VERILOG
Hardware Description Language

About Verilog

- Along with VHDL, Verilog is among the most widely used HDLs.
- Main differences:
  - VHDL was designed to support system-level design and specification.
  - Verilog was designed primarily for digital hardware designers developing FPGAs and ASICs.

Concept of Verilog "Module"

- In Verilog, the basic unit of hardware is called a ***module***.
  - Modules cannot contain definitions of other modules.
  - A module can, however, be instantiated within another module.
  - Allows the creation of a *hierarchy* in a Verilog description.

Basic Syntax of Module Definition

```
module  module_name  (list_of_ports);

        input/output declarations;

        local net declarations;

        parallel statements;

endmodule
```

Example 1 :: simple AND gate

```
module  simpleand (f, x, y);
   input  x, y;
   output  f;
   assign  f = x & y;
endmodule
```


Example 2 :: two-level circuit

```
module  two_level (a, b, c, d, f);
   input  a, b, c, d;
   output  f;
   wire  t1, t2;
   assign  t1 = a & b;
   assign  t2 = ~ (c | d);
   assign  f = t1 ^ t2;
endmodule
```

Variable Data Types

- A variable belongs to one of two data types:
  - ***Net***
    - Must be continuously driven
    - Used to model connections between continuous assignments & instantiations
  - ***Register***
    - Retains the last value assigned to it
    - Often used to represent storage elements

Net data type

- Different 'net' types supported for synthesis:
  - *wire, wor, wand, tri, supply0, supply1*
- 'wire' and 'tri' are equivalent; when there are multiple drivers driving them, the outputs of the drivers are shorted together.
- 'wor' / 'wand' inserts an OR / AND gate at the connection.
- 'supply0' / 'supply1' model power supply connections.

```
module  using_wired_and  (A, B, C, D, f);
   input    A, B, C, D;
   output  f;
   wand    f;          // net f declared as 'wand'

   assign  f = A & B;
   assign  f = C | D;
endmodule
```



```
module  using_supply_wire  (A, B, C, f);
   input      A, B, C;
   output    f;
   supply0  gnd;
   supply1  vdd;
   nand   G1  (t1, vdd, A, B);
   xor     G2  (t2, C, gnd);
   and     G3  (f, t1, t2);
endmodule
```

Register data type

- Different 'register' types supported for synthesis:
  - reg, integer
- The 'reg' declaration explicitly specifies the size.

```
reg  x, y;  // single-bit register variables
reg [15:0] bus; // 16-bit bus, bus[15] MSB
```

- For 'integer', it takes the default size, usually 32-bits.
  - Synthesizer tries to determine the size.

Other differences:

- In arithmetic expressions,
  - An 'integer' is treated as a 2's complement signed integer.
  - A 'reg' is treated as an unsigned quantity.
- General rule of thumb
  - 'reg' used to model actual hardware registers such as counters, accumulator, etc.
  - 'integer' used for situations like loop counting.

```
module  simple_counter  (clk, rst, count);
   input    clk, rst;
   output  count;
   reg [31:0]  count;

   always  @(posedge  clk)
   begin
      if  (rst)
         count = 32’b0;
      else
         count = count + 1;
   end
endmodule
```


- When ‘integer’ is used, the synthesis system often carries out a data flow analysis of the model to determine its actual size.

- Example:

```
wire [1:10]  A, B;
integer       C;
C  =  A + B;
```

➔The size of C can be determined to be equal to 11 (ten bits plus a carry).

Specifying Constant Values

- A value may be specified in either the 'sized' or the 'un-sized' form.
  - Syntax for 'sized' form:

    <size>'<base><number>

- <u>Examples</u>:

```
8'b01110011  // 8-bit binary number
12'hA2D      // 1010 0010 1101 in binary
12'hCx5      // 1100 xxxx 0101 in binary
25           // signed number, 32 bits
1'b0         // logic 0
1'b1         // logic 1
```


Parameters

- A *parameter* is a constant with a name.
- No size is allowed to be specified for a parameter.
  - The size gets decided from the constant itself (32-bits if nothing is specified).
- <u>Examples</u>:

```
parameter  HI = 25, LO = 5;
parameter  up = 2b'00, down = 2b'01,
           steady = 2b'10;
```

Logic Values

- The common values used in modeling hardware are:
  - 0 :: Logic-0 or FALSE
  - 1 :: Logic-1 or TRUE
  - x :: Unknown (or don't care)
  - z :: High impedance
- Initialization:
  - All unconnected nets set to 'z'
  - All register variables set to 'x'

- Verilog provides a set of predefined logic gates.
  - They respond to inputs (0, 1, x, or z) in a logical way.
  - Example :: AND

0 & 0 → 0	0 & x → 0
0 & 1 → 0	1 & z → x
1 & 1 → 1	z & x → x
1 & x → x	

Primitive Gates

- **Primitive logic gates (instantiations):**

```
and   G (out, in1, in2);
nand  G (out, in1, in2);
or    G (out, in1, in2);
nor   G (out, in1, in2);
xor   G (out, in1, in2);
xnor  G (out, in1, in2);
not   G (out1, in);
buf   G (out1, in);
```


- **Primitive Tri-State gates (instantiation)**

```
bufif1  G (out, in, ctrl);
bufif0  G (out, in, ctrl);
notif1  G (out, in, ctrl);
notif0  G (out, in, ctrl);
```

Some Points to Note

- For all primitive gates,
  - The output port must be connected to a net (a wire).
  - The input ports may be connected to nets or register type variables.
  - They can have a single output but any number of inputs.
  - An optional delay may be specified.
    - *Logic synthesis tools ignore time delays.*


```
`timescale 1 ns / 1ns
module exclusive_or (f, a, b);
      input a, b;
      output f;
      wire t1, t2, t3;
      nand #5 m1 (t1, a, b);
      and  #5 m2 (t2, a, t1);
      and  #5 m3 (t3, t1, b);
      or   #5 m4 (f, t2, t3);
endmodule
```

Hardware Modeling Issues

- The values computed can be held in
  - A ‘wire’
  - A ‘flip-flop’ (edge-triggered storage cell)
  - A ‘latch’ (level-sensitive storage cell)
- A variable in Verilog can be of
  - ‘net data type
    - Maps to a ‘wire’ during synthesis
  - ‘register’ data type
    - Maps either to a ‘wire’ or to a ‘storage cell’ depending on the context under which a value is assigned.


```
module  reg_maps_to_wire  (A, B, C, f1, f2);
   input    A, B, C;
   output  f1, f2;
   wire      A, B, C;
   reg        f1, f2;
   always  @(A or B or C)
   begin
      f1 = ~(A & B);
      f2 = f1  ^ C;
   end
endmodule
```

The synthesis system will generate a wire for f1

```
module  a_problem_case  (A, B, C, f1, f2);
   input    A, B, C;
   output  f1, f2;
   wire     A, B, C;
   reg       f1, f2;
   always  @(A or B or C)
   begin
      f2 = f1 ^ f2;
      f1 = ~(A & B);
   end
endmodule
```

The synthesis system will not generate a storage cell for f1


```
// A latch gets inferred here
module  simple_latch  (data, load, d_out);
   input    data, load;
   output  d_out;

   always @(load or data)
   begin
      if (!load)
         t = data;
      d_out = !t;
   end
endmodule
```

Else part missing; so latch is inferred.

Verilog Operators

- Arithmetic operators

  *, /, +, -, %
- Logical operators

  ! ➔ logical negation

  && ➔ logical AND

  | | ➔ logical OR
- Relational operators

  >, <, >=, <=, ==, !=
- Bitwise operators

  ~, &, |, ^, ~^

- Reduction operators (operate on all the bits within a word)

  &, ~&, |, ~|, ^, ~^

  ➔ accepts a single word operand and produces a single bit as output
- Shift operators

  >>, <<
- Concatenation { }
- Replication { n { } }
- Conditional

  <condition> ? <expression1> : <expression2>

```
// An 8-bit adder description

module parallel_adder (sum, cout, in1, in2, cin);
   input  [7:0] in1, in2;   input  cin;
   output [7:0] sum;        output cout;

   assign #20 {cout, sum} = in1 + in2 + cin;
endmodule
```


Some Points

- The presence of a 'z' or 'x' in a *reg* or *wire* being used in an arithmetic expression results in the whole expression being unknown ('x').
- The logical operators (!, &&, | |) all evaluate to a 1-bit result (0, 1 or x).
- The relational operators (>, <, <=, >=, ~=, ==) also evaluate to a 1-bit result (0 or 1).
- Boolean *false* is equivalent to 1'b0

  Boolean *true* is equivalent to 1'b1.

Some Valid Statements

```
assign  outp = (p == 4'b1111);
if  (load  &&  (select == 2'b01)) .......
assign   a = b >> 1;
assign   a = b << 3;
assign  f = {a, b};
assign f = {a, 3'b101, b};
assign f = {x[2], y[0], a};
assign f = { 4{a} };   // replicate four times
assign f = {2'b10, 3{2'b01}, x};
```


Description Styles in Verilog

- Two different styles of description:
  1. <u>Data flow</u>
     - Continuous assignment
  2. <u>Behavioral</u>
     - Procedural assignment
       - ❖ Blocking
       - ❖ Non-blocking

Data-flow Style: Continuous Assignment

- Identified by the keyword "assign".

```
assign   a = b & c;
assign   f[2] = c[0];
```

- Forms a static binding between
  - The 'net' being assigned on the LHS,
  - The expression on the RHS.
- The assignment is continuously active.
- Almost exclusively used to model combinational logic.

- A Verilog module can contain any number of continuous assignment statements.
- For an "assign" statement,
  - The expression on RHS may contain both "register" or "net" type variables.
  - The LHS must be of "net" type, typically a "wire".
- Several examples of "assign" illustrated already.

```
module   generate_mux (data, select, out);
   input  [0:7]  data;
   input  [0:2]  select;
   output  out;

   assign   out  =  data [select];
endmodule
```

Non-constant index in expression on RHS generates a MUX


```
module generate_decoder (out, in, select);
   input  in;
   input [0:1]  select;
   output  [0:3]  out;

   assign   out [select]  =  in;
endmodule
```

Non-constant index in expression on LHS generates a decoder

```
module  generate_set_of_MUX (a, b, f, sel);
   input [0:3]  a, b;
   input  sel;
   output  [0:3]  f;

   assign  f  =  sel  ?  a  :  b;
endmodule
```

Conditional operator generates a MUX

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```
module   level_sensitive_latch  (D, Q, En);
   input  D, En;
   output  Q;

   assign  Q  =  en  ?  D  :  Q;
endmodule
```

Using "assign" to describe sequential logic

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Behavioral Style: Procedural Assignment

- The procedural block defines
  - A region of code containing *sequential* statements.
  - The statements execute in the order they are written.
- Two types of procedural blocks in Verilog
  - The "always" block
    - A continuous loop that never terminates.
  - The "initial" block
    - Executed once at the beginning of simulation (used in Test-benches).

- A module can contain any number of "always" blocks, all of which execute concurrently.
- Basic syntax of "always" block:

```
always  @ (event_expression)
begin
    statement;      }  Sequential
                    }  statements
    statement;      }
end
```

- The @(event_expression) is required for both combinational and sequential logic descriptions.

- Only “reg” type variables can be assigned within an “always” block.

Sequential Statements in Verilog

```
1.  begin
        sequential_statements
    end
2.  if  (expression)
        sequential_statement
    [else
        sequential_statement]
3.  case  (expression)
        expr:     sequential_statement
        .......
        default:  sequential_statement
    endcase
```

begin...end not required if there is only 1 stmt.

4. forever
   sequential_statement
5. repeat (expression)
   sequential_statement
6. while (expression)
   sequential_statement
7. for (expr1; expr2; expr3)
   sequential_statement

8. # (time_value)
   - Makes a block suspend for "time_value" time units.
9. @ (event_expression)
   - Makes a block suspend until event_expression triggers.

```
//  A combinational logic example

module  mux21  (in1, in0, s, f);
   input  in1, in0, s;
   output  f;
   reg  f;

   always  @ (in1  or  in0  or  s)
      if  (s)
         f  =  in1;
      else
         f  =  in0;
endmodule
```



```
// A sequential logic example

module  dff_negedge  (D, clock, Q, Qbar);
   input  D, clock;
   output  Q, Qbar;
   reg  Q, Qbar;

   always  @ (negedge clock)
      begin
           Q  =  D;
           Qbar  =  ~D;
       end
endmodule
```

```
// Another sequential logic example

module  incomp_state_spec  (curr_state, flag);
   input    [0:1]  curr_state;
   output  [0:1]  flag;
   reg       [0:1]  flag;

   always  @ (curr_state)
      case  (curr_state)
         0, 1  :  flag = 2;
         3      :  flag = 0;
      endcase
endmodule
```

The variable 'flag' is not assigned a value in all the branches of case.
➔ Latch is *inferred*


```
// A small change made

module  incomp_state_spec  (curr_state, flag);
   input    [0:1]  curr_state;
   output  [0:1]  flag;
   reg       [0:1]  flag;

   always  @ (curr_state)
      flag = 0;
      case  (curr_state)
         0, 1  :  flag = 2;
         3      :  flag = 0;
      endcase
endmodule
```

'flag' defined for all values of curr_state.
➔ Latch is *avoided*

```
module  ALU_4bit  (f, a, b, op);

   input   [1:0]  op;        input [3:0]  a, b;
   output [3:0]  f;          reg    [3:0]  f;

   parameter  ADD=2'b00, SUB=2'b01,
                   MUL=2'b10, DIV=2'b11;

   always  @ (a or b or op)
      case (op)
         ADD : f = a + b;
         SUB : f = a – b;
         MUL : f = a * b;
         DIV   : f = a / b;
      endcase
endmodule
```


Blocking & Non-blocking Assignments

- Sequential statements within procedural blocks ("always" and "initial") can use two types of assignments:
  - Blocking assignment
    - Uses the '=' operator
  - Non-blocking assignment
    - Uses the '<=' operator

Blocking Assignment (using '=')

- Most commonly used type.
- The target of assignment gets updated before the next sequential statement in the procedural block is executed.
- A statement using blocking assignment blocks the execution of the statements following it, until it gets completed.
- Recommended style for modeling combinational logic.

Non-Blocking Assignment (using '<=')

- The assignment to the target gets scheduled for the end of the simulation cycle.
  - Normally occurs at the end of the sequential block.
  - Statements subsequent to the instruction under consideration are not blocked by the assignment.
- Recommended style for modeling sequential logic.
  - Can be used to assign several 'reg' type variables synchronously, under the control of a common clock.

Some Rules to be Followed

- Verilog synthesizer ignores the delays specified in a procedural assignment statement.
- A variable cannot appear as the target of *both* a blocking and a non-blocking assignment.
  - Following is not permissible:

```
value = value + 1;
value <= init;
```

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```
// Up-down counter (synchronous clear)

module  counter (mode, clr, ld, d_in, clk, count);
   input mode, clr, ld, clk;     input [0:7] d_in;
   output [0:7]  count;          reg [0:7]  count;
   always  @ (posedge  clk)
      if  (ld)
         count  <= d_in;
      else  if  (clr)
               count  <= 0;
            else  if  (mode)
                     count  <=  count + 1;
                  else
                     count  <=  count + 1;
endmodule
```

CAD for VLSI 54

```
// Parameterized design:: an N-bit counter

module counter (clear, clock, count);
  parameter N = 7;
  input clear, clock;
  output [0:N] count;        reg [0:N] count;

  always @ (negedge clock)
    if (clear)
       count <= 0;
     else
       count <= count + 1;
endmodule
```



```
// Using more than one clocks in a module

module multiple_clk (clk1, clk2, a, b, c, f1, f2);
  input clk1, clk2, a, b, c;
  output f1, f2;
  reg f1, f2;
  always @ (posedge clk1)
    f1 <= a & b;
  always @ (negedge clk2)
    f2 <= b ^ c;
endmodule
```

```
// Using multiple edges of the same clock

module multi_phase_clk (a, b, f, clk);
   input  a, b, clk;
   output  f;
   reg  f, t;
   always  @ (posedge  clk)
      f  <=  t & b;
   always  @ (negedge  clk)
      t  <=  a | b;
endmodule
```


A Ring Counter Example

```
module  ring_counter  (clk, init, count);
   input  clk, init;       output [7:0]  count;
   reg [7:0]  count;
   always  @ (posedge clk)
   begin
      if  (init)
         count  =  8'b10000000;
      else  begin
               count      =  count  <<  1;
               count[0]  =  count[7];
            end
   end
endmodule
```

A Ring Counter Example (Modified)

```
module  ring_counter_modi1  (clk, init, count);
   input  clk, init;       output [7:0]  count;
   reg [7:0]  count;
   always  @ (posedge clk)
   begin
      if  (init)
         count  =  8'b10000000;
      else  begin
               count      <=  count  <<  1;
               count[0]  <=  count[7];
            end
   end
endmodule
```


About "Loop" Statements

- Verilog supports four types of loops:
  - 'while' loop
  - 'for' loop
  - 'forever' loop
  - 'repeat' loop
- Many Verilog synthesizers supports only 'for' loop for synthesis:
  - Loop bound must evaluate to a constant.
  - Implemented by unrolling the 'for' loop, and replicating the statements.

Modeling Memory

- Synthesis tools are usually not very efficient in synthesizing memory.
  - Best modeled as a component.
  - Instantiated in a design.
- Implementing memory as a two-dimensional register file is inefficient.

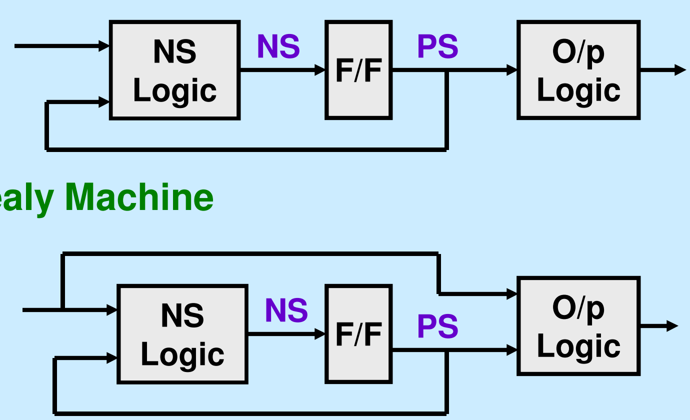

```
module  memory_example (en, clk, adbus, dbus,
                                          rw);
   parameter  N = 16;
   input  en, rw, clk;
   input  [N-1:0]  adbus;
   output [N-1:0]  dbus;
   …………
   ROM  Mem1  (clk, en, rw, adbus, dbus);
   …………
endmodule
```

Modeling Tri-state Gates

```
module  bus_driver  (in, out, enable);
   input  enable;            input [0:7]  in;
   output [0:7]  out;        reg [0:7]  out;

   always  @ (enable or in)
      if  (enable)
         out = in;
      else
         out = 8'bz;
endmodule;
```

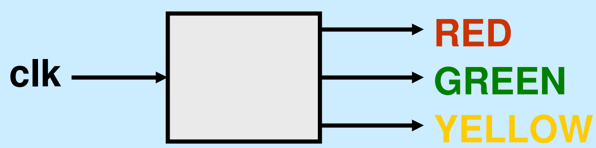

Modeling Finite State Machines

- Two types of FSMs
  - Moore Machine
  - Mealy Machine



Moore Machine : Example 1

- Traffic Light Controller
  - Simplifying assumptions made
  - Three lights only (RED, GREEN, YELLOW)
  - The lights glow cyclically at a fixed rate
    - Say, 10 seconds each
    - The circuit will be driven by a clock of appropriate frequency




```
module  traffic_light  (clk, light);
   input  clk;
   output [0:2]  light;      reg  [0:2]  light;
   parameter  S0=0, S1=1, S2=2;
   parameter  RED=3'b100, GREEN=3'b010,
                    YELLOW=3'b001;
   reg [0:1]  state;
   always  @ (posedge  clk)
      case  (state)
         S0:  begin                    // S0 means RED
                  light  <=  YELLOW;
                  state <=  S1;
              end
```

```
    S1:  begin                  // S1 means YELLOW
             light  <=  GREEN;
             state <=  S2;
         end
    S2:  begin                  // S2 means GREEN
             light  <=  RED;
             state <=  S0;
          end
    default:  begin
                  light  <=  RED;
                  state <=  S0;
              end
  endcase
endmodule
```


- **Comment on the solution**
  - Five flip-flops are synthesized
    - Two for ‘state’
    - Three for ‘light’ (outputs are also latched into flip-flops)
  - If we want non-latched outputs, we have to modify the Verilog code.
    - Assignment to ‘light’ made in a separate ‘always’ block.
    - Use blocking assignment.

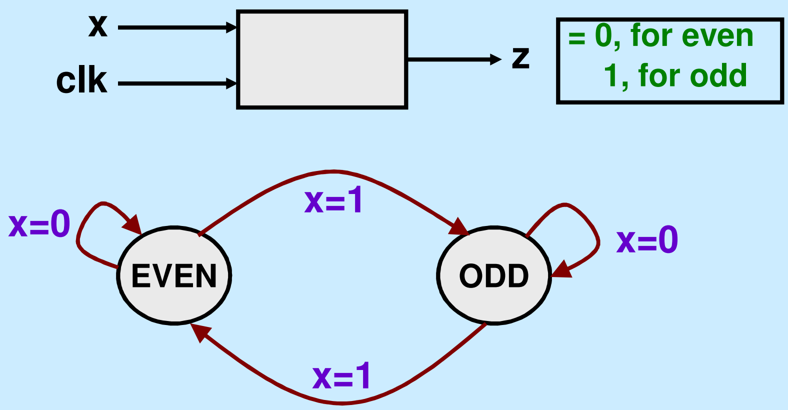
```
module  traffic_light_nonlatched_op  (clk, light);
   input  clk;
   output [0:2]  light;      reg  [0:2]  light;
   parameter  S0=0, S1=1, S2=2;
   parameter  RED=3'b100, GREEN=3'b010,
                    YELLOW=3'b001;
   reg [0:1]  state;
   always  @ (posedge  clk)
      case  (state)
         S0:        state  <=  S1;
         S1:        state  <=  S2;
         S2:        state  <=  S0;
         default:  state  <=  S0;
      endcase
```



```
   always  @ (state)
      case  (state)
         S0:        light  =  RED;
         S1:        light  =  YELLOW;
         S2:        light  =  GREEN;
         default:  light  =  RED;
      endcase
endmodule
```

Moore Machine: Example 2

- Serial parity detector



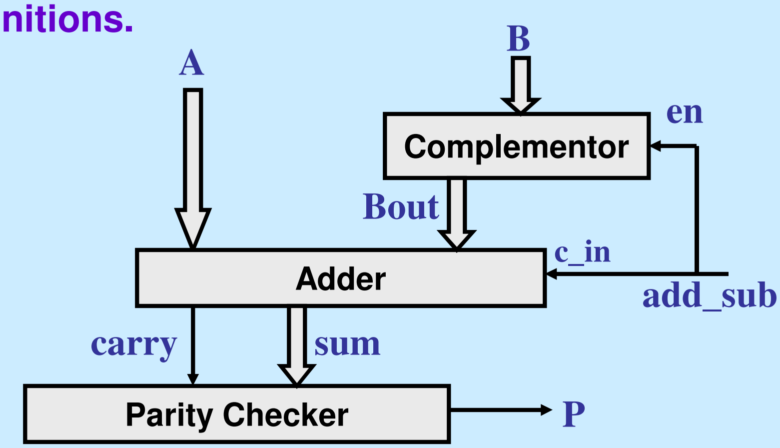

```
module  parity_gen  (x, clk, z);
   input  x, clk;
   output  z;        reg  z;
   reg  even_odd;    // The machine state
   parameter  EVEN=0, ODD=1;

   always  @ (posedge  clk)
      case  (even_odd)
         EVEN:  begin
                     z  <=  x ? 1 : 0;
                     even_odd  <=  x ? ODD : EVEN;
                  end
```

```
        ODD:   begin
                    z  <=  x ? 0 : 1;
                    even_odd  <=  x ? EVEN : ODD;
               end
    endcase
endmodule
```

• If no output latches need to be synthesized, we can follow the principle shown in the last example.

Example with Multiple Modules

- A simple example showing multiple module definitions.



```
module  complementor (Y, X, comp);
   input [7:0]  X;
   input  comp;
   output [7:0]  Y;      reg [7:0]  Y;

   always  @ (X or comp)
      if  (comp)
         Y = ~X;
      else
         Y = X;
endmodule
```



```
module  adder  (sum, cy_out, in1, in2, cy_in);
   input [7:0]  in1, in2;
   input  cy_in;
   output [7:0]  sum;       reg [7:0]  sum;
   output  cy_out;          reg  cy_out;

   always  @ (in1 or in2 or cy_in)
      {cy_out, sum}  =  in1  +  in2  +  cy_in;
endmodule
```

```
module  parity_checker (out_par, in_word);
   input  [8:0]  in_word;
   output  out_par;

   always  @ (in_word)
      out_par  =  ^ (in_word);
endmodule
```

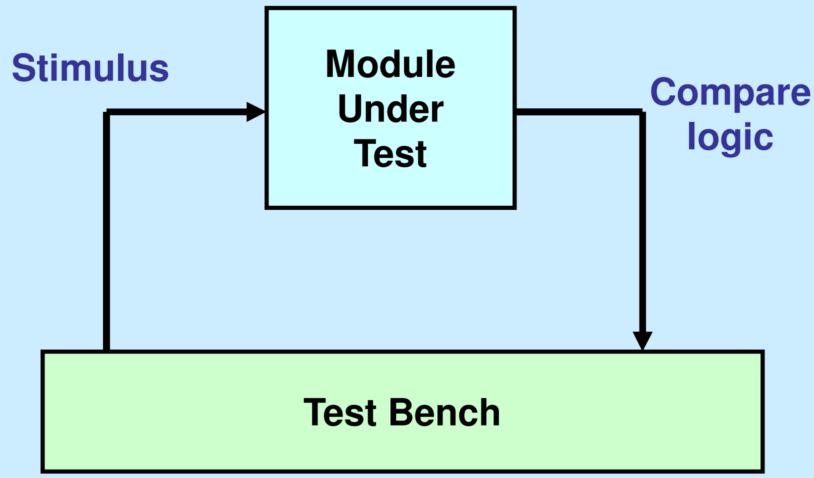


```
// Top level module
module  add_sub_parity  (p, a, b, add_sub);
   input [7:0]  a, b;
   input  add_sub;      // 0 for add, 1 for subtract
   output  p;              // parity of the result
   wire [7:0]  Bout, sum;    wire  carry;

   complementor  M1 (Bout, B, add_sub);
   adder  M2 (sum, carry, A, Bout, add_sub);
   parity_checker  M3 (p, {carry, sum});
endmodule
```

Verilog Test Bench

Introduction

- What is test bench?
  - A Verilog procedural block which executes only once.
  - Used for simulation.
  - Testbench generates clock, reset, and the required test vectors.



How to Write Testbench?

- Create a dummy template
  - Declare inputs to the module-under-test (MUT) as “reg”, and the outputs as “wire”.
  - Instantiate the MUT.
- Initialization
  - Assign some known values to the MUT inputs.
- Clock generation logic
  - Various ways to do so.
- May include several simulator directives
  - Like $display, $monitor, $dumpfile, $dumpvars, $finish.

- **$display**
  - Prints text or variables to stdout.
  - Syntax same as "printf".
- **$monitor**
  - Similar to $display, but prints the value whenever the value of some variable in the given list changes.
- **$finish**
  - Terminates the simulation process.
- **$dumpfile**
  - Specify the file that will be used for storing the waveform.
- **$dumpvars**
  - Starts dumping all the signals to the specified file.

Example Test Bench

```
module  shifter_toplevel;
        reg  clk, clear, shift;
        wire [7:0]  data;

        shift_register S1 (clk, clear, shift, data);
        initial
           begin
                clk = 0;   clear = 0;   shift = 0;
           end
        always
                #10 clk = !clk;
  endmodule
```

Test Bench: More Complete Version

```
module  shifter_toplevel;
        reg  clk, clear, shift;
        wire [7:0]  data;

        shift_register S1 (clk, clear, shift, data);
        initial
           begin
                clk = 0;   clear = 0;   shift = 0;
           end
        always
                #10 clk = !clk;
```

contd..


```
        initial
          begin
                $dumpfile ("shifter.vcd");
                $dumpvars;
          end
        initial
          begin
                $display ("\ttime, \tclk, \tclr, \tsft, \tdata);
                $monitor ("%d, %d, %d, %d, %d", $time,
                               clk, reset, clear, shift, data);
          end
        initial
                #400  $finish;
       ***** REMAINING CODE HERE  ******
endmodule
```

A Complete Example

```
module  testbench;
   wire  w1, w2, w3;
   xyz  m1  (w1, w2, w3);
   test_xyz  m2  (w1, w2, w3);
endmodule

module  xyz  (f, A, B);
   input  A, B;    output  f;
   nor  #1 (f, A, B);
endmodule
```

contd..


```
module  test_xyz  (f, A, B);
   input  f;
   output  A, B;
   reg  A, B;
   initial
        begin
           $monitor ($time, “A=%b”, “B=%b”, f=%b”,
                                          A, B, f);
           #10  A = 0;  B = 0;
           #10  A = 1;  B = 0;
           #10  A = 1;  B = 1;
           #10  $finish;
        end
endmodule
```

Pipelining Example

- Consider the following arithmetic computation:

  X = (A + B) * (B – C + D)

  Y = (B – C + D)

- Suppose we break into three stages:
  - S1: S1_T1 = A+B; S1_T2 = B-C; S1_T3 = D;
  - S2: S2_T1 = S1_T1; S2_T4 = S1_T2 + S1_T3;
  - S3: S3_X = S2_T1 * S2_T4; S3_Y = S2_T4;


```
module pipeline_example (A, B, C, D, X, Y, clk);
      input [0:7]  A, B, C, D, clk;
      output X, Y;
      wire [0:18] X;    wire [0:9] Y;
      reg [0:8] S1_T1, S2_T1, S1_T2;
      reg [0:7] S1_T3;   reg [0:9] S2_T4, S3_Y;   reg [0:18] S3_X;

      assign  X = S3_X;    assign  Y = S3_Y;
      always  @(posedge clk)
      begin
        S1_T1 <= A + B;    S1_T2 <= B – C;    S1_T3 <= D;
        S2_T1 <= S1_T1;    S2_T4 <= S1_T2 + S1_T3;
        S3_X <= S2_T1 * S2_T4;    S3_Y <= S2_T4;
      end;
endmodule
```