ECE 120 Final Exam
Fall 2016

Wednesday, December 14, 2016

Name: SOLUTIONS

NetID: ____________

Discussion Section:

9:00 AM		
10:00 AM		
11:00 AM	☐ AB1	☐ AB8
12:00 PM	☐ AB2	☐ AB9
1:00 PM	☐ AB3	☐ ABA
2:00 PM	☐ AB4	☐ ABB
3:00 PM	☐ AB5	
4:00 PM	☐ AB6	☐ ABC
5:00 PM	☐ AB7	☐ ABD

- **Be sure that your exam booklet has 14 pages.**
- **Write your name, netid and check discussion section on the title page.**
- **Do not tear the exam booklet apart, except for the last four pages.**
- **Use backs of pages for scratch work if needed.**
- **This is a closed book exam. You may not use a calculator.**
- **You are allowed two handwritten 8.5 x 11" sheets of notes (both sides).**
- **Absolutely no interaction between students is allowed.**
- **Clearly indicate any assumptions that you make.**
- **The questions are not weighted equally. Budget your time accordingly.**

Problem 1	20 points	____________
Problem 2	16 points	____________
Problem 3	14 points	____________
Problem 4	21 points	____________
Problem 5	14 points	____________
Problem 6	8 points	____________
Problem 7	7 points	____________

Total	100 points	____________

Problem 1 (20 points): Binary Representation and Operations, Hamming codes

1. **(2 points)** There are 365 days in a year. If we want to uniquely identify each day using **2's complement** binary representation, what is the minimum number of bits we should use?

   Minimum number of bits: 10 (decimal number)

2. **(4 points)** Convert the following 24-bit pattern to hexadecimal:

   1100 0000 1111 1111 1110 1110_2 = xC0FFEE (hexadecimal number)

3. **(4 points)** Perform the following **bitwise** logical operations.

   a) 0110 NAND 0011 = 1101

   b) 1001 XOR (NOT(0101)) = 0011

4. **(4 points)** Perform the following operation in **four-bit 2's complement** representation.

   0101 + 101 = 0 010

   Circle one: Carry out? [✓ **YES**] **NO**

   Circle one: Overflow? **YES** [✓ **NO**]

5. **(6 points)** Someone just sent you the following 7-bit Hamming code: $X_7X_6X_5X_4X_3X_2X_1$ = 1010111. Does the message have an error or not?

   Circle one: [✓ **YES**] **NO**

   If you think there is an error, write the position where there is an error:

   There is an error in position 2

Problem 2 (16 points): LC-3 Assembly Programming

Greetings, ECE 120 student.

Your mission, should you choose to accept it, is to **write the missing lines of code**, so the program can properly print on screen a message to wish you an enjoyable break. Additionally, you must **write the missing entries in the symbol table** associated with this program.
As always, should you or any of your friends be caught or killed, the ECE 120 instructors will disavow any knowledge of your actions. This page will self-destruct by the end of the semester.

Good luck, ECE 120 student.

1. **(11 points)** Write the missing lines of code. You must **write one instruction per missing line**.

```
            .ORIG x6000
            LEA R0, PROMPT              ; Print "Choose message: "
            PUTS                        ;
            LD R1, OPTION               ; R1 <- M[OPTION]
            GETC                        ; Read from keyboard
            NOT R0, R0                  ; R0 <- R1-R0
            ADD R0, R0, #1              ;
            ADD R0, R1, R0              ;
            BRnp DIFFERENT              ; Character typed = R1?
            ; Case: character typed = R1
EQUAL       LEA R0, HOLIDAYS            ; R0 <- HOLIDAYS
            BRnzp PRINTOUT              ; Go to PRINTOUT
            ; Case: character typed ≠ R1
DIFFERENT   LEA R0, NEWYEAR             ; R0 <- NEWYEAR
PRINTOUT    PUTS                        ; Print selected message
            HALT                        ;
PROMPT      .STRINGZ "Choose message: "
OPTION      .FILL x0031                 ; ASCII '1'
HOLIDAYS    .STRINGZ "Happy Holidays!"
NEWYEAR     .STRINGZ "Happy New Year!"
            .END
```

Problem 2 (16 points): LC-3 Assembly Programming, continued

2. (5 points) Write the missing entries in the symbol table. Answers in **hexadecimal only**.

```
// Symbol table
// Scope level 0:
//     Symbol Name           Page Address
//     ----------------      ------------
//     EQUAL                 6008
//     DIFFERENT             600A
//     PRINTOUT              600B
//     PROMPT                600D
//     OPTION                601E
//     HOLIDAYS              601F
//     NEWYEAR               602F
```

Problem 3 (14 points): Synchronous Counter

1. **(11 points)** Using D flip-flops, design a 3-bit counter that counts the prime number sequence 2, 3, 5, 7, and repeats. The current state of the counter is denoted by $S_2S_1S_0$. Fill in the K-maps for S_2^+, S_1^+ and S_0^+ **using don't cares wherever possible**.

S_2^+

S_2 \ S_1S_0	00	01	11	10
0	X	X	1	0
1	X	1	0	X

S_1^+

S_2 \ S_1S_0	00	01	11	10
0	X	X	0	1
1	X	1	1	X

S_0^+

S_2 \ S_1S_0	00	01	11	10
0	X	X	1	1
1	X	1	0	X

Write **minimal SOP** Boolean expressions for S_2^+, S_1^+, and S_0^+.

$S_2^+ = \overline{S_1} + \overline{S_2} S_0$

$S_1^+ = S_2 + \overline{S_0}$

$S_0^+ = \overline{S_2} + \overline{S_1}$

2. **(3 points)** Suppose you have already designed a 2-bit binary up-counter that counts in the sequence 0, 1, 2, 3, and repeats. You could attach output logic so that the 2-bit state of this counter produces a 3-bit output: the repeating prime number sequence 2, 3, 5, 7. Write down **one advantage of the approach described here compared to the implementation in part 1**. Express your answer in 10 words or fewer. (**We will not read more than 10 words**.)

fewer flip-flops

modular design

easy to change output sequence

don't need to worry whether it's self-starting

Problem 4 (21 points): LC-3 Data Path and Control Unit

1. **(12 points)** The registers of an LC-3 processor have the values shown below to the right.

R4	x4444
R5	x5555
R6	x6666
R7	x7777

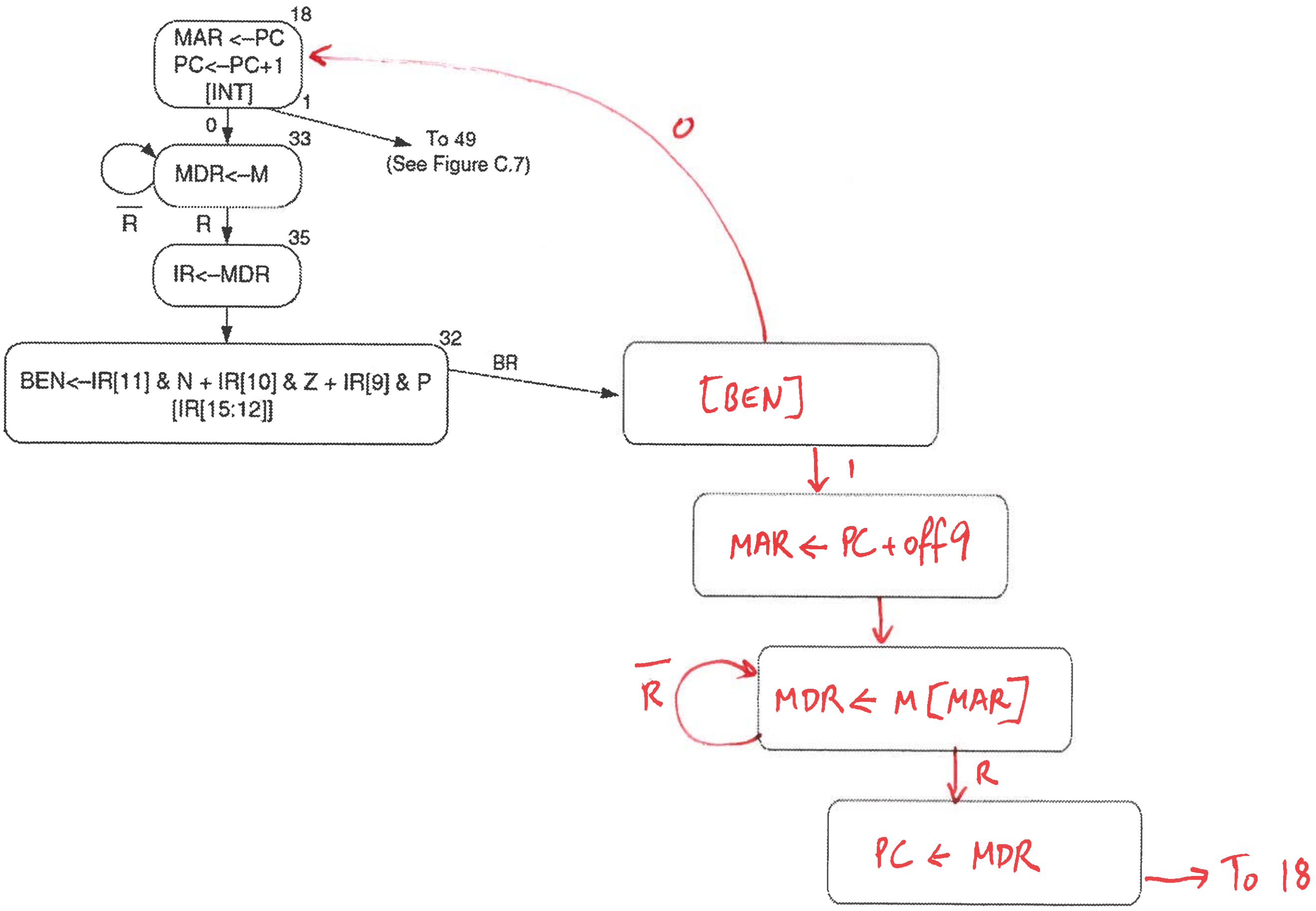
Consider the LC-3 instructions shown in the table below. For the **execute state** of each instruction (state number is provided), fill in the values in the instruction register (IR), at the A input of the ALU, at the B input of the ALU, and on the bus. Write all answers in **hexadecimal**.

Instruction	State number	IR	A input of ALU	B input of ALU	Bus
`AND R1, R5, R5`	5	x5345	x5555	x5555	x5555
`ADD R0, R4, #8`	1	x1128	x4444	x0008	x444C
`NOT R2, R7`	9	x95FF	x7777	xFFFF	x8888

2. **(9 points)** Suppose the LC-3 designers redefine the **BR** instruction. The 16-bit format stays the same, but the new RTL (after fetch and decode phases) is:

BEN: **PC ← M[PC + SEXT(PCoffset9)]**

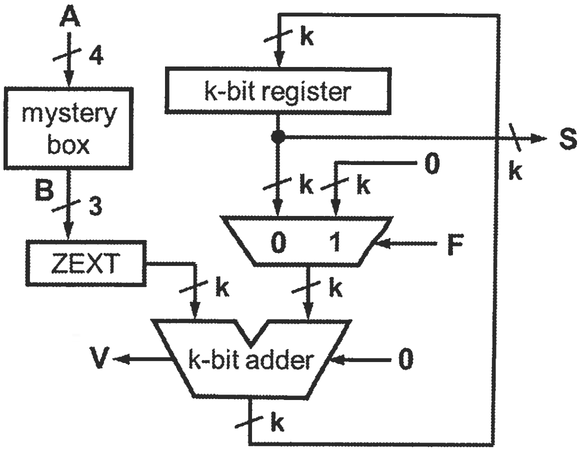
In other words, if BEN=1 then PC changes. Complete the LC-3 FSM diagram below. Fill in the four states for **BR** with RTL, and draw state transitions with labels (if appropriate). **Do NOT number the states.**

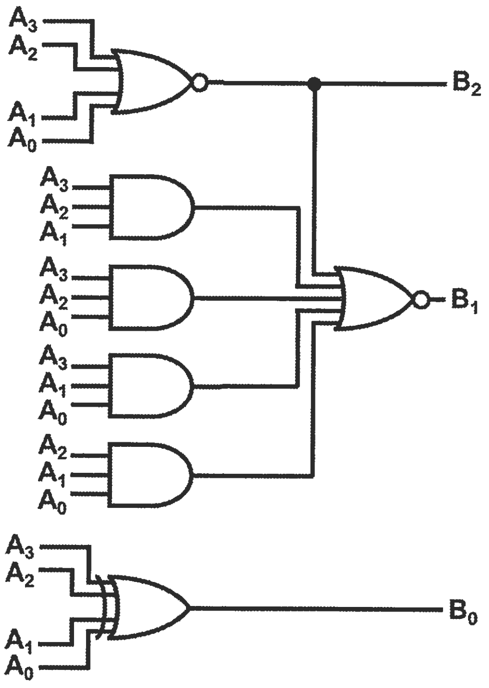


Problem 5 (14 points): FSM Analysis

The FSM on the left below performs a serial calculation on an input A. Four bits are provided through A each cycle. In the first cycle, the F input ("first bits") is set to 1. In all subsequent cycles, F=0. After N cycles, the value S provides the answer as an unsigned number.

The size of the FSM depends on the parameter k, which must be at least 3. Notice that the FSM makes use of a register to hold the state (S is just the stored register value), a set of k 2-to-1 muxes controlled by F, and a k-bit adder. The mystery box (implementation shown on the right below) transforms A into a 3-bit value B, which is then treated as an unsigned number and zero-extended (padded with leading 0s) to k bits.





The questions you need to answer are in the following page.

Tear the last page and use it as scratch paper.

Problem 5 (14 points): FSM Analysis, continued

Answer the questions below based on the FSM design and description on the previous page. In order to help you solving these questions, **we strongly suggest that you fill in the truth table for the mystery box**. To do that, feel free to tear apart the last page of the exam and use it as scratch paper, because **we will NOT grade the truth table**.

Circle **EXACTLY ONE ANSWER** for each question.

1. **(3 points)** What is the smallest possible value represented by the unsigned bit pattern B, **given the implementation of the mystery box**?

   a) -4 **b)** 4 **c)** 1 **d)** -3 [✓ **e)** 0]

2. **(3 points)** What is the largest possible value represented by the unsigned bit pattern B, **given the implementation of the mystery box**?

   a) 7 **b)** 0 **c)** 3 [✓ **d)** 4] **e)** -4

3. **(4 points)** The V output from the adder signifies overflow in the stored value. In terms of k, what is the minimum number of cycles (including the F=1 cycle) for which the FSM can execute before V=1?

   a) 1 [✓ **b)** 2^{k-2} - 1] **c)** 2^{k-1} - 1 **d)** 1 - 2^k **e)** ceil (2^k / 7) – 1

4. **(4 points)** What is the meaning of the output S?
   - **a)** S is the number of cycles in which input A has an odd number of 1 bits.
   - **b)** S is the number of 1 bits passed in through A.
   - **c)** S is the sum of 2's complement values passed in through A.
   - [✓ **d)**] S is the number of 0 bits passed in through A.
   - **e)** None of the above.

Problem 6 (8 points): LC-3 Instructions and Assembler

1. **(5 points)** Decode each of the following LC-3 instructions, writing the RTL in the box beside the instruction. For full credit, your RTL must include specific values for each operand (for example, "R4" rather than "DR"), and must be sign-extended when appropriate. **Do not perform calculations such as addition of the PC value**.

   You may write any immediate values either as hexadecimal (prefix them with "x") or as decimal (prefix them with "#").

   Hint: Draw lines between bits to separate the instructions into appropriate fields.

Instruction bits	**RTL Meaning**
0001 1110 1011 0010	R7 ← R2 - #14, setcc
1100 0001 0100 0000	PC←R5
1011 0010 0101 0011	M[M[PC+x0053]]←R1
0110 0010 1000 0011	R1←M[R2+x0003], setcc

2. **(3 points)** The LC-3 assembler finds **a single error** in the following code. State the nature of the error and in which pass the assembler identifies the error (first or second).

```
        .ORIG x3000
        LEA R1,STRING
PRINT   LDR R0,R1,#0
        BRz DONE
        TRAP x21        ; OUT
        ADD R1,R1,#1
        BRnzp PRINT
DONE    LEA R1,STRING
AGAIN   LDR R0,R1,#0
        BRz DONE
        TRAP x21        ; OUT
        ADD R1,R1,#1
        BRnzp AGAIN
DONE    HALT
STRING  .STRINGZ "This is my string."
DATA    .FILL xFFFF
        .END
```

Circle one: [✓ **PASS 1**] **PASS 2**

Nature of error: DONE label is multiply-defined

Express your answer in 10 words or fewer. (**We will not read more than 10 words.**)

Problem 7 (7 points): LC-3 Assembly Language Interpretation

All questions for this problem pertain to the following code.

```
        .ORIG x3000
        LDI R1,MAGIC
        AND R3,R3,#0
OUTER   AND R2,R2,#0   ; outer loop starts here
        AND R0,R0,#0
INNER   ADD R0,R0,R0   ; inner loop starts here
        ADD R1,R1,#0   ; the inner loop left shifts bits R1[15:12]
        BRzp ZEROBIT   ;    out of R1 and into R0[3:0] to form
        ADD R0,R0,#1   ;    a single hex digit
ZEROBIT ADD R1,R1,R1
        ADD R2,R2,#1
        ADD R4,R2,#-4
        BRn INNER      ; end of inner loop
        ADD R4,R0,#-10 ; start of 'curious code'
        BRzp FORWARD
        LD R2,DIGIT0
        ADD R0,R0,R2
        BRnzp LABEL
FORWARD LD R2,LETTERA
        ADD R0,R4,R2
LABEL   OUT            ; end of 'curious code'
        ADD R3,R3,#1
        ADD R4,R3,#-4
        BRn OUTER      ; end of outer loop
        LD R0,NEWLN
        OUT
        HALT
MAGIC   .FILL x4000
DIGIT0  .FILL x30     ; ASCII digit 0 ('0')
LETTERA .FILL x41     ; ASCII letter A ('A')
NEWLN   .FILL x0A     ; ASCII newline character ('\n')
        .END
```

1. **(1 point)** How many times does the body of the `outer loop` execute? 4

2. **(1 point)** How many times does the body of the `inner loop` execute (for each outer loop iteration)? 4

3. **(3 points)** What does the `'curious code'` marked in the comments do? Express your answer in 10 words or fewer. (**We will not read more than 10 words**.)

   translates hex digit in R0 to ASCII and prints it

4. **(2 points)** Explain how to make the program print "`ECEB`" followed by a newline character to the LC-3 display. Express your answer in 10 words or fewer. (**We will not read more than 10 words**.)

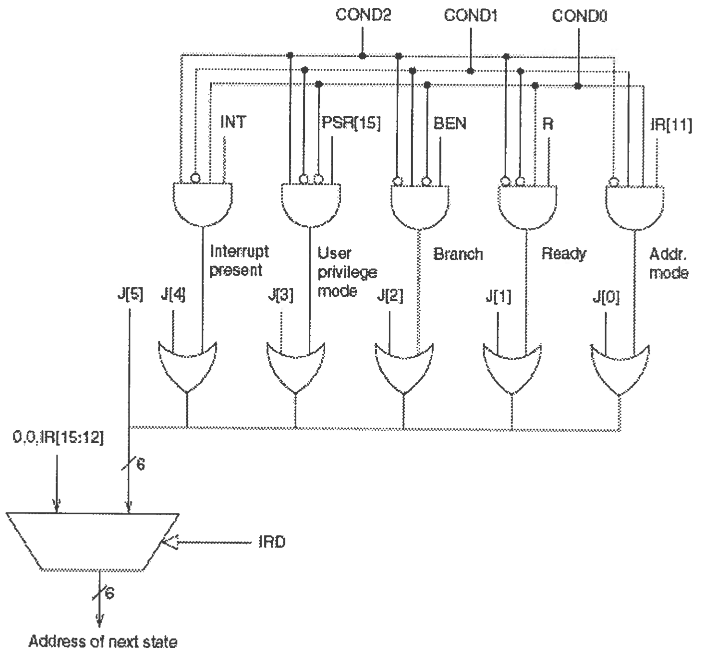
   put xECEB in M[x4000] and run code

LC-3 Control Word Fields

CAR	IRD	COND[2:0]	J[5:0]	LD.BEN	LD.MAR	LD.MDR	LD.IR	LD.PC	LD.REG	LD.CC	GateMARMUX	GateMDR	GateALU	GatePC	MARMUX	PCMUX	ADDR1MUX	ADDR2MUX	DRMUX	SR1MUX	ALUK	MIO.EN	R.W		

LC-3 Microsequencer Control

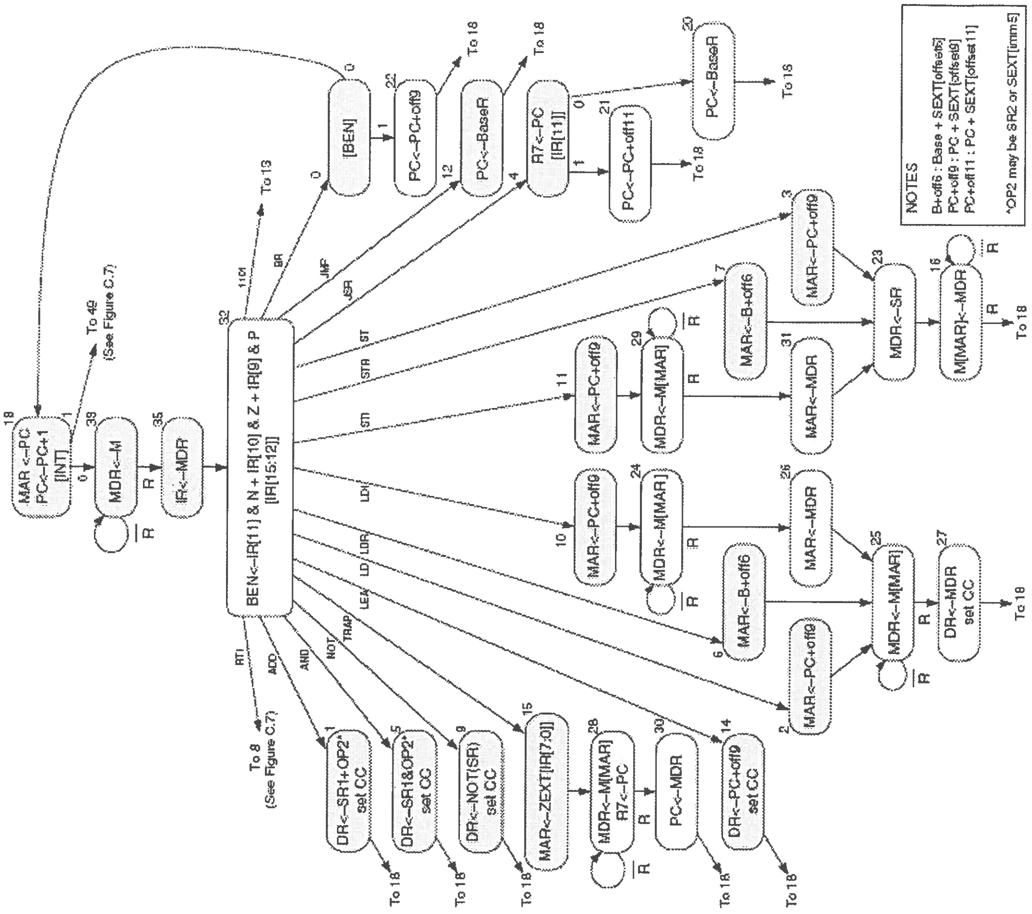
Signal	Description
IRD	= 1, CAR ← 00||opcode (opcode = IR[15:12]), only during decode = 0, CAR ← J (plus 1,2,4,8,16 depending on COND bits)
COND	= 000, CAR ← J = 001, IF (R=1 and J[1]=0) THEN (CAR ← J plus 2) ELSE (CAR ← J) = 010, IF (BEN=1 and J[2]=0) THEN (CAR ← J plus 4) ELSE (CAR ← J) = 011, IF (IR[11]=1 and J[0]=0) THEN (CAR ← J plus 1) ELSE (CAR ← J)
J	6-bit next value for CAR (plus modifications depending on COND bits)



LC-3 TRAP Service Routines

Trap Vector	Assembler Name	Description
x20	GETC	Read a single character from the keyboard. The character is not echoed onto the console. Its ASCII code is copied into R0. The high eight bits of R0 are cleared.
x21	OUT	Write a character in R0[7:0] to the console display.
x22	PUTS	Write a string of ASCII characters to the console display. The characters are contained in consecutive memory locations, one character per memory location, starting with the address specified in R0. Writing terminates with the occurrence of x0000 in a memory location.
x23	IN	Print a prompt on the screen and read a single character from the keyboard. The character is echoed onto the console monitor, and its ASCII code is copied into R0. The high eight bits of R0 are cleared.
x24	PUTSP	Write a string of ASCII characters to the console. The characters are contained in consecutive memory locations, two characters per memory location, starting with the address specified in R0. The ASCII code contained in bits [7:0] of a memory location is written to the console first. Then the ASCII code contained in bits [15:8] of that memory location is written to the console. (A character string consisting of an odd number of characters to be written will have x00 in bits [15:8] of the memory location containing the last character to be written.) Writing terminates with the occurrence of x0000 in a memory location.
x25	HALT	Halt execution and print a message on the console.

LC-3 FSM



NOTES: RTL corresponds to execution (after fetch!); JSRR not shown

LC-3 Instructions

ADD	0001	DR	SR1	0	00	SR2	ADD DR, SR1, SR2

DR ← SR1 + SR2, Setcc

ADD	0001	DR	SR1	1	imm5	ADD DR, SR1, *imm5*

DR ← SR1 + SEXT(imm5), Setcc

AND	0101	DR	SR1	0	00	SR2	AND DR, SR1, SR2

DR ← SR1 AND SR2, Setcc

AND	0101	DR	SR1	1	imm5	AND DR, SR1, *imm5*

DR ← SR1 AND SEXT(imm5), Setcc

BR	0000	n	z	p	PCoffset9	BR{nzp} *PCoffset9*

((n AND N) OR (z AND Z) OR (p AND P)):
PC ← PC + SEXT(PCoffset9)

JMP	1100	000	BaseR	000000	JMP BaseR

PC ← BaseR

JSR	0100	1	PCoffset11	JSR *PCoffset11*

R7 ← PC, PC ← PC + SEXT(PCoffset11)

TRAP	1111	0000	trapvect8	TRAP *trapvect8*

R7 ← PC, PC ← M[ZEXT(trapvect8)]

LD	0010	DR	PCoffset9	LD DR, *PCoffset9*

DR ← M[PC + SEXT(PCoffset9)], Setcc

LDI	1010	DR	PCoffset9	LDI DR, *PCoffset9*

DR ← M[M[PC + SEXT(PCoffset9)]], Setcc

LDR	0110	DR	BaseR	offset6	LDR DR, BaseR, *offset6*

DR ← M[BaseR + SEXT(offset6)], Setcc

LEA	1110	DR	PCoffset9	LEA DR, *PCoffset9*

DR ← PC + SEXT(PCoffset9), Setcc

NOT	1001	DR	SR	111111	NOT DR, SR

DR ← NOT SR, Setcc

ST	0011	SR	PCoffset9	ST SR, *PCoffset9*

M[PC + SEXT(PCoffset9)] ← SR

STI	1011	SR	PCoffset9	STI SR, *PCoffset9*

M[M[PC + SEXT(PCoffset9)]] ← SR

STR	0111	SR	BaseR	offset6	STR SR, BaseR, *offset6*

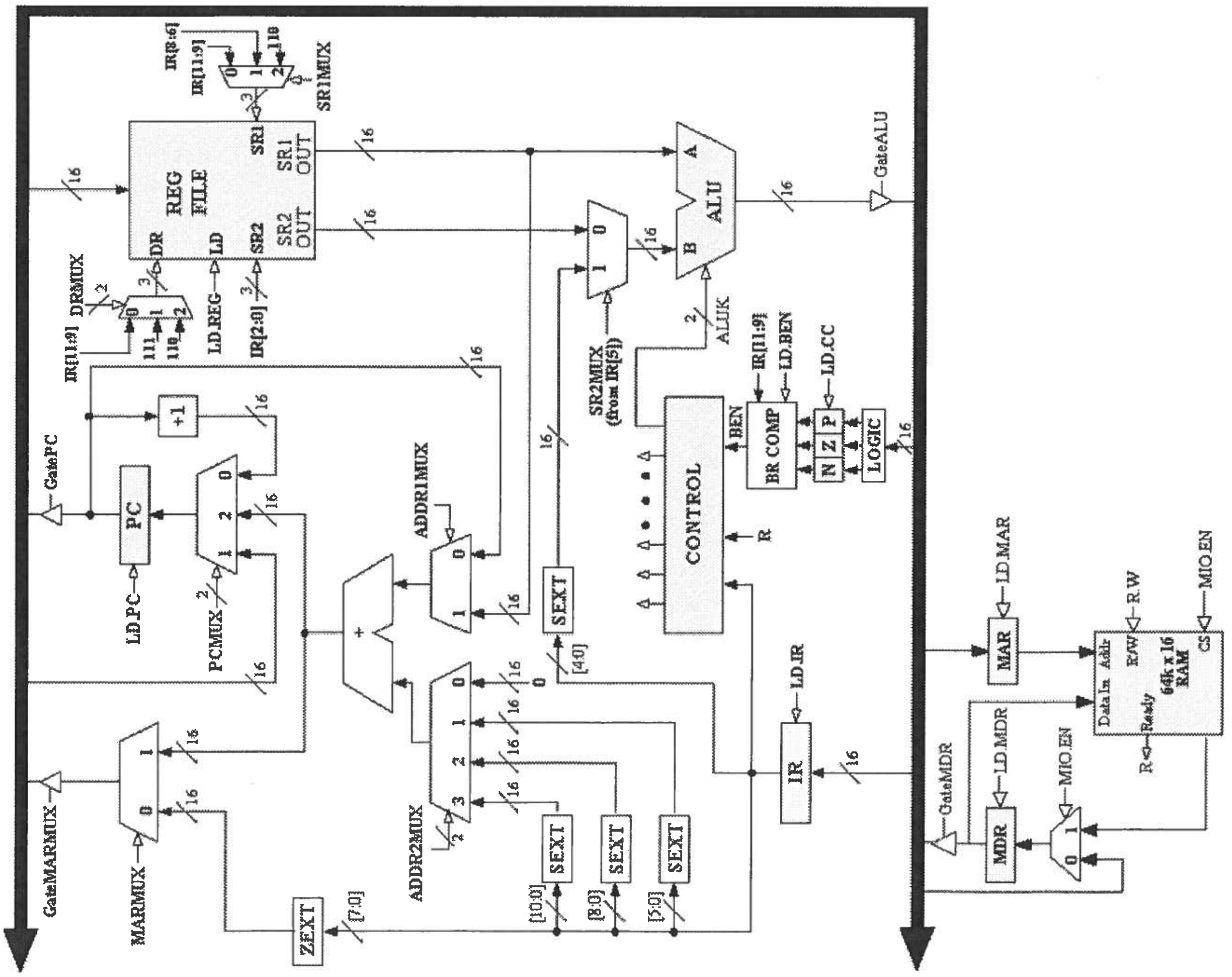
M[BaseR + SEXT(offset6)] ← SR

LC-3 Datapath Control Signals

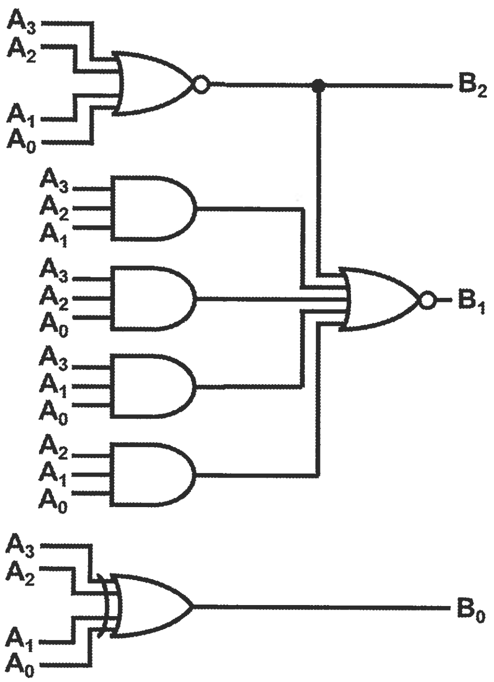
Signal	Description
LD.MAR	= 1, MAR is loaded
LD.MDR	= 1, MDR is loaded
LD.IR	= 1, IR is loaded
LD.PC	= 1, PC is loaded
LD.REG	= 1, register file is loaded
LD.BEN	= 1, updates Branch Enable (BEN) bit
MARMUX	= 0, chooses ZEXT IR[7:0] = 1, chooses address adder output
ADDR1MUX	= 0, chooses PC = 1, chooses reg file SR1OUT
ADDR2MUX	= 00, chooses "0...00" = 01, chooses SEXT IR[5:0] = 10, chooses SEXT IR[8:0] = 11, chooses SEXT IR[10:0]
PCMUX	= 00, chooses PC + 1 = 01, chooses system bus = 10. chooses address adder output
SR1MUX	= 00, chooses IR[11:9] = 01, chooses IR[8:6] = 10, chooses "110"

Signal	Description
LD.CC	= 1, updates status bits from system bus
GateMARMUX	= 1, MARMUX output is put onto system bus
GateMDR	= 1, MDR contents are put onto system bus
GateALU	= 1, ALU output is put onto system bus
GatePC	= 1, PC contents are put onto system bus
MIO.EN	= 1, Enables memory, chooses memory output for MDR input = 0, Disables memory, chooses system bus for MDR input
R.W	= 1, M[MAR]<-MDR when MIO.EN = 1 = 0, MDR<-M[MAR] when MIO.EN = 1
ALUK	= 00, ADD = 01, AND = 10, NOT A = 11, PASS A
DRMUX	= 00, chooses IR[11:9] = 01, chooses "111" = 10, chooses "110"

LC-3 Datapath



Problem 5's help page (use as scratch copy, we will NOT grade it)



A_3	A_2	A_1	A_0	B_2	B_1	B_0
0	0	0	0			
0	0	0	1			
0	0	1	0			
0	0	1	1			
0	1	0	0			
0	1	0	1			
0	1	1	0			
0	1	1	1			
1	0	0	0			
1	0	0	1			
1	0	1	0			
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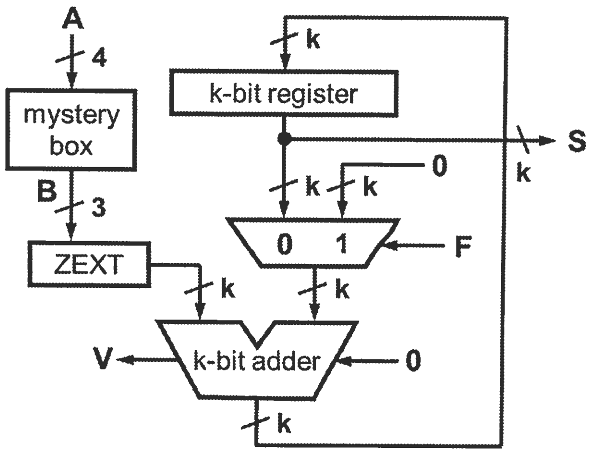
1	1	1	0			
1	1	1	1			



REPLICATED FROM PROBLEM STATEMENT FOR YOUR CONVENIENCE:

The FSM on the left performs a serial calculation on an input A. Four bits are provided through A each cycle. In the first cycle, the F input ("first bits") is set to 1. In all subsequent cycles, F=0. After N cycles, the value S provides the answer as an unsigned number.

The size of the FSM depends on the parameter k, which must be at least 3. Notice that the FSM makes use of a register to hold the state (S is just the stored register value), a set of k 2-to-1 muxes controlled by F, and a k-bit adder. The mystery box (implementation shown above on the left) transforms A into a 3-bit value B, which is then treated as an unsigned number and zero-extended (padded with leading 0s) to k bits.