

Intro to Digital Design

L2: More CL, Verilog Basics

Instructor: Naomi Alterman

Teaching Assistants:

Derek de Leuw

Isabel Froelich

Kevin Hernandez

Sathvik Kanuri

Aadithya Manoj

Administrivia

- ❖ Lab demo time slots have been assigned on Canvas
 - Check the comment on the “Demo Time Slot” assignment
- ❖ Lab 1 & 2 – Basic Logic and Verilog
 - Digit(s) recognizer using switches and LED (for full credit, find minimal logic)
 - Check the lab report requirements closely
- ❖ We’re out of lab kits, but we’ve ordered more.
 - Just keep doing your lab anyway – we’ll get you a kit soon!
 - For now, you can hardware test on [LabsLand](#)
 - Can use loaner FPGA for your lab demo time

When last we left off...

Combinational Logic

Basic Boolean Identities

$$\diamond X + 0 = X$$

$$\diamond X \cdot 1 = X$$

$$\diamond X + 1 = 1$$

$$\diamond X \cdot 0 = 0$$

$$\diamond X + X = X$$

$$\diamond X \cdot X = X$$

$$\diamond X + \bar{X} = 1$$

$$\diamond X \cdot \bar{X} = 0$$

$$\diamond \bar{\bar{X}} = X$$

Translating between Truth Tables and Boolean Equations

- ❖ Terms of equation come from rows of table
 - For 1, write variable name
 - For 0, write complement of variable
- ❖ Sum of Products (SoP)
 - From CSE311, “DNF” (disjunctive normal form)
 - Take truth table rows that output 1:
 - AND the inputs together, OR the rows together
- ❖ Product of Sums (PoS)
 - From CSE311, “CNF” (conjunctive normal form)
 - Take truth table rows that output 0:
 - OR the complemented inputs together, AND the rows together

$$\text{SoP: } C = \overline{A}B + \overline{B}A$$
$$\text{PoS: } C = (A + B) \cdot (\overline{A} + \overline{B})$$

a	b	c
0	0	0
0	1	1
1	0	1
1	1	0

Basic Boolean Algebra Laws

- ❖ **Commutative Law:**

$$X + Y = Y + X$$

$$X \cdot Y = Y \cdot X$$

- ❖ **Associative Law:**

$$X + (Y + Z) = (X + Y) + Z$$

$$X \cdot (Y \cdot Z) = (X \cdot Y) \cdot Z$$

- ❖ **Distributive Law:**

$$X \cdot (Y + Z) = X \cdot Y + X \cdot Z$$

$$X + YZ = (X + Y) \cdot (X + Z)$$

Advanced Laws (Absorption)

$$\diamond X + XY = X$$

$$\diamond XY + X\bar{Y} = X$$

$$\diamond X + \bar{X}Y = X + Y$$

$$\diamond X(X + Y) = X$$

$$\diamond (X + Y)(X + \bar{Y}) = X$$

$$\diamond X(\bar{X} + Y) = XY$$

Practice Problem

- ❖ Boolean Function: $F = \bar{X}YZ + XZ$

Truth Table:

X	Y	Z	F
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	0
1	1	1	1

Simplification:

$$= \bar{X}YZ + X\bar{Y}Z + XYZ$$

$$= \bar{X}YZ + XZ$$

$$= (\bar{X}Y + X)Z$$

$$= (X + Y)Z$$

$$= XZ + YZ$$

Which of these
is “simpler”?

Are Logic Gates Created Equal?

- ❖ No!

2-Input Gate Type	# of CMOS transistors
NOT	2
AND	6
OR	6
NAND	4
NOR	4
XOR	8
XNOR	8

- ❖ Can recreate all other gates using only NAND or only NOR gates
 - Called “universal” gates
 - e.g., $A \text{ NAND } A = \bar{A}$, $B \text{ NOR } B = \bar{B}$
 - DeMorgan’s Law helps us here!

Logic minimization

- ❖ Reduce complexity at gate level
 - Allows us to build smaller and faster hardware
 - Care about both # of gates, # of literals (gate inputs), # of gate levels, and types of logic gates

Logic minimization

- ❖ Reduce complexity at gate level
 - Allows us to build smaller and faster hardware
 - Care about both # of gates, # of literals (gate inputs), # of gate levels, and types of logic gates
- ❖ Faster hardware?
 - Fewer inputs implies faster gates in some technologies
 - Fan-ins (# of gate inputs) are limited in some technologies
 - Fewer levels of gates implies reduced signal propagation **delays**
 - # of gates (or gate packages) influences manufacturing costs
 - Simpler Boolean expressions → smaller transistor networks → smaller circuit delays → faster hardware

DeMorgan's Law

- ❖ $\overline{X + Y} = \overline{X} \cdot \overline{Y}$
- ❖ $\overline{X \cdot Y} = \overline{X} + \overline{Y}$

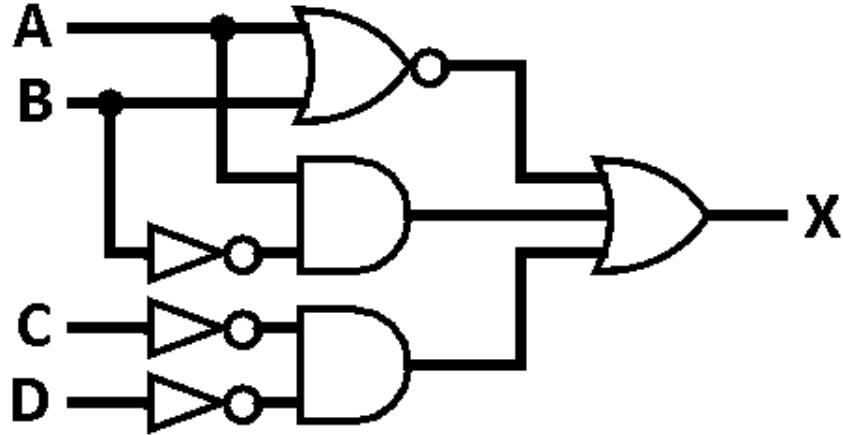
X	Y	NOR		NAND	
		$\overline{X + Y}$	$\overline{X} \cdot \overline{Y}$	$\overline{X \cdot Y}$	$\overline{X} + \overline{Y}$
0	0	1	1	1	1
0	1	1	0	0	1
1	0	0	1	0	1
1	1	0	0	0	0

- ❖ In Boolean Algebra, converts between AND-OR and OR-AND expressions
 - $Z = \overline{ABC} + \overline{ABC} + A\overline{BC}$
 - $\overline{Z} = (A + B + \overline{C}) \cdot (A + \overline{B} + \overline{C}) \cdot (\overline{A} + B + \overline{C})$
- ❖ At gate level, can convert from AND/OR to NAND/NOR gates
 - “Flip” all input/output bubbles and “switch” gate



DeMorgan's Law Practice Problem

- ❖ Simplify the following diagram:



$$X = \overline{A + B} + A\overline{B} + \overline{C}\overline{D}$$

$$X = \overline{AB} + A\overline{B} + \overline{C}\overline{D}$$

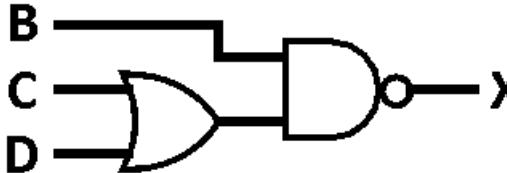
$$X = \overline{B} + \overline{C}\overline{D}$$

$$X = \overline{B} + \overline{C + D}$$

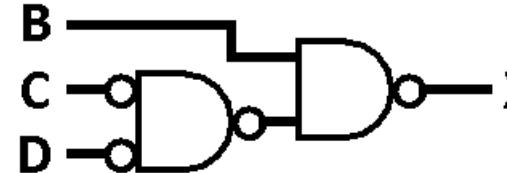
$$X = \overline{B(C + D)}$$

- ❖ Then implement with only NAND gates:

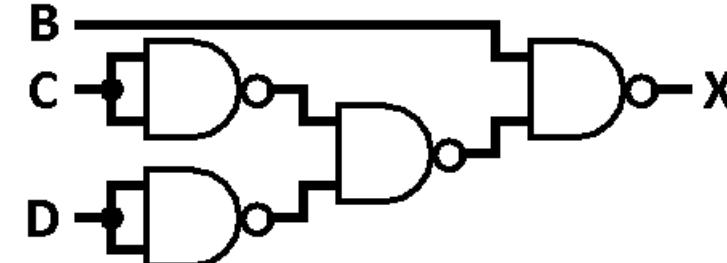
1)



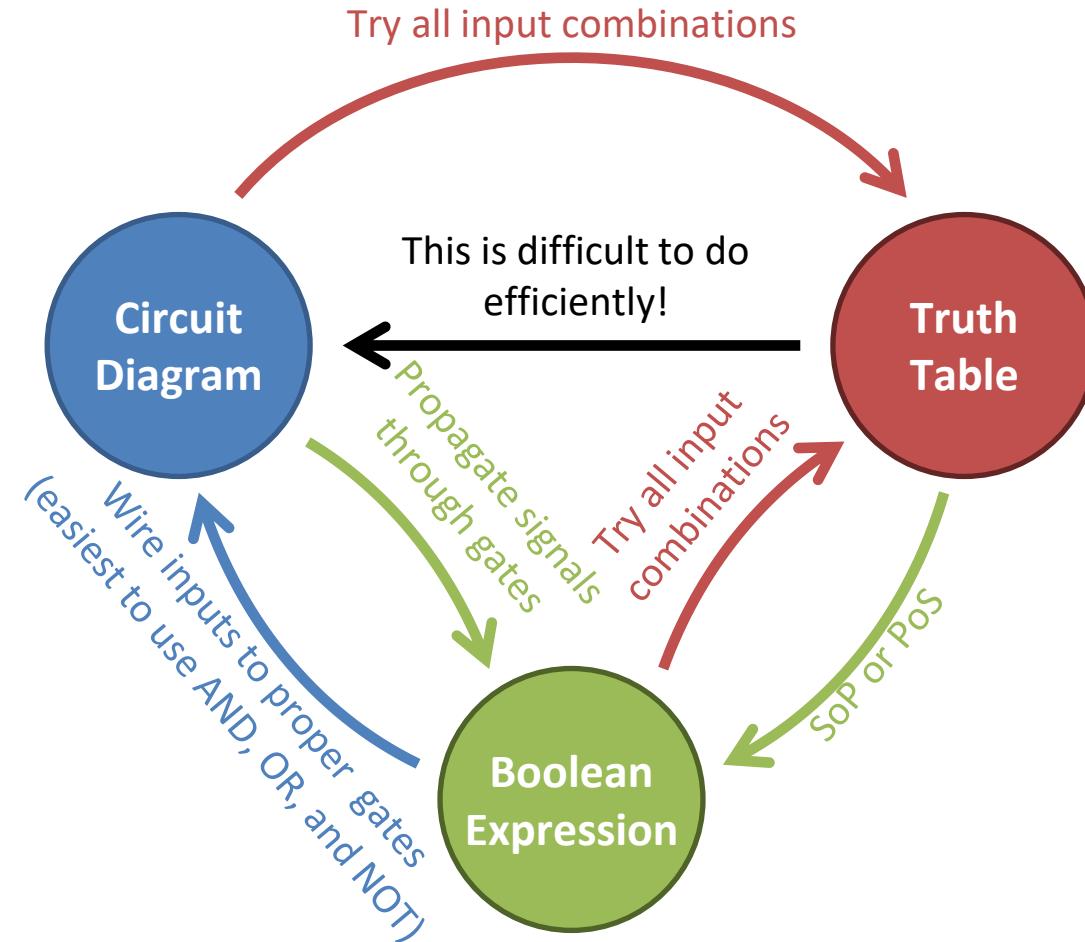
2)



3)



Our three forms



Miso Moment



Lecture Outline

- ❖ Combinational Logic (cont'd from L1)
- ❖ **Thinking About Hardware**
- ❖ Verilog Basics
- ❖ Debugging, Simulations and Waveform Diagrams

Verilog

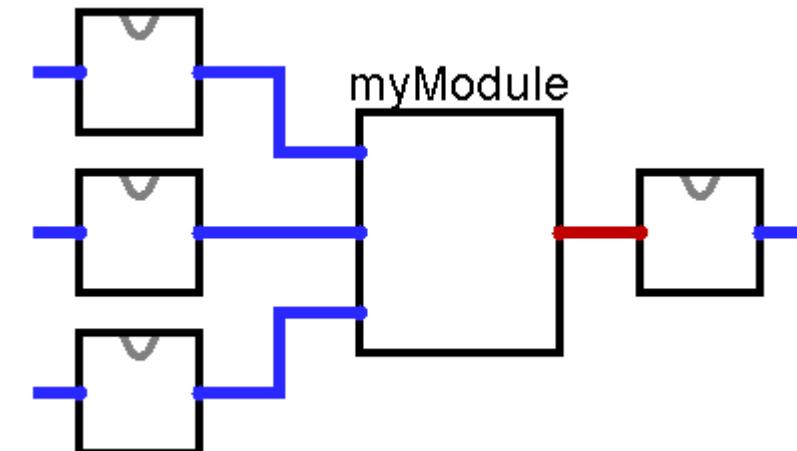
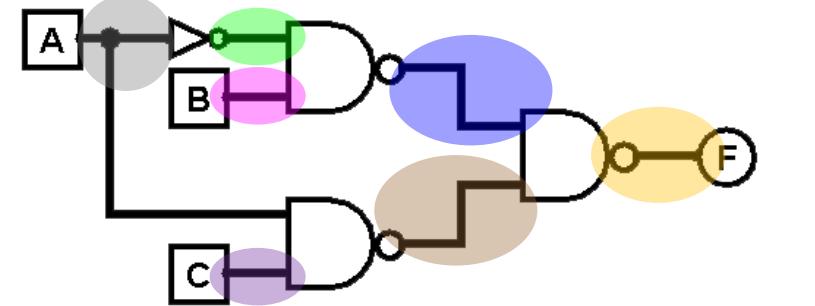
- ❖ A hardware description language (**HDL**)
 - Define circuit schematics using text editors
 - Simulate behavior before (wasting time) implementing
 - Find bugs early
- ❖ **Syntax** is like C/C++/Java, but **meaning** is *very* different
 - Borrows heavily from early concurrency-focused languages like *Modula*
 - VHDL (the other major HDL) is more similar to ADA
- ❖ Modern version is **SystemVerilog**
 - Superset of previous; cleaner and more efficient

Verilog: Hardware Descriptive Language

- ❖ Although it looks like code:
- ❖ Keep the hardware in mind:

```
module myModule (F, A, B, C);
  output logic F;
  input logic A, B, C;
  logic AN, AB, AC;

  nand gate1(AB,AN, B);
  nand gate2(AC, A, C);
  nand gate3( F,AB,AC);
  not  not1(AN, A);
endmodule
```



Verilog Primitives

- ❖ **Nets:** carry bits from one gate to another
 - SystemVerilog type: “**wire**”
 - Think of it *like* an immutable reference to mutable data in C++
- ❖ **Variables:** like a net, but the circuit setting the voltage can change
 - SystemVerilog type: “**reg**” or “**logic**”
 - NB: nothing to do with “registers” from Assembly (ಠ_ಠ) !
 - “Variable” refers to the *source* of the data, not the data itself (“**driving the voltage**”)
 - Think of it *like* a pointer whose location is determined by a switch case in C++
- ❖ ...In this class, we’ll just use “**logic**” for everything

Verilog Primitives

❖ Logic Values

- **0** = zero, low, FALSE
- **1** = one, high, TRUE
- **X** = unknown, uninitialized, contention (conflict)
- **Z** = floating (disconnected), high impedance

Verilog Primitives

- ❖ **Gates:**

Gate	Verilog Syntax
NOT a	$\sim a$
a AND b	$a \& b$
a OR b	$a b$
a NAND b	$\sim(a \& b)$
a NOR b	$\sim(a b)$
a XOR b	$a \wedge b$
a XNOR b	$\sim(a \wedge b)$

- ❖ **Modules:** “classes” in Verilog that define *blocks*
 - **Input:** Signals passed from outside to inside of block
 - **Output:** Signals passed from inside to outside of block

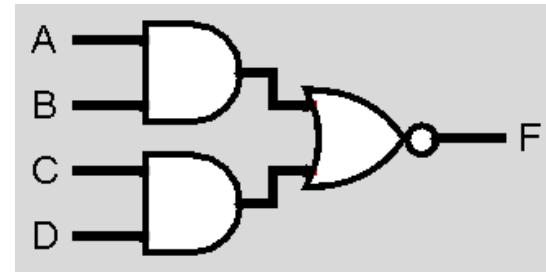
Verilog Execution

- ❖ Physical wires transmit voltages (electrons) near-instantaneously
 - Wires by themselves have no notion of sequential execution
- ❖ Gates and modules are **constantly** performing computations
 - Can be hard to keep track of!
- ❖ In pure hardware, there is **no** notion of **initialization**
 - A wire that is not driven by a voltage will naturally pick up a voltage from the environment
- ❖ In pure hardware, there is **no** notion of **reassignment**
 - Verilog variables represent physical wires. The value carried by the wire can change, but the wire's endpoints do not

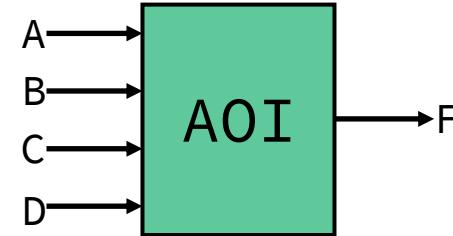
Lecture Outline

- ❖ Combinational Logic (cont'd from L1)
- ❖ Thinking About Hardware
- ❖ **Verilog Basics**
- ❖ Debugging, Simulations and Waveform Diagrams

Structural Verilog



Block Diagram:



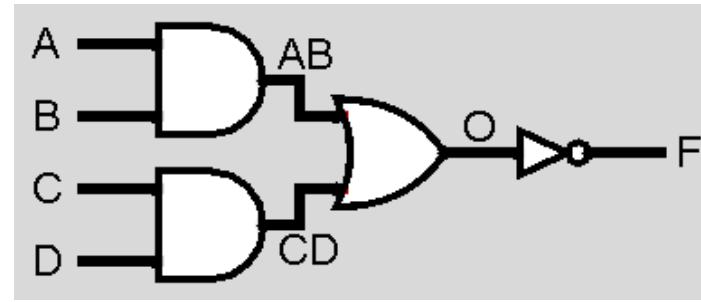
// Verilog code for AND-OR-INVERT gate

```
module AOI (F, A, B, C, D);
  output logic F;
  input logic A, B, C, D;

  assign F = ~((A & B) | (C & D));
endmodule
```

// end of Verilog code

Verilog Wires

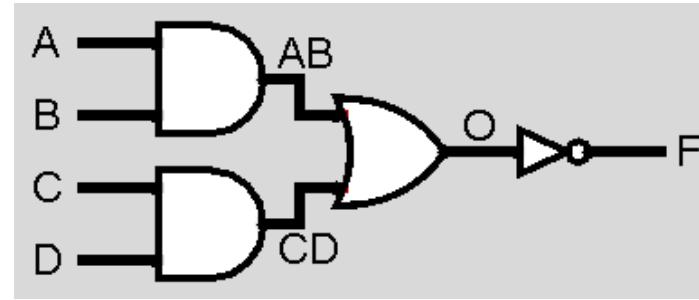


// Verilog code for AND-OR-INVERT gate

```
module AOI (F, A, B, C, D);
    output logic F;
    input logic A, B, C, D;
    logic AB, CD, O; // now necessary

    assign AB = A & B;
    assign CD = C & D;
    assign O = AB | CD;
    assign F = ~O;
endmodule
```

Verilog Gate Level



// Verilog code for AND-OR-INVERT gate

```
module AOI (F, A, B, C, D);
  output logic F;
  input logic A, B, C, D;
  logic AB, CD, O; // now necessary
```

```
  and a1(AB, A, B);
  and a2(CD, C, D);
  or  o1(O, AB, CD);
  not n1(F, O);
```

```
endmodule
```

} was:

```
assign AB = A & B;
assign CD = C & D;
assign O = AB | CD;
assign F = ~O;
```

Verilog Hierarchy

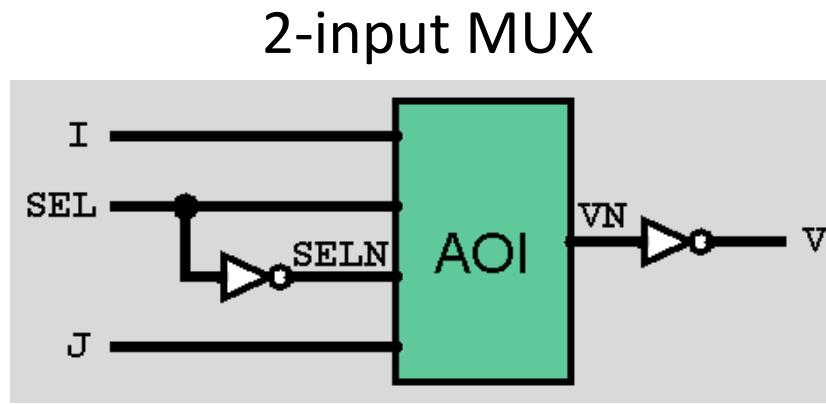
// Verilog code for 2-input multiplexer

```
module AOI (F, A, B, C, D);
  output logic F;
  input  logic A, B, C, D;
  assign F = ~((A & B) | (C & D));
endmodule
```

module MUX2 (V, SEL, I, J); // 2:1 multiplexer

```
  output logic V;
  input  logic SEL, I, J;
  logic  SELN, VN;

  not G1 (SELN, SEL);
  AOI G2 (.F(VN), .A(I), .B(SEL), .C(SELN), .D(J));
  not G3 (V, VN);
endmodule
```



Miso Moment



Lecture Outline

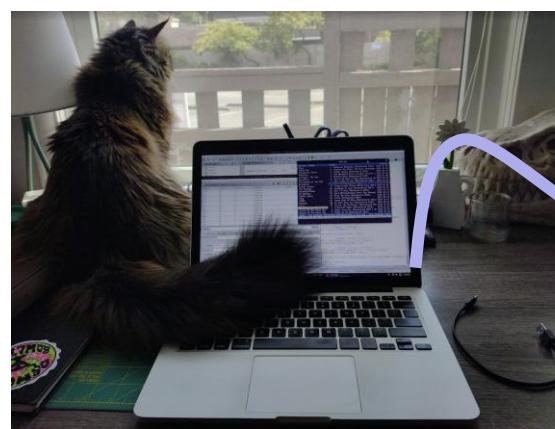
- ❖ Combinational Logic (cont'd from L1)
- ❖ Thinking About Hardware
- ❖ Verilog Basics
- ❖ **Debugging, Simulations and Waveform Diagrams**

Using an FPGA

```
// Verilog code for 2-input
multiplexer
module AOI (F, A, B, C, D);
  output logic F;
  input logic A, B, C, D;
  assign F = ~((A & B) | (C & D));
endmodule

module MUX2 (V, SEL, I, J); // 2:1 multiplexer
  output logic V;
  input logic SEL, I, J;
  logic SELB, VB;
  not G1 (SELB, SEL);
  AOI G2 (VB, I, SEL, SELB, J);
  not G3 (V, VB);
endmodule
```

Verilog

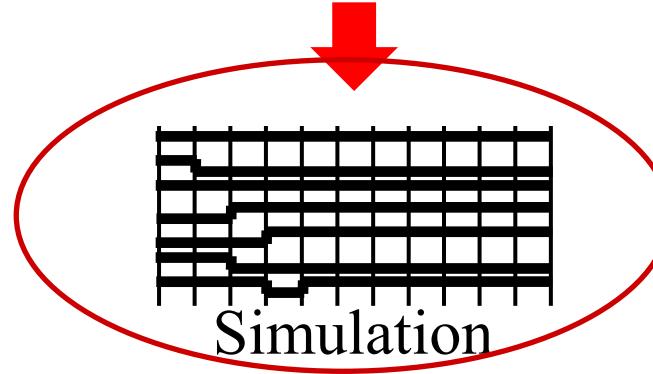


FPGA
CAD
Tools



```
00101010001010010
10010010010011000
10101000101011000
10101001010010101
00010110001001010
10101001111001001
01000010101001010
10010010000101010
10100101010010100
01010110101001010
01010010100101001
```

Bitstream



Simulation

Testbenches

- ❖ **ModelSim** is a digital logic simulator
 - Runs entirely on your computer and simulates the operation of your FPGA
 - Used for debugging the internals of buggy Verilog
 - No such thing as `printf()` in a physical circuit (at least not without microscopic tweezers)
- ❖ **Testbench** – a Verilog module that instantiates the circuit you’re testing *and* provides a `lil` script to generate fake input signals
 - We need to mockup fake signals for *every* input to our module, *and* the timing of how they change.
 - Doesn’t/can’t get synthesized
 - **You need a testbench for every single module you write. Period.**

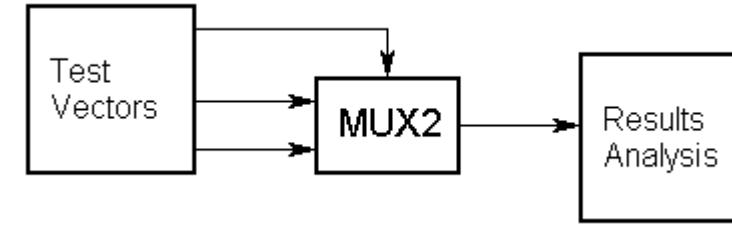
Verilog Testbenches

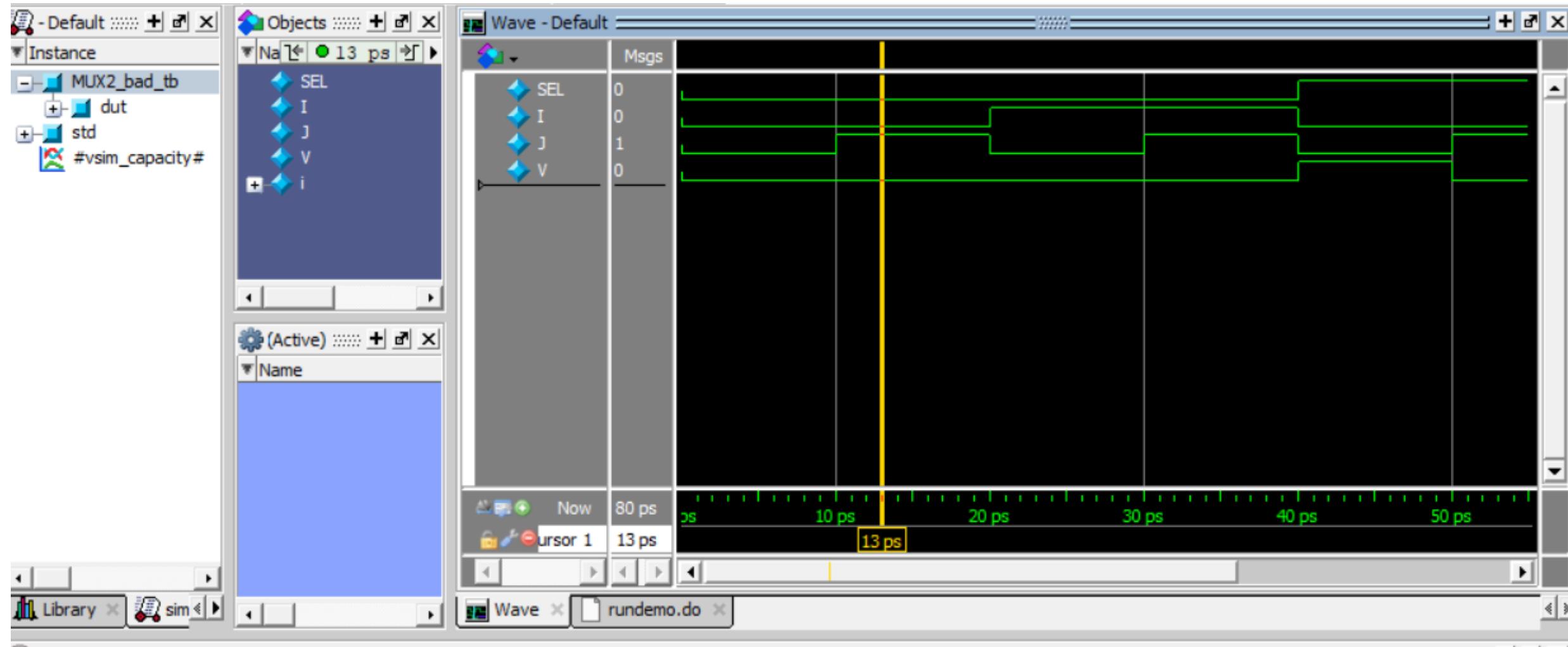
```
module MUX2_tb ();
    logic SEL, I, J; // variables remember values
    logic V;          // acts as net for reading output

    initial // build stimulus (test vectors)
    begin // start of "block" of code
        SEL = 1; I = 0; J = 0; #10; // t=0: S=1, I=0, J=0 -> V=0
        I = 1;           #10; // t=10: S=1, I=1, J=0 -> V=1
        SEL = 0;           #10; // t=20: S=0, I=1, J=0 -> V=0
        J = 1;           #10; // t=30: S=0, I=1, J=1 -> V=1
    end // end of "block" of code
    // Device Under Test
    MUX2 dut (.V, .SEL, .I, .J);

endmodule // MUX2_tb
```

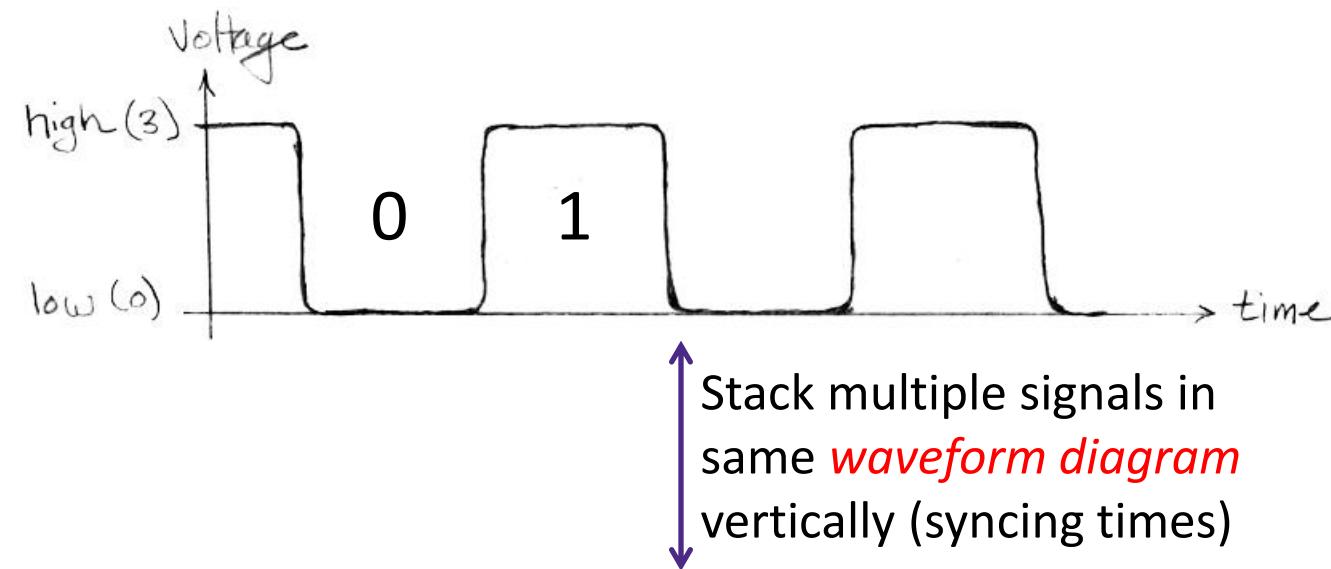
No ports



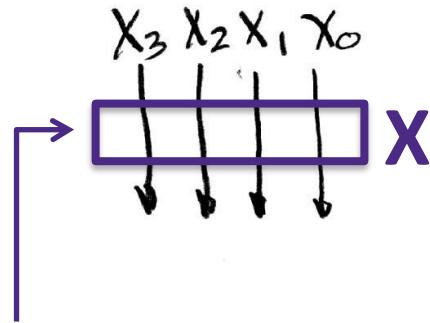


Signals and Waveforms

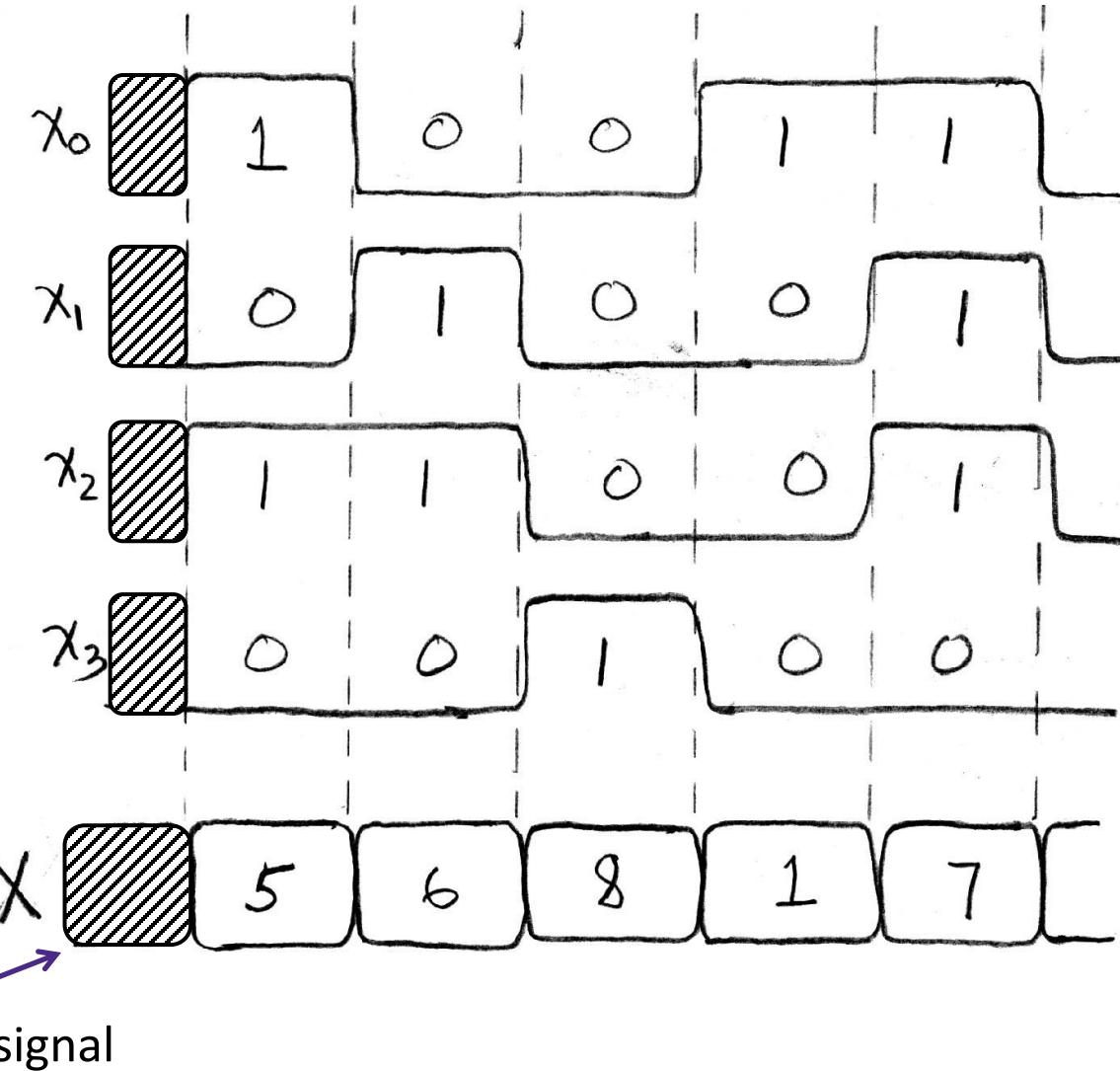
- ❖ **Signals** transmitted over wires continuously
 - Transmission is effectively instantaneous
(a wire can only contain one value at any given time)
 - In digital system, a wire holds either a 0 (low voltage) or 1 (high voltage)



Signal Grouping

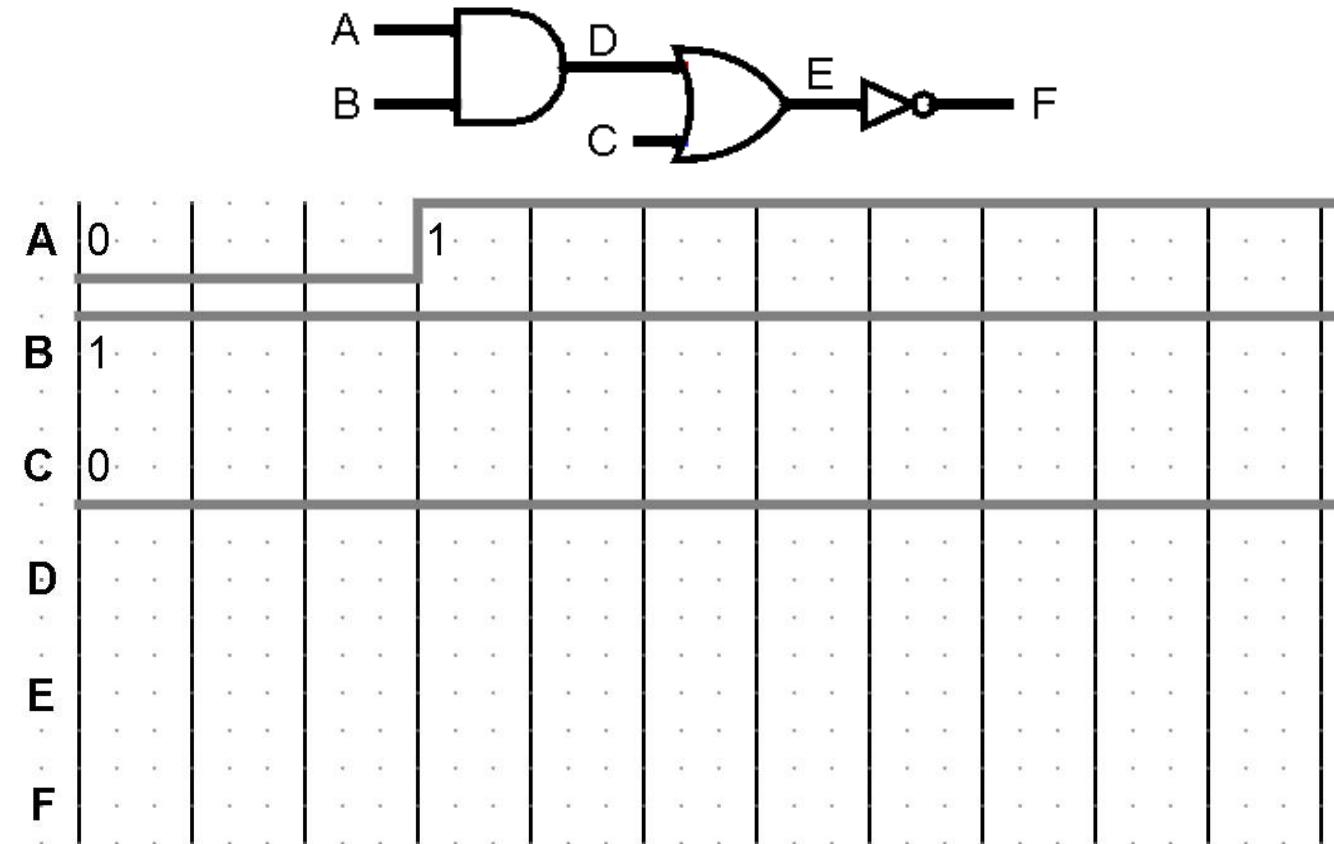


A group of wires when interpreted as a bit field is called a *bus*



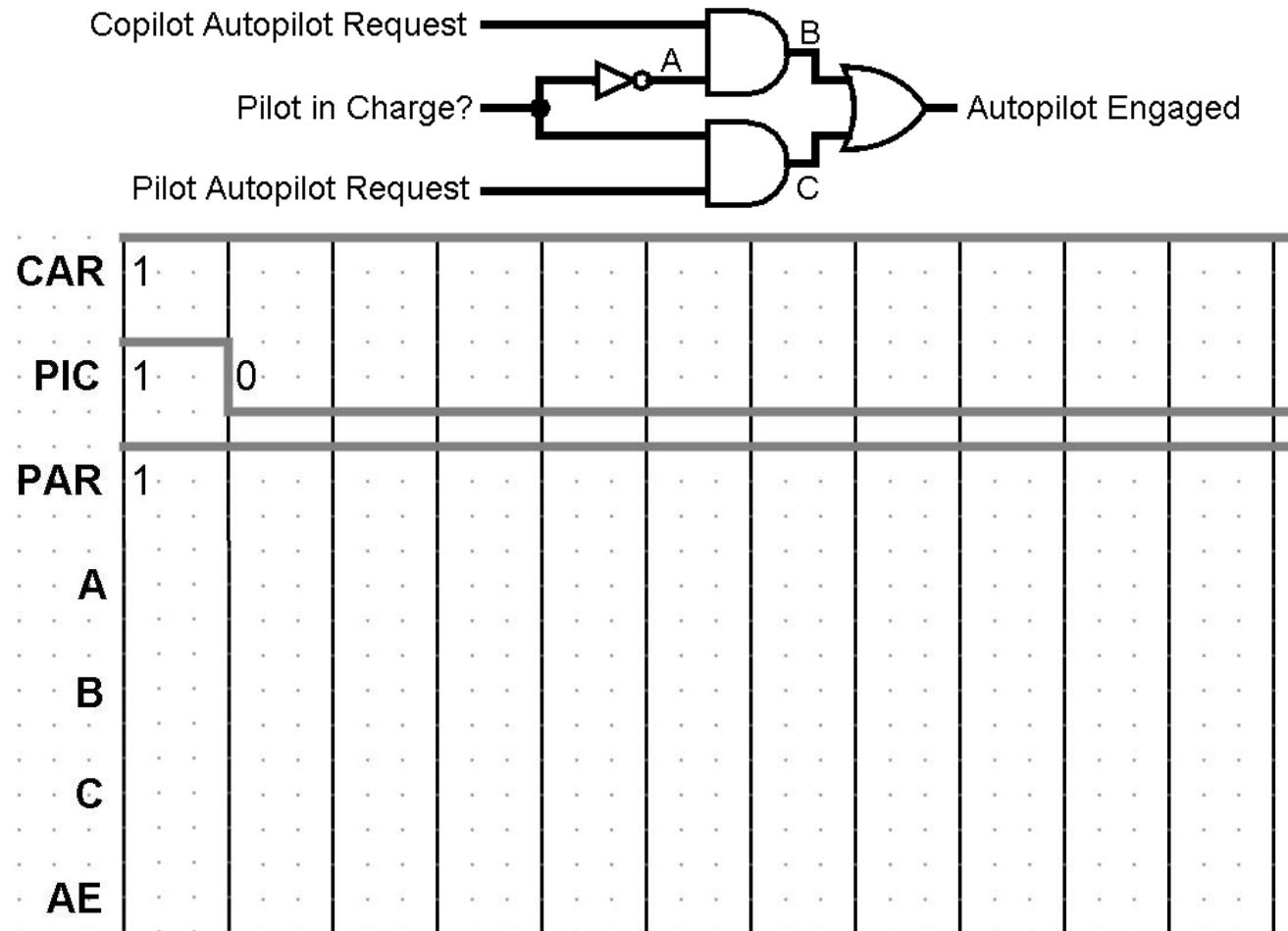
Circuit Timing Behavior

- ❖ **Simple Model:** Gates “react” after fixed delay
- ❖ Example: Assume delay of all gates is 1 ns (= 3 ticks)



Circuit Timing: Hazards/Glitches

- ❖ Circuits can temporarily go to incorrect states!
 - Assume 1 ns delay (3 ticks) for all gates



Summary

- ❖ Verilog is a hardware description language (HDL) used to program your FPGA
 - Programmatic syntax used to describe the connections between gates and registers
- ❖ Waveform diagrams used to track intermediate signals as information propagates through CL
- ❖ Hardware debugging is a critical skill
 - Similar to debugging software, but using different tools