Problem Set 2 Solutions
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Problem 1: Counters

Part (a)
128 is the seventh power of 2. Hence, cascading two 74LS163s as you have done in the laboratory 1 would be sufficient. The third output bit of the higher order 74LS163 is the 14.4KHz clock. Figure 1 shows the wiring diagram.

Part (b)
We would like to divide our clock by 1843200. 1843200 in decimal is 1C2000 in hexadecimal. We need 21 bits to represent 0h1C2000, so we will need to count to a 21 bit number with our 163s. Therefore, we need at least 6 74LS163s to produce a 1Hz clock.

Figure 1: Cascading 74LS163s
Part (c)

74LS163 is a synchronous 4-bit counter, in which all output bits update at the rising edge clock. 74LS393 is a asynchronous 4-bit counter, in which lower order output bits update before the higher order bits. There are 4 parallel J-K registers within a 74LS163 that drive the output bits $Q_A..Q_D$. These parallel J-K registers are all clocked with the same clock signal, and hence all of them update at the same instant (as all the J-K registers have the same amount of clock to Q delay. In the architecture of 74LS393s, 4 serial T-registers are used. Hence, the higher order outputs can only change after the lower output bits have updated.

Part (d)

Verilog code for 1 Hz timer is shown below. As instructed in the problem set, your solution to this part should not be a 1Hz 50% duty cycle clock signal. Instead, we wanted you to create a pulse of one clock period width once with a frequency of 1 second.

```verilog
module one_hz(clk, reset, one_hz_clk);
input clk;
input reset;
output one_hz_clk;
reg one_hz_clk;
reg [20:0] cnt;

// 1.8432MHz = 0h1C2000

always @(posedge clk)
begin
  if(reset == 1)
    begin
      cnt <= 2'b0;
      one_hz_clk <= 1'b0;
    end
  else if(cnt == 2'b111111111111111111) // else if (cnt == 2'b10431999) --> shorter cycle for test purposes.
    begin
      one_hz_clk <= 1'b1;
      cnt <= 2'b0;
    end
  else
    begin
      cnt <= cnt + 1;
      one_hz_clk <= 1'b0;
    end
end
endmodule
```
Problem 2:
Part (a)
State transition diagram.

Figure 2: Transition diagram

Part (b)
Assuming the rover will start from Killian:
(Killian) -> Kresge, Stata, Tang, Tang, Student Center

Part (c)
Z-Center. There is no arrow with an input '1' to Z-Center from other states. So starting from any other state, with all '1's as inputs the rover cannot ever reach the Z-Center.
Part(d)
Verilog code for StataRover.v

module stataRover (clk, fsmreset, fsminput, state);
// System Clk
input clk;
// Global Reset signal
input fsmreset;
// output[2:0] state;
// internal state
reg [2:0] state;
reg [2:0] nextstate;

// State declarations
parameter KILLIAN = 0;
parameter KRESGE = 1;
parameter TANG = 2;
parameter ZCENTER = 3;
parameter STUDENTCENTER = 4;
parameter BUILDING34 = 5;
parameter LCS = 6;
parameter STATACENTER = 7;
always @(posedge clk)
begin
  if (fsmreset) state <= KILLIAN;
  else state <= nextstate;
end
always @(state or fsminput) begin
  nextstate = 3'b000;
  case (state)
    KILLIAN: if (fsminput) nextstate = KRESGE;
    else nextstate = KILLIAN;
    KRESGE: if (fsminput) nextstate = TANG;
    else nextstate = KILLIAN;
    TANG: if (fsminput) nextstate = STUDENTCENTER;
    else nextstate = TANG;
    ZCENTER: if (fsminput) nextstate = ZCENTER;
    else nextstate = KILLIAN;
    STUDENTCENTER: if (fsminput) nextstate = LCS;
    else nextstate = ZCENTER;
    BUILDING34: if (fsminput) nextstate = STATACENTER;
    else nextstate = LCS;
    LCS: if (fsminput) nextstate = BUILDING34;
    else nextstate = LCS;
    STATACENTER: if (fsminput) nextstate = KILLIAN;
    else nextstate = TANG;
  endcase // case(state)
end // always @(state or fsminput)
endmodule //
**Problem 3:**
The code for top level module(top.v) and the testbench(tbRover.v). For simulation purposes, a 9.2 kHz enable signal was used instead of a 1 Hz enable signal.

top.v

```verilog
module top(clk, reset, fminput, fsmreset, state);
  input clk, reset, fminput, fsmreset;
  output[2:0] state;
  wire one_hz_clk;
  always @(posedge clk)
  begin
    one_hz_clk <= 1'b1;
    if (reset) one_hz_clk <= 1'b0;
  end
  fsmreset <= one_hz_clk;
endmodule
```

tbRover.v

```verilog
//timescale 1ns/10ps
module tbRover;
  reg clk;
  reg reset;
  reg fminput;
  reg fsmreset;
  wire [2:0] fsm_state;
  top top [clk(clk), reset(reset), fminput(fminput), fsmreset(fsmreset), state(fsm_state)];

initial begin
  clk = 0;
  reset = 0;
  fminput = 0;
  fsmreset = 0;
  // #20
  // #1084
  reset = 1;
  fsmreset = 1;
  // #20
  // #1084
  reset = 0;
  fsmreset = 0;
  // #40
  // #2168
  fminput = 1;
  // #20
  // #1084
  fminput = 0;
  // #100
  // #5420
  fminput = 1;
end
always #271 clk = ~clk;
endmodule
```
The screenshot of the simulation.

Figure 3: Screenshot
Problem 4:
We are going to use a major-minor FSM scheme to implement this memory controller. Basically, we will write a 'major FSM' to control the multi-cycle access FSM shown in lecture 7. The major FSM will use the multi-cycle access FSM to write to the memory, and then to read back from the memory. When the multi-cycle access FSM is carrying out a read or write operation the major FSM will have to wait for the completion of the operation. There are many ways to this, if you draw the state transition diagram for the multi-cycle access FSM, you will realize that after a read or a write operation it goes back to the idle state, hence we can use the 'state' output of the multi-cycle access FSM to tell when a read or a write operation is completed. The state transition diagram for the 'major FSM' is as follows:

Note: This state diagram is different in terms of structure than the one implemented in the code for illustrative purposes. The outputs are updated during transitions in this diagram, but the outputs are updated within the states in the Verilog code. (Now, what kind of state machine does the diagram represent? How about the code?)

Figure 4: Memory Tester State Transition Diagram
memory_tester.v (major FSM):

// Module for testing a memory.
module memory_tester(clk, reset, start_test, failure, success, read_data, ext_data, state, memory_state, count, failure_count);

  output [2:0] state; // state of the memory tester
  output [3:0] count; // the address for writing
  output [3:0] failure_count; // number of failures
  // state of the memory controller
  output [2:0] memory_state;
  output [7:0] read_data;
  // output signals
  output failure, success;

  input clk;
  input reset;
  // we are going to sit in the idle state until
  // this signal is asserted.
  input start_test;

  reg [3:0] failure_count;
  reg [3:0] failure_count_int;
  reg read, write, read_int, write_int;
  reg failure, success;
  reg failure_int;
  reg success_int;
  wire data_oen, data_sample, address_load;
  // state of the memory tester
  reg [3:0] state, next;
  // address for reading/writing
  reg [3:0] count;
  reg [3:0] count_int;
  wire G_b, W_b;
  input [7:0] ext_data;
  wire [12:0] ext_address;
  reg [7:0] write_data;
  reg [7:0] address;
  // we are going to use the simple multi-cycle read scheme shown
  // in the lecture. The state output of this module tells us
  // whether a read/write operation is complete.

memory_controller memory_controller2(
  .clk(clk), .reset(reset), .G_b(G_b), .W_b(W_b), .address(address), .ext_address(ext_address), .write_data(write_data), .read_data(read_data),
  .ext_data(ext_data), .read(read), .write(write), .state(memory_state), .data_oen(data_oen), .address_load(address_load),
  .data_sample(data_sample));

parameter IDLE = 0;
parameter INITIATE_WRITE = 1;
parameter WRITE_WAIT = 2;
parameter WRITE_WAIT2 = 3;
parameter WRITE = 4;
parameter INITIATE_READ = 5;
parameter WAIT_READ = 6;
parameter WAIT_READ2 = 7;
parameter READ_1 = 8;
parameter COMPARE = 9;
always @posedge clk
begin
  if (reset) state <= IDLE;
  else state <= next;
  failure <= failure_int;
  success <= success_int;
  // update the outputs
  failure_count <= failure_count_int;
  read <= read_int;
end

write <= write_int;
count <= count_int;
address <= count;
write_data <= count;
end // always @(posedge clk)
always @(state or start_test) begin
    failure_int = 0;
    success_int = 0;
    read_int = 0;
    write_int = 0;
    case(state)
    IDLE:
        if (start_test) begin
            next = INITIATE_WRITE;
            write_int = 1;
            count_int <= 4'b000;
            failure_count_int <= 4'b000;
        end
        else next = IDLE;
    INITIATE_WRITE: begin
        write_int = 1;
        next = WRITE_WAIT;
    end
    WRITE_WAIT: begin
        write_int = 0;
        next = WRITE_WAIT2;
    end
    WRITE_WAIT2: begin
        write_int = 0;
        next = WRITE_16;
    end
    WRITE_16: begin
        if (memory_state == 4'b000) begin
            if (count == 4'b1111) begin
                count_int <= 4'b000;
            end
            else begin
                next = INITIATE_WRITE;
                count_int <= count + 1;
            end
        end
        else begin
            next = WRITE_WAIT;
        end
    end
    INITIATE_READ: begin
        read_int = 1;
        write_int = 0;
        next = WAIT_READ;
    end
    WAIT_READ: begin
        next = WAIT_READ2;
        read_int = 0;
    end
    WAIT_READ2: begin
        next = READ_1;
end

READ_1:
begin
if (memory_state == 'h0000)
next = COMPARE;
else
next = WAIT_READ; // wait till read is done
end

COMPARE:
begin
if (address == read_data)
success_int = 1;
else begin
failure_int = 1;
failure_count_int <= failure_count_int + 1;
end
if (count >= 'h1111)
next = IDLE;
else begin
next = INITIATE_READ;
count_int = count_int + 1;
end
end
endcase // case(state)
end // always @(state or start_test)
endmodule // memtest

memory_controller.v (multi-cycle access FSM)

// Verilog for Simple Multi-Cycle Access
// 6.11Lecture 7
module memory_controller(clk, reset, G_b, W_b, address, ext_address, write_data, read_data, ext_data, read, write, state, data_oen, address_load, data_sample);

input clk, reset, read, write;
output G_b, W_b;
output [15:0] ext_address;
reg [12:0] ext_address;
input [12:0] address;
input [7:0] write_data;

output [7:0] read_data;
reg [7:0] read_data;
input [7:0] ext_data;
reg [7:0] int_data;
output [2:0] state;
reg [2:0] state, next;
output data_oen, address_load, data_sample;
reg G_b, W_b, G_b_int, W_b_int, address_load, data_oen, data_oen_int, data_sample;
wire [7:0] ext_data;
wire [7:0] ext_data;

parameter IDLE = 0;
parameter write1 = 1;
parameter write2 = 2;
parameter write3 = 3;
parameter read1 = 4;
parameter read2 = 5;
parameter read3 = 6;

//Sequential always block for state assignment
assign ext_data = data_oen ? int_data : 8'bZ;

10
always @(posedge clk)
begin
if (reset) state <= IDLE;
else state <= next;
G_b <= G_b_int;
W_b <= W_b_int;
data_oen <=data_oen_int;
if (address_load) ext_address <= address;
if (data_sample) read_data <= ext_data;
if (address_load) int_data <= write_data;
end // always @(posedge clk)
// note that address_load and data_sample are not
// registered signals.
// Combinational always block for next-state
// computation
always @(state or read or write) begin
W_b_int = 1;
G_b_int = 1;
address_load = 0;
data_oen_int = 0;
data_sample = 0;
case(state)
IDLE:
if (write) begin
next = write1;
address_load=1;
data_oen_int=1;
end
else if (read) begin
next = read1;
address_load =1;
G_b_int =0;
end
else next=IDLE;
write1:
begin
next =write2;
W_b_int =0;
data_oen_int=1;
end
write2:
begin
next = write3;
data_oen_int=1;
end
write3:
begin
next = IDLE;
data_oen_int=0;
end
read1:
begin
next = read2;
G_b_int = 0;
data_sample = 1;
end
read2:
begin
next = read3;
end
read3:
begin
end
end
next ← IDLE;
end
default: next ← IDLE;
endcase; // case(state)
end // always @(state or read or write)
endmodule // memtest

tb_memory_tester.v (testbench)

// Testbench for memory_tester.
// This testbench will produce only 1 success.
// All the other reads will result in a failure.
module tb_memory_tester;

reg clk;
reg reset;
reg start_test;
wire success, failure;
wire [7:0] ext_data;
wire [12:0] ext_address;
wire [7:0] read_data;
wire [3:0] failure_count;
wire [3:0] state;
wire [2:0] mem_state;
wire [3:0] count;
reg enable_data;
reg [7:0] data_out;

assign ext_data ← enable_data ? data_out:8'hZ;

memory_tester mtest1(clk, reset, start_test, failure, success, read_data, ext_data, state, mem_state, count, failure_count);
always #25 clk ← ~clk;

initial begin
clk ← 0;
reset ← 0;
start_test ← 0;
#75
reset ← 1;
#50
start_test ← 1;
data_out ← 0;
enable_data ← 0;
#50
data_out ← 8'h0;
#5700
data_out ← 8'h0;
enable_data ← 1;
end
endmodule
Figure 5: Screenshot of Memory Tester