Simulation of Digital Systems

Simulation —
- What do you do to test a software program you write?
  - Give it some inputs, and see if it does what you expect
  - When done testing, is there any assurance the program is bug free? — NO!
- But, to the extent possible, you have determined that the program does what you want it to do
- Simulation tests a model of the system you wish to build
  - Is the design correct? Does it implement the intended function correctly? For instance, is it a UART
  - Also, is it the correct design?
  - Might there be some other functions the UART could do?

Simulation checks two properties
- functional correctness — is the logic correct
  - correct design, and design correct
- timing correctness — is the logic/interconnect timing correct
  - e.g. are the set-up times met?

It has all the limitations of software testing
- Have I tried all the cases?
- Have I exercised every path? Every option?

Modern Design Methodology

Simulation and Synthesis are components of a design methodology

Place and Route

Synthesis

Technology Mapping

Gates, gates, gates, ...

Selects, Selects, Selects, ...

Complex Integrated Circuit Blocks

Module mux (f, a, b, sel);
  output f;
  input a, b, sel;
  and #5 g1 (f1, a, nsel),
  g2 (f2, b, sel);
  or #5 g3 (f, f1, f2);
  not g4 (nsel, sel);
endmodule

Representation: Structural Models

Structural models
- Are built from gate primitives and/or other modules
- They describe the circuit using logic gates — much as you would see in an implementation of a circuit.
  - You could describe your lab1 circuit this way

```
module mux (f, a, b, sel);
  output f;
  input a, b, sel;
  and #5 g1 (f1, a, nsel),
  g2 (f2, b, sel);
  or #5 g3 (f, f1, f2);
  not g4 (nsel, sel);
endmodule
```

Representation: Gate-Level Models

Need to model the gate's:
- Function
- Delay

Function
- Generally, HDLs have built-in gate-level primitives
  - Verilog has NAND, NOR, AND, OR, XOR, XNOR, BUF, NOT, and some others
  - The gates operate on input values producing an output value
  - Typical Verilog gate instantiation is:
    ```
    optional "many"
    ```
    and #delay instance-name (out, in1, in2, in3, ...);
### Four-Valued Logic

#### Verilog Logic Values
- The underlying data representation allows for any bit to have one of four values:
  - \(1\), \(0\), \(x\) (unknown), \(z\) (high impedance)
- \(x\) — one of: \(1\), \(0\), \(z\), or in the state of change
- \(z\) — the high impedance output of a tri-state gate.

#### What basis do these have in reality?
- \(0, 1\) … no question
- \(z\) … A tri-state gate drives either a zero or one on its output. If it’s not doing that, its output is high impedance (z). Tri-state gates are real devices and z is a real electrical affect.
- \(x\) … not a real value. There is no real gate that drives an \(x\) on to a wire. \(x\) is used as a debugging aid. \(x\) means the simulator can’t determine the answer and so maybe you should worry!

**BTW …**
- some simulators keep track of more values than these. Verilog will in some situations.

### Logic with multi-level logic values
- Logic with these four values make sense:
  - Nand anything with a 0, and you get a 1. This includes having an \(x\) or \(z\) on the other input. That’s the nature of the nand gate
  - Nand two \(x\)’s and you get an \(x\)
- Note: \(z\) treated as an \(x\) on input. Their rows and columns are the same
- If you forget to connect an input … it will be seen as an \(z\).

#### A 4-valued truth table for a Nand gate with two inputs

<table>
<thead>
<tr>
<th>Input A</th>
<th>Input B</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>(x)</td>
</tr>
<tr>
<td>(x)</td>
<td>0</td>
<td>(x)</td>
</tr>
<tr>
<td>(x)</td>
<td>1</td>
<td>(x)</td>
</tr>
<tr>
<td>(x)</td>
<td>(x)</td>
<td>(x)</td>
</tr>
</tbody>
</table>

### How to build and test a module

#### Construct a “test bench” for your design
- Develop your hierarchical system within a module that has input and output ports (called “design” here)
- Develop a separate module to generate tests for the module (“test”)
- Connect these together within another module (“testbench”)

```verilog
module design (a, b, c);
input a, b;
output c;
...
module test (q, r);
output q, r;
initial begin
  //drive the outputs with signals
  ...
module testbench ();
wire l, m, n;
design d (l, m, n);
test t (l, m);
initial begin
  //monitor and display
  ...
```

### Another view of this

- 3 chunks of verilog, one for each of:
  - Your hardware called DESIGN
  - Another piece of hardware, called TEST, to generate interesting inputs
  - The test module

### The test module
- It’s the test generator
  - \$monitor
    - prints its string when executed
    - after that, the string is printed when one of the listed values changes.
    - only one monitor can be active at any time
    - prints at end of current simulation time
- Function of this tester
  - at time zero, print values and set any\(\text{#}b\)\(\text{#a}\)
  - after 10 time units, set \(\text{#}b\)\(\text{#b}\)
  - after another 10 set \(\text{#}b\)\(\text{#a}\)
  - after another 10 and finish

```verilog
module testAdd(a, b, sum, cOut);
input sum, cOut;
output a, b;
reg a, b;
initial begin
  $monitor ($time, "%d %d %d %d", a, b, sum, cOut);
  a = 0; b = 0;
  #10 b = 1;
  #10 a = 1;
  #10 b = 0;
  #10 $finish;
end
```
Other things you can do

More than modeling hardware

- $monitor — give it a list of variables. When one of them changes, it prints the information. Can only have one of these active at a time.
  - e.g. ...
    - $monitor ($time,, "a=%b, b=%b, sum=%b, cOut=%b", a, b, sum, cOut); extra commas print a spaces
    - The above will print:
      2 a=0, b=0, sum=0, cOut=0

- $display() — sort of like printf()
  - $display ("Hello, world — %h", hexvalue)
  - %b is binary (also, %h, %d and others)
  - newline automatically included
  - display contents of data item called "hexvalue" using hex digits (0-9, A-F)

What if what you print has the value x or z?

Structural vs Behavioral Models

- Structural model
  - Just specifies primitive gates and wires
  - i.e., the structure of a logical netlist
  - You basically know how to do this now.

- Behavioral model
  - More like a procedure in a programming language
  - Still specify a module in Verilog with inputs and outputs...
  - ...but inside the module you write code to tell what you want to have happen, NOT what gates to connect to make it happen
  - i.e., you specify the behavior you want, not the structure to do it

Why use behavioral models

- For testbench modules to test structural designs
- For high-level specs to drive logic synthesis tools (Lab 2)

How do behavioral models fit in?

- How do they work with the event list and scheduler?
  - Initial (and always) begin executing at time 0 in arbitrary order
  - They execute until they come to a "$delay" operator
  - They then suspend, putting themselves in the event list 10 time units in the future (for the case at the right)
  - At 10 time units in the future, they resume executing where they left off.

- Some details omitted
  - more to come

Two initial statements?

- Things to note
  - Which initial statement starts first?
  - What are the values of a, b, and out when the simulation starts?
  - These appear to be executing concurrently (at the same time). Are they?

What do we mean by “Synthesis”?

- Logic synthesis
  - A program that “designs” logic from abstract descriptions of the logic
  - takes constraints (e.g. size, speed)
  - uses a library (e.g. 3-input gates)

- How?
  - You write an “abstract” Verilog description of the logic
  - The synthesis tool provides alternative implementations

An example

- What’s cool?
  - You type the left, synthesis gives you the gates
  - It used a different library than you did. (2-input gates only)
  - One description suffices for a variety of alternate implementations!

- Hmmm ...
  - ... but this assumes you know a gate level implementation — that’s not an “abstract” Verilog description.
**What Do We Want Here...?**

- **Goal**
  - To specify a combination ckt, inputs->outputs...
  - ... in a form of Verilog that synthesis tools will correctly read
  - ... and then use to make the right logic
- **And...**
  - We know the function we want, and can specify in C-like form...
  - ... but we don't now the exact gates: we want the tool to do this.

**Combinational Logic**

A  B  C  F

**Behavioral Modeling**

- **Procedural statements are used**
  - Statements using “always” Verilog construct
  - Can specify both combinational and sequential circuits
- **Normally don’t think of procedural stuff as “logic”**
  - They look like C: mix of ifs, case statements, assignments ...
  - ... but there is a semantic interpretation to put on them to allow them to be used for simulation and synthesis (giving equivalent results)
- **Current technology**
  - You can do combinational (and later, sequential) design
  - Sizable designs can take hours ... days ... to run
  - Companies pay $50K - 80K per copy for such software
    - This ain’t shrink-wrap software!
  - The software we’ll use is more like $10-15K

**Behavioral Constructs**

- **Behavioral descriptions are introduced by initial and always statements**

<table>
<thead>
<tr>
<th>Statement</th>
<th>Looks like</th>
<th>Starts</th>
<th>How it works</th>
<th>Use in Synthesis?</th>
</tr>
</thead>
<tbody>
<tr>
<td>initial</td>
<td>begin</td>
<td>end</td>
<td>Execute once and stop</td>
<td>Not used in synthesis</td>
</tr>
<tr>
<td>always</td>
<td>begin</td>
<td>end</td>
<td>Continually loop—while (power on) do statements.</td>
<td>Used in synthesis</td>
</tr>
</tbody>
</table>

- **Points:**
  - They all execute concurrently
  - They contain behavioral statements like if-then-else, case, loops, functions, ...

**Behavioral Statements**

- **if-then-else**
  - What you would expect, except that it’s doing 4-valued logic. 1 is interpreted as True; 0, x, and z are interpreted as False
  - If (select == 1)
    - f = in1;
  - else f = in0;

- **case**
  - What you would expect, except that it’s doing 4-valued logic
  - If “selector” is 2 bits, there are 4^2 possible case-items to select between
  - There is no break statement — it is assumed.

- **Funny constants?**
  - Verilog allows for sized, 4-valued constants
  - The first number is the number of bits, the letter is the base of the following number that will be converted into the bits.

```
module silly (q, r);
  reg [3:0] a, b;
  wire [3:0] q, r;
  always begin
    a = (b & r) | q;
  end
  endmodule
```

- **Statements**
  - left-hand side = right-hand side
  - left-hand side must be a register

**Statements, Registers and Wires**

- **Registers**
  - Define storage, can be more than one bit
  - Can only be changed by assigning value to them on the left-hand side of a behavioral expression.

- **Wires (actually “nets”)**
  - Electrically connect things together
  - Can be used on the right-hand side of an expression
    - Thus we can tie primitive gates and behavioral blocks together!

- **Statements**
  - start when simulation starts
  - Execute once and stop
  - Continually loop—while (power on) do statements.

**Behavioral Statements**

- **Loops**
  - There are restrictions on using these for synthesis — don’t.
  - They are mentioned here for use in test modules

- **Two main ones — for and while**
  - Just like in C
  - There is also repeat and forever — see the book

```
reg [3:0] testOutput, i;
for (i = 0; i <= 15; i = i + 1) begin
  testOutput = i;
  #20;
end
```

```
reg [3:0] testOutput, i;
i = 0;
while (i <= 15) begin
  testOutput = i;
  #20 i = i + 1;
end
```

**Important:** Loops must have a delay operator (or as we’ll see later, an @ or wait(FALSE)). Otherwise, the simulator never stops executing them.

---

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FAQs: behavioral model execution

How does an always or initial statement start?
- That just happens at the start of simulation — arbitrary order

Once executing, what stops it?
- Executing either a #delay, @event, or wait(FALSE)
- All always blocks need to have at least one of these. Otherwise, the simulator will never stop running the model -- (it's an infinite loop!)

How long will it stay stopped?
- Until the condition that stopped it has been resolved
  - #delay ... until the delay time has been reached
  - @ (var) ... until var changes
  - wait(var) ... until var becomes TRUE

Does time pass when a behavioral model is executing?
- No. The statements (if, case, etc) execute in zero time.
- Time passes when the model stops for #, @, or wait.

Will an always stop looping?
- No. But an initial will only execute once.

A Combinational Circuit

Using behavioral constructs
- Logic for a simple MUX is specified procedurally here
- This example is synthesizable

module mux (f, sel, b, c);
  output f;
  input sel, b, c;
  reg f;
  always @ (sel or b or c)
    if (sel == 1)
      f = b;
    else
      f = c;
endmodule

This "if" functionally describes the MUX

Using procedural statements in Verilog
- Logic is specified in "always" statements ("initial" statements are not allowed).
- Each "always" statement turns into Boolean functions

module mux (f, a, b, c);
  output f;
  input a, b, c;
  reg f;
  always @ (a or b or c)
    begin
      stuff...
    end
endmodule

You have to list all the block's inputs here in the "sensitivity list"

Synthesis Template

module blah (f, a, b, c);
  output f;
  input a, b, c;
  reg f, a, b, c;
  always @ (a or b or c)
    begin
      stuff...
    end
endmodule

You need to have to declare the combinational outputs like this, for synthesis, i.e., tool needs to think you are putting these computed outputs somewhere.

Problem?
- Where's the register?
  - The synthesis tool figures out that this is a combinational circuit. Therefore, it doesn't need a register.
  - The register is there as an "artifact" of the descriptions — things on the left-hand side have to be registers.
  - How does it figure out that this is combinational?
    - The output is only a function of the inputs (and not of previous values)
    - Anytime an input changes, the output is re-evauated
    - Think about the module as being a black box...
  - Could you tell that there is a register in there?

Concurrent Constructs
- We already saw #delay
- Others
  - @ (var) waiting for a change in a value — used in synthesis
  - This says wait for var to change from its current value. When it does, resume execution of the statement by setting w = 4.
- Wait ... Waiting for a value to be a certain level — not used in synthesis
  - wait (f == 0) q = 3;
  - This says that if f is equal to zero, then continue executing and set q = 3.
  - But if f is not equal to zero, then suspend execution until it does.
  - When it does, this statement resumes by setting q = 3.

Why are these concurrent?
- Because the event being waited for can only occur as a result of the concurrent execution of some other always/initial block or gate.
- They're happening concurrently

Test Module, continued

Bit Selects and Part Selects
- This expression extracts bits or ranges of bits or a wire or register

The individual bits of register i are made available on the ports. These are later connected to individual input wires in module design.

module testgen (i);
  output i;
endmodule
**How? ... A Few Definitions**

- **Input set of an “always” statement** — the set of all variables that are used on the right-hand side of procedural assignments or in conditionals. i.e. anything "sourced".

- **Sensitivity list of an “always” statement** — the set of all names that appear in the event ("@") list.

The elements in these lists are:

```verilog
module mux (f, sel, b, c);
output f;
input sel, b, c;
reg f;
always @ (sel or b or c)
if (sel == 1)
f = b;
else
f = c;
endmodule
```

**More Definitions...**

- **Control path of an “always” statement** — a sequence of operations performed when executing the always statement.

- **Combinational output of an “always” statement** — a variable (or variables) assigned to in every control path.

What are they here...

```verilog
module mux (f, sel, b, c);
output f;
input sel, b, c;
reg f;
always @ (sel or b or c)
if (sel == 1)
f = b;
else
f = c;
endmodule
```

**The Basic Rules**

- The rules for specifying combinational logic using procedural statements
- Every element of the input set must be in the sensitivity list
- The combinational output must be assigned in every control path

Walking this narrow line allows you to specify and synthesize combinational logic.

```verilog
module mux (f, sel, b, c);
output f;
input sel, b, c;
reg f;
always @ (sel or b or c)
if (sel == 1)
f = b;
else
f = c;
endmodule
```

**What If You Mess Up?**

- If you don’t follow the rules...? ... you’re dead meat

Verilog assumes you are trying to do something clever with the timing

- It’s legal, but it won’t be combinational
- The rules for what it does make sense -- but not yet for us.

What’s wrong?

- f doesn’t appear in every control path in the always block (neither does g).

This says: as long as a==1, then f follows b. (i.e. when b changes, so does f.) But, when a==0, f remembers the old value of b.

Combinational circuits don’t remember anything!

**Typical Style**

- Your Verilog for combination stuff will look like this:

```verilog
module blah (f, g, a, b, c);
output f, g;
input a, b, c;
reg f, g;
always @ (a or b or c)
if (a == 1)
f = b;
else if (c > 2’b01)
g = a;
else if ( ... )
g = c;
endmodule
```

Yes...it’s a pretty restricted subset of the language...

**A Difficulty**

- Assigning in every control path
- If the function is complex, you don’t know if you assigned to the outputs in every control path.
- So, set all outputs to some known value (zero here) and write the code to set them to other values as needed.
- Synthesis tools will figure it out.

Assigning in every control path

```verilog
always @(coke or cola) begin
  blah1 = 0;
  blah2 = 0;
  if (coke)
    blah1 = 1;
  else if (cola > 2’b01)
    blah2 = coke;
  else if ( ... )

end
```

```verilog
always @(coke or cola) begin
  if (coke)
    blah1 = 1;
  else if (cola > 2’b01)
    blah2 = coke;
  else if ( ... )

end
```
Using a case statement

Truth table method
- List each input combination
- Assign to output(s) in each case item.

Concatenation
- \( (a, b, c) \) concatenates \( a \), \( b \), and \( c \) together, considering them as a single item.
- Example
  \[ a = 4'b0111 \]
  \[ b = 6'b10001 \]
  \[ c = 2'bzx \]
  \[ \text{then } (a, b, c) = 12'b011110001zx \]

module fred (f, a, b, c);
output f;
input a, b, c;
reg f;
always @ (a or b or c)
case ({a, b, c})
  3'b000: f = 1'b0;
  3'b001: f = 1'b1;
  3'b010: f = 1'b1;
  3'b011: f = 1'b1;
  3'b100: f = 1'b1;
  3'b101: f = 1'b0;
  3'b110: f = 1'b0;
  3'b111: f = 1'b1;
endcase
endmodule

Check the rules...

Don’t Cares in Synthesis

Rules
- You can’t say “if (a == 1'bxx)” — this has meaning in simulation, but not in synthesis.
- However, an unknown \( x \) on the right-hand side will be interpreted as a don’t care.

module caseExample(f, a, b, c);
output f;
input a, b, c;
reg f;
always @ (a or b or c)
case ({a, b, c})
  3'b001: f = 1'b1;
  3'b010: f = 1'b1;
  3'b011: f = 1'b1;
  3'b100: f = 1'b1;
  3'b111: f = 1'b1;
  3'b110: f = 1'b0;
  default: f = 1'b1;
endcase
endmodule

The inverse function was implemented; \( x \)'s taken as ones.

Alternatively...

module fred1 (f, a, b, c);
output f;
input a, b, c;
reg f;
always @ (a or b or c)
f = ~(a & b & ~c);
endmodule

module fred2 (f, a, b, c);
output f;
input a, b, c;
reg f;
always @ (a or b or c)
f = ~a | c | ~b;
endmodule

module fred3 (f, a, b, c);
output f;
input a, b, c;
reg f;
always @ (a or b or c)
begin
  if (c ==0)
    f = a~&b;
  else f = 1'b1;
end
endmodule

Two inputs, Three outputs

reg [1:0] newJ; 
reg out;
input i, j;
always @ (i or j)
case (j)
  2'b00: begin
    newJ = (i == 0) ? 2'b00 : 2'b01;
    out = 0;
  end
  2'b01 : begin
    newJ = (i == 0) ? 2'b00 : 2'b01;
    out = 1;
  end
  2'b10 : begin
    newJ = 2'b00;
    out = 0;
  end
  default: begin
    newJ = 2'b00;
    out = 1'bx;
  end
endcase

Works like the C conditional operator.
(\( \text{expr} \) ? \( a \) : \( b \))
If the \( \text{expr} \) is true, then the resulting value is \( a \), else it’s \( b \).

Behavioral Model Sensitivity

Quick example
- Gate A changes its output, gates B and C are evaluated to see if their outputs will change, if so, their fanouts are also followed.
- The behavioral model will only execute if it was waiting for a change on the D input.
- What order will the gates and behavioral model execute in.

Check the rules...
What about time delay

Could we have described the module as shown here?
- Note the delays. There is a different delay from the b input than from the c input.
- Yes, you could write this

But,
- Synthesis tools will ignore the time delays.
- Generally, they try to minimize the propagation from any combinational input to any combinational output in the system.

```verilog
module mux (f, sel, b, c);
    output f;
    input sel, b, c;
    reg f;
    always @ (sel or b or c)
        if (sel == 1)
            #5 f = b;
        else
            #88 f = c;
endmodule
```

Model Organization

Here's an always block for a combinational function.
- What Boolean functions can it model?
- Can I have more than one of these always blocks in a module? Yes
- Can two separate always calculate function f? No

```verilog
module xyzzy (ports);
    ...
    always @(b1 or b2 or b3)
        begin
            yadda yadda
        end
    always @(r1 or r2 or r3)
        begin
            s = yadda yadda yadda
        end
endmodule
```

Model Organization Trade-Off

Module partitioning can affect logic optimizations
- Here are two modules
  - The output of blob1 is connected to blob2
  - The synthesis tool will optimize them separately
    - No common prime implicants, etc, will be shared or optimized between the two modules.

```verilog
module blob1(inputs, outputs1);
    ...
    always @(inputs)
        outputs1 = blah & inputs;
    endmodule
module blob2(inputs, outputs2);
    ...
    always @(inputs)
        outputs2 = blah & inputs;
    endmodule
module blob1_2(inputs, outputs);
    ...
    always @(inputs)
        outputs1 = blah & inputs;
    always @(outputs1)
        outputs = blah & outputs1;
    endmodule
```

Verilog Overview

- Verilog is a concurrent language
  - Aimed at modeling hardware — optimized for it!
  - Typical of hardware description languages (HDLs), it:
    - provides for the specification of concurrent activities
    - stands on its head to make the activities look like they happened at the same time
    - allows for intricate timing specifications

A concurrent language allows for:
- Multiple concurrent “elements”
- An event in one element to cause activity in another. (An event is an output or state change at a given time)
  - based on interconnection of the element's ports
  - Further execution to be delayed
  - until a specific event occurs

Discrete Event Simulation

Quick example
- Gate A changes its output. This causes gates B and C to execute
  - But as we'll see, A doesn't call B and C (as in a function call)
  - Rather, they execute because they're connected

Observation
- The elements in the diagram don't need to be logic gates
- SimCity is a discrete event simulator, Verilog too

Discrete Event Simulation
- Events — changes in state — occur at discrete times.
  - These cause other events to occur.
- Time advances in discrete (not continuous) steps

Contrast

Non-discrete Event Simulation
- Continuous systems — all elements and state are updated at every simulation time
- Could you do logic circuits that way too?
  - ...?
  - e.g. analog circuits, numerical integration ...
    - differential equations to solve
Discrete Event Simulation

- Basic models — things not found in C
  - gate level — built-in models for AND, OR, ...
  - When an input to one of these changes, the model executes to see if its output should change
  - behavioral level — sort-of C-like programs but with a few extra operators
  - Executes until it blocks for one of three reasons — #delay, wait(level), or @(event) — when the reason for blocking is resolved, it continues executing
  - Does C have any notion of these?
- Gate and behavioral models can advance time

How does it keep track of time?

- Explicitly
  - Events are stored in an event list (actually a 2-D list) ordered by time
  - Events execute at a time and possibly schedule their output to change at a later time (a new event)
  - When no more events for the current time, move to the next
  - Events within a time are executed in arbitrary order

Approach to Simulating a System

- Two pieces of a simulation
  - The model — an executable specification including timing, interconnect, and input vectors
    - Written in a language like Verilog or VHDL
    - What's a VHDL?
  - The simulation scheduler —
    - keeps track of when events occur,
    - communicates events to appropriate parts of the model,
    - executes the model of those parts, and
    - as a result, possibly schedules more events for a future time.
    - it maintains “simulated time” and the event list.

Verilog Levels of Abstraction

- Gate modeling
  - the system is represented in terms of primitive gates and their interconnections
    - NANDs, NORs, ...
- Behavioral modeling
  - the system is represented by a program-like language

Mixing Levels

- Generally there is a mix of levels in a model
  - e.g. part of the system is at the gate level and another part is at the behavioral level.
  - Why?
    - Early in design process you might not have fully-detailed models — you don’t actually know all the gate implementations of the multipliers, adders, register files
    - You might want to think of the design at a conceptual level before doing all the work to obtain the gate implementations
    - There might be a family of implementations planned
  - Levels — switch, gate, functional block (e.g. ALUs), register-transfer, behavioral
    - for now, we’ll deal with gate and behavioral models
  - These are all modeled as discrete systems — no continuous modeling of analog behavior

A Gate Level Model

- A Verilog description of an SR latch
A Gate Level Model

A Verilog description of an SR latch

A module is defined

name of the module

the module has ports

module nandLatch (q, qBar, set, reset);

output q, qBar;

input set, reset;

nand #2

g1 (q, qBar, set),
g2 (qBar, q, reset);

endmodule

Things to note:

- It doesn’t appear “executable” — no for loops, if-then-else, etc.
  - It’s not in a programming sense, rather it describes the interconnection of elements
- A new module made up of other modules has been defined
  - Software engineering aspect — we can hide detail

But, there is an execution model

Gate-level timing model

- Timing model — how time is advanced, what triggers new processing in the model
- Here — when any of the inputs of a primitive gate change, the output is re-evaluated. If there is a new result, it is passed on to other gates on its fanout.

module nandLatch (q, qBar, set, reset);

output q, qBar;

input set, reset;

nand #2

g1 (q, qBar, set),
g2 (qBar, q, reset);

endmodule

Why not describe a module’s function and delay using a language like C?

- Sound like fun, here goes

module d_type_FF (q, clock, data);

output q;

reg q;

input clock, data;

always

@ (negedge clock) q = #10 data;

endmodule

At first look, it is a lot like C

- Most of the operators are the same as C
  - ^ is XOR, etc.
  - makes it easy to read
- But there are major differences (quick list, we’ll get to these)
  - Statements like #delay, @event, wait(level)
  - The language is concurrent — can specify many things that can happen at the same time.
  - Four-valued logic (1, 0, x, z) and the operators to go with them
  - Arbitrary bit width specification
  - There are a couple of procedural assignments (=, <=) with subtle differences
  - A different timing model

Comparison

- These two models are interchangeable — either could have been instantiated into a register
  - Ports in same order
  - Same delay from clock to q
  - One is abstract, clear
  - One is specific
  - There are subtle differences
Behavioral Timing Model (Not fully detailed here)

How does the behavioral model advance time?
- # — delaying a specific amount of time
- @ — delaying until an event occurs ("posedge", "negedge", or any change)
  - this is edge-sensitive behavior
- wait — delaying until an event occurs ("wait (f == 0)")
  - this is level sensitive behavior

What is a behavioral model sensitive to?
- any change on any input? — No
- any event that follows, say, a "posedge" keyword
  - e.g. @posedge clock
  - Actually "not" here too. — not always

What are behavioral models sensitive to?
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- any event that follows, say, a "posedge" keyword
  - e.g. @posedge clock
  - Actually "no" here too. — not always

Order of Execution

In what order do these models execute?
- Assume A changes. Is B, C, or the behavioral model executed first?
  - Answer: the order is defined to be arbitrary
- All events that are to occur at a certain time will execute in an arbitrary order.
- The simulator will try to make them look like they all occur at the same time — but we know better.

Arbitrary Order?  Oops!

Sometimes you need to exert some control
- Consider the interconnections of this D-FF
- At the positive edge of c, what models are ready to execute?
- Which one is done first?

Some more gate level examples

An adder

module adder (carryOut, sum, alinput, blinput, carryIn);
output carryOut, sum;
input alinput, blinput, carryIn;
xor (sum, alinput, blinput, carryIn);
or (ab, alinput, blinput),
(bc, blinput, carryIn),
(ac, alinput, carryIn);
endmodule

Adder with delays

module adder (carryOut, sum, alinput, blinput, carryIn);
output carryOut, sum;
input alinput, blinput, carryIn;
xor #(3, 5) (sum, alinput, blinput, carryIn);
or #2 (carryOut, ab, bc, ac);
and #(3, 2) (ab, alinput, blinput),
(bc, blinput, carryIn),
(ac, alinput, carryIn);
endmodule

An adder with delays

module adder (carryOut, sum, alinput, blinput, carryIn);
output carryOut, sum;
input alinput, blinput, carryIn;
xor #\(3, 5\) (sum, alinput, blinput, carryIn);
or #2 (carryOut, ab, bc, ac);
and #\(3, 2\) (ab, alinput, blinput),
(bc, blinput, carryIn),
(ac, alinput, carryIn);
endmodule

What's this mean?

each AND gate instance has the same delay

list of gate instances of same function (and)
implicit wire declarations
no instance names or delays
Continuous assignment assigns continuously
- delays can be specified (same format as for gates) on whole equation
- no instances names — nothing is being instantiated.
- given the same delays in this and the gate-level model of an adder, there is no functional difference between the models
- FYI, the gate-level model gives names to gate instances, allowing back annotation of times.

module adder (carryOut, sum, aInput, bInput, carryIn);
output carryOut, sum;
input aInput, bInput, carryIn;
assign sum = aInput ^ bInput ^ carryIn;
assign #(3, 5) carryOut = (aInput & bInput) | (bInput & carryIn) | (aInput & carryIn);
endmodule
**Events**

- Two types of events
  - Evaluation events — evaluate, or execute, a gate model or continuous assign.
  - Update events — propagate new values along a fanout.
- We'll treat these as separate types of events
  - gate level simulators generally combine them for efficiency
  - i.e. when an output is updated, instead of scheduling an evaluation, just do the evaluation and schedule any updates resulting from it.
  - We'll keep them separate for now — it will help in the later discussion of behavioral models

**Gate level timing model**

- What if an update event is already scheduled for an output?
  - If the value being scheduled is different, the currently scheduled value is removed from the event list; the new is not scheduled
  - thus, any input pulse shorter than the propagation delay will not be seen (inertial delay)

**Event-Driven Simulation**

while something in time-ordered event list {
advance simulation time to top event’s time retrieve all events for this time
For each event in arbitrary order
  if it’s an update event
    Update the value specified.
    Follow fanout and evaluate gate models.
    Schedule any new updates from gates.
  else // it’s an evaluation event
    evaluate the model
    schedule resulting update events
}

**Scheduling and event list management**

- Can think of the event list as a 2-D linked list
  - One dimension links all the events for a given time
  - The second dimension links these lists in ascending order
- Problem
  - inefficient — most events are near in time to the current one, thus lots of linked list bashing
**Scheduling and event list management**

- Hack of the rich and famous — “Timing wheel”
  - M nearest time slots stored in an array — M is a power of two
  - Access a list by (time mod M) — a table lookup
  - Essentially turned first linked list access into an array access saving time
  - Further out times are kept in linked list. As time is advanced, further out times are brought into wheel

- Timing wheel

  ![Timing Wheel Diagram](image.png)

**Asides**

- Can a gate model be executed several times in a time step?

- Does the order of execution of the gates in a combinational circuit matter?

**Summary on gate evaluation**

- Timing model
  - timing-execution model
    - how time is advanced and new values created
  - Any gate input or assign right-hand-side change causes the model to be evaluated during the time step
    - this is the case for behavioral models — they have a different timing model
  - Fanout list is static — design never changes

- Gate level modeling
  - detailed timing
  - Continuous timing

- What if you don’t like these models?
  - e.g., inertial delays?
  - use behavioral models

**Review Stuff**

- Update Events
  - A new value appears at some simulated time

- Evaluation Events
  - A model is executed (evaluated) at some simulated time

- Event List
  - A time-ordered list of events

- Simulation scheduler
  - Software program that manages the event list by scheduling update and evaluation events, tracing fanouts to propagate values, and manages simulated time

**Behavioral Timing Model**

- How does the behavioral model advance time?
  - # — delaying a specific amount of time
  - @ — delaying until an event occurs — e.g. @v
    - “posedge”, “negedge”, or any change
    - this is edge-sensitive behavior
    - When the statement is encountered, the value v is sampled.
    - When v changes in the specified way, execution continues.
  - wait — delaying until an event occurs (“wait f == 0”)
    - this is level sensitive behavior
  - While one model is waiting for one of the above reasons, other models execute — time marches on

**Wait**

- Wait — waits for a level on a line
  - How is this different from an “@”?

- Semantics
  - wait (expression) statement;
    - e.g. wait (a == 35) q = q + 4;
    - if the expression is FALSE, the process is stopped
    - when a becomes 35, it resumes with q = q + 4
    - if the expression is TRUE, the process is not stopped
    - it continues executing

- Partial comparison to @ and #
  - @ and # always “block” the process from continuing
  - wait blocks only if the condition is FALSE
An example of wait

```
module handshake (ready, dataOut, ...)
    input ready;
    output [7:0] dataOut;
    reg [7:0] someValueWeCalculated;
    always begin
        wait (ready);
        dataOut = someValueWeCalculated;
        wait (~ready)
    end
endmodule
```

Do you always get the value right when ready goes from 0 to 1? Isn’t this edge behavior?

Wait vs. While

- Are these equivalent?
  - No: The left example is correct, the right one isn’t — it won’t work
  - Wait is used to wait for an expression to become TRUE
    - the expression eventually becomes TRUE because a variable in the expression is changed by another process
  - While is used in the normal programming sense
    - in the case shown, if the expression is TRUE, the simulator will continuously execute the loop. Another process will never have the chance to change “in”; infinite loop!
    - while can’t be used to wait for a change on an input to the process. Need other variable in loop, or # or @ in loop.

```
module yes (in, ...);
    input in;
    ...
    wait (in == 1);
    ...
endmodule
```

```
module no (in, ...);
    input in;
    ...
    while (in != 1);
    ...
endmodule
```

Blocking procedural assignments and #

- We’ve seen blocking assignments — they use =
  - Options for specifying delay
    - `#n a = b + c;` is an intra-assignment time delay
    - `a = #n b + c;` is the difference?
  - The differences:
    - an intra-assignment time delay
    - execution of the always statement is blocked (suspended) in the middle of the assignment for `n` time units.
    - how is this done?

```
module d_type_FF (q, clock, data);
    input clock, data;
    output q;
    nor #10 a (q, qBar, r);
    nor b (qBar, q, s),
    c (a, r, clock, s1),
    d (s1, s, data),
    e (r, r1, clock),
    f (r1, s1, r);
endmodule
```

Events — @something

- Action
  - when first encountered, sample the expression
  - wait for expression to change in the indicated fashion
  - This always blocks

```
always @(posedge ck)
    q <= d;
```

```
always @(hello or goodbye)
    a = b;
```

```
always @(posedge hello or negedge goodbye)
    a = b;
```

Sensitivity Lists

- In the gate level timing model…
  - model execution was sensitive to any change on any of the inputs at any time.
  - sensitivity list — a list of inputs that a model is sensitive to
    - a change on any of them will cause execution of the model
  - in the gate level timing model, the lists don’t change.
  - Ditto with continuous assign

- In procedural models …
  - the sensitivity list changes as a function of time and execution

```
module d, type, FF (q, clock, data);
    input clock, data;
    output q;
    nor #10 a (q, qBar, r);
    nor b (qBar, q, s),
    c (a, r, clock, s1),
    d (s1, s, data),
    e (r, r1, clock),
    f (r1, s1, r);
endmodule
```

Fanout Lists

- Outputs of things are connected to inputs of other things
  - No surprise
  - The simulator maintains a list of inputs driven by each “output”

- Why?
  - When the output changes, it’s easy to figure out what other models need (to be) evaluated

- What’s an “output” in the above sense?
  - Because of procedural models …
  - Fanout lists change
  - Fanout lists ↔ Sensitivity lists
### Behavioral Timing Model

#### What is the behavioral model sensitive to?
- The behavioral statements execute in sequence (one then the next)
- Therefore, what a behavioral model is sensitive to is context specific —
  - i.e. it is only sensitive to what it is currently waiting for
  - time, edge, level — (#, @, wait)
- The model is not sensitive to a change on y, or w.

```verilog
counter = #10 counter + 1;
end
```

- Here, it is only sensitive to clock1
- Here, it is only sensitive to clock2. A posedge on clock1 will have no effect when waiting here.
- It is never sensitive to changes on y or w.

### Scheduling #, @, and Wait

#### How are #, @, and wait tied into the event list?
- **#** delay
  - schedule the resumption of the process — put it in the event queue
delay units into the future. Essentially an evaluation event scheduled in the future
- **@** change
  - when suspended for an @v, the behavioral model is put on the fanout list of the variable v. i.e., the behavioral model is now sensitive to v.
  - When an update event for v occurs, (e.g. posedge), then the behavioral model is scheduled to resume at the current time — an evaluation event.
- **Wait (exp)**
  - if exp is TRUE, don’t stop
  - if exp is FALSE, then the behavioral model is put on the fanout list(s) of the variable(s) in exp. (it’s now sensitive to the variable(s))
  - When there is an update event for any of the variables in exp , exp is evaluated. If exp is TRUE, resume executing in the current time (schedule an eval event), else go back to sleep.

### Non-blocking assignments (<=)

#### Two important aspects to these
- an intra-assignment time delay doesn’t stop them (they’re non-blocking)
- they implement a concurrent assignment

#### Example — intra-assignment time delay
- non-blocking assignments use “<=”

```verilog
always begin
  q <= y;
  q = w;
  q <= #3 w;
end
```

- It is never sensitive to changes on y or w.

### Intra-Assignment Non-blocking Example

#### What’s the difference?

```verilog
module procAnd1 (a1, b, c);
  input b, c;
  output a1;
  always @(b or c)
    a1 = #5 b & c;
endmodule
```

Which is similar to an AND primitive?

### Edges in time — concurrent assignment

```verilog
module fsm (Q1, Q0, in, clock);
  output Q1, Q0;
  input clock, in;
  reg Q1, Q0;
  always @ (posedge clock) begin
    Q1 <= in & Q0;
    Q0 <= in | Q1;
  end
endmodule
```

- Values after the clock edge (t+)
  - calculated in response to the clock edge, using values at the clock edge
- Values at the clock edge (At t+)
  - calculated in response to the clock edge, using values at the clock edge
Alternates — not all equivalent

```vhdl
module fsm (Q1, Q0, in, clock);
output Q1, Q0;
input clock, in;
reg Q1, Q0;
always @(posedge clock) begin
  Q1 <= in & Q0;
  Q0 <= in | Q1;
end
endmodule
```

The same?

```vhdl
module fsm (Q1, Q0, in, clock);
output Q1, Q0;
input clock, in;
reg Q1, Q0;
always @(posedge clock) begin
  Q0 <= in | Q1;
  Q1 <= in & Q0;
end
endmodule
```

A very different animal?

```vhdl
module fsm0 (Q1, Q0, in, clock);
output Q0;
input clock, in, Q1;
reg Q0;
always @(posedge clock) begin
  Q0 <= in | Q1;
end
endmodule
```

```vhdl
module fsm1 (Q1, Q0, in, clock);
output Q1;
input clock, in, Q0;
reg Q1;
always @(posedge clock) begin
  Q1 = in & Q0;
end
endmodule
```

How about these?

```vhdl
module fsm1 (Q1, Q0, in, clock);
output Q1;
input clock, in, Q0;
reg Q1;
always @(posedge clock) begin
  Q1 <= in & Q0;
end
endmodule
```

```vhdl
module fsm0 (Q1, Q0, in, clock);
output Q0;
input clock, in, Q1;
reg Q0;
always @(posedge clock) begin
  Q0 = in | Q1;
end
endmodule
```

Will these work?

```vhdl
module fsm1 (Q1, Q0, in, clock);
output Q1;
input clock, in, Q0;
reg Q1;
always @(posedge clock) begin
  Q1 = in & Q0;
end
endmodule
```

```vhdl
module fsm0 (Q1, Q0, in, clock);
output Q0;
input clock, in, Q1;
reg Q0;
always @(posedge clock) begin
  Q0 = in | Q1;
end
endmodule
```

These?

The Important Aspect ...

- Non-Blocking Concurrent transfers
  - Across the whole design,
    - all right-hand sides are evaluated
    - before any left-hand sides are updated.
  - Thus, the order of r-hs's evaluated and l-hs's updated can be arbitrary (but separate)
- This allows us to …
  - handle concurrent specification in major systems
  - reduce the complexity of our descriptions
  - attach lots of actions to one event — the clock

A State Change

- Find all of your “state” variables
  - Not just FSM state, but registers in a datapath too
  - They’re probably all keyed to an edge of a clock
  - Use <= to assign to them at the edge
  - You’re guaranteed they’ll all be sampled before any of them are updated.
  - A clock: in many cases, the only #delay operator you need is in the clock (for functional specification)

Event List: We told a fib

- This is what we told you before:

  ![Event List Diagram]

- Issues
  - In a concurrent language, there are some very dirty issues regarding the “arbitrary order” of execution.
  - In software, such issues are handled by synchronization primitives
    - Some of you have probably seen semaphores in the OS or real-time (embedded systems) course
    - They only allow other concurrent parts of a system to see full state changes, not partial. State changes appear “atomic”
    - These provide a very clean way to enforce order (actually, mutual exclusion) within “zero time”
  - In hardware, such issues are handled by the clock

Differences in the Event List Scheduling

- Previous picture of doubly linked event list

  ![Previous Event List Diagram]

- More detailed view
  - Three lists per time

  ![More Detailed Event List Diagram]
What gets scheduled when/where

- While there are regular events:
  - retrieve all regular events for current time and execute in arb. order
  - Note: These may produce more regular events for current time

- Retrieve all non-blocking events for the current time and execute
  - these may produce more regular events for current time, if so

When no more events, do monitor events. No new events produced

Follow the Execution

module fsm (Q1, Q0, in, clock);
output Q1, Q0;
input clock, in;
reg Q1, Q0;
always @ (posedge clock) begin
  Q1 <= in & Q0;
  Q0 <= in | Q1;
end
endmodule

Follow the Execution

module dff (Q, D, clock);
output Q;
input clock, D;
reg Q;
always @(posedge clock) Q <= D;
always #10 clock = ~clock;
endmodule

More Scheduling

previous values:
A = 1
B = 0
S = 0
new values at time 10:
A = 0
B = 1
S = 1

previous values: x
always begin
  a = 0;
  #0 q = 1;
  ...
  #10 ...
  initial
  b = 1;
Other strange things you can do

A 4-stage pipelined multiplier

- every clock edge, the a and b inputs are read and their product is scheduled to appear three clock periods later

```verilog
module pipeMult (product, a, b, ck);
  input ck;
  input [9:0] a, b;
  output [19:0] product;
  reg [19:0] product;
  always @ (posedge ck)
    product <= repeat (3) @ (posedge ck) a * b;
endmodule
```

Some ugly ramifications

You need to be careful when mixing blocking and non-blocking assignments

- blocking — you can read it like regular C language assignments. The value of the variable on the left-hand side can be used in the next statement on the right-hand side
- non-blocking — the assignment is scheduled to appear at a later time. The value on the left-hand side is not available in the next statement.

```
module pipeMult (product, a, b, ck);
  input ck;
  input [9:0] a, b;
  output [19:0] product;
  reg [19:0] product;
  always @ (posedge ck)
    product <= repeat (3) @ (posedge ck) a * b;
endmodule
```

Closer Look at the Scheduler

while (there are events in the event list) {
  if (there are no events for the current time)
    advance currentTime to the next event time
  if (there are no regular events for the current time)
    if (there are non-blocking assignment update events)
      turn these into regular events for the current time
    else
      if (there are any monitor events)
        turn these into regular events for the current time
  Unschedules (remove) all the regular events scheduled for currentTime
  For each of these events, in arbitrary order {
    if (this is an update event) {
      Update the value specified
      Evaluate gates on the fanout of this value and Schedule update events for gate outputs that change
      Schedule evaluation events for behaviors waiting for this value
    } else{ // it's an evaluation event
      Evaluate the model
      Schedule any update events resulting from the evaluation
    }
  }
}

Gate-Level Modeling

- Need to model the gate’s:
  - function
  - delay
- Function
  - Generally, HDLs have built-in gate-level primitives
    - Verilog has NAND, NOR, AND, OR, XOR, XNOR, BUF, NOT, and some others
  - The gates operate on input values producing an output value
    - typical Verilog gate instantiation is:
      ```
      and #delay  name (out, in1, in2, in3, ...)
      ```
    - multi-level logic used in some models to represent:
      - values, edges, unknowns, high impedances, ...
- Delay Models
  - delay models for gates: views and definitions
    - Basic view: the function and delay are separate
      - The function is handled by model execution, the delay by the simulator scheduler
      - An evaluation event causes this value to be calculated...
        - then it's scheduled as an update event and propagated here.
Kinds of delays

- **Definitions**
  - **Zero delay models** — functional testing
    - there’s no delay, not cool for circuits with feedback!
  - **Unit delay models** — all gates have delay 1. OK for feedback
  - **Transport delay** — input to output delay
  - **Inertial delay** — how long must an input spike be to be seen?
    - in Verilog, inertial == transport

\[
\begin{array}{c}
\text{a} \quad \text{b} \quad \text{c} \\
\text{τ} \quad \text{transport delay}
\end{array}
\]

\[
\begin{array}{c}
\text{a} \quad \text{b} \quad \text{c} \\
\text{τ} \quad \text{inertial delay} \quad \text{too small, no output change}
\end{array}
\]

Delay Models

- **Other factors**
  - Delay can be a function of output transition
  - Need a number for each of the arrowheads

\[
\text{not \ # (3, 5, 7) (nbar, n)}
\]

Verilog example

\[
\begin{array}{c}
\text{inertial delay} \quad \text{too small, no output change}
\end{array}
\]

Delays on Wires

- **How do you drive wires?**
  - gate outputs can drive wires
  - gate outputs implicitly define wires
  - wires can also be defined — with or without delay

\[
\begin{array}{c}
\text{wire <size> <delay> name;}
\end{array}
\]

\[
\begin{array}{c}
\text{wire \#5 \ LM;}
\end{array}
\]

\[
\begin{array}{c}
\text{and \#6 \ a (L, M, M);}
\end{array}
\]

\[
\begin{array}{c}
\text{not \ b (MA, MB, LM);}
\end{array}
\]

- The delay on a wire is added to any delay in the gate(s) that drive the wire

\[
\begin{array}{c}
\text{L} \quad \text{M} \quad \text{LM}
\end{array}
\]

Model Evaluation

- **Gate evaluation**
  - the design is made up of primitive gates and behaviors
  - we’re only considering primitive gates now

\[
\begin{array}{c}
\text{Truth Table for Nand}
\end{array}
\]

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

- **Approach #1**
  - Performing (A nand B nand ...) is slow
    - especially in multi-valued logic
  - Use table lookup — takes up memory, but it’s fast
    - Encode 0 as 00, 1 as 01, x as 10, z as 11

\[
\begin{array}{c}
\text{Truth Table for Nand}
\end{array}
\]

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

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Model Evaluation

"Oh that was fun, let’s do more of it"
- Variation on table lookup — "Zoom table"
  - the table includes all primitive functions as well as variables
- Essentially this is the "programming pearl" that says:
  - If it takes too much time to calculate something, precalculate it, store the results in a table, and look up the answer

Truth Table for Nand and And

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Zoom Truth Table

Truth Table

Approach #2 — Input counting method
- input width independent (as compared to Zoom tables)
- represents functions by controlling and inversion values
  - output is c ⊕ i
- Evaluation function:
  
  if (v == c) return (c ⊕ i)
  if (v == x) return (c ⊕ i)

Simulation: Model Evaluation

Approach #3: Input counting
- An update event keeps count of various features
  - when 1 -> 0 on AND gate, increment c_count (the number of controlling inputs)
  - when 0 -> x on AND gate, decrement c_count, increment x_count
- an evaluation event becomes
  - if (c_count > 0) return c ⊕ i
  - if (x_count > 0) return x
  - return (c ⊕ i)

Can you make this work with XORs?

Behavioral Models

Interpreted
- Compile to an intermediate representation
- To execute, interpret it — slow

Code Generation
- Compile behavioral Verilog directly to assembly code — treat it as a programming language
- Long compile times, but fast execution
  - Still slower than regular C — why?
- Not limited to behavioral models
  - Who said computer engineers don’t need to know how a compiler works!

Tying behavior and gate models together

Real designs mix behavior and gate models

module putTogether ();
wire [ ] w1, w2, w3, w4;
beh inst1 duh (w1, w2, w3, w4);
endmodule

module behstr (clk);
reg [ ] a, b, o1in1;
input clk;
wire [ ] #10 out1i2 = o1in1 | a;
nand #(2, 5) (out2in1[0], o1in1[0], b[0]);
nand #(2, 5) (out2in1[1], o1in1[1], b[1]);
always begin
@ (posedge clk);
endmodule

An alternate version
- modules may contain mixture of behavior and gate models

module behstr (clk);
reg [ ] a, b, o1in1;
input clk;
wire [ ] #10 out1i2 = o1in1 | a;
nand #(2, 5) (out2in1[0], o1in1[0], b[0]);
nand #(2, 5) (out2in1[1], o1in1[1], b[1]);
always begin
@ (posedge clk);
endmodule

note that the assign turned into a wire declaration with an assign.
changes will be propagated to a and o1in1 after the behavioral model stops again at the "@"
### Names of things

- **Thus far, we've seen names of...**
  - registers, variables, inputs, outputs, instances, integers
  - Their scope is the begin-end block within which they were defined
    - module — endmodule
    - task — endtask
    - function — endfunction
    - begin:name — end
    - ... nothing else within that scope may already have that name

- **Types of references**
  - **Forward referenced** — Identifiers for modules, tasks, functions, and named begin-end blocks may be used before being defined
  - **Not Forward referenced** — must be defined before use
    - wires and registers
  - **Hierarchical references** — named through the instantiation hierarchy
    - "a.b" references identifier b in namespace a
      - forward referenced

### Identifiers

- **Forward referenced**
  - Identifiers of modules, tasks, functions, named-blocks
  - Hierarchical search tree defined by module instantiation
    - Identifiers within each higher scope are known
  - After all instantiations are known, search upward for the first identifier
    - a.b.e.d
    - When found go down through the rest of the name

- **Non-Forward referenced**
  - Identifiers for registers and wires (non-hierarchical)
  - Hierarchical search tree defined by nested procedural blocks
    - rooted in module
    - Search doesn't cross module instantiation boundaries

- **Hierarchical — registers and wires**
  - These are forward referenced — see above

### Scope of functions and tasks

- **Where defined**
  - functions and tasks are defined within modules

- **Scope**
  - As with other names, the scope of the functions and tasks is the begin-end block (module-endmodule) within which they are defined
  - They can also be accessed hierarchically
    - define "global" functions and tasks in the "top" module
    - they'll be accessible from any (recursively) instantiated module.

### A few examples

```verilog
module a (...);
    reg e;
    task b;
        reg c;
        begin : d
            reg e;
            e = 1;
            a.e = 0;
        end
    endtask
    always
        begin : f
            reg g;
            a.b.d.e = 2;
            g = q.a.b.d.e;
        end
endmodule
```

- e's hierarchical name is ...a.b.d.e
- g's hierarchical name is ...a.f.g

Assumes a is instantiated in q

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