

## Labs

- Some of these labs are adapted from Clint Cole's *Real Digital*, published by Digilent.
- Your incentive to complete the labs (besides love of learning, and the fact that they're kind of fun) is that the tests will include Verilog and may cover specific details taught only through these labs.
- We use the Xilinx ISE software to describe and simulate our circuits, and to generate the programming file for the FPGA. If you'd like to work outside the lab, you may download a free (WebPACK) version of this software from <http://www.xilinx.com/support/download/index.html/content/xilinx/en/downloadNav/design-tools.html>.
- We use the Digilent Adept software to load the programming files onto our FPGAs. I'd prefer to leave the FPGA boards in the lab, so you don't need to install Digilent Adept on your own computer.

## Lab 1

Names:

### Introduction

In this lab project, you will download a .bit file to your board to configure the FPGA with eight different logic circuits. The circuits use buttons and switches for inputs, and LEDs for outputs. You must probe the logic circuits by applying all possible combinations of input signals, and from the results write logic equations that describe the circuit's behavior.

Set the blue "jumper" in the upper right corner of your board to PC mode.

Obtain the file "lab1\_Basys2.bit" from

<https://learn.digilentinc.com/Classroom/RealDigital/M2/Lab1BitFiles.zip>, and download it to your Basys 2 Digilent board using the Digilent Adept software. (Click Browse to find the file, then Program. Click Yes in response to any warning messages.) Your board will be configured with eight logic circuits that drive the eight on-board LEDs. You must find logic equations to describe the circuits. After the FPGA is configured with the bit file, apply all combinations of relevant inputs (hint: see the input variable names on the top row of each truth table), and use the output LED status to complete the following truth tables. Write a logic assignment equation that shows the behavior of each circuit (the equations do not need to be minimum).

swt7	btn3	LED7
0	0	
0	1	
1	0	
1	1	

LED7 =

swt6	btn3	LED6
0	0	
0	1	
1	0	
1	1	

LED6 =

swt7	swt6	swt5	LED5
0	0	0	
0	0	1	
0	1	0	
0	1	1	
1	0	0	
1	0	1	
1	1	0	
1	1	1	

LED5 =

btn3	btn2	LED4
0	0	
0	1	
1	0	
1	1	

LED4 =

swt4	swt3	btn1	LED3
0	0	0	
0	0	1	
0	1	0	
0	1	1	
1	0	0	
1	0	1	
1	1	0	
1	1	1	

LED3 =

btn1	btn0	LED1
0	0	
0	1	
1	0	
1	1	

LED1 =

swt2	btn0	LED2
0	0	
0	1	
1	0	
1	1	

LED2 =

swt2	swt1	swt0	LED0
0	0	0	
0	0	1	
0	1	0	
0	1	1	
1	0	0	
1	0	1	
1	1	0	
1	1	1	

LED0 =

## Lab 2

**Problem 1:** Complete Exercise 1 from Matthew Vonk's "[IntroGuide to FPGA's.](#)" I recommend that you skip the bottom half of p. 3: I recommend that you do **not** "SELECT JTAG CLOCK INSTEAD OF CCLK."

**Problem 2:** Use the Xilinx HDL tool to enter and synthesize a 4-input, 2-output logic system that behaves according to the logic equations below. Assign the inputs A, B, C, and D to SW1, SW2, SW3, and SW4, and assign the X and Y outputs LD0 and LD1. Synthesize and implement the circuits.

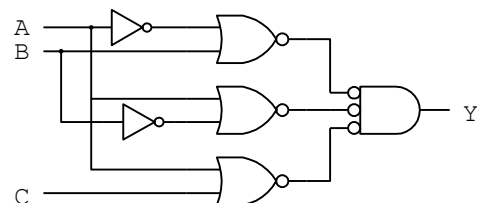
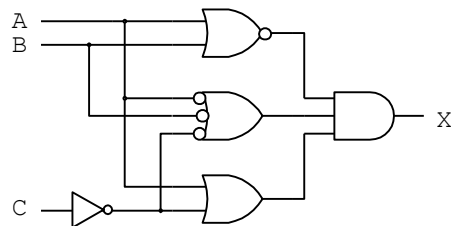
$$X = \bar{A} \cdot \bar{C} + \bar{C} \cdot D + \bar{A} \cdot B + A \cdot \bar{B} \cdot D$$

$$Y = (A+B+C) \cdot (\bar{A}+\bar{C}+D) \cdot (\bar{A}+\bar{B}+\bar{C})$$

**Problem 3.** Use the Xilinx HDL tool to enter, simulate, and synthesize a 3-input, 2-output logic system that behaves according to the two logic equations shown. Assign the inputs A, B, and C to SW1, SW2, and SW3, and assign the X and Y outputs LD2 and LD3 (note that this circuit can be co-resident with the circuit in problem 2, since different LEDs are used as outputs). Simulate the source file by creating and executing a Verilog test fixture.

$$X = \bar{A} \cdot \bar{C} + A \cdot B \cdot C \qquad Y = \bar{X} \cdot C$$

**Problem 4.** Use the Xilinx HDL tool to implement the two logic circuits shown below.



- Problem 5.** Use the Xilinx HDL tool to enter and simulate a three-input, two-output circuit that behaves according to the truth table shown. You do not need to implement the circuit.

A	B	C	F	G
0	0	0	1	1
0	0	1	0	1
0	1	0	1	0
0	1	1	0	1
1	0	0	0	1
1	0	1	1	1
1	1	0	0	0
1	1	1	1	1

- Problem 6.** Use the Xilinx HDL tool to create a circuit that can perform the logical AND of two four-bit numbers represented as two four-bit busses. Simulate the circuit. Implement the circuit by connecting four switches to one 4-bit bus, four switches to a second 4-bit bus, and the outputs to 4 LED's.

## Lab 3

This lab project presents several worded problems that serve as behavioral specifications for digital circuits. Your job is to design, simulate, and download those circuits to your board.

**Problem 1.** Amy, Baker, Cathy, and David, the bean buyers for the "Overhead Coffee Company", have designed a more complex voting system to decide when to buy new beans. Design and implement a logic circuit that they can use to indicate whether they should buy new beans. Use slide switches for vote entry (either "buy" or "not buy"), and an LED to indicate when beans should be purchased. A "buy" order is placed if:

- Amy, Cathy, and David vote NO and Baker votes YES,
- or Amy and David vote NO and the rest vote YES,
- or Baker and David vote YES and the rest vote NO,
- or Amy votes NO and the others vote YES,
- or Baker votes NO and the others vote YES,
- or Baker and Amy vote YES and the others vote NO,
- or Cathy votes NO and the others vote YES,
- or David votes NO and the others vote YES,
- or Amy and Cathy vote YES and the others vote NO,
- or they all vote YES.

Implement your circuit.

**Problem 2.** Define and simulate a circuit that can detect all prime numbers less than 16. Assume that the four inputs to your circuit ( $B_3B_2B_1B_0$ ) are used to form a four-bit binary number in the range 0 to 15. Your circuit should illuminate an LED whenever the input binary number is a prime number. One way to solve this problem is to create a truth-table or K-map, and then place a '1' in the appropriate row or cell to indicate a prime number. Verify your circuit's behavior through simulation, then synthesize and download it to your board. Use four slide switches as inputs, and a single LED as output. Note that this circuit can co-reside in your board with the previous problem if you use a different LED for the output.

**Problem 3.** Use twelve 1's in three groups of four cells to specify a 5-input, one output circuit to serve as your K-map battleship field in the diagram below. You may want to print additional copies of the K-map to practice designing a circuit that you think will be the hardest to guess. Find a minimum circuit, and enter and simulate it

using the Xilinx tools. Name the inputs A,B,C,D, and E, and name the output OUTPUT.

Download the circuit to your board, test it, and demonstrate it. Then have a neighboring student attempt to locate all the minterms in your circuit by moving one slide switch at a time. Before starting, the visitor can request that the five input switches be set to any initial pattern. The visitor hunts for your minterms by sliding the input switches one at a time to new positions. The visitor should record their path through your K-maps in the “offense” K-map in their submission form, and you should also record the path in your “defense” K-map. The visitor keeps changing the input pattern until all the 1’s have been discovered. After all 1’s have been discovered, enter the total number of moves the visitor required in the “defense” blank below. Then change roles, and probe your neighbor’s map. Enter the total number of moves required in the “offense” blank below.

E

		C D			
		A B	0 0	0 1	1 1
0	0 0				
	0 1				
	1 1				
	1 0				

1

		C D			
		A B	0 0	0 1	1 1
0 0					
0 1					
1 1					
1 0					

E

		C D			
		A B	0 0	0 1	1 1
0	0 0				
	0 1				
	1 1				
	1 0				

1

		C D			
		A B	0 0	0 1	1 1
0 0					
0 1					
1 1					
1 0					

“Offensive” moves:\_\_\_\_\_

“Defensive” moves:\_\_\_\_\_

Use this map when probing another’s  
circuit

## Lab 4

This lab project presents several more complex combinational logic systems that would be quite challenging to implement using structural methods, but are rather simple using Verilog.

**Problem 1:** Six judges need a device to help indicate particular judgments. Each judge can enter “good” or “bad” with a single switch - your job is to build a circuit that can indicate three separate conditions: A strong majority (i.e., 5 or 6 “good” votes); a simple majority (4 or more “good” votes), and a tie (exactly 3 “good” votes). Use LEDs to indicate the outputs.

**Problem 2.** A digital thermometer produces a continuously varying voltage signal between 0V and 5V, where 0V represents 0 degrees, and 5V represents 100 degrees. The thermometer outputs an 8-bit binary number proportional to the temperature – “00000000” represents 0 degrees, each increasing binary number from “00000000” represents a temperature increase of  $100/256$  degrees, and “11111111” represents 100 degrees. Design a circuit that outputs a logic high signal whenever the temperature is between 50 and 60 degrees. Use switches to emulate the thermometer's output, and an LED to indicate when the temperature is in the desired range.

**Problem 3.** Design a circuit that can show an 8-bit 2's complement number multiplied by -1. Use the eight slide switches to enter any number (positive or negative), and show the answer on the 8 LED's.



## Lab 5

**Problem 1.** Use the Xilinx tools to define and simulate an 8-bit shifter that can shift or rotate left or right by 0, 1, 2, or 3 bit positions. Implement the circuit using the 8 slide switches as inputs to the shifter, and 8 LEDs as outputs from the shifter. Use the pushbuttons to control the functions of the shifter.

**Problem 2.** Design and simulate an 8-bit magnitude comparator.

**Problem 3.** Design and simulate a behavioral 8-bit adder that can produce a 9-bit result. Show a case where the ninth bit is a '1'.

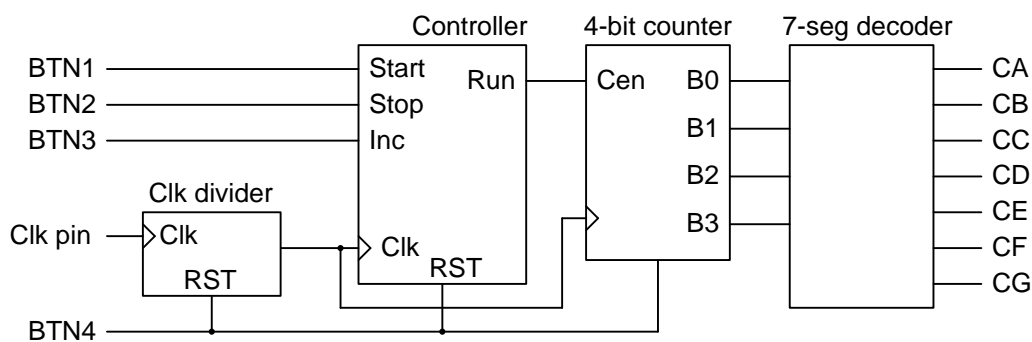
**Problem 4:** Design and implement a 4-bit ALU that can perform the operations shown. Assign inputs to slide switches and pushbuttons as you see fit, and assign outputs to LEDs or the 7sd.

Op Code	Function
000	A PLUS B
001	A PLUS 1
010	A MINUS B
011	A MINUS 1
100	A XOR B
101	Not A
110	A OR B
111	A AND B

## Lab 6

**Problem 1.** Build a 4-bit binary counter with Enable and Terminal Count functions (Terminal Count, or TC, is asserted in the last count state before the counter resets back to all zeros). Simulate the counter, showing the TC and Enable functions.

**Problem 2.** Design a circuit that increments a digit (0 – F) shown on the seven-segment display once each second. The circuit has four pushbutton inputs: one button starts the counter, a second button stops the counter, a third button increments the counter, and the fourth button asynchronously resets all memory devices in the design. The system has the block diagram shown below. Use the 4-bit counter from problem #1 as a component, and create components for a clock divider, seven-segment display decoder, and a controller circuit.



**Problem 3.** Build a 4-digit decimal stopwatch, with the least-significant digit counting a rate of 1KHz (1ms update rate), and the most-significant digit incrementing once per second (each digit on the seven-segment display will be driven from a separate decimal counter). Use the same controller as was used for Problem 2.

This circuit requires a scanning display controller which is discussed in your board's Reference Manual.

## **Lab 7**

**Problem 1:** Design and implement a Mealy machine to detect the sequence 1101. Observe the difference between a combinational output and a latched output.

**Problem 2:** Design and implement a Moore machine to detect the sequence 110. Make sure it works!

## Lab 8

To use Python to communicate with the FPGA at 19200 baud, open Spyder, and in the “console” in the lower right, type

```
import serial
```

```
a=serial.Serial('COM10',19200)
```

but first replace COM10 with the COMmunication port number assigned to the UART device; look in Devices and Printers in the Start menu, and then click on the Hardware tab for the device.

**Problem 1.** Design a circuit that receives 1 byte of data from the computer and displays it on the LEDs.

To send a hexadecimal value to the FPGA, use

```
a.write(b'\x41')           #sends 41 in hexadecimal
```

To send the ascii code for a character, use

```
a.write(b'a')             #sends ascii code for 'a'
```

**Problem 2.** Design a circuit that transmits 1 byte of data to the computer. To display the data in base 10, use

```
a.read()[0]
```

If you omit the [0], you'll see b'\x' followed by the hexadecimal value, followed by '

**Problem 3.** Design a circuit that transmits 4 bytes of data to the computer representing how many tenths of second each of the four buttons was pressed over the past second.

## Lab 9

**Problem 1.** Create a circuit that displays the greatest common divisor of two four-bit numbers read from a Verilog ROM (Example 68 from the book).

**Problem 2.** Implement the following four modules in your FPGA. **top** instantiates the other three modules. **interface** connects the microprocessor to the inputs and outputs. **MemProg** contains the machine language instructions (what do they mean?). **RISCuva1** is a simple microprocessor created by de Pablo *et al* ([https://www.researchgate.net/profile/Luis\\_Carlos\\_Herrero-De\\_Lucas/publication/267766934\\_A\\_very\\_simple\\_8-bit\\_RISC\\_processor\\_for\\_FPGA/links/56f17c0108ae1cb29a3d116d/A-very-simple-8-bit-RISC-processor-for-FPGA.pdf](https://www.researchgate.net/profile/Luis_Carlos_Herrero-De_Lucas/publication/267766934_A_very_simple_8-bit_RISC_processor_for_FPGA/links/56f17c0108ae1cb29a3d116d/A-very-simple-8-bit-RISC-processor-for-FPGA.pdf)). You will need to make the implementation constraints file (just look at the inputs and outputs in **top**).

```
module top(
    input [7:0] sw,
    output [7:0] ld,
        input clk, // The 50 MHz clock
        input Reset // This can be btn0
);
wire [7:0] dataIn;
wire [7:0] dataOut;
wire [7:0] portAddress;
wire portRead;
wire portWrite;
wire intAck;
wire intReq;
wire [9:0] addr;
wire [13:0] do;
wire progReset;

interface u1 (.sw(sw),.ld(ld),.dataIn(dataIn),.dataOut(dataOut),.portAddress(portAddress),
    .portRead(portRead),.portWrite(portWrite),.intAck(intAck),.intReq(intReq),.clk(clk));

MemProg u2 (.addr(addr),.do(do),.rst(progReset),.clk(clk));

RISCuva1 u3 (.clk(clk), .reset(Reset),
    .progAddress(addr), .progData(do), .progReset(progReset),
    .dataIn(dataIn), .dataOut(dataOut),
    .portAddress(portAddress), .portRead(portRead), .portWrite(portWrite),
    .intReq(intReq), .intAck(intAck));

endmodule

module interface(
    input [7:0] sw,
    output reg [7:0] ld,
        output reg [7:0] dataIn,
        input [7:0] dataOut,
        input [7:0] portAddress,
        input portRead,
        input portWrite,
        input intAck,
```

```

        output intReq,
        input clk);
always @(posedge clk)
    if ((portWrite==1)&(portAddress==225))
ld=dataOut;
always@(*)
    if ((portRead==1)&(portAddress==224))
        dataIn=sw;
assign intReq=0;
endmodule

module MemProg(input [9:0] addr,
               output reg [13:0] do,
               input rst,
               input clk);
always @ (posedge clk)
if (rst==1)
    do<=14'b0000000000000000;
else
    case(addr)
    0:do<=14'b1111100000000000;
    1:do<=14'b00111000010000;
    2:do<=14'b0001000000000000;
    endcase
endmodule

module RISCuva1 ( clk, reset,
progAddress, progData, progReset,
dataIn, dataOut,
portAddress, portRead, portWrite,
intReq, intAck );
// Inputs and outputs:
input clk, reset; // Clock and Reset
output [9:0] progAddress; // Up to 1K instructions (10 bits)
input [13:0] progData; // Current instruction code
output progReset; // Reset of Program Memory
input [7:0] dataIn; // Data input (from an I/O port)
output [7:0] dataOut; // Data output (through a port)
output [7:0] portAddress; // Addressed I/O Port (0..255)
output portRead; // Read signal
output portWrite; // Write signal
input intReq; // Interrupt request
output intAck; // Interrupt Acknowledge
// Instruction decoding from the instruction code:
wire [13:0] opCode = progData; // Instruction code
wire [1:0] opA = opCode[13:12]; // 1st operation code
wire [1:0] opB = opCode[11:10]; // 2nd operation code
wire [1:0] opC = opCode[ 9: 8]; // 3rd operation code
wire [3:0] rM = opCode[ 7: 4]; // Source register
wire [3:0] rN = opCode[ 3: 0]; // Destination register
wire [9:0] immAddr = opCode[ 9:0]; // Address for jumps
wire [7:0] immData = opCode[11:4]; // Immediate data
wire [4:0] immPort = opCode[ 8:4]; // For direct access
wire MISC = (opA == 2'b00);
wire JP = (opA == 2'b01);
wire LOAD = (opA == 2'b10);

```

```

wire ALU = (opA == 2'b11);
wire CALL = (opB == 2'b00);
wire GOTO = (opB == 2'b01);
wire RETS = (opB == 2'b10);
wire MOVOUT = (opB == 2'b11);
wire RET = (opC == 2'b00);
wire RETI = (opC == 2'b01);
wire DI = (opC == 2'b10);
wire EI = (opC == 2'b11);
wire FLAG_Z = (opB == 2'b00);
wire FLAG_NZ = (opB == 2'b01);
wire FLAG_C = (opB == 2'b10);
wire FLAG_NC = (opB == 2'b11);
wire LOGIC = (opB == 2'b00);
wire ARITH = (opB == 2'b01);
wire SHIFT = (opB == 2'b10);
wire MOVIN = (opB == 2'b11);
wire MOV = (opC == 2'b00);
wire XNOR = (opC == 2'b01);
wire OR = (opC == 2'b10);
wire AND = (opC == 2'b11);
wire ADD = (opC == 2'b00);
wire ADC = (opC == 2'b01);
wire SUB = (opC == 2'b10);
wire SBC = (opC == 2'b11);
wire ASR = (opC == 2'b00);
wire RRC = (opC == 2'b01);
wire ROR = (opC == 2'b10);
wire ROL = (opC == 2'b11);
wire IND = (opC == 2'b00);
wire SEQ = (opC == 2'b01);
wire DIR = (opC == 2'b10);
// General Resources:
reg zeroFlag, carryFlag; // DFFs used by flags
wire [7:0] dataBus; // Data bus for all operations
wire [2+9:0] stackValue; // Internal stack output
// Register file (r0-r15) and operand buses:
reg [7:0] registerFile[0:15]; // 16x8 dual-port memory
always@(posedge clk)
begin
if (LOAD | ALU)
registerFile[rN] <= dataBus; // Synchronous write
end
wire [7:0] busN = registerFile[rN]; // Async. read of rN
wire [7:0] busM = registerFile[rM]; // Async. read of rM
// Port signals for direct, indirect and sequential accesses:
reg [7:0] nextPort;
always@(posedge clk)
begin
if (portRead | portWrite)
nextPort <= portAddress + 1; // For sequential use
end
assign dataOut = busN; // Output from rN
assign portRead = ALU & MOVIN; // Read signal
assign portWrite = MISC & MOVOUT; // Write signal
assign portAddress = IND ? busM : // Indirect

```

```

SEQ ? nextPort : // Sequent.
{3'b111,immPort}; // Direct
// Logic ALU: AND, OR, XNOR and MOV.
wire logicCarry = AND ? 1'b1 : OR ? 1'b0 : carryFlag;
wire [7:0] logicALU = AND ? busN & busM :
OR ? busN | busM :
XNOR ? busN ~^ busM :
busM ;
// Arithmetic ALU: ADD, ADC, SUB and SBC.
wire [7:0] arithALU, altM;
wire arithCarry, x, y, z;
assign x = ADD ? 1'b0 : ADC ? carryFlag :
SUB ? 1'b1 : ~carryFlag;
assign altM = (SUB | SBC) ? ~busM : busM;
assign {z, arithALU, y} = {busN, 1'b1} + {altM, x};
assign arithCarry = (SUB | SBC) ? ~z : z;
// Shifter: ASR, RRC, ROR and ROL.
wire [7:0] shiftALU;
wire shiftCarry;
assign {shiftALU, shiftCarry} =
ASR ? {busN[7], busN} :
RRC ? {carryFlag, busN} :
ROR ? {busN[0], busN} :
{busN[6:0], busN[7], busN[7]};
// This data bus collects results from all sources:
assign dataBus = (LOAD | MISC) ? immData : 8'bz;
assign dataBus = (ALU | JP) & LOGIC ? logicALU : 8'bz;
assign dataBus = (ALU | JP) & ARITH ? arithALU : 8'bz;
assign dataBus = (ALU | JP) & SHIFT ? shiftALU : 8'bz;
assign dataBus = (ALU | JP) & MOVIN ? dataIn : 8'bz;
// Interrupt Controller:
reg userEI, callingIRQ, intAck;
wire mayIRQ = ! (MISC & RETS
| MISC & MOVOUT
| ALU & MOVIN);
wire validIRQ = intReq & ~intAck & userEI & mayIRQ;
wire [9:0] destIRQ = callingIRQ ? 10'h001 : 10'h000;
always@(posedge clk or posedge reset)
begin
if (reset) userEI <= 0;
else if (MISC & RETS & DI) userEI <= 0;
else if (MISC & RETS & EI) userEI <= 1;
if (reset) intAck <= 0;
else if (validIRQ) intAck <= 1;
else if (MISC & RETS & RETI) intAck <= 0;
if (reset) callingIRQ <= 0;
else callingIRQ <= validIRQ;
end
// Flag DFFs:
always@(posedge clk)
begin
if (MISC & RETS & RETI) // Flags recovery when 'reti'
{carryFlag,zeroFlag} <= stackValue[11:10];
else begin
if (LOAD | ALU) // 'Z' changes with registers
zeroFlag <= (dataBus == 8'h00);

```



```

if (ALU & ~MOVIN) // but 'C' only with ALU ops
carryFlag <= LOGIC ? logicCarry :
SHIFT ? shiftCarry :
arithCarry ;
end
end
// 'validFlag' evaluates one of four conditions for jumps.
wire validFlag = FLAG_Z ? zeroFlag :
FLAG_NZ ? ~zeroFlag :
FLAG_C ? carryFlag :
~carryFlag ;
// Program Counter (PC): the address of current instruction.
reg [9:0] PC;
wire [9:0] nextPC, incrPC;
wire onRet = MISC & RETS & (RETI|RET);
wire onJump = MISC & (GOTO | CALL) | JP & validFlag;
assign incrPC = PC + (callingIRQ ? 0 : 1);
assign nextPC = onRet ? stackValue[9:0] : 10'bz;
assign nextPC = onJump ? immAddr | destIRQ : 10'bz;
assign nextPC = ~(onRet | onJump) ? incrPC : 10'bz;
always@(posedge clk)
begin
PC <= nextPC;
end
// When using Xilinx BlockRAM as program memory:
assign progAddress = nextPC;
assign progReset = reset | validIRQ;
// Internal stack for returning addresses (16 levels):
reg [3:0] SP; // Stack Pointer register
always@(posedge clk or posedge reset)
begin
if (reset) SP <= 0;
else if (MISC & CALL) SP <= SP + 1;
else if (MISC & RETS & (RETI|RET)) SP <= SP - 1;
end
wire [3:0] mySP = (CALL | GOTO) ? SP : SP - 1;
reg [2+9:0] stackMem[0:15]; // Stack 16x12 memory
always@(posedge clk)
begin
if (MISC & CALL) // Keep returning address and flags
stackMem [mySP] <= {carryFlag, zeroFlag, incrPC};
end
assign stackValue = stackMem[mySP];
endmodule /// RISCuva1 (all in one file!)

```

**Problem 3.** Modify the instructions in MemProg so that the output will equal the input plus 1. You will need to store the number 1 in a register and then add.

**Problem 4.** Now modify the instructions so that the output equals the slide-switch input unless BTN1 is pushed, in which case the output becomes 0. You will need to modify **top** (adding an input) and **interface**. You must assign BTN1 (preceded by 7 zeros) a different port number than the slide switches.