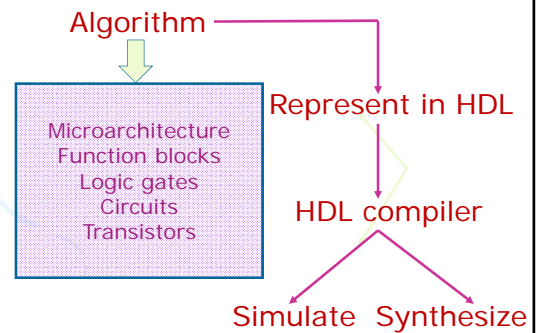


Introduction to Verilog HDL

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Hardware design



HDLs

- Hardware description languages
 - Offers an abstract language for representing computation that needs to be realized in hardware
 - Verilog
 - C-like syntax
 - We will use this
 - VHDL
 - VHSIC HDL
 - Very high speed integrated circuit HDL
 - Ada-like syntax
 - BSV
 - Bluespec System Verilog

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What is Verilog?

- A Hardware description language
 - Describes digital systems in a convenient way
 - Faster than gate-level simulation
 - Still models the hardware concurrency in detail
 - Possible to carry out both behavioral/functional and structural simulations
 - We will do only behavioral simulation
 - C-like syntax
 - Remember: you are designing hardware; a new variable means you just added a new signal to your circuit
 - Two major types of variables: wire and reg
 - Wire used for direct communication of signals
 - Reg used to store value

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Verilog program

- A Verilog program represents the target hardware
 - Usually a collection of modules
 - A module is similar to a C function except that it has no return type and there can be **multiple instances** of a module
 - All inputs and outputs are module arguments
 - The modules are arranged in a hierarchy to represent the target hardware
 - Example: consider designing a four-bit adder
 - A full-adder module
 - A four-bit adder module that **instantiates** four full-adder modules and connects them properly
 - A top-level module representing the environment of the four-bit adder
 - The top-level module instantiates the target hardware (e.g., four-bit adder module), generates the inputs, and collects the outputs

Example: Full adder

/* this module receives as input three bits and outputs the sum bit and the carry bit */

```
module fulladder(a,b,c,sum,carry);
input a,b,c;
output sum,carry;
wire sum,carry;

assign sum=a^b^c; // sum bit
assign carry=((a&b) | (b&c) | (a&c)); //carry bit

endmodule
```

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Example: Full adder

```
module fulladder_top;
reg a, b, c;
wire sum, carry;

fulladder uut(a,b,c,sum,carry);
always @(sum or carry)
begin
$display("time=%d: %b + %b + %b = %b, carry = %b", $time, a, b, c, sum, carry);
end

initial
begin
#40
$finish;
end
endmodule
```

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Full adder output

```
time=0: 0 + 0 + 0 = 0, carry = 0
time=5: 0 + 1 + 0 = 1, carry = 0
time=10: 1 + 0 + 1 = 0, carry = 1
time=15: 1 + 1 + 1 = 1, carry = 1
```

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Verilog syntax

- A concurrent language

```
assign a = ~b;
assign c = d;
```

Both take place concurrently
- Combinational logic
 - Use *assign* statements
 - AND, OR, NOT, XOR, ... (&, |, ~, ^, ...)
 - `assign x = (a & ~b) | (~a & b);`
 - `assign y = a ^ b;`
 - LHS signal must be declared as a wire (cannot hold value; values can be held only in sequential logic)
 - You can use == and != (but remember this will create a comparator in hardware)
 - `assign x = (opcode==6'h4);`

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Combinational logic

- Four data values
 - 0, 1, x, z
 - Possible to specify data representation format: most commonly used are binary and hex
 - `6'b100101, 6'h25`
- Do not use +, -, <<, >> carelessly
 - These are costly hardware
- Never use *, /
 - If you must multiply or divide, implement one (e.g. Booth's algorithm)

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Combinational logic

- 2-input AND

```
module and (x, y, out);
input x;
input y;
output out; wire out; /* Note: type specification of output */
assign out = x & y;
endmodule
```
- 2-input NAND

```
module nand (x, y, out);
input x;
input y;
output out; wire out;
assign out = ~(x & y);
endmodule
```

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Combinational logic

- A more realistic simulation of CMOS AND (structural simulation)

```
module and (x, y, out);
input x;
input y;
output out; wire out;
wire a;
nand my_nand (.x(x), .y(y), .out(a));
assign out = ~a;
endmodule
```

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Combinational logic

- 3-input OR

```
module OR3 (a, b, c, z);
input a;
input b;
input c;
output z; wire z;
    assign z = a | b | c;
endmodule
```
- 3-input NOR

```
module NOR3 (a, b, c, z);
input a; input b; input c; output z; wire z; wire w;
    OR3 level_one_or (.a(a), .b(b), .c(c), .z(w));
    assign z = ~w;
endmodule
```

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Busses

- Handles multiple bits in parallel
 - 8 2-input ANDs (this is not 8-input AND)
- ```
module AND8 (x, y, z);
input [7:0] x;
input [7:0] y;
output [7:0] z; wire [7:0] z;
 assign z = x & y;
endmodule
```
- In programming language terms it is an array of signals

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## Sequential logic

- How does a D flip-flop work?

```
module DFF (d, q, clk);
input d;
input clk;
output q;
reg q;
 always @(posedge clk) begin
 q <= #2 d;
 end
endmodule
```
- Did we make any assumption regarding clock period here?
- Can put multiple *non-blocking* assignments in the same always block

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## Sequential logic

- Always use non-blocking assignment <=
- Always use a delay before RHS (avoid race-through and anyway that's how things work)
- LHS must be a reg
- Hoist as much combinational logic as possible outside always blocks
- Can use negedge also if that is the intended behavior
- What's wrong with the following?

```
#2 q <= d;
```
- Combinational always blocks are also possible

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## Control flow

- What is control flow in hardware?
  - Simple example is multiplexer (if-else)
  - Use if-else inside always blocks
  - Example: DFF with asynchronous reset

```
module DFF_r (d, q, r, clk);
 input d; input r; input clk;
 output q;
 reg q;
 always @(posedge clk) begin
 if (r==1'b1) begin
 q <= #2 1'b0;
 end
 else begin
 q <= #2 d;
 end
 end
end
endmodule
```

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## Example: JK flop

```
/* MODULE TO SIMULATE A JK FLIP-FLOP WITH
DIRECT RESET */
```

```
`define TICK #2 //Flip-flop time delay 2 units
```

```
module jkflop(j,k,clk,rst,q);
```

```
 input j,k,clk,rst;
```

```
 output q;
```

```
 reg q;
```

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## Example: JK flop

```
// module jkflop continues
always @(posedge clk)begin
 if(j==1 & k==1)begin
 q <= `TICK ~q; //Toggles
 end
 else if(j==1 & k==0)begin
 q <= `TICK 1; //Set
 end
 else if(j==0 & k==1)begin
 q <= `TICK 0; //Cleared
 end
end

always @(posedge rst)begin
 q <= 0; //The reset normally has negligible delay and hence ignored.
end
endmodule
```

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## Example: JK flop

```
/* ENVIRONMENT FOR JK FLIP-FLOP */
module jkflop_top;
 reg j,k,clk,rst;
 wire q;
 jkflop uut(j,k,clk,rst,q); // Unit under test
 //Always at rising edge of clock display the status of flip-flop
 always @(posedge clk)begin
 $display("<d>: j=%b,k=%b,clk=%b,rst=%b,q=%b", $time,j,k,clk,rst,q);
 end
 //Module to generate clock with period 10 time units
 initial begin
 forever begin
 clk=0;
 #5
 clk=1;
 #5
 clk=0;
 end
 end
end
```

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## Example: JK flop

```
//Sample test values to run simulation (module jkflop_top continues)
initial begin
 j=0; k=0; rst=1;
 #4
 j=1; k=1; rst=0;
 #50
 j=0; k=1; rst=0;
 #20
 j=1; k=1; rst=0;
end
//Carry out simulation for 100 units of time
initial begin
 #100
 $finish;
end
endmodule
```

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## JK flop output

```
< 5>: j=1,k=1,clk=1,rst=0,q=0
< 15>: j=1,k=1,clk=1,rst=0,q=1
< 25>: j=1,k=1,clk=1,rst=0,q=0
< 35>: j=1,k=1,clk=1,rst=0,q=1
< 45>: j=1,k=1,clk=1,rst=0,q=0
< 55>: j=0,k=1,clk=1,rst=0,q=1
< 65>: j=0,k=1,clk=1,rst=0,q=0
< 75>: j=1,k=1,clk=1,rst=0,q=0
< 85>: j=1,k=1,clk=1,rst=0,q=1
< 95>: j=1,k=1,clk=1,rst=0,q=0
```

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## Combinational always

- All read signals must appear in sensitivity list
  - Same set of LHS on all paths
  - All cases must be covered (otherwise state-holding)
- ```
always @(sel or a) begin
  if (sel==2'b0) begin
    z = 1'b0;
  end
  else if (sel==2'b1) begin
    z = a;
  end
end
```

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Blocking assignments

- Use of blocking assignment "=" inside always block
 - Executes before the next assignment can begin
 - Unlike non-blocking assignment "<=" where all RHS signals are evaluated simultaneously
 - Example:
- ```
always begin
 C = 1;
 A <= C;
 B = C;
end
```

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## Case statement

- Helps in simulating wide multiplexors
- ```
always @(sel or a or b or c) begin
    case (sel)
        2'b00: z = a;
        2'b01: z = b;
        2'b10: z = c;
        default: z = 1'b x; // Note that x is a constant here
                           // (don't care)
    endcase
end
```

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Concatenation

- Syntax: R[E1, E2, ..., En] means R repetitions of concatenation of E1, ..., En.

```
reg [15:0] a;
reg [31:0] b;
wire [31:0] out;
assign out = {16{a[15]}, a} + b;
```

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Register file/memory

- Essentially a 2D array of "signals"
- ```
reg [31:0] register_file [0:7];
wire [31:0] rf_bus;
wire r2b4;
assign rf_bus = register_file [2];
assign r2b4 = rf_bus[4];
```
- Cannot do register\_file[2][4]; (this is illegal because this is not how memory works)

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## Tri-state

- Use of the z state
- ```
reg [31:0] mem [0:7];
wire [2:0] a;
wire [31:0] d;
wire read_enable;
assign d = read_enable ? mem[a] : 32'b z;
```

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Extra hardware

- Think while writing your program
 - You are building a hardware, not software
- ```
always @(posedge clk) begin
 if (x) begin
 z <= #2 a + b;
 end
 else if (y) begin
 w <= #2 a + b;
 end
 else begin
 r <= #2 a + b;
 end
end
```

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## Verilog is concurrent

- The big difference with C (get used to it)

```
initial begin
 a = 1'b0;
 b = 1'b0;
end

always @(posedge clk) begin
 a <= #1 1'b1;
 b <= #1 a;
end
```

What are the waveforms of a and b? (assume clk is 10 units and 50% duty cycle)

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## Built-in functions

- Very useful for debugging
  - Can use \$display to print signals (allowed inside always and initial blocks)
  - Can use \$monitor to catch changes on signals (allowed inside initial blocks only)
  - \$time returns verilog's in-built clock time
  - \$finish terminates simulation

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## Verilog preprocessor

- Just like C, minor difference in syntax

```
`define store_opcode 6'h4
`define TICK #2
`include "opcodes.h"

always @(posedge clk) begin
 q <= `TICK d;
end
```

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## Register or wire?

- General confusion: how do I decide if a signal should be declared as a reg or a wire?
  - Forget about the programming language and think about the hardware
  - If in the hardware something turns out to be a wire, it should be declared as wire and driven every cycle (otherwise it becomes Z or X)
  - Otherwise make it reg (state holding)

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## Verilog tips

- Suppose module M has an output Q of type reg
- Module M' instantiates M and passes a reg R for Q
- This is illegal
  - A very common mistake observed in beginners
  - Illegal because this instantiation implicitly connects a register to another register without specifying a clock
- Can connect only a wire to a register through instantiation
  - This will make sense if you think about the hardware
- Module M' can only pass a wire for Q

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## Verilog tips

- If the LHS of an assignment is a reg, use non-blocking assignment i.e., <=
  - This will generate flip-flops, which is what we want
  - Blocking assignment inside always block is typically used to model combinational logic only
  - Careless use of blocking assignment inside always blocks can lead to generation of latches
  - Latches are difficult to handle in terms of timing

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## Verilog tips

- If there are non-blocking assignments inside an always block, make the logic edge-triggered
  - This will generate flip-flops as opposed to latches
  - Use posedge or negedge clock as the triggering signal as opposed to posedge or negedge of some other signals
    - Leads to cleaner and simpler circuits because all flip-flops can have a common clock

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A decorative graphic in the top-left corner of the slide featuring three balloons: a green one at the top, a light blue one in the middle, and a purple one at the bottom. Each balloon has a yellow string and small yellow starburst-like shapes around it.

## Verilog tips

- Avoid always blocks as much as possible and do as much computation combinationaly as possible
  - Leads to smaller compact circuits

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