

DESIGN OF DIGITAL CIRCUITS AND SYSTEMS

SystemVerilog Review & Tips

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Lecture Outline (1/4)

- ❖ **Course Introduction**
- ❖ Course Policies
- ❖ Hardware Description Language
- ❖ SystemVerilog Review & Tips

Introductions: Course Staff

- ❖ Your Instructor: just call me Justin
 - CSE Associate Teaching Professor
 - From California (UC Berkeley and the Bay Area)
 - Raising two kids takes up energy and dictates my schedule

- ❖ TAs:



- ❖ Get to know us – we are here to help you succeed!
 - Available in lecture, office hours, and discussion board
 - An invaluable source of information and help



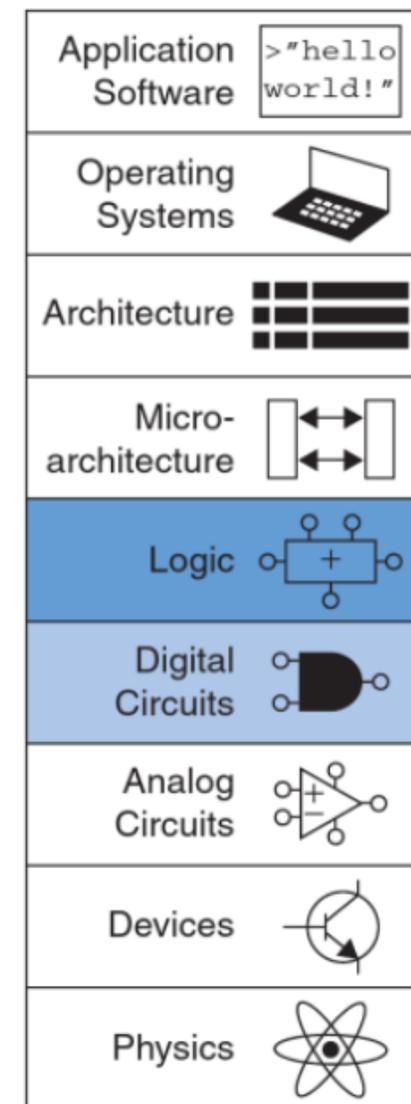
Introductions: Students

- ❖ 95 students registered, split across ECE and CSE
 - Different perspectives; can learn a lot from each other!
 - If you know others interested in adding, use the UW system as space becomes available (no add codes)
- ❖ Expected background
 - **Prereq:** EE 271 or CSE 369 – construction of synchronous digital systems (combinational + sequential logic), timing introduction, SystemVerilog introduction
 - **Prereq:** EE 205 or EE 215 – familiarity with circuits

Course Motivation (1/3)

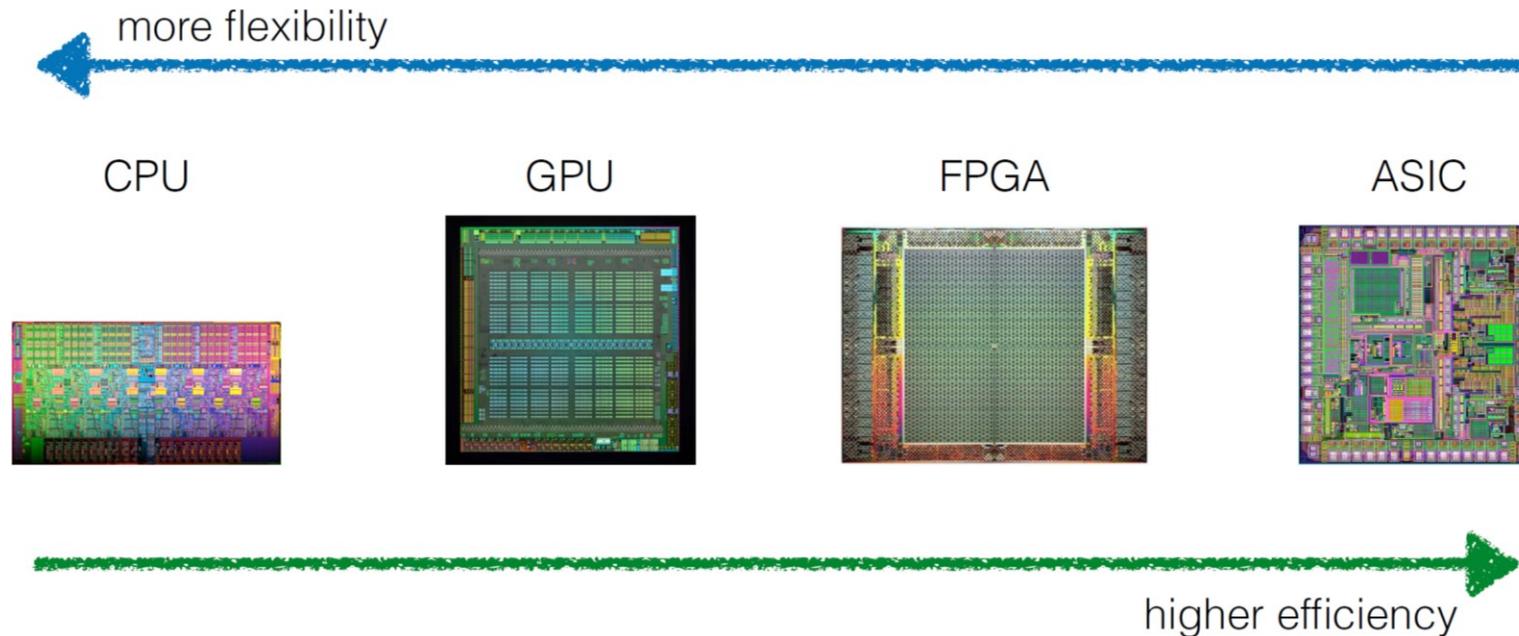
- ❖ More advanced digital logic design
 - Higher-level circuit design and analysis techniques
 - Interfacing with various devices/peripherals
 - How to implement algorithms *in hardware*
 - Practical timing analysis
 - “Verilog finishing school”

Harris and Harris. “Digital Design and Computer Architecture” 2nd ed.



Course Motivation (2/3)

- ❖ Heavy computational loads have put us in a golden age of **hardware specialization**
 - Tailor your chip architecture to the characteristics of a **stable** workload
 - More and more companies are building specialized chips



Course Motivation (3/3)

- ❖ Example: *FPGAs could replace GPUs in many deep learning applications*
 - <https://bdtechtalks.com/2020/11/09/fpga-vs-gpu-deep-learning/>
 - FPGAs have advantages in terms of power consumption, environmental robustness, and lifespan
 - “FPGA is a type of processor that can be customized after manufacturing, which makes it more efficient than generic processors.”
 - “But the problem with FPGAs is that they are very hard to program.” 😞

Technical Communication

- ❖ Many of you are graduating soon!
 - Going off to do and build wonderful things
 - Try as you might, you can't really avoid society and other people
- ❖ It's no longer good enough to just get something working – you have to be able to explain it
 - Working in a group/team
 - Someone taking over as maintainer
 - Convince a client or venture capitalist or funding agency or students
- ❖ The lab reports and demos might seem tedious at first, but are valuable practice!

Lecture Outline (2/4)

- ❖ Course Introduction
- ❖ **Course Policies**
 - <https://courses.cs.washington.edu/courses/cse371/26sp/syllabus.html>
- ❖ Hardware Description Language
- ❖ SystemVerilog Review & Tips

Course Meetings

❖ Lectures

- Lecture slides found on the website schedule
- Group work most lectures – with TAs available to help!
- “Worksheets” available for note-taking and group work
 - Feel free to decline if you don’t want one – saves trees 🌲

❖ Office Hours and Lab Demos

- Live demo using remote FPGA lab (LabsLand) and answering TA questions
 - Will support both in-person (ECE 347) and remote demos (Zoom)
 - When a TA is available, lab demo times are also office hours
- Office hours will use a Google Sheet queuing system (Tools → Office Hours Queue)

“Straight-scale” Grading Scheme

- ❖ Labs (50%) – Partner optional
 - 5 regular labs and 1 “final project”
 - Combination of (1) lab reports, (2) code submission, and (3) lab demos
- ❖ Homework (20%) – Groups of ≤ 4
 - Interspersed between the labs
 - Combination of theoretical and coding questions (simulation, no hardware)
- ❖ Quizzes (30%) – Individual
 - 5 roughly equally weighted quizzes, in person at end of Thursday lectures
 - Uploaded and graded in Gradescope

Academic Integrity and Student Conduct

- ❖ We trust you implicitly and will follow up if that trust is violated
 - Don't attempt to gain credit (for yourself or others) for something you didn't do
 - You are not allowed to *generate* or *rewrite* any code using [generative AI](#)
- ❖ This does **not** mean suffer in silence – learn from the course staff and peers, *but* don't share or copy work that is supposed to be yours
- ❖ If you find yourself in a situation where you are tempted to perform academic misconduct, please reach out to the instructor to explain your situation instead
 - See the [Extenuating Circumstances](#) section of the syllabus

Collaboration Notes

- ❖ Make sure to add your groupmate(s) to your submissions in Gradescope
- ❖ Working in a group isn't a guarantee for success
 - Don't just split up the work: work simultaneously or at least communicate frequently (more brains are better than one!)
- ❖ We will provide GitLab repos for your convenience
- ❖ See the [Collaboration page](#) on the website (Course Info → Collaboration) for more info and tips

Deadlines

- ❖ Gradescope lateness counted in *days* beyond **11:59 PM deadlines**
 - You are given **6 late day tokens**; 10% penalty for each late day after that
 - **Homework** submissions close 1 day after the deadline
 - Solution outlines released shortly afterward for quiz studying
 - **Lab reports & code** submissions are due **Fridays** and close 2 days later (Sundays)
- ❖ 15-min **lab demos** are due **within a week of the report deadline**
 - *i.e.*, by the end of the last office hour on the *next* Friday
 - Usually in assigned Monday/Tuesday demo slot (sign-up process)

Please talk to a staff member (preferably Justin) about extenuating circumstances *as soon as they come up*

To-do List

- ❖ Website: <https://courses.cs.washington.edu/courses/cse371/26sp/>
 - Read over [course policies](#) and [Assignment Requirements page](#)
 - Fill out pre-course survey (due 4/3)
 - Homework 1 (4/6) & Lab 1 (4/10) posted today
- ❖ Discussion: <https://edstem.org/us/courses/96855/>
- ❖ Course setup:
 - Install ModelSim on your machine, if desired (CAD → [Quartus Install Files](#))
 - Register on LabsLand (CAD → [LabsLand Setup](#))
 - Look for partner(s) for homework and lab
 - Figure this out *before* signing up for a lab demo slot

Lecture Outline (3/4)

- ❖ Course Introduction
- ❖ Course Policies
- ❖ **Hardware Description Language**
- ❖ SystemVerilog Review & Tips

Hardware Description Language (HDL)

- ❖ HDL is a specialized computer language used to describe the structure and behavior of digital logic circuits
 - Useful for rapid prototyping of digital hardware
- ❖ Comparison with programming language (*e.g.*, C)
 - Describes *hardware* instead of software
 - Intrinsically parallel instead of sequential
 - Includes explicit notion of time instead of just instructions
 - Compiled to target FPGAs and ASICs via netlists (more specific) instead of compiled to target CPUs via machine code (more general)

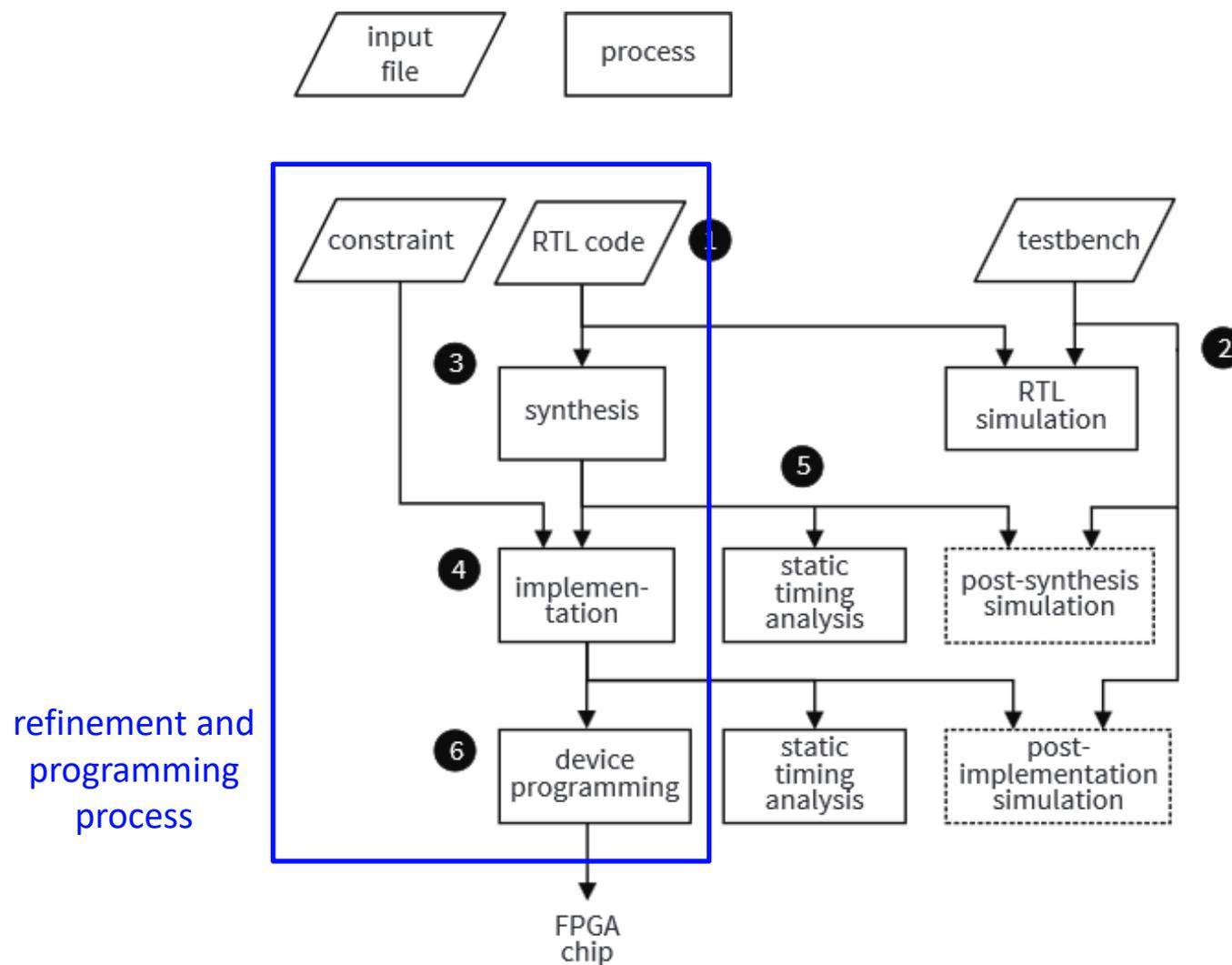
Electronic Design Automation (EDA)

- ❖ EDA is a type of computer-aided design (CAD) specific to designing electronic systems
 - EDA tools allow for *simulation* and *synthesis*
- ❖ **Synthesis:** Compile HDL code into a netlist (*i.e.*, list of electronic components and wires that connect them)
- ❖ **Simulation:** Apply inputs to the simulated circuit so we can check output for correctness without involving or endangering hardware
 - Tracks the state of each structural element, handles the interactions between concurrent elements, and models the passage of time

Synchronous Digital System Design Flow Using Gates

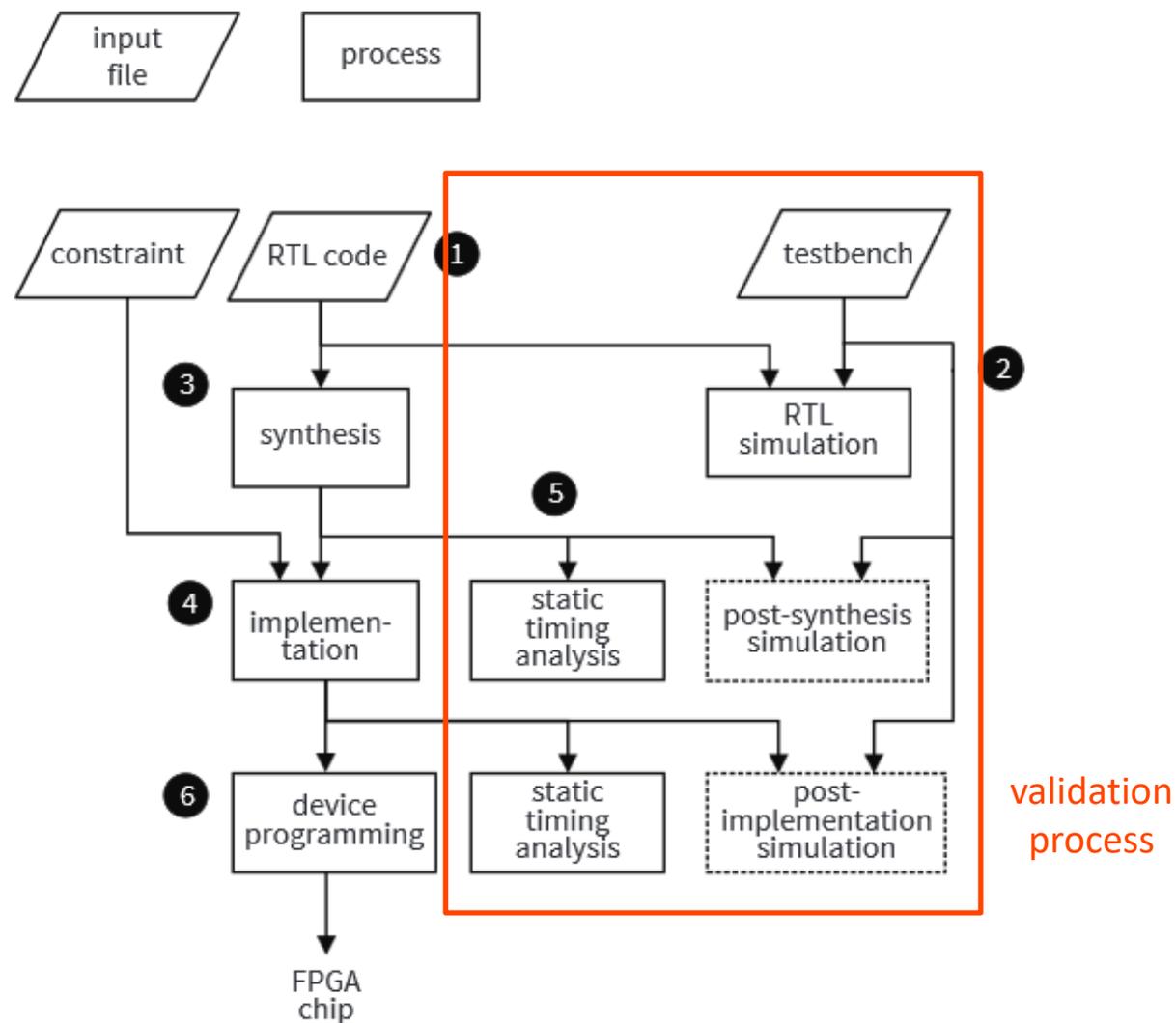
- 1) Write an overall specification
 - If necessary, decompose the design further and write a specification for each part
- 2) From the specification, draw a state diagram
 - Minimize the number of states
- 3) Assign a binary encoding to represent each state
- 4) Derive the next state and output logic
 - Optimize the logic to minimize the number of gates needed
- 5) Choose a suitable placement for the gates to optimize integrated circuit reuse and distance on printed circuit board
- 6) Design the routing between the integrated circuits

FPGA-Based Design Flow: Programming



Source: Figure 2.3 from "FPGA Prototyping" by P. Chu

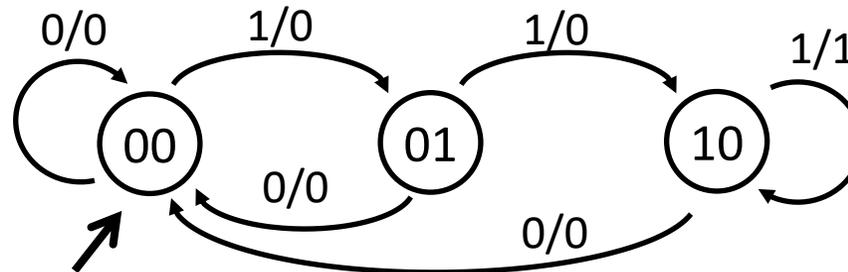
FPGA-Based Design Flow: Validation



Source: Figure 2.3 from "FPGA Prototyping" by P. Chu

Quartus/ModelSim/LabsLand Demo

- ❖ Using threeOnes FSM from 271/369



- Quartus/LabsLand and ModelSim have separate compilations
 - Clock divider is NOT FOR SIMULATION
 - Simulations can be run from a .do file or from individual ModelSim commands
 - Submodule signals can be added to waveforms!
 - Logical correctness can still lead to unexpected/unintuitive behaviors...
- ❖ For more, see CAD → [ModelSim Usage Guide](#) on website

TECHNOLOGY

BREAK

Lecture Outline (4/4)

- ❖ Course Introduction
- ❖ Course Policies
- ❖ Hardware Description Language
- ❖ **SystemVerilog Review & Tips**
 - One of two leading HDLs along with VHDL-2019

HDL Organization

- ❖ Most problems are best solved with multiple pieces – how to best organize your system and code?
- ❖ Everything is computed in parallel
 - We use routing elements to select between (or ignore) multiple outcomes/parts
 - This is why we use block diagrams and waveforms
- ❖ A module is not a *function*, it is closest to a *class*
 - Something that you *instantiate*, not something that you *call* – hardware cannot appear and disappear spontaneously
 - Should treat modules as *resource managers* rather than temporary helpers
 - This can include having internal modules

HDL Implementation & Testing

- 1) Design your overall system – block diagram or similar
- 2) Create individual submodules
- 3) Create submodules test benches – test as usual
 - CL – run through all input combinations
 - SL – take every transition that you care about
- 4) Create top-level module
 - Create instance of each submodule
 - Create wires/nets to connect signals between submodules, inputs, and outputs
- 5) Create top-level test bench
 - Goal is to check the interconnections between submodules – does input/state change in one submodule trigger the expected change in other submodules?

Justin's SystemVerilog Tips

- ❖ Always plan out your design before you ever touch your keyboard
 - Block diagram naturally maps into module port lists
- ❖ Always think of the underlying hardware when you write your code
 - 1) **Structural:** Lower-level modeling of gate-level connections
 - 2) **Behavioral:** Higher-level modeling of logical behaviors
- ❖ Most modules are organized similarly, so develop and use coding patterns
- ❖ Comment your code and test thoroughly as you go
- ❖ Pay attention to compiler warnings and errors

SystemVerilog Review Question

❖ Will the following compile? Is there a difference?

- `logic v, w, x, y, z;`
`and g1 (x, v, w);`
`xor g2 (y, v, w);`
`nor g3 (z, x, y);`
- `logic v, w, x, y, z;`
`nor g3 (z, x, y);`
`and g1 (x, v, w);`
`xor g2 (y, v, w);`
- `and g1 (x, v, w);`
`logic v, w, x, y, z;`
`xor g2 (y, v, w);`
`nor g3 (z, x, y);`

Types of Logic

❖ Combinational logic:

- Usually in `assign` or `always_comb` blocks and use blocking assignment (`=`)
- *Implicit* sensitivity list – updates anytime any input changes
- Testbenches for CL should just cycle through all input combinations at fixed time intervals (*e.g.*, `#20;`)

❖ Sequential logic:

- Usually in `always_ff` blocks and use non-blocking assignment (`<=`)
- *Explicit* sensitivity list – usually `@(posedge clk)`
- Testbenches for SL should take every transition that you care about, achieved by changing inputs every clock cycle

Blocking vs. Nonblocking Assignment

- ❖ **Blocking** statement (=): the effects of these statements are “evaluated” sequentially
- ❖ **Nonblocking** statement (<=): the effects of these statements “evaluated” in parallel
- ❖ Exercise: draw out implied hardware

```
always_ff @ (posedge clk)
begin
    b = a;
    c = b;
end
```

```
always_ff @ (posedge clk)
begin
    b <= a;
    c <= b;
end
```

Data Types

- ❖ We generally default to using `logic` for all signals, which is a 4-state data type that can be used as either a *net* or *variable*
 - Possible states (`logic` defaults to `X`):
 - `0` = zero, low, FALSE
 - `1` = one, high, TRUE
 - `X` = unknown, uninitialized, contention (conflict)
 - `Z` = floating (disconnected), high impedance
 - **Nets** (e.g., `wire`) transmit values and **variables** (e.g., `reg`) store data

Arrays

- ❖ Multiple signals can be organized under the same name as a bus or array
 - A *bus*, also known as a *vector* or *packed array*, is a collection of a single data type
 - e.g., `logic [31:0] divided_clocks;`
 - “Regular” array syntax is known as an *unpacked array*
 - e.g., `logic an_unpacked_array[4:0];`
 - *Multidimensional arrays* can be combinations of packed and unpacked dimensions
 - e.g., `logic [3:0] two_D_array[4:0];`
 - Dimensions accessed left to right, starting with unpacked
 - Numbering matters (i.e., $[n-1:0] \neq [0:n-1]$)

Integers in Computing

❖ Unsigned integers follow the standard base 2 system

- $b_7b_6b_5b_4b_3b_2b_1b_0 = b_72^7 + b_62^6 + \dots + b_12^1 + b_02^0$
- In n bits, represent integers 0 to $2^n - 1$

❖ Signed integers use *Two's Complement representation*

- b_{w-1} has weight -2^{w-1} , other bits have usual weights $+2^i$



- In n bits, represent integers -2^{n-1} to $2^{n-1} - 1$
 - Most significant bit acts as a *sign bit* (0 = pos, 1 = neg)
 - Negation procedure: take the bitwise complement and add one ($\sim x + 1 == -x$)
- ## ❖ ⚠ The choice affects the behavior of operations such as bit extension, shifting, and comparisons

Constants

- ❖ Multi-bit constants: `<n> ' <s>#...#`
 - `<n>` is width (*unsized* by default)
 - `<s>` is signed designation (omit or 's')
 - `` is radix/base specifier (decimal by default)
 - All letters are case-*insensitive*, `_` can be used to add spaces

Literal	Width	Base	Bits
3'd6			
6'o42			
8'hAB			

Literal	Width	Base	Bits
42			
'b101			
-3'd5			

- ❖ Compiler will usually warn you if there is a size mismatch
 - Can “cast” using `#' (<sig>)` syntax

Basic Operators

❖ Possibly new:

- $371 \% 271 \rightarrow 100$
- $2^{**}3 \rightarrow 8$

Type	Symbol	Description
Arithmetic	+	addition
	-	subtraction
	*	multiplication
	/	division
	%	modulus
	**	exponentiation
Shift	>>	logical right shift
	<<	logical left shift
	>>>	arithmetic right shift
	<<<	logical left shift
Relational	>	greater than
	<	less than
	>=	greater than or equal to
	<=	less than or equal to
Equality	==	equality
	!=	inequality
	===	case equality
	!==	case inequality
Bitwise	~	bitwise negation
	&	bitwise and
		bitwise or
	^	bitwise xor
Logical	!	logical negation
	&&	logical and
		logical or

Ternary Operator

❖ Conditional assignment

- `<select> ? <then_expr> : <else_expr>`
 - If `<select>` is true, then evaluates to `<then_expr>`, otherwise evaluates to `<else_expr>`
- What does this look like in hardware?

❖ **Example:** tristate buffer

- `enable ? in : 'bZ`
 - When enabled, pass the input to the output, otherwise be high impedance

Bit Manipulation

- ❖ Concatenation: $\{sig, \dots, sig\}$
 - Ordering matters; result will have combined widths of all signals
- ❖ Replication operator: $\{n\{m\}\}$
 - repeats value m , n times
- ❖ Exercise: Arithmetic right shift preserves the sign bit
 - **8-bit examples:**
 - $0b\underline{1}000\ 0000 \gg 3 \rightarrow 0b\ ___1\ 0000$ (logical)
 - $0b\underline{1}000\ 0000 \ggg 3 \rightarrow 0b\ ___1\ 0000$ (arithmetic)
 - $0b\underline{0}100\ 0000 \ggg 3 \rightarrow 0b\ ___0\ 1000$ (arithmetic)

```
logic [7:0] x = <some 8-bit constant>;  
// replicate the behavior of y = x >>> 3  
assign y =
```

“Looping”

- ❖ Code is compiled to hardware, so no execution
 - “Loops” must be *statically unrolled* into multiple statements
 - Loops are just for convenience in code writing
- ❖ `repeat (#) <statement(s)>`
 - Makes # copies of statement(s) – don’t forget `begin` and `end` if multiple
- ❖ `for (i=0; i<#; ++i) <statement(s)>`
 - Makes # copies of statement(s) that vary based on `i`
- ❖ `generate` (see reference docs)
 - More “powerful” for-loop typically used for:
 - 1) Module instantiation
 - 2) Changing the structure of parameterized modules
 - 3) Functional and formal verification using assertions

Modules

- ❖ “Black boxes” that we define and instantiate that form the basic building blocks of our design hierarchy
 - **Ports** form the connections between a module and its environment
 - Ports have directionality (**input**, **output**, **inout**), which can be declared within the module or within the port list

```
module tristate(out, in, enable);  
    input logic in, enable;  
    output tri out;  
  
    assign out = enable ? in : 'Z;  
endmodule
```

```
module tristate(output tri out,  
                input logic in,  
                input logic enable);  
    assign out = enable ? in : 'Z;  
endmodule
```

Module Instantiation

- ❖ Name an instance and define its port connections

- `<type> <name> (<port connections>);`

- ❖ Assume we have:

```
logic in, enable; tri out;
```

- 1) Positional connections:

```
// must follow defined port ordering  
// signal names can be anything  
tristate my_tri(out, in, enable);
```

- 2) Named/explicit connections:

```
// any ordering & names allowed  
tristate my_tri(.out(out), .in(in), .enable(enable));
```

- 3) *.name* implicit connection:

```
// signal and port names must match exactly  
tristate my_tri(.out, .in, .enable);
```

Parameters

- ❖ A **parameter** is a named constant
 - Typically used for widths and timing

```
parameter N = 8;           // bus width
parameter period = 100;   // timing constant
```

- ❖ A parameterized module:
 - `module <name> #(<parameter list>) (<port list>);`
 - Parameters should be given default values
 - *e.g.*, `#(parameter N = 8)`
- ❖ Extra exercises:
 - Define a parameterized tristate (tristate buffer)
 - Define a parameterized multibitAND

Lab 1 Notes

- ❖ Read the spec carefully!
 - For scenarios that are not described, it's up for you to define; describe and defend your decisions in your report
 - Also read [HW/Lab Requirements page](#) and [Example Lab Report](#)
- ❖ Plan and design *before* you start coding!
- ❖ Test your code in small pieces *as you go*
 - Lab report due before your demo
 - Short sessions (3 min) on LabsLand

