Laboratory Exercise 5

Introduction to Graphics and Animation

The purpose of this exercise is to learn how to display images and perform animation. You will be writing C code that runs on the ARM processor in the DE1-SoC Computer. On a DE1-SoC board, graphics can be displayed by connecting a VGA monitor to the *video-out* port on the board. The Monitor Program allows you to compile C programs and download the resulting executable code into the DE1-SoC board.

You may want to use the *CPUlator* to develop and debug your code. The CPUlator supports programs written in C. In addition to other I/O ports that you have used in previous lab exercises, the CPUlator simulates the DE1-SoC board's video-out port—graphics that would normally appear on a VGA display are instead rendered inside a sub-window, labeled `VGA pixel buffer`, within CPUlator. This subwindow can be set to various sizes and it can also be "popped out" of the main browser window, if desired.

To do this exercise you need to know how to use C code with the ARM processor, and how to use the video-out port. You should be familiar with the material in the DE1-SoC Computer system documentation about the video-out port.

Background Information - the Pixel Buffer

The computer system used with this exercise 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 × 480 pixels, but we'll be using it at a lower resolution. The image displayed by the VGA controller is in a region of memory called the *pixel buffer*. This 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 × 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 × 480, the controller replicates each pixel value from the pixel buffer in both the *x* and *y* dimensions when displaying an image on the VGA screen.

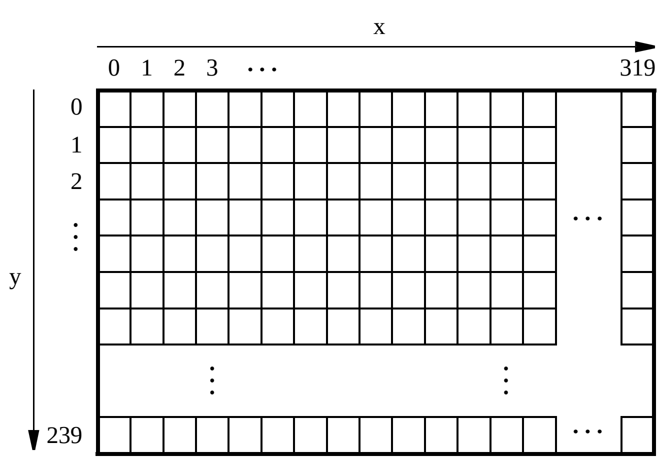


Figure 1: VGA screen coordinates.

Figure 2a shows that each pixel color is represented as a 16-bit halfword (two bytes) 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 system for your board the default address of the start of the pixel buffer is 0xC8000000. This address corresponds to the beginning of a memory block that is located inside the FPGA chip in the computer system. Using the addressing scheme in Figure 2*b*, the pixel at location 0,0 has the address 0xC8000000, the pixel 1,0 has the address *base* + $(00000000\ 000000001\ 0)_2$ = 0xC8000002, the pixel 0,1 has the address *base* + $(00000001\ 000000000\ 0)_2$ = 0xC8000400, and the pixel at location 319,239 has the address *base* + $(11101111\ 100111111\ 0)_2$ = 0xC803BE7E.

You can create an image on the screen by writing color values into the pixel addresses as described above. A dedicated *pixel buffer controller* (which is hardware in the FPGA) 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 for the upper-left corner of the VGA screen and proceeding to read the whole buffer until it reaches 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 register at address 0xFF203020 is called the *Buffer* register, and the register at address 0xFF203024 is the *Backbuffer* register. Each of these registers stores 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 of the computer systems the Buffer register is set to the address 0xC8000000, which points to the start of the FPGA on-chip memory. The default value of the Backbuffer register is also 0xC8000000, which means that there is only one pixel buffer. But 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, at address 0xFF20302C, 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 contains additional bits of information, shown in Figure 3. The

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.

Address	31 ... 24	23 ... 16	15 ... 12	11 ... 8	7	6	5 ... 2	1	0	
0xFF203020	front buffer address									Buffer register
0xFF203024	back buffer address									Backbuffer register
0xFF203028	Y		X							Resolution register
0xFF20302C	m	n	Unused	BS	SB	Unused		A	S	Status register

Figure 3: Pixel buffer controller registers.

m and n bits specify the number of y and x VGA address bits, respectively. The *BS* bits indicate pixel-size; for a pixel size of two bytes, this field is set to 15. Also, the programming interface includes a *Resolution* register, shown in the figure, that contains the X and Y resolution 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, 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, in the C programming language. 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 squares 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.

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:

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

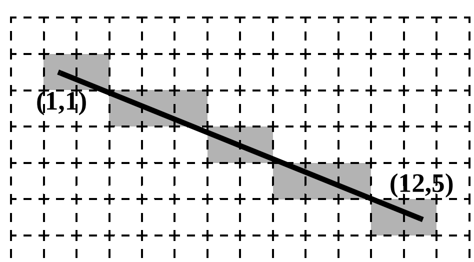


Figure 4: Drawing a line between points $(1, 1)$ and $(12, 5)$.

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 $y = 3$. 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 the algorithm make the needed adjustments depending on whether or not the line is steep, and on its vertical (down or up) and horizontal (left or right) directions. Then, in lines 17 to 25 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 *error* variable takes into account the relative difference between the width (*deltax*) and height of the line (*deltay*) in deciding how often *y* should be incremented. The version of the algorithm shown in Figure 5 uses only integers to perform all calculations.

```
1    draw_line(x0, x1, y0, y1)
2        boolean is_steep = abs(y1 - y0) > abs(x1 - x0)
3        if is_steep then
4           swap(x0, y0)
5           swap(x1, y1)
6        if x0 > x1 then
7           swap(x0, x1)
8           swap(y0, y1)
9
10       int deltax = x1 - x0
11       int deltay = abs(y1 - y0)
12       int error = -(deltax / 2)
13       int y = y0
14       if y0 < y1 then y_step = 1 else y_step = -1
15
16       for x from x0 to x1
17          if is_steep then
18             draw_pixel(y, x)
19          else
20             draw_pixel(x, y)
21          error = error + deltay
22          if error > 0 then
23             y = y + y_step
24             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, and is included in the design files provided with this lab, in a file named *part1.c* (Note: this file also includes constants for various addresses in the DE1-SoC Computer. Such constants would normally be stored in a '*.h*' *header* file, but we have placed everything inside the file *part1.c* so that the code is compatible with CPUlator, since it supports only one file at a time). You are to write the *draw_line* function, which takes in the end points of the line and the colour to be drawn, as illustrated 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. 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*. This function implements the pixel addressing scheme from Figure 2*b*.

2. Compile, test and debug your program.

```
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: Part of the 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 your DE1-SoC board's computer system redraws 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 the VGA image is changed only once every $1/60^{th}$ of a second, you can use the pixel buffer controller to synchronize with the vertical synchronization cycle of the VGA controller. As described 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

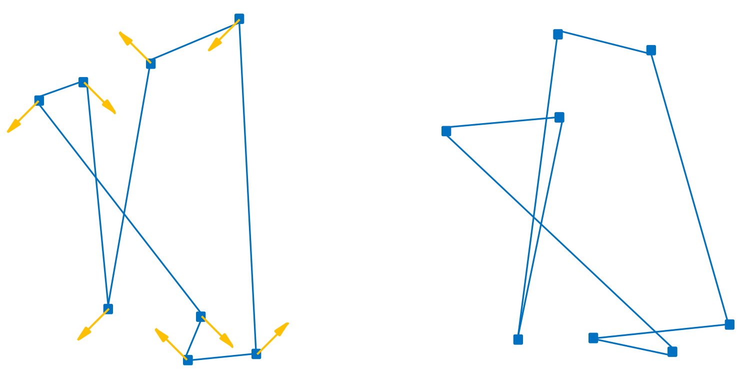
a starting row on the screen. Then, in an endless loop you should erase the line (by drawing the line using black), and redraw it one row above or below the last one. When the line reaches the top, or bottom, of the screen it should start moving in the opposite direction.

2. Put your program into a file called *part2.s*, and compile, run and debug your code. When your code is running on a DE1-SoC board, it will take a fixed amount of time for the horizontal line to move through the 240 lines of the VGA display, which is $240 \times 1/60 = 4$ seconds. However, if your code is running on CPUlator, which performs a software *simulation* of this process, it is slower—measure how long it takes on your computer.

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 eight small filled boxes on the screen. These boxes should appear to be moving continuously and "bouncing" off the edges of the screen. 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.

Perform the following:

1. Write a C-language 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 is given in Figure 8 and provided in the file *part3.c*. The code sets the location in memory of *both* the front and back pixel buffers—the front buffer is set to the start of the FPGA on-chip memory (0xC8000000), and the back buffer to the starting address of the *SDRAM* memory (0xC0000000) that is included on the DE1-SoC.

   In each iteration of the while loop, the code removes from the screen any boxes and lines that have been drawn in the previous loop-iteration (note: if you clear the entire screen, rather than just "erasing" the boxes and lines that are currently visible, you may find that your animation runs more slowly than expected), then draws new 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, run and debug your code.

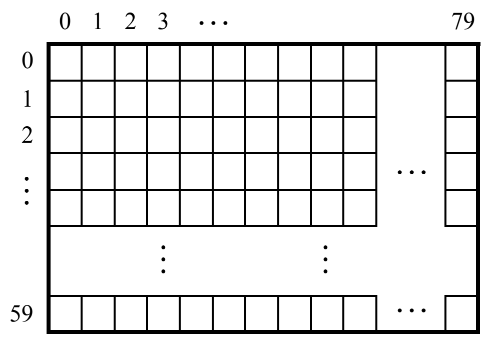
3. Experiment with your code by modifying it to use just a single pixel buffer (simply change the address of the back buffer to be the same as the front buffer). Explain what you see in the `VGA pixel buffer` subwindow as a result of this change.

```
volatile int pixel_buffer_start; // global variable

int main(void)
{
    volatile int * pixel_ctrl_ptr = (int *)0xFF203020;
    // declare other variables(not shown)
    // initialize location and direction of rectangles(not shown)

    /* set front pixel buffer to start of FPGA On-chip memory */
    *(pixel_ctrl_ptr + 1) = 0xC8000000; // first store the address in the
                                        // back buffer
    /* now, swap the front/back buffers, to set the front buffer location */
    wait_for_vsync();
    /* initialize a pointer to the pixel buffer, used by drawing functions */
    pixel_buffer_start = *pixel_ctrl_ptr;
    clear_screen(); // pixel_buffer_start points to the pixel buffer
    /* set back pixel buffer to start of SDRAM memory */
    *(pixel_ctrl_ptr + 1) = 0xC0000000;
    pixel_buffer_start = *(pixel_ctrl_ptr + 1); // we draw on the back buffer
    clear_screen(); // pixel_buffer_start points to the pixel buffer

    while (1)
    {
        /* Erase any boxes and lines that were drawn in the last iteration */
        ...

        // code for drawing the boxes and lines (not shown)
        // code for updating the locations of boxes (not shown)

        wait_for_vsync(); // swap front and back buffers on VGA vertical sync
        pixel_buffer_start = *(pixel_ctrl_ptr + 1); // new back buffer
    }
}

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

Figure 8: Main program for Part III.

Appendix

As we mentioned earlier, on a DE1-SoC board the image displayed by the VGA controller is based on the data in the pixel buffer, which displays graphics. But there is also a *character* buffer, which makes it easy to display text. This information may come in handy for the project in this course. The character buffer is stored in FPGA on-chip memory in the DE1-SoC Computer. Figure 9a depicts the character buffer for the VGA display, which has a resolution of 80 $\times$ 60 characters. Each character occupies an 8 $\times$ 8 block of pixels on the screen. Characters are stored in each of the locations shown in Figure 9a using their ASCII codes; when you store an ASCII character into the buffer, a corresponding pattern of pixels is automatically generated and displayed using a built-in font. Part b of Figure 9 shows that characters are addressed in the memory by using the combination of a *base* address, which has the value $(\text{C9000000})_{16}$, and an *x,y* offset. Using this scheme, the character at coordinates $(0, 0)$ has the address $(\text{C9000000})_{16}$, $(1, 0)$ has the address *base* $+$ $(000000\ 0000001)_2$ = $(\text{C9000001})_{16}$, $(0, 1)$ has the address *base* $+$ $(000001\ 0000000)_2$ = $(\text{C9000080})_{16}$, and the character at location $(79, 59)$ has the address *base* $+$ $(111011\ 1001111)_2$ = $(\text{C9001DCF})_{16}$.



(a) Character buffer coordinates

31 ... 13	12 ... 7	6 ... 0
1100100100000000000	y	x

(b) Character buffer addresses

Figure 9: Character buffer coordinates and addresses.

The character buffer has an associated controller, with a register interface like the one shown in Figure 3. This controller has the base address `0xFF203030`. You can read from the *Resolution* register to obtain the number of text columns (X) and rows (Y) on the screen. For the VGA screen, the values will be 80 columns $\times$ 60 rows.