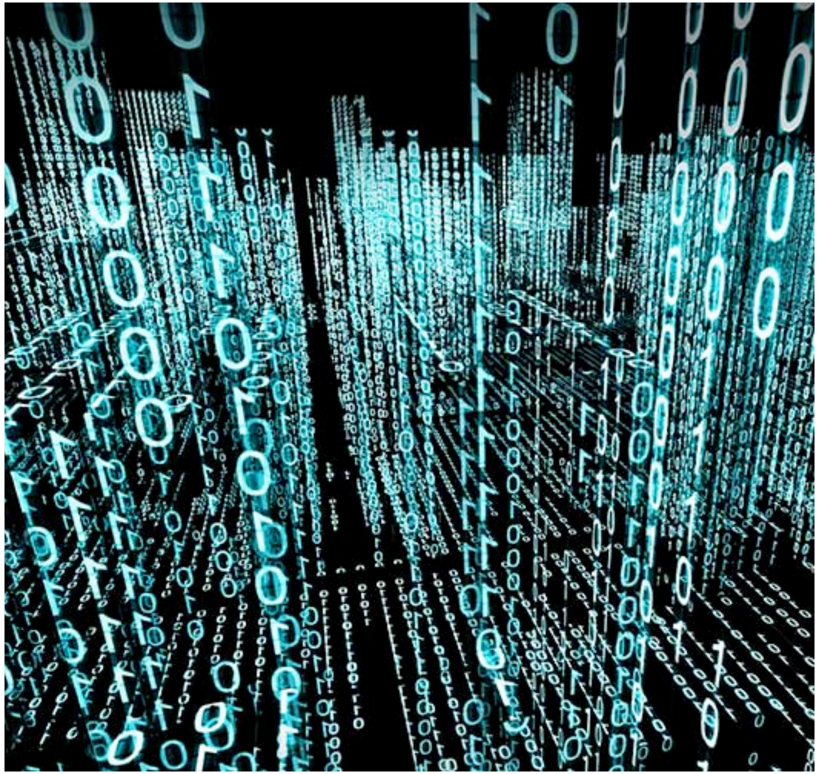
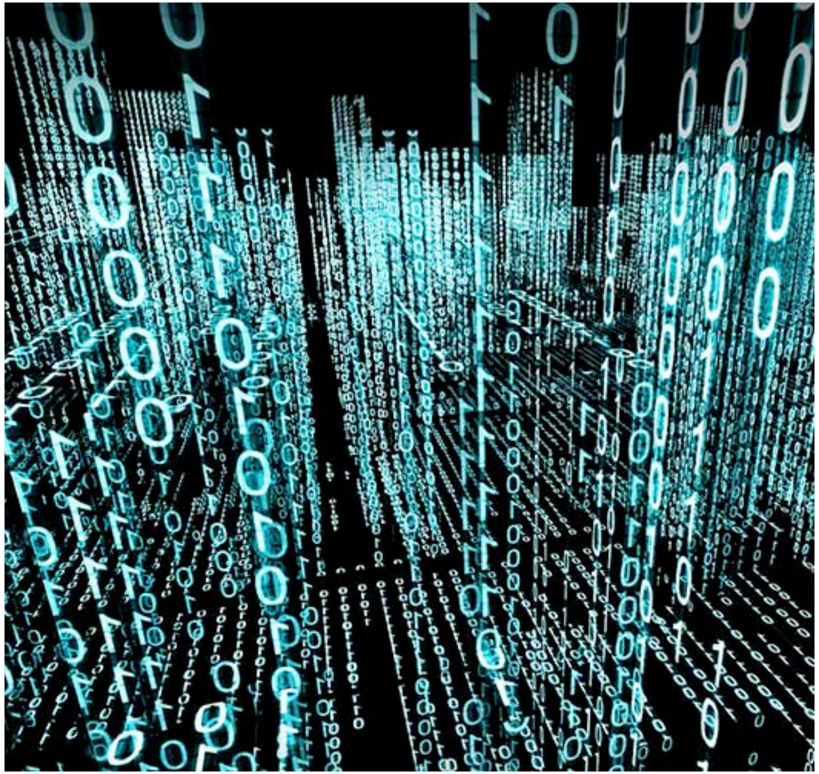


EECS 151/251A
Spring 2024
Digital Design and Integrated Circuits

Instructor: Wawrzynek

Lecture 3: Verilog 1: Combinational Logic Circuits



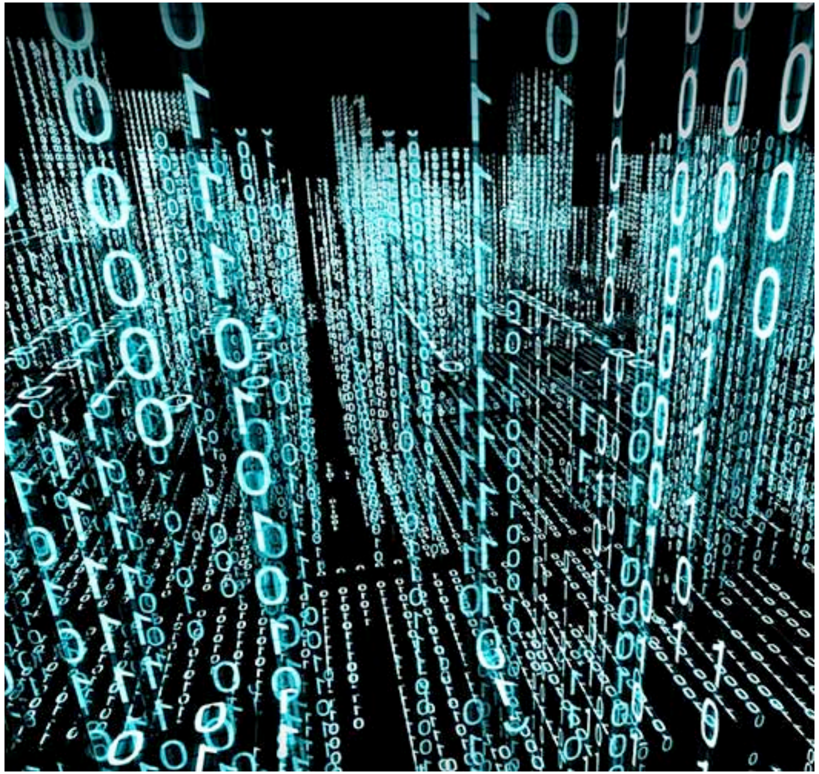
Outline

Hardware Description Language Overview

Verilog Introduction

Announcements

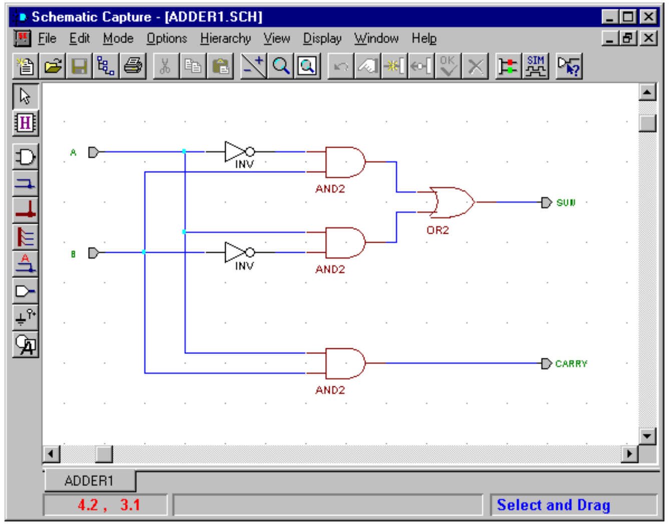
- Problem Set one posted. Start soon!
  - Due next Monday (another out Friday)
- Contact me if you are still trying to get enrolled.



Hardware Description Languages

Design Entry

- ❑ Schematic entry/editing used to be the standard method in industry and universities.
- ☺ Schematics are intuitive. They match our use of gate-level or block diagrams.
- ☺ Somewhat physical. They imply a physical implementation.
- ☹ Require a special tool (editor).
- ☹ Unless hierarchy is carefully designed, schematics can be confusing and difficult to follow on large designs.



Schematic Capture - [ADDER1.SCH]
File Edit Mode Options Hierarchy View Display Window Help
A
B
INV
INV
AND2
AND2
AND2
OR2
SUM
CARRY
ADDER1
4.2 , 3.1
Select and Drag

- Hardware Description Languages (HDLs) are the new standard
  - except for PC board design, where schematics are still used.

Hardware Description Languages

- Basic Idea:
  - Language constructs describe circuits with two basic forms:
    - **Structural descriptions:** connections of components. Nearly one-to-one correspondence to with schematic diagram.
    - **Behavioral descriptions:** use high-level constructs (similar to conventional programming) to describe the circuit function.
- Originally invented for simulation.
  - "logic synthesis" tools exist to automatically convert to gate level representation.
  - High-level constructs greatly improves designer productivity.
  - However, this may lead you to falsely believe that hardware design can be reduced to writing programs*

"Structural" example:

```
Decoder(output x0,x1,x2,x3;
    inputs a,b)
    {
        wire abar, bbar;
        inv(bbar, b);
        inv(abar, a);
        and(x0, abar, bbar);
        and(x1, abar, b   );
        and(x2, a,    bbar);
        and(x3, a,    b   );
    }
```

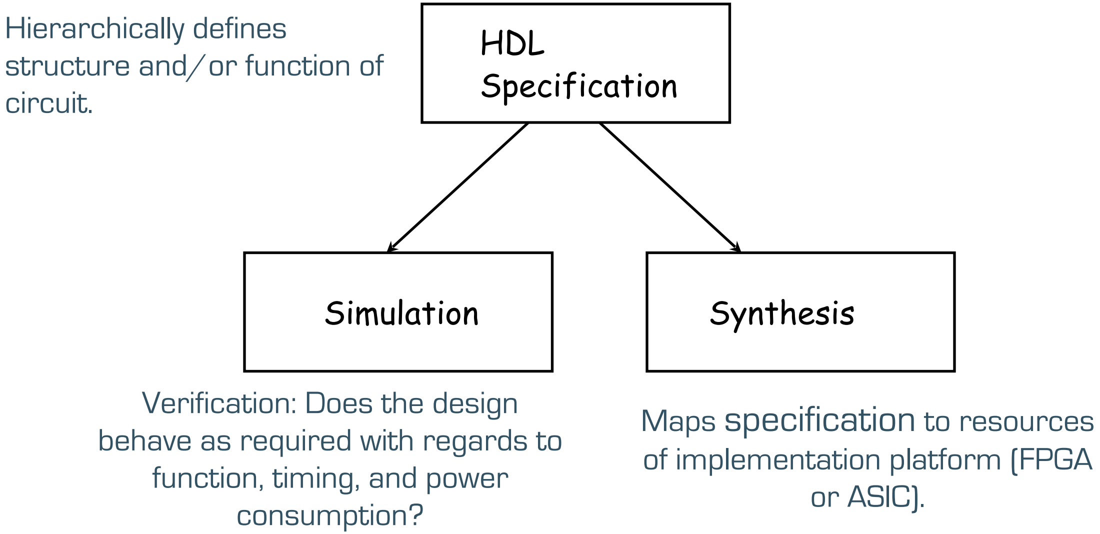
"Behavioral" example:

```
Decoder(output x0,x1,x2,x3;
    inputs a,b)
    {
        switch [a b]
               case 00: [x0 x1 x2 x3] = 0x8;
               case 01: [x0 x1 x2 x3] = 0x4;
               case 10: [x0 x1 x2 x3] = 0x2;
               case 11: [x0 x1 x2 x3] = 0x1;
        endswitch;
    }
```

Warning: this is a fake HDL!

*New tools and languages exist for this - called "high level synthesis".

Sample Design Methodology


Hierarchically defines structure and/or function of circuit.
HDL Specification
Simulation
Synthesis
Verification: Does the design behave as required with regards to function, timing, and power consumption?
Maps specification to resources of implementation platform (FPGA or ASIC).

Note: This in not the entire story. Other tools are useful for analyzing HDL specifications. More on this later.

Some Hardware Description Languages

Verilog:

- Simple C-like syntax for structural and behavior hardware constructs
- Mature set of commercial tools for synthesis and simulation
- Used in EECS 151 / 251A

VHDL:

- Semantically very close to Verilog
- More syntactic overhead
- Extensive type system for "synthesis time" checking

System Verilog:

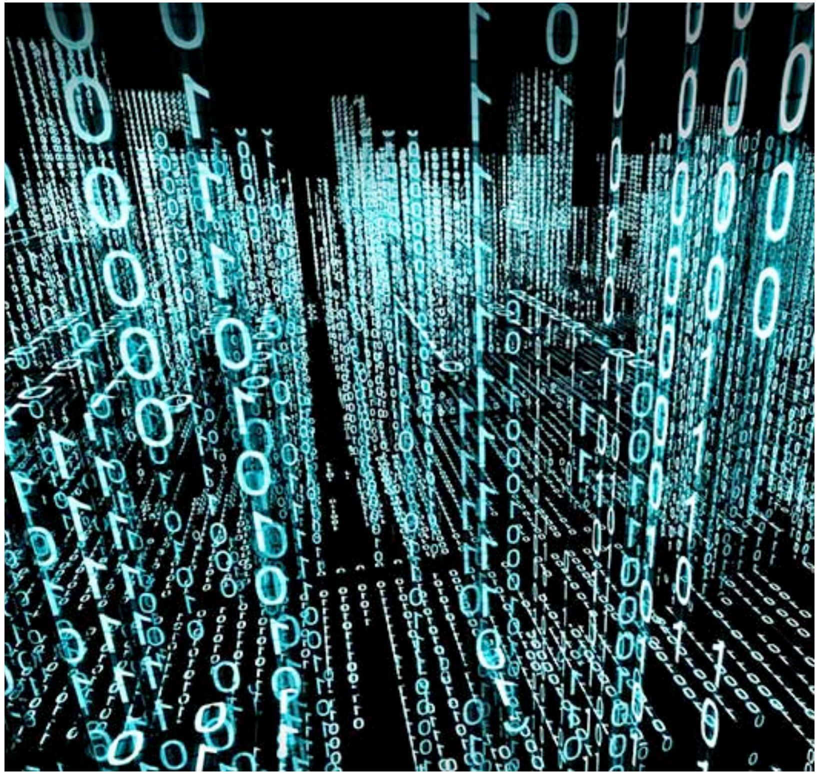
- Enhances Verilog with strong typing along with other additions
- Somewhat less mature tool-flow

BlueSpec:

- Invented at MIT
- Originally built within the Haskell programming language
- Now available commercially: bluespec.com

Chisel:

- Developed at UC Berkeley
- Used in CS152, and research projects
- Available at: www.chisel-lang.org



Verilog Introduction

Verilog Introduction

- A `module` definition describes a component in a circuit
- Two ways to describe module contents:
  - Structural Verilog
    - List of sub-components and how they are connected
    - Just like schematics, but using text
    - You get precise control over circuit details
    - May be necessary to map to special resources of the FPGA/ASIC
  - Behavioral Verilog
    - Describe what a component does, not how it does it
    - May be simpler to write than structural description
    - Synthesized into a circuit that has this behavior
    - Result is only as good as the tools
- Build up a hierarchy of modules. Top-level module is your entire design (or the environment to test your design).
- *Common approach is to use behavioral descriptions for "leaf cells" and structural to build hierarchy.*

Verilog Modules and Instantiation

- Modules define circuit components.
- Instantiation defines hierarchy of the design.

name *port list*

keywords

```
module addr_cell (a, b, cin, s, cout);
  input     a, b, cin;
  output    s, cout;
```

port declarations (input, output, or inout)

module body

```
endmodule

module adder (A, B, S);
```

Instance of addr_cell

```
addr_cell ac1 ( ... connections ... );

endmodule
```

Note: A module is not a function in the C sense. There is no call and return mechanism. Think of it more like a hierarchical data structure.

Note: Verilog syntax allows port declarations in port list.

Structural Model - XOR example

module name

port list

port declarations

internal signal declarations

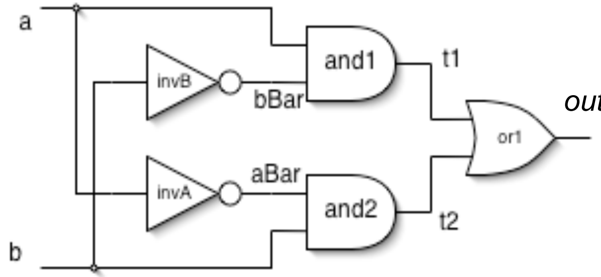
Built-in gates

instances

Interconnections (note output is first)

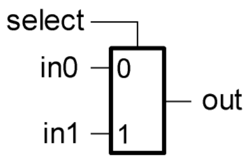
Instance name

```
module xor_gate ( out, a, b );
   input     a, b;
   output    out;
   wire      aBar, bBar, t1, t2;

   not invA (aBar, a);
   not invB (bBar, b);
   and and1 (t1, a, bBar);
   and and2 (t2, b, aBar);
   or  or1 (out, t1, t2);

endmodule
```

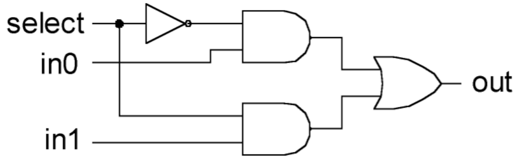


- Notes:
  - The instantiated gates are not “executed”. They are active always.
  - xor gate already exists as a built-in (so really no need to define it).

Structural Example: 2-to1 mux



a) 2-input mux symbol



b) 2-input mux gate-level circuit diagram

```
/* 2-input multiplexor in gates */
module mux2 (in0, in1, select, out);
   input in0,in1,select;
   output out;
   wire s0,w0,w1;

   not (s0, select);
   and (w0, s0, in0),
       (w1, select, in1);
   or  (out, w0, w1);

endmodule // mux2
```

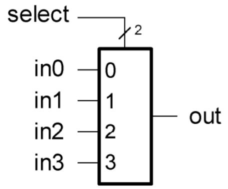
C++ style comments

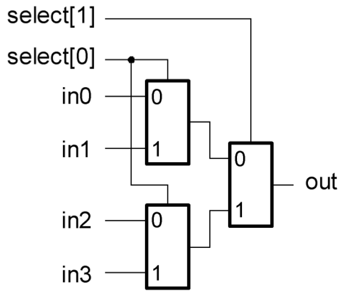
Built-ins don't need Instance names

Multiple instances can share the same "master" name.

Built-ins gates can have > 2 inputs. Ex:
`and (w0, a, b, c, d);`

Instantiation, Signal Array, Named ports





```
'* 2-input multiplexor in gates */
odule mux2 (in0, in1, select, out);
  input in0,in1,select;
  output out;
  wire s0,w0,w1;
  not (s0, select);
  and (w0, s0, in0),
      (w1, select, in1);
  or  (out, w0, w1);
ndmodule // mux2
```

a) 4-input mux symbol b) 4-input mux implemented with 2-input muxes

```
module mux4 (in0, in1, in2, in3, select, out);
input in0,in1,in2,in3;
input [1:0] select;
output out;
wire w0,w1;
  mux2
    m0 (.select(select[0]), .in0(in0), .in1(in1), .out(w0)),
    m1 (.select(select[0]), .in0(in2), .in1(in3), .out(w1)),
    m3 (.select(select[1]), .in0(w0), .in1(w1), .out(out));
endmodule // mux4
```

Signal array. Declares select[1], select[0]

Named ports. Highly recommended.

Simple Behavioral Model

```
module foo (out, in1, in2);
  input         in1, in2;
  output        out;

     assign out = in1 & in2;

endmodule
```

“continuous assignment”

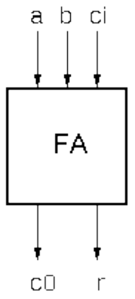
Connects out to be the “and” of in1 and in2.

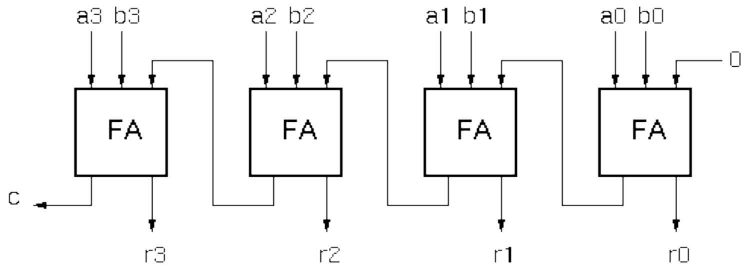
The assignment continuously happens, therefore any change on the rhs is reflected in out immediately (except for the small delay associated with the implementation of the &).

Not like an assignment in C that takes place when the program counter gets to that place in the program.

Example - Ripple Adder

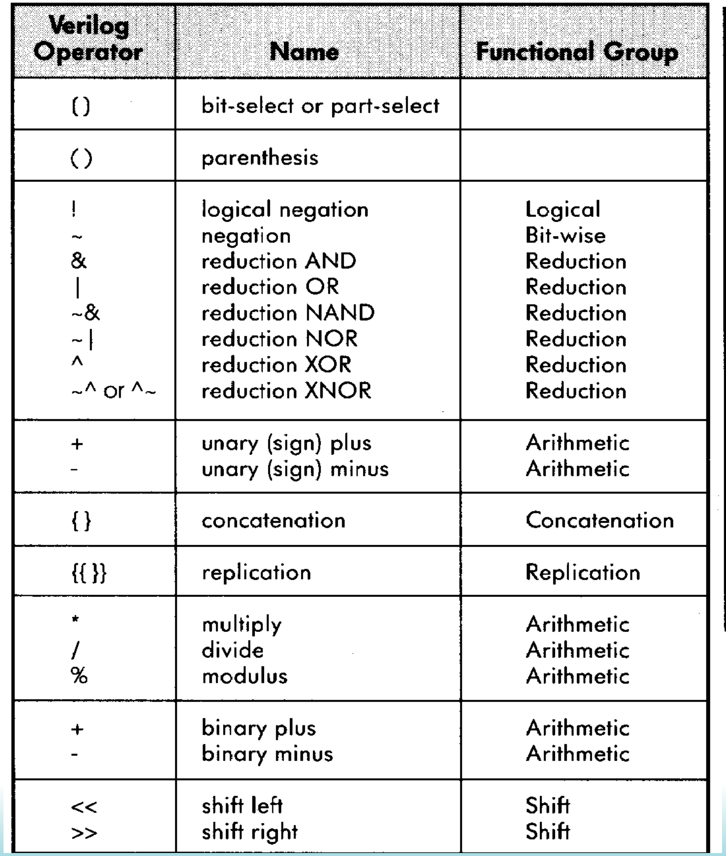
```
module FullAdder(a, b, ci, r, co);
   input a, b, ci;
   output r, co;

   assign r = a ^ b ^ ci;
  assign co = a&ci | a&b | b&ci;

endmodule
```



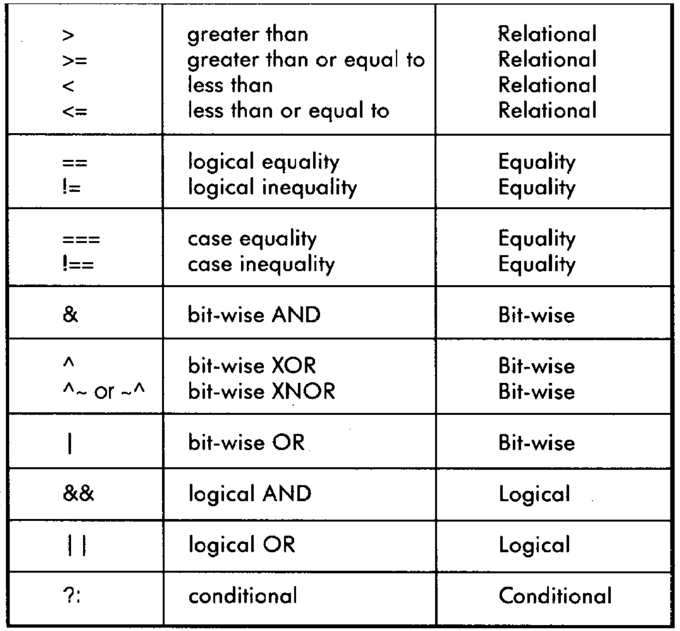


```
module Adder(A, B, R);
   input [3:0] A;
   input [3:0] B;
   output [4:0] R;

   wire c1, c2, c3;

   FullAdder
   add0(.a(A[0]), .b(B[0]), .ci(1'b0), .co(c1),   .r(R[0]) ),
   add1(.a(A[1]), .b(B[1]), .ci(c1),   .co(c2),   .r(R[1]) ),
   add2(.a(A[2]), .b(B[2]), .ci(c2),   .co(c3),   .r(R[2]) ),
   add3(.a(A[3]), .b(B[3]), .ci(c3),   .co(R[4]), .r(R[3]) );
endmodule
```

Verilog Operators



Verilog Operator	Name	Functional Group
[ ]	bit-select or part-select	
( )	parenthesis	
!	logical negation	Logical
~	negation	Bit-wise
&	reduction AND	Reduction
|	reduction OR	Reduction
~&	reduction NAND	Reduction
~|	reduction NOR	Reduction
^	reduction XOR	Reduction
~^ or ^~	reduction XNOR	Reduction
+	unary (sign) plus	Arithmetic
-	unary (sign) minus	Arithmetic
{ }	concatenation	Concatenation
{{ }}	replication	Replication
*	multiply	Arithmetic
/	divide	Arithmetic
%	modulus	Arithmetic
+	binary plus	Arithmetic
-	binary minus	Arithmetic
<<	shift left	Shift
>>	shift right	Shift



>	greater than	Relational
>=	greater than or equal to	Relational
<	less than	Relational
<=	less than or equal to	Relational
==	logical equality	Equality
!=	logical inequality	Equality
===	case equality	Equality
!==	case inequality	Equality
&	bit-wise AND	Bit-wise
^	bit-wise XOR	Bit-wise
^~ or ~^	bit-wise XNOR	Bit-wise
|	bit-wise OR	Bit-wise
&&	logical AND	Logical
| |	logical OR	Logical
?:	conditional	Conditional

Verilog Numbers

Constants:

`14` ordinary decimal number

`-14` 2's complement representation

`12'b0000_0100_0110` binary number ("_" is ignored)

`12'h046` hexadecimal number with 12 bits

Signal Values:

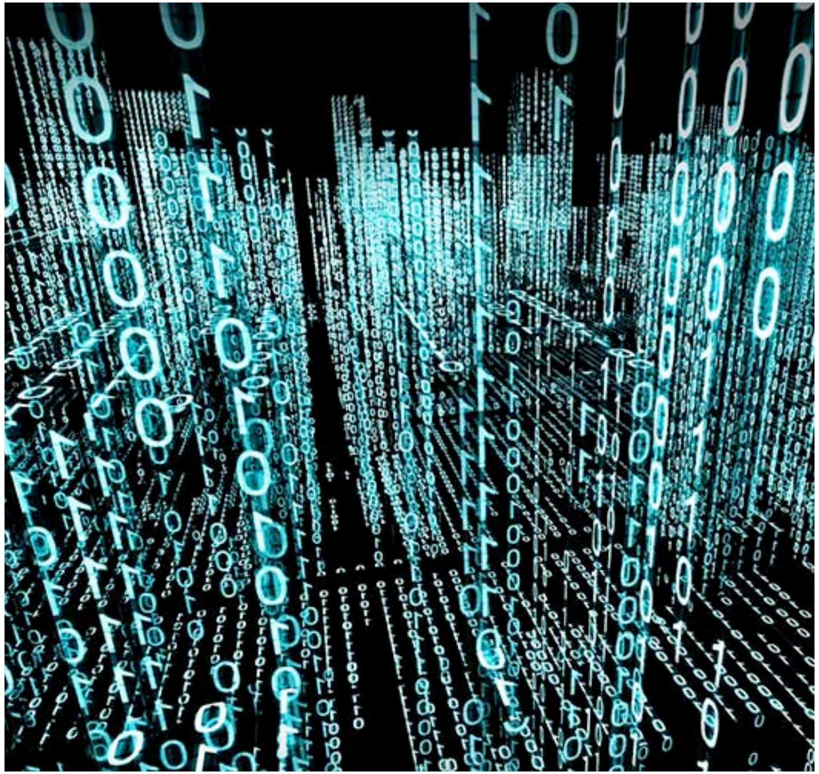
By default, Values are unsigned

e.g., **`C[4:0] = A[3:0] + B[3:0];`**

if A = 0110 (6) and B = 1010 (treated as 10 not -6)
C = 10000 not 00000
i.e., B is zero-padded, not sign-extended

`wire signed [31:0] x;`

Declares a signed (2's complement) signal array.



Verilog Assignment Types

Continuous Assignment Examples

```
wire [3:0] A, X,Y,R,Z;
wire [7:0] P;
wire r, a, cout, cin;
```

```
assign R = X | (Y & ~Z);
assign r = &X;
assign R = (a == 1'b0) ? X : Y;
assign P = 8'hff;
assign P = X * Y;
assign P[7:0] = {4{X[3]}, X[3:0]};
assign {cout, R} = X + Y + cin;
assign Y = A << 2;
assign Y = {A[1], A[0], 1'b0, 1'b0};
```

use of bit-wise Boolean operators

example reduction operator

conditional operator

example constants

arithmetic operators (use with care!)

(ex: sign-extension)

bit field concatenation

bit shift operator

equivalent bit shift

Non-continuous Assignments

A bit strange from a hardware specification point of view. Shows off Verilog roots as a simulation language.

"always" block example:

```
module and_or_gate (out, in1, in2, in3);
  input      in1, in2, in3;
  output     out;
  reg        out;

  always @(in1 or in2 or in3) begin
     out = (in1 & in2) | in3;
  end

endmodule
```

"reg" type declaration, needed for always block assignment. Not really a register in this case. Just a Verilog idiosyncrasy.

keyword

"sensitivity" list, triggers the action in the body.

brackets multiple statements (not necessary in this example.

Isn't this just: `assign out = (in1 & in2) | in3;`?

Why bother?

Always Blocks

Always blocks give us some constructs that are impossible or awkward in continuous assignments.

case statement example:

```
module mux4 (in0, in1, in2, in3, select, out);
    input in0,in1,in2,in3;
    input [1:0] select;
    output      out;
    reg         out;

   always @ (in0 in1 in2 in3 select)
        case (select)
              2'b00: out=in0;
              2'b01: out=in1;
              2'b10: out=in2;
              2'b11: out=in3;
        endcase
endmodule // mux4
```

keyword

The statement(s) corresponding to whichever constant matches "select", get applied.

Couldn't we just do this with nested "if"s?

Well yes and no!

Always Blocks

Nested if-else example:

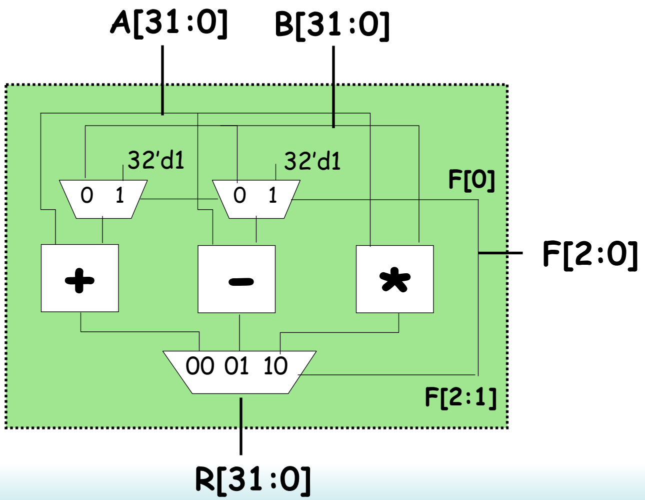
```
module mux4 (in0, in1, in2, in3, select, out);
   input in0,in1,in2,in3;
   input [1:0] select;
   output      out;
   reg         out;

  always @ (in0 in1 in2 in3 select)
        if (select == 2'b00) out=in0;
      else if (select == 2'b01) out=in1;
           else if (select == 2'b10) out=in2;
                else out=in3;
endmodule // mux4
```

Nested if structure leads to “priority logic” structure, with different delays for different inputs (in3 to out delay > than in0 to out delay). Case version treats all inputs the same.

Defining Processor ALU in 5 mins

- Modularity is essential to the success of large designs
- High-level primitives enable direct synthesis of behavioral descriptions (functions such as additions, subtractions, shifts (<< and >>), etc.

Example: A 32-bit ALU



Function Table

F2	F1	F0	Function
0	0	0	A + B
0	0	1	A + 1
0	1	0	A - B
0	1	1	A - 1
1	0	X	A * B

Module Definitions

2-to-1 MUX

```
module mux32two(i0,i1,sel,out);

input [31:0] i0,i1;
input sel;
output [31:0] out;

assign out = sel ? i1 : i0;

endmodule
```

32-bit Adder

```
module add32(i0,i1,sum);

input [31:0] i0,i1;
output [31:0] sum;

assign sum = i0 + i1;

endmodule
```

32-bit Subtracter

```
module sub32(i0,i1,diff);

input [31:0] i0,i1;
output [31:0] diff;

assign diff = i0 - i1;

endmodule
```

3-to-1 MUX

```
module mux32three(i0,i1,i2,sel,out);
input [31:0] i0,i1,i2;
input [1:0] sel;
output [31:0] out;
reg [31:0] out;

always @ (i0 or i1 or i2 or sel)
begin
  case (sel)
    2'b00: out = i0;
    2'b01: out = i1;
    2'b10: out = i2;
    default: out = 32'bx;
  endcase
end
endmodule
```

16-bit Multiplier

```
module mul16(i0,i1,prod);

input [15:0] i0,i1;
output [31:0] prod;

// this is a magnitude multiplier
// signed arithmetic later
assign prod = i0 * i1;

endmodule
```

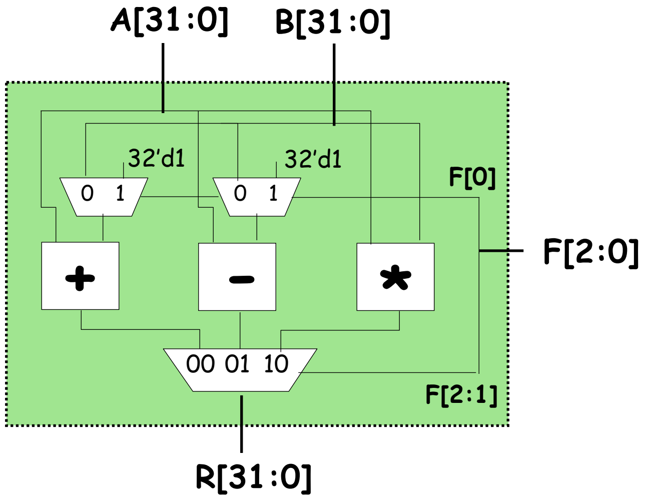
Top-Level ALU Declaration

- Given submodules:

```
module mux32two(i0,i1,sel,out);
module mux32three(i0,i1,i2,sel,out);
module add32(i0,i1,sum);
module sub32(i0,i1,diff);
module mul16(i0,i1,prod);
```

- Declaration of the ALU Module:

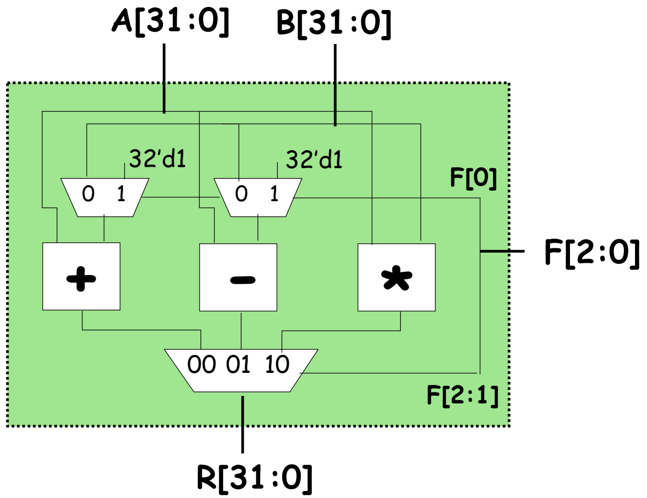
```
module alu(a, b, f, r);
  input [31:0] a, b;
  input [2:0] f;
  output [31:0] r;

  wire [31:0] addmux_out, submux_out;
  wire [31:0] add_out, sub_out, mul_out;

  mux32two   adder_mux(.io(b), .i1(32'd1), .sel(f[0]), .out(addmux_out));
  mux32two   sub_mux(.io(b), .i1(32'd1), .sel(f[0]), .out(submux_out));
  add32      our_adder(.i0(a), .i1(addmux_out), .sum(add_out));
  sub32      our_subtracter(.i0(a), .i1(submux_out), .diff(sub_out));
  mul16      our_multiplier(.i0(a[15:0]), .i1(b[15:0]), .prod(mul_out));
  mux32three output_mux(.i0(add_out), .i1(sub_out), .i2(mul_out), .sel(f[2:1]), .out(r));
endmodule
```



Top-Level ALU Declaration, take 2

- No Hierarchy:
- Declaration of the ALU Module:

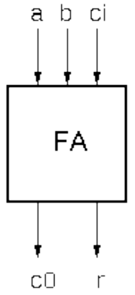
```
module alu(a, b, f, r);
  input [31:0] a, b;
  input [2:0] f;
  output [31:0] r;
  always @ (a or b or f)
    case (f)
      3'b000:  r = a + b;
      3'b001:  r = a + 1'b1;
      3'b010:  r = a - b;
      3'b011:  r = a - 1'b1;
      3'b100:  r = a * b;
      default: r = 32'bx;
    endcase
endmodule
```

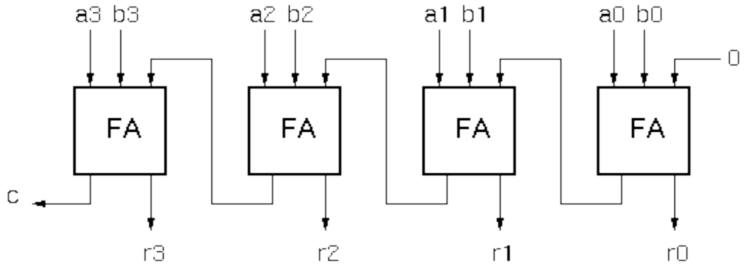


Will this synthesize into 2 adders and 2 subtractors or 1 of each?

Review - Ripple Adder Example

```
module FullAdder(a, b, ci, r, co);
   input a, b, ci;
   output r, co;

   assign r = a ^ b ^ ci;
  assign co = a&ci + a&b + b&cin;

endmodule
```





```
module Adder(A, B, R);
  input [3:0] A;
  input [3:0] B;
  output [4:0] R;

  wire c1, c2, c3;
  FullAdder
  add0(.a(A[0]), .b(B[0]), .ci(1'b0), .co(c1),   .r(R[0]) ),
  add1(.a(A[1]), .b(B[1]), .ci(c1),   .co(c2),   .r(R[1]) ),
  add2(.a(A[2]), .b(B[2]), .ci(c2),   .co(c3),   .r(R[2]) ),
  add3(.a(A[3]), .b(B[3]), .ci(c3),   .co(R[4]), .r(R[3]) );
endmodule
```

Example - Ripple Adder Generator

Parameters give us a way to generalize our designs. A module becomes a "generator" for different variations. Enables design/module reuse. Can simplify testing.

```
module Adder(A, B, R);
  parameter N = 4;
  input [N-1:0] A;
  input [N-1:0] B;
  output [N:0] R;
  wire [N:0] C;

  genvar i;

  generate
    for (i=0; i<N; i=i+1) begin:bit
      FullAdder add(.a(A[i], .b(B[i]), .ci(C[i]), .co(C[i+1]), .r(R[i]));
   end
  endgenerate

  assign C[0] = 1'b0;
  assign R[N] = C[N];
endmodule
```

Declare a parameter with default value.

Note: this is not a port. Acts like a "synthesis-time" constant.

Replace all occurrences of "4" with "N".

variable exists only in the specification - not in the final circuit.

Keyword that denotes synthesis-time operations

For-loop creates instances (with unique names)

```
Adder adder4 ( ... );

Adder #(.N(64))
adder64 ( ... );
```

Overwrite parameter N at instantiation.

More on Generate Loop

Permits variable declarations, modules, user defined primitives, gate primitives, continuous assignments, initial blocks and always blocks to be instantiated multiple times using a for-loop.

```
//Gray-code to binary-code converter
module gray2bin1 (bin, gray);
    parameter SIZE = 8;
    output [SIZE-1:0] bin;
    input  [SIZE-1:0] gray;

    genvar i;

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

variable exists only in the specification - not in the final circuit.

Keywords that denotes synthesis-time operations

For-loop creates instances of assignments

Loop must have constant bounds

generate if-else-if based on an expression that is deterministic at the time the design is synthesized.

generate case : selecting case expression must be deterministic at the time the design is synthesized.

Verilog in EECS 151/251A

- We use behavioral modeling at the bottom of the hierarchy
- Use instantiation to 1) build hierarchy and, 2) map to FPGA and ASIC resources not supported by synthesis.
- Favor continuous assign and avoid always blocks unless:
  - no other alternative: ex: state elements, case
  - helps readability and clarity of code: ex: large nested if else
- Use named ports.
- Verilog is a big language. This is only an introduction.
  - Complete IEEE Verilog-Standard document (1364-2005) linked to class website.
  - Harris & Harris book chapter 4 is a good source.
  - ***Be careful of what you read on the web***. Many bad examples out there.
  - We will be introducing more useful constructs throughout the semester. Stay tuned!