CHULA ENGINEERING
Foundation toward Innovation

COMPUTER

Hardware Synthesis Laboratory

1st semester

Academic Year 2022

```
module fulladder (cout,s,a,b,cin);
    output cout;
    output s;
    input a,b,cin;

//assign {cout,s}=a+b+cin;
reg cout, s;
always @(a or b or cin)
begin
    {cout,s}=a+b+cin;
end

endmodule
```

Krerk Piromsopa, Ph. D.

Preface

Since the exploding complexity of digital electronic circuits in the 1970s, Hardware Descriptive Language (HDL) has evolved. With the rise of FPGA, Hardware Synthesis (together with HDL) has become a fundamental skill in Computer Engineering.

The department of Computer Engineering, Chulalongkorn University is among the first universities (in Thailand) to teach VerilogHDL and Hardware Synthesis Lab. (We have done this for more than 20 years.) This course has evolved from an in-house FPGA board to the standardized developer boards. Generations of students have enjoyed (and weeped) for this class. The success of this class is evidenced by a number of students that have graduated and worked in semiconductor industries (Intel, AMD, IBM, etc.)

As a hardware design enthusiasm, I recreated this Lab book to ease the study of Hardware Descriptive Language (HDL) and Hardware Synthesis Lab. My personal belief is the more you understand hardware is the better you are as a programmer.

For those that may want to further their study in digital design, this is one chance for you to show your skill. Note that we have 2-3 persons per academic year that are natural at hardware descriptive language. Most (if not all) of them usually got a Ph.D. in Hardware-related fields and work in the industries. For those of you that may not be comfortable with hardware design, the minimum requirement for this class is to understand and use the digital tools.

Hopefully, students will learn something useful for their future from this class

Enjoy,

Krerk Piromsopa, Ph.D.

Associate Professor

Department of Computer Engineering

Chulalongkorn University

(Updated: August 9, 2022)

Table of Contents

Laboratory 1: Introduction to VerilogHDL and Digital Simulation

Objectives

1. Get students to familiar with the simulation tool (Vivado)
2. Demonstrate the basic of Verilog simulation and waveform output
3. Able to explain structural model and behavioral model
4. Able to explain the differences between blocking and non-blocking assignments

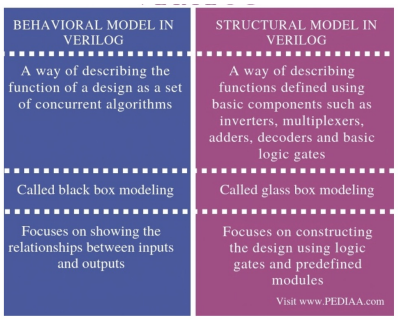
Background

In this lab, you will learn the fundamentals of VerilogHDL and Digital Simulation using the Vivado Design suite. Firstly, please download the free (webpack) version of Vivado Design Suite from Xilinx Web site[1]. The whole download is about 20GB. Alternatively, you may download it from the department server[2] . Should you have trouble finding a machine for installing the software, please contact the instructors. A (virtual) machine can be provided for you to remotely work with the tool. However, you may still have to install the Lab Edition to download the design to the FPGA board. For more information about the installation and Vivado IDE, please what the Xilinx tutorials' videos[3].

Please watch the demonstration video on how to use the simulation.

Exercises

1. Complete the following 1-bit full adder and a test bench to validate such design by simulating all possible inputs. Use the Vivado tool to simulate and validate the design.



1 https://www.xilinx.com/products/design-tools/vivado.html

2 https://mis.cp.eng.chula.ac.th/krerk/teaching/2018s2-HWSynLab/
Username: student, password: HWSynLab

3 https://www.xilinx.com/products/design-tools/vivado.html#video

```
module fullAdder(cout, s, a, b, cin);

output cout;
output s;
input a;
input b;
input cin;
reg cout, s;

always @(a,b, cin )
begin
   { cout, s } = a+b+ cin
end
endmodule

`timescale 1ns/1ns

module tester;
```

assign wire = wire

wire

หน่วยเวลาของอันนี้

Simulate สิ้นนาที

```
      reg a,b,cin;
      wire cout,s;

      fullAdder a1(cout,s,a,b,cin);

initial
begin
      //$dumpfile("time.dump");
      //$dumpvars(2,a1);
      $monitor("time %t: {%b %b} <-
{%d %d %d}", $time,cout,s,a,b,cin);
      #0;
      a=0;
      b=0;
      cin=0;

      //.....
      $finish;
end
endmodule
```

เขียน test

delay

* ต้องเขียน test case ด้วย!

2. What would happen if we replace the always block of the full adder in question 1 with the following module? Would it give the same result? Please run the test bench and provide your analysis.

"เหมือนกัน"

```
module fullAdder(cout, s, a, b, cin);

output cout;
output s;
input a;
input b;
input cin;

assign {cout,s} = a + b + cin;

endmodule
```

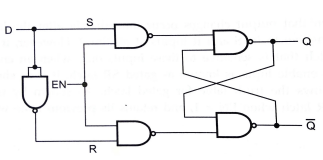
```
module fullAdder(
   output cout,
   output s,
   input a,
   input b,
   input cin
);
```

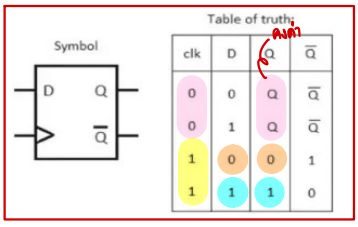
3. Please modify the following latch to be a (positive edge triggering) flip flop with asynchronous reset. Please also modify the test bench to validate your design.

```
`timescale 1ns/1ns

module DFlipFlop(q,clock,nreset,d);

output q;
input clock,nreset,d;

reg q;
always @(clock)
begin
      if (nreset==1)
            q=d;
      else
            q=0;
end
endmodule
```

posedge clock , posedge nreset

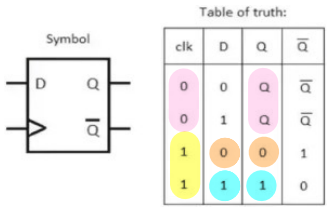
```
module testDFlipFlop();
reg clock, nreset, d;
DFlipFlop D1(q,clock,nreset,d);
always
```



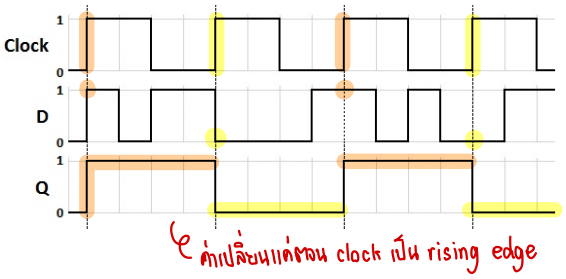


Krerk Piromsopa, Ph.D.

testcast ต้องทำให้ถูกต้อง




```
      #10   clock=~clock;

initial
begin

//$dumpfile("testDFlipFlop.dump");
      //$dumpvars(1,D1);
      #0 d=0;
      clock=0;
      nreset=0;
      #50 nreset=1;
      #1000 $finish;
end
always
      #8 d=~d;
endmodule
```



4. What are the differences between the 2 provided designs? Please write a test bench to show your analysis.

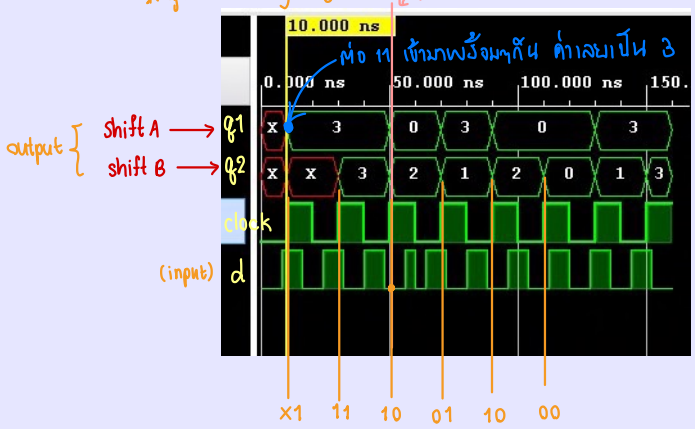
ต้องเข้าใจเรื่อง blocking กับ non blocking

Bus

```
module shiftA(q,clock,d);
output [1:0] q;
input clock,d;

reg [1:0] q;

always @(posedge clock)
begin
      q[0]=d;
      q[1]=q[0];
end
endmodule

module shiftB(q,clock,d);
output [1:0] q;
input clock,d;

reg [1:0] q;

always @(posedge clock)
begin
      q[0]<=d;
      q[1]<=q[0];
end
endmodule
```

* ดูแค่ตอน rising edge

เป็น 00 เพราะค่อง 0 มาพร้อมๆกัน



Shift Register

Non-blocking assignment

(ลำดับไม่มีผล เหมือนค่อพร้อมๆกัน)

5. Please answer the following questions and submit (in PDF format) to CourseVille on Friday before 23:59 (midnight).
   1. Please draw a schematic representing the logical blocks of both shiftA and shiftB in exercise 4.
   2. What is the difference between blocking and non-blocking assignments?

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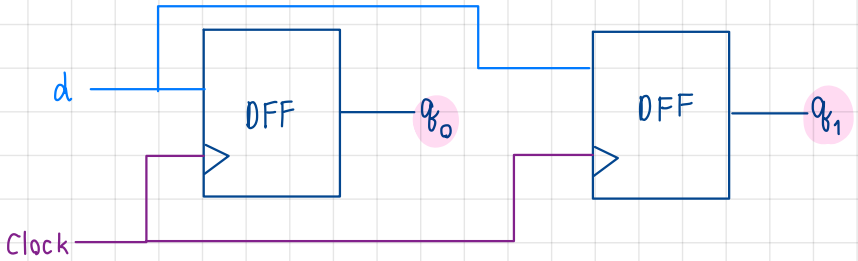
5. Please answer the following questions and submit (in PDF format) to CourseVille on Friday before 23:59 (midnight).
   1. Please draw a schematic representing the logical blocks of both shiftA and shiftB in exercise 4.
   2. What is the difference between blocking and non-blocking assignments?

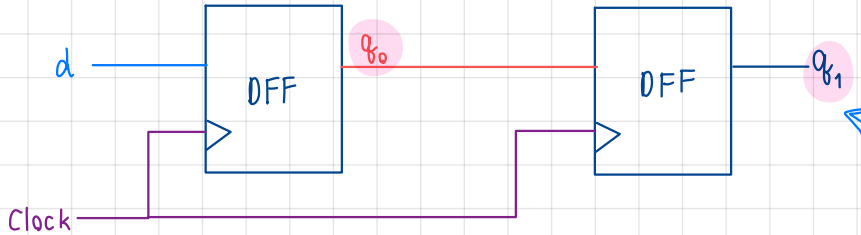
Soln 1.) Shift A



= output

```
module shiftA(q,clock,d);
output [1:0] q;
input clock,d;

reg [1:0] q;

always @(posedge clock)
begin
      q[0]=d;
      q[1]=q[0];
end
endmodule

module shiftB(q,clock,d);
output [1:0] q;
input clock,d;

reg [1:0] q;

always @(posedge clock)
begin
      q[0]<=d;
      q[1]<=q[0];
end
endmodule
```

Shift B



2) blocking = ลำดับการเขียนมีผล
   nonblocking = ลำดับการเขียนไม่มีผล

3. Is it possible to apply parameters to the design in exercise 4 to create shiftRegister with any number of bits? If Yes, please explain how.

ตอบ เป็นไปได้ โดยการกำหนดขนาด output ให้เป็นพารามิเตอร์ และใช้การ Design แบบ Shift B

Laboratory 2: Time-Division Multiplexing and Clock Divider

Objectives

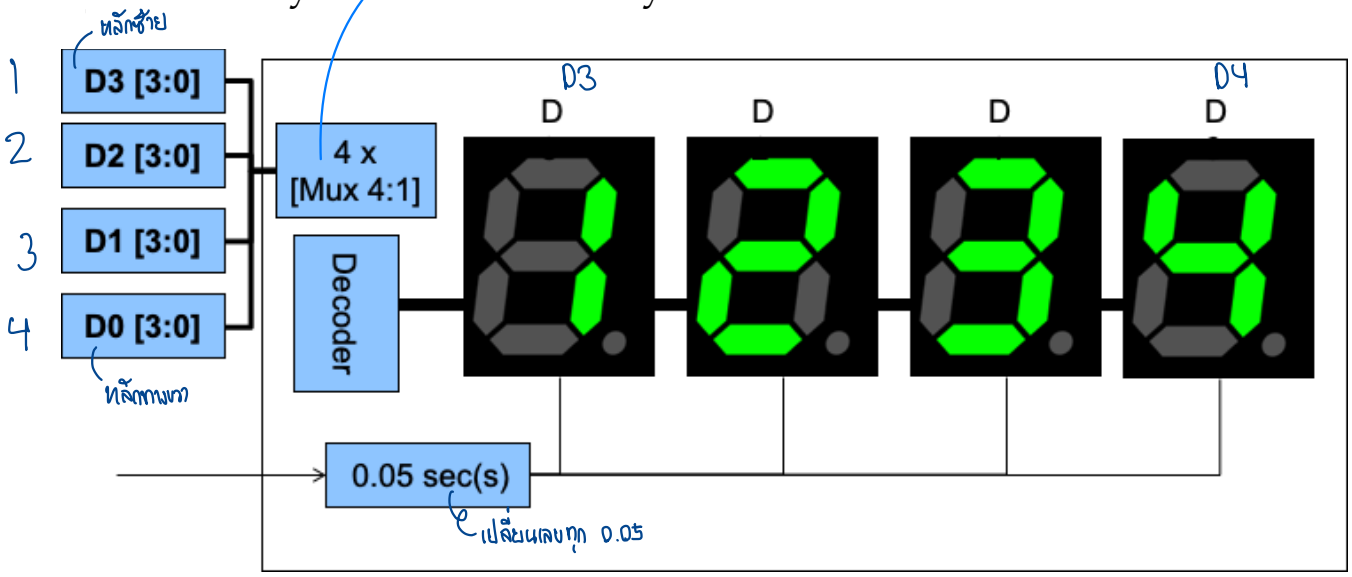
1. Get students to familiar with the synthesis tool (Vivado)
2. Synthesis FPGA
3. Able to explain time-division multiplexing
4. Able to design clock divider
5. Able to use a language template.

Background

TDM

To drive a seven-segment display (whether it is common anode or common cathode), each digit would require 9 wires (a to g, dot, common ground or common vcc). With several digits of seven-segment display, the number of wires would intuitively multiplied. For example, 4 digits of seven-segment displays may require up to 33 wires (a to g and dot for each digit with a sharing common wire). It is not practical to have so many wires. To share (reduce) physical wires, Time-Division Multiplexor is introduced.

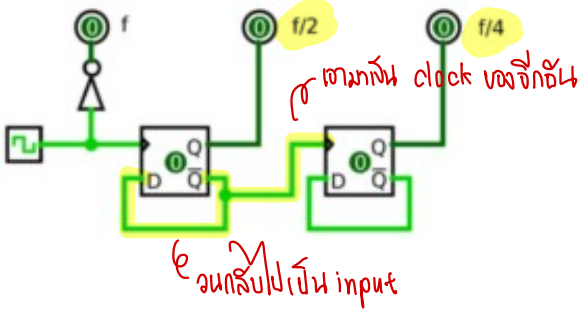
With time-division multiplexing, we can share 8 wires (a to g and dot) among the displays. Only a digit will be active at a time. If the segments turn on and off at the appropriate rate (I.e. 15 frames per second or more), the observer would see it as if all segments are on at the same time.--hence the term time-division multiplexing. This way, four digits of seven-segment displays can be connected with only 12 wires (8 from a to g and dot + 4 for activating digits) .

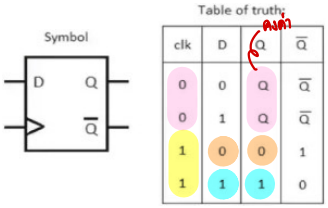


For more details about time-division multiplexing, please watch the demonstration video.

Clock Division

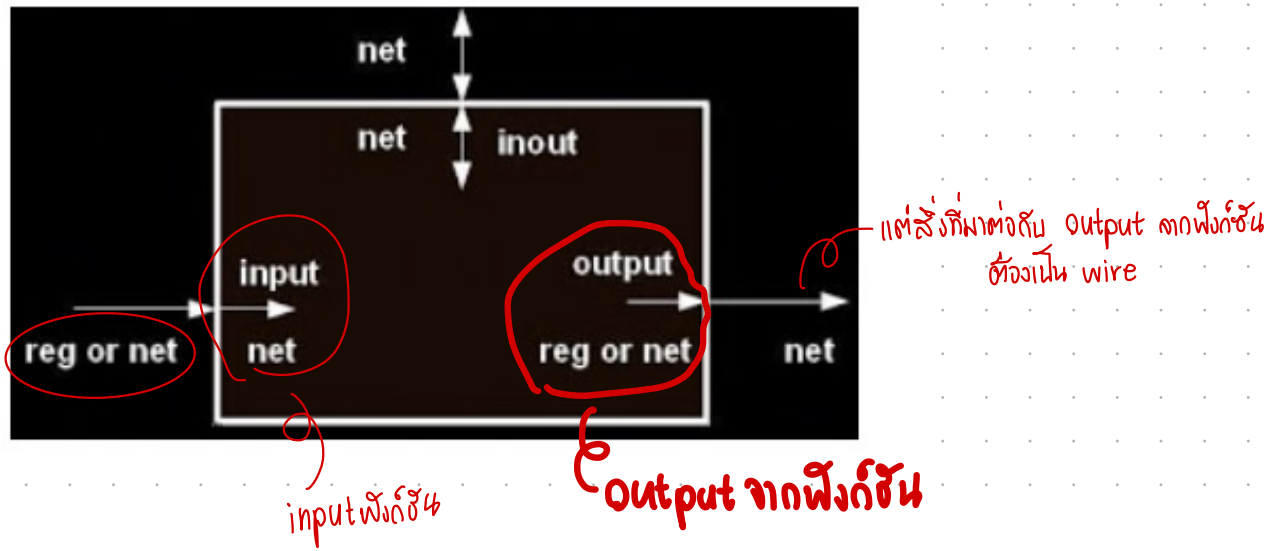
There are several ways to divide high frequency clocks into slower clocks. A simple solution is to cascade D flip flops (or even T flip flops) together by feeding ~Q0 to D0 and feed Q0 as a clock for D1 (and so on). Nonetheless, this is just one implementation of the clock division. You may use a counter to set and clear a bit as a clock division as well.





Language Templates

Vivado IDE tool comes bundled with language templates. Language templates are basically code snippets for HDL. You may access the language templates from ***menu > Tools > Language Templates***. A language template that might be useful for this lab is 7-segment encoding.



Wire:-

Wires are used for connecting different elements. They can be treated as physical wires. They can be read or assigned. No values get stored in them. They need to be driven by either continuous assign statement or from a port of a module.

Reg:-

Contrary to their name, regs don't necessarily correspond to physical registers. They represent data storage elements in Verilog/SystemVerilog. They retain their value till next value is assigned to them (not through assign statement). They can be synthesized to FF, latch or combinatorial circuit. (They might not be synthesizable !!!)

Wires and Regs are present from Verilog timeframe. SystemVerilog added a new data type called logic to them. So the next question is what is this logic data type and how it is different from our good old wire/reg.

Exercises

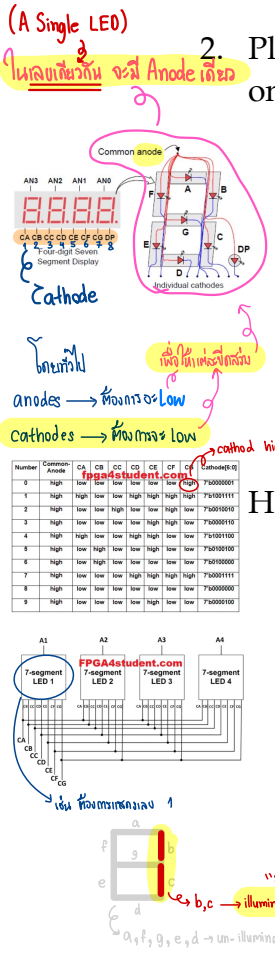
1. Use your knowledge from clock division and time-division multiplexor to display a 4-digit hexadecimal number (0x1234) to the seven-segment display of the BASYS 3 board. Your design should be modularized (You can save the component for reuse later). There should be at least 3 modules: clock divider, hex (or bcd) to 7-segment encoder and 7-segment TDM.

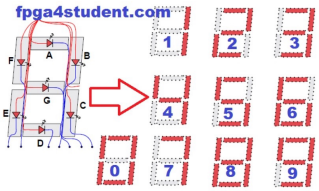
2. Please answer the following questions and submit (in PDF format) to CourseVille on Friday before 23:59 (midnight).

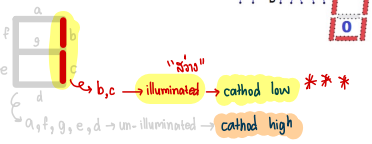
   a. Is the 4-digit seven-segment display on the BASYS 3 board a common anode for common cathode? Please explain.

   b. From the wiring of the board, which logic do you have to assign to the 7-segment pins (a to g and dot) to turn the LED on.

   c. Given that the clock of the BASYS3 is around 10ns, how many bits do you have to divide the clock with to get the appropriate clock for the TDM. Please provide your analysis (calculation).







Hint

1. Use the BASYS 3 XDC[4] file as a base constraint file.
2. Read the datasheet to determine the interconnection in the board.
3. Use the language templates for 7-segment encoder

```
genvar index;
generate for(index = 0; index<18; index = index+1)
    begin
        ClockDivision ClockDivision(tmpClock[index+1], tmpClock[index]);
    end
endgenerate

ClockDivision ClockDivision(CorrectClock, tmpClock[18]);
```

4https://mis.cp.eng.chula.ac.th/krerk/teaching/2018s2-HaWSynLab/downloads/Basys-3-Master.xdc

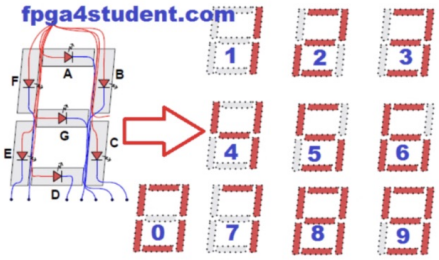
2. Please answer the following questions and submit (in PDF format) to CourseVille

on Friday before 23:59 (midnight).

a. Is the 4-digit seven-segment display on the BASYS 3 board a common anode

or common cathode? Please explain.

Ans In each digit, it shares a common anode because seven anodes (A to G) of the seven segments in each digit are connected together. As show in the picture below



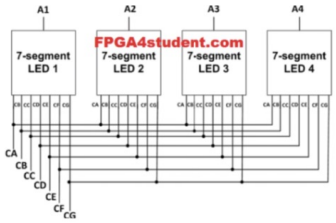
b. From the wiring of the board, which logic do you have to assign to the 7-

segment pins (a to g and dot) to turn the LED on.

Ans Common anode must be activate low each of the seven-segment LED display. For cathodes, they can be low (to illuminated segment LED display) or high (to un-illuminated segment LED display) As show in the table below

Number	Common-Anode	CA	CB	CC	CD	CE	CF	CG	Cathode[6:0]
0	high	low	low	low	low	low	low	high	7'b0000001
1	high	high	low	low	high	high	high	high	7'b1001111
2	high	low	low	high	low	low	high	low	7'b0010010
3	high	low	low	low	low	high	high	low	7'b0000110
4	high	high	low	low	high	high	low	low	7'b1001100
5	high	low	high	low	low	high	low	low	7'b0100100
6	high	low	high	low	low	low	low	low	7'b0100000
7	high	low	low	low	high	high	high	high	7'b0001111
8	high	low	low	low	low	low	low	low	7'b0000000
9	high	low	low	low	low	high	low	low	7'b0000100

low



c. Given that the clock of the BASYS3 is around 10ns, how many bits do you

have to divide the clock with to get the appropriate clock for the TDM.

Please provide your analysis (calculation).

Ans the 4-digit seven-segment display should be continuously refreshed at about 1KHz to 60Hz or (1ms to 16ms). Because human eyes can see between 30 and 60 frames per second.

The clock divider that I write will divide the clock by 2,

Let x is the frame per second that we want.

n is the how many times that we must divide the clock

If the clock of the BASYS3 is around 10ns → it has $\frac{1}{10*10^{-9}} = 10^8\ Hz$

So, $\frac{10^8}{2^n} * \frac{1}{4} = x$

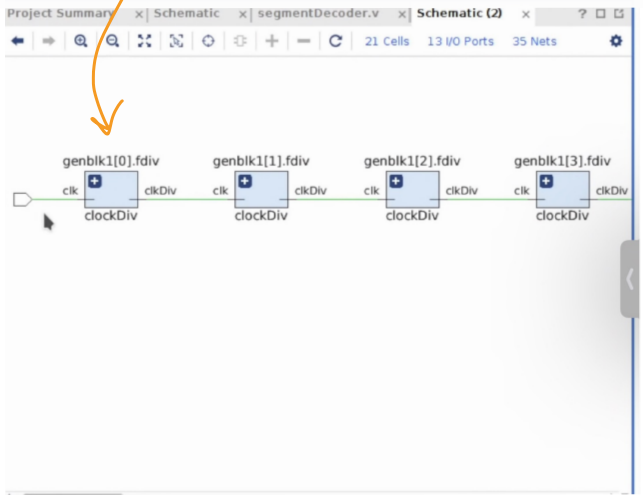
Because there is 4 digits, we must divide by 4 to get frame per second of each digit.

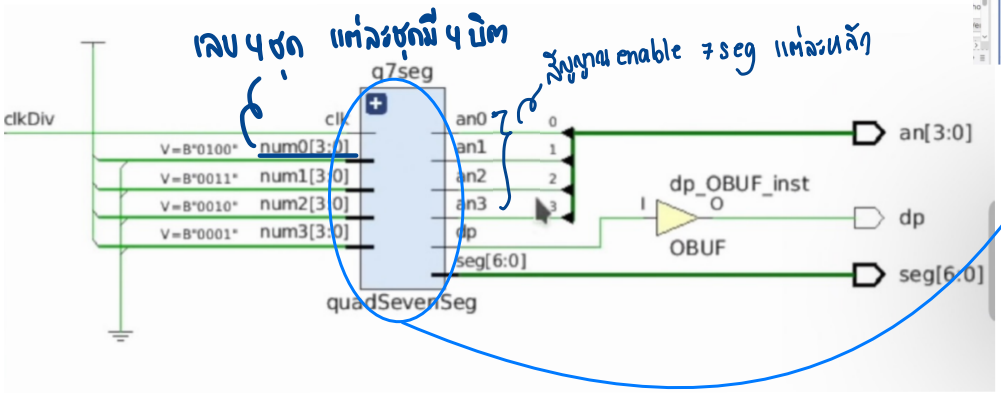
$$\frac{10^8}{2^n} * \frac{1}{4} = 15$$

เราต้องการ 15 Frame/sec

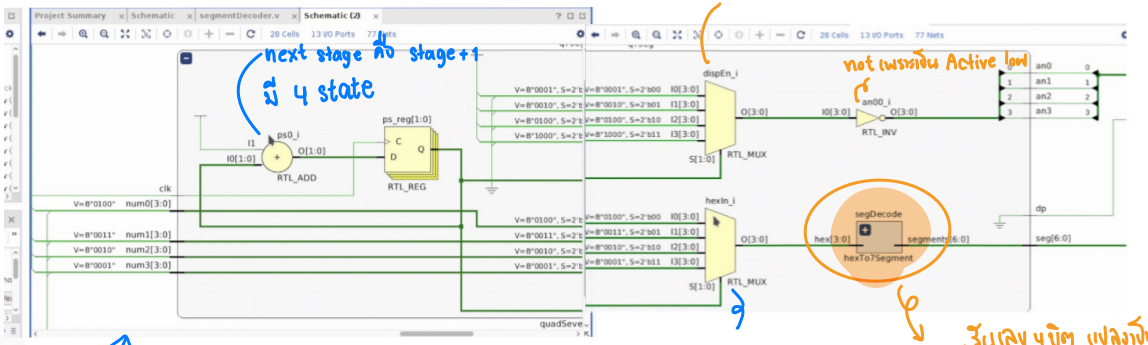
ดังนั้น n มีค่าประมาณ 20 บิต

เพราะมี 4 ช่อง





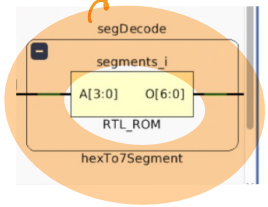
ภายใน

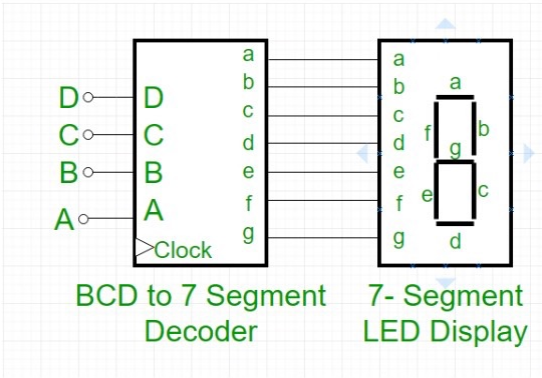


เอาstate มาเลือก ว่าจะให้หลักไหนสว่าง

แต่ละ state จะเอามา enable ต่างๆ เพื่อเลือกว่าจะเอาหลักไหน และส่งเข้า SegDecode

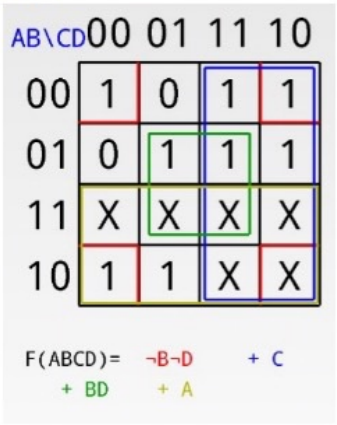
รับเลข 4 บิต แปลงเป็น 7 บิต



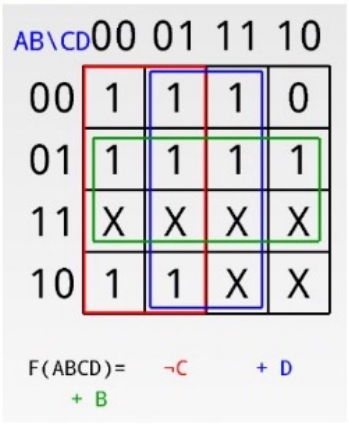


A	B	C	D	a	b	c	d	e	f	g
0	0	0	0	1	1	1	1	1	1	0
0	0	0	1	0	1	1	0	0	0	0
0	0	1	0	1	1	0	1	1	0	1
0	0	1	1	1	1	1	1	0	0	1
0	1	0	0	0	1	1	0	0	1	1
0	1	0	1	1	0	1	1	0	1	1
0	1	1	0	1	0	1	1	1	1	1
0	1	1	1	1	1	1	0	0	0	0
1	0	0	0	1	1	1	1	1	1	1
1	0	0	1	1	1	1	1	0	1	1

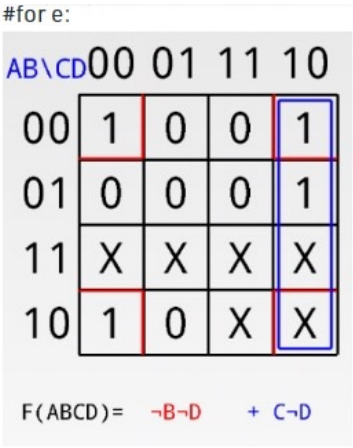
#for a:



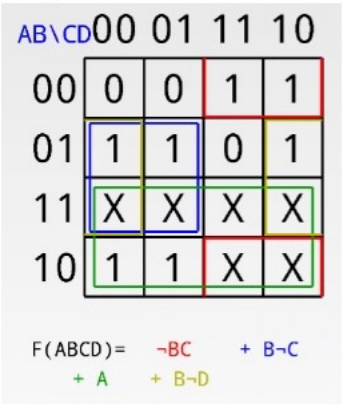
#for c:



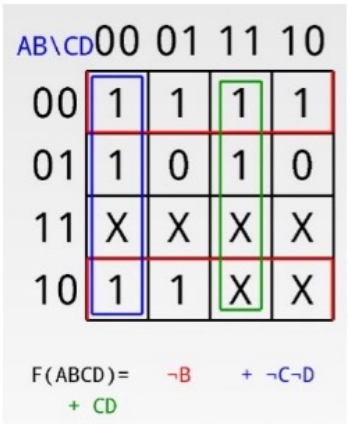
#for e:



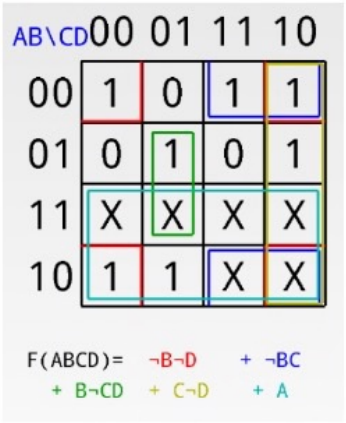
#for g:



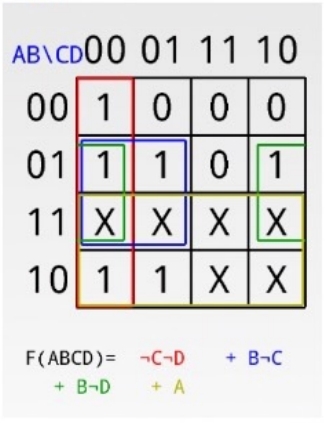
#for b:



#for d:

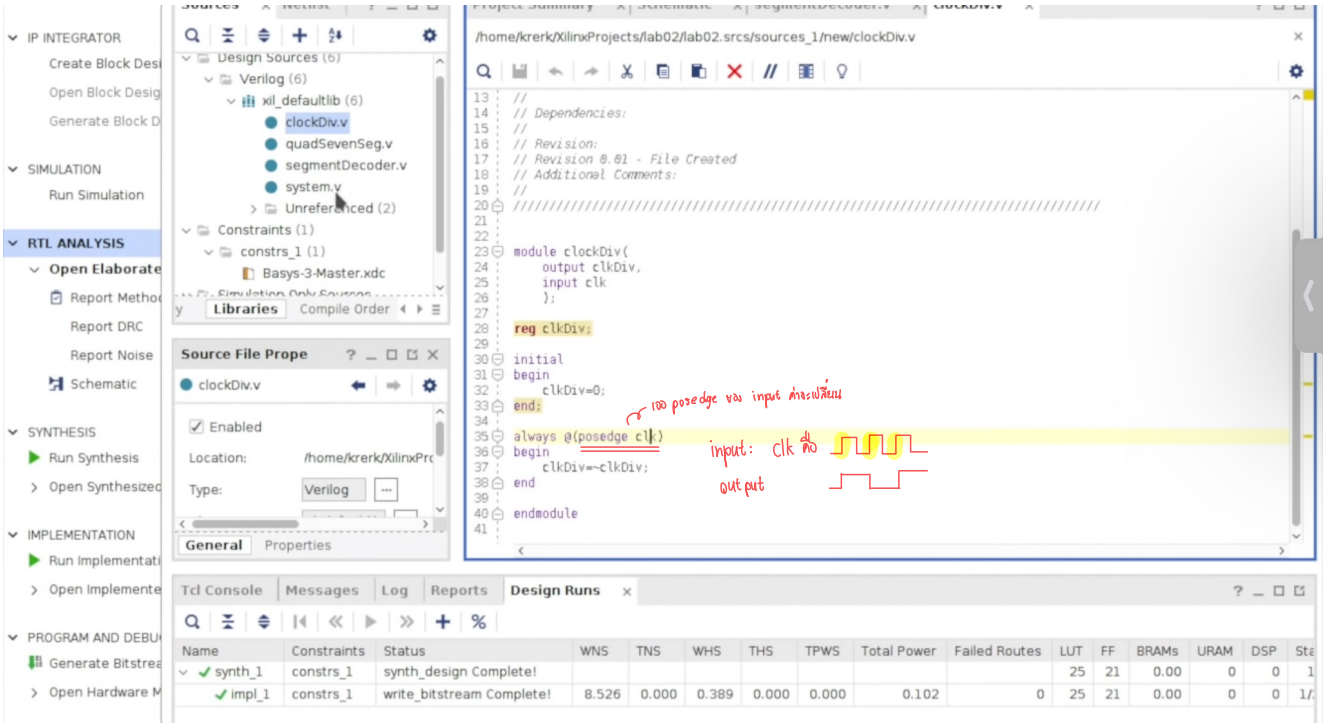


#for f:




```
## Clock signal
set_property -dict { PACKAGE_PIN W5   IOSTANDARD LVCMOS33 } [get_ports clock]
create_clock -add -name sys_clk_pin -period 10.00 -waveform {0 5} [get_ports clock]
```

คาบ เริ่มที่ 0 ถึง toggle เป็น 1 ที่ 5

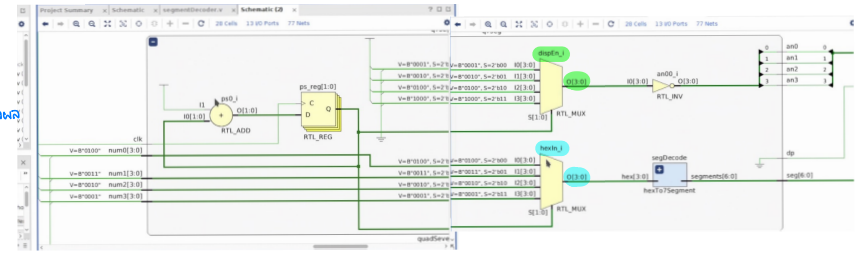



```
module quadSevenSeg(
    output [6:0] seg,
    output dp,
    output an0,
    output an1,
    output an2,
    output an3,
    input [3:0] num0,
    input [3:0] num1,
    input [3:0] num2,
    input [3:0] num3,
    input clk
    );

    reg [1:0] ns;
    reg [1:0] ps;
    reg [3:0] dispEn;

    reg [3:0] hexIn;
    wire [6:0] segments;
    assign seg=segments;
    hexTo7Segment segDecode(segments,hexIn);
    assign dp=0;
    assign {an3,an2,an1,an0} = ~dispEn;

    always @(posedge clk)
    begin
        ps=ns;
    end

    always @(ps)
    begin
        ns=ps+1;
    end

    always @(ps)
    begin
        case(ps)
            2'b00: dispEn=4'b0001;
            2'b01: dispEn=4'b0010;
            2'b10: dispEn=4'b0100;
            2'b11: dispEn=4'b1000;
        endcase
    end

    always @(ps)
    begin
        case(ps)
            2'b00: hexIn=num0;
            2'b01: hexIn=num1;
            2'b10: hexIn=num2;
            2'b11: hexIn=num3;
        endcase
    end
endmodule
```

next stage

previous stage

ใส่ wire, ใส่ 7 บิตสำหรับแสดงผล



สนใจ displayEn

สนใจ hexIn

Laboratory 3: Counter and Switch (Debounce)

Objectives

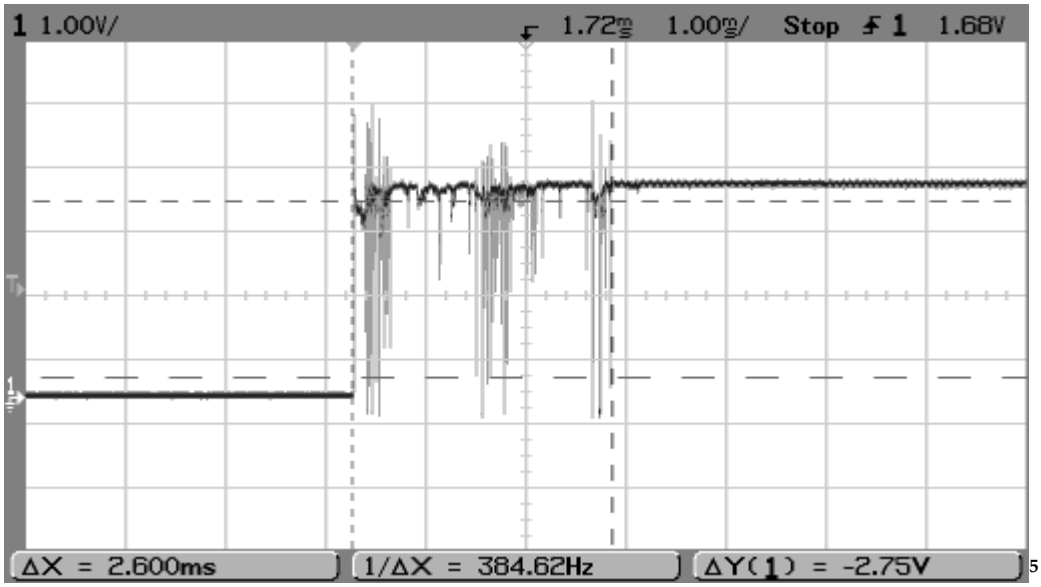
1. Synthesis FPGA
2. Able to design debounce switch and input
3. Able to design up and down Counter

Background

Debouncing is a programming pattern or a technique to restrict the calling of a time-consuming function frequently, by delaying the execution of the function until a specified time to avoid unnecessary CPU cycles, and API calls and improve performance.

Switch and Bounce

Mechanic switches and relays have a common issue called contact bounce (aka. chatter). Switch and relay contacts are usually made of metals. When the contacts strike together, their momentum and elasticity act together to cause them to bounce apart one or more times before making steady contact. (Imagine a ball falling on a fall, it would bounce several times before coming to a complete stop.)

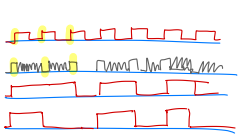


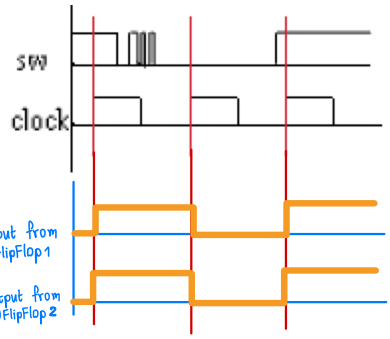
[5]

There are several ways to debounce. Debouncing methods include using capacitor, SR Latch, or Low-pass filtered schmitt trigger. However, those methods usually required special hardware.

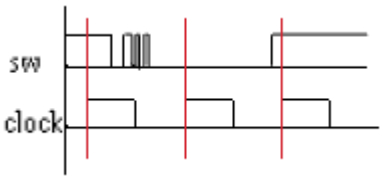
To debounce without using special hardware, we can use software methods by

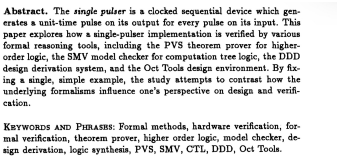
5 Image taken from https://upload.wikimedia.org/wikipedia/commons/thumb/a/ac/Bouncy_Switch.png/400px-Bouncy_Switch.png





resampling for input several times.




Abstract. The *single pulser* is a clocked sequential device which generates a unit-time pulse on its output for every pulse on its input. This paper explores how a single-pulser implementation is verified by various formal reasoning tools, including the PVS theorem prover for higher-order logic, the SMV model checker for computation tree logic, the DDD design derivation system, and the Oct Tools design environment. By fixing a single, simple example, the study attempts to contrast how the underlying formalisms influence one's perspective on design and verification.

Keywords and Phrases: Formal methods, hardware verification, formal verification, theorem prover, higher order logic, model checker, design derivation, logic synthesis, PVS, SMV, CTL, DDD, Oct Tools.

สำหรับ Debounce

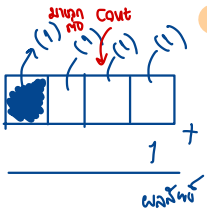
Please also note that there is a metastable issue. To avoid this, it is generally advised that two D flip flops be placed between the input and the digital circuit.

Exercises

1. Create an up/down 1-digit BCD counter with 4-bit outputs (DCBA) and 1 overflow output (cout), 1 borrow (bout) and 6 inputs (up, down, set9, set0,clock). Write a simulator to show that the counter functions correctly.

2. Create a single pulser with one input, clock, and one output. Write a simulator to show that the single pulser works correctly.

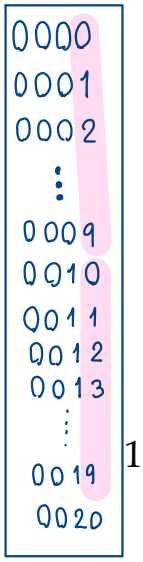
3. Use 4 counters from exercise 1 to create 4 digits BCD counters. Connect all displays to 4 digits seven-segment displays. (Use the display components from Laboratory II.) Use BTNU for set9 (set the number to 9999). Use BTNC for reset (set the number to 0000). Use SW0 for countdown by 1. Use SW1 for count up by 1. Use SW2 for countdown by 10. Use SW3 for count up by 10. Use SW4 for countdown by 100. Use SW5 for count up by 100. Use SW6 for countdown by 1000. Use SW7 for count up by 1000. If the number is at 0000, a countdown would not decrease the number. If the number is at 9999, a count up would not increase the number. Do not worry about the bounce at the moment. We will fix it in the next exercise.



*ในการเลข cout จะกลายเป็นตัวเลขของหลักต่อไป

แต่ถ้าเป็นการลบ bout จะกลายเป็นตัวลบของหลักต่อไป

4. Correct the bounce in exercise 2 by implementing a debounce component for each input.



5. Please answer the following questions and submit (in PDF format) to CourseVille on Friday before 23:59 (midnight).
   a. From the circuit diagram, the BTNx is active High or active Low? Please provide your analysis.
   b. What is a bounce? How do you programmatically debounce the input?

Please provide your analysis.

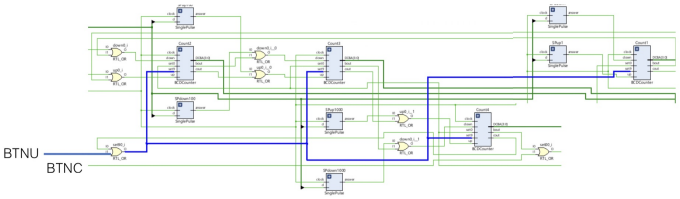
c. Please show your method for implementing a single pulser. (e.g. draw a state diagram, or verilogHDL code)

5. Please answer the following questions and submit (in PDF format) to CourseVille

on Friday before 23:59 (midnight).

a. From the circuit diagram, the BTNx is active High or active Low? Please provide your analysis.

ตอบ เป็น Active High เพราะ มีการทำงานตอนที่มีการกดปุ่ม หรือก็คือตอนที่ค่าเป็น 1 นั่นเอง และจาก Circuit Diagram

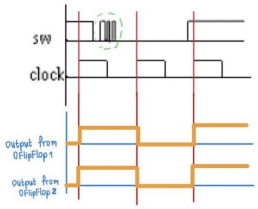


จะเห็นว่า ถ้า BTNx มีค่าเป็น 1 วงจรจะเกิดการทำงาน ดังนั้นจึงเป็น Active High

b. What is a bounce? How do you programmatically debounce the input? Please provide your analysis.

ตอบ bounce = When two metal contacts to generate multiple signals as the contacts close or open, i.e., when switch is pressed, it can cause 'bounce' that makes multiple signal.

การแก้ปัญหาการ bounce หรือที่เรียกว่า debounce นั้นทำได้โดยการใช้เขียนโค้ดให้มีการนำอินพุตไปใส่ใน DFlipFlop ก่อน เพื่อทำการกรองสัญญาณ ดังรูปด้านล่างที่ได้ทำการวิเคราะห์ไว้



จะเห็นว่าส่วนสีเขียว ซึ่งก็คือส่วนที่เกิดการ bounce ได้ถูกกำจัดออกไป โดย D FlipFlop

c. Please show your method for implementing a single pulser. (e.g. draw a state diagram, or verilogHDL code)

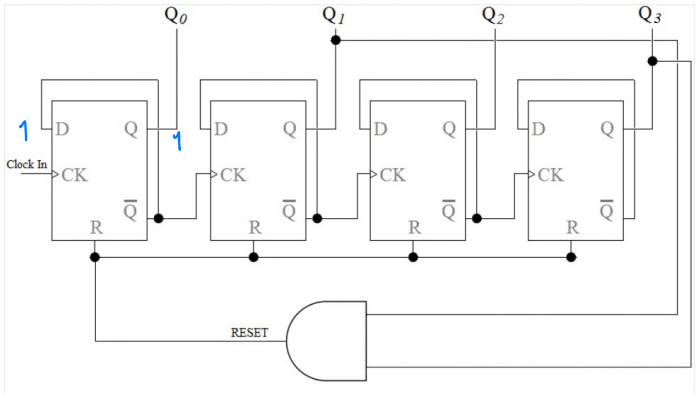
ตอบ verilogHDL code:

```
module SinglePulse(
    output reg answer,
    input d,
    input clock
    );

    wire tmp1, tmp2;                //**must be wire
    DFlipFlop DFlipFlop1(tmp1, clock, 1, d);
    DFlipFlop DFlipFlop2(tmp2, clock, 1, tmp1);     //for module AllSevenSegment

    wire dd;
    assign dd = tmp2;
    //assign dd = d;
    reg usedBe1 = 0;
    reg show1 = 0;
    always @(posedge clock)
        begin
            if (dd == 1 && usedBe1 == 0) begin
                answer = 1;
                usedBe1 = 1;
            end
            else if (dd == 1 && usedBe1 == 1) begin
                answer = 0;
            end
            else if (dd == 0 && usedBe1 == 1) begin
                answer = 0;
                usedBe1 = 0;        //Reset
            end
            else begin
                answer = 0;
                usedBe1 = 0;
            end
        end
endmodule
```

มีเสเตทที่เก็บว่าผลลัพธ์เคยเป็น 1 หรือยัง ถ้ามี input = 1 เข้ามาแต่ผลลัพธ์เคยเป็น 1 มาแล้ว output จะไม่เป็น 1 แต่จะเป็น 0 แทน แต่ในทางกลับกันถ้า input เป็น 1 แต่สเตทนี้เป็น 0 ผลลัพธ์ถึงจะแสดง 1 ออกมา แต่ถ้า input เป็น 0 ไม่ว่าอย่างไรก็ตาม output จะเป็น 0 เสมอ

1. Create an up/down 1-digit BCD counter with 4-bit outputs (DCBA) and 1 overflow output (cout), 1 borrow (bout) and 6 inputs (up, down, set9, set0,clock). Write a simulator to show that the counter functions correctly.

0 0000
1 0001
2 0010
3 0011
4 0100
5 0101
6 0110
7 0111
8 1000
9 1001



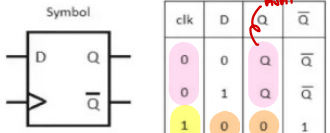
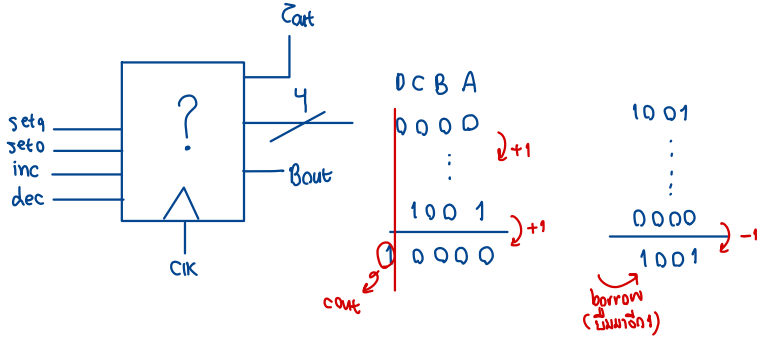


Table of truth:

clk	D	Q	$\bar{Q}$
0	0	Q	$\bar{Q}$
0	1	Q	$\bar{Q}$
1	0	0	1
1	1	1	0




```
module BCDCounter(
    output reg [3:0] outputs,
    output reg cout,
    output reg bout,
    input set9,
    input set0,
    input inc,
    input dec,
    input clk
```

```
module hexTo7Segment(
    output [6:0] segments,
    input [3:0] hex
    );

    reg [6:0] segments;
```

```
module BCDCounter(
    output reg [3:0] outputs,
    output reg cout,
    output reg bout,
    input set9,
    input set0,
    input inc,
    input dec,
    input clk
```

```
odule fullAdderTester(

    );
    reg a,b,cin;
    wire cout,s;
    fullAdder a1(cout,s,a,b,cin);
```

A B C D
0-9

D, C_1 = D+1
C, C_2 = C+C_1
B, C_3 = B+C_2
=

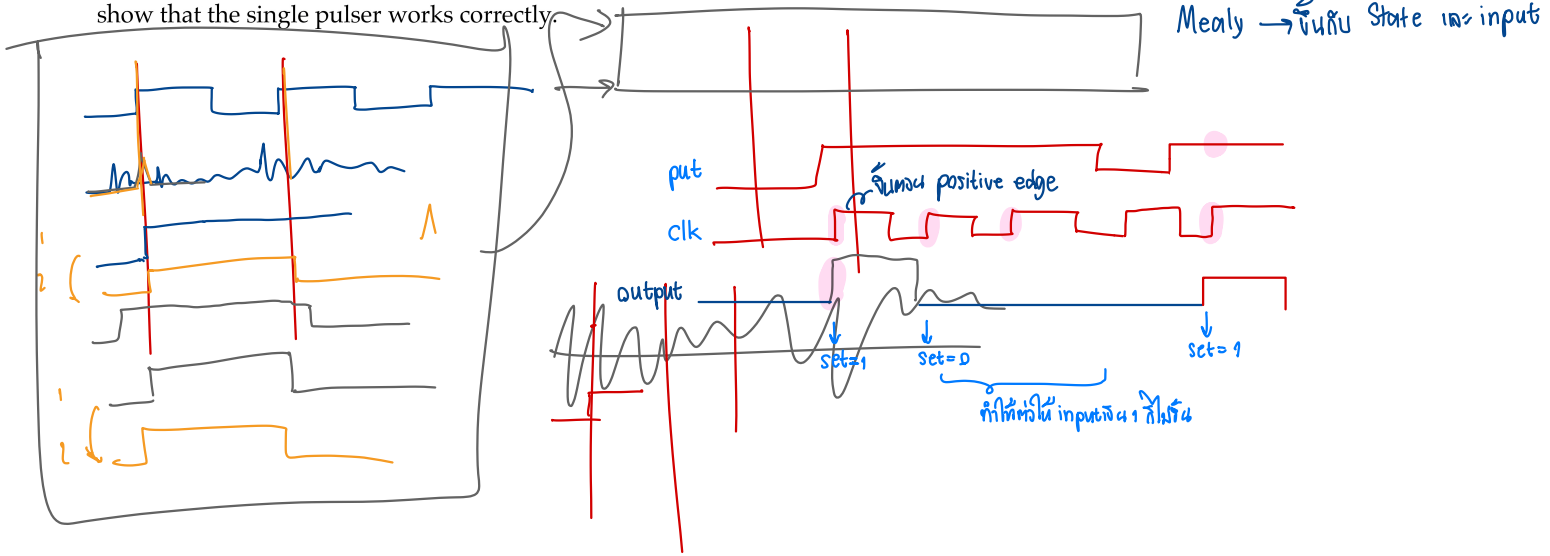
bcd (up) return cout, n
A B C D
A = bcd( )
B =
C =
D =

C = D(1)

2. Create a single pulser with one input, clock, and one output. Write a simulator to show that the single pulser works correctly.

Moore → ขึ้นกับ State

Mealy → ขึ้นกับ State และ input



Laboratory 4: Memory

Objectives

1. Able to implement memory in HDL
2. Able to instantiate internal FPGA memory

Background

We would be soon implementing our first processor in the next Lab!. Now, you should have an understanding of how to implement a FSM with Verilog. What you are missing is how to implement a memory model on Verilog such that you can use it on your very first processor. We will be looking at read-only-memory (ROM), random-access-memory (RAM), and first-in-first-out (FIFO)

ROM

The first kind of memory you are going to implement is read-only-memory (ROM). So far, you have been using only Verilog for synthesizing registers (D-Flip Flop). However, it's costly to implement memory using purely registers. Field-programmable gate array (FPGA) manufacturers often include blocks of memory inside the FPGA such that you can use.

Typical ROM instantiation looks like the following

```
module rom case(
      (* synthesis , rom block = "ROM CELLXYZ01" *)
      output reg [3:0] z ,
      input wire [2:0] a); // address- 8 deep memory
always@* begin // @(a)
      case (a)
      3'b000: z = 4'b1011;
      3'b001: z = 4'b0001;
      3'b100: z = 4'b0011;
      3'b110: z = 4'b0010;
      3'b111: z = 4'b1110;
      default : z =4'b0000 ;
      endcase
end
endmodule // rom case
```

The code above would generate ROM with 8 addresses, each address is 4 bits.

You might notice the synthesis suggestion keyword (* synthesis, rom_block = "ROM_CELLXYZ01" *). This tells the synthesis tools to try to use the dedicated ROM inside the FPGA instead of implementing it as a block of registers. The keywords may differ from one FPGA vendor from another. Note that most synthesis tools nowadays are smart enough to detect the access pattern that you can remove that out.

Second, the ROM in is actually asynchronous. You could make it a synchronous ROM by adding a clock, i.e.

```
module rom case(
      (* synthesis , rom block = "ROM CELLXYZ01" *) input clk ,
      output reg [3:0] z ,
      input wire [2:0] a); // address- 8 deep memory
always@(posedge clk)
      begin
      case (a)
      3'b000: z = 4'b1011;
      3'b001: z = 4'b0001;
      3'b100: z = 4'b0011;
      3'b110: z = 4'b0010;
      3'b111: z = 4'b1110;
      default : z =4'b0000 ;
      endcase
end
endmodule // rom case
```

Having the data inside your program is extremely inconvenient especially if you have a large file set of data. Verilog allows you to "read" data from a file.

```
// Verilog-2001 style
// ROM module using two dimensional arrays with
// memory defined in text file with $readmemb or $readmemh
// NOTE: This style can lead to simulation/synthesis mismatch
//       if the content of data file changes after synthesis
module rom_2dimarray_initial_readmem (
  output wire [3:0] z,
  input  wire [2:0] a);
  // declares a memory rom of 8 4-bit registers.
  //The indices are 0 to 7
  (* synthesis, rom_block = "ROM_CELL XYZ01" *)
  reg    [3:0] rom[0:7];
  // NOTE:  To infer combinational logic instead of a ROM, use
  // (* synthesis, logic_block *)
  initial \$readmemb("rom.data", rom);
  assign z = rom[a];
endmodule
```

b = binary
d = decimal
h = hex

The rom.data would look like this

```
1011 // addr=0
1000 // addr=1
0000 // addr=2
1000 // addr=3
0010 // addr=4
0101 // addr=5
1111 // addr=6
1001 // addr=7
```

จะใส่ไม่ต้องเขียนแกสแบบนี้ก็ได้เลย

RAM

Another useful primitive for the FPGA is random-access-memory (RAM). Again, as in the ROM case, we could have implemented RAM as a set of registers, but it's expensive and costly to do so. Typical FPGAs have dedicated areas for RAMs, (BlockRAM for Xilinx, Memory Block for Altera, etc.) The following code will generate RAM with 128x8 bits.

```
module SinglePortRAM (
inout wire [7:0] d, // Data In and Out
input wire [6:0] addr , // Address
input wire oe , // Output Enable
input wire clk , we) ;
(* synthesis , ram block *)

reg [7:0] mem [127:0];

always @(posedge clk)
if(we)
      mem[addr] <= d;

assign d = oe ? mem[addr] : 8'bZ;
endmodule
```

You may see the inout port in the example. The idea is that the port can be used as both input and output (at different times). To read, you have to assign Z to the wire before reading the data. To write, just connect the register to the wire. This line "assign d = oe ? mem[addr] : 8'bZ; " explains such a connection.

Block RAM

As you can see, we can write a HDL code to generate registers, and we can potentially implement a memory using it. However, a FPGA has a small number of these CLB, and it is a bit overkill since these logic can do much greater things than being just memory. So, most FPGA vendors have specialized memory units that we can use on these FPGAs. Each vendor has a different name, but for Xilinx, we call it Block RAMs. Typically, each bRAMs has a size of 10-20Kbit depending on the FPGA, and each FPGA may have from ten to thousands of these bRAMs.

There are several ways to initiate bRAMs on Xilinx, but in general Xilinx Synthesis step can recognize if you are going to generate a bRAMs from a following pattern

```
parameter RAM WIDTH = <ram width >;

parameter RAM ADDR BITS = <ram addr bits >;

reg [RAMWIDTH-1:0] <ram name> [(2**RAMADDRBITS)- 1:0]; reg [RAM WIDTH-1:0]
<output   data >;

<reg or wire> [RAMADDRBITS-1:0] <address>;

<reg or wire> [RAMWIDTH-1:0] <input data >; always @(posedge <clock>)

if (<ram enable>) begin

if (<write enable>) begin

<ram name>[<address >] <= <input data >; <output data> <= <input data >;

end else

<output data> <= <ram name>[<address >]; end
```

Note that bRAMs is not the only type of construct that the Synthesizer can recognize. There are many other types of construct. Some of these are even more complicated. So most FPGA vendors has a so called language template. For Xilinx, you can find these out in the menu by going to Tools > Language Templates. For memory, it is in Verilog > Synthesis Constructs > Coding Examples > RAM > BlockRAM. We recommend you explore these constructs.

Most FPGAs have what is called Distributed RAM. This essentially uses the logic gate and registers to implement the memory. Usually, Distributed RAM is faster than bRAMs, but it is smaller. 1

Note that there is also another method for instantiating the bRAMs. This is through the use of Block Design. We recommend you take a look at this document https://www.xilinx.com/support/documentation/university/Vivado-Teaching/Digital-Design/2014x/docs-pdf/Vivado_tutorial.pdf for more information about how to use IP Integrator and Block Design.

Exercises

1. Design and build a circuit to work as a Stack (LIFO). The user can use two push buttons in order to PUSH (BTNU) or POP (BTNC). Use 8 switches on the board as a value. When a user hits a PUSH button, it will store the value from the switches to the stack. When the user hits the POP switch, it will display the value from the top of the stack in the two hex displays on the left. The other hex displays are used to display the number of elements currently in the stack. The stack can keep up to 256 elements. If the stack is full, hitting the PUSH button should not do anything.

   We recommend using a PUSH button as a reset (BTND).

2. Read an input from 5 binary switches. (You are welcome to use any switch. If you have no preference, use SW[4..0].) This should give you a number ranging from 0 to 31. Use distributed memory or bRAMs as the ROM for converting binary to 2 BCD for displaying on a seven-segment display. Use 5 bit binary as an address. The output can be either 2x4 BCD for applying to BCDtoSevenSegment (as used in the previous lab) or 2x8 for feeding directly to a seven-segment display.

   Note: You may want to initialize the memory from data. Please see the language template for more information

3. Use Block Design to create a simple calculator 4-bit calculator. You will assign 4 switches as the 4-bits input for A and another 4 switches for B. You will assign 4 push buttons to do 4 different operations.
   a. When BTNU is pushed, you will display the result of A+B in base 10 using the three 7-segment displays.
   b. When BTNL is pushed, you will display the result of A-B in base 10 using the three 7-segment displays.
   c. When BTND is pushed, you will display the result of A*B in base 10 using the three 7-segment displays.
   d. When BTNR is pushed, you will display the result of A/B in base 10 using the three 7-segment displays.
4. Please answer the following questions and submit (in PDF format) to CourseVille on Friday before 23:59 (midnight).
   a. Explain your ROM for mapping 5-bit binary to 2-digit BCDs (or 2x8 bits seven segment displays depending on your design in Exercise.2).

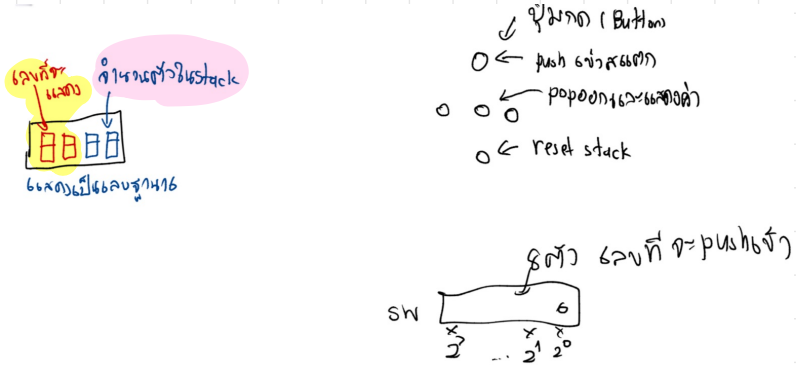
4. Please answer the following questions and submit (in PDF format) to CourseVille on Friday before 23:59 (midnight).

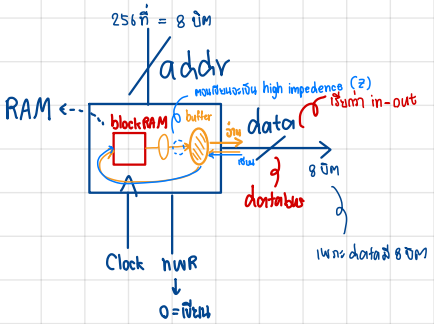
a. Explain your ROM for mapping 5-bit binary to 2-digit BCDs (or 2x8 bits seven segment displays depending on your design in Exercise.2).

ตอบ ROM นั้น จะมี Look up table ซึ่งเปรียบเสมือนตารางที่มีคำตอบที่เกิดจาก input ที่เป็นไปได้ ทุกรูปแบบเก็บไว้ ถ้า input แบบหนึ่งเข้ามา ก็จะสามารถส่งคำตอบออกไปได้เลยทันที โดยที่ไม่ต้องคำนวณใหม่ เช่น ถ้าเลข 5 บิตที่เข้ามาเป็น 10100 ก็จะส่งค่าเอาทพุตออกไปเป็น 0010 กับ 0000 ทันที โดยที่ไม่ต้องมีการคำนวณใหม่ ซึ่งไฟล์คำตอบทั้งหมดนั้นจะอยู่ในไฟล์ชื่อว่า romData.data และมีการใช้คำสั่งชื่อว่า $readmemb ในการ map ตัวไฟล์คำตอบ เข้ากับ array ขนาด 32*8 (ซึ่งจะมองเสมือนว่าเป็นตัวจำค่าต่างๆ) และเพราะคำตอบที่ออกมาจาก ROM นั้นต้องมีขนาด 8 บิต และ เนื่องจากอินพุตนั้นมีจำนวน 5 บิต แสดงว่ามีคำตอบที่เป็นไปได้อยู่ทั้งหมด 2^5 = 32 รูปแบบนั่นเอง

1. Design and build a circuit to work as a Stack (LIFO). The user can use two push buttons in order to PUSH (BTNU) or POP (BTNC). Use 8 switches on the board as a value. When a user hits a PUSH button, it will store the value from the switches to the stack. When the user hits the POP switch, it will display the value from the top of the stack in the two hex displays on the left. The other hex displays are used to display the number of elements currently in the stack. The stack can keep up to 256 elements. If the stack is full, hitting the PUSH button should not do anything.

   We recommend using a PUSH button as a reset (BTND).



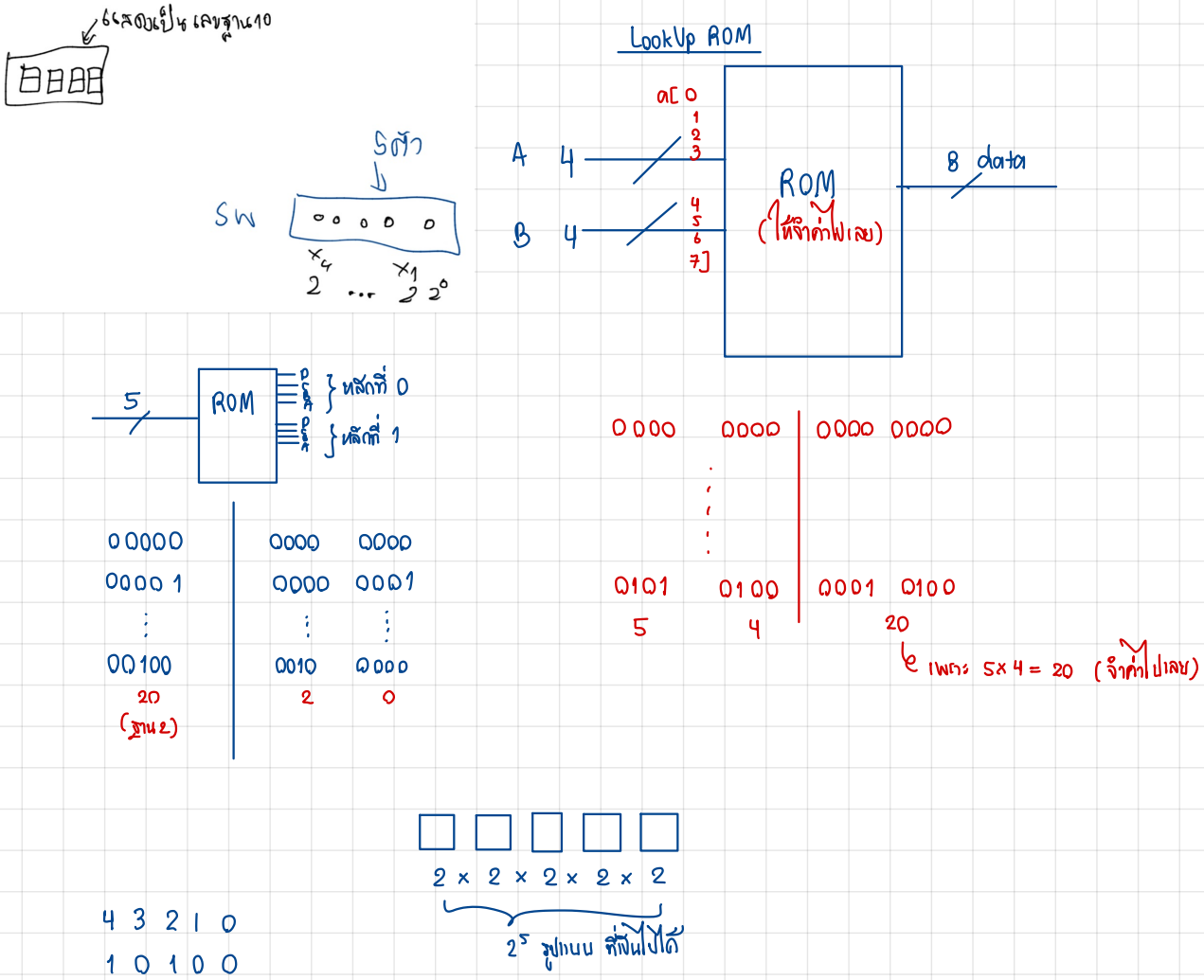


PUSH = เขียน
POP = อ่าน

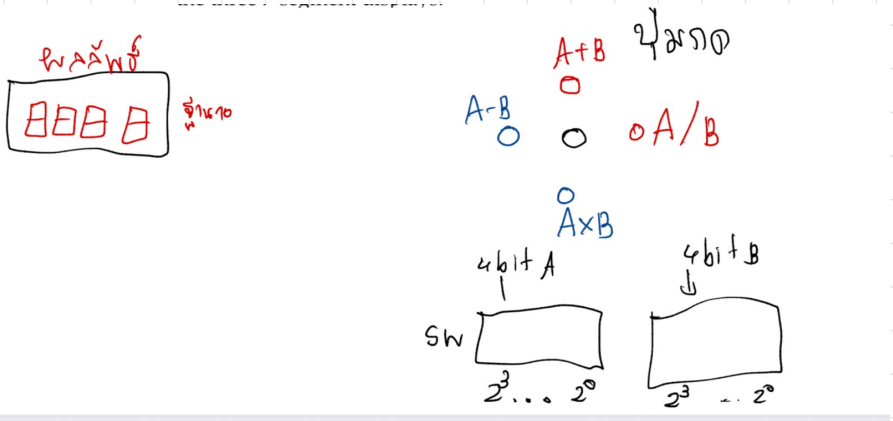
2. Read an input from 5 binary switches. (You are welcome to use any switch. If you have no preference, use SW[4..0].) This should give you a number ranging from 0 to 31. Use distributed memory or bRAMs as the ROM for converting binary to 2 BCD for displaying on a seven-segment display. Use 5 bit binary as an address. The output can be either 2x4 BCD for applying to BCDtoSevenSegment (as used in the previous lab) or 2x8 for feeding directly to a seven-segment display.

** เอาอันนี้

Note: You may want to initialize the memory from data. Please see the language template for more information



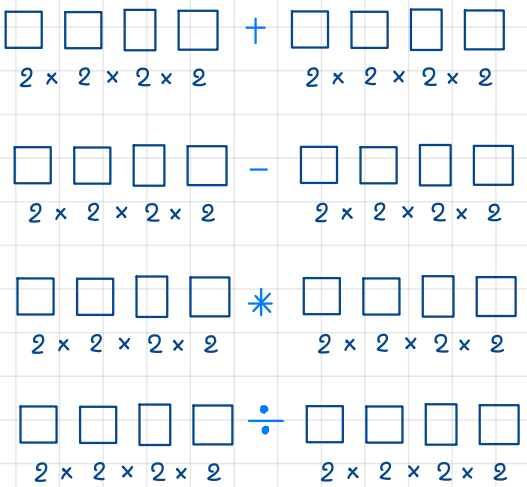
3. Use Block Design to create a simple calculator 4-bit calculator. You will assign 4 switches as the 4-bits input for A and another 4 switches for B. You will assign 4 push buttons to do 4 different operations.
    a. When BTNU is pushed, you will display the result of A+B in base 10 using the three 7-segment displays.
    b. When BTNL is pushed, you will display the result of A-B in base 10 using the three 7-segment displays.
    c. When BTND is pushed, you will display the result of A*B in base 10 using the three 7-segment displays.
    d. When BTNR is pushed, you will display the result of A/B in base 10 using the three 7-segment displays.



A+B; 0+0
0+1
0+

A+B = 0
A-B = 1
A*B = 2
A/B = 3

3 2 1 0
1111 x 1111 ⇒ 255
8+4+2+1
↳ 15



4(2⁴ x 2⁴) = 1024 รูปแบบ

Laboratory 5: Simple CPU and Memory Mapped I/O

Objectives

1. Able to implement Simple CPU in VerilogHDL
2. Able to implement the memory mapped I/O

Background

I/O ที่เราจะต่อคือ จาก 7-segment และ switch

แนวที่ 3 คือ I/O Prosessor (ไม่เน้นม.)

Memory Mapped I/O and Port-Mapped I/O

Memory Mapped I/O and Port-Mapped I/O are two different methods for implementing input/output between CPU and peripheral devices in a computer.

1 ** จากที่ memory address หนึ่ง ซึ่งถูกผ่องไว้กับ I/O

Memory Mapped I/O uses the same address to address both memory and I/O devices. The memory and registers of devices are associated with physical addresses. Each I/O device monitors the CPU's address bus and responds to any CPU access of an address assigned to that device, connecting the data bus to the desired device's hardware register. This type of I/O allows software to interact with I/O directly using standard load and store instructions.

จาก micro-controller

เช่น I/O ใส่ไว้ที่ตำแหน่ง 500 ของ Mem เลย

2 (Port) I/O ต่อกับตัวพิเศษ เลี่ยงเวลาว่าจะอ่านจาก Port

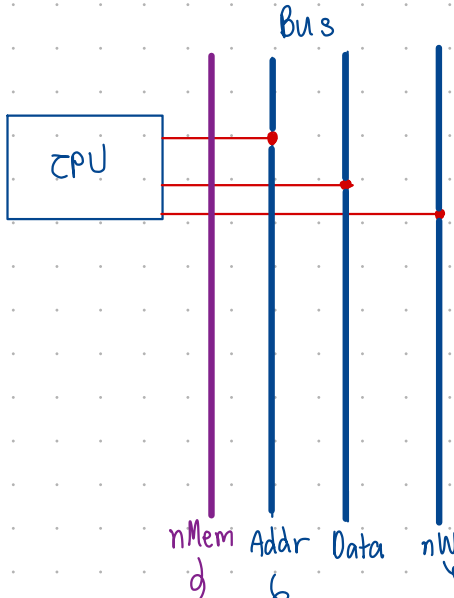
Unlike the Memory Mapped I/O, Port-mapped I/O uses special CPU instructions for performing I/O, such as the inp and outp. The benefit of Port-mapped I/O is the separation of address spaces between I/O and memory.

* memory ตำแหน่งที่ 500 กับ I/O ตำแหน่งที่ 500 เป็นคนละเรื่อง

To connect a device to either memory mapped I/O or port-mapped I/O, a decoder must be added to the address. When an address is matched, accessing (reading and writing) to the data bus will be relayed to a device. In certain cases (eg. microcontroller), control registers (and buffers) will be added to related addresses in order to act as an interface between processor and devices.

(For more information, see the video clips.)

I/O



I/O

7 Seg

แต่ละหลักคือ Register

Memory

nWR เขียนหรือไม่

Addr ผ่านการ Decode แล้วได้ MEM, บางอันได้ 7-Seg → Memory Mapped I/O

สำหรับ Port Mapped โดยถ้าเส้นนี้

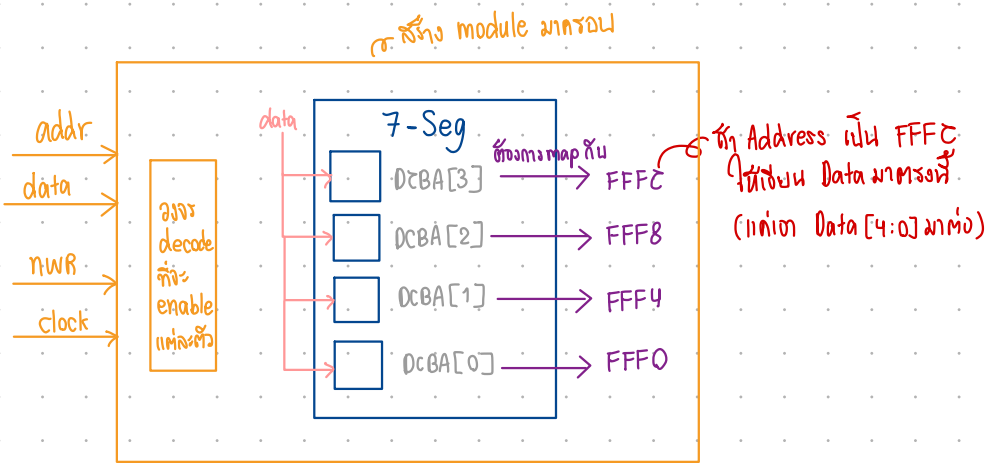
มีค่าเป็น 0 → ค่า Addr ตัวนี้จะเป็นของ 7-Seg

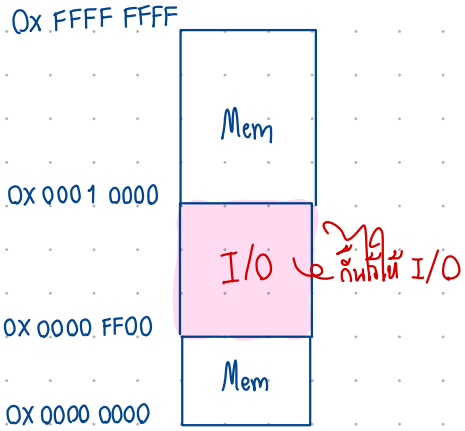
1 → MEM

(มี 32 ขีด)

addr

เช่น

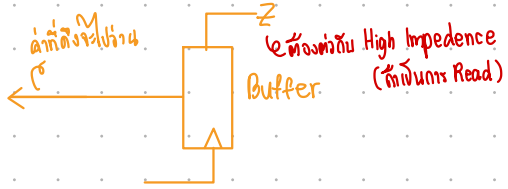




nWR = 0 && 0x 0000 FFFC

ถ้าเงื่อนไขนี้เป็นจริง DCBA[3] จะติด!

— = สิ่งที่ต้องทำ



Exercises

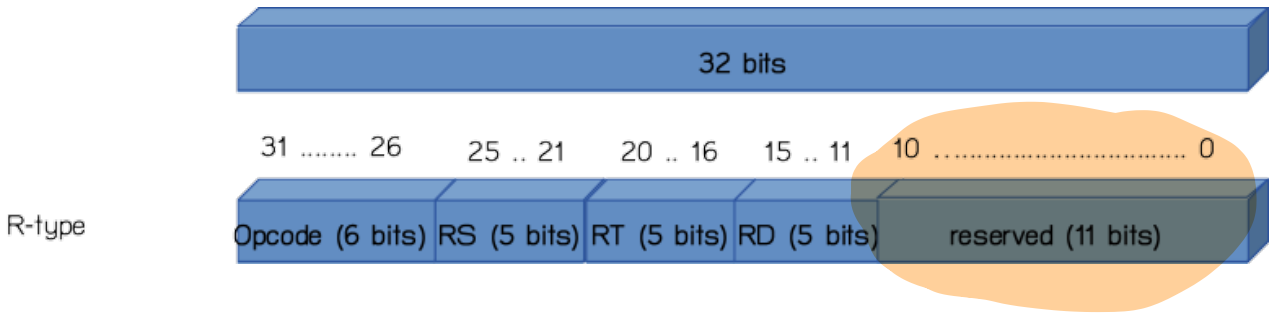
Please use nanoLADA CPU code[6] as a base.

1. Based on the given ALU, extend the ALU to support the following operations.

ALU OP	Operations
000	{Cout,S}=A+B+Cin;
001	{Cout,S}=A-B;
010	S=A | B; Cout=0; (or)
011	S=A & B; Cout=0; (and)
100	S=A ^ B; Cout=0; (xor)
101	S=-A; Cout=0; (2's complement)
110	S=~A; Cout=0; (not)
111	S=~B; Cout=0; (not)

Use the simulator to validate your ALU.

2. . Extend the R-type instruction format to support the following operations.



6Available at https://www.cp.eng.chula.ac.th/~krerk/books/Computer%20Architecture/nanoLADA/

p_address = pc
p_data ⟶ instruction
d_address = data_S = address of data
d_data ⟶ data_M = data

Original instruction

	Opcode (6 bits)	RS (5 bits)	RT (5 bits)	RD (5 bits)	Reserved (11bits)
ADD rd, rs, rt R[rd] ← R[rs] + R[rt];	000001				

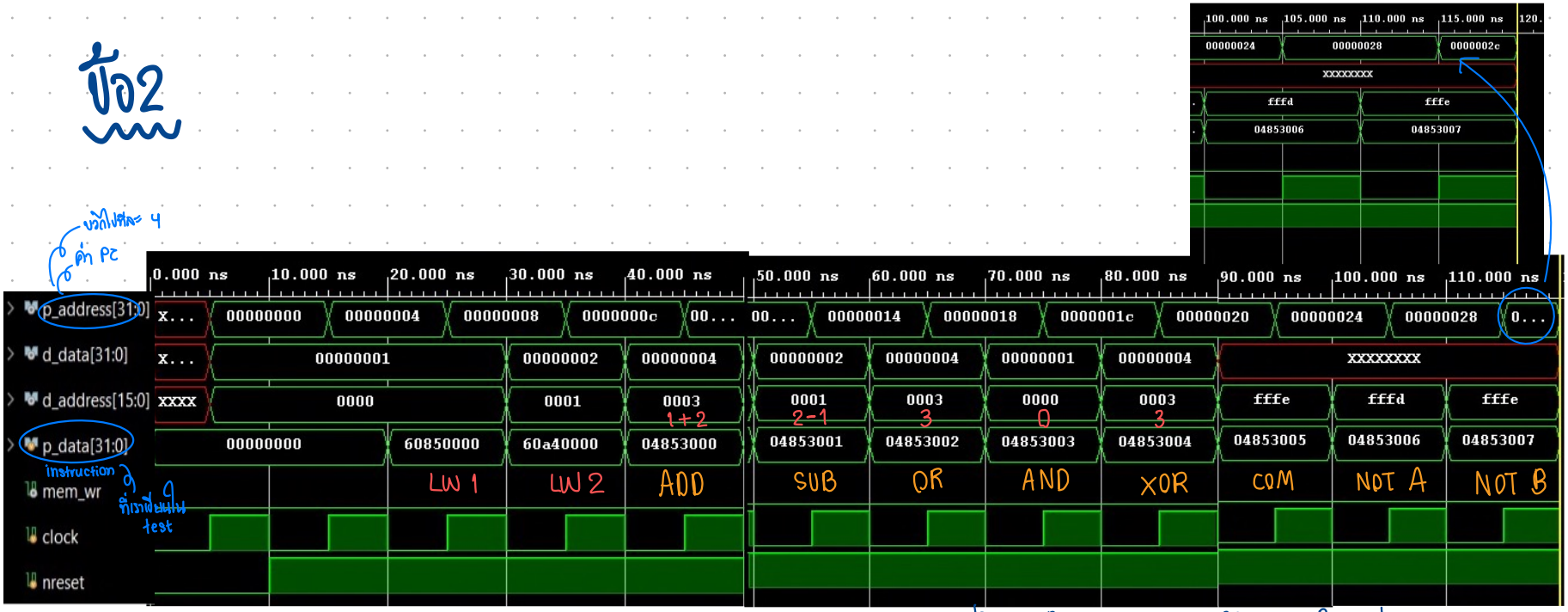
New instructions.

ใน Reserve 11 bits เดิม

	Opcode (6 bits)	RS (5 bits)	RT (5 bits)	RD (5 bits)	ALU Operation (11 bits)
ADD rd, rs, rt R[rd] ← R[rs] + R[rt];	000001				00000000_000
SUB rd, rs, rt R[rd] ← R[rs] - R[rt];	000001				00000000_001
OR rd, rs, rt R[rd] ← R[rs] | R[rt];	000001				00000000_010
AND rd, rs, rt R[rd] ← R[rs] & R[rt];	000001				00000000_011
XOR rd, rs, rt R[rd] ← R[rs] ^ R[rt];	000001				00000000_100
COM rd, rs,xx R[rd] ← -R[rt];	000001				00000000_101
NOT rd, rs, xx R[rd] ← ~R[rs]	000001				00000000_110

ไฟล์ ROM มีไฟล์ prog ที่เก็บคำสั่งต่างๆ

ข้อ2



001 OR 010 = 011

New instructions.

	Opcode (6 bits)	RS (5 bits)	RT (5 bits)	RD (5 bits)	ALU Operation (11 bits)
ADD rd, rs, rt R[rd] ← R[rs] + R[rt];	000001				00000000_000
SUB rd, rs, rt R[rd] ← R[rs] - R[rt];	000001				00000000_001
OR rd, rs, rt R[rd] ← R[rs] | R[rt];	000001				00000000_010
AND rd, rs, rt R[rd] ← R[rs] & R[rt];	000001				00000000_011
XOR rd, rs, rt R[rd] ← R[rs] ^ R[rt];	000001				00000000_100
COM rd, rs,xx R[rd] ← -R[rt];	000001				00000000_101
NOT rd, rs, xx R[rd] ← ~R[rs]	000001				00000000_110

เอา Reserve 11 bits มาใส่

opcode RS RT RD Reserved

```
LW 1  #10 p_data = 32'b011000_00100_00101_00000_00000000000; // LW $r5, 0($r4) = 1
LW 2  #10 p_data = 32'b011000_00101_00100_00000_00000000000; // LW $r4, 0($r5) = 2

      31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
      #10 p_data = 32'b000001_00100_00101_00110_00000000000; // ADD $r6, $r5, $r4
      #10 p_data = 32'b000001_00100_00101_00110_00000000001; // SUB $r6, $r5, $r4
      #10 p_data = 32'b000001_00100_00101_00110_00000000010; // OR $r6, $r5, $r4
      #10 p_data = 32'b000001_00100_00101_00110_00000000011; // AND $r6, $r5, $r4
      #10 p_data = 32'b000001_00100_00101_00110_00000000100; // XOR $r6, $r5, $r4
      #10 p_data = 32'b000001_00100_00101_00110_00000000101; // -A $r6, $r5, $r4
      #10 p_data = 32'b000001_00100_00101_00110_00000000110; // NOT A $r6, $r5, $r4
      #10 p_data = 32'b000001_00100_00101_00110_00000000111; // NOT B $r6, $r5, $r4
```

ตัวบอกต่างที่ใช้ทำงาน

```
# run 1000ns
         0 - mem[zzzxxxx] -  xxxxxxxx

         1 - A(REG[ 0]) -  00000000, B(REG[ 0]) -  00000000

         5 - mem[zzz0000] -  xxxxxxxx

         2 - A(REG[ 0]) -  00000000, B(REG[ 0]) -  00000000

         3 - A(REG[ 4]) -  00000000, B(REG[ 5]) -  00000000
         3 - REG[ 5] <- 00000001
        30 - mem[zzz0001] -  00000001

         4 - A(REG[ 5]) -  00000001, B(REG[ 4]) -  00000000
         4 - REG[ 4] <- 00000002
        40 - mem[zzz0002] -  00000002

        40 - mem[zzz0003] -  00000003

         5 - A(REG[ 4]) -  00000002, B(REG[ 5]) -  00000001
         5 - REG[ 6] <- 00000003
        50 - mem[zzz0001] -  00000004

         6 - REG[ 6] <- 00000001
        60 - mem[zzz0003] -  00000002

         7 - A(REG[ 4]) -  00000002, B(REG[ 5]) -  00000001

         7 - REG[ 6] <- 00000003
        70 - mem[zzz0000] -  00000004

         8 - A(REG[ 4]) -  00000002, B(REG[ 5]) -  00000001

         8 - REG[ 6] <- 00000000
        80 - mem[zzz0003] -  00000001

         9 - A(REG[ 4]) -  00000002, B(REG[ 5]) -  00000001

         9 - REG[ 6] <- 00000003
        90 - mem[zzzfffe] -  00000004

        10 - A(REG[ 4]) -  00000002, B(REG[ 5]) -  00000001

        10 - REG[ 6] <- fffffffe
       100 - mem[zzzfffd] -  xxxxxxxx

        11 - A(REG[ 4]) -  00000002, B(REG[ 5]) -  00000001
        11 - REG[ 6] <- fffffffd
       110 - mem[zzzfffe] -  xxxxxxxx

        12 - A(REG[ 4]) -  00000002, B(REG[ 5]) -  00000001

        12 - REG[ 6] <- fffffffe
```

มาจากไฟล์ data.list (มีนำไปเอาแรมที่ตำแหน่งที่ 0 มา)

memory address

ค่าในแรมที่ 1 จาก data.list

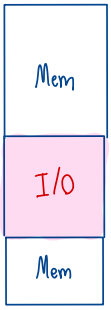
opcode RS RT RD Reserved

```
#10 p_data = 32'b011000_00100_00101_00000_00000000000; // LW $r5, 0($r4) = 1
#10 p_data = 32'b011000_00101_00100_00000_00000000000; // LW $r4, 0($r5) = 2

#10 p_data = 32'b000001_00100_00101_00110_00000000000; // ADD $r6, $r5, $r4
#10 p_data = 32'b000001_00100_00101_00110_00000000001; // SUB $r6, $r5, $r4
#10 p_data = 32'b000001_00100_00101_00110_00000000010; // OR $r6, $r5, $r4
#10 p_data = 32'b000001_00100_00101_00110_00000000011; // AND $r6, $r5, $r4
#10 p_data = 32'b000001_00100_00101_00110_00000000100; // XOR $r6, $r5, $r4
#10 p_data = 32'b000001_00100_00101_00110_00000000101; // -A $r6, $r5, $r4
#10 p_data = 32'b000001_00100_00101_00110_00000000110; // NOT A $r6, $r5, $r4
#10 p_data = 32'b000001_00100_00101_00110_00000000111; // NOT B $r6, $r5, $r4
```

ต้องลองดูว่าทำอะไร

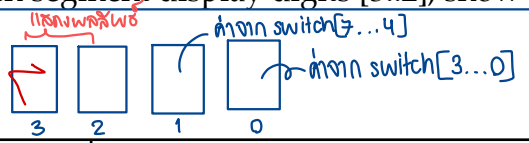
Use the simulator to validate your extended CPU.

3. Use the knowledge from memory-mapped I/O to map the following devices to associated addresses. (You have to add a few registers and buffers to the associated address.) Note that you have to take away memory from those addresses.



Address	Device	Note
0xFFF0	4-bit register for driving Seven-segment display digit 0.	Use last 4 bits
0xFFF4	4-bit register for driving Seven-segment display digit 1.	Use last 4 bits
0xFFF8	4-bit register for driving Seven-segment display digit 2.	Use last 4 bits
0xFFFC	4-bit register for driving Seven-segment display digit 3.	Use last 4 bits
0xFFE0	4-bit buffer for reading Switch [3..0] (A)	Use last 4 bits
0xFFE4	4-bit buffer for reading Switch [7..4] (B)	Use last 4 bits
0xFFE8	4-bit buffer for reading Switch [11..8] (Op)	Use last 4 bits

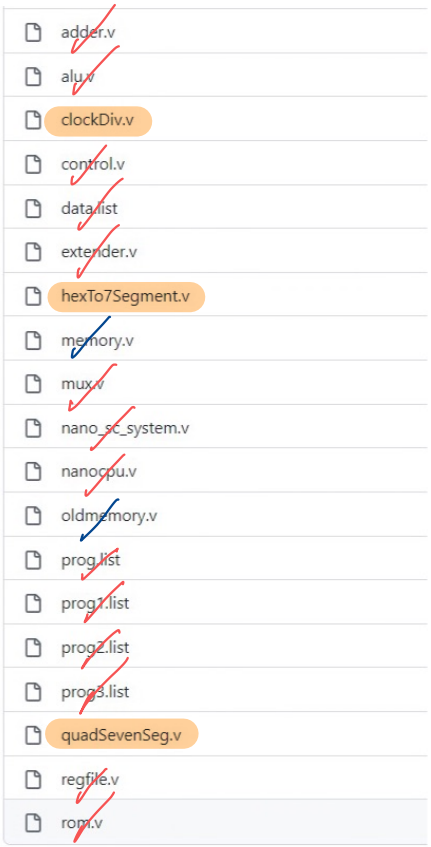
Write a simple software to your ROM to repeatedly read from switches. Display the value of switch [3..0] to seven-segment display digit 0. Display the value of switch [7..4] to seven-segment display digit 1. For seven segment display digits [3..2], show the result from the following operations.



Switches [10..8] (Op)	**Seven segment display [3..2]**
000	Show A+B

001	Show A-B
010	Show A | B
011	Show A&B
100	Show A^B
101	Show ~A (not A)
110	Show -A
111	Show -B

Demonstrate your design in our BASYS 3 FPGA board.



Laboratory 6: VGA and UART

(This lab is partly taken from Pitchaya Sitti-Amorn, Ph.D.)

Objectives

1. Understand the asynchronous serial communication
2. Understand how to use FPGA to interface with external devices

Background

One use of the FPGA is to interface with external devices that require precise timing. In this lab, we will be looking at two devices: VGA (Display), and a serial communication (UART).

VGA

VGA protocol is designed when computer monitors still used cathode ray tube (CRT) devices. In those times, most of the controls are actually analog. While FPGA cannot output the analog signal to control the VGA port directly, it can be used with a resistor ladder to create a simple digital to analog signal (DAC) (See VGA Port section of the BASYS3 reference[7]) .

And due to the analog design of the VGA signal, it will also require precise timing. In this lab, you will be interfacing with the VGA and make some adjustments from the given code. You can also get code and more information from embedded thoughts[8].

Note. Please make sure that you understand H-Sync, V-Sync, and related signals. You may find it in a quiz.

UART

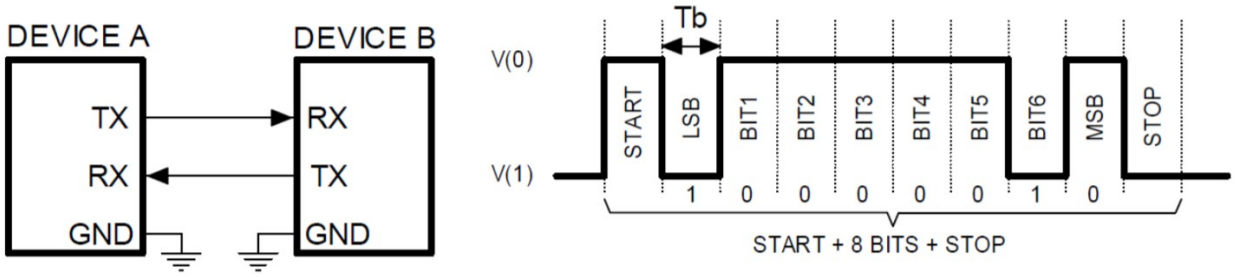
Universal Asynchronous Receiver/transmitter or UART is a computer protocol that enables data transfer between two devices. UARTs are commonly used with the electrical layer standard such as TIA, RS-232, RS-422 or RS-485. The board you have in the lab has a UART port through the USB.

7https://reference.digilentinc.com/basys3/refmanual

8https://embeddedthoughts.com/2016/07/29/driving-a-vga-monitor-using-an-fpga/

The minimal communication requirement by UART uses only two wires, TX and RX. Figure 1 shows a typical UART communication.

In order for a device to send the data out, both devices must use the same clock rate (baud), data bit size, parity and stop bits.
http://www.unm.edu/~zbaker/ece238/slides/UART.pdf provides good details on the protocol.



In order to communicate with the UART on the Basys 3 board, you will need to install some serial communication software such as Putty, Tera Term, etc. You can also find more information about the USB-UART Bridge on the Basys 3 in the reference manual.

Exercises

1. VGA: Either modify the example code or rewrite your own code so that the board will display gradients between two colors set by the switches. The gradient can be changed back and forth between horizontal to vertical via a push-button.
2. UART: You will implement a simple program that receives UART inputs, add one to each input character, then returns to the UART. If you test this with a console. For example, if you type "***abcde***" in the console, you should receive "***bcdef***".

   You may choose any baud rate you would like to use. I recommend testing with 9600bps or 115200bps. You may also want to test the loopback, i.e. wiring TX and RX together.

Note: You might need terminal software to connect your computer to BASYS3. On Linux (and Mac OS X), try minicom or screen. On Windows, try RealTerm[9], TerraTerm, or PuTTY.

9https://sourceforge.net/projects/realterm/