Welcome to The Hardware Design & Lab!

Fall 2023
Lab 3: Sequential Circuits

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Agenda

- Lab 3 Outline
- Lab 3 Basic Questions
- Lab 3 Advanced Questions

Lab 3 Outline

- Basic questions (1.5%)
  - Individual assignment
  - Due on 10/19/2023. In class.
  - Only demonstration is necessary. Nothing to submit.

- Advanced questions (5%)
  - Individual assignment
  - EEClass submission due on 10/26/2023. 23:59:59.
  - Demonstration on your FPGA board (In class)
  - Assignment submission (Submit to eeclass)
    - Source codes and testbenches
    - Lab report in PDF

Lab 3 Rules

- Please note that grading will be based on **NCVerilog**
- You can use **ANY** modeling techniques

- If not specifically mentioned, we assume the following SPEC
  - **clk** is **positive edge triggered**
  - Synchronously reset the Flip-Flops when **rst_n == 1'b0, if there exists one rst_n signal in the specification**

Lab 3 Submission Requirements

- Source codes and testbenches
  - Please follow the templates EXACTLY
  - We will test your codes by TAs' testbenches

- Lab 3 report
  - Please submit your report in a single PDF file
  - Please draw the block diagrams of your designs using software
  - Please explain your designs in detail
  - Please explain how you test your design
  - What you have learned from Lab 3

Agenda

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- Lab 3 Advanced Questions

Basic Questions

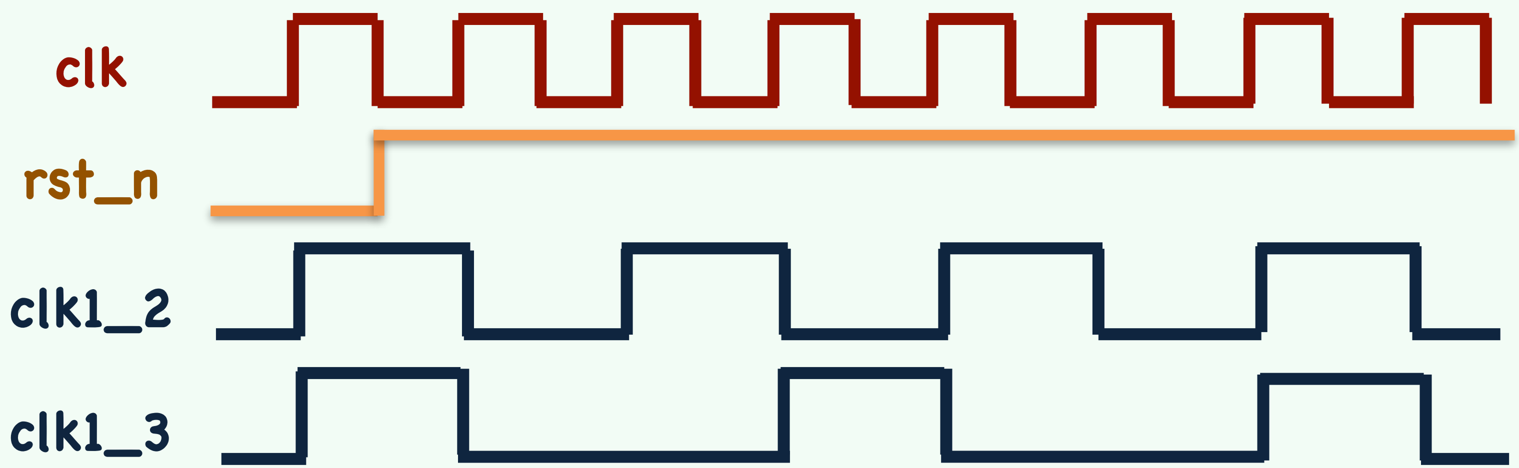
- Individual assignment

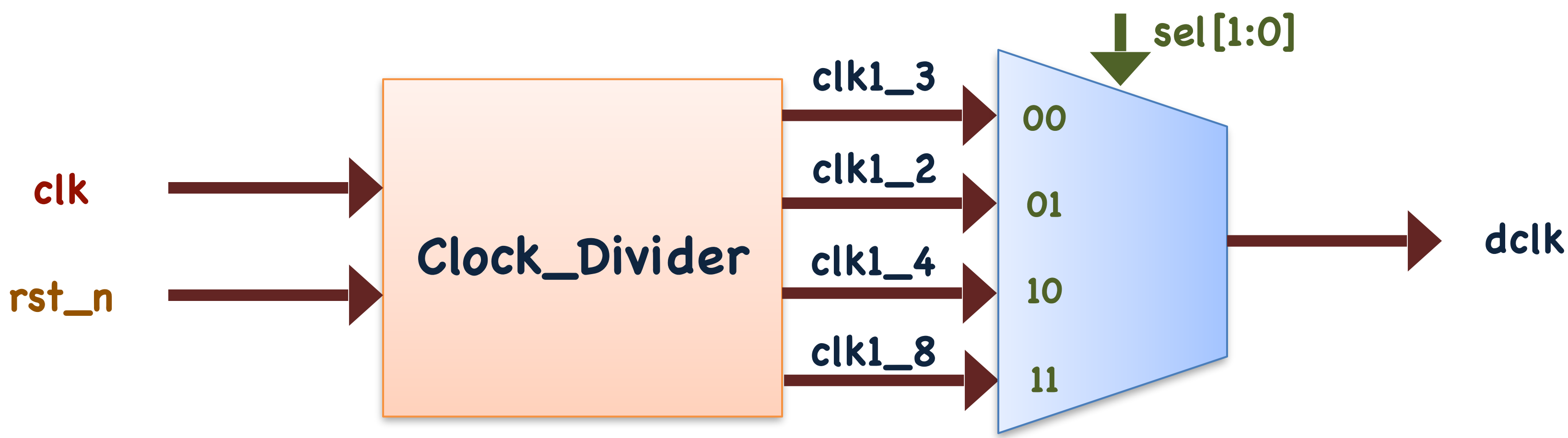
- Verilog questions (due on 10/19/2023. In class.)
  - Clock Divider
  - 128 x 8 Memory Array

- Demonstrate your work by waveforms

Verilog Basic Question 1

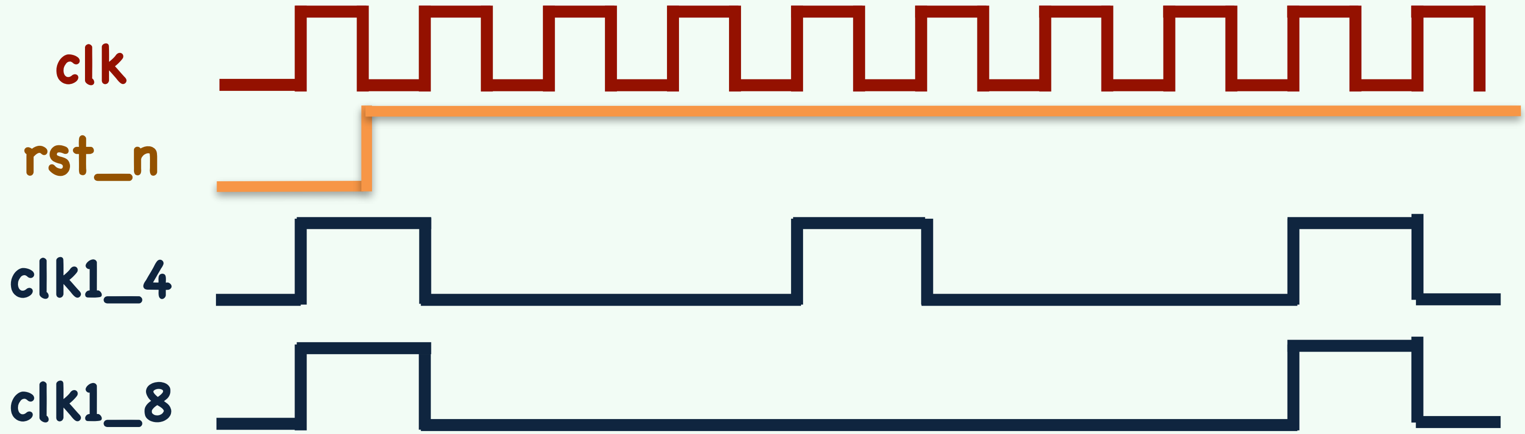
- Clock Divider
  - **sel[1:0]** and the mux are combinational, not triggered by **clk**
  - Outputs: **clk1_2, clk1_3, clk_1_4, clk1_8, dclk**

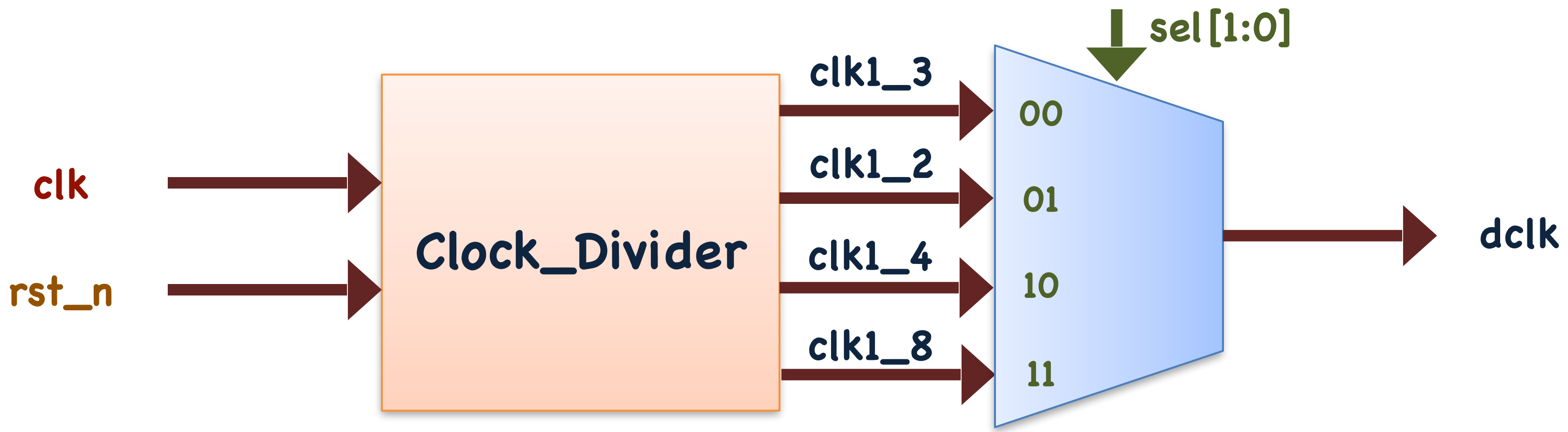




Verilog Basic Question 1(Con't)

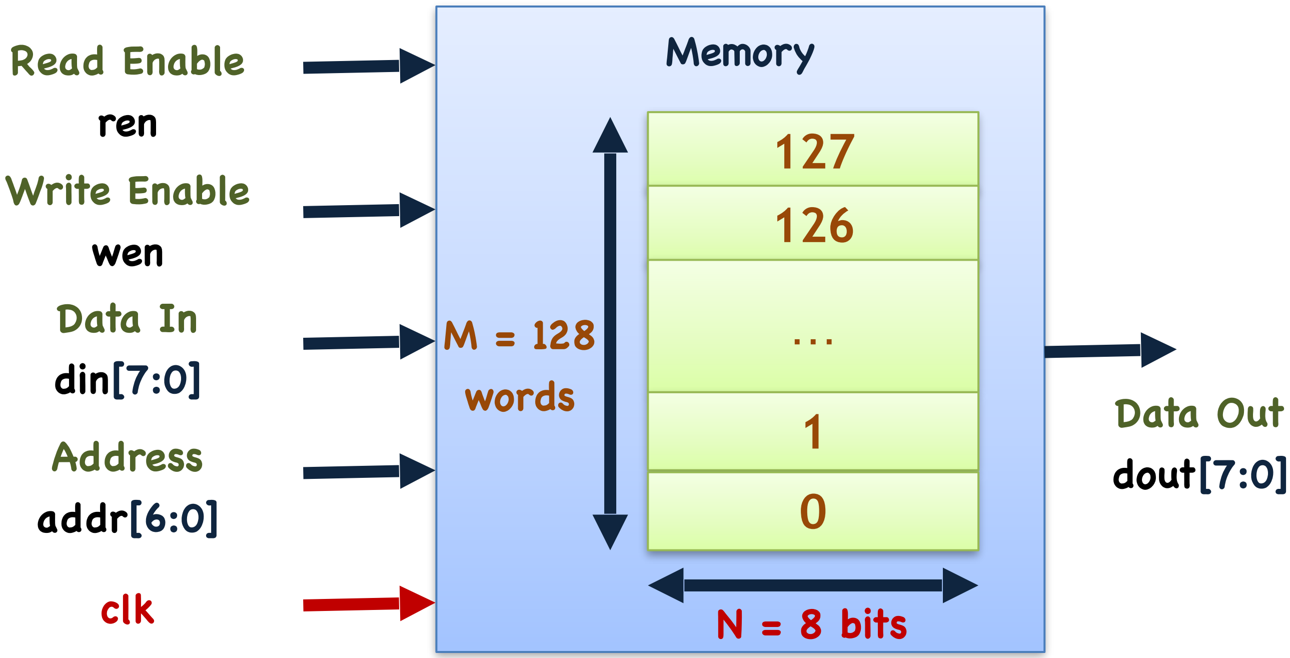
- Clock Divider
  - **sel[1:0]** and the mux are combinational, not triggered by **clk**
  - When **rst_n** == 1'b0, all signals out the clock divider are **one**
  - Outputs: **clk1_2, clk1_3, clk1_4, clk1_8, dclk**





Verilog Basic Question 2

- 128 x 8 Memory Array **Memory**
- M = 128, N = 8
  - Inputs: **clk, ren, wen, addr[6:0], din[7:0]**
  - Outputs: **dout[7:0]**



Note: Memory Array in Verilog

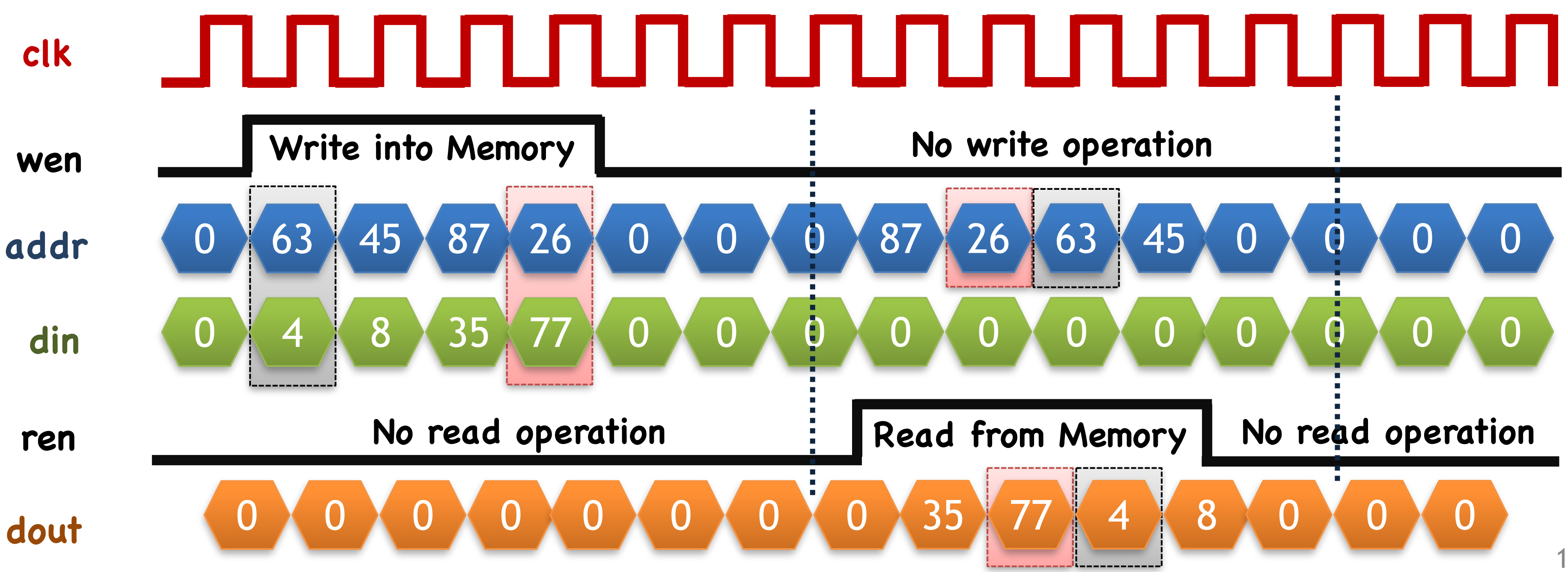
- A collection of registers in Verilog to mimic memory arrays
  - In reality, it is **NOT** made from registers
  - Real memory is made from SRAMs or DRAMs

- Declaration
  - Similar to regular reg arrays
  - **reg** [$\underbrace{\textbf{N-1:0}}_{\text{N bits per word}}$] **Your_Memory** [$\underbrace{\textbf{M-1:0}}_{\text{M words}}$];

- Access
  - Use your address register **ADDR**
  - E.g., One_word[**N-1:0**] = **Your_Memory**[**ADDR**]
  - If your **M** is **256**, you only need **8 bits** for **ADDR** (**2^8 = 256**)

Verilog Basic Question 2 (Con't)

- Specification
  - When **wen** == 1'b1, write **din** to **Memory**[**addr**]
  - When **ren** == 1'b1, output **Memory**[**addr**] to **dout**; otherwise **dout** = 8'd0
  - **If both are 1, do only the read operation**
  - **Memory** does not need to be reset



Agenda

- Lab 3 Outline
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- Lab 3 Advanced Questions

Advanced Questions

- Individual assignment

- Verilog questions (due on 10/26/2023. 23:59:59.)
  - Optional: 4-bit Ping-Pong Counter
  - Optional: First-In First Out (FIFO) Queue
  - Optional: Multi-Bank Memory
  - Necessary: Round-Robin FIFO Arbiter
  - Necessary: 4-bit Paramterized Ping-Pong Counter

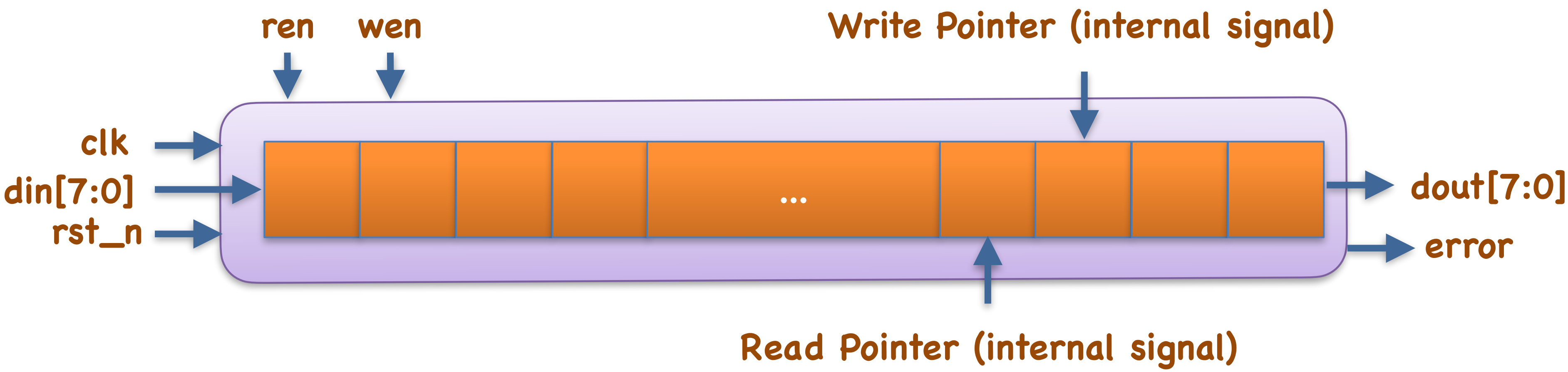
- FPGA demonstration (due on 10/26/2023. In class.)
  - Necessary: 4-bit Paramterized Ping-Pong Counter on FPGA

Verilog Advanced Question 1

- Design a 4-bit Ping-Pong Counter
  - **out:** 0,1,2,...,13,14,15,14,13,...,2,1,0,1,2,...
  - **direction:** 1,1,1,.....,1, 1, 1, 0, 0,..., 0,0,0,1,1,...
- SPEC
  - When **rst_n == 1'b0**, the counter resets its value to 4'b0000, and the **direction** to 1'b1
  - When **enable == 1'b1**, the counter begins its operation. Otherwise, the counter holds its current value

Verilog Advanced Question 2

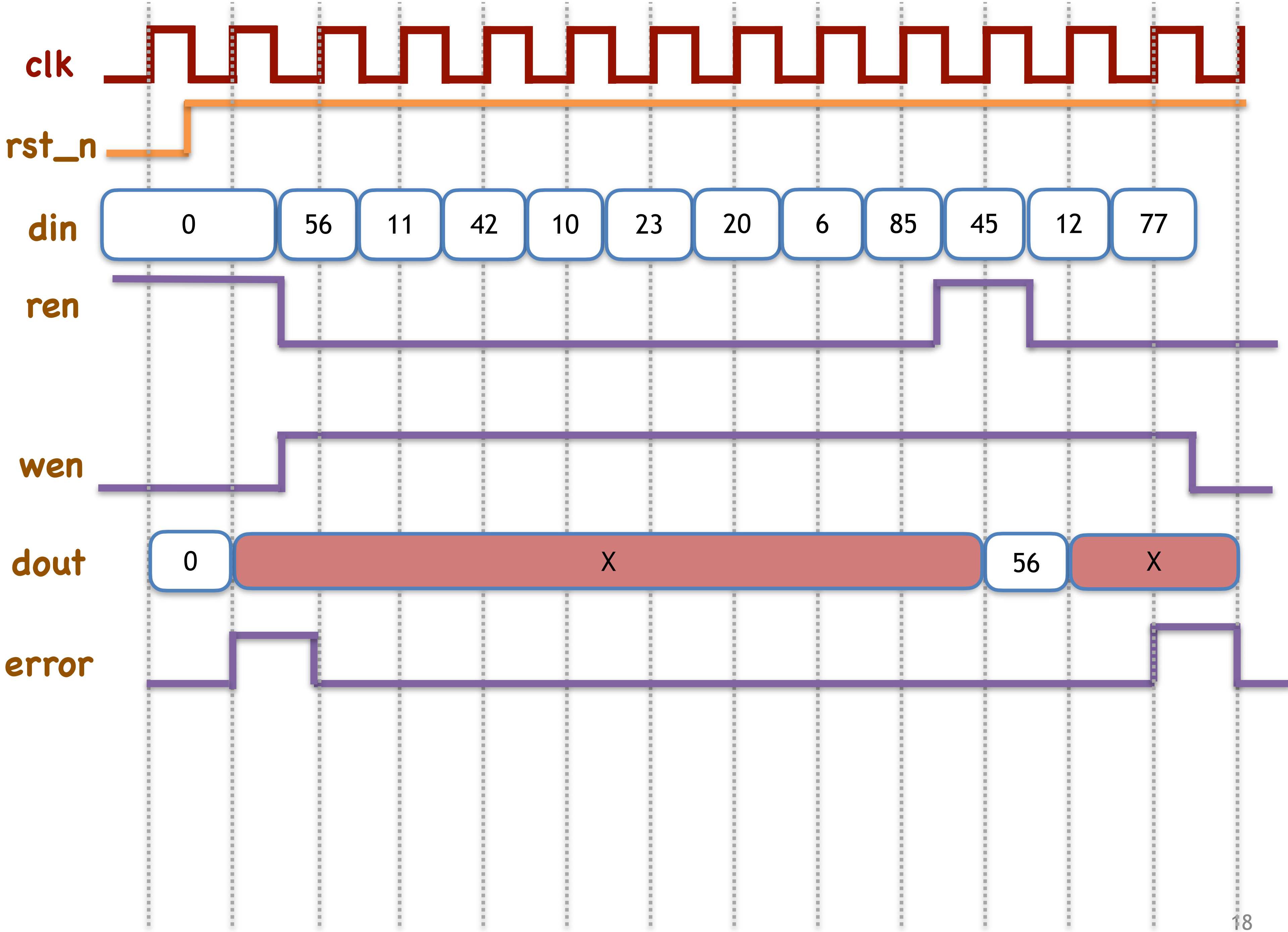
- First-In First Out (FIFO) Queue



- Design a circular FIFO that stores eight entries of 8-bit data
- The order of the read should follow the FIFO pattern, in which the first data written would be read out first
- The behavior of the FIFO
  - By setting **ren=1'b1**, the FIFO should output the oldest data to **dout** . On the other hand, if **wen=1'b1**, the value of **din** signal is written into the FIFO. If both **ren** and **wen** are set to **1'b1**, **only the read operation is performed**
  - The FIFO should be able to be written when ren=1'b0 **unless it is full**, and should be able to be read **unless it is empty**

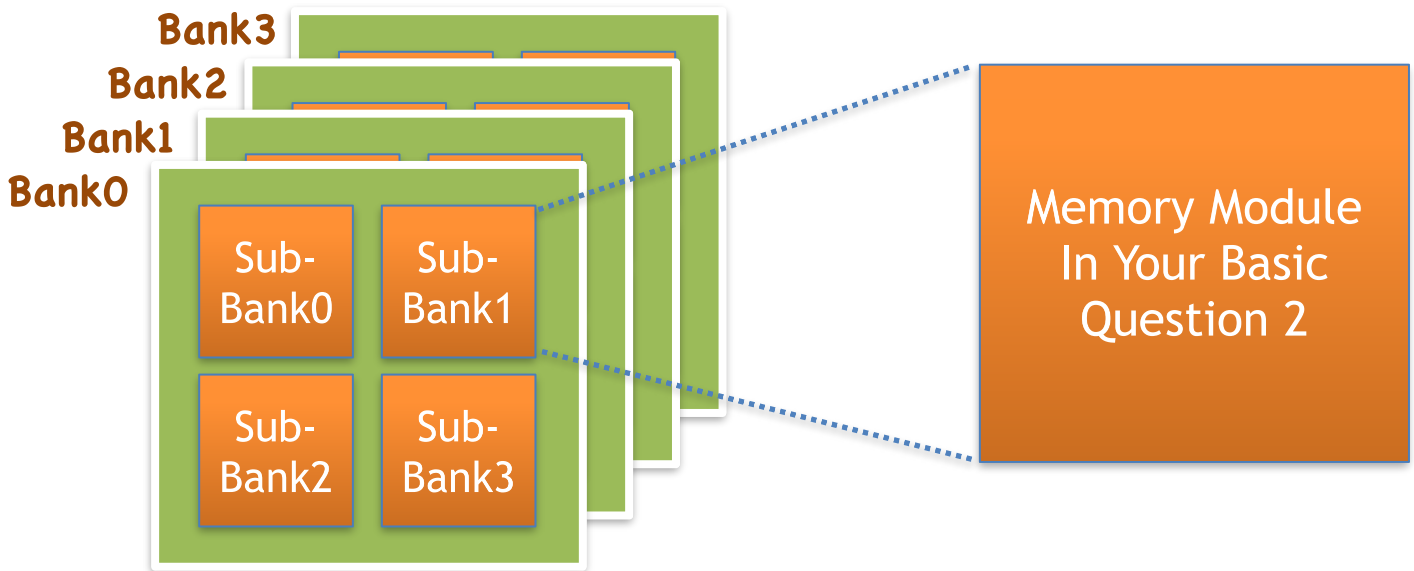
Verilog Advanced Question 2 (Con't)

- Error condition
  - If a **read / write** is issued to an **empty** / a **full** FIFO, the **error** bit should be set to **1'b1**. Otherwise, the **read** / **write** is valid and the **error** bit should be set to **1'b0**
- The values of **dout**
  - If there's an error, we do not care about the value of **dout**
  - If the FIFO is performing a write operation, we also do not care about the value of **dout**
  - If both **ren** and **wen** are zero, we also do not care about the value of **dout**
- If **rst_n** == 1'b0, empty the FIFO, and set both **dout** and **error** to **zero**
- Please note that the values of **dout** and **error** should change synchronously, i.e., **their values should only change at the positive edges of clk**
- Please refer to the next slides for example waveform


clk
rst_n
din
0
56
11
42
10
23
20
6
85
45
12
77
ren
wen
dout
0
X
56
X
error

Verilog Advanced Question 3

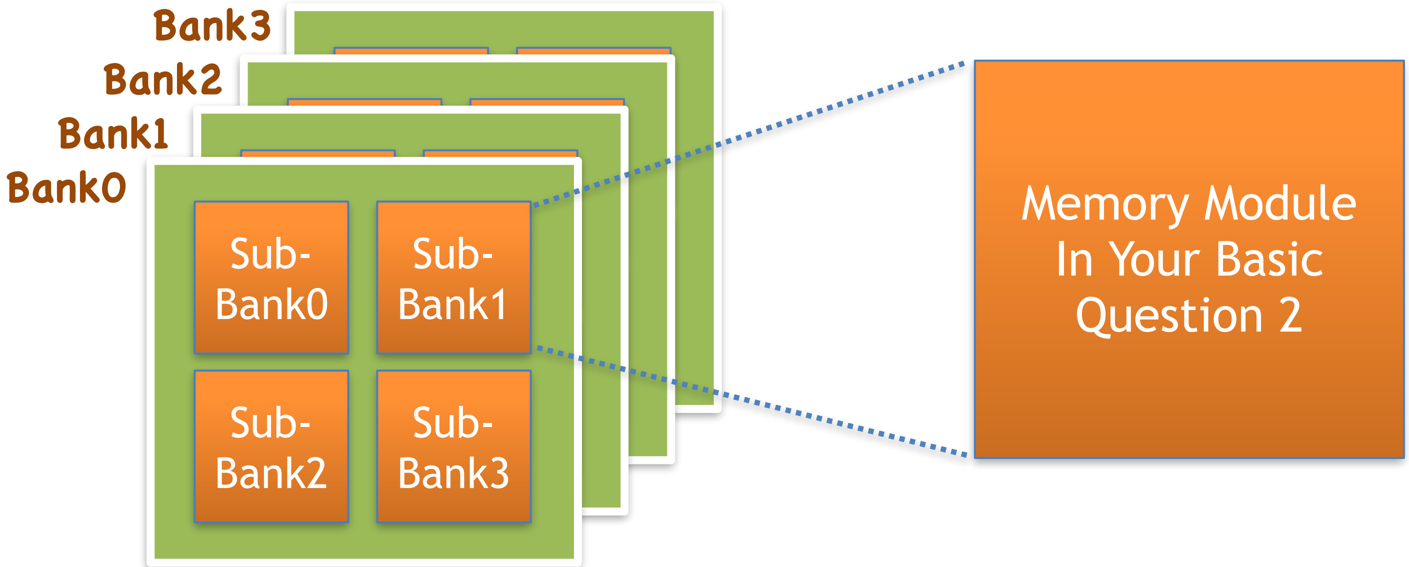
- Multi-Bank Memory



- Design a memory hierarchy containing **4** banks of memory. Each bank consists of **4** sub-bank memory modules. (A total of **16** sub-banks)
- Points will be deducted if the specified hierarchy is not followed
- Please reuse the module from **Basic Question 2** for each sub-bank
- Input: **clk**, **ren**, **wen**, **raddr[10:0]**, **waddr[10:0]**, **din[7:0]**
- Output: **dout[7:0]**

Verilog Advanced Question 3 (Con't)

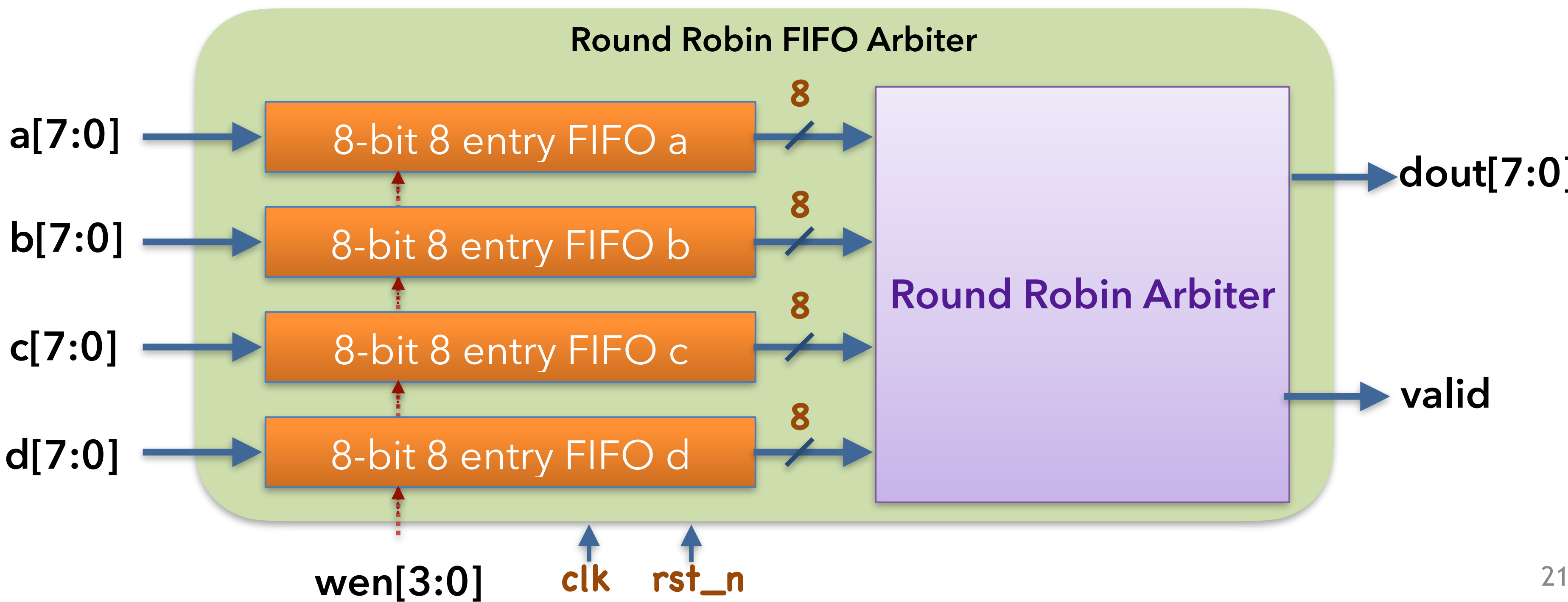
- Multi-Bank Memory



- The most significant four bits of **raddr** (i.e. **raddr[10:7]**, read address) and **waddr** (i.e. **waddr[10:7]**, write address) address different sub-banks of different banks. For example, waddr[10:7] == 4'b0110 addresses bank1's (01) sub-bank2 (10)
- When **wen** == **1'b1**, write **din** to **Memory**[**addr**]
- When **ren** == **1'b1**, output **Memory**[**addr**] to **dout**; otherwise **dout** = **8'd0**
- When both **wen** and **ren** are **1'b1**, they can be serviced simultaneously if they are directed for **different sub-banks**. Otherwise, only read request is serviced

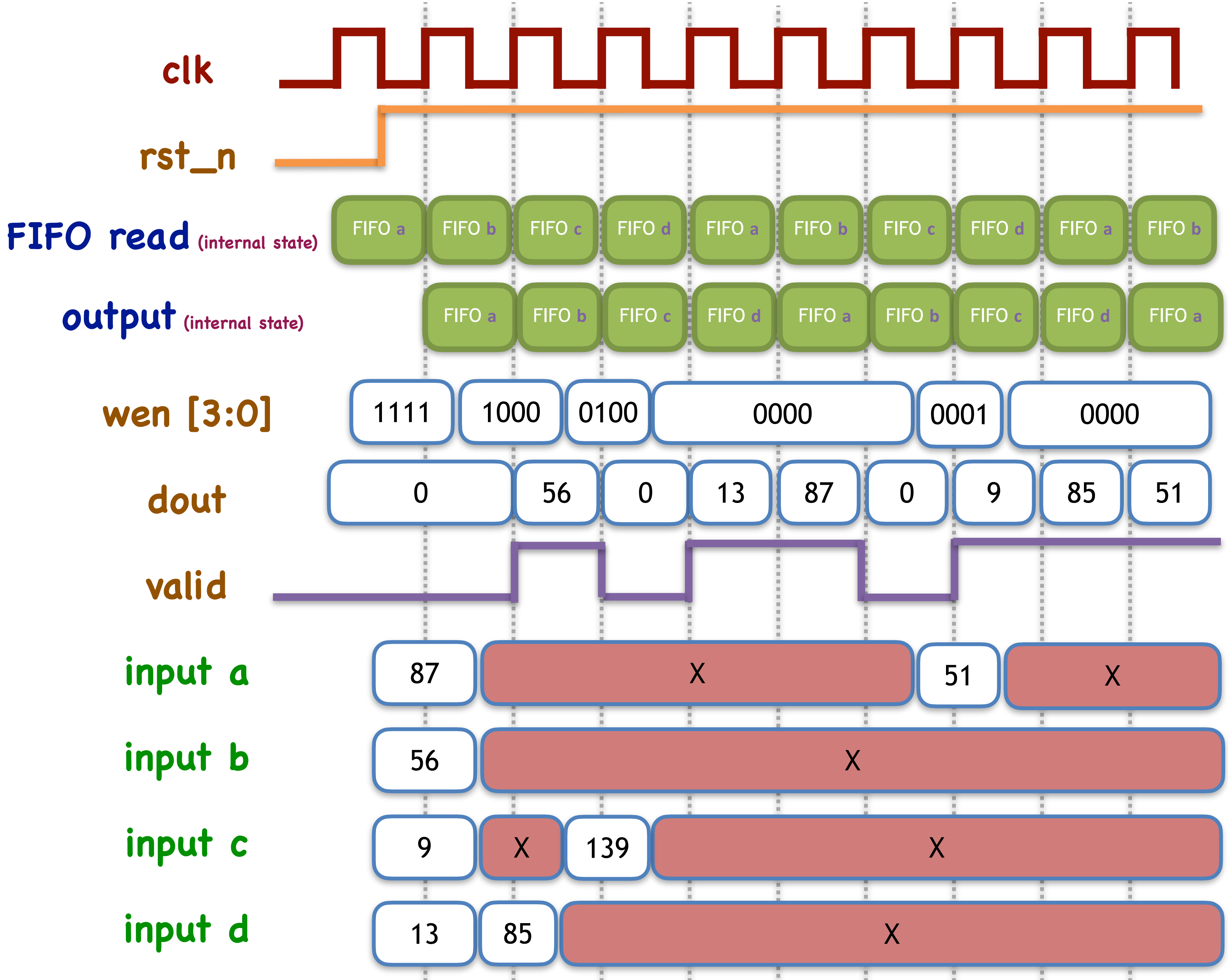
Verilog Advanced Question 4

- Design a **Round-Robin FIFO Arbiter** based on **Advanced Q2**
  - Input: **clk, rst_n, wen[3:0], a[7:0], b[7:0], c[7:0], d[7:0]**
  - output: **valid, dout[7:0]**
- Four FIFOs in advanced question Q2 are connected to a round robin arbiter, which controls their **ren** signals to make them output their contents via **dout** in a round robin fashion.



Verilog Advanced Question 4 (Con't)

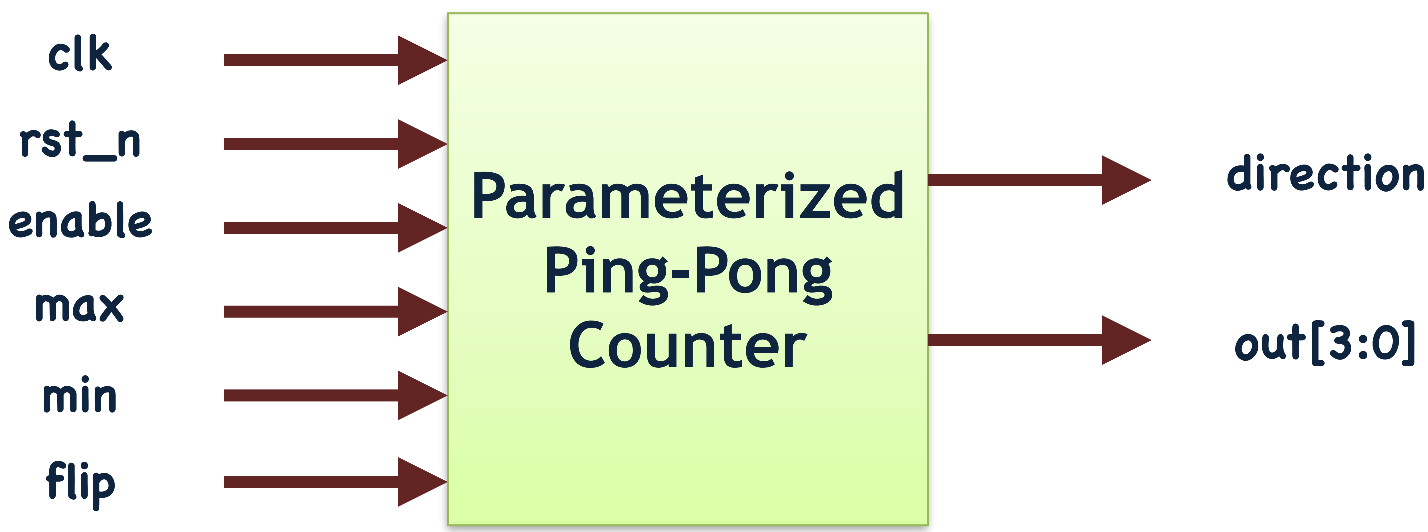
- Each FIFO is written independently by setting the corresponding bit in **wen** to **1'b1,** e.g., setting **wen** to 4'b0001 will write **a** to FIFO a, 4'b1001 will write **d** to FIFO d and **a** to FIFO a
- The input data of FIFOs a, b, c, and d are supplied via input ports **a**, **b**, **c**, and **d**, respectively
- However, if the FIFO that is being accessed by the arbiter is also being written or its **error** signal is **1'b1**, the access is considered invalid. In such a situation, the **valid** and the **dout** signal should be set to **1'b0** and **no data is read out from the FIFO**. Otherwise, the read access is valid and **valid** should be set to **1'b1**.
- Please note that the values of **dout** and **valid** should change synchronously, i.e., **their values should only change at the positive edges of clk.**
- Please refer to the next slide for a sample waveform.



clk
rst_n
FIFO read (internal state)
FIFO a
FIFO b
FIFO c
FIFO d
FIFO a
FIFO b
FIFO c
FIFO d
FIFO a
FIFO b
output (internal state)
FIFO a
FIFO b
FIFO c
FIFO d
FIFO a
FIFO b
FIFO c
FIFO d
FIFO a
wen [3:0]
1111
1000
0100
0000
0001
0000
dout
0
56
0
13
87
0
9
85
51
valid
input a
87
X
51
X
input b
56
X
input c
9
X
139
X
input d
13
85
X

Verilog Advanced Question 5

- Design a **4-bit Parameterized Ping-Pong Counter** with **max** and **min**
  - Input: **clk, rst_n, enable, flip, max[3:0], min[3:0]**
  - **out[3:0]**: 0,1,2,…,7,8,9,8,7,…,2,1,0,1,2,…
  - **direction**: 1,1,1,…,1,1,1,0,0,…,0,0,0,1,1,…
  - In the above example, **max** is 9 and **min** is 0



Verilog Advanced Question 5 (Con't)

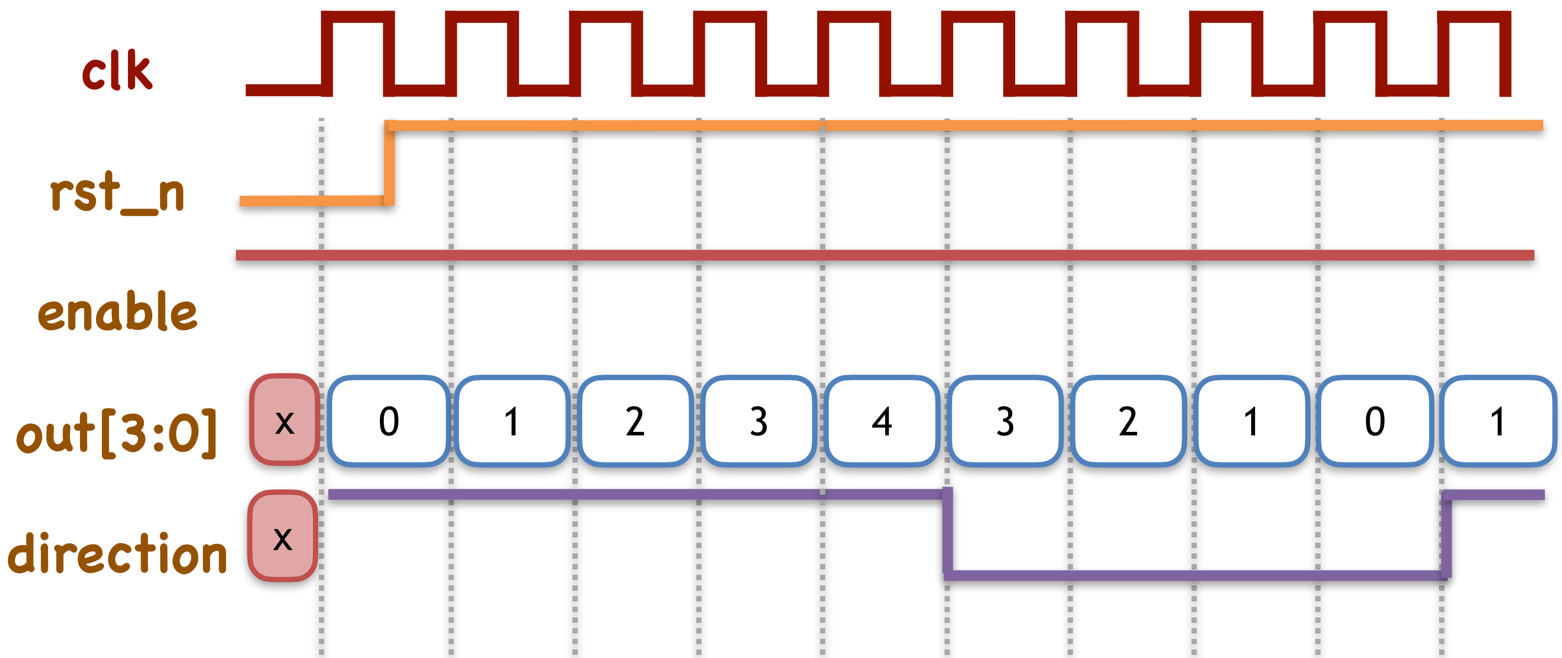
- **rst_n** and **enable**
  - When **rst_n == 1'b0**, resets **out** to **min** and **direction** to **1'b1**
  - When **enable == 1'b1**, the counter begins its operation. Otherwise, the counter holds its current value
- **max** and **min**
  - **max** and **min** values are the maximum and minimum values for the counter
  - **max** > **min**. Otherwise, the counter holds its current value
  - When counter > **max** or counter < **min**, counter holds its current value
- **flip**
  - When **flip** == 1'b1, counter flips its direction
  - Flip occurs when counter < **MAX** and counter > **MIN**

Verilog Advanced Question 5 (Con't)

- **Notes**
  - Be careful that **max** and **min** will change during counting
  - Once the value of the counter is out of range, hold the value and direction
  - If **max** == **min** == **output**, please hold the **output** and **direction**
  - The following slides provide some example waveforms

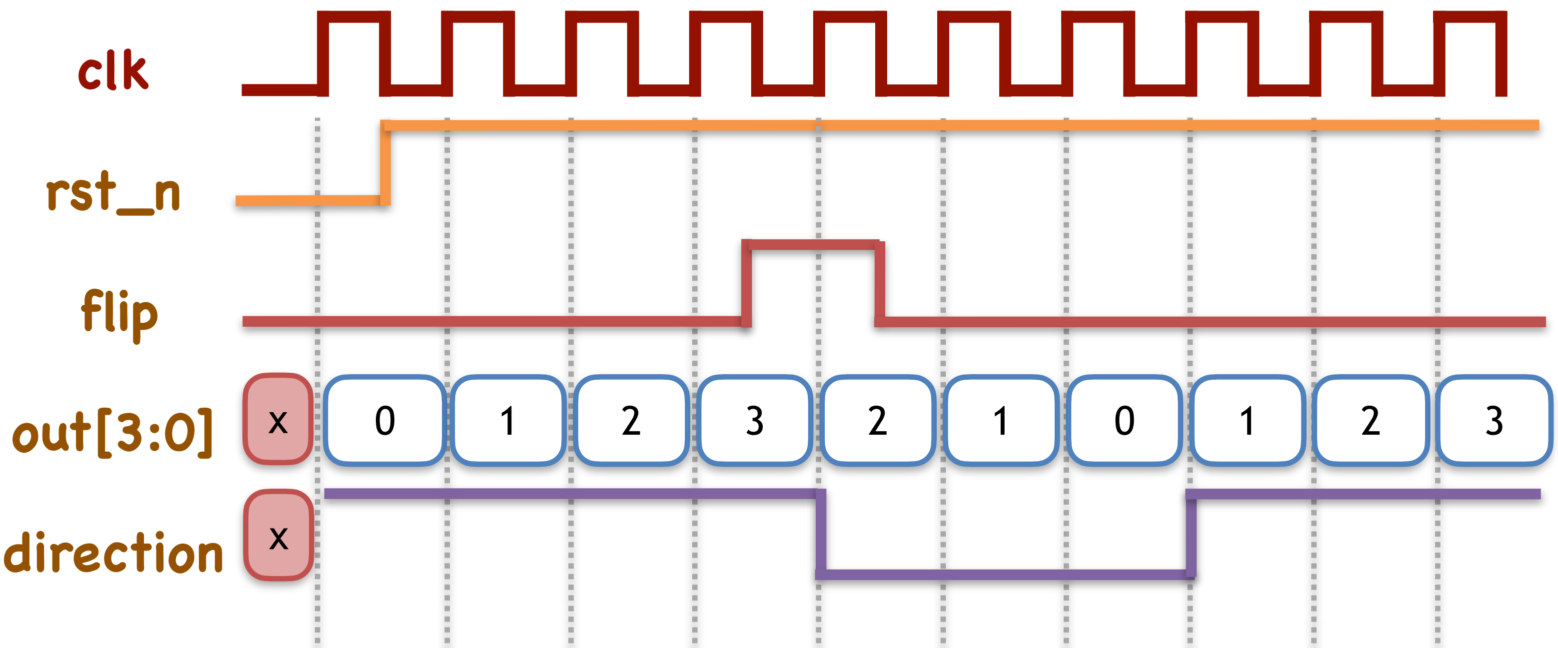
Verilog Advanced Question 5 (Con’t)

- An example waveform where **flip** is set to 1'b0 and **enable** is set to 1'b1
- In this example **min** = 4’d0 and **max** = 4'd4



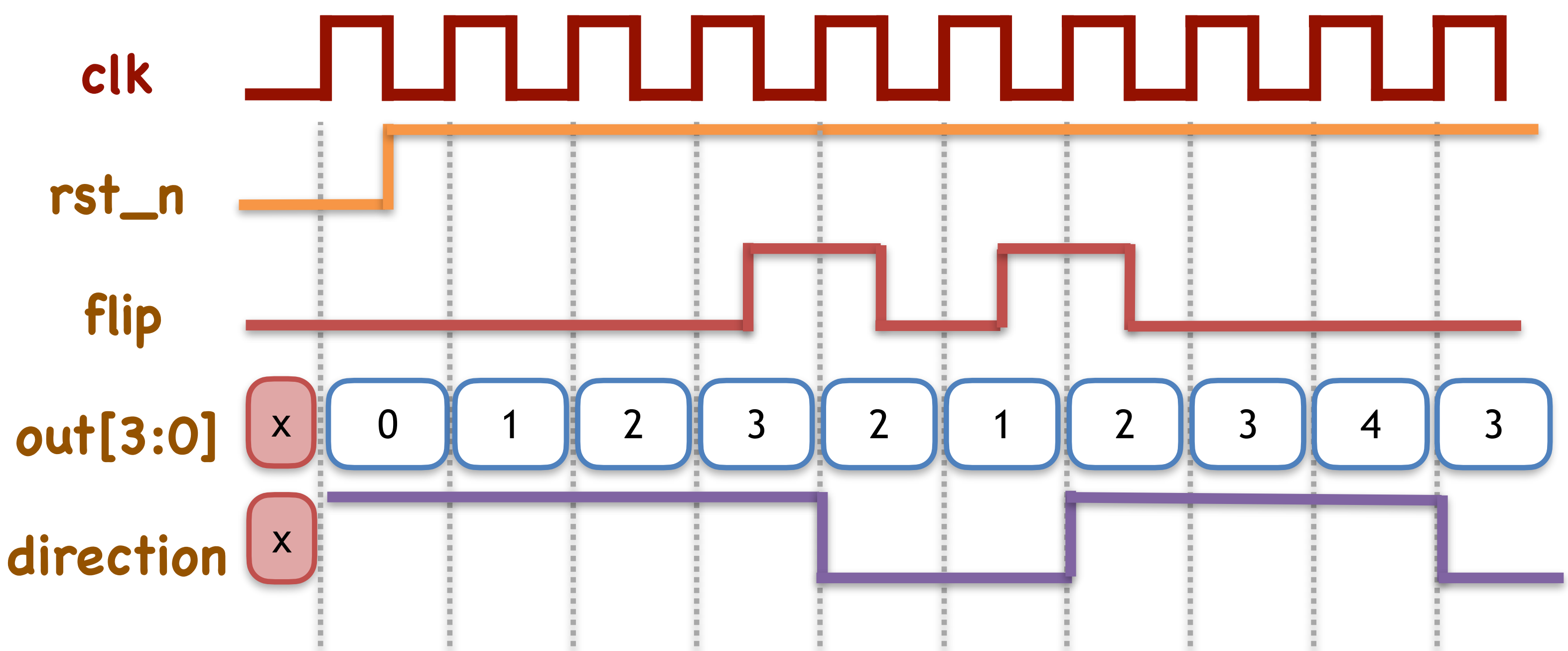
Verilog Advanced Question 5 (Con't)

- An example waveform where there is one **flip** and **enable** is set to 1'b1
- In this example **min** = 4′d0 and **max** = 4'd4



Verilog Advanced Question 5 (Con't)

- An example waveform where there are two **flips** and **enable** is set to 1'b1
- In this example **min** = 4'd0 and **max** = 4'd4



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  - Optional: 4-bit Ping-Pong Counter
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- FPGA demonstration (due on 10/26/2023. In class.)
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FPGA Demonstration 1

- 4-bit Paramterized Ping-Pong Counter on FPGA
- **Behavior specification**
  - In the beginning, the digits showing on the 7-segment display should be the value of **min**
  - Once **enable** is on, the Ping-Pong Counter starts counting
  - When **enable** is off, the Ping-Pong Counter holds its value
  - The Ping-Pong Counter only counts when **max** > **min**
- **Switches**
  - **SW[15]** stands for **enable**
  - **SW[14:11]** stand for **max**
  - **SW[10:7]** stand for **min**

FPGA Demonstration 1

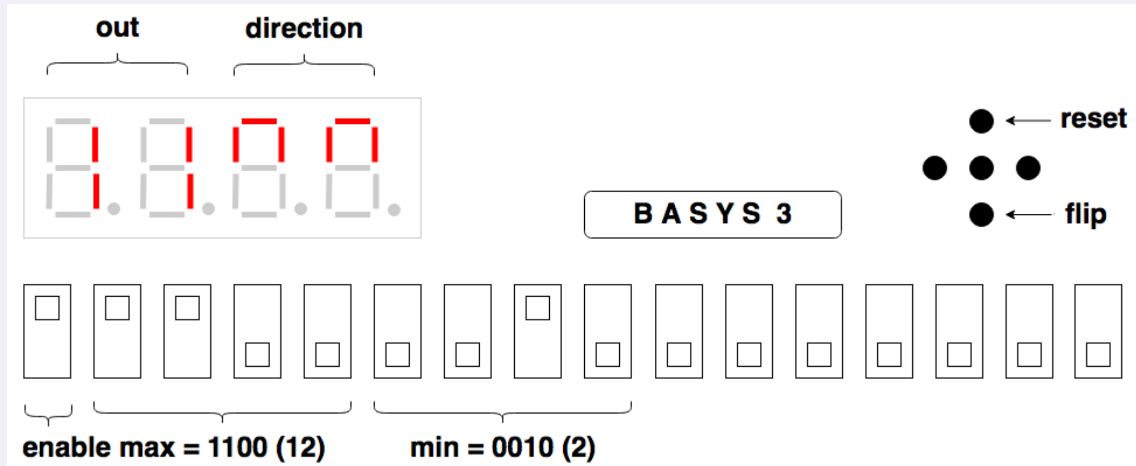
- **Buttons**
  - "**DOWN**" button stands for **flip**
    - Once flip occurs, you should change your direction
    - Flip only occurs when **min** <= output <= **max**
  - “**UP**" button stands for **rst_n**
    - Once the button is pushed, the output is set to the value of **min**, which is determined by **SW[10:7]**
    - The direction is set to “**counting up**"
- **Please present your output signal on the two leftmost 7-segment displays**

FPGA Demonstration 1

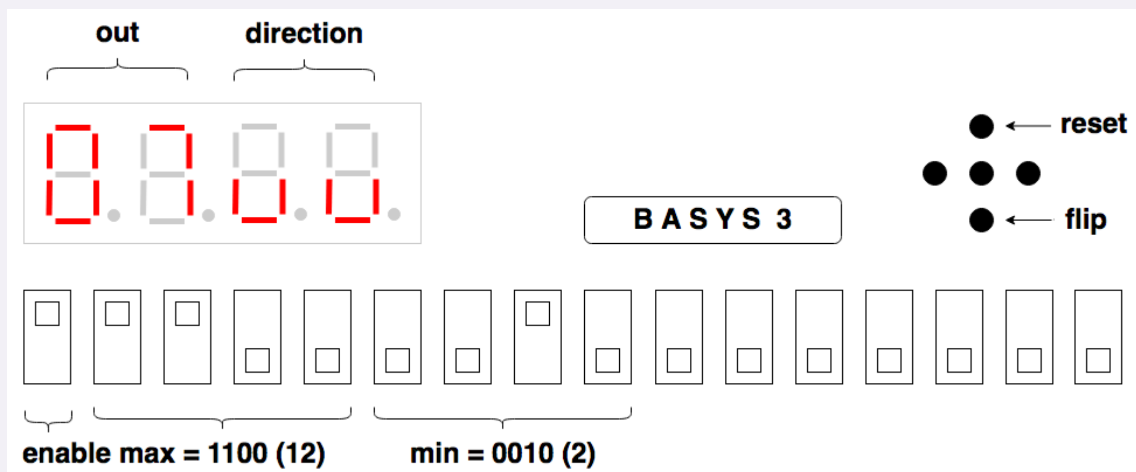
- **7-segment display**
  - The rightmost two digits of the 7-segment displays stand for **direction**
  - Please illuminates the upper three segments when counting up, and illuminates the lower three segments otherwise
  - Please see the figure on the next page for more details

FPGA Demonstration 1

Counting Up



Counting Down



FPGA Demonstration 1

- Notes
  - Be careful that **max** and **min** will change during counting
  - Once the value of the counter is out of range, hold the value and direction
  - If **max** == **min** == **output**, please hold the **output** and **direction**
  - You **MUST** add debounce and one-pulse circuits for your buttons
  - **Remember to add debounce and one-pulse circuits to your design**
  - We use the **100MHz** clock which is provided by the FPGA board. Please set **clk** as input and connect it with the **W5** port on the FPGA board.
  - Your counter should count in an observable frequency so that TAs can tell whether your design is correct or not

Thank you for your attention!

*Balloon Festival at Reno, Nevada, USA
This picture is taken by Chun-Yi Lee himself, who is also a fan of photography