Verilog 1995, 2001, and SystemVerilog 3.1

Languages for Embedded Systems

Prof. Stephen A. Edwards

Columbia University

March 2009

The Verilog Language

Originally a modeling language for a very efficient event-driven digital logic simulator

Later pushed into use as a specification language for logic synthesis

Now, one of the two most commonly-used languages in digital hardware design (VHDL is the other)

Virtually every chip (FPGA, ASIC, etc.) is designed in part using one of these two languages

Combines structural and behavioral modeling styles

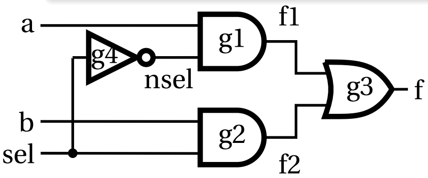
Multiplexer Built From Primitives

```
module mux(f, a, b, sel);
output f;
input a, b, sel;

and g1(f1, a, nsel),
    g2(f2, b, sel);
or  g3(f, f1, f2);
not g4(nsel, sel);

endmodule
```

Verilog programs built from modules

Each module has an interface

Module may contain structure: instances of primitives and other modules

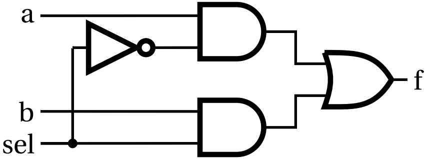


Multiplexer Built with Always

```
module mux(f, a, b, sel);
output f;
input a, b, sel;
reg f;

always @(a or b or sel)
  if (sel) f = a;
  else f = b;

endmodule
```

Modules may contain one or more always blocks

Sensitivity list contains signals whose change makes the block execute

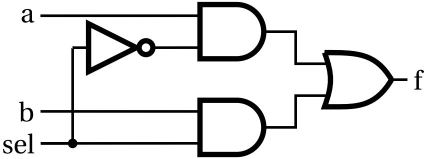


Multiplexer Built with Always

```
module mux(f, a, b, sel);
output f;
input a, b, sel;
reg f;

always @(a or b or sel)
  if (sel) f = a;
  else f = b;

endmodule
```

A `reg` behaves like memory: holds its value until imperatively assigned otherwise

Body of an always block contains traditional imperative code

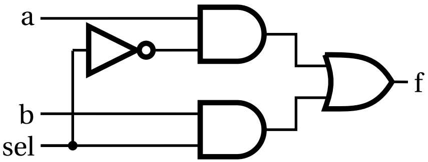


Mux with Continuous Assignment

```
module mux(f, a, b, sel);
output f;
input a, b, sel;

assign  f = sel ? a : b;

endmodule
```

LHS is always set to the value on the RHS

Any change on the right causes reevaluation

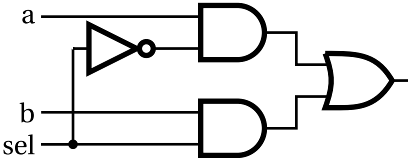


Mux with User-Defined Primitive

```
primitive mux(f, a, b, sel);
output f;
input a, b, sel;

table
   1?0 : 1;
   0?0 : 0;
   ?11 : 1;
   ?01 : 0;
   11? : 1;
   00? : 0;
endtable
endprimitive
```

Behavior defined using a truth table that includes “don’t-cares”

This is a less pessimistic than others: when a & b match, sel is ignored; others produce X

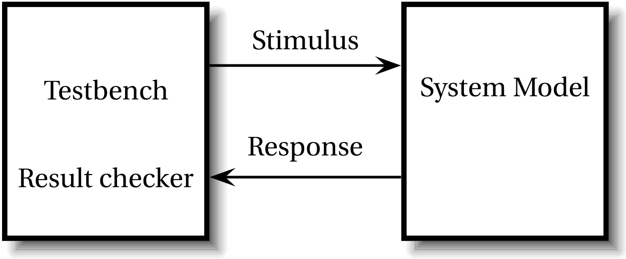


How Are Simulators Used?

Testbench generates stimulus and checks response

Coupled to model of the system

Pair is run simultaneously



Testbench

Result checker

Stimulus

Response

System Model

Structural Modeling

When Verilog was first developed (1984) most logic simulators operated on netlists

Netlist: list of gates and how they're connected

A natural representation of a digital logic circuit

Not the most convenient way to express test benches

Behavioral Modeling

A much easier way to write testbenches

Also good for more abstract models of circuits

- Easier to write
- Simulates faster

More flexible

Provides sequencing

Verilog succeeded in part because it allowed both the model and the testbench to be described together

How Verilog Is Used

Virtually every ASIC is designed using either Verilog or VHDL (a similar language)

Behavioral modeling with some structural elements

“Synthesis subset” can be translated using Synopsys’ Design Compiler or others into a netlist

Design written in Verilog

Simulated to death to check functionality

Synthesized (netlist generated)

Static timing analysis to check timing

Two Main Components of Verilog: Behavioral

Concurrent, event-triggered processes (behavioral)

Initial and Always blocks

Imperative code that can perform standard data manipulation tasks (assignment, if-then, case)

Processes run until they delay for a period of time or wait for a triggering event

Two Main Components of Verilog: Structural

Structure (Plumbing)

Verilog program build from modules with I/O interfaces

Modules may contain instances of other modules

Modules contain local signals, etc.

Module configuration is static and all run concurrently

Two Main Data Types: Nets

Nets represent connections between things

Do not hold their value

Take their value from a driver such as a gate or other module

Cannot be assigned in an initial or always block

Two Main Data Types: Regs

Regs represent data storage

Behave exactly like memory in a computer

Hold their value until explicitly assigned in an initial or always block

Never connected to something

Can be used to model latches, flip-flops, etc., but do not correspond exactly

Actually shared variables with all their attendant problems

Discrete-event Simulation

Basic idea: only do work when something changes

Centered around an event queue that contains events labeled with the simulated time at which they are to be executed

Basic simulation paradigm

- Execute every event for the current simulated time
- Doing this changes system state and may schedule events in the future
- When there are no events left at the current time instance, advance simulated time soonest event in the queue

Four-valued Data

Verilog's nets and registers hold four-valued data

0, 1: Obvious

Z: Output of an undriven tri-state driver. Models case where nothing is setting a wire's value

X: Models when the simulator can't decide the value

- Initial state of registers
- When a wire is being driven to 0 and 1 simultaneously
- Output of a gate with Z inputs

Four-valued Logic

Logical operators work on three-valued logic

	0	1	X	Z
0	0	0	0	0
1	0	1	X	X
X	0	X	X	X
Z	0	X	X	X

Outputs 0 if either input is 0

Outputs X if both inputs are gibberish

Part I

Structural Modeling

Nets and Registers

Wires and registers can be bits, vectors, and arrays

```
wire a;                      // Simple wire
tri [15:0] dbus;             // 16-bit tristate bus
tri #(5,4,8) b;              // Wire with delay
reg [-1:4] vec;              // Six-bit register
trireg (small) q;            // Wire stores a small charge
integer imem[0:1023];        // Array of 1024 integers
reg [31:0] dcache[0:63];     // A 32-bit memory
```

Modules and Instances

Basic structure of a Verilog module:

```
module mymod(out1, out2, in1, in2);
output out1;
output [3:0] out2;
input in1;
input [2:0] in2;

// Body of the module

endmodule
```

Verilog convention lists outputs first

Instantiating a Module

Instances of

```
module mymod(y, a, b);
```

look like

```
mymod mm1(y1, a1, b1); // Connect-by-position
mymod (y2, a1, b1),
      (y3, a2, b2);   // Instance names omitted

// Connect-by-name
mymod mm2(.a(a2), .b(b2), .y(c2));
```

Gate-level Primitives

Verilog provides the following:

and	nand	logical AND/NAND
or	nor	logical OR/NOR
xor	xnor	logical XOR/XNOR
buf	not	buffer/inverter
bufif0	notif0	Tristate with low enable
bifif1	notif1	Tristate with high enable

Delays on Primitive Instances

Instances of primitives may include delays

```
buf            b1(a, b);   // Zero delay
buf #3         b2(c, d);   // Delay of 3
buf #(4,5)     b3(e, f);   // Rise=4, fall=5
buf #(3:4:5)   b4(g, h);   // Min-typ-max
```

Switch-level Primitives

Verilog also provides mechanisms for modeling CMOS transistors that behave like switches

A more detailed modeling scheme that can catch some additional electrical problems when transistors are used in this way

Now, little-used because circuits generally aren't built this way

More seriously, model is not detailed enough to catch many of the problems

These circuits are usually simulated using SPICE-like simulators based on nonlinear differential equation solvers

User-Defined Primitives

Way to define gates and sequential elements using a truth table

Often simulate faster than using expressions, collections of primitive gates, etc.

Gives more control over behavior with X inputs

Most often used for specifying custom gate libraries

A Carry Primitive

```
primitive carry(out, a, b, c);
output out;
input a, b, c;
table
   00? : 0;
   0?0 : 0;
   ?00 : 0;
   11? : 1;
   1?1 : 1;
   ?11 : 1;
endtable
endprimitive
```

Always has exactly one output

Truth table may include don't-care (?) entries

A Sequential Primitive

```
Primitive dff( q, clk, data);
output q; reg q;
input clk, data;
table
//clk data   q  new-q
(01)    0   : ? :  0;  // Latch a 0
(01)    1   : ? :  1;  // Latch a 1
(0x)    1   : 1 :  1;  // Hold when d and q both 1
(0x)    0   : 0 :  0;  // Hold when d and q both 0
(?0)    ?   : ? :  -;  // Hold when clk falls
?     (??)  : ? :  -;  // Hold when clk stable
endtable
endprimitive
```

Continuous Assignment

Another way to describe combinational function

Convenient for logical or datapath specifications

```
wire [8:0] sum;
wire [7:0] a, b;
wire carryin;

assign sum = a + b + carryin;
```

Define bus widths

Continuous assignment: permanently sets the value of sum to be a+b+carryin. Recomputed when a, b, or carryin changes

Part II

Behavioral Modeling

Initial and Always Blocks

```
initial
  begin
    // statements
  end
```

Runs when simulation starts

Terminates when control reaches the end

Good for providing stimulus

```
always
  begin
    // statements
  end
```

Runs when simulation starts

Restarts when control reaches the end

Good for modeling or specifying hardware

Initial and Always

Run until they encounter a delay

```
initial begin
  #10 a = 1; b = 0;
  #10 a = 0; b = 1;
end
```

or a wait for an event

```
always @(posedge clk) q = d;

always begin
   wait(i);
   a = 0;
   wait(~i);
   a = 1;
end
```

Procedural Assignment

Inside an initial or always block:

```
sum = a + b + cin;
```

Just like in C: RHS evaluated and assigned to LHS before next statement executes

RHS may contain wires and/or regs

LHS must be a reg

(only primitives or continuous assignment may set wire values)

Imperative Statements

```
if (select == 1) y = a;
else y = b;

case (op)
  2'b00: y = a + b;
  2'b01: y = a - b;
  2'b10: y = a ^ b;
  default: y = 'hxxxx;
endcase
```

For Loops

Example generates an increasing sequence of values on an output

```
reg [3:0] i, output;

for ( i = 0 ; i <= 15 ; i = i + 1 ) begin
   output = i;
   #10;
end
```

While Loops

A increasing sequence of values on an output

```
reg [3:0] i, output;

i = 0;
while (i <= 15) begin
  output = i;
  #10 i = i + 1;
end
```

Modeling A Flip-Flop With Always

Very basic: an edge-sensitive flip-flop

```
reg q;

always @(posedge clk)
   q = d;
```

q = d assignment runs when clock rises: exactly the behavior you expect

Blocking vs. Nonblocking

Verilog has two types of procedural assignment

Fundamental problem:

- In a synchronous system, all flip-flops sample simultaneously
- In Verilog, `always @(posedge clk)` blocks run in some undefined sequence

A Flawed Shift Register

This does not work as you would expect:

```
reg d1, d2, d3, d4;

always @(posedge clk) d2 = d1;
always @(posedge clk) d3 = d2;
always @(posedge clk) d4 = d3;
```

These run in some order, but you don’t know which

Non-blocking Assignments

This version does work:

```
reg d1, d2, d3, d4;

always @(posedge clk) d2 <= d1;
always @(posedge clk) d3 <= d2;
always @(posedge clk) d4 <= d3;
```

Nonblocking rule: RHS evaluated when assignment runs

LHS updated only after all events for the current instant have run

Nonblocking Can Behave Oddly

Nonblocking assignments in sequence do not communicate:

```
a = 1;
b = a;
c = b;
```

Blocking assignment:

a = b = c = 1

```
a <= 1;
b <= a;
c <= b;
```

Nonblocking assignment:

a = 1

b = old value of a

c = old value of b

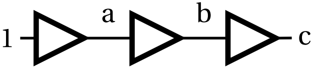
Nonblocking Looks Like Latches

RHS of nonblocking taken from latches

RHS of blocking taken from wires

```
a = 1;
b = a;
c = b;
```

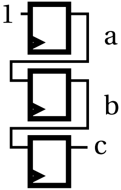
“



”

```
a <= 1;
b <= a;
c <= b;
```

“



”

Part III

Building Behavioral Models

Modeling FSMs Behaviorally

There are many ways to do it:

- Define the next-state logic combinationally and define the state-holding latches explicitly
- Define the behavior in a single `always @(posedge clk)` block
- Variations on these themes

FSM with Combinational Logic

```
module FSM(o, a, b, reset);
output o;
reg o;
input a, b, reset;
reg [1:0] state, nextState;

always @(a or b or state)
 case (state)
    2'b00: begin
      o = a & b; nextState = a ? 2'b00 : 2'b01;
    end
    2'b01: begin
      o = 0; nextState = 2'b10;
    end
 endcase

always @(posedge clk or reset)
  if (reset) state <= 2'b00;
  else       state <= nextState;
endmodule
```

Output o is declared a reg because it is assigned procedurally, not because it holds state

FSM with Combinational Logic

```
module FSM(o, a, b, reset);
output o;
reg o;
input a, b, reset;
reg [1:0] state, nextState;

always @(a or b or state)
 case (state)
    2'b00: begin
      o = a & b; nextState = a ? 2'b00 : 2'b01;
    end
    2'b01: begin
      o = 0; nextState = 2'b10;
    end
 endcase

always @(posedge clk or reset)
  if (reset) state <= 2'b00;
  else       state <= nextState;
endmodule
```

Combinational block must be sensitive to any change on any of its inputs (Implies state-holding elements otherwise)

Latch implied by sensitivity to the clock or reset only

FSM from a Single Always Block

```
module FSM(o, a, b);
output o; reg o;
input a, b;
reg [1:0] state;

always @(posedge clk or reset)
  if (reset) state <= 2'b00;
  else case (state)
    2'b00: begin
       state <= a ? 2'b00 : 2'b01;
       o <= a & b;
    end
    2'b01: begin
       state <= 2'b10;
       o <= 0;
    end
 endcase
```

Expresses Moore machine behavior: Outputs are latched. Inputs only sampled at clock edges

Nonblocking assignments used throughout to ensure coherency. RHS refers to values calculated in previous clock cycle

Writing Testbenches

```
module test;
reg a, b, sel;

mux m(y, a, b, sel);

initial begin
  $monitor($time,,"a=\%b b=\%b sel=\%b y=\%b",
                   a, b, sel, y);
  a = 0; b= 0; sel = 0;
  #10 a = 1;
  #10 sel = 1;
  #10 b = 1;
end
```

Inputs to device under test

Device under test

$monitor is a built-in event-driven printf

Stimulus generated by sequence of assignments and delays

Part IV

Simulating Verilog

Simulation Behavior

Scheduled using an event queue

Non-preemptive, no priorities

A process must explicitly request a context switch

Events at a particular time unordered

Scheduler runs each event at the current time, possibly scheduling more as a result

Two Types of Events

Evaluation events compute functions of inputs

Update events change outputs

Split necessary for delays, nonblocking assignments, etc.

Update event writes new value of a and schedules any evaluation events that are sensitive to a change on a

```
a <= b + c
```

Evaluation event reads values of b and c, adds them, and schedules an update event

Simulation Behavior

Concurrent processes (initial, always) run until they stop at one of the following

- `#42`

  Schedule process to resume 42 time units from now
- `wait(cf & of)`

  Resume when expression “cf & of” becomes true
- `@(a or b or y)`

  Resume when a, b, or y changes
- `@(posedge clk)`

  Resume when clk changes from 0 to 1

Simulation Behavior

Infinite loops are possible and the simulator does not check for them This runs forever: no context switch allowed, so ready can never change

```
while (~ready)
  count = count + 1;
```

Instead, use

```
wait(ready);
```

Simulation Behavior

Race conditions abound in Verilog

These can execute in either order: final value of a undefined:

```
always @(posedge clk) a = 0;
always @(posedge clk) a = 1;
```

Simulation Behavior

Semantics of the language closely tied to simulator implementation

Context switching behavior convenient for simulation, not always best way to model

Undefined execution order convenient for implementing event queue

Compiled-Code Discrete-Event Sim.

Most modern simulators use this approach

Verilog program compiled into C

Each concurrent process (e.g., continuous assignment, always block) becomes one or more C functions

Initial and always blocks split into multiple functions, one per segment of code between a delay, a wait, or event control (@)

Central, dynamic event queue invokes these functions and advances simulation time

Part V

Verilog and Logic Synthesis

Logic Synthesis

Verilog is used in two ways

Model for discrete-event simulation

Specification for a logic synthesis system

Logic synthesis converts a subset of the Verilog language into an efficient netlist

One of the major breakthroughs in designing logic chips in the last 20 years

Most chips are designed using at least some logic synthesis

Logic Synthesis Tools

Mostly commercial tools

- Very difficult, complicated programs to write well
- Limited market
- Commercial products in \$10k – \$100k price range

Major vendors

- Synopsys Design Compiler, FPGA Express
- Cadence BuildGates
- Synplicity (FPGAs)
- Exemplar (FPGAs)

Academic tools

- SIS (UC Berkeley)

Logic Synthesis

Takes place in two stages:

1. Translation of Verilog (or VHDL) source to a netlist
   Register inference performed here
2. Optimization of the resulting netlist to improve speed and area
   Most critical part of the process
   Algorithms very complicated and beyond the scope of this class

Logic Optimization

Netlist optimization the critical enabling technology

Takes a slow or large netlist and transforms it into one that implements the same function more cheaply

Typical operations:

- Constant propagation
- Common subexpression elimination
- Function factoring

Time-consuming operation. Can take hours for large chips

Translating Verilog into Gates

Parts of the language easy to translate

Structural descriptions with primitives is already a netlist

Continuous assignment expressions turn into little datapaths

Behavioral statements the bigger challenge

What Can Be Translated

Every structural definition

Behavioral blocks

- Depends on sensitivity list
- Only when they have reasonable interpretation as combinational logic, edge, or level-sensitive latches
- Blocks sensitive to both edges of the clock, changes on unrelated signals, changing sensitivity lists, etc. cannot be synthesized

User-defined primitives

- Primitives defined with truth tables
- Some sequential UDPs can’t be translated (not latches or flip-flops)

What Is Not Translated

Initial blocks

- Used to set up initial state or describe finite testbench stimuli
- Don’t have obvious hardware component

Delays

- May be in the Verilog source; are simply ignored

A variety of other obscure language features

- In general, things heavily dependent on discrete-event simulation semantics
- Certain “disable” statements
- Pure events

Register Inference

The main trick

A `reg` is not always a latch or flip-flop

Rule: Combinational if outputs always depend exclusively on sensitivity list

Sequential if outputs may also depend on previous values

Register Inference

Combinational:

```
reg y;
always @(a or b or sel)
  if (sel) y = a;
  else y = b;
```

Sensitive to changes on all the variable it reads

y is always assigned

Sequential:

```
reg q;
always @(d or clk)
  if (clk) q = d;
```

q only assigned when clk is 1

Register Inference

A common mistake is not completely specifying a `case` statement

This implies a latch:

```
always @(a or b)
case ({a, b})
   2'b00 : f = 0;
   2'b01 : f = 1;
   2'b10 : f = 1;
endcase
```

f is not assigned when `{a,b} = 2'b11`

Register Inference

The solution is to always have a default case

```
always @(a or b)
case ({a, b})
   2'b00 : f = 0;
   2'b01 : f = 1;
   2'b10 : f = 1;
   default : f = 0;
endcase
```

f is always assigned

Inferring Latches with Reset

Latches and Flip-flops often have reset inputs

Can be synchronous or asynchronous

Asynchronous positive reset:

```
always @(posedge clk or posedge reset)
  if (reset)
   q <= 0;
  else q <= d;
```

Simulation-synthesis Mismatches

Many possible sources of conflict

- Synthesis ignores delays (e.g., #10), but simulation behavior can be affected by them
- Simulator models X explicitly, synthesis does not
- Behaviors resulting from shared-variable-like behavior of regs is not synthesized:
  `always @(posedge clk) a = 1;`
  New value of a may be seen by other @(posedge clk) statements in simulation, never in synthesis

Summary of Verilog 1995

Systems described hierarchically

- Modules with interfaces
- Modules contain instances of primitives, other modules
- Modules contain initial and always blocks

Based on discrete-event simulation semantics

- Concurrent processes with sensitivity lists
- Scheduler runs parts of these processes in response to changes

Modeling Tools

Switch-level primitives: CMOS transistors as switches that move around charge

Gate-level primitives: Boolean logic gates

User-defined primitives: Gates and sequential elements defined with truth tables

Continuous assignment: Modeling combinational logic with expressions

Initial and always blocks: Procedural modeling of behavior

Language Features

Nets (wires) for modeling interconnection

- Non state-holding
- Values set continuously

Regs for behavioral modeling

- Behave exactly like memory for imperative modeling
- Do not always correspond to memory elements in synthesized netlist

Blocking vs. nonblocking assignment

- Blocking behaves like normal “C-like” assignment
- Nonblocking delays update, modeling synchronous behavior

Language Uses

Event-driven simulation

- Event queue containing things to do at particular simulated times
- Evaluate and update events
- Compiled-code event-driven simulation for speed

Logic synthesis

- Translating Verilog (structural and behavioral) into netlists
- Register inference: whether output is always updated
- Logic optimization for cleaning up the result

Little-used Language Features

Switch-level modeling

- Much slower than gate or behavioral-level models
- Insufficient detail for modeling most electrical problems
- Delicate electrical problems simulated with a SPICE-like differential equation simulator

Delays

- Simulating circuits with delays does not improve confidence enough
- Hard to get timing models accurate enough
- Never sure you have simulated the worst case
- Static timing analysis has taken its place

Compared to VHDL

Verilog and VHDL are comparable languages

VHDL has a slightly wider scope

- System-level modeling
- Exposes even more discrete-event machinery

VHDL is better-behaved: Fewer sources of nondeterminism (e.g., no shared variables)

VHDL is harder to simulate quickly

VHDL has fewer built-in facilities for hardware modeling

VHDL is a much more verbose language: Most examples don't fit on slides

In Conclusion

Verilog is a deeply flawed language

- Nondeterministic
- Often weird behavior due to discrete-event semantics
- Vaguely defined synthesis subset
- Many possible sources of simulation/synthesis mismatch

Verilog is widely used because it solves a problem

- Good simulation speed that continues to improve
- Designers use a well-behaved subset of the language
- Makes a reasonable specification language for logic synthesis
- Logic synthesis one of the great design automation success stories

Part VI

Verilog 2001

Verilog 2001

Revised version of the Verilog language

IEEE Standard 1364-2001

Minor changes to the language:

ANSI C style ports
standard file I/O
(* attributes *)
multi dimensional arrays
generate
$value$plusargs
configurations
signed types

localparam
‘ifndef ‘elsif ‘line
memory part selects
automatic
constant functions
@*
variable part select
** (power operator)

Implicit event lists

Common mistake: forgetting a variable in combinational sensitivity list

Forgot to include d

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

Does not simulate like hardware behaves.

Verilog 2001's implicit sensitivity list:

```
always @*
  f = a & b | c & d;
```

Makes process sensitive to all variables on right-hand side of assignments.

Generate

Hardware structures often very regular. Want to create them algorithmically.

Verilog's generate: very clever macro expansion.

```
module gray2bin1 (bin, gray);
  parameter SIZE = 8;
  output [SIZE-1:0] bin;
  input [SIZE-1:0] gray;

  genvar i;  // Compile-time only
  generate for (i=0; i<SIZE; i=i+1)
    begin:bit
      assign bin[i] = ^gray[SIZE-1:i];
    end
  endgenerate
endmodule
```

Attributes

Logic synthesis has relied on hints in comments:

```
always @(posedge clk)
  begin
    case (instr[6:5]) // synopsys full_case parallel_case
    0 : mask <= 8'h01;
    1 : mask <= 8'h02;
    2 : mask <= 8'h04;
    3 : mask <= 8'h08;
    endcase
  end
```

`full_case` means one case will always be true, `parallel_case` means at most one will be true.

Can greatly simplify the generated logic, but simulation/synthesis mismatch if assertion is not true.

Attributes

Such attributes now a first-class part of the language. Simulator understands and checks validity.

```
always @(posedge clk)
  begin
    (* full_case, parallel_case=1 *)
    case (instr[6:5])
    0 : mask <= 8'h01;
    1 : mask <= 8'h02;
    2 : mask <= 8'h04;
    3 : mask <= 8'h08;
    endcase
  end
```

ANSI C-style ports

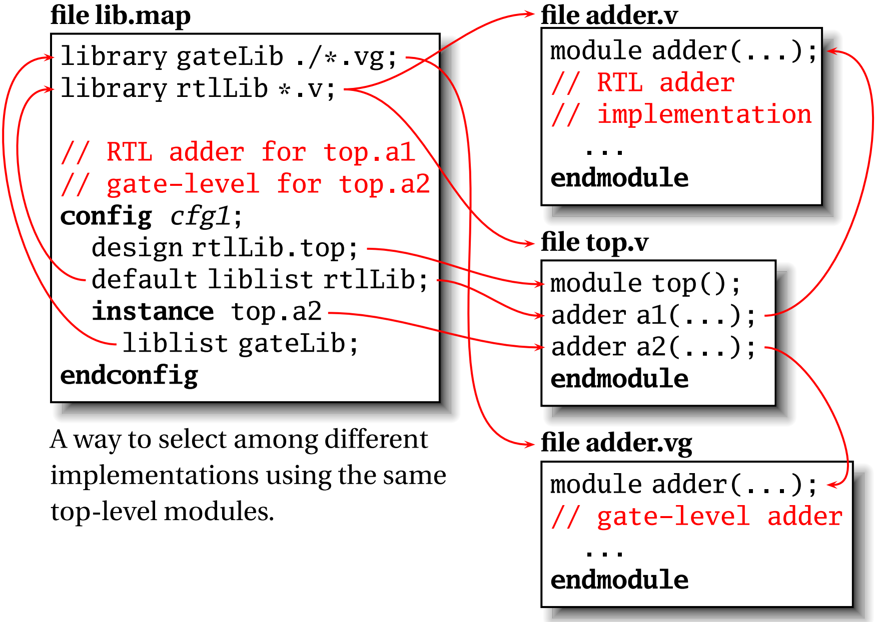
Verilog 1995 ports could require three declarations:

```
module foo(myport1, myport2);
output myport1;
reg [7:0] myport1;
input [3:0] myport2;
...
endmodule
```

Verilog 2001 reduces this to one:

```
module foo(output reg [7:0] myport1,
           input [3:0] myport2);
...
endmodule
```

Configurations



file lib.map

```
library gateLib ./*.vg;
library rtlLib *.v;

// RTL adder for top.a1
// gate-level for top.a2
config cfg1;
  design rtlLib.top;
  default liblist rtlLib;
  instance top.a2
    liblist gateLib;
endconfig
```

file adder.v

```
module adder(...);
// RTL adder
// implementation
  ...
endmodule
```

file top.v

```
module top();
adder a1(...);
adder a2(...);
endmodule
```

file adder.vg

```
module adder(...);
// gate-level adder
  ...
endmodule
```

A way to select among different implementations using the same top-level modules.

Part VII

SystemVerilog

SystemVerilog

Much bigger change to the language.

Verification Features

assertions
biased random variables
test program blocks
process control
mailboxes
semaphores
clocking domains
direct C function calls

C++-like features

classes
dynamic arrays
inheritance
associative arrays
strings
references

More System Verilog Features

C-like features

`int shortint`
`longint byte`
`shortreal void`
`alias enum`
`struct union`
`const typedef`
`break continue`
`return do while`
casting
globals
`++ –`
`+= -= *= /=`
`»= «= »>= «<=`
`&= |= ^= %=`

Modeling Features

interfaces
dynamic processes
nested hierarchy
2-state modeling
unrestricted ports
packed arrays
implicit port connections
array assignments
enhanced literals
enhanced event control
time values & units
unique/priority case/if
logic-specific processes
root name space access

Part VIII

C-like Features

New Types

type	**values**	**width**	**new**
reg	{ 0, 1, X, Z }	1+	
logic	{ 0, 1, X, Z }	1+	✓
integer	{ 0, 1, X, Z }	32	
bit	{ 0, 1 }	1+	✓
byte	{ 0, 1 }	8	✓
shortint	{ 0, 1 }	16	✓
int	{ 0, 1 }	32	✓
longint	{ 0, 1 }	64	✓

reg & logic now the same: both permit either continuous or procedural assignment, but not both.

Other new types for two-valued functional simulation.

‘ifdef and typedef

Can define aliases for existing types. Useful, e.g., for switching between four- and two-valued simulation:

```
‘ifdef TWOSTATE
  typedef bit   bit_t;
‘else
  typedef logic bit_t;
‘endif

module dff (
  output bit_t q,
  input  bit_t d, clk, rst);

  always @(posedge clk)
    if (rst) q <= 0;
    else     q <= d;
endmodule
```

Structs and Unions

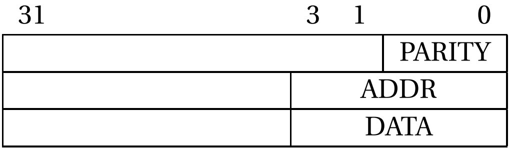
SystemVerilog provides C-like *structs* and *unions* in both packed and unpacked forms.

```
typedef struct {
  logic PARITY;
  logic[3:0] ADDR;
  logic[3:0] DEST;
} pkt_t;

pkt_t mypkt;
mkpkt.ADDR = 12;
```

Packed vs. Unpacked

Structs are *unpacked* by default. The alignment of their fields is implementation-dependent for efficiency, e.g., chosen by the C compiler.

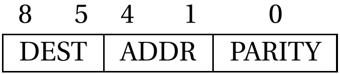
```
typedef struct {
  logic PARITY;
  logic[3:0] ADDR;
  logic[3:0] DEST;
} pkt_t;
```



Packed vs. Unpacked

Marking them *packed* removes padding: useful in unions.

```
typedef struct packed {
  logic PARITY;
  logic[3:0] ADDR;
  logic[3:0] DEST;
} pkt_t;
```



Packed Structs and Unions

```
typedef struct packed {
  logic [15:0] source_port;
  logic [15:0] dest_port;
  logic [31:0] sequence;
} tcp_t;

typedef struct packed {
  logic [15:0] source_port;
  logic [15:0] dest_port;
  logic [15:0] length;
  logic [15:0] checksum;
} udp_t;
```

```
typedef union packed {
  tcp_t tcp_h;
  udp_t udp_h;
  bit [63:0] bits;
  bit [7:0][7:0] bytes;
} ip_t;

ip_t ip_h;
logic parity;

// all are equivalent
ip_h.upd_h.length = 5;
ip_h.bits[31:16] = 5;
ip_h.bytes[3:2] = 5;
```

tcp_t	source_port	dest_port	sequence	
udp_t	source_port	dest_port	length	checksum

Operator Overloading

SystemVerilog provides operator overloading facilities like those in C++ through the *bind* keyword.

```
typedef struct {
   bit sign;
   bit [3:0] exponent;
   bit [10:0] mantissa;
} float;

bind + function float faddfr(float, real);
bind + function float faddff(float, float);

float A, B, C, D;

assign A = B + C;   // means A = faddff(B, C);
assign D = A + 1.0; // means A = faddfr(A, 1.0);
```

Classes

SystemVerilog provides C++-like classes with automatic garbage collection.

```
class Packet;
  bit [3:0] cmd;
  int status;
  header_t header;

  function int get_status();
    return status;
  endfunction
  extern task set_cmd(input bit [3:0] a);
endclass

task Packet::set_cmd(input bit [3:0] a);
  cmd = a;
endtask

initial begin
  Packet myPkt = new; // Create a new packet
end
```

Inheritance

As in C++, classes can inherit from other classes:

```
class ErrPkt extends Packet;
  bit [3:0] err;

  // New function
  function bit [3:0] show_err;
    return err;
  endfunction

  // Overrides Packet::set_cmd
  task set_cmd(input bit [3:0] a);
    cmd = a + 1;
  endtask

endclass
```

Packages

```
package ComplexPkg;
  typedef struct { float i, r; } Complex;

  function Complex add(Complex a, b);
    add.r = a.r + b.r;
    add.i = a.i + b.i;
  endfunction
  function Complex mul(Complex a, b);
    mul.r = (a.r * b.r) + (a.i * b.i);
    mul.i = (a.r * b.i) + (a.i * b.r);
  endfunction
endpackage : ComplexPkg

module foo (input bit clk);
  import ComplexPkg::*;
  Complex a,b;

  always @(posedge clk) c = add(a,b);
endmodule
```

Part IX

Hardware Modeling Features

always_comb, _latch, and _ff

In RTL design, a Verilog *always* block models combinational logic, sequential logic driving flip-flops, or sequential logic driving latches, never more than one.

SystemVerilog's always_comb, always_ff, and always_latch keywords make the designer's intent clear to the compiler so it can issue error messages.

always_comb, _latch, and _ff

```
// Probably intended combinational, but c becomes latch
always @(a or b)
  if (b) c = a;

// Error: "missing else branch: c is not assigned"
always_comb
  if (b) c = a;

// A correct level-sensitive latch
always_latch
  if (clk)
    if (en) q <= d;

// Error: "q always assigned: it is not a latch"
always_latch
  q <= d
```

always_comb, _latch, and _ff

Compiler verifies coding style.

```
// Correct edge-sensitive FF with asynchronous reset
always_ff @(posedge clk, negedge rst_n)
  if (!rst_n) q <= 0;
  else        q <= d;

// Error: sensitivity not on edges
always_ff @(clk, rst_n)
  if (!rst_n) q <= 0;
  else        q <= d;

// Error: combinational logic loop
always_latch
  if (en)   q <= d;
  else      q <= q; // Error
```

Unique/Priority

Verilog 1995 had no provision for checking uniqueness of conditions: synthesis tools placed pragmas in comments.

Verilog 2001 added attributes for such conditions as first-class entities.

SystemVerilog introduces new keywords implying unique and complete conditions.

	Cases must be complete	**Condition must be unique**
priority	✓	
unique	✓	✓

Priority Examples

```
// error if none of irq0-irq2 is true
priority case (1'b1)
  irq0: irq = 3'b1 << 0;
  irq1: irq = 3'b1 << 1;
  irq2: irq = 3'b1 << 2;
endcase

// error if none of irq0-irq2 is true
priority if (irq0) irq = 3'b1;
else     if (irq1) irq = 3'b2;
else     if (irq2) irq = 3'b4;

// Default or else ignores priority
priority if (irq0) irq = 3'b1; // never an error
else               irq = 3'b0;

priority case (1'b1) // never an error
  irq0:     irq = 3'b1 << 0;
  default: irq = 0;
endcase
```

Unique Examples

```
// Error if not exactly one of irq0-irq2 is true
unique case (1'b1)
  irq0: irq = 3'b1 << 0;
  irq1: irq = 3'b1 << 1;
  irq2: irq = 3'b1 << 2;
endcase
// Error if not exactly one of irq0-irq2 is true
unique if (irq0) irq = 3'b1;
else   if (irq1) irq = 3'b2;
else   if (irq2) irq = 3'b4;
// Error if both irq0 and irq1 are true
unique if (irq0) irq = 3'b1;
else   if (irq1) irq = 3'b2;
else             irq = 3'b0;
// Error if both irq0 and irq1 are true:
unique case (1'b1)
  irq0:    irq = 3'b1 << 0;
  irq1:    irq = 3'b1 << 1;
  default: irq = 0;
endcase
```

Implicitly named ports

Hierarchy in Verilog usually for separating namespaces. Net and port names typically common across modules. Verbose in Verilog 1995:

```
module top;
  wire [3:0] a;
  wire [7:0] b;
  wire [15:0] c;

  foo foo1(a, b, c);
  bar bar1(a, b, c);
endmodule
```

```
module foo(a, b, c);
  input [3:0] a;
  input [7:0] b;
  input [15:0] c;

endmodule

module bar(a, b, c);
  output a;
  output b;
  output c;
  reg [3:0] a;
  reg [7:0] b;
  reg [15:0] c;

endmodule
```

Implicitly named Ports

Implicit ports plus ANSI-style declarations makes this cleaner, especially for modules with many ports.

```
module top;
  wire [3:0] a;
  wire [7:0] b;
  wire [15:0] c;

  foo foo1(.*);
  bar bar1(.*);
endmodule
```

```
module foo(
  input [3:0] a,
  input [7:0] b,
  input [15:0] c);

endmodule

module bar(
  output reg [3:0] a,
  output reg [7:0] b,
  output reg [15:0] c);

endmodule
```

Implicitly named Ports

Port renaming also supported. Allows specific ports to be overridden or renamed as necessary.

```
module top;
  wire [3:0] a;
  wire [7:0] b;
  wire [15:0] c;

  foo foo1(.*);
  bar bar1(.*, .other(c));
endmodule
```

```
module foo(
  input [3:0] a,
  input [7:0] b,
  input [15:0] c);

endmodule

module bar(
  output reg [3:0] a,
  output reg [7:0] b,
  output reg [15:0] other);

endmodule
```

Interfaces

For communication among modules. Like a collection of shared variables.

```
interface simple_bus;
  logic req, gnt;
  logic [7:0] addr, data;
  logic [1:0] mode;
  logic start, rdy;
endinterface : simple_bus

module top;
  logic clk = 0;
  simple_bus mybus;

  memory mem(mybus, clk);
  cpu cpu(.b(mybus),
          .clk(clk));
endmodule
```

```
module memory(
    simple_bus a,
    input bit clk);

  always @(posedge clk)
    a.gnt <= a.req & avail;

  ...
endmodule

module cpu(simple_bus b,
           input bit clk);
 ...
endmodule
```

Interfaces with implicit ports

Even more simple. Use the same names and let the compiler do the rest.

```
interface simple_bus;
  logic req, gnt;
  logic [7:0] addr, data;
  logic [1:0] mode;
  logic start, rdy;
endinterface : simple_bus

module top;
  logic clk = 0;
  simple_bus bus;

  memory mem(.*);
  cpu cpu(.*);
endmodule
```

```
module memory(
    simple_bus bus,
    input bit clk);

  always @(posedge clk)
    bus.gnt <= bus.req & av;

  ...
endmodule

module cpu(simple_bus bus,
           input bit clk);
 ...
endmodule
```

Generic bundles

You can leave the exact type of an interface unspecified to allow different implementations. Must connect explicitly.

```
interface simple_bus;
  logic req, gnt;
  logic [7:0] addr, data;
  logic [1:0] mode;
  logic start, rdy;
endinterface : simple_bus

module top;
  logic clk = 0;
  simple_bus bus;

  memory mem(.*,
             .bus(bus));
  cpu cpu(.*,
          .bus(bus));
endmodule
```

```
module memory(
    interface bus,
    input bit clk);

  always @(posedge clk)
    bus.gnt <= bus.req & av;

  ...
endmodule

module cpu(interface bus,
           input bit clk);
 ...
endmodule
```

Ports on interfaces

Interfaces are groups of shared variables. Ports on interfaces can bring connections in or out.

```
interface bus(
   input bit clk,
   output bit bus_error);
  logic req, gnt;
  logic [7:0] addr, data;
  logic [1:0] mode;
  logic start, rdy;
endinterface : bus

module top;
  logic clk = 0,
        bus_error;
  bus b(clk, bus_error);

  memory mem(.*);
  cpu cpu(.*);
endmodule
```

```
module memory(bus b);

  always @(posedge b.clk)
    b.gnt <= b.req & av;
  ...
endmodule

module cpu(bus b);

  always @(posedge b.clk)
    b.bus_error <=
           cpu_error;
 ...
endmodule
```

Modports in interfaces

A way to constrain signal directions in interfaces.

```
interface bus(
  input bit clk);
  logic req, gnt, rdy;
  logic [7:0] addr, data;

  modport slave(
   input req, addr, clk,
   output gnt, rdy,
   inout data);

  modport master(
   output req, addr,
   input gnt, rdy, clk,
   inout data)

endinterface : bus
```

```
module top;
  logic clk = 0;
  bus b(clk);

  memory mem(.*);
  cpu cpu(.*);
endmodule

module memory(bus.slave b);

  always @(posedge bus.clk)
    b.gnt <= b.req & av;
  ...
endmodule

module cpu(bus.master b);
 ...
endmodule
```

Tasks and Functions in Interfaces

```
interface bus;
  logic start;

  task slaveRead(
    input logic[7:0] addr);
    ...
  endtask: slaveRead

  task masterRead(
    input logic[7:0] addr);
    ...
  endtask: masterRead

  modport slave(
  import task slaveRead(
    input logic[7:0] addr);
  );

endinterface: bus
```

```
module memory(interface b);
  logic[7:0] addr;
  always @(posedge b.clk)
    b.slaveRead(addr);
endmodule

module omnip(interface b);
  always @(posedge b.clk)
    b.masterRead(addr);
  always @(posedge b.clk)
    b.slaveRead(addr);
endmodule

module top;
  bus b;
  // can only use slaveRead
  memory m(b.slave);
  // can use both
  omnip o(b);
endmodule
```

Dynamically-sized Arrays

Truly software-like behavior.

```
module dynamic_array;

  bit[3:0] myarray[]; // Creates null reference

  initial begin
    myarray = new[4]; // Allocate four 4-bit words

    // Double the size of the array,
    // preserving its contents
    myarray = new[myarray.size() * 2](myarray);
  end

endmodule
```

Associative Arrays

Very abstract notion. Like maps in C++, hashtables in Java, or associative arrays in Perl, Python, Awk.

```
module associative_array;
  typedef struct packed {
    int a;
    logic [7:0] b;
  } mykey_t;

  int myarray[mykey_t]; // new, empty associative array

  initial begin
    mykey_t key1 = { -3, 8'xFE }; // structure literal
    myarray[key1] = 10;

    if (myarray.exists(key1)) myarray[key1] = -5;
    myarray.delete(key1);
  end
endmodule
```

Queues

Often used to communicate between processes.

```
module queues;

  int q[$] = { 2, 4, 8 }; // initial contents

  int sq[$:15]; // maximum size is 16

  initial begin
   int e = q[0]; // first item: 2
   e = q[$];     // last item: 8
   q = { q, 6 }; // append: now 2, 4, 8, 6
   q = { e, q }; // insert: now 8, 2, 4, 8, 6
   q = q[1:$];   // remove: now 2, 4, 8, 6
   q = q[1:$-1]; // delete first, last: now 4, 8
  end

endmodule
```

Process Management: join

Fork starts processes; join terminates when *all* blocks terminate.

```
fork

  begin
    $display("0ns have elapsed\n");
    # 20ns;   // delay
  end

  begin
    # 20ns;
    $display("20ns have elapsed\n");
    # 5ns;
  end

join
# 5ns;
$display("30ns have elapsed\n");
```

Process Management: join_any

Fork starts processes; join_any terminates when *any* of its blocks terminate.

```
fork

  begin
    $display("0ns have elapsed\n");
    # 20ns;    // delay
  end

  begin
    # 20ns;
    $display("20ns have elapsed\n");
    # 5ns;
  end

join_any
# 5ns;
$display("25ns have elapsed\n");
```

Process Management: join_none

Fork starts processes; join_none terminates *immediately*, leaving its blocks running.

```
fork

  begin
    $display("0ns have elapsed\n");
    # 20ns;   // delay
  end

  begin
    # 20ns;
    $display("20ns have elapsed\n");
    # 5ns;
  end

join_none
# 5ns;
$display("5ns have elapsed\n");
```

Process Management: wait fork

`wait fork` waits for all children to terminate.

```
task wait_fork_demo;

  fork
    task1();  // start task1 and task2 concurrently
    task2();
  join_any    // terminates when task1 or task2 does

  fork
    task3();  // start task3 and task4 concurrently
    task4();
  join_none;

  // task3 and task4 and either task1 or task2 running

  wait fork; // wait for all to complete
endtask
```

Process Management: disable fork

`disable fork` terminates all its children.

```
task wait_for_first( output int adr );

  fork

    wait_device( 1, adr); // user-defined task that waits
    wait_device( 7, adr); // all three started
    wait_device(13, adr); // concurrently

  join_any        // terminate when one has arrived

  disable fork;   // terminate other two
```

Process control

```
task run_n_jobs_and_terminate_after_first(int N);
  process job[1:N];  // The processes we spawn

  for (int j = 1 ; j <= N ; j++)
    fork
      automatic int k = j;   // k is the job number
      begin
        job[j] = process::self(); // record who I am
        ...                       // the job itself
      end
    join_none // spawn next job immediately

  for (int j = 1 ; j <= N ; j++)
    wait( job[j] != null );    // wait for jobs to start
  job[1].await(); // wait for first job to finish
  for (int k = 1 ; k <= N ; k++ ) begin
    if (job[k].status != process::FINISHED) // done?
      job[k].kill();                        // kill it
  end
endtask
```

Semaphores

Mutually-exclusive keys in a bucket. `get` blocks if not enough keys are available.

```
semaphore we_are_there = new; // initialize with no keys

task drive;
  fork
    begin
      # 100ns;  // delay 100ns
     we_are_there.put(1); // put one key in semaphore
    end

    begin
      $display("Are we there yet?\n");
      we_are_there.get(1); // wait for a key
      $display("We made it\n");
    end
  join
endtask
```

Semaphores and events

```
event ask, answered;
semaphore answer = new;
int winner; // only valid after answer
task gameshow;
  fork
    begin // the host}
      -> ask; // Start the two contestants
      answer.put(1); // let them compete}
      @answered; $display("%d was first\n", winner);
    end begin // contestant one
      @ask; // wait for the question
      think_about_answer(); answer.get(1); // answer (?)
      winner = 1; -> answered;       // signal success
    end begin // contestant two
      @ask;
      think_about_answer(); answer.get(1);
      winner = 2; -> answered;
    end
  join    // Does this behave properly?
endtask
```

Mailboxes

Possibly bounded semaphore-like queues.

```
mailbox #(string) mybox =
  new(2); // capacity set to two
task mailbox_demo;
  fork
    begin
      mybox.put("first letter");
      $display("sent first\n");
      mybox.put("second letter");
      $display("sent second\n");
      mybox.put("third letter");
      $display("sent third\n");
    end
    begin
      $display("%s\n", mybox.get);
      $display("%s\n", mybox.get);
      $display("%s\n", mybox.get);
    end
  join
endtask
```

Prints

```
sent first
sent second
first letter
second letter
sent third
third letter1
```

Part X

Verification Features

Constrained Random Variables

Manually creating test cases tedious and difficult, yet appears necessary for functional verification.

Current best practice: Constrained random tests.

SystemVerilog has features for creating such tests.

Constrained Random Variables

```
class Bus;
  rand bit[15:0] addr;
  rand bit[31:0] data;

  constraint world_align { addr[1:0] = 2’b0; }
endclass

Bus bus = new;

repeat (50) begin
  if (bus.randomize() == 1)
    $display("addr = %16h data = %h\n",
              bus.addr, bus.data);
  else
    $display("overconstrained!\n");
end
```

Adding constraints

```
class Bus;
  rand bit[15:0] addr;
  rand bit[31:0] data;

  constraint world_align { addr[1:0] = 2'b0; }
endclass

Bus bus = new;

repeat (50) begin
  if (bus.randomize() with { addr[31] == 0 } == 1)
    $display("addr = %16h data = %h\n",
              bus.addr, bus.data);
  else
    $display("overconstrained\n");
end
```

Layering constraints

Constraints inherited, can be added in derived classes.

```
class Bus;
  rand bit[15:0] addr;
  rand bit[31:0] data;
  constraint world_align { addr[1:0] = 2’b0; }
endclass

typedef enum { low, mid, high } AddrType;

class MyBus extends Bus;
  rand AddrType atype; // Additional random variable

  // Additional address constraint (still word-aligned)
  constraint addr_range {
    (atype == low ) -> addr inside { [0:15] };
    (atype == mid ) -> addr inside { [16:127] };
    (atype == high) -> addr inside { [128:255] };
  }
endclass
```

Using Constraints

Very powerful constraint solving algorithm.

```
task exercise_bus;
  int res;

  // Restrict to low addresses
  res = bus.randomize() with { atype == low; };
  // Restrict to particular address range
  res = bus.randomize()
        with { 10 <= addr && addr <= 20 };
  // Restrict data to powers of two
  res = bus.randomize() with { data & (data - 1) == 0 };
  // Disable word alignment
  bus.word_align.constraint_mode(0);
  res = bus.randomize with { addr[0] || addr[1] };
  // Re-enable word alignment
  bus.word_align.constraint_mode(1);
endtask
```

Other types of constraints

```
// Set membership constraints
rand integer x, y, z;
constraint c1 { x inside {3, 5, [9:15], [y:2*y], z}; }

integer fives[0:3] = { 5, 10, 15, 20 };
rand integer v;
constraint c2 { v inside fives; }

// Distribution constraints
rand integer w;
// make w 100 1/8 of time, 200 2/8, 300 5/8
constraint c3 {
   w dist { 100 := 1, 200 := 2, 300 := 5 }; }

// Implication constraints
bit [3:0] a, b;
// force b to 1 when a is 0
constraint c4 { (a == 0) -> (b == 1); }
```

Many, many more features

Variables that step through random permutations (randc)
If-then-else constraints
Algorithmic constraints over array entries (foreach)
Constraints among multiple objects
Variable ordering constraints (solve..before)
Static constraints controlled by one constraint_mode() call
Functions in constraints
Guarded constraints
pre- and post-randomize functions
Random variable disabling
Explicit randomization of arbitrary variables
Random sequence generation from a grammar

Coverage Checks

Once we have generated our tests, how good are they?

Current best practice: monitoring and improving *coverage*

Coverage: how many cases, statements, values, or combinations have the test cases exercised?

Covergroup

Defines something whose coverage is to be checked. Creates bins and tracks whether values ever appeared.

```
// color: a three-valued variable to be checked
enum { red, green, blue } color;

covergroup g1 @(posedge clk); // Sample at posedge clk
   c: coverpoint color;
endgroup

g1 g1_inst = new; // Create the coverage object
```

At the end of simulation, reports whether `color` took all three of its values.

Cross Coverage

May want to monitor combinations of variables.

```
enum { red, green, blue } color;
bit [3:0] pixel_adr, pixel_offset;

covergroup g2 @(posedge clk);
  Hue:    coverpoint pixel_hue;
  Offset: coverpoint pixel_offset;

  // Consider (color, pixel_adr) pairs, e.g.,
  // (red, 3'b000), (red, 3'b001), ..., (blue, 3'b111)
  AxC:    cross color, pixel_adr;

  // Consider (color, pixel_hue, pixel_offset) triplets
  // Creates 3 * 16 * 16 = 768 bins
  all:    cross color, Hue, Offset;
endgroup

g2 g2_inst = new; // Create a watcher
```

Covergroup in classes

Individual coverage of each object of a class.

```
class xyz;
  bit [3:0] x;
  int y;
  bit z;

  covergroup cov1 @z; // At every change of z,
    coverpoint x;     // sample x
    coverpoint y;     // and sample y.
  endgroup

  function new();
    // Create a watcher; variable cov1 implicit
    cov1 = new;
  endfunction
endclass
```

Predicated coverage

May want to selectively disable coverage:

```
covergroup g4 @(posedge clk);

  // check s0 only if reset is true
  coverpoint s0 iff(!reset);

endgroup
```

User-defined bins

May only want to track certain values of a variable.

```
bit [9:0] a; // Takes values 0--1023}

covergroup cg @(posedge clk);
  coverpoint a {
    // place values 0--63 and 65 in bin a
    bins a = { [0:63], 65 };
    // create 65 bins, one for 127, 128, ..., 191
    bins b[] = { [127:150], [148:191] };
    // create three bins: 200, 201, and 202
    bins c[] = { 200, 201, 202 };
    // place values 1000--1023 in bin d
    bins d = { [1000:$] };
    // place all other values (64, 66, .., 126, 192, ...)
    // in their own bin
    bins others[] = default;
  }
endgroup
```

Covering Transitions

May want to check transitions, not just a variable's values.

```
bit [3:0] a;
covergroup cg @(posedge clk);
  coverpoint a {
    // Place any of the sequences 4→5→6, 7→11, 8→11,
    // 9→11, 10→11, 7→12, 8→12, 9→12, and
    // 10→12 into bin sa.
    bins sa = (4 => 5 => 6), ([7:9],10 => 11,12);
    // Bins for 4→5→6, 7→10, 8→10, and 9→10}
    bins sb[] = (4 => 5 => 6), ([7:9] => 10);
    // Look for 3→3→3→3
    bins sc = 3 [* 4];
    // Look for 5→5, 5→5→5, or 5→5→5→5
    bins sd = 5 [* 2:4];
    // Look for sequences of the form 6→···→ 6→···→ 6
    // where "···" is any sequence that excludes 6
    bins se = 6 [-> 3];
  }
endgroup
```

Assertions

We have generated our tests, they do a reasonable job covering the design, but how do we find problems?

Current best practice: Add assertions to the design that check for unwanted conditions.

Currently, the most effective way to reduce debugging time: bugs found more quickly, and easier to remedy.

Long used in software, growing use in hardware.

Main challenge in hardware: asserting temporal behavior. SystemVerilog has constructs specifically for checking sequences of things.

Immediate Assertions

Simplest assertions check an condition only when they are executed.

```
// Make sure req1 or req2 is true
// if we are in the REQ state
always @(posedge clk)
  if (state == REQ)
    assert (req1 || req2);

// Same, but report the error ourselves
always @(posedge clk)
  if (state == REQ)
    assert (req1 || req2)
    else
      $error("In REQ; req1 || req2 failed (%0t)",
             $time);
```

Concurrent Assertions

Concurrent assertions check a property that spans time. Data sampled at a clock and observed sequence checked.

For example, say we insist that `ack` must be asserted between one and three cycles after `req` is asserted.

```
property req_ack;
  @(posedge clk) // Sample req, ack at rising clock edge
    // After req is true, between one and three
    // cycles later, ack must have risen.
    req ##[1:3] $rose(ack);
endproperty

// Assert that this property holds
// i.e., create a checker
as_req_ack: assert property (req_ack);
```

Concurrent Assertions

Another example: make sure the address strobe is not true for two consecutive cycles.

```
property no_two_astr;
  @(posedge clk)
     // Unless reset is true, make sure astr is
     // not true for two cycles in a row.
     disable iff (reset) not (astr [*2]);
endproperty
assert property (no_two_astr);

// Non-overlapping implication |=> waits a cycle
property no_two_astr2;
  @(posedge clk)
  disable iff (reset)
  (astr |=> !astr); // When astr=1, astr=0 next cycle.
endproperty
assert property (no_two_astr2);
```

Sequences and Properties

Sequences can be defined in isolation and used elsewhere.

```
// The own_bus signal goes high in 1 to 5 cycles,
// then the breq signal goes low one cycle later.
sequence own_then_release_breq;
  ##[1:5] own_bus ##1 !breq
endsequence

property legal_breq_handshake;
  @(posedge clk)        // On every clock,
  disable iff (reset) // unless reset is true,
  // once breq has risen,
  // own_bus should rise; breq should fall.
  $rose(breq) |-> own_then_release_breq;
endproperty

assert property (legal_breq_handshake);
```

Sequences (partial syntax)

seq :=

expr	Expression over signals
expr [∗ *int-or-range*]	Consecutive repetition
expr [= *int-or-range*]	Non-consecutive repetition
expr [-> *int-or-range*]	Goto repetition
seq ## *int-or-range* *seq* ...	Delay between sequences
seq `or` *seq*	Either true
seq and *seq*	Both true
seq `intersect` *seq*	Both true, end simultaneously
seq `within` *seq*	Second starts/ends within first

Properties (partial syntax)

prop :=

seq	Sequence
prop `or` *prop*	Either holds
prop `and` *prop*	Both hold
`not` *prop*	Does not hold
seq `|->` *prop*	Prop holds when sequence ends
seq `|=>` *prop*	Prop holds cycle after sequence ends
`if (` *expr* `)` *prop* [`else` *prop*]	If-then-else

SystemVerilog: Summary

Huge language that reflects changing design methodologies:

Switch-level charge-transfer modeling (deprecated)

Gate-level structural modeling

RTL modeling

High-level software-like modeling

Assertions, random simulation, and coverage

Will it succeed?

Maybe.

Substantial industrial support (Cadence, Synopsys).

More of an incremental change than SystemC.

Reasonable, fairly clear, synthesizable subset.

Verilog, with all its flaws, has proven its worth.

Large language, but still fairly succinct.

Does it support the right set of methodologies?