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2. Registers

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Lesson Overview



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Exercises

- What is a register (**reg**)?
- How do things change with time?
- Discover the system clock

Objectives

- Learn how to create combinatorial logic with registers
- Learn to create clocked (synchronous) logic
- Understand that registers can “remember” things
- Understand where your System Clock comes from
- Timing Checks, and why they are important



Registers



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Exercises

Why use registers?

- Wires have no memory
- Only registers can hold state (data)

Two basic types, both set with an **always**

1. Combinatorial: Like wires

```
always @(*)  
    A = B;
```

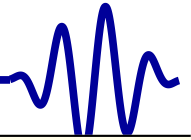
This form can be easier to read when the logic becomes complex

2. Synchronous: Only changes values on a clock

```
always @(posedge i_clk)  
    A <= B;
```



Combinatorial Regs



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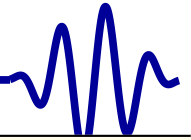
```
always @(*)  
    A = 9'h87;
```

- Registers can only be assigned in **always** blocks.
- Always blocks may consist of one statement, or
- Many statements between a **begin** and **end** pair

```
always @(*)  
begin  
    o_led = A ^ i_sw;  
    o_led = o_led + 7;  
    if (i_reset)  
        o_led = 0;  
end
```



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```
always @(*)  
begin  
    o_led = A ^ i_sw;  
    o_led = o_led + 7;  
    if (i_reset)  
        o_led = 0;  
end
```

This block

- Looks like software
 - Acts like you would expect in a simulator
 - Takes no time at all in hardware
- The hardware acts as if all statements were done at once

Only use “=” in a combinational always block



Latches



What happens here?

```
input          i_S ;
input [7:0]    i_V ;
output [7:0]   o_R ;

always @(*)
if (i_S)
    o_R = i_V ;
```

This is called a latch

- It requires memory
- May do one thing in simulation, another in hardware
- Most FPGA's don't support latches
- Can have subtle timing problems in hardware

Avoid using latches!



Last Assignment Wins



What happens here?

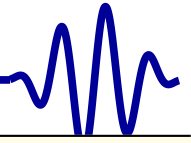
```
always @(*)  
begin  
    o_R = 0;  
    if (i_S)  
        o_R = i_V;  
end
```

No latch is inferred

- This is a very useful pattern!
- o_R now has a default value
This prevents a latch from being inferred
- No memory is required
- The last assignment gives o_R its final value



Flip Flops



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```
reg      [9:0]  A;  
  
always  @(posedge i_clk)  
    A <= A + 1'b1;
```

- Any registers set within an **always** @(posedge i_clk) block will transitions to their new values on the next clock edge only
 - *Only put a bonafide clock edge should be used*
 - Do not transition on anything you create in logic
- Note that we are using <= for assignment
 - This is a *non-blocking* assignment
 - Most, if not all, clocked register should be set with <=



Blocking



- This is a non-blocking assignment

```
always @(posedge i_clk)
    A <= A + 1'b1;
```

- Blocking assignment

```
always @(posedge i_clk)
    A = A + 1'b1;
```

- A blocking assignment's value may be referenced again before the clock edge
 - Creates the appearance of time passing within the block
 - *It may also cause simulation-hardware mismatch*
 - *Use with caution*
- In this case, both generate the same logic



Non-Blocking



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Exercises

What value will be given for A?

- Assume it starts at zero
- What will it be after one clock tick?

```
always @(posedge i_clk)
begin
    A <= 5;
    A <= A + 1'b1;
end
```

- The assignment only takes place on the clock edge
- Last assignment wins
- A is set to 1'b1



Blocking



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Exercises

Now what value will be given for A?

- Assume it starts at zero
- What will it be after one clock tick?

```
always @(posedge i_clk)
begin
    A = 5;
    A = A + 1'b1;
end
```

- Again, the assignment only takes place on the clock edge
- It appears as though it took several steps
- A is set to 6



Blocking



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Exercises

What if something depends upon A in another block?

- Assume A=0 before the clock tick

```
always @(posedge i_clk)
begin
    A = 5;
    A = A + 1'b1;
end

always @(posedge i_clk)
    B <= A;
```

- This result is *simulation dependent*!
- B may be set to 0, or it may be set to 6

Don't do this! Use <= within an **always** @(posedge i_clk)



Non-Blocking



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Now what will B be set to?

- Assume A=0 before the clock tick

```
always @(posedge i_clk)
begin
    A <= 5;
    A <= A + 1'b1;
end

always @(posedge i_clk)
    B <= A;
```

- A will be set to 1
- B will always be set to 0

Now simulation matches hardware



All in Parallel



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- A design may contain multiple always blocks
- The hardware will execute all at once
- The simulator will execute one at a time

Rules: When using the simulator, ...

- Make sure your design can be synthesized
- Make sure it fits within your chosen device
 - This is not a synthesizer task
 - Requires using the synthesizer periodically
- Make sure it maintains an appropriate clock rate
 - We'll get to timing checks in a moment



Feedback



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Exercises

- Wires in a loop created circular logic
- Clocked registers in a loop creates feedback

```
assign err = i_actual - o_command;  
always @(posedge i_clk)  
begin  
    o_command <= o_command + (err >> 5);  
end
```

Feedback is used commonly in control systems



Blinky



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Exercises

Let's make an LED blink!

```
module blinky(i_clk, o_led);  
    input    wire    i_clk;  
    output   wire    o_led;  
  
    reg      [26:0]   counter;  
  
    always @(posedge i_clk)  
        counter <= counter + 1'b1;  
  
    assign   o_led = counter[26];  
endmodule
```

Feel free to synthesize and try this

- The LED should blink at a steady rate
- Rate is determined by the 26 above



Broken Blinky



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Exercises

Here's a common beginner mistake

```
reg        counter;  
always @(posedge i_clk)  
    counter <= counter + 1'b1;  
assign o_led = counter;
```

Don't make this mistake

- Notice that counter is only 1-bit
- This will blink at half the `i_clk` frequency
- Result is typically way too fast to see any changes
- LED may glow dimly
- Need to slow it down



Verilator



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Simulating our design (blinky) now requires a clock:

```
void      tick(Vblinky *tb) {  
    // The following eval() looks  
    // redundant ... many of hours  
    // of debugging reveal its not  
    tb→eval();  
    tb→i_clk = 1;  
    tb→eval();  
    tb→i_clk = 0;  
    tb→eval();  
}
```

- We'll need to toggle the clock input for anything to happen
- This operation is so common, it deserves its own function, **tick()**



Verilator



We can now simplify our main loop a touch

```
int main(int argc, char **argv) {  
    int last_led;  
    // .... Setup  
  
    last_led = tb->o_led;  
    for(int k=0; k<(1<<20); k++) {  
        // Toggle the clock  
        tick(tb);  
  
        // Now let's print the LEDs value  
        // anytime it changes  
        if (last_led != tb->o_led) {  
            printf("k_=%7d, ", k);  
            printf("led_=%d\n", tb->o_led);  
        } last_led = tb->o_led;  
    }  
}
```

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Can we simulate this? Not easily

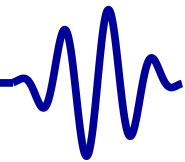
- Counting to 2^{27} may take seconds in hardware, but ...
- It's extreme slow in simulation.
- Let's speed blinky up—just for simulation
- We can do this by adjusting the width of the counter

We'll use a parameter to do this

```
parameter          WIDTH=27;
reg                [WIDTH-1:0]    counter;
// .....
assign o_led = counter[WIDTH-1];
```



Parameters



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Parameters are very powerful! They allow us to

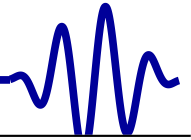
- Reconfigure a design, after it's been written
- Examples:
 - ZipCPU cache sizes can be adjusted by parameters
 - Internal memory sizes, implement the divide instruction or not, specify the type of multiply
 - Default serial port speed, number of GPIO pins supported by a GPIO controller, and more

Verilator argument `-GWIDTH=12` sets the `WIDTH` parameter to 12

```
% verilator -Wall -GWIDTH=12 -cc blinky.v
```



Sim Result

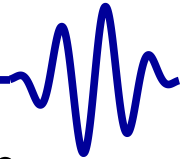


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```
% ./blinky
k =      2047 , led = 1
k =      4095 , led = 0
k =      6143 , led = 1
k =      8191 , led = 0
k =     10239 , led = 1
k =     12287 , led = 0
k =     14335 , led = 1
k =     16383 , led = 0
k =     18431 , led = 1
k =     20479 , led = 0
# .... (Lines skipped for brevity)
%
```



Trace Generation



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This is easy. For more complex designs, we'll need a trace

- That means writing to a trace file on every clock

Steps

1. Add the `--trace` option to the Verilator command line

```
% verilator -Wall --trace -GWIDTH=12 \  
-cc blinky.v
```

2. Create a trace from your `.cpp` file

```
#include "verilated_vcd_c.h"  
// ...  
int main(int argc, char **argv) {  
    // ...  
    unsigned tickcount = 0;  
    // ...  
}
```



Trace Generation



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Create the trace file within C++

```
// ...
int main(int argc , char **argv) {
    // ...
    // Generate a trace
    Verilated::traceEverOn(true);
    VerilatedVcdC* tfp = new VerilatedVcdC;
    tb->trace(tfp , 99);
    tfp->open("blinkytrace.vcd");

    // ...
    for(int k=0; k<(1<<20); k++) {
        tick(++tickcount , tb , tfp);
        // ...
    }
}
```




Trace Generation



3. Write trace data on every clock

```
void      tick(int tickcount , Vblinky *tb ,
               VerilatedVcdC* tfp) {
    tb->eval();
    if (tfp) // dump 2ns before the tick
        tfp->dump(tickcount * 10 - 2);
    tb->i_clk = 1;
    tb->eval();
    if (tfp) // Tick every 10ns
        tfp->dump(tickcount * 10);
    tb->i_clk = 0;
    tb->eval();
    if (tfp) { // Trailing edge dump
        tfp->dump(tickcount * 10 + 5);
        tfp->flush();
    }
}
```



Trace Generation



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- Now, running blinky will generate a trace

```
% ./blinky
```

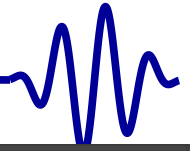
```
# . . .
```

- You can view it with GTKwave

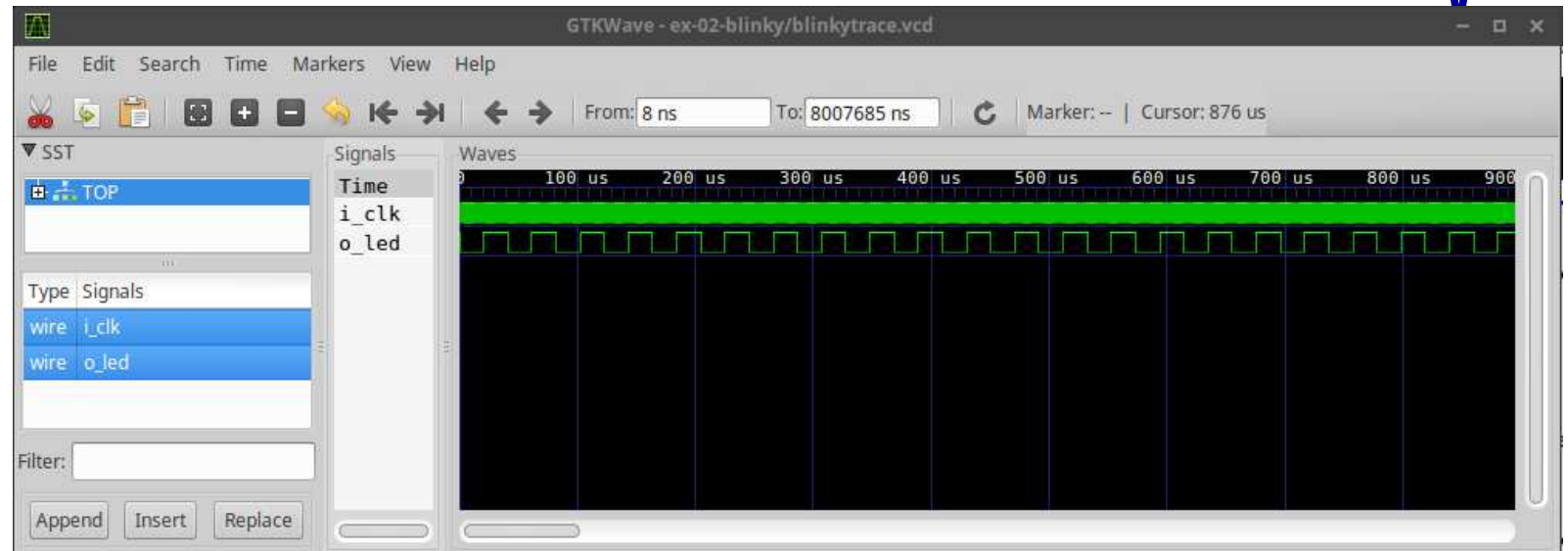
```
% gtkwave blinkytrace.vcd
```



GTKWave



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This is how logic debugging is done

- The simulator trace shows you every register's value
- ... at every clock tick
- You can zoom in to find any bugs



Strobe



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How is this design different from blinky?

```
module strobe(i_clk, o_led);  
    input    wire    i_clk;  
    output   wire    o_led;  
  
    reg      [26:0]   counter;  
  
    always @(posedge i_clk)  
        counter <= counter + 1'b1;  
  
    assign   o_led = &counter[26:24];  
endmodule
```



Toggled



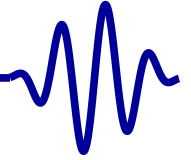
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How is this design different from blinky?

```
module blinky(i_clk, i_sw, o_led);  
    input    wire    i_clk, i_sw;  
    output   wire    o_led;  
  
    reg      [26:0]   counter;  
  
    always @(posedge i_clk)  
    if (i_sw)  
        counter <= counter + 1'b1;  
  
    assign   o_led = counter[26];  
endmodule
```

How does the switch affect things?

This design is actually broken, and will fail in practice



Can we get an LED to blink once per second?

```
always @(posedge i_clk)
  if (counter >= CLOCK_RATE_HZ/2-1)
    begin
      counter <= 0;
      o_led <= !o_led;
    end else
      counter <= counter + 1;
```

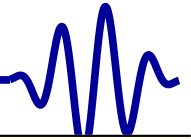
When $\text{CLOCK_RATE_HZ}/2$ ticks have passed, the LED will toggle

- This structure is known as an integer clock divider
- It offers an exact division



Can we get an LED to blink once per second?

```
module pps(i_clk, o_led);  
    parameter CLOCK_RATE_HZ = 100_000_000;  
    parameter [31:0] INCREMENT  
                = (1<<30)/(CLOCK_RATE_HZ/4);  
  
    input      wire      i_clk;  
    output    wire      o_led;  
  
    reg        [31:0]    counter;  
  
    always @(posedge i_clk)  
        counter <= counter + INCREMENT;  
  
    assign    o_led = counter[31];  
endmodule
```



```
parameter CLOCK_RATE_HZ = 100_000_000;  
parameter [31:0] INCREMENT  
               = (1<<30)/(CLOCK_RATE_HZ / 4);  
always @(posedge i_clk)  
    counter <= counter + INCREMENT;
```

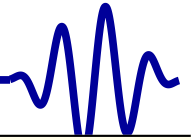
- After CLOCK_RATE_HZ clock edges, the counter will roll over
- The divide by four above, on both numerator and denominator, is just to keep this within 32-bit arithmetic

$$\text{INCREMENT} = \frac{2^{32}}{\text{CLOCK_RATE_HZ}}$$

- This is called a *fractional clock divider*
 - The division isn't exact
 - It's often good enough



Stretch



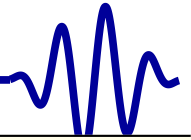
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```
module stretch(i_clk, i_event, o_led);  
    input    wire    i_clk, i_event;  
    output   wire    o_led;  
  
    reg      [26:0]   counter;  
  
    always @(posedge i_clk)  
    if (i_event)  
        counter <= 0;  
    else if (! (&counter))  
        counter <= counter + 1;  
  
    assign   o_led = !counter[26];  
endmodule
```

FPGA signals are often too fast to see



Stretch



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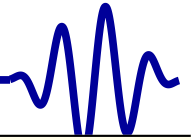
```
module stretch(i_clk, i_event, o_led);  
    // ...  
    reg [26:0] counter;  
    always @(posedge i_clk)  
        if (i_event)  
            counter <= 0;  
        else if (! (&counter))  
            counter <= counter + 1;  
    assign o_led = !counter[26];  
endmodule
```

FPGA signals are often too fast to see

- This slows them down to eye speed
- Only works for a single event though
- Multiple events would overlap, and be no longer distinct



Too Slow



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```
module tooslow(i_clk, o_led);  
    input    wire    i_clk;  
    output   wire    o_led;  
  
    parameter                                NBITS = 1024;  
    reg      [NBITS-1:0] counter;  
  
    always @(posedge i_clk)  
        counter <= counter + 1;  
  
    assign  o_led = counter[NBITS-1];  
endmodule
```

This is guaranteed to fail a timing check

- It's now time to learn how to check timing
- This design should fail, for reasonable clock speeds



Too Slow



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Follow your chip vendor's instructions to do a timing check

- Use your system clock frequency
 - For now, that's the clock frequency coming into your board
 - We'll adjust it later
- Make sure this design fails
 - The carry chain takes time to propagate
 - Extra long carry chains take extra long
 - If the propagation doesn't complete before the next clock ... your design will fail (like this one)
- From now on, *always* check timing for a design
 - Before loading it onto a board
 - Every now and then while simulating



Dimmer



Can you tell me what this will do?

```
module dimmer(i_clk, o_led);  
    input    wire    i_clk;  
    output   wire    o_led;  
  
    reg      [27:0]   counter;  
  
    always @(posedge i_clk)  
        counter <= counter + 1;  
  
    assign   o_led = (counter[7:0]  
        < counter[27:20]);  
  
endmodule
```

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Exercises



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- Implement blinky on your hardware
- Implement one of the two PPS designs
 - Using a stopwatch, verify the blink rate of 1Hz
 - Make the blinks shorter, but at the same frequency
- Implement the dimmer