The Final Report for FPGA Cat Invaders

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Spring 2024

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1 Introduction

This final report will describe the hardware and software details for implementing FPGA Cat Invaders, a game based on the classic Space Invader arcade game [1] with appearance and gaming control variations.

The FPGA Cat Invader game storyline goes as follows, the cats have invaded and our hero the poodle is defending Earth. The poodle launches a femur bone projectile and barks at the incoming cat enemies, and while this happens, the cats are launching mice back at the poodle. In the event the femur bone collides with an enemy the enemy lets out a meow and disappears. If the poodle collides with the mouse, the poodle loses a life. The cats are lined up at the top of the screen in a matrix of 9x5, and their movement pattern shifts right until at the wall, shifts down one slot, shifts left until at the wall, shifts down, shifts right. The level is completed when all the cats on screen have been eliminated and the game is over if the poodle loses three lives. The game's difficulty is controlled by the speed of cat movement and the rate of mice being launched at the poodle, as the levels progress the cats are faster and launch mice more frequently.

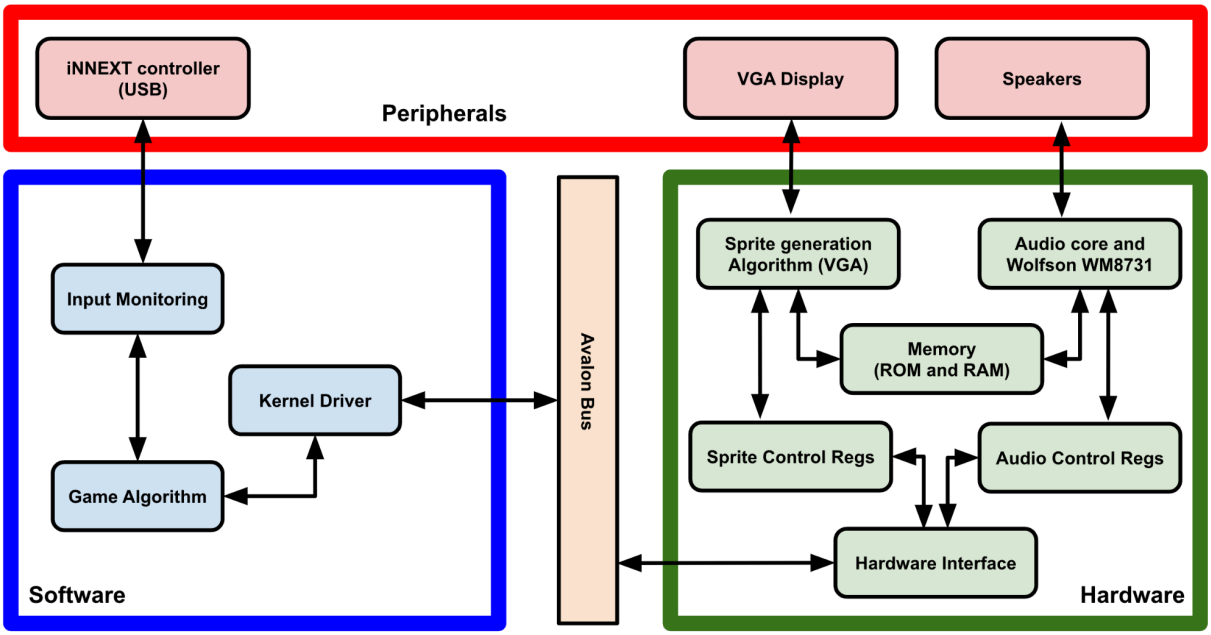
The game is played through a combination of hardware, software, and peripherals. The player uses an iNNEXT controller (Figure 10) to control the movement of the poodle and launch the femur bones. The game is displayed through a VGA monitor and the audio is played through mono speakers. The game algorithm runs in software, monitoring inputs from the iNNEXT controller and communicating with the FPGA hardware registers through the Avalon Bus [7]. The FPGA hardware is responsible for outputting the video to the VGA monitor and the audio to the mono speakers.

This final report is divided into sections that cover the details of the FPGA Cat Invaders system architecture. See the Table of Contents on page 1 for further information.

2 Block Diagram

The architecture of the FPGA Cat Invaders game is organized into three main categories, peripherals, software, and hardware. Figure 1 is the high-level block diagram of the overall hardware/peripheral/software system. The iNNEXT controller will be communicating both input and output commands/responses using USB to the software system. A software control loop will be running that will make all algorithm decisions for the FPGA Cat Invader game. This software will communicate through the kernel, over the Avalon bus, to both the VGA hardware algorithm and Audio hardware algorithm. The hardware process through internal algorithms and output to the VGA monitor peripheral and speaker peripheral.

Figure 1: Block Diagram describing the software and hardware at a high level.

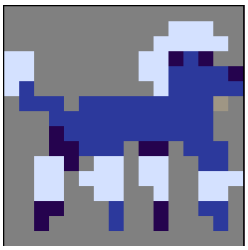
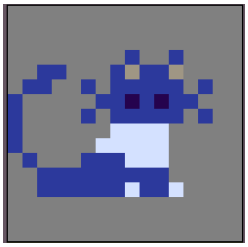


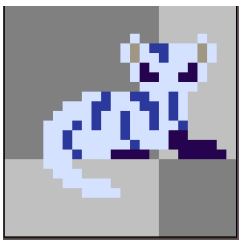
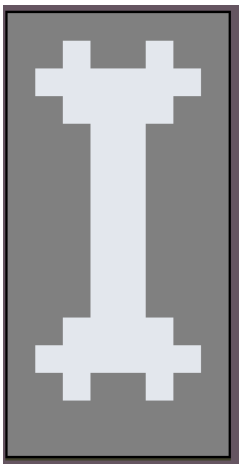
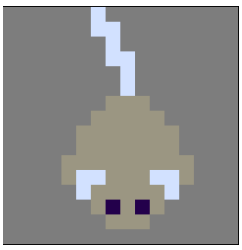
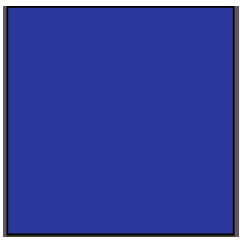
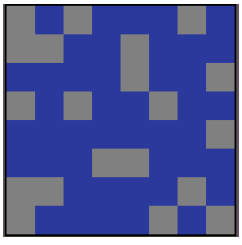
3 Resource Budget

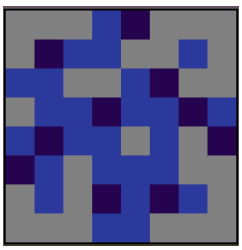
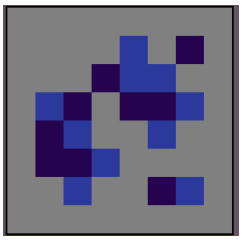
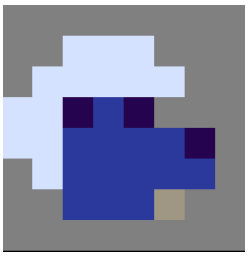
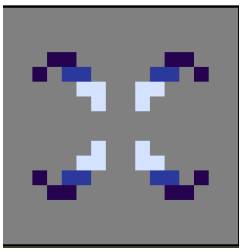
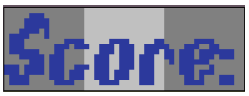
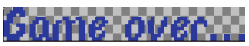
The DE1-SoC has 256 KB of BRAM organized as 64K x 32 bits on the DE1_SoC FPGA [3]. See Table 1 and 2 below for the sprites and audio being included in this project and the memory required for each. The sprites and audio will be stored in the FPGA read-only memory (ROM) in mif format [8]. In our ROM, image pixels are stored as 8-bit binary numbers. The highest three bits are the R data, the middle three bits are the G data, and the lowest two bits are the B data. When used as 24-bit RGB input for VGA, the R/G/B data are respectively shifted left by 5,

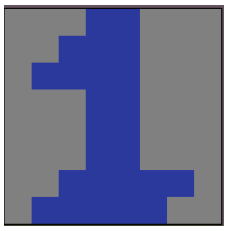
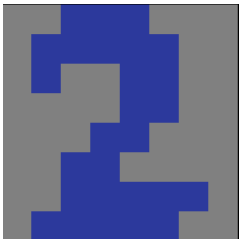
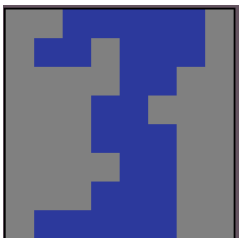
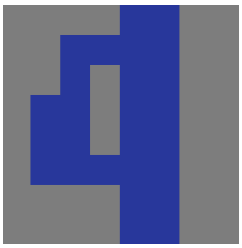
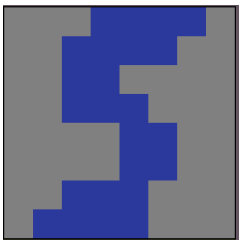
5, and 6 bits. Using this method, we are able to significantly reduce the amount of memory occupied by the image. All sprites and audio will fit ROM/RAM based on these calculations.

Table 1: Table organizing memory required per sprite and total amount of memory required.

Name	Sprite	Size (bits)	Color (bits)	# of Frames	Total Size (bits)
Poodle		32 x 32	8	10	81920
Cat 1		32 x 32	8	2	16384
Cat 2		32 x 32	8	2	16384
Cat 3		32 x 32	8	2	16384
Cat 4		32 x 32	8	2	16384

Mystery		48 x 48	8	2	36864
Projectile (femur bone)		8 x 24	8	1	1536
Projectile (mouse)		8 x 16	8	1	1024
Barriers - solid		16 x 16	8	1	2048
Barrier - damaged 1		16 x 16	8	1	2048

Barrier - damaged 2		16 x 16	8	1	2048
Barrier - damaged 3		16 x 16	8	1	2048
Lives		32 x 32	8	1	8192
Explosion		32 x 32	8	2	16384
Level (text)		96 x 32	8	1	24576
Score (text)		96 x 32	8	1	24576
Start (text)		144 x 48	8	1	55296
Game Over (text)		196x 28	8	1	43904

0 (text)		32 x 32	8	1	8192
1 (text)		32 x 32	8	1	8192
2 (text)		32 x 32	8	1	8192
3 (text)		32 x 32	8	1	8192
4 (text)		32 x 32	8	1	8192
5 (text)		32 x 32	8	1	8192

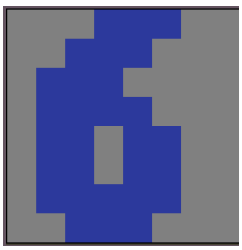
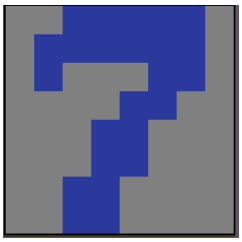
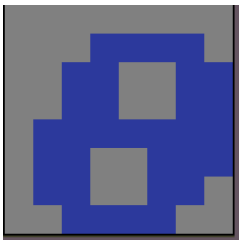
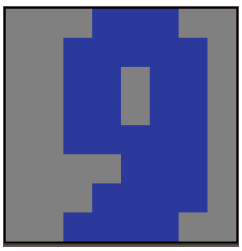
6 (text)		32 x 32	8	1	8192
7 (text)		32 x 32	8	1	8192
8 (text)		32 x 32	8	1	8192
9 (text)		32 x 32	8	1	8192
Total Size (bits) (KiloBytes)					449920 (54.9 KB)

Table 2: Table organizing memory required per audio and the total amount of memory required.

Name	Size (bits)	Total Size (bits)
Bark	4097 x 16	65552
Meow	6178 x 16	98848
Background music	35644 x 16	832224
Total Size (bits) (KiloBytes)		734704 (89.7 KB)

Table 3: Table organizing memory required per RAM and the total amount of memory required.

Name	Size (bits)	Total Size (bits)
Barrier	24 x 8	192
Cat	55 x 8	440
Total Size (bits) (Bytes)		79 B

4 Algorithms

Function Descriptions:

init_cat_matrix() - Initializes the cat matrix with random cats.
controller_init() - Finds a connected controller and initializes it in software.
init_driver() - Opens the file descriptor for the Cat Invaders interface.
reset_barrier_matrix() - Resets each individual barrier to its solid, undamaged state.
reset_objects() - Resets all positions and visibilities to their default state. In addition, resets the timer used for the mystery and logic used for projectiles.
play_background() - Begins the playing of the background music.
check_all_eliminated() - Checks if all of the cats have been eliminated by the player. If they have, the player advances a level, retaining their lives.
bone_collision() - Checks for collisions between the bone and barriers, cats, and the mystery using Axis Aligned Bounding Boxes (AABB). If a collision is detected, then the bone is despawned and interacts with the collided object. Colliding with or mystery would eliminate them, and collisions with barriers updates their state.
mouse_collision() - Checks for collisions between the mouse and the barriers and dog using Axis Aligned Bounding Boxes (AABB). If a collision is detected with the player, then the player loses a life. If the mouse collides with the barrier, then the barrier updates its state. The mouse despawns on impact.
move_cats() - Moves the cat array. The cat initially moves right until it hits the edge of the screen. When the cats hit the edge of the screen, they move down and change direction.
animate_cats() - Changes the cat frames on a fixed interval to simulate animation.
move_player() - Moves the player in response to the joypad input. The player would move left or right corresponding to the button held on the joypad. If the player reaches the edge, then the plate will not move past it.
animate_player() - Changes the player's animation frames according to their state. If the player is walking, then the player cycles through the walk animations. Otherwise, if they are not moving, then the player idles. The player has animations in both directions.
fire_cat_projectile() - Spawns a mouse at a random cat left in the matrix. May spawn up to 3 mice at once until a mouse must despawn before another is fired.

move_cat_projectile() - Moves the mouse downward, maintaining its horizontal position. If the projectile moves past the dog without colliding, it is despawned.
update_dog_projectile() - Spawns a bone whenever the player presses 'A' and there is not currently a bone on screen. If a bone has been fired, then it is moved upwards periodically until it either collides or reaches the top of the screen, in which case it is despawned.
set_score() - Updates the score, a representation of how many cats and mysteries have been eliminated.
reached_bottom() - Determines if the cats have reached the bottom of the screen. If there is at least one cat that makes it to the bottom of the screen, then the player loses all of their lives.
check_lives() - Checks if the player lost all of their lives. If the player has, then a 'Game Over' is displayed. The player may play again starting from Level 1 by pressing 'Start.'
set_status() - Sets the status of the game, whether there is a Game Over or the player is still alive.
spawn_mystery() - Spawns the mystery according to a random timer. The timer may range from 20 seconds to 30 seconds. On timeout, the mystery is spawned at an initial position.
update_mystery() - Moves the mystery if it is spawned. Moves rightward with a fixed vertical position. Despawns the mystery if it reaches the left end of the screen.

Figure 2: Pseudocode of the software algorithm for the FPGA Cat Invaders game.

```
C/C++
Game {
        Cat cats[][]; // All of the cats that are currently on screen.
        Poodle player; // The poodle that the player moves.
        int level = 1; // The current level that the player is on.
        int lives = 3; // The number of lives that the player currently has.

        init_cat_matrix();

        controller_init();
        init_driver();

        reset_barrier_matrix();
        reset_objects();
        play_background();


        while (true) {
                // 1. Check if all of the cats have been eliminated
               check_all_eliminated();

               // 2. Check for player collisions (mouse)
               bone_collision();

               // 3. Check for cat collisions (bone)
               mouse_collision();

               // 4. Move the cats (including animations)
                move_cats();
               animate_cats();
```

```
                // 5. Move the player (including animations)
                move_player();
                animate_player();

                // 6. Fire (if applicable) and move cat projectiles
                 fire_cat_projectile();
                move_cat_projectile();

                // 7. Fire (if applicable) and move player projectile
                update_bone_projectile();

                // 8. Update score
                set_score();

                // 9. Check if cats reached the bottom
                reached_bottom();

                // 10. Update status
                check_lives();
                set_status();

                // 11. Update the mystery
                spawn_mystery();
                update_mystery();

        }
}
```

5 The Hardware/Software Interface

Control Registers:

The hardware and software will communicate bidirectionally in 2 byte (16bit) chunks over the Avalon Bus. Tables 3-6 below describe the registers the software and hardware can read and write to. These registers contain movement and visibility information for the sprites. Table 7 describes what each field in the audio registers represent.
Some audio notes:

- Volume: Writing a 15 sets the volume to 0; writing a 0 sets the volume to 15
- Speed: Numbers should between 0 and 6
- Play:
    - When set to 1 Background music will play continuously, 0 will turn it off
    - Bark and Meow will play once. To play Bark or Meow multiple times write a 0 to reset and then a 1.

Table 8 below contains the registers available for reading. The test_reg contains a value to ensure that reads are enabled. The frame_reg contains the current frame count for software hardware synchronization.

Table 3: Register contains - Dog position, and projectile position and visibility.

Register #	Register Name	R/W	Bit description		
			[15:0]		
0	dog_pos_x	R/W	Reserved [5:0]		Dog Position X [9:0]
1	project_d_x	R/W	Reserved [5:0]		Projectile Dog X [9:0]
2	project_d_y	R/W	Dog Bullet visible?	Reserved [4:0]	Projectile Dog Y [9:0]
3	project_c0_x	R/W	Reserved [5:0]		Projectile Cat0 X [9:0]
4	project_c0_y	R/W	Cat0 Bullet visible?	Reserved [4:0]	Projectile Cat0 Y [9:0]
5	project_c1_x	R/W	Reserved [5:0]		Projectile Cat1 X [9:0]
6	project_c1_y	R/W	Cat1 Bullet visible?	Reserved [4:0]	Projectile Cat1 Y [9:0]
7	project_c2_x	R/W	Reserved [5:0]		Projectile Cat2 X [9:0]
8	project_c2_y	R/W	Cat2 Bullet visible?	Reserved [4:0]	Projectile Cat2 Y [9:0]
9	project_c3_x	R/W	Reserved [5:0]		Projectile Cat3 X [9:0]
10	project_c3_y	R/W	Cat3 Bullet visible?	Reserved [4:0]	Projectile Cat3 Y [9:0]

Table 4: Register category - Cat array position, and mystery position

Register #	Register Name	R/W	Bit description		
			[15:0]		
11	cat_array_pos_x	R/W	Reserved [5:0]		Cat Array Position X [9:0]
12	cat_array_pos_y	R/W	Reserved [5:0]		Cat Array Position Y [9:0]
13	mystery_pos_x	R/W	Visibility?	Reserved [4:0]	Mystery Position X [9:0]

Table 5: Register category - Miscellaneous

Register #	Register Name	R/W	Bit description			
			[15:0]			
14	status	R/W	Reserved [7:0]	Level [3:0]	Game Status [1:0]	Life [1:0]
15	score	R/W	Score [15:0]			
16	dog_ani	R/W	Reserved [11:0]	Dog Animation State [3:0]		
17	cat_ani	R/W	Reserved [14:0]	Cat Animation State		

Table 6: RAM category - barrier and cat matrix

Register #	Register Name	R/W	Bit description	
			[7:3]	[2:0]
28	Barrier Matrix	R/W	Address (0 to 23)	Value (0 to 5)
29	Cat Matrix	R/W	Address (0 to 55)	Value (0 to 5)

Table 7: Audio register map

Register #	Register Name	R/W	Bit description			
			[15:6]	5	4	3..0
42	Background Music	R/W	Reserved	Play	Reserved	Volume
43	Meow	R/W	Reserved	Play	Reserved	Volume
44	Bark	R/W	Reserved	Play	Reserved	Volume
45	Speed	R/W	Reserved			Speed

Table 8: Test and Frame registers

Register #	Register Name	R/W	Bit description	
			[15]	[14:0]
48	Test Reg	R	Return test value of D065	
49	Frame Reg	R/W	Frame Active	Frame Count

Polling and Interrupt:

In order to make sure the writing operation of the registers did not interfere with the refresh of the screen we added a register to poll. This method would prevent ghosting, a trail of phantom pixels trailing the sprites. Originally we had planned to implement an interrupt, which is basically a signal generated from the hardware every time the frame updates are complete. However, through reading the documentation and testing we were unable to configure the Global Interrupt Controller (GIC) on the Arm processor to accept the hardware interrupt. Instead we turned towards using the aforementioned polling to provide this synchronization rather than an interrupt. The idea of polling was, on the hardware side, to use one register to store both the active frame bit signal and a frame counter. In the middle of the frame the active frame bit is 1, and outside it is 0. Additionally, once every frame the frame counter is incremented by 1. On the software side, there is a while loop querying this register and comparing it to the previous value. If not equal the software is safe to write to registers on the hardware. This technique ensures the writing and screen refreshing work synchronized.

Cat Matrix:

In the game, all cats are displayed and moved in the form of a matrix. It is controlled by a coordinate that indicates the position of its upper left corner, and an array of display states for the cat matrix. The coordinate is stored in control registers, while the display statuses are stored in a consecutive RAM space named Cat Matrix RAM. Both controlled through software. For each position in the matrix there is an 8 bit display state word that tells the hardware what to display.

Table.9: Matrix states value and display content

Cat States	8'd0	8'd1	8'd2	8'd3	8'd4	8'd5
Display Content	Nothing	Cat1	Cat2	Cat3	Cat4	Explosion

Table.9 shows the correspondence between the value of cat states and display content in a particular position. If the cat state is 0, it means the cat at that position has been destroyed and should display nothing. If catstatus ranges from 1-4, one of the four kinds of cats (stored in four separate ROMs) should be fetched from the image ROM and displayed. Status being 5 means the cat at that position was just hit by a dog projectile and should display the explosion image.

Barrier Matrix:

Similar to cat matrix, the barriers are also displayed as a matrix and are managed through an array of damage rate stored in a consecutive RAM space named Barrier Matrix RAM. Since the barriers do not move, no control registers are needed to control their positions. There are 4

barriers, and each barrier consists of 12 barrier blocks. For each barrier block, there is an 8 bit word that represents the damage rate from 0 to 4, where damage rate 0 means the block is undamaged and damage rate 4 means the block is fully damaged and no longer exists. The barrier block has 4 images in the same ROM with different offsets, representing 4 damage rates. The hardware will choose which image to display based on the damage rates in the Barrier Matrix RAM.

Movement Control:

In the game, movable objects are dog, cat matrix, mystery and projectiles, in which dog and mystery can only move in one direction and cat matrix and projectiles can move in all directions. Movable objects have either X or both XY coordinates stored in the control registers. During the game, software can make them move by constantly changing the coordinates of the objects.

Visibility:

Besides movement, the control registers also control the visibility of objects. For projectile and mystery, the MSB of their coordinate registers are used to control their visibility. And for life, barrier and cat matrix, visibility is controlled in their own state register/RAM. Pixel selector will omit the objects if they are turned invisible.

Numbers:

The numbers were stored in ROM and displayed for the level and the score. The software converted the decimal numbers into 4 bit binary coded decimal numbers and wrote these values to registers. The hardware used these bits to draw the correct number to the screen from the ROM.

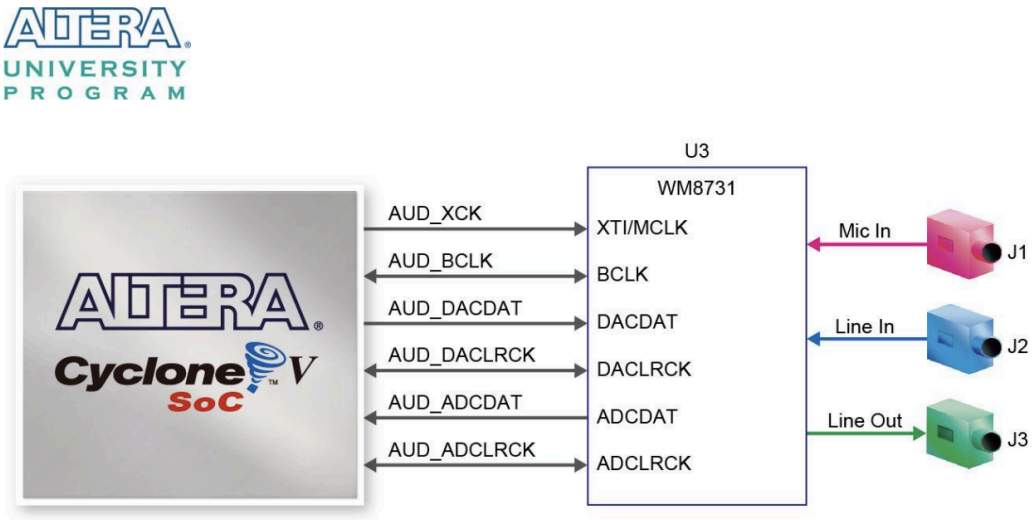
Userspace/Kernel interface:

In order to make userspace communicate with the hw through the kernel conveniently, we created an interface between the userspace and the kernel, and translated the writing register operation into user friendly functions, like setting the position of the dog, setting the statue of the cat matrix and barrier, set the score number(do the decimal to binary) and so on. In the interface, not only do the kernel command calling, but also deal with the data that need to be reformulated or shifted to the right position, some of them also need to be combined together, and the header of the interface is shown in the code below.

6 Audio Interface

The FPGA Cat Invader games will output background music and sound effects. The DE1-SoC contains a Wolfson WM8731 audio CODEC [4] for handling 24-bit audio. Figure 3 shows the WM8731 physical connections to the rest of the FPGA as well as the Mic in, Line-in In, and Line-out jacks for microphone input and speaker output. The audio CODEC settings are adjustable supporting a range of 8ks/s to 96 ks/s sample rates for both the ADC and DAC, for this project the sample rate will be set to 8ks/s for both the ADC and DAC. This sample rate was chosen to keep the overall memory footprint of the audio small without sacrificing the overall quality of the sound.

Figure 3: Wolfsom WM8731 connection to the FPGA (image source [4]).



The ALTERA University Program provides two Intellectual Property (IP) blocks of use for the control of the audio. Figure 4 is a high-level block diagram of the Audio/Video Configuration core IP block which handles the configuration and control of both Audio and Video. This core will be used for the overall configuration of the onboard audio control and datapath through the Avalon Bus. Figure 5 is the Audio core block which handles the input and output of audio through the Wolfson WM8731 audio CODEC. For this project, the IP will be set to Memory-Mapped Interface. As seen in Figure 5 the IP supports both input (Deserializer) and output, however for this project only the output path will be configured for use.

Additionally, the IP supports both right and left audio output, the same sample will be fed into both channels. Lastly, the FIFO has synchronization feedback to control the flow of the data into the FIFOs, if the FIFO reports it is filled the overall audio pipeline will halt until space has been freed up.

Figure 4: Block diagram for Audio and Video core (image source [6]).

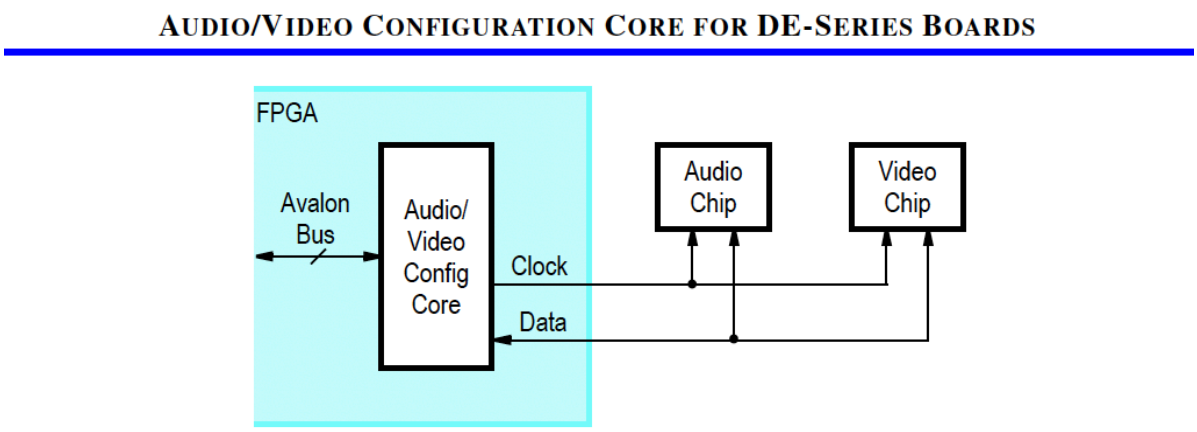
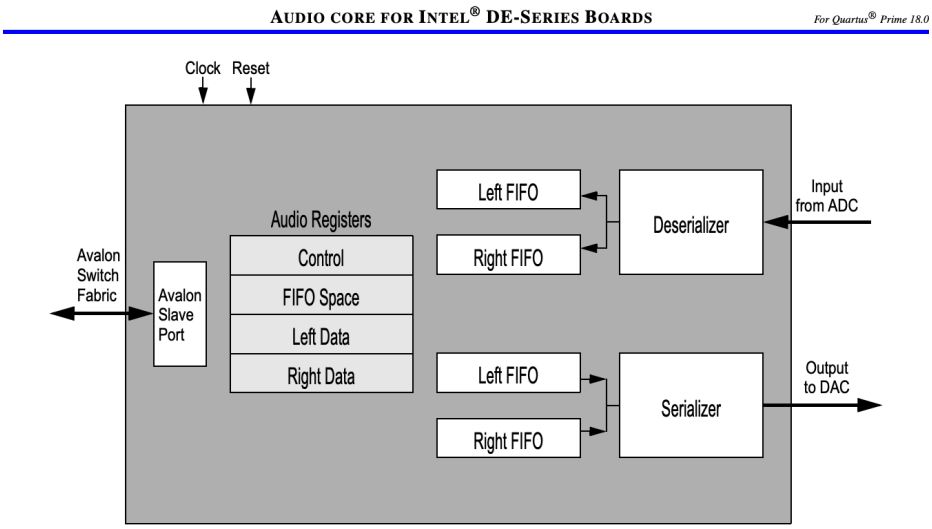


Figure 5: Block diagram for Audio core with Memory-Mapped Interface (image source [5]).



To facilitate multiple audio clips played together simultaneously the audio will first be divided by a power of two based on the volume set for that clip (0 to 15). After reducing the amplitude the clips will be added together and placed in the audio core's left and right fifo.

In summary, the overall flow of the audio is as follows:

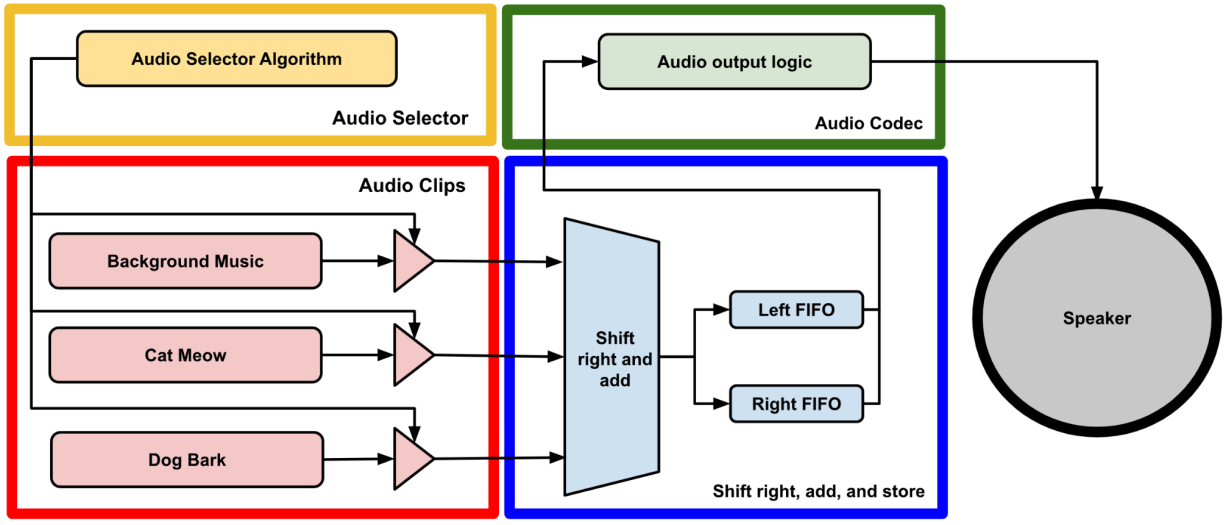
1. On FPGA boot-up the Audio IP core is configured to the preset configuration.
2. The software writes to one of the audio registers with the play bit to 1.
3. The FPGA reads the sample from ROM (one at a time starting at offset 0) and copies the value into the left data of the audio core IP. If more than one audio sample is being played the samples will be added together and played through the speaker.
4. The audio core outputs the 8kHz sample and outputs 48kHz (due to the chosen phase lock loop (PLL) clock frequency). If the number of samples has been reached:

- If the loop value is 0 the FPGA will stop playing the audio.
- If the loop value is 1 the FPGA will start at the top and copy samples from offset 0.

The audio registers support both a speed and volume register. These were mainly used for debugging purposes to determine the optimal volume and speed settings for each audio clip. Speed control works by setting a number (in the register) that dictates how many times the same audio sample should be repeatedly loaded into the audio FIFOs. Volume control was implemented by using a signed right shift (shift for 0 to 15). In the end the speed register was hardcoded to a value of 2 and volume was hardcoded to 0.

Figure 6 below shows the high level implementation for the audio hardware. The audio clips are the audio mif files stored in Read Only Memory (ROM). The Audio Selector algorithm will decide based on the speed control if the ROM will be incremented to the next address or output the duplicate sample. Additionally, this logic decides which of the clips will be fed into shift and add logic before reaching the Left and Right FIFO. The Audio output logic containing the Audio IP and Codec takes the supplied samples and outputs them to the speaker.

Figure 6: Flowchart of audio implementation.



7 Video Display

For basic image display, we use logic similar to that in lab3. When hcount and vcount scan to a specific area, we read the corresponding image pixel data from the ROM and perform the aforementioned RGB bit-shifting expansion before using it as VGA input.

Among all the images, the cat matrix, explosion, poodle, bone, mouse, and mystery are movable. They need to receive starting coordinate information (for the top-left pixel) from the ctrl_reg, which is sent by the software. The remaining images such as barriers, numbers, scores, and lives are set in fixed positions on the hardware side.

We have added animation effects for cats and poodles by emitting animation state signals through the software-side control logic. The hardware side receives these signals and selects which image from the ROM to display based on the state. Through rapid state switching, the hardware can quickly switch between different images to achieve the effect of animation.
The FPGA Cat Invader games will output the game to a VGA monitor. In order to accomplish this, the onboard the DE1-SoC FPGA produces the synchronization and red, green, blue (RGB) signals through the ADV7123 DAC and out a 15-pin D-SUB connector. Additionally, the circuit is capable of supporting up to 1280x1024 at 100MHz. For this project the display monitor will output 640x480 resolution. Figure 7 shows the signals connected between the FPGA and ADV7123 VGA DAC [3].

Figure 7: Connections between the FPGA and VGA(image source [3]).

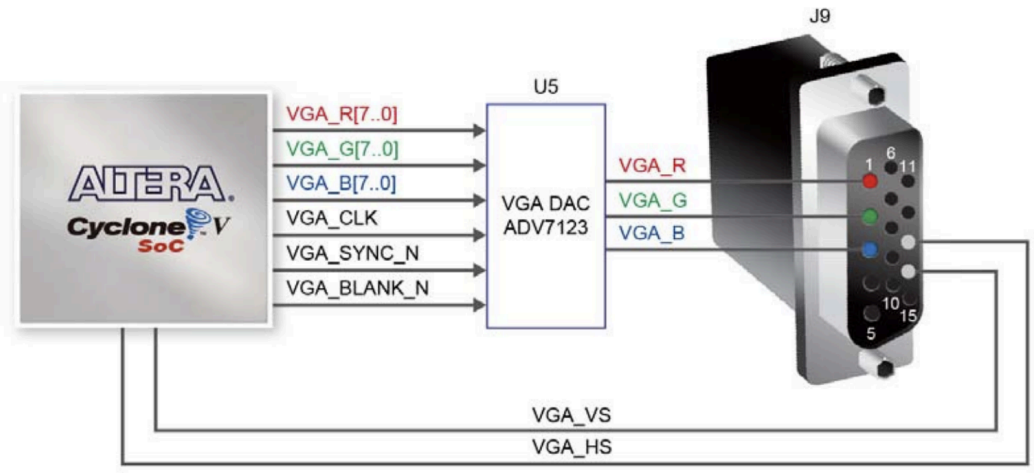
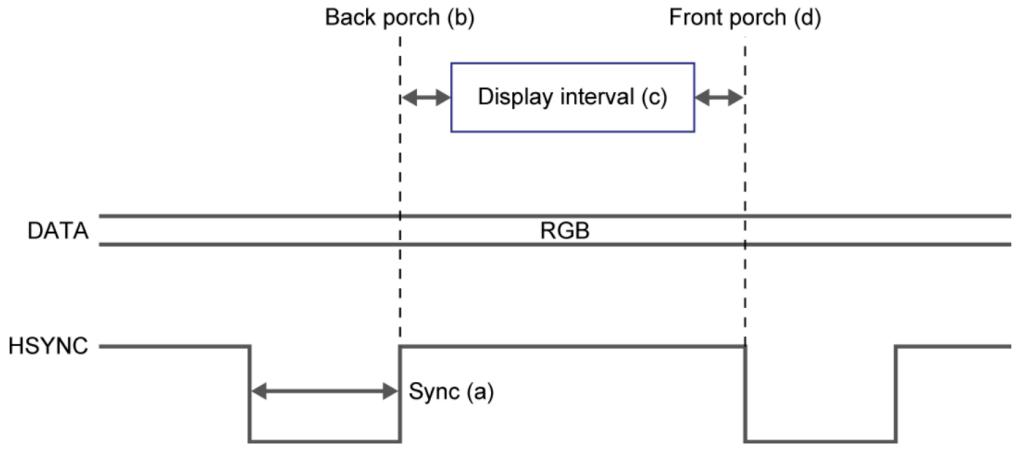


Figure 8 outlines the key timing for displaying a row on a VGA screen. An active-low hsync pulse indicates the end of one row and the start of the next. After this pulse, the RGB data must be off during the back porch, then on during the display interval as pixels are activated across the row. The RGB is off again during the front porch before the next hsync pulse. Vsync timing is similar but marks the end and start of entire frames, not just rows [3].

Figure 8: VGA horizontal timing specification(image source [3]).

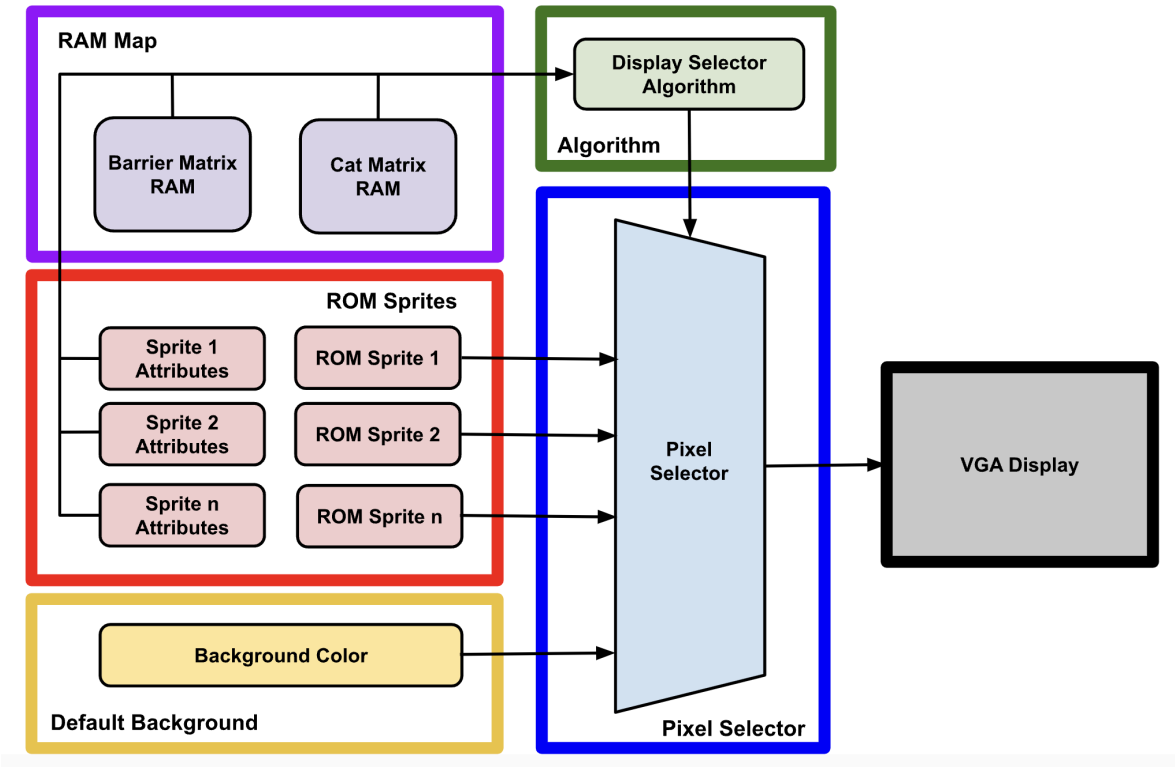


Display Hardware Architecture:

Figure 9 shows the overall hardware architecture of the display. All pixel information is stored in separate ROMs and will be read out one pixel every VGA cycle. During the game, ROM address generation and pixel selection works in parallel to ensure that pixels are displayed correctly right after they are read from the ROMs.

On the address generation side, the next address of each ROM is decided according to the current hcount & vcount, current ROM address, visibility and other important factors such as the states of barrier and cat matrix. On the pixel selection side, pixel data from every ROM will be sorted by priority and decide which pixel to put on the screen in this cycle.

Figure 9: Block diagram of hardware display architecture



As an example, the following code demonstrates the address generation and pixel selection logic of mystery. The address generation logic is designed like a counter that is enabled when hcount and vcount enter the display region of the mystery. As for the pixel selection logic, it can be seen that all objects are put in the cascade of if-else statements, which functions as pixel selector. This mechanism can ensure that when two objects overlap, only the object with higher priority will be displayed.

```
always_ff @(posedge clk)begin
……
   if(~hcount[0]) begin
      if (hcount[10:1]>= mystery_pos_x && hcount[10:1]<(mystery_pos_x+48)
          && vcount>=mystery_pos_s_y && vcount<(mystery_pos_e_y)) begin
         if (hcount[10:1] == (mystery_pos_x+47)
              && vcount == (mystery_pos_e_y-1)) mystery_addr <= 0;
         else mystery_addr <= mystery_addr + 1;
      end
……
   end
end

……
```

```
always_comb begin
   {VGA_R, VGA_G, VGA_B} = {8'h0, 8'h0, 8'h0};
   if (VGA_BLANK_n )
   /* start */
      if (hcount[10:1]>=start_s_x && hcount[10:1]< start_e_x && vcount>=
          start_s_y && vcount< start_e_y && others_data != 8'd0 &&
          game_status == 2'b00)
         {VGA_R, VGA_G, VGA_B} = {{others_data[7:5], 5'd0},
                                  {others_data[4:2], 5'd0}, {others_data[1:0], 6'd0}} ;
……

   /* mystery */
      else if (hcount[10:1]>= mystery_pos_x && hcount[10:1]<
                (mystery_pos_x+48) && vcount>=mystery_pos_s_y &&
               vcount<(mystery_pos_e_y) && mystery_data != 8'd0)
         {VGA_R, VGA_G, VGA_B} = {{mystery_data[7:5], 5'd0},
                                 {mystery_data[4:2], 5'd0}, {mystery_data[1:0], 6'd0}};

……
   end
end
```

8 Memory

In this game, we use ROMs to store all pixel data, and we use RAMs for control purposes. The following tables show the memory contents and their address range.

ROM Layout:

Table 10: Cat 1 memory layout (ROM)

	Address range
Pose 1	0x0000 - 0x03FF
Pose 2	0x0400 - 0x07FF

Table 11: Cat 2 memory layout (ROM)

	Address range
Pose 1	0x0000 - 0x03FF
Pose 2	0x0400 - 0x07FF

Table 12: Cat 3 memory layout (ROM)

	Address range
Pose 1	0x0000 - 0x03FF
Pose 2	0x0400 - 0x07FF

Table 13: Cat 4 memory layout (ROM)

	Address range
Pose 1	0x0000 - 0x03FF
Pose 2	0x0400 - 0x07FF

Table 14: Poodle memory layout (ROM)

Poodle Pose	Address range
Pose 1	0x0000 - 0x03FF
Pose 2	0x0400 - 0x07FF
Pose 3	0x0800 - 0x0BFF
Pose 4	0x0C00 - 0x0FFF
Pose 5	0x1000 - 0x13FF
Pose 6	0x1400 - 0x17FF
Pose 7	0x1800 - 0x1BFF
Pose 8	0x1C00 - 0x1FFF
Pose 9	0x2000 - 0x23FF
Pose 10	0x2400 - 0x27FF

Table 15: Barrier memory layout (ROM)

Barrier state	Address range
Barrier 1	0x0000 - 0x00FF
Barrier 2	0x0100 - 0x01FF
Barrier 3	0x0200 - 0x02FF
Barrier 4	0x0300 - 0x03FF

Table 16: Mystery ROM

	address range
Pose 1	0x0000 - 0x08FF
Pose 2	0x0900 - 0x11FF

Table 17: Bone ROM

	address range
Pose 1	0x0000 - 0x00C0

Table 18: Number memory layout (ROM)

Number	Address range
0	0x0000 - 0x03FF
1	0x0400 - 0x07FF
2	0x0800 - 0x0BFF
3	0x0C00 - 0x0FFF
4	0x1000 - 0x13FF
5	0x1400 - 0x17FF
6	0x1800 - 0x1BFF
7	0x1C00 - 0x1FFF
8	0x2000 - 0x23FF
9	0x2400 - 0x27FF

Table 19: Others ROM

Other	Address range
explode	0x0000 - 0x03FF
level	0x0400 - 0x0FFF
Life	0x1000 - 0x13FF
mouse	0x1400 - 0x147F
score	0x1480 - 0x207F
start	0x2080 - 0x3B7F

Table 20: Background ROM

Audio Clip	Address range
Background Music	0x0000 - 0x8B3C

Table 21: Cat Meow ROM

Audio Clip	Address range
Cat meow	0x0000 - 0x1822

Table 22: Dog Bark ROM

Audio Clip	Address range
Dog Bark	0x0000 - 0x1001

RAM Layout:

Table 23: Barrier Matrix RAM

	Address range
Barrier Matrix	0x0000 - 0x0018

Table 24: Cat Matrix RAM

	Address range
Cat Matrix	0x0000 - 0x0037

We categorize images and audios by type and store them in different ROMs. We first created the audio mifs by modifying 365-audio-tools wavToMif.py [15] python script and the sprite mifs with by modifying Nananas, ImageToMIf python script [14]. We merge mif files of the same category using a Python script, then use Qsys Platform Designer to create the corresponding IP core. Since a ROM often contains multiple mif files of images, we also generate an address map when creating the merged mif file. This facilitates reading different image data from the same ROM in the hardware display code.

9 Game Controller

The player will interact with the game using a iNNEXT joypad, which is shown in Figure 10. The controller sends and receives over the usb connection and the software uses the libusb library to communicate.

Figure 10: Image of iNNEXT Joypad.

The buttons on the joypad and their corresponding functions are shown in Table 25. In summary, there will be 4 buttons used in the whole game; the left and right arrows for moving the dog on the horizontal axis, the ‘start’ button for starting the game, and the ‘A’ button for attacking. When holding either the left or right arrows the dog will move repeatedly in the direction of the arrow until reaching the boundary. Similarly, holding the attack (‘A’) button will cause the dog to keep firing at a fixed interval.

Table 25: Buttons and corresponding functions.

Button	Function
Left arrow	Move Left
Right arrow	Move right
Start	Start the game
A	Attack

Just as the keyboard USB interface does, the joypad will be configured through libusb, which follows USB protocol. To be specific, the protocol message is 8 bytes for each event; some of the parameters are displayed in Table 26.

Table 26: Communication parameters of the device over libusb.

idvendor (VID)	0x0079
idProduct (PID)	0x0011
Packet size	1*8 bytes

The full detail of the communication protocol is demonstrated in the Table 27 below, including all the single button events and combo events which may happen in the game. When each button is pressed the value at the corresponding byte changes from its default value to the new value.

Table 27: Communication protocol packet definition of button presses over libusb.

Byte	0	1	2	3	4	5	6	7
default	01	7F	7F	7F	0F	00	002	202
A					2F			
B					4F			
X					1F			
Y					8F			
Up arrow				00				
Down arrow				FF				
Left arrow			00					
Right arrow			FF					
L2						01		
R2						02		
Start						20		
Select						10		
Left arrow + A			00		2F			
Right arrow +A			FF		2F			

10 Conclusion

The FPGA Cat Invaders game is a fully functional demo complete with all features described in this report. The cat matrix moved in the correct pattern and dropped mice, the poodle fired bones and eliminated the cats (+1 point) using the controller, a mystery sprite appeared at random intervals (+10 points), and all the music/sound clips played. In the end, the hardware and software worked together to make this game possible.

10.1 Challenges and Lesson learned

A lesson we learned is to always have a good debugging tool in hand. In our case, we did not make use of simulation and waveform display tools such as Verilator and GTKwave when debugging and validating our Verilog code. Instead we debug by loading the code to the FPGA everytime and see what shows up, which turned out to be very inefficient and slowed down our progress in hardware development.

Another lesson we learned is to budget all available resources carefully before implementing. We ran out of memories several times in the course of development due to the large audio files. Each time we have to reallocate the memory, which takes a lot of time.

Working on a team interfacing both hardware and software, it very quickly became apparent that cross referencing hardware implementation was extremely important when developing the software. Some hardware bugs may be less obvious only until a significant portion of software has been implemented, and at times it is easier to work with and try to correct the errors in software rather than trying to solve the issue in hardware.

Communication and coordination was also something that we began to get better at as time progressed. Scheduling meetings and discussing what has been done and what needed to be done became easier and more productive as the project progressed and we began to settle more comfortably as a group.

10.2 Contributions

Adam Jablonski: Responsible for audio section from generating the mifs to playing out of the speakers, barrier matrix with RAM implementation, hardware cleanup, software help, and project coordination.

Yuxiang Xia: Responsible for memory management, image ROM generation, display logic for movable images, image animation logic, and overall adjustment and optimization of hardware display.

Yilei Meng: Responsible for software kernel stuff, corresponding to the register table and enable the write data into the register; Programmed the interface for the software user space to use for each commands todo with the hardware; Enable the controller input through the usb protocol; Generated the display of top level signs including score, level and life in HW.

Zhili Yan: Responsible for display logic for cat matrix, specification and hardware implementation of control registers. Added movement and visibility control to the hardware display.

Fernandos Magee: Responsible for creating sprites and animations, generating MIFs for sprites with RGB 332 color mapping, and designing and implementation of software algorithms used in the final product's game logic.

10.3 Acknowledgement

We would like to thank Marc Jablonski, a New York City based sound designer for providing all the audio clips used in this project [9][10][11].

11 References

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Appendix A: Code

12.1 cat_invaders.sv

```
/*
 * Avalon memory-mapped peripheral that generates VGA
 *
 * Stephen A. Edwards
 * Columbia University
 */


module cat_invaders(input logic        clk,
            input logic         reset,


        input logic         left_channel_ready,
        input logic         right_channel_ready,


        input logic [15:0]  writedata,
        input logic         write,
        input           chipselect,
        input logic [7:0]   address,


        output logic [15:0] readdata,


        output logic [7:0]  VGA_R, VGA_G, VGA_B,
        output logic        VGA_CLK, VGA_HS, VGA_VS,
                            VGA_BLANK_n,
        output logic        VGA_SYNC_n,


        output logic        left_channel_valid,
        output logic        right_channel_valid,


        output logic [15:0] left_channel_data,
```

```
        output logic [15:0] right_channel_data,


                output logic        eof_irq


);
parameter CAT_SIZE = 32;
parameter CAT_MATRIX_SIZE_X = 352;
parameter CAT_MATRIX_SIZE_Y = 160;


/*****************************************
   Register Group #0
   Dog position; and projectile position and visibility
*****************************************/
     logic [3:0] cat_bullet;              //cat bullet in flight?
     logic       dog_bullet;              //dog bullet in flight?
     logic [9:0] dog_pos_x;               //dog position x
     logic [9:0] dog_project_x;           //dog bullet position x
     logic [9:0] dog_project_y;           //dog bullet position y
     logic [9:0] cat_project_x[3:0];      //cat 0~3 bullet position x
     logic [9:0] cat_project_y[3:0];      //cat 0~3 bullet position y
     logic [9:0] cat_array_pos_x;         //cat upper west corner position x
     logic [9:0] cat_array_pos_y;         //cat upper west corner position y
     logic [9:0] mystery_pos_x;           //mystery position
     logic       mystery_vis;         // mystery visible




/*****************************************
   Register Group #1
   Miscellaneous
*****************************************/
     logic [3:0]  level;           //game difficulty level 0~7
```

```
    logic [1:0]  game_status;     //game status (start, in process, game over)
    logic [1:0]  life;            //lives remaining 0~3
    logic [15:0] score;          //score
    logic [3:0]  dog_ani_state;
    logic        cat_ani_state;



ctrl_regs ctr_regs_0(.*);




   logic [10:0]    hcount;
   logic [9:0]     vcount;
   logic           irq;
   logic [14:0]    frame_cnt;
   logic           frame_active;

   logic [7:0]     background_r, background_g, background_b;
   logic play, play_cat, play_dog;
   logic [3:0]  vol, vol_cat, vol_dog;
   logic [3:0] delay;



   vga_counters counters(.clk50(clk), .*);

   audio_player audio(.clk50(clk), .*);



/*****************************************************************
display start
*****************************************************************/
```

```
logic [23:0] display_rgb;


logic [10:0] display_addr;


logic test;


logic [10:0] cat2_addr;
logic [10:0] cat3_addr;
logic [10:0] cat4_addr;
logic [10:0] explode_addr;
logic [15:0] poodle_addr;
logic [15:0] mystery_addr;
logic [15:0] barrier_addr;
logic [15:0] game_over_addr;
logic [15:0] num_addr;
logic [15:0] others_addr;
//logic [15:0] others_explosion_addr;
logic [15:0] cat_mat_addr;
logic [15:0] barrier_mat_addr;
logic [15:0] bone_addr;


logic [7:0] display_data;
logic [7:0] cat2_data;
logic [7:0] cat3_data;
logic [7:0] cat4_data;
logic [7:0] explode_data;
logic [7:0] poodle_data;
logic [7:0] mystery_data;
logic [7:0] barrier_data;
logic [7:0] game_over_data;
logic [7:0] num_data;
logic [7:0] others_data;
```

```
logic [7:0] cat_mat_data;
logic [7:0] barrier_mat_data;
logic [7:0] bone_data;

logic [7:0] output_data;

logic [15:0] cat_mat_s_x;
logic [15:0] cat_mat_s_y;

logic [15:0] cat_mat_e_x;
logic [15:0] cat_mat_e_y;

//////////////////////////mouse
logic [15:0] mouse1_s_x;
logic [15:0] mouse1_s_y;

logic [15:0] mouse1_e_x;
logic [15:0] mouse1_e_y;

logic [15:0] mouse2_s_x;
logic [15:0] mouse2_s_y;

logic [15:0] mouse2_e_x;
logic [15:0] mouse2_e_y;

logic [15:0] mouse3_s_x;
logic [15:0] mouse3_s_y;

logic [15:0] mouse3_e_x;
logic [15:0] mouse3_e_y;

//////////////////////////
```

```
//bone


logic [15:0] bone_s_x;

logic [15:0] bone_s_y;


logic [15:0] bone_e_x;

logic [15:0] bone_e_y;


//

logic [4:1] ccc;


logic b_write;

logic b_cs;

logic [17:0] b_write_addr;

logic [15:0] b_writedata;




logic c_write;

logic c_cs;

logic [17:0] c_write_addr;

logic [15:0] c_writedata;




soc_system_ROM_cat_1 cat_display(.address(display_addr), .clk(clk), .clken(1),
.reset(reset), .reset_req(0), .readdata(display_data));

soc_system_ROM_cat_2 cat2_display(.address(cat2_addr), .clk(clk), .clken(1),
.reset(reset), .reset_req(0), .readdata(cat2_data));

soc_system_ROM_cat_3 cat3_display(.address(cat3_addr), .clk(clk), .clken(1),
.reset(reset), .reset_req(0), .readdata(cat3_data));

soc_system_ROM_cat_4 cat4_display(.address(cat4_addr), .clk(clk), .clken(1),
.reset(reset), .reset_req(0), .readdata(cat4_data));

soc_system_ROM_explode explode_display(.address(explode_addr), .clk(clk), .clken(1),
.reset(reset), .reset_req(0), .readdata(explode_data));

soc_system_cat_matrix cat_mat_display(.address(cat_mat_addr), .address2(c_write_addr),
.chipselect2(c_cs), .clk(clk), .clken(1), .clken2(1), .reset(reset), .reset_req(0),
.write2(c_write), .writedata2(c_writedata), .readdata(cat_mat_data));
```

```
soc_system_ROM_Poodles poodle_display(.address(poodle_addr), .clk(clk), .clken(1),
.reset(reset), .reset_req(0), .readdata(poodle_data));

soc_system_ROM_mystery mystery_display(.address(mystery_addr), .clk(clk), .clken(1),
.reset(reset), .reset_req(0), .readdata(mystery_data));



soc_system_ROM_barrier barrier_display(.address(barrier_addr), .clk(clk), .clken(1),
.reset(reset), .reset_req(0), .readdata(barrier_data));

soc_system_barrier_matrix barrier_mat(.address(barrier_mat_addr),
.address2(b_write_addr), .chipselect2(b_cs), .clk(clk), .clken(1), .clken2(1),
.reset(reset), .reset_req(0), .write2(b_write), .writedata2(b_writedata),
.readdata(barrier_mat_data));



soc_system_ROM_game_over game_over_display(.address(game_over_addr), .clk(clk),
.clken(1), .reset(reset), .reset_req(0), .readdata(game_over_data));



soc_system_ROM_num num_display(.address(num_addr), .clk(clk), .clken(1),
.reset(reset), .reset_req(0), .readdata(num_data));



soc_system_ROM_others others_display(.address(others_addr), .clk(clk), .clken(1),
.reset(reset), .reset_req(0), .readdata(others_data));



soc_system_ROM_bone bone_display(.address(bone_addr), .clk(clk), .clken(1),
.reset(reset), .reset_req(0), .readdata(bone_data));




/*****************************************************************

display end

*****************************************************************/

logic [4:0] cat_cnt_x;

logic [4:0] cat_cnt_y;

logic [10:0] cat_offset_x;

logic [10:0] cat_offset_y;

logic [10:0] cat_addr;

logic [15:0] explosion_addr;

logic in_box;
```

```
assign cat_cnt_x = ({1'b0,hcount[10:1]}-cat_mat_s_x+1)>>5;

assign cat_cnt_y = ({1'b0,vcount}-cat_mat_s_y)>>5;

assign cat_offset_x = ({1'b0,hcount[10:1]}-cat_mat_s_x[10:0]+1) & 11'h1f;

assign cat_offset_y = ({1'b0,vcount}-cat_mat_s_y[10:0]) & 11'h1f;

assign cat_addr = {cat_ani_state, cat_offset_y[4:0],cat_offset_x[4:0]};

//assign cat_addr = {1'd0,cat_offset_y[4:0],cat_offset_x[4:0]};


assign in_box = (hcount[10:1]>=(cat_mat_s_x-1)) && (hcount[10:1]<cat_mat_e_x) &&
(vcount>=cat_mat_s_y) && (vcount<cat_mat_e_y);

assign display_addr = {16{in_box}} & cat_addr;

assign cat2_addr= {16{in_box}} & cat_addr;

assign cat3_addr= {16{in_box}} & cat_addr;

assign cat4_addr= {16{in_box}} & cat_addr;

assign explode_addr = {16{in_box}} & cat_addr;

/*****************************mice*************************/

/* mouse */

    logic [15:0] mouse1_addr, mouse2_addr, mouse3_addr;

    logic [10:0] mouse1_offset_x;

    logic [10:0] mouse1_offset_y;

    logic [10:0] mouse2_offset_x;

    logic [10:0] mouse2_offset_y;

    logic [10:0] mouse3_offset_x;

    logic [10:0] mouse3_offset_y;

    logic in_box_mouse1;

    logic in_box_mouse2;

    logic in_box_mouse3;


    assign mouse1_offset_x = ({1'b0,hcount[10:1]}-mouse1_s_x[10:0]+2) & 11'h1f;

    assign mouse1_offset_y = ({1'b0,vcount}-mouse1_s_y[10:0]) & 11'h1f;

    assign mouse1_addr = {9'd0, mouse1_offset_y[3:0], mouse1_offset_x[2:0]};


    assign mouse2_offset_x = ({1'b0,hcount[10:1]}-mouse2_s_x[10:0]+2) & 11'h1f;

    assign mouse2_offset_y = ({1'b0,vcount}-mouse2_s_y[10:0]) & 11'h1f;
```

```
    assign mouse2_addr = {9'd0, mouse2_offset_y[3:0], mouse2_offset_x[2:0]};


    assign mouse3_offset_x = ({1'b0,hcount[10:1]}-mouse3_s_x[10:0]+2) & 11'h1f;

    assign mouse3_offset_y = ({1'b0,vcount}-mouse3_s_y[10:0]) & 11'h1f;

    assign mouse3_addr = {9'd0, mouse3_offset_y[3:0], mouse3_offset_x[2:0]};


    assign in_box_mouse1 = (hcount[10:1]>=(mouse1_s_x-2)) && (hcount[10:1]<mouse1_e_x)
&& (vcount>=mouse1_s_y) && (vcount<mouse1_e_y);

    assign in_box_mouse2 = (hcount[10:1]>=(mouse2_s_x-2)) && (hcount[10:1]<mouse2_e_x)
&& (vcount>=mouse2_s_y) && (vcount<mouse2_e_y);

    assign in_box_mouse3 = (hcount[10:1]>=(mouse3_s_x-2)) && (hcount[10:1]<mouse3_e_x)
&& (vcount>=mouse3_s_y) && (vcount<mouse3_e_y);


    assign bone_s_x = dog_project_x;

    assign bone_s_y = dog_project_y;

    assign bone_e_x = bone_s_x + 16'd8;

    assign bone_e_y = bone_s_y + 16'd24;


    assign mouse1_s_x = cat_project_x[1];

    assign mouse2_s_x = cat_project_x[2];

    assign mouse3_s_x = cat_project_x[3];

    assign mouse1_s_y = cat_project_y[1];

    assign mouse2_s_y = cat_project_y[2];

    assign mouse3_s_y = cat_project_y[3];


    assign mouse1_e_x = mouse1_s_x + 4'd8;

    assign mouse2_e_x = mouse2_s_x + 4'd8;

    assign mouse3_e_x = mouse3_s_x + 4'd8;

    assign mouse1_e_y = mouse1_s_y + 5'd16;

    assign mouse2_e_y = mouse2_s_y + 5'd16;

    assign mouse3_e_y = mouse3_s_y + 5'd16;


    assign cat_mat_s_x = cat_array_pos_x;

    assign cat_mat_s_y = cat_array_pos_y;
```

```
    assign cat_mat_e_x = cat_mat_s_x + CAT_MATRIX_SIZE_X;

    assign cat_mat_e_y = cat_mat_s_y + CAT_MATRIX_SIZE_Y;



/*************************************************************/



logic [15:0] level_addr, level_num_addr, score_addr, score_n0_addr, score_n1_addr,
score_n2_addr, life1_addr, life2_addr, life3_addr, start_addr;


parameter level_s_x = 10; parameter level_e_x = level_s_x + 96;

parameter level_num_s_x = 110; parameter level_num_e_x = level_num_s_x + 32;

parameter score_s_x = 400; parameter score_e_x = score_s_x + 96;

parameter score_n0_s_x = 500; parameter score_n0_e_x = score_n0_s_x + 32;

parameter score_n1_s_x = 540; parameter score_n1_e_x = score_n1_s_x + 32;

parameter score_n2_s_x = 580; parameter score_n2_e_x = score_n2_s_x + 32;

parameter life1_s_x = 200; parameter life1_e_x = life1_s_x + 32;

parameter life2_s_x = 240; parameter life2_e_x = life2_s_x + 32;

parameter life3_s_x = 280; parameter life3_e_x = life3_s_x + 32;

parameter start_s_x = 248; parameter start_e_x = 392 ;

parameter start_s_y = 210; parameter start_e_y = 258 ;

parameter dog_pos_s_y = 430; parameter dog_pos_e_y = 462 ;

parameter mystery_pos_s_y = 50; parameter mystery_pos_e_y = 98 ;

parameter game_over_s_x = 222; parameter game_over_e_x = 418 ;

parameter game_over_s_y = 210; parameter game_over_e_y = 238;


always_ff @(posedge clk)begin

   if (reset) cat_mat_addr <= 0;

   else begin

      if(cat_offset_x == 31 && in_box && ~hcount[0]) begin

         if(cat_cnt_x == 10) begin

            if(cat_offset_y == 31) cat_mat_addr <= (cat_cnt_y == 4)? 0 : (cat_mat_addr
+ 1);
```

```
            else cat_mat_addr <= cat_mat_addr - 10;

        end

        else cat_mat_addr <= cat_mat_addr + 1;

      end

      else cat_mat_addr <= cat_mat_addr;

   end

end




always_comb begin

   if ((hcount[10:1]>=cat_mat_s_x) && (hcount[10:1]<cat_mat_e_x) &&
(vcount>=cat_mat_s_y) && (vcount<cat_mat_e_y)) begin

      case(cat_mat_data)

      0: output_data = 8'd0;

      1: output_data = display_data;

      2: output_data = cat2_data;

      3: output_data = cat3_data;

      4: output_data = cat4_data;

      5: output_data = explode_data;

      default: output_data = 8'hff;

      endcase

   end

   else output_data = 8'd0;

end


logic [15:0] cat_mat_count;

logic [7:0] i_barrier_cnt;

logic [4:0] o_barrier_cnt;

parameter delta_x = 70;

parameter delta_y = 10;


always_ff @(posedge clk)begin

   if (reset) begin
```

```
    cat_mat_count <= 0;

        test <= 0;

        barrier_addr <= 0;

    i_barrier_cnt <= 0;

    o_barrier_cnt <= 0;

  end

  else

     if(~hcount[0]) begin




         if (hcount[10:1]>=dog_pos_x && hcount[10:1]<(dog_pos_x +32) &&
vcount>=dog_pos_s_y && vcount<(dog_pos_e_y)) begin

        test <=1;

        if (hcount[10:1] == (dog_pos_x+31) && vcount == (dog_pos_e_y-1))
//poodle_addr <= 16'h0000;

        begin

           case(dog_ani_state)

               4'd0:  poodle_addr <= 16'h0000 ;

               4'd1:  poodle_addr <= 16'h0400 ;

               4'd2:  poodle_addr <= 16'h0800 ;

               4'd3:  poodle_addr <= 16'h0C00 ;

               4'd4:  poodle_addr <= 16'h1000 ;

               4'd5:  poodle_addr <= 16'h1400 ;

               4'd6:  poodle_addr <= 16'h1800 ;

               4'd7:  poodle_addr <= 16'h1C00 ;

               4'd8:  poodle_addr <= 16'h2000 ;

               4'd9:  poodle_addr <= 16'h2400 ;

               default:  poodle_addr <= 16'h0000 ;

                   endcase

        end

        else poodle_addr <= poodle_addr + 1;

         end
```

```
          if (hcount[10:1]>= mystery_pos_x && hcount[10:1]<(mystery_pos_x+48) &&
vcount>=mystery_pos_s_y && vcount<(mystery_pos_e_y)) begin

         test <=1;

         if (hcount[10:1] == (mystery_pos_x+47) && vcount == (mystery_pos_e_y-1))
mystery_addr <= 0;

         else mystery_addr <= mystery_addr + 1;

          end



          if (hcount[10:1]>=game_over_s_x && hcount[10:1]<(game_over_e_x) &&
vcount>=game_over_s_y && vcount<(game_over_e_y) && ~hcount[0]) begin

         test <=1;

         if (hcount[10:1] == (game_over_e_x-1) && vcount == (game_over_e_y-1))
game_over_addr <= 0;

         else game_over_addr <= game_over_addr + 1;

          end

          if (hcount[10:1]>=bone_s_x && hcount[10:1]<bone_e_x && vcount>=bone_s_y &&
vcount<bone_e_y && ~hcount[0]) begin

         test <=1;

         if (hcount[10:1] == bone_e_x-1 && vcount == bone_e_y-1) bone_addr <= 0;

         else bone_addr <= bone_addr + 1;

          end




          if ((hcount[10:1]>=54+delta_x && hcount[10:1]<102+delta_x &&
vcount>=336+delta_y && vcount<368+delta_y) || (hcount[10:1]>=154+delta_x &&
hcount[10:1]<202+delta_x && vcount>=336+delta_y && vcount<368+delta_y) ||
(hcount[10:1]>=254+delta_x && hcount[10:1]<302+delta_x && vcount>=336+delta_y &&
vcount<368+delta_y) || (hcount[10:1]>=354+delta_x && hcount[10:1]<402+delta_x &&
vcount>=336+delta_y && vcount<368+delta_y)) begin







             if(i_barrier_cnt == 191 && vcount == 351+delta_y) begin

            o_barrier_cnt <= 0;

            i_barrier_cnt <= 0;

            barrier_mat_addr <= 12;

             end else if(i_barrier_cnt == 191 && vcount != 351+delta_y) begin
```

```
            o_barrier_cnt <= o_barrier_cnt + 1;
            i_barrier_cnt <= 0;
            barrier_mat_addr <= (vcount < 352+delta_y) ? 0 : 12;
             end else if(i_barrier_cnt[3:0] == 15) begin
            barrier_mat_addr <= barrier_mat_addr + 1;
            i_barrier_cnt <= i_barrier_cnt + 1;
             end else begin
            i_barrier_cnt <= i_barrier_cnt + 1;
             end
              end
                 case(barrier_mat_data)
             1: barrier_addr = {8'h0, o_barrier_cnt[3:0], i_barrier_cnt[3:0]};
             2: barrier_addr = {8'h1, o_barrier_cnt[3:0], i_barrier_cnt[3:0]};
             3: barrier_addr = {8'h2, o_barrier_cnt[3:0], i_barrier_cnt[3:0]};
             4: barrier_addr = {8'h3, o_barrier_cnt[3:0], i_barrier_cnt[3:0]};
             default: barrier_addr = 16'h3F0;
            endcase
         if(hcount[10:1] == 52 && vcount == 336) begin
        barrier_mat_addr <= 0;
        o_barrier_cnt <= 0;
        i_barrier_cnt <= 0;
         end
 /* level*/
        if (hcount[10:1]>=level_s_x && hcount[10:1]<(level_e_x) && vcount>=10 &&
vcount<(42) && ~hcount[0]) begin
            test <=1;
            if (hcount[10:1] == (level_s_x) && vcount == (10)) level_addr <= 16'h0400;
```

```
            else begin

                level_addr <= level_addr + 1;

                others_addr <= level_addr;

            end

        end

        /* level number */

        if (hcount[10:1]>=level_num_s_x && hcount[10:1]<(level_num_e_x) && vcount>=10
&& vcount<(42) && ~hcount[0]) begin

            test <=1;

            if (hcount[10:1] == (110) && vcount == (10)) begin

            case(level)

                0: level_num_addr <= 16'h0000;

                1: level_num_addr <= 16'h0400;

                2: level_num_addr <= 16'h0800;

                3: level_num_addr <= 16'h0C00;

                4: level_num_addr <= 16'h1000;

                5: level_num_addr <= 16'h1400;

                6: level_num_addr <= 16'h1800;

                7: level_num_addr <= 16'h1C00;

                8: level_num_addr <= 16'h2000;

                9: level_num_addr <= 16'h2400;

                default: level_num_addr <= 16'h0000;

            endcase

            end

            else begin

                level_num_addr <= level_num_addr + 1;

                num_addr <= level_num_addr;

            end

        end



/* mice */

        if (hcount[10:1]>= mouse1_s_x-2 && hcount[10:1]<mouse1_e_x &&
vcount>=mouse1_s_y && vcount<mouse1_e_y && ~hcount[0] ) begin
```

```
            test <=1;

                others_addr <= mouse1_addr + 16'h1400;

        end

        else if (hcount[10:1]>= mouse2_s_x-2 && hcount[10:1]<mouse2_e_x &&
vcount>=mouse2_s_y && vcount<mouse2_e_y && ~hcount[0] ) begin

            test <=1;

                others_addr <= mouse2_addr + 16'h1400;

        end

        else if (hcount[10:1]>= mouse3_s_x-2 && hcount[10:1]<mouse3_e_x &&
vcount>=mouse3_s_y && vcount<mouse3_e_y && ~hcount[0] ) begin

            test <=1;

                others_addr <= mouse3_addr + 16'h1400;

        end




/* lives */

        if (hcount[10:1]>= life1_s_x && hcount[10:1]<(life1_e_x) && vcount>=10 &&
vcount<(42) && ~hcount[0] && life>0 && life <4) begin

            test <=1;

            if (hcount[10:1] == (life1_s_x) && vcount == (10)) life1_addr <= 16'h1000;

            else begin

                life1_addr <= life1_addr + 1;

                others_addr <= life1_addr;

            end

        end



        if (hcount[10:1]>= life2_s_x && hcount[10:1]<(life2_e_x) && vcount>=10 &&
vcount<(42) && ~hcount[0] && life>1 && life <4) begin

            test <=1;

            if (hcount[10:1] == (life2_s_x) && vcount == (10)) life2_addr <= 16'h1000;

            else begin

                life2_addr <= life2_addr + 1;

                others_addr <= life2_addr;

            end
```

```
            end


        if (hcount[10:1]>= life3_s_x && hcount[10:1]<(life3_e_x) && vcount>=10 &&
vcount<(42) && ~hcount[0] && life == 3) begin

            test <=1;

            if (hcount[10:1] == (life3_s_x) && vcount == (10)) life3_addr <= 16'h1000;

            else begin

                life3_addr <= life3_addr + 1;

                others_addr <= life3_addr;

            end

            end



/* score */

        if (hcount[10:1]>= score_s_x && hcount[10:1]<(score_e_x) && vcount>=10 &&
vcount<(42) && ~hcount[0]) begin

            test <=1;

            if (hcount[10:1] == (score_s_x) && vcount == (10)) score_addr <= 16'h1480;

            else begin

                score_addr <= score_addr + 1;

                others_addr <= score_addr;

            end

            end



        /* score num 0*/

        if (hcount[10:1]>=score_n0_s_x && hcount[10:1]<(score_n0_e_x) && vcount>=10 &&
vcount<(42) && ~hcount[0]) begin

            test <=1;

            if (hcount[10:1] == (score_n0_s_x) && vcount == (10)) begin

            case(score[3:0])

                0: score_n0_addr <= 16'h0000;

                1: score_n0_addr <= 16'h0400;

                2: score_n0_addr <= 16'h0800;

                3: score_n0_addr <= 16'h0C00;

                4: score_n0_addr <= 16'h1000;
```

```
                5: score_n0_addr <= 16'h1400;

                6: score_n0_addr <= 16'h1800;

                7: score_n0_addr <= 16'h1C00;

                8: score_n0_addr <= 16'h2000;

                9: score_n0_addr <= 16'h2400;

                default: score_n0_addr <= 16'h0000;

            endcase

            end

            else begin

                score_n0_addr <= score_n0_addr + 1;

                num_addr <= score_n0_addr;

            end

        end

        /* score num 1*/

        if (hcount[10:1]>=score_n1_s_x && hcount[10:1]<(score_n1_e_x) && vcount>=10 &&
vcount<(42) && ~hcount[0]) begin

            test <=1;

            if (hcount[10:1] == (score_n1_s_x) && vcount == (10)) begin

            case(score[7:4])

                0: score_n1_addr <= 16'h0000;

                1: score_n1_addr <= 16'h0400;

                2: score_n1_addr <= 16'h0800;

                3: score_n1_addr <= 16'h0C00;

                4: score_n1_addr <= 16'h1000;

                5: score_n1_addr <= 16'h1400;

                6: score_n1_addr <= 16'h1800;

                7: score_n1_addr <= 16'h1C00;

                8: score_n1_addr <= 16'h2000;

                9: score_n1_addr <= 16'h2400;

                default: score_n1_addr <= 16'h0000;

            endcase

            end

            else begin
```

```
                score_n1_addr <= score_n1_addr + 1;

                num_addr <= score_n1_addr;

        end

        end



        /* score num 2*/

        if (hcount[10:1]>=score_n2_s_x && hcount[10:1]<(score_n2_e_x) && vcount>=10 &&
vcount<(42) && ~hcount[0]) begin

            test <=1;

            if (hcount[10:1] == (score_n2_s_x) && vcount == (10)) begin

            case(score[11:8])

                0: score_n2_addr <= 16'h0000;

                1: score_n2_addr <= 16'h0400;

                2: score_n2_addr <= 16'h0800;

                3: score_n2_addr <= 16'h0C00;

                4: score_n2_addr <= 16'h1000;

                5: score_n2_addr <= 16'h1400;

                6: score_n2_addr <= 16'h1800;

                7: score_n2_addr <= 16'h1C00;

                8: score_n2_addr <= 16'h2000;

                9: score_n2_addr <= 16'h2400;

                default: score_n2_addr <= 16'h0000;

            endcase

            end

            else begin

                score_n2_addr <= score_n2_addr + 1;

                num_addr <= score_n2_addr;

        end

        end



/* Start */

    if (hcount[10:1]>= start_s_x && hcount[10:1]< start_e_x && vcount>= start_s_y &&
vcount< start_e_y && ~hcount[0] && (game_status == 2'b00)) begin
```

```
        test <=1;

        if (hcount[10:1] == (start_s_x) && vcount == (start_s_y)) start_addr <=
16'h2080;

        else begin

            start_addr <= start_addr + 1;

            others_addr <= start_addr;

        end

        end


    end

end







/*************************************************************

     VGA Display combo logic

*************************************************************/



   always_comb begin

      {VGA_R, VGA_G, VGA_B} = {8'h0, 8'h0, 8'h0};

      if (VGA_BLANK_n )



    /* Start */

     if (hcount[10:1]>=start_s_x && hcount[10:1]< start_e_x && vcount>= start_s_y &&
vcount< start_e_y && others_data != 8'd0 && game_status == 2'b00)

                {VGA_R, VGA_G, VGA_B} = {{others_data[7:5], 5'd0}, {others_data[4:2],
5'd0}, {others_data[1:0], 6'd0}} ;



    /* Game Over */

         else if (hcount[10:1]>=game_over_s_x && hcount[10:1]<(game_over_e_x) &&
vcount>=game_over_s_y && vcount<(game_over_e_y) && game_over_data != 8'd0 &&
game_status == 2'b10)

            {VGA_R, VGA_G, VGA_B} = {{game_over_data[7:5], 5'd0},
{game_over_data[4:2], 5'd0}, {game_over_data[1:0], 6'd0}};
```

```
    /* Bone */

     else if (hcount[10:1]>=bone_s_x && hcount[10:1]<bone_e_x && vcount>=bone_s_y &&
vcount<bone_e_y && bone_data != 8'd0 && dog_bullet)

            {VGA_R, VGA_G, VGA_B} = {{bone_data[7:5], 5'd0}, {bone_data[4:2], 5'd0},
{bone_data[1:0], 6'd0}};




    /* Mouse 1 */

    else if (((hcount[10:1]>=(mouse1_s_x)) && (hcount[10:1]<mouse1_e_x) &&
(vcount>=mouse1_s_y) && (vcount<mouse1_e_y) && others_data != 8'd0) && cat_bullet[1] )

        {VGA_R, VGA_G, VGA_B} = {{others_data[7:5], 5'd0}, {others_data[4:2], 5'd0},
{others_data[1:0], 6'd0}};



    /* Mouse 2 */

    else if (((hcount[10:1]>=(mouse2_s_x)) && (hcount[10:1]<mouse2_e_x) &&
(vcount>=mouse2_s_y) && (vcount<mouse2_e_y) && others_data != 8'd0) && cat_bullet[2] )

            {VGA_R, VGA_G, VGA_B} = {{others_data[7:5], 5'd0}, {others_data[4:2],
5'd0}, {others_data[1:0], 6'd0}};



    /* Mouse 3 */

    else if (((hcount[10:1]>=(mouse3_s_x)) && (hcount[10:1]<mouse3_e_x) &&
(vcount>=mouse3_s_y) && (vcount<mouse3_e_y) && others_data != 8'd0) && cat_bullet[3] )

        {VGA_R, VGA_G, VGA_B} = {{others_data[7:5], 5'd0}, {others_data[4:2], 5'd0},
{others_data[1:0], 6'd0}};



    /* Cat Matrix */

     else if ((hcount[10:1]>=cat_mat_s_x) && (hcount[10:1]<cat_mat_e_x) &&
(vcount>=cat_mat_s_y) && (vcount<cat_mat_e_y) && output_data != 8'd0 )

            {VGA_R, VGA_G, VGA_B} = {{output_data[7:5], 5'd0}, {output_data[4:2],
5'd0}, {output_data[1:0], 6'd0}};



    /* Mystery */

         else if (hcount[10:1]>= mystery_pos_x && hcount[10:1]<(mystery_pos_x+48) &&
vcount>=mystery_pos_s_y && vcount<(mystery_pos_e_y) && mystery_data != 8'd0 &&
mystery_vis)

            {VGA_R, VGA_G, VGA_B} = {{mystery_data[7:5], 5'd0}, {mystery_data[4:2],
5'd0}, {mystery_data[1:0], 6'd0}};



    /* Poodle */
```

```
        else if (hcount[10:1]>=dog_pos_x && hcount[10:1]<(dog_pos_x + 32) &&
vcount>=dog_pos_s_y && vcount<(dog_pos_e_y) && poodle_data != 8'd0)

            {VGA_R, VGA_G, VGA_B} = {{poodle_data[7:5], 5'd0}, {poodle_data[4:2],
5'd0}, {poodle_data[1:0], 6'd0}};



    /* Explosion */

        // else if (hcount[10:1]>=532 && hcount[10:1]<(564) && vcount>=400 &&
vcount<(432) && others_data != 8'd0)

        //    {VGA_R, VGA_G, VGA_B} = {{others_data[7:5], 5'd0}, {others_data[4:2],
5'd0}, {others_data[1:0], 6'd0}};




     /* Barriers */

         else if (((hcount[10:1]>=54+delta_x && hcount[10:1]<102+delta_x &&
vcount>=336+delta_y && vcount<368+delta_y) || (hcount[10:1]>=154+delta_x &&
hcount[10:1]<202+delta_x && vcount>=336+delta_y && vcount<368+delta_y) ||
(hcount[10:1]>=254+delta_x && hcount[10:1]<302+delta_x && vcount>=336+delta_y &&
vcount<368+delta_y) || (hcount[10:1]>=354+delta_x && hcount[10:1]<402+delta_x &&
vcount>=336+delta_y && vcount<368+delta_y)) && barrier_data != 8'd0)

            {VGA_R, VGA_G, VGA_B} = {{barrier_data[7:5], 5'd0}, {barrier_data[4:2],
5'd0}, {barrier_data[1:0], 6'd0}};



    /* level*/

         else if ((hcount[10:1]>=level_s_x && hcount[10:1]<(level_e_x) && vcount>=10
&& vcount<(42) && others_data != 8'd0) )

            {VGA_R, VGA_G, VGA_B} = {{others_data[7:5], 5'd0}, {others_data[4:2],
5'd0}, {others_data[1:0], 6'd0}};



    /* level number*/

         else if (hcount[10:1]>=level_num_s_x && hcount[10:1]<(level_num_e_x) &&
vcount>=10 && vcount<(42) && num_data != 8'd0)

            {VGA_R, VGA_G, VGA_B} = {{num_data[7:5], 5'd0}, {num_data[4:2], 5'd0},
{num_data[1:0], 6'd0}};



    /* score */

    else if (hcount[10:1]>=score_s_x && hcount[10:1]<(score_e_x) && vcount>=10 &&
vcount<(42) && others_data != 8'd0)

        {VGA_R, VGA_G, VGA_B} = {{others_data[7:5], 5'd0}, {others_data[4:2], 5'd0},
{others_data[1:0], 6'd0}};
```

```
    /* score numbers */

    else if (((hcount[10:1]>=score_n0_s_x && hcount[10:1]<score_n0_e_x) ||
(hcount[10:1]>=score_n1_s_x && hcount[10:1]<score_n1_e_x) ||

                (hcount[10:1]>=score_n2_s_x && hcount[10:1]<score_n2_e_x)) &&
vcount>=10 && vcount<(42)    && num_data != 8'd0)

        {VGA_R, VGA_G, VGA_B} = {{num_data[7:5], 5'd0}, {num_data[4:2], 5'd0},
{num_data[1:0], 6'd0}};



    /* lives */

    else if (((hcount[10:1]>=life1_s_x && hcount[10:1]<(life1_e_x) && life>0 && life
<4) || (hcount[10:1]>=life2_s_x && hcount[10:1]<(life2_e_x) && life>1 && life <4)||

                (hcount[10:1]>=life3_s_x && hcount[10:1]<(life3_e_x) && life == 3)) &&
vcount>=10 && vcount<(42) && others_data != 8'd0)

        {VGA_R, VGA_G, VGA_B} = {{others_data[7:5], 5'd0}, {others_data[4:2], 5'd0},
{others_data[1:0], 6'd0}};









         else

         {VGA_R, VGA_G, VGA_B} = {background_r, background_g, background_b};

   end




/*****************************************************************

     Avalon Bus start

*****************************************************************/

   assign eof_irq =irq;

   always_ff @(posedge clk) begin


    if((hcount[10:0] == 0) && (vcount[9:0] == 463)) begin

    irq <= 1'b1;

    frame_cnt <= frame_cnt + 1;

    end else if ((hcount[10:0] >= 0) && (hcount[10:0] <= 1280) && (vcount[9:0] >= 0)
&& (vcount[9:0] < 463)) begin

       frame_active <= 1;
```

```
end else begin
   frame_active <= 0;
end

 if (reset) begin
background_r <= 8'h0;
background_g <= 8'h0;
background_b <= 8'h0;

irq <= 1'b0;

    play <= 0;
    play_cat <=0;
    play_dog <= 0;
    delay <= 3;

 end else if (chipselect && write) begin
   case (address)

 7'h29: begin
     c_write <= 1;
             c_cs <= 1;
     c_write_addr <= writedata[15:4];
     c_writedata <= writedata[3:0];
             end

     7'h2A : begin
               play <= writedata[5];
               vol[3:0] <= writedata[3:0];
             end
     7'h2B : begin
               play_cat <= writedata[5];
```

```
                  vol_cat[3:0] <= writedata[3:0];
                end
        7'h2C : begin
                  play_dog <= writedata[5];
                  vol_dog[3:0] <= writedata[3:0];
                end
        7'h2D : delay <= writedata;



    7'h2E: begin
        b_write <= 1;
                b_cs <= 1;
        b_write_addr <= writedata[15:4];
        b_writedata <= writedata[3:0];
                end
        7'h2F : irq <= 0;
      endcase
    end else if(chipselect && !write && address == 7'h30) begin
   readdata <= 16'hD065;
    end else if(chipselect && !write && address == 7'h31) begin
   readdata <= {frame_active, frame_cnt[14:0]};
    end else begin
        b_write <= 0;
        b_cs <= 0;
    c_write <= 0;
        c_cs <= 0;
    end



  end


endmodule
```

```
/*****************************************************************
    VGA counter module
*****************************************************************/

module vga_counters(
 input logic         clk50, reset,
 output logic [10:0] hcount,  // hcount[10:1] is pixel column
 output logic [9:0]  vcount,  // vcount[9:0] is pixel row
 output logic VGA_CLK, VGA_HS, VGA_VS, VGA_BLANK_n, VGA_SYNC_n);

/*
 * 640 X 480 VGA timing for a 50 MHz clock: one pixel every other cycle
 *
 * HCOUNT 1599 0             1279       1599 0
 *             _______________              ________
 * ____________|    Video      |____________|  Video
 *
 *
 * |SYNC| BP |<-- HACTIVE -->|FP|SYNC| BP |<-- HACTIVE
 *       _____________________      _____________
 * |____|       VGA_HS          |____|
 */
   // Parameters for hcount
   parameter HACTIVE      = 11'd 1280,
             HFRONT_PORCH = 11'd 32,
             HSYNC        = 11'd 192,
             HBACK_PORCH  = 11'd 96,
             HTOTAL       = HACTIVE + HFRONT_PORCH + HSYNC +
                            HBACK_PORCH; // 1600
```

```
// Parameters for vcount
parameter VACTIVE      = 10'd 480,
          VFRONT_PORCH = 10'd 10,
          VSYNC        = 10'd 2,
          VBACK_PORCH  = 10'd 33,
          VTOTAL       = VACTIVE + VFRONT_PORCH + VSYNC +
                         VBACK_PORCH; // 525

logic endOfLine;

always_ff @(posedge clk50 or posedge reset)
  if (reset)          hcount <= 0;
  else if (endOfLine) hcount <= 0;
  else            hcount <= hcount + 11'd 1;

assign endOfLine = hcount == HTOTAL - 1;

logic endOfField;

always_ff @(posedge clk50 or posedge reset)
  if (reset)          vcount <= 0;
  else if (endOfLine)
    if (endOfField)   vcount <= 0;
    else              vcount <= vcount + 10'd 1;

assign endOfField = vcount == VTOTAL - 1;

// Horizontal sync: from 0x520 to 0x5DF (0x57F)
// 101 0010 0000 to 101 1101 1111
assign VGA_HS = !( (hcount[10:8] == 3'b101) &
           !(hcount[7:5] == 3'b111));
```

```
   assign VGA_VS = !( vcount[9:1] == (VACTIVE + VFRONT_PORCH) / 2);


   assign VGA_SYNC_n = 1'b0; // For putting sync on the green signal; unused


   // Horizontal active: 0 to 1279     Vertical active: 0 to 479
   // 101 0000 0000  1280          01 1110 0000  480
   // 110 0011 1111  1599          10 0000 1100  524
   assign VGA_BLANK_n = !( hcount[10] & (hcount[9] | hcount[8]) ) &
            !( vcount[9] | (vcount[8:5] == 4'b1111) );


   /* VGA_CLK is 25 MHz
    *             __    __    __
    * clk50    __|  |__|  |__|
    *
    *             _____       __
    * hcount[0]__|     |_____|
    */
   assign VGA_CLK = hcount[0]; // 25 MHz clock: rising edge sensitive


endmodule
```

12.2 ctrl_reg.sv

```
module ctrl_regs(
    input logic            clk,
    input logic        reset,
    input logic [15:0] writedata,
    input logic        write,
    input          chipselect,
    input logic [7:0]  address,


/*****************************************
```

```
   Register Group #0
   Dog position, and projectile position and visibility
*****************************************/
    output logic [3:0] cat_bullet,              //cat bullet in flight?
    output logic       dog_bullet,              //dog bullet in flight?
    output logic [9:0] dog_pos_x,               //dog position x
    output logic [9:0] dog_project_x,           //dog bullet position x
    output logic [9:0] dog_project_y,           //dog bullet position y
    output logic [9:0] cat_project_x[3:0],      //cat 0~3 bullet position x
    output logic [9:0] cat_project_y[3:0],      //cat 0~3 bullet position y
    output logic [9:0] cat_array_pos_x,         //cat upper west corner position x
    output logic [9:0] cat_array_pos_y,         //cat upper west corner position y
    output logic [9:0] mystery_pos_x,           //mystery position
    output logic       mystery_vis,

/*****************************************
   Register Group #1
   Miscellaneous
*****************************************/
    output logic [3:0]  level,           //game difficulty level 0~7
    output logic [1:0]  game_status,     //game status (start, in process, game over)
    output logic [1:0]  life,            //lives remaining 0~3
    output logic [15:0] score,          //score
    output logic [3:0]  dog_ani_state,
    output logic        cat_ani_state
);

logic [15:0] control_regs[17:0];     //all control registers

//update values from avalon bus
genvar i, j;
generate
```

```
    for(i=0; i<=17; i=i+1)begin:loop

        always_ff @(posedge clk)begin

            if(reset) control_regs[i] <= 16'd0;

            else control_regs[i] <= (write && chipselect && (address == i))? writedata
: control_regs[i];

        end

    end

endgenerate




//output decode & data alignment

assign cat_bullet = {control_regs[10][15], control_regs[8][15], control_regs[6][15],
control_regs[4][15]};

assign dog_bullet = control_regs[2][15];

assign dog_pos_x = control_regs[0][9:0];

assign dog_project_x = control_regs[1][9:0];

assign dog_project_y = control_regs[2][9:0];

assign cat_project_x[0] = control_regs[3][9:0];

assign cat_project_y[0] = control_regs[4][9:0];

assign cat_project_x[1] = control_regs[5][9:0];

assign cat_project_y[1] = control_regs[6][9:0];

assign cat_project_x[2] = control_regs[7][9:0];

assign cat_project_y[2] = control_regs[8][9:0];

assign cat_project_x[3] = control_regs[9][9:0];

assign cat_project_y[3] = control_regs[10][9:0];

assign cat_array_pos_x = control_regs[11][9:0];

assign cat_array_pos_y = control_regs[12][9:0];

assign mystery_pos_x = control_regs[13][9:0];

assign mystery_vis = control_regs[13][15];


assign level = control_regs[14][7:4];

assign game_status = control_regs[14][3:2];

assign life = control_regs[14][1:0];
```

```
assign score = control_regs[15];

assign dog_ani_state = control_regs[16][3:0];

assign cat_ani_state = control_regs[17][0];



endmodule
```

12.3 audio.sv

```
module audio_player(
                input logic      clk50, reset,
    input logic         left_channel_ready,
    input logic         right_channel_ready,
                input logic         play,
                input logic         play_cat,
                input logic         play_dog,

                input logic [3:0]  vol,
                input logic [3:0] vol_cat,
                input logic [3:0] vol_dog,
                input logic [3:0] delay,

    output logic         left_channel_valid,
    output logic         right_channel_valid,

    output logic [15:0] left_channel_data,
    output logic [15:0] right_channel_data
);

    parameter MAX_BG  = 17'd 34680, MAX_CAT = 15'd 6170, MAX_DOG = 15'd 4090;
```

```
    logic [3:0] counter;
    //logic [3:0] slowdown;



   logic[17:0] addr;
   logic[17:0] cat_addr;
   logic[17:0] dog_addr;


   logic[15:0] data;
   logic[15:0] cat_data;
   logic[15:0] dog_data;


   soc_system_background_music music(.address(addr), .clk(clk50), .clken(1),
.reset(reset), .reset_req(0), .readdata(data));
   soc_system_ROM_cat_meow cat(.address(cat_addr), .clk(clk50), .clken(1),
.reset(reset), .reset_req(0), .readdata(cat_data));
   soc_system_ROM_dog_bark dog(.address(dog_addr), .clk(clk50), .clken(1),
.reset(reset), .reset_req(0), .readdata(dog_data));


   always_ff @(posedge clk50 or posedge reset) begin
     if (reset) begin
         counter <= 0;
        // slowdown <= 6;
         left_channel_data <= 15'b0;
         right_channel_data <= 15'b0;
         left_channel_valid <= 0;
         right_channel_valid <= 0;
         addr <= 16'b0;
         cat_addr <= 16'b0;
         dog_addr <= 16'b0;
     end else begin



         /*if(left_channel_ready == 1 && counter < 6250) begin
```

```
             counter = counter + 1;

            left_channel_valid <= 0;

            right_channel_valid <= 0;

         end else */

         if(left_channel_ready == 1 && right_channel_ready == 1 ) begin //&& counter
>= 6250) begin

            //counter <= 0;

            left_channel_valid <= 1;

            right_channel_valid <= 1;


            if(counter == delay)

              counter <= 0;

            else

              counter <= counter + 1;


      case ({play, play_cat, play_dog})

        3'b001   : begin

                          left_channel_data <= dog_data;

                          right_channel_data <= dog_data;


                          if(counter == delay) dog_addr <= (dog_addr > MAX_DOG) ?
MAX_DOG : dog_addr + 1;


                        end

        3'b010   : begin

                          left_channel_data <= cat_data;

                          right_channel_data <= cat_data;


                          if(counter == delay) cat_addr <= (cat_addr > MAX_CAT) ?
MAX_CAT : cat_addr + 1;


                        end

        3'b011   : begin
```

```
                        left_channel_data <= (cat_data >>> vol_cat) + (dog_data >>>
vol_dog);

                        right_channel_data <= (cat_data >>> vol_cat) + (dog_data >>>
vol_dog);


                    if(counter == delay)  begin

                            cat_addr <= (cat_addr > MAX_CAT) ? MAX_CAT : cat_addr +
1;

                            dog_addr <= (dog_addr > MAX_DOG) ? MAX_DOG : dog_addr +
1;

                        end

                    end

        3'b100  : begin

                        left_channel_data <= data;

                        right_channel_data <= data;


                    if(counter == delay) addr <= addr + 1;




                    end

        3'b101  : begin

                        left_channel_data <= (data >>> vol) + (dog_data >>>
vol_dog);

                        right_channel_data <= (data >>> vol) + (dog_data >>>
vol_dog);


                    if(counter == delay)  begin

                            addr <= addr + 1;

                            dog_addr <= (dog_addr > MAX_DOG) ? MAX_DOG : dog_addr +
1;

                        end

                    end

        3'b110  : begin

                        left_channel_data <= (data >>> vol) + (cat_data >>>
vol_cat);

                        right_channel_data <= (data >>> vol) + (cat_data >>>
vol_cat);
```

```
                    if(counter == delay)  begin
                              addr <= addr + 1;
                              cat_addr <= (cat_addr > MAX_CAT) ? MAX_CAT : cat_addr +
1;
                           end
                         end
        3'b111  : begin
                           left_channel_data <= (data >>> vol) + (cat_data >>> vol_cat)
+ (dog_data >>> vol_cat);
                           right_channel_data <= (data >>> vol) + (cat_data >>>
vol_cat) + (dog_data >>> vol_cat);

                           if(counter == delay)  begin
                              addr <= addr + 1;
                              cat_addr <= (cat_addr > MAX_CAT) ? MAX_CAT : cat_addr +
1;
           dog_addr <= (dog_addr > MAX_DOG) ? MAX_DOG : dog_addr + 1;
                           end
                         end

        default : begin
                            addr <= 0;
                            cat_addr <= 0;
                            dog_addr <= 0;
                         end
      endcase

         end else begin
            left_channel_valid <= 0;
            right_channel_valid <= 0;
         end
            if(addr > MAX_BG || play == 0)
              addr <= 0;
```

```
            if(play_cat == 0)
              cat_addr <= 0;

            if(play_dog == 0)
              dog_addr <= 0;




     end
   end


endmodule
```

12.4 hello.c

```
#include <stdio.h>
#include <unistd.h>
#include <stdlib.h>
#include <stdbool.h>
#include <string.h>
#include <arpa/inet.h>
#include <unistd.h>
#include <time.h>


#include "interface.h"
#include "cat_invaders.h"
```

```c
#include "../controller/usbjoypad.h"


#define MIN_X 0

#define MAX_X 640 - 32

#define BONE_START_Y 416

#define BONE_END_Y 24

#define PROJ_SPEED 2

#define MYSTERY_SPEED 1

#define BONE_SPEED 3

#define MYSTERY_Y_POS 50

#define POODLE_Y_POS 430

#define MOUSE_END_Y 500

#define DOG_SPEED 2

#define CAT_SPEED 1

#define BOTTOM_CUTOFF 378

#define CAT_LEFT_WALL 1

#define CAT_RIGHT_WALL 288 // Only stores the value for the left

#define max(a, b) ((a) > (b) ? (a) : (b))

#define min(a, b) ((a) < (b) ? (a) : (b))


typedef struct {

    unsigned short x1Min;

    unsigned short x1Max;

    unsigned short y1Min;

    unsigned short y1Max;
```

```
    unsigned short x2Min;
    unsigned short x2Max;
    unsigned short y2Min;
    unsigned short y2Max;
} CollisionBoxes;


unsigned short dogPos;
unsigned short mysteryPos;
Position catMatPos;
unsigned char explode_cnt[55];
unsigned char numCats;
unsigned short score = 0;
unsigned char level = 1;
unsigned char lives = 3;
unsigned short gameStatus = 0;
Position bonePos;
Position micePos[4];



void init_cat_matrix(unsigned short (*catMatrix)[55]);
void reset_cat_matrix(unsigned short (*catMatrix)[55]);
void *explode_cat(void *catNum);


/* ------------------------------------------------- General Functions
-------------------------------------------------- */
```

```
// Might need a tracker for cat movement
void *animation_tracker(void *frame) {
    unsigned short *frameNum = (unsigned short *) frame;
    *frameNum = *frameNum == 5 ? 0 : *frameNum + 1;
}

void reset_objects(unsigned short (*catMatrix)[55], int *mysterySpawnTime,
bool *mysteryInPlay) {
    dogPos = 300;
    catMatPos.x = 40;
    catMatPos.y = 90;
    numCats = 55;
    *mysterySpawnTime = -1;
    *mysteryInPlay = false;
    set_ufo_pos(mysteryPos, 0);

    reset_cat_matrix(catMatrix);
    set_sprite_pos(catMatPos.x, catMatPos.y);
    set_dog_pos(dogPos);
    set_projectile_dog_position(dogPos+16, BONE_START_Y, 0);

    for (int i = 1; i < 4; i++) {
        set_projectile_sprite(i, 0, 0, 0);
```

```
    }


     for(int i = 0; i < 55; i++) {

        explode_cnt[i] = 0;

     }


}


unsigned short clamp(unsigned short val, unsigned short minV, unsigned
short maxV) {

    return (unsigned short) max(min(val, maxV), minV);

}



bool barrier_hit(unsigned short (*barrierMatrix)[24], Position projPos,
unsigned

short projW, unsigned short projH) {

    Position barrierStart;

    barrierStart.y = 346;



    for (int j = 0; j < 2; j++) {

        for (int k = 0; k < 12; k++) {

            if ( k >= 9 ) {

                barrierStart.x = 424;

            }
```

```
            else if ( k >= 6) {
                barrierStart.x = 324;
            }
            else if( k >= 3) {
               barrierStart.x = 224;
            }
            else {
                barrierStart.x = 124;
            }



            int barrierNum = k + 12 * j;


            Position blockPos = {barrierStart.x + (16 * (k%3)),
barrierStart.y + 16 * j};
            CollisionBoxes collision = {projPos.x, projPos.x + projW,
                projPos.y, projPos.y + projH,
                blockPos.x, blockPos.x + 16,
                blockPos.y, blockPos.y + 16};


            if ( collision.x1Min < collision.x2Max &&
                collision.x1Max > collision.x2Min &&
                collision.y1Min < collision.y2Max &&
                collision.y1Max > collision.y2Min &&
                (*barrierMatrix)[barrierNum] != 0) {
```

```
                    (*barrierMatrix)[barrierNum] = (
(*barrierMatrix)[barrierNum] == 4 ) ? 0  :
                    (*barrierMatrix)[barrierNum] + 1;
                    set_barrier(barrierNum*2,
(*barrierMatrix)[barrierNum]);


                    return true;
            }



        }
    }

    return false;
}



void reset_cat_matrix(unsigned short (*catMatrix)[55]) {
    for (int i = 0; i < 55; i++) {
        (*catMatrix)[i] = 0;
        set_sprite_matrix(i*2, 0);
    }
}

void init_cat_matrix(unsigned short (*catMatrix)[55]) {
    time_t t;
```

```
    srand((unsigned) time(&t));


    for (int i = 0; i < 55; i++) {
        int status = (rand() % 4) + 1;


        (*catMatrix)[i] = status;
        set_sprite_matrix(i*2, status);
    }
}


void reset_barrier_matrix(unsigned short (*barrierMatrix)[24]) {
    for (int i = 0; i < 24; i++) {
        (*barrierMatrix)[i] = 1;
        set_barrier(i*2, 1);
    }
}


void check_lives( unsigned short (*catMatrix)[55], unsigned short
(*barrierMatrix)[24], int *mysterySpawnTime, bool *mysteryInPlay) {
    if( lives == 0) {
        reset_cat_matrix(catMatrix);
        set_status(level, 2, lives);


        while(controller_get_state().startPressed == 0);
        while(controller_get_state().startPressed == 1);
```

```
        lives = 3;
        gameStatus = 0;
        score = 0;

        set_score(score);
        level = 1;
        set_status(level, gameStatus, lives);
        reset_objects(catMatrix, mysterySpawnTime, mysteryInPlay);
        reset_barrier_matrix(barrierMatrix);

        while(controller_get_state().startPressed == 0);
        while(controller_get_state().startPressed == 1);

        gameStatus = 1;
        set_status(level, gameStatus, lives);
        init_cat_matrix(catMatrix);
    }
}

/* ------------------------------------------------- General Functions
---------------------------------------------------- */
/* ------------------------------------------------- Player Functions
---------------------------------------------------- */

void animate_player(unsigned short frame, bool dogDir, bool isWalking) {
```

```
    // Frame cycles through 0,1,2:


    // Assuming that left is 0-4, right is 5-9
    // Walking animation
    if (isWalking) {
        // Assuming that there is a 2 offset because of the two idle
animation frames
        unsigned short walkFrame = 2 + frame % 3;
        set_dog_ani(dogDir ? walkFrame : walkFrame + 5);
    }
    // Idle animation
    else {
        // NOTE: Not suse if i can use the dogDirection with the standard
that i've placed but-
        unsigned short idleFrame = frame % 2;
        set_dog_ani(dogDir ? idleFrame : idleFrame + 5);
    }


}


void move_player(ControllerState state) {
    // If the player is trying to move left, move if they are not at the
boundary.
    if (state.leftArrowPressed && dogPos > MIN_X ) {
        if (dogPos < DOG_SPEED) {
            dogPos = 0;
```

```
        }
        else {
            dogPos = clamp(dogPos - DOG_SPEED,
            (unsigned short) MIN_X, (unsigned short) MAX_X);
        }
        set_dog_pos(dogPos);
    }
    else if (state.rightArrowPressed && dogPos < MAX_X) {
        dogPos = clamp(dogPos + DOG_SPEED,
        (unsigned short) MIN_X, (unsigned short) MAX_X);
        set_dog_pos(dogPos);
    }

}

void update_player_state(bool *dogDir, bool *isWalking, ControllerState
state) {
    if (state.leftArrowPressed) {
        *dogDir = true;
        *isWalking = true;
        return;
    }
    else if (state.rightArrowPressed) {
        *dogDir = false;
        *isWalking = true;
```

```
        return;
    }

    *isWalking = false;
}

void update_bone_projectile(ControllerState state, bool *dogInFlight) {
    // If there is no bullet currently flying and the player presses A
    if (state.buttonAPressed && !(*dogInFlight) ) {
        bonePos.x = dogPos + 16;
        bonePos.y = BONE_START_Y;
        set_projectile_dog_position(bonePos.x, bonePos.y, 1);
        *dogInFlight = true;
        play_bark(0);
    }
    else if ( *dogInFlight ) {
        if (bonePos.y < BONE_END_Y) {
            *dogInFlight = false;
            set_projectile_dog_position(dogPos, BONE_START_Y, 0);
        }
        else {
            bonePos.y -= BONE_SPEED;
            set_projectile_dog_position(bonePos.x, bonePos.y, 1);
        }
    }
```

```
}


void bone_collision(bool *dogInFlight, bool *mysteryInPlay, int
*mysterySpawnTime,
unsigned short (*catMatrix)[55], unsigned short (*barrierMatrix)[24]) {
    if (!(*dogInFlight)) {
        return;
    }

    unsigned short catNum = 0;



    // Barrier hit
    if ( barrier_hit(barrierMatrix, bonePos, 8, 24) ) {
        set_projectile_dog_position(dogPos + 16, BONE_START_Y, 0);
        *dogInFlight = false;
        return;
    }
    // Mystery hit
    else if (*mysteryInPlay) {

        CollisionBoxes mysteryCollision = {bonePos.x, bonePos.x + 8,
                                    bonePos.y, bonePos.y + 24,
                                    mysteryPos, mysteryPos + 48,
```

```
                                    MYSTERY_Y_POS, MYSTERY_Y_POS + 48};

        if ( mysteryCollision.x1Min < mysteryCollision.x2Max &&
             mysteryCollision.x1Max > mysteryCollision.x2Min &&
             mysteryCollision.y1Min < mysteryCollision.y2Max &&
             mysteryCollision.y1Max > mysteryCollision.y2Min ) {

            *mysteryInPlay = false;
            *mysterySpawnTime = -1;
            score += 10;

            set_ufo_pos(mysteryPos, 0);
            set_projectile_dog_position(dogPos + 16, BONE_START_Y, 0);
            *dogInFlight = false;
        }


    }

    // Checking cat collisions
    for (int i = 0; i < 5; i++) {
        for (int j = 0; j < 11; j++) {
            catNum = 11 * i + j;
            Position catPos = {catMatPos.x + 32 * j, catMatPos.y + 32 * i
};
```

```
        CollisionBoxes collision = {bonePos.x, bonePos.x + 8,
                                    bonePos.y, bonePos.y + 24,
                                    catPos.x, catPos.x + 32,
                                    catPos.y, catPos.y + 32};




        // Collision detected between cat
        if ( collision.x1Min < collision.x2Max &&
             collision.x1Max > collision.x2Min &&
             collision.y1Min < collision.y2Max &&
             collision.y1Max > collision.y2Min &&
             (*catMatrix)[(int) catNum] != 0 ) {


            (*catMatrix)[(int) catNum] =  0;
            explode_cat(&catNum);


            play_meow(0);
            set_projectile_dog_position(dogPos + 16, BONE_START_Y, 0);
            *dogInFlight = false;


            return;
        }
    }
```

```
    }


}


/* ------------------------------------------------------ Player Functions
------------------------------------------------------ */

/* ------------------------------------------------------ Cat Functions
------------------------------------------------------ */


void *explode_cat(void *catNum) {

    unsigned char *target = (unsigned char *) catNum;

    set_sprite_matrix(*target * 2, 5);

    explode_cnt[*target] = 1;


    numCats--;

    (score < 1000) ? score++ : 0;


}


void move_cats(bool *catDir) {

    // Move right

    if (*catDir && catMatPos.x < CAT_RIGHT_WALL) {

        catMatPos.x = clamp(catMatPos.x + CAT_SPEED,

        (unsigned short) CAT_LEFT_WALL, (unsigned short) CAT_RIGHT_WALL);


        set_sprite_pos(catMatPos.x, catMatPos.y);
```

```
    }

    // Move left

    else if (!(*catDir) && catMatPos.x > CAT_LEFT_WALL) {

        if (catMatPos.x < CAT_SPEED) {

            catMatPos.x = 0;

        }

        else {

            catMatPos.x = clamp(catMatPos.x - CAT_SPEED,

            (unsigned short) CAT_LEFT_WALL, (unsigned short)
CAT_RIGHT_WALL);

        }


        set_sprite_pos(catMatPos.x, catMatPos.y);

    }

    // Move down

    else if ( ( *catDir && catMatPos.x == CAT_RIGHT_WALL ) ||

            ( !(*catDir) && catMatPos.x == CAT_LEFT_WALL ) ) {

        catMatPos.y += 16;

        set_sprite_pos(catMatPos.x, catMatPos.y);

        *catDir = !(*catDir);

    }

}
```

```
void check_all_eliminated(unsigned short (*catMatrix)[55], bool
*dogInFlight, bool (*catInFlight)[4], int *mysterySpawnTime, bool
*mysteryInPlay) {

    if(numCats == 0) {

            (level<10) ? level++ : 0;

            numCats = 55;

            reset_objects(catMatrix, mysterySpawnTime, mysteryInPlay);

            sleep(2);

            init_cat_matrix(catMatrix);


            *dogInFlight = false;

            for (int i = 0; i < 4; i++) {

                (*catInFlight)[i] = false;

            }


            bonePos.x = dogPos + 16;

            bonePos.y =  BONE_START_Y;

            set_projectile_dog_position(bonePos.x, bonePos.y, 0);


            for (int i = 1; i < 4; i++) {

                micePos[i].x = 0;

                micePos[i].y = 0;

                set_projectile_sprite(i, micePos[i].x, micePos[i].y, 0);

            }

    }

}
```

```
 void animate_cats(unsigned short frame) {
     set_cat_ani(frame % 2);
 }


unsigned short pick_random_cat(unsigned short catMatrix[55], unsigned
short numCats) {
    unsigned short tmp[numCats];
    int counter = 0;


    for (int i = 0; i < 55; i++) {
        if (catMatrix[i] != 0) {
            tmp[counter++] = i;
        }
    }


    time_t t;
    srand((unsigned) time(&t));


    unsigned short randCat = tmp[rand() % numCats];
    return randCat;


}


int fire_cat_projectile(bool (*catInFlight)[4], unsigned short
catMatrix[55], unsigned short numCats) {
```

```
    // Just picks the first available projectile slot
    for (int i = 1; i < 4; i++) {
        if (!((*catInFlight)[i])) {
            (*catInFlight)[i] = true;

            // Spawns the selected prjectile
            unsigned short randCat = pick_random_cat(catMatrix, numCats);

            Position mousePos = {catMatPos.x + 32 * (randCat % 11) + 16,
                                 catMatPos.y + ( 32 * ((int) (randCat /
11)) ) + 10};

            micePos[i].x = mousePos.x;
            micePos[i].y = mousePos.y;

            set_projectile_sprite(i, micePos[i].x, micePos[i].y, 1);

            return i;
        }
    }
}

void move_cat_projectile(bool (*catInFlight)[4], int *lastShot) {
    for (int i = 1; i < 4; i++) {
        // Shoots the rest if they are in flight
```

```
        if ((*catInFlight)[i] && i != *lastShot) {
            if (micePos[i].y > MOUSE_END_Y) {
                (*catInFlight)[i] = false;
                set_projectile_sprite(i, micePos[i].x, micePos[i].y, 0);
            }
            else {
                micePos[i].y = micePos[i].y + PROJ_SPEED;
                set_projectile_sprite(i, micePos[i].x, micePos[i].y, 1);
            }
        }
    }

    *lastShot = 5;
}

void mouse_collision(bool (*catInFlight)[4], unsigned short
(*barrierMatrix)[24]) {

    for (int i = 1; i < 4; i++) {
        bool *currentCatInFlight = &((*catInFlight)[i]);

        if (!(*currentCatInFlight)) {
            continue;
        }
```

```
// Checking dog collisions
Position completeDogPos = {dogPos, POODLE_Y_POS};

CollisionBoxes collision = {micePos[i].x, micePos[i].x + 8,
                            micePos[i].y, micePos[i].y + 16,
                            completeDogPos.x, completeDogPos.x + 32,
                            completeDogPos.y, completeDogPos.y + 32};


// Barrier hit
if ( barrier_hit(barrierMatrix, micePos[i], 8, 16) ) {
    set_projectile_sprite(i, micePos[i].x, micePos[i].y, 0);
    (*catInFlight)[i] = false;
}
// Collision detected between dog
else if ( collision.x1Min < collision.x2Max &&
    collision.x1Max > collision.x2Min &&
    collision.y1Min < collision.y2Max &&
    collision.y1Max > collision.y2Min) {

    lives--;

    play_bark(0);
    set_projectile_sprite(i, micePos[i].x, micePos[i].y, 0);
```

```
            (*catInFlight)[i] = false;
        }
    }

}

int pick_mystery_spawn() {
    time_t t;
    srand((unsigned) time(&t));
    int offset = rand() % 6;

    if (rand() % 2 == 0) {
        offset *= -1;
    }

    return (25 + offset) * 60;
}

void spawn_mystery(bool *mysteryInPlay) {
    printf("Mystery spawned\n");
    *mysteryInPlay = true;
    mysteryPos = 640;
    set_ufo_pos(mysteryPos, 1);
}
```

```
void update_mystery(bool *mysteryInPlay, int *mysterySpawnTime) {

    if (*mysteryInPlay) {

        if (mysteryPos != 0) {

            if (mysteryPos < MYSTERY_SPEED) {

                mysteryPos = 0;

            }

            else {

                mysteryPos -= MYSTERY_SPEED;

            }


            printf("Mystery Moving: %u\n", mysteryPos);

            set_ufo_pos(mysteryPos, 1);

        }

        else {

            *mysteryInPlay = false;

            *mysterySpawnTime = -1;


            printf("Mystery despawned\n");

            set_ufo_pos(mysteryPos, 0);

        }

    }

}


void reached_bottom(unsigned short catMatrix[55]) {

    int bottomMostRow;
```

```
    bool broke = false;


    for (int i = 4; i >= 0; i--) {
        bottomMostRow = i;


        for (int j = 0; j < 11; j++) {
            int catNum = j + 11 * i;


            if (catMatrix[catNum] != 0) {
                broke = true;
                break;
            }
        }


        if (broke) {
            break;
        }
    }


    unsigned short bottomY = catMatPos.y + 32 * (bottomMostRow + 1);
    if (bottomY > BOTTOM_CUTOFF) {
        lives = 0;
        printf("Cats reached the bottom, you lose.\n");
    }
```

```
}


/* ------------------------------------------------------ Cat Functions
------------------------------------------------------ */



void start_game() {

    unsigned short catMatrix[55];

    unsigned short barrierMatrix[24];

    unsigned short tmp = 0;

    int lastShot = 5;


    unsigned short frame = 0;


    unsigned long long counter = 0;


    // true = left, false = right

    bool dogDir = true;

    bool catDir = true;


    bool isWalking = false;


    bool dogInFlight = false;

    bool catInFlight[4] = {false, false, false, false};

    bool mysteryInPlay = false;
```

```
    int mysterySpawnTime = -1;


    controller_init();
    init_driver();


    reset_barrier_matrix(&barrierMatrix);
    reset_objects(&catMatrix, &mysterySpawnTime, &mysteryInPlay);
    set_speed(2);
    play_background(0);


    set_status(level, gameStatus, lives);


    while(controller_get_state().startPressed == 0);
    while(controller_get_state().startPressed == 1);
    init_cat_matrix(&catMatrix);
    gameStatus = 1;




    // Update this thing
    while (true) {
        // Wait
        while( (tmp&0x7FFF) == (get_frame_reg()&0x7FFF));
        tmp = get_frame_reg();


        if(counter % 30 == 0) {
```

```
            animation_tracker(&frame);
        }
        counter++;



        ControllerState state = controller_get_state();
        update_player_state(&dogDir, &isWalking, state);

        // If the spawn time hasn't been found yet, then pick one
        if (mysterySpawnTime < 0) {
            mysterySpawnTime = pick_mystery_spawn();
            printf("New mystery timer: %i\n", mysterySpawnTime);
        }

        // 1. Check if all of the cats have been eliminated
        check_all_eliminated(&catMatrix, &dogInFlight, &catInFlight,
&mysterySpawnTime, &mysteryInPlay);

        // 2. Check for player collisions (mouse)
        bone_collision(&dogInFlight, &mysteryInPlay, &mysterySpawnTime,
&catMatrix, &barrierMatrix);

        // 3. Check for cat collisions (bone)
        mouse_collision(&catInFlight, &barrierMatrix);

        // 4. Move the cats (including animations)
```

```
        // Calls move more often when there are less cats.
        if( (numCats != 0) && ( counter % (5 - ( (int) ( ( 55 - numCats ) / 11 )) )  == 0)) {
            move_cats(&catDir);
         }
        if(counter % 60 == 0) {
            // Q: i was 56, was there a reason for that? wouldn't that overflow?
            for(int i = 0; i < 55; i++) {
                if(explode_cnt[i] == 1) {
                    set_sprite_matrix(i * 2, 0);
                    explode_cnt[i] = 0;
                }

            }
         }
         animate_cats(frame);

        // 5. Move the player (including animations)
        move_player(state);
        animate_player(frame, dogDir, isWalking); // Change the frame to the updated thing

        // 6. Fire (if applicable) and move cat projectiles
        if( counter % (330 - (30 * level)) == 0)
```

```
            lastShot = fire_cat_projectile(&catInFlight, catMatrix,
numCats);
        move_cat_projectile(&catInFlight, &lastShot);

        // 7. Fire (if applicable) and move player projectile
        update_bone_projectile(state, &dogInFlight);

        // 8. Update score
        set_score(score);

        // 9. Check if cats reached the bottom
        reached_bottom(catMatrix);

        // 10. Update status
        check_lives(&catMatrix, &barrierMatrix, &mysterySpawnTime,
&mysteryInPlay);
        set_status(level, gameStatus, lives);

        // 11. Update the mystery
        if (counter % mysterySpawnTime == 0)
            spawn_mystery(&mysteryInPlay);
        update_mystery(&mysteryInPlay, &mysterySpawnTime);

    }

}
```

```
int main() {

    start_game();

    return 0;
}
```

12.5 interface.c

```
/*
 * Userspace program that communicates with the cat_invaders device driver
 * through ioctls
 *
 * Stephen A. Edwards
 * Columbia University
 */

#include <stdio.h>
#include "cat_invaders.h"
#include "interface.h"
#include <sys/ioctl.h>
#include <sys/types.h>
#include <sys/stat.h>
#include <fcntl.h>
#include <string.h>
```

```c
#include <unistd.h>


int cat_invaders_fd;

cat_invaders_arg_t vla;


void init_driver(){

    static const char filename[] = "/dev/cat_invaders";

    if ( (cat_invaders_fd = open(filename, O_RDWR)) == -1) {

        fprintf(stderr, "could not open %s\n", filename);

    }

    printf("driver init");

}




void set_dog_pos(unsigned short value){

    vla.dog_p_x = value;


    if (ioctl(cat_invaders_fd, WRITE_DOG_POSITION , &vla)) {

      perror("ioctl(WRITE_DOG_POSITION) failed");

    }

    //printf("Write DOG X_LSB: 0x%X X_MSB: 0x%X\n", reg_lsb, reg_msb);

}
```

```
void set_projectile_dog(unsigned short x, unsigned short y, unsigned short
visibility){

    vla.projectile_dog.p_x = x;

    vla.projectile_dog.p_y = (y |= (visibility << 15));



    if (ioctl(cat_invaders_fd, WRITE_PROJECTILE_DOG , &vla)) {

      perror("ioctl(WRITE_PROJECTILE_DOG) failed");

    }



    //printf("Write X_LSB: 0x%X X_MSB: 0x%X Y:0x%X\n", reg_lsb, reg_msb,
y);



}



void set_projectile_sprite(unsigned char number, unsigned short x,
unsigned short y, unsigned short visibility){



    switch (number){

        case 0:   vla.projectile_cat_group.c0.x = x;

                  vla.projectile_cat_group.c0.y = (y |= (visibility <<
15)) ;

                  if (ioctl(cat_invaders_fd, WRITE_PROJECTILE_CAT_0 ,
&vla)) {

                  perror("ioctl(WRITE_PROJECTILE_SPRITES_0) failed");}

                  break;

        case 1:  vla.projectile_cat_group.c1.x = x;
```

```
                    vla.projectile_cat_group.c1.y = (y |= (visibility <<
15)) ;

                    if (ioctl(cat_invaders_fd, WRITE_PROJECTILE_CAT_1 ,
&vla)) {

                    perror("ioctl(WRITE_PROJECTILE_SPRITES_1) failed");}

                    break;

        case 2:     vla.projectile_cat_group.c2.x = x;

                    vla.projectile_cat_group.c2.y = (y |= (visibility <<
15)) ;

                    if (ioctl(cat_invaders_fd, WRITE_PROJECTILE_CAT_2 ,
&vla)) {

                    perror("ioctl(WRITE_PROJECTILE_SPRITES_2) failed");}

                    break;

        case 3:     vla.projectile_cat_group.c3.x = x;

                    vla.projectile_cat_group.c3.y = (y |= (visibility <<
15)) ;

                    if (ioctl(cat_invaders_fd, WRITE_PROJECTILE_CAT_3 ,
&vla)) {

                    perror("ioctl(WRITE_PROJECTILE_SPRITES_3) failed");}

                    break;

        default: break;

    }



    //printf("Write S%X: X:0x%X  Y:0x%X\n", number, *x, *y);

}
```

```
void set_sprite_pos(unsigned short x, unsigned short y){

    vla.cat_matrix_pos.x = x;

    vla.cat_matrix_pos.y = y;



    if (ioctl(cat_invaders_fd, WRITE_CAT_MATRIX_POSITION , &vla)) {

      perror("ioctl(WRITE_SPRITE_POSITION) failed");}


    //printf("Write SPRITE POS: X: 0x%X  Y:0x%X\n", *x, *y);

}




void set_ufo_pos(unsigned short x, unsigned short visibility){

    vla.mystery_pos_x = x;

    if (ioctl(cat_invaders_fd, WRITE_MYSTERY_POSITION , &vla)) {

      perror("ioctl(WRITE_UFO_POSITION) failed");}


    //printf("Write UFO POS: X_LSB: 0x%X X_MSB: 0x%X\n", reg_lsb,
reg_msb);

}



void set_level(unsigned short value){

    unsigned short status = vla.status;

    status &= 0xF0FF;

    status |= (value << 4);

    vla.status = status;
```

```
    if (ioctl(cat_invaders_fd, WRITE_STATUS , &vla))
{perror("ioctl(WRITE_level) failed");}

}


void set_lives(unsigned short value){

    unsigned short status = vla.status;

    status &= 0xFFFC;

    status |= value;

    vla.status = status;

    if (ioctl(cat_invaders_fd, WRITE_STATUS , &vla))
{perror("ioctl(WRITE_lives) failed");}

}


void set_gameStatus(unsigned short value){

    unsigned short status = vla.status;

    status &= 0xFFF3;

    status |= value<<2;

    vla.status = status;

    if (ioctl(cat_invaders_fd, WRITE_STATUS , &vla))
{perror("ioctl(WRITE_gameStatus) failed");}

}


void set_score(unsigned short score){

    unsigned short units = score % 10;

    unsigned short tens = (score / 10) % 10;

    unsigned short hundreds = (score / 100) % 10;
```

```
    vla.score = hundreds | (tens << 4) | (units << 8);

    if (ioctl(cat_invaders_fd, WRITE_SCORE , &vla))
{perror("ioctl(WRITE_SCORE ) failed");}

   // printf("Write score: %X\n", *score);

}



void set_dog_ani(unsigned short state){

    vla.dog_ani = state;

    if (ioctl(cat_invaders_fd, WRITE_DOG_ANIMATION , &vla))
{perror("ioctl(WRITE_ANIMATION ) failed");}

    //printf("Write animation target: %X, direction: %X, state:%X\n",
target, *direction, *state)

}



void set_cat_ani(unsigned short state){

    vla.cat_ani = state;

    if (ioctl(cat_invaders_fd, WRITE_CAT_ANIMATION , &vla))
{perror("ioctl(WRITE_ANIMATION ) failed");}

    //printf("Write animation target: %X, direction: %X, state:%X\n",
target, *direction, *state)

}



void set_barrier(unsigned short number, unsigned short status){

    unsigned short barrier = (number << 3) | status;

    vla.barrier_mat = barrier;

    if (ioctl(cat_invaders_fd, WRITE_BARRIER , &vla))
{perror("ioctl(WRITE_BARRIER ) failed");}
```

```
    //printf("Write Barrier: %X, state:%X\n", *number, *status);
}
void set_sprite_matrix(unsigned char target, unsigned short status){
    vla.cat_mat = (target << 3) | status;

    if (ioctl(cat_invaders_fd, WRITE_CAT_MATRIX , &vla))
{perror("ioctl(WRITE_CAT_MATRIX) failed"); }
}

void play_background(unsigned char volume){
    //vla.audio.background = (0x20 | volume);
    vla.audio.background = 0xf0;

    if (ioctl(cat_invaders_fd, WRITE_BG , &vla)) {perror("ioctl(WRITE_BG )
failed");}
    //printf("Play Background: %X\n", *state);
}

void play_bark(unsigned char volume){
    vla.audio.bark = 0x00;
    if (ioctl(cat_invaders_fd, WRITE_BARK , &vla))
{perror("ioctl(WRITE_BARK ) failed");}
    vla.audio.bark = (0x20 | volume);
```

```
    if (ioctl(cat_invaders_fd, WRITE_BARK , &vla))
{perror("ioctl(WRITE_BARK ) failed");}

    //printf("Play Bark: %X\n", *state);

}


void play_meow(unsigned char volume){

    vla.audio.meow = 0x00;

    if (ioctl(cat_invaders_fd, WRITE_MEOW , &vla))
{perror("ioctl(WRITE_MEOW ) failed");}

    vla.audio.meow = (0x20|volume);

    if (ioctl(cat_invaders_fd, WRITE_MEOW , &vla))
{perror("ioctl(WRITE_MEOW ) failed");}

    //printf("Play Meow: %X\n", *state);

}


void set_speed(unsigned char speed){

    vla.audio.speed = speed;

    if (ioctl(cat_invaders_fd, WRITE_SPEED , &vla))
{perror("ioctl(WRITE_MEOW ) failed");}

    //printf("Play Meow: %X\n", *state);

}


void clear_irq(unsigned short irq){

    vla.irq = irq;

    if (ioctl(cat_invaders_fd, CLEAR_IRQ , &vla))
{perror("ioctl(WRITE_MEOW ) failed");}

    //printf("Play Meow: %X\n", *state);
```

```
}
```

12.6 interface.h

```
#ifndef CAT_INVADERS_INTERFACE_H

#define CAT_INVADERS_INTERFACE_H



//#include <sys/types.h>

#include "cat_invaders.h"



typedef struct {

   unsigned short x;

   unsigned short y;

} Position;

cat_invaders_arg_t vla;

void init_driver(void);



/*set the dog's x position, y is fixed*/

void set_dog_pos(unsigned short x);



/*dog bullet position x and y, idk what is the visibility used for in hw, but should
be added when calling the function*/

void set_projectile_dog_position(unsigned short x, unsigned short y, unsigned short
visibility);



/*set the 4 projectile positions for cats. num: 0-3; position x, y*/
```

```
void set_projectile_sprite(unsigned char number, unsigned short x, unsigned short y,
unsigned short visibility);


/*set the cat matrix position (Left Top position)*/
void set_sprite_pos(unsigned short x, unsigned short y);


/*set ufo's x position, y is fixed*/
void set_ufo_pos(unsigned short x, unsigned short vis);
void set_status(unsigned short level, unsigned short gameStatus, unsigned short
life);
/*set level range: 0-8*/
void set_level(unsigned short value);
/*set lives range: 0-3*/
void set_lives(unsigned short value);
/*set game status: 0: 1: 2: */
void set_gameStatus(unsigned short value);
/*set score range: 0-999*/
void set_score(unsigned short value);
void set_dog_ani(unsigned short state);
void set_cat_ani(unsigned short state);


/*To set the four barrier's state, number 0-23 (0-5, 6-11, 12-17, 18-23 for each
barrier respectively)
and status 0-4 (from full to destroyed)  */


void set_barrier(unsigned short number, unsigned short status);
/*set a cat's statue, cat should be 0-54, and status:0-4 */
```

```
void set_sprite_matrix(unsigned char target, unsigned short status);



/* volume from 0 - 15*/

void play_background(unsigned char volume);

void play_bark(unsigned char volume);

void play_meow(unsigned char volume);

/*speed ranging from 0 - 6*/

void set_speed(unsigned char speed);

void set_explosion(unsigned short x, unsigned short y, unsigned short visibility);

void clear_irq(unsigned short irq);



unsigned short get_test_reg(void);

unsigned short get_frame_reg(void);



// unsigned char get_bullet(void);

// unsigned short get_dog_pos(void);

// Position get_projectile_dog(void);

// Position get_projectile_sprites(unsigned char target);

// Position get_sprite_pos(void);

// void get_sprite_matrix(void);

// unsigned short get_ufo_pos(void);

// unsigned char get_misc1(void);

// unsigned short get_score(void);

// unsigned char get_barrier(unsigned char target);

// unsigned char get_animation_dog(void);

// unsigned char get_animation_cat(void);
```

```
// unsigned char get_background(void);

// unsigned char get_bark(void);

// unsigned char get_meow(void);



#endif
```

12.7 cat_invaders.c

```
/* * Device driver for the VGA video and audio generator

 *

 * A Platform device implemented using the misc subsystem

 *

 * Stephen A. Edwards

 * Columbia University

 *

 * References:

 * Linux source: Documentation/driver-model/platform.txt

 *               drivers/misc/arm-charlcd.c

 * http://www.linuxforu.com/tag/linux-device-drivers/

 * http://free-electrons.com/docs/

 *

 * "make" to build

 * insmod cat_invaders.ko

 *

 * Check code style with
```

```
 * checkpatch.pl --file --no-tree cat_invaders.c
 */


#include <linux/module.h>
#include <linux/init.h>
#include <linux/errno.h>
#include <linux/version.h>
#include <linux/kernel.h>
#include <linux/platform_device.h>
#include <linux/miscdevice.h>
#include <linux/slab.h>
#include <linux/io.h>
#include <linux/of.h>
#include <linux/of_address.h>
#include <linux/fs.h>
#include <linux/uaccess.h>
#include "cat_invaders.h"
#include <linux/interrupt.h>
#include <linux/ioport.h>


#define DRIVER_NAME "cat_invaders"


/* Device registers */
#define DOG_POS(x) (x)
#define PROJECT_D_X(x) ((x)+2)
```

```
#define PROJECT_D_Y(x) ((x)+4)

#define PROJECT_C0_X(x) ((x)+6)

#define PROJECT_C0_Y(x) ((x)+8)

#define PROJECT_C1_X(x) ((x)+10)

#define PROJECT_C1_Y(x) ((x)+12)

#define PROJECT_C2_X(x) ((x)+14)

#define PROJECT_C2_Y(x) ((x)+16)

#define PROJECT_C3_X(x) ((x)+18)

#define PROJECT_C3_Y(x) ((x)+20)

#define CAT_ARRAY_POS_X(x) ((x)+22)

#define CAT_ARRAY_POS_Y(x) ((x)+24)

#define MYSTERY_POS_X(x) ((x)+26)

#define STATUS(x) ((x)+28)

#define SCORE(x) ((x)+30)

#define DOG_ANI(x) ((x)+32)

#define CAT_ANI(x) ((x)+34)

#define BARRIER_MAT(x) ((x)+(46*2))

#define CAT_MAT(x) ((x)+58)

#define AUDIO_BG(x) ((x)+84)

#define AUDIO_BARK(x) ((x)+86)

#define AUDIO_MEOW(x) ((x)+88)

#define AUDIO_SPEED(x) ((x)+90)

#define EOF_IRQ(x) ((x)+94)

#define EXPLOSION_X(x) ((x) + 18*2)

#define EXPLOSION_Y(x) ((x) + 19 *2)
```

```
#define UINPUT_INT_NUM 72

/*
 * Information about our device
 */
struct cat_invaders_dev {
    struct resource res; /* Resource: our registers */
    void __iomem *virtbase; /* Where registers can be accessed in memory
*/
    unsigned short dog_p_x;
    projectile_dog_t projectile_dog;
    projectile_cat_group_t projectile_cat_group;
    cat_matrix_position_t cat_matrix_pos;
    unsigned short mystery_pos_x;
    unsigned short status;
    unsigned short score;
    unsigned short dog_ani;
    unsigned short cat_ani;
    unsigned short barrier_mat;
    unsigned short cat_mat;
    audio_t audio;
    unsigned short irq;
            explosion_t explosion;
} dev;
```

```
/* IRQ STUFF*/

static DECLARE_WAIT_QUEUE_HEAD(interrupt_wq);

static int interrupt_flag = 0;

static DEFINE_SPINLOCK(interrupt_flag_lock);


/*functions*/


/*dog position*/

static void write_dog_pos(unsigned short *value)

{

    iowrite16(*value, DOG_POS(dev.virtbase));

    dev.dog_p_x = *value;

}


/*projectile dog*/

static void write_projectile_dog(projectile_dog_t *pos)

{

    iowrite16(pos->p_x, PROJECT_D_X(dev.virtbase));

    iowrite16(pos->p_y, PROJECT_D_Y(dev.virtbase));

    dev.projectile_dog = *pos;

}


/*projectile cats*/

static void write_projectile_cats(projectile_cat_group_t *pro_cats,
unsigned char num)
```

```
{
    switch(num){
        case 0: iowrite16(pro_cats->c0.x, PROJECT_C0_X(dev.virtbase));
                iowrite16(pro_cats->c0.y, PROJECT_C0_Y(dev.virtbase));
                dev.projectile_cat_group.c0 = pro_cats->c0; break;
        case 1: iowrite16(pro_cats->c1.x, PROJECT_C1_X(dev.virtbase));
                iowrite16(pro_cats->c1.y, PROJECT_C1_Y(dev.virtbase));
                dev.projectile_cat_group.c1 = pro_cats->c1; break;
        case 2: iowrite16(pro_cats->c2.x, PROJECT_C2_X(dev.virtbase));
                iowrite16(pro_cats->c2.y, PROJECT_C2_Y(dev.virtbase));
                dev.projectile_cat_group.c2 = pro_cats->c2; break;
        case 3: iowrite16(pro_cats->c3.x, PROJECT_C3_X(dev.virtbase));
                iowrite16(pro_cats->c3.y, PROJECT_C3_Y(dev.virtbase));
                dev.projectile_cat_group.c3 = pro_cats->c3; break;
    default: break;
    }

}

/*cat matrix position*/
static void write_cat_pos(cat_matrix_position_t *pos)
{
    iowrite16(pos->x, CAT_ARRAY_POS_X(dev.virtbase));
    iowrite16(pos->y, CAT_ARRAY_POS_Y(dev.virtbase));
    dev.cat_matrix_pos = *pos;
```

```
}


/*ufo position*/
static void write_ufo_pos(unsigned short *value)
{
    iowrite16(*value, MYSTERY_POS_X(dev.virtbase));
    dev.mystery_pos_x = *value;
}


/* misc 1*/
static void write_status(unsigned short *status)
{
    iowrite16(*status, STATUS(dev.virtbase));
    dev.status = *status;
}


/* score*/
static void write_score(unsigned short *score)
{
    iowrite16(*score, SCORE(dev.virtbase));
    dev.score = *score;
}


/* dog animation*/
static void write_dog_animation(unsigned short *dog_ani)
```

```
{
    iowrite16(*dog_ani, DOG_ANI(dev.virtbase));
    dev.dog_ani = *dog_ani;
}


/* cat animation*/
static void write_cat_animation(unsigned short *cat_ani)
{
    iowrite16(*cat_ani, CAT_ANI(dev.virtbase));
    dev.cat_ani = *cat_ani;
}


/* barrier*/
static void write_barrier(unsigned short *barrier)
{
    iowrite16(*barrier, BARRIER_MAT(dev.virtbase));
    dev.barrier_mat = *barrier;
}


/* cat matrix*/
static void write_cat_matrix(unsigned short *value)
{
    iowrite16(*value, CAT_MAT(dev.virtbase));
    dev.cat_mat = *value;
}
```

```
/* audio*/
static void write_bg(unsigned short *value)
{
    iowrite16(*value, AUDIO_BG(dev.virtbase));
    dev.audio.background = *value;
}
static void write_bark(unsigned short *value)
{
    iowrite16(*value, AUDIO_BARK(dev.virtbase));
    dev.audio.bark = *value;
}
static void write_meow(unsigned short *value)
{
    iowrite16(*value, AUDIO_MEOW(dev.virtbase));
    dev.audio.meow = *value;
}
static void write_speed(unsigned short *value)
{
    iowrite16(*value, AUDIO_SPEED(dev.virtbase));
    dev.audio.speed = *value;
}
static void clear_irq(unsigned short *value)
{
    iowrite16(*value,  EOF_IRQ(dev.virtbase));
```

```
    dev.irq = *value;
}
static void write_explosion(explosion_t *explosion){

        iowrite16(explosion->x, EXPLOSION_X(dev.virtbase));
        iowrite16(explosion->y, EXPLOSION_Y(dev.virtbase));
        dev.explosion = *explosion;
    }

/*
 * Handle ioctl() calls from userspace:
 * Read or write the segments on single digits.
 * Note extensive error checking of arguments
 */
static long cat_invaders_ioctl(struct file *f, unsigned int cmd, unsigned
long arg)
{
    cat_invaders_arg_t vla;
    switch (cmd) {

    case WRITE_DOG_POSITION:

        if (copy_from_user(&vla, (cat_invaders_arg_t *) arg,
sizeof(cat_invaders_arg_t)))
            return -EACCES;
        write_dog_pos(&vla.dog_p_x);
```

```
        break;


    case WRITE_PROJECTILE_DOG:


        if (copy_from_user(&vla, (cat_invaders_arg_t *) arg,
sizeof(cat_invaders_arg_t)))
            return -EACCES;
        write_projectile_dog(&vla.projectile_dog);
        break;


    case WRITE_PROJECTILE_CAT_0:


        if (copy_from_user(&vla, (cat_invaders_arg_t *) arg,
sizeof(cat_invaders_arg_t)))
            return -EACCES;
        write_projectile_cats(&vla.projectile_cat_group, 0);
        break;


    case WRITE_PROJECTILE_CAT_1:


        if (copy_from_user(&vla, (cat_invaders_arg_t *) arg,
sizeof(cat_invaders_arg_t)))
            return -EACCES;
        write_projectile_cats(&vla.projectile_cat_group, 1);
        break;
```

```
    case WRITE_PROJECTILE_CAT_2:


        if (copy_from_user(&vla, (cat_invaders_arg_t *) arg,
sizeof(cat_invaders_arg_t)))
            return -EACCES;
        write_projectile_cats(&vla.projectile_cat_group, 2);
        break;


    case WRITE_PROJECTILE_CAT_3:


        if (copy_from_user(&vla, (cat_invaders_arg_t *) arg,
sizeof(cat_invaders_arg_t)))
            return -EACCES;
        write_projectile_cats(&vla.projectile_cat_group, 3);
        break;


    case WRITE_CAT_MATRIX_POSITION:


        if (copy_from_user(&vla, (cat_invaders_arg_t *) arg,
sizeof(cat_invaders_arg_t)))
            return -EACCES;
        write_cat_pos(&vla.cat_matrix_pos);
        break;


    case WRITE_MYSTERY_POSITION:
```

```
        if (copy_from_user(&vla, (cat_invaders_arg_t *) arg,
sizeof(cat_invaders_arg_t)))
            return -EACCES;
        write_ufo_pos(&vla.mystery_pos_x);
        break;



    case WRITE_STATUS:


        if (copy_from_user(&vla, (cat_invaders_arg_t *) arg,
sizeof(cat_invaders_arg_t)))
            return -EACCES;
        write_status(&vla.status);
        break;


    case WRITE_SCORE:


        if (copy_from_user(&vla, (cat_invaders_arg_t *) arg,
sizeof(cat_invaders_arg_t)))
            return -EACCES;
        write_score(&vla.score);
        break;


    case WRITE_DOG_ANIMATION:
```

```
        if (copy_from_user(&vla, (cat_invaders_arg_t *) arg,
sizeof(cat_invaders_arg_t)))
            return -EACCES;
        write_dog_animation(&vla.dog_ani);
        break;

    case WRITE_CAT_ANIMATION:

        if (copy_from_user(&vla, (cat_invaders_arg_t *) arg,
sizeof(cat_invaders_arg_t)))
            return -EACCES;
        write_cat_animation(&vla.cat_ani);
        break;

    case WRITE_BARRIER:

        if (copy_from_user(&vla, (cat_invaders_arg_t *) arg,
sizeof(cat_invaders_arg_t)))
            return -EACCES;
        write_barrier(&vla.barrier_mat);
        break;

    case WRITE_CAT_MATRIX:

        if (copy_from_user(&vla, (cat_invaders_arg_t *) arg,
sizeof(cat_invaders_arg_t)))
```

```
            return -EACCES;

        write_cat_matrix(&vla.cat_mat);

        break;


    case WRITE_BG:


        if (copy_from_user(&vla, (cat_invaders_arg_t *) arg,
sizeof(cat_invaders_arg_t)))

            return -EACCES;

        write_bg(&vla.audio.background);

        break;


    case WRITE_BARK:


        if (copy_from_user(&vla, (cat_invaders_arg_t *) arg,
sizeof(cat_invaders_arg_t)))

            return -EACCES;

        write_bark(&vla.audio.bark);

        break;


    case WRITE_MEOW:


        if (copy_from_user(&vla, (cat_invaders_arg_t *) arg,
sizeof(cat_invaders_arg_t)))

            return -EACCES;

        write_meow(&vla.audio.meow);
```

```
        break;


    case WRITE_SPEED:


        if (copy_from_user(&vla, (cat_invaders_arg_t *) arg,
sizeof(cat_invaders_arg_t)))
            return -EACCES;
        write_speed(&vla.audio.speed);
        break;


    case CLEAR_IRQ:
        if (copy_from_user(&vla, (cat_invaders_arg_t *) arg,
sizeof(cat_invaders_arg_t)))
            return -EACCES;
        clear_irq(&vla.irq);
        break;
 case WRITE_EXPLOSION:
    if (copy_from_user(&vla, (cat_invaders_arg_t *) arg,
sizeof(cat_invaders_arg_t)))
            return -EACCES;
        write_explosion(&vla.explosion);
        break;
    default:
        return -EINVAL;
    }
    return 0;
```

```
}


/* The operations our device knows how to do */
static const struct file_operations cat_invaders_fops = {
    .owner      = THIS_MODULE,
    .unlocked_ioctl = cat_invaders_ioctl,
};


/* Information about our device for the "misc" framework -- like a char
dev */
static struct miscdevice cat_invaders_misc_device = {
    .minor      = MISC_DYNAMIC_MINOR,
    .name       = DRIVER_NAME,
    .fops       = &cat_invaders_fops,
};


/*
 * Initialization code: get resources (registers) and display
 * a welcome message
 */
static int __init cat_invaders_probe(struct platform_device *pdev)
{
        //cat_invaders_color_t beige = { 0xf9, 0xe4, 0xb7 };
        //audio_t audio_begin = { 0x00, 0x00, 0x00 };
    int ret;
```

```
/* Register ourselves as a misc device: creates /dev/cat_invaders */
ret = misc_register(&cat_invaders_misc_device);

/* Get the address of our registers from the device tree */
ret = of_address_to_resource(pdev->dev.of_node, 0, &dev.res);
if (ret) {
    ret = -ENOENT;
    goto out_deregister;
}

/* Make sure we can use these registers */
if (request_mem_region(dev.res.start, resource_size(&dev.res),
                DRIVER_NAME) == NULL) {
    ret = -EBUSY;
    goto out_deregister;
}

/* Arrange access to our registers */
dev.virtbase = of_iomap(pdev->dev.of_node, 0);
if (dev.virtbase == NULL) {
    ret = -ENOMEM;
    goto out_release_mem_region;
}
```

```
    return 0;


out_release_mem_region:
    release_mem_region(dev.res.start, resource_size(&dev.res));
out_deregister:
    misc_deregister(&cat_invaders_misc_device);
    return ret;
}


/* Clean-up code: release resources */
static int cat_invaders_remove(struct platform_device *pdev)
{
    iounmap(dev.virtbase);
    release_mem_region(dev.res.start, resource_size(&dev.res));
    misc_deregister(&cat_invaders_misc_device);
    return 0;
}


/* Which "compatible" string(s) to search for in the Device Tree */
#ifdef CONFIG_OF
static const struct of_device_id cat_invaders_of_match[] = {
    { .compatible = "csee4840,cat_invaders-1.0" },
    {},
};
```

```
MODULE_DEVICE_TABLE(of, cat_invaders_of_match);
#endif


/* Information for registering ourselves as a "platform" driver */
static struct platform_driver cat_invaders_driver = {
    .driver = {
        .name   = DRIVER_NAME,
        .owner  = THIS_MODULE,
        .of_match_table = of_match_ptr(cat_invaders_of_match),
    },
    .remove = __exit_p(cat_invaders_remove),
};


/* Called when the module is loaded: set things up */
static int __init cat_invaders_init(void)
{
    pr_info(DRIVER_NAME ": init\n");
    return platform_driver_probe(&cat_invaders_driver,
cat_invaders_probe);
}


/* Calball when the module is unloaded: release resources */
static void __exit cat_invaders_exit(void)
{
    platform_driver_unregister(&cat_invaders_driver);
```

```
    pr_info(DRIVER_NAME ": exit\n");
}


module_init(cat_invaders_init);
module_exit(cat_invaders_exit);


MODULE_LICENSE("GPL");
MODULE_AUTHOR("Stephen A. Edwards, Columbia University");
MODULE_DESCRIPTION("cat_invaders driver");
```

12.8 cat_invaders.h

```
#ifndef _CAT_INVADERS_H
#define _CAT_INVADERS_H


#include <linux/ioctl.h>


/*projectile_dog*/
typedef struct{
   unsigned short p_x;
   unsigned short p_y;
}projectile_dog_t;


/*projectile_cat_sprite*/
typedef struct {
```

```
 unsigned short x;
 unsigned short y;
}projectile_cat_t;


typedef struct {
 projectile_cat_t c0;
 projectile_cat_t c1;
 projectile_cat_t c2;
 projectile_cat_t c3;
}projectile_cat_group_t;


typedef struct {
 unsigned short x;
 unsigned short y;
} explosion_t;




/*cat matrix position*/
typedef struct {
 unsigned short x;
 unsigned short y;
}cat_matrix_position_t;


/*score*/
typedef struct{
   unsigned short score_lsb;
```

```
   unsigned short score_msb;
}score_t;


/*animation*/
typedef struct {
 unsigned short dog_ani;
 unsigned short cat_ani;
}animation_t;


/*audio*/
typedef struct {
 unsigned short background;
 unsigned short bark;
 unsigned short meow;
 unsigned short speed;
}audio_t;


/*Argument*/
typedef struct {
 unsigned short dog_p_x;
 projectile_dog_t projectile_dog;
 projectile_cat_group_t projectile_cat_group;
 explosion_t explosion;
 cat_matrix_position_t cat_matrix_pos;
 unsigned short mystery_pos_x;
 unsigned short status;
```

```
 unsigned short score;
 unsigned short dog_ani;
 unsigned short cat_ani;
 unsigned short barrier_mat;
 unsigned short cat_mat;
 audio_t audio;
 unsigned short irq;
 unsigned short test_reg;
 unsigned short frame_reg;
} cat_invaders_arg_t;



#define CAT_INVADERS_MAGIC 'q'


/* ioctls and their arguments */
//#define WRITE_MISC_0 _IOW(CAT_INVADERS_MAGIC, 1, cat_invaders_arg_t *)
#define WRITE_DOG_POSITION _IOW(CAT_INVADERS_MAGIC, 1, cat_invaders_arg_t *)
#define WRITE_PROJECTILE_DOG _IOW(CAT_INVADERS_MAGIC, 2, cat_invaders_arg_t *)
#define WRITE_PROJECTILE_CAT_0 _IOW(CAT_INVADERS_MAGIC, 3, cat_invaders_arg_t *)
#define WRITE_PROJECTILE_CAT_1 _IOW(CAT_INVADERS_MAGIC, 4, cat_invaders_arg_t *)
#define WRITE_PROJECTILE_CAT_2 _IOW(CAT_INVADERS_MAGIC, 5, cat_invaders_arg_t *)
#define WRITE_PROJECTILE_CAT_3 _IOW(CAT_INVADERS_MAGIC, 6, cat_invaders_arg_t *)
#define WRITE_CAT_MATRIX_POSITION _IOW(CAT_INVADERS_MAGIC, 7, cat_invaders_arg_t *)
#define WRITE_MYSTERY_POSITION _IOW(CAT_INVADERS_MAGIC, 8, cat_invaders_arg_t *)
#define WRITE_STATUS _IOW(CAT_INVADERS_MAGIC, 9, cat_invaders_arg_t *)
#define WRITE_SCORE _IOW(CAT_INVADERS_MAGIC, 10, cat_invaders_arg_t *)
```

```
#define WRITE_BARRIER _IOW(CAT_INVADERS_MAGIC, 11, cat_invaders_arg_t *)

#define WRITE_CAT_MATRIX _IOW(CAT_INVADERS_MAGIC, 12, cat_invaders_arg_t *)

#define WRITE_DOG_ANIMATION _IOW(CAT_INVADERS_MAGIC, 13, cat_invaders_arg_t *)

#define WRITE_CAT_ANIMATION _IOW(CAT_INVADERS_MAGIC, 14, cat_invaders_arg_t *)

#define WRITE_BG _IOW(CAT_INVADERS_MAGIC, 15, cat_invaders_arg_t *)

#define WRITE_BARK _IOW(CAT_INVADERS_MAGIC, 16, cat_invaders_arg_t *)

#define WRITE_MEOW _IOW(CAT_INVADERS_MAGIC, 17, cat_invaders_arg_t *)

#define WRITE_SPEED _IOW(CAT_INVADERS_MAGIC, 18, cat_invaders_arg_t *)

#define CLEAR_IRQ _IOW(CAT_INVADERS_MAGIC, 19, cat_invaders_arg_t *)

#define WRITE_EXPLOSION _IOW(CAT_INVADERS_MAGIC, 20, cat_invaders_arg_t*)


#define READ_TEST_REG _IOR(CAT_INVADERS_MAGIC, 21, cat_invaders_arg_t *)

#define READ_FRAME_REG _IOR(CAT_INVADERS_MAGIC, 22, cat_invaders_arg_t*)


// #define READ_MISC_0 _IOR(CAT_INVADERS_MAGIC, 18, cat_invaders_arg_t *)

// #define READ_DOG_POSITION _IOR(CAT_INVADERS_MAGIC, 19, cat_invaders_arg_t *)

// #define READ_PROJECTILE_DOG _IOR(CAT_INVADERS_MAGIC, 20, cat_invaders_arg_t *)

// #define READ_PROJECTILE_SPRITES _IOR(CAT_INVADERS_MAGIC, 24, cat_invaders_arg_t *)

// #define READ_SPRITE_POSITION _IOR(CAT_INVADERS_MAGIC, 25, cat_invaders_arg_t *)

// #define READ_SPRITE_MATRIX _IOR(CAT_INVADERS_MAGIC, 26, cat_invaders_arg_t *)

// #define READ_UFO_POSITION _IOR(CAT_INVADERS_MAGIC, 27, cat_invaders_arg_t *)

// #define READ_MISC_1 _IOR(CAT_INVADERS_MAGIC, 28, cat_invaders_arg_t *)

// #define READ_SCORE _IOR(CAT_INVADERS_MAGIC, 29, cat_invaders_arg_t *)

// #define READ_BARRIER _IOR(CAT_INVADERS_MAGIC, 30, cat_invaders_arg_t *)

// #define READ_ANIMATION _IOR(CAT_INVADERS_MAGIC, 31, cat_invaders_arg_t *)

// #define READ_BG _IOR(CAT_INVADERS_MAGIC, 32, cat_invaders_arg_t *)
```

```
// #define READ_BARK _IOR(CAT_INVADERS_MAGIC, 33, cat_invaders_arg_t *)

// #define READ_MEOW _IOR(CAT_INVADERS_MAGIC, 34, cat_invaders_arg_t *)



#endif
```

12.9 usbjoypad.c

```
#include "usbjoypad.h"

#include <stdio.h>

#include <stdlib.h>

#include <string.h>

#include <arpa/inet.h>

#include <unistd.h>

#include <pthread.h>



/* References on libusb 1.0 and the USB HID/joypad protocol

*

* http://libusb.org

*
https://web.archive.org/web/20210302095553/https://www.dreamincode.net/forums/topic/148707-introduction-to-using-libusb-10/

*

* https://www.usb.org/sites/default/files/documents/hid1_11.pdf

*

* https://usb.org/sites/default/files/hut1_5.pdf

*/
```

```
/*
* Find and return a USB joypad device or NULL if not found
* The argument con
*
*/
struct libusb_device_handle *openjoypad(uint8_t *endpoint_address) {
 libusb_device **devs;
 struct libusb_device_handle *joypad = NULL;
 struct libusb_device_descriptor desc;
 ssize_t num_devs, d;
 uint8_t i, k;
  /* Start the library */
 if ( libusb_init(NULL) < 0 ) {
   fprintf(stderr, "Error: libusb_init failed\n");
   exit(1);
 }

 /* Enumerate all the attached USB devices */
 if ( (num_devs = libusb_get_device_list(NULL, &devs)) < 0 ) {
   fprintf(stderr, "Error: libusb_get_device_list failed\n");
   exit(1);
 }

 /* Look at each device, remembering the first HID device that speaks
    the joypad protocol */
```

```
for (d = 0 ; d < num_devs ; d++) {
  libusb_device *dev = devs[d];
  if ( libusb_get_device_descriptor(dev, &desc) < 0 ) {
    fprintf(stderr, "Error: libusb_get_device_descriptor failed\n");
    exit(1);
  }

  if (desc.bDeviceClass == LIBUSB_CLASS_PER_INTERFACE) {
    struct libusb_config_descriptor *config;
    libusb_get_config_descriptor(dev, 0, &config);
    for (i = 0 ; i < config->bNumInterfaces ; i++)
for ( k = 0 ; k < config->interface[i].num_altsetting ; k++ ) {
  const struct libusb_interface_descriptor *inter =
    config->interface[i].altsetting + k ;
  if ( inter->bInterfaceClass == LIBUSB_CLASS_HID &&
       inter->bInterfaceProtocol == USB_HID_joypad_PROTOCOL) {
    int r;
    if ((r = libusb_open(dev, &joypad)) != 0) {
      fprintf(stderr, "Error: libusb_open failed: %d\n", r);
      exit(1);
    }
    if (libusb_kernel_driver_active(joypad,i))
      libusb_detach_kernel_driver(joypad, i);
    libusb_set_auto_detach_kernel_driver(joypad, i);
    if ((r = libusb_claim_interface(joypad, i)) != 0) {
      fprintf(stderr, "Error: libusb_claim_interface failed: %d\n", r);
```

```
       exit(1);
     }
     *endpoint_address = inter->endpoint[0].bEndpointAddress;
     goto found;
   }
 }
   }
 }

found:
 libusb_free_device_list(devs, 1);

 return joypad;
}



struct libusb_device_handle *joypad;
uint8_t endpoint_address;
volatile ControllerState state = {false, false, false, false};
pthread_mutex_t stateMutex;



void* controller_update_thread(void* arg) {
   struct usb_joypad_packet packet;
   int transferred;
   while (1) {
```

```
       int result = libusb_interrupt_transfer(joypad, endpoint_address, (unsigned
char*)&packet, sizeof(packet), &transferred, 0);

       if (result == 0 && transferred == sizeof(packet)) {

           pthread_mutex_lock(&stateMutex);

           state.leftArrowPressed = (packet.keycode[1] == 0x00);

           state.rightArrowPressed = (packet.keycode[1] == 0xFF);

           state.buttonAPressed = (packet.keycode[3] == 0x2F);

           state.startPressed = (packet.keycode[4] == 0x20);

           pthread_mutex_unlock(&stateMutex);

       } else {

           continue;

       }

 usleep(100000);

   }

   return NULL;

}



void controller_init() {

   pthread_t threadId;

   pthread_mutex_init(&stateMutex, NULL);



   if ( (joypad = openjoypad(&endpoint_address)) == NULL ) {

       fprintf(stderr, "Did not find a joypad\n");

       exit(1);

   }
```

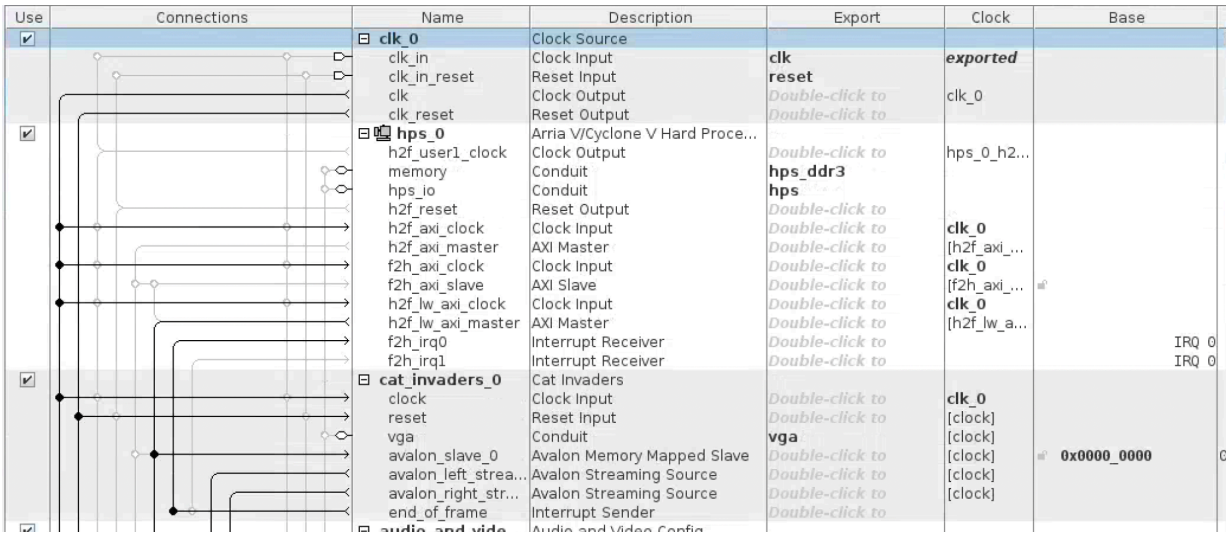
```
    pthread_create(&threadId, NULL, controller_update_thread, NULL);
}


ControllerState controller_get_state() {
    ControllerState currentState;
    pthread_mutex_lock(&stateMutex);
    currentState = state;
    pthread_mutex_unlock(&stateMutex);
    return currentState;
}
```

12.10 usbjoypad.h

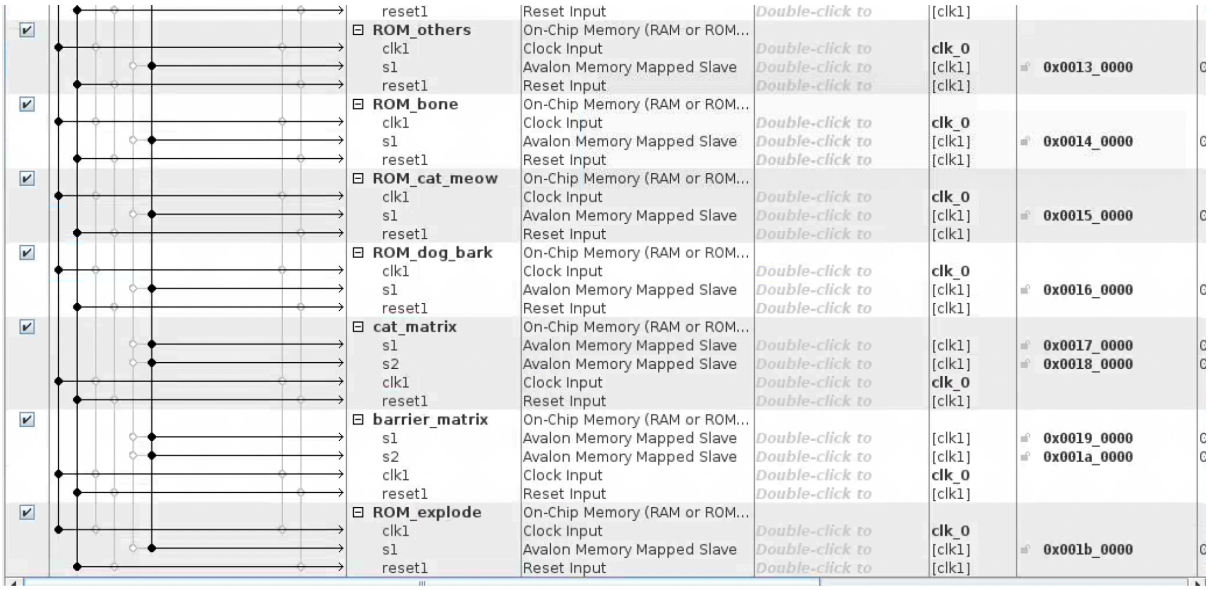
```
#ifndef _USBjoypad_H
#define _USBjoypad_H


#include <libusb-1.0/libusb.h>
#include <stdbool.h>
#define USB_HID_joypad_PROTOCOL 0


struct usb_joypad_packet {
 uint8_t modifiers;
 uint8_t reserved;
```

```
 uint8_t keycode[6];

};



typedef struct {

   bool leftArrowPressed;

   bool rightArrowPressed;

   bool buttonAPressed;

   bool startPressed;

} ControllerState;



void controller_init();

void controller_update();

ControllerState controller_get_state();




/* Find and open a USB joypad device.  Argument should point to

  space to store an endpoint address.  Returns NULL if no joypad

  device was found. */

extern struct libusb_device_handle *openjoypad(uint8_t *);



#endif
```

Appendix B: Platform Design



Use	Connections	Name	Description	Export	Clock	Base
		ROM_cat_2	On-Chip Memory (RAM or ROM...			
		clk1	Clock Input	Double-click to	clk_0	
		s1	Avalon Memory Mapped Slave	Double-click to	[clk1]	0x000b_0000
		reset1	Reset Input	Double-click to	[clk1]	
☑		ROM_cat_3	On-Chip Memory (RAM or ROM...			
		clk1	Clock Input	Double-click to	clk_0	
		s1	Avalon Memory Mapped Slave	Double-click to	[clk1]	0x000c_0000
		reset1	Reset Input	Double-click to	[clk1]	
☑		ROM_cat_4	On-Chip Memory (RAM or ROM...			
		clk1	Clock Input	Double-click to	clk_0	
		s1	Avalon Memory Mapped Slave	Double-click to	[clk1]	0x000d_0000
		reset1	Reset Input	Double-click to	[clk1]	
☑		ROM_Poodles	On-Chip Memory (RAM or ROM...			
		clk1	Clock Input	Double-click to	clk_0	
		s1	Avalon Memory Mapped Slave	Double-click to	[clk1]	0x000e_0000
		reset1	Reset Input	Double-click to	[clk1]	
☑		ROM_barrier	On-Chip Memory (RAM or ROM...			
		clk1	Clock Input	Double-click to	clk_0	
		s1	Avalon Memory Mapped Slave	Double-click to	[clk1]	0x000f_0000
		reset1	Reset Input	Double-click to	[clk1]	
☑		ROM_num	On-Chip Memory (RAM or ROM...			
		clk1	Clock Input	Double-click to	clk_0	
		s1	Avalon Memory Mapped Slave	Double-click to	[clk1]	0x0010_0000
		reset1	Reset Input	Double-click to	[clk1]	
☑		ROM_mystery	On-Chip Memory (RAM or ROM...			
		clk1	Clock Input	Double-click to	clk_0	
		s1	Avalon Memory Mapped Slave	Double-click to	[clk1]	0x0011_0000
		reset1	Reset Input	Double-click to	[clk1]	
☑		ROM_game_over	On-Chip Memory (RAM or ROM...			
		clk1	Clock Input	Double-click to	clk_0	
		s1	Avalon Memory Mapped Slave	Double-click to	[clk1]	0x0012_0000
		reset1	Reset Input	Double-click to	[clk1]	



		reset1	Reset Input	Double-click to	[clk1]	
☑		ROM_others	On-Chip Memory (RAM or ROM...			
		clk1	Clock Input	Double-click to	clk_0	
		s1	Avalon Memory Mapped Slave	Double-click to	[clk1]	0x0013_0000
		reset1	Reset Input	Double-click to	[clk1]	
☑		ROM_bone	On-Chip Memory (RAM or ROM...			
		clk1	Clock Input	Double-click to	clk_0	
		s1	Avalon Memory Mapped Slave	Double-click to	[clk1]	0x0014_0000
		reset1	Reset Input	Double-click to	[clk1]	
☑		ROM_cat_meow	On-Chip Memory (RAM or ROM...			
		clk1	Clock Input	Double-click to	clk_0	
		s1	Avalon Memory Mapped Slave	Double-click to	[clk1]	0x0015_0000
		reset1	Reset Input	Double-click to	[clk1]	
☑		ROM_dog_bark	On-Chip Memory (RAM or ROM...			
		clk1	Clock Input	Double-click to	clk_0	
		s1	Avalon Memory Mapped Slave	Double-click to	[clk1]	0x0016_0000
		reset1	Reset Input	Double-click to	[clk1]	
☑		cat_matrix	On-Chip Memory (RAM or ROM...			
		s1	Avalon Memory Mapped Slave	Double-click to	[clk1]	0x0017_0000
		s2	Avalon Memory Mapped Slave	Double-click to	[clk1]	0x0018_0000
		clk1	Clock Input	Double-click to	clk_0	
		reset1	Reset Input	Double-click to	[clk1]	
☑		barrier_matrix	On-Chip Memory (RAM or ROM...			
		s1	Avalon Memory Mapped Slave	Double-click to	[clk1]	0x0019_0000
		s2	Avalon Memory Mapped Slave	Double-click to	[clk1]	0x001a_0000
		clk1	Clock Input	Double-click to	clk_0	
		reset1	Reset Input	Double-click to	[clk1]	
☑		ROM_explode	On-Chip Memory (RAM or ROM...			
		clk1	Clock Input	Double-click to	clk_0	
		s1	Avalon Memory Mapped Slave	Double-click to	[clk1]	0x001b_0000
		reset1	Reset Input	Double-click to	[clk1]	

Appendix C: The Screen Layout