Computer Organization
Laboratory Exercise 8

Introduction to Graphics and Animation

The purpose of this exercise is to learn how to display images and perform animation. We assume that you are using the *DE1-SoC Computer System with Nios V*, which is described as part of the `Computer Organization` course on the website FPGAcademy.org. A good approach is to first implement your C code for each part of this exercise by using the *CPUlator* simulator, and then to implement your solution in a hardware board, if available. If a hardware system other than the DE1-SoC Computer is being used, then some parts of this exercise may need to be modified to suit the features of your board.

Background Information

The *DE1-SoC Computer with Nios V* includes a video-out port with a VGA controller that can be connected to a standard VGA monitor. The VGA controller supports a screen resolution of 640 $\times$ 480. The image that is displayed by the VGA controller is derived from two sources: a *pixel* buffer, and a *character* buffer. We will mainly focus on the pixel buffer in this exercise.

Pixel Buffer

The pixel buffer for the video-out port holds the data (color) for each pixel that is displayed by the VGA controller. As illustrated in Figure 1, the pixel buffer provides an image resolution of 320 $\times$ 240 pixels, with the coordinate 0,0 being at the top-left corner of the image. Since the VGA controller supports the screen resolution of 640 $\times$ 480, each of the pixel values in the pixel buffer is replicated in both the *x* and *y* dimensions when it is being displayed on the VGA screen.

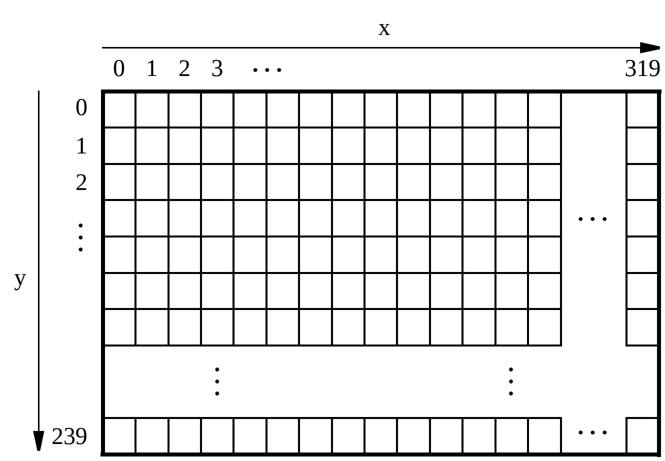


Figure 1: Pixel buffer coordinates.

Figure 2a shows that each pixel color is represented as a 16-bit halfword, with five bits for the blue and red components, and six bits for green. As depicted in part b of Figure 2, pixels are addressed in the pixel buffer by using the combination of a *base* address and an *x,y* offset. In the computer systems the default address of the pixel buffer is 0x08000000, which corresponds to the starting address of the FPGA on-chip memory. Using this scheme, the pixel at location 0,0 has the address 0x08000000, the pixel 1,0 has the address *base* + $(00000000\ 000000001\ 0)_2$ = 0x08000002, the pixel 0,1 has the address *base* + $(00000001\ 000000000\ 0)_2$ = 0x08000400, and the pixel at location 319,239 has the address *base* + $(11101111\ 100111111\ 0)_2$ = 0x0803BE7E.

15 ··· 11	10 ··· 5	4 ··· 0
red	green	blue

(a) Pixel color

31 ··· 18	17 ··· 10	9 ··· 1	0
00000000000000	y	x	0

(b) Pixel (x,y) offset

Figure 2: Pixel values and addresses.

You can create an image by writing color values into the pixel addresses as described above. A dedicated *pixel buffer controller* reads this pixel data from the memory and sends it to the VGA display. The controller reads the pixel data in sequential order, starting with the pixel data corresponding to the upper-left corner of the VGA screen and proceeding to read the whole buffer until it reaches the data for the lower-right corner. This process is then repeated, continuously. You can modify the pixel data at any time, by writing to the pixel addresses. Writes to the pixel buffer are automatically interleaved in the hardware with the read operations that are performed by the pixel buffer controller.

It is also possible to prepare a new image for the VGA display without changing the content of the pixel buffer, by using the concept of *double-buffering*. In this scheme two pixel buffers are involved, called the *front* and *back* buffers, as described below.

Double Buffering

As mentioned above, a pixel buffer controller reads data out of the pixel buffer so that it can be displayed on the VGA screen. This pixel buffer controller includes a programming interface in the form of a set of registers, as illustrated in Figure 3. The *Buffer* and *Backbuffer* registers each store the starting address of a pixel buffer. The Buffer register holds the address of the pixel buffer that is displayed on the VGA screen. As mentioned above, in the default configuration this Buffer register is set to the address `0x08000000`. The default value of the Backbuffer register is also `0x08000000`, which means that there is only one pixel buffer. Software can modify the address stored in the Backbuffer register, thereby creating a second pixel buffer. An image can be drawn into this second buffer by writing to its pixel addresses. This image is not displayed on the VGA monitor until a pixel buffer *swap* is performed, as explained below.

A pixel buffer swap is caused by writing the value 1 to the Buffer register. This write operation does not directly modify the content of the Buffer register, but instead causes the contents of the Buffer and Backbuffer registers to be swapped. The swap operation does not happen right away; it occurs at the end of a VGA screen-drawing cycle, after the last pixel in the bottom-right corner has been displayed. This time instance is referred to as the *vertical synchronization* time, and occurs every 1/60 seconds. Software can poll the value of the S bit in the *Status* register to see when the vertical synchronization has happened. Writing the value 1 into the Buffer register causes S to be set to 1. Then, when the swap of the Buffer and Backbuffer registers has been completed S is reset back to 0. The *Status* register, shown in Figure 3, contains additional bits of information, but these bits are not needed for this exercise. Also, the programming interface includes a *Resolution* register, shown in the figure, that contains the X and Y dimensions of the pixel buffer(s).

In a typical application the pixel buffer controller is used as follows. While the image contained in the pixel buffer that is pointed to by the Buffer register is being displayed, a new image is drawn into the pixel buffer pointed to by the Backbuffer register. When this new image is ready to be displayed, a pixel buffer swap is performed. Then, the pixel buffer that is now pointed to by the Backbuffer register, which was already displayed, is cleared and the next new image is drawn. In this way, the next image to be displayed is always drawn into the "back" pixel buffer,

Address	31 ... 24	23 ... 16	15 ... 8	7 ... 4	3	2	1	0	
0xFF203020	front buffer address								Buffer register
0xFF203024	back buffer address								Backbuffer register
0xFF203028	Y		X						Resolution register
0xFF20302C	m	n	Unused	B	Unused		A	S	Status register

Figure 3: Pixel buffer controller registers.

and the "front" and "back" buffer pointers are swapped when the new image is ready to be displayed. Each time a swap is performed software has to synchronize with the VGA controller by waiting until the S bit in the Status register becomes 0.

Part I

In this part you will learn how to implement a simple line-drawing algorithm.

Drawing a line on a screen requires coloring pixels between two points (x_1, y_1) and (x_2, y_2), such that the pixels represent the desired line as closely as possible. Consider the example in Figure 4, where we want to draw a line between points $(1, 1)$ and $(12, 5)$. The boxes in the figure represent the location and size of pixels on the screen. As indicated in the figure, we cannot draw the line precisely—we can only draw a shape that is similar to the line by coloring the pixels that fall closest to the line's ideal location on the screen.

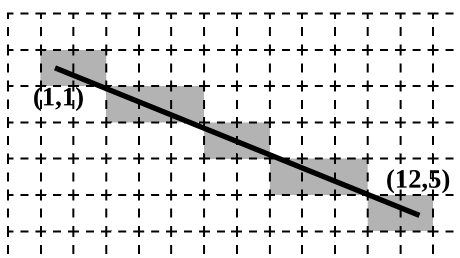


Figure 4: Drawing a line between points $(1, 1)$ and $(12, 5)$.

We can use algebra to determine which pixels to color. This is done by using the end points and the slope of the line. The slope of our example line is $slope = (y_2 - y_1)/(x_2 - x_1) = 4/11$. Starting at point $(1, 1)$ we move along the x axis and compute the y coordinate for the line as follows:

$$y = y_1 + slope \times (x - x_1)$$

Thus, for column $x = 2$, the y location of the pixel is $1 + \frac{4}{11} \times (2 - 1) = 1\frac{4}{11}$. Since pixel locations are defined by integer values we round the y coordinate to the nearest integer, and determine that in column $x = 2$ we should color the pixel at $y = 1$. For column $x = 3$ we perform the calculation $y = 1 + \frac{4}{11} \times (3 - 1) = 1\frac{8}{11}$, and round the result to $y = 2$. Similarly, we perform such computations for each column between x_1 and x_2.

The approach of moving along the x axis has drawbacks when a line is steep. A steep line spans more rows than it does columns, and hence has a slope with absolute value greater than 1. In this case our calculations will not produce a smooth-looking line. Also, in the case of a vertical line we cannot use the slope to make a calculation. To address this problem, we can alter the algorithm to move along the y axis when a line is steep. With this change, we can implement a line-drawing algorithm known as *Bresenham's algorithm*. Pseudo-code for this algorithm is given in Figure 5. The first 15 lines of code set up the variables needed by the algorithm. Then, in lines 17 to 22 the algorithm increments the x variable 1 step at a time and computes the y value. The y value is incremented when needed to stay as close to the ideal location of the line as possible. Bresenham's algorithm calculates an *error* variable to decide whether or not to increment each y value. The version of the algorithm shown in Figure 5 uses only integers to perform all calculations. To understand how this algorithm works, you can read about Bresenham's algorithm in a textbook or by searching for it on the internet.

```
1     draw_line(x0, x1, y0, y1)
2
3         boolean is_steep = abs(y1 - y0) > abs(x1 - x0)
4         if is_steep then
5            swap(x0, y0)
6            swap(x1, y1)
7         if x0 > x1 then
8            swap(x0, x1)
9            swap(y0, y1)
10
11        int deltax = x1 - x0
12        int deltay = abs(y1 - y0)
13        int error = -(deltax / 2)
14        int y = y0
15        if y0 < y1 then y_step = 1 else y_step = -1
16
17        for x from x0 to x1
18           if is_steep then draw_pixel(y, x) else draw_pixel(x, y)
19           error = error + deltay
20           if error >= 0 then
21              y = y + y_step
22              error = error - deltax
```

Figure 5: Pseudo-code for a line-drawing algorithm.

Perform the following:

1. Write a C-language program that implements Bresenham's line-drawing algorithm, and uses this algorithm to draw a few lines on the screen. An example of a suitable main program is given in Figure 6. The code first determines the address of the pixel buffer by reading from the pixel buffer controller, and stores this address into the global variable *pixel_buffer_start*. The main program clears the screen, and then draws four lines. You have to write the *clear_screen* function, which sets all pixels to the color black (0), and the *draw_line* function that implements Bresenham's algorithm. An example of a function that uses the global variable *pixel_buffer_start* is shown at the end of Figure 6. The function *plot_pixel ()* sets the pixel at location x, y to the color *line_color*.

2. Compile and test your solution. If you are using the *CPUlator*, then your VGA output will be shown in the simulated `VGA pixel buffer` window pane. If you are using an actual DE1-SoC board, then connect a VGA monitor to the board to see the video output.

```
volatile int pixel_buffer_start; // global variable

int main(void)
{
    volatile int * pixel_ctrl_ptr = (int *)0xFF203020;
    // Read location of the pixel buffer from the pixel buffer controller
    pixel_buffer_start = *pixel_ctrl_ptr;

    clear_screen();
    draw_line(0, 0, 150, 150, 0x001F);   // this line is blue
    draw_line(150, 150, 319, 0, 0x07E0); // this line is green
    draw_line(0, 239, 319, 239, 0xF800); // this line is red
    draw_line(319, 0, 0, 239, 0xF81F);   // this line is a pink color
}

// code not shown for clear_screen() and draw_line() subroutines

void plot_pixel(int x, int y, short int line_color) {
    *(short int *)(pixel_buffer_start + (y << 10) + (x << 1)) = line_color;
}
```

Figure 6: Main program for Part I.

Part II

Animation is an exciting part of computer graphics. Moving a displayed object is an illusion created by showing this same object at different locations on the screen. A simple way to "move" an object is to first draw the object at one position, and then after a short time erase the object and draw it again at another nearby position.

To realize animation it is necessary to move objects at regular time intervals. The VGA controller in the DE1-SoC Computer redraw the screen every $1/60^{th}$ of a second. Since the image on the screen cannot change more often than that, it is reasonable to control an animation using this unit of time.

To ensure that you change the image only once every $1/60^{th}$ of a second, use the pixel buffer controller to synchronize with the vertical synchronization cycle of the VGA controller. As we discussed in the background section of this exercise, synchronizing with the VGA controller can be accomplished by writing the value 1 into the *Buffer* register in the pixel buffer controller, and then waiting until bit S of the *Status* register becomes equal to 0. For this part of the exercise you do not need to use a back buffer, so ensure that the *Buffer* and *Backbuffer* addresses in the pixel buffer controller are the same. In this approach, a pixel buffer "swap" can be used as a way of synchronizing with the VGA controller via the *S* bit in the *Status* register.

Perform the following:

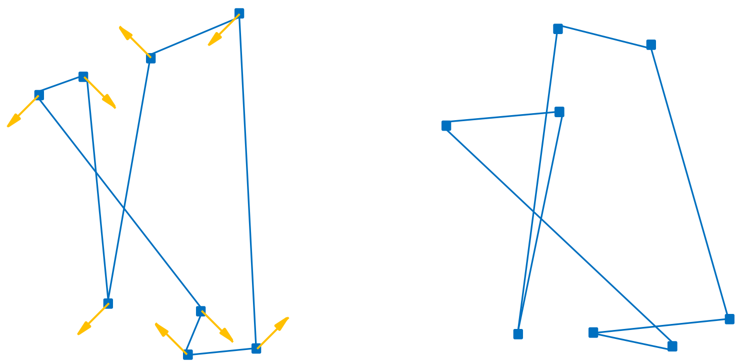
1. Write a C-language program that moves a horizontal line up and down on the screen and "bounces" the line off the top and bottom edges of the display. Your program should first clear the screen and draw the line at a starting row on the screen. Then, in an endless loop you should erase the line (by drawing the line using black), and redraw it one row above or below the last one. When the line reaches the top, or bottom, of the screen it should start moving in the opposite direction.

2. Compile and test your solution. Notice how long it takes for the horizontal line to move through the 240 lines of the VGA display. On an actual DE1-SoC board, it should take $240 \times 1/60 = 4$ seconds. If using the *CPUlator* simulator, then the movement of the line up and down on the simulated screen will likely be somewhat slower than in the real hardware.

Part III

Having gained the basic knowledge about displaying images and animations, you can now create a more interesting animation.

You are to create an animation of several small square boxes on the screen. These boxes should appear to be moving continuously and "bouncing" off the edges of the screen. Each box should be filled with a color and the boxes should be connected with lines to form a chain. An illustration of the animation is given in Figure 7. Part a of the figure shows one position of the boxes with arrows that indicate the directions of movement, and Figure 7b shows a subsequent position of the boxes. In each step of your animation each of the boxes should appear to "move" on a diagonal line: up/left, up/right, down/left, or down/right. Move the boxes one row and one column at a time on the VGA screen.



(a) (b)

Figure 7: Two instants of the animation.

To make the animation look slightly different each time you run it, use the C library function *rand ()* to help calculate initial positions for each of the boxes, and to determine their directions of movement. To add variety to your animations, you might randomly have some boxes moving on diagonals, some moving vertically or horizontally, and some in fixed positions.

Perform the following:

1. Write a C program to implement your animation. Use both a front and back buffer in your program, so that you can avoid making changes to the image while it is being displayed by the pixel buffer controller. An example of a suitable main program (not all of the code is shown) is given in Figure 8. The code sets one pixel buffer to be in the FPGA on-chip memory (which is its default location), and declares an array in the SDRAM memory to use as the location of the other pixel buffer (the FPGA on-chip memory is not large enough to hold two pixel buffers). In each iteration of the while loop the code clears the entire screen, draws the boxes and lines, and then updates the locations of boxes. At the bottom of the while loop the code calls the function *wait_for_vsync ()*, which synchronizes with the VGA controller and swaps the front and back pixel buffer pointers.

2. Compile, debug, and test your code.

3. Experiment with your code by modifying it to use just a single pixel buffer (simply change the address of the back buffer to be the same as the front buffer). Observe what you see on the VGA screen as a result of this change.

```c
volatile int pixel_buffer_start;        // global variable
// declare other variables (code not shown)
...
.
.
short int SDRAM_back_buffer[512 * 256]; // space for pixel buffer

int main(void) {
    volatile int * pixel_ctrl_ptr = (int *)0xFF203020;
    // declare other variables (not shown)
    ...
    .
    .
    // initialize locations and directions of boxes (not shown)
    ...
    .
    .
    // set location of the front pixel buffer
    *(pixel_ctrl_ptr + 1) = 0x08000000; // FPGA on-chip memory
    // now, swap the back/front buffers to set the front buffer
    wait_for_vsync();

    // set pointer to pixel buffer, used by drawing functions
    pixel_buffer_start = *pixel_ctrl_ptr;
    clear_screen(); // uses pixel_buffer_start

    // set location of back buffer
    *(pixel_ctrl_ptr + 1) = SDRAM_back_buffer;  // location in SDRAM memory
    pixel_buffer_start = *(pixel_ctrl_ptr + 1); // draw on the back buffer

    while (1) {
        // erase the screen
        clear screen();

        // code for drawing the boxes and lines (not shown)
        ...
        .
        .
        // code for updating the locations of boxes (not shown)
        ...
        .
        .
        wait_for_vsync(); // swap back/front buffers on VGA sync
        pixel_buffer_start = *(pixel_ctrl_ptr + 1); // update pointer
    }
}

// code for subroutines (not shown)
...
.
.
```

Figure 8: Main program for Part III.

Instead of clearing the whole screen in each step of the animation, you may want to keep track of where boxes and lines are drawn and then clear only the corresponding pixels (by drawing in black) rather than the whole screen. This optimization makes your animation more efficient and may make the boxes and lines move more smoothly.

Part IV

For this part of the exercise you are to enhance the animation from Part III so that during the animation the following changes can take place:

1. The speed of movement of the boxes can be increased or decreased
2. The number of boxes can be increased or decreased
3. The lines between boxes can be drawn or not drawn

In Part III the speed of animation was set by the 1/60 seconds VGA vertical synchronization time. One way to structure the program such that the animation timing can be changed is to use a timer. In this scheme you would wait for the timer, using polled-I/O before drawing each frame of the animation. Reducing the timer frequency would cause the animation to appear to move more slowly. Increasing the timer frequency would make the animation move more quickly, with the maximum speed being limited by the 1/60 seconds VGA synchronization time, as it was in Part III. To cause the animation to appear to move more quickly than in Part III, you have to increase the amount that the boxes are moved for each animation frame.

Perform the following:

1. Implement the speed control discussed above for the animation. The speed of animation should approximately double when you press pushbutton KEY_0, and it should reduce by the same amount when you press KEY_1. Pressing KEY_2 should add a box to the animation, up to some maximum of your choosing. Pressing KEY_3 should remove a box. Finally, when any of the *SW* slider switches is set to the 1 position the lines between boxes should not be drawn; only when all switches are set to the 0 position should the lines appear.
2. Compile, debug, and test your code.
3. Add any other animation features that you may find interesting. As an example, you could make use of the character buffer in the DE1-SoC Computer to display text with your animation. You could show a frame counter that indicates how many frames have been displayed as the animation proceeds. The character buffer is described in the documentation for the *DE1-SoC Computer with Nios V*.