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DEPARTMENT OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCE

6.111 Lab #4 Checkoff List

Please be ready with the following when checking off Lab #4:

1. A printout of your Verilog code (put your name at the top!) that will be collected by the staff and evaluated.

2. Set the labkit's switches to 0 (i.e., zero puck velocity) and demonstrate your game in its reset state.

3. Demonstrate the paddle moving along the left edge of the screen in response to pushing the UP and DOWN buttons.

4. Enter a small velocity in switch[7:4] and demonstrate the puck moving and bouncing off the top, right and bottom of the screen.

5. Demonstrate the puck bouncing off the paddle, and how your game halts when the puck reaches the left edge of the screen.

6. Demonstrate that your game can be restarted after halting by pressing the ENTER button.

During checkoff you may be asked to discuss one or more of the following questions:

1. What would have to change in your Verilog code if the size of playing screen was reduced to 800x600? [Hint: it's always a good idea to use the **parameter** statement to give a symbolic name to important constants rather than scattering numbers all through your code.]

2. If the display were being driven from a frame buffer memory that supplies 8-bits for each of red, green and blue for each pixel, how much memory would be needed? If we used the labkit's ZBT rams for the frame buffer, what fraction of the memory bandwidth would be used by refreshing the screen? (Look at the labkit's documentation for the ZBT memories to get the throughput information you need to answer this question.)

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6.111 Lab #4

Goal: Implement a simple Pong game on a video monitor.

Video display technologies

Most video displays accept the image to be displayed in a serial fashion, usually a sequence of *horizontal scan lines* to be displayed one under another with a small vertical offset to create a *raster image*. Typically the raster is transmitted in left-to-right, top-to-bottom order. A complete raster image is called a *frame* and one can create the appearance of motion by displaying frames in rapid succession (24 frames/sec in movies, 30 frames/sec in broadcast TV, 60+ frames/sec in computer monitors).

To transmit a raster image, one must encode the color image information and provide some control signals that indicate the end of each horizontal scan line (*horizontal sync*) and frame (*vertical sync*). The display device creates the image using red, green and blue emitters, so an obvious way to encode the color information is to send separate signals that encode the appropriate intensity of red, green and blue. This is indeed how most analog computer monitors work – they accept 5 analog signals (red, green, blue, hsync, and vsync) over a standardized HD15 connector. The signals are transmitted as 0.7V peak-to-peak (1V peak-to-peak if the signal also encodes sync). The monitor supplies a 75Ω termination for each signal, which if matched with a driver and cable with a characteristic impedance of 75Ω minimizes the interference due to signal reflections. The labkit incorporates an integrated circuit – the ADV7125 Triple 8-bit high-speed video DAC – which produces the correct analog signals given the proper digital inputs: three 8-bit values for R, G and B intensity, hsync, vsync, and blanking.

[Small digression on other video encodings; feel free to skip to the end of the digression.]

When encoding a color video image for broadcast or storage, it's important to use the bandwidth/bits as efficiently as possible. And, in the case of broadcast, there was the issue of backwards compatibility with black-and-white transmissions. Since the human eye has less resolution for color than intensity, the color image signal is separated into luminance (Y, essentially the old black-and-white signal) and chrominance (U/Cr/Pr, V/Cb/Pb). YUV are related to RGB as follows:

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.229 & 0.587 & 0.114 \\ -0.147 & -0.289 & 0.436 \\ 0.615 & -0.515 & -0.100 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Luminance and chrominance are encoded separately and transmitted/stored at different bandwidths. In most systems the chrominance bandwidth is a half (4:2:2 format) or a quarter (4:2:0 format) of the luminance bandwidth. There are several common ways of transmitting Y, U and V:

- *Composite video* where Y and the composite sync are combined to form a 1V peak-to-peak signal. U+V and U-V are used to modulate orthogonal phases of a color subcarrier (3.58MHz in NTSC broadcasts) and then mixed with a low-pass-filtered version of Y/sync signal.

- *S-Video* where Y and the modulated color subcarrier are transmitted on separate signal/ground pairs. This avoids the low-pass filtering of Y used in composite video, resulting in a higher-resolution video image.

- *Component video* where Y, Cr/Pr, and Cb/Pb are transmitted on separate signal ground pairs (Cr and Cb are just scaled versions of U and V).

Some transmission schemes break a frame into an even field (containing the even numbered scan lines) and an odd field (containing the odd numbered scan lines) and then transmit the fields in alternation. This technique is called *interlacing* and permits slower frame rates (and hence lower bandwidths) while still avoiding the problem of image flicker. When higher bandwidths are available, non-interlaced transmissions are preferred (often called *progressive scan*).

The labkit contains interface chips for encoding (ADV7194) and decoding (ADV7185) composite and S-Video signals. The decoder chip is particularly useful if you want to use a video camera signal as part of your project.

[End of digression.]

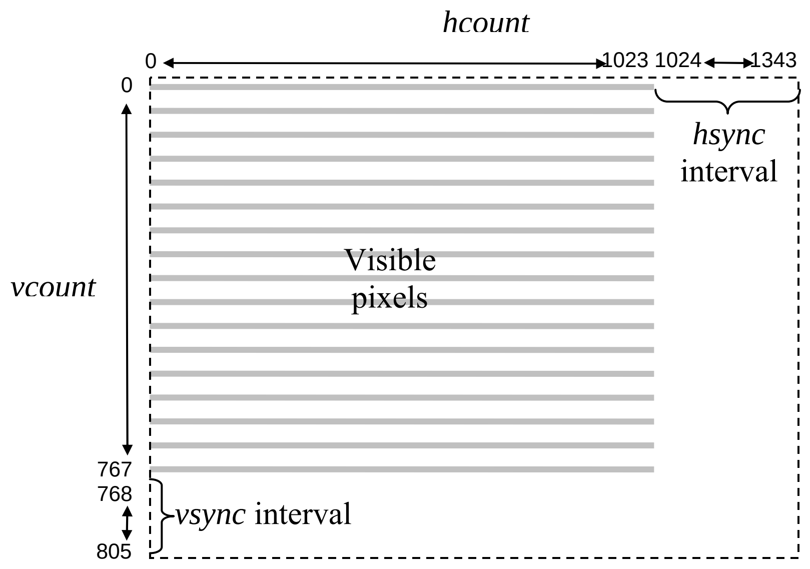
To create a video image for our Pong game, it's helpful to think of the image as a rectangular array of picture elements or *pixels*. There are several common choices for the dimensions (HxV) of the rectangle:

640x480 (VGA), requires 25MHz (40ns) pixel clock for 60Hz refresh
800x600 (SVGA), requires 40MHz (25ns) pixel clock for 60Hz refresh
1024x768 (XVGA), requires 65MHz (15ns) pixel clock for 60Hz refresh

The computer monitors in the lab support resolutions up to 1280x1024 but the required pixel clock doesn't leave much time for the game logic to figure out the pixel to display, so let's go with a 1024x768 display for our game.

Please take a moment to read through the "VGA Video" hardware tutorial that's part of the on-line Labkit documentation. You'll see that the timings for the RGB image information relative to the horizontal and vertical syncs are somewhat complicated. For example, the horizontal sync goes active in the interval between the end of one scan line and the beginning of the next – the exact timings are specified by the XVGA specification. Lab4.v includes an *xvga* module that generates the necessary signals; it uses two counters:

> *hcount* counts pixels in a horizontal scan line. Values 0 through 1023 are the 1024 displayed pixels, values 1024 through 1343 time the interval between the end of one scan line and the start of the next. Specific values in this interval are decoded to time the beginning and end of the active-low horizontal sync signal (*hsync*).
>
> *vcount* counts scan lines in a frame. Values 0 through 767 are the 768 displayed scan lines, values 768 through 805 time interval between end of one frame and the start of the next. Specific values in this interval are decoded to time the beginning and end of the active-low vertical sync signal (*vsync*).

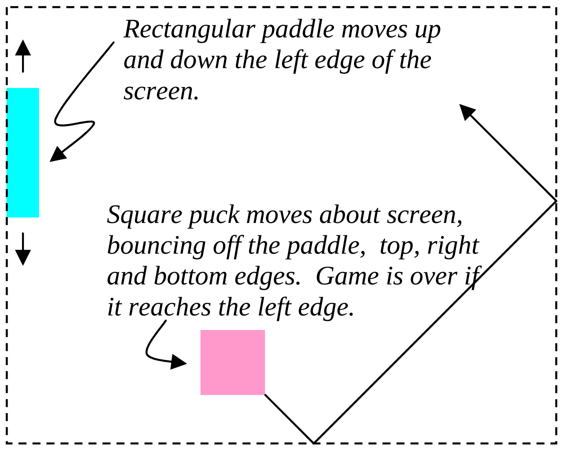


The *xvga* module also generates *blank*, a signal that's 0 when a pixel value will be displayed and 1 when the pixel would be off the screen (hcount > 1023 or vcount > 767). The inversion of this signal is required by the AD7125 VGA interface chip

You can use (*hcount*,*vcount*) as the (x,y) coordinate of the pixel to be displayed: (0,0) is the top-left pixel, (1023,0) is the top-right pixel, (1023,767) is the bottom-right pixel, etc. Given the coordinates and dimensions of a graphic element, your game logic can use (*hcount,vcount*) to determine the contribution the graphic element makes to the current pixel. If you are storing the pixels in a memory array (called a frame buffer) then the index of the current pixel would be H·*vcount* + *hcount[9:0]*, where H is the number of displayed pixels in each scan line.

Pong Game

Pong was one of the first mass-produced video games, a hit more because of its novelty than because of the gaming experience itself. Our version will be a single-player variation where the player is defending a "goal" by moving a rectangular paddle up and down the left edge of the screen. The puck moves about the screen with a fixed velocity, bouncing off the paddle and the implicit walls at the top, right and bottom edges of the screen. If the puck reaches the left edge of the screen (i.e., it wasn't stopped by bouncing off the paddle), the player looses and the game is over:


Rectangular paddle moves up and down the left edge of the screen.
Square puck moves about screen, bouncing off the paddle, top, right and bottom edges. Game is over if it reaches the left edge.

A 65MHz clock serves as the system clock and times the duration of a single pixel. The position of moving objects (e.g., the paddle and puck) are changed once every frame (1/60 second) as triggered by the high-to-low transition of *vsync*.

To keep the initial implementation easy, let's make the puck a 64-pixel by 64-pixel square and have it move at move diagonally at a constant velocity. We'll use switch[7:4] to set the puck's velocity in terms of pixels/frame: 4'b0000 means no motion, 4'b0101 would cause the puck to change both its x and y coordinate by 5 every frame (the sign of the change for each coordinate would be determined by which of the 4 possible headings the puck is following at the moment). When the puck collides with an edge or the paddle, its heading changes appropriately, e.g., a collision with the bottom edge changes the sign of the puck's y velocity.

Make the paddle 16 pixels wide and 128 pixels high. It should move up and down the left edge of the screen at 4 pixels/frame in response to the user pressing the UP or DOWN buttons on the labkit.

Pressing the ENTER button should reset the game to its initial state: the paddle centered on the left edge, and the puck somewhere in the middle of the screen, heading southeast. If the puck reaches the left edge, the game should stop (it can be restarted by pressing the ENTER button).

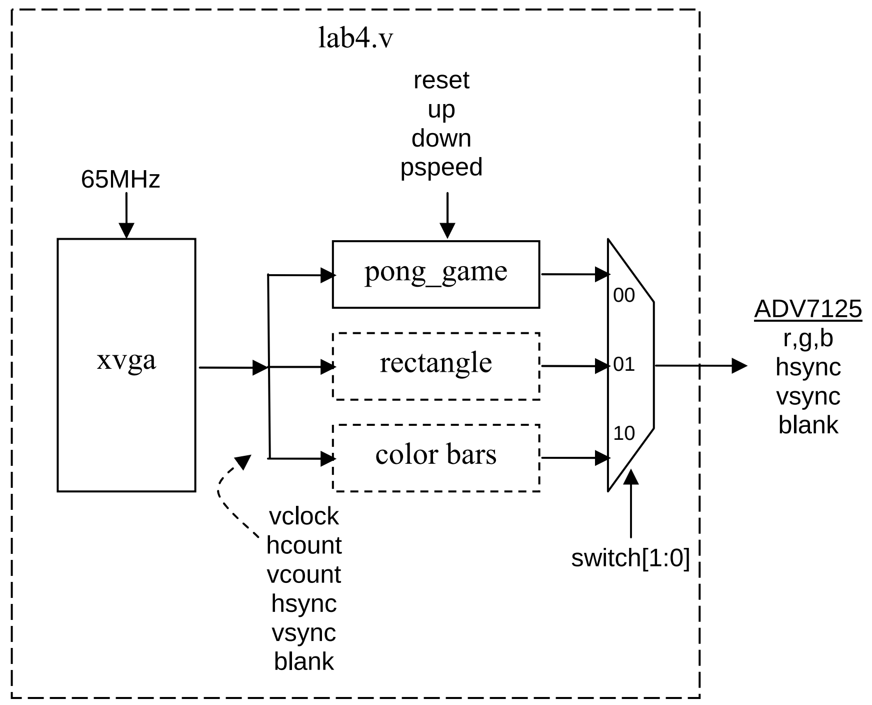
Implementation steps

1. Download lab4.v from the course website, compile it using the Xilinx tools, and then load it onto the labkit. Connect the VGA cable from your computer monitor to the VGA connector on the left-hand side of the labkit's main board. The VGA cable is the one with blue connector housings – the computer is connected to the same monitor with a DVI cable that has white connector housings. Select the VGA input by pressing the input select button on the lower right bezel of the monitor (it's embossed with "—").

   Set the labkit's slide switches so that switch[1:0] is 2'b10. You should see vertical colored bars on the monitor; the color sequence progresses through the eight possible colors where each of R, G or B is on or off. If don't see this image, make sure the monitor is reading from the VGA input, the cable is connected properly and the download to the FPGA completed successfully.

   Now set the slide switches so that switch[1:0] is 2'b01. This should produce a one-pixel wide white outline around the edge of the screen. If one or more of the edges isn't visible, the image size and position can be adjusted using the monitor's controls. Push the "menu" button and use the "+" and "-" buttons to navigate to the Position and Size selections. Adjust until all four edges of the white rectangle are visible.

   Finally set the slide switches so that switch[1:0] is 2'b00. You should see a color checkerboard that's being produced by the Verilog code inside of *pong_game* module. This is the code you'll modify to implement your pong game.



2. Modify the *pong_game* module so that it produces a white square in the middle of the screen. See the implementation tips below for some hints about how to do this. The *pong_game* module has the following inputs and outputs:

vclock	input	65MHz pixel clock
reset	input	1 to reset the module to its initial state, hooked to the ENTER pushbutton via a debouncing circuit
up	input	1 to move paddle up, 0 otherwise. Hooked to the UP pushbutton via a debouncing circuit.
down	input	1 to move paddle down, 0 otherwise. Hooked to the DOWN pushbutton via a debouncing circuit.
pspeed[3:0]	input	Puck horizontal & vertical velocity in pixels per frame. Hooked to switch[7:4]
hcount[10:0]	input	Counts pixels on the current scan line, generated by the *xvga* module.
vcount[9:0]	input	Counts scan lines in the current frame, generated by the *xvga* module.
hsync	input	Active-low horizontal sync signal generated by the *xvga* module
vsync	input	Active-low vertical sync signal generated by the *xvga* module
blank	input	Active-high blanking signal generated by the *xga* module
phsync	output	Active-low horizontal sync signal generated by your Pong game. Often this is just *hsync*, perhaps delayed by a vclock if your pixel generating circuitry takes an additional vclock.
pvsync	output	Active-low horizontal sync signal generated by your Pong game. Often this is just *vsync*, perhaps delayed by a vclock if your pixel generating circuitry takes an additional vclock.
pblank	output	Active-high blanking signal generated by your Pong game. Often this is just *blank*, perhaps delayed by a vclock if your pixel generating circuitry takes an additional vclock.
pixel[2:0]	output	The {R,G,B} value for the current pixel, one bit for each color.

3. Add logic to make the puck move along one of the four possible diagonal directions, making it "bounce" off the edges of the screen. The speed of the puck is set by the *pspeed* input to the *pong_game* module.

4. Add logic to display a paddle along the left edge of the screen which moves up and down at 4 pixels/frame in response to the *up* and *down* inputs to the

pong_game module.

5. Finally, add logic to make the puck bounce off the paddle and to end the game if the puck reaches the left edge of the screen. The game should stay halted until the *reset* input is asserted by pressing the ENTER button.

6. [optional] There are many possible improvements to this implementation: a two-player version with another paddle along the right edge of the screen, more interesting puck motion and puck shapes, sound effects, displaying a score at the top of the screen, etc. If you have the time and inclination, it can be fun to hack around a bit!

Implementation Tips

You may find it useful to use the following parameterized module in your implementation of Pong. Given the pixel coordinate (hcount,vcount) it returns a non-black pixel if the coordinate falls with the appropriate rectangular area. The coordinate of the top-left corner of the rectangle is given by the *x* and *y* inputs; the width and height of the rectangle, as well as its color, are determined by module's parameters.

```
//////////////////////////////////////////////////////////////////////
//
// blob: generate rectangle on screen
//
//////////////////////////////////////////////////////////////////////
module blob(x,y,hcount,vcount,pixel);
   parameter WIDTH = 64;      // default width: 64 pixels
   parameter HEIGHT = 64;     // default height: 64 pixels
   parameter COLOR = 3'b111;  // default color: white

   input [10:0] x,hcount;
   input [9:0] y,vcount;
   output [2:0] pixel;

   reg [2:0] pixel;
   always @ (x or y or hcount or vcount) begin
      if ((hcount >= x && hcount < (x+WIDTH)) &&
          (vcount >= y && vcount < (y+HEIGHT)))
         pixel = COLOR;
      else pixel = 0;
   end
endmodule
```

You can instantiate several instances of *blob* to create different rectangles on the screen, using **defparam** to specify the instance's parameters:

```
   reg [9:0]  paddle_y;
   wire [2:0] paddle_pixel;
   blob paddle1(11'd0,paddle_y,hcount,vcount,paddle_pixel);
   defparam paddle1.WIDTH = 16;
   defparam paddle1.HEIGHT = 128;
   defparam paddle1.COLOR = 3'b110;   // yellow!
```

[From the "more than you wanted to know" department:] *blob* is a very simple example of what game hardware hackers call a *sprite*: a piece of hardware that generates a pixel-by-pixel image of a game object. A sprite pipeline connects the output (pixel & sync signals) of one sprite to the input of the next. A sprite passes along the incoming pixel if the object the sprite represents is transparent at the current coordinate, otherwise it generates the appropriate pixel of its own. The generated pixel might come from a small image map and/or depend in some way on the sprite's internal state. Images produced by sprites later in the pipeline appear in front of sprites earlier in the pipeline, giving a pseudo 3D look to the same. This becomes even more realistic if sprites scale the image they produce so that it gets smaller if the object is supposed to be further away. The order of the pipeline becomes unimportant if a "Z" or depth value is passed along the pipeline with each pixel. The current sprite only replaces the incoming pixel/Z-value if its Z-value puts it in front of the Z-value for the incoming pixel. Simple, but sprites produced surprisingly playable games in the era before the invention of 3D graphic pipelines that can render billions of shaded triangles per second.