



Gisselquist
Technology, LLC

2. Registers

Daniel E. Gisselquist, Ph.D.





Lesson Overview



▷ Lesson Overview

Registers
Combinatorial
Latches
Flip Flops
Blocking
All in Parallel
Feedback
Blinky
Broken Blinky
Verilator
Parameters
Sim Result
Trace Generation
GTKWave
Strobe
PPS-I
PPS-II
Stretch
Too Slow
Too Slow
Dimmer
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



Lesson Overview

▷ Registers

Combinatorial

Latches

Flip Flops

Blocking

All in Parallel

Feedback

Blinky

Broken Blinky

Verilator

Parameters

Sim Result

Trace Generation

GTKWave

Strobe

PPS-I

PPS-II

Stretch

Too Slow

Too Slow

Dimmer

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;
```

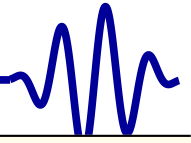
This form can be easier to read when the logic becomes complex

2. Synchronous: Only changes values on a clock

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



Combinatorial Regs



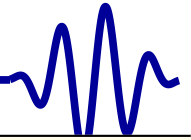
```
always @(*)  
    A = 9'h87;
```

- 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
```



Combinatorial Regs



- Lesson Overview
- Registers
 - ▷ Combinatorial
- Latches
- Flip Flops
- Blocking
- All in Parallel
- Feedback
- Blinky
- Broken Blinky
- Verilator
- Parameters
- Sim Result
- Trace Generation
- GTKWave
- Strobe
- PPS-I
- PPS-II
- Stretch
- Too Slow
- Too Slow
- Dimmer
- Exercises

```
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



Lesson Overview

Registers

Combinatorial

▷ Latches

Flip Flops

Blocking

All in Parallel

Feedback

Blinky

Broken Blinky

Verilator

Parameters

Sim Result

Trace Generation

GTKWave

Strobe

PPS-I

PPS-II

Stretch

Too Slow

Too Slow

Dimmer

Exercises

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?

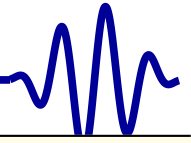
```
always @(*)  
begin  
    o_R = 0;  
    if (i_S)  
        o_R = i_V;  
end
```

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



- Lesson Overview
- Registers
- Combinatorial
- Latches
- ▷ Flip Flops
- Blocking
- All in Parallel
- Feedback
- Blinky
- Broken Blinky
- Verilator
- Parameters
- Sim Result
- Trace Generation
- GTKWave
- Strobe
- PPS-I
- PPS-II
- Stretch
- Too Slow
- Too Slow
- Dimmer
- Exercises

```
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



Lesson Overview

Registers

Combinatorial

Latches

Flip Flops

▷ Blocking

All in Parallel

Feedback

Blinky

Broken Blinky

Verilator

Parameters

Sim Result

Trace Generation

GTKWave

Strobe

PPS-I

PPS-II

Stretch

Too Slow

Too Slow

Dimmer

Exercises

- 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



Lesson Overview

Registers

Combinatorial

Latches

Flip Flops

▷ Blocking

All in Parallel

Feedback

Blinky

Broken Blinky

Verilator

Parameters

Sim Result

Trace Generation

GTKWave

Strobe

PPS-I

PPS-II

Stretch

Too Slow

Too Slow

Dimmer

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



Lesson Overview

Registers

Combinatorial

Latches

Flip Flops

▷ Blocking

All in Parallel

Feedback

Blinky

Broken Blinky

Verilator

Parameters

Sim Result

Trace Generation

GTKWave

Strobe

PPS-I

PPS-II

Stretch

Too Slow

Too Slow

Dimmer

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



Lesson Overview

Registers

Combinatorial

Latches

Flip Flops

▷ Blocking

All in Parallel

Feedback

Blinky

Broken Blinky

Verilator

Parameters

Sim Result

Trace Generation

GTKWave

Strobe

PPS-I

PPS-II

Stretch

Too Slow

Too Slow

Dimmer

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



Lesson Overview

Registers

Combinatorial

Latches

Flip Flops

▷ Blocking

All in Parallel

Feedback

Blinky

Broken Blinky

Verilator

Parameters

Sim Result

Trace Generation

GTKWave

Strobe

PPS-I

PPS-II

Stretch

Too Slow

Too Slow

Dimmer

Exercises

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



- Lesson Overview
- Registers
- Combinatorial
- Latches
- Flip Flops
- Blocking
- ▷ All in Parallel
- Feedback
- Blinky
- Broken Blinky
- Verilator
- Parameters
- Sim Result
- Trace Generation
- GTKWave
- Strobe
- PPS-I
- PPS-II
- Stretch
- Too Slow
- Too Slow
- Dimmer
- Exercises

- 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



Lesson Overview

Registers

Combinatorial

Latches

Flip Flops

Blocking

All in Parallel

▷ Feedback

Blinky

Broken Blinky

Verilator

Parameters

Sim Result

Trace Generation

GTKWave

Strobe

PPS-I

PPS-II

Stretch

Too Slow

Too Slow

Dimmer

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



- Lesson Overview
- Registers
- Combinatorial
- Latches
- Flip Flops
- Blocking
- All in Parallel
- Feedback
- ▷ Blinky
- Broken Blinky
- Verilator
- Parameters
- Sim Result
- Trace Generation
- GTKWave
- Strobe
- PPS-I
- PPS-II
- Stretch
- Too Slow
- Too Slow
- Dimmer
- 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



Lesson Overview

Registers

Combinatorial

Latches

Flip Flops

Blocking

All in Parallel

Feedback

Blinky

▷ Broken Blinky

Verilator

Parameters

Sim Result

Trace Generation

GTKWave

Strobe

PPS-I

PPS-II

Stretch

Too Slow

Too Slow

Dimmer

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



- Lesson Overview
- Registers
- Combinatorial
- Latches
- Flip Flops
- Blocking
- All in Parallel
- Feedback
- Blinky
- Broken Blinky
- ▷ Verilator
- Parameters
- Sim Result
- Trace Generation
- GTKWave
- Strobe
- PPS-I
- PPS-II
- Stretch
- Too Slow
- Too Slow
- Dimmer
- Exercises

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



- Lesson Overview
- Registers
- Combinatorial
- Latches
- Flip Flops
- Blocking
- All in Parallel
- Feedback
- Blinky
- Broken Blinky
- ▷ Verilator
- Parameters
- Sim Result
- Trace Generation
- GTKWave
- Strobe
- PPS-I
- PPS-II
- Stretch
- Too Slow
- Too Slow
- Dimmer
- Exercises

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;  
    }  
}
```



Verilator



Lesson Overview

Registers

Combinatorial

Latches

Flip Flops

Blocking

All in Parallel

Feedback

Blinky

Broken Blinky

▷ Verilator

Parameters

Sim Result

Trace Generation

GTKWave

Strobe

PPS-I

PPS-II

Stretch

Too Slow

Too Slow

Dimmer

Exercises

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



- Lesson Overview
- Registers
- Combinatorial
- Latches
- Flip Flops
- Blocking
- All in Parallel
- Feedback
- Blinky
- Broken Blinky
- Verilator
 - ▷ Parameters
- Sim Result
- Trace Generation
- GTKWave
- Strobe
- PPS-I
- PPS-II
- Stretch
- Too Slow
- Too Slow
- Dimmer
- Exercises

Parameters are very powerful! They allow us to

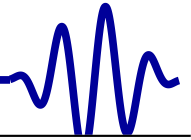
- Reconfigure a design, after it's been written
- Examples:
 - ZipCPU cache sizes can be adjusted by parameters
 - Internal memory sizes, implement the divide instruction or not, specify the type of multiply
 - Default serial port speed, number of GPIO pins supported by a GPIO controller, and more

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

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



Sim Result

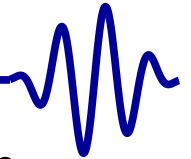


- Lesson Overview
- Registers
- Combinatorial
- Latches
- Flip Flops
- Blocking
- All in Parallel
- Feedback
- Blinky
- Broken Blinky
- Verilator
- Parameters
- ▷ Sim Result
- Trace Generation
- GTKWave
- Strobe
- PPS-I
- PPS-II
- Stretch
- Too Slow
- Too Slow
- Dimmer
- Exercises

```
% ./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



Lesson Overview

Registers

Combinatorial

Latches

Flip Flops

Blocking

All in Parallel

Feedback

Blinky

Broken Blinky

Verilator

Parameters

Sim Result

Trace

▷ Generation

GTKWave

Strobe

PPS-I

PPS-II

Stretch

Too Slow

Too Slow

Dimmer

Exercises

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



Lesson Overview

Registers

Combinatorial

Latches

Flip Flops

Blocking

All in Parallel

Feedback

Blinky

Broken Blinky

Verilator

Parameters

Sim Result

Trace
▷ Generation

GTKWave

Strobe

PPS-I

PPS-II

Stretch

Too Slow

Too Slow

Dimmer

Exercises

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



Lesson Overview

Registers

Combinatorial

Latches

Flip Flops

Blocking

All in Parallel

Feedback

Blinky

Broken Blinky

Verilator

Parameters

Sim Result

Trace

▷ Generation

GTKWave

Strobe

PPS-I

PPS-II

Stretch

Too Slow

Too Slow

Dimmer

Exercises

- Now, running blinky will generate a trace

```
% ./blinky
```

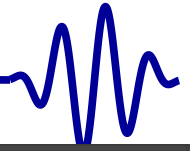
```
# . . .
```

- You can view it with GTKwave

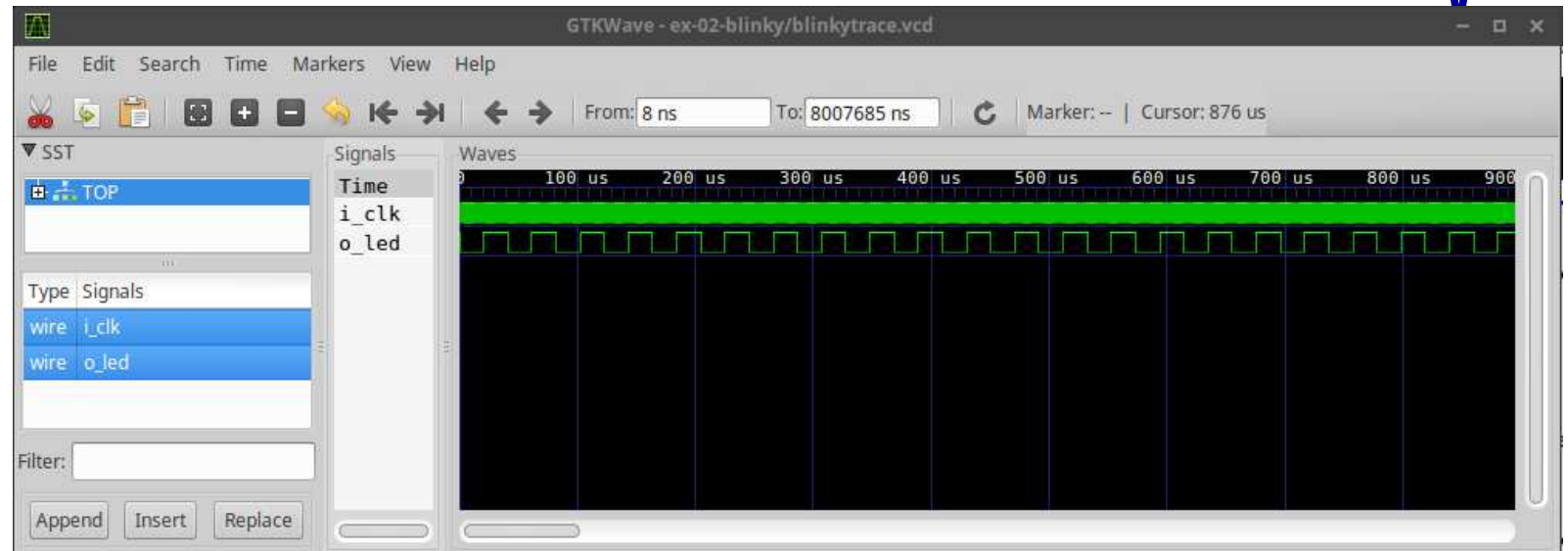
```
% gtkwave blinkytrace.vcd
```



GTKWave



Lesson Overview
Registers
Combinatorial
Latches
Flip Flops
Blocking
All in Parallel
Feedback
Blinky
Broken Blinky
Verilator
Parameters
Sim Result
Trace Generation
▷ GTKWave
Strobe
PPS-I
PPS-II
Stretch
Too Slow
Too Slow
Dimmer
Exercises



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



- Lesson Overview
- Registers
- Combinatorial
- Latches
- Flip Flops
- Blocking
- All in Parallel
- Feedback
- Blinky
- Broken Blinky
- Verilator
- Parameters
- Sim Result
- Trace Generation
- GTKWave
- ▷ Strobe
- PPS-I
- PPS-II
- Stretch
- Too Slow
- Too Slow
- Dimmer
- Exercises

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
```



Lesson Overview

Registers

Combinatorial

Latches

Flip Flops

Blocking

All in Parallel

Feedback

Blinky

Broken Blinky

Verilator

Parameters

Sim Result

Trace Generation

GTKWave

Strobe

▷ PPS-I

PPS-II

Stretch

Too Slow

Too Slow

Dimmer

Exercises

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



Lesson Overview

Registers

Combinatorial

Latches

Flip Flops

Blocking

All in Parallel

Feedback

Blinky

Broken Blinky

Verilator

Parameters

Sim Result

Trace Generation

GTKWave

Strobe

PPS-I

▷ PPS-II

Stretch

Too Slow

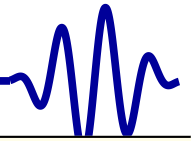
Too Slow

Dimmer

Exercises

Can we get an LED to blink once per second?

```
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;  
  
initial     counter = 0;  
always @(posedge i_clk)  
         counter <= counter + INCREMENT;  
  
assign     o_led = counter[31];
```



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

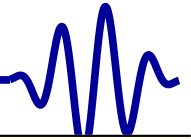
- After CLOCK_RATE_HZ clock edges, the counter will roll over
- The divide by four above, on both numerator and denominator, is just to keep this within 32-bit arithmetic

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

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



Stretch



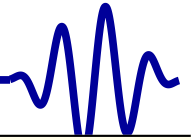
- Lesson Overview
- Registers
- Combinatorial
- Latches
- Flip Flops
- Blocking
- All in Parallel
- Feedback
- Blinky
- Broken Blinky
- Verilator
- Parameters
- Sim Result
- Trace Generation
- GTKWave
- Strobe
- PPS-I
- PPS-II
- ▷ Stretch
- Too Slow
- Too Slow
- Dimmer
- Exercises

```
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



- Lesson Overview
- Registers
- Combinatorial
- Latches
- Flip Flops
- Blocking
- All in Parallel
- Feedback
- Blinky
- Broken Blinky
- Verilator
- Parameters
- Sim Result
- Trace Generation
- GTKWave
- Strobe
- PPS-I
- PPS-II
- ▷ Stretch
- Too Slow
- Too Slow
- Dimmer
- Exercises

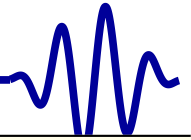
```
module stretch(i_clk, i_event, o_led);  
    // ...  
    reg [26:0] counter;  
    always @(posedge i_clk)  
        if (i_event)  
            counter <= 0;  
        else if (! (&counter))  
            counter <= counter + 1;  
    assign o_led = !counter[26];  
endmodule
```

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



- Lesson Overview
- Registers
- Combinatorial
- Latches
- Flip Flops
- Blocking
- All in Parallel
- Feedback
- Blinky
- Broken Blinky
- Verilator
- Parameters
- Sim Result
- Trace Generation
- GTKWave
- Strobe
- PPS-I
- PPS-II
- Stretch
- ▷ Too Slow
- Too Slow
- Dimmer
- Exercises

```
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



Lesson Overview

Registers

Combinatorial

Latches

Flip Flops

Blocking

All in Parallel

Feedback

Blinky

Broken Blinky

Verilator

Parameters

Sim Result

Trace Generation

GTKWave

Strobe

PPS-I

PPS-II

Stretch

Too Slow

▷ Too Slow

Dimmer

Exercises

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?

```
////////////////////////////////////  
//  
//  Filename:      dimmer.v  
//  
//  Project:       Verilog Tutorial Example file  
//  
//  Purpose:       LED project to adjust the brightness  
//  
//               Unlike the other projects in this directory ,  
//               a Verilator script , nor a Makefile.  
//               Hopefully you have learned by this  
//               point in time to create them yourself.  
//               If not , please look back  
//               at the other similar files and copy and paste  
//  
//  Creator:       Dan Gisselquist , Ph.D.  
//               Gisselquist Technology , LLC  
//  
////////////////////////////////////
```

Lesson Overview

Registers

Combinatorial

Latches

Flip Flops

Blocking

All in Parallel

Feedback

Blinky

Broken Blinky

Verilator

Parameters

Sim Result

Trace Generation

GTKWave

Strobe

PPS-I

PPS-II

Stretch

Too Slow

Too Slow

▷ Dimmer

Exercises



Exercises



- Lesson Overview
- Registers
- Combinatorial
- Latches
- Flip Flops
- Blocking
- All in Parallel
- Feedback
- Blinky
- Broken Blinky
- Verilator
- Parameters
- Sim Result
- Trace Generation
- GTKWave
- Strobe
- PPS-I
- PPS-II
- Stretch
- Too Slow
- Too Slow
- Dimmer
- ▷ Exercises

- 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