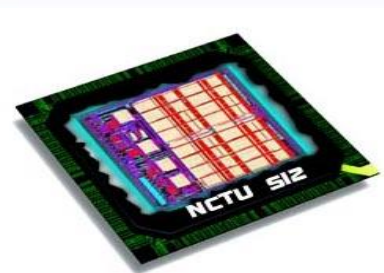


Introduction to SystemVerilog & Advanced Testbench

Lecturer: Chih-Wei Peng



Outline

- ✓ **Section 1 Introduction**
- ✓ **Section 2 Design using SystemVerilog**
 - Data Type, enumerate, structure, union
 - Procedure Block
 - Interface
- ✓ **Section 3 Verification using SystemVerilog**
 - OOP (Object-Oriented Programming)
 - Randomization



Outline

✓ Section 1 Introduction

✓ Section 2 Design using SystemVerilog

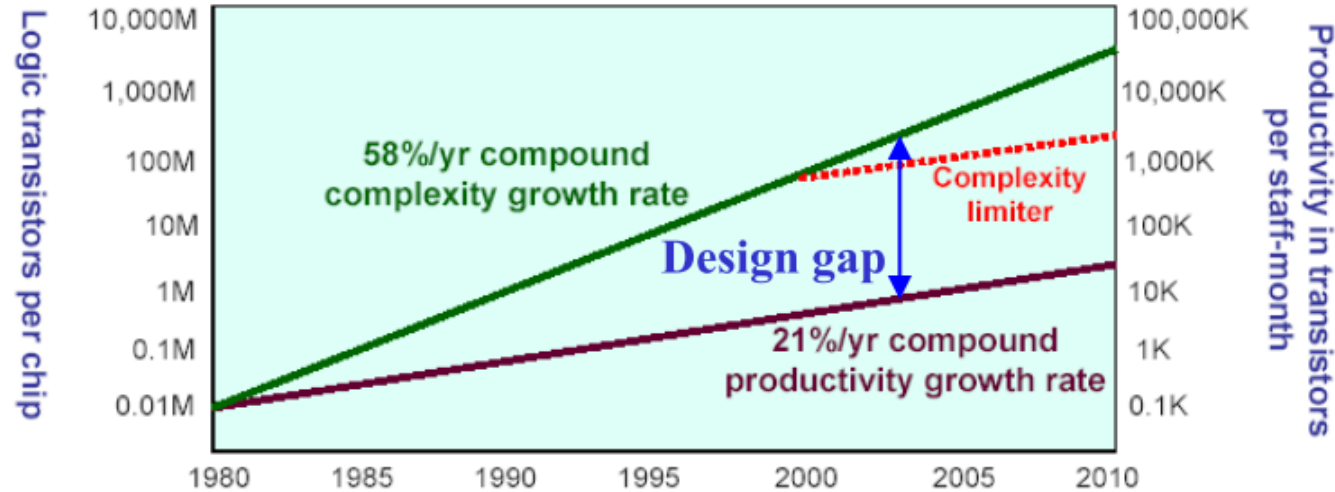
- Data Type, enumerate, structure, union
- Procedure Block
- Interface

✓ Section 3 Verification using SystemVerilog

- OOP (Object-Oriented Programming)
- Randomization



Why SystemVerilog?



- ✓ **Human factors may limit design more than technology**
- ✓ **Keys to solve the productivity crisis**
 - Higher abstract language to enhance design & verification
 - Design techniques: hierarchical design, SoC design (IP reuse, platform-based design), etc
 - CAD: algorithms & methodology

Source: http://access.ee.ntu.edu.tw/course/under_project_1011/slides/20120925_IC_Design_Flow.pdf



Why SystemVerilog?

✓ Designs efficiency

- Need to code for reuse and **higher abstraction**
- Need more efficient coding constructs with **native language support**

✓ System level hardware design/verification languages

- Unification of both syntax and semantics with one language improves communication between design team and verification team

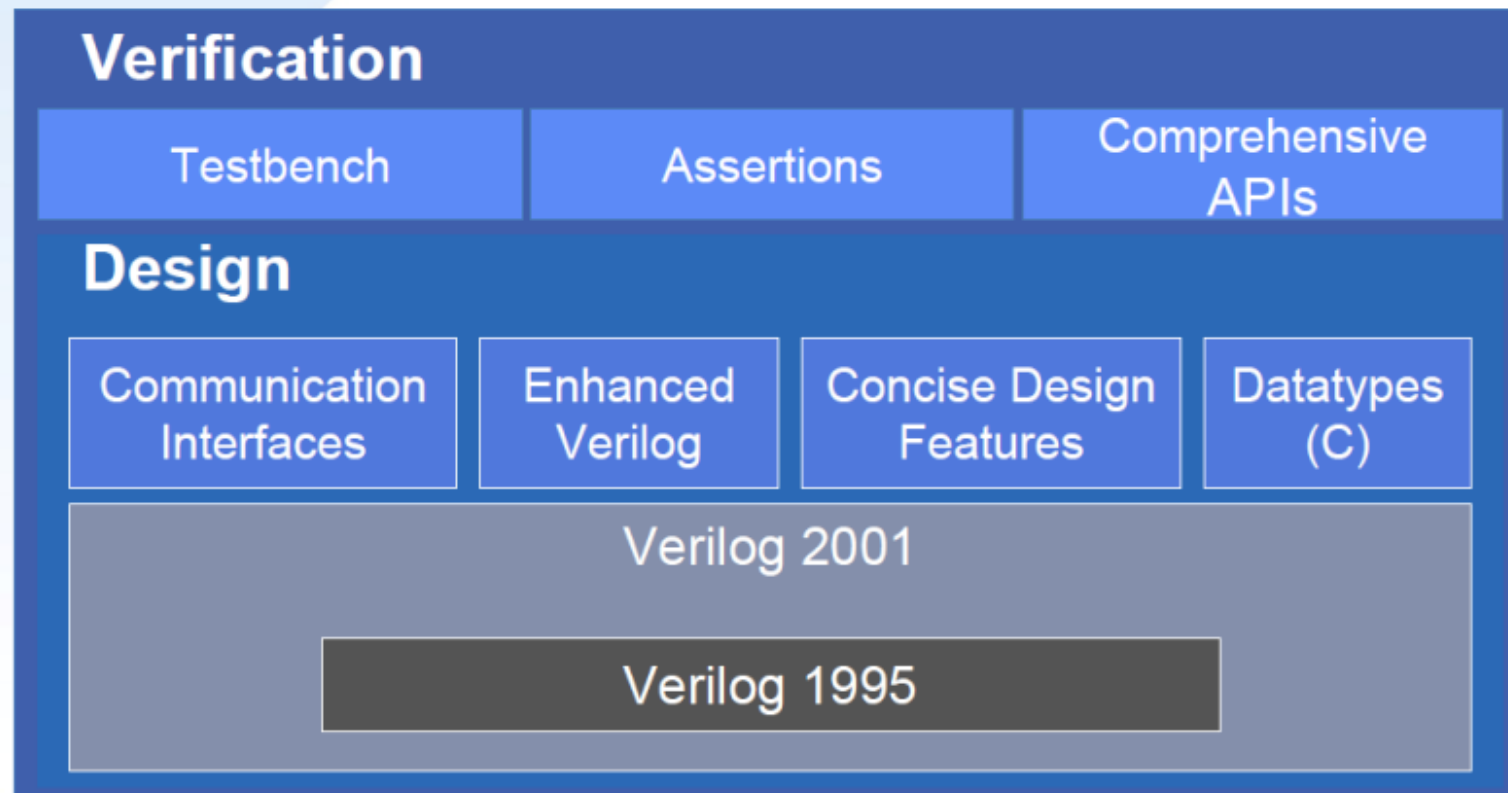
✓ Testbenches are growing exponentially

- Find a way to **generate more useful test data and make testing faster**
- More advanced verification techniques (ex: OOP)
- Verification Library (ex: UVM, Universal Verification Methodology)

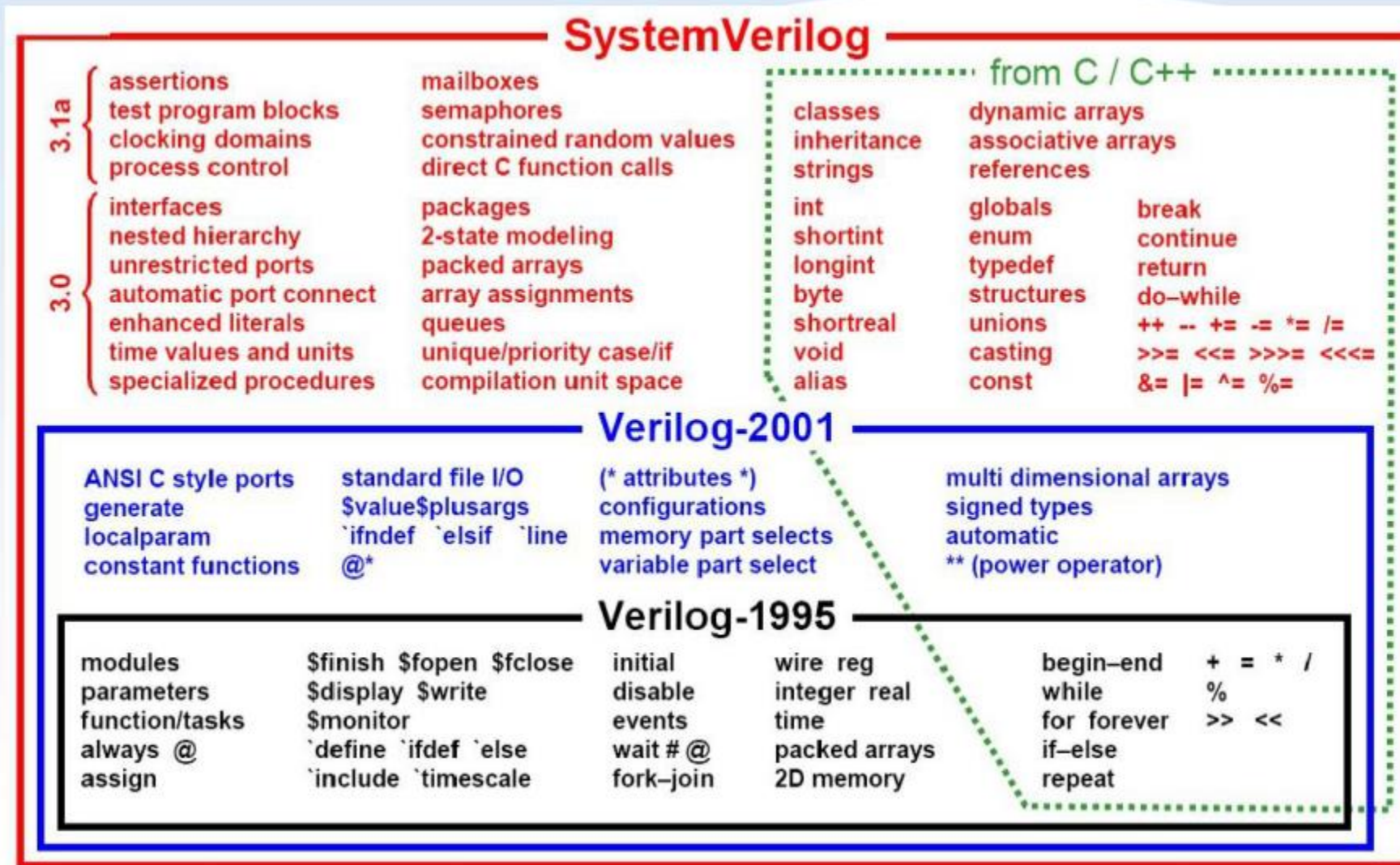


What is SystemVerilog?

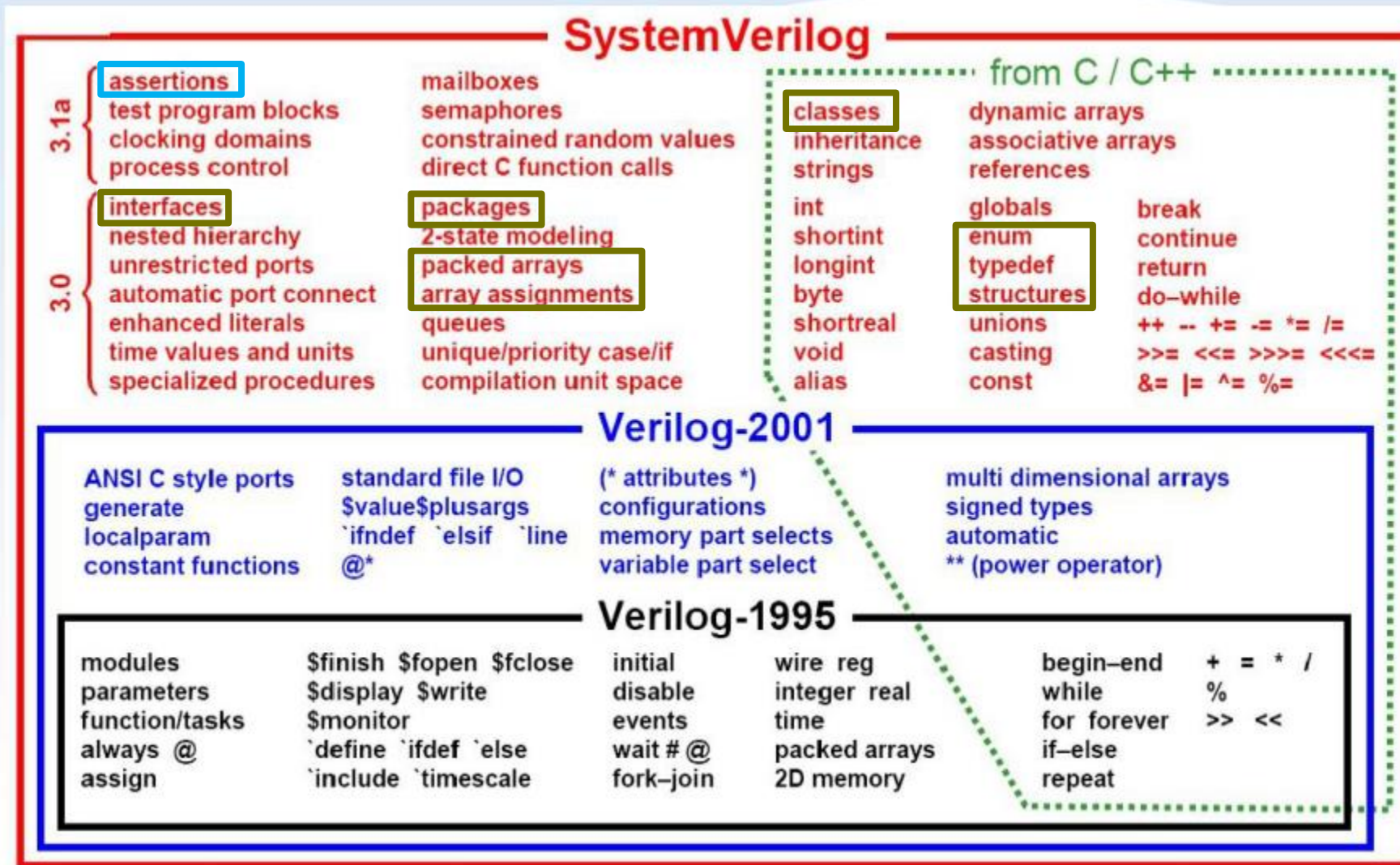
- ✓ **The third generation of Verilog**
 - Specified in IEEE Std 1800-2005
- ✓ **Fully backward compatible with Verilog 2001**



Overview of SystemVerilog



Overview of SystemVerilog



The SystemVerilog Design Environment

✓ **testbed.sv**

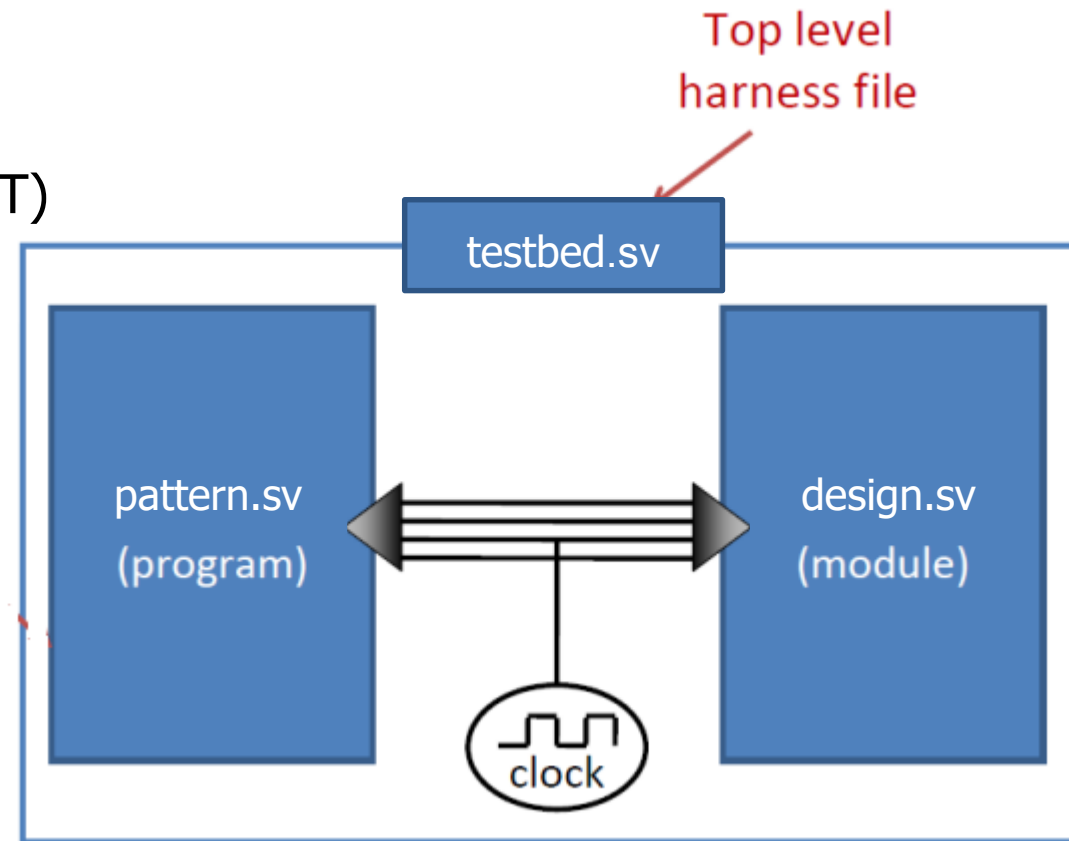
- Connecting testbench and design modules
- Generating clock
- Dump waveform

✓ **design.sv**

- Design under test (DUT)

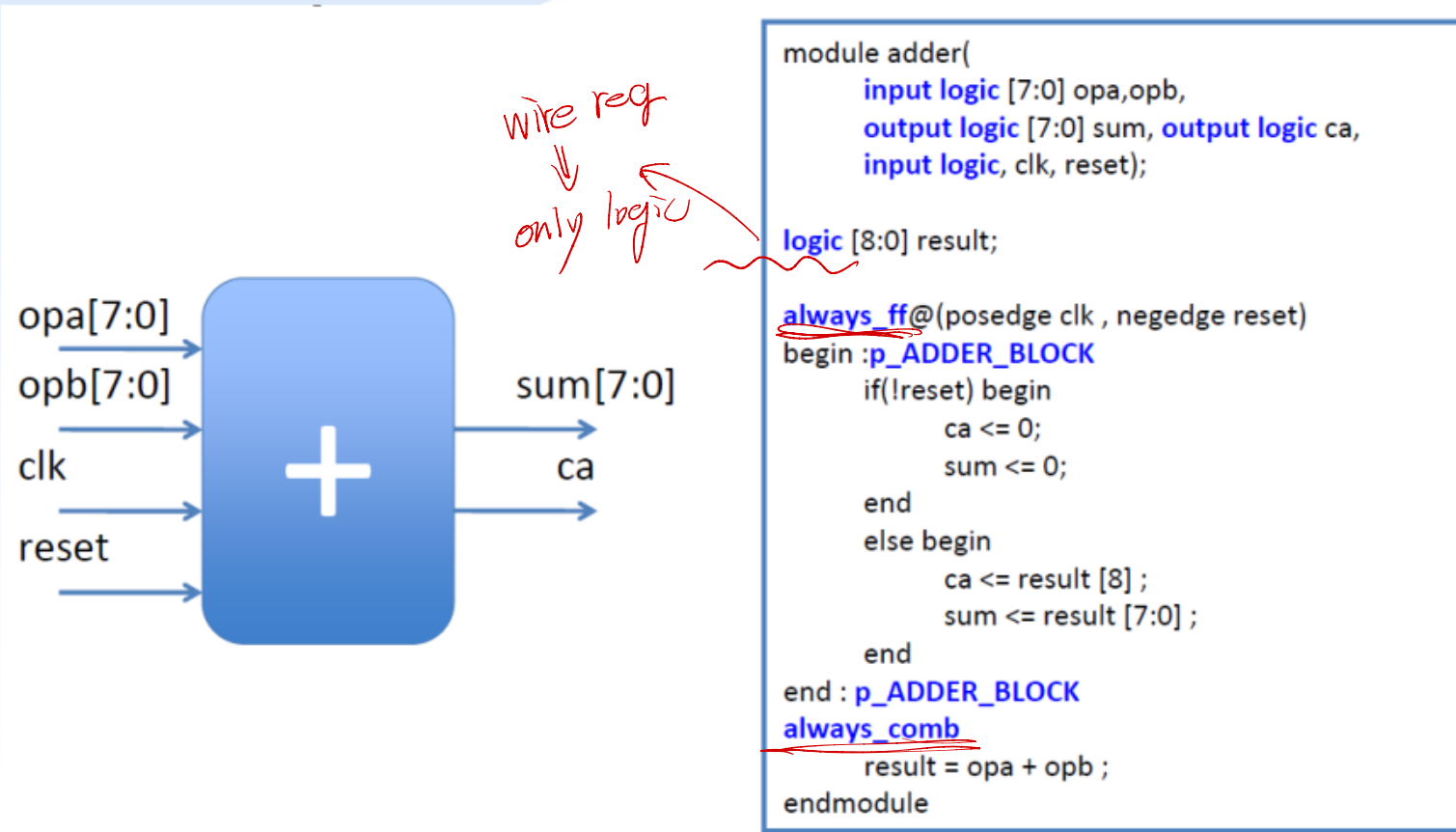
✓ **pattern.sv**

- Pattern
- Test program
- Assertion
- Coverage



Simple Example: 8-bit Adder (1/3)

✓ RTL description



Simple Example: 8-bit Adder (2/3)

✓ Test pattern

- Generate stimulus
- Monitor response

```
program automatic test(output logic [7:0] opa,  
                        output logic [7:0] opb,  
                        output logic reset,  
                        input wire clock,  
                        input logic [7:0] sum,  
                        input logic ca);
```

initial begin

```
    reset <= 1'b1;  
    opa <= 0;  
    opb <= 0;  
    repeat(5) @ (posedge clock);  
    reset <= 1'b0;  
    repeat(5) @ (posedge clock);  
    reset <= 1'b1;  
    opa <= 10;  
    opb <= 20;  
    @(posedge clock);  
    $display("%d + %d = %d", opa, opb, sum);  
    repeat(5) @(posedge clock);  
    $display("Adder Simulation End");
```

end

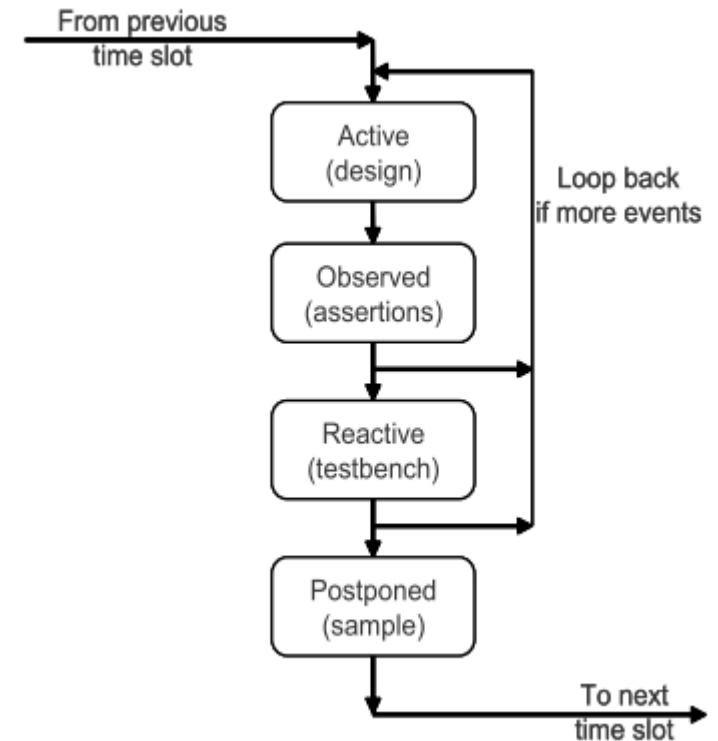
endprogram



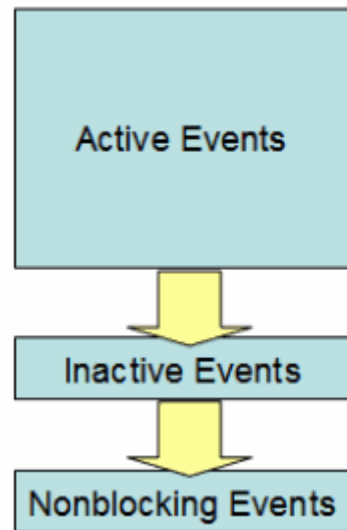
Program Block

- ✓ **Purpose: Identifies verification code**
- ✓ **A program differs from a module**
 - Only initial blocks allowed
 - Execute in reactive region

```
program name (<port_list>);  
  <declarations>; // type, func, class, clocking...  
  <continuous_assign>  
  initial <statement_block>  
endprogram
```



Program Block



Blocking assignments

Evaluate RHS of nonblocking assignments

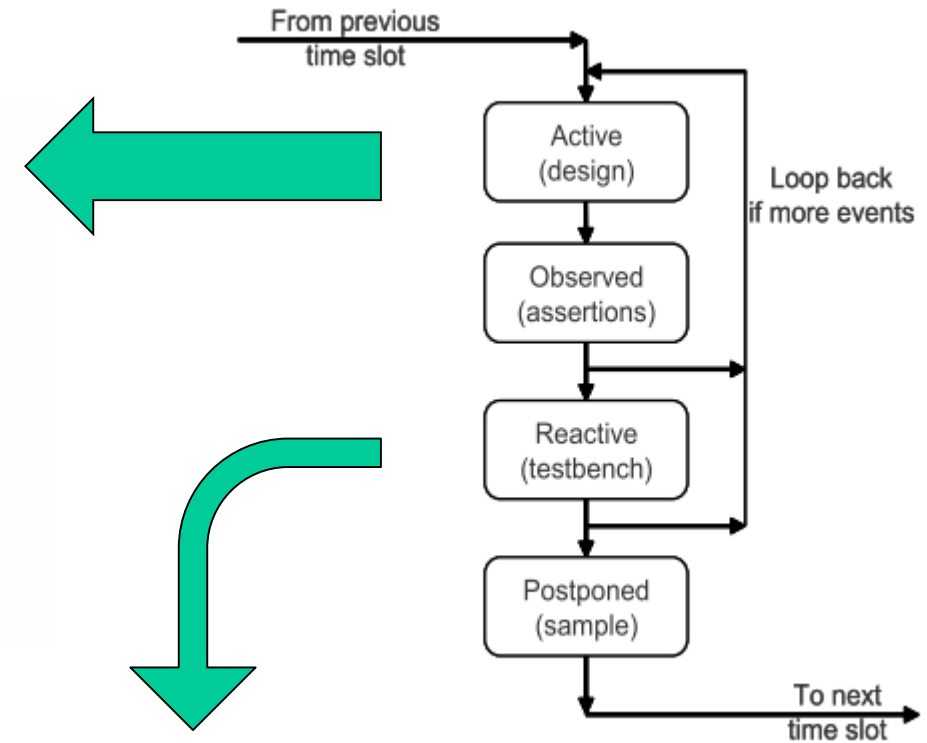
Continuous assignments

\$display command execution

\$fwrite command execution

#0 blocking assignments

Update LHS of nonblocking assignments



Program block will be executed In reactive region

Program Block

```
module DUT();  
  reg q = 0;  
  reg clk = 0;  
  initial  
    #10 clk = 1;  
  
  always @(posedge clk)  
    q <= 1;  
  
endmodule  
  
module Module_based_TB();  
  
  always @ (posedge DUT.clk) $display("Module_based_TB : q = %b\n", DUT.q);  
  
endmodule  
  
program Program_based_TB();  
  
  initial  
    forever @(posedge DUT.clk) $display("Program_based_TB : q = %b\n", DUT.q);  
  
endprogram  
RESULT:  
  
Module_based_TB : q = 0  
  
program_based_TB : q = 1
```



Simple Example: 8-bit Adder (3/3)

✓ Top Level Harness file

```
`timescale 1ns/100ps
module top;
  parameter simulation_cycle = 100;
  bit SystemClock;
  logic [7:0] opa, opb, sum;
  logic      reset, ca;
  test test_p( .opa (opa), .opb(opb), .clock(SystemClock), .reset(reset), .sum(sum), .ca (ca) );

  adder dut( .opa(opa), .opb(opb), .clock(SystemClock), .reset(reset), .sum(sum), .ca(ca) );

  initial begin
    SystemClock = 0;
    forever begin
      #(simulation_cycle/2)
        SystemClock = ~SystemClock;
    end
  end
  initial begin
    $fsdbDumpfile();
  end
endmodule
```

instance testbench

instance design

Generate clock

Dump waveform



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Data Type in Verilog

- ✓ **The Verilog language uses the reg type as a general purpose variable**
 - Both combinational and sequential circuits can be model using reg
 - reg type has no connection to register, which often causes misunderstanding
- ✓ **Lacks of user-defined type**



Data Type in SystemVerilog

✓ 4-State Variables (1|0|Z|X) ➡ ✗

(default value is X if not initialized)

- `logic w;` // can be used in both assignment and procedure blocks
 - No input and output restriction anymore
 - No continuous or block procedure restriction
- `reg r;` // the same as Verilog
- `integer i;` // Verilog-2001 >= fixed size (32-bit data type)

```
1 logic net_A, net_B;  
2  
3 assign net_A = y;  
4  
5 always @* begin  
6     net_B = y ;  
7 end
```

✓ 2-State Variables (1|0) ➡ ✓ *more use*

(default value is 0 if not initialized)

- `shortint s;` // 16-bit signed integer
- `int i;` // 32-bit signed integer
- `longint l;` // 64-bit signed integer
- `byte b8;` // 8-bit signed integer
- `bit b;` // 1-bit integer

Array

✓ Verilog-2001:

- A dimension declared before the object name is referred to as the “vector width” dimension.
- The dimensions declared after the object name are referred to as the “array” dimensions.

`reg [7:0] r1 [1:256];` // [7:0] is the vector width, [1:256] is the array size

✓ SystemVerilog :

object name 前的大小

- “***packed array***” refers to the dimensions declared before the object name (what Verilog-2001 refers to as the vector width)
- “***unpacked array***” refers to the dimensions declared after the object name

object name 後的大小

- Example

1 bit [3:0] [7:0] test [1:10]; // 10 entries of 4 bytes (packed into 32 bits)
2 // can be used as follows:
3 test [9] = test[8] + 1; // 4 byte add
4 test [7][3:2] = test [6][1:0]; // 2 byte copy

unpacked array



Typedef

✓ Make code clear

- SystemVerilog's data type system allows you to define quite complex types. To make this kind of code clear, the **typedef** facility was introduced
- **typedef** allows users to create their own names for type definitions that they will use frequently in their code

✓ Example1:

```
1 typedef reg [7:0] octet;  
2 octet b;  
3 // is the same as  
4 reg [7:0] b;
```

✓ Example2:

```
1 typedef octet [3:0] quadOctet;  
2 quadOctet qBytes [1:10];  
3 // is the same as  
4 reg [3:0][7:0] qBytes [1:10];
```



Enumerate

✓ Create enumerated data types:

- Defines a set of named values, which provides built-in assertion!!
- Data type defaults to **int** (32-bit, 2state, signed int)
- **Variable initialized to 0** if initial values aren't specified

✓ Create enum variables:

// anonymous enumerated type

- **enum** <type> {lists_of_enumerations} <enumvar>;
 enum { circle, ellipse, freeform } c;

// typed enumerated type

- **typedef enum** <type> {lists_of_enumerations} <enumtype>; enumtype variable_name;
 typedef enum { circle, ellipse, freeform } ClosedCurve;
 ClosedCurve c;

✓ Often use to represent state machine



Enumerate

✓ Example1:

```
1 // default int type
2 enum {red, yellow, green} light1, light2;
3 enum {bronze=3, silver, gold} medal;           // silver=4, gold=5
4 enum {a=0, b=7, c, d=8} alphabet;             // Syntax error
5
6 // enumerated type with a 2-bit logic type
7 typedef enum logic [1:0] {WAIT, LOAD, READY} state_t;
8 state_t state, next_state;
```

```
typedef enum logic [2:0]
{ a=3'd0, b=3'd1, c, d=3'd5 } // ok, c=2
{ a=3'd0, b=3'd1, c, d=3'd2 } // error!
{ a=3'd0, b=3'd1, c=3'd7, d } // error!
```

✓ Example2:

```
1 // Must match the size of the base type (default to int)
2 enum logic [2:0] {WAIT=3'b001, LOAD=3'b010, READY=3'b100} state;
3
4 //syntax error!!! (Error enum value size)
5 enum {WAIT=3'b001, LOAD=3'b010, READY=3'b100} state;
```

→ default is int (32-bit)



Structure

- ✓ **Group related signals to enhance readability and clearly convey designer's intent (ex: CPU's instruction)**
- ✓ **Create structures data types:**
 - Structures are a collection of variables
 - **typedef struct{**
 <data_type> variable0;
 <data_type> variable1;
}struct_type;
- ✓ **Create structure variables:**
 - **struct{**
 <data_type> variable0;
 <data_type> variable1;
}struct_variable;



Structure

✓ Example:

```
1 typedef struct{
2     int a,b;
3     opcode_t opcode;
4     logic[31:0] address;
5     bit error;
6 }Instruction;
7
8 Instruction IR;
9 IR.address = 32'hF000001E;
```

```
1 struct{
2     int a,b;
3     opcode_t opcode;
4     logic[31:0] address;
5     bit error;
6 }IR;
7
8 IR.address = 32'hF000001E;
9
```

Union

- ✓ A SystemVerilog union allows a **single piece of storage** to be represented different ways using **different named member types**.

```
typedef logic [3:0] type_A;
typedef logic [7:0] type_B;
typedef type_B[1:0] type_C;
// 2個8ビット = 16ビット
typedef struct packed {
    integer    temp_int;    // 32-bits
    type_C     c;           // 16-bits
    logic[15:0] d;          // 16-bits
} type_struct ;           // 64-bits

typedef union packed{
    type_struct    mem_struct;
    type_A         [15:0] mem_a;
    type_B         [7:0]  mem_b;
    type_C         [3:0]  mem_c;
}my_union_type;
```

```
my_union_type my_union;
type_A        get_a;
type_B        get_b;
always_ff@(posedge clk or negedge inf.rst_n) begin
    if(!inf.rst_n)begin
        get_a <= 'b0;
    end
    else begin
        get_a <= my_union.mem_a[0];
    end
end
always_ff@(posedge clk or negedge inf.rst_n) begin
    if(!inf.rst_n)begin
        get_b <= 'b0;
    end
    else begin
        get_b <= my_union.mem_b[1];
    end
end
end
```



Package

- ✓ To enable sharing a user-defined type definition across multiple modules, SystemVerilog adds ***packages*** to the Verilog language

```
package definitions;

    parameter VERSION = "1.1";

    typedef enum {ADD, SUB, MUL} opcodes_t;

    typedef struct {
        logic [31:0] a, b;
        opcodes_t    opcode;
    } instruction_t;

endpackage
```



Package in module

- ✓ When the case statement references the enumerated labels of ADD, SUB, and MUL, as well as the function multiplier, it will find the definitions of these names in the **definitions package**

```
module ALU
(input  definitions::instruction_t  IW,
 input  logic                      clock,
 output logic [31:0]              result
);

    always_comb begin
        case (IW.opcode)
definitions::ADD : result = IW.a + IW.b;
definitions::SUB : result = IW.a - IW.b;
definitions::MUL : result = multiplier(IW.a, IW.b);
        endcase
    end
endmodule
```

```
package definitions;
    parameter VERSION = "1.1";
    typedef enum {ADD, SUB, MUL} opcodes_t;
    typedef struct {
        logic [31:0] a, b;
        opcodes_t    opcode;
    } instruction_t;
endpackage
```



Package in module

- ✓ When the case statement references the enumerated labels of ADD, SUB, and MUL, as well as the function multiplier, it will find the definitions of these names in the **definitions package**

```
module ALU
(input  definitions::instruction_t  IW,
 input  logic                      clock,
 output logic [31:0]              result
);
import definitions::*; // wildcard import

always_comb begin
    case (IW.opcode)
        ADD : result = IW.a + IW.b;
        SUB : result = IW.a - IW.b;
        MUL : result = multiplier(IW.a, IW.b);
    endcase
end
endmodule
```



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Procedure Block in Verilog

- ✓ In Verilog, there are 2 kinds of procedure block
 - initial
 - always



Procedure Block

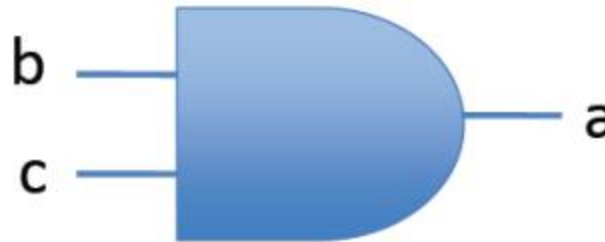
- ✓ In Verilog, **always** is a general purpose procedure block
 - Can be use to model testbench, combination circuits, sequential circuits...etc
 - Depend on context which is not intuitive
 - Cannot be placed inside program or class and other procedure blocks
- ✓ System Verilog adds three new logic specific processes to show designers intent:
 - always_comb
 - always_ff
 - always_latch
- ✓ In program, we may use forever@ to replace always blocks

```
initial begin
    forever@(posedge clk)begin
        // do something
    end
end
```



always_comb

- ✓ The `always_comb` procedural block is used to indicate the intent to model combinational logic.



Verilog2001

```
always@( b or c)  
a=b&c;
```



SystemVerilog

```
always_comb  
a=b&c;
```

always_ff

- ✓ The **always_ff** procedural block is used to indicate that the intent to model synthesizable sequential logic behavior.
- ✓ **Example:**
 - `always_ff @ (posedge clock or negedge resetN)`
 `if (!resetN) q <= 0;`
 `else q <= d;`



always_latch

- ✓ The `always_latch` procedural block is used to indicate that the intent to model combinational logic with latch in it.

- ✓ **Example:**

- `always_latch`
 `if (enable)`
 `a_latch = a;`

no use

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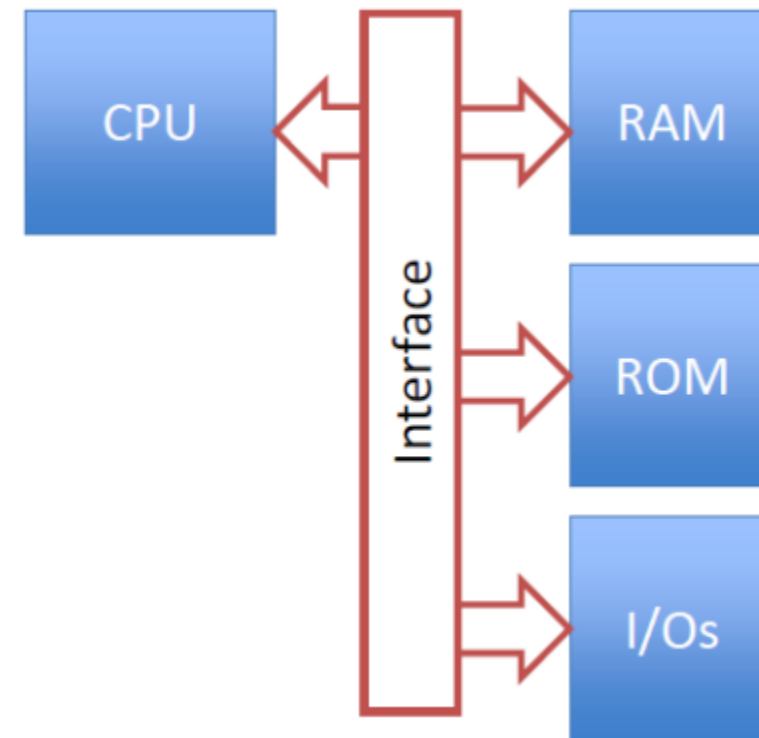
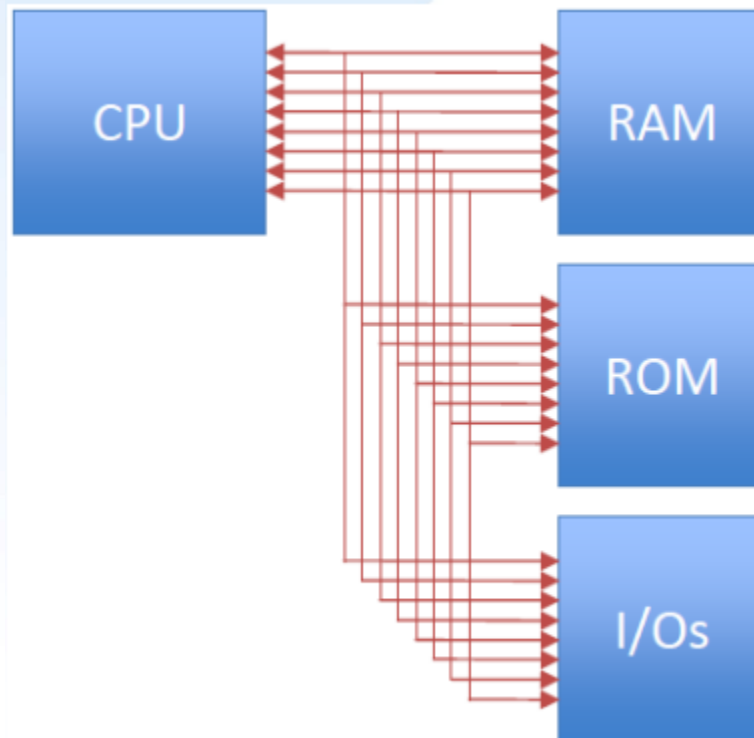
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Interface

✓ **The interface encapsulate communication between design blocks, and between design and verification blocks.**

- Replacing a group of names by a single one
- An interface is a named bundle of wires, similar to a struct, except that an interface is allowed as a module port, while a struct is not.



Example

```
3 module moduleA ( input bit      clk
4                 , input logic   ack
5                 , input logic   ready
6
7                 , output logic   send
8                 , output logic [31:0] data
9             );
10     ... // actual module definition here
11 endmodule
12
13 module moduleB ( input bit      clk
14                 , input logic   send
15                 , input logic [31:0] data
16
17                 , output logic   ack
18                 , output logic   ready
19             );
20     ... // actual module definition here
21 endmodule
22
23 module top;
24 ...
25     clockgen CLOCKGEN (clk); // the clock generator
26
27     moduleA  AA (clk, ack, ready, send, data);
28     moduleB  BB (clk, send, data, ack, ready);
29 endmodule
30
31
```

```
3 interface intf_AB;
4 logic      ack;
5 logic      ready;
6 logic      send;
7 logic [31:0] data;
8     ... // actual interface definition here
9 endinterface
10
11 module moduleA ( input bit clk
12                 , intf_AB intf1
13             );
14     ... // actual module definition here
15 endmodule
16
17 module moduleB ( input bit clk
18                 , intf_AB intf2
19             );
20     ... // actual module definition here
21 endmodule
22
23 module top;
24 ...
25     intf_AB intf(); // the interface declaration
26     clockgen CLOCKGEN (clk); // the clock generator
27
28     moduleA  AA ( .clk      (clk )
29                 , .intf1    (intf)
30             );
31     moduleB  BB ( .clk      (clk )
32                 , .intf2    (intf)
33             );
34 endmodule
```



Modports of interface

- ✓ Modports are used to define direction of signal inside interface.

```
22 interface INF(input bit clk);
23     logic    reset;
24     instr_t  IW;
25     data_t   OUT;
26
27     modport PATTERN(
28         output reset,
29         output IW,
30         input  OUT
31     );
32
33     modport DESIGN(
34         input  reset,
35         input  IW,
36         output OUT
37     );
38
39 endinterface
40
```

INF.sv

```
40 reg    SystemClock;
41
42 INF    inf(SystemClock);
43
44 PATTERN test_p(
45     .clk    (SystemClock),
46     .inf    (inf.PATTERN)
47 );
48
49 `ifdef RTL
50 ALU dut(
51     .clk    (SystemClock),
52     .inf    (inf.DESIGN)
53 );
54 `endif
```

TESTBED.sv

```
23 module ALU(
24     input clk,
25     INF.DESIGN inf
26 );
27 // input instr_t IW, output data_t OUT, input clk, reset);
28 // shortint temp;
29 logic [16:0] temp;
30 // logic [16:0] temp_ttt;
31 logic temp_ovf;
32 // Output sequential logic
33 always_ff @(posedge clk)
34 begin : p_OUTPUT_REG_LOGIC
35     if(inf.reset)
36     begin
37         inf.OUT.result<='0;
38         inf.OUT.ovf<='0;
39     end
40     else
41     begin
42         inf.OUT.result<=temp[15:0];
43         inf.OUT.ovf<=temp[16];
44     end
45 end : p_OUTPUT_REG_LOGIC
```

DESIGN.sv



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Object-oriented programming

- ✓ **Objects, instances of classes**
- ✓ **Contents of “objects”**
 - Data field
 - Constructor
 - Methods
- ✓ **Each object should do what it should do, rather than several roles.**
- ✓ **Interaction between object and the object should be reduced as much as possible.**



Object-oriented programming

```
1 class Transcation
2     //number of objects created
3     static int count = 0;
4     //unique instance ID
5     int id;
6     logic [31:0] addr, crc, data[8];
7
8     function new();
9         id = count++;
10    endfunction
11
12    function void display_id;
13        $display("%d",id);
14    endfunction
15
16 endclass
```

```
1 program test;
2
3     /* other codes ...*/
4
5     Transcation t;
6     initial begin
7         repeat(n)begin
8             t = new();
9             t.addr = $random();
10            transmit(t); // user defined task
11        end
12    end
13
14    /* other codes ...*/
15
16 endprogram
```



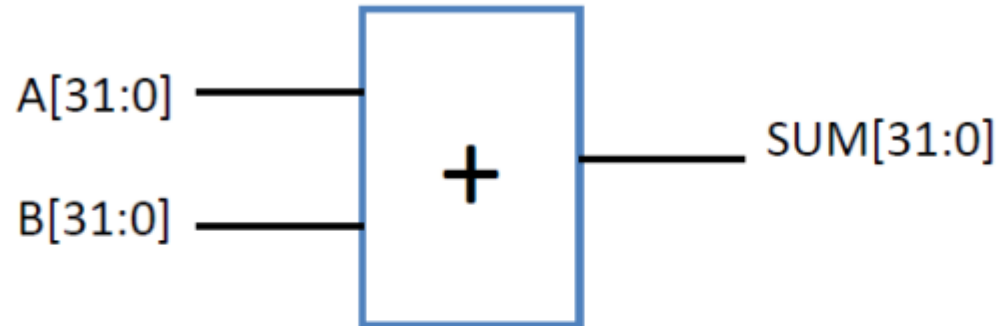
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How To Do Verification?

- ✓ **How long will simulation run if exhaustive testing of a 32-bit adder is required?**
 - Assume that one set of input and output can be verified every 1ns.



A day?
A week?
A year?

Alternatives to Exhaustive Verification?

- ✓ What is the goal of verification if exhaustive verification is unachievable?
- ✓ Verify with sufficient set of vectors to gain a level of confidence that product will ship with a tolerable field-failure rate.
- ✓ The best known mechanism is **randomization**:
 - Randomization of data
 - Use constraints to narrow the scope



Randomization

- ✓ **Two types of random properties are supported:**
 - rand
 - randc
- ✓ **rand properties can assume any legal value:**
 - Values can repeat without exhausting all possible values
- ✓ **randc properties can be up to 16 bits:**
 - Exhaust all values before repeating any individual value
 - For non-repeating bit values > 16 bits, use concatenation
- ✓ **rand and randc properties are randomized when the class method randomize() is called:**
 - randomize() is built-in with every class
 - 1 is returned if successful, 0 if randomization failed



Randomization Example

```
class random_interval;  
    rand int interval ;  
    function new ( int seed );  
        this.srandom(seed) ;  
    endfunction  
    constraint limit  
    {  
        interval inside{1 , 2 , 3};  
    }  
endclass
```

```
random_interval interval_rand = new(1) ;  
int i ;  
  
initial  
begin  
    i = interval_rand.randomize() ;  
    if(i == 0 ) $display("ERROR") ;  
end
```

↳ 1 or 2 or 3



Constraints

✓ Class properties are constrained in a **constraint block**

- Use **operator** or **distribution** constraints
- Arrays can be constraint with functions like size()

✓ For distribution specification:

- Distributed over a specified range with keyword **inside**:

```
constraint Limit1 {  
  class member ← sa inside { [5:7], 10, 15 };  
  // 5,6,7,10,15 equally weighted probability  
}
```

- Excluded from a specified range with **!** operator:

```
constraint Limit2 {  
  !( sa inside { [1:10], 15 } );  
  // not 1 through 10 or 15  
}
```



Appendix: Constraints

✓ Operator Constraints

✓ Implication operators:

- >
- if(...)...[else]

```
typedef enum { low, mid, high } AddrType;
class MyBus;
rand bit[7:0] addr;
rand AddrType atype;
constraint addr_range {
  (atype == low ) -> addr inside { [0:15] };
  (atype == mid ) -> addr inside { [16:127] };
  (atype == high) -> addr inside { [128:255] };
  // same as:
  // if (atype == low) addr inside { [0:15] };
  // if (atype == mid) addr inside { [16:127] };
  // if (atype == high) addr inside { [128:255] };
}
endclass
```



Appendix: Generate

- ✓ Useful for vector or array

```
3  genvar i;
4
5  logic [1:0] temp_test [0:3];
6
7  generate
8      for(i=0;i<4;i=i+1)
9      begin:test_for
10         always_ff @(posedge clk)
11         begin
12             if(inf.reset)
13                 temp_test[i] <= 0;
14             else
15                 temp_test[i] <= i;
16         end
17     end
18 endgenerate
19
```

Appendix : More about randomize()

✓ When randomize() executes, three events occur:

- pre_randomize() is called
- Randomization is executed
- post_randomize() is called

✓ pre_randomize()

- Optional
- Set/Correct constraints before randomization

✓ post_randomize()

- Optional
- Make corrections after randomization

```
function void pre_randomize ();  
    $display ("This will be called just before randomization");  
endfunction
```

```
function void post_randomize ();  
    $display ("This will be called just after randomization");  
endfunction
```



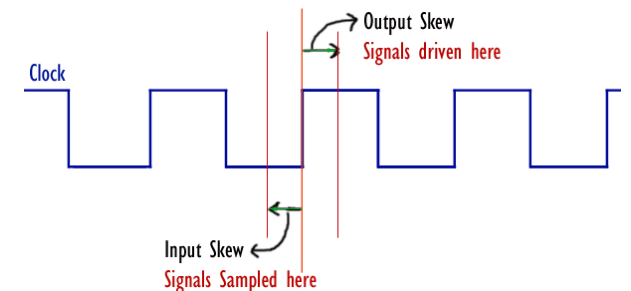
Appendix : Clocking Block

- ✓ **Verilog have timing problem about driven and sample**
 - In previous labs, the pattern often catch the result in negative edge to avoid this problem
- ✓ **SystemVerilog adds clocking block to facilitate**
 - Sampling for verification
 - Driving stimulus (can use in module, program block or interface)

by default specified input(s) are sampled
10ns before the posedge clk and output(s)
are driven 2ns after the posedge clk

```
clocking bus @(posedge clk)
    default input # 10ns output #2ns;
    input data, ready, enable = top.mem1.enable; //input(s) to sample
    output done; // output(s) to drive
    output negedge ack; // special output (driven this one on negedge clk)
    input #1step addr; // special input (sample this one on #1step before the posedge clk)
endclocking
```

Determined by time precision



Reference

- ✓ ASIC World (<http://www.asic-world.com/systemverilog/index.html>)
- ✓ electroSofts (<http://electrosofts.com>)
- ✓ AsicGuru.com (<http://www.asicguru.com/home/6/>)
- ✓ Verification Guide (<http://www.verificationguide.com/p/systemverilog-tutorial.html>)
- ✓ Project VeriPage (<http://www.project-veripage.com/index.php>)
- ✓ Language Reference Manual
(http://www.ece.uah.edu/~gaede/cpe526/SystemVerilog_3.1a.pdf)
- ✓ SV scheduler (https://blog.csdn.net/wonder_coole/article/details/82182850)
- ✓ Clocking Block (<https://staging.doulos.com/knowhow/systemverilog/systemverilog-tutorials/systemverilog-clocking-tutorial/>)

