

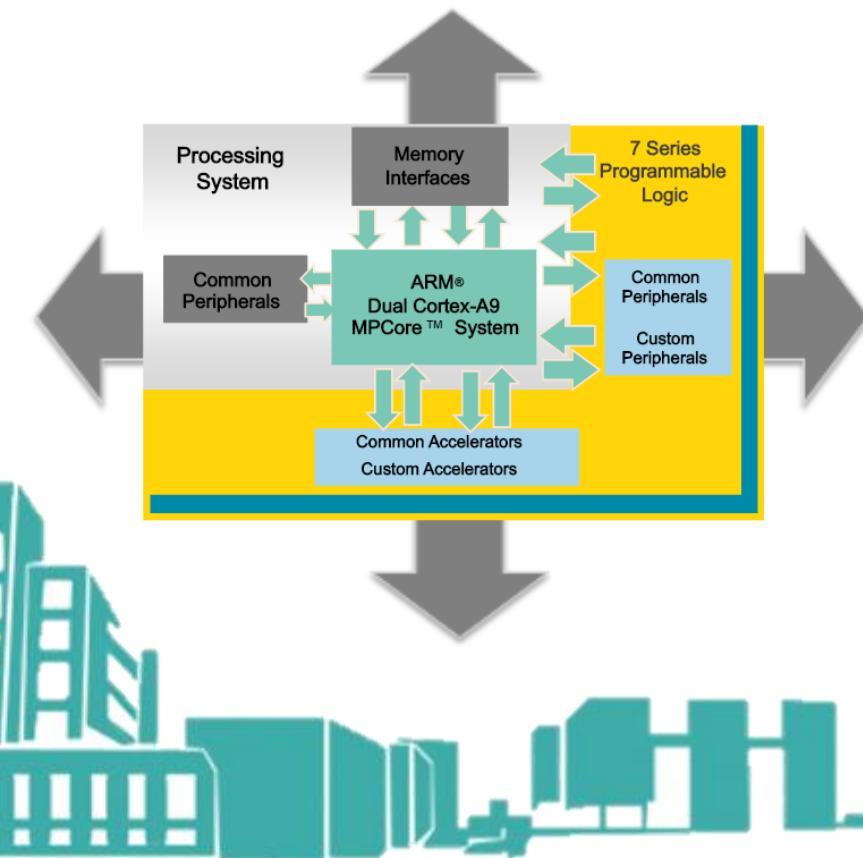
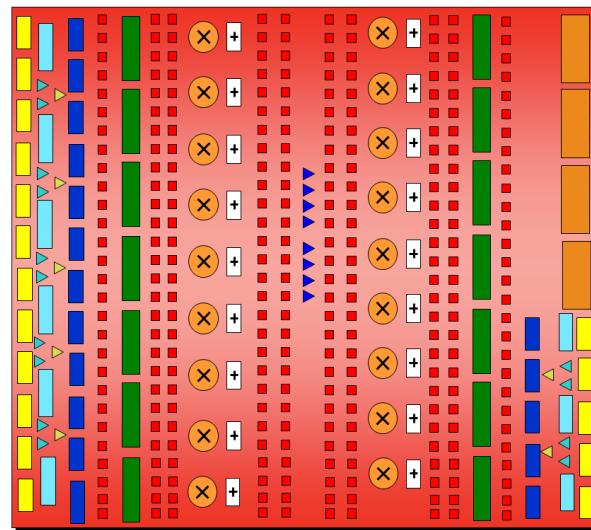


ECE  
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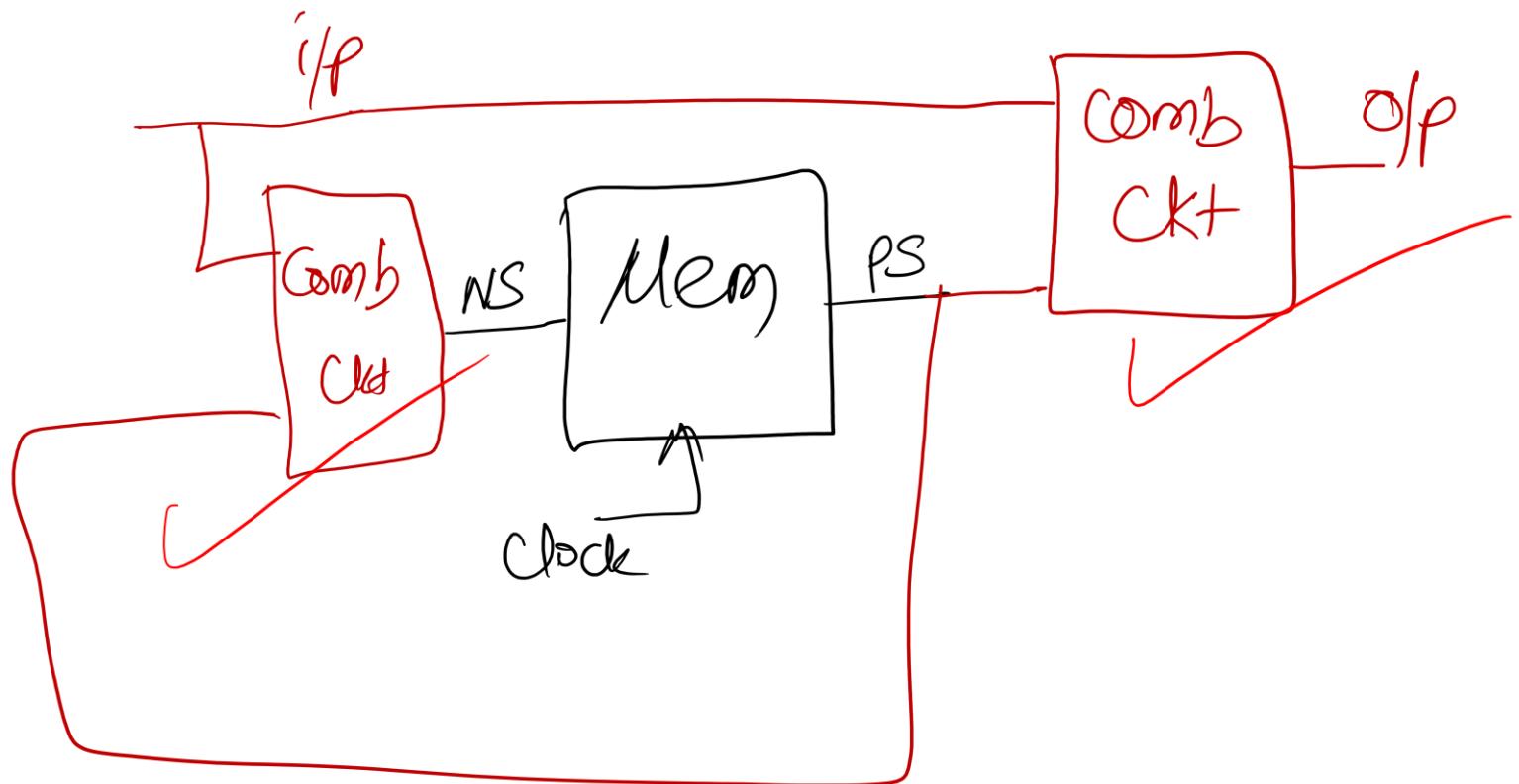
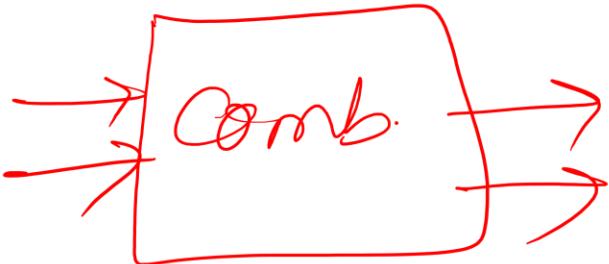
A2A  
*Algorithms to Architecture*

# ECE 270: Embedded Logic Design



# Digital Circuits Revisited!

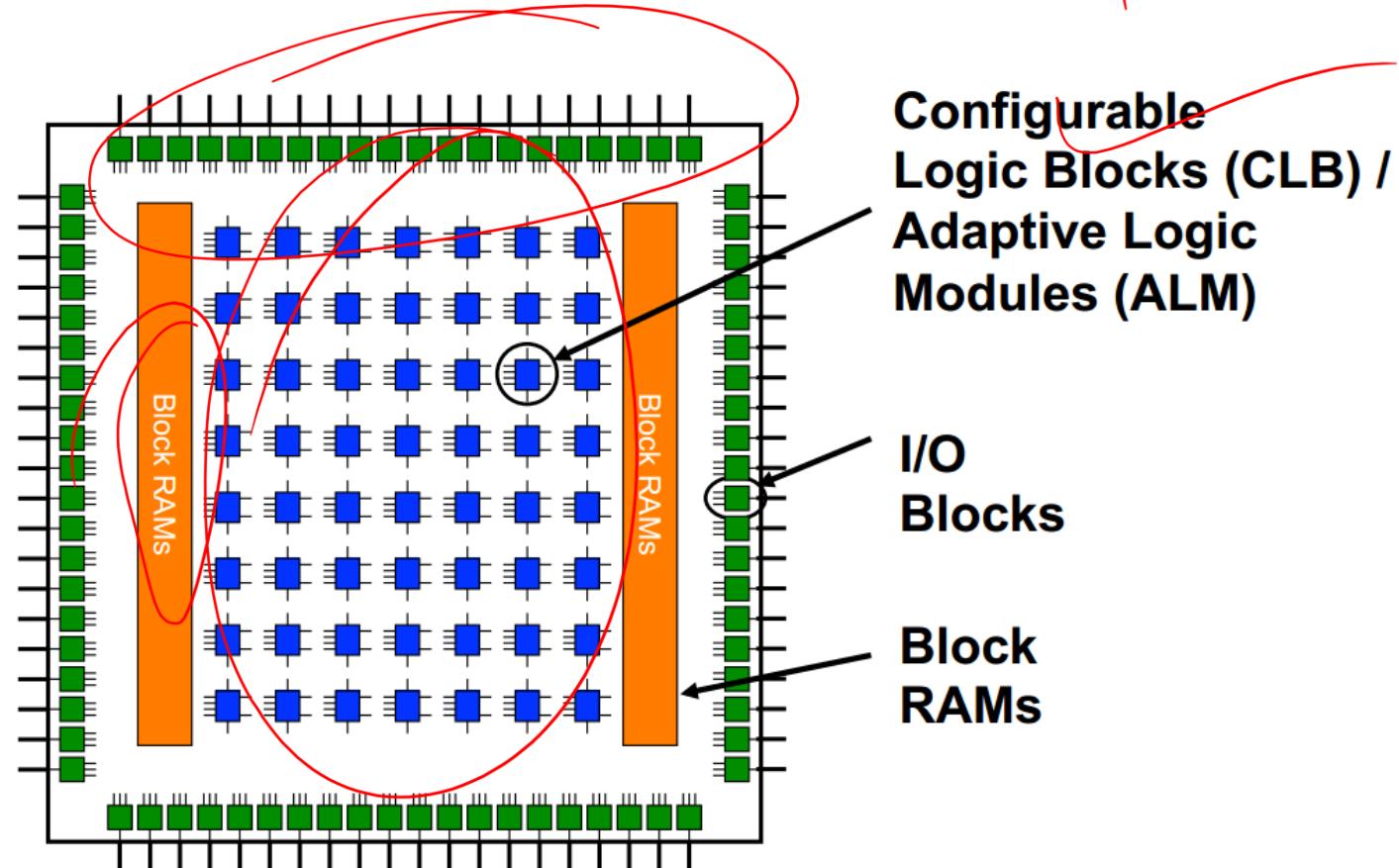
# Combinational vs Sequential Circuits



# FPGA: Field Programmable Gate Array

1984

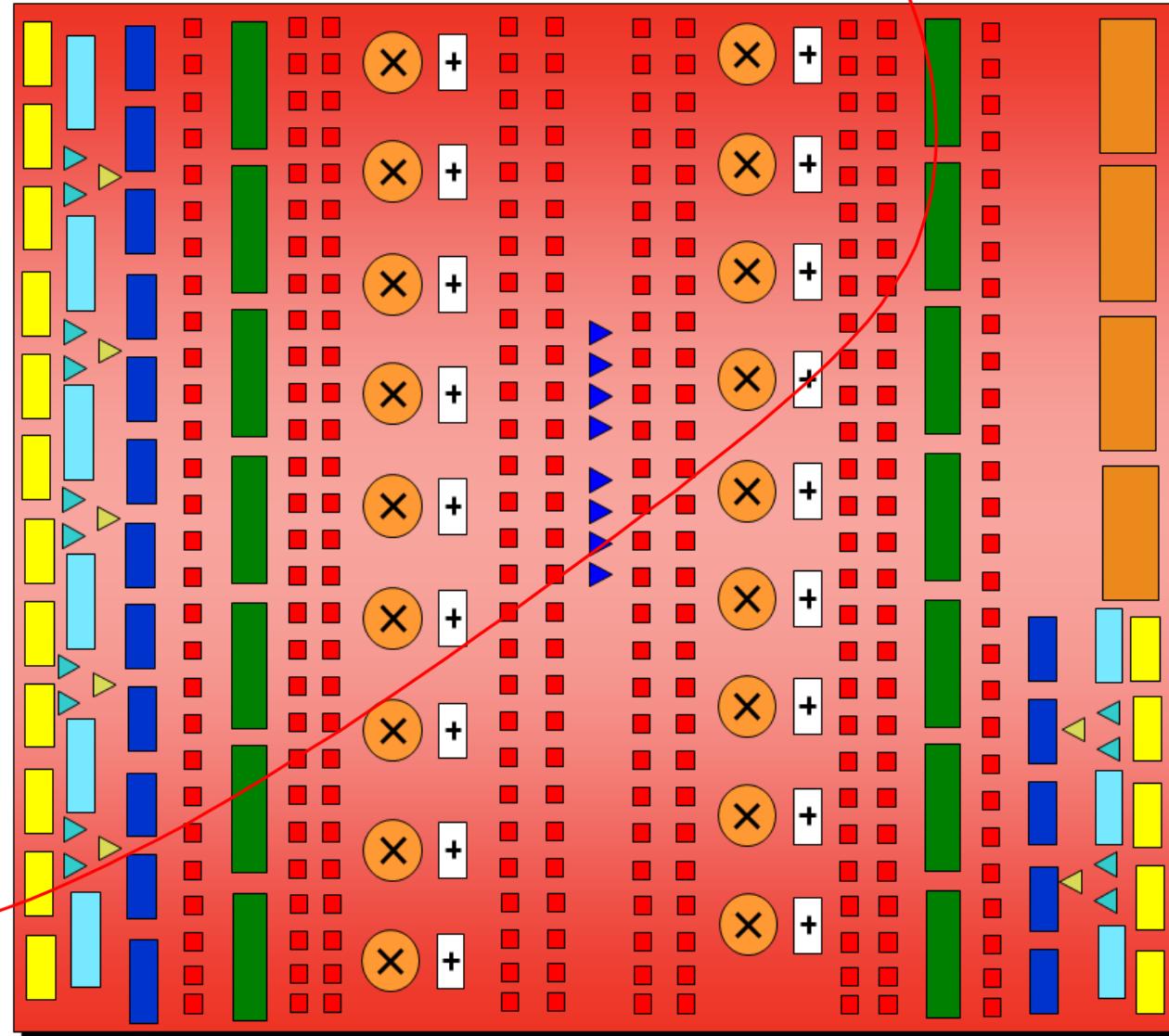
- **Array** of generic logic gates
- **Gates** where logic function can be programmed
- **Programmable** interconnection between gates
- **Field**: System can be reprogrammed in the field (After fabrication)



# FPGA Architecture

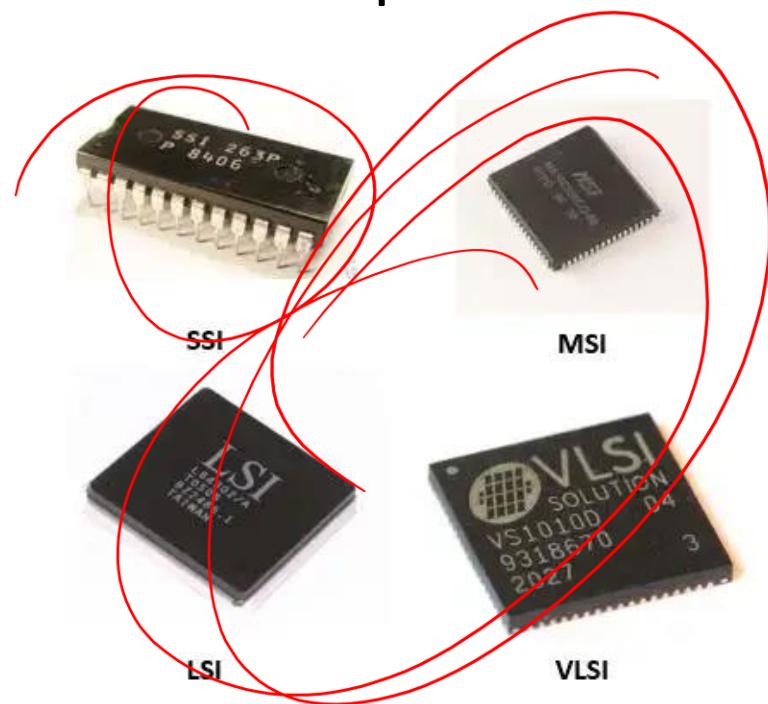
202X

- CLB
- BRAM
- I/O
- CMT
- FIFO Logic
- ▶ BUFG
- X + DSP
- △ ▲ BUFI & BUFR
- MGT



# Integrated Circuits (IC)

- Integrated circuit technology has improved to allow more and more components on chip



| Integration Level | Numbers of Transistors | Equivalent Gates | Typical Functions of Systems                | Typical Number I/Os |
|-------------------|------------------------|------------------|---|---------------------|
| <b>SSI</b>        | 1-40                   | 1-10             | Single Circuit Function (e.g., Transistors) | 14                  |
| <b>MSI</b>        | 40-400                 | 10-100           | Functional Network                          | 24                  |
| <b>LSI</b>        | 400-4,500              | 100-1000         | Hand Calculator or Digital Watch            | 48                  |
| <b>VLSI</b>       | 4,500-300,000          | 1,000-80,000     | Microprocessor                              | 64-300              |
| <b>ULSI</b>       | Over 300,000           | Over 80,000      | Small computer on a chip                    | 300+                |
| <b>GSI</b>        | 1 Billion              | Over 100 Million | Supercomputer                               | 10,000+             |

PC - Comb & Seq clk + .  
- Breadboard ICs.

# Generic FPGA Design Flow

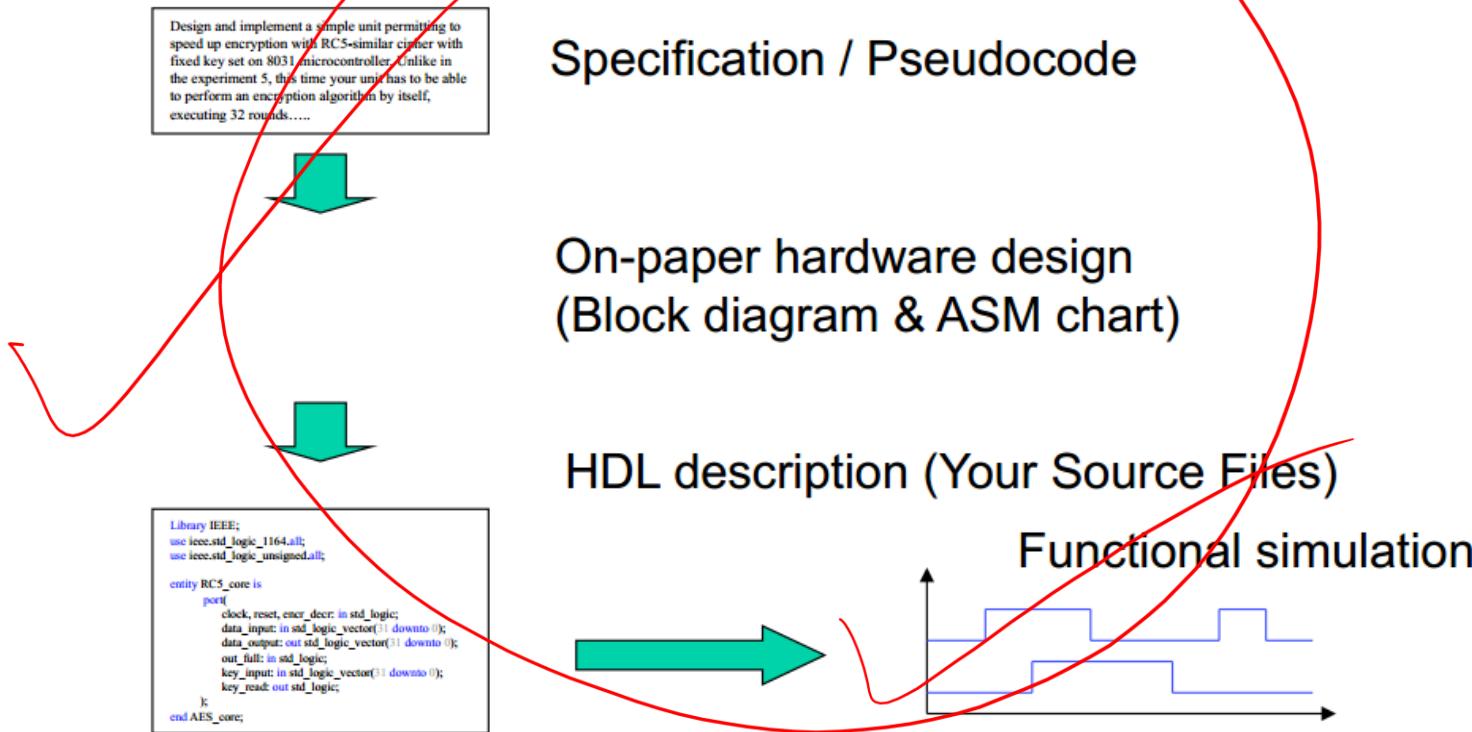
# FPGA Design Flow

- All the designs start with design requirements and design specifications
- Next step is to formulate the design conceptually either at block diagram level or at an algorithmic level

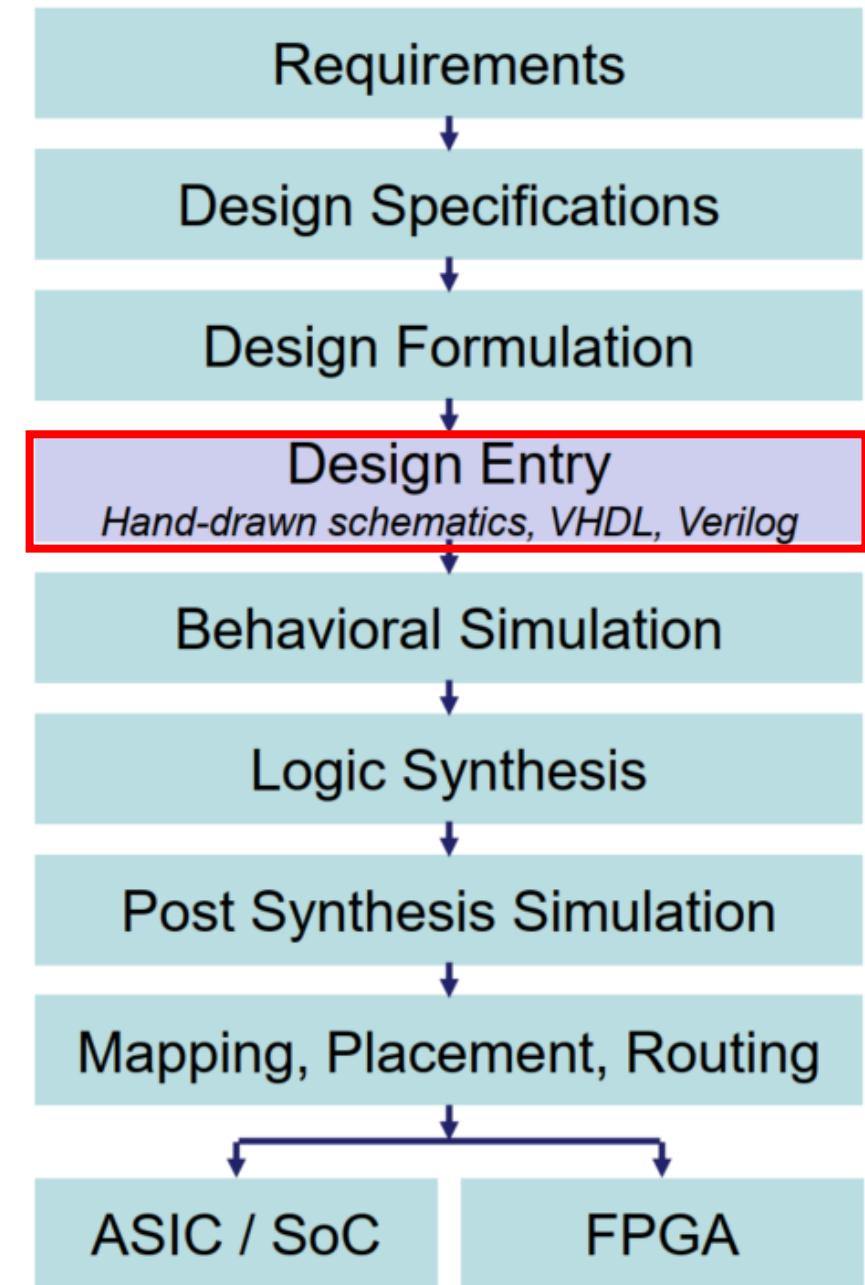


# FPGA Design Flow

- Design Entry:
- Olden days: Hand-drawn schematic
- Now, computer-aided design (CAD) tools: Mostly using HDLs

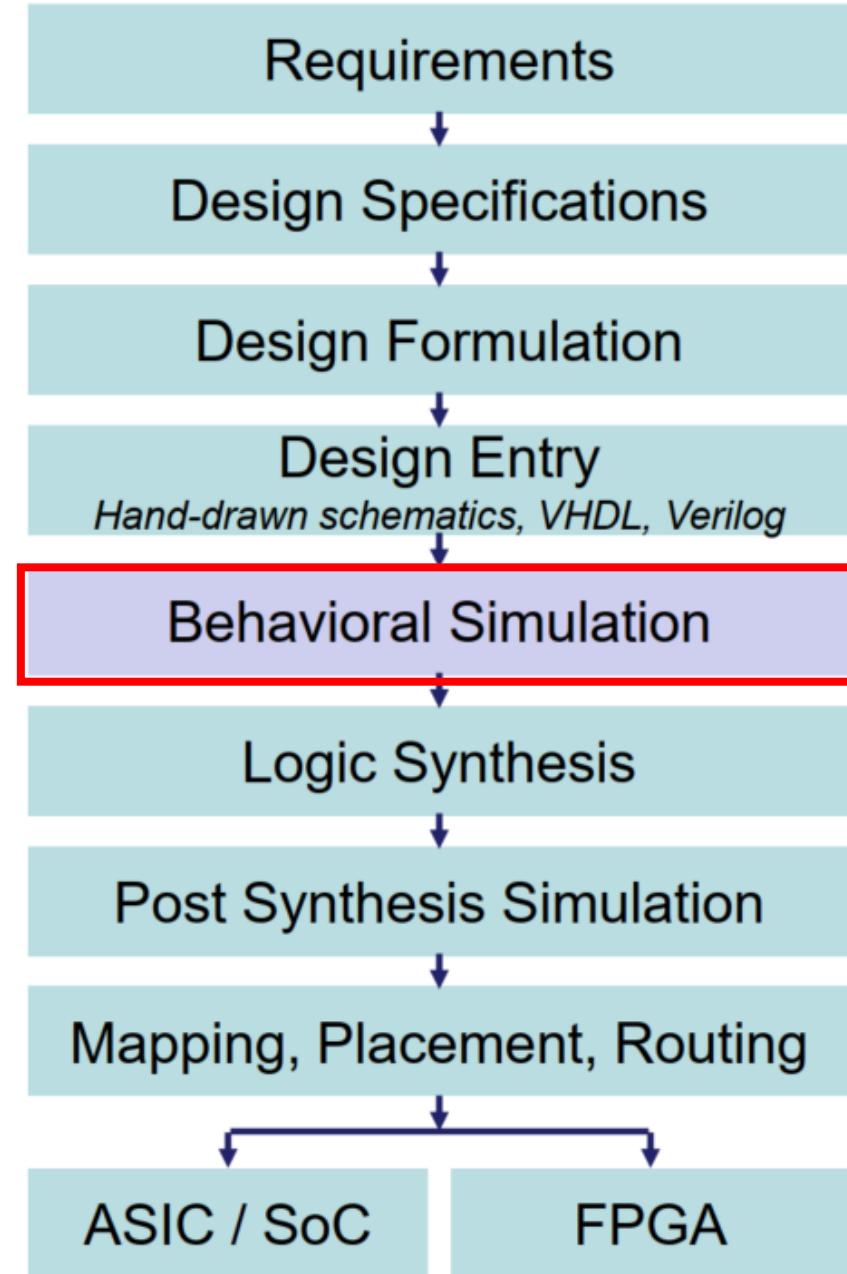


Lab L

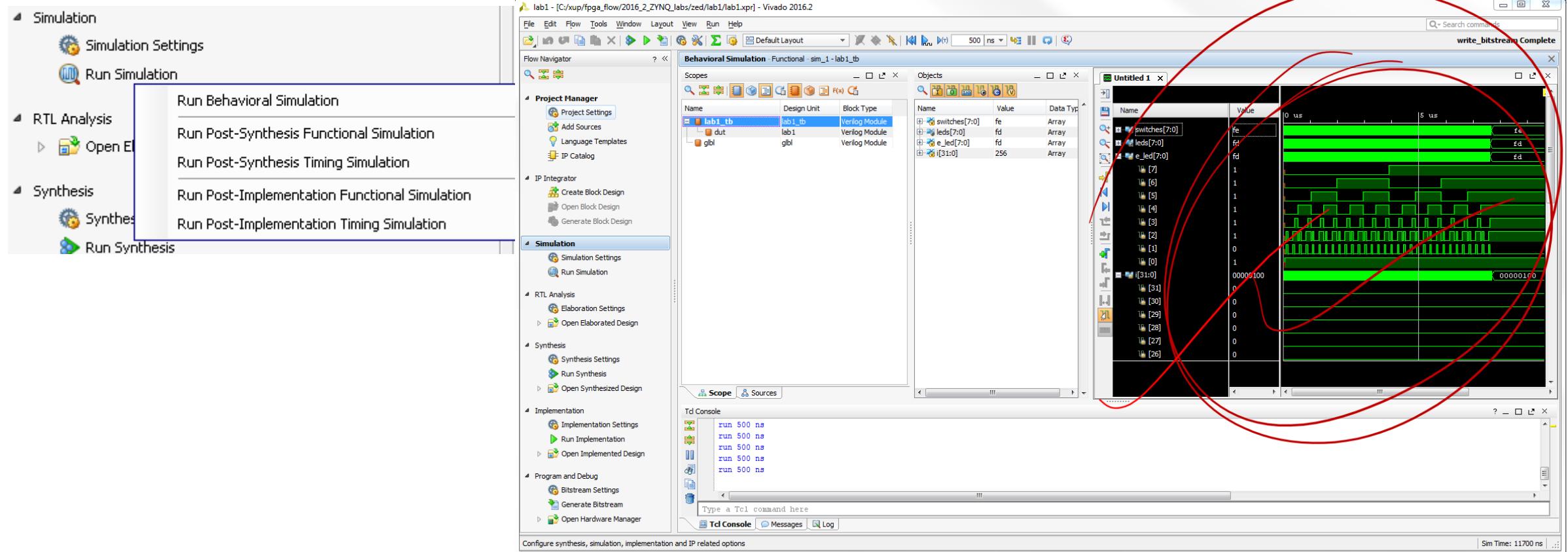


# FPGA Design Flow

- Behavioral simulation to ensure that the design is functionally correct
- Can be done using: Test benches, test bench waveforms



# Functional (HDL/RTL) Simulation



# HDL/RTL Simulation

- **Self-checking test bench:** Contains output data and self-checking code that can be used to compare the data from later simulation runs
- When running a simulation with this kind of test bench, simulation outputs will be monitored. If a difference is detected between the predicted and the actual outputs, an error is reported.
- Automate the task of verifying simulation results i.e. no need to manually check waveform results

# HDL/RTL Simulation

```
module testbench2();
    reg a, b, c;
    wire y;

    // instantiate device under test
    sillyfunction dut(.a(a), .b(b), .c(c), .y(y));

    // apply inputs one at a time
    initial begin
        a = 0; b = 0; c = 0; #10; // apply input, wait
        if (y !== 1) $display("000 failed."); // check
        c = 1; #10; // apply input, wait
        if (y !== 0) $display("001 failed."); // check
        b = 1; c = 0; #10; // etc.. etc..
        if (y !== 0) $display("010 failed."); // check
    end
endmodule
```

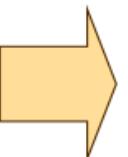
# FPGA Design Flow

## VHDL description

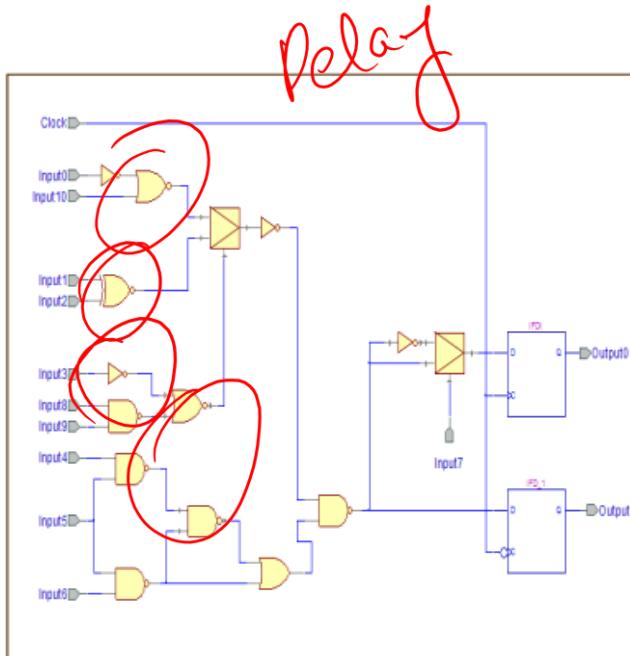
```
architecture MLU_DATAFLOW of MLU is
signal A1:STD_LOGIC;
signal B1:STD_LOGIC;
signal Y1:STD_LOGIC;
signal MUX_0, MUX_1, MUX_2, MUX_3: STD_LOGIC;
begin
    A1<=A when (NEG_A='0') else
        not A;
    B1<=B when (NEG_B='0') else
        not B;
    Y1<=Y1 when (NEG_Y='0') else
        not Y1;

    MUX_0<=A1 and B1;
    MUX_1<=A1 or B1;
    MUX_2<=A1 xor B1;
    MUX_3<=A1 xnor B1;

    with (L1 & L0) select
        Y1<=MUX_0 when "00",
                    MUX_1 when "01",
                    MUX_2 when "10",
                    MUX_3 when others;
end MLU_DATAFLOW;
```



## Circuit netlist



Requirements

Design Specifications

Design Formulation

Design Entry

*Hand-drawn schematics, VHDL, Verilog*

Behavioral Simulation

Logic Synthesis

Post Synthesis Simulation

Mapping, Placement, Routing

ASIC / SoC

FPGA

# FPGA Design Flow

## VHDL description

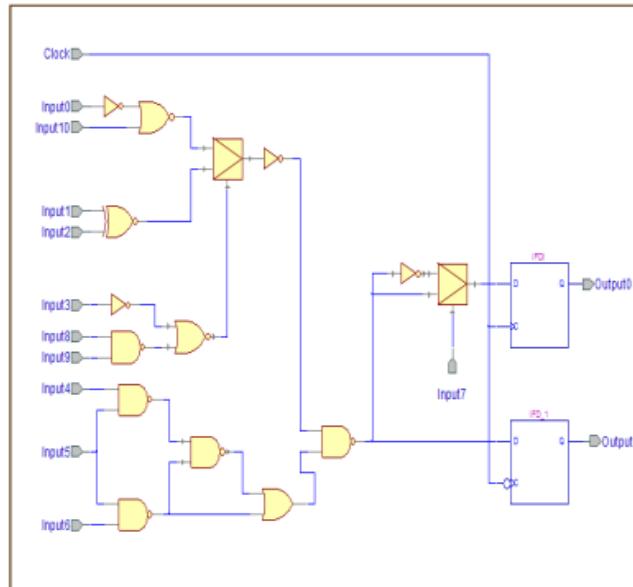
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signal MUX_0, MUX_1, MUX_2, MUX_3: STD_LOGIC;
begin
    A1<=A when (NEG_A='0') else
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    B1<=B when (NEG_B='0') else
        not B;
    Y1<=Y1 when (NEG_Y='0') else
        not Y1;

    MUX_0<=A1 and B1;
    MUX_1<=A1 or B1;
    MUX_2<=A1 xor B1;
    MUX_3<=A1 xnor B1;

    with (L1 & L0) select
        Y1<=MUX_0 when "00",
                    MUX_1 when "01",
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                    MUX_3 when others;
end MLU_DATAFLOW;
```



## Circuit netlist



Requirements

Design Specifications

Design Formulation

Design Entry

*Hand-drawn schematics, VHDL, Verilog*

Behavioral Simulation

Logic Synthesis

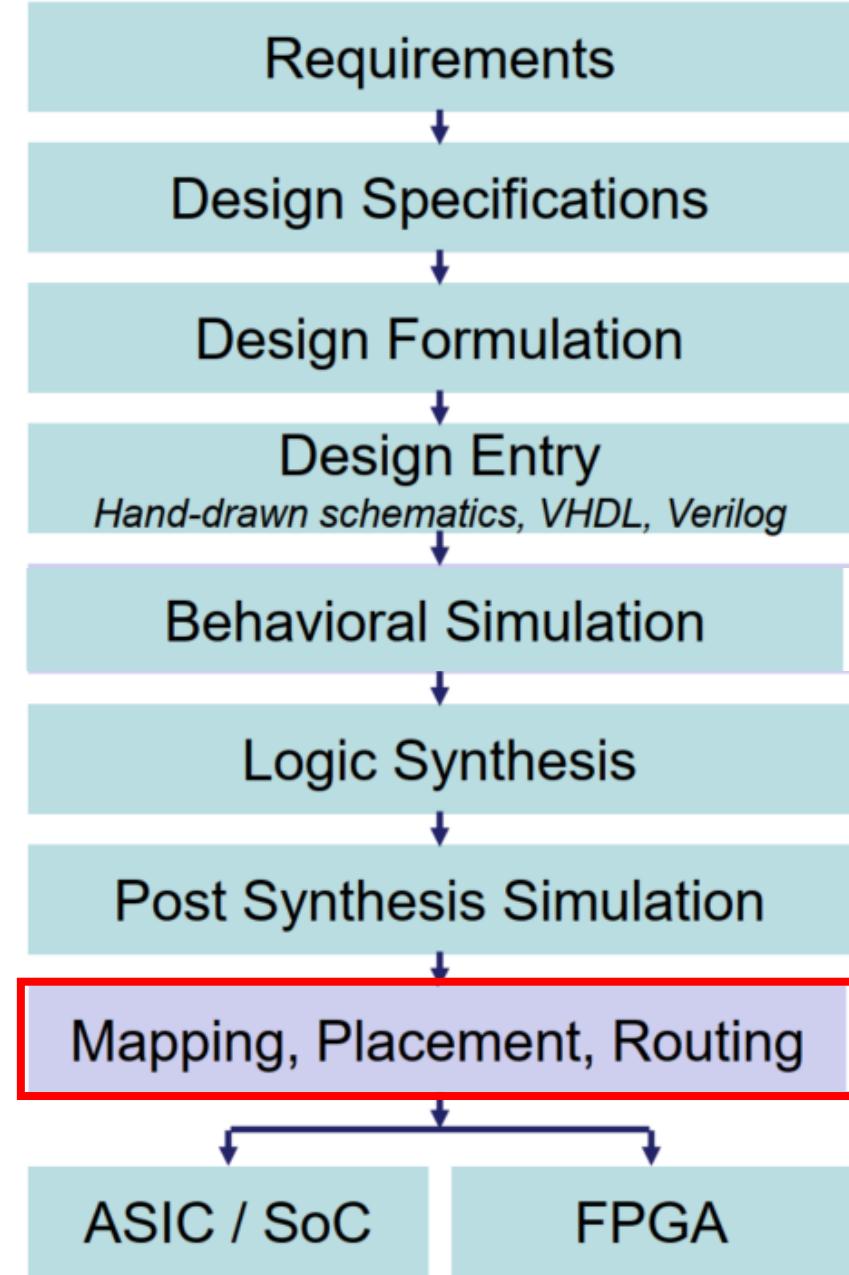
Post Synthesis Simulation

Mapping, Placement, Routing

ASIC / SoC

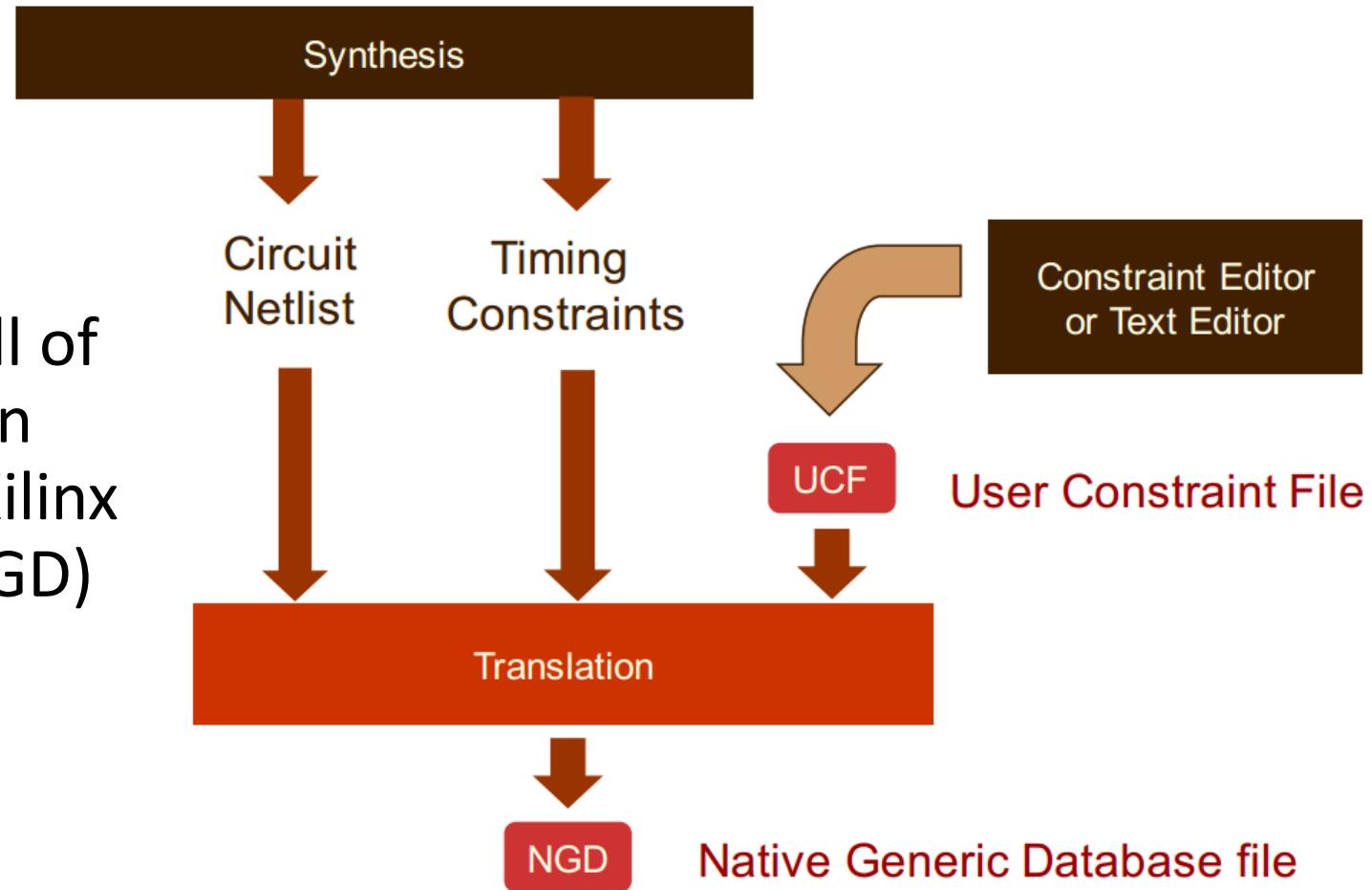
FPGA

# FPGA Design Flow



# Translation

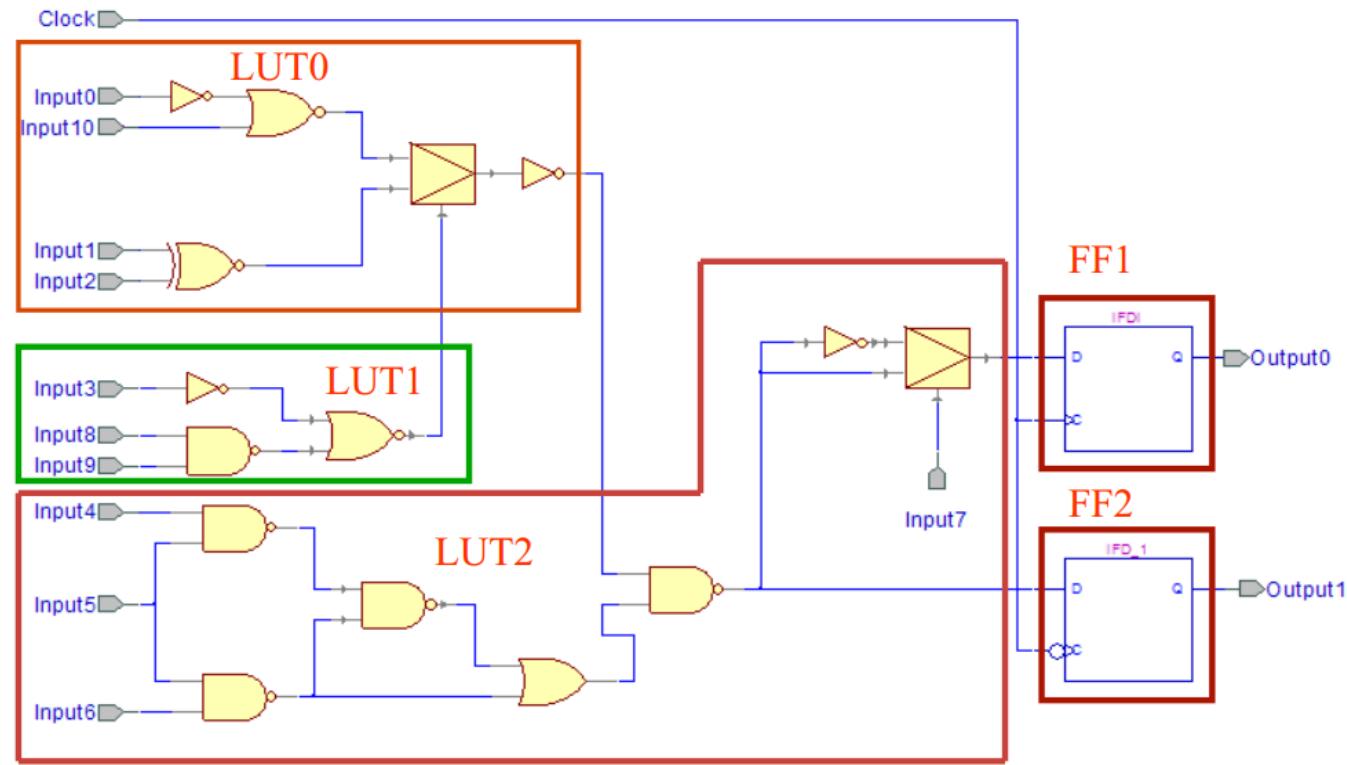
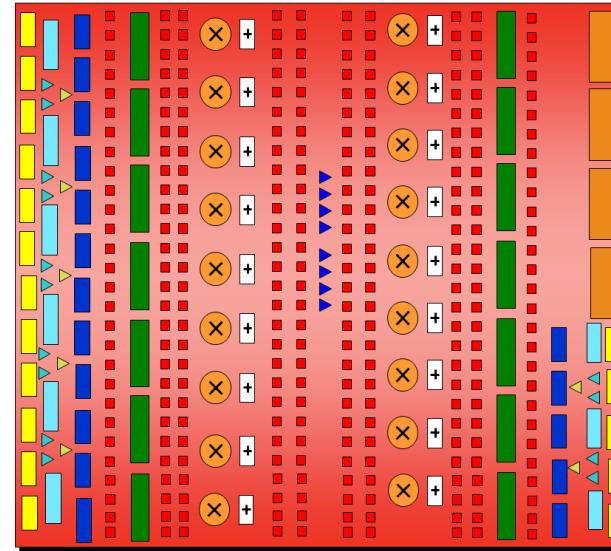
- Translate process merges all of the input netlists and design constraints and outputs a Xilinx native generic database (NGD) file



# Mapping

- The Map process maps the logic defined by an NGD file into FPGA elements, such as CLBs and IOBs.
- The output design is a **native circuit description (NCD)** file that physically represents the design mapped to the components in the FPGA.

|   |             |
|---|-------------|
| ■ | CLB         |
| ■ | BRAM        |
| ■ | I/O         |
| ■ | CMT         |
| ■ | FIFO Logic  |
| ► | BUFG        |
| ● | DSP         |
| △ | BUFO & BUFR |
| ■ | MGT         |

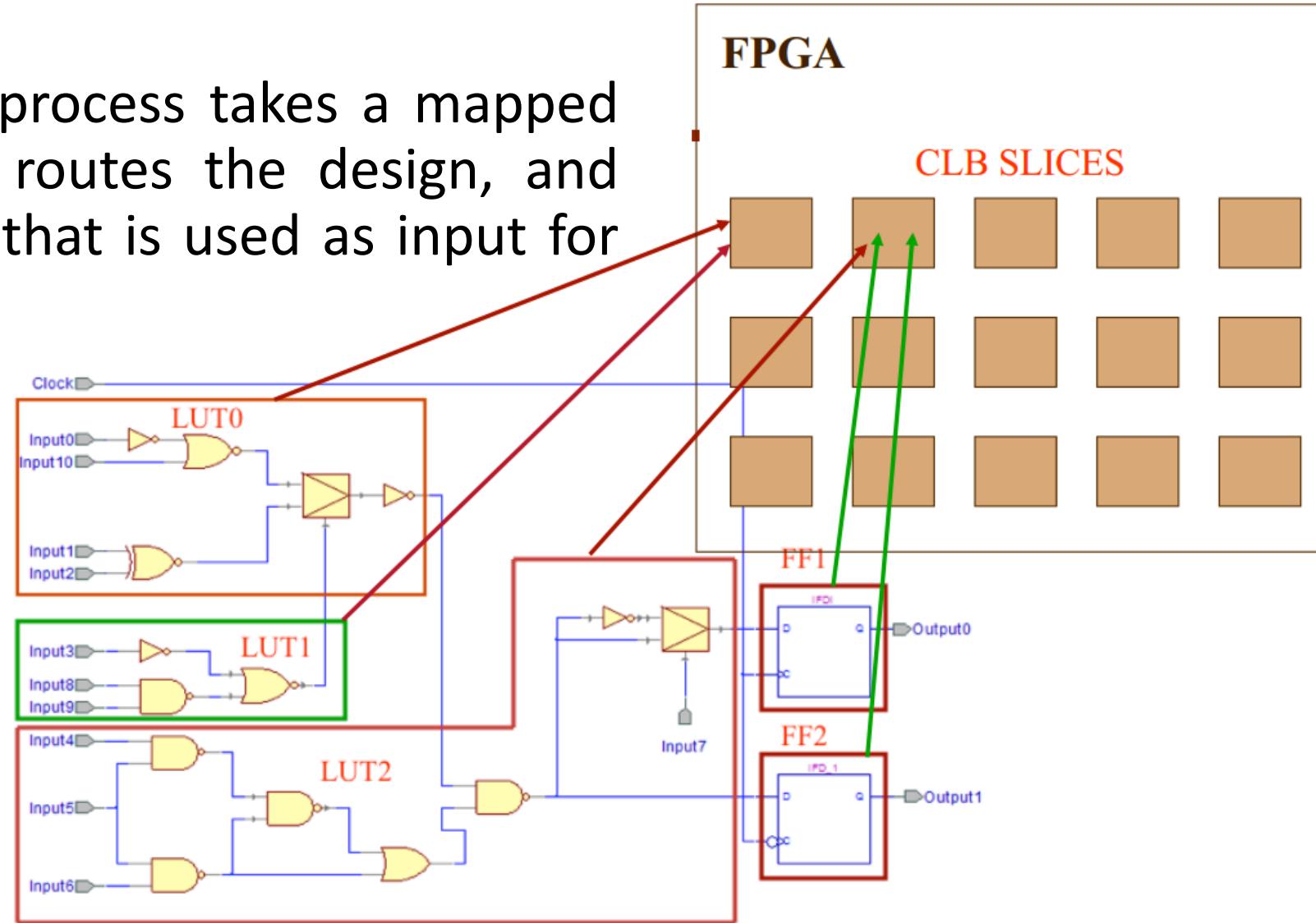


# Post-map Static Timing

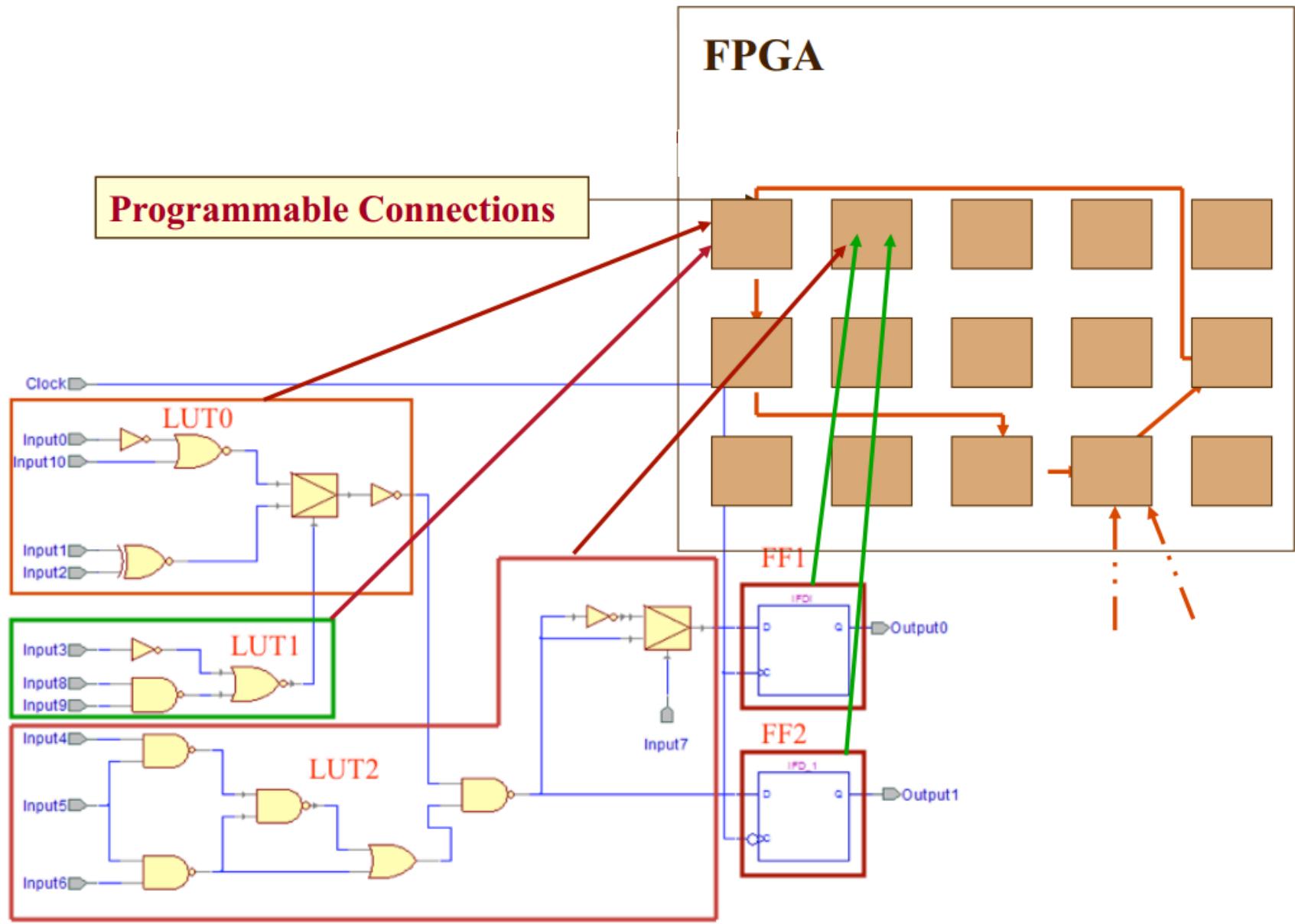
- You can generate a post-map static timing report for your design.
- It lists only the **signal path delays** in your design, derived from the design logic.
- Useful in evaluating timing performance of the logic paths, particularly if your design does not meet timing requirements
- **Route delays are not accounted** (You can eliminate potential problems before investing time in examining routing delays)
- To eliminate problems, you may choose to **redesign** the logic paths to use fewer levels of logic, tag the paths for specialized routing resources, move to a **faster device**, or allocate **more time** for the path.

# Placing

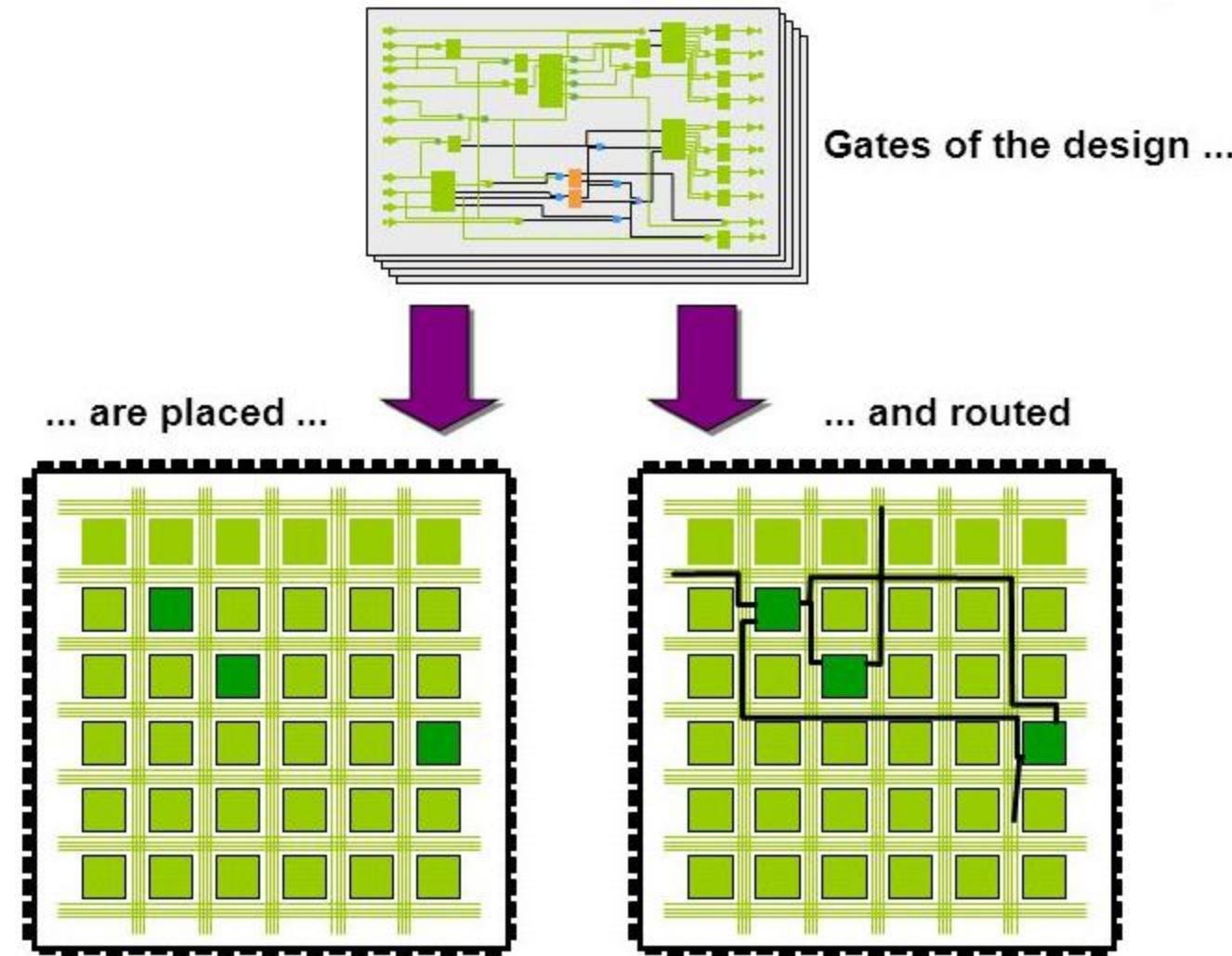
- The Place and Route process takes a mapped NCD file, places and routes the design, and produces an NCD file that is used as input for bitstream generation.



# Routing



# Routing

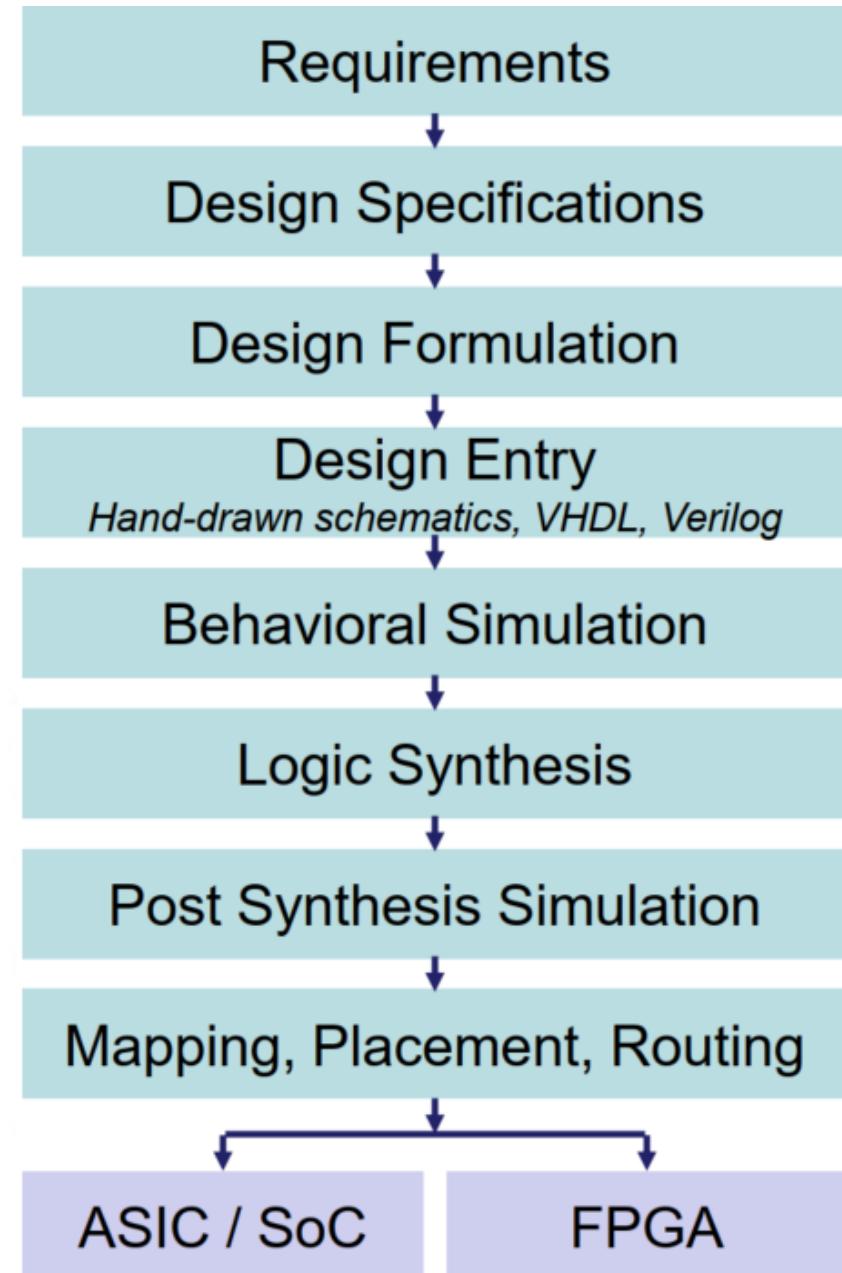


# Post-place and Route Static Timing

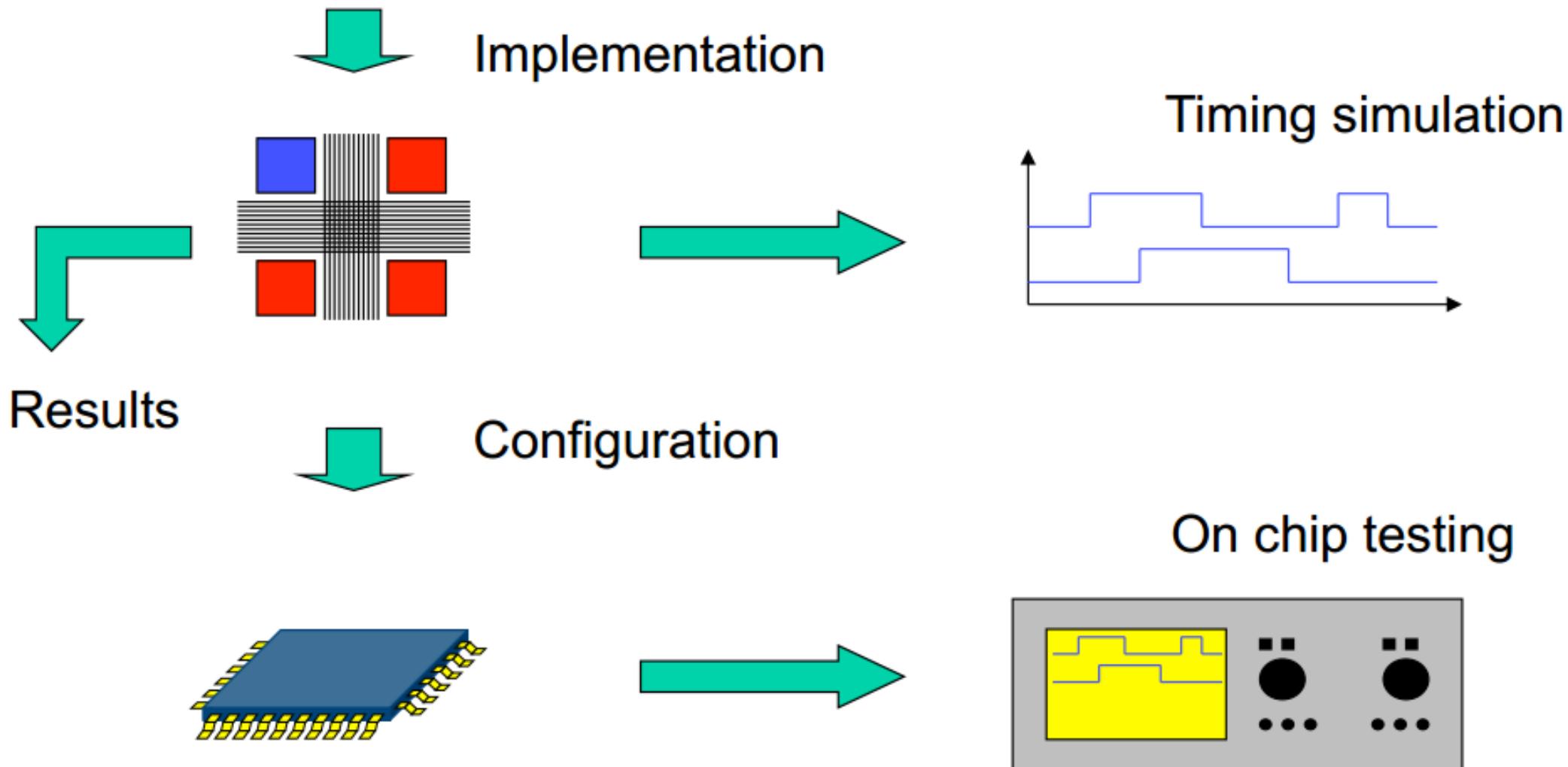
- Incorporates timing delay (**signal and routing delay**) information to provide a comprehensive timing summary of your design
- If you identify problems in the timing report, you can try fixing the problems by **increasing the placer effort level**, using **re-entrant routing**, or using **multi-pass place and route**.
- You can also redesign the logic paths to use fewer levels of logic, move to a faster device, or allocate more time for the paths.
- If a placed and routed design has met all of your timing constraints, then you can then create configuration data.

# FPGA Design Flow

- FPGA programming simply involves writing a sequence of 0 and 1 into the programmable cells of FPGAs
- Once a design is implemented, you must create a file that the FPGA can understand. This file is called a **bitstream**: a BIT file (.bit extension)
- The BIT file can be downloaded directly to the FPGA or can be converted into a PROM file which stores the programming information.

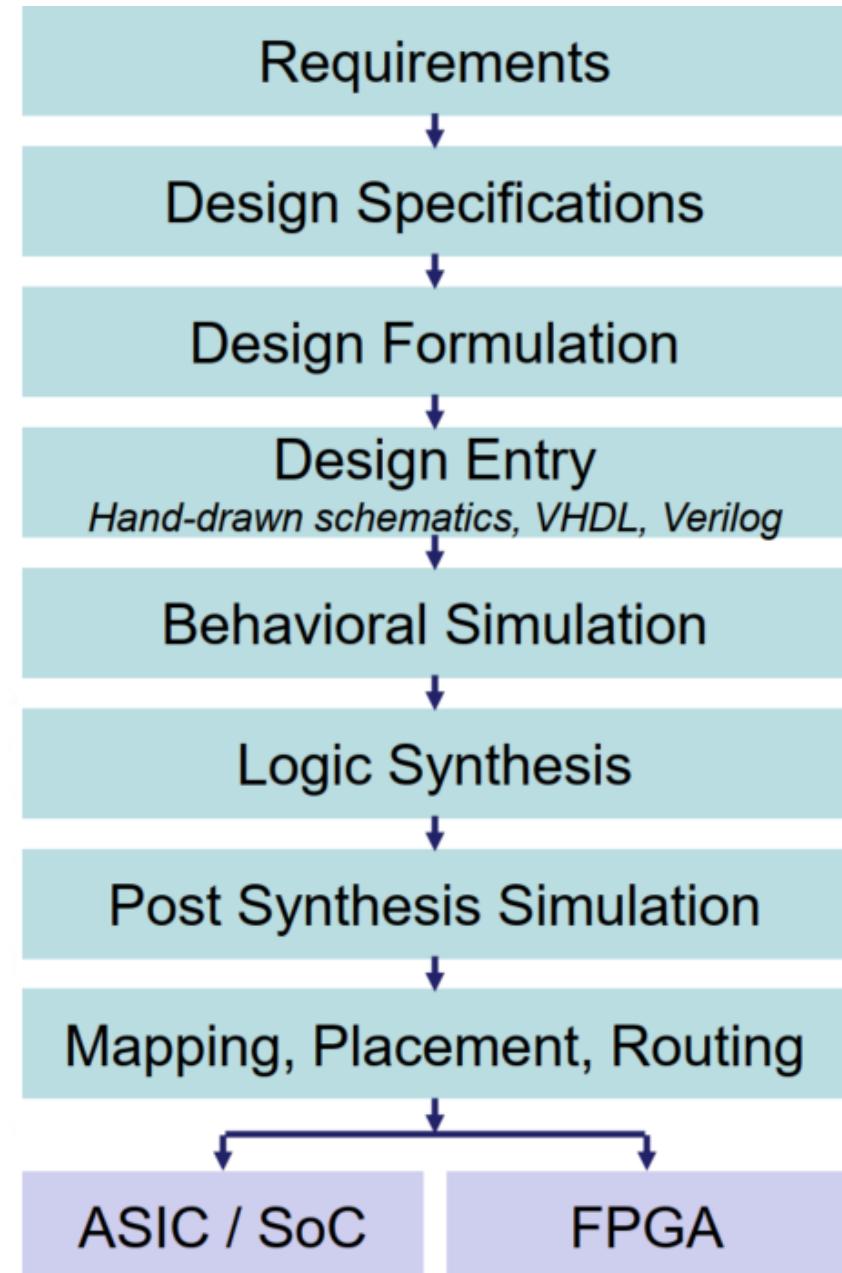
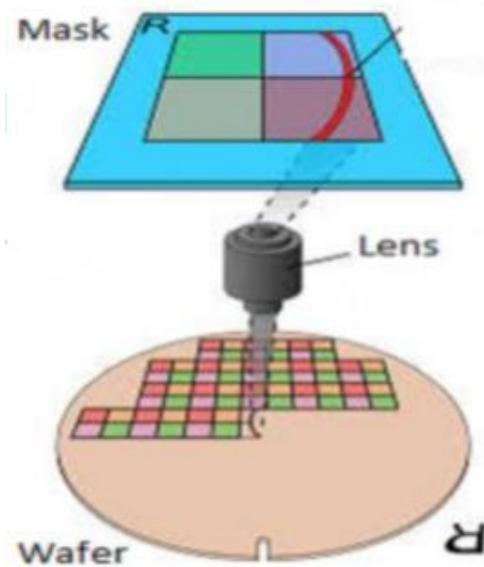


# FPGA Design Process



# ASIC Design Flow

- In ASIC, routed design is used to generate photomask for producing integrated circuits

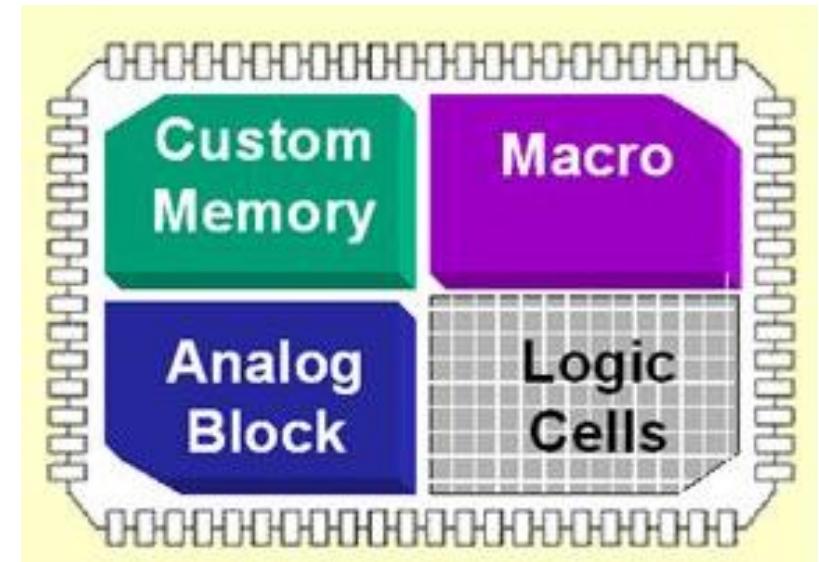


# ASIC vs. FPGA vs. Microcontroller\*

<https://www.youtube.com/watch?v=vxSvQ-lcmHM>

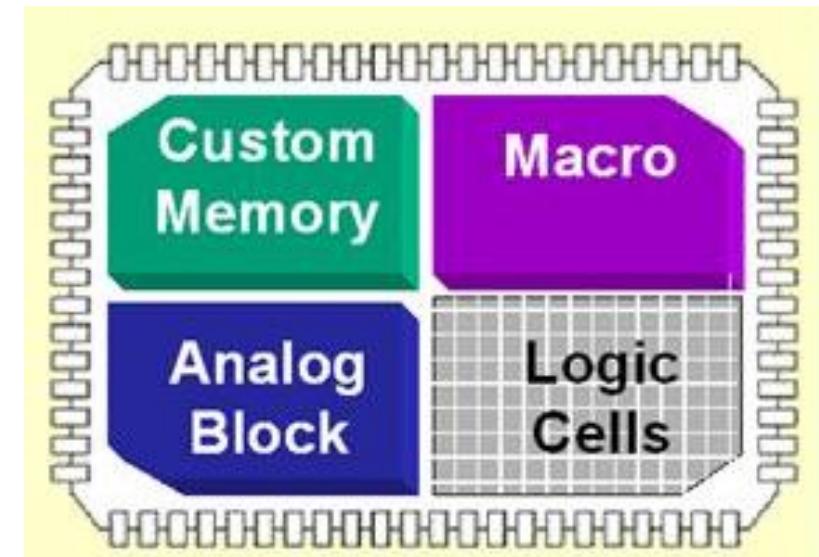
# ASIC

- **ASIC:** Application Specific Integration Circuits



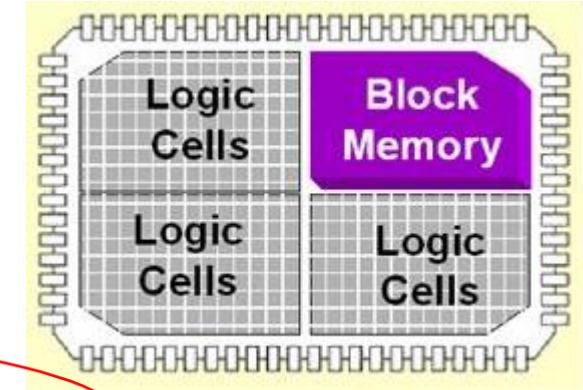
# ASIC

- **ASIC**: Application Specific Integration Circuits
- High non-recurring engineering cost (one-time cost to research, design, develop and test a new product) and longest design cycle
- High cost for engineering change orders (**Testing is critical!** And hence, preferred when design is finalized)
- Lowest price for high volume production
- Fastest clock performance (high performance)
- Unlimited size and Low power
- Design and test tools are **expensive**
- **Expensive IPs**



# FPGA

- Lowest cost for low to medium volume
- No NRE cost and Fastest time to market
- Field reconfigurable and partial reconfigurable
- Slower performance than ASIC (still 550 MHz)
- Limited size and steep learning curve
- Digital only\*
- Industry often use FPGAs to prototype their chips before creating them (FPGA before ASIC).



FPGA / ASIC

# FPGA vs ASIC

## FPGA

## ASIC

Reconfigurable circuitry after manufacturing

Suitable for digital designs only

Can be purchased as off-the-shelf products

Low-performance efficiencies, higher power consumption

No non-recurring engineering (NRE) costs

Difficult to attain high-frequency rates

Faster time-to-market, high per unit costs

Are typically larger than ASICs

Prototyping and validating with FPGAs is easier

Lower barrier to entry for competitors

Fixed circuitry for product's lifespan

Analog/mixed-signal circuitry can be fully implemented

Can only be designed as custom, private-label devices

Low power consumption, high-performance efficiencies

NRE costs are part of the design process

Operate at higher frequency rates

Long time-to-market, lower per unit costs

Can be much smaller than FPGA devices

Prototypes must be accurately validated to avoid design iterations

Higher barrier to entry for competitors

- Demand for specialized systems and short device life -> FPGAs

# Microcontrollers

- Similar to **simple computer** placed in a single chip with all necessary components like memory, timers etc. embedded inside and **performs a specific task.**
- **Example:** Arduino, Pic
- **Sequential execution, easy to use, control over software**
- Consumes **less power** than FPGAs and mostly suitable for edge operations.
- **Supports** fixed as well as floating point operations
- **Microprocessors:** Completely different than microcontrollers.

# Microprocessors

- ICs that come with a computer or CPU inside and are equipped with processing power. Examples: Pentium 3, 4, i5 etc.
- **No peripherals** such as RAM, ROM on the chip.
- Microprocessors form the heart of a computing system (general complex high-speed tasks) while microcontrollers drive embedded systems (specific tasks).
- **Bulky** due to the external peripherals
- **Expensive than micro-controllers**

# Microprocessor vs FPGA vs ASIC

|  | Microprocessor | FPGA                  | ASIC         |
|--|----------------|-----------------------|--------------|
| Example                                    | ARM Cortex-A9  | Virtex Ultrascale 440 | Bitfury 16nm |
| Flexibility during development             | Medium         | High                  | Very high    |
| Flexibility after development <sup>1</sup> | High           | High                  | Low          |
| Parallelism                                | Low            | High                  | High         |
| Performance <sup>2</sup>                   | Low            | Medium                | High         |
| Power consumption                          | High           | Medium                | Low          |
| Development cost                           | Low            | Medium                | High         |
| Production setup cost <sup>3</sup>         | None           | None                  | High         |
| Unit cost <sup>4</sup>                     | Medium         | High                  | Low          |
| Time-to-market                             | Low            | Medium                | High         |

<sup>1</sup>E.g. to fix bugs, add new functionality when already in production

<sup>2</sup>For a sufficiently parallel application

<sup>3</sup>Cost of producing the first chip

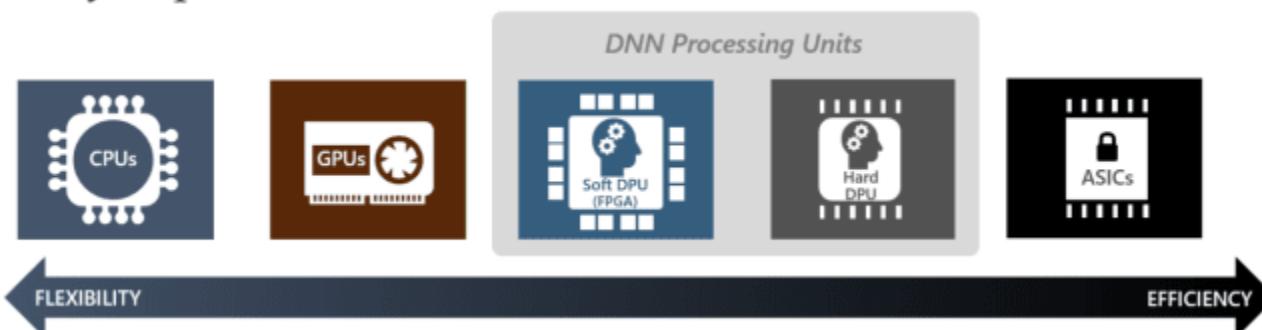
# Microprocessor vs FPGA vs ASIC vs GPU

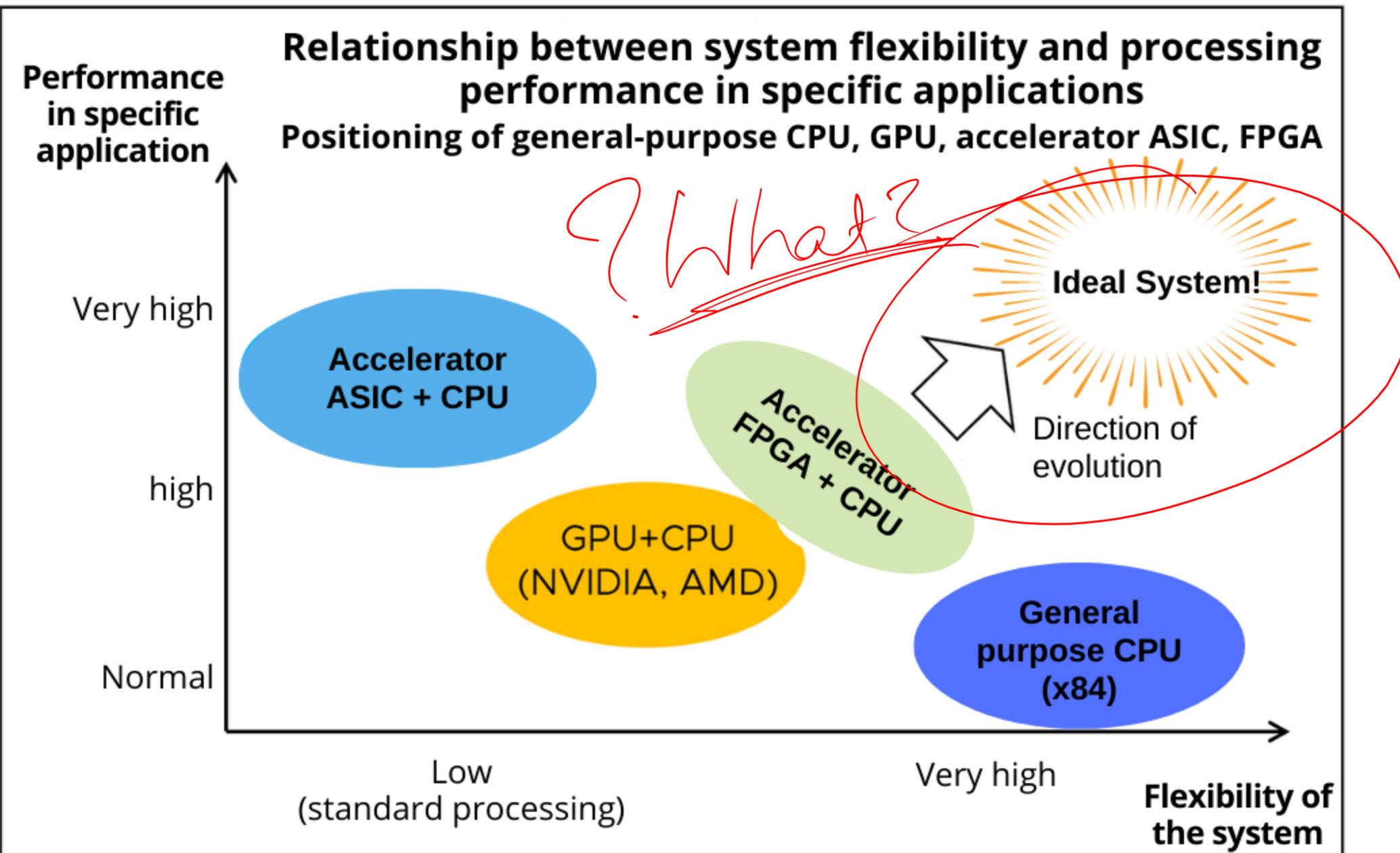
|  | Microprocessor | FPGA                  | ASIC         | GPU            |
|--|----------------|-----------------------|--------------|----------------|
| Example                                    | ARM Cortex-A9  | Virtex Ultrascale 440 | Bitfury 16nm | Nvidia Titan X |
| Flexibility during development             | Medium         | High                  | Very high    | Low            |
| Flexibility after development <sup>1</sup> | High           | High                  | Low          | High           |
| Parallelism                                | Low            | High                  | High         | Medium         |
| Performance <sup>2</sup>                   | Low            | Medium                | High         | Medium         |
| Power consumption                          | High           | Medium                | Low          | High           |
| Development cost                           | Low            | Medium                | High         | Low            |
| Production setup cost <sup>3</sup>         | None           | None                  | High         | None           |
| Unit cost <sup>4</sup>                     | Medium         | High                  | Low          | High           |
| Time-to-market                             | Low            | Medium                | High         | Medium         |

<sup>1</sup>E.g. to fix bugs, add new functionality when already in production

<sup>2</sup>For a sufficiently parallel application

<sup>3</sup>Cost of producing the first chip





# Summary

- **FPGA/ASIC:** Parallel execution, HDL (Verilog/VHDL), control over **hardware**
- You can make microcontroller inside FPGA/ASIC but not the other way round
- **Time vs space limited**
- FPGAs can perform any task while microcontrollers are limited by instruction sets while ASICs are application specific. **FPGA are field-reconfigurable.**
- **Power consumption is high in FPGA**
- FPGAs/ASICs can not be avoided in applications with stringent computational and memory requirements or applications with high level of determinism
- New world SoC: ARM + FPGA + GPU

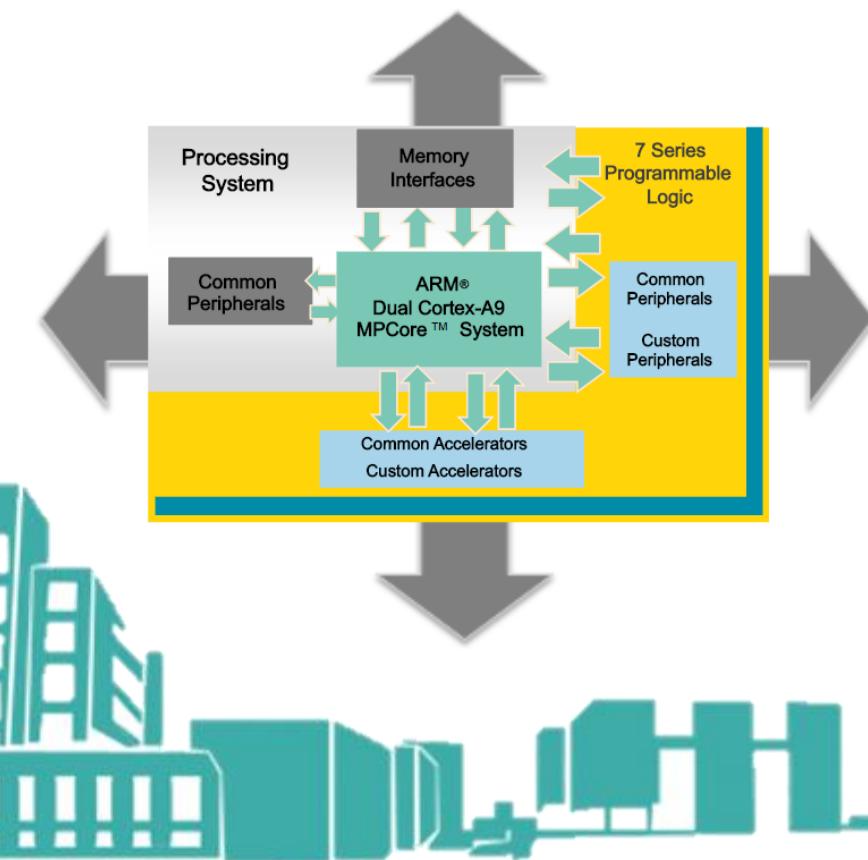
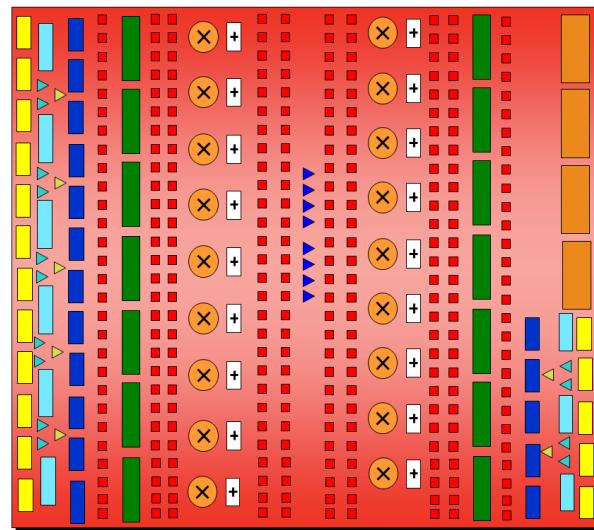


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A2A  
*Algorithms to Architecture*

# ECE 270: Embedded Logic Design



Module Mix (in1, in2, in3, in4, in5, in6, in7, in8, sel, out);  
input in1, in2, in3, in4, in5, in6, in7, in8;  
input [2:0] sel;  
output reg out;

always @(\*)

begin

if (sel == 3'b000)

out = in1;

else if (sel == 3'b001)

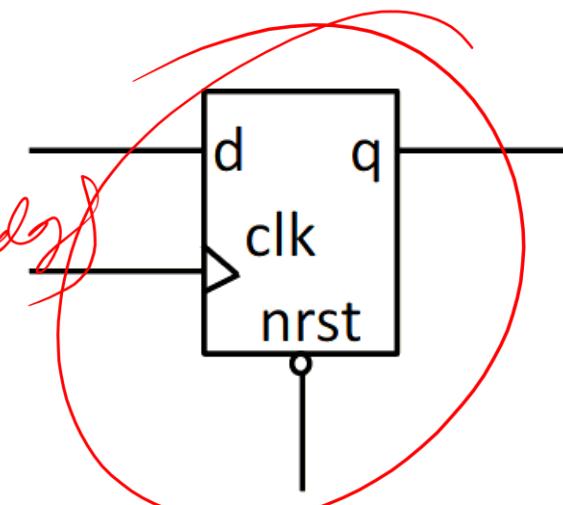
out = in2;

# Verilog

# Verilog: Module (Examples)

```
module D_FF(clk, nrst, d, q) ;  
    input clk, nrst, d ;  
    output reg q ;  
    always @(*posedge clk or negedge nrst)  
        // Event-based Timing Control  
        if (!nrst)  
            // reset state  
            q <= 0 ;  
        else  
            // normal operation  
            q <= d ;  
endmodule
```

Most all  
always @(\*posedge clk or negedge nrst)  
always @(\*)  
always @(\*)

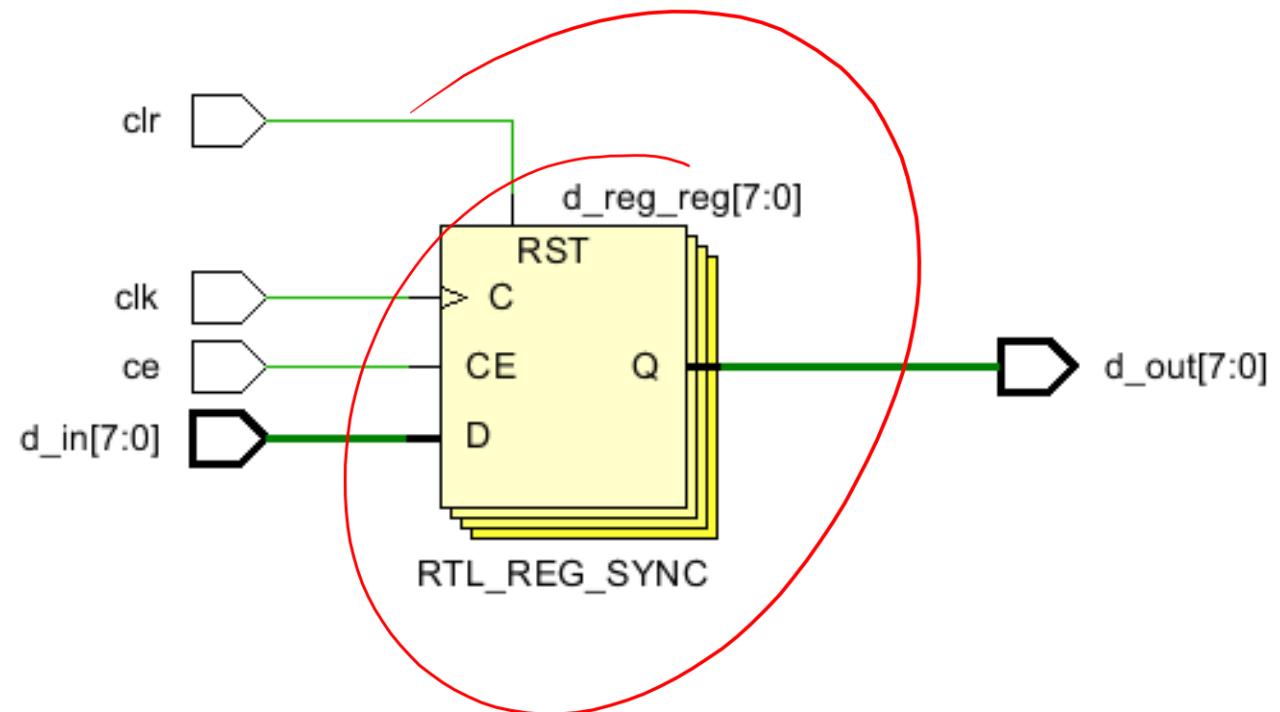


- 1) Design comb. ckt:- Use always@(\*)  
2) Design FFs :- Use always@(\*posedge clk)

# Verilog: Register

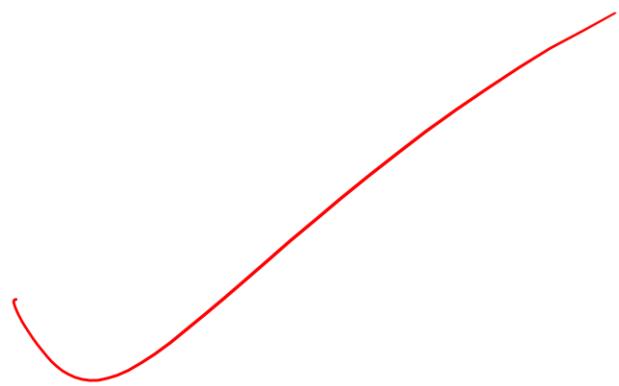
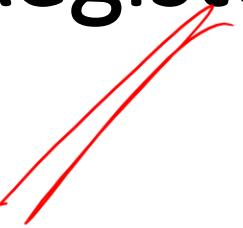
```
module test_1(
    input [7:0] d_in,
    input ce,
    input clk,
    input clr,
    output [7:0] d_out
);

reg [7:0] d_reg;
always@(posedge clk)
begin
    if(clr)
        d_reg <= 8'b00000000;
    else if (ce)
        d_out <= d_in;
end
assign d_out = d_reg;
endmodule
```



# Register and Wire

33.).



# Module Ports

# Verilog: Module Ports

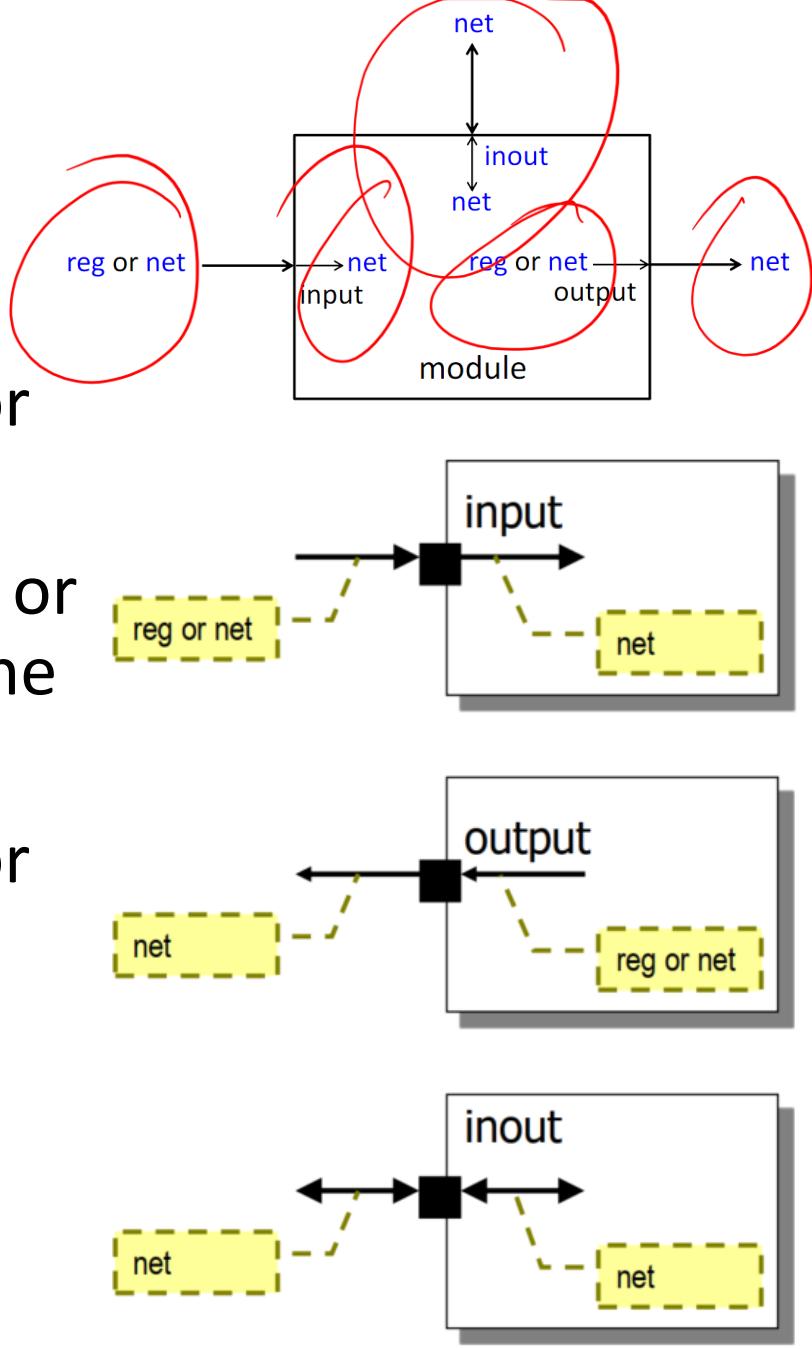
Reg / Wire

- Ports provide **interface** for the module to **communicate** with its environment
- Declaration: <Port direction> <width> <port\_name>;
- Port **direction** can be *input, output, inout*.

```
module my_module (my_input_port, my_inout_port,  
                  my_output_port );  
    input [4:0] my_input_port ;  
    inout  my_inout_port ;  
    output wire (or reg) [14:0] my_output_port ;  
endmodule
```

# Verilog: Module Ports

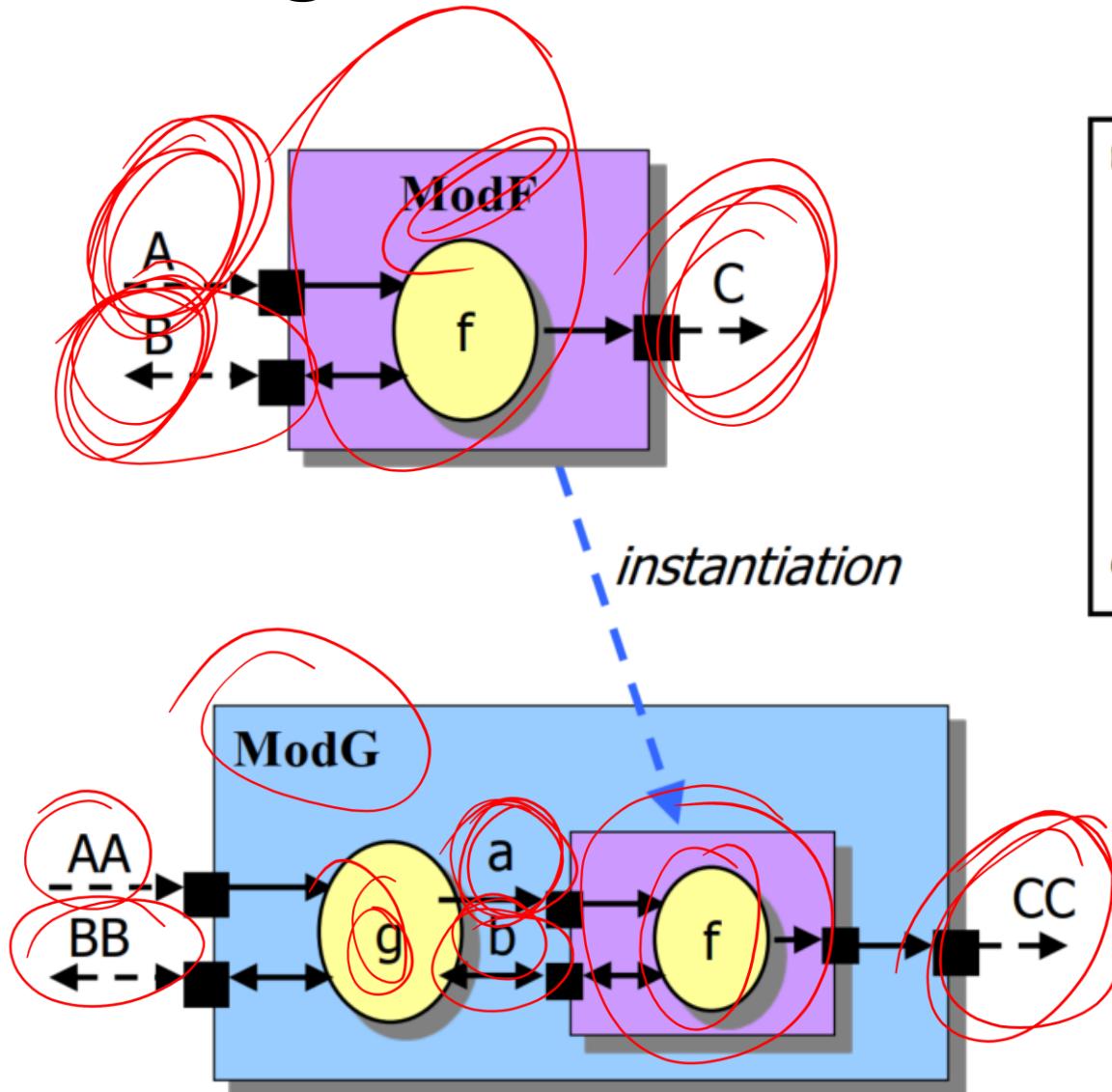
- An **input port** specifies an internal name for a vector or scalar, **driven by external entity**.
- An **output port** specifies an internal name for a vector or scalar, **driven by internal entity**, available external to the module.
- An **inout port** specifies an internal name for a vector or scalar **driven either by an internal or external entity**.
- Input or inout ports **cannot** be declared as of type **register**.
- Port is always considered as **net**, unless declared elsewhere as **reg** (only for output port)



# Module Interconnections

# Verilog: Module Interconnections

named  
association



```
module ModG (AA, BB, CC);
    input AA;
    inout [7:0] BB;
    output [7:0] CC;
    wire a;
    wire [7:0] b;
    // description of 'g'
    ModF Umodgf(.A(a), .B(b), .C(CC));
endmodule
```

- Port connection
- Instance name
- Module name

# Verilog: Module Interconnections

- Ports of the instances could be connected by name or by order list.

```
module fa_tb;  
    reg [3:0] A, B;  
    reg CIN;  
    wire [3:0] SUM;  
    wire COUT;  
endmodule
```

```
module FA4 (sum, cout, a, b, cin);  
    output wire [3:0] sum;  
    output wire cout;  
    input [3:0] a, b;  
    input cin;  
endmodule
```

Order  
Association

~~// Instantiate/connect by Positional association (order list):~~

```
FA4 fa_byorder (SUM, COUT, A, B, CIN);
```

~~// Instantiate/connect by Named association (port name):~~

```
FA4 fa_byname (.cout(COUT), .sum(SUM), .b(B), .cin(CIN), .a(A));
```

# Verilog: Module Interconnections

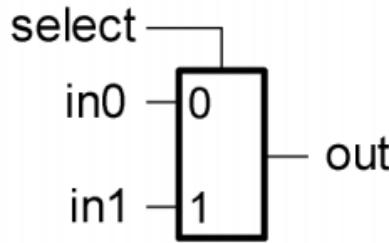
```
module topmod;
  wire [4:0] v;
  wire a,b,c,w;
  modB b1 (v[0], v[3], w, v[4]);
endmodule

module modB (wa, wb, c, d);
  inout wa, wb;
  input c, d;
  tranif1 g1 (wa, wb, cinvert);
  not #(2, 6) n1 (cinvert, int);
  and #(6, 5) g2 (int, c, d);
endmodule
```

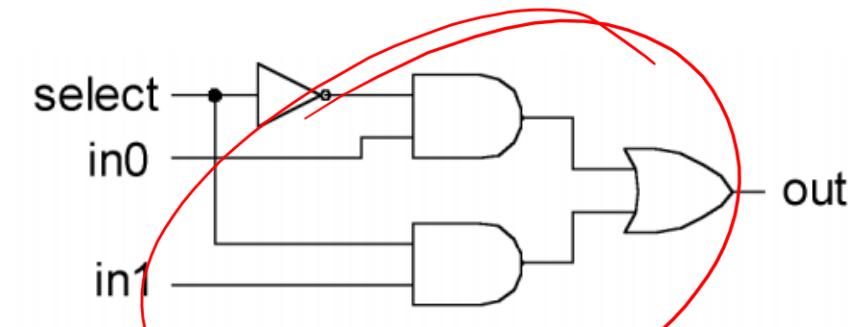
```
module topmod;
  wire [4:0] v;
  wire a,b,c,w;
  modB b1 (.wb(v[3]),.wa(v[0]),.d(v[4]),.c(w));
endmodule

module modB (wa, wb, c, d);
  inout wa, wb;
  input c, d;
  tranif1 g1(wa, wb, cinvert);
  not #(6, 2) n1(cinvert, int);
  and #(5, 6) g2(int, c, d);
endmodule
```

# Multiplexer



a) 2 input mux symbol



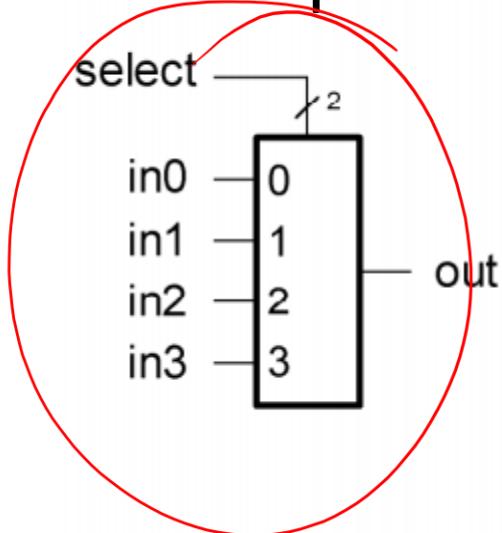
b) 2-input mux gate-level circuit diagram

```
module mux2 (in0, in1, select, out);
    input in0, in1, select;
    output out;
    wire s0, w0,w1;

    not (s0, select);
    and (w0, s0, in0),
        (w1, select, in1);
    or (out, w0,w1);

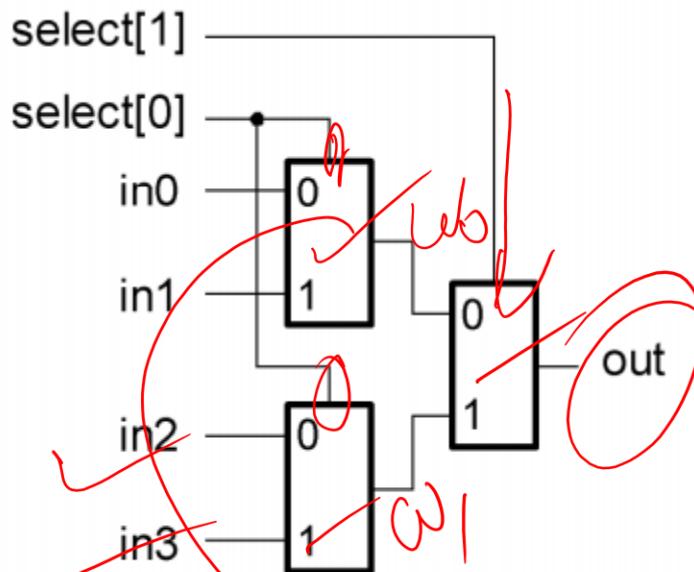
endmodule
```

# Multiplexer



```
module mux4 (in0, in1, in2, in3, select, out);
    input in0, in1, in2, in3;
    input [1:0] select;
    output out;
    wire w0,w1;

    mux2
        m0 (.select(select[0]), .in0(in0), .in1(in1), .out(w0)),
        m2 (.select(select[0]), .in0(in2), .in1(in3), .out(w1));
    mo (.select(select[1]), .in0(w0), .in1(w1), .out(out));
endmodule
```



```
module mux2 (in0, in1, select, out);
    input in0, in1, select;
    output out;
    wire s0, w0,w1;

    not (s0, select);
    and (w0, s0, in0),
    (w1, select, in1);
    or (out, w0,w1);

endmodule
```

If your design contains more than one module, put each in a separate file.

Instantiation: Prefer named association. It prevents incorrect connections for the ports of instantiated components.

# 3-bit Full Adder

```
→module top_adder(  
→    →    input [2:0] A,  
→    →    input [2:0] B,  
→    →    output [3:0] Sum  
→);  
→    →    wire c1,c2;  
→    →  
→    →    fa.in1(.A(A[0]),.B(B[0]),.C(1'b0),.Sum(Sum[0]),.Carry(c1));  
→    →    fa.in2(.A(A[1]),.B(B[1]),.C(c1),.Sum(Sum[1]),.Carry(c2));  
→    →    fa.in3(.A(A[2]),.B(B[2]),.C(c2),.Sum(Sum[2]),.Carry(Sum[3]));  
→endmodule  
→  
→module fa(  
→    →    input A,  
→    →    input B,  
→    →    input C,  
→    →    output Sum,  
→    →    output Carry  
→);  
→    →  
→    →    assign Sum = A ^ B ^ C;  
→    →    assign Carry=((A ^ B) & C)|(A & B);  
→endmodule
```

# 3-bit Multiplier (Self Study)

```
→module top_multiplier(  
→    input [2:0] A,  
→    input [2:0] B,  
→    output [5:0] Mul_Op  
→);  
→  
→    wire c1,c2,c3,c22,c32;  
→    wire s1,s2;  
→    assign Mul_Op[0]=A[0] & B[0];  
→    fa in1(.A(A[0] & B[1]),.B(A[1] & B[0]),.C(1'b0),.Sum(Mul_Op[1]),.Carry(c1));  
→    fa in2(.A(A[2] & B[0]),.B(A[1] & B[1]),.C(c1),.Sum(s1),.Carry(c2));  
→    fa in3(.A(A[0] & B[2]),.B(s1),.C(1'b0),.Sum(Mul_Op[2]),.Carry(c22));  
→    fa in4(.A(A[2] & B[1]),.B(1'b0),.C(c2),.Sum(s2),.Carry(c3));  
→    fa in5(.A(A[1] & B[2]),.B(s2),.C(c22),.Sum(Mul_Op[3]),.Carry(c32));  
→    fa in6(.A(A[2] & B[2]),.B(c3),.C(c32),.Sum(Mul_Op[4]),.Carry(Mul_Op[5]));  
→endmodule
```

```
→module fa(  
→    input A,  
→    input B,  
→    input C,  
→    output Sum,  
→    output Carry  
→);  
→  
→    assign Sum = A ^ B ^ C;  
→    assign Carry=((A ^ B) & C)|(A & B);  
→endmodule
```

# Homework

*Design*

- Using module for 2:1 mux (~~data flow level~~ approach), design 8:1 mux via module interconnections
- Design comparator for 2-bit inputs using **data flow level** approach.
- Using comparator for 1-bit inputs, design comparator for 2-bit inputs via module interconnections

# Number Representation

# Verilog: Number Representation

- Verilog HDL allows integer numbers to be specified as: Sized or Unsized numbers ( Unsized is 32 bits)
- In a radix of **binary**, **octal**, **decimal**, or **hexadecimal**
- Syntax: <size> '<radix> <value>  
size in bits, radix in b, d, o, h
- **Spaces are allowed** between the size, radix and value
- **Underscore character (\_)** is ignored and can be used to enhance readability. It cannot be the first character in number.

# Verilog: Number Representation

549

// unsized decimal number

'h 8FF

// unsized hex number

'o765

// unsized octal number

4'b11

// 4-bit binary number 0011

3'b10x

// 3-bit binary number with LSB unknown

5'd3

// 5-bit decimal number

32'd549

32'h8FF

32'o765

4'b0011

5'd3

↓ 0001

# Verilog: Number Representation

792

// a decimal number

8d9

// ~~Illegal~~, hexadecimal must be specified with 'h

'h 7d9

// an unsized hexadecimal number - 000007d9

'o 7746

// an unsized octal number - 00000007746

1

// stored as 00000000000000000000000000000001

12 'h x

// a 12 bit unknown number

10 'd 17

// a 10 bit constant with the value 17

4 'b 110z

// a 4 bit binary number

8'hAA

// stored as 10101010

# Verilog: Negative Numbers

0111  
1001

- Any number that does not have negative sign prefix is a **positive number**. Or indirect way would be "**Unsigned**"
- Negative numbers can be specified by putting a minus sign before the size for a constant number, thus become signed numbers.
- Verilog internally represents negative numbers in **2's compliment format**.

-4'b11 // 4-bit two's complement of 0011 = 1101 = 4'dd

4'd-2 // Illegal specification  
-5'ha // stored as 10110  
-4'b101 // stored as 1011

0011  
1101

# Verilog: Number Representation

| number    | stored value                               | comment                 |
|-----------|--|-------------------------|
| 5'b11010  | 11010                                      |                         |
| 5'b11_010 | 11010                                      | - ignored               |
| 5'o32     | 11010                                      |                         |
| 5'h1a     | 11010                                      |                         |
| 5'd26     | 11010                                      |                         |
| 5'b0      | 00000                                      | 0 extended              |
| 5'b1      | 00001                                      | 0 extended              |
| 5'bz      | zzzzz                                      | z extended              |
| 5'bx      | xxxxx                                      | x extended              |
| 5'bx01    | xxx01                                      | x extended              |
| -5'b00001 | 11111                                      | 2's complement of 00001 |
| 'b11010   | 0000000000000000000000000011010            | extended to 32 bits     |
| 'hee      | 0000000000000000000000000011101110         | extended to 32 bits     |
| 1         | 0000000000000000000000000000000000000001   | extended to 32 bits     |
| -1        | 11 | extended to 32 bits     |

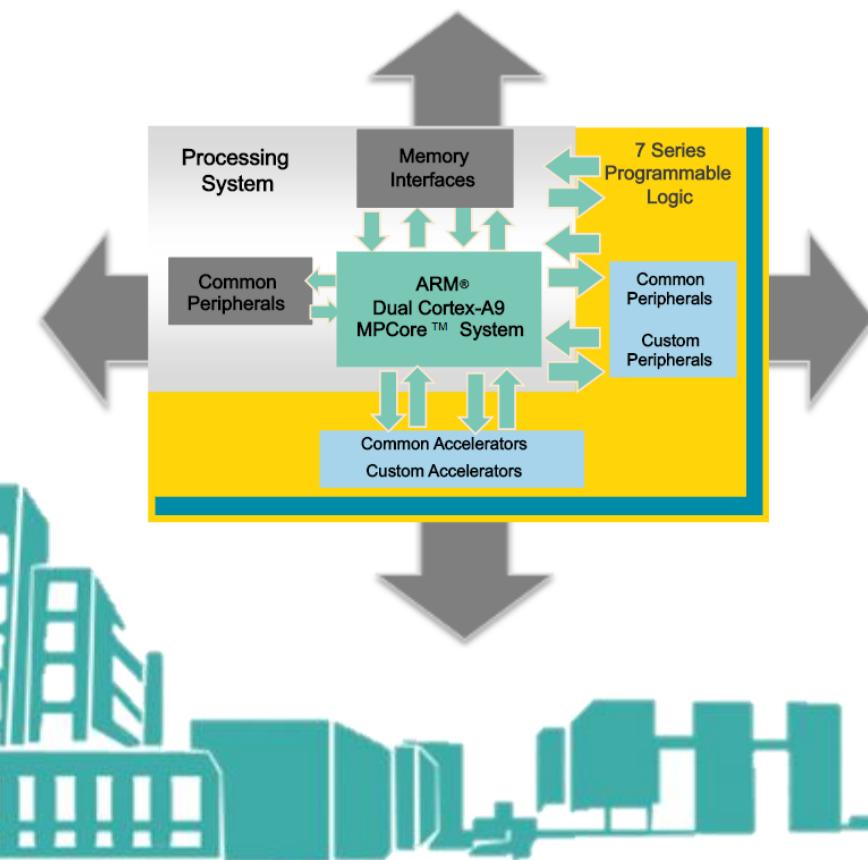
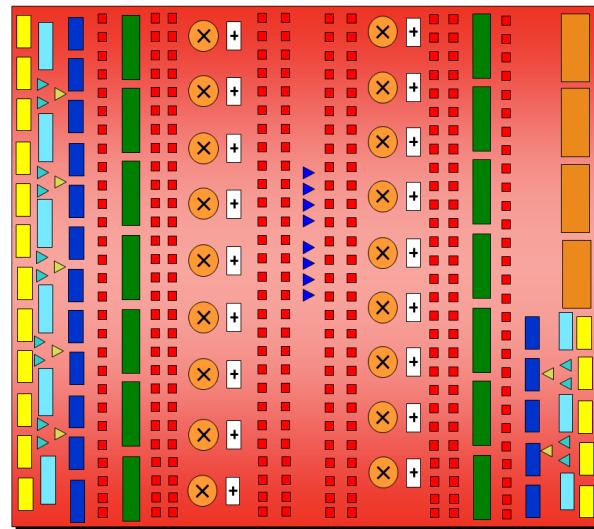


ECE  
IITD

DEPARTMENT OF ELECTRONICS &  
COMMUNICATIONS ENGINEERING

A2A  
*Algorithms to Architecture*

# ECE 270: Embedded Logic Design



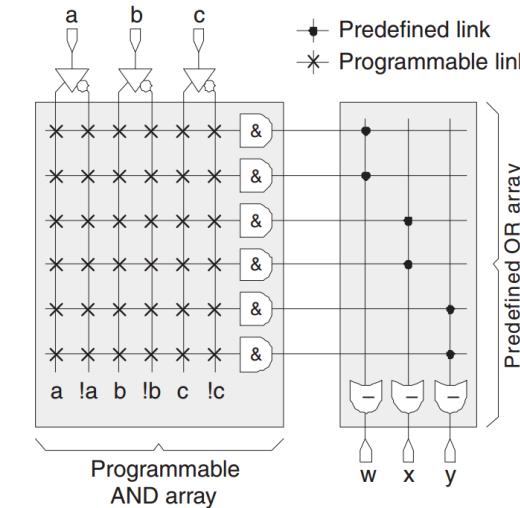
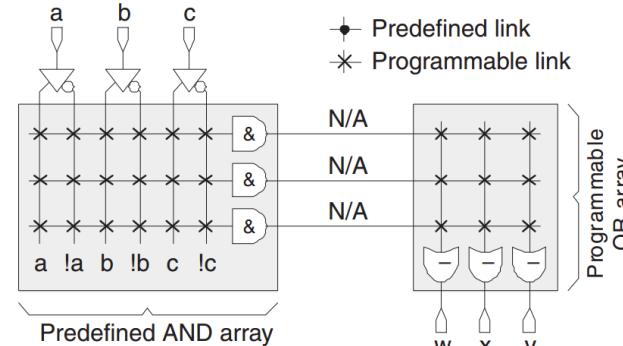
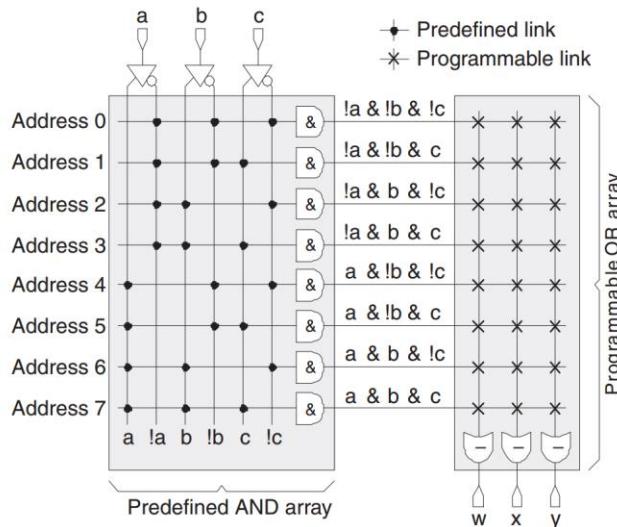
# Evolution of Programmable Logic Device (PLD)

# PLD

- **Programmable logic devices (PLD):** Devices whose **internal architecture is predetermined** by manufacturer but which are created in such a way that they can be **configured in the field** to perform variety of functions
- How to make device field programmable?

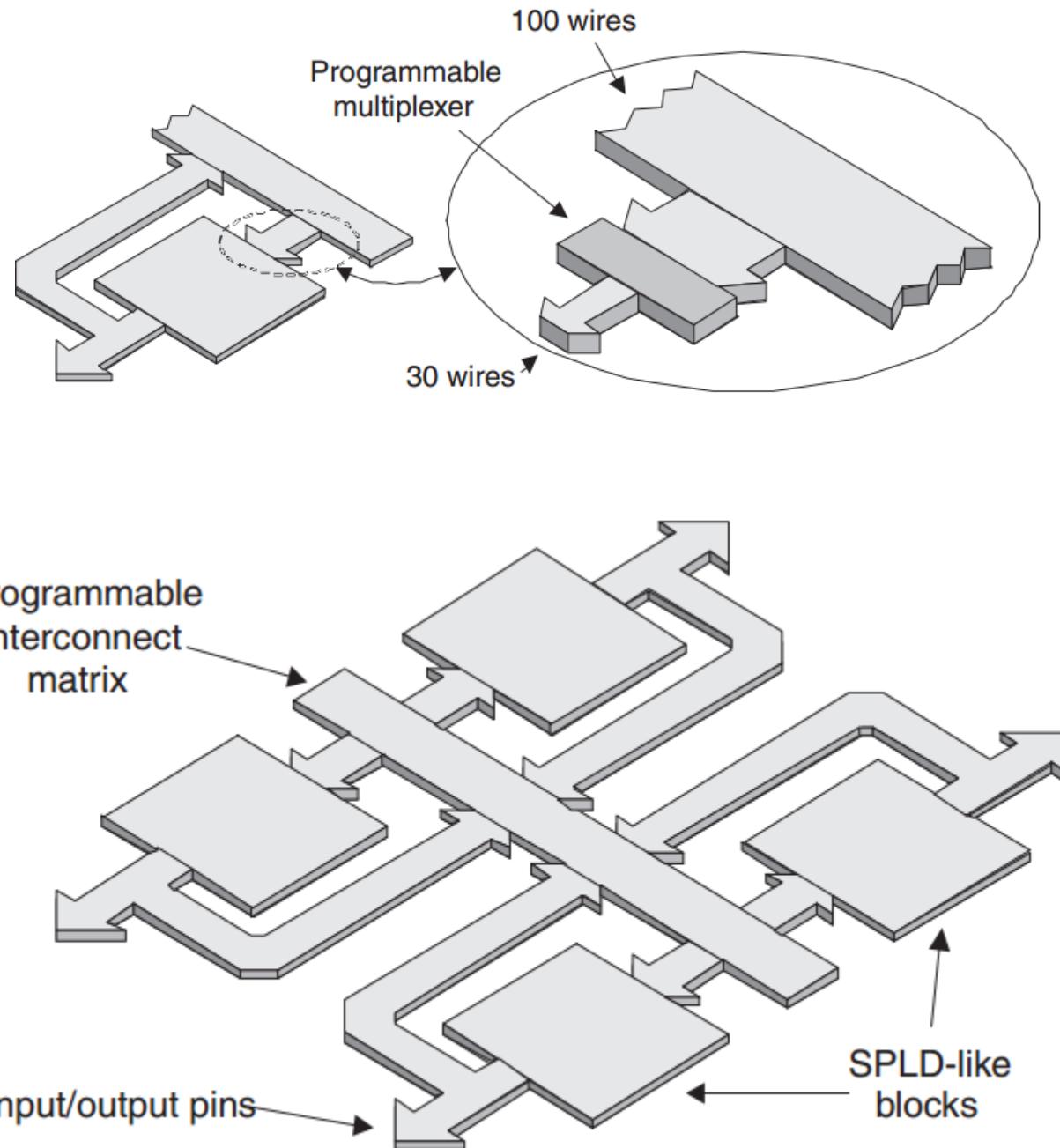
# PLD

- **Programmable logic devices (PLD)**: Devices whose internal architecture is predetermined by manufacturer but which are created in such a way that they can be configured in the field to perform variety of functions



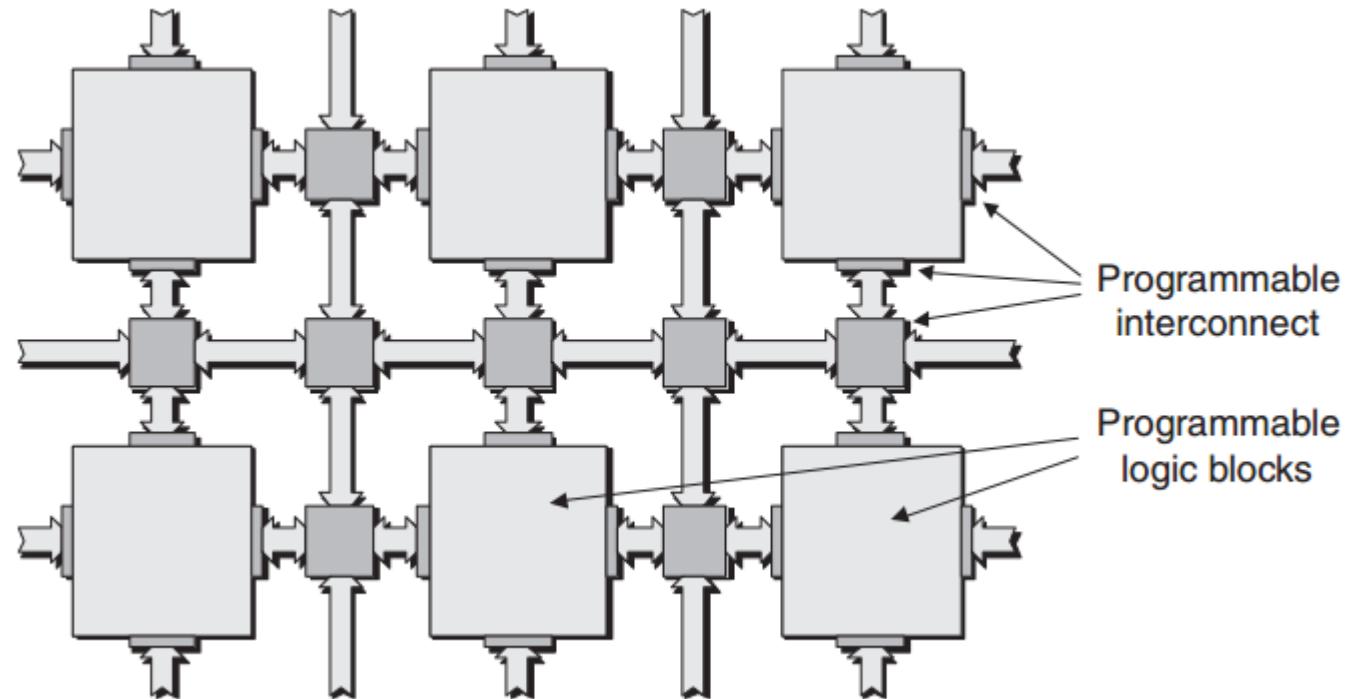
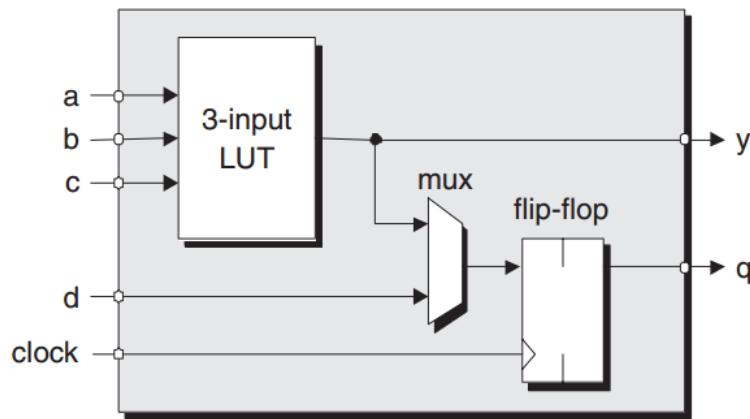
# PAL: Complex PLDs

- Novelty: Central interconnect
- In addition to programming SPLD (PAL), connections can also be programmed using **programmable interconnect matrix**
- This leads to increase in the complexity of software tools

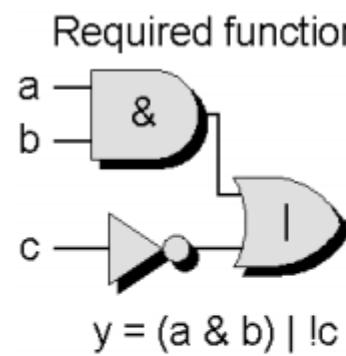
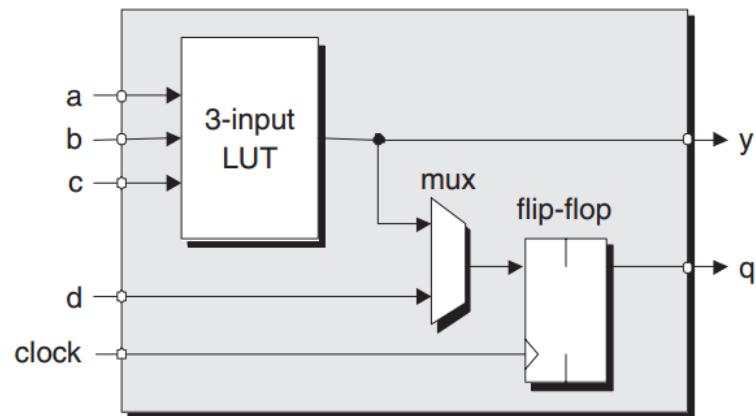


# FPGA Architecture

# FPGA (1984)

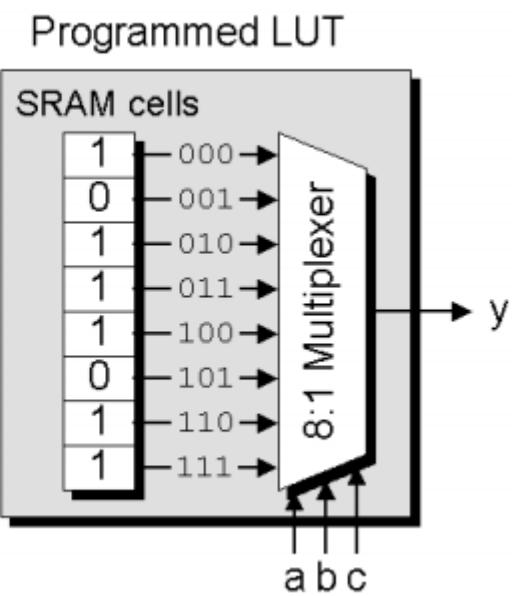


# FPGA (1984)



Truth table

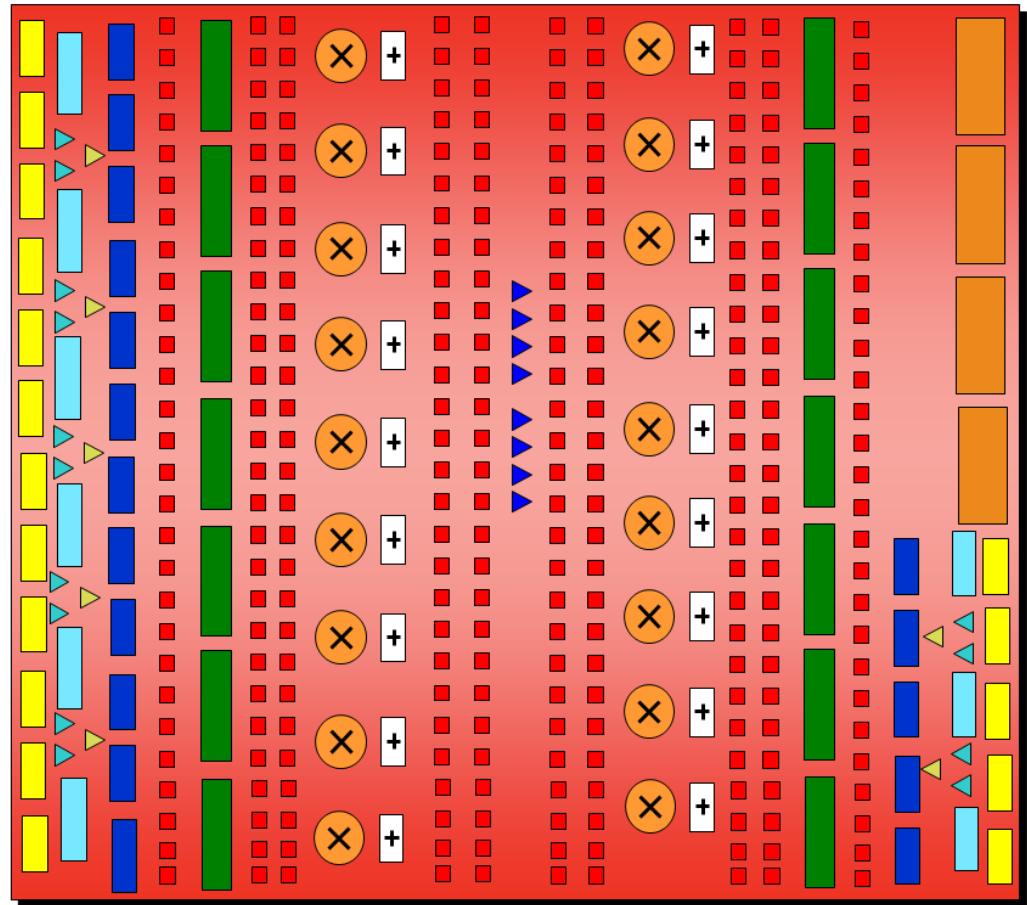
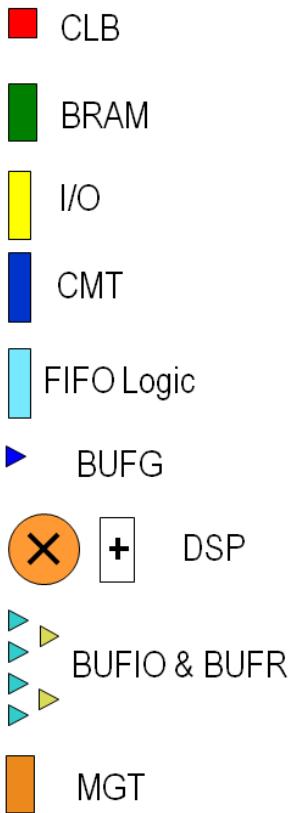
| a | b | c | y |
|---|---|---|---|
| 0 | 0 | 0 | 1 |
| 0 | 0 | 1 | 0 |
| 0 | 1 | 0 | 1 |
| 0 | 1 | 1 | 1 |
| 1 | 0 | 0 | 1 |
| 1 | 0 | 1 | 0 |
| 1 | 1 | 0 | 1 |
| 1 | 1 | 1 | 1 |



# LUT as Memory and LUT as ALU

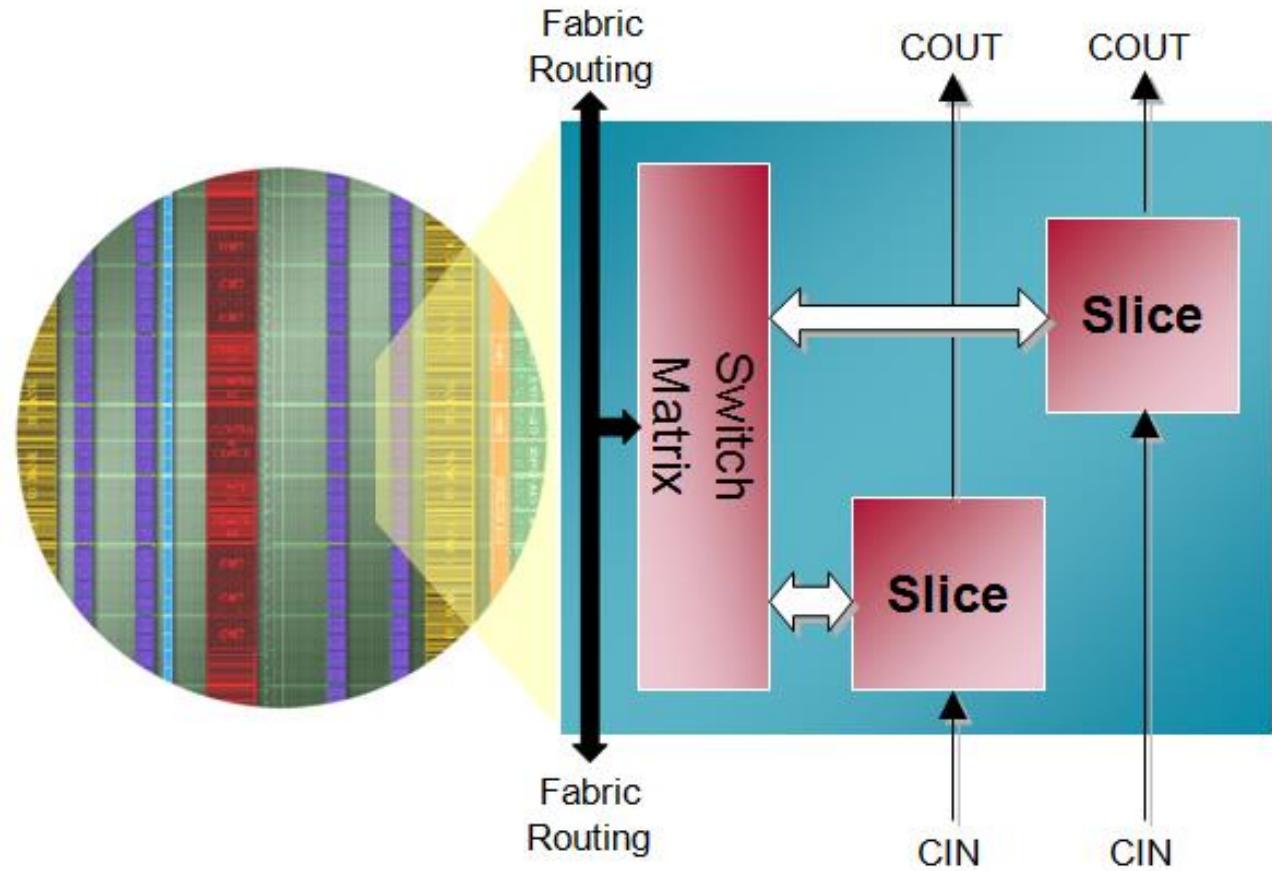
# FPGA Architecture

- All **7-series** families share the same basic building blocks.
- The **mixture and number of these resources varies** across families

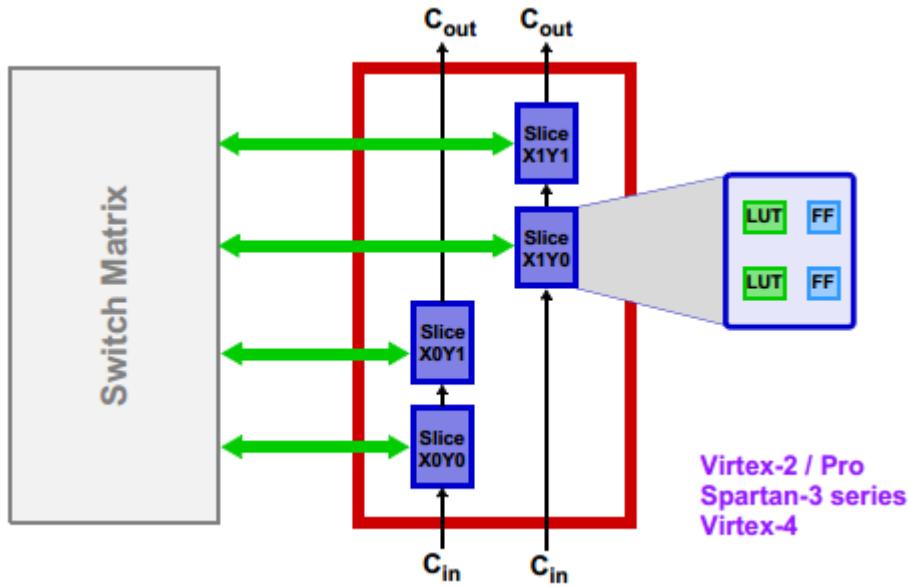


# Configurable Logic Block (CLB)

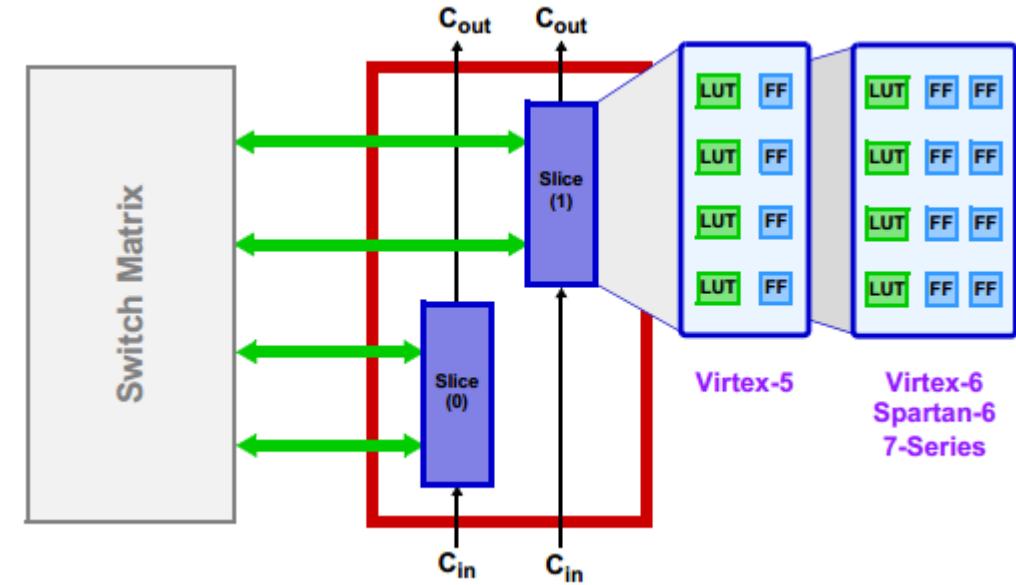
- Primary resource for design in Xilinx FPGAs
- CLB contains more than one slice
- Connected to switch matrix for routing to other FPGA resources
- Carry chain runs vertically in a column from one slice to the one above



# Configurable Logic Block (CLB)



Virtex-2 / Pro  
Spartan-3 series  
Virtex-4

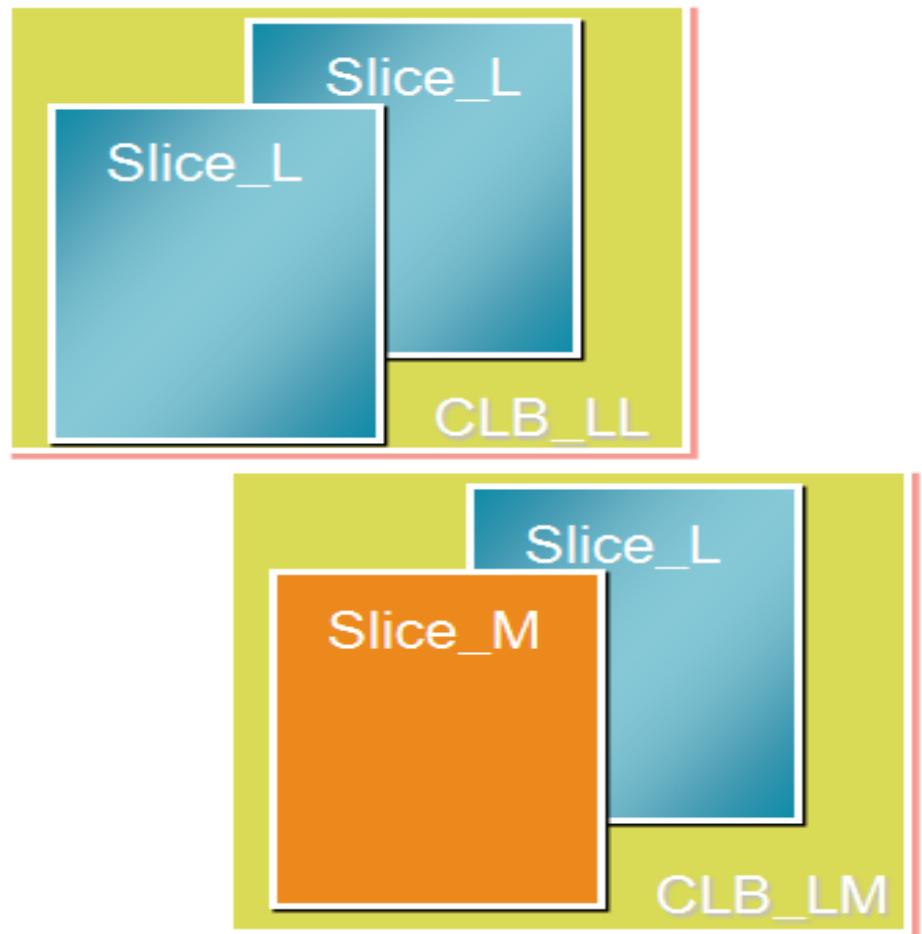


Virtex-5  
Virtex-6  
Spartan-6  
7-Series

| Slices | LUTs | Flip-Flops | Arithmetic and Carry Chains |
|--------|------|------------|-----------------------------|
| 2      | 8    | 16         | 2                           |

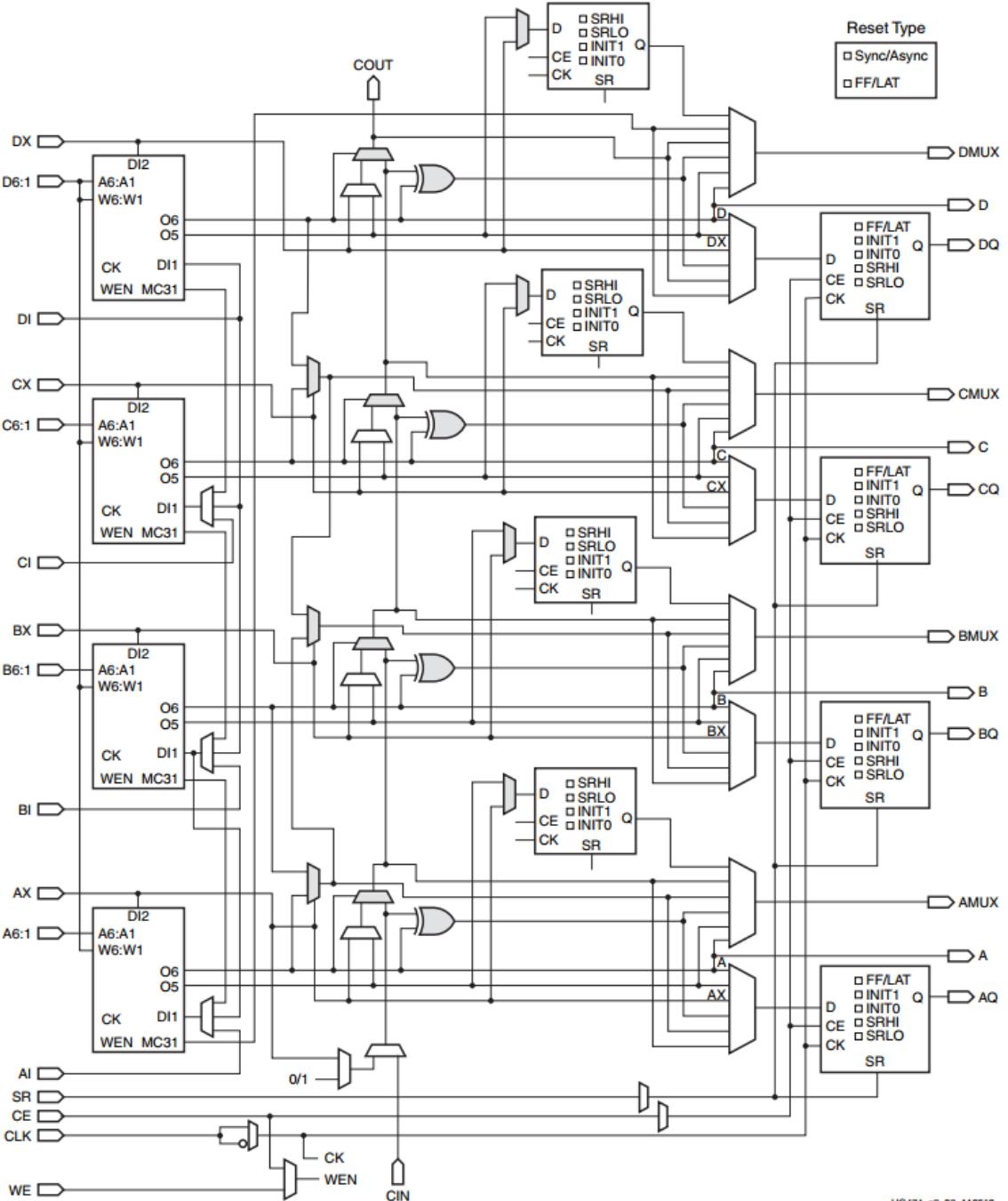
# Types of CLB Slices

- **SLICEM: Full slice**
  - LUT can be used for logic and memory/SRL
- **SLICEL: Logic and arithmetic only**
  - LUT can only be used for logic (not memory/SRL)
- Each CLB can contain **two SLICEL** or a **SLICEL** and a **SLICEM**.
- In the 7-series FPGAs, **approximately  $\frac{1}{4}$  of slices** are SLICEM, the remainder are SLICEL.



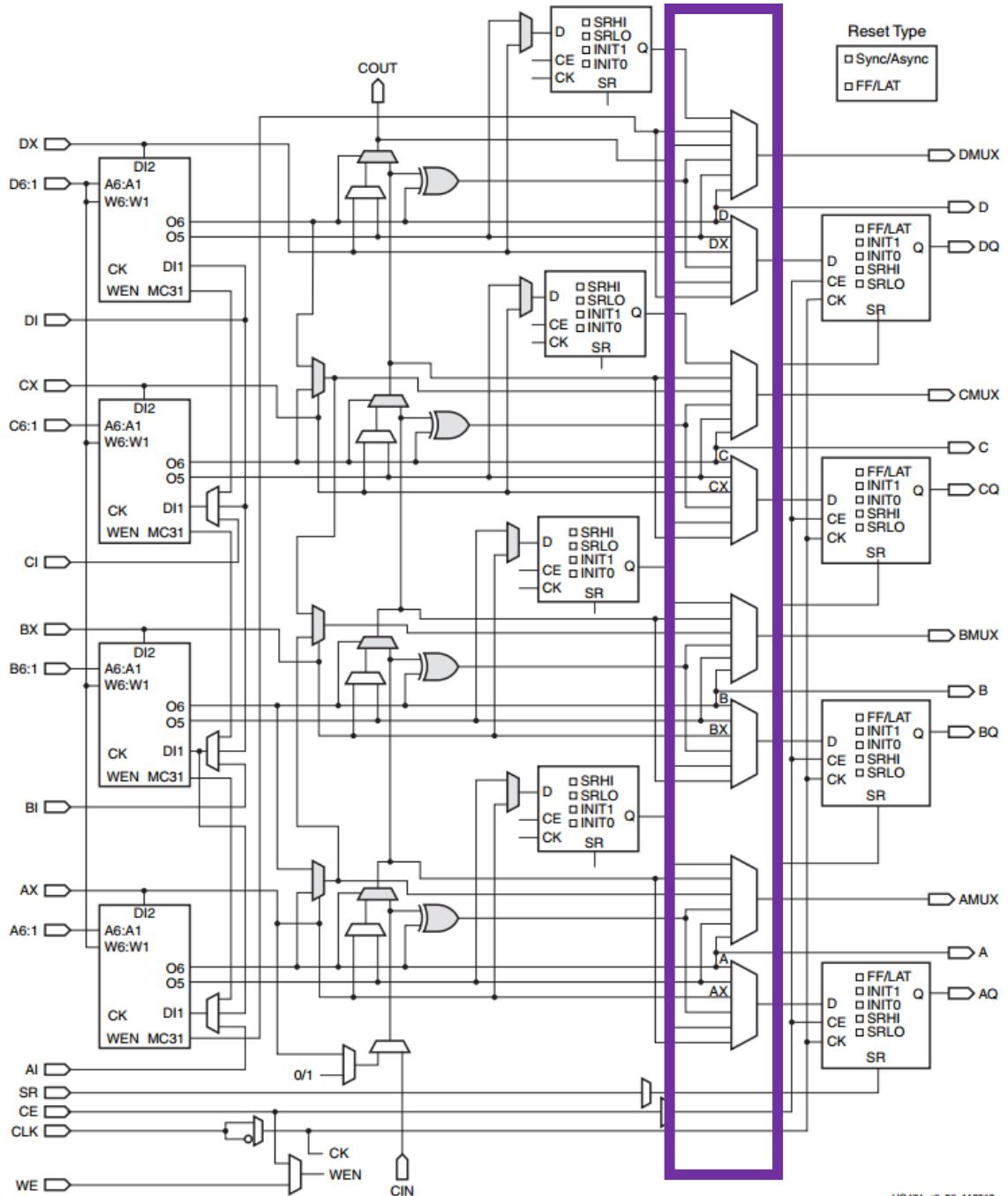
# Slice Resource

- Four six-input Look-Up Tables (LUT)
- Multiplexers
- Carry chains
- Four flip-flops/latches
- Four additional flip-flops
- Four 6-input LUTs and their eight flip-flops as well as multiplexers and arithmetic carry logic form a slice, and two slices form a CLB.



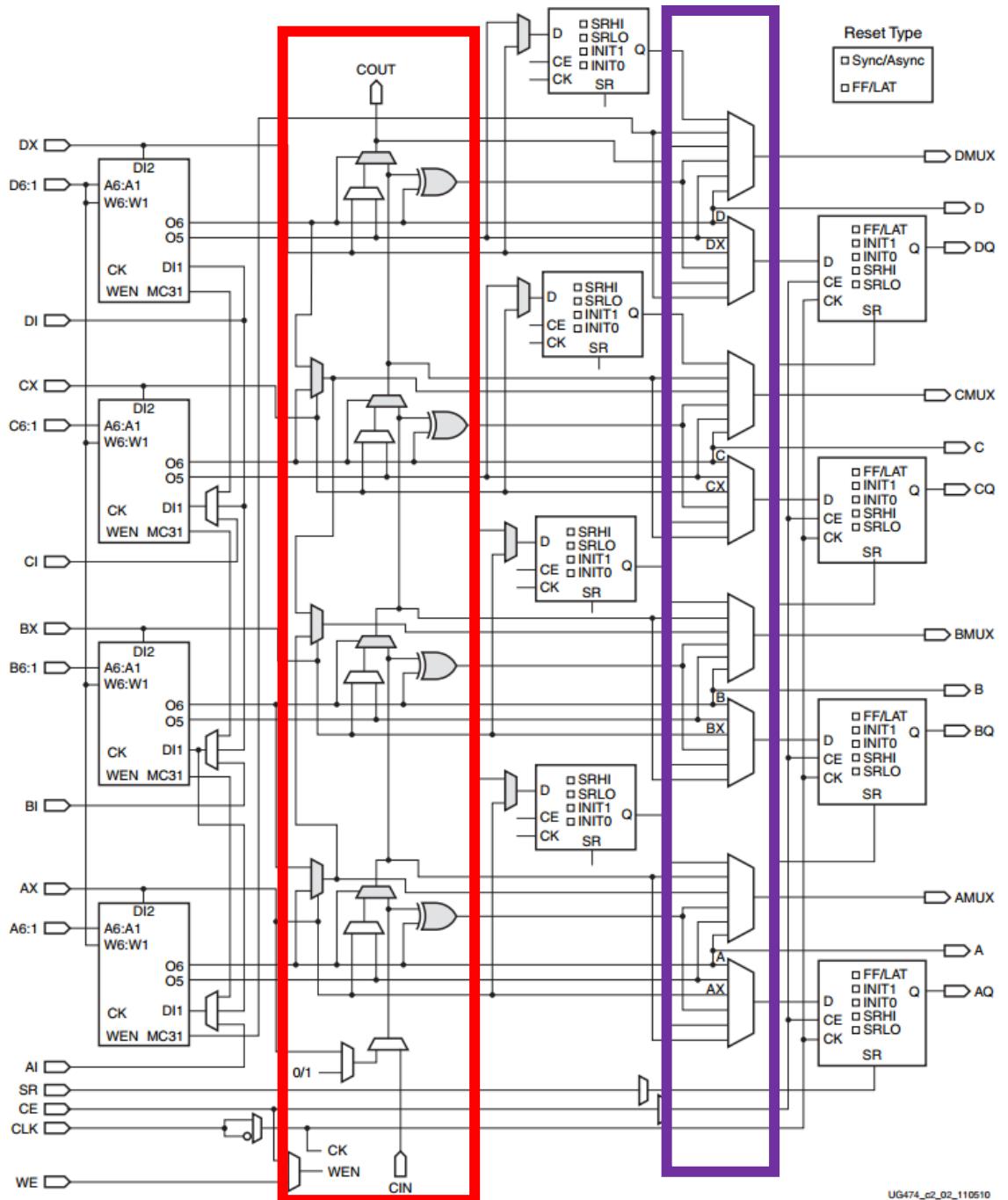
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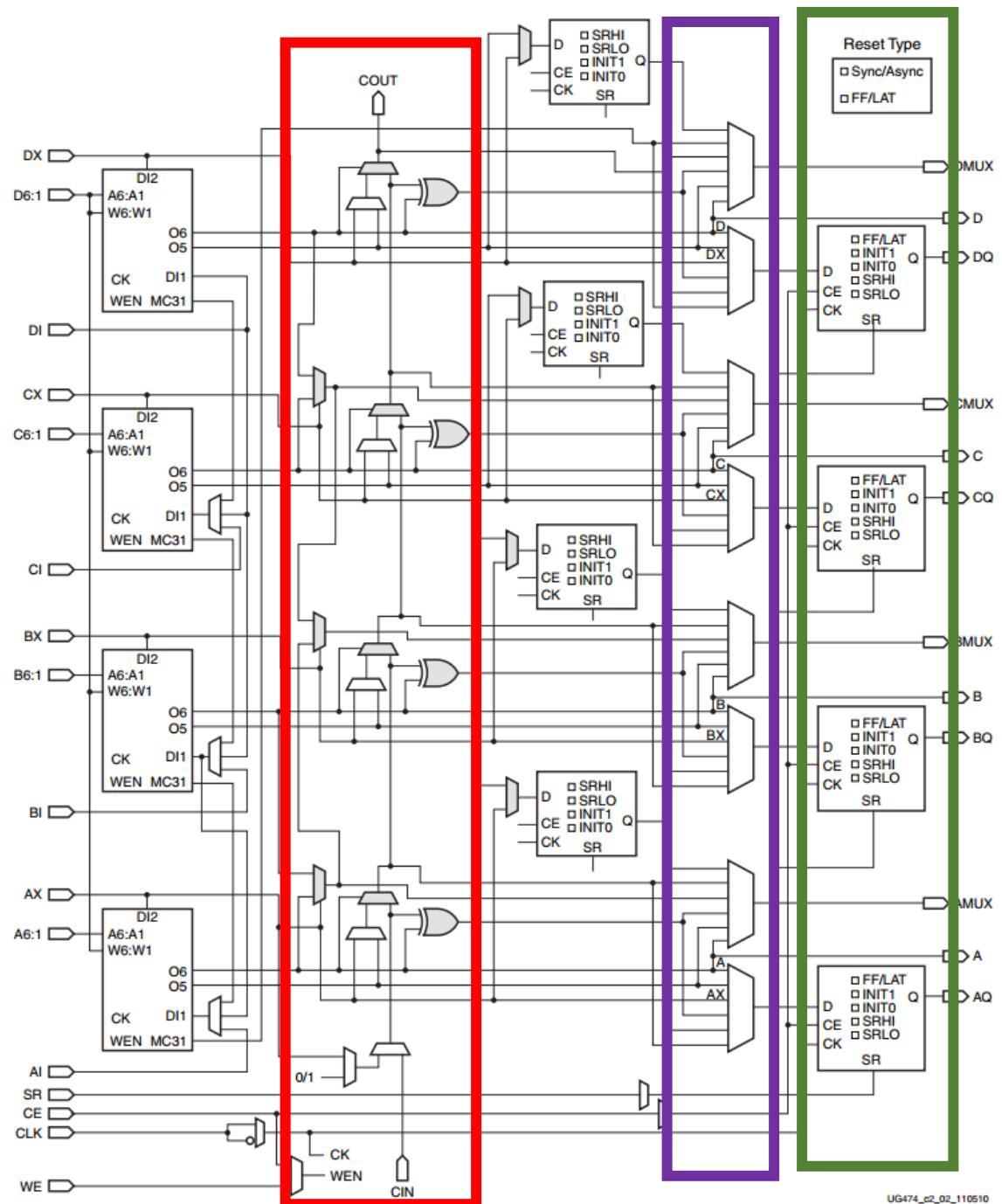
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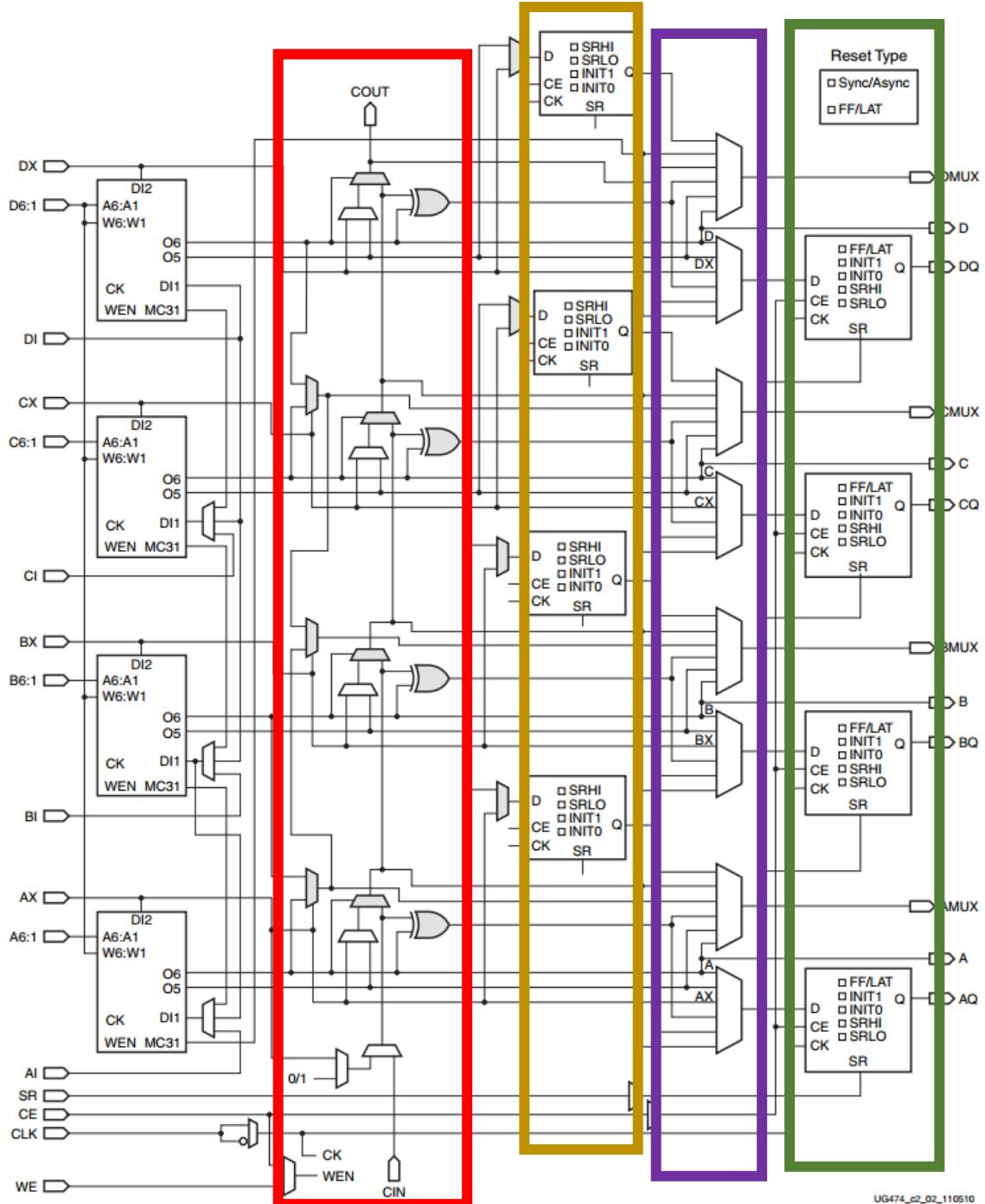
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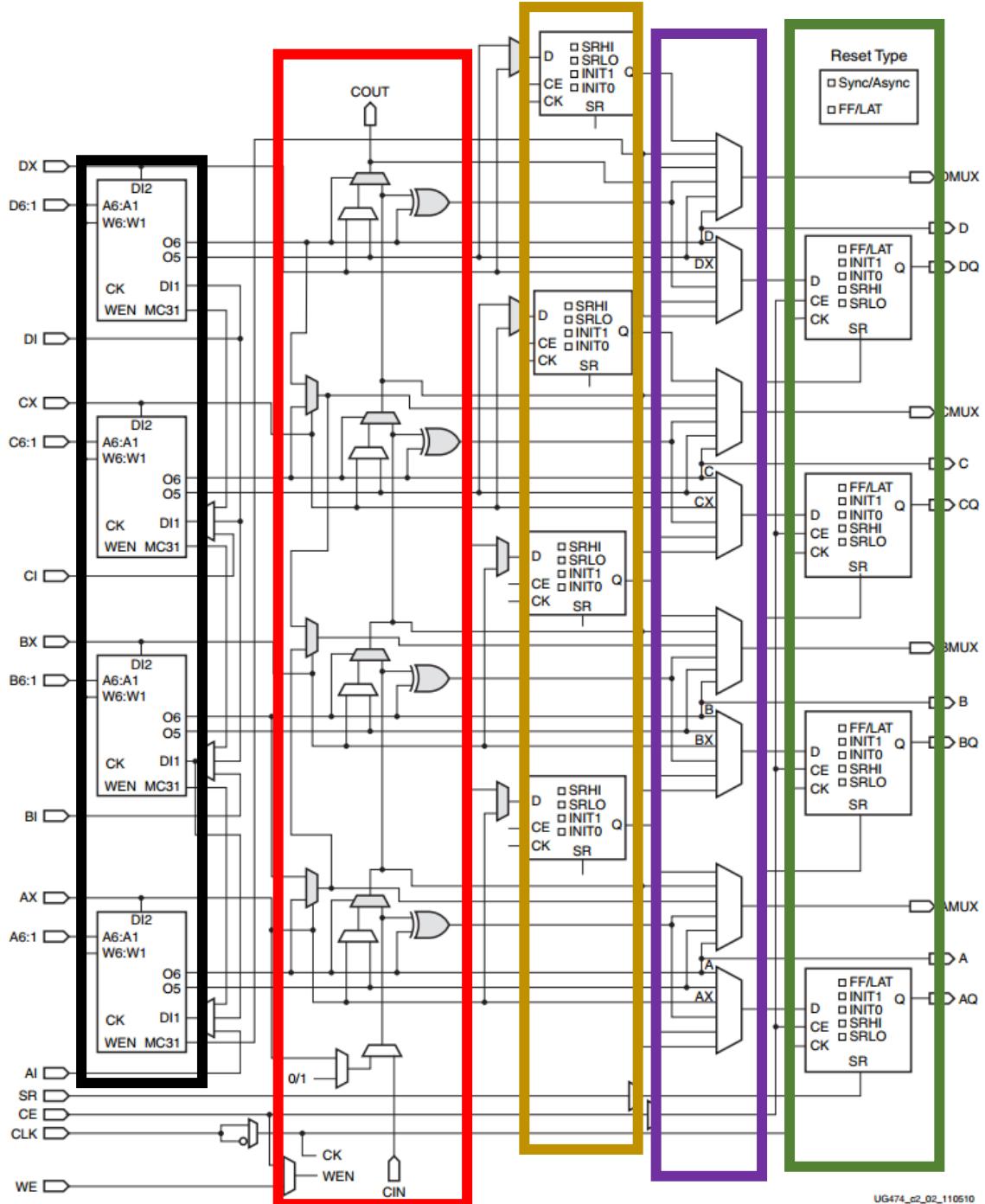
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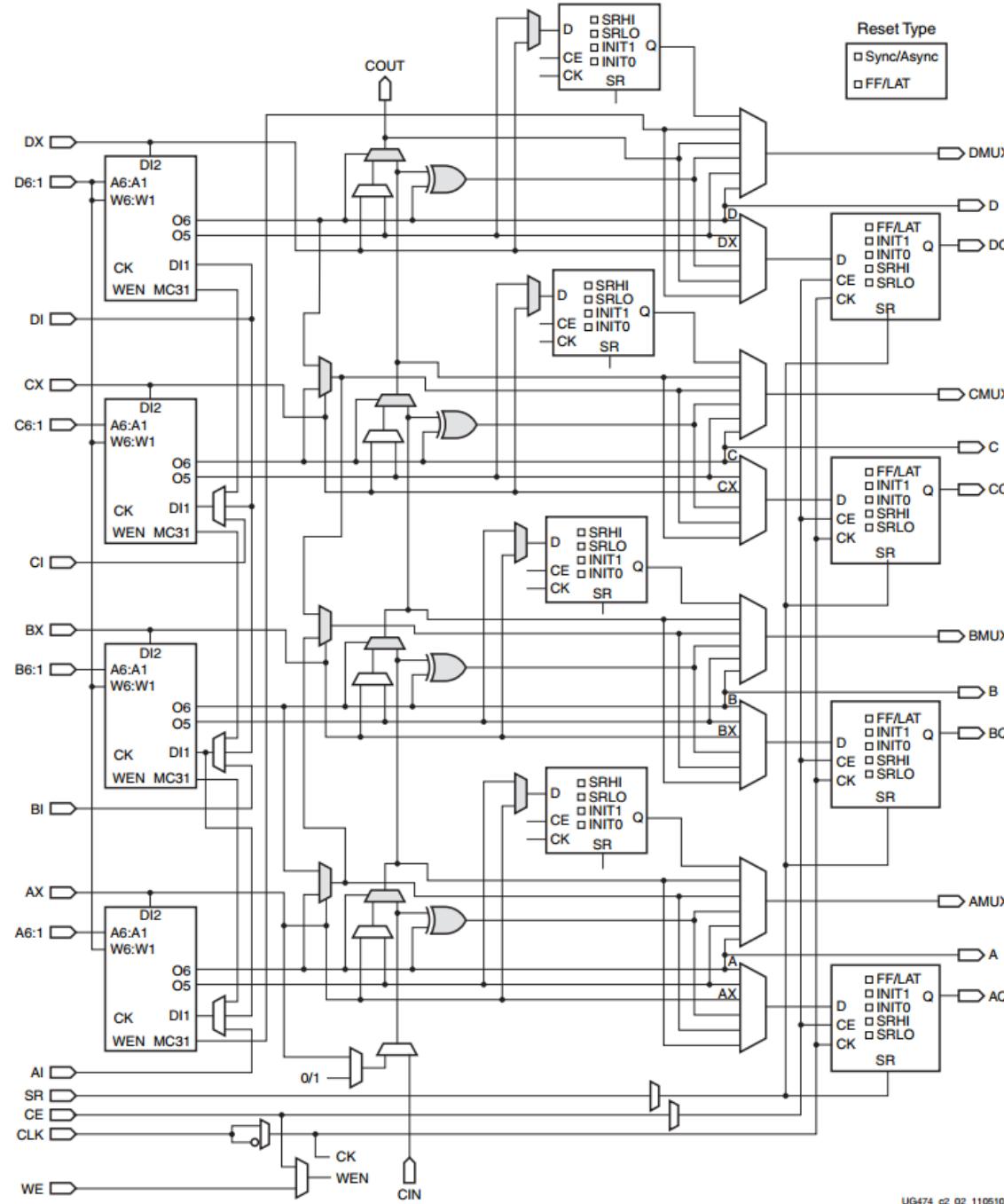


# Slice Resource

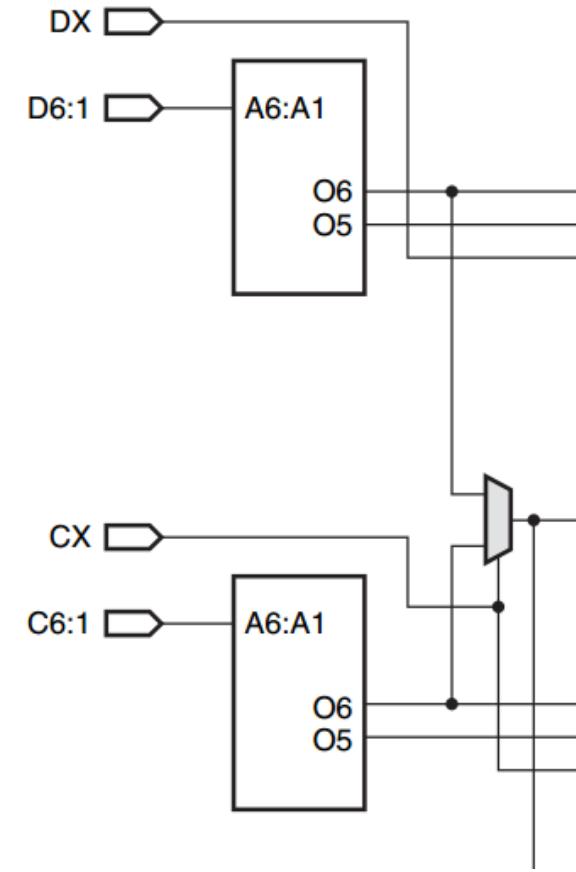
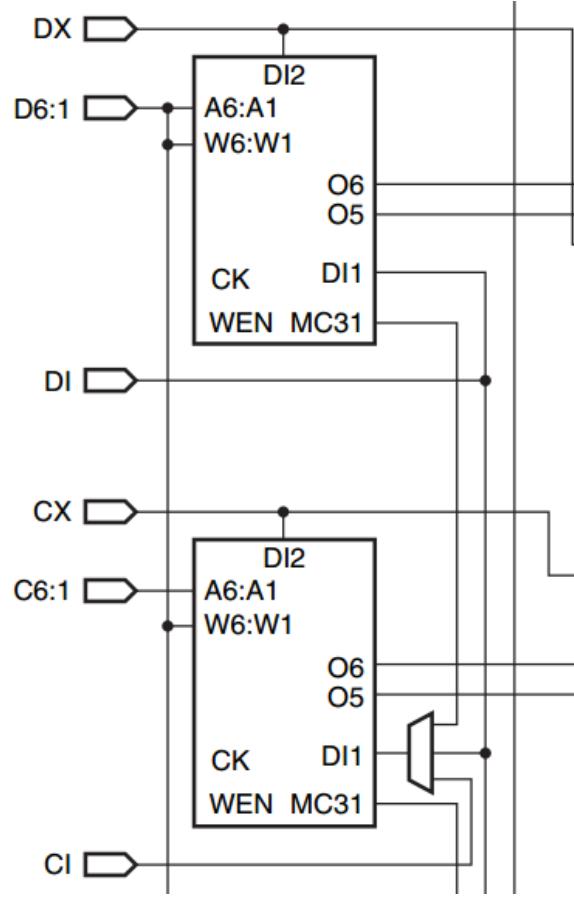
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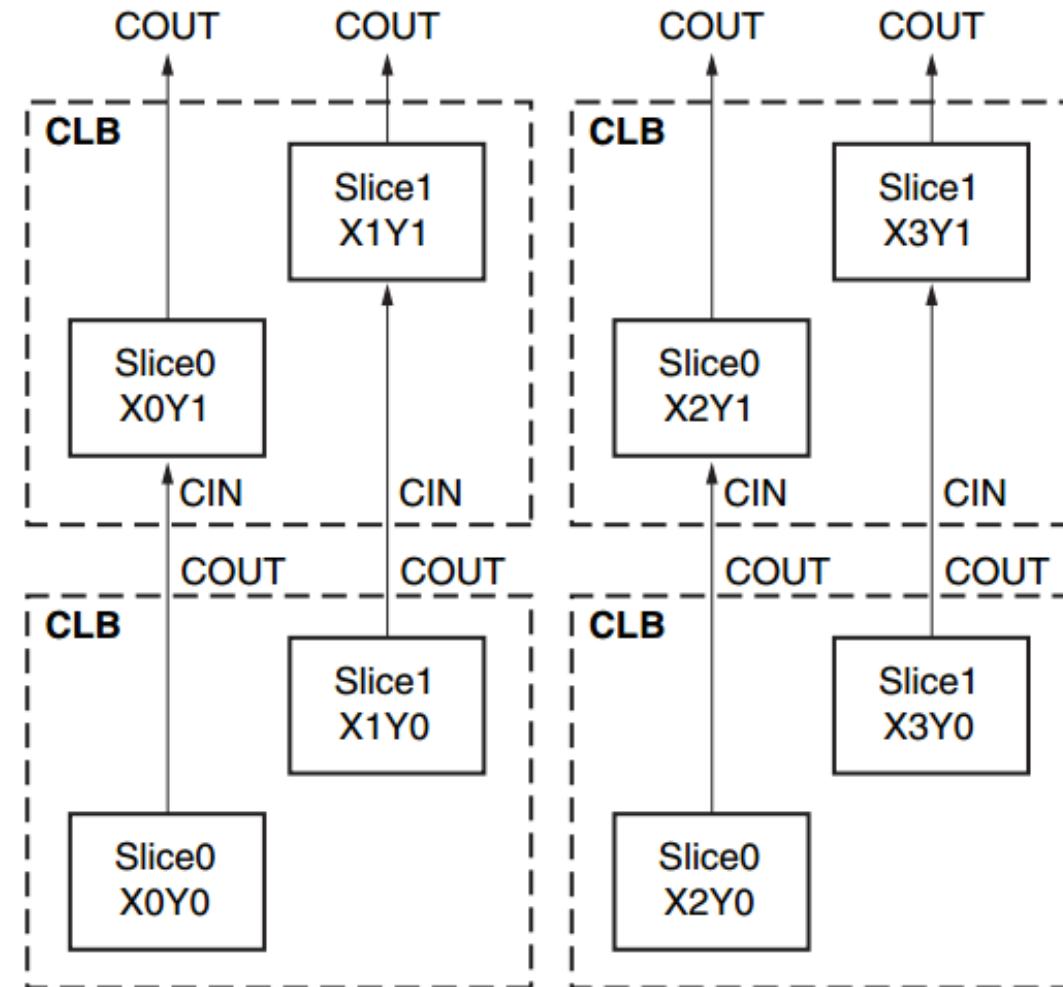
# SLICEM



# SLICEM Vs SLICEL

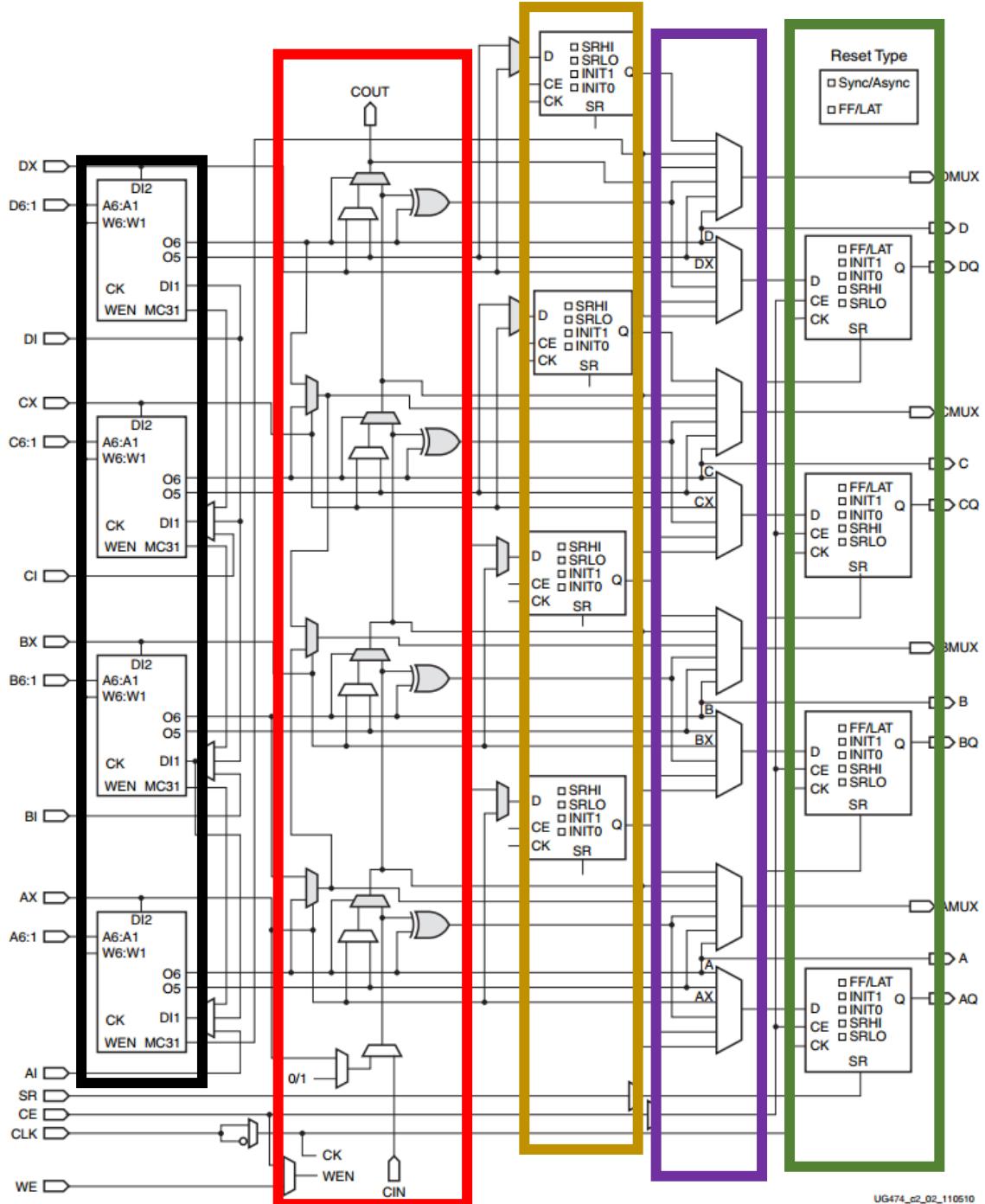


# Configurable Logic Block (CLB)



# Slice Resource

- Four six-input Look-Up Tables (LUT)
- Multiplexers
- Carry chains
- Four flip-flops/latches
- Four additional flip-flops
- Four 6-input LUTs and their eight flip-flops as well as multiplexers and arithmetic carry logic form a slice, and two slices form a CLB.



# Vector and Memory

# Verilog: Vectors

- Only “**net**” or “**reg**” data types can be declared as vectors (multiple bit width).
- Specifying vectors for **integer**, **real**, **realtime**, and **time** data types is **illegal**.
- Default: 1 bit (scalar). Example: **wire** [7:0] a\_byte; **reg** [31:0] a\_word;

```
reg [11:0] counter ;
reg a ;
reg [2:0] b ;
a = counter[7] ; // bit seven is loaded into a
b = counter[4:2] ; // bits 4, 3, and 2 are loaded into b
```

# Verilog: Vectors

- **MSB and LSB expressions** should be constant expressions and may be positive, negative, or zero.
- The LSB constant expression may be greater, equal or less than the MSB constant expression.
- **reg** [3:0] addr;

The 'addr' variable is a 4-bit vector register made up of addr[3] (the most significant bit), addr[2], addr[1], and addr[0] (the least significant bit).

- **wire** [-3:4] data;

The data variable is 8-bit vector net made up of data[-3] (msb), data[-2], data[-1], data[0], data[1], data[2], data[3], data[4] (lsb).

# Verilog: Vectors

- 8-bit vector net called a\_in:

```
wire [7:0] a_in ;
```

- A 32-bit storage register called address:

```
reg [31:0] address ;
```

- Set the value of the register to 32-bit decimal number equal to 3

```
address = 32'd3 ;
```

# Verilog: Vector Indexing

```
// Break down a 40-bit vector string into 5 separate bytes
Use 5 bytes hard-coded slices

module indexarr ;
    reg [39:0] str ; // string
initial
begin
    str = "abcde";
    $display("%s", str[7:0]);
    $display("%s", str[15:8]);
    $display("%s", str[23:16]);
    $display("%s", str[31:24]);
    $display("%s", str[39:32]);
end
endmodule // output: e, d, c, b, a
```

# Verilog: Vector Indexing

```
reg [63:0] word ;  
reg [3:0] byte_num ; //a value from 0 to 7.  
reg [7:0] byteN ;  
  
// If byte_num = 4  
byteN = word[byte_num*8 +: 8] ; //= word[39:32]  
  
reg [31:0] a ;  
b = a[8+:16] ; // b = a[23:8]  
c = a[31-:8] ; // c = a[31-24]
```

# Verilog: Vector Indexing

- Verilog allows indexing vectors using variable expression to perform dynamic parts select
- The syntax is as follows:
  - [base\_expression **+:** width\_expression] or
  - [base\_expression **-:** width\_expression]
- The base\_expression can be a variable expression but **width\_expression must be a constant**
- Offset direction indicates if the width\_expression is added (+:) or subtracted (-:) from the base\_expression

# Verilog: Vector Indexing

// Break down a 40-bit vector string into 5 separate bytes

Use 5 bytes hard-coded slices

```
module indexarr ;
    reg [39:0] str ; // string
    initial
        begin
            str = "abcde";
            $display("%s", str[7:0]);
            $display("%s", str[15:8]);
            $display("%s", str[23:16]);
            $display("%s", str[31:24]);
            $display("%s", str[39:32]);
        end
    endmodule
```

// output: e, d, c, b, a

Use indexed part select

```
module indexarr ;
    reg [39:0] str ; // string
    integer i ;
    initial
        begin
            str = "abcde";
            for (i = 0 ; i < 5 ; i = i + 1)
                $display("%s", str[i*8 +: 8]);
        end
    endmodule
```

# Verilog: Memory

- Registers and memories can be declared in the same line
- **reg** [3:0] mem[255:0], red;
- This line declares **4-bit register 'red'** and **memory 'mem'**, which contains 256 4-bit words.

# Verilog: Memory

- Elements of memory type can be accessed by memory index
- **reg** [7:0] mem [3:0], red;  
mem[0] = 7;  
red = mem[3];  
mem[1] = red;

# Verilog: Memory

- Vector and memory declarations are NOT the same.
- If a variable is declared as a **vector**, all bits can be assigned a value in one statement.
- If a variable is declared as **memory**, then a value to each element should be assigned separately

• **reg [7:0] vect= 8'b11001010;**

**reg array[7:0];**

array[7] = 1'b1;

array[6] = 1'b1;

array[5] = 1'b0;

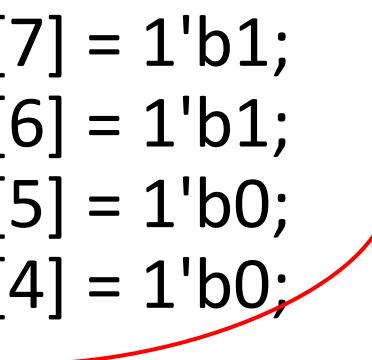
array[4] = 1'b0;

array[3] = 1'b1;

array[2] = 1'b0;

array[1] = 1'b1;

array[0] = 1'b0;



# Verilog: Memory

```
reg [7:0] my_reg [0:31];      // Array of 32 byte-wide registers  
  
integer matrix [4:0] [0:255]; // 2-dimentional Array of integers  
  
my_reg[15]; // Referencing the 16th byte of the array register
```

# Verilog: Memory

```
wire [1:0] my_reg [0:3];
wire [1:0] my_reg1 [3:0];

assign my_reg[1]=2'b10;
assign my_reg[3]=2'b11;
assign my_reg1[1]=2'b10;
assign my_reg1[3]=2'b11;
```

- The content of my\_reg will be {Z,2,Z,3} and my\_reg1 will be {3,Z,2,Z}

# Verilog: Memory

```
reg [31:0] array2 [0:255][0:15] ;
```

- Select fourth byte from 101<sup>th</sup> row and 8<sup>th</sup> column.

```
wire [7:0] out2 = array2[100][7][31:24] ;
```

# Verilog: Memory

1. Read 2nd byte from address 11 to data\_out1.
2. Read 2nd and 3rd bytes from address 77 to data\_out2.

```
reg [31:0] Data_RAM[0:255] ;  
output reg [7:0] data_out1 ;  
output reg [15:0] data_out2 ;
```

1. data\_out1 = Data\_RAM[11][15:8] ;
2. data\_out2 = Data\_RAM[77][23:8] ;

# Verilog: Memory

- Memories are modeled as array of registers.

```
reg [7:0] my_memory[0:1023] ; // 1K bytes memory  
// read a byte from address 511  
data_out = my_memory[511] ;  
// Write a byte to address 374  
my_memory[374] = data_in ;
```

# Self-study

## ■ Array declarations

```
reg [7:0] mema[0:255]; // declares a memory mema of 256 8-bit registers. The indices are 0 to 255  
reg arrayb[7:0][0:255]; // declare a two-dimensional array of one bit registers  
wire w_array[7:0][5:0]; // declare array of wires  
integer inta[1:64]; // an array of 64 integer values  
time chng_hist[1:1000] // an array of 1000 time values  
integer t_index;
```

## ■ Assignment to array elements

```
mema = 0; // Illegal syntax- Attempt to write to entire array  
arrayb[1] = 0; // Illegal Syntax - Attempt to write to elements [1][0]..[1][255]  
arrayb[1][12:31] = 0; // Illegal Syntax - Attempt to write to elements [1][12]..[1][31]  
mema[1] = 0; // Assigns 0 to the second element of mema  
arrayb[1][0] = 0; // Assigns 0 to the bit referenced by indices [1][0]  
inta[4] = 33559; // Assign decimal number to integer in array  
chng_hist[t_index] = $time; // Assign current simulation time to element addressed by integer index
```

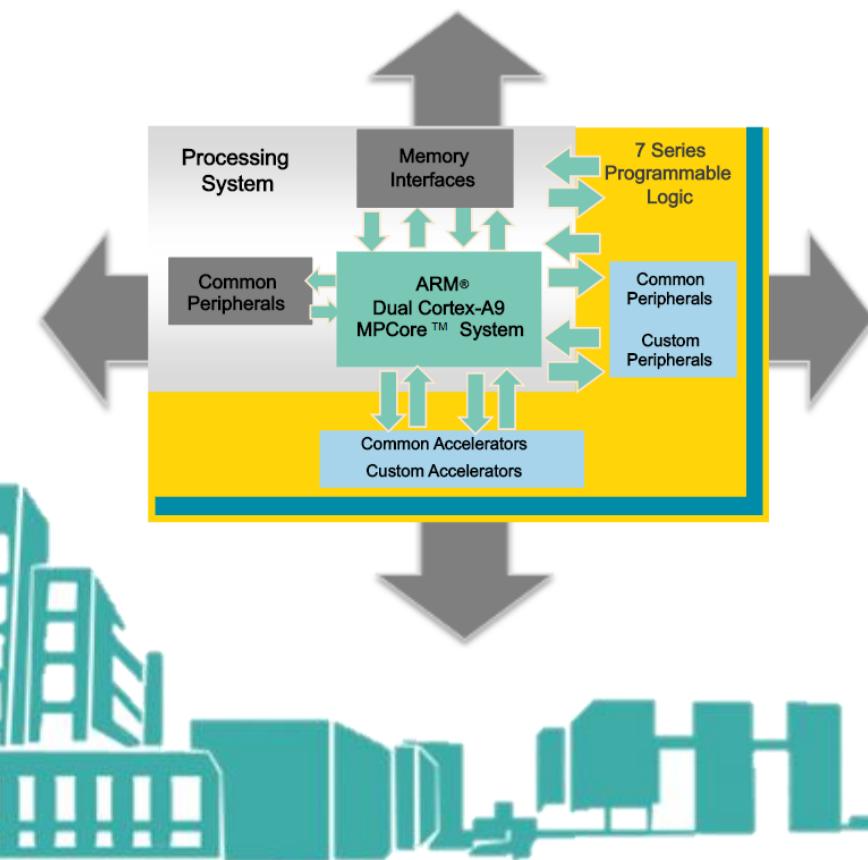
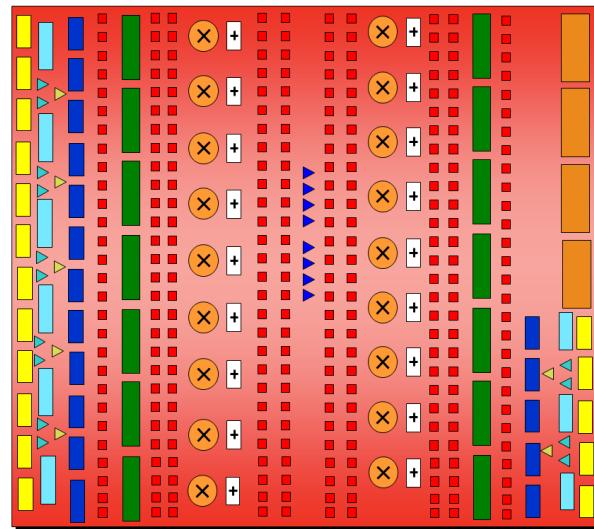


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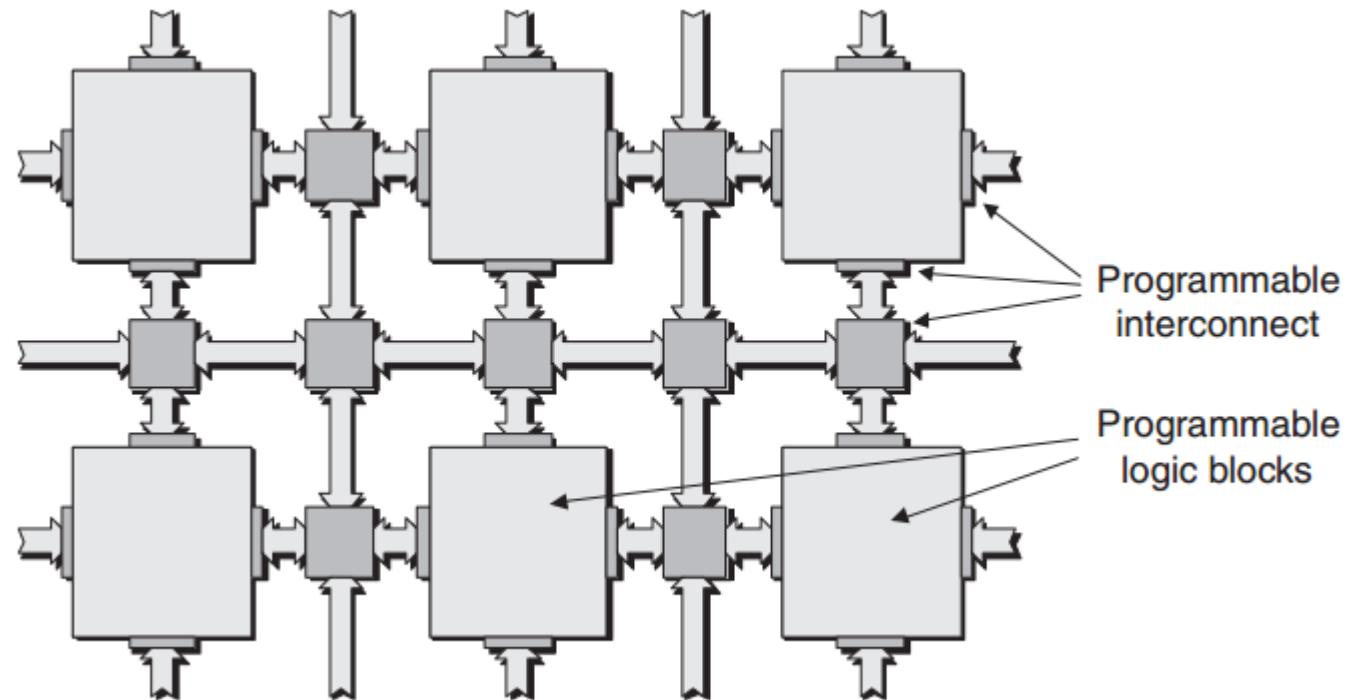
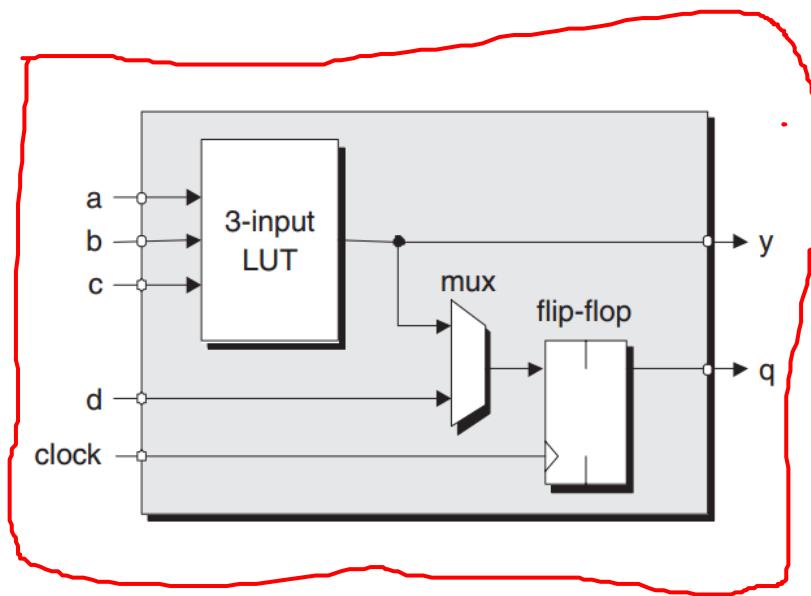
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# ECE 270: Embedded Logic Design

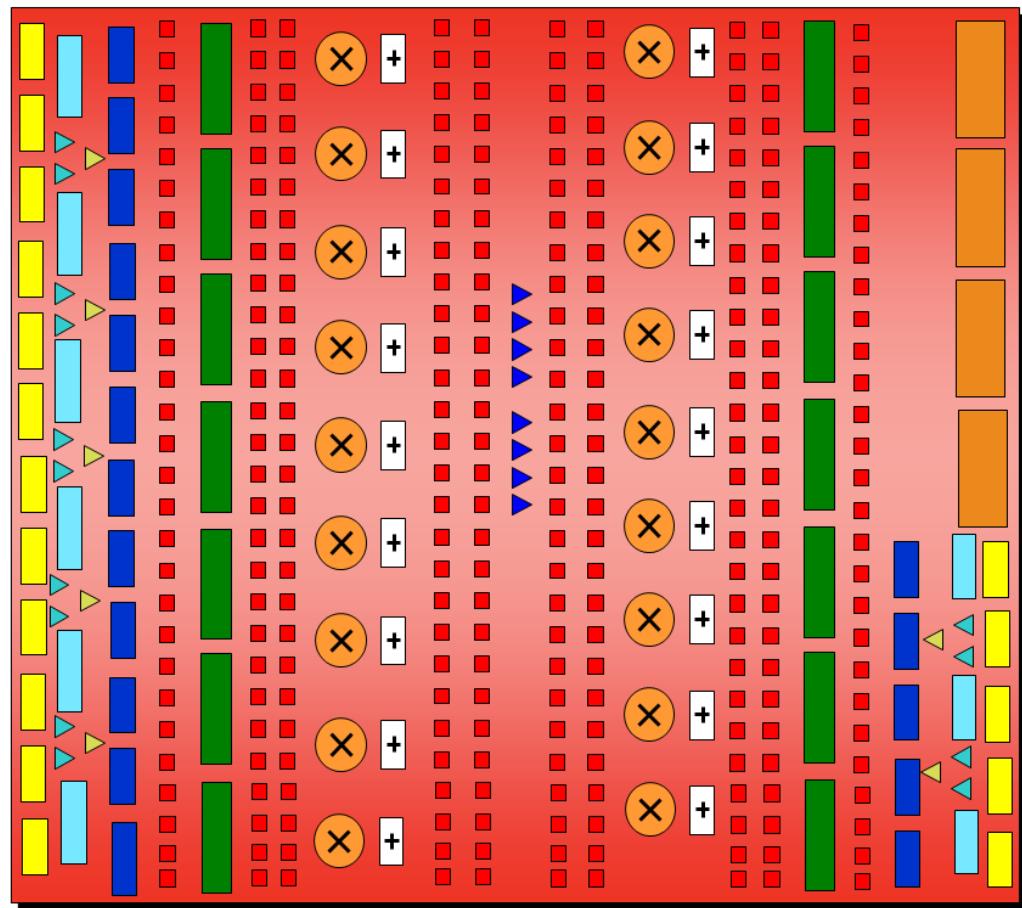
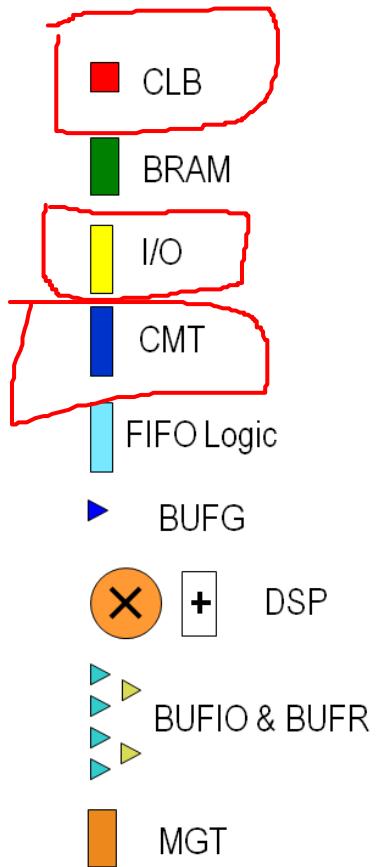


# FPGA (1984)



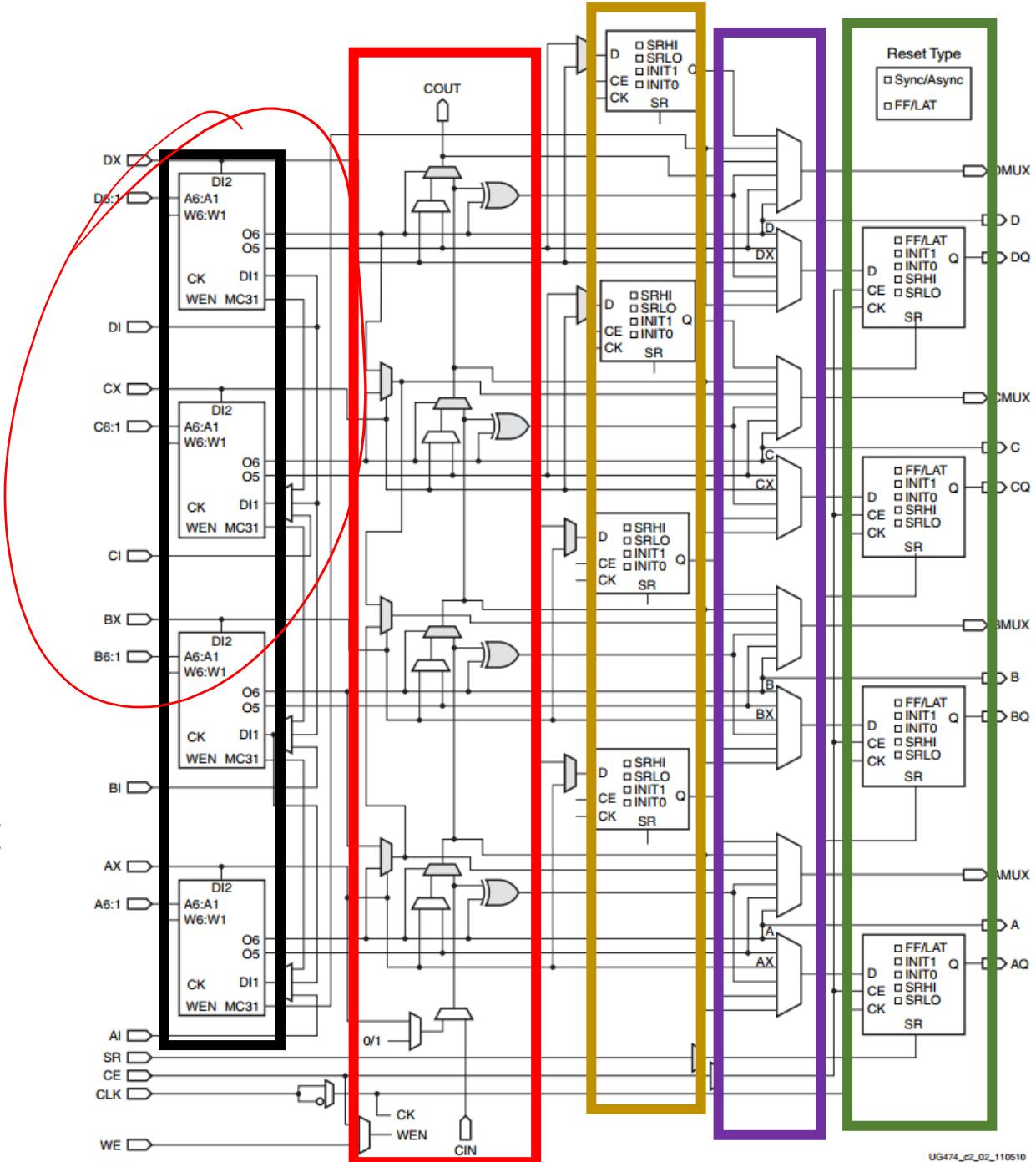
# FPGA Architecture

- All **7-series** families share the same basic building blocks.
- The **mixture and number of these resources varies** across families

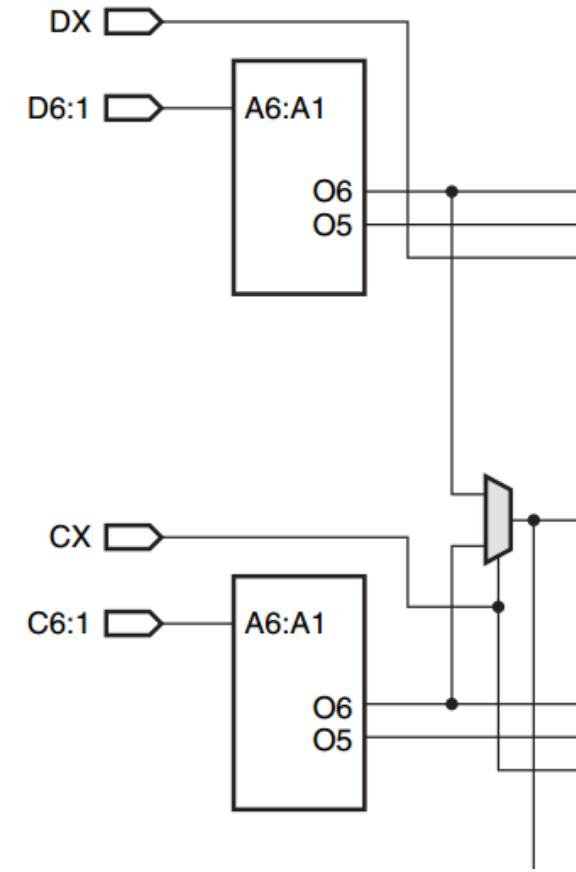
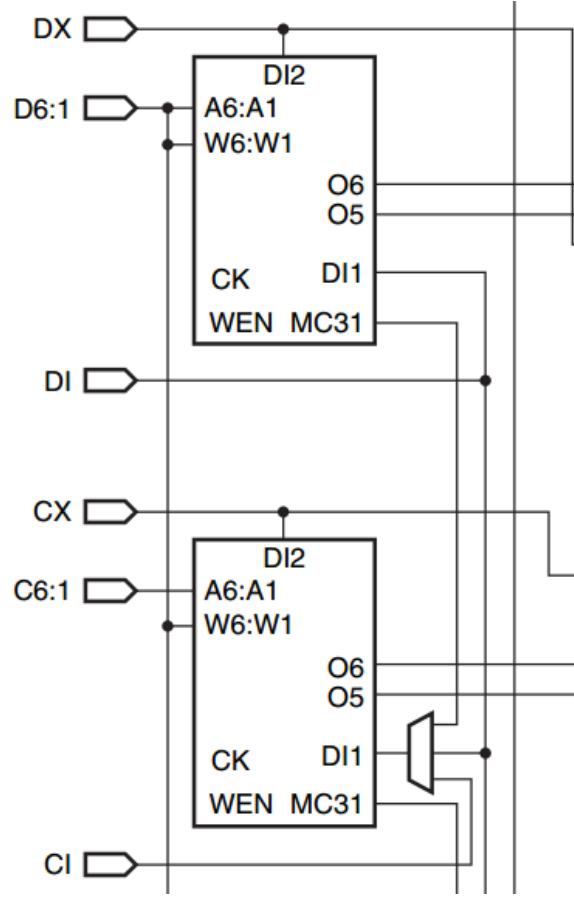


# Slice Resource

- Four six-input Look-Up Tables (LUT)
- Multiplexers
- Carry chains
- Four flip-flops/latches
- Four additional flip-flops
- Four 6-input LUTs and their eight flip-flops as well as multiplexers and arithmetic carry logic form a slice, and two slices form a CLB.



# SLICEM Vs SLICEL



# Vector and Memory

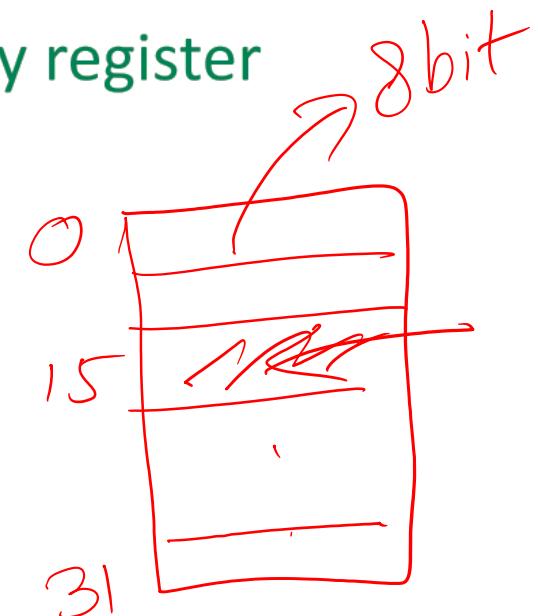
# Verilog: Memory

32bit

reg [7:0] my\_reg [0:31]; // Array of 32 byte-wide registers

? integer matrix [4:0] [0:255]; // 2-dimentional Array of integers

my\_reg[15]; // Referencing the 16th byte of the array register

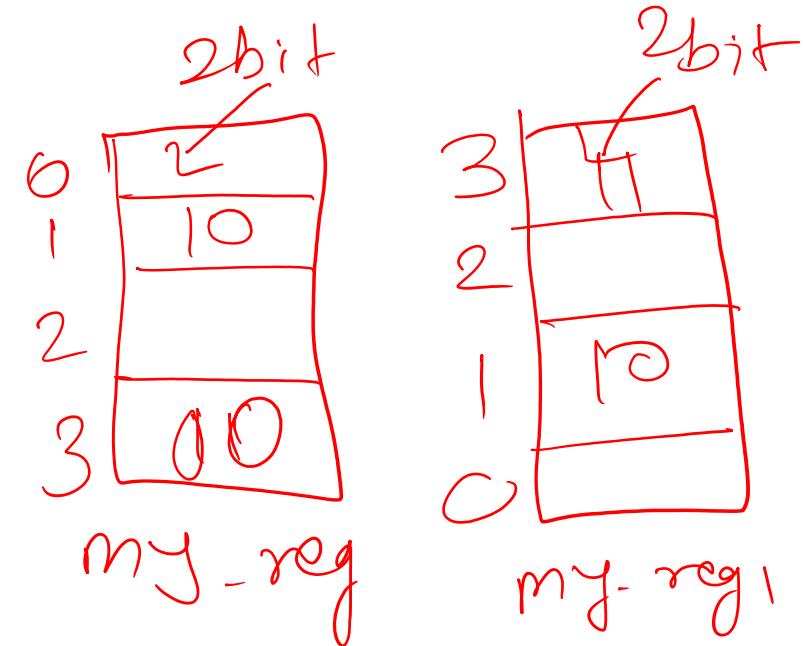


# Verilog: Memory

```
wire [1:0] my_reg [0:3];  
wire [1:0] my_reg1 [3:0];
```

✓  
assign my\_reg[1]=2'b10;  
assign my\_reg[3]=2'b11;  
assign my\_reg1[1]=2'b10;  
assign my\_reg1[3]=2'b11;

Assign my\_reg[3]=2'b00;



- The content of `my_reg` will be {Z,2,Z,3} and `my_reg1` will be {3,Z,2,Z}

# Verilog: Memory

```
reg [31:0] array2 [0:255][0:15];
```

- Select fourth byte from 101<sup>th</sup> row and 8<sup>th</sup> column.

```
wire [7:0] out2 = array2[100][7][31:24];
```

# Verilog: Memory

1. Read 2nd byte from address 11 to data\_out1.
2. Read 2nd and 3rd bytes from address 77 to data\_out2.

```
reg [31:0] Data_RAM[0:255] ;  
output reg [7:0] data_out1 ;  
output reg [15:0] data_out2 ;
```

1.  $\text{data\_out1} = \text{Data\_RAM}[11][15:8]$  ;
2.  $\text{data\_out2} = \text{Data\_RAM}[77][23:8]$  ;

# Verilog: Memory

- Memories are modeled as array of registers.

```
reg [7:0] my_memory[0:1023] ; // 1K bytes memory  
// read a byte from address 511  
data_out = my_memory[511] ;  
// Write a byte to address 374  
my_memory[374] = data_in ;
```

# Self-study

## ■ Array declarations

```
reg [7:0] mema[0:255]; // declares a memory mema of 256 8-bit registers. The indices are 0 to 255  
reg arrayb[7:0][0:255]; // declare a two-dimensional array of one bit registers  
wire w_array[7:0][5:0]; // declare array of wires  
integer inta[1:64]; // an array of 64 integer values  
time chng_hist[1:1000] // an array of 1000 time values  
integer t_index;
```

## ■ Assignment to array elements

```
mema = 0; // Illegal syntax- Attempt to write to entire array  
arrayb[1] = 0; // Illegal Syntax - Attempt to write to elements [1][0]..[1][255]  
arrayb[1][12:31] = 0; // Illegal Syntax - Attempt to write to elements [1][12]..[1][31]  
mema[1] = 0; // Assigns 0 to the second element of mema  
arrayb[1][0] = 0; // Assigns 0 to the bit referenced by indices [1][0]  
inta[4] = 33559; // Assign decimal number to integer in array  
chng_hist[t_index] = $time; // Assign current simulation time to element addressed by integer index
```

# Verilog: Vector Indexing

```
// Break down a 40-bit vector string into 5 separate bytes
Use 5 bytes hard-coded slices

module indexarr ;
    reg [39:0] str ; // string
initial
begin
    str = "abcde";
    $display("%s", str[7:0]);
    $display("%s", str[15:8]);
    $display("%s", str[23:16]);
    $display("%s", str[31:24]);
    $display("%s", str[39:32]);
end
endmodule // output: e, d, c, b, a
```

# Verilog: Vector Indexing

```
reg [63:0] word ;  
reg [3:0] byte_num ; //a value from 0 to 7.  
reg [7:0] byteN ;  
  
// If byte_num = 4  
byteN = word[byte_num*8 +: 8] ; //= word[39:32]
```

```
reg [31:0] a ;  
b = a[8+:16] ; // b = a[23:8]  
c = a[31-:8] ; // c = a[31-:24]
```



# Verilog: Vector Indexing

- Verilog allows indexing vectors using variable expression to perform dynamic parts select
- The syntax is as follows:
  - [base\_expression **+:** width\_expression] or
  - [base\_expression **-:** width\_expression]
- The base\_expression can be a variable expression but **width\_expression must be a constant**
- Offset direction indicates if the width\_expression is added (+:) or subtracted (-:) from the base\_expression

# Verilog: Vector Indexing



// Break down a 40-bit vector string into 5 separate bytes

Use 5 bytes hard-coded slices

```
module indexarr ;  
    reg [39:0] str ; // string  
    initial  
        begin  
            str = "abcde";  
            $display("%s", str[7:0]);  
            $display("%s", str[15:8]);  
            $display("%s", str[23:16]);  
            $display("%s", str[31:24]);  
            $display("%s", str[39:32]);  
        end  
    endmodule
```

// output: e, d, c, b, a

Use indexed part select

```
module indexarr ;  
    reg [39:0] str ; // string  
    integer i ;  
    initial  
        begin  
            str = "abcde";  
            for (i = 0 ; i < 5 ; i = i + 1)  
                $display("%s", str[i*8 +: 8]);  
        end  
    endmodule
```

$$c = str[6:0]$$

# ~~With reg~~ Reg Integer Verilog: Register vs. Integer Numbers ~~Sum~~ Reg [1:0] sum;

- The **reg** register is a 1-bit wide data type. If more than one bit is required then range declaration should be used.
- The **integer** register is a 32-bit wide data type.
- Integer declarations **cannot** contain range specification.

integer i j

For (i >= 0; j < 10; j += t)

```
module test_1(  
    input [3:0] in_1,  
    input [3:0] in_2,  
    input sel,  
    output integer [3:0] out_1  
)
```

Error: Cannot have packed dimensions of type integer

- Typically used for **constants or loop variables** in Verilog.
- Vivado will automatically trim any unused bits in integer. For e.g., if we declare an integer with a value of 255 then it will be trimmed to 8 bits.

# Verilog: Real Numbers (Homework)

# Verilog: Operators

- Operators are of three types:
  - Unary
  - Binary
  - Ternary
- Unary operators precede the operand
- Binary operators appear between two operands
- Ternary operators have two separate operators that separate three operands

`a = ~ b ;` // ~ is a unary operator. b is the operand

`a = b && c ;` // && is the binary operator. a and b are operands

`a = b ? c : d ;` // ?: is a ternary operator. b, c and d are operands

# Verilog: Operators

- Bus Operators
- Arithmetic Operators
- Bitwise Operators
- Reduction Operators
- Logical Operators
- Conditional Operators
- Relational Operators (HW)

# Verilog: Bus Operators

A = 8'b10001011

| Operator | Description     | Example                             |
|----------|-----------------|-------------------------------------|
| [ ]      | Bit/Part Select | A[0] = 1'b1; A[5:2] = 4'b0010 ;     |
| { }      | Concatenation   | {A[5:2],A[7:6],2'b01} = 8'b00101001 |
| {{ }}    | Replication     | {3{A[7:6]}} = 6'b101010             |

# Verilog: Bus Operators (Self-Study)

The concatenation operator `{ }` provides mechanism to append multiple operands. Operands *must* be sized.

Examples:

```
// A = 1'b1, B = 2'b00, C = 2'b10, D = 3'b110  
Y = {B, C} ; // Result Y is 4'b0010  
Y = {A, B, C, D, 3'b001} ; // Result Y is 11'b10010110001  
Y = {A, B[0], C[1]} ; // Result Y is 3'b101  
  
assign {b [7:0], b[15:8]} = {a[15:8], a [7:0]} ; // Byte swap  
assign FA_out = {cout, sum} ; // Full Adder output: carry out + Sum
```

$$Q = 8'h \underline{AB}$$

$$= 16'h \underline{\underline{00AB}}$$

$$\underline{\underline{AB}} \underline{\underline{00}}$$

Repetitive concatenation of the same number, can be expressed by using the replication constant.

```
Y = {4{A}} ; // Result Y is 4'b1111  
Y = {4{A}, 2{B}, C} ; // Result Y is 10'b1111000010
```

# Verilog: Bus Operators

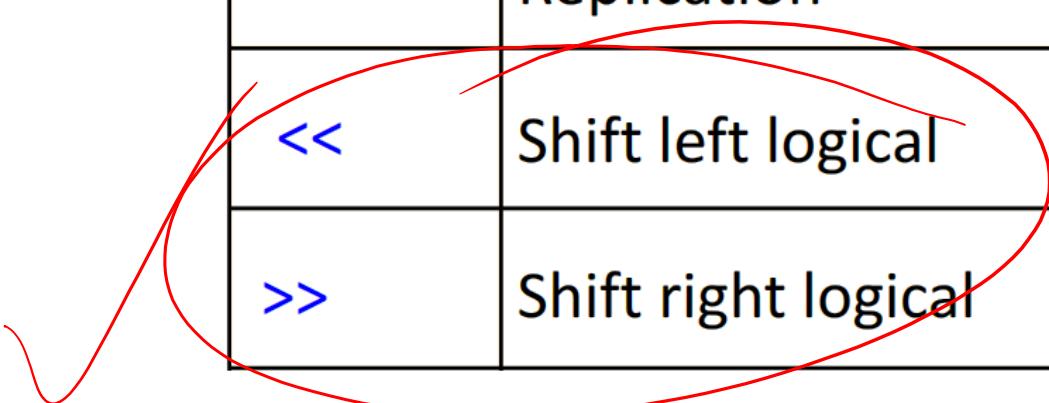
A = 8'b10001011

| Operator | Description         | Example                             |
|----------|---------------------|-------------------------------------|
| [ ]      | Bit/Part Select     | A[0] = 1'b1; A[5:2] = 4'b0010 ;     |
| { }      | Concatenation       | {A[5:2],A[7:6],2'b01} = 8'b00101001 |
| {{ }}    | Replication         | {3{A[7:6]}} = 6'b101010             |
| <<       | Shift left logical  | A<<2 =                              |
| >>       | Shift right logical | A>>3 =                              |

# Verilog: Bus Operators

A = 8'b10001011

| Operator | Description         | Example                             |
|----------|---------------------|-------------------------------------|
| [ ]      | Bit/Part Select     | A[0] = 1'b1; A[5:2] = 4'b0010 ;     |
| { }      | Concatenation       | {A[5:2],A[7:6],2'b01} = 8'b00101001 |
| {{ }}    | Replication         | {3{A[7:6]}} = 6'b101010             |
| <<       | Shift left logical  | A<<2 = 8'b001011 <u>00</u>          |
| >>       | Shift right logical | A>>3 = 8'b <u>000</u> 10001         |



# Verilog: Bus Operators

A = 8'b10001011

- Shifting bits is a very cheap (only signal renaming) way to perform multiplication and division by powers of two
- Take the value 6 (4'b0110). If we shift it to the left one bit we get 4'b1100 or 12 and if we shift it to the right one bit we get 4'b0011 or 3.
- Now what about the value -4 (4'b1100)?
- If we shift it to the left one bit we get 4'b1000 or -8. However if we shift it to the right one bit we get 4'b0110 or 6!

| Operator | Description         | Example                             |
|----------|---------------------|-------------------------------------|
| [ ]      | Bit/Part Select     | A[0] = 1'b1; A[5:2] = 4'b0010;      |
| { }      | Concatenation       | {A[5:2],A[7:6],2'b01} = 8'b00101001 |
| { { } }  | Replication         | { {A[7:6]} } = 6'b101010            |
| <<       | Shift left logical  | A<<2 = 8'b00101100                  |
| >>       | Shift right logical | A>>3 = 8'b00010001                  |

$$\begin{array}{ccccccc} & -8 & & 1000 & \rightarrow & & \\ X & 6 & & 0110 & & & \\ & & & | & & & \\ & & & 100 & & & \\ & & & & & & \end{array}$$

# Verilog: Bus Operators

A = 8'b10001011

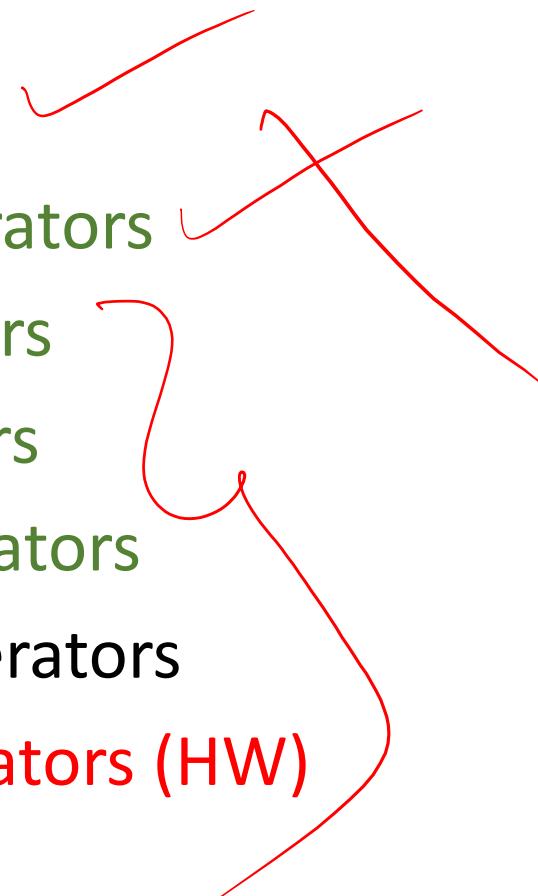
- Shifting bits is a very cheap (only signal renaming) way to perform multiplication and division by powers of two
- Take the value 6 (4'b0110). If we shift it to the left one bit we get 4'b1100 or 12 and if we shift it to the right one bit we get 4'b0011 or 3.
- Now what about the value -4 (4'b1100)?
- If we shift it to the left one bit we get 4'b1000 or -8. However if we shift it to the right one bit we get 4'b0110 or 6!
- This is why we need to use the arithmetic shift. If we use the arithmetic shift we get 4'b1110 or -2!

| Operator | Description            | Example                             |
|----------|------------------------|-------------------------------------|
| [ ]      | Bit/Part Select        | A[0] = 1'b1; A[5:2] = 4'b0010;      |
| { }      | Concatenation          | {A[5:2],A[7:6],2'b01} = 8'b00101001 |
| { { } }  | Replication            | {3{A[7:6]}} = 6'b101010             |
| <<       | Shift left logical     | A<<2 = 8'b00101100                  |
| >>       | Shift right logical    | A>>3 = 8'b00010001                  |
| >>>      | Shift right arithmetic | A>>>3 = 8'b11110001                 |

| a         | a >> 2    | a >>> 2   | a << 2    | a <<< 2   |
|-----------|-----------|-----------|-----------|-----------|
| 0100_1111 | 0001_0011 | 0001_0011 | 0011_1100 | 0011_1100 |
| 1100_1111 | 0011_0011 | 1111_0011 | 0011_1100 | 0011_1100 |

# Verilog: Operators

- Bus Operators
- Arithmetic Operators
- Bitwise Operators
- Logical Operators
- Reduction Operators
- Conditional Operators
- Relational Operators (HW)



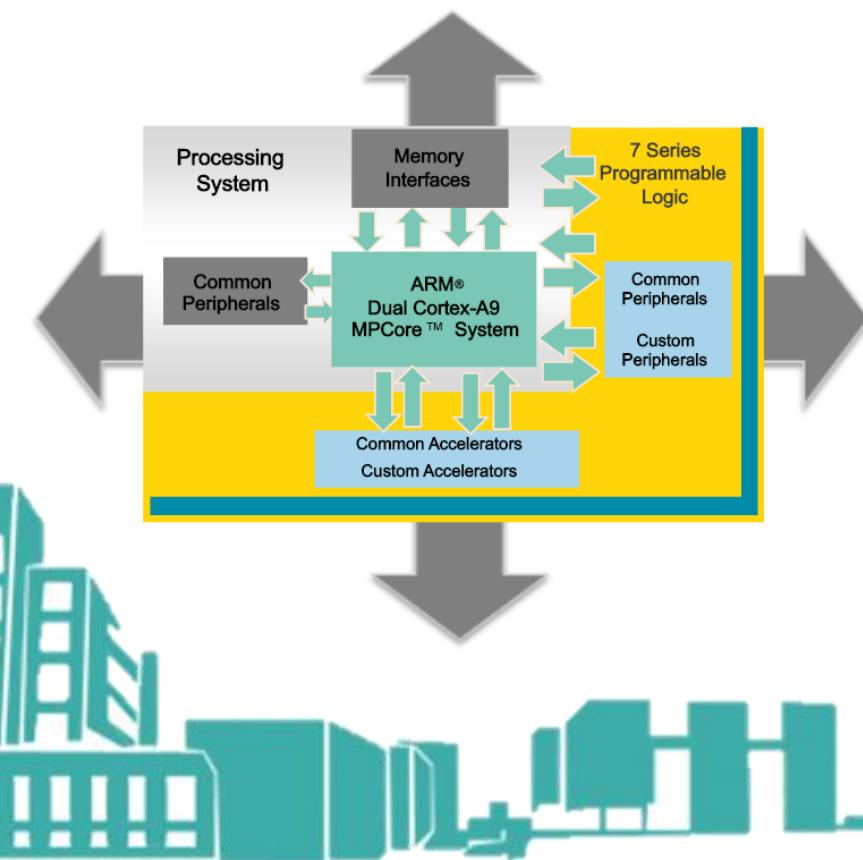
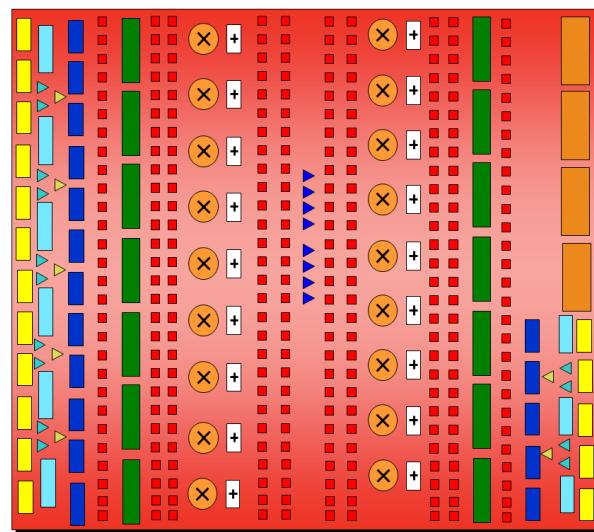


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*Algorithms to Architecture*

# ECE 270: Embedded Logic Design



# Verilog: Operators

- Operators are of three types:
  - Unary
  - Binary
  - Ternary
- Unary operators precede the operand
- Binary operators appear between two operands
- Ternary operators have two separate operators that separate three operands

`a = ~ b ;` // ~ is a unary operator. b is the operand

`a = b && c ;` // && is the binary operator. a and b are operands

`a = b ? c : d ;` // ?: is a ternary operator. b, c and d are operands

# Verilog: Operators

- Bus Operators
- Arithmetic Operators
- Bitwise Operators
- Reduction Operators
- Logical Operators
- Conditional Operators
- Relational Operators (HW)

# Verilog: Bus Operators

A = 8'b10001011

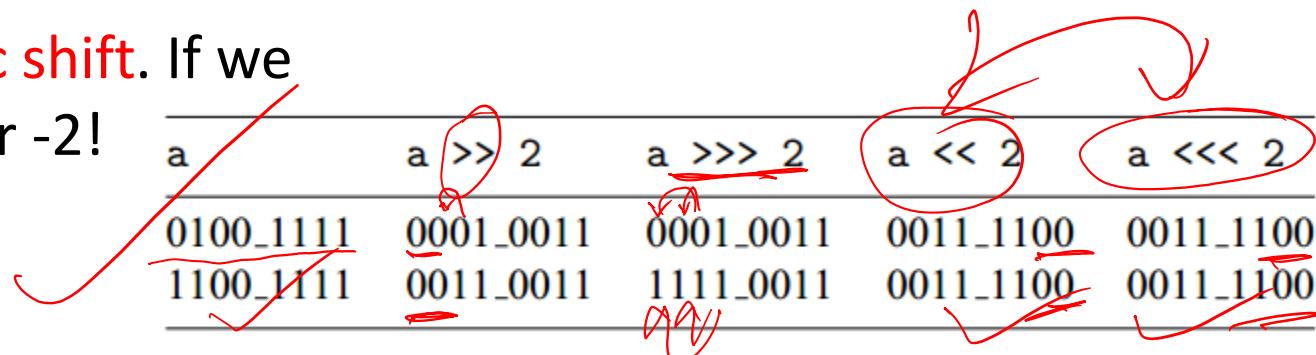
| Operator | Description         | Example                             |
|----------|---------------------|-------------------------------------|
| [ ]      | Bit/Part Select     | A[0] = 1'b1; A[5:2] = 4'b0010 ;     |
| { }      | Concatenation       | {A[5:2],A[7:6],2'b01} = 8'b00101001 |
| {{ }}    | Replication         | {3{A[7:6]}} = 6'b101010             |
| <<       | Shift left logical  | A<<2 = 8'b001011 <u>00</u>          |
| >>       | Shift right logical | A>>3 = 8'b <u>000</u> 10001         |

# Verilog: Bus Operators

A = 8'b10001011  
0 1 0 0 0 1 0 1 1  
0 1 0 0 0 1 0 1 1

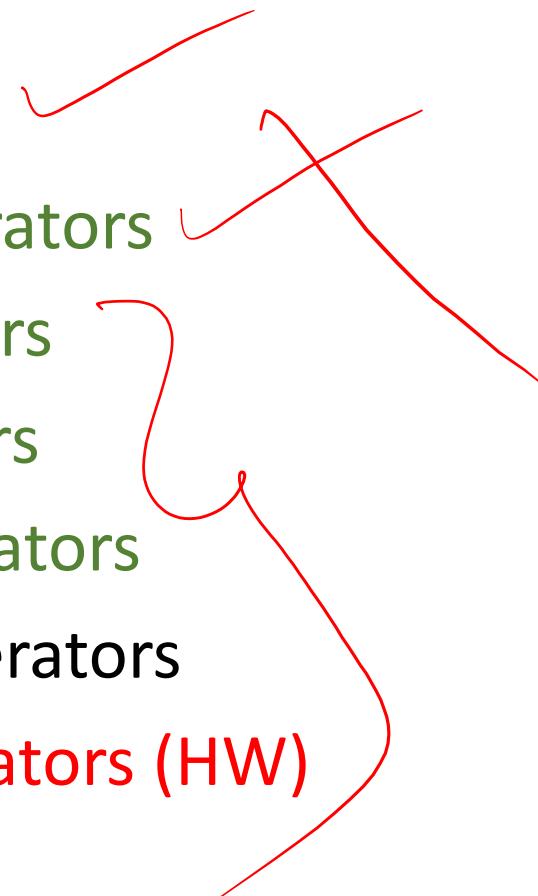
- Shifting bits is a very cheap (only signal renaming) way to perform multiplication and division by powers of two
- Take the value 6 (4'b0110). If we shift it to the left one bit we get 4'b1100 or 12 and if we shift it to the right one bit we get 4'b0011 or 3.
- Now what about the value -4 (4'b1100)?
- If we shift it to the left one bit we get 4'b1000 or -8. However if we shift it to the right one bit we get 4'b0110 or 6!
- This is why we need to use the arithmetic shift. If we use the arithmetic shift we get 4'b1110 or -2!

| Operator | Description            | Example                             |
|----------|------------------------|-------------------------------------|
| [ ]      | Bit/Part Select        | A[0] = 1'b1; A[5:2] = 4'b0010;      |
| { }      | Concatenation          | {A[5:2],A[7:6],2'b01} = 8'b00101001 |
| { { } }  | Replication            | {3{A[7:6]}} = 6'b101010             |
| <<       | Shift left logical     | A<<2 = 8'b00101100                  |
| >>       | Shift right logical    | A>>3 = 8'b00010001                  |
| >>>      | Shift right arithmetic | A>>>3 = 8'b11110001                 |



# Verilog: Operators

- Bus Operators
- Arithmetic Operators
- Bitwise Operators
- Logical Operators
- Reduction Operators
- Conditional Operators
- Relational Operators (HW)



| Operator | Description      | Example                    |
|----------|------------------|----------------------------|
| +        | Addition         | A + 12 = 151 = 8'b10010111 |
| -        | Subtraction      | A - 10 = 129 = 8'b10000001 |
| *        | Multiplication   | A * 3 = 417 = 9'b110100001 |
| /        | Division         | A / 2 = 69 = 7'b1000101    |
| %        | Modulus          | A % 5 = 4 = 3'b100         |
| **       | Power (exponent) | B ** 2 = 144 = 8'b10010000 |

# Verilog: Arithmetic Operators

A = 8'b10001011 = 139  
B = 8'b00001100 = 12

- For multiplication, many FPGAs have special resources ~~(DSP48)~~ dedicated to fast math.
- If these are available they will be used, however, if you run out of them a multiplication circuit will have to be generated (using CLB) which can be large and slow.
- **Never multiply by a power of two, but use shift instead.**
- ~~Most tools are smart enough to do this for you but it is good practice not to rely on that.~~

| Operator | Description      | Example                    |
|----------|------------------|----------------------------|
| +        | Addition         | A + 12 = 151 = 8'b10010111 |
| -        | Subtraction      | A - 10 = 129 = 8'b10000001 |
| *        | Multiplication   | A * 3 = 417 = 9'b110100001 |
| /        | Division         | A / 2 = 69 = 7'b1000101    |
| %        | Modulus          | A % 5 = 4 = 3'b100         |
| **       | Power (exponent) | B ** 2 = 144 = 8'b10010000 |

# Verilog: Arithmetic Operators

A = 8'b10001011 = 139  
B = 8'b00001100 = 12

- When two **N-bit numbers** are added or subtracted, an **N+1-bit number** is produced.
- If you add or subtract two N-bit numbers and store the value in an N-bit number you need to think about **overflow**.
- For example, if you have a two bit number 3 (2'b11) and you add it to 2 (2'b10) the result will be 5 (3'b101) but if you store the value in a two bit number you get 1 (2'b01).
- For multiplication of two **N-bit numbers**, the result will be an **N\*2-bit number**.

| Operator | Description      | Example                    |
|----------|------------------|----------------------------|
| +        | Addition         | A + 12 = 151 = 8'b10010111 |
| -        | Subtraction      | A - 10 = 129 = 8'b10000001 |
| *        | Multiplication   | A * 3 = 417 = 9'b110100001 |
| /        | Division         | A / 2 = 69 = 7'b1000101    |
| %        | Modulus          | A % 5 = 4 = 3'b100         |
| **       | Power (exponent) | B ** 2 = 144 = 8'b10010000 |

# Verilog: Arithmetic Operators (Self-Study)

~~ED = X Z~~

```
//suppose that: a = 4'b0011;  
//  
//  
//  
//then,  
a + b //add a and b; evaluates to 4'b0111  
b - a //subtract a from b; evaluates to 4'b0001  
a * b //multiply a and b; evaluates to 4'b1100  
d / e //divide d by e, evaluates to 4'b0001. Truncates fractional part  
e ** f //raises e to the power f, evaluates to 4'b1111  
//power operator is most likely not synthesizable
```

If any operand bit has a value "x", the result of the expression is all "x".  
If an operand is not fully known the result cannot be either.

# Verilog: Bitwise Operators

A = 8'b10001011

- Operate **on each bit** individually.
- When you perform a bitwise operator on multi-bit values, you are essentially using **multiple gates** to perform the bitwise operation.
- If the two values used by a bitwise operator are different in length, the shorter one is filled with zeros to make the lengths match.  
*2's complement*

| Operator     | Description   | Example                       |
|--------------|---------------|-------------------------------|
| $\sim$       | Inverse / NOT | $\sim A = 8'b01110100$        |
| $\&$         | AND           | $A[2] \& A[1] = 1'b0$         |
| $ $          | OR            | $A[2]   A[1] = 1'b1$          |
| $\wedge$     | XOR           | $A[2] \wedge A[1] = 1'b1$     |
| $\sim\wedge$ | XNOR          | $A[2] \sim\wedge A[1] = 1'b0$ |

wire [2:0] B; wire [3:0] C; C & B

# Verilog: Logical Operators

A = 8'b10001011

A & B

| Operator  | Description | Example  |
|-----------|-------------|--|
| !         | NOT         | $\text{!A[1]} = \text{FALSE}$ , $\text{!A[2]} = \text{TRUE}$ |
| &&        | AND         | $\text{A[0] \&\& A[1]} = \text{TRUE}$                        |
|           | OR          | $\text{A[0]    A[2]} = \text{TRUE}$                          |
| ==        | EQUAL       | $\text{A[3:0] == 4'b1011} = \text{TRUE}$                     |
| !=        | NOT EQUAL   | $\text{A[3:0] != 4'b1011} = \text{FALSE}$                    |
| <,<=,>,>= | COMPARE     | $\text{A[3:0] < 13} = \text{TRUE}$                           |

# Verilog: Logical and Bitwise Operators

|   |            |            | Bitwise    | logical    |                  |
|---|------------|------------|------------|------------|------------------|
|   | a          | b          | a&b        | a b        | a&&b             |
| 1 | 0          | 1          | <u>0</u>   | <u>1</u>   | <u>0 (false)</u> |
| 2 | 000        | 000        | <u>000</u> | <u>000</u> | <u>0 (false)</u> |
| 3 | 000        | 001        | <u>000</u> | <u>001</u> | <u>0 (false)</u> |
| 4 | <u>011</u> | <u>001</u> | <u>001</u> | <u>011</u> | <u>1 (true)</u>  |

if case

# Verilog: Reduction Operators

A = 8'b10001011

- **Reduce** the number of bits to one by performing the specified function on every bit.
- Similar to the bitwise operators, except they are performed on all the bits of a single value

| Operator     | Description | Example  |
|--------------|-------------|--|
| &            | AND         | $\&A = A[0] \& A[1] \& \dots A[7] = 1'b0$                        |
| $\sim\&$     | NAND        | $\sim\&A = \sim(A[0] \& A[1] \& \dots A[7]) = 1'b1$              |
|              | OR          | $ A = A[0]   A[1]   \dots A[7] = 1'b1$                           |
| $\sim $      | NOR         | $\sim A = \sim(A[0]   A[1]   \dots A[7]) = 1'b0$                 |
| $\wedge$     | XOR         | $\wedge A = A[0] \wedge A[1] \wedge \dots A[7] = 1'b0$           |
| $\sim\wedge$ | XNOR        | $\sim\wedge A = \sim(A[0] \wedge A[1] \wedge \dots A[7]) = 1'b1$ |

# Verilog: Operators (Self-Study)

| a b | a==b | a==!=b | a!=b | a!!=b | a&b | a&&b | a b | a  b | a^b |
|-----|------|--------|------|-------|-----|------|-----|------|-----|
| 0 0 | 1    | 1      | 0    | 0     | 0   | 0    | 0   | 0    | 0   |
| 0 1 | 0    | 0      | 1    | 1     | 0   | 0    | 1   | 1    | 1   |
| 0 x | x    | 0      | x    | 1     | 0   | 0    | x   | x    | x   |
| 0 z | x    | 0      | x    | 1     | 0   | 0    | x   | x    | x   |
| 1 0 | 0    | 0      | 1    | 1     | 0   | 0    | 1   | 1    | 1   |
| 1 1 | 1    | 1      | 0    | 0     | 1   | 1    | 1   | 1    | 0   |
| 1 x | x    | 0      | x    | 1     | x   | x    | 1   | 1    | x   |
| 1 z | x    | 0      | x    | 1     | x   | x    | 1   | 1    | x   |
| x 0 | x    | 0      | x    | 1     | 0   | 0    | x   | x    | x   |
| x 1 | x    | 0      | x    | 1     | x   | x    | 1   | 1    | x   |
| x x | x    | 1      | x    | 0     | x   | x    | x   | x    | x   |
| x z | x    | 0      | x    | 1     | x   | x    | x   | x    | x   |
| z 0 | x    | 0      | x    | 1     | 0   | 0    | x   | x    | x   |
| z 1 | x    | 0      | x    | 1     | x   | x    | 1   | 1    | x   |
| z x | x    | 0      | x    | 1     | x   | x    | x   | x    | x   |
| z z | x    | 1      | x    | 0     | x   | x    | x   | x    | x   |

# Verilog: Operators

- Bus Operators
- Arithmetic Operators
- Bitwise Operators
- Logical Operators
- Reduction Operators
- Conditional Operators
- Relational Operators (HW)

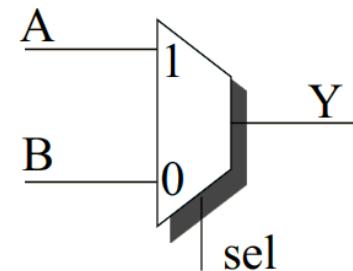
# Verilog: Conditional Operator

- Can be used in place of *if* statement when one of the two or more values is to be selected for assignment

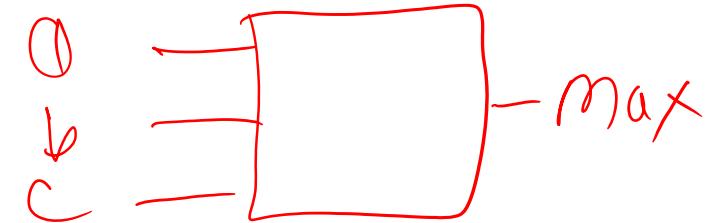
**condition ? value\_if\_true : value\_if\_false**

- Can be part of procedural or continuous assignment

*Assign*  $\text{Y} = (\text{sel})? \text{A} : \text{B};$



# Verilog: Conditional Operator



- Design maximal circuit to return the maximum of a, b and c.

```
assign max = (a>b) ? ((a>c) ? a : c) :  
              ((b>c) ? b : c);
```

*True*  
*False*

- Design 4:1 Multiplexer using conditional operator
- Design 1-bit equality comparator using conditional operator

# Verilog: Operator Precedence



- If no parentheses are used to separate operands, then Verilog uses the following rules of precedence (**Good practice: use parentheses**)



| Operators                 | Operators Symbols  |                    |
|---------------------------|--------------------|--------------------|
| Unary                     | + - ! ~            | Highest Precedence |
| Multiply, Divide, Modulus | * / %              |                    |
| Add, Subtract             | + -                |                    |
| Shift                     | << >> >>>          |                    |
| Relational                | < <= > >=          |                    |
| Equality                  | == != === !==      |                    |
| Reduction                 | &, ~&, ^, ^~,  , ~ |                    |
| Logical                   | &&                 |                    |
| Conditional               | ?:                 | Lowest Precedence  |

# Verilog: Hint for \$signed

When you write this in Verilog:

```
wire [7:0] a;
wire [7:0] b;
wire less;
assign less = (a < b);
```

the comparison between a and b is *unsigned*, that is a and b are numbers in the range 0-255. Writing this instead:

```
wire [7:0] a;
wire [7:0] b;
wire less;
assign less = ($signed(a) < $signed(b));
```

means that the comparison treats a and b as *signed* 8-bit numbers, which have a range of -128 to +127. Another way of writing the same thing is:

```
wire signed [7:0] a;
wire signed [7:0] b;
wire less;
assign less = (a < b);
```

# Verilog (Three Concepts)

- Difference between Register and Wire (Next two lectures)
- **Efficient Behavioral modelling**
- Difference between blocking and non-blocking assignments

# Behavioral Modeling

# Behavioral Modeling

- There are two basic statements in behavioral modeling: *initial* and *always*
- All other statements appear inside these statements.
- All *initial* and *always* blocks run in parallel
- All of them start at simulation time 0.
- *Initial* block starts at time 0 and executes only once. The *initial* statement provides a means of initiating input waveforms and initializing simulation variables before the actual description/simulation begins.
- Once the statements in the *initial* are exhausted, statement becomes inactive.

# Behavioral Modeling

initial

begin /\* multiple statements, need to be grouped –  
begin/end \*/

clock = 1'b0; // clock initial logic state

nrst = 1'b0 // reset initial logic state

end

initial

begin

# 5 a = 1'b1; // set a to 1 @ simulation time 5

# 25 b = 1'b1; // set b to 1 @ simulation time 30

# 50 \$finish; // end simulation after 50 time ticks

end

$t=0 \quad a=1, b=1;$

$t=50 \quad a=0, b=1;$

$t=80 \quad a=1, b=1;$

initial

begin

4

$t=0$

$t=5$

$d = \#5 \underline{a \& b};$

$t=5$

$t=85$

$\#80 e = a \& b;$

$e = 1$

end

# Behavioral Modeling

```
module Reg_File  
.....  
reg [31:0] RegFile[0:31] ;  
integer i ;  
initial  
begin  
  for(i = 0 ; i < 32 ; i = i + 1)  
    RegFile[i] = 32'h0 ;  
end  
.....  
endmodule
```

# Behavioral Modeling

- *always block* starts at time 0 and executes statements continuously in a loop.
- Describes the function of a circuit.
- Can contain many statements like **if**, **for**, **while**, **case**
- Statements in the *always* block are executed sequentially (= assignment) or in parallel (<= assignment). *Blocking* *Non blocking*.
- The *final* result describes the function of the circuit for current set of inputs.

// clock declaration, used mainly in Test Benches  
always  
# 10 clock = ~clock ; // Toggle clock every half-cycle

# Behavioral Modeling

## always block

- Always waiting for a change to a trigger signal
- Then executes the body

```
module and_gate (out, in1, in2) ;  
    input  in1, in2 ;  
    output reg out ;
```

```
always @ (in1 or in2)  
begin  
    out = in1 & in2 ;  
end  
endmodule
```

Specifies when block is executed  
i.e., triggered by which signals

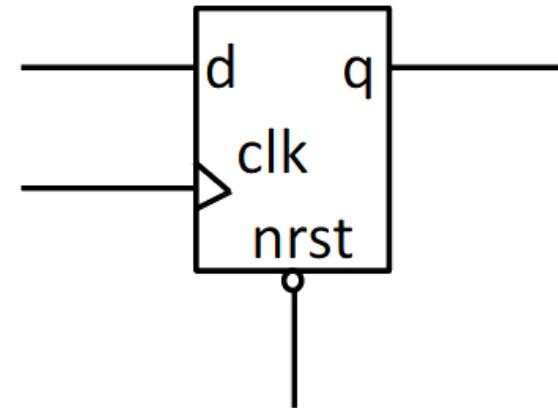
# Behavioral Modeling

```
module full_adder (sum, cout, a, b, cin) ;  
    input a, b, cin ;  
    output reg sum, cout ; // implicit register  
  
    always @ (a or b or cin) // Verilog 2001 allows (a, b, cin)  
        {cout, sum} = a + b + cin;  
endmodule  
// If sensitivity list is too long, use (*), i.e. all inputs
```

# Verilog: Module (Examples)

```
module D_FF(clk, nrst, d, q) ;  
    input clk, nrst, d ;  
    output reg q ;  
    always @(posedge clk or negedge nrst)  
        // Event-based Timing Control  
        if (!nrst)  
            q<=0 ;  
        else  
            q<=d ;  
endmodule
```

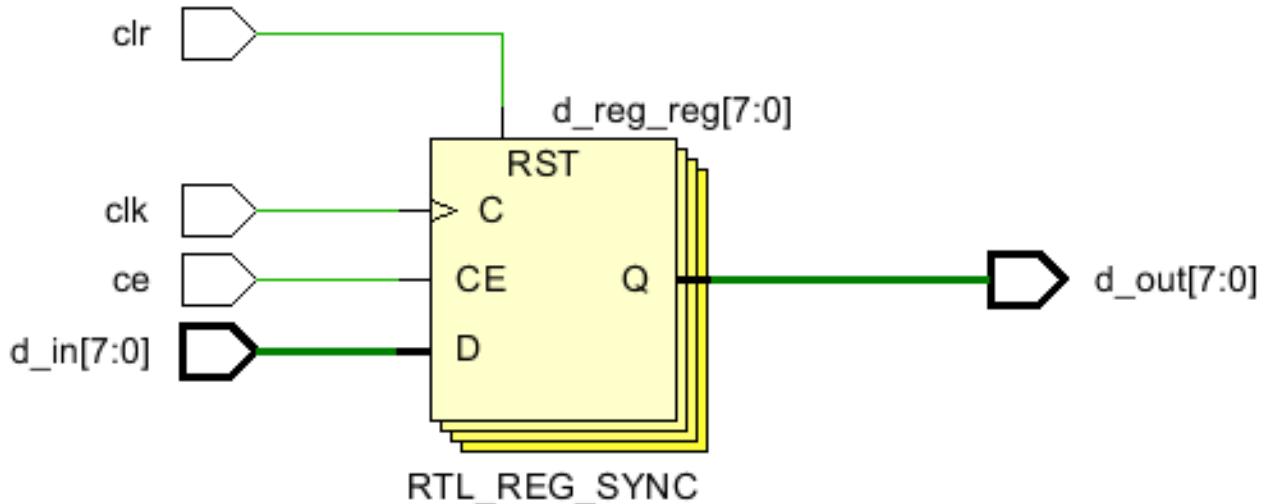
The code highlights two specific assignments with red circles:  
1. `q<=0` under the `if (!nrst)` condition.  
2. `q<=d` under the `else` condition.



# Verilog: Register

```
module test_1(
    input [7:0] d_in,
    input ce,
    input clk,
    input clr,
    output [7:0] d_out
);

reg [7:0] d_reg;
always@(posedge clk)
begin
    if(clr)
        d_reg <= 8'b00000000;
    else if (ce)
        d_reg <= d_in;
end
assign d_out = d_reg;
endmodule
```



# Behavioral Modeling for Combinational Circuits

- While writing Verilog code for synthesis, we need to be aware of how the various language constructs are mapped to hardware.
- **Common errors:**
  1. Variable assigned in **multiple always blocks**
  2. Incomplete **sensitivity** list
  3. Incomplete **branch** and incomplete **output** assignments

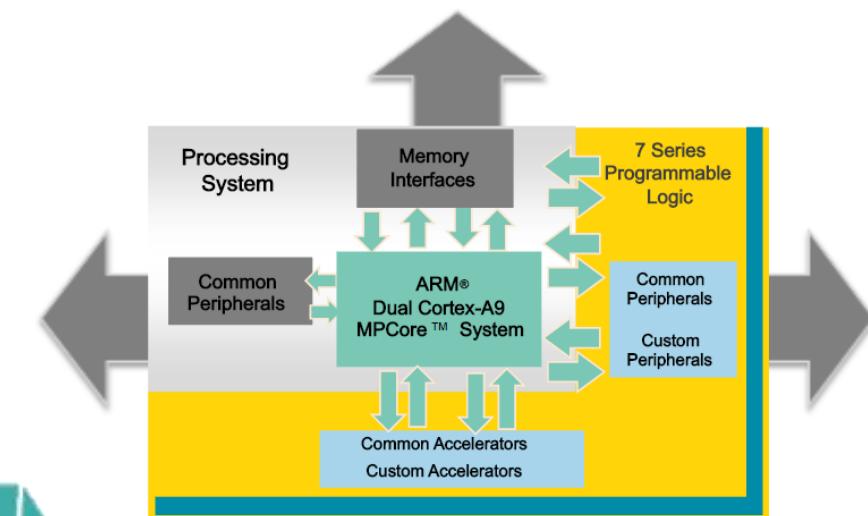
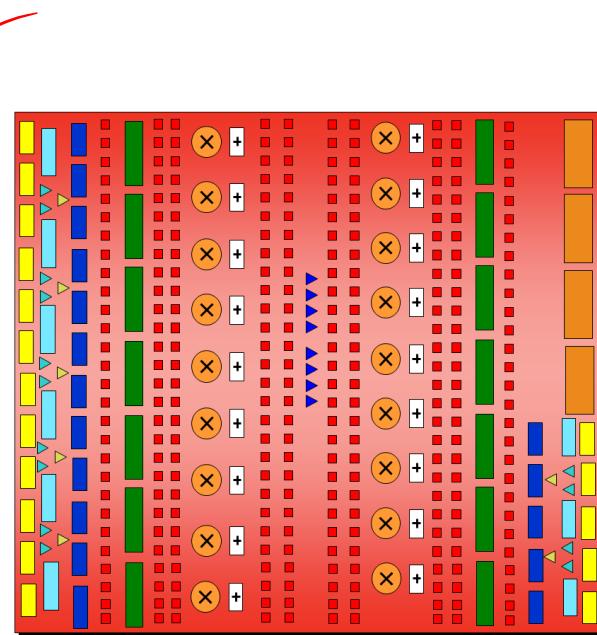


ECE  
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DEPARTMENT OF ELECTRONICS &  
COMMUNICATIONS ENGINEERING

A2A  
*Algorithms to Architecture*

# ECE 270: Embedded Logic Design



# Course Feedback

- Quiz will be announced few days in advance. Exact date and time will NOT be announced.
- **Tuesday Timetable:** Please reach out to academic team to explore if there is any alternative option.

~~Always (name.)~~

# Behavioral Modeling for Combinational Circuits

- While writing Verilog code for synthesis, we need to be aware of how the various language constructs are mapped to hardware.

- **Common errors:**

1. Variable assigned in **multiple always blocks**
2. Incomplete **sensitivity** list
3. Incomplete **branch** and incomplete **output** assignments

# Behavioral Modeling: Guidelines

- Variable assigned in multiple always blocks

```
reg y;  
reg a, b, clear;  
.  
.  
.  
always @*  
    if (clear) y = 1'b0;  
  
always @*  
    y = a & b;
```

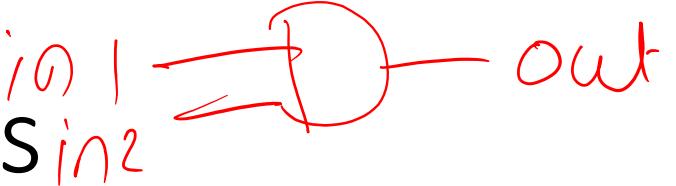
```
always @*  
    if (clear)  
        y = 1'b0;  
    else  
        y = a & b;
```

1) Separate ALWAYS block for every identifier

2) Don't update multiple identifiers in one ALWAYS Block.

- LHS code is not synthesizable since output y is driven by two blocks (i.e. two different circuits).
- No physical circuit exhibits such behaviour.

# Behavioral Modeling: Guidelines



- Incomplete sensitivity list

```
module and_gate (out, in1, in2) ;  
  input  in1, in2 ;  
  output reg out ;  
  
  always @(*)
    begin
      if (in1 & in2)
        out = 1;
      else
        out = 0;
    end
endmodule
```

- Leaving out an input trigger usually results in a sequential circuit
- Use **always@\*** for combinational circuits

③

# Behavioral Modeling: Guidelines

1) Else is MUST  
in if-else loop -

- Incomplete branch and incomplete output assignment

```
always @*
  if (a > b)      // eq not assigned in this branch
    gt = 1'b1;
  else if (a == b) // gt not assigned in this branch
    eq = 1'b1;
                // final else branch is omitted
```

```
always @*
begin
  gt = 1'b0;    // default value for gt
  eq = 1'b0;    // default value for eq
  if (a > b)
    gt = 1'b1;
  else if (a == b)
    eq = 1'b1;
end
```

```
always @*
if (a > b)
begin
  gt = 1'b1;
  eq = 1'b0;
end
else if (a == b)
begin
  gt = 1'b0;
  eq = 1'b1;
end
else // i.e., a < b
begin
  gt = 1'b0;
  eq = 1'b0;
end
```

# Behavioral Modeling: Guidelines

- Incomplete branch and incomplete output assignment

```
reg [1:0] s
.
.
case (s)
  2'b00: y = 1'b1;
  2'b10: y = 1'b0;
  2'b11: y = 1'b1;
endcase
```

```
case (s)
  2'b00: y = 1'b1;
  2'b10: y = 1'b0;
  2'b11: y = 1'b1;
  default: y = 1'b1; // y gets 1 for 2'b01
endcase

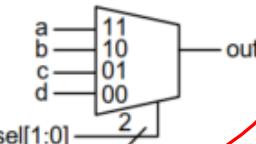
case (s)
  2'b00: y = 1'b1;
  2'b10: y = 1'b0;
  2'b11: y = 1'b1;
  default: y = 1'bx; // y gets x for 2'b01
endcase
```

```
y = 1'b0; // can also use y = 1'bx for don't-care
case (s)
  2'b00: y = 1'b1;
  2'b10: y = 1'b0;
  2'b11: y = 1'b1;
endcase
```

# Case Statement: Full and Parallel

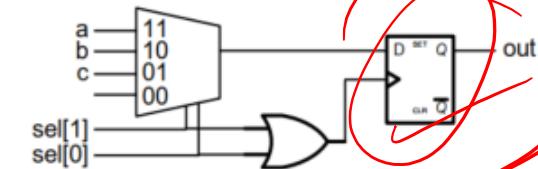
- Full Case Statement: all possible outcomes are accounted
- Parallel Case Statement: all stated alternatives are mutually exclusive

```
module full_par (sel, a, b, c, d, out);
input [1:0] sel;
input a, b, c, d;
output out; reg out;
always @ (sel or a or b or c or d)
  case (sel)
    2'b11: out <= a;
    2'b10: out <= b;
    2'b01: out <= c;
    default: out <= d; // 2'b00
  endcase
endmodule
```



full  
parallel

```
module par_not_full (sel, a, b, c, out);
input [1:0] sel;
input a, b, c;
output out; reg out;
always @ (sel or a or b or c)
  case (sel)
    2'b11: out <= a;
    2'b10: out <= b;
    2'b01: out <= c;
  endcase
endmodule
```

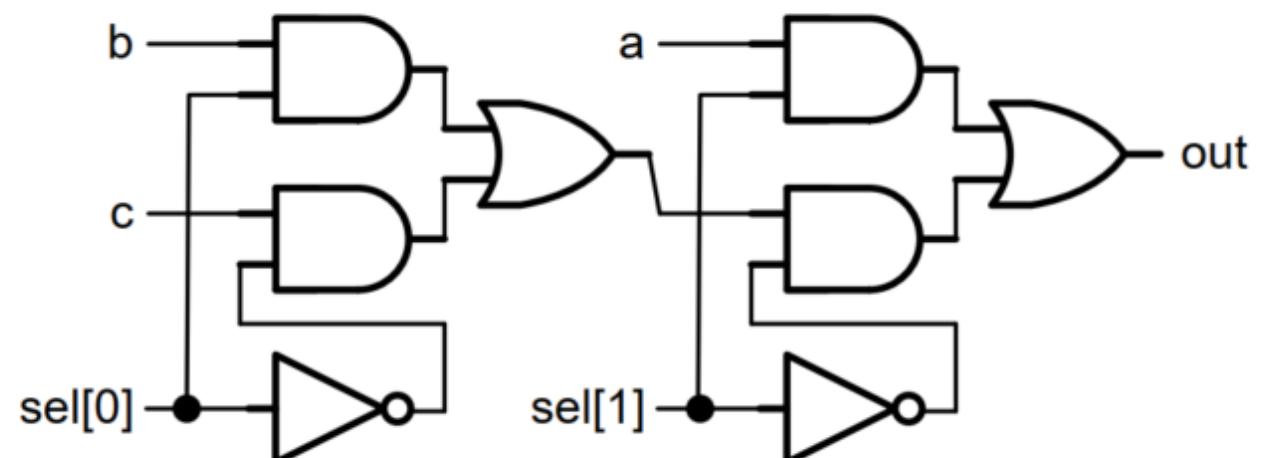


Non Full  
Parallel

# Case Statement: Full and Parallel

- Full Case Statement: all possible outcomes are accounted
- Parallel Case Statement: all stated alternatives are mutually exclusive

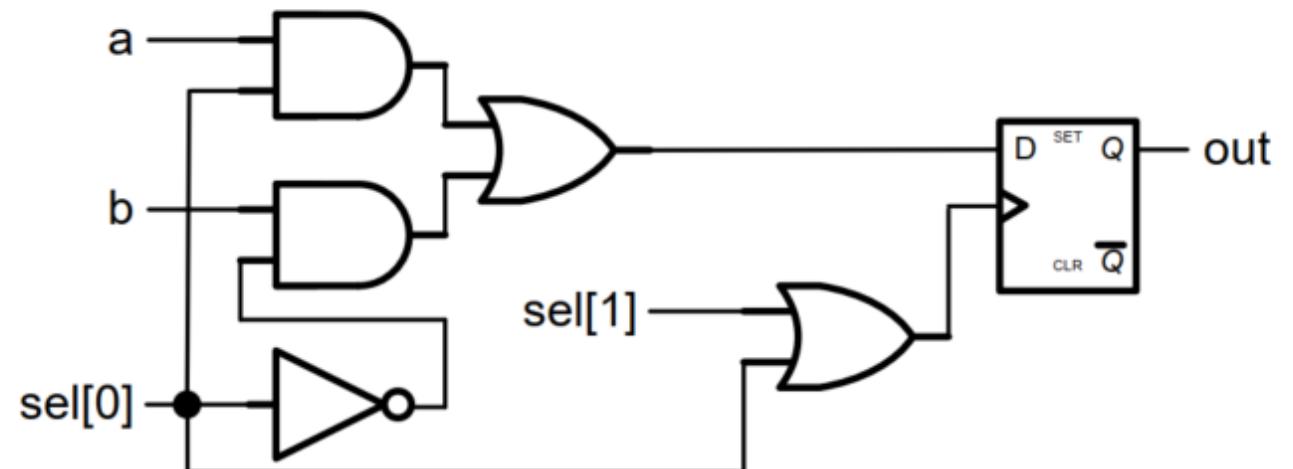
```
module full_not_par (sel, a, b, c, out);
input [1:0] sel;
input      a, b, c;
output     out; reg out;
always @ (sel or a or b or c)
  case (sel)
    2'b1?:  out <= a; // 2'b10, 2'b11
    2'b?1:  out <= b; // 2'b01, 2'b11
    default: out <= c; // 2'b00
  endcase
endmodule
// If the case is 2'b11 occurs, the first outcome gets higher priority because it is closer to the output.
```



# Case Statement: Full and Parallel

- Full Case Statement: all possible outcomes are accounted
- Parallel Case Statement: all stated alternatives are mutually exclusive

```
module not_full_not_par (sel, a, b, out);
  input [1:0] sel;
  input      a, b;
  output     out; reg out;
  always @ (sel or a or b)
    case (sel)
      2'b1?: out <= a; // 2'b10, 2'b11
      2'b?1: out <= b; // 2'b01, 2'b11
    endcase
  endmodule
```



# Behavioral Modeling for Combinational Circuits

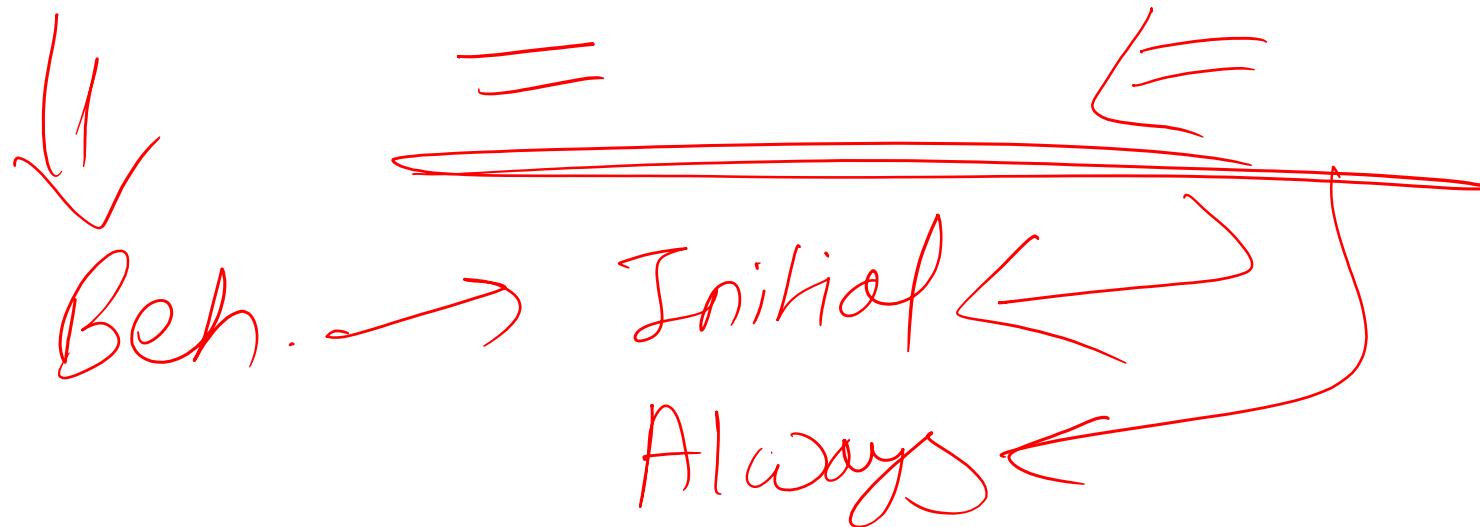
- If an always block executes and a variable is ***NOT*** assigned:
  - Variable keeps its old value
  - ***NOT*** combinational logic -> latch is inserted (implied memory)
  - This is usually ***NOT*** what you want
- Any variable assigned in an always block **SHOULD** be assigned for any (and every!) execution of the block
- Poorly coded always block leads to unnecessarily complex implementation or can not be synthesized at all.

# Behavioral Modeling: Summary

- Assign a variable **ONLY** in a single **always** block
- **Use @\*** to include all the desired identifiers automatically in the sensitivity list
- Make sure that **all branches** of the *if and case statements* are included
- Make sure that the **outputs** are assigned in **all branches**
- One way to satisfy previous two guidelines is to **assign default values for outputs** in the beginning of the always block
- **Use blocking assignments for combinational circuits** ~~for sequential circuits~~
- Think hardware, not C or Python or MATLAB code

# Verilog (Three Concepts)

- Difference between Register and Wire (Next two lectures)
- Efficient Behavioral modelling
- **Difference between blocking and non-blocking assignments**



# Blocking Vs Non-Blocking Assignments

# Behavioral Modeling

- **Blocking assignment** statements are executed in the order they are specified in a sequential block
- A blocking assignment will **NOT** block execution of statements that follows in a parallel block
- The **=** operator is used to specify blocking assignments
- **Non-blocking assignments** allow scheduling of assignments **without locking execution** of the statements that follow in a sequential block
- A **<=** operator is used to specify non-blocking assignments

# Behavioral Modeling

```
reg_a = 16'b0 ;
```

```
reg [15:0] reg_a, reg_b ;
```

```
reg x, y, z ;
```

```
integer count ;
```

```
Initial
```

```
begin
```

```
x = 0, y = 0, z = 0, count = 0 ;
```

```
reg_b = reg_a ;
```

```
#15 reg_a[2] = 1'b1 ;
```

```
#10 reg_b[15:13] = {x, y, z} ;
```

```
count = count + 1 ;
```

```
end
```

# Behavioral Modeling

```
reg_a = 16'b0 ;
```

```
reg [15:0] reg_a, reg_b ;
```

```
reg x, y, z ;
```

```
integer count ;
```

Initial

```
begin
```

```
x <= 0 ; y <= 0; z <= 0 ; count <= 0 ;
```

```
reg_b <= reg_a ;
```

```
#15 reg_a[2] <= 1'b1 ;
```

```
#10 reg_b[15:13] <= {x, y, z} ;
```

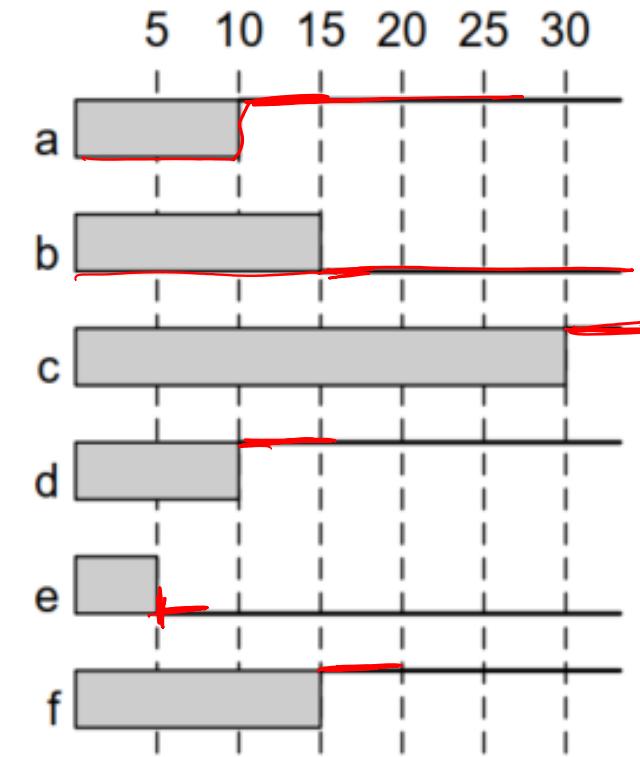
```
count <= count + 1 ;
```

```
end
```

# Behavioral Modeling

2

```
module top;
reg a, b, c, d, e, f;
initial begin
    a = #10 1;
    b = #5 0;
    c = #15 1;
end
initial begin
    d <= #10 1;
    e <= #5 0;
    f <= #15 1;
end
endmodule
```



Note that what are different with blocking and non-blocking assignments.

# Behavioral Modeling

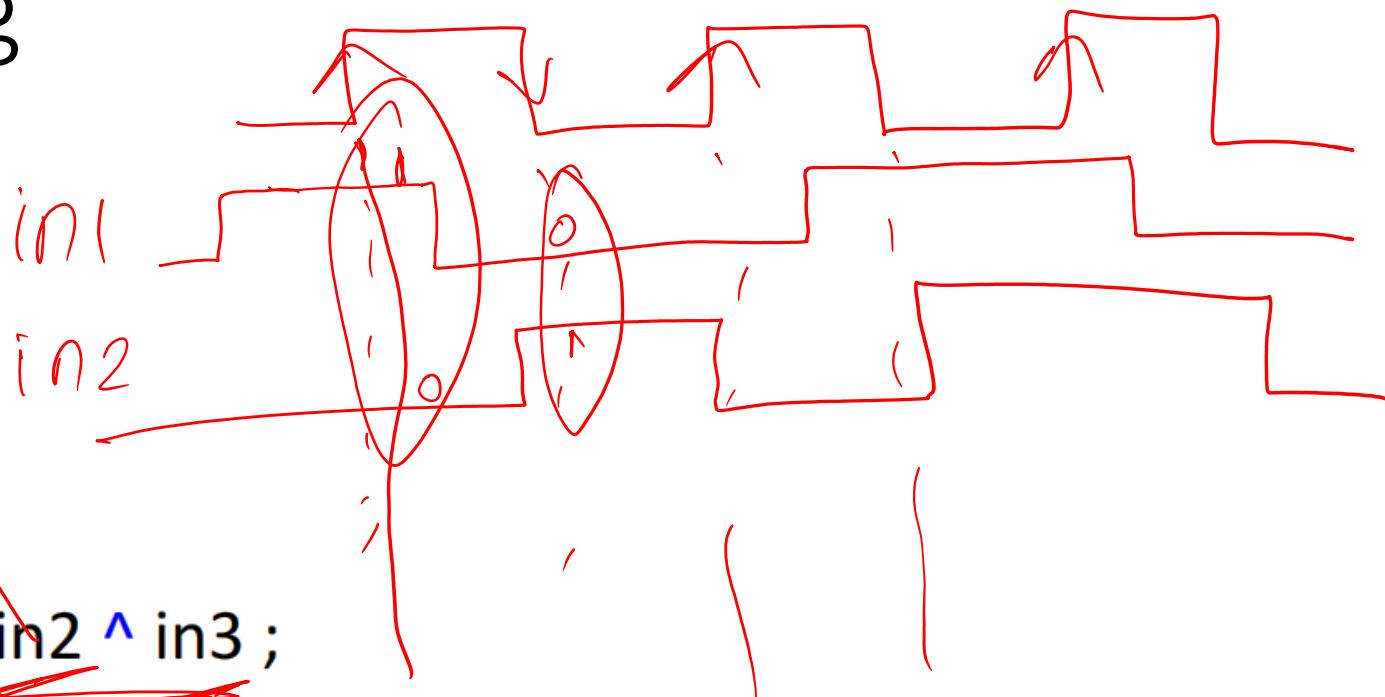
always @(posedge clock)

begin reg1 <= #1 in1 ;

~~reg2 <= @(negedge clock) in2 ^ in3 ;~~

~~reg3 <= #1 reg1 ;~~

end



# Behavioral Modeling: Swapping

Race Conditions:

// Two concurrent always blocks with blocking

~~✓ always @ (posedge clock)~~

~~a = b ; ✓ ① ②~~

~~✓ always @ (posedge clock)~~

~~b = a ; ✓ ② ③~~

1)  $a=b$     2)  $a=b$     3)  $b=a$   
 $b=a$      $b=b$      $a=a$

The values of both registers will not be swapped \*/

Race Conditions: /\* Two concurrent always blocks with non-blocking

~~always @ (posedge clock)~~

~~a <= b ; ① ② ③~~

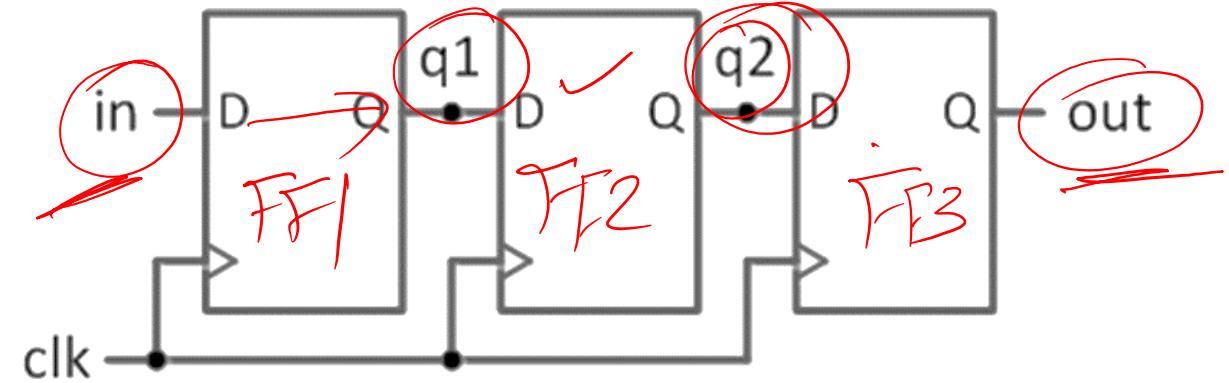
~~always @ (posedge clock)~~

~~b <= a ; ② ③~~

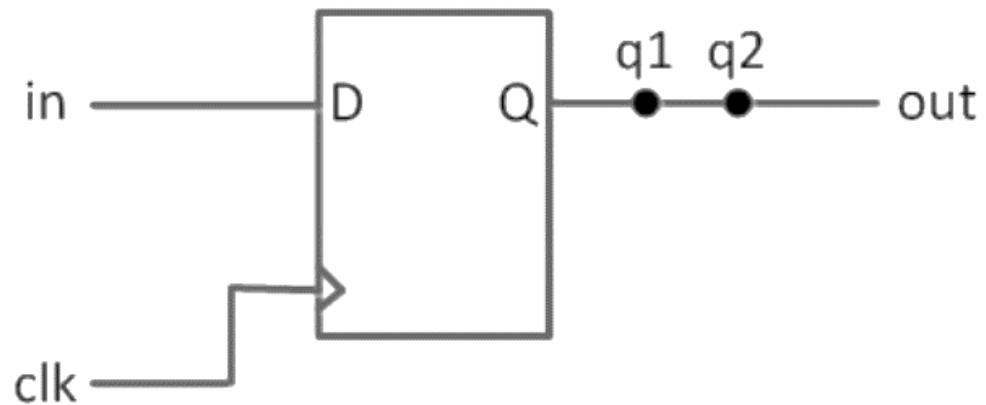
1)  $a=b$     2)  $a=b_{old}$     3)  $b=b_{old}$   
 $b=a$      $b=a_{old}$      $a=b_{old}$

# Behavioral Modeling

```
module blocking (in,clk,out) ;  
    input in, clk ;  
    output reg out ;  
    reg q1, q2 ;  
    always @(posedge clk)  
        begin  
            ✓ q1 = in ;      out = in ;  
            ✓ q2 = q1 ;  
            ✓ out = q2 ;  
        end  
    endmodule
```

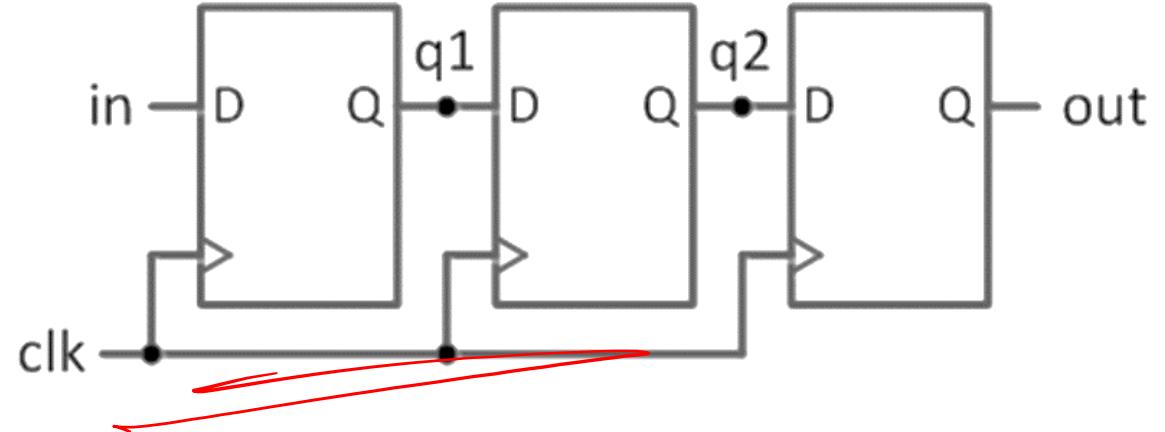


“at each rising clock edge,  $q1 = \text{in}$ ,  
**after that,  $q2 = q1 = \text{in}$**   
**after that,  $\text{out} = q2 = q1 = \text{in}$**   
Therefore,  $\text{out} = \text{in}$ ”



# Behavioral Modeling

```
module nonblocking (in,clk,out) ;  
    input in, clk ;  
    output reg out ;  
    reg q1, q2;  
    always @(posedge clk)  
        begin  
            q1 <= in ;  
            q2 <= q1 ;  
            out <= q2 ;  
        end  
    endmodule
```

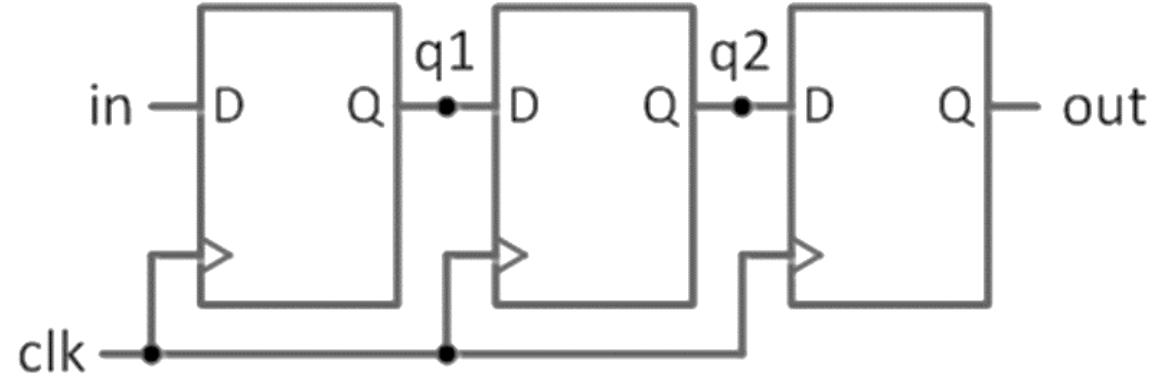


“at each rising clock edge, q1, q2 and out **simultaneously receive the old values** of in, q1 and q2. Therefore, out = q2”

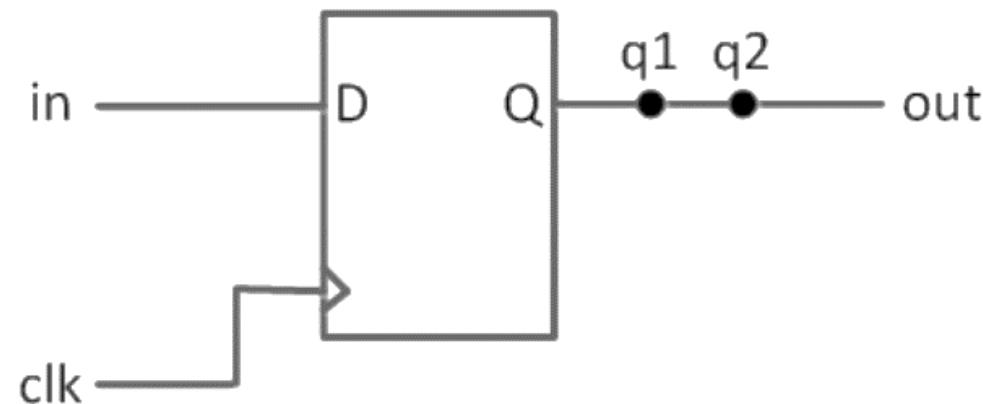
- Blocking assignments do not reflect the intrinsic behaviour of multi-stage sequential logic
- Use non-blocking assignments for sequential always blocks

# Behavioral Modeling

```
module blocking (in,clk,out) ;  
    input in, clk ;  
    output reg out ;  
    reg q1, q2 ;  
    always @(posedge clk)  
        begin  
            q1 = in ;  
            q2 = q1 ;  
            out = q2 ;  
        end  
endmodule
```

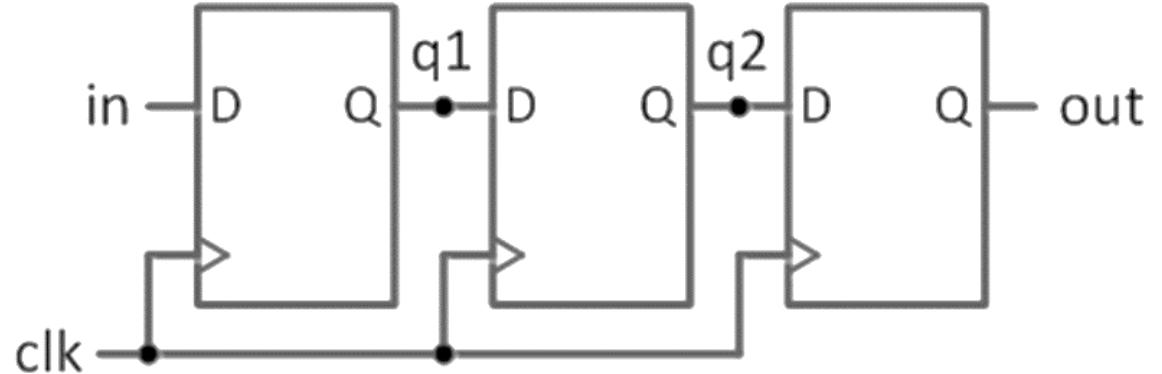


“at each rising clock edge,  $q1 = \text{in}$ ,  
**after that,  $q2 = q1 = \text{in}$**   
**after that,  $\text{out} = q2 = q1 = \text{in}$**   
Therefore,  $\text{out} = \text{in}$ ”



# Behavioral Modeling

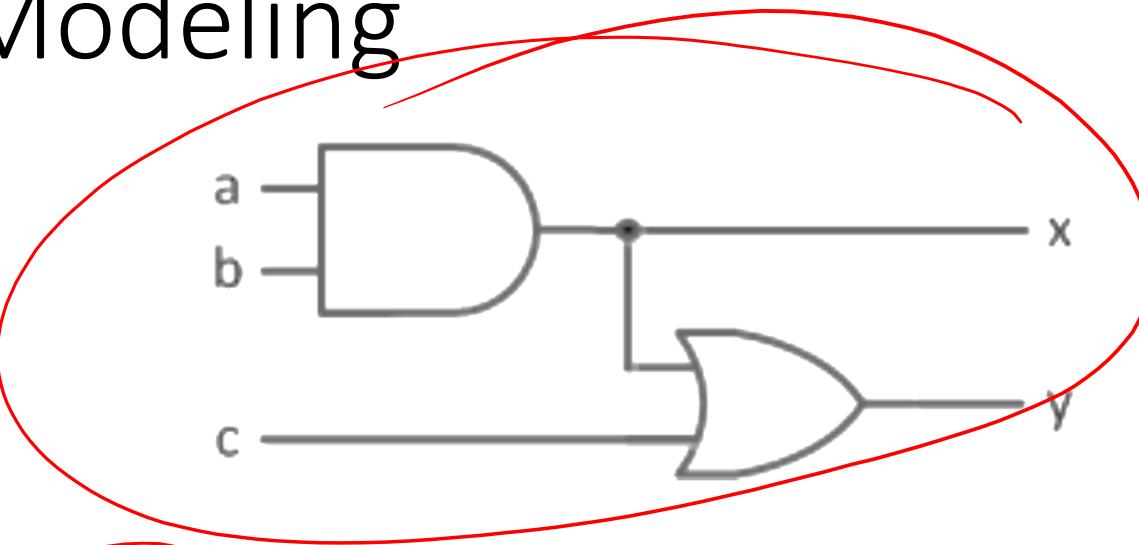
```
module nonblocking (in,clk,out) ;  
    input in, clk ;  
    output reg out ;  
    reg q1, q2;  
    always @(posedge clk)  
        begin  
            q1 <= in ;  
            q2 <= q1 ;  
            out <= q2 ;  
        end  
    endmodule
```



“at each rising clock edge, *q*<sub>1</sub>, *q*<sub>2</sub> and *out* **simultaneously receive the old values** of *in*, *q*<sub>1</sub> and *q*<sub>2</sub>. Therefore, *out* = *q*<sub>2</sub>”

- Blocking assignments do not reflect the intrinsic behaviour of multi-stage sequential logic
- Use non-blocking assignments for sequential always blocks

# Behavioral Modeling

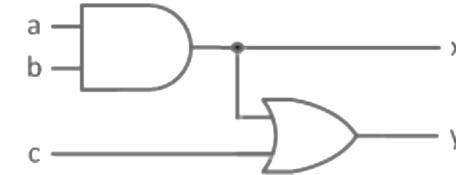


```
module blocking(a, b, c, x, y);
    input a, b, c;
    output reg x, y;
    always @ (a or b or c)
        begin
            x = a & b;
            y = x | c;
        end
    endmodule
```

```
module nonblocking (a, b, c, x, y);
    input a, b, c;
    output reg x, y;
    always @ (a or b or c)
        begin
            x <= a & b;
            y <= x | c;
        end
    endmodule
```

# Behavioral Modeling

- Given initial conditions:  
 $a=1, b=1, c=0, x=1, y=1.$
- $a$  changes to 0. always block triggered.
- Blocking behaviour of simulator: 1st calculates  $x = a \& b = 0$ . Then calculates  $y = x | c = 0$
- Non-Blocking behavior of simulator: Concurrently calculates  $x(\text{new}) = a \& b = 0$ .  $y = x(\text{old}) | c = 1$
- Non-blocking assignment *do not* reflect the intrinsic behavior of multi-stage combinational logic
- While non-blocking assignments can be hacked to simulate correctly (expand sensitivity list), its not elegant
- Guideline: Use blocking assignments for combinational always blocks**



```
module blocking (a, b, c, x, y) ;  
  input a, b, c ;  
  output reg x, y ;  
  always @ (a or b or c)  
    begin  
      x = a & b ;  
      y = x | c ;  
    end  
  endmodule
```

```
module nonblocking (a, b, c, x, y) ;  
  input a, b, c ;  
  output reg x, y ;  
  always @ (a or b or c)  
    begin  
      x <= a & b ;  
      y <= x | c ;  
    end  
  endmodule
```

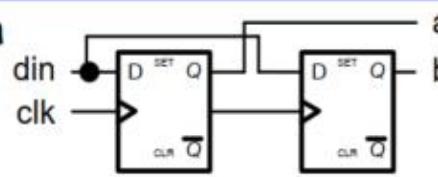
# Behavioral Modeling

- When modelling sequential logic, use non-blocking assignments.
- When modelling combinational logic with an always block, use blocking assignments.
- When modelling both sequential and combinational logic within the same always block, use non-blocking assignments.
- Do not mix blocking and non-blocking assignments in the same always block.

# Behavioral Modeling (Self Study)

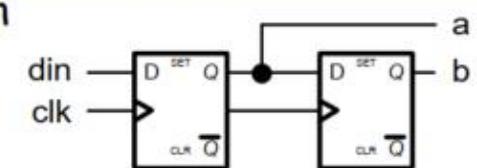
Blocking assignments (1/2)

```
always @ (posedge clk) begin  
    a = din;  
    b = a;  
end
```



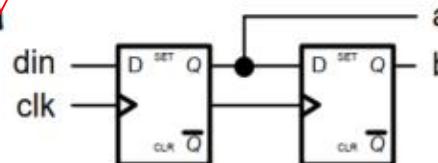
Non-blocking assignments (1/2)

```
always @ (posedge clk) begin  
    a <= din;  
    b <= a;  
end
```



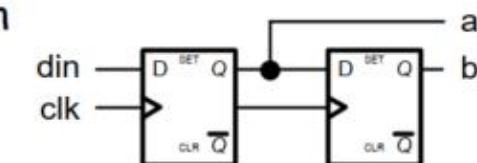
Blocking assignments (2/2)

```
always @ (posedge clk) begin  
    b = a;  
    a = din;  
end
```



Non-blocking assignments (2/2)

```
always @ (posedge clk) begin  
    b <= a;  
    a <= din;  
end
```



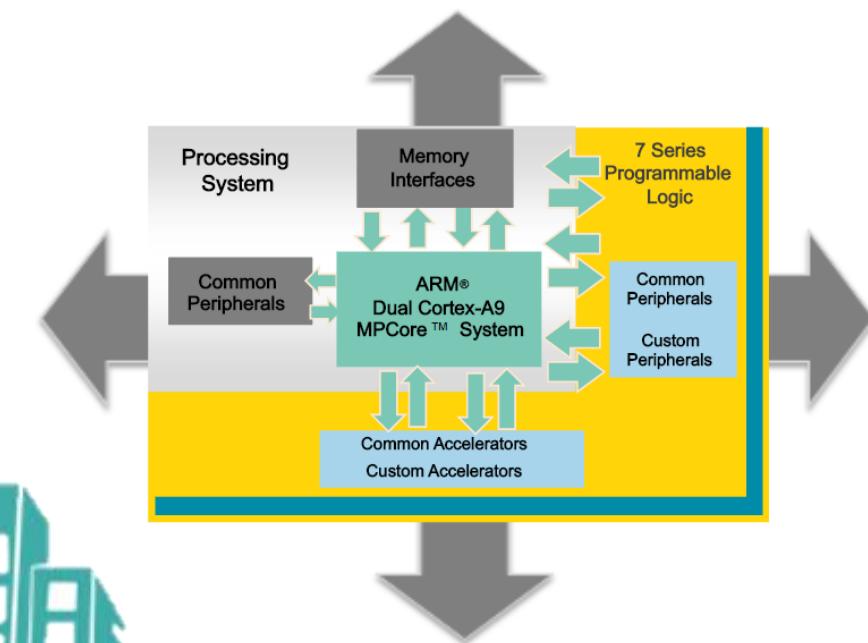
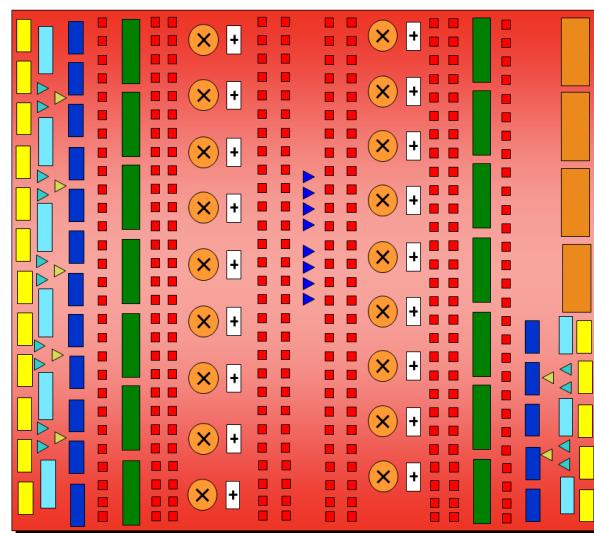


ECE  
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A2A  
*Algorithms to Architecture*

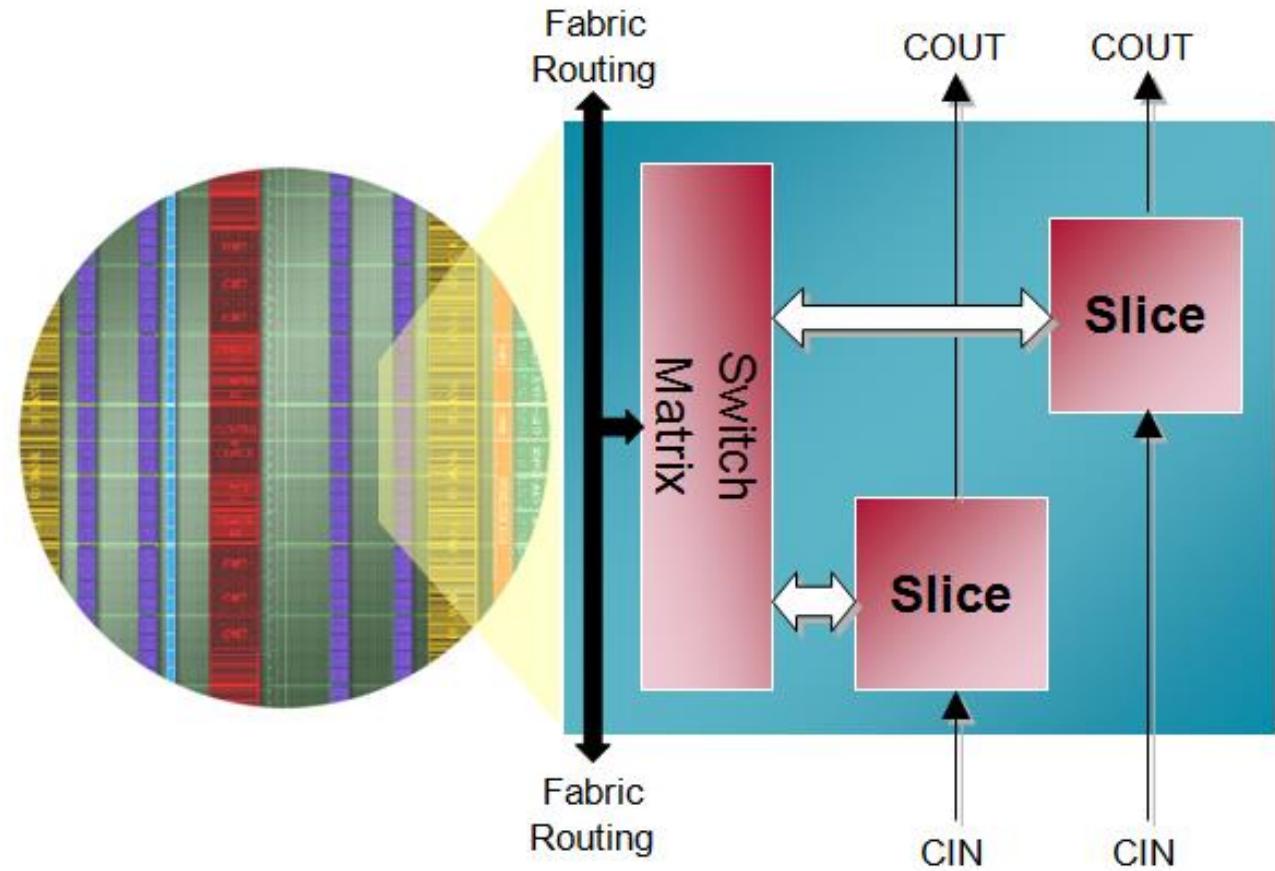
# ECE 270: Embedded Logic Design



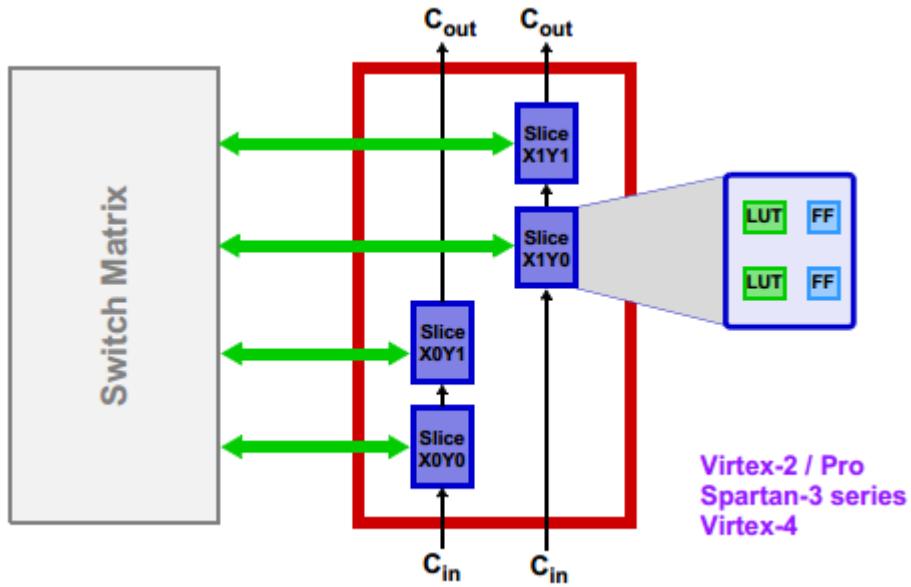
# FPGA Architecture

# Configurable Logic Block (CLB)

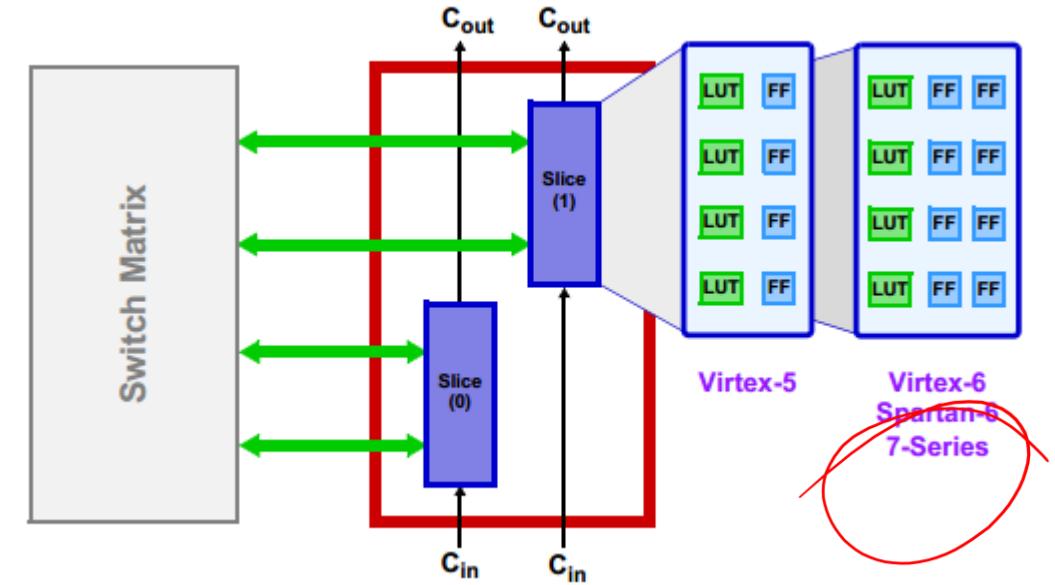
- Primary resource for design in Xilinx FPGAs
- CLB contains more than one slice
- Connected to switch matrix for routing to other FPGA resources
- Carry chain runs vertically in a column from one slice to the one above



# Configurable Logic Block (CLB)



Virtex-2 / Pro  
Spartan-3 series  
Virtex-4

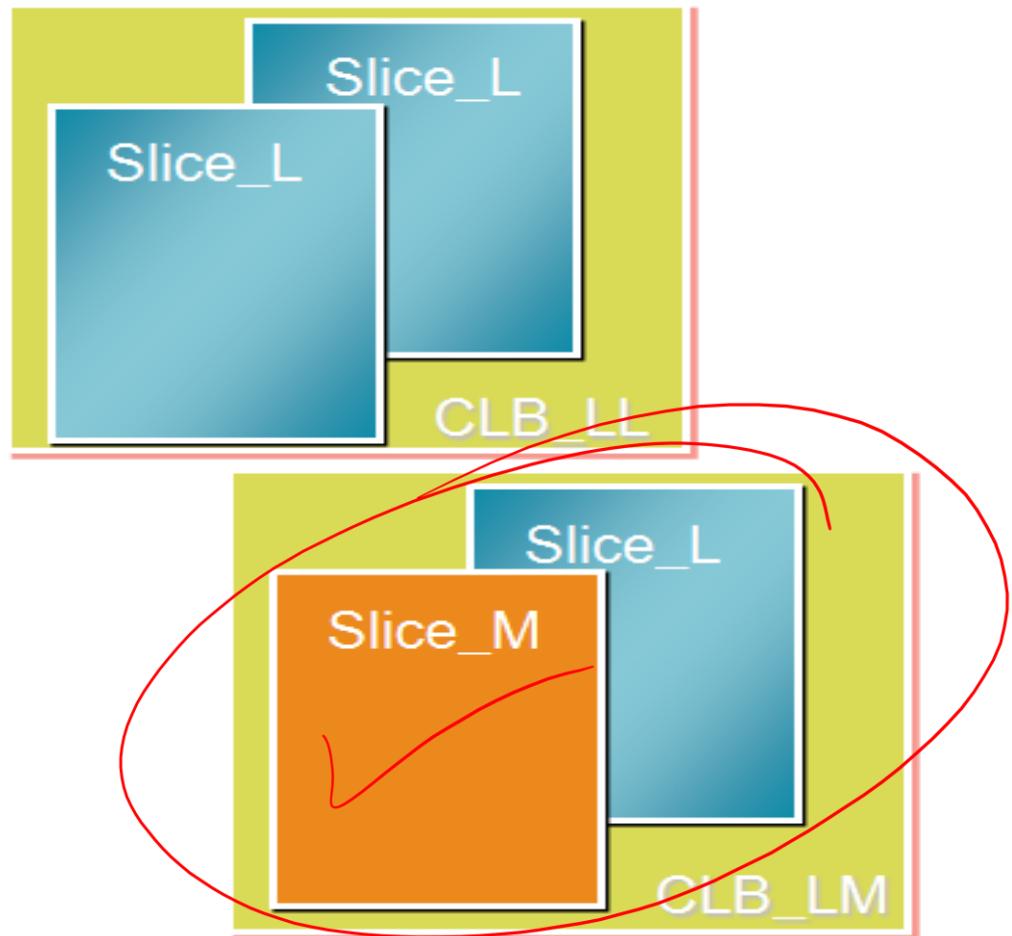


Virtex-5  
Virtex-6  
Spartan-6  
7-Series

| Slices | LUTs | Flip-Flops | Arithmetic and Carry Chains |
|--------|------|------------|-----------------------------|
| 2      | 8    | 16         | 2                           |

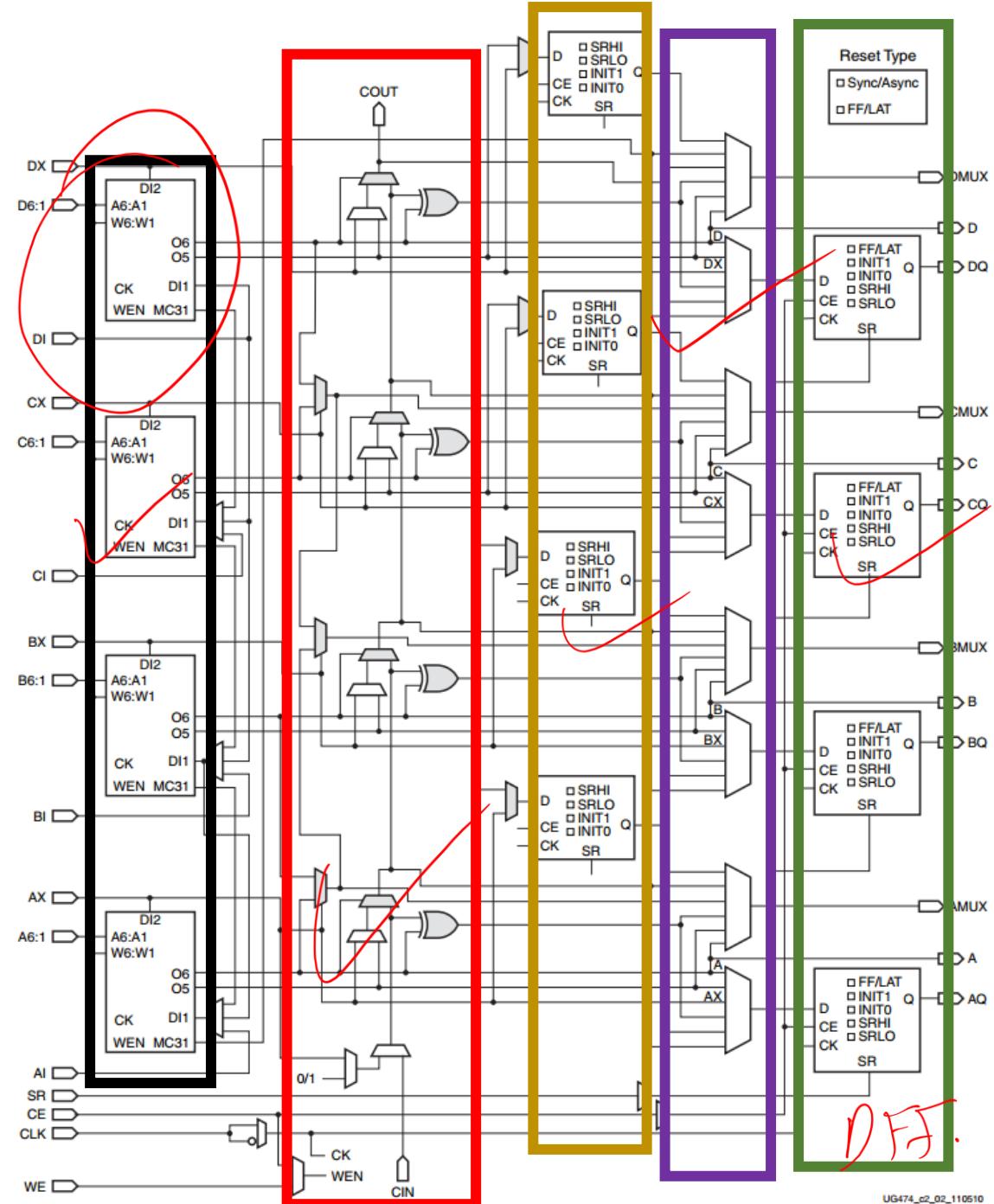
# Types of CLB Slices

- **SLICEM: Full slice**
  - LUT can be used for logic and memory/SRL
- **SLICEL: Logic and arithmetic only**
  - LUT can only be used for logic (not memory/SRL)
- Each CLB can contain **two SLICEL** or a **SLICEL** and a **SLICEM**.
- In the 7-series FPGAs, **approximately  $\frac{1}{4}$  of slices** are SLICEM, the remainder are SLICEL.

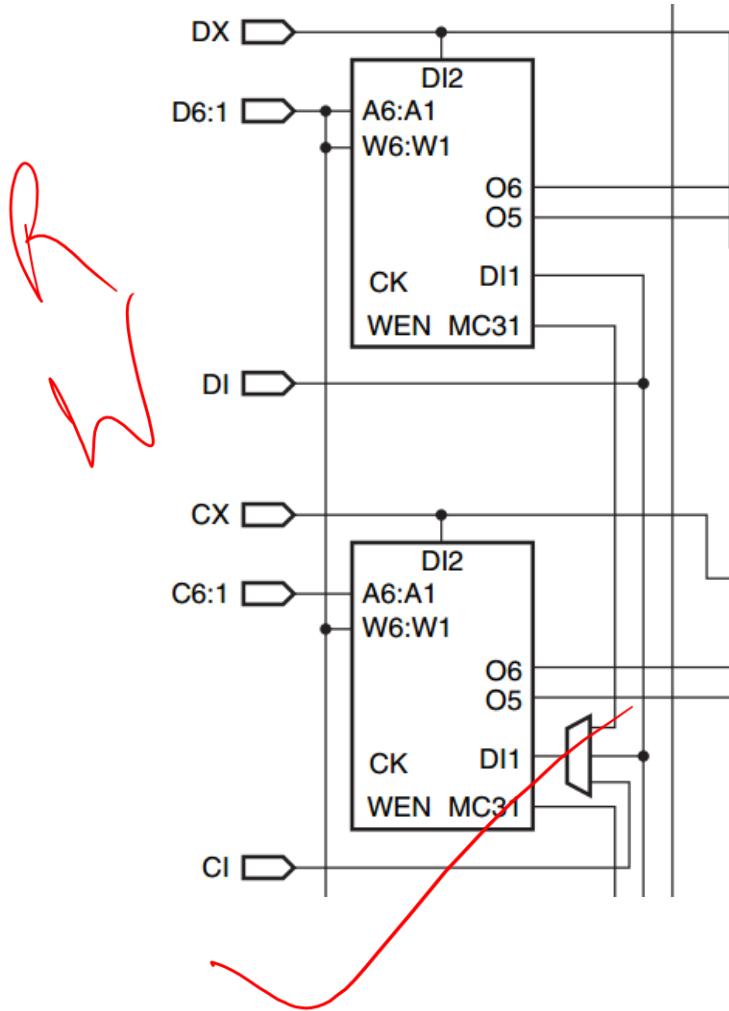


# Slice Resource

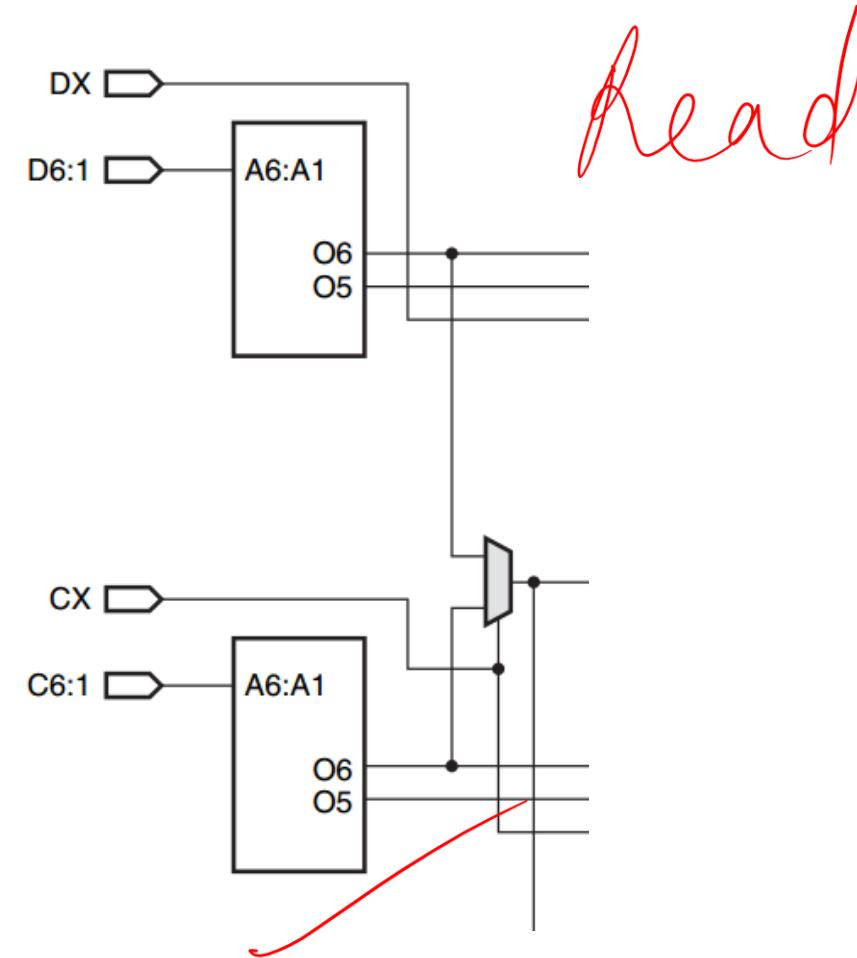
- Four six-input Look-Up Tables (LUT)
- Multiplexers
- Carry chains
- Four flip-flops/latches
- Four additional flip-flops
- Four 6-input LUTs and their eight flip-flops as well as multiplexers and arithmetic carry logic form a slice, and two slices form a CLB.



# SLICEM Vs SLICEL

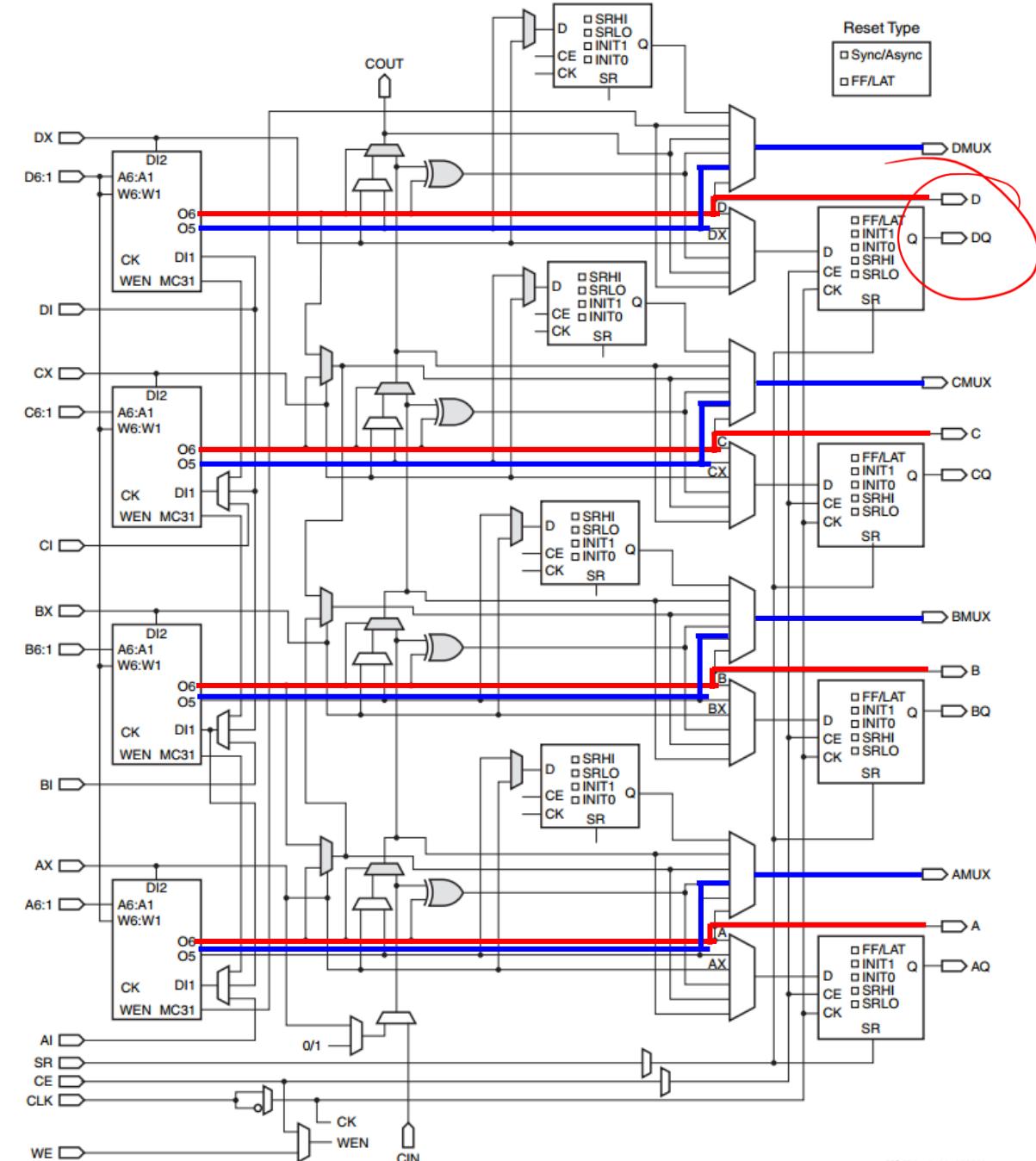


LUT → read  
— write



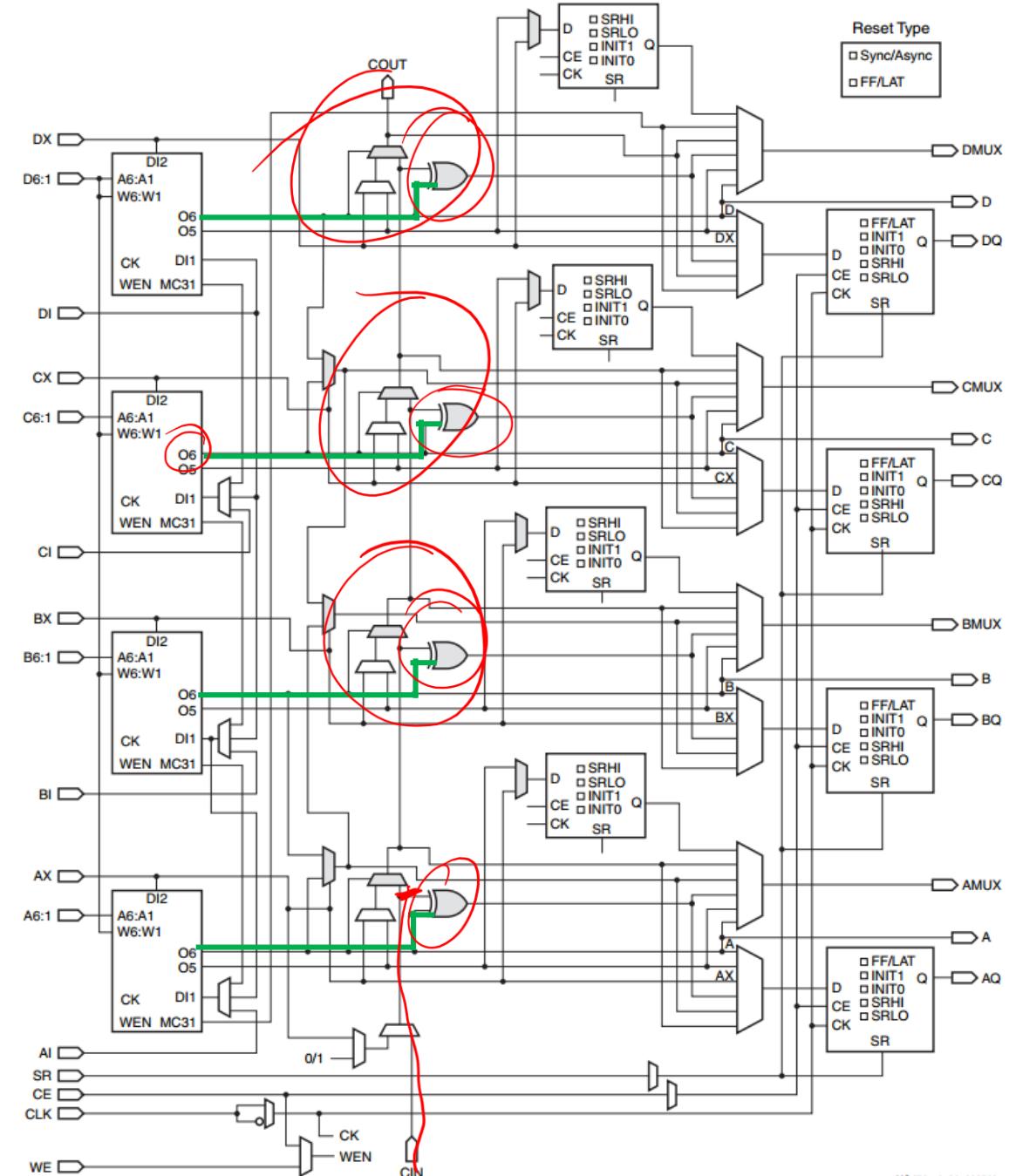
# LUT

- Signals from the LUT can:
  - Exit the slice (through A, B, C, D output for O6 or AMUX, BMUX, CMUX, DMUX output for O5)



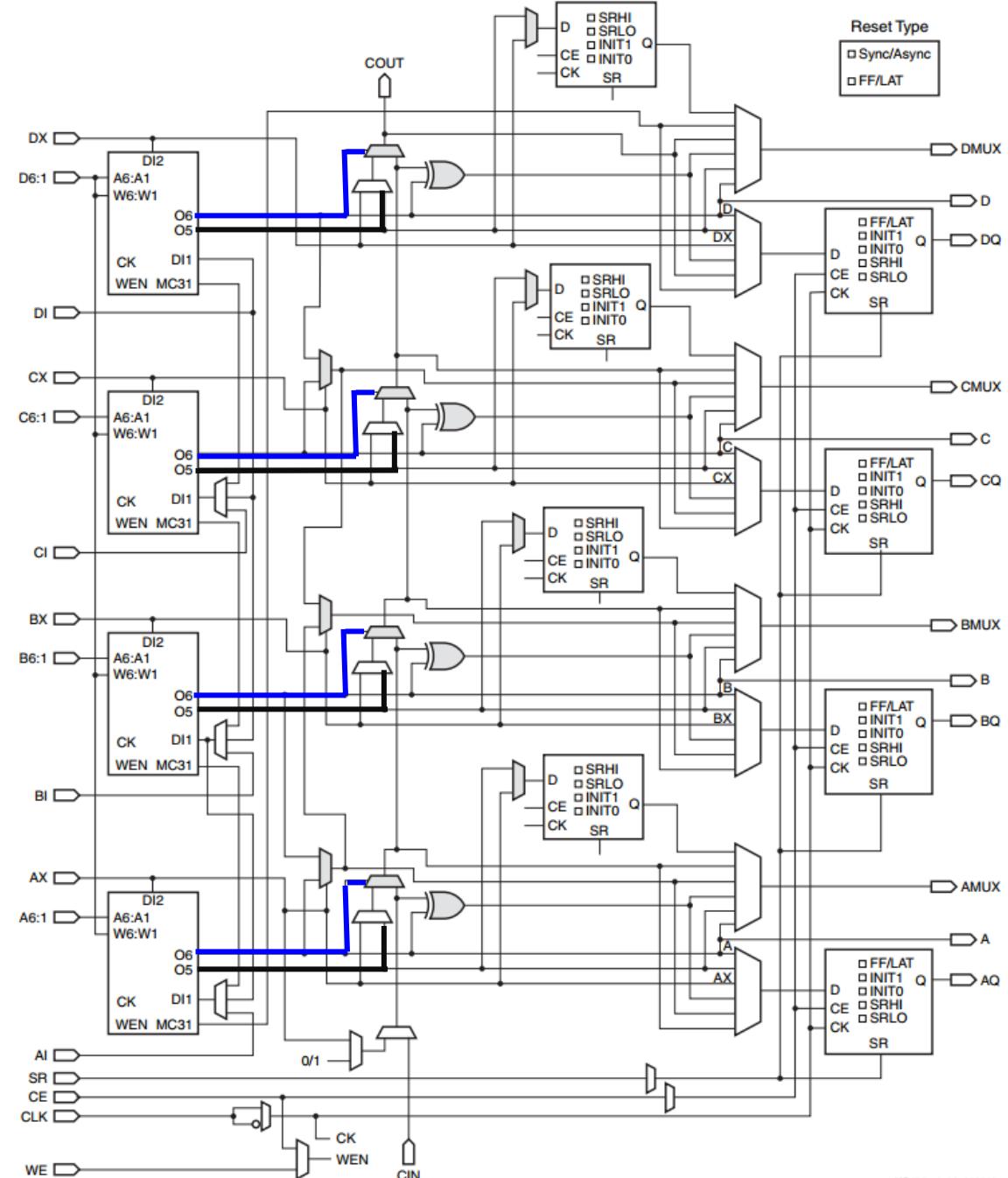
# LUT

- Signals from the LUT can:
  - Exit the slice (through A, B, C, D output for O6 or AMUX, BMUX, CMUX, DMUX output for O5)
  - Enter the XOR dedicated gate from an O6 output



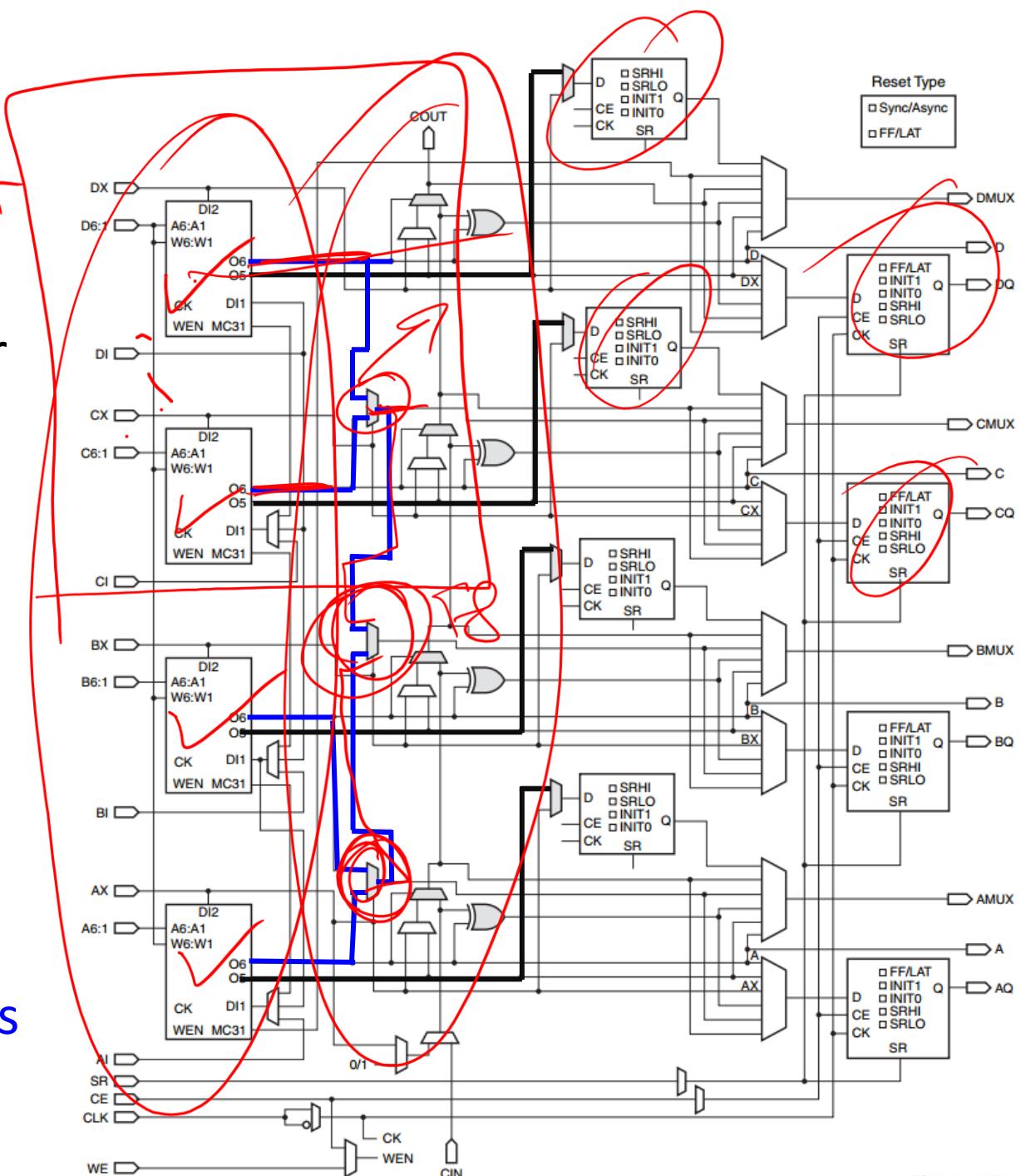
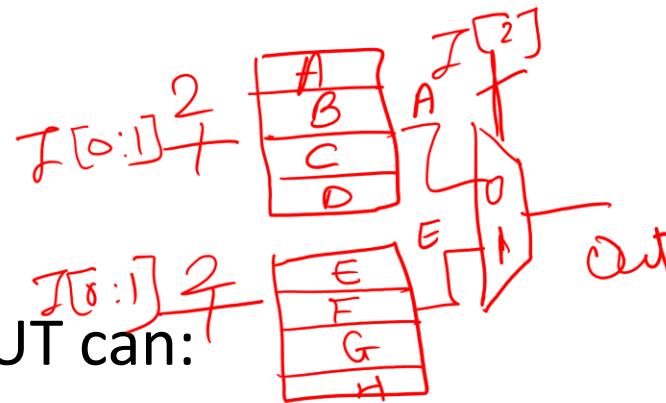
# LUT

- Signals from the LUT can:
  - Exit the slice (through A, B, C, D output for O6 or AMUX, BMUX, CMUX, DMUX output for O5)
  - Enter the XOR dedicated gate from an O6 output
- **Enter the carry-logic chain from an O5 output**
- **Enter the select line of the carry-logic multiplexer from O6 output**



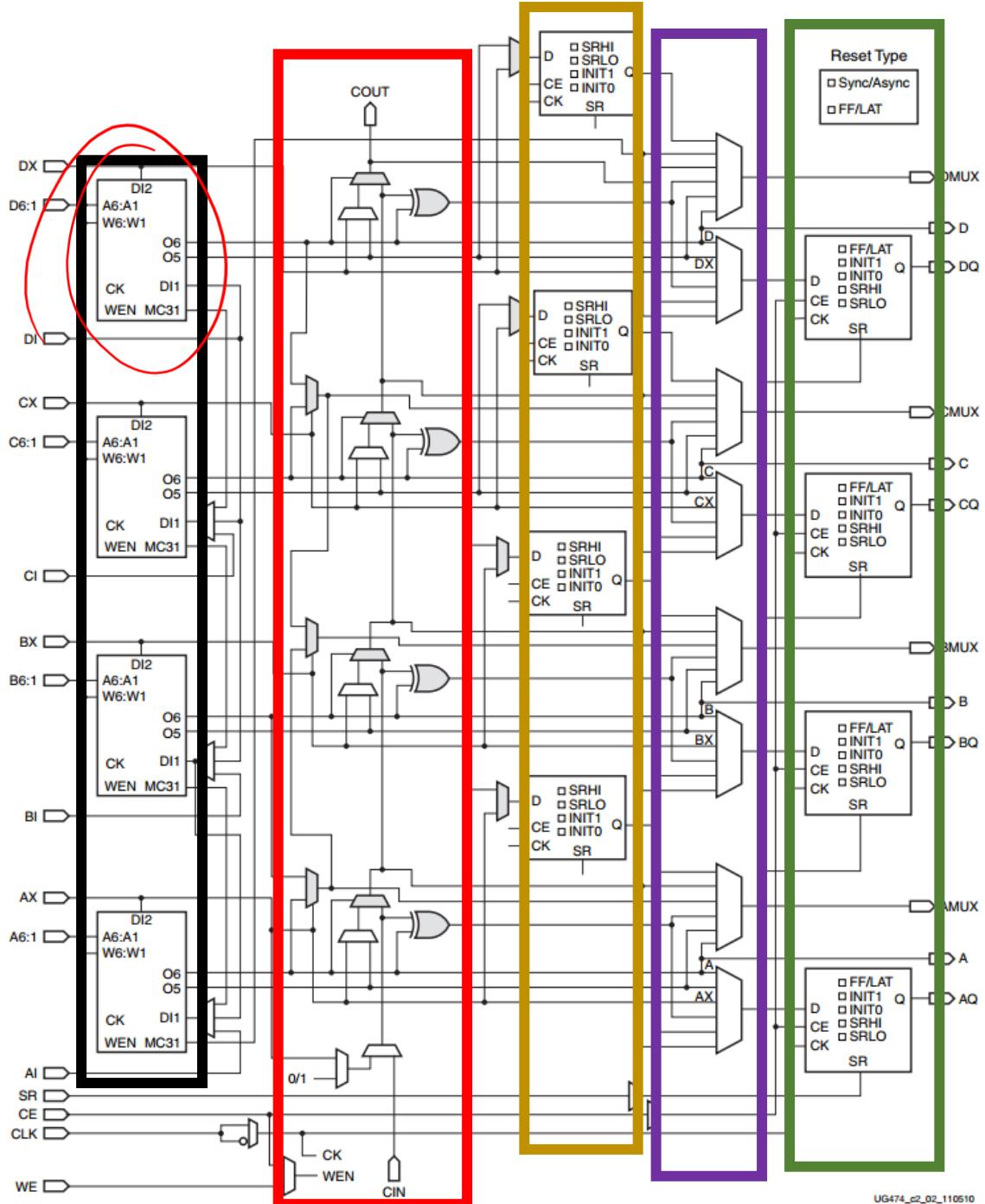
# LUT

- Signals from the LUT can:
- Exit the slice (through A, B, C, D output for O6 or AMUX, BMUX, CMUX, DMUX output for O5)
- Enter the XOR dedicated gate from an O6 output
- Enter the carry-logic chain from an O5 output
- Enter the select line of the carry-logic multiplexer from O6 output
- **Feed the D input of the storage element**
- **Go to F7AMUX/F7BMUX wide multiplexers from O6 output**



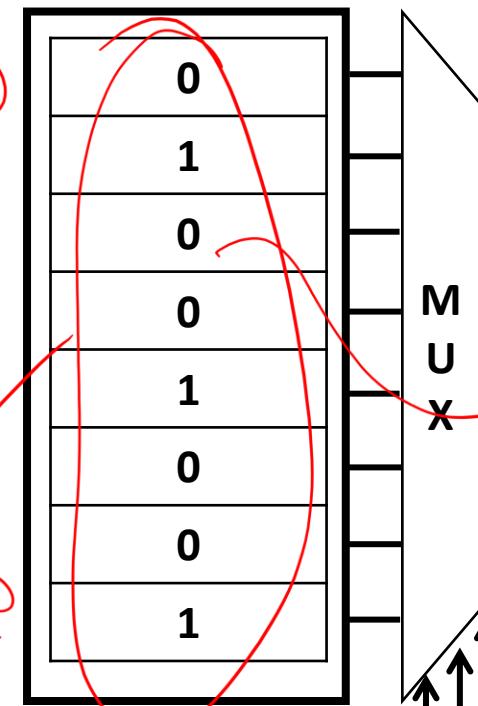
# Slice Resource

- Four six-input Look-Up Tables (LUT)
- Multiplexers
- Carry chains
- Four flip-flops/latches
- Four additional flip-flops
- Four 6-input LUTs and their eight flip-flops as well as multiplexers and arithmetic carry logic form a slice, and two slices form a CLB.



# 3 Input LUT

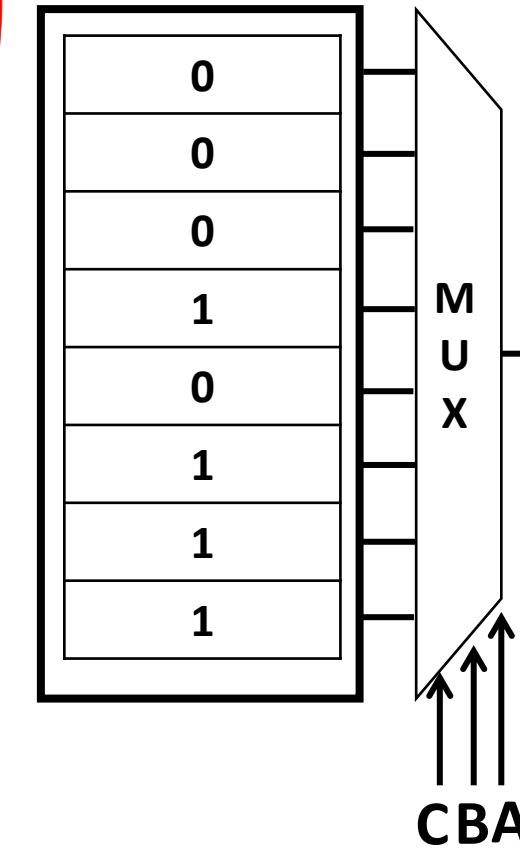
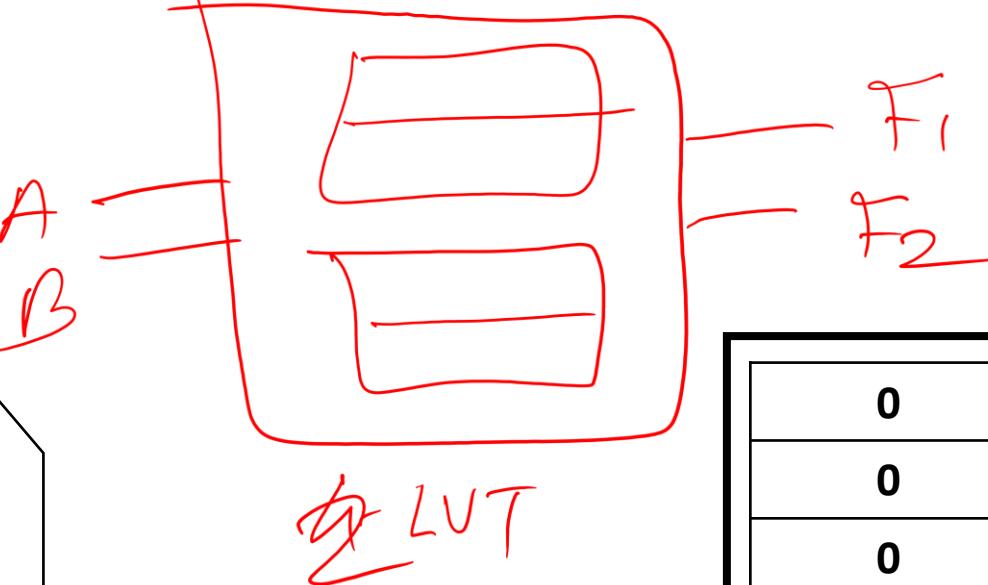
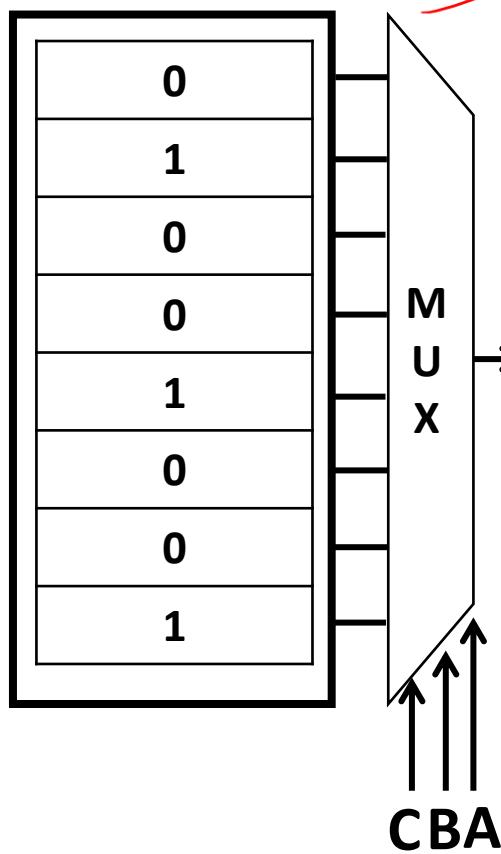
| C | B | A | F1 |
|---|---|---|----|
| 0 | 0 | 0 | 0  |
| 0 | 0 | 1 | 1  |
| 0 | 1 | 0 | 0  |
| 0 | 1 | 1 | 0  |
| 1 | 0 | 0 | 1  |
| 1 | 0 | 1 | 0  |
| 1 | 1 | 0 | 0  |
| 1 | 1 | 1 | 1  |



$$F1 = \sum m(1, 4, 7)$$

CBA

# 3 Input LUT



LUT



LUT3

- There are six independent inputs (A inputs - A1 to A6) and two independent outputs (O5 and O6)

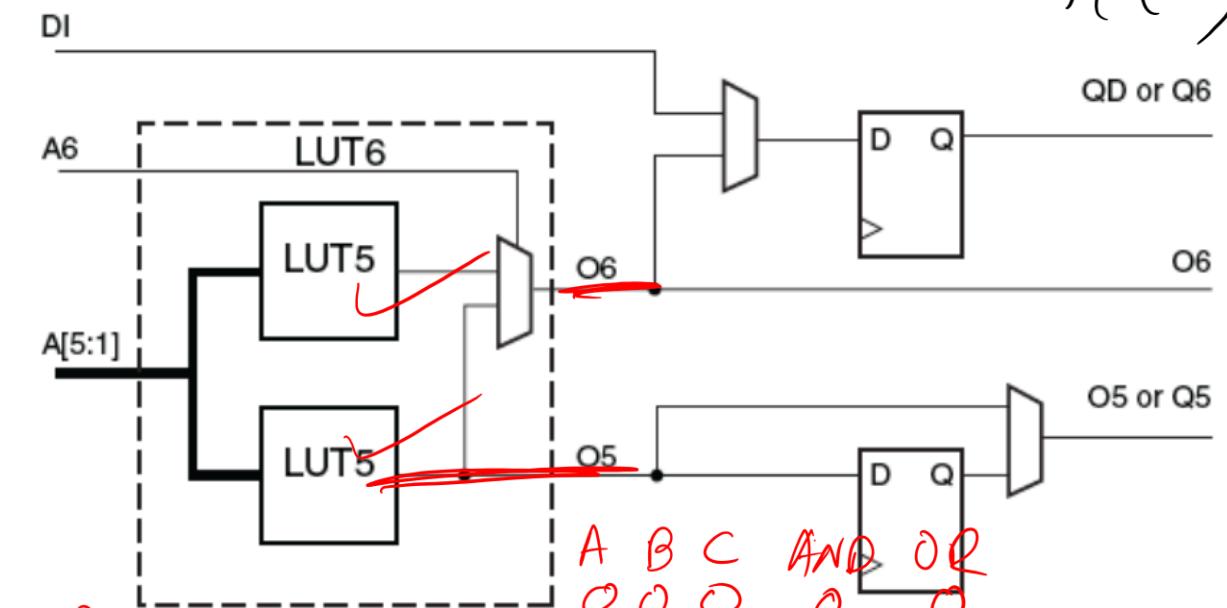
$f_1(A, B)$

$f_2(C, D)$

$f_1(A, B)$  AND  
 $f_2(A, B)$

$f_1(A, B)$  AND

$f_2(A, C)$  OR X



UG384\_06new\_021210

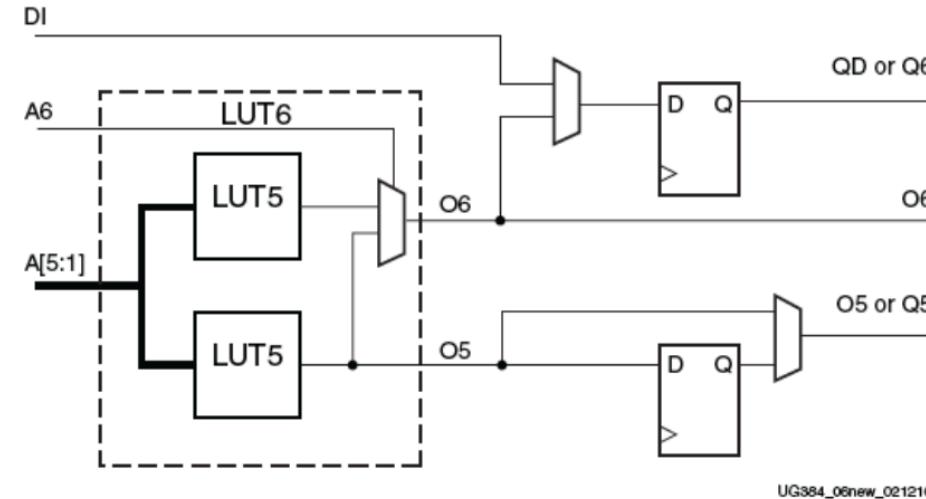
| A | B | C | AND | OR |
|---|---|---|-----|----|
| 0 | 0 | 0 | 0   | 0  |
| 0 | 0 | 1 | 0   | 1  |
| 0 | 1 | 0 | 0   | 1  |
| 0 | 1 | 1 | 1   | 1  |
| 1 | 0 | 0 | 0   | 1  |
| 1 | 0 | 1 | 0   | 1  |
| 1 | 1 | 0 | 1   | 1  |
| 1 | 1 | 1 | 1   | 1  |

# 3-Input LUT for Logic

- Any single arbitrarily defined 3-input Boolean function
- A 3-input function uses: A1-A3 inputs and O3 output
- Two arbitrarily defined 2-input Boolean functions, as long as these two functions share common inputs
- Two 2-input or less functions use: A1–A2 inputs, A3 driven High, O2 and O3 outputs
- Two arbitrarily defined Boolean functions of 1 input

# 6-Input LUT for Logic

$$f_1(A, B, C)$$
$$f_2(D, E)$$



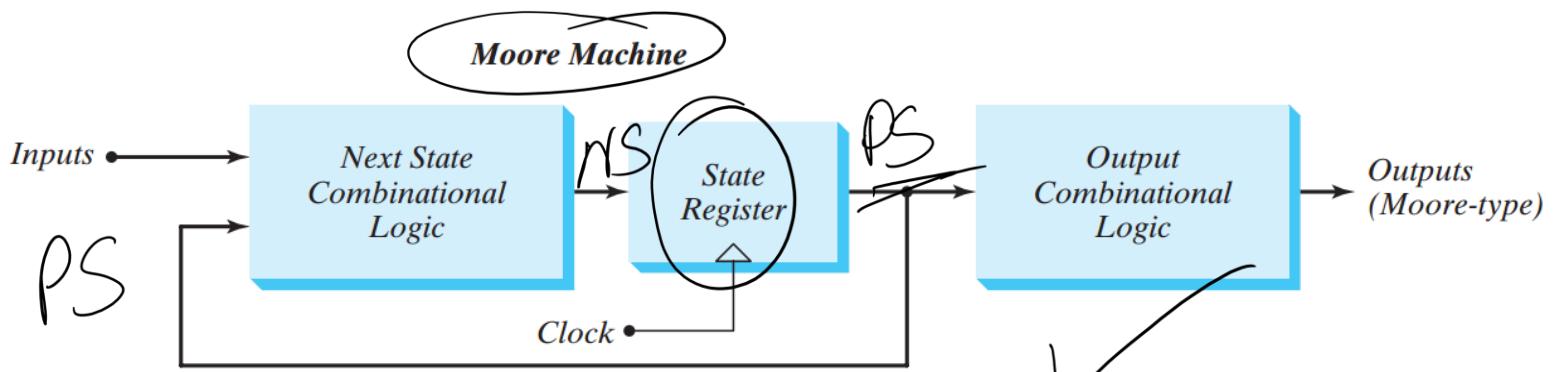
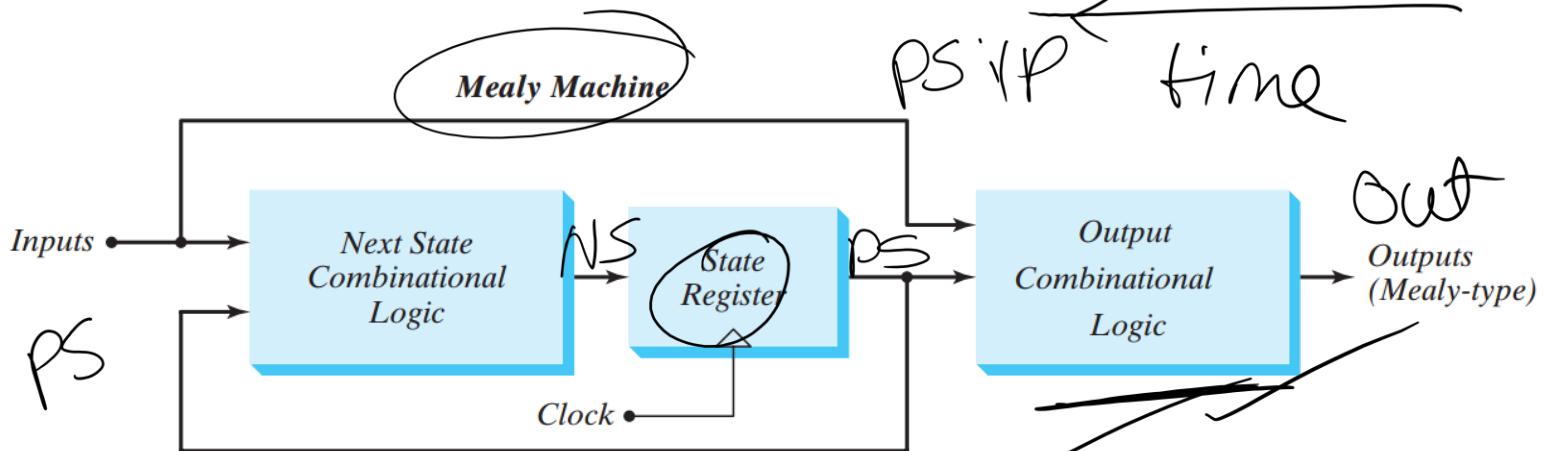
UG384\_06new\_021210

- Any arbitrarily defined six-input Boolean function
- A six-input function uses:  $A1-A6$  inputs and  $O6$  output
- Two arbitrarily defined five-input Boolean functions, as long as these two functions share common inputs
- Two five-input or less functions use:  $A1-A5$  inputs,  $A6$  driven High,  $O5$  and  $O6$  outputs
- Two arbitrarily defined Boolean functions of 3 and 2 inputs or less

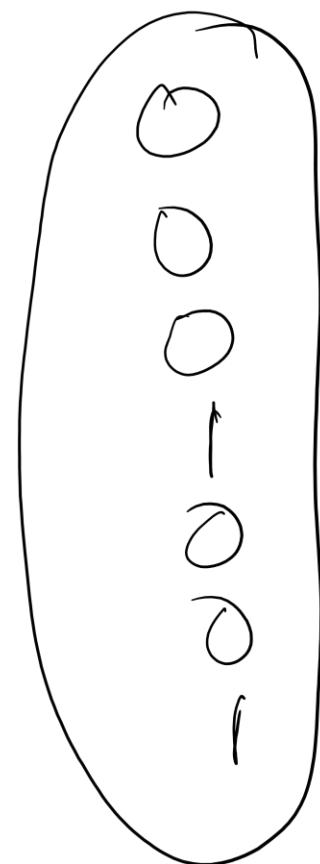
# Finite State Machines

10110110  
PS/P time

110



✓ FSN



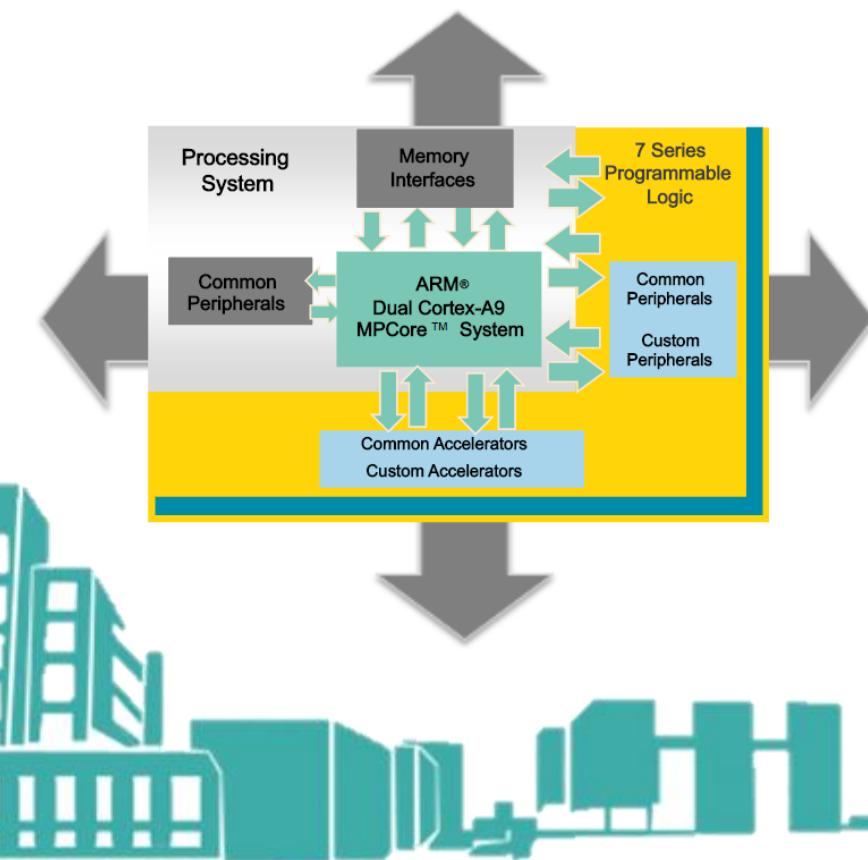
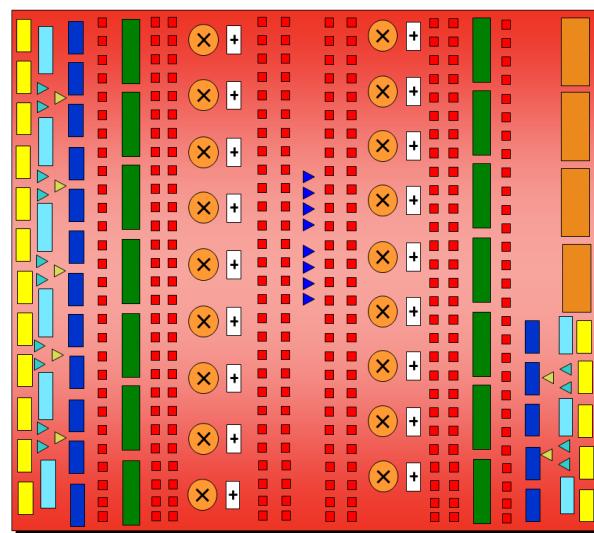


ECE  
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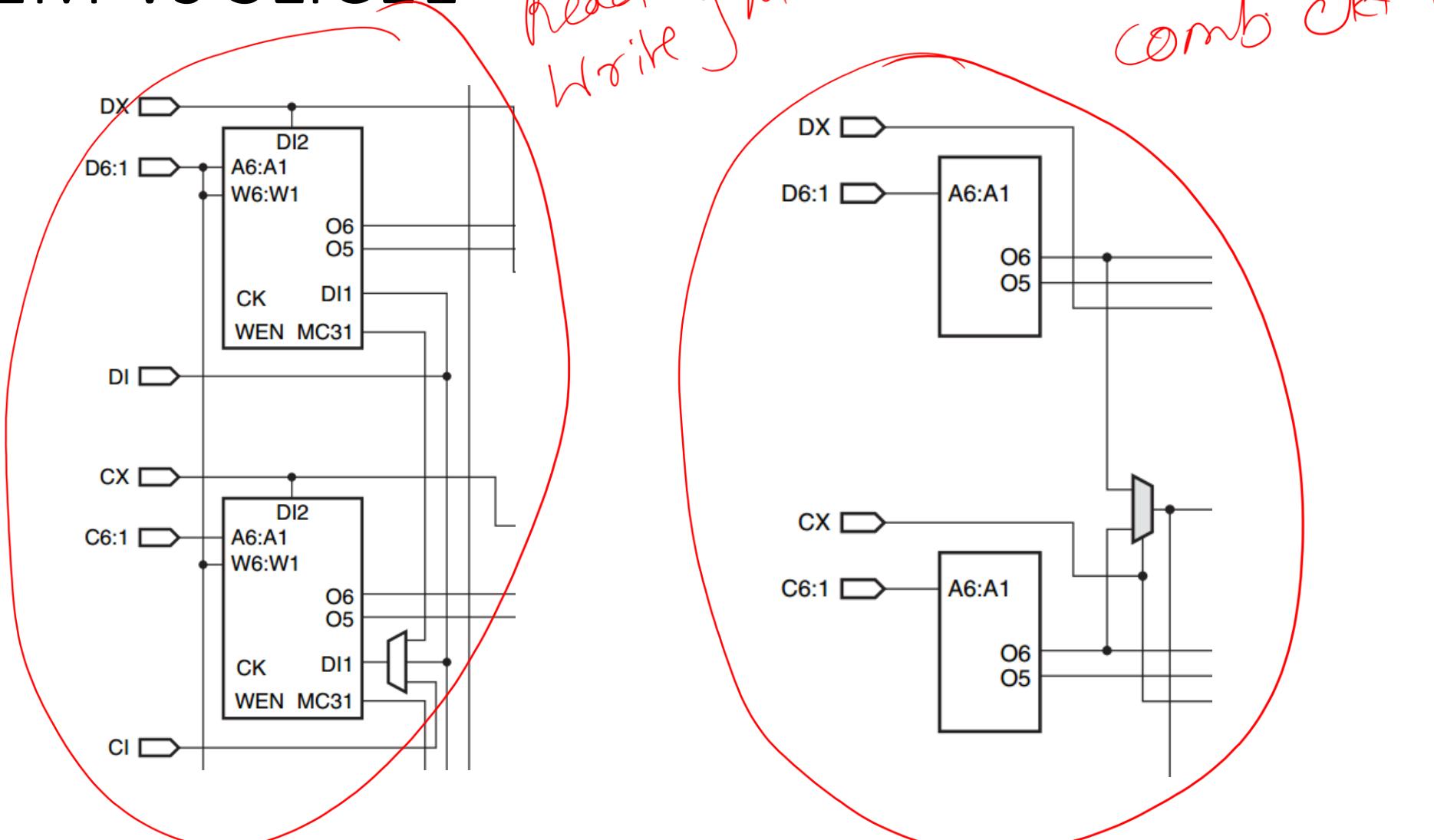
DEPARTMENT OF ELECTRONICS &  
COMMUNICATIONS ENGINEERING

A2A  
*Algorithms to Architecture*

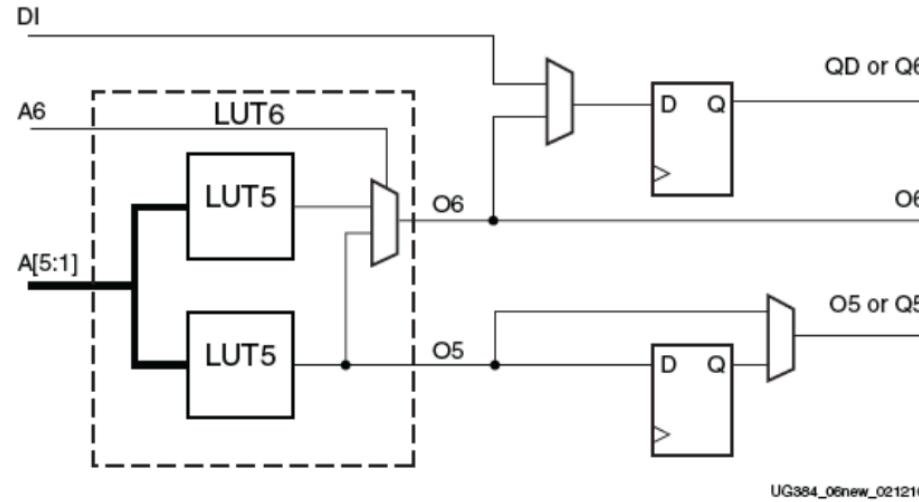
# ECE 270: Embedded Logic Design



# SLICEM Vs SLICEL



# 6-Input LUT for Logic

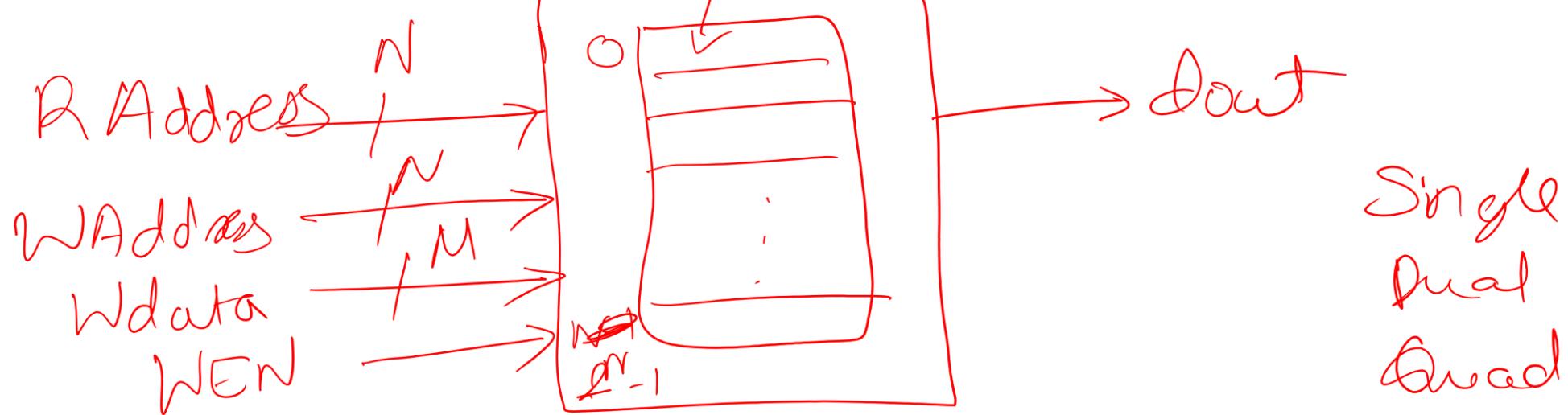


UG384\_06new\_021210

- Any arbitrarily defined six-input Boolean function
- A six-input function uses:  $A_1-A_6$  inputs and  $O_6$  output
- Two arbitrarily defined five-input Boolean functions, as long as these two functions share common inputs
- Two five-input or less functions use:  $A_1-A_5$  inputs,  $A_6$  driven High,  $O_5$  and  $O_6$  outputs
- Two arbitrarily defined Boolean functions of 3 and 2 inputs or less

# What is Memory?

LUT  
M  
Comb dkt,  
Mem.  
Shift. reg.



Read  
Write

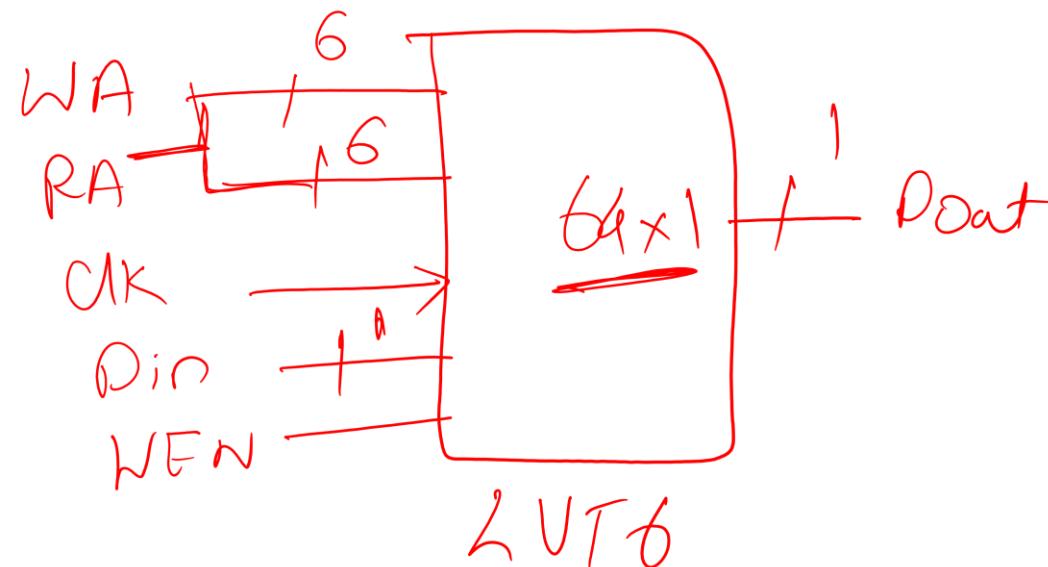
M N bits.

# LUT as Memory

- Only in **SLICEM**
- Multiple LUTs in a SLICEM can be combined in various ways to store large amount of data
- **Synchronous** write operation, **WEN must be high**
- **Asynchronous or synchronous read** (using **flip-flop** in the same slice)

# LUT as Memory

- **Single port:** Common address port for synch write and asynch read i.e.  
read and write addresses share the same address bus

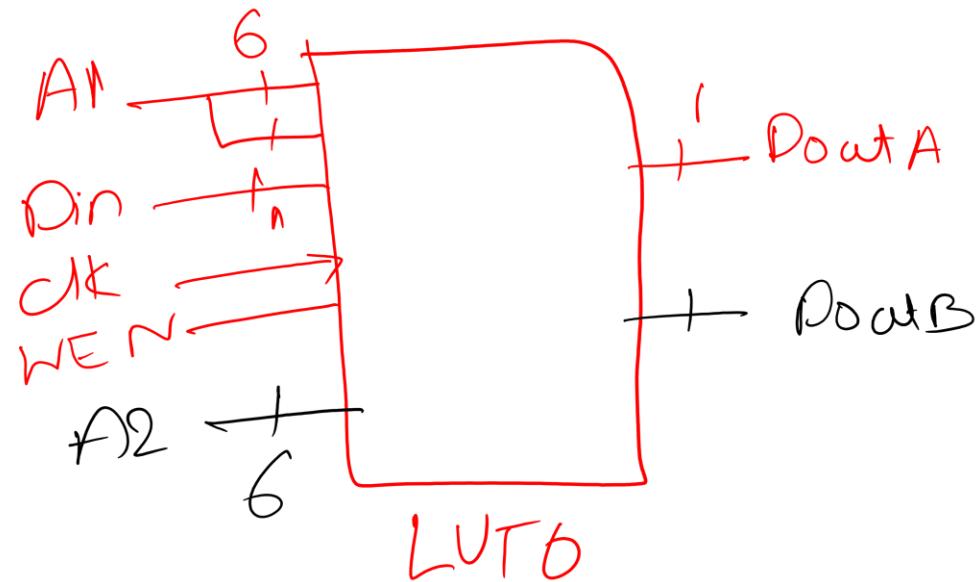


WEN=0 Read  
WEN=1 Write  
Read.

# LUT as Memory

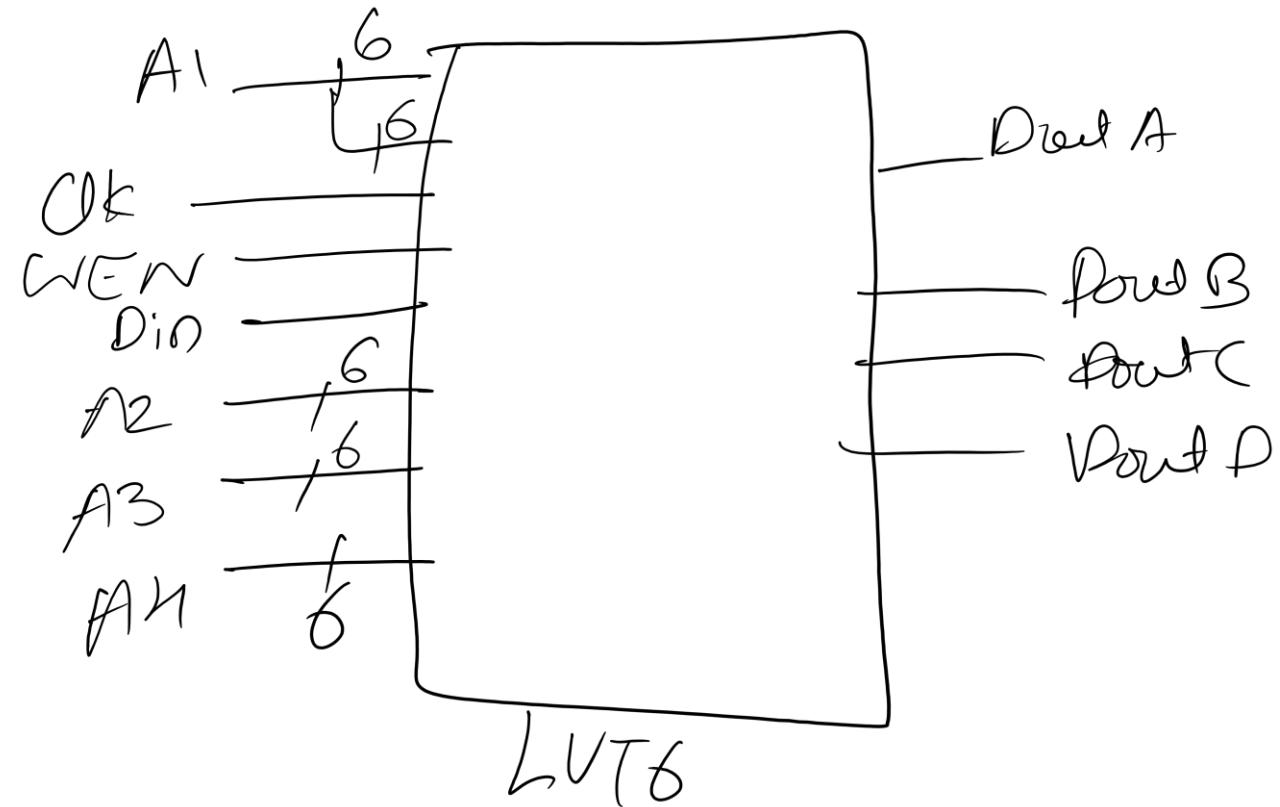
Quad Port

- **Dual port:** One port for synch write and asynch read, one port for asynch read



# LUT as Memory

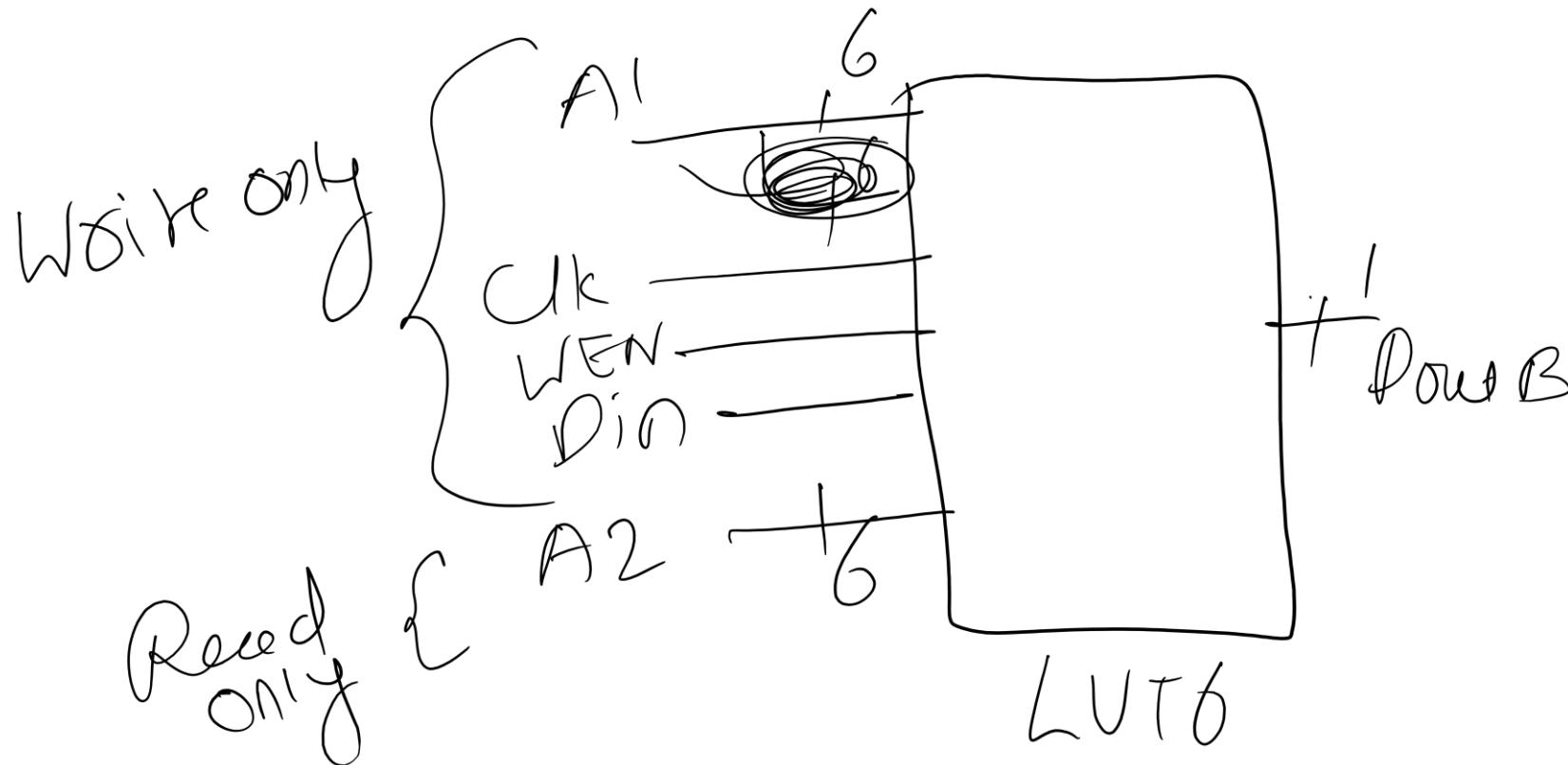
- **Quad port:** One port for synchronous write and asynchronous read and three ports for asynchronous reads



## LUT as Memory

64x4  
64x1 Single Port  
Read Port  
128x2 Single Port

- **Simple dual port:** One port for synchronous write (no data out/read port from the write port) and one port for asynchronous reads



1) Clock of all LUTs is common ,

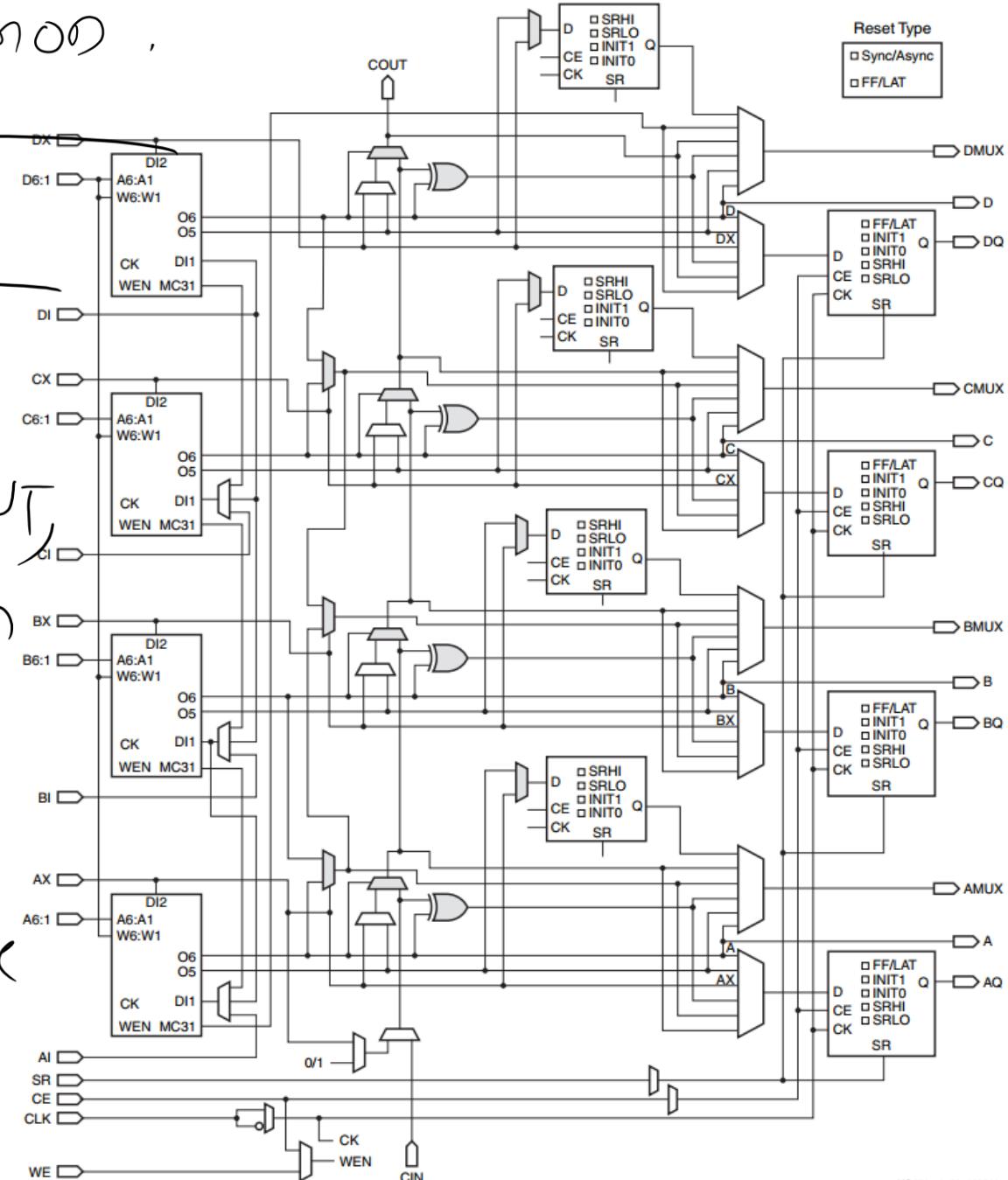
2) WEN → EO

3) WA → CI

→ When you perform  
write op<sup>n</sup> on any LUT,  
Write op<sup>n</sup> will happen on  
all LUTs . X

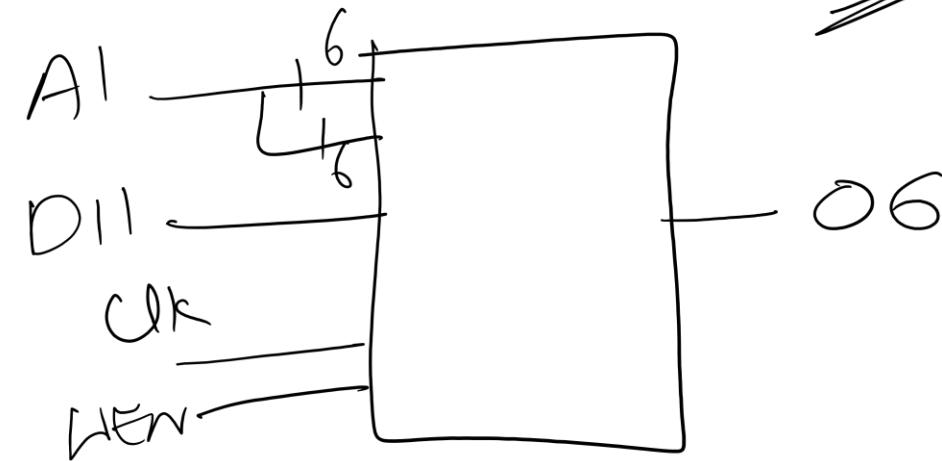
4) RA of all LUTs are diff

5) For first LUT, RA & WA are  
Same .

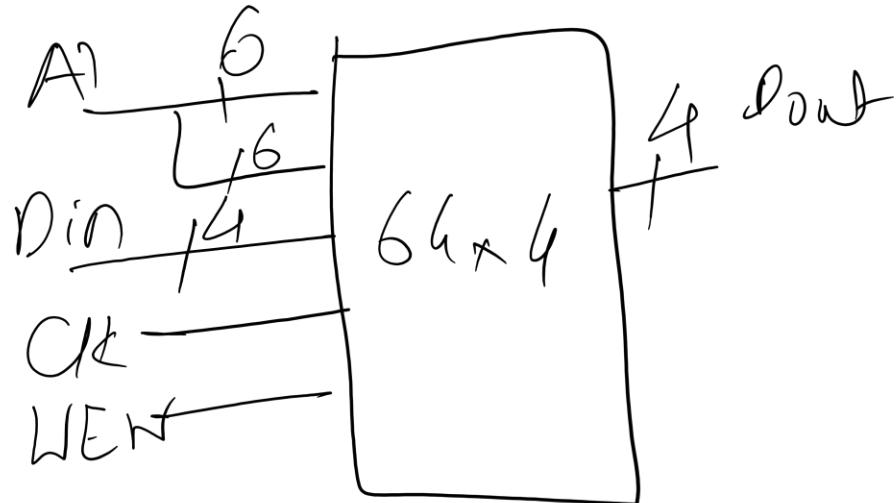


# LUT as Memory: 64X1 Single Port

- How many LUTs are needed? 1



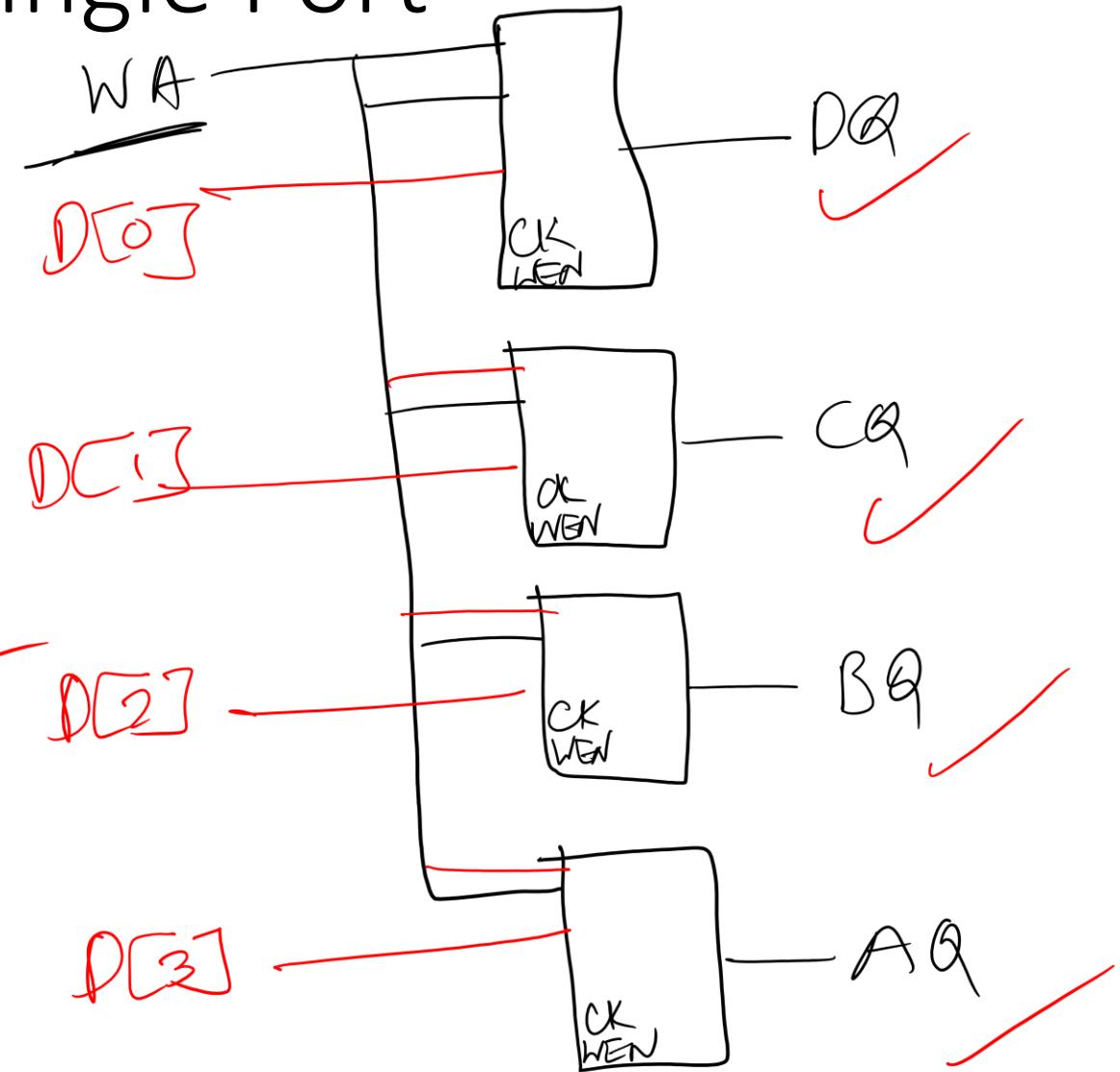
# LUT as Memory: 64X4 Single Port



What is diff. b/w?

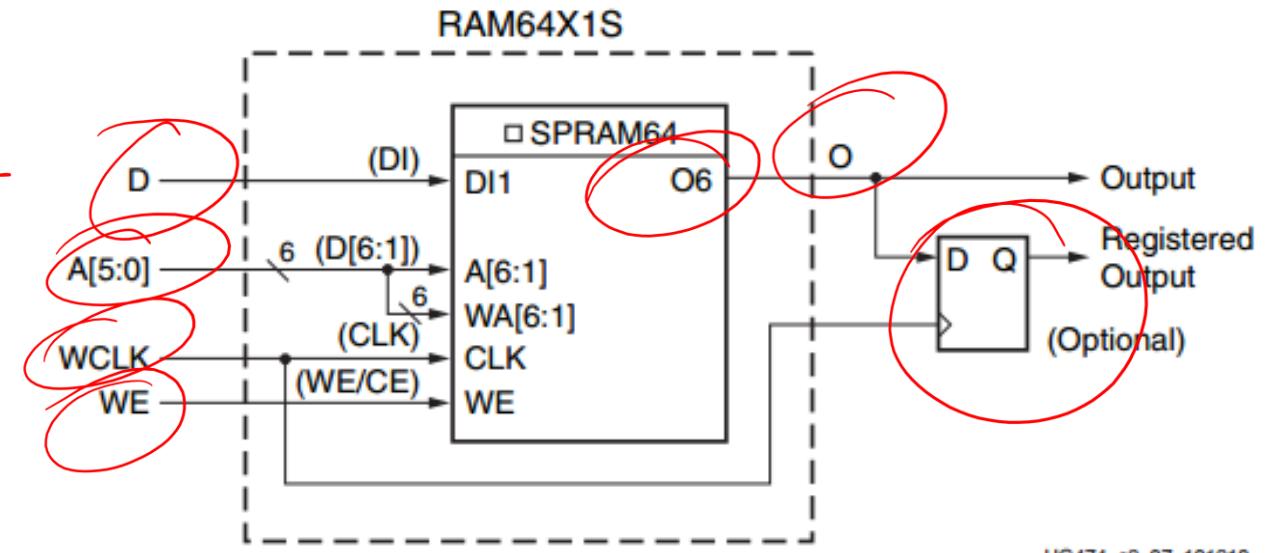
1) 64x4 single port.

2) Four 64x1 single port



# LUT as Memory: 64X1 Single Port

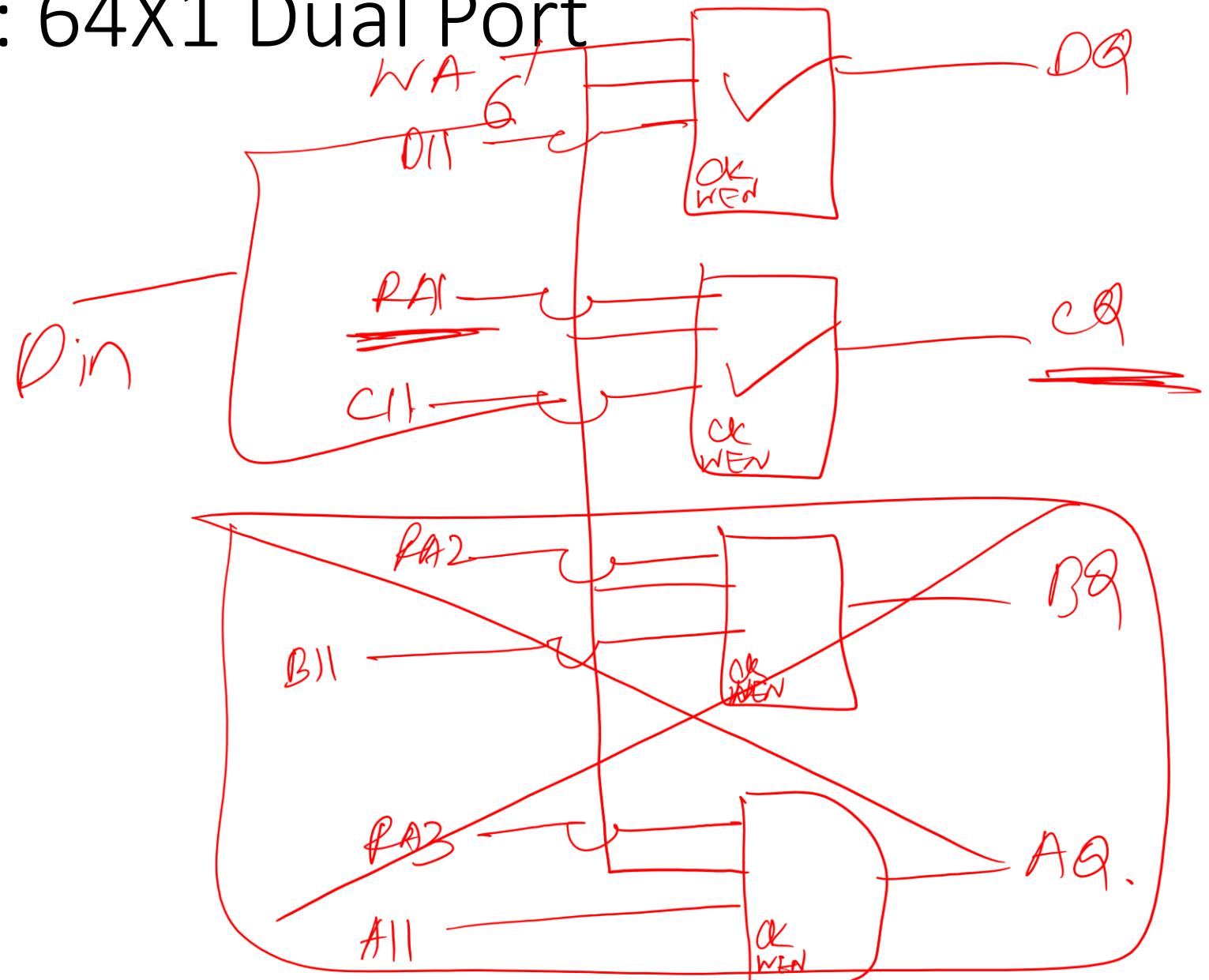
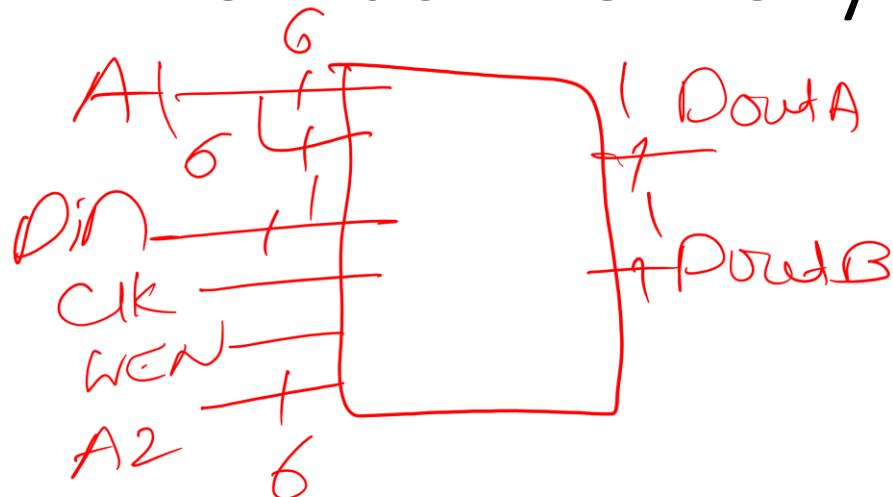
- **Single port:** Common address port for synch write and asynch read
- One SLICEM can have FOUR 64 x 1-bit memories as long as they share the same clock, write enable, and shared read and write port address inputs
- This configuration equates to a 64 x 4-bit single-port distributed RAM.
- What about O5 output?



64 X 1 Single Port Distributed RAM (RAM64X1S)

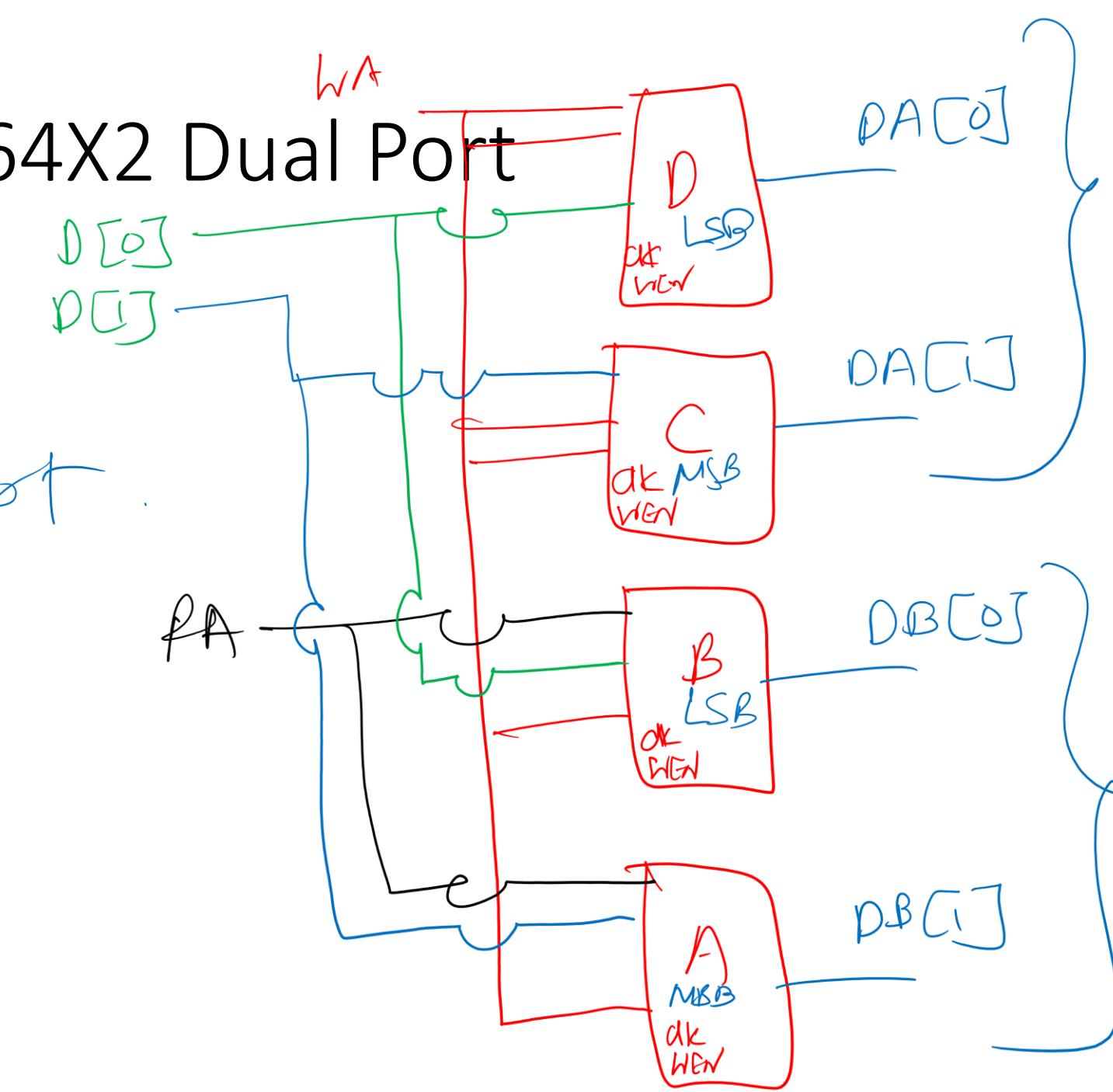
UG474\_c2\_07\_101210

# LUT as Memory: 64X1 Dual Port



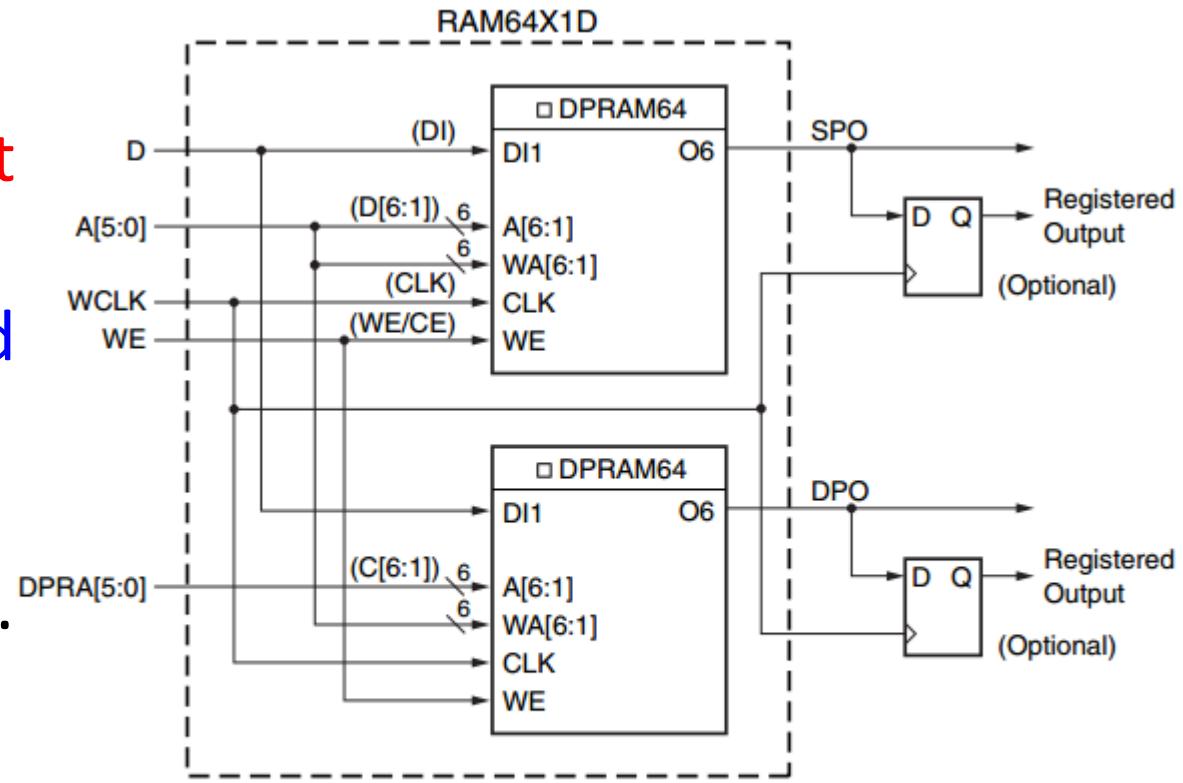
# LUT as Memory: 64X2 Dual Port

64x1 Read Port.



# LUT as Memory: 64X1 Dual Port

- One SLICEM can have **TWO 64 x 1-bit memories** as long as they share the same clock, write enable, and shared read and write port address inputs
- This configuration equates to a **64 x 2-bit dual-port distributed RAM**.



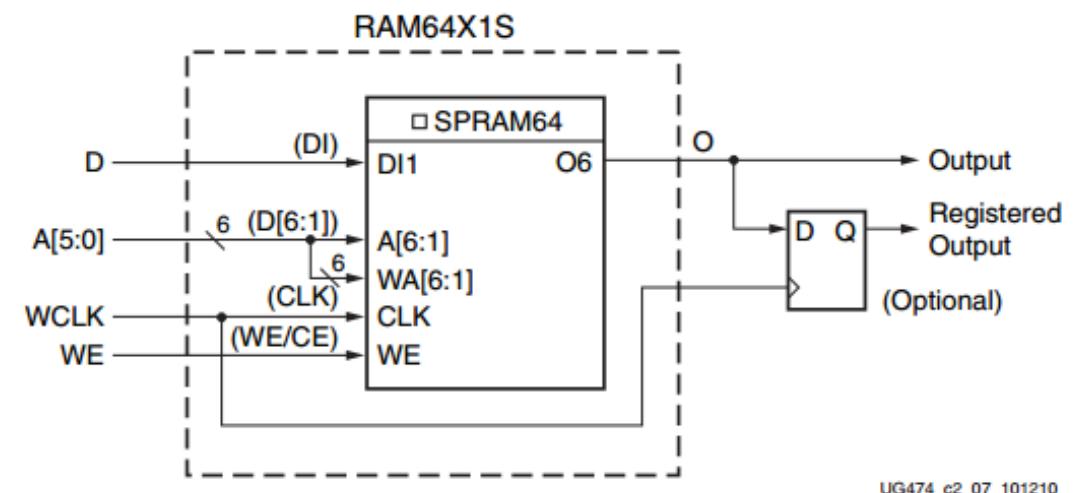
64 X 1 Dual Port Distributed RAM (RAM64X1D)

UG474\_c2\_08\_101210

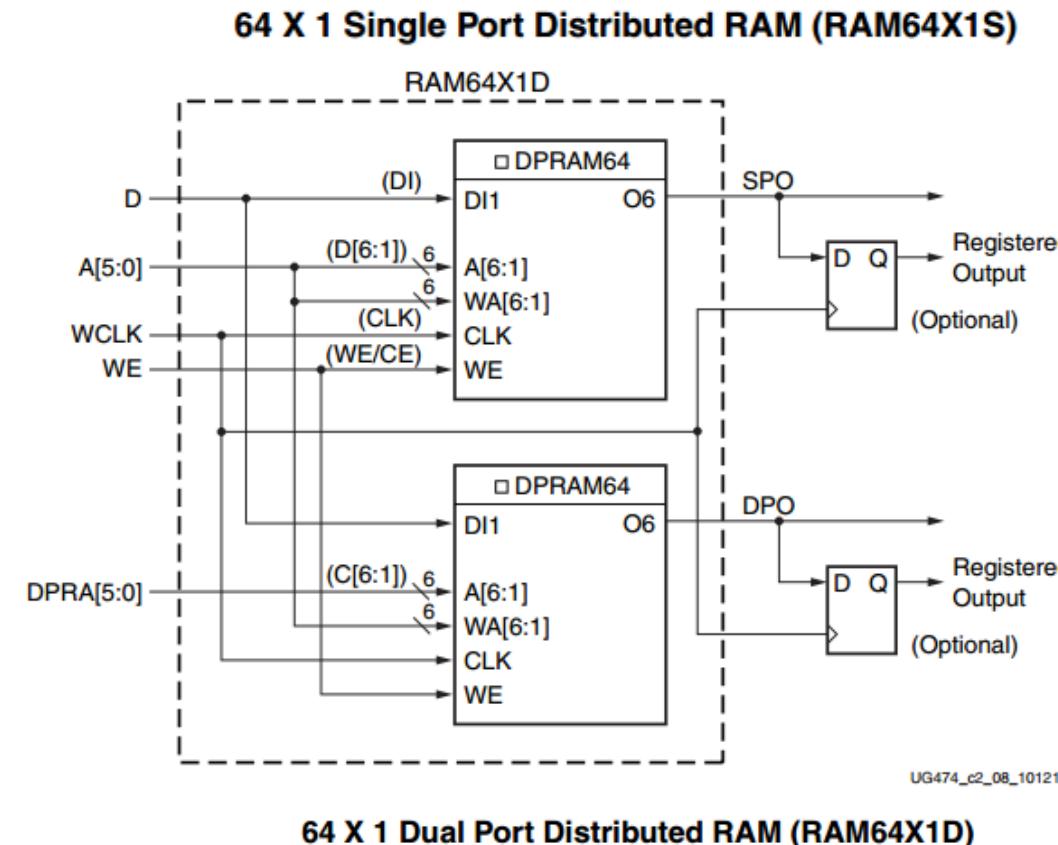
# LUT as Memory

- **Synchronous Write Operation**

The synchronous write operation is a single clock-edge operation with an active-High write-enable (WE) feature. When WE is High, the input (D) is loaded into the memory location at address A.



UG474\_c2\_07\_101210



UG474\_c2\_08\_101210

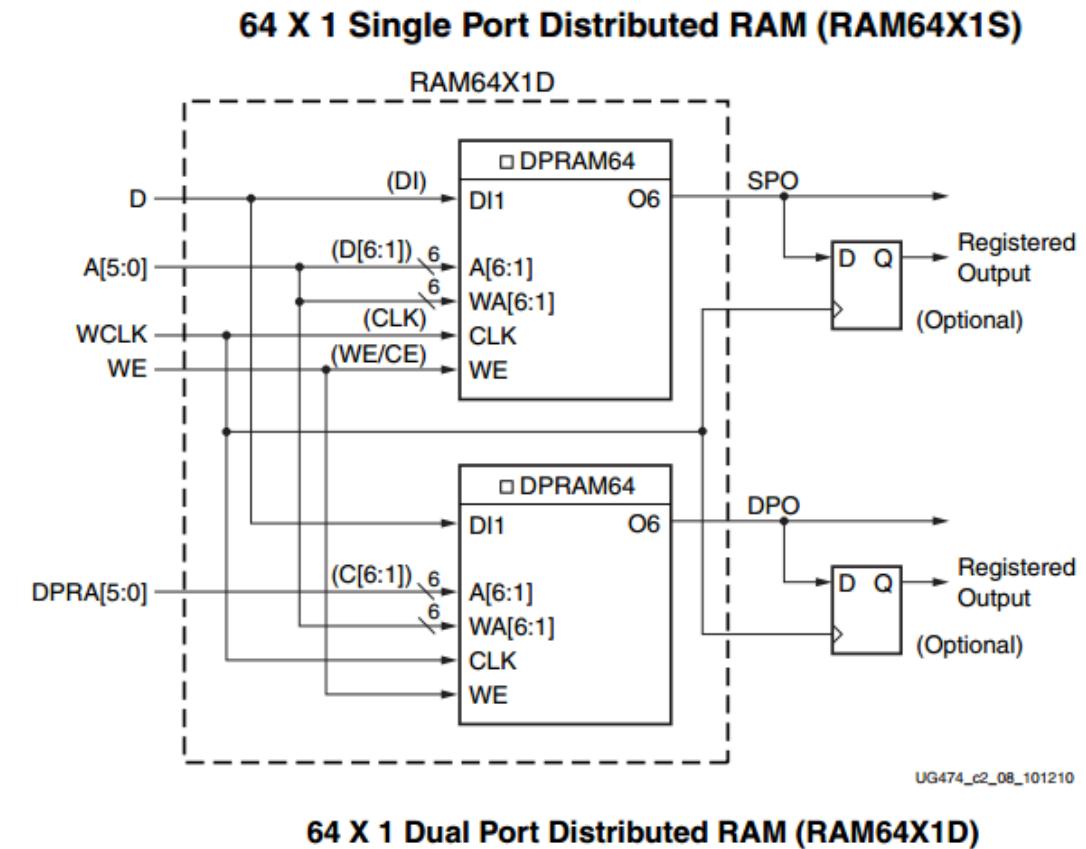
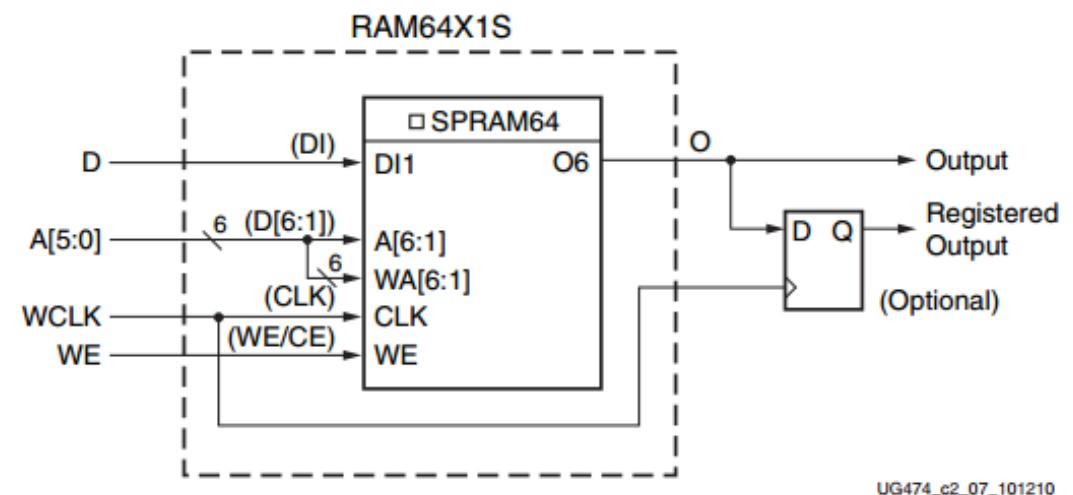
64 X 1 Dual Port Distributed RAM (RAM64X1D)

# LUT as Memory

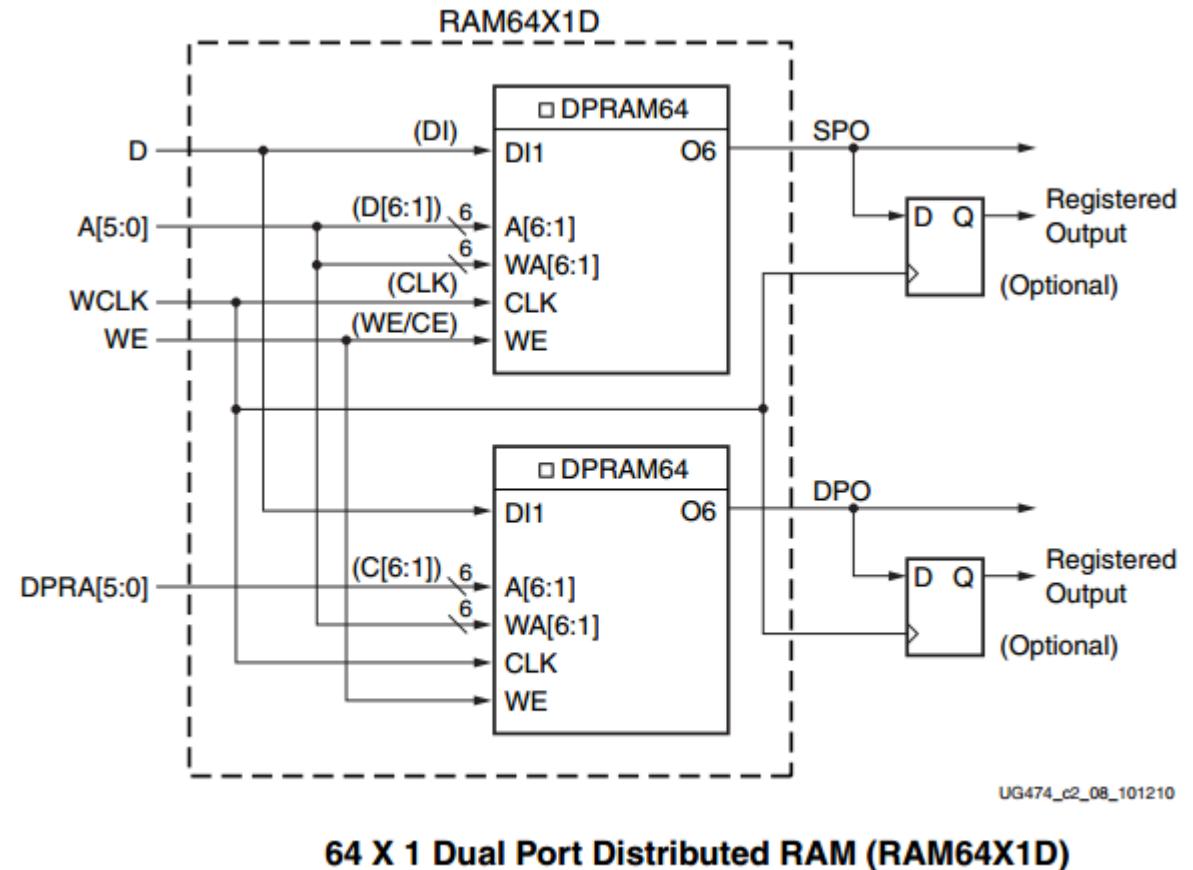
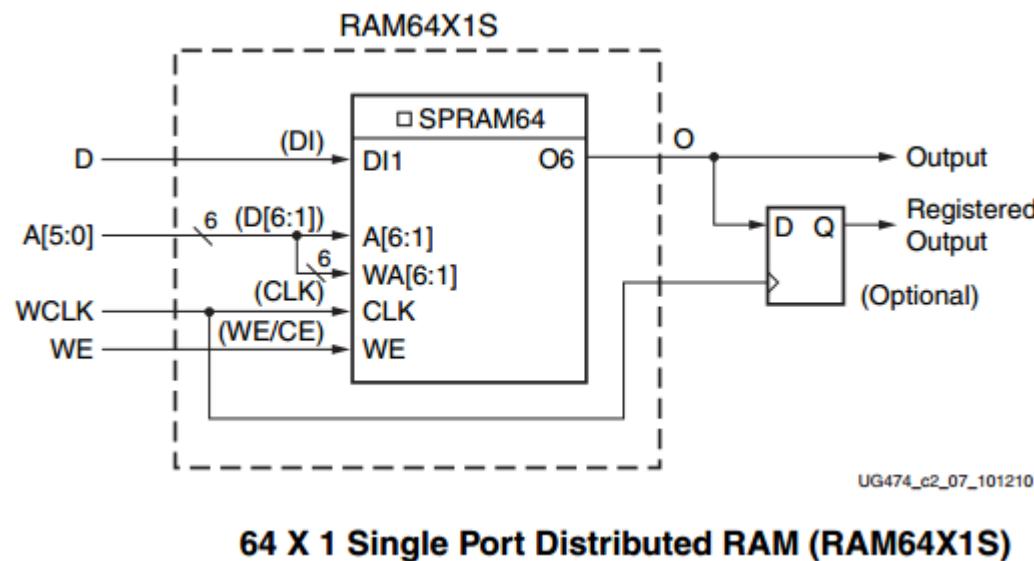
- **Asynchronous Read Operation**

The output (or output SPO of dual-port mode) is determined by the address A for the single-port mode or address DPRA determines the DPO output of dual-port mode.

- Each time a new address is applied to the address pins, the data value in the memory location of that address is available on the output.
- This operation is asynchronous and independent of the clock signal.

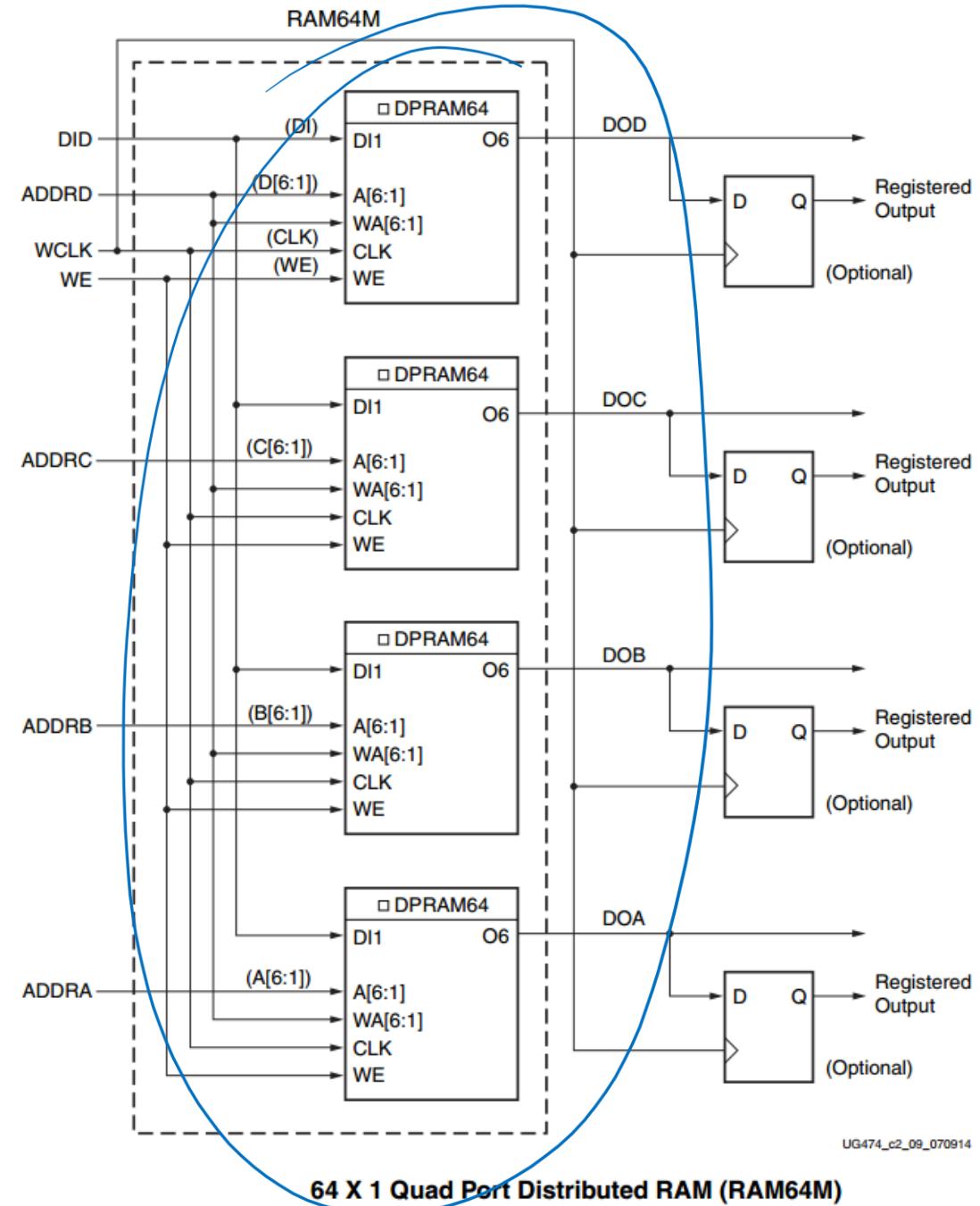


# LUT as Memory: 64X1 Dual Port

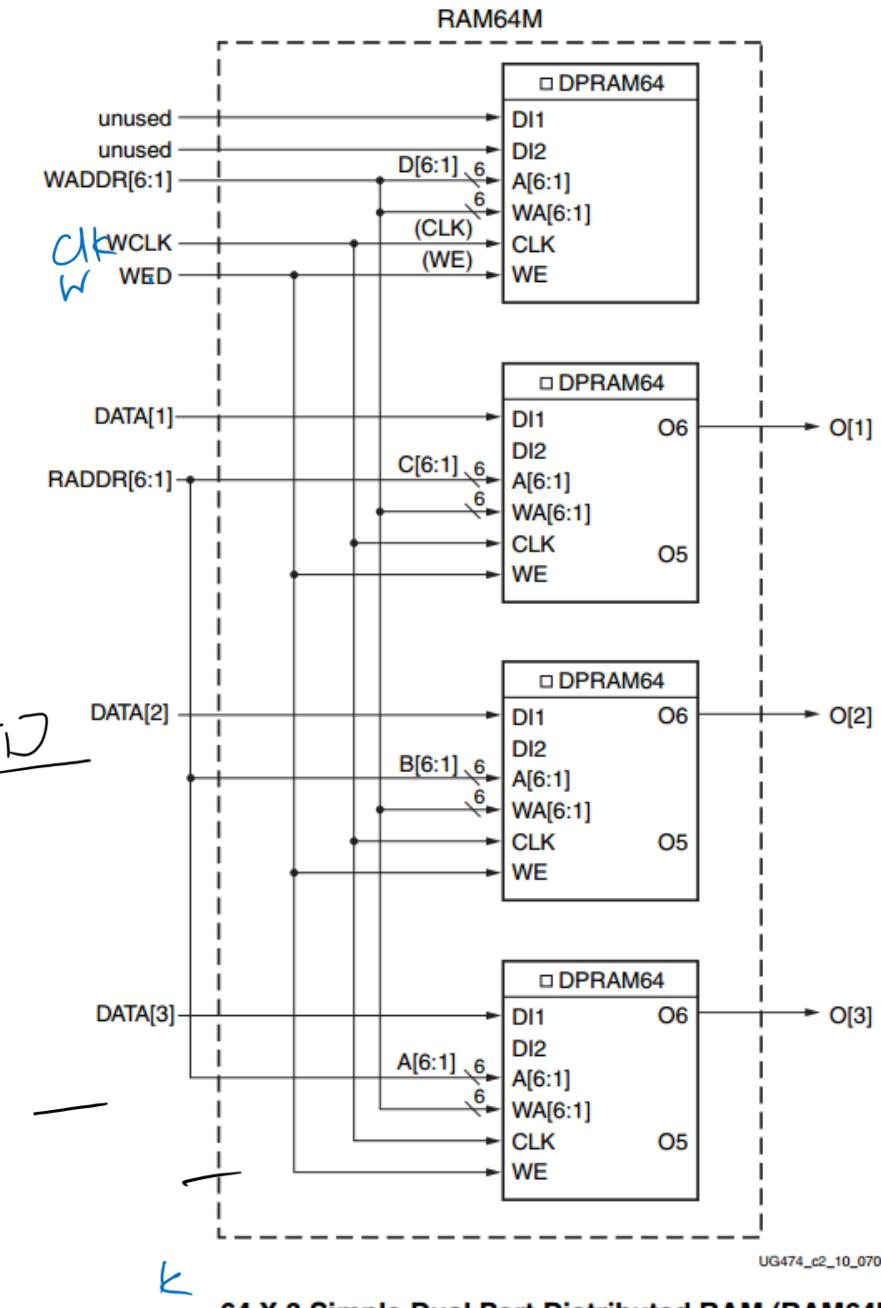
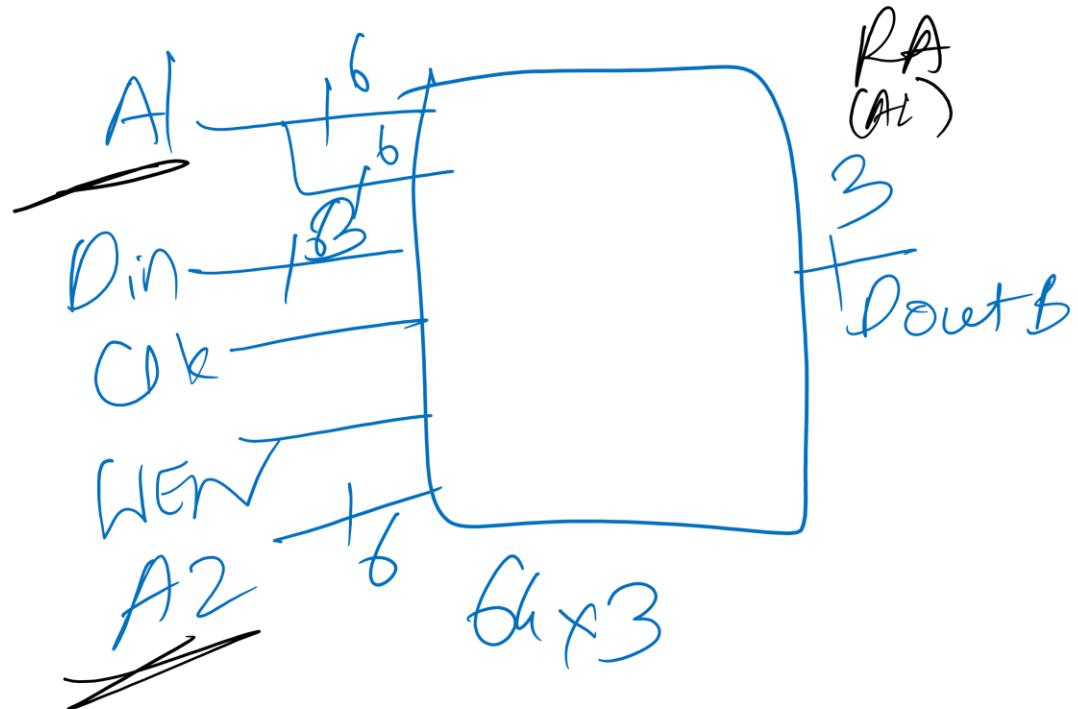


# LUT as Memory: 64X1 Quad Port

6x2 Quad Port X

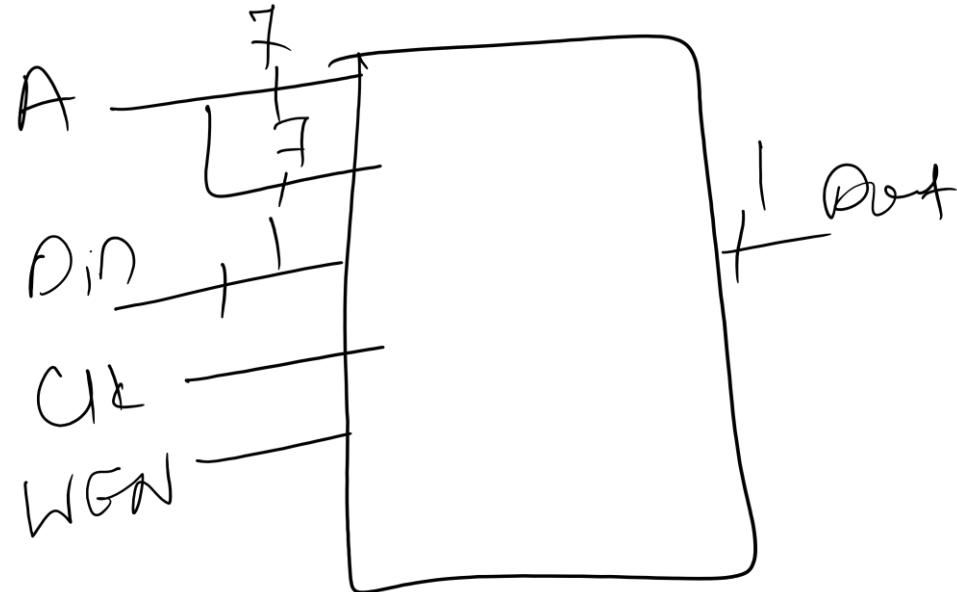


# LUT as Memory: (A') WA 64X3 Simple Dual Port



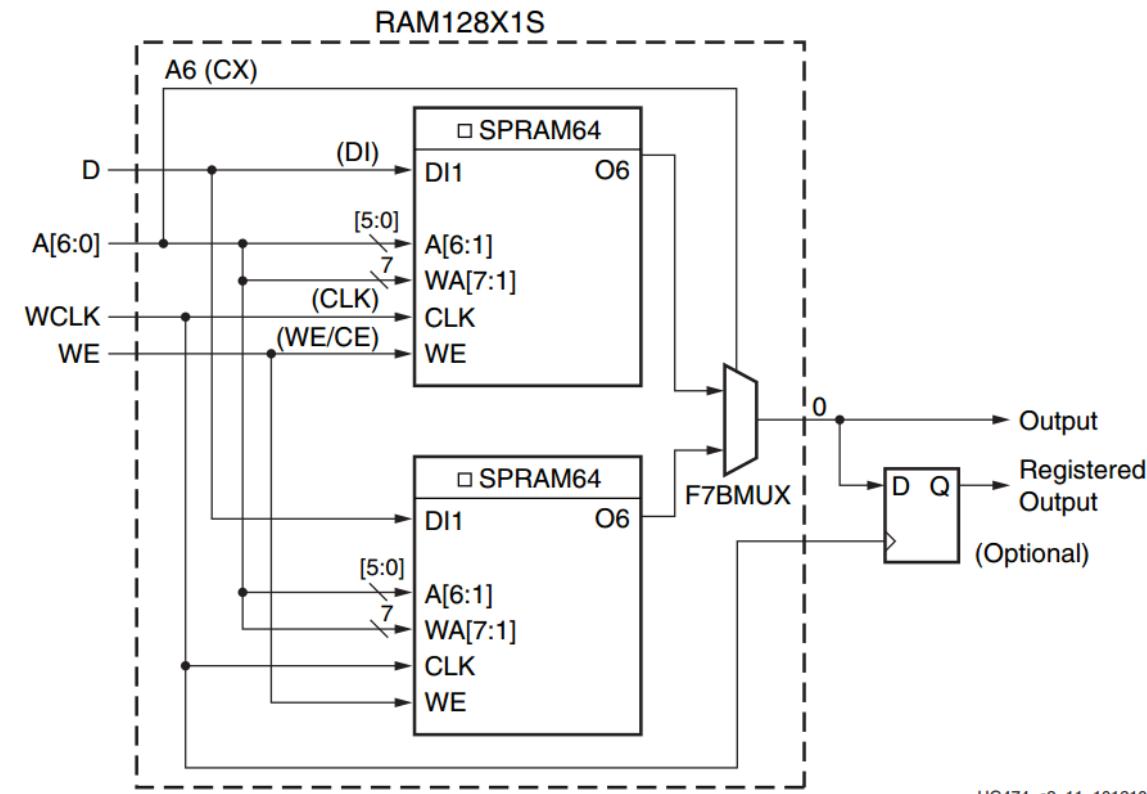
64 X 3 Simple Dual Port Distributed RAM (RAM64)

# LUT as Memory: 128X1 Single Port



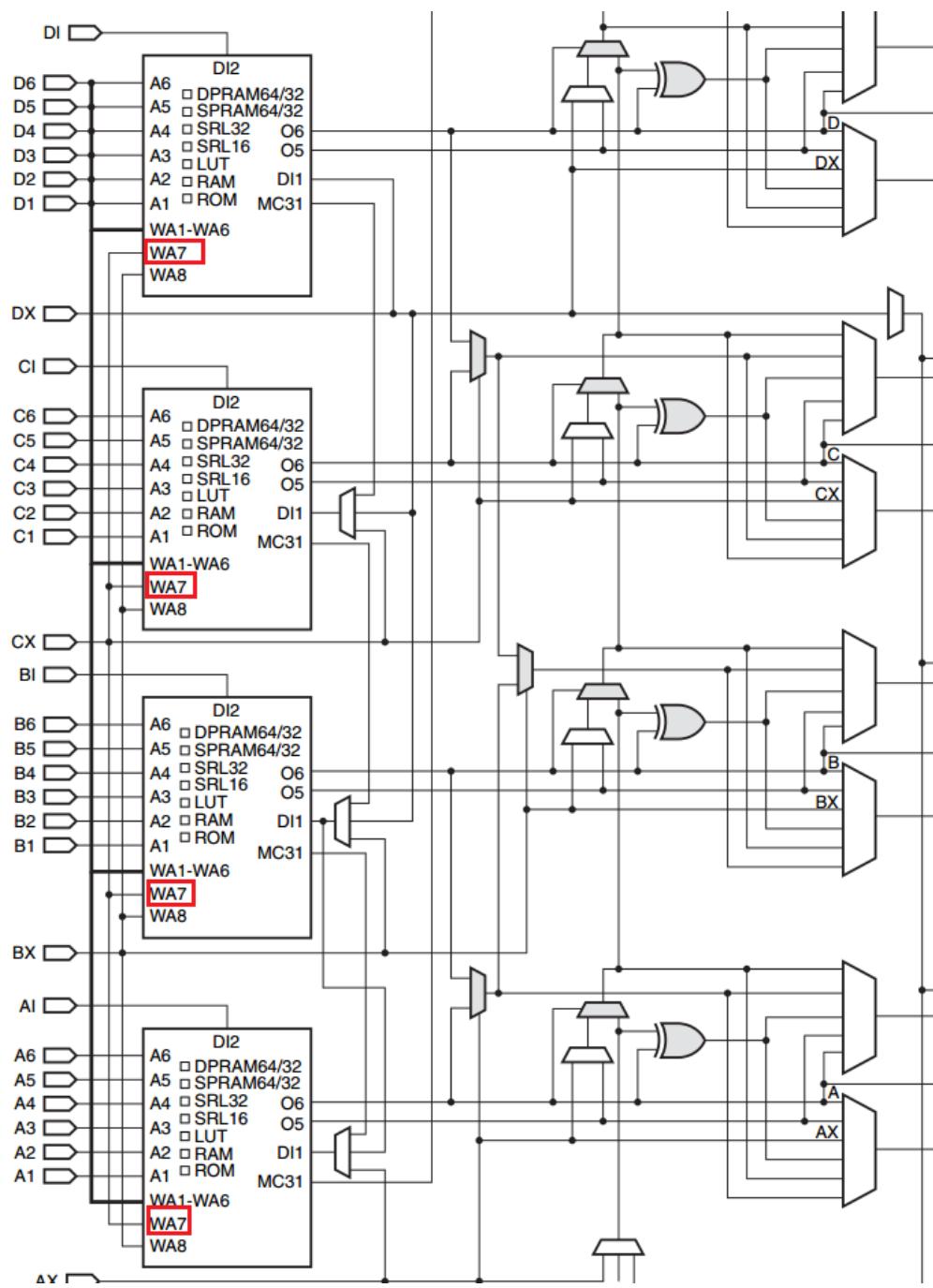
# LUT as Memory: 128X1 Single Port

- Implementation of **distributed RAM configurations** with depth greater than 64 requires the usage of wide-function multiplexers (F7AMUX, F7BMUX, and F8MUX)
- One SLICEM can have **TWO** single port  $128 \times 1$ -bit memories as long as they share **the same clock, write enable, and shared read and write port address inputs**
- This configuration equates to a  $128 \times 2$ -bit single-port distributed RAM.

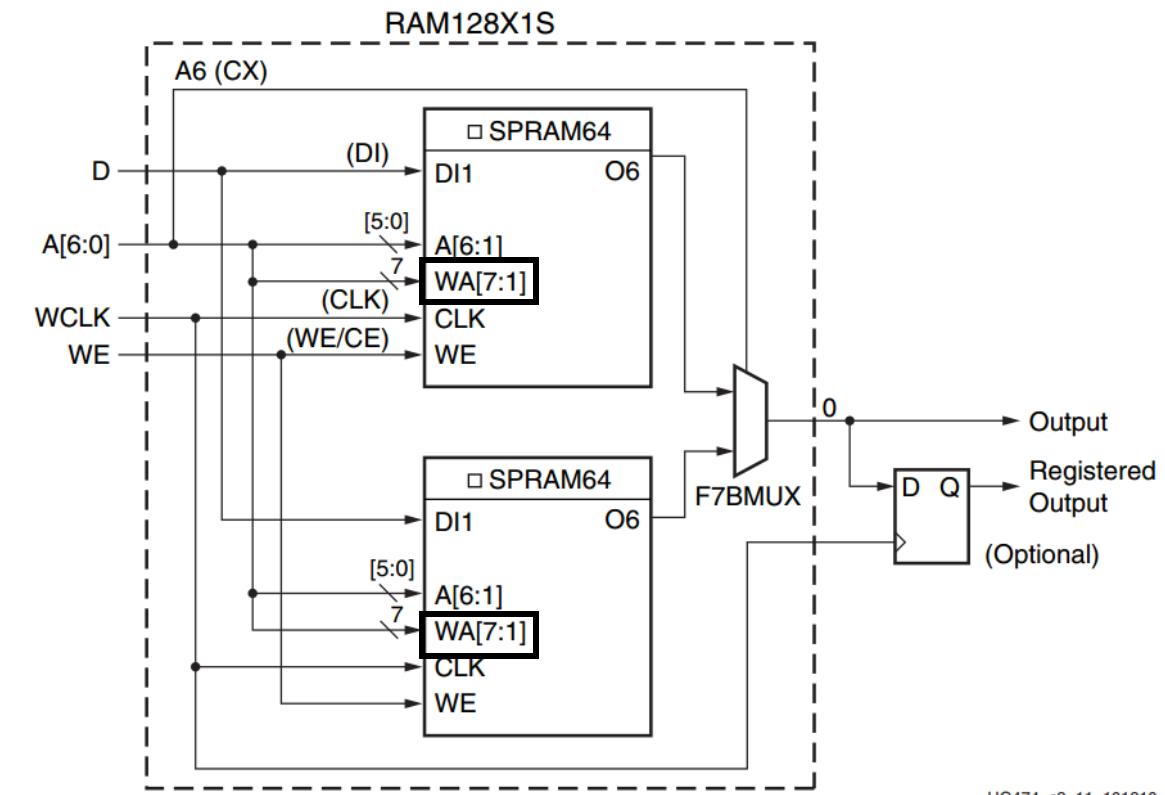


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128 X 1 Single Port Distributed RAM (RAM128X1S)



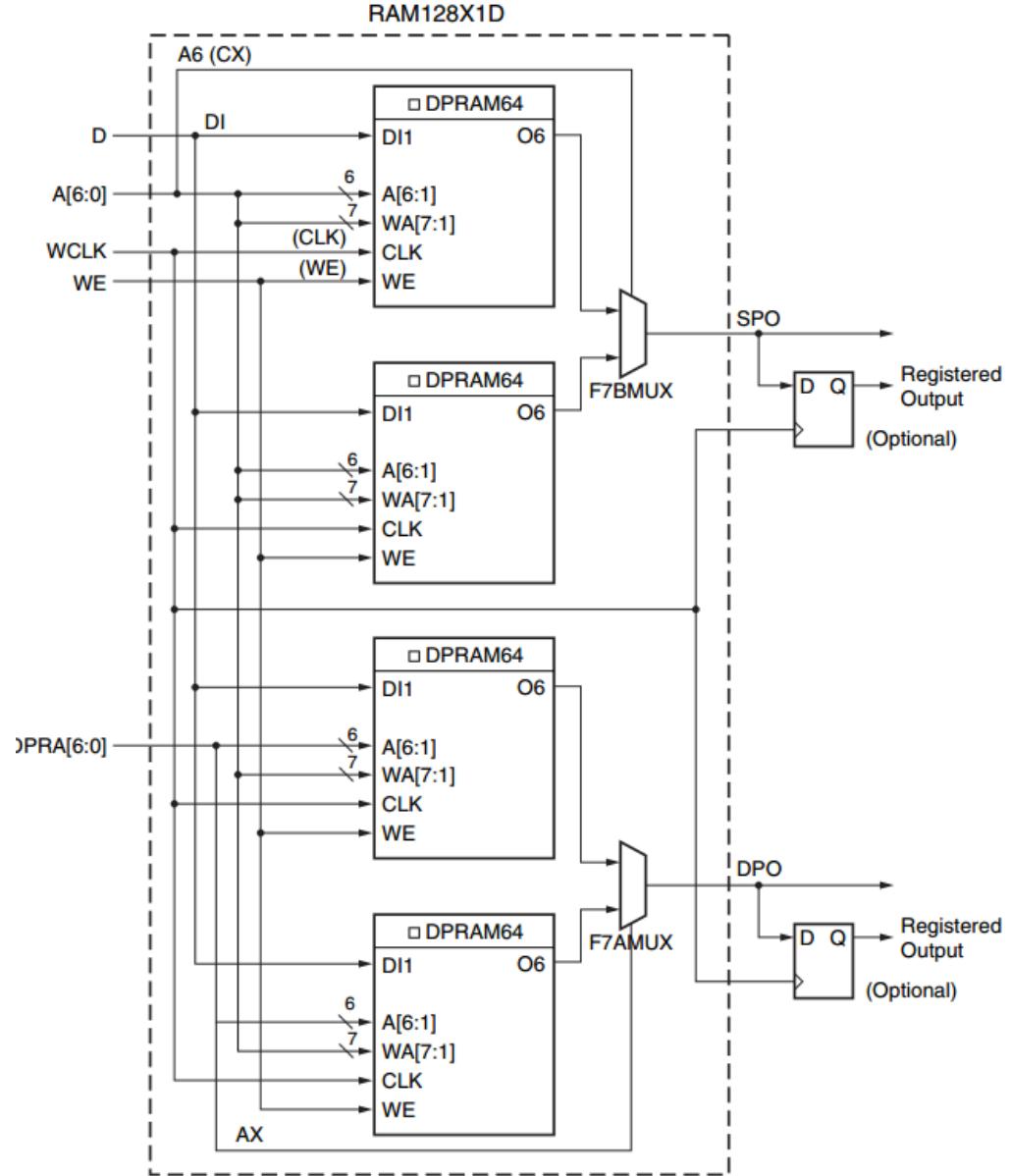
WA7: Enable for 7-input LUT  
WA8: Enable for 8-input LUT



128 X 1 Single Port Distributed RAM (RAM128X1S)

# LUT as Memory: 128X1 Dual Port

- 128X1 Quad Port?
- 128X2 Dual Port?



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128 X 1 Dual Port Distributed RAM (RAM128X1D)

# LUT as Memory: 256X1 Single Port

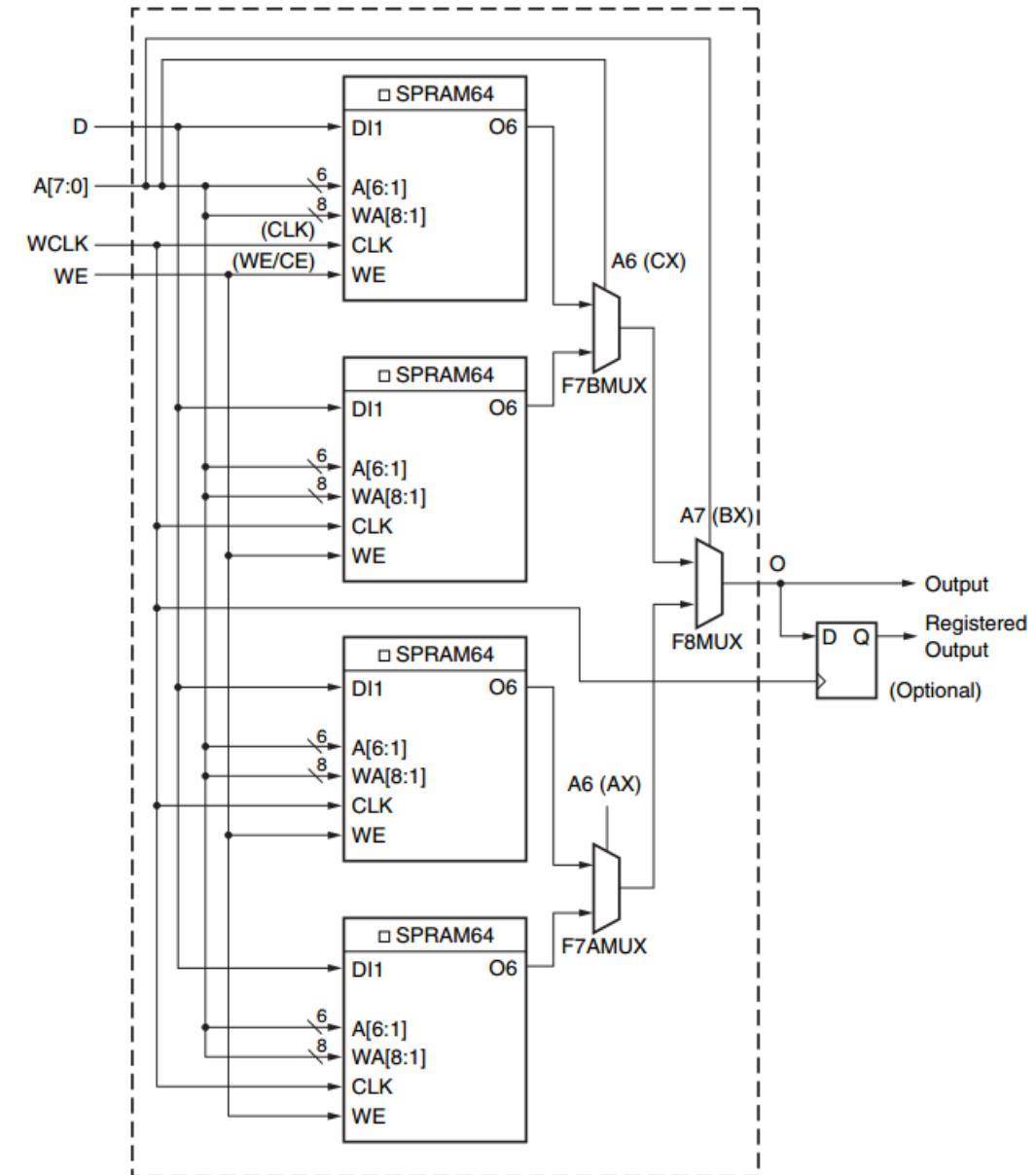
32x16 Single Port  
X

256x1  
X

128x1  
X

128x1  
X

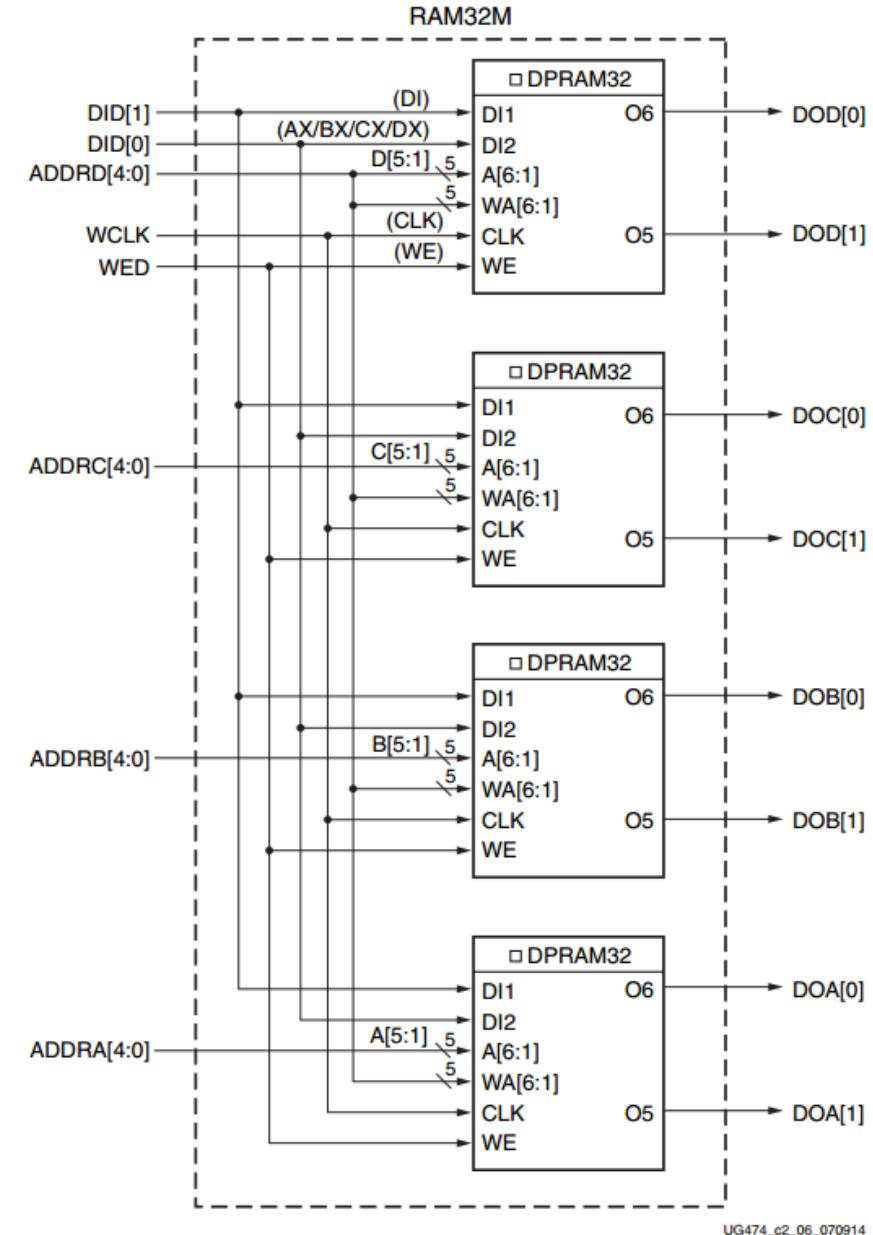
128x1  
X



256 X 1 Single Port Distributed RAM (RAM256X1S)

UG474\_c2\_13\_101210

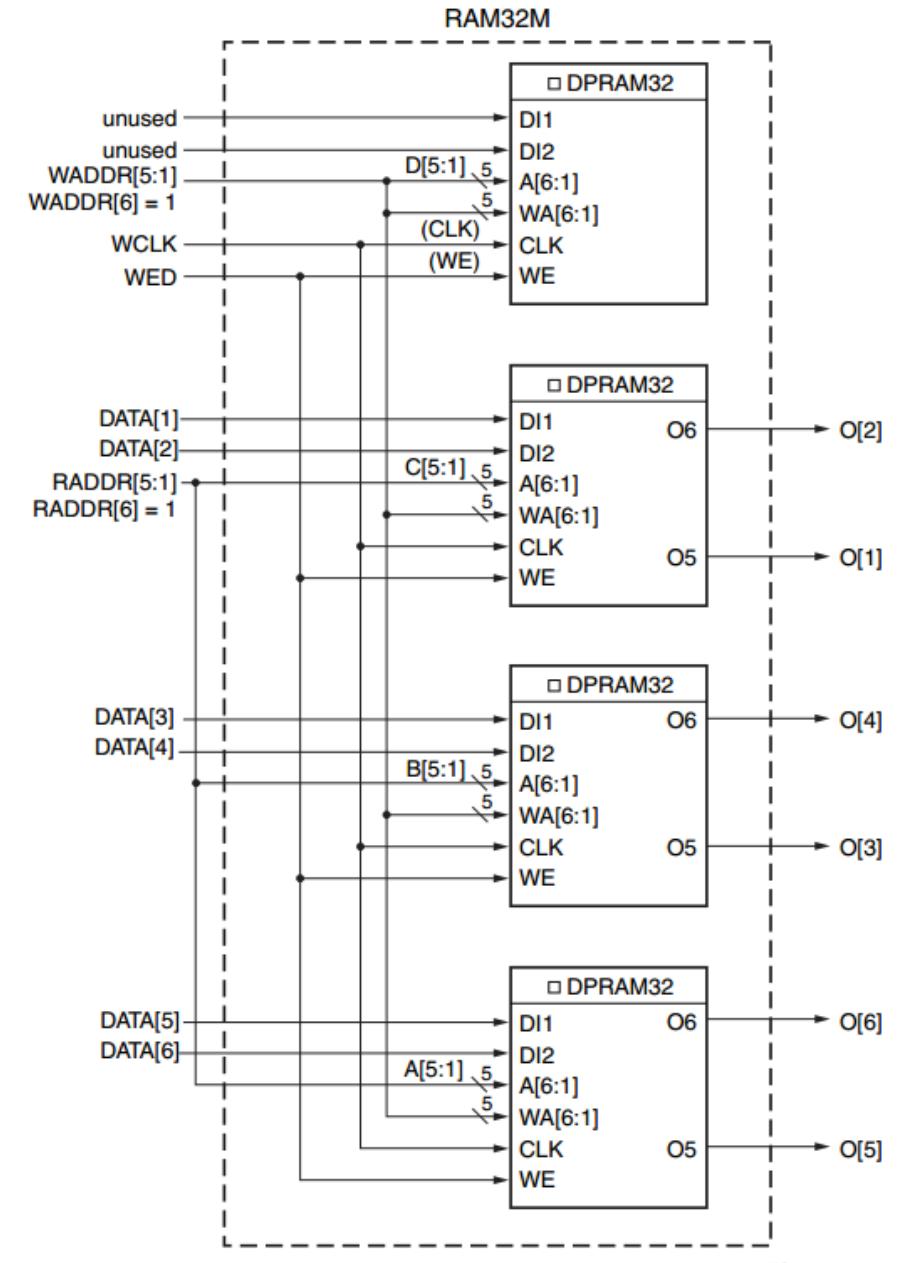
# LUT as Memory: 32X2 Quad Port



32 X 2 Quad Port Distributed RAM (RAM32M)

# LUT as Memory: 32X8 Simple Dual Port

# LUT as Memory: 32X6 Simple Dual Port



UG474\_c2\_06\_07091

32 X 6 Simple Dual Port Distributed RAM (RAM32M)

# LUT as Memory

| <b>RAM</b> | <b>Description</b> | <b>Primitive</b> | <b>Number of LUTs</b> |
|------------|--------------------|------------------|-----------------------|
| 32 x 1S    | Single port        | RAM32X1S         | 1                     |
| 32 x 1D    | Dual port          | RAM32X1D         | 2                     |
| 32 x 2Q    | Quad port          | RAM32M           | 4                     |
| 32 x 6SDP  | Simple dual port   | RAM32M           | 4                     |
| 64 x 1S    | Single port        | RAM64X1S         | 1                     |
| 64 x 1D    | Dual port          | RAM64X1D         | 2                     |
| 64 x 1Q    | Quad port          | RAM64M           | 4                     |
| 64 x 3SDP  | Simple dual port   | RAM64M           | 4                     |
| 128 x 1S   | Single port        | RAM128X1S        | 2                     |
| 128 x 1D   | Dual port          | RAM128X1D        | 4                     |
| 256 x 1S   | Single port        | RAM256X1S        | 4                     |

| <b>Single Port</b> | <b>Dual Port</b> | <b>Simple Dual Port</b> | <b>Quad Port</b> |
|--------------------|------------------|-------------------------|------------------|
| 32x2               | 32x2D            | 32x6SDP                 | 32x2Q            |
| 32x4               | 32x4D            | 64x3SDP                 | 64x1Q            |
| 32x6               | 64x1D            |                         |                  |
| 32x8               | 64x2D            |                         |                  |
| 64x1               | 128x1D           |                         |                  |
| 64x2               |                  |                         |                  |
| 64x3               |                  |                         |                  |
| 64x4               |                  |                         |                  |
| 128x1              |                  |                         |                  |
| 128x2              |                  |                         |                  |
| 256x1              |                  |                         |                  |

**Each Port Has Independent Address Inputs**

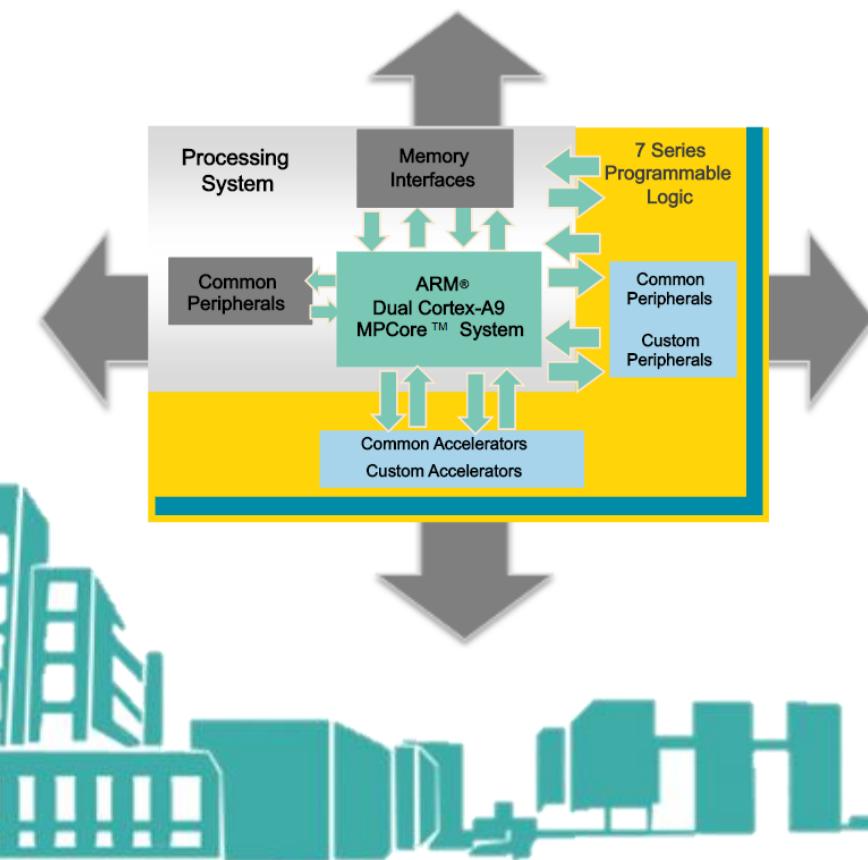
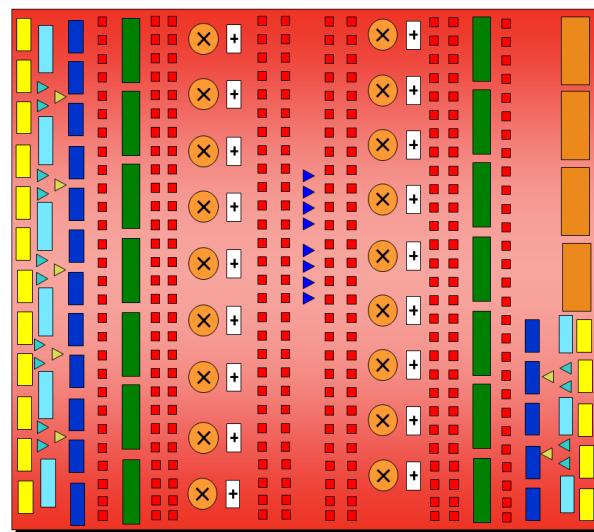


ECE  
IITD

DEPARTMENT OF ELECTRONICS &  
COMMUNICATIONS ENGINEERING

A2A  
*Algorithms to Architecture*

# ECE 270: Embedded Logic Design



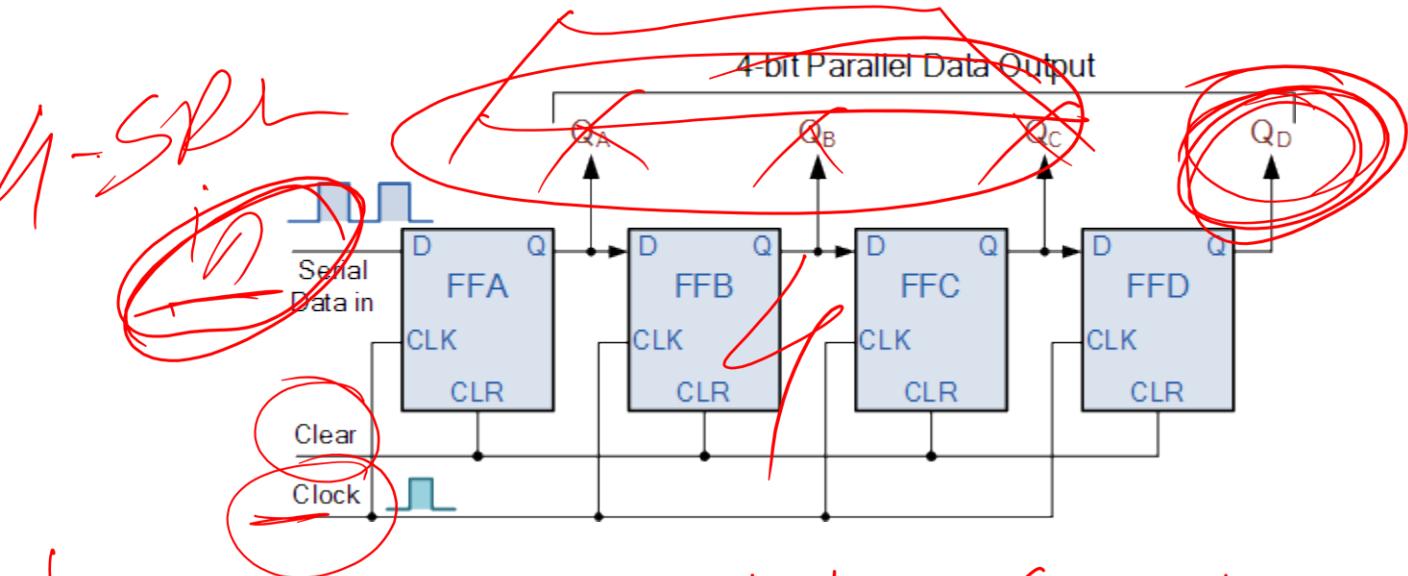
SISO

LUT as SRL

# Sequential Circuits

- 4-bit serial shift register:

```
module ShiftReg(  
    input wire clk,  
    input wire clr,  
    input wire data_in,  
    output reg [3:0] Q  
)  
  
//      4-bit Shift Register  
always @ (posedge clk or posedge clr)  
begin  
    if (clr == 1)  
        Q <= 0;  
    else  
        begin  
            Q[3] <= data_in;  
            Q[2:0] <= Q[3:1];  
        end  
end  
endmodule
```



module (in,clr,clk,QD)  
always @ (posedge clk or posedge clr)  
if (clr)  
 QB <= 0;  
else  
 QB <= QA;

Output seq QD;

wire QA, QB, QC;

always @ (posedge clk or posedge d)

if (d)

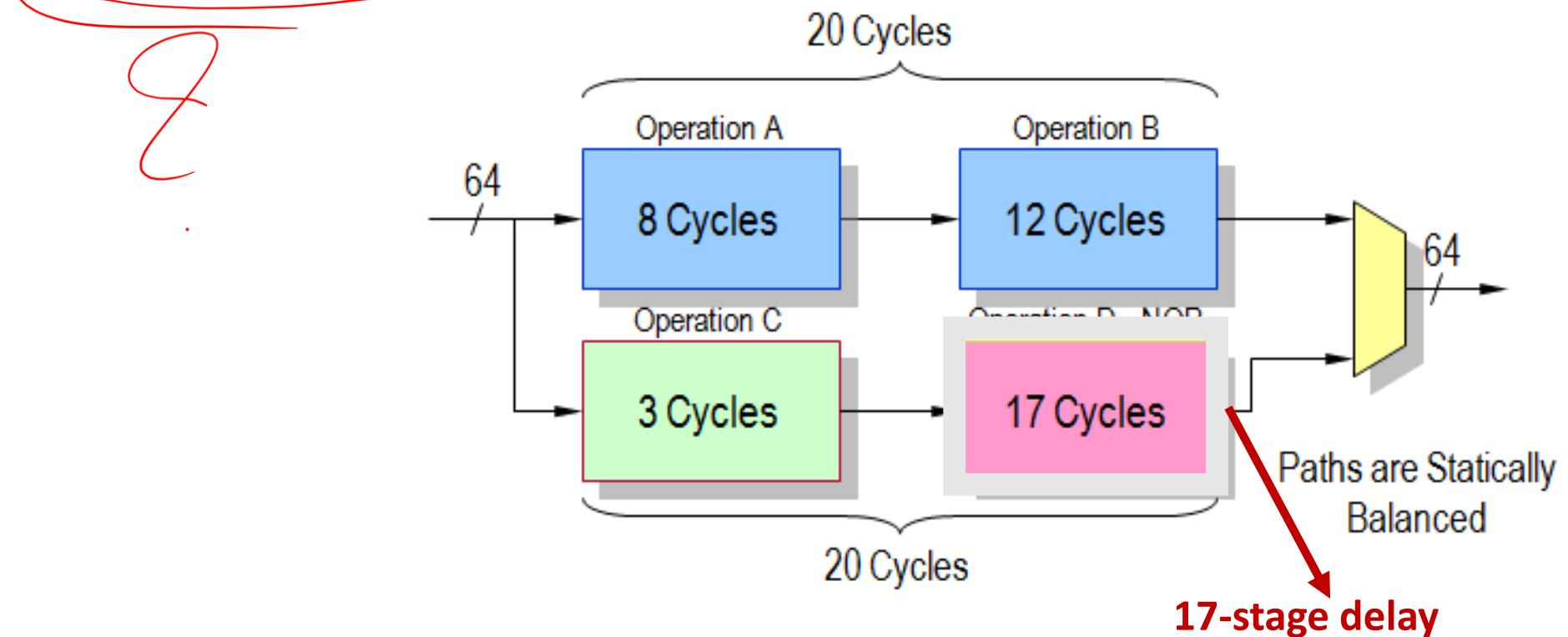
QA <= 0;

else QA <= i0;

# Shift Register Using FFs

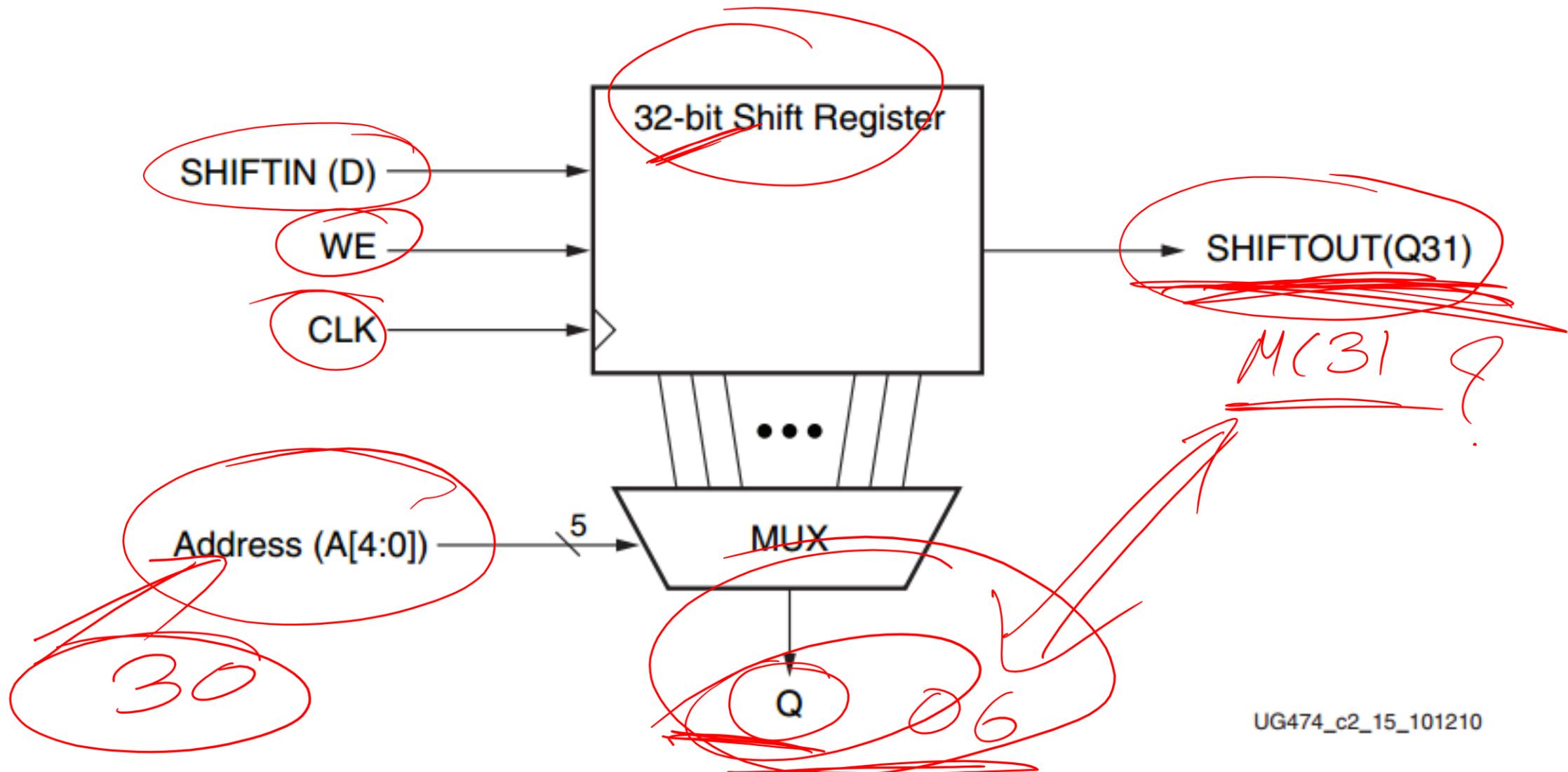
LUT  $\Rightarrow$  FPGA

- Operation D - NOP must add 17 pipeline stages of 64 bits each
- 1,088 flip-flops (hence 136 slices)

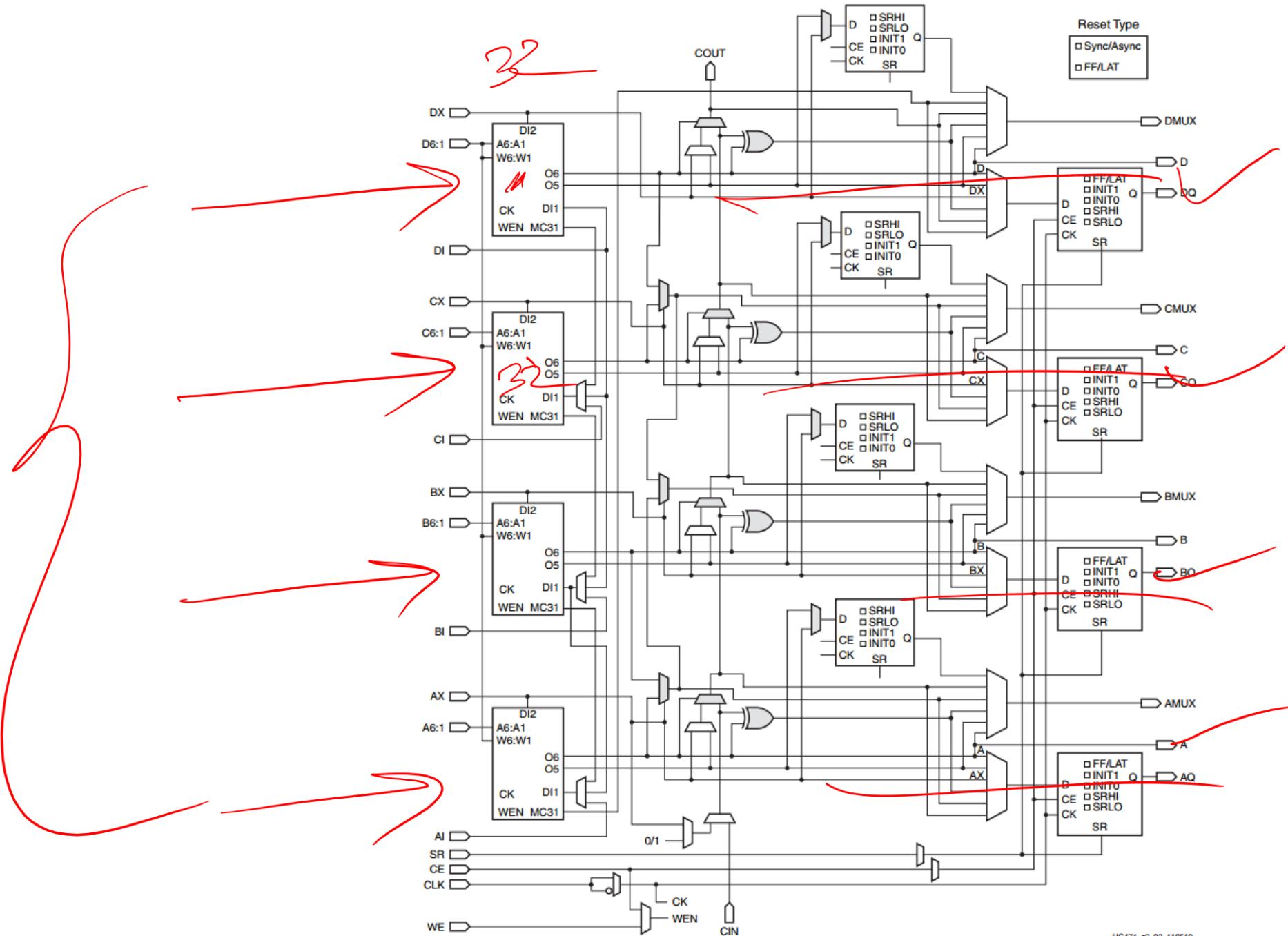


# LUT as Shift Registers (only in SLICEM)

6-LUT

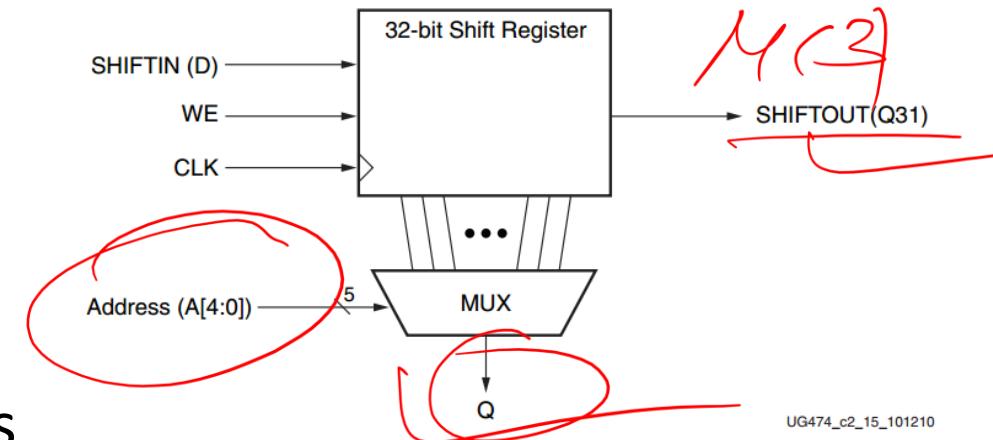


# SLICEM



# LUT as Shift Registers (only in SLICEM)

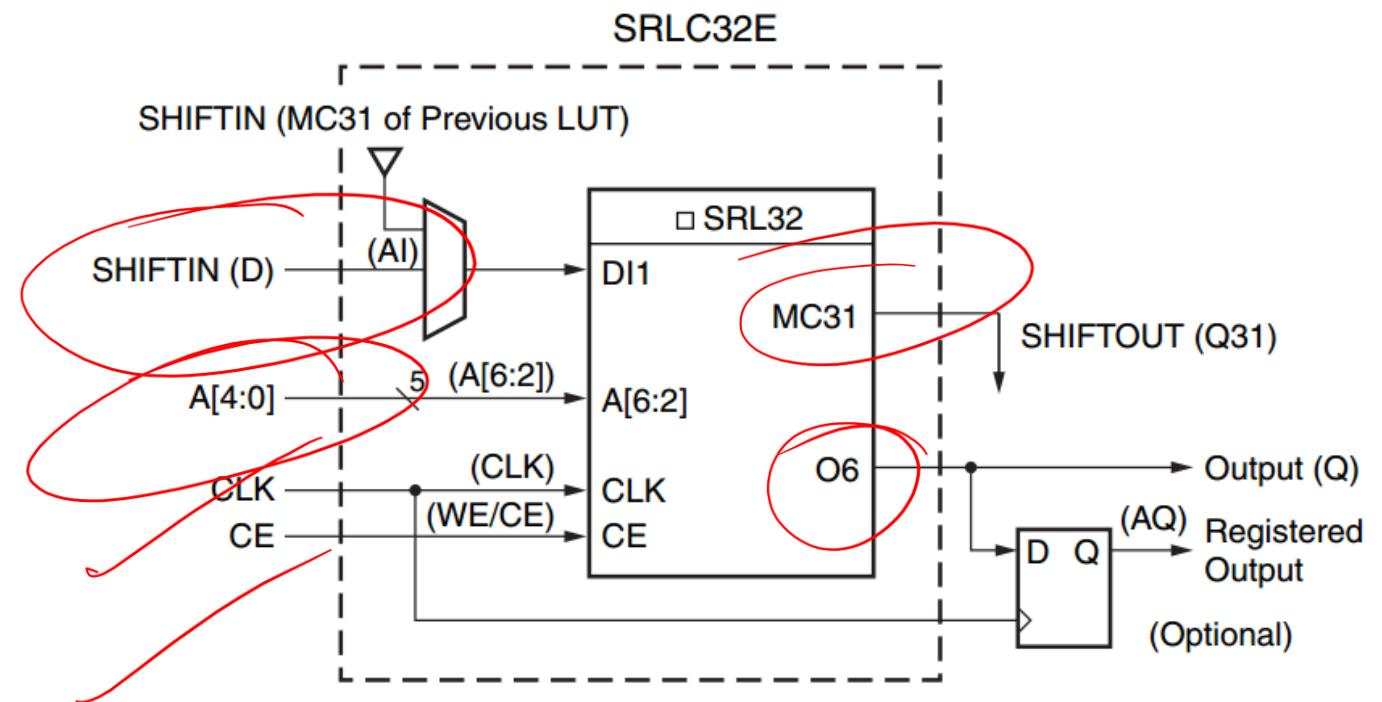
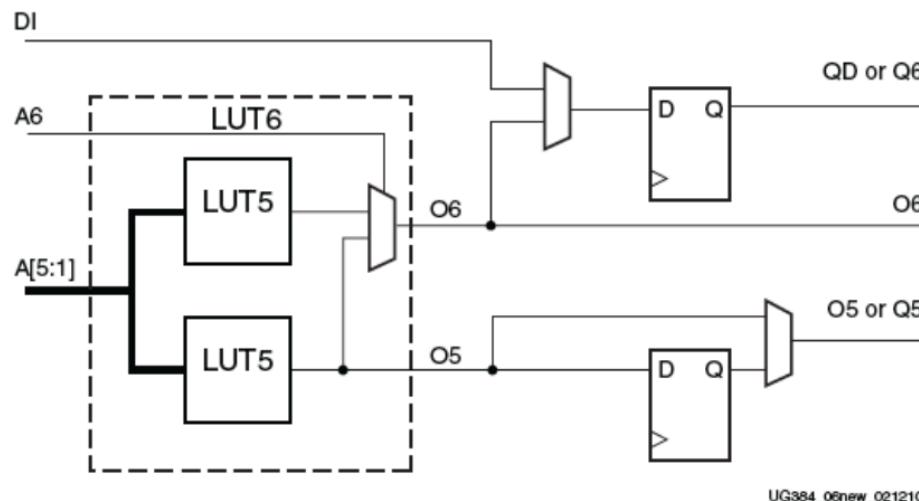
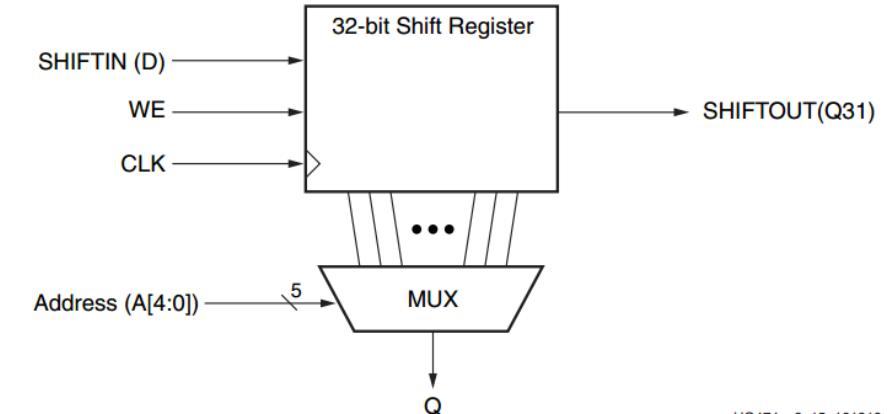
- Shift register functions include:
  - Write operation (Synchronous with a clock input and an optional clock enable)
  - Fixed read access to Q31
  - Dynamic read access:
    - Performed through 5-bit address bus (LSB is unused)
    - Any of the 32 bits can be read out **asynchronously** by controlling the address
    - Useful for **smaller shift registers**
  - Flip-flop can be used for synchronous read with one additional latency
  - Set/reset is not supported**



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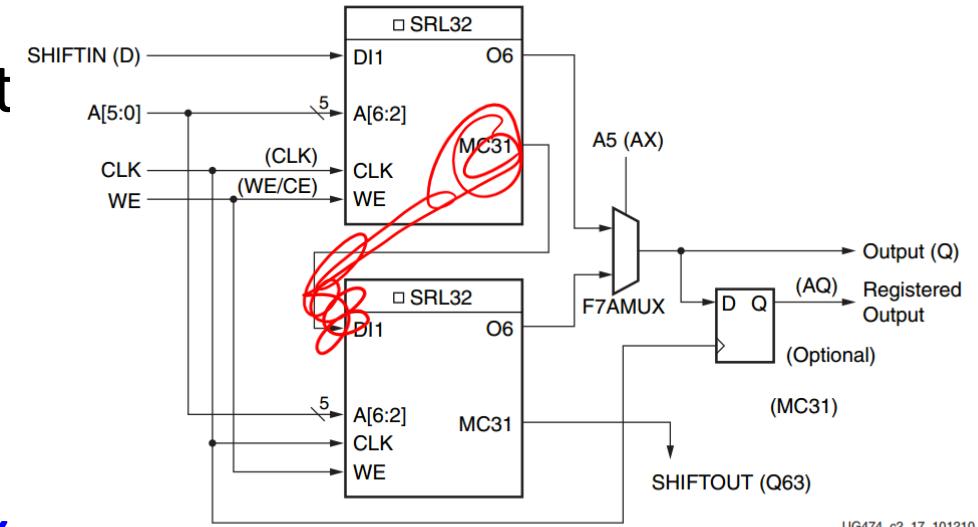
# LUT as Shift Registers (only in SLICEM)

- A **SLICEM LUT** can be configured as a **32-bit shift register** without using the flip-flops available in a slice.



# LUT as Shift Registers: 64 Bit

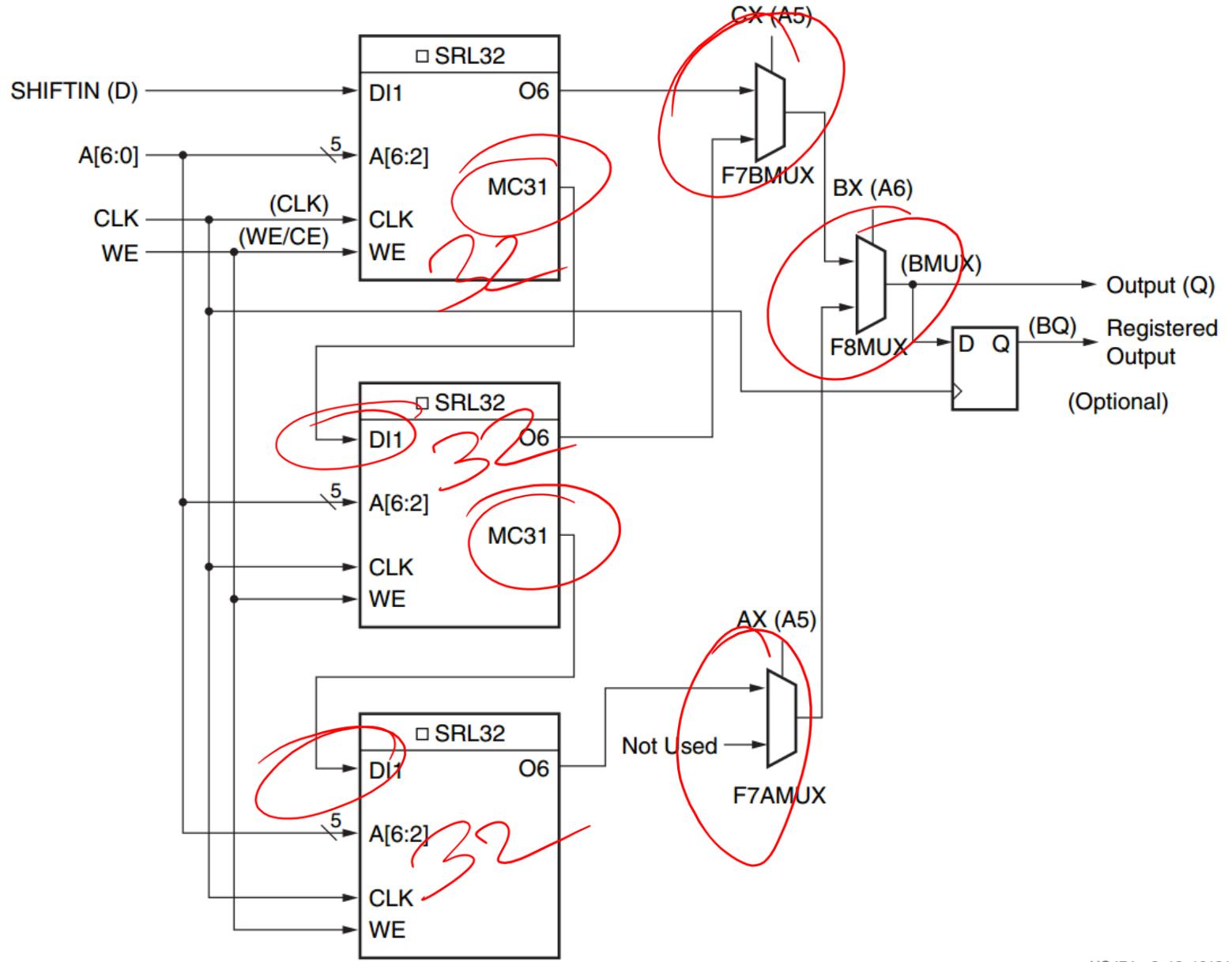
- MC31 output and a dedicated connection between LUTs allows connecting the last bit of one shift register to the first bit of the next, without using the LUT O6 output.
- Longer shift registers can be built with dynamic access to any bit in the chain.
- The shift register chaining and the F7AMUX F7BMUX, and F8MUX multiplexers allow up to a 128-bit shift register with addressable access to be implemented in one SLICEM



64-Bit Shift Register Configuration

UG474\_c2\_17\_101210

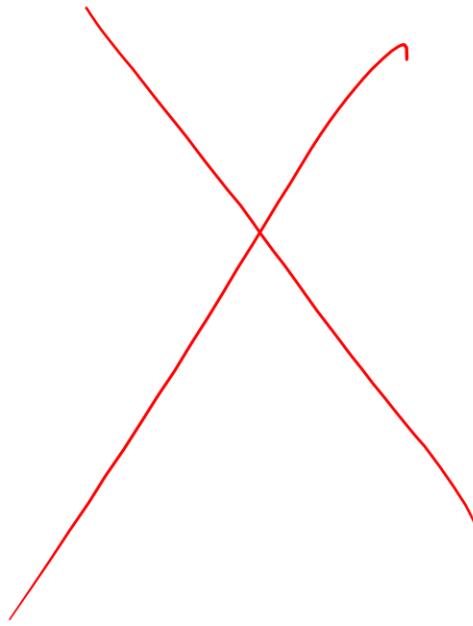
# Shift Register 96 Bit



UG474\_c2\_18\_101210

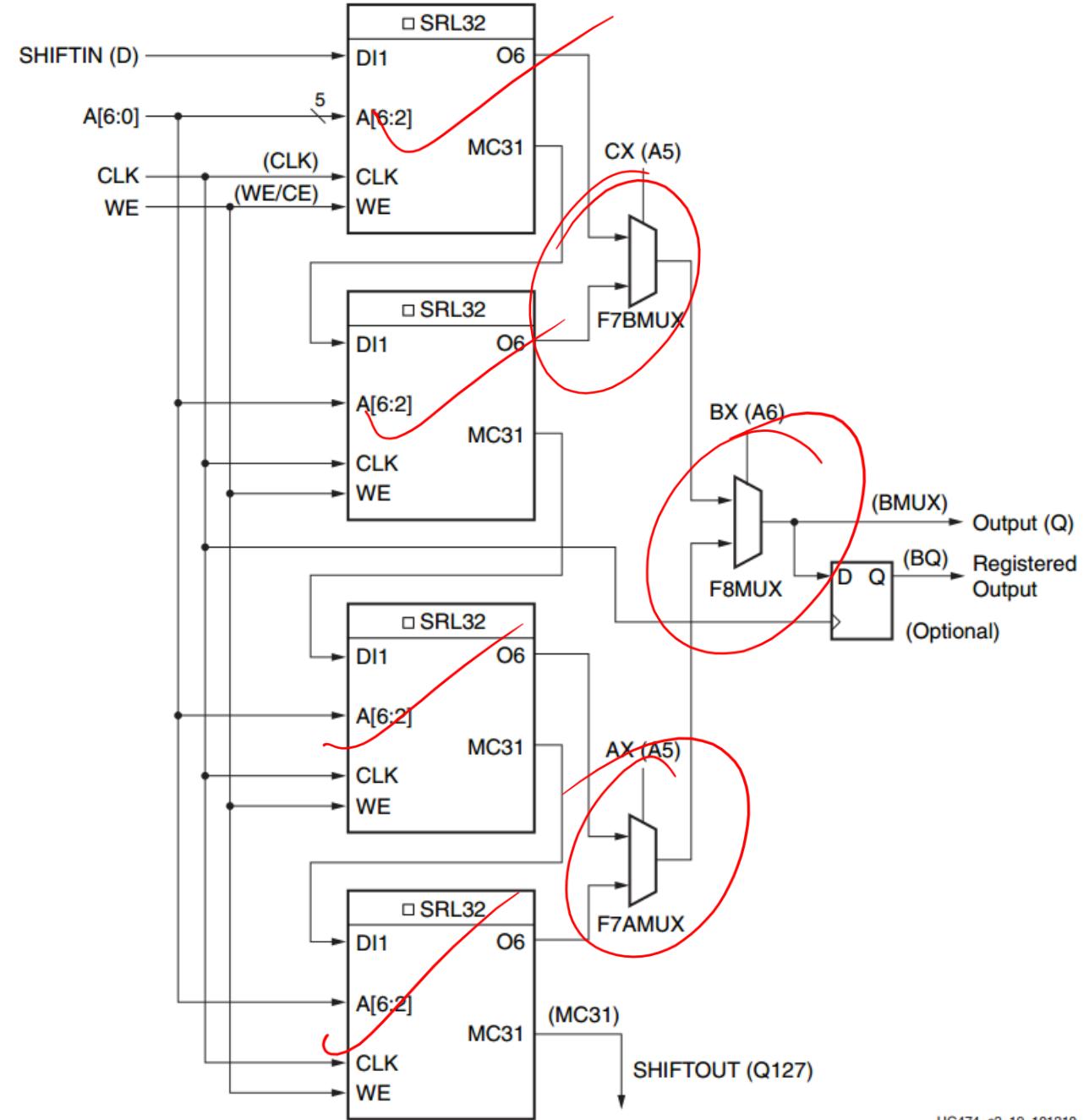
96-Bit Shift Register Configuration

Shift Register  
**256 Bit**

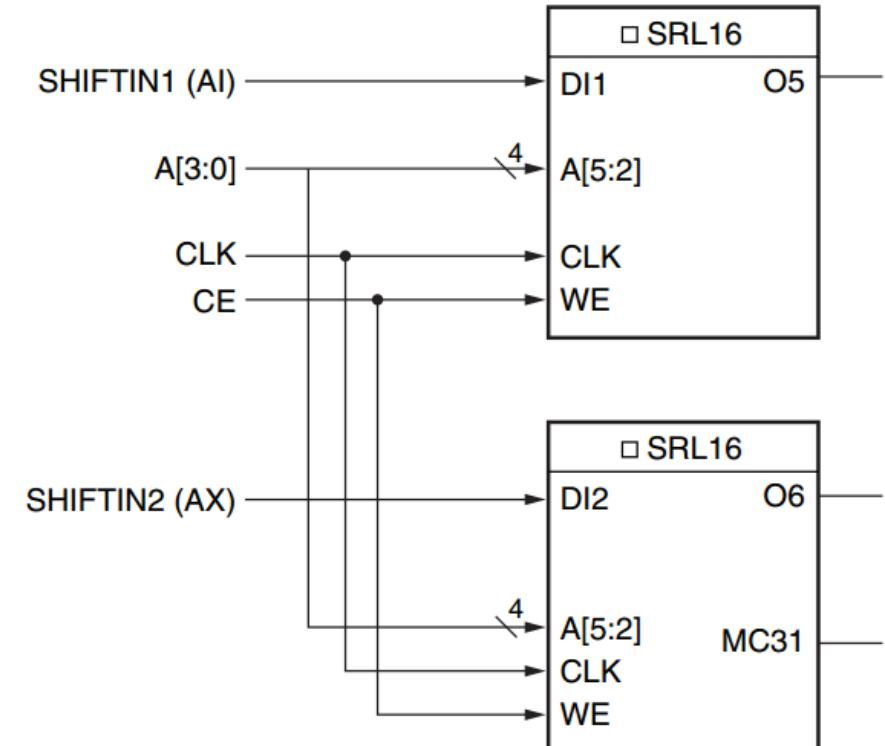


Slice 8

# Shift Register 128 Bit



# Dual 16-bit SRL in One LUT



UG474\_c2\_16\_101210

**Dual 16-Bit Shift Register Configuration**

# LUT as SRL

- There are **no set or reset capabilities**, it is **not loadable**, and data can only be read serially.
- Each LUT6 can implement a maximum **delay of 32 clock cycles**. The SRLs within a slice can be **cascaded** for longer shift registers (**up to 128**).
- The shift register length can be changed **asynchronously** by changing the value applied to the **address pins (A)**. This means that you can dynamically change the **pipeline** delay associated with an SRL.

| SRL Configurations<br>in One Slice (4 LUTs) |
|---|
| 16x1, 16x2, 16x4, 16x6, 16x8                |
| 32x1, 32x2, 32x3, 32x4                      |
| 64x1, 64x2                                  |
| 96x1  |
| 128x1                                       |

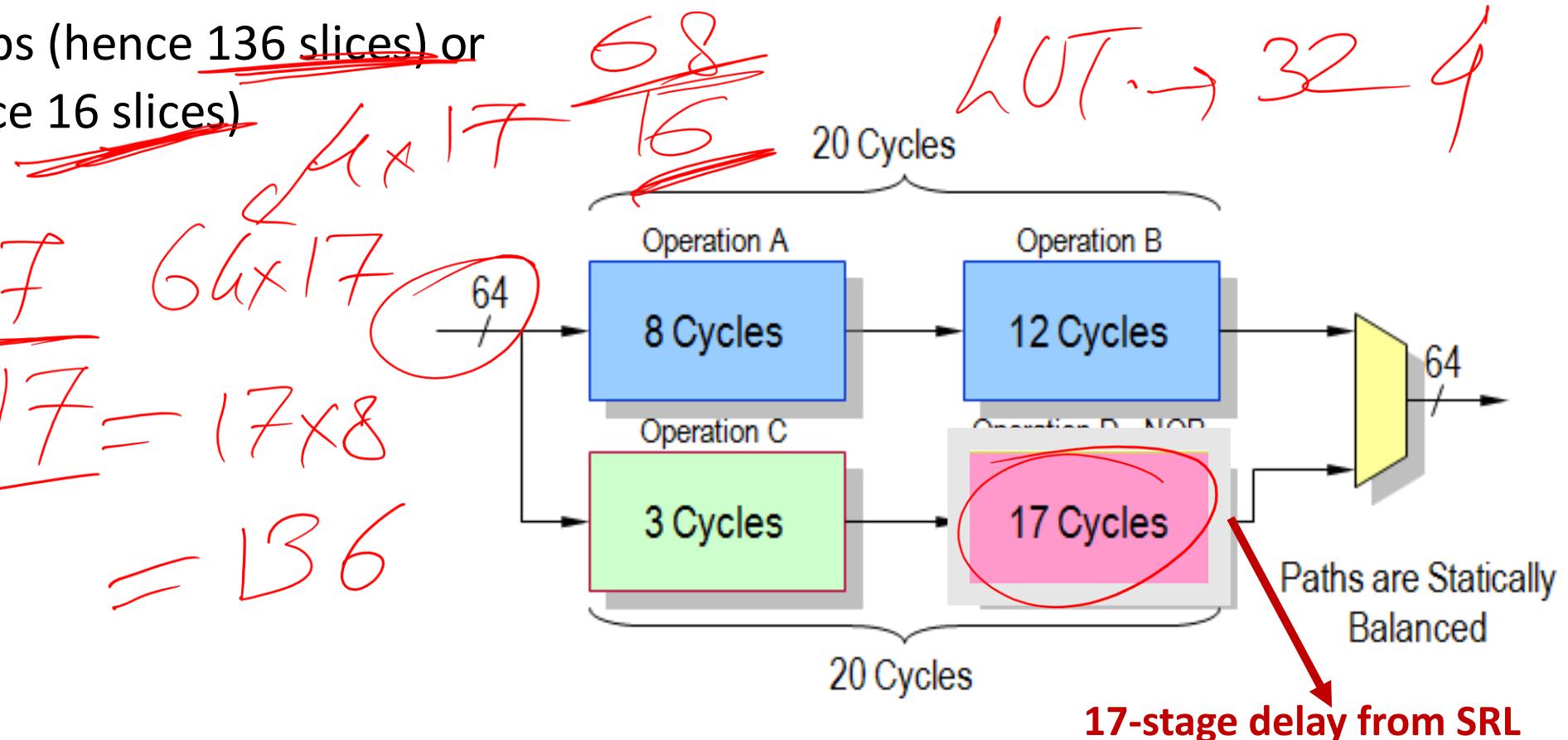
# Shift Register LUT Example

68 → ? CLB  
16 → ?

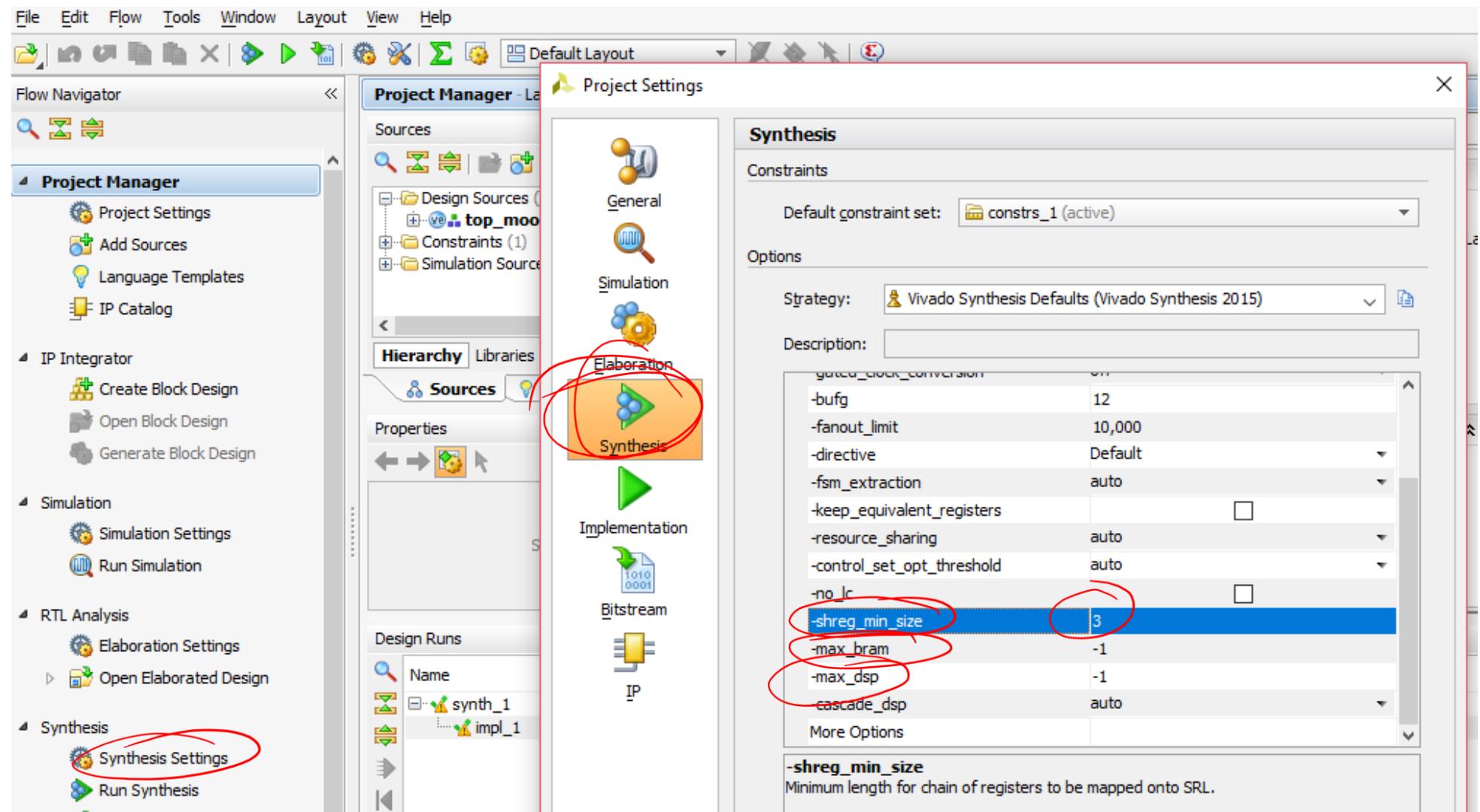
- Operation D - NOP must add 17 pipeline stages of 64 bits each

- 1,088 flip-flops (hence 136 slices) or
- 64 SRLs (hence 16 slices)

$$\begin{aligned} 64 &\rightarrow 17 \\ 64 \times 17 &= 17 \times 8 \\ 8 &= 136 \end{aligned}$$



# Shift Register LUT Example

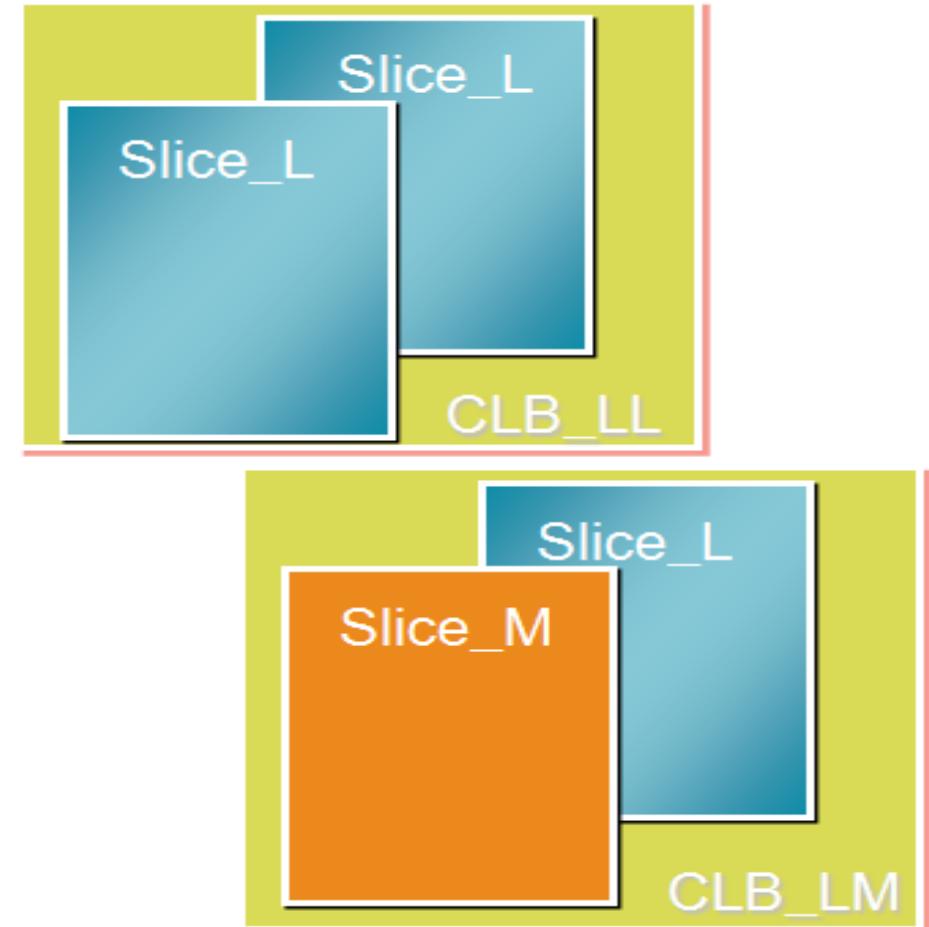


# Types of CLB Slices

| Slices | LUTs | Flip-Flops | Arithmetic and Carry Chains | Distributed RAM <sup>(1)</sup> | Shift Registers <sup>(1)</sup> |
|--------|------|------------|-----------------------------|--------------------------------|--------------------------------|
| 2      | 8    | 16         | 2                           |                                |                                |

# Types of CLB Slices

| Slices | LUTs | Flip-Flops | Arithmetic and Carry Chains | Distributed RAM <sup>(1)</sup> | Shift Registers <sup>(1)</sup> |
|--------|------|------------|-----------------------------|--------------------------------|--------------------------------|
| 2      | 8    | 16         | 2                           |                                |                                |

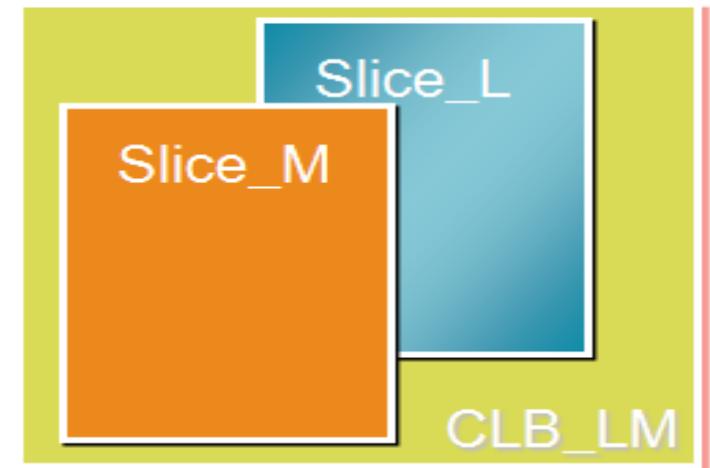
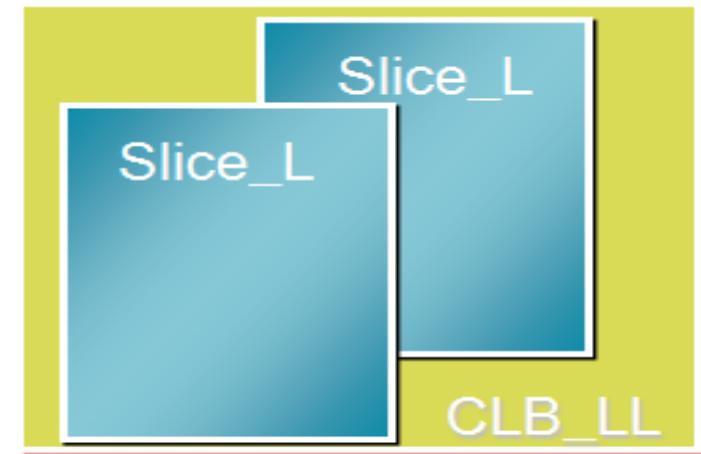


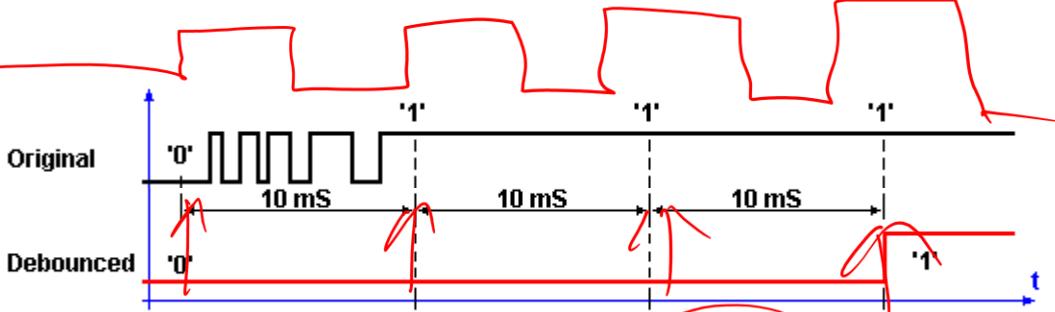
# Types of CLB Slices

BRAM / FIFO

| Slices | LUTs | Flip-Flops | Arithmetic and Carry Chains | Distributed RAM <sup>(1)</sup> | Shift Registers <sup>(1)</sup> |
|--------|------|------------|-----------------------------|--------------------------------|--------------------------------|
| 2      | 8    | 16         | 2                           | 256 bits                       | 128 bits                       |

LOT  $\Rightarrow$  CLB



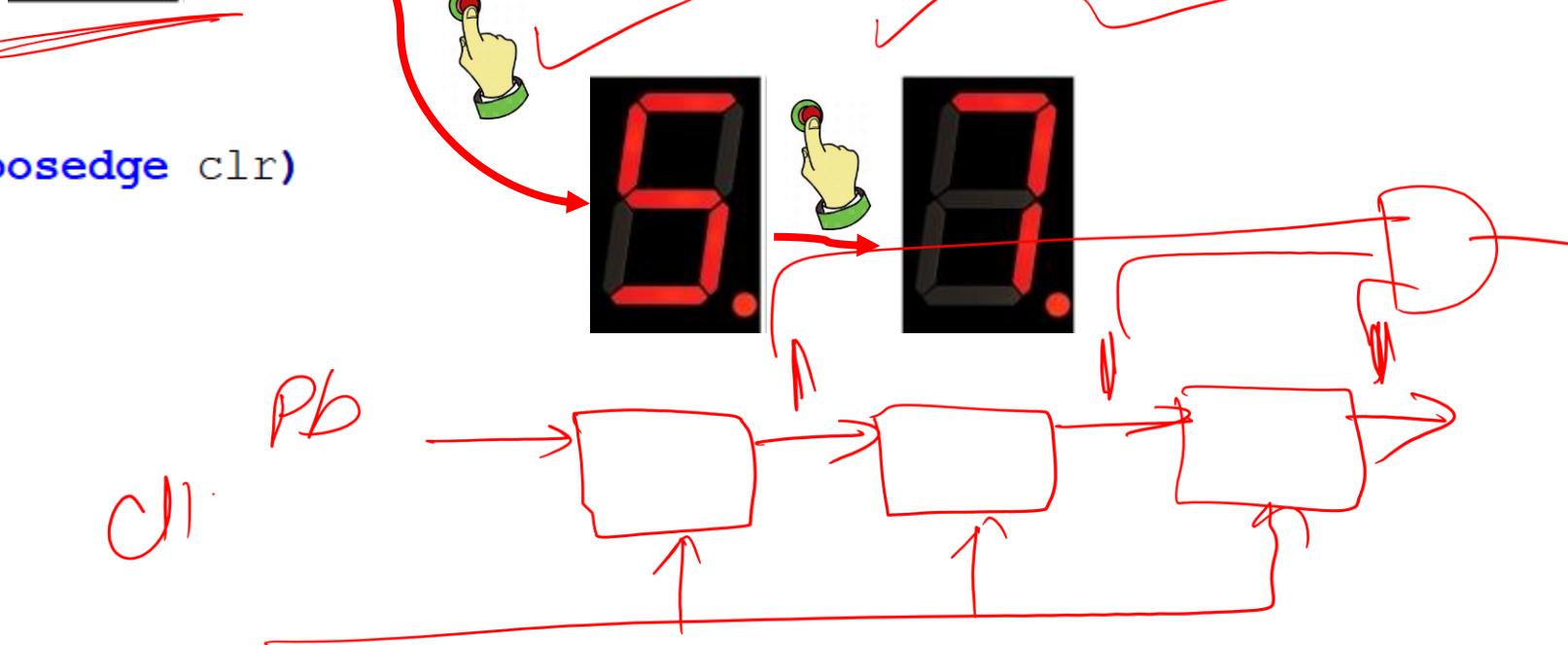
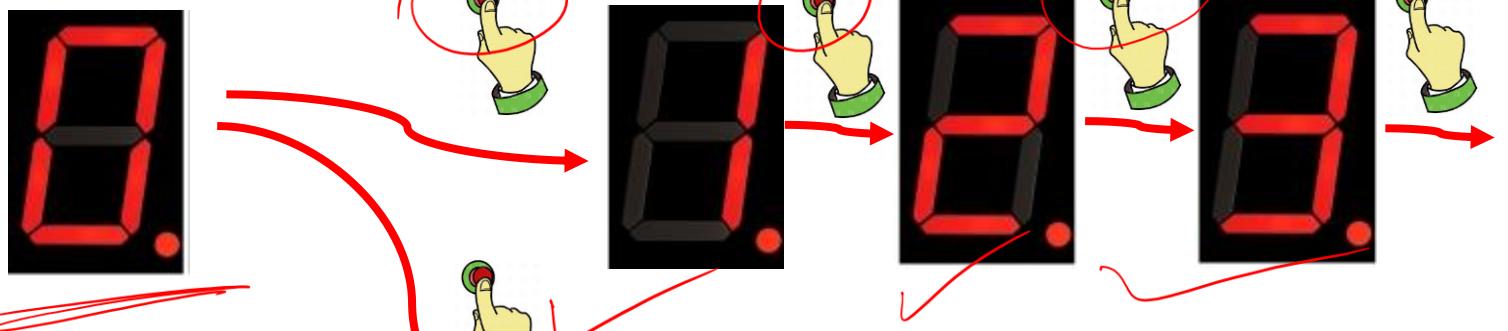


```
module count_3b (
  input wire clr ,
  input wire push_b ,
  output reg [2:0] q
);
```

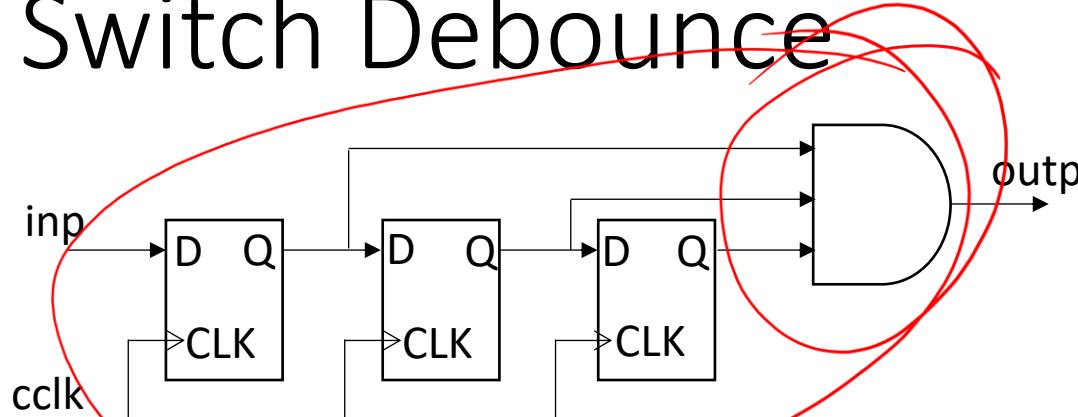
*q = 0*      3-bit counter

```
always @ (posedge push_b or posedge clr)
begin
  if(clr == 1)
    q <= 0;
  else
    q <= q + 1;
end
```

```
endmodule
```



# Switch Debounce

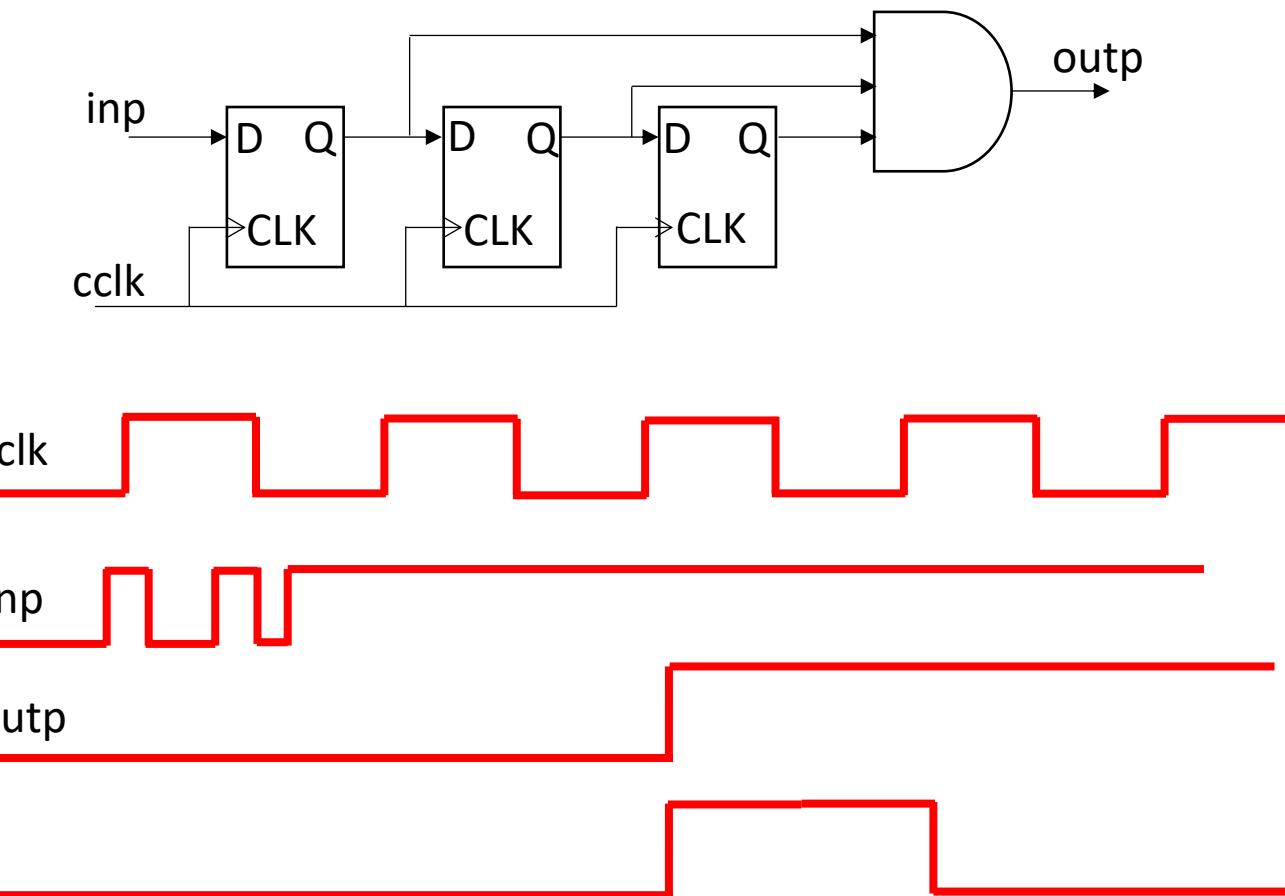


- When you press any of the pushbuttons on FPGA board, they may bounce slightly for a few milliseconds before settling down.
- This means that instead of the input to the FPGA going from 0 to 1 cleanly, it may bounce back and forth between 0 and 1 for a few milliseconds.
- Clock, cclk, frequency must be low enough that the switch bouncing is over before three clock periods.

```
module debounce (
    input wire inp ,
    input wire cclk ,
    input wire clr ,
    output wire outp
);
reg delay1;
reg delay2;
reg delay3;

always @ (posedge cclk or posedge clr)
begin
    if(clr == 1)
        begin
            delay1 <= 1'b0;
            delay2 <= 1'b0;
            delay3 <= 1'b0;
        end
    else
        begin
            delay1 <= inp;
            delay2 <= delay1;
            delay3 <= delay2;
        end
end
assign outp = delay1 & delay2 & delay3;
endmodule
```

# Clock Pulse



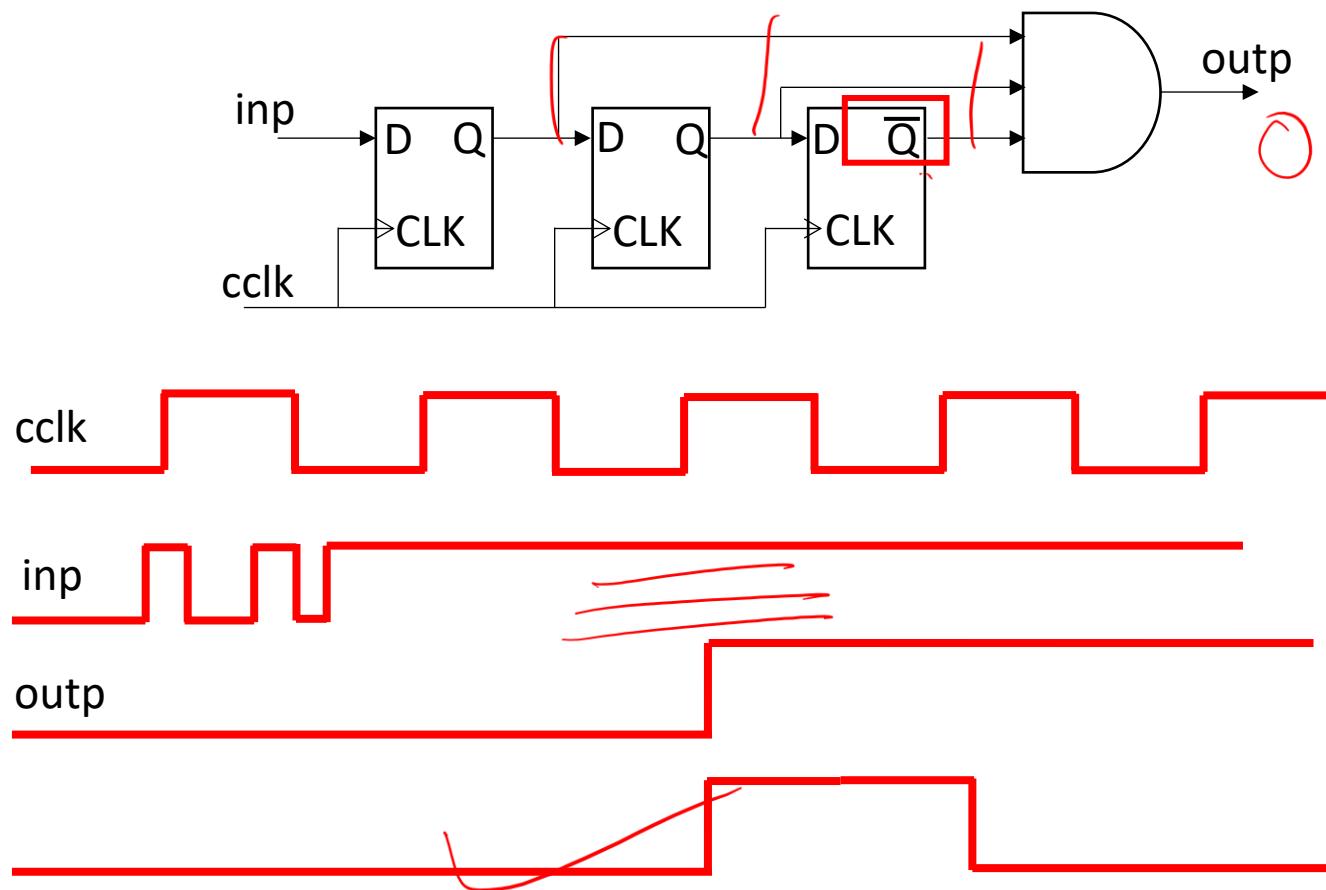
```
module debounce (
    input wire inp ,
    input wire cclk ,
    input wire clr ,
    output wire outp
);
reg delay1;
reg delay2;
reg delay3;

always @ (posedge cclk or posedge clr)
begin
    if(clr == 1)
        begin
            delay1 <= 1'b0;
            delay2 <= 1'b0;
            delay3 <= 1'b0;
        end
    else
        begin
            delay1 <= inp;
            delay2 <= delay1;
            delay3 <= delay2;
        end
    end
assign outp = delay1 & delay2 & delay3;

endmodule
```

# Clock Pulse

- Circuit to produce a single clean clock pulse



```
module clkp (
    input wire inp ,
    input wire cclk ,
    input wire clr ,
    output wire outp
);
reg delay1;
reg delay2;
reg delay3;

always @ (posedge cclk or posedge clr)
begin
    if(clr == 1)
        begin
            delay1 <= 1'b0;
            delay2 <= 1'b0;
            delay3 <= 1'b0;
        end
    else
        begin
            delay1 <= inp;
            delay2 <= delay1;
            delay3 <= ~delay2;
        end
end
assign outp = delay1 & delay2 & delay3;
endmodule
```

