

Unit 1

Basic Digital Logic

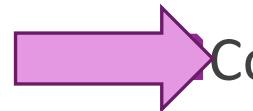
EL-GY 9463: INTRODUCTION TO HARDWARE DESIGN

PROFS. SUNDEEP RANGAN, SIDDHARTH GARG

Learning Objectives

- ❑ Write **SystemVerilog** descriptions for simple hardware **modules**
- ❑ Draw high-level **block diagram** representations of the module implementations
- ❑ Identify the **critical path** and its delay from the block diagram
- ❑ Implement simple functions in synchronous logic
- ❑ Visualize signals in a **timing diagram**
- ❑ Write a **testbench** for the hardware modules
- ❑ Simulate, and **synthesize** the SystemVerilog using **Vivado** tools
- ❑ Extract **value-change dump** (VCD) files and **synthesis reports** and process them in **python**

Outline



- Combinational Logic
- Timing Diagrams for Combinational Logic
- Registers, Clocks and Sequential Logic
- Simulating and Synthesizing Simple Modules in Vivado

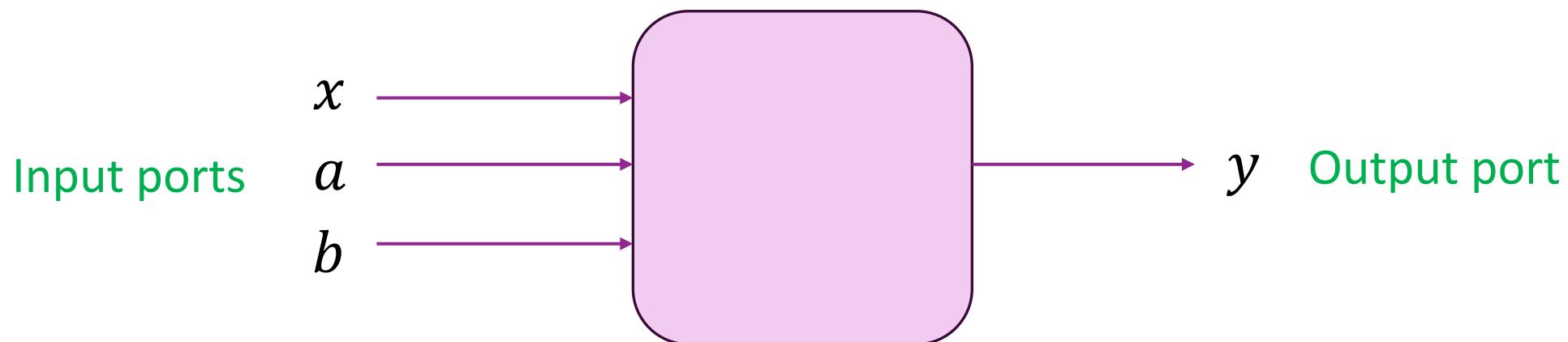


Simple Example: ReLU + Linear

Goal: Implement a module for the function

$$y = \max\{ax + b, 0\}$$

- Linear function + ReLU
- Used widely in machine learning



SystemVerilog Description

❑ SystemVerilog:

- Language for **behavioral** description
- What the module should do

❑ Each block is a **module**

- Has inputs and outputs
- Logical mapping from inputs to outputs

❑ Description is behavioral only

- Does not say how it will be implemented
- We discuss that later

```
module relu_lin (
    input logic int x,
    input logic int a,
    input logic int b,
    output logic int y
);
    always_comb begin
        logic int mult_out, add_out;
        mult_out = x * a;
        add_out = mult_out + b;
        y = (add_out > 0) ? add_out : 0;
    end
endmodule
```

Module Components in SV

```
module relu_lin ( ←
  input logic int x,
  input logic int a,
  input logic int b,
  output logic int y
);
  always_comb begin
    logic int mult_out, add_out;
    mult_out = x * a; ←
    add_out = mult_out + b;
    y = (add_out > 0) ? add_out : 0;
  end
endmodule
```

❑ Module name

❑ Ports:

- Defines inputs and outputs
- Each has a type (e.g., int)

❑ Behavioral description

- In this case, a **combinational block**
- Sequence of operations
- From input to output



System Verilog vs Verilog

❑ Verilog

- Created in 1983-84
- Standardized in 1995. Became mainstream RTL
- Largely used for legacy designs

VERILOG

❑ System Verilog (this unit)

- Developed in 2002
- Extends Verilog
- Better abstraction, parameterization
- Significantly improved testbench
- Overwhelming design choice today



Synthesis

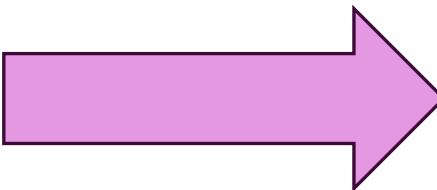
Behavioral Description

What module does?

Ex: Verilog, HLS, SV

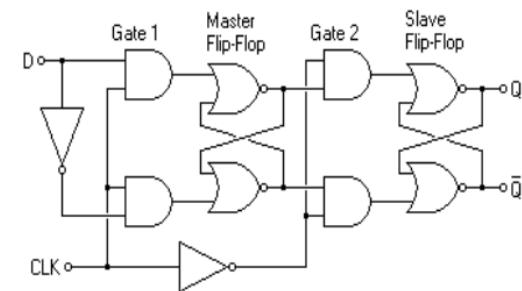
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endmodule
```

Synthesis



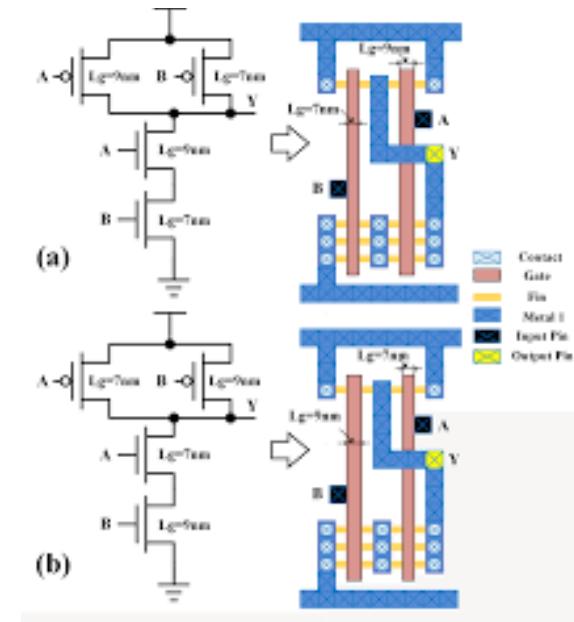
Implementation

How functions maps to hardware



Implementation Depends on the Target

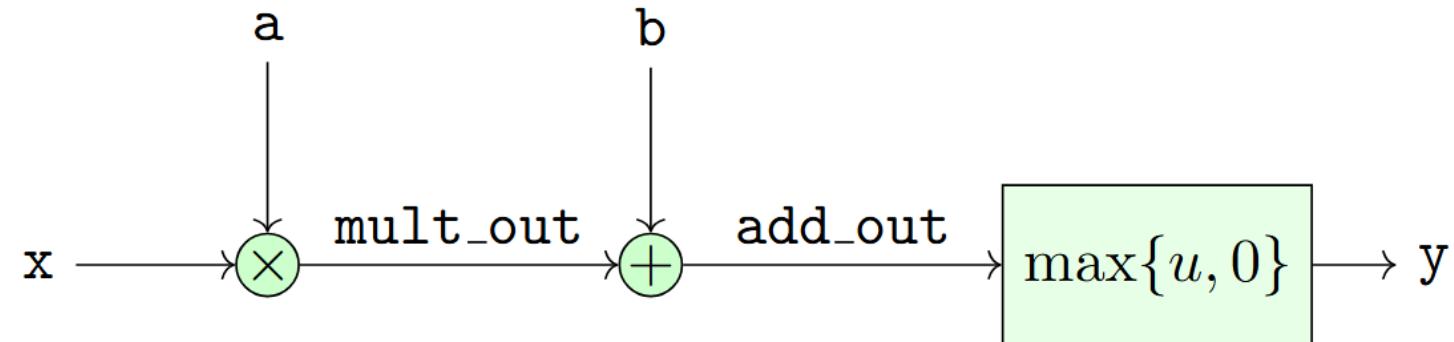
- ❑ Components for implementation depend on target
- ❑ Gate-level netlist (classic implementation)
 - AND, OR, XOR, NOT gates
 - Multiplexers, adders, subtractors, flip-flops, latches
- ❑ Technology-mapped standard cells for ASICs
 - NAND2_X1, DFFR_X2, AOI21_X4, INV_X1
 - Actual cells in foundry's library
- ❑ FPGA primitives
 - DSP units, LUTS, BRAM, ...



Cui, Tiansong, et al. "An exploration of applying gate-length-biasing techniques to deeply-scaled FinFETs operating in multiple voltage regimes." *IEEE Transactions on Emerging Topics in Computing* 6.2 (2016): 172-183.

Block Diagram

- ❑ Function of a module typically represented by a **block diagram**
- ❑ Graphical representation of a potential implementation
- ❑ Typically, diagram is at high-level
 - Adders, multipliers not low-level details components like gates

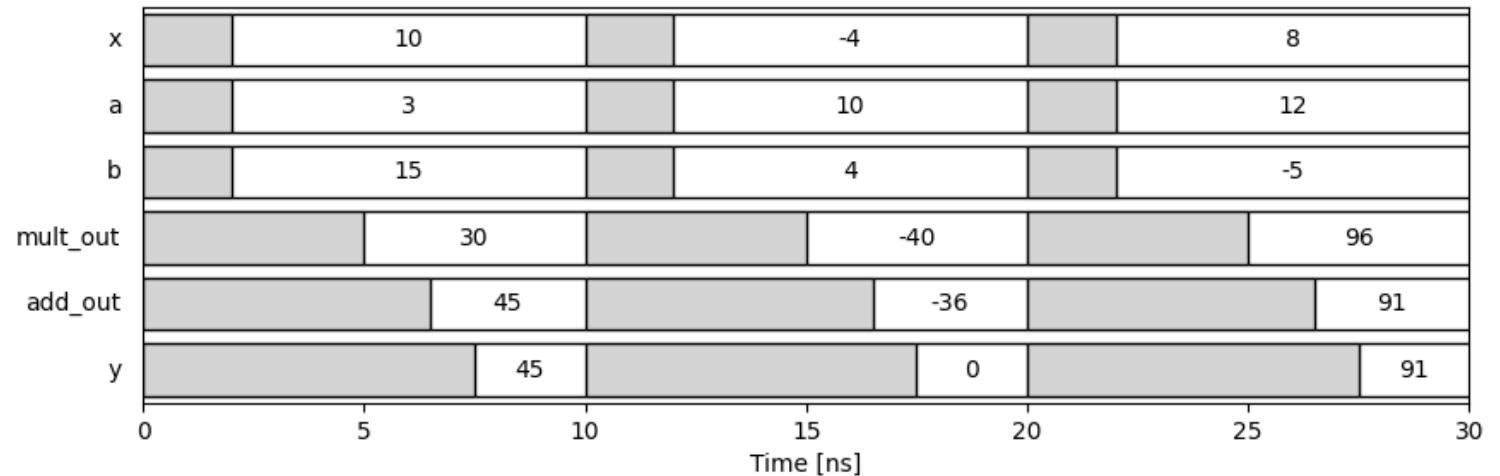


Outline

- ❑ Combinational Logic
-  Timing Diagrams for Combinational Logic
- ❑ Registers, Clocks and Sequential Logic
- ❑ Simulating and Synthesizing Simple Modules in Vivado

Timing Diagrams

- ❑ Graphical representation of the signals in the circuit over time
- ❑ Key to analyzing circuits
- ❑ Demonstrates:
 - Sequence of operations
 - Latency in each step
 - Critical paths

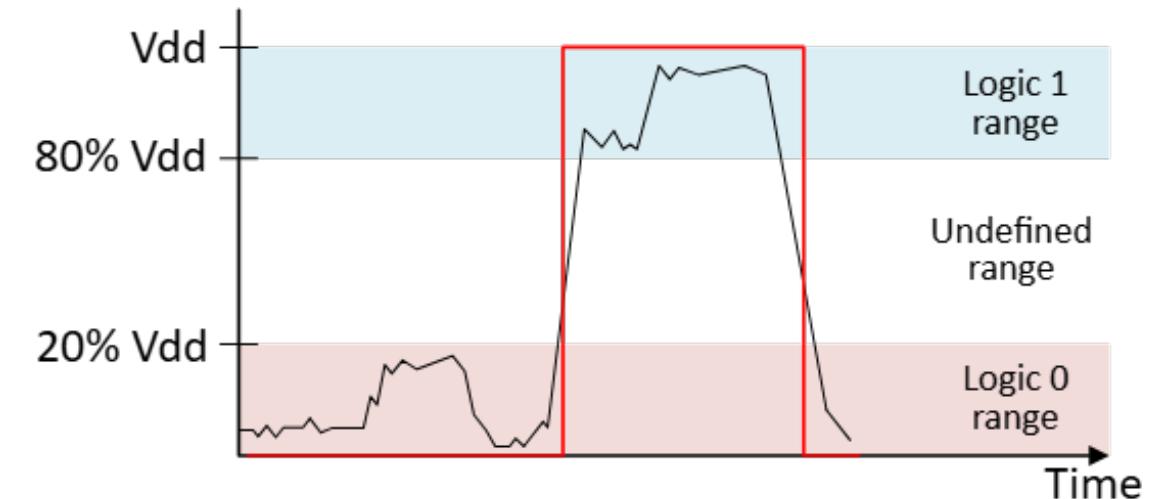


Binary Signals

□ Signal: Any time-varying quantity

□ Digital Binary Signals:

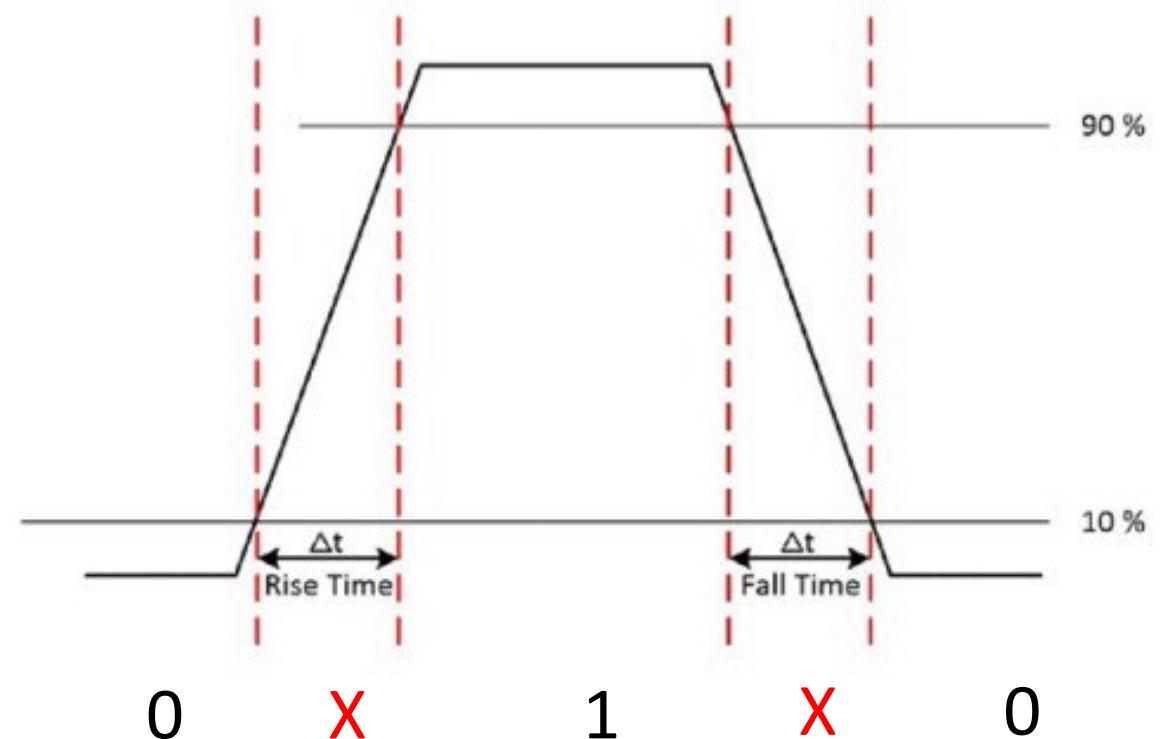
- Two logical values: 0 or 1
- Physically: Typically, a continuous voltage
- Logical value by thresholding



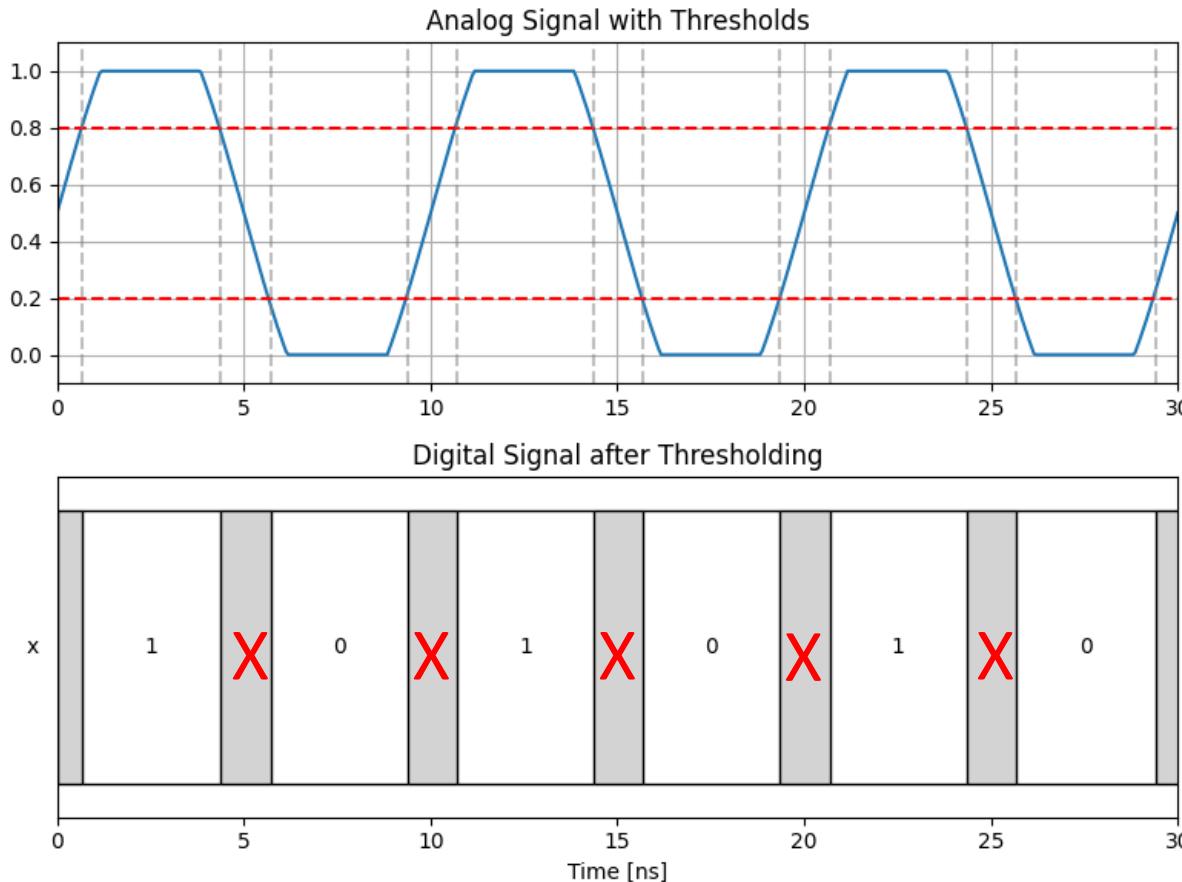
□ Other signals (e.g. integer, floats) built from binary signals

Undefined Logic Value: 'X'

- Signals take time to transition
 - They are outputs of physical circuits
 - Gates, computational units, ...
- Creates an **undefined** period
 - Also called indeterminate, unknown, ...
- Usually denoted as X
- So binary logic signals have three values:
 - 0, 1 and X
 - Will discuss a fourth value Z later



Undefined Regions Illustrated



❑ Analog physical signal

- Typically, a voltage
- Continuous valued
- Has finite transition periods

❑ Digital logic signal

- Three values 0, 1 and X
- X value shown in gray



Value-Change Points

In digital logic, signals are often described by their **value-change points**

Definition: A signal $x(t)$ has **value-change points** $\{(t_i, x_i), i = 0, \dots, n - 1\}$ if:

$$x(t) = \begin{cases} X & t < t_0 \\ x_i & t_i \leq t < t_{i+1}, \quad i = 0, \dots, n - 2 \\ x_{n-1} & t \geq t_{n-1} \end{cases}$$

- Value change points also called **valued change events, transitions, ...**

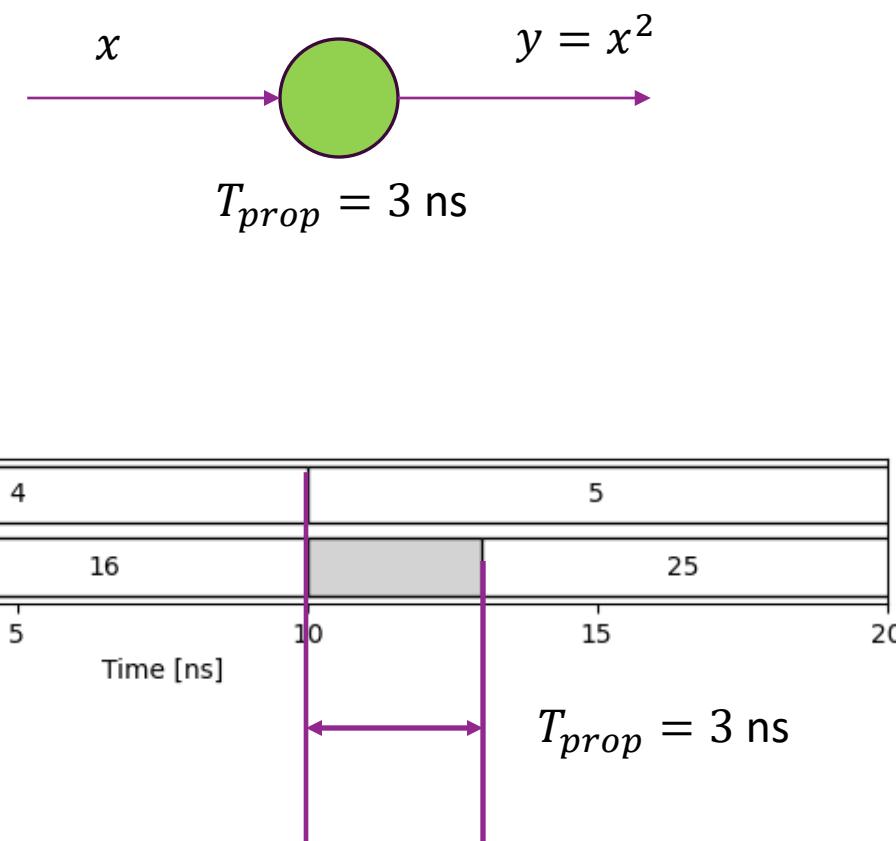
Timing Diagram

- ❑ **Timing diagram:** A plot of signals over time showing value-change points
- ❑ Example with two signals:
- ❑ VC points for x : $\{(3,5), (20,17), (40,8)\}$
- ❑ VC points for y : $\{(12,3), (25,12), (35,0)\}$
- ❑ In this plot, times are in ns



Propagation Delays

- ❑ Each circuit element incurs a **propagation delay**
 - Time for the output to settle after the input changes
- ❑ On transition of input
 - Output is initially unknown ‘X’
 - We cannot assume the value is stable during transition
 - After propagation delay, output settles at value
- ❑ Example:
 - $y = x^2$
 - x has VC points $\{(0,4), (10,5)\}$
 - Prop delay is 3 ns
 - y has VC points $\{(0,X), (3,16), (10,X), (13,25)\}$



Drawing Timing Diagrams in Python

❑ Course repo contains a [xilinxutils package](#)

- Custom package in this class
- Many helper routines for Xilinx tools

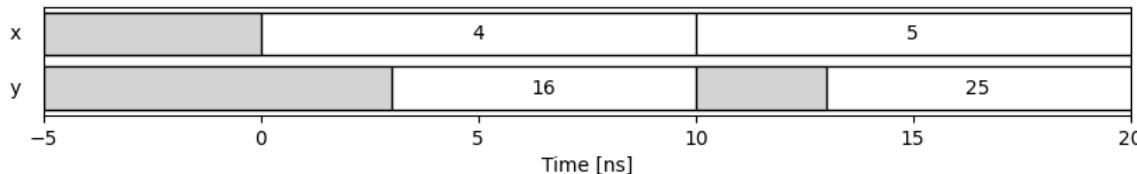
[Hardware Design](#) / [Support Material](#) / [GitHub Repository](#) / Inst:

Installing `xilinxutils`

❑ Tools for parsing and visualizing VCD files

Installing the package

❑ Code to produce timing diagram



```
xvals = ['x', '5', '17', '8']
yvals = ['x', '3', '12', '0']
xtimes = [0, 3, 20, 40]
ytimes = [0, 12, 25, 35]

xsig = SigTimingInfo("x", xtimes, xvals)
ysig = SigTimingInfo("y", ytimes, yvals)
td = TimingDiagram()
td.add_signals([xsig, ysig])
ax = td.plot_signals(trange=[0,50])
_ = ax.set_xlabel("Time [ns]")
```

Propagation Delays of a Series

- ❑ Our example: Three propagation delays

- Multiplier
- Adder
- Max operator

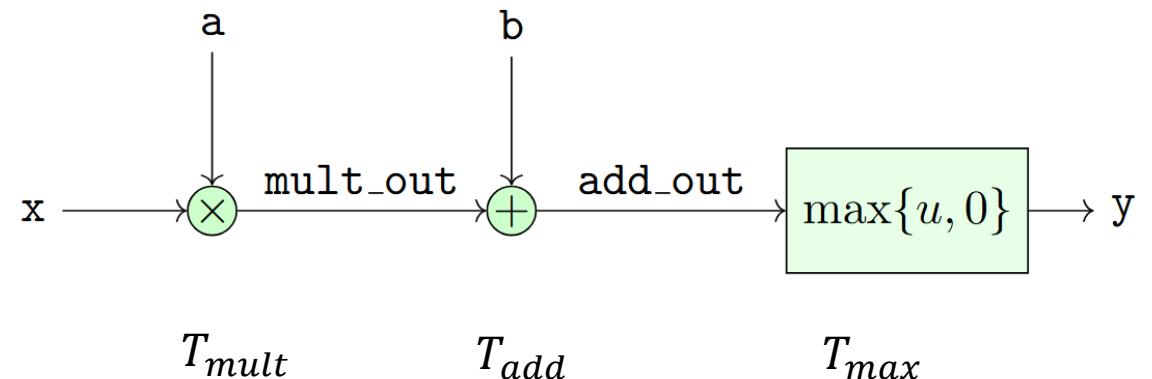
- ❑ Propagation delays will add

- ❑ Called the **total propagation delay**

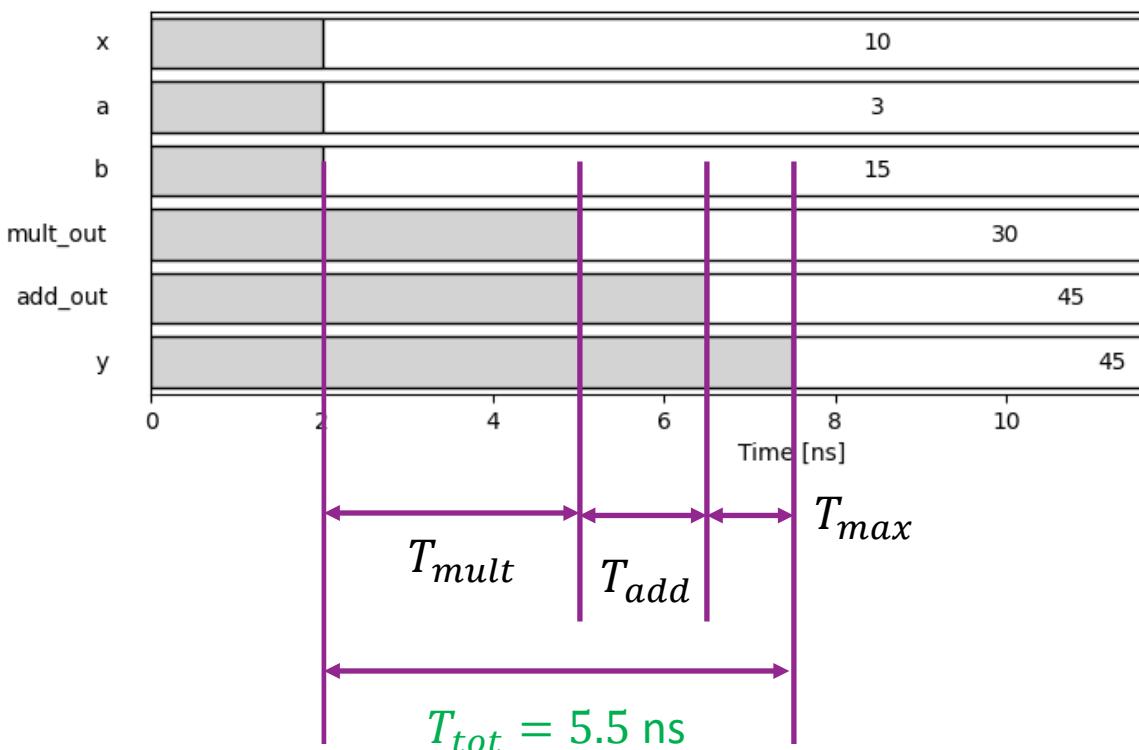
- Or **total path delay**

- ❑ Key property: When input x changes

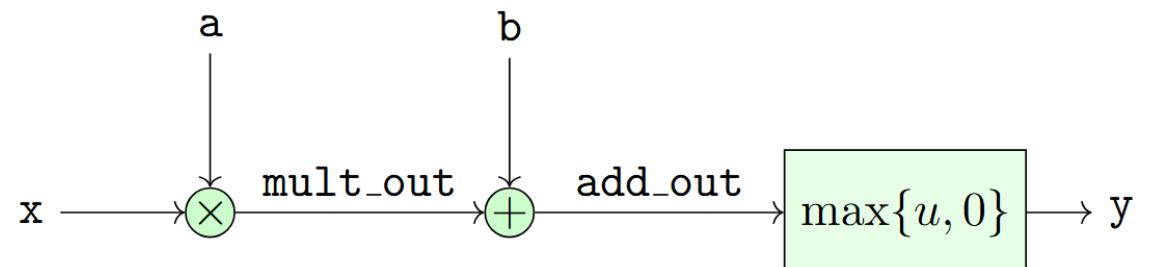
- All downstream values initially go to X



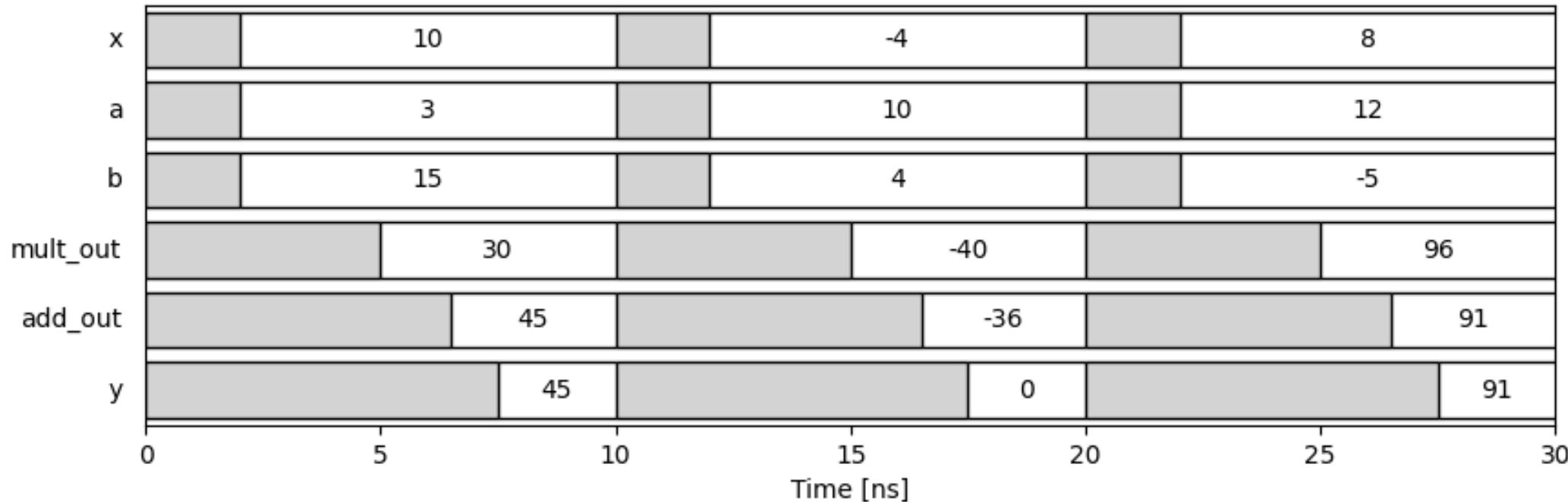
Example Total Propagation Delay



Hardware block	Example Value
Multiplier	$T_{mult} = 3 \text{ ns}$
Adder	$T_{add} = 1.5 \text{ ns}$
Max operator	$T_{max} = 1 \text{ ns}$
Total	$T_{tot} = 5.5 \text{ ns}$



Example Timing Over Multiple Inputs



Typical Propagation Delays: Low-End FPGA

Hardware block	FPGA resource	Typical range
32-bit adder	LUT + dedicated carry chain	1.5–3.0 ns
16-bit multiplier	DSP48E1 block	2.5–5.0 ns
16-bit comparator	LUT logic + carry chain	1.0–2.0 ns

- ❑ Rough delays for a low-end FPGA (e.g., Pynq Z2)
- ❑ We will explain the FPGA resources more in later units
- ❑ Routing delays not included
 - May be large for more complex designs

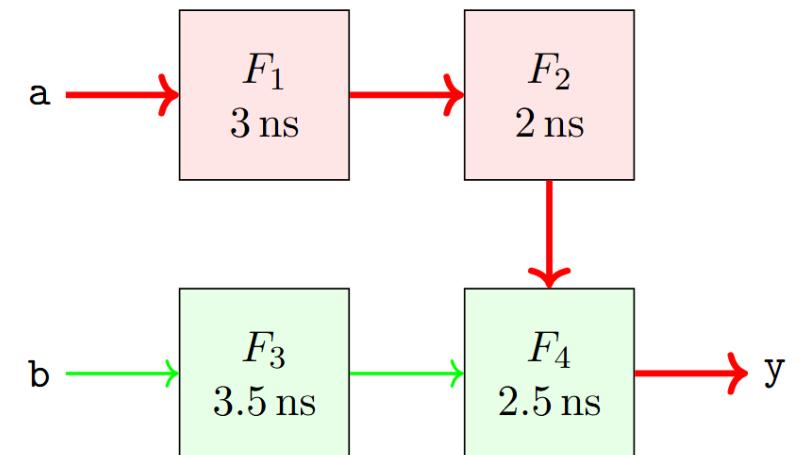
Typical Propagation Delays: ASIC

Hardware block	Typical structure	Typical range
32-bit adder	Kogge-Stone / Brent-Kung / hybrid	150-450 ps
16-bit multiplier	Wallace/Dadda tree + final adde	300-700 ps
16-bit comparator	XOR/AND/OR chain with early-out	50-300 ps

- ❑ Rough delays for TSMC 16nm
- ❑ Custom ASICs are much faster than FPGAs
 - Easily 5 to 10x faster

Critical Path

- ❑ Signals may need to propagate over multiple **paths**
- ❑ Each path accumulates different path delay
 - Total propagation time on path
- ❑ **Critical path:**
 - The path with the highest total propagation delay
- ❑ Critical path will determine total delay of module



Critical Path Example

□ Example: For some functions F_1, \dots, F_4

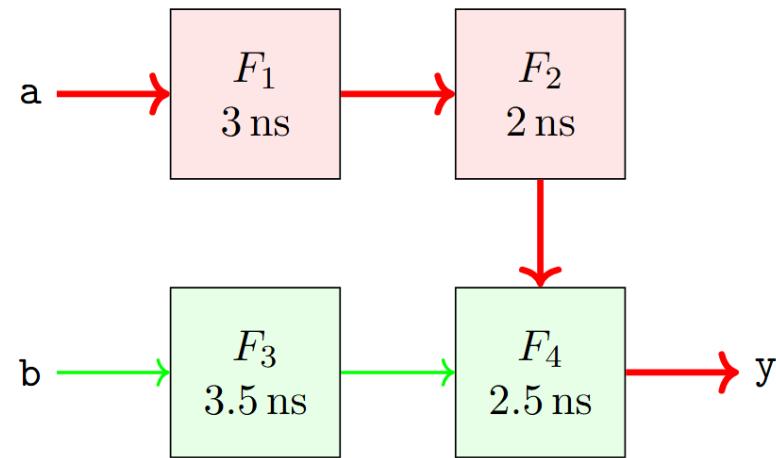
- $x_1 = F_2(F_1(a))$
- $x_2 = F_3(b)$
- $y = F_4(x_1, x_2)$

□ Path 1 ($F_1 \rightarrow F_2 \rightarrow F_4$):

- Delay = $3+2+2.5 = 7.5$ ns
- Longest = Critical path

□ Path 2 ($F_3 + F_4$):

- Delay = $3.5 + 2.5 = 6$ ns
- Shorter = Non-critical

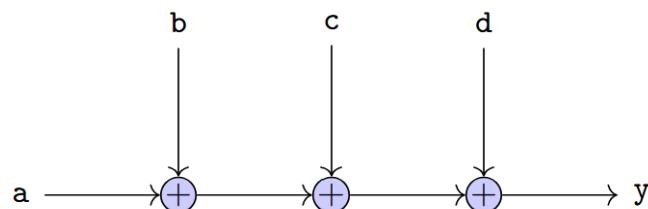


Delay Depends on Implementation

- ❑ Example: Consider $y = a + b + c + d$
- ❑ Suppose each add takes D seconds
- ❑ Synthesis tools try to find low delay implementations

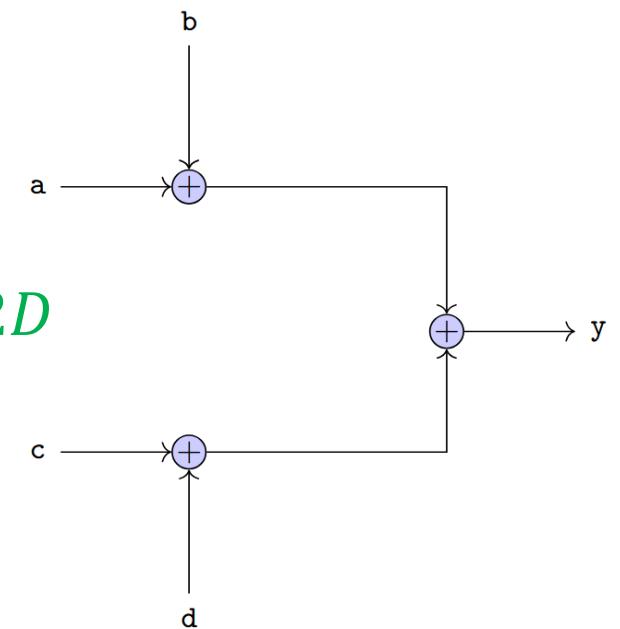
Serial implementation

Prop delay = $3D$



Parallel

Prop delay = $2D$

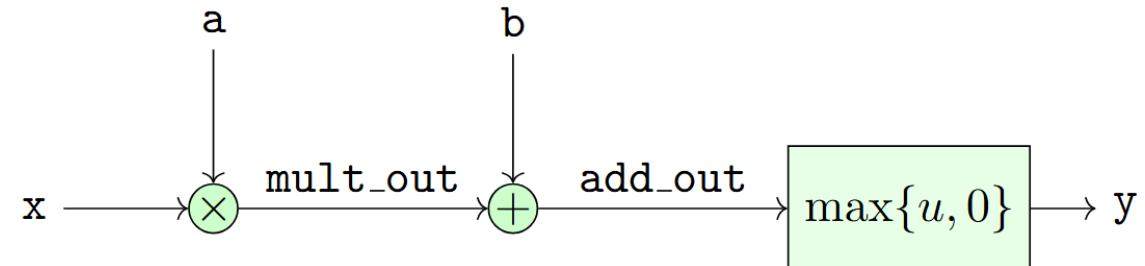


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Limitations of Combinational Logic

- ❑ No memory — cannot store past values
- ❑ Output changes immediately with input changes (no control over timing)
- ❑ Long combinational paths lead to large propagation delays
- ❑ Hard to build large systems without controlled timing boundaries
- ❑ Glitches and hazards can propagate freely
- ❑ No notion of “steps” or “cycles” — everything is continuous



Synchronous (Sequential) Logic

- ❑ Introduces **state** via **flip-flops** or **registers**
- ❑ Breaks long logic into **clocked stages**, improving performance
- ❑ Provides **predictable timing** — changes only occur on clock edges
- ❑ Makes large systems modular and easier to reason about
- ❑ Eliminates most hazards/glitches from propagating across stages
- ❑ Enables pipelining, finite-state machines, and sequential algorithms
- ❑ Allows clean interfaces between modules (valid/ready, handshakes, etc.)

Synchronous logic is the dominant paradigm for design

Clock Signal

❑ **Clock**: An alternating binary signal

- Visualized as a square wave

❑ Each period is called a **clock cycle**

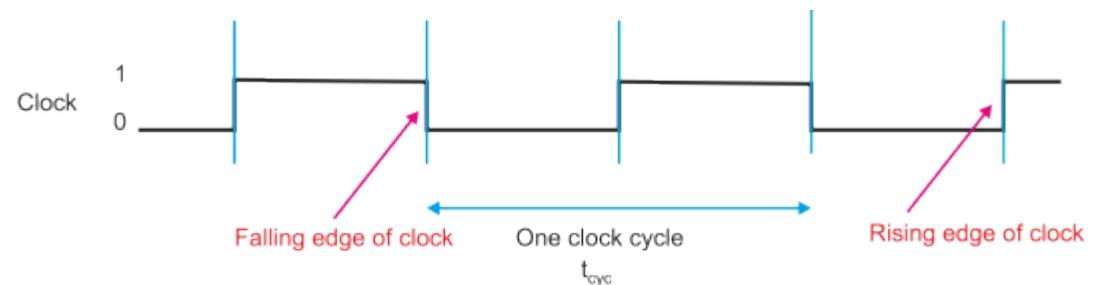
- Typically, between two **rising edges**

❑ **Parameters:**

- Clock **period** T
- Frequency $f = \frac{1}{T}$

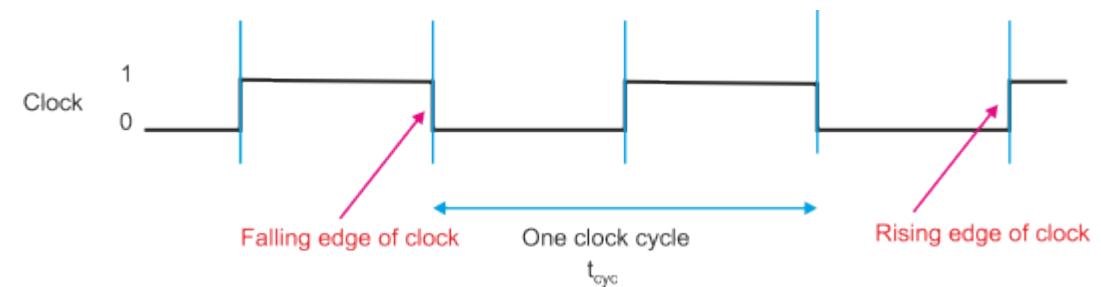
❑ **Typical parameters:**

- FPGA logic: 100 to 500 MHz
- ASIC: 500 MHz to 1 GHz



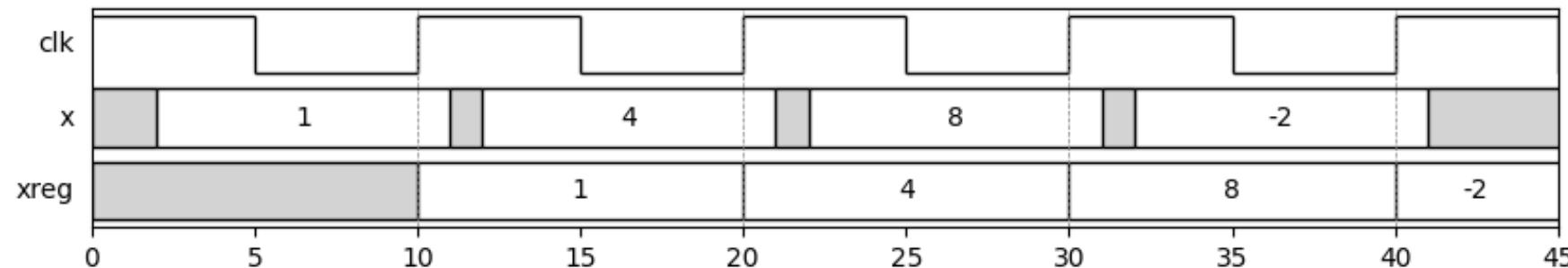
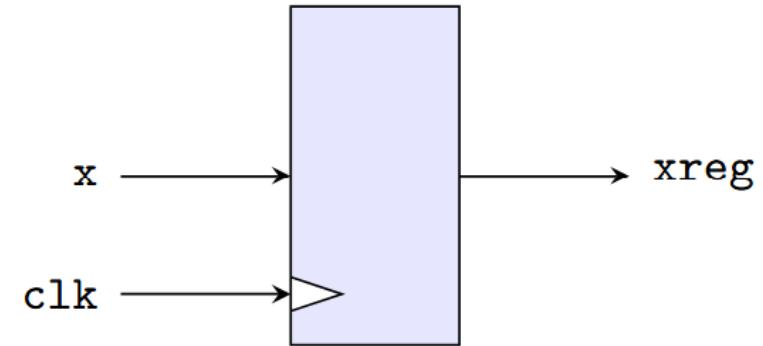
Synchronous Logic

- ❑ Key idea: Save system state on each rising edge
- ❑ Save state in a storage element
 - This unit we will use **registers** (next slide)
- ❑ Brings system to a known state in each cycle
- ❑ Computation can be performed in known steps



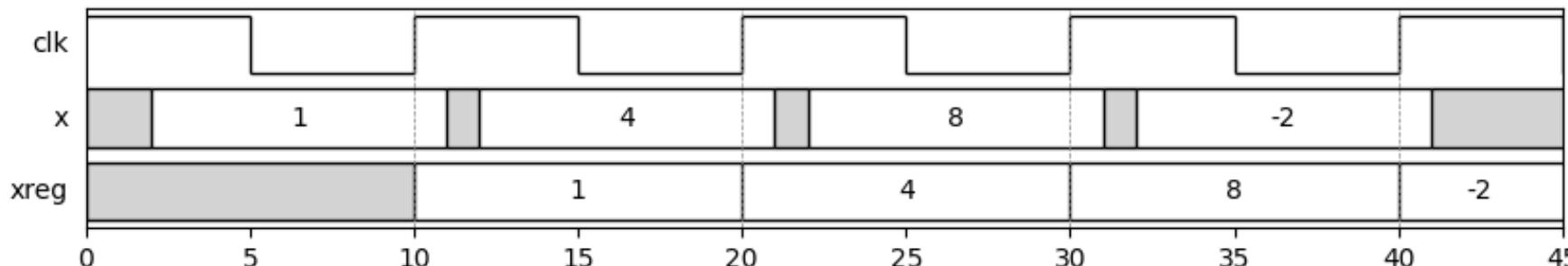
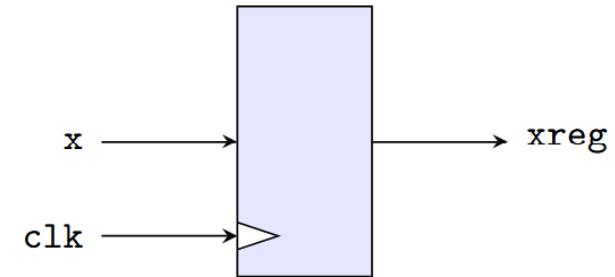
Register

- ❑ Basic storage element in synchronous logic
- ❑ On each rising edge of clk:
 - Assigns xreg to x
- ❑ Value of xreg is maintained even if x changes
- ❑ Example below: Input is “sampled” at rising edges
 - Unknown periods not propagated



Register

- ❑ Samples input at each rising edge
- ❑ Input may have X values
 - Not propagated assuming input is valid on positive edges



Making the Module Synchronous

- ❑ Making module synchronous is easy
- ❑ First add two inputs to ports
 - Clock signal
 - Reset on negative edge

```
module relu_lin (
    input logic clk,
    input logic rst_n, ← Clock
    input logic int x,
    input logic int a,
    input logic int b,
    output logic int y
);
```

← Reset

System Verilog Main Body

❑ Synchronous logic has two parts

❑ `always_ff`:

- Assigns register outputs
- All operations are in parallel (non-blocking)
- Our example: Saves inputs to registers

❑ `always_comb`:

- Assigns signals via combinational logic
- Operations are sequential (blocking)
- Our example: Computes output from registered inputs

```
int x_reg, a_reg, b_reg;

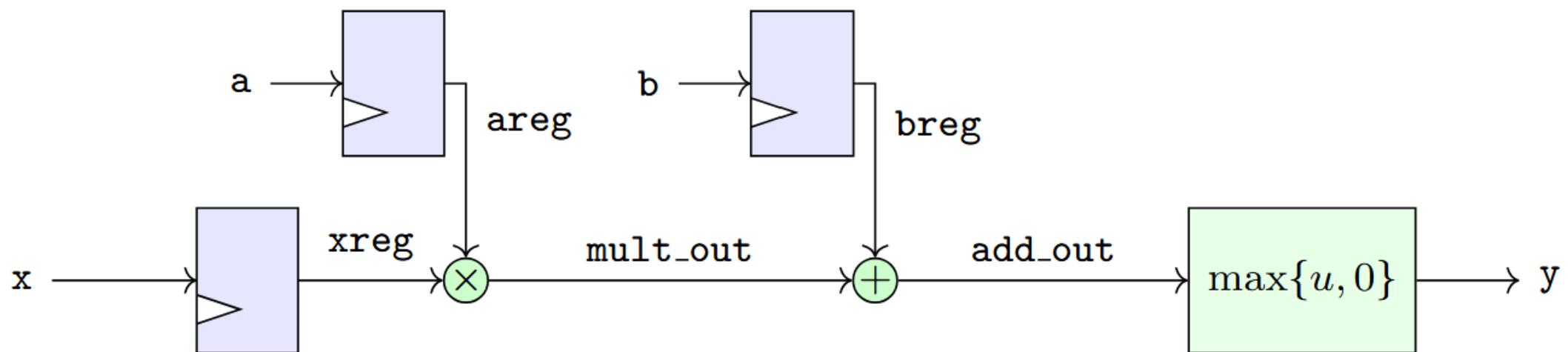
always_ff @(posedge clk or negedge rst_n) begin
    if (!rst_n) begin
        x_reg <= 0;
        a_reg <= 0;
        b_reg <= 0;
    end else begin
        x_reg <= x;
        a_reg <= a;
        b_reg <= b;
    end
end

always_comb begin
    logic int mult_out, add_out;
    mult_out = x_reg * a_reg;
    add_out = mult_out + b_reg;
    y = (add_out > 0) ? add_out : 0;
end
endmodule
```

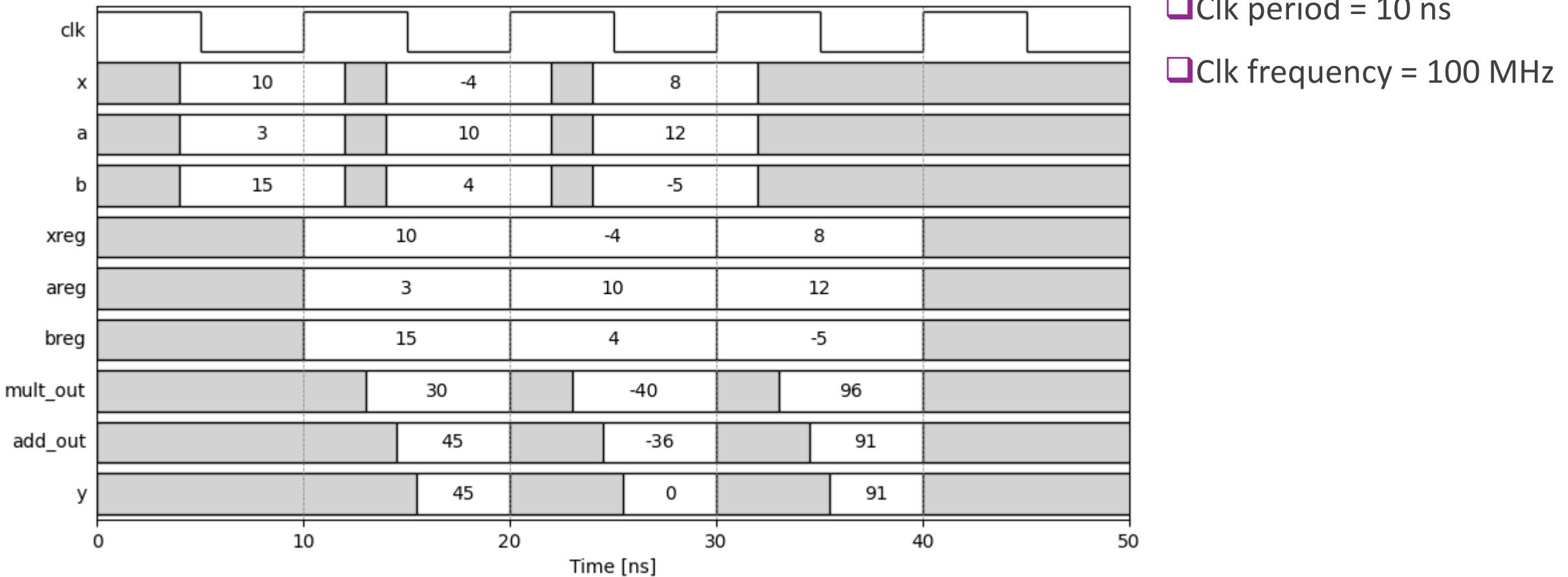


Synchronous Block Diagram

- ❑ Inputs are registered
- ❑ Output is combinational from input



Synchronous Timing Diagram



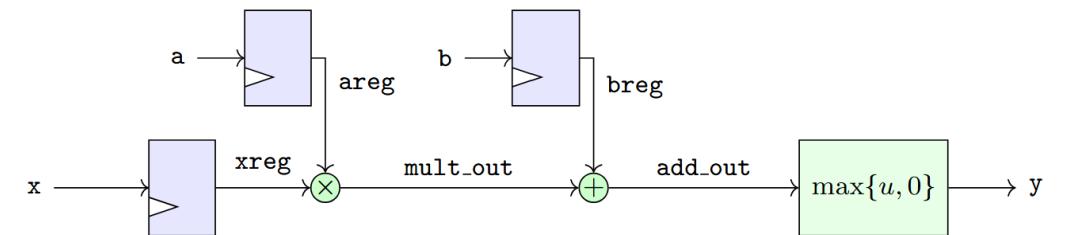
- Clk period = 10 ns
- Clk frequency = 100 MHz

Maximum Clock Frequency

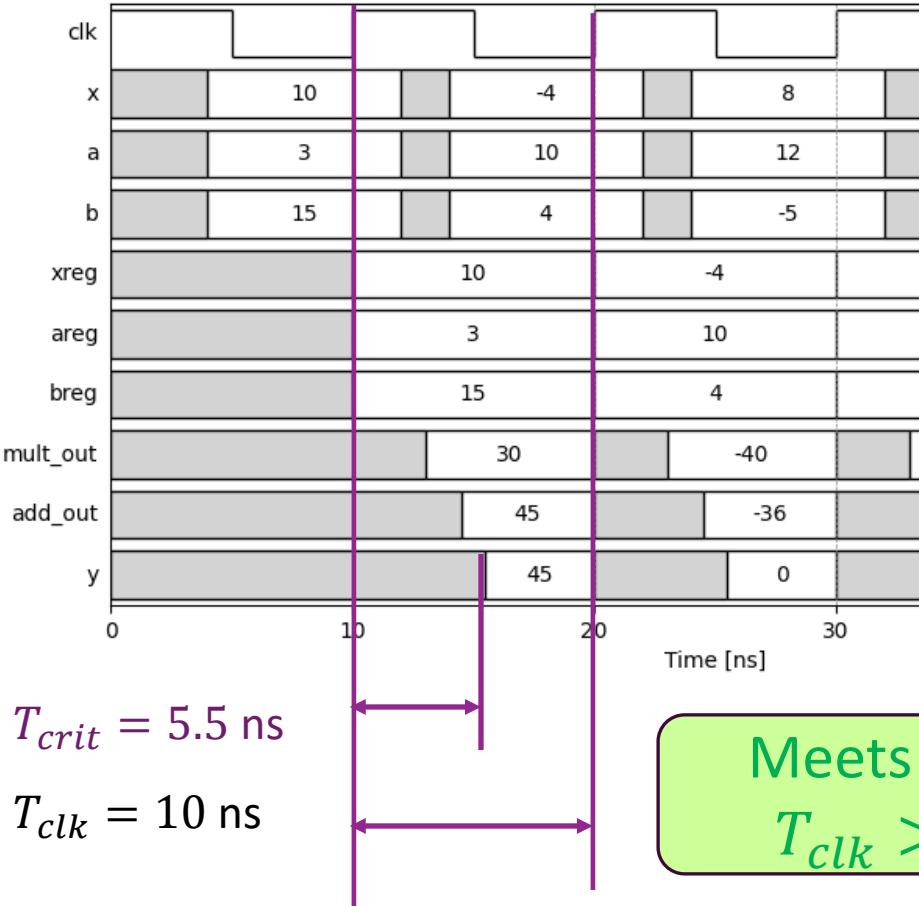
- ❑ Consider combinational path
 - $x_{reg}, a_{reg}, b_{reg} \rightarrow y$
- ❑ This path must complete within one clock cycle
- ❑ Otherwise, next input to next stage not correctly sampled

To meet timing: $T_{clk} > T_{crit}$

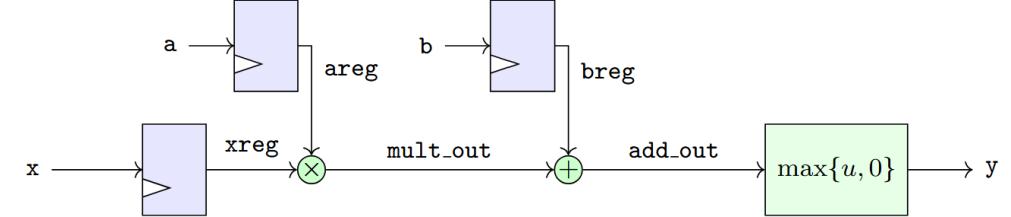
- $T_{crit} = \text{delay of critical path}, T_{clk} = \text{clock period}$
- ❑ $T_{clk} > T_{crit}$: System **meets timing**
- ❑ $T_{clk} < T_{crit}$: System **fails timing / timing violation**



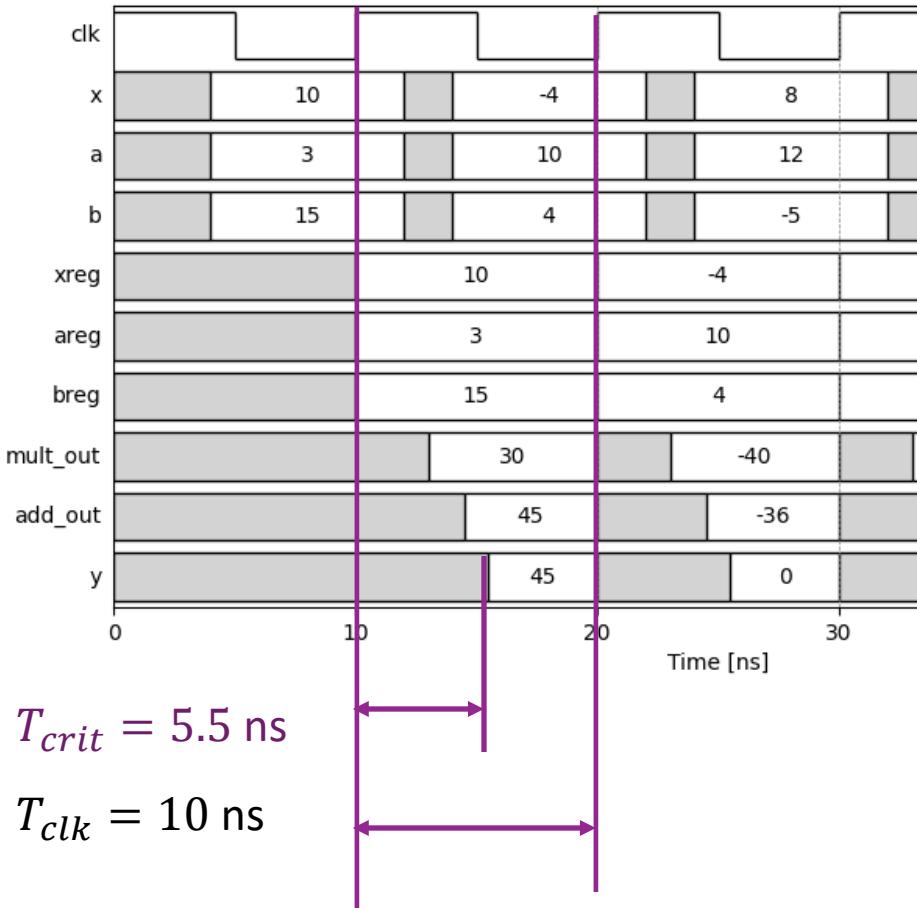
ReLU+Linear Example



Hardware block	Example Value
Multiplier	$T_{mult} = 3 \text{ ns}$
Adder	$T_{add} = 1.5 \text{ ns}$
Max operator	$T_{max} = 1 \text{ ns}$
Total =critical path	$T_{crit} = 5.5 \text{ ns}$

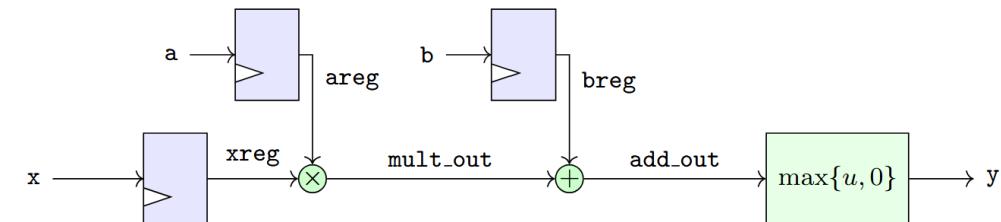


Max Clock Frequency Example



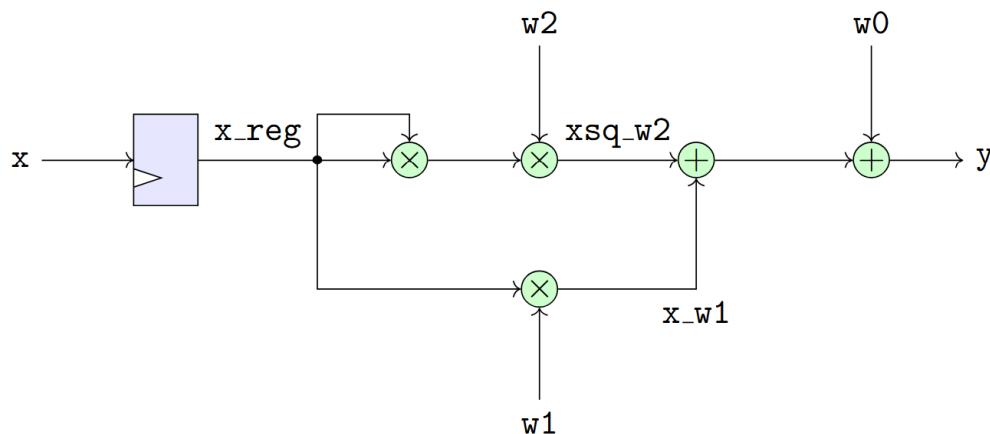
□ Max clock frequency in our example:

- Min $T_{clk} = T_{crit} = 5.5 \text{ ns}$
- Max clock frequency = $\frac{1}{5.5} \cong 180 \text{ MHz}$



A More Complex Example

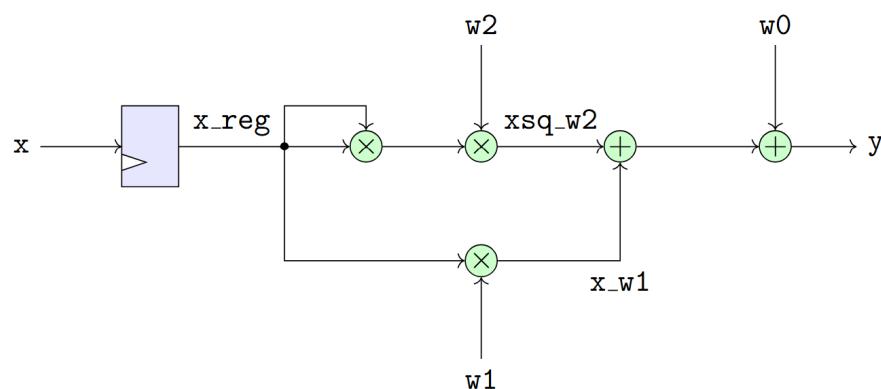
- Consider a quadratic function: $y = w_2x^2 + w_1x + w_0$
- For simplicity, assume w_0, w_1, w_2 are fixed parameters
- Single cycle implementation to the right



```
module quad_func #(  
    parameter int w2 = 0,  
    parameter int w1 = 0,  
    parameter int w0 = 0  
) (  
    input logic clk,  
    input logic int x,  
    output logic int y  
    int xreg;  
    always_ff @ (posedge clk) begin  
        xreg <= x;  
    end  
    always_comb begin  
        logic int xsq, xsq_w2, x_w1;  
        xsq = xreg * xreg;  
        xsq_w2 = w2 * xsq;  
        x_w1 = w1 * xreg;  
        y = xsq_w2 + x_w1 + w0;  
    end
```

Finding the Critical Path

Hardware block	Example Value
Register	$T_{reg} = 1 \text{ ns}$
Multiplier	$T_{mult} = 4 \text{ ns}$
Adder	$T_{add} = 1.5 \text{ ns}$
Path 1	$1+4+4+1.5+1.5 = 12$
Path 2	$1+4+1.5+1.5=8$

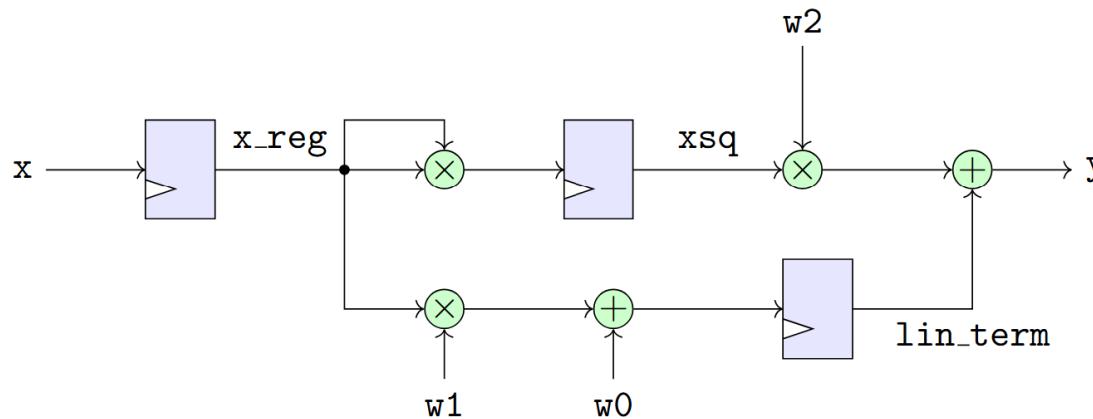


- ❑ Consider implementation with times in table
- ❑ Two paths:
 - ❑ Path 1: x, x_reg, xsq_w2, y
 - 1 register, 2 mults, 2 adders = 12 ns
 - ❑ Path 2: x, x_reg, x_w1, y
 - 1 register, 1 mult, 2 adders = 8 ns
- ❑ Path 1 is critical
- ❑ Max clock frequency = $\frac{1}{12 \text{ ns}} = 83 \text{ MHz}$
- ❑ Would **fail timing** at 100 MHz

A Two Cycle Design

- ❑ We can improve throughput by breaking computation over two cycles
- ❑ Register two intermediate terms:

- $x_{sq} = x_{reg} * x_{reg}$
- $lin_term = w_1 * x_{reg} + w_0$



```
int xreg;
always_ff @(posedge clk) begin
    xsq <= xreg * xreg;
    lin_term <= w1 * xreg + w0;
    xreg <= x;
end
always_comb begin
    y = w2*xsq + lin_term;
end
```

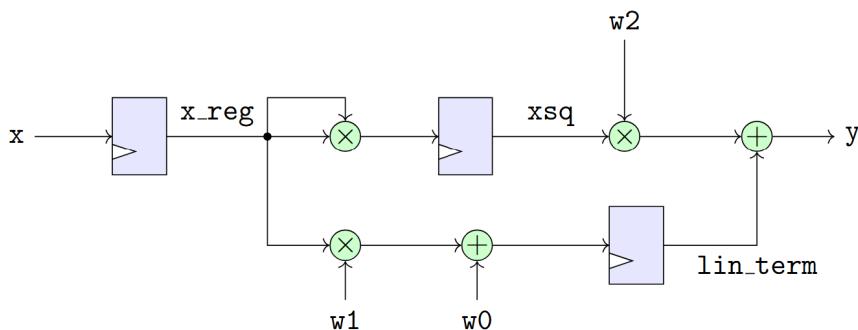
Three Stages

- ❑ Design is processed in three stages = 2 cycles
- ❑ Stage 0
 - Register input x to $xreg$
- ❑ Stage 1: Compute and register:
 - $xsq = xreg * xreg$
 - $lin_term = w1 * xreg + w0$
- ❑ Stage 2: Compute output
 - $y = w2 * xsq + lin_term$

```
int xreg;
always_ff @(posedge clk) begin
    xsq <= xreg * xreg;
    lin_term <= w1 * xreg + w0;
    xreg <= x;
end
always_comb begin
    y = w2*xsq + lin_term;
end
```

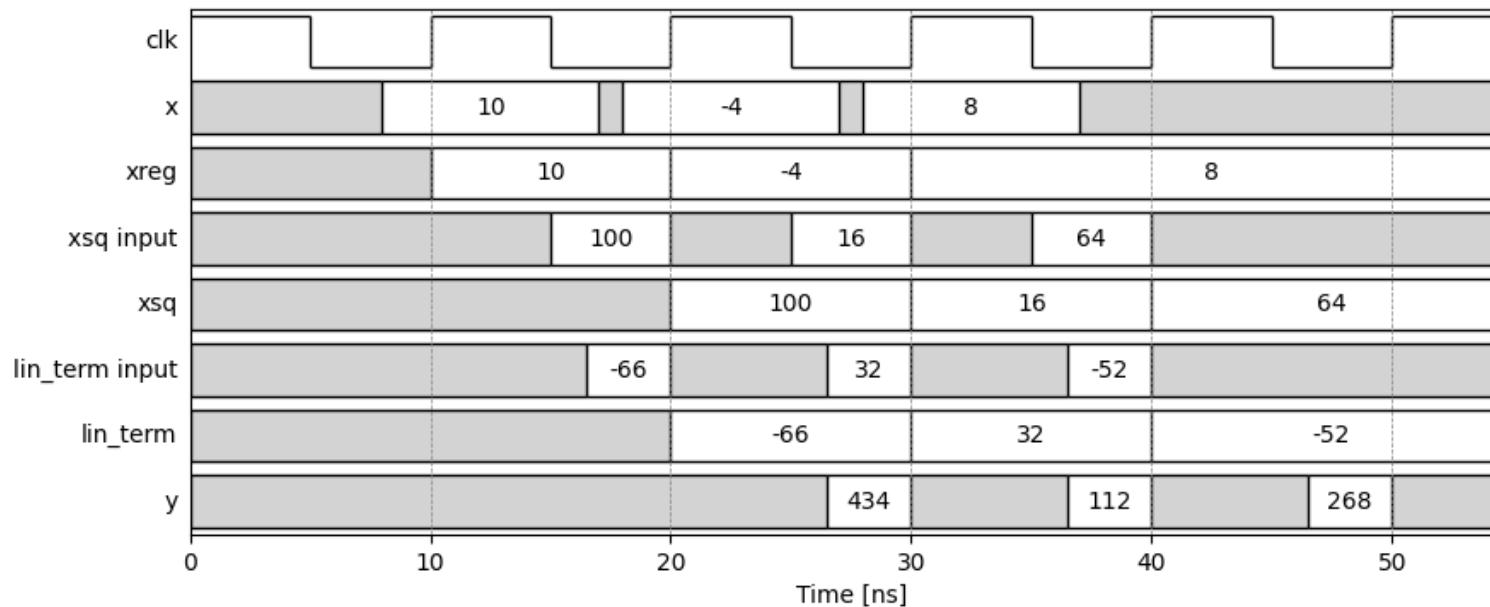
Critical Path with Three Stages

Hardware block	Example Value
Register	$T_{reg} = 1 \text{ ns}$
Multiplier	$T_{mult} = 4 \text{ ns}$
Adder	$T_{add} = 1.5 \text{ ns}$
Path 1	$1+4=5$
Path 2	$1+4+1.5=6.5$
Path 3	$1+4+1.5=6.5$



- ❑ Measure paths from register to register
- ❑ Path 1: x, x_reg, xsq input
 - 1 register, 1 mult = 5 ns
- ❑ Path 2: $x, x_reg, w1_x, lin_x$ input
 - 1 register, 1 mult, 1 add = 6.5 ns
- ❑ Path 3: $xsq_reg, lin_x, w2_xsq, y$
 - 1 register, 1 mult, 1 add = 6.5 ns
- ❑ Critical path delay = 6.5 ns
- ❑ Max freq = $\frac{1}{6.5} \approx 153 \text{ MHz}$

Two Cycle Timing Diagram



❑ Example with

- $w = [4, -7, 5]$

❑ x inputs 10, -4, 8

Latency, Throughput and Pipelining

❑ Suppose that we run at our design at 100 MHz clock

❑ Latency:

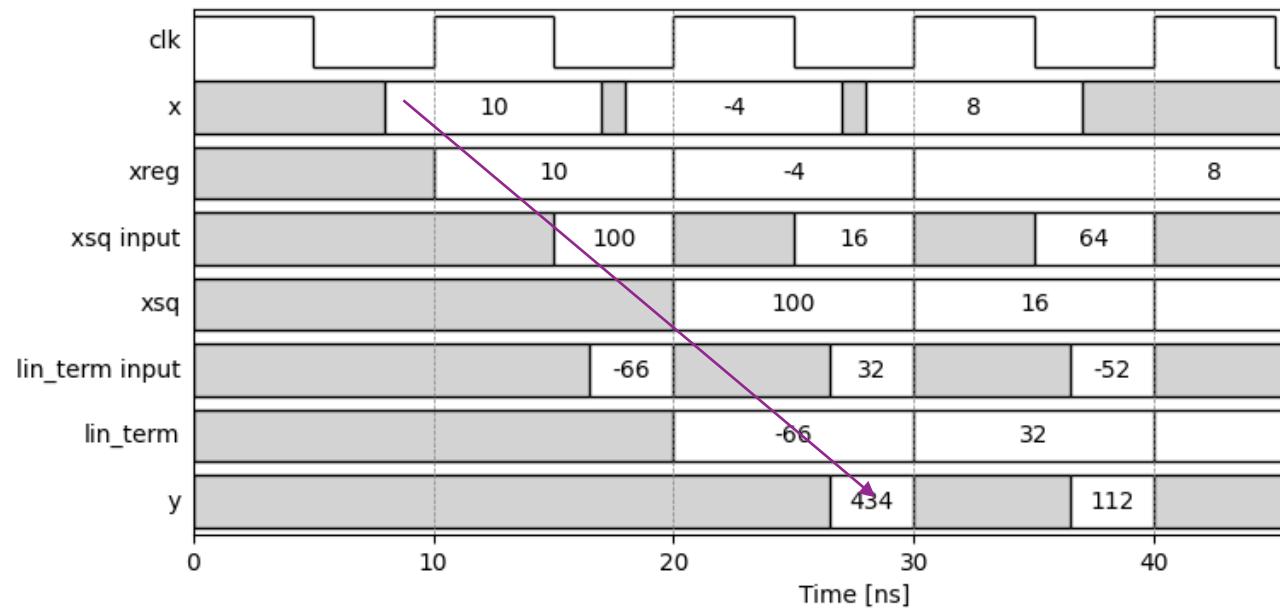
- Suppose input is valid on rising edge of clock n
- Then output is valid before rising edge of clock $n + 2$
- Latency = 2 clock cycles = 20 ns

❑ Throughput:

- Circuit can take a new input each cycle
- Throughput = 1 input / cycle = 100 MHz

❑ Process is called a pipeline

- Circuit is processing multiple inputs at the same time



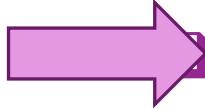
Performance Comparison

	Single Cycle Design	Two Cycle Design
Critical path	12 ns	6.5 ns
Max clock frequency	≈ 80 MHz	≈ 150 MHz
Max throughput	80 MHz	150 MHz
Latency	1 cycle = 12 ns	2 cycles = 13 ns

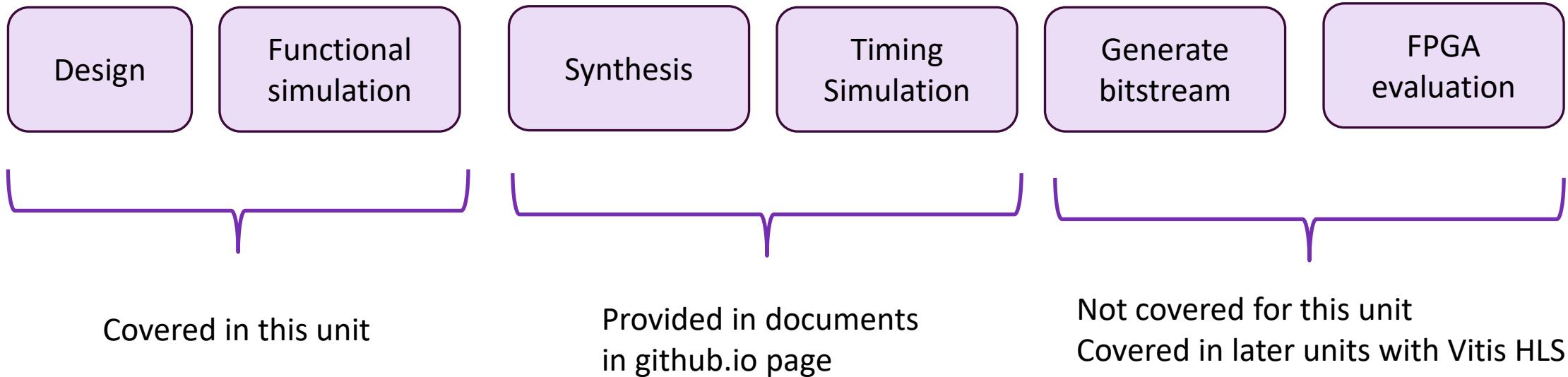
Pipelining benefit:

For small increase in latency, we dramatically improve throughput

Outline

- ❑ Combinational Logic
 - ❑ Timing Diagrams for Combinational Logic
 - ❑ Registers, Clocks and Sequential Logic
-  Simulating and Synthesizing Simple Modules in Vivado

FPGA Development Flow



We only show the first two steps

Linear+ReLU Example

- ❑ All code in [github repo](#)
- ❑ We test code on the right
- ❑ Similar to discussed
- ❑ Main difference:
 - Module in test uses 16-bit integer
 - Code before used int = 32 bit

```
module lin_relu #(  
    parameter WIDTH = 16  
)  
(  
    input logic clk,  
    input logic rst, // synchronous reset  
    input logic signed [WIDTH-1:0] w_in,  
    input logic signed [WIDTH-1:0] b_in,  
    input logic signed [WIDTH-1:0] x_in,  
    output logic signed [WIDTH-1:0] y_out  
)
```

Test Vectors

- ❑ Create a set of test inputs
- ❑ Loop through inputs
- ❑ Put one new input each clock cycle
- ❑ Testbench uses an initial construct
 - Enables sequential set of events

```
// Define test vectors
test_vector_t test_vectors[] = ^{
    '{x: 10,  w: 3,  b: 15},
    '{x: -4,  w: 10, b: 4},
    '{x: 8,   w: 12, b: -5}
};
```

```
for (int i = 0; i < test_vectors.size(); i++) begin

#(0.1*CLK_PERIOD) // hold time before changing input
x_in = 'x; // initial indeterminate value
w_in = 'x;
b_in = 'x;
#(0.15*CLK_PERIOD); // Small delay for propagation time
x_in = test_vectors[i].x;
w_in = test_vectors[i].w;
b_in = test_vectors[i].b;

// Clock cylce
@(posedge clk);

// Compute expected value for verification (optional)
x = test_vectors[i].x;
w = test_vectors[i].w;
b = test_vectors[i].b;
y_exp = (w * x + b > 0) ? (w * x + b) : 0;

$display("Test %0d: x_in=%0d, y_out=%0d, y_exp=%0d",
         | | | i, x, y_out, y_exp);
end
```



Testbench Declaration

❑ Testbench: a module to test the module

- Will not be synthesized
- Can have un-synthesizable constructs
- Ex: Read / write from file

```
module tb_lin_relu;  
  
localparam WIDTH = 16;  
localparam time CLK_PERIOD = 10ns;  
  
logic clk = 0;  
logic rst = 1;  
logic signed [WIDTH-1:0] x_in;  
logic signed [WIDTH-1:0] w_in;  
logic signed [WIDTH-1:0] b_in;  
logic signed [WIDTH-1:0] y_out;
```

❑ Create a clock

❑ Instantiate an instance of module to test

- Called the **DUT** = device under test
- Connect DUT to testbench signals

```
// Clock generation  
always #(CLK_PERIOD/2) clk = ~clk;  
  
// Instantiate DUT  
lin_relu #(  
    .WIDTH(WIDTH)  
) dut (  
    .clk(clk),  
    .rst(rst),  
    .w_in(w_in),  
    .b_in(b_in),  
    .x_in(x_in),  
    .y_out(y_out)  
) ;
```

Run Simulation

- ❑ We show how to run from the command-line
 - A Vivado GUI option is also available
 - But command-line is more flexible and automatable
- ❑ Start a virtual environment with xilinxutils
 - Xilinxutils: Python package provided in the course repo

❑ Run command

- ❑ Command is equivalent to
 - sv_sim is a short-cut

(env) sv_sim --source simp_fun.sv --tb tb_simp_fun.sv

```
xvlog -sv simp_fun.sv tb_simp_fun.sv
xelab tb_simp_fun -s tb_simp_fun_sim -log logs/xelab
xsim tb_simp_fun_sim -t run.tcl -log logs/xsim.lo
```

Parsing the VCD File

- ❑ Simulation produces a VCD file: Value Change Dump
 - File with value-change points of all the signals
- ❑ VCD can be parsed in a jupyter notebook
- ❑ Use Xilinxutils to:
 - Parse the VCD file
 - Visualize the timing diagram

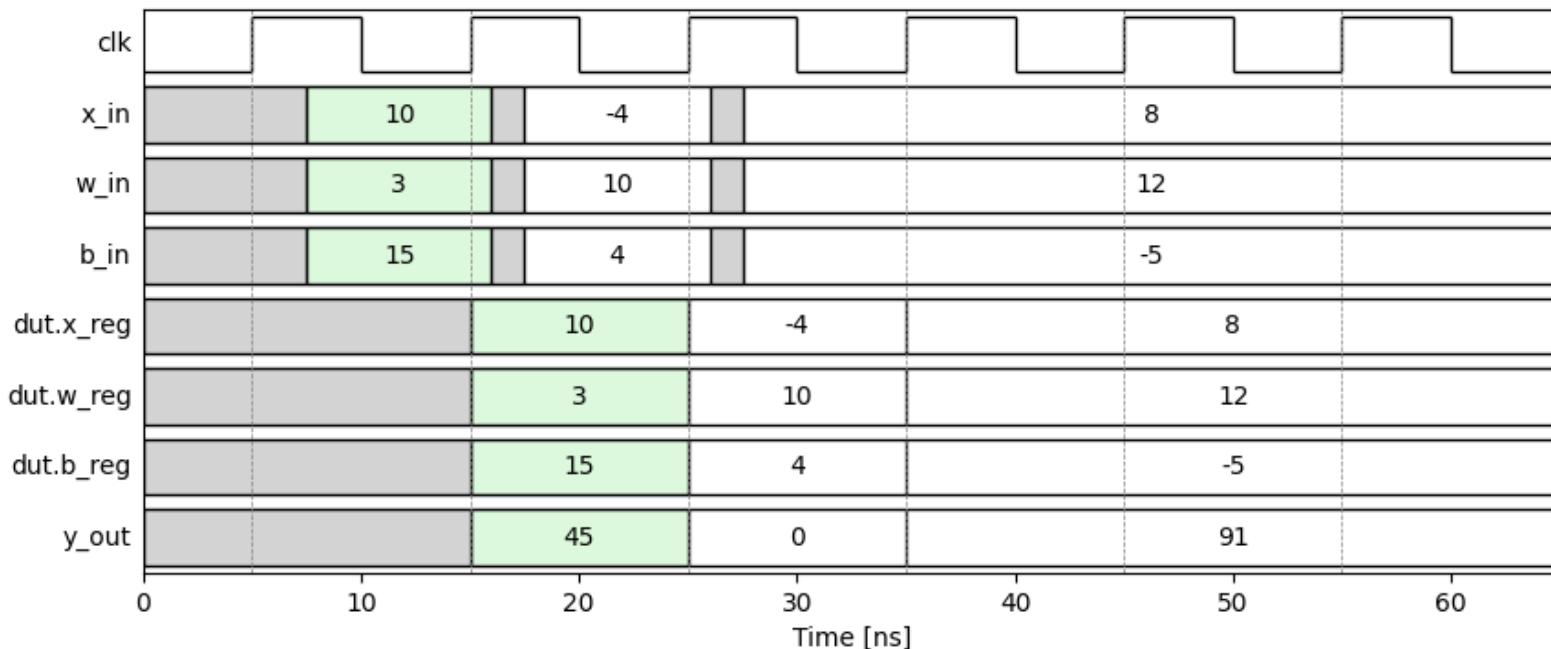
Timing for Basic Digital Circuits

In this notebook, we will show how to view the timing diagram for the simple digital circuits we have simulated. Before running the notebook, you should complete one of the following simulations:

- [scalar function simulation](#): Simulates a simple function multiplying two numbers.
- [linear+ReLU](#): Simulates a linear function followed by a ReLU activation function.
- [polynomial simulation](#): Simulates a quadratic function of a single input variable over 100 cycles to complete.

Timing Diagram

- ❑ Matches expected value output
- ❑ Produces an idealized timing diagram
 - Timing simulation requires synthesis



Quadratic Example

- ❑ Code in github repo
- ❑ We use 16-bit integers with wraparound
- ❑ Process is similar

```
module poly_fun #(  
    parameter int WIDTH = 16,  
    parameter signed [WIDTH-1:0] W2 = 3,  
    parameter signed [WIDTH-1:0] W1 = 2,  
    parameter signed [WIDTH-1:0] W0 = 4  
) (  
    input logic clk,  
    input logic rst,  
    input signed [WIDTH-1:0] x,  
    output logic signed [WIDTH-1:0] y  
) ;  
  
logic signed [WIDTH-1:0] x_reg, lin_term, xsq;  
always_ff @(posedge clk) begin  
    if (rst) begin  
        x_reg <= '0;  
        lin_term <= '0;  
        xsq <= '0;  
    end else begin  
        x_reg <= x;  
        lin_term <= (W1 * x_reg) + W0; // WIDTH-bit wraparound  
        xsq <= x_reg * x_reg; // WIDTH-bit wraparound  
    end  
end  
always_comb begin  
    y = W2 * xsq + lin_term; // WIDTH-bit wraparound  
end
```

Quadratic Timing Diagram

- ❑ Can see two cycle latency and pipelining

