EECS150 - Digital Design
Lecture 3 - Verilog Introduction

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Prof. Ronald Fearing
Electrical Engineering and Computer Sciences
University of California, Berkeley

http://www-inst.eecs.berkeley.edu/~cs150

(slides courtesy of Prof. John Wawrzynek)

Outline

- Recap Mux logic example
- Background and History of Hardware Description
- Brief Introduction to Verilog Basics
- Lots of examples
  - structural, data-flow, behavioral
- Verilog in EECS150

Design Entry

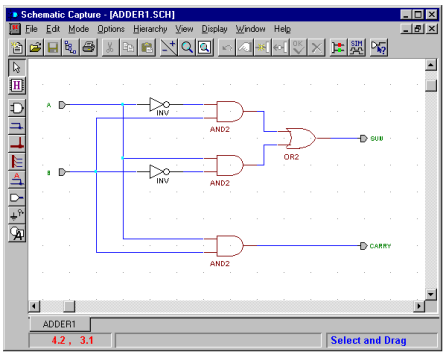
- Schematic entry/editing used to be the standard method in industry and universities.
- Used in EECS150 until 2002

☺ 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.



- 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.
  - Now "logic synthesis" tools exist to automatically convert from HDL source to circuits.
  - 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   );
}
```

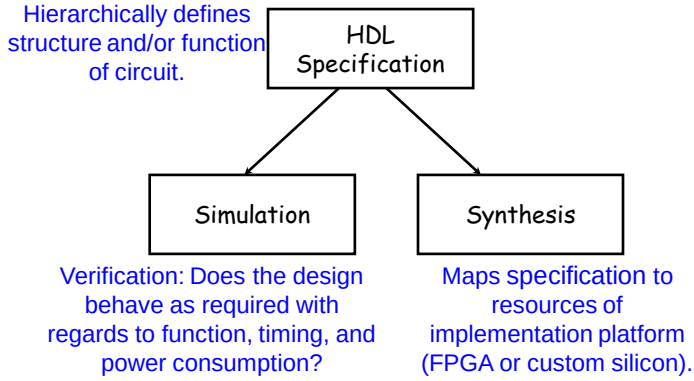
"Behavioral" example:

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

Warning: this is a fake HDL!

*Describing hardware with a language is similar, however, to writing a parallel program.

Sample Design Methodology



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

Verilog

- A brief history:
  - Originated at Automated Integrated Design Systems (renamed Gateway) in 1985. Acquired by Cadence in 1989.
  - Invented as simulation language. Synthesis was an afterthought. Many of the basic techniques for synthesis were developed at Berkeley in the 80's and applied commercially in the 90's.
  - Around the same time as the origin of Verilog, the US Department of Defense developed VHDL (A double acronym! VHSIC (Very High-Speed Integrated Circuit) HDL). Because it was in the public domain it began to grow in popularity.
  - Afraid of losing market share, Cadence opened Verilog to the public in 1990.
  - An IEEE working group was established in 1993, and ratified IEEE Standard 1394 (Verilog) in 1995. We use IEEE Std 1364-2001.
  - Verilog is the language of choice of Silicon Valley companies, initially because of high-quality tool support and its similarity to C-language syntax.
  - VHDL is still popular within the government, in Europe and Japan, and some Universities.
  - Most major CAD frameworks now support both.
  - Latest Verilog version is "system Verilog" .
  - Latest HDL: C++ based. OSCI (Open System C Initiative).

Verilog Introduction

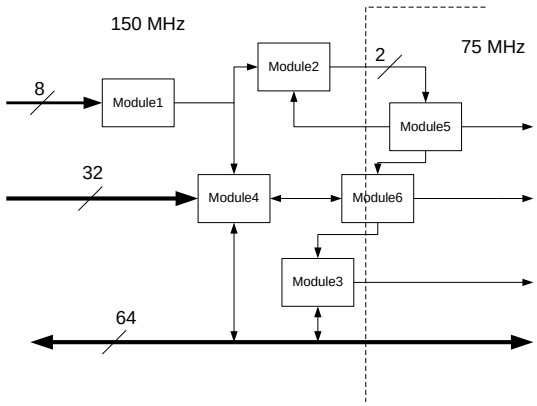
- A **`module`** definition describes a component in a circuit
- Two ways to describe module contents:
  - Structural Verilog
    - List of sub-components and how they are connected
    - Just like schematics, but using text
    - tedious to write, hard to decode
    - You get precise control over circuit details
    - May be necessary to map to special resources of the FPGA
  - Behavioral Verilog
    - Describe what a component does, not how it does it
    - 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).

TOP DOWN ARCH (1)

- Top Down Refinement Process
- Start Here:

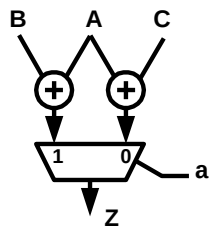
TOP DOWN ARCH (2)

- End Here:

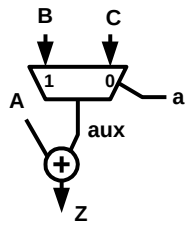


"Think Hardware (1)"

```
If(a == 1)
  Z= A + B;
Else
  Z= A + C;
```

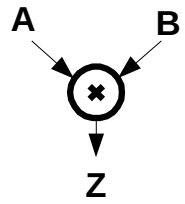



```
if(a == 1)
  aux = B;
else
  aux = C;
Z = A + aux;
```

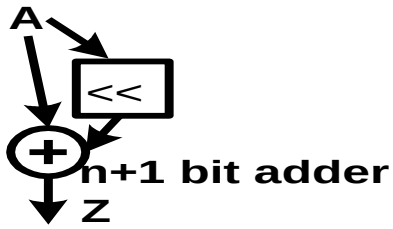


“Think Hardware (2)”

```
assign B = 3;
assign Z = A * B;
```

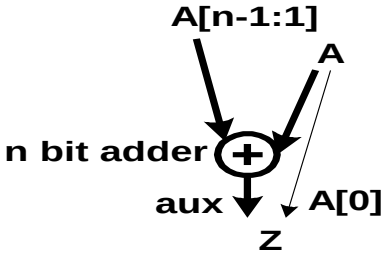



```
assign Z = A + 2 * A;
```



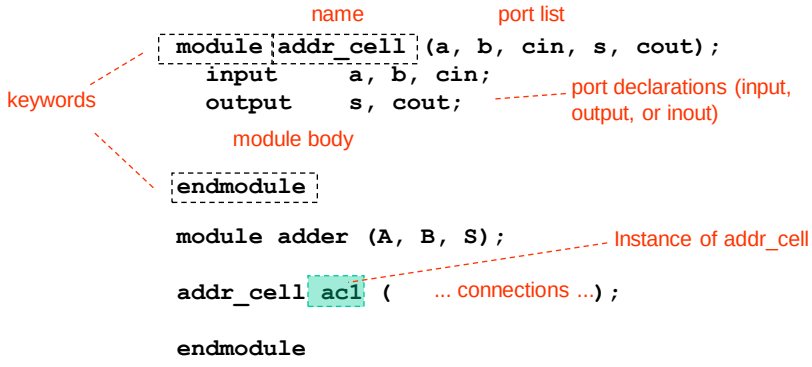
“Think Hardware (3)”

```
assign aux = {1'b0, A[n-1:1]} + A[n-1:0];
assign Z = {aux, A[0]};
```



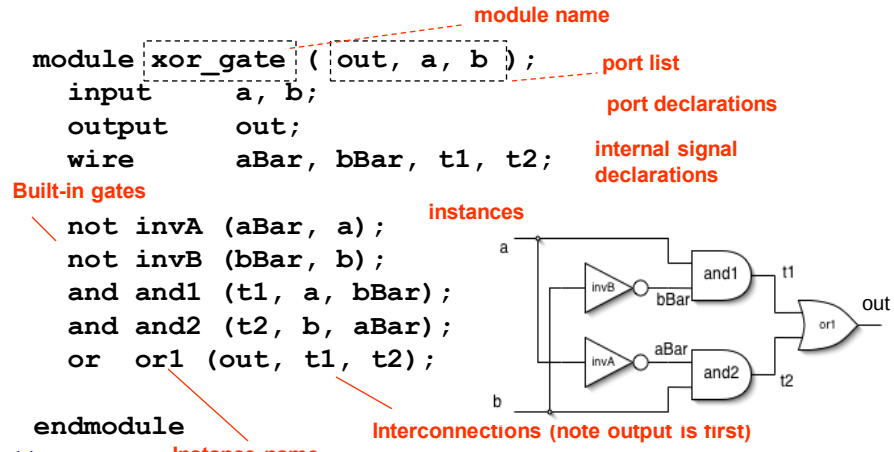
Verilog Modules and Instantiation

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



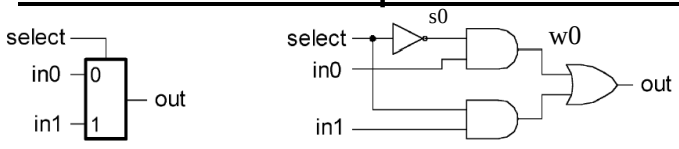
Note: A module is not a function in the C sense. There is no call and return mechanism. Think of it more like a hierarchical data structure.

Structural Model - XOR example



– 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).
  - Undeclared variables assumed to be wires. Don't let this happen to you!

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
```

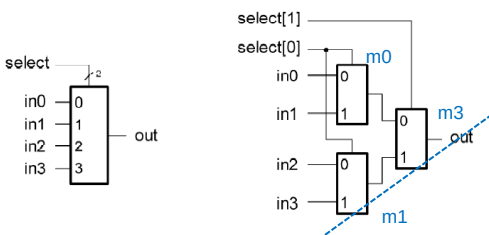
C++ style comments

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



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

```
/* 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
```

```
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

& = AND
| = OR
^ = XOR

```
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.

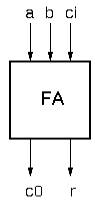
Shorthand for explicit instantiation of "and" gate (in this case).

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.

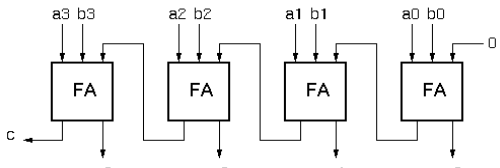
Example - Ripple Adder

```
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&cin;

endmodule
```



check truth table…

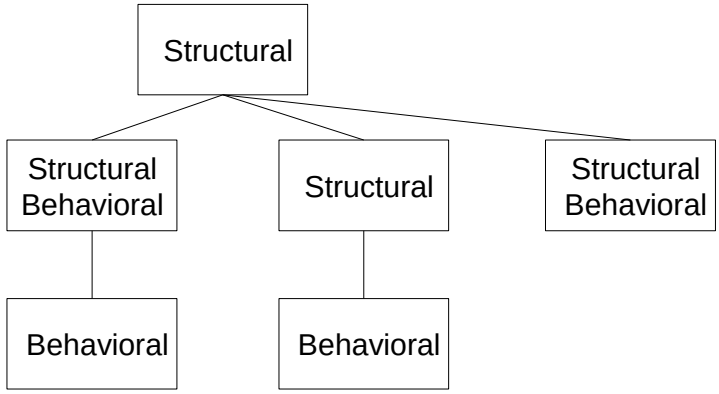
```
module Adder(A, B, R);
  input [3:0] A;
  input [3:0] B;
  output [4:0] R;

  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
```



Behavioral vs Structural (1)

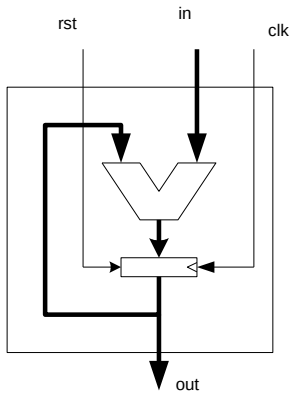
- Rule of thumb:
  - Behavioral doesn't have sub-components
  - Structural has sub-components:
    - Instantiated Modules
    - Instantiated Gates
    - Instantiated Primitives
- Most levels are mixed

Behavioral vs Structural (2)



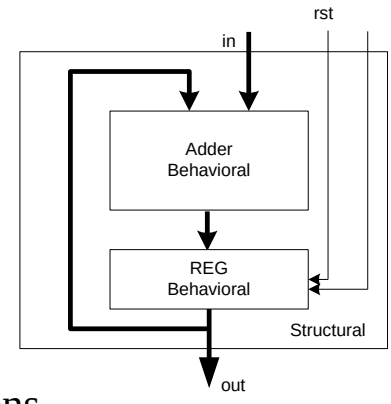
Behavioral Example

- Behavioral Only
- No Instantiations

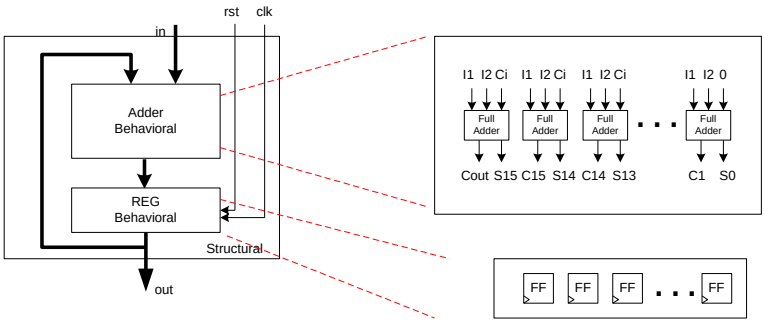


Behavioral and Structural

- Behavioral:
  - Adder
  - Register
- Structural:
  - Top
  - Two Instantiations



low level details



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

Verilog Operators

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

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. Not really a register in this case. Just a Verilog rule.

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

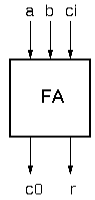
Nested if-else example:

```
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
```

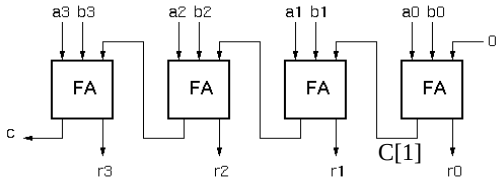
Nested if structure leads to "priority logic" structure, with different delays for different inputs (in3 to out delay > than in0 to out delay). Case version treats all inputs the same.

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.

Declare a parameter with default value.

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

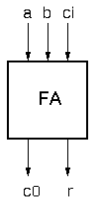
Replace all occurrences of "4" with "N".

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

Keyword that denotes synthesis-time operations

For-loop creates instances (with unique names)

```
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
```




```
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 EECS150

- We will primarily use behavioral modeling along with instantiation to 1) build hierarchy and, 2) map to FPGA 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.
  - Our text book is a good source. Read and use chapter 4.
  - 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!

Final thoughts on Verilog Examples

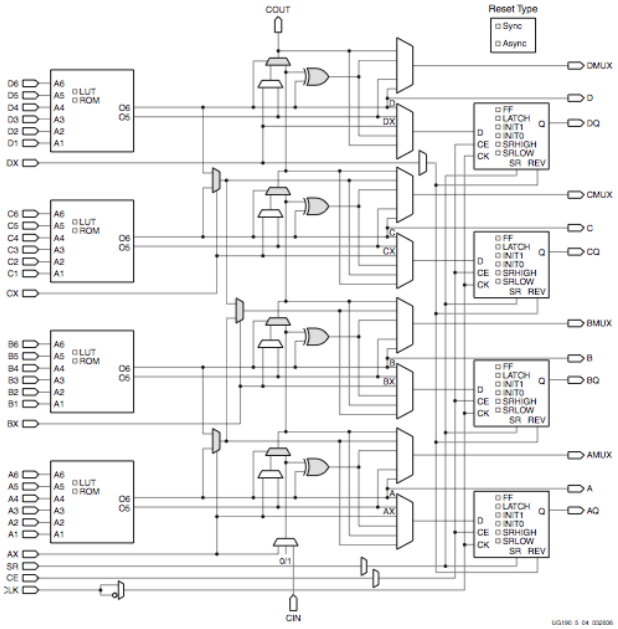
Verilog looks like C, but it describes hardware

Multiple physical elements with parallel activities and temporal relationships.

A large part of digital design is knowing how to write Verilog that gets you the desired circuit. First understand the circuit you want then figure out how to code it in Verilog. If you do one of these activities without the other, you will struggle. These two activities will merge at some point for you.

Be suspicious of the synthesis tools! Check the output of the tools to make sure you get what you want.

Putting it all together ... a SLICEL.

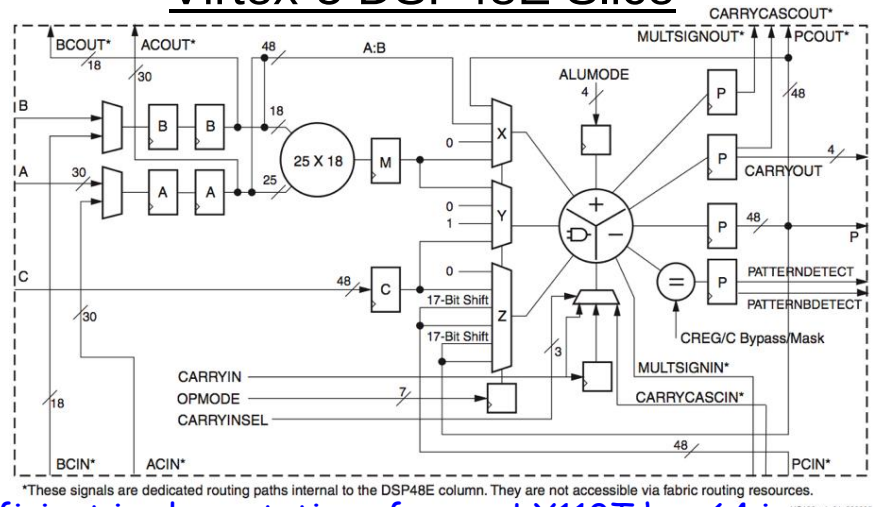


The previous slides explain all SLICEL features.

About 50% of the 17,280 slices in an LX110T are SLICELs.

The other slices are SLICEMs, and have extra features.

Virtex-5 DSP48E Slice



*These signals are dedicated routing paths internal to the DSP48E column. They are not accessible via fabric routing resources.

Efficient implementation of multiply, add, bit-wise logical.

LX110T has 64 in a single column.

Table 1: **Virtex-5 FPGA Family Members**

Device	Configurable Logic Blocks (CLBs)			DSP48E Slices[2]	Block RAM Blocks			CMTs[4]	PowerPC Processor Blocks	Endpoint Blocks for PCI Express	Ethernet MACs[5]	Max RocketIO Transceivers[6]		Total I/O Banks[8]	Max User I/O[7]
	Array (Row x Col)	Virtex-5 Slices[1]	Max Distributed RAM (Kb)		18 Kb[3]	36 Kb	Max (Kb)					GTP	GTX		
XC5VLX30	80 x 30	4,800	320	32	64	32	1,152	2	N/A	N/A	N/A	N/A	N/A	13	400
XC5VLX50	120 x 30	7,200	480	48	96	48	1,728	6	N/A	N/A	N/A	N/A	N/A	17	560
XC5VLX85	120 x 54	12,960	840	48	192	96	3,456	6	N/A	N/A	N/A	N/A	N/A	17	560
XC5VLX110	160 x 54	17,280	1,120	64	256	128	4,608	6	N/A	N/A	N/A	N/A	N/A	23	800
XC5VLX155	160 x 76	24,320	1,640	128	384	192	6,912	6	N/A	N/A	N/A	N/A	N/A	23	800
XC5VLX220	160 x 108	34,560	2,280	128	384	192	6,912	6	N/A	N/A	N/A	N/A	N/A	23	800
XC5VLX330	240 x 108	51,840	3,420	192	576	288	10,368	6	N/A	N/A	N/A	N/A	N/A	33	1,200
XC5VLX20T	60 x 26	3,120	210	24	52	26	936	1	N/A	1	2	4	N/A	7	172
XC5VLX30T	80 x 30	4,800	320	32	72	36	1,296	2	N/A	1	4	8	N/A	12	360
XC5VLX50T	120 x 30	7,200	480	48	120	60	2,160	6	N/A	1	4	12	N/A	15	480
XC5VLX85T	120 x 54	12,960	840	48	216	108	3,888	6	N/A	1	4	12	N/A	15	480
XC5VLX110T	160 x 54	17,280	1,120	64	296	148	5,328	6	N/A	1	4	16	N/A	20	680
XC5VLX155T	160 x 76	24,320	1,640	128	424	212	7,632	6	N/A	1	4	16	N/A	20	680
XC5VLX220T	160 x 108	34,560	2,280	128	424	212	7,632	6	N/A	1	4	16	N/A	20	680
XC5VLX330T	240 x 108	51,840	3,420	192	648	324	11,664	6	N/A	1	4	24	N/A	27	960
XC5VSX35T	80 x 34	5,440	520	192	168	84	3,024	2	N/A	1	4	8	N/A	12	360
XC5VSX50T	120 x 34	8,160	780	288	264	132	4,752	6	N/A	1	4	12	N/A	15	480
XC5VSX95T	160 x 46	14,720	1,520	640	488	244	8,784	6	N/A	1	4	16	N/A	19	640
XC5VSX240T	240 x 78	37,440	4,200	1,056	1,032	516	18,576	6	N/A	1	4	24	N/A	27	960
XC5VTX150T	200 x 58	23,200	1,500	80	456	228	8,208	6	N/A	1	4	N/A	40	20	680
XC5VTX240T	240 x 78	37,440	2,400	96	648	324	11,664	6	N/A	1	4	N/A	48	20	680
XC5VFX30T	80 x 38	5,120	380	64	136	68	2,448	2	1	1	4	N/A	8	12	360
XC5VFX70T	160 x 38	11,200	820	128	296	148	5,328	6	1	3	4	N/A	16	19	640
XC5VFX100T	160 x 56	16,000	1,240	256	456	228	8,208	6	2	3	4	N/A	16	20	680
XC5VFX130T	200 x 56	20,480	1,580	320	596	298	10,728	6	2	3	6	N/A	20	24	840
XC5VFX200T	240 x 68	30,720	2,280	384	912	456	16,416	6	2	4	8	N/A	24	27	960

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