode: __0010 (LD)__________ Operands: __R7, #9_____________

Addressing Mode: ___Register+PC Relative_ Task: ___R7 = M[PC+9]_________

Question 5 (15 points) Encode each of the following tasks into **an** equivalent LC-3 **machine language** instruction. Where needed, the address of the current instruction is provided.:

A. `R6 = NOT(R6)`

1001 110 110 111111

B. `x600A R4 = M[x6000]`

0010 100 111 110 101 ; R4 = M[PC - 11]

C. `R3 = M[R0]`

0110 011 000 000000

D. `x600D Branch if Positive x6008`

0000 001 1111 1010 ; BR if P to PC-6

E. `R5 = R5 - 3`

0001 101 101 1 11101

Question 6 (15 points) Write a sequence of LC-3 assembly language instructions to accomplish the tasks given (use comments to indicate what each instruction does):

A. **R7 = R3 - R0**

```
1001 110 000 111111      NOT   R6, R0        ; R6 = NOT(R0)
0001 110 110 1 00001     ADD   R6, R6, #1    ; R6 = R6 + 1
; Now R6 is -R0
0001 111 011 000 110     ADD   R7, R3, R6    ; R7 = R3 + R6
```

[Note: Not a good idea to change values in R3 or R0. Why?]

B. **R7 = R6**

```
0101 111 111 1 00000     AND   R7, R7, #0    ; First, set R7 =0
0001 111 111 000 110     ADD   R7, R7, R6    ; Add R6 to R7
```

Alternately:

```
0001 111 110 1 00000     ADD   R7, R6, #0    ; R7 = R6 + 0
```

C. **R7 = R7 * 2**

There is no multiply instruction. But multiplication by 2 can be achieved by adding the number to itself.

```
0001 111 111 000 111     ADD   R7, R7, R7    ; R7 = R7 + R7
```

D. Swap the contents of **R6** and **R7**.

```
; We will use R5 as temp
0001 101 110 1 00000     ADD   R5, R6, #0    ; R5 = R6 + 0
0001 110 111 1 00000     ADD   R6, R7, #0    ; R6 = R7 + 0
0001 111 101 1 00000     ADD   R7, R5, #0    ; R7 = R5 + 0
```

E. **R7 = R1 + R2 + R3**

```
0001 111 001 0 00 010    ADD   R7, R1, R2    ; R7 = R1 + R2
0001 111 111 0 00 011    ADD   R7, R7, R3    ; R7 = R7 + R3
```

Question 7 (15 points) Write an LC-3 Assembly Language program to add a bunch of integers (quantity unknown). The integers are stored starting from address x3100. A sentinel value of -1 will indicate the end of input. Below, an algorithm, register allocations, and a flow chart for accomplishing the task are provided.

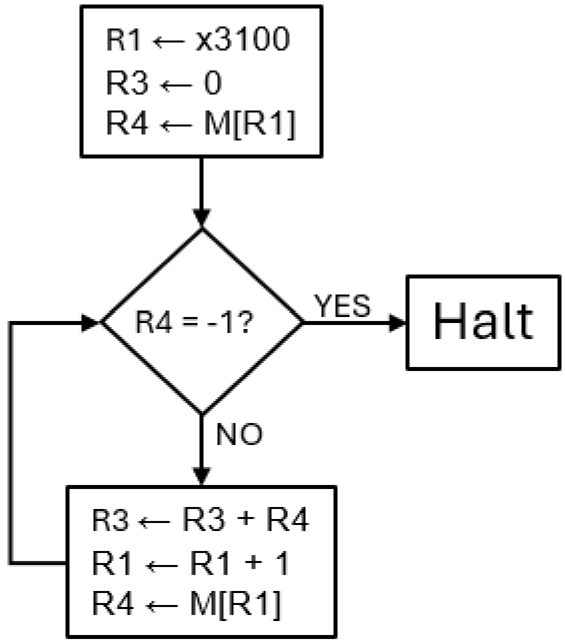
Algorithm:

```
sum ← 0
n ← first number
while n != -1 do
    sum ← sum + n
    n ← next number
```

We will use the following registers:

```
R1: starting address of data (x3100)
R3: sum
R4: n
```

The flowchart is shown on the right.



Your task is to code the flowchart, into a <u>complete</u> <u>LC-3 Assembly Language Program</u>. The program should be stored starting from x3000. Continue on next page if needed.

```
        .ORIG   x3000
START   LEA     R1, DATA        ; R1 < x3100
        AND     R3, R3, #0  ; R3 <- 0
        LDR     R4, R1, #0  ; R4 <- M[R1]
; while R4 != -1
LOOP    BRn     DONE        ;   YES (R4 = -1)
; do
        ADD     R3, R3, R4  ; R3 <- R3 + R4
        ADD     R1, R1, #1  ; R1 <- R1 + 1
        LDR     R4, R1, #0  ; R4 <- M[R1]
        BR      LOOP
DONE    HALT
        .END
; Data
        .ORIG   x3100
DATA    .FILL   n1
        .FILL   n2
        … … …
        .END
```