Introduction to Verilog

Review on Digital Logic Design

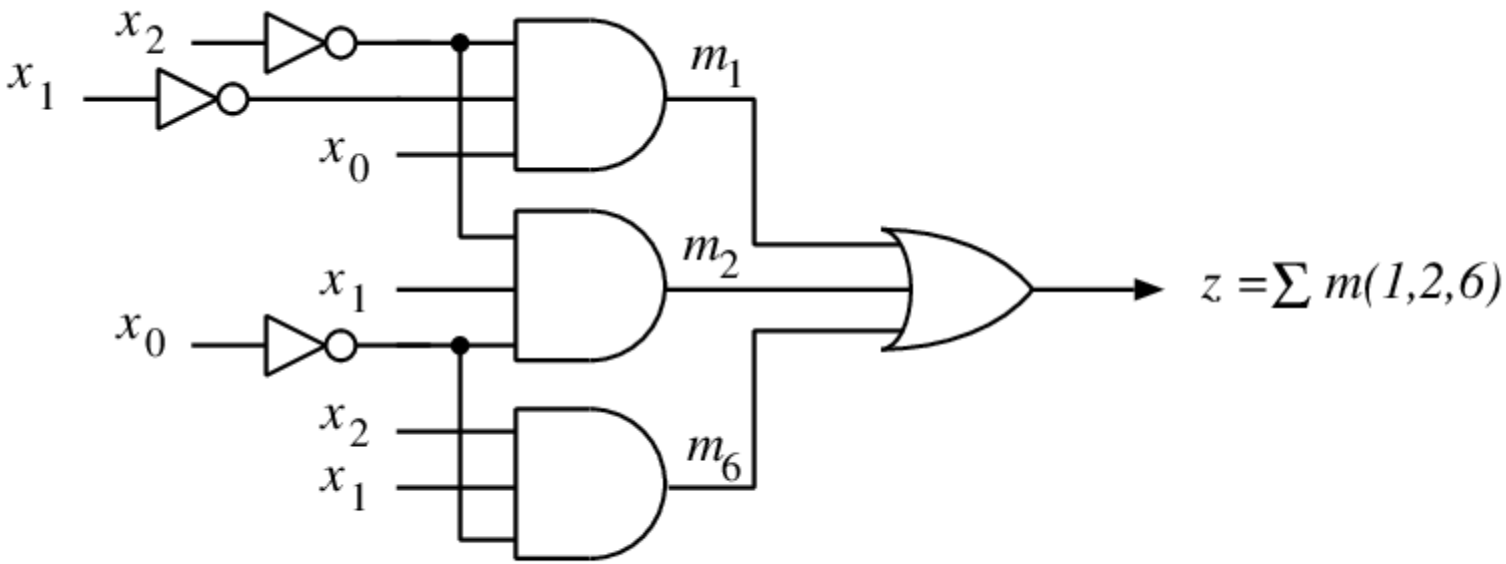


Figure 2.8: Gate network corresponding to $E(x_2, x_1, x_0) = \sum m(1, 2, 6)$.

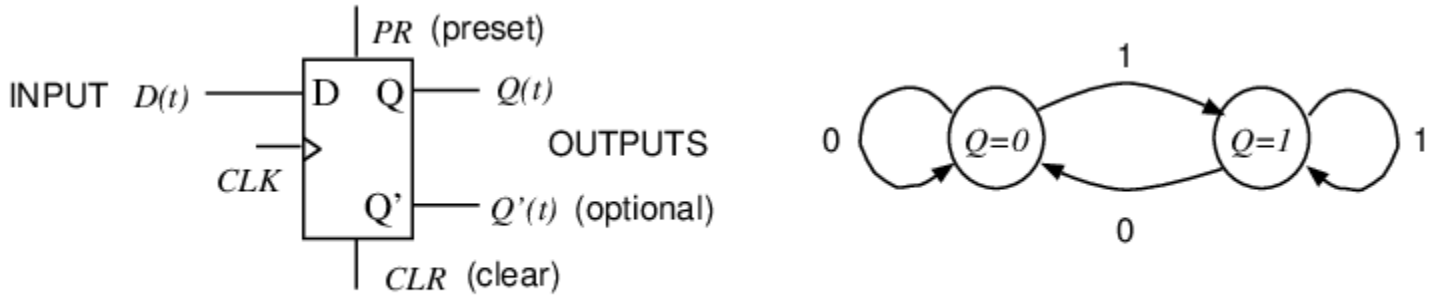
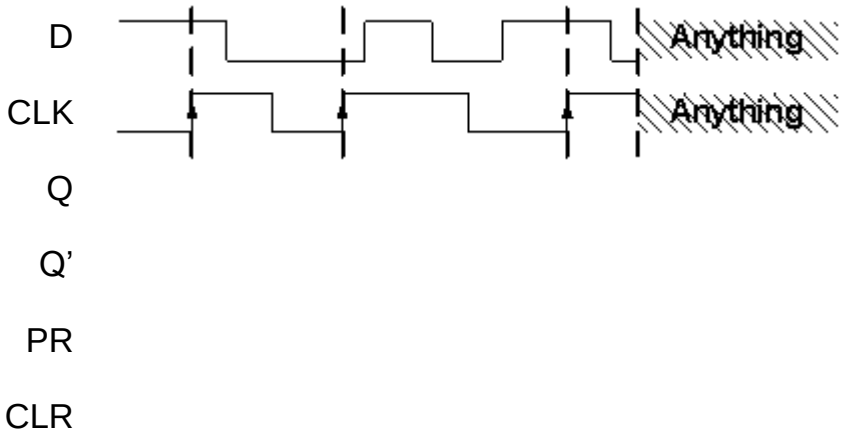
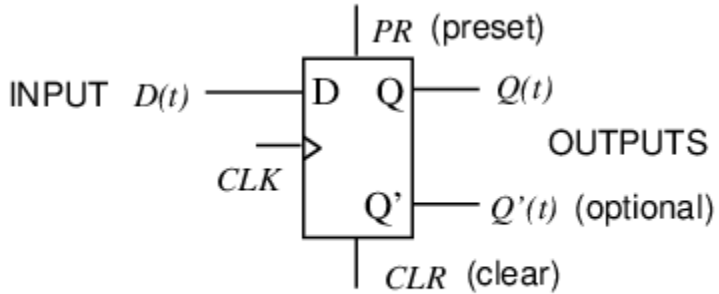


Figure 8.12: D flip-flop and its state diagram.





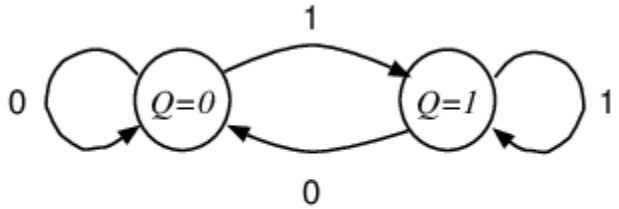
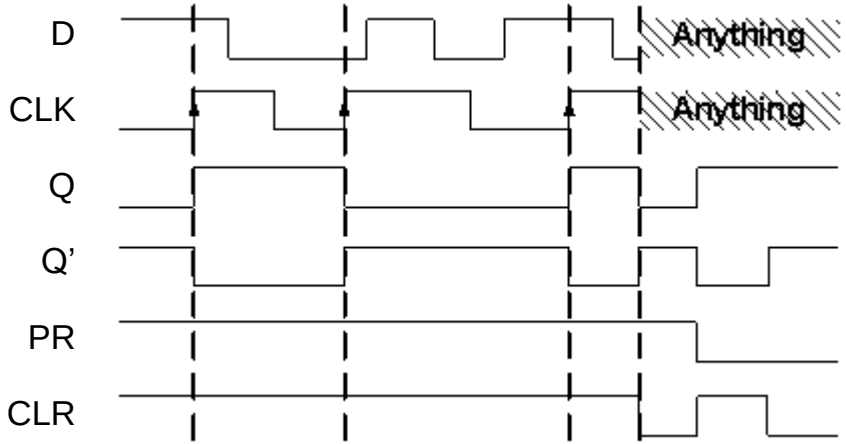


Figure 8.12: D flip-flop and its state diagram.



Input: $x(t) \in \{a, b, c\}$
Output: $z(t) \in \{0, 1\}$
State: $s(t) \in \{A, B, C, D\}$
Initial state: $s(0) = A$

Functions: The state-transition and output functions

PS	Input		
	$x = a$	$x = b$	$x = c$
A	C,0	B,1	B,0
B	D,0	B,0	A,1
C	A,0	D,1	D,0
D	B,0	A,0	D,1
	$NS,\ z$		

Coding:

Input code

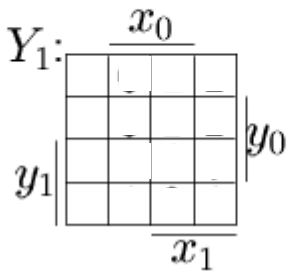
x	x_1	x_0
a	0	1
b	1	0
c	1	1

State code

s	y_1	y_0
A	0	0
B	1	0
C	0	1
D	1	1

- State-transition and output functions

PS	x_1x_0		
y_1y_0	01	10	11
00	01,0	10,1	10,0
10	11,0	10,0	00,1
01	00,0	11,1	11,0
11	10,0	00,0	11,1
	$Y_1Y_0,\ z$		
	NS, Output		



- State-transition and output functions

PS	x_1x_0		
y_1y_0	01	10	11
00	01,0	10,1	10,0
10	11,0	10,0	00,1
01	00,0	11,1	11,0
11	10,0	00,0	11,1
	$Y_1Y_0,\ z$		
	NS, Output		

Y_1:

y_1 \ x_0	0	1	1
-	0	1	1
-	0	1	1
-	1	1	0
-	1	0	1

(y_0 on the rows, x_1 on the columns)

- State-transition and output functions

PS	x_1x_0		
y_1y_0	01	10	11
00	01,0	10,1	10,0
10	11,0	10,0	00,1
01	00,0	11,1	11,0
11	10,0	00,0	11,1
	$Y_1Y_0,\ z$		
	NS, Output		

Y_1:

y_1 \ x_0	0	1	1
-	0	1	1
-	0	1	1
-	1	1	0
-	1	0	1

(y_0 on the rows, x_1 on the columns)

$$Y_1 = y_1'x_1 + y_1x_1' + y_0'x_0' + y_0x_1x_0$$

- State-transition and output functions

PS	x_1x_0		
y_1y_0	01	10	11
00	01,0	10,1	10,0
10	11,0	10,0	00,1
01	00,0	11,1	11,0
11	10,0	00,0	11,1
	$Y_1Y_0,\ z$		
	NS, Output		

Y_1:

$y_1 \backslash x_1x_0$	01	11	10
0	-	0	1	1
1	-	0	1	1
1	-	1	1	0
0	-	1	0	1

y_0

Y_0:

$y_1 \backslash x_1x_0$	01	11	10
0	-	1	0	0
1	-	0	1	1
1	-	0	1	0
0	-	1	0	0

y_0

z:

$y_1 \backslash x_1x_0$	01	11	10
0	-	0	0	1
1	-	0	0	1
1	-	0	1	0
0	-	0	1	0

y_0

$$Y_1 = y_1'x_1 + y_1x_1' + y_0'x_0' + y_0x_1x_0$$
$$Y_0 = y_0'x_1' + y_1'y_0x_1 + y_0x_1x_0$$
$$z = y_1'x_0' + y_1x_1x_0$$

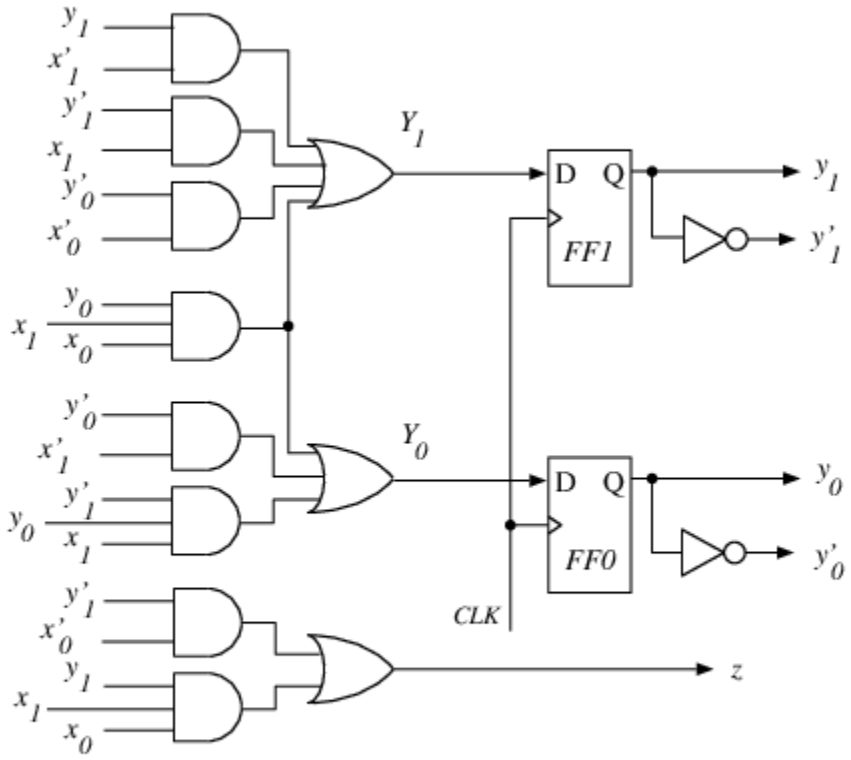


Figure 8.19: Sequential network in Example 8.4.

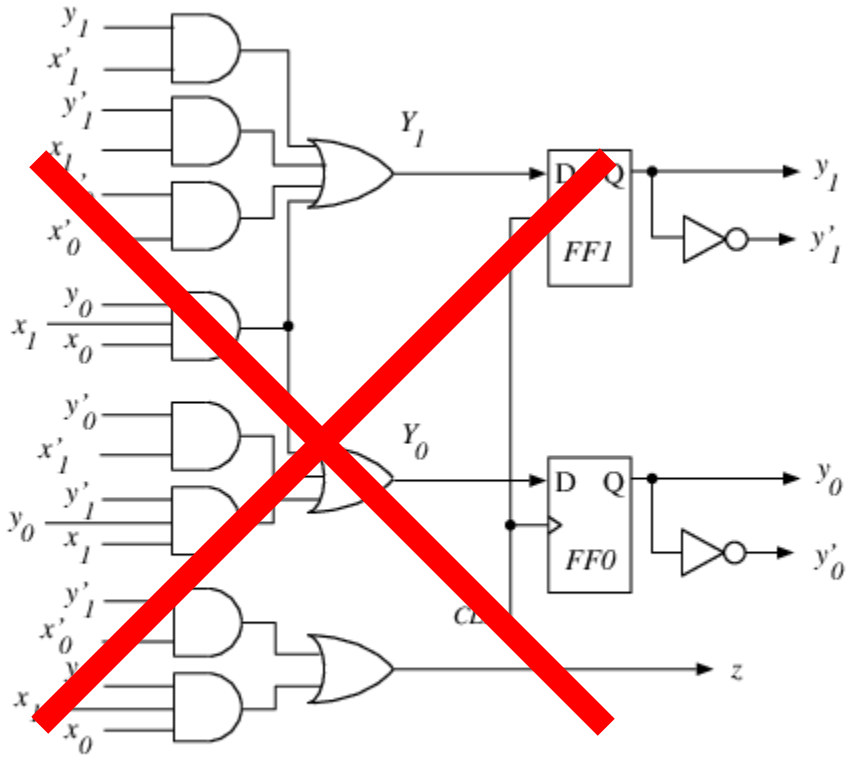


Figure 8.19: Sequential network in Example 8.4.

Verilog

Introduction to Verilog

Overview of Verilog

1. Resemblance to C: case sensitive, same style comments, operators, etc.

2. Two standards: Verilog-1995, Verilog-2001, both supported by ISE

3. VHDL is the other widely used HDL.

Behavioral vs Synthesizable code

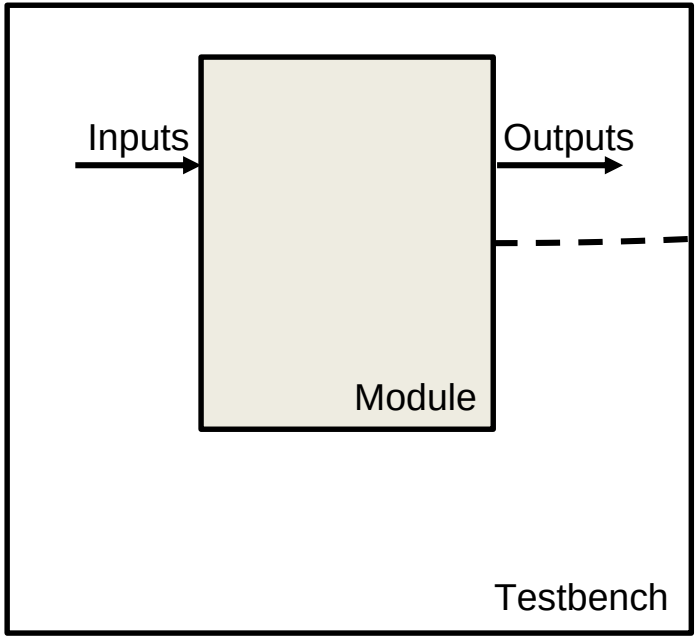
Historically Verilog has always served two functions:

1. Describe your digital logic design in a high-level way instead of using schematics (synthesizable code).
2. Model elements that interact with your design (behavioral models/testbenches)

You should **always** have a clear conscience of whether you are writing behavioral or synthesizable code.

Better yet, know what your synthesizable code translates to in **physical hardware**.

Behavioral vs Synthesizable code



PC

Program

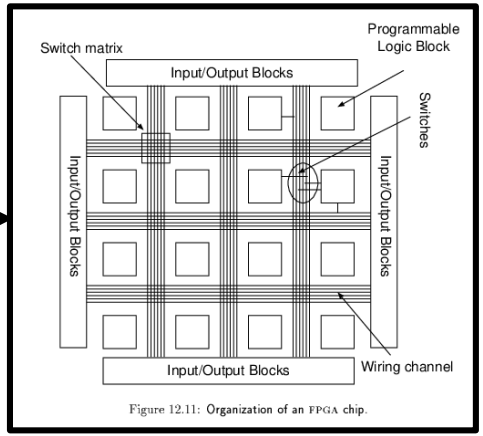


Figure 12.11: Organization of an FPGA chip.

FPGA

Which part corresponds to behavioral / synthesizable code?

Data types: wire, reg

Variables must be declared before used; wire/reg are the most common data types.

wire:

- models basic wire that holds transient values

reg:

- anything that stores a value

Data Values

Values: 1, 0, x/X (unknown), z/Z (high impedance)
Radices: d(decimal), h(hex), o(octal), b(binary)
Format: <size>'<radix><value>

```
123          // default: decimal radix, unspecified width
'd123        // 'd = decimal radix
8'h7B        // 'h = hex radix
'o173        // 'o = octal radix
'b111_1011   // 'b = binary radix, "_" are for readability
```

Signed number (rarely used):

```
8'shFF (8-bit twos-complement representation of -1)
```

Operators

Bitwise: ~a, a&b, a|b, a^b, a~^b

Reduction: bitwise operation on a **single** operand and produces one bit result.
&a, ~&a, |a, ~|a, ^a, ~^a
Example: ^4'b1001 = 1'b0

Logical: output one bit result
!a, a&&b, a||b, ==/!=, ===/!== (also compares x/z)

Arithmetic: +,-,*,/,% (mod, takes the sign of operand 1)

Operators, ctd.

Can you tell the difference between the following expressions? What are the sizes of each expression and what do they mean?

Declaration: wire [31:0] a,b

- a & b
- a && b
- (&a) & (&b)
- (&a) && (&b)
- &(a && b)
- a && (&b)

Operators, ctd.

Shift: <<, >>(logical)
<<<, >>> (arithmetic)

Conditional: sel ? a : b

Concatenation: {a, b}

Replication: {n{m}}

Assignment: =(blocking), <= (non-blocking)

Blocking/Non-blocking assignments

Blocking assignments (=):

assignment immediate, happens first

Non-blocking assignment(<=):

assignments deferred until all right hand sides has been evaluated, closer to actual hardware register behavior.

Assignment operator guidelines

1. Sequential logic: use nonblocking (<=)
2. Pure combinational logic in “always” block: use blocking (=)
3. Do not mix blocking/non-blocking in the same “always” block
4. Both sequential and “combinational” logic in the same “always” block: use non-blocking (<=)

```
y <= a ^ b;
```

Recommendation: in complex sequential circuit, use two always blocks, one for combinational circuit, one for state update.

Basic building block: modules

1. port: input / output / inout
2. Signal declarations: `wire [3:0] a;`
   a. Rule-of-thumb: stick to [MSB:LSB]
3. Concurrent logic blocks, one of the following:
   a. continuous assignments
   b. always blocks (either sequential or combinatorial)
   c. initial blocks (only used in behavioral modeling)
   d. forever blocks (only used in behavioral modeling)
4. Instantiations of sub-modules

```
module top(a, b, ci, s, co
    );
  input a, b, ci;
  output s, co;

  wire s;
  reg g, p, co;

  assign s = a ^ b ^ ci;
  // combinatorial always
  // block using begin/end
  always @* begin
    g = a & b;
    p = a | b;
    co = g | (p & ci);
  end

endmodule
```

Basic building block: modules

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  input a, b, ci;
  output s, co;

  wire s;
  reg g, p, co;

  assign s = a ^ b ^ ci;
  // combinatorial always
  // block using begin/end
  always @* begin
    g = a & b;
    p = a | b;
    co = g | (p & ci);
  end

endmodule
```

Always Block

```
// combinatorial always
// block using begin/end
always @* begin
   g = a & b;
   p = a | b;
   co = g | (p & ci);
end
```

Sensitivity list

Code that describes the real "function"

Always Block: Sensitivity list

1. Level sensitive: changes to any signals on the sensitivity list will invoke the always block. Used in combinational circuits.

```
always @ (a or b) / always @* (verilog-2001, recommended)
```

1. Edge sensitive: invoke always block on specified signal edges. Used in sequential circuits.

```
always @ (posedge clk or posedge reset)
```

Aways Block: case, if/else

```
case (sel)
  val0: statements
  val1: statements
  …
  default: statements
endcase
```

```
if (condition)
  statements
else if (condition)
  statements
…
else
  statements
```

Aways Blocks: case, if/else ctd.

```
module ALU(a, b, f, z
    );
input [3:0] a, b;
input [1:0] f;
output reg [3:0] z;

always @(*)
  z = 4'bx; (#1)
  case (f)
    0: z = a + b;
    1: z = a * b;
    2: z = a & b;
    3: z = a | b;
    default: z = 4'bx; (#2)
  endcase
endmodule
```

if/else or case statement fails to cover all cases → **inferred latch**

Example:

```
if (x == 2'b00)
  z = a;
else if (x == 2'b01)
  z = b;
```

What about other cases? The circuit will hold previous value

To avoid: add #1 or #2

Always Block: Looping (mostly for testing)

```
while (condition)
  statements

for (initialization; condition; increment)
  statements

repeat (n)
  statements
```

Data types: wire, reg

Variables must be declared before used; wire/reg are the most common data types.

wire:

- models basic wire that holds transient values
- **only wires can be used on the LHS of continuous assign statement**
- input/output port signals default to wire

reg:

- anything that stores a value
- can appear in both combinational and sequential circuits
- **only regs can be used on the LHS of non-continuous assign statement**

Wire vs. reg

When to use wire:
Left hand side of “assign”

```
wire s;

assign s = a ^ b ^ ci;
```

When to use reg:
Left hand side of “=” or “<=” in “always” blocks

```
reg g, p, co;
always @* begin
  g = a & b;
  p = a | b;
  co = g | (p & ci);
end
```

Sequential circuit example: modulo 64 counter

```
module counter(clk, rst, out
    );
  input clk, rst;
  output [5:0] out;

  reg [5:0] out;
  always @(posedge clk or posedge rst)
  begin
    if (rst)
      out <= 6'b000000;
    else
      out <= out + 1;
  end

endmodule
```

Module instantiation

Achieve hierarchical design by using other modules inside one module.

Recommended format:

type name (.port1(w1),.port2(w2).....);

1. Port order doesn’t matter
2. Unused output port allowed
3. Name must be unique within module

Example

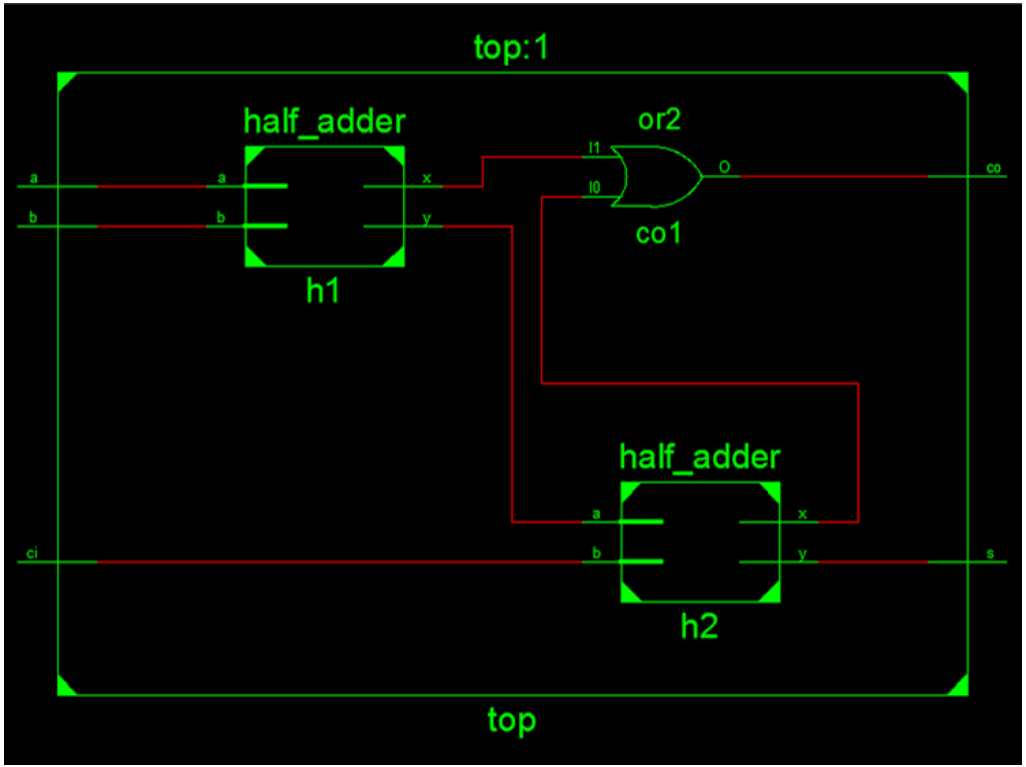
```
module half_adder(a, b, x, y
    );
  input a, b;
  output x, y;

  assign x = a & b;
  assign y = a ^ b;
endmodule
```

```
module full_adder(a, b, ci, s, co
    );
  input a, b, ci;
  output s, co;
  wire g, p, pc;

  half_adder h1(.a(a), .b(b),
    .x(g), .y(p));
  half_adder h2(.a(p), .b(ci),
    .x(pc), .y(s));
  assign co = pc | g;
endmodule
```

Schematics output



Testbench

Testing is important and engineers spend more time testing for complex digital circuits.

Procedures for creating testbench:

1. Instantiate unit under test (uut)
2. Provide input for uut: clk, rst, data...
3. Simulate and verify behavior

Initial block

```
initial begin
  // Initialize Inputs
  clk = 0;
  rst = 0;
  // Wait 100 ns for global reset
   to finish
  #100;
  // Add stimulus here
  rst = 1;
  #20 rst = 0;
  // add verification routine here
  #1000 $finish;
end
```

Initial block starts execution at time 0.

#n : wait n time units

$finish: stop simulation

Parameter

```
module ALU #(parameter W=4)(a, b, f, z);
input [W-1:0] a, b;
input [1:0] f;
output reg [W-1:0] z;

always @(*)
  case (f)
    0: z = a + b;
    1: z = a * b;
    2: z = a & b;
    3: z = a | b;
    default: z = {(W){1'bx}};
  endcase
endmodule
```

Instantiation of Parameterized Module:

Default parameter W=4. Instantiate a 16-bit ALU:

Format:

type #(params) name (ports);

Example:

```
ALU #(.W(16)) alu16 (.a(a), .b(b), .f(f), .z(z));
```

Preparation Tasks

- Read *An Old Tutorial* on the course web
  - *Ignore the device parameters for Spartan-3*
  - *Ignore contents beyond* **Create Timing Constraints**
- Create projects, write code and simulate:
  - 2:1 mux
  - `mux2( input din0, din1, sel, output out);`
  - 8 bit counter
  - `counter( output [7:0] out, input clk, ena, rst);`
  - 16-4 encoder
  - `encoder ( input [15:0] in, input enable, output [3:0] out);`

References

1. MIT 6.111 course notes,
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4. Sunburst Design (Read on assignment operators)
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5. ISE Quick Start Guide
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