CSE140L: Components and Design Techniques for Digital Systems Lab

Tajana Simunic Rosing

Source: Vahid, Katz, Culler
Announcements & Outline

• CAPE season is open!!!!
  – Please go to http://www.cape.ucsd.edu/ and fill out your evaluation

• Check webct for the grades!!! CSE140L grade distribution:
  – 70% Labs
    • 20% Lab 4
    • 20% Lab 3
    • 20% Lab 2
    • 10% Lab 1
  – 30% Final exam

• Exam – next week at class time
  – Everything covered in labs, lectures, book & handouts
  – Format:
    • Multiple choice and/or T/F questions on the assigned reading & labs
    • Problems to solve based on the lectures, labs and textbook
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Synthesis

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Logic Synthesis

• Verilog and VHDL started out as simulation languages, but soon programs were written to automatically convert Verilog code into low-level circuit descriptions (netlists).

• Synthesis converts Verilog (or other HDL) descriptions to an implementation using technology-specific primitives:
  – For FPGAs: LUTs, flip-flops, and RAM blocks
  – For ASICs: standard cell gate and flip-flop libraries, and memory blocks
Why Perform Logic Synthesis?

1. Automatically manages many details of the design process:
   • Fewer bugs
   • Improves productivity

2. Abstracts the design data (HDL description) from any particular implementation technology
   • Designs can be re-synthesized targeting different chip technologies; E.g.: first implement in FPGA then later in ASIC

3. In some cases, leads to a more optimal design than could be achieved by manual means (e.g.: logic optimization)
How Does It Work?

- **Variety of general and ad-hoc (special case) methods:**
  - **Instantiation:** maintains a library of primitive modules (AND, OR, etc.) and user defined modules
  - **“Macro expansion”/substitution:** a large set of language operators (+, -, Boolean operators, etc.) and constructs (if-else, case) expand into special circuits
  - **Inference:** special patterns are detected in the language description and treated specially (e.g., inferring memory blocks from variable declaration and read/write statements, FSM detection and generation from “always @ (posedge clk)” blocks)
  - **Logic optimization:** Boolean operations are grouped and optimized with logic minimization techniques
  - **Structural reorganization:** advanced techniques including sharing of operators, and retiming of circuits (moving FFs), and others
Operators

- Logical operators map into primitive logic gates
- Arithmetic operators map into adders, subtractors, …
  - Unsigned 2s complement
  - Model carry: target is one-bit wider than source
- Relational operators generate comparators
- Shifts by constant amount are just wire connections
  - No logic involved
- Variable shift amounts a whole different story --- shifter
- Conditional expression generates logic or MUX

\[ Y = \sim X \ll 2 \]
Synthesis vs. Compilation

Levels of Representation

- **High Level Language Program (e.g., C)**
  - Recognizes all possible constructs in a formally defined program language
  - Translates them to a machine language representation of execution process

- **Assembly Language Program (e.g., MIPS)**
  - Compiler
  - Synthesis

- **Machine Language Program (MIPS)**

- **Control Signal Specification**

- **Compiler**
  - Recognizes all possible constructs in a formally defined program language
  - Translates them to a machine language representation of execution process

- **Synthesis**
  - Recognizes a target dependent subset of a hardware description language
  - Maps to collection of concrete hardware resources
  - Iterative tool in the design flow
Simple Example

module foo (a,b,s0,s1,f);
input [3:0] a;
input [3:0] b;
input s0,s1;
output [3:0] f;
reg f;
always @ (a or b or s0 or s1)
  if (!s0 && s1 || s0) f=a; else f=b;
endmodule

- Should expand if-else into 4-bit wide multiplexer (a, b, f are 4-bit vectors) and optimize/minimize the control logic:
Verilog has two types of assignments within always blocks:

- **Blocking** procedural assignment “=”
  - RHS is executed and assignment is completed before the next statement is executed; e.g.,
    
    Assume A holds the value 1 … A=2; B=A; A is left with 2, B with 2.

- **Non-blocking** procedural assignment “<=“
  - RHS is executed and assignment takes place at the end of the current time step (not clock cycle); e.g.,
    
    Assume A holds the value 1 … A<=2; B<=A; A is left with 2, B with 1.
Supported Verilog Constructs

- Net types: wire, tri, supply1, supply0; register types: reg, integer, time (64 bit reg); arrays of reg
- Continuous assignments
- Gate primitive and module instantiations
- always blocks, user tasks, user functions
- inputs, outputs, and inouts to a module
- All operators (+, -, *, /, %, <, >, <=, >=, ==, !==, !!!=, &&, ||, !, ~, &~, ~&, |, ~|, ^~, ^~, ^, <<<, >>>, ?::, { }, {{ }}) [Note: / and % are supported for compile-time constants and constant powers of 2]
- Procedural statements: if-else-if, case, casex, casez, for, repeat, while, forever, begin, end, fork, join
- Procedural assignments: blocking assignments =, nonblocking assignments <= (Note: <= cannot be mixed with = for the same register).
- Compiler directives: `define, `ifdef, `else, `endif, `include, `undef
- Miscellaneous:
  - Integer ranges and parameter ranges
  - Local declarations to begin-end block
  - Variable indexing of bit vectors on the left and right sides of assignments
Unsupported Language Constructs

**Generate error and halt synthesis**

- Net types: trireg, wor, trior, wand, triand, tri0, tri1, and charge strength;
- Register type: real
- Built-in unidirectional and bidirectional switches, and pull-up, pull-down
- Procedural statements: assign (different from the “continuous assignment”), deassign, wait
- Named events and event triggers
- UDPs (user defined primitives) and specify blocks
- Force, release, and hierarchical net names (for simulation only)

**Simply ignored**

- Delay, delay control, and drive strength
- Scalared, vectored
- Initial block
- Compiler directives (except for `define, `ifdef, `else, `endif, `include, and `undef, which are supported)
- Calls to system tasks and system functions (they are only for simulation)
Combinational Logic

CL can be generated using:

1. Primitive gate instantiation:
   \[
   \text{AND, OR, etc.}
   \]

2. Continuous assignment (assign keyword), example:
   
   Module adder_8 (cout, sum, a, b, cin);
   output cout;
   output [7:0] sum;
   input cin;
   input [7:0] a, b;
   assign {cout, sum} = a + b + cin;
   endmodule

3. Always block:
   
   always @ (event_expression)
   begin
   // procedural assignment statements, if statements,
   // case statements, while, repeat, and for loops.
   // Task and function calls
   end
Combinational Logic Always Blocks

- Make sure all signals assigned in a combinational always block are explicitly assigned values every time that the always block executes—otherwise latches will be generated to hold the last value for the signals not assigned values!

Example:

- Sel case value 2’d2 omitted
- Out is not updated when select line has 2’d2
- Latch is added by tool to hold the last value of out under this condition

```verilog
module mux4to1 (out, a, b, c, d, sel);
output out;
input a, b, c, d;
input [1:0] sel;
reg out;
always @(sel or a or b or c or d)
begin
    case (sel)
        2'd0: out = a;
        2'd1: out = b;
        2'd3: out = d;
    endcase
end
endmodule
```
Combinational Logic Always Blocks (cont.)

• To avoid synthesizing a latch in this case, add the missing select line:

  \[
  2\text{'d}2: \text{out} = \text{c};
  \]

• Or, in general, use the “default” case:

  \[
  \text{default: out} = \text{foo};
  \]

• If you don’t care about the assignment in a case (for instance you know that it will never come up) then assign the value “x” to the variable; E.g.:

  \[
  \text{default: out} = 1\text{bx};
  \]

  The x is treated as a “don’t care” for synthesis and will simplify the logic

  (The synthesis directive “full_case” will accomplish the same, but can lead to differences between simulation and synthesis.)
Latch Rule

• If a variable is not assigned in all possible executions of an always statement then a latch is inferred
  – E.g., when not assigned in all branches of an if or case
  – Even a variable declared locally within an always is inferred as a latch if incompletely assigned in a conditional statement
Encoder Example

• Nested IF-ELSE might lead to “priority logic”
  – Example: 4-to-2 encoder

always @(x)
begin : encode
  if (x == 4'b0001) y = 2'b00;
  else if (x == 4'b0010) y = 2'b01;
  else if (x == 4'b0100) y = 2'b10;
  else if (x == 4'b1000) y = 2'b11;
  else y = 2'bxx;
end

• This style of cascaded logic may adversely affect the performance of the circuit
Encoder Example (cont.)

- To avoid “priority logic” use the case construct:

```verilog
always @(x)
begin : encode
    case (x)
        4'b0001: y = 2'b00;
        4'b0010: y = 2'b01;
        4'b0100: y = 2'b10;
        4'b1000: y = 2'b11;
        default: y = 2'bxx;
    endcase
end
```

- All cases are matched in parallel
- Note, you don’t need the “parallel case” directive (except under special circumstances, described later)
Encoder Example (cont.)

- Circuit would be simplified during synthesis to take advantage of constant values as follows and other Boolean equalities:

A similar simplification would be applied to the if-else version also
• If you can guarantee that only one 1 appears in the input (one hot encoding), then simpler logic can be generated:

```verilog
always @(x)
begin : encode
if (x[0]) y = 2'b00;
else if (x[1]) y = 2'b01;
else if (x[2]) y = 2'b10;
else if (x[3]) y = 2'b11;
else y = 2'bxx;
end
```

• If the input applied has more than one 1, then this version functions as a “priority encoder” -- least significant 1 gets priority (the more significant 1’s are ignored); the circuit will be simplified when possible.
Encoder Example (cont.)

- Parallel version, assuming we can guarantee only one 1 in the input:
  ```vhdl
  always @(x)
  begin : encode
    casex (x) // synthesis parallel_case
    4'bxxxx1: y = 2'b00;
    4'bxx1x: y = 2'b01;
    4'bx1xx: y = 2'b10;
    4'b1xxx: y = 2'b11;
    default: y = 2'bxx;
  endcase
  end
  ```

- Note now more than one case might match the input
- Therefore use “parallel case” directive: without it, synthesis adds appropriate matching logic to force priority
  - Semantics of case construct says that the cases are evaluated from top to bottom
  - *Only an issue for synthesis when more than one case could match input*
Encoder Example (cont.)

- Parallel version of “priority encoder”:

```verilog
always @(x)
begin : encode
case(x)
  4'bxxxx1: y = 2'b00;
  4'bx1xx: y = 2'b10;
  4'bxx1x: y = 2'b01;
  4'bxxx1: y = 2'b11;
  default: y = 2'bxx;
endcase
end
```

- Note: “parallel case” directive is not used, synthesis adds appropriate matching logic to force priority
  - Just what we want for a priority encoder

- Behavior matches that of the if-else version presented earlier
Sequential Logic

- Example: D flip-flop with synchronous set/reset:

```verbatim
module dff(q, d, clk, set, rst);
input d, clk, set, rst;
output q;
reg q;
always @(posedge clk)
  if (reset)
    q <= 0;
  else if (set)
    q <= 1;
  else
    q <= d;
endmodule
```

- “@ (posedge clk)” key to flip-flop generation
- Note in this case, priority logic is appropriate
- For Xilinx Virtex FPGAs, the tool infers a native flip-flop
  - No extra logic needed for set/reset

We prefer synchronous set/reset, but how would you specify asynchronous preset/clear?

![Flip-flop diagram](https://via.placeholder.com/150)
module FSM1(clk, rst, enable, data_in, data_out);
input clk, rst, enable;
input data_in;
output data_out;

/* Defined state encoding;
this style preferred over `defines */
parameter default=2'bxx;
parameter idle=2'b00;
parameter read=2'b01;
parameter write=2'b10;
reg data_out;
reg [1:0] state, next_state;

/* always block for sequential logic */
always @(posedge clk)
  if (rst) state <= idle;
  else state <= next_state;

• Style guidelines (some of these are to get the right result, and some just for readability)
  – Must have reset
  – Use separate always blocks for sequential and combination logic parts
  – Represent states with defined labels or enumerated types
FSMs (cont.)

/* always block for CL */
always @(state or enable or data_in)
begin
  case (state)
  /* For each state def output and next */
    idle : begin
      data_out = 1'b0;
      if (enable)
        next_state = read;
      else next_state = idle;
    end
  read : begin … end
  write : begin … end
  default : begin
    next_state = default;
    data_out = 1’bx;
  end
endcase
end
endmodule

- Use CASE statement in an always to implement next state and output logic
- Always use default case and assert the state variable and output to ‘bx:
  - Avoids implied latches
  - Allows use of don’t cares leading to simplified logic
- “FSM compiler” within synthesis tool can re-encode your states; Process is controlled by using a synthesis attribute (passed in a comment).
More information

• Bhasker is a good synthesis reference: