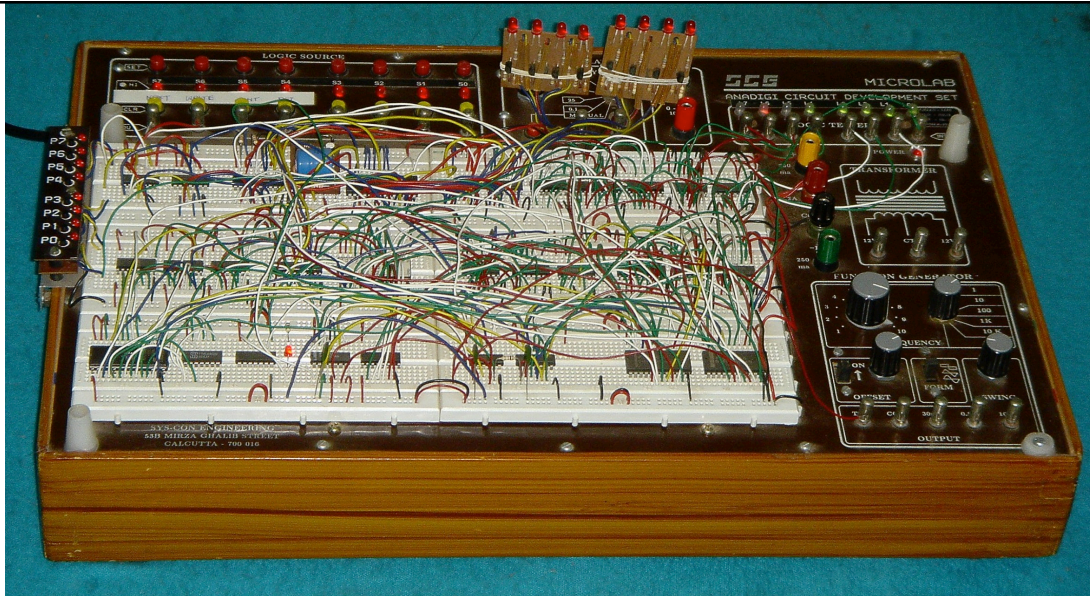# VERILOG
Hardware Description Language

1

Before we start …

4-Bit CPU implemented on breadboard
192 instructions : indexed addressing : battery back-up
Hardware Lab. CSE-IIT-KGP : 2003-04

3

FPGA Board

A programmable
device where a
design specified in
Verilog can be
downloaded.

1	Power select jumper and battery header	13	FPGA configuration reset button
2	Shared UART/ JTAG USB port	14	CPU reset button (for soft cores)
3	External configuration jumper (SD / USB)	15	Analog signal Pmod connector (XADC)
4	Pmod connector(s)	16	Programming mode jumper
5	Microphone	17	Audio connector
6	Power supply test point(s)	18	VGA connector
7	LEDs (16)	19	FPGA programming done LED
8	Slide switches	20	Ethernet connector
9	Eight digit 7-seg display	21	USB host connector
10	JTAG port for (optional) external cable	22	PIC24 programming port (factory use)
11	Five pushbuttons	23	Power switch
12	Temperature sensor	24	Power jack
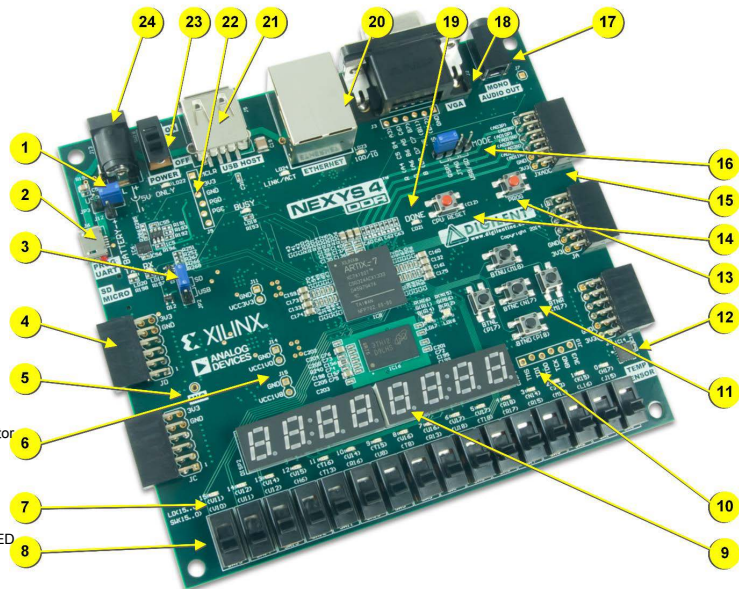
4

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.
- The differences become clear if someone analyzes the language features.

5

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.

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Basic Syntax of Module Definition

```
module  module_name  (list_of_ports);
        input/output declarations
        local net declarations
        Parallel  statements
endmodule
```

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Example 1: A simple AND function

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

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Example 2 :: A 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
```

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Example 3 :: A hierarchical design

```
module add (co, sum, a, b, cin);
    input a, b, cin;
    output co;
    assign co = (a & b) | (b & cin)
                        | (cin & a);
    assign sum = a ^ b ^ cin;
endmodule
```

```
module add3 (s, cy3, cy_in, x, y);
    input [2:0] x, y;
    input cy_in;
    output [2:0] s;
    output cy3;
    wire [1:0]  cy_out;
    add B0 (cy_out[0], s[0], x[0], y[0], cy_in);
    add B1 (cy_out[1],s[1],x[1],y[1],cy_out[0]);
    add B2 (cy3, s[2], x[2], y[2], cy_out[1]);
endmodule
```

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Specifying Connectivity

- There are two alternate ways of specifying connectivity:
  - Positional association
    - The connections are listed in the same order
      ```
      add  A1 (c_out, sum, a, b, c_in);
      ```
  - Explicit association
    - May be listed in any order
      ```
      add A1 (.in1(a),.in2(b),.cin(c_in),.sum(sum),.cout(c_out));
      ```

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Variable Data Types

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

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(1) "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.

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

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

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```
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
```

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(2) "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] is MSB

• For 'integer', it takes the default size, usually 32-bits.
  • The synthesis tool tries to determine the size.

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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.

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Specifying Constant Values

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

    <size>'<base><number>

- Examples:

  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

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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).
- Examples:

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

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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'

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• Verilog provides a set of predefined logic gates.
  • AND, OR, XOR, NAND, NOR, NOT.
  • 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

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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);
```

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- 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);
```

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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.

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```
`timescale  10ns / 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
```

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Hardware Modeling Issues

21/08/23

Some Facts

- 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.

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```
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

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```
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

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```
// A latch gets inferred here
module  simple_latch  (data, load, d_out);
   input    data, load;
   output  d_out;
   wire t;
   always @(load or data)
    begin
        if (!load)
            t = data;
        d_out = t;
    end
endmodule
```

Else part missing; so latch is inferred.

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Verilog Operators

- Arithmetic operators

    *, +, -, %

- Logical operators

    !   → logical negation

    && → logical AND

    | | → logical OR

- Relational operators

    >, <, >=, <=, ==, !=

- Bitwise operators

    ~, &, |, ^, ~^

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- 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   { { } }

- Conditional

    <condition> ? <expression1> : <expression2>

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```
module  operator_example  (x, y, f1, f2);
    input   x, y;
    output  f1, f2;
    wire [9:0] x, y;
    wire [4:0] f1;
    wire  f2;

    assign   f1  =  x[4:0]  &  y[4:0];
    assign   f2  =  x[2]  |  ~f1[3];
    assign   f2  =  ~&  x;
    assign   f1  =  f2  ?  x[9:5]  :  x[4:0];
endmodule
```

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```
//  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
```

34   34

Description Styles in Verilog

Introduction

- Two different styles of description:
  1) Data flow
     - Continuous assignment
  2) Behavioral
     - Procedural assignment
       a) Blocking
       b) Non-blocking

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(1) 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.

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- 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.

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```
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

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```
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

40

```
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

41   41

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

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

Using "assign" to describe sequential logic

42   42

(2) 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
  a) The "always" block
     - A continuous loop that never terminates.
  b) The "initial" block
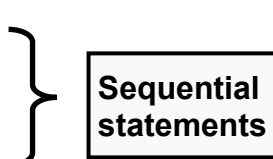   - Executed once at the beginning of simulation (used in Test-benches).

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

```
always @(event_expression)
    begin
        statement;
           :
        statement;
    end
```

Sequential statements

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

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- Only "reg" type variables can be assigned within an "always" block. Why??
  - The sequential "always" block executes only when the event expression triggers.
  - At other times the block is doing nothing.
  - An object being assigned to must therefore remember the last value assigned (not continuously driven).
  - So, only "reg" type variables can be assigned within the "always" block.
  - Any kind of variable may appear in the event expression (reg, wire, etc.).

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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.**

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```
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.
```

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```
//  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
```

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```
// 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
```

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```
// 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***

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```
// 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*

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```
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
```

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```
module  priority_encoder (in, code);
    input  [0:3] in;
    output [0:1] code;
    reg [0:1] code;
    always  @(in)
        case (1'b1)
            input[0] : code = 2'b00;
            input[1] : code = 2'b01;
            input[2] : code = 2'd10;
            input[3] : code = 2'b11;
        endcase
endmodule
```

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Verilog Test Bench

Verilog Test Bench

- What is test bench?
  - A Verilog procedural block that executes only once.
  - Used for simulation.
  - Test bench generates clock, reset, and the required test vectors for a given *design-under-test* (DUT).
  - The test bench can monitor the DUT outputs and present them in a way as specified by the creator.
    - Print the values of the signal lines.
    - Dump the values in a file from where waveforms can be viewed.

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- Basic requirements:
  - The inputs of the DUT need to be connected to the test bench.
  - The outputs of the DUT needs also to be connected to the test bench.
- Points to note:
  - Test benches use the "*initial*" procedural block that executes only once.
  - Can also use "*always*" for generating some test inputs, like a clock signal.

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TEST BENCH

Stimulus

Design Under Test
(DUT)
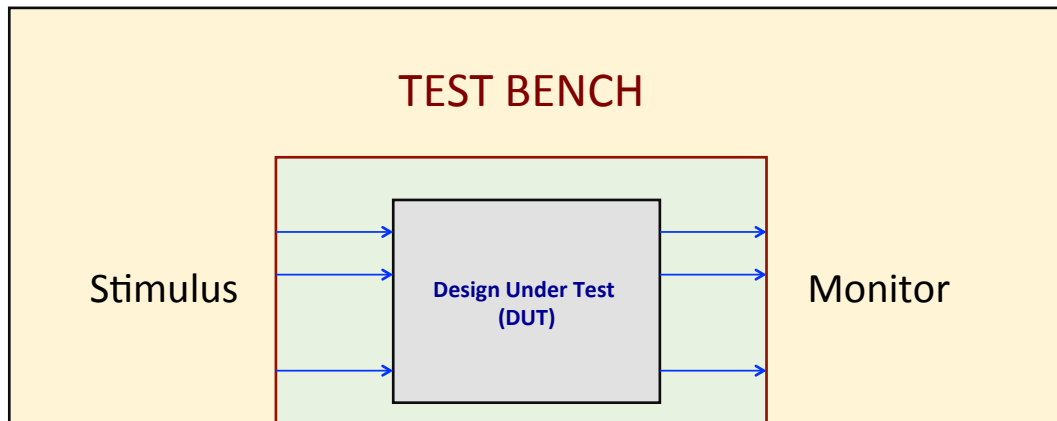
Monitor

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A Simple Example

```
module example (A,B,C,D,E,F,Y);
  input A,B,C,D,E,F;
  output Y;
  wire  t1, t2, t3, Y;

  nand  #1 G1 (t1,A,B);
  and   #2 G2 (t2,C,~B,D);
  nor   #1 G3 (t3,E,F);
  nand  #1 G4 (Y,t1,t2,t3);
endmodule
```

```
module  testbench;
  reg  A,B,C,D,E,F;  wire Y;
  example DUT(A,B,C,D,E,F,Y);

  initial
    begin
      $monitor ($time," A=%b, B=%b, C=%b,
        D=%b, E=%b, F=%b, Y=%b",
        A,B,C,D,E,F,Y);
      #5 A=1; B=0; C=0; D=1; E=0; F=0;
      #5 A=0; B=0; C=1; D=1; E=0; F=0;
      #5 A=1; C=0;
      #5 F=1;
      #5 $finish;
    end
endmodule
```

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How to write test benches?

- Create a dummy template
  - Declare inputs to the design-under-test (DUT) as "*reg*", and the outputs as "*wire*".
    - Because we have to initialize the DUT inputs inside procedural block(s), typically "*initial*", where only "*reg*" type variables can be assigned.
  - Instantiate the DUT.
- Initialization and Monitoring
  - Assign some known values to the DUT inputs.
  - Monitor the DUT outputs for functional verification.

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- For synchronous sequential circuits:
  - We need some clock generation logic.
  - Various ways to specify clock signal.
- Test bench can include various simulator directives:
  - *$display*, *$monitor*, *$dumpfile*, *$dumpvars*, *$finish*, etc.
- Important point:
  - We do not need test bench when we are synthesizing a design.
  - Required only during simulation.

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The Simulator Directives

- **$display ("<format>", expr1, expr2, ...);**
  - Used to print the immediate values of text or variables to stdout.
  - Syntax is very similar to "printf" in C.
  - Additional format specifiers are supported, like "b" (binary), "h" (hexadecimal), etc.
- **$monitor ("<format>", var1, var2, ...);**
  - Similar in syntax to *$display*, but does not print immediately.
  - It will print the value(s) whenever the value of some variable(s) in the given list changes.
  - Has the functionality of *event-driven* print.

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- **$finish;**
  - Terminates the simulation process.
- **$dumpfile (<filename>);**
  - Specifies the file that will be used for storing the values of the selected variables so that they can be graphically visualized later.
  - The file typically has an extension *.vcd (Value Change Dump)*, and contains information about any value changes on the selected variables.
- **$dumpoff;**
  - This directive stops the dumping of variables. All variables are dumped with "x" values and the next change of variables will not be dumped.
- **$dumpon;**
  - This directive starts previously stopped dumping of variables.

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- **$dumpvars (level, list_of_variables_or_modules);**
  - Specifies which variables should be dumped to the *.vcd* file.
  - Both the parameters are optional; if both are omitted, all variables are dumped.
  - If *level=0*, then all variables within the modules from the list will be dumped. If any module from the list contains module instances, then all variables from these modules will also be dumped.
  - If *level=1*, then only listed variables and variables of listed modules will be dumped.
- **$dumpall;**
  - The current values of all variables will be written to the file, irrespective of whether there has been any change in their values or not.
- **$dumplimit (filesize);**
  - Used to set the maximum size of the .vcd file.

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Example 1: Full Adder

```
module full_adder (s, co, a, b, c);
   input a, b, c;
   output s, co;
   assign  s = a ^ b ^ c;
   assign  co = (a & b) | (b & c) | (c & a);
endmodule
```

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```
module  testbench_1;
   reg  a, b, c;  wire sum, cout;
   full_adder FA (sum, cout, a, b, c);

   initial
     begin
       $monitor ($time," a=%b, b=%b, c=%b, sum=%b, cout=%b",
                    a, b, c, sum, cout);
       #5 a=0; b=0; c=1;
       #5 b=1;
       #5 a=1;
       #5 a=0; b=0; c=0;
       #5 $finish;
     end
endmodule
```

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```
module  testbench_2;
  reg  a, b, c;  wire sum, cout;
  integer i;
  full_adder FA (sum, cout, a, b, c);

  initial
    begin
      for (i=0; i<8; i=i+1)
       begin
         {a,b,c} = i;  #5;
         $display ("T=%2d, a=%b, b=%b, c=%b, sum=%b, cout=%b",
                    $time, a, b, c, sum, cout);
       end
      #5 $finish;
    end
endmodule
```

```
T= 5, a=0, b=0, c=0, sum=0, cout=0
T=10, a=0, b=0, c=1, sum=1, cout=0
T=15, a=0, b=1, c=0, sum=1, cout=0
T=20, a=0, b=1, c=1, sum=0, cout=1
T=25, a=1, b=0, c=0, sum=1, cout=0
T=30, a=1, b=0, c=1, sum=0, cout=1
T=35, a=1, b=1, c=0, sum=0, cout=1
T=40, a=1, b=1, c=1, sum=1, cout=1
```

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Example 2: Generating random test vectors

```
module adder (out, cout, a, b);
  input [7:0] a, b;
  output [7:0] out;
  output cout;

  assign #5 {cout,out} = a + b;
endmodule
```

- The system task *$random* can be used to generate a random number.
- It is called as : *$random (<seed>)*
    - The value of *<seed>* is optional and is used to ensure that the same sequence of random numbers are generated each time the test is run.

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```
module test_adder;
  reg [7:0] a, b;
  wire [7:0] sum;  wire cout;
  integer myseed;

  adder ADD (sum, cout, a, b);

  initial  myseed = 15;

  initial
    begin
      repeat (5)
        begin
          a = $random(myseed);
          b = $random(myseed); #10;
          $display ("T: %3d, a: %h, b: %h, sum: %h", $time, a, b, sum);
        end
    end
endmodule
```

```
T:  10, a: 00, b: 52, sum: 52
T:  20, a: ca, b: 08, sum: d2
T:  30, a: 0c, b: 6a, sum: 76
T:  40, a: b1, b: 71, sum: 22
T:  50, a: 23, b: df, sum: 02
```

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