

# CSEE 4840

## Embedded System Design

### Lab 3: Peripherals and Device Drivers

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Implement on the `FPGA` a memory-mapped peripheral that can receive communication from the `ARM` processors on the Cyclone V. Communicate with your peripheral through a Linux userspace program that accesses a device driver you have written.

Your peripheral should display a ball on the `VGA` screen at coordinates given to it through software. Your device driver should implement an `ioctl` that takes coordinates from the user and sends it to your peripheral

#### 1 Introduction

In this lab, you will control your own hardware from your own software, communicating through a Linux device driver. We supply a base hardware design to extend and a working example of a `VGA` peripheral you will have to modify, and a working device driver for the existing peripheral that you will have to adapt to work with your own peripheral.

You will implement a video bouncing ball in this setting. Your peripheral will generate an `VGA` raster consisting of a ball at a particular location, your userspace C program (software) will make this ball bounce around the screen, and your device driver will mediate between your program and your peripheral.

#### 2 Compile the `VGA` Component Into a New `FPGA` Image

In this section, you will tell Qsys about a new peripheral component, connect it ultimately to the `ARM` processors, and synthesize a new `FPGA` configuration bitstream.

##### 2.1 Create the `VGA` Ball Component

Download `lab3-hw.tar.gz` from the class website and unpack it on your workstation. Change to the `lab3-hw` directory. Run `qsys-edit soc_system.qsys`, which will bring up a GUI.

Create a new `VGA_BALL` component and connect it to the base design. Select File→New Component. This should open the Component Editor window.

In the *Component Type* tab, set Name to `vga_ball` and Display Name to *VGA Ball*.

In the *Files* tab, click *Add File...* under *Synthesis Files* and select the *vga\_ball.sv* file. Click on *Analyze Synthesis Files*. This should quickly complete successfully; close the pop-up window. Set *Top-Level Module* to *vga\_ball*. Some warnings and errors should appear in the *Messages* tab; we will fix them.

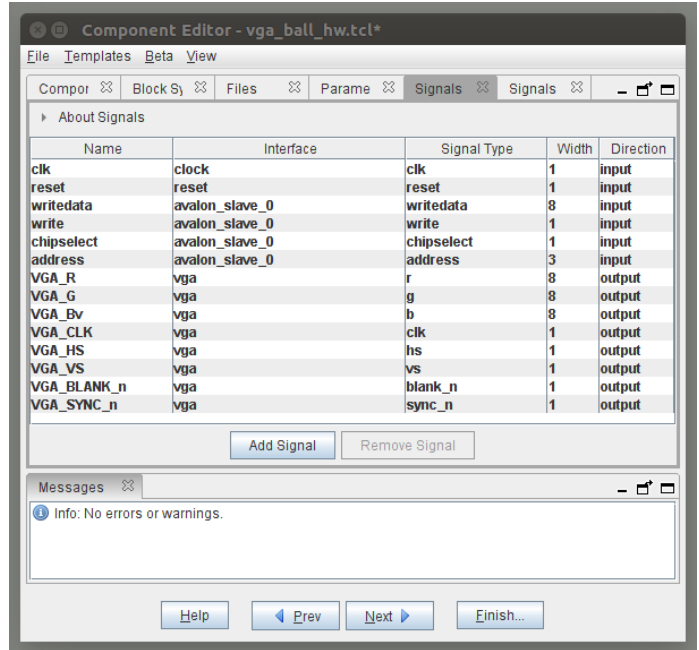
## 2.2 Assign the Interface Signals on the VGA Ball Component

When Qsys analyzes the synthesis files, it makes some good guesses about the meaning of each signal on the peripheral, but it is not perfect. Below, you will fix these mistakes.

Click on the *Signals & Interfaces* tab. Click on *avalon\_slave\_0* and set its *Associated Reset* to *reset*. Click on *<<add interface>>* in the left box and select *Conduit*. Set the name of the new conduit to *vga*.

Select *View*→*Signals* from the top menu. This should bring up a new *Signals* tab.

Change the *Interface* column of each of the *VGA\_* signals to *vga*. Change the *Signal Type* of each signal to a lower-case version of the name after the *VGA\_*, e.g., *VGA\_BLANK\_n* should become *blank\_n*.



Your signals show now appear like the list on the right. If it complains about *avalon\_slave\_0* not having an associated reset, click on *Signals & Interfaces*, click on *avalon\_slave\_0*, and set *Associated Reset* to *reset*.

Once you have eliminated all errors, click on *Finish*. It will warn you that it is saving *vga\_ball\_hw.tcl*; click on *Yes, Save*. The Component Editor window should close.

Open *vga\_ball\_hw.tcl* with a text editor and add the following three lines after the *module vga\_ball* section:

```
set_module_assignment embeddedsw.dts.vendor "csee4840"
set_module_assignment embeddedsw.dts.name "vga_ball"
set_module_assignment embeddedsw.dts.group "vga"
```

These make the device show up as compatible with *csee4840,vga\_ball-1.0* in the *.dtb* file, which we will discuss below.

### 2.3 Connect the VGA Ball Component

Qsys now knows about your custom component, so connect it to the rest of your design.

In Qsys, add an instance of the new *VGA Ball* component by selecting it under “Project” in the library and clicking on the + Add button. By default, it will be named *vga\_ball\_o*.

On the new *vga\_ball\_o* component instance, connect the clock to *clk* from *clk\_o* and connect *reset* to *clk\_reset* from *clk\_o*.

Connect the *avalon\_slave\_o* port on *vga\_ball\_o* to the *h2f\_lw\_axi\_master* port on the *hps\_o* component (this is the slower bus from the ARM processors).

Double-click to export *vga\_ball\_o*'s *vga* conduit in the Export column. Set the name of the export to *vga*.

The System Contents tab should now look like this:

The screenshot shows the Qsys System Contents window for the system `soc_system` at path `clk_0`. The window is divided into several panes:

- IP Catalog:** Shows the project structure with "VGA Ball" added to the Project.
- System Contents:** A table listing components and their connections. The `vga_ball_o` component is highlighted, showing its connections to `clk_0` and `hps_0`.
- Connections:** A diagram showing the physical connections between the components.
- Messages:** A list of messages, including warnings and info messages.

Use	Connections	Name	Description	Export	Clock
<input checked="" type="checkbox"/>		<b>clk_0</b>	Clock Source		
		clk_in	Clock Input	<b>clk</b>	
		clk_in_reset	Reset Input	<b>reset</b>	
		clk	Clock Output		clk_0
		clk_reset	Reset Output		
<input checked="" type="checkbox"/>		<b>hps_0</b>	Arria V/Cyclone V Hard Processor ...		
		h2f_user1_clock	Clock Input		hps_0_h2f...
		memory	Conduit		
		hps_io	Conduit		
		h2f_reset	Reset Output		
		h2f_axi_clock	Clock Input		
		h2f_axi_master	AXI Master		clk_0
		f2h_axi_clock	Clock Input		
		f2h_axi_slave	AXI Slave		clk_0
		h2f_lw_axi_clock	Clock Input		clk_0
		h2f_lw_axi_master	AXI Master		clk_0
		f2h_irq0	Interrupt Receiver		
		f2h_irq1	Interrupt Receiver		
<input checked="" type="checkbox"/>		<b>vga_ball_o</b>	VGA Ball		
		clock	Clock Input		clk_0
		reset	Reset Input		[clock]
		avalon_slave_o	Avalon Memory Mapped Slave		[clock]
		vga	Conduit	<b>vga</b>	[clock]

**Messages:**

Type	Path	Message
Warning	2 Warnings	
Warning	soc_system.hps_0	"Configuration:HPS-to-FPGA user 0 clock frequency" (desired_cfg_clk_mhz) requested 100.0 MHz, but only a
Warning	soc_system.hps_0	1 or more output clock frequencies cannot be achieved precisely, consider revising desired output clock frequer
Info	2 Info Messages	
Info	soc_system.hps_0	HPS Main PLL counter settings: n = 0 m = 73
Info	soc_system.hps_0	HPS peripheral PLL counter settings: n = 0 m = 39

0 Errors, 2 Warnings

Buttons: Generate HDL... Finish

You may ignore the “user 0 clock frequency” warning as that clock is unused.

Save the system (File→Save), which should write *soc\_system.qsys*.

Generate the Verilog for the design by clicking on *Generate HDL...* (accept the defaults) or running *make qsys*.

## 2.4 Connect the VGA Peripheral to its Pins

Your VGA Ball peripheral needs to communicate through its conduit through pins to an off-chip VGA DAC. To do this, edit `soc_system_top.sv` with a text editor to add the following connections within the instance of `soc_system` near the end of the file:

```
.vga_r (VGA_R),  
.vga_g (VGA_G),  
.vga_b (VGA_B),  
.vga_clk (VGA_CLK),  
.vga_hs (VGA_HS),  
.vga_vs (VGA_VS),  
.vga_blank_n (VGA_BLANK_N),  
.vga_sync_n (VGA_SYNC_N)
```

Delete the two `assign` statements to the various VGA signals at the bottom of `soc_system_top.sv`.

## 2.5 Compile the Hardware Design with Quartus

Either run `make quartus` or open the `soc_system` project in Quartus to compile the Qsys-generated system (whose source is in the `soc_system` subdirectory) to generate the “SRAM object file” `output_files/soc_system.sof`.

After Quartus compilation, convert the `.sof` file to an `.rbf` file by running `make rbf`.

Copy the `output_files/soc_system.rbf` into the boot partition of your SD card. You can mount your SD card on your workstation and copy the file. Alternatively, mount the boot partition by running `mount /dev/mmcblkop1 /mnt` on your DE1-SoC then use `scp` to copy the file from your workstation to your board, e.g.,

```
scp sedwards@micro11.ee.columbia.edu:lab3/soc_system.rbf /mnt
```

Make sure the file has actually been written out to the card: type `sync` at the command-line.

## 3 Tell the Linux Kernel About Your Peripheral

The Linux kernel employs a persistent data structure known as the Device Tree to describe the structure of a hardware platform. It contains information about processors, memory regions, bus bridges, and most importantly, the types and memory location of peripherals such as the VGA Ball. Qsys generates a similar `soc_system.sopcinfo` file that, in concert with the `soc_system_board_info.xml` file, can be used to generate an appropriate `soc_system.dtb` file, a binary representation of the Device Tree that is normally loaded as part of the boot process.

Generate `soc_system.dtb` by running `make dtb`. This needs `sopc2dts` to be in your path, which you can add by running `embedded_command_shell.sh` (on the lab computers, this is an alias; just type it at the command line).

Verify that the vga Ball peripheral appears in the `soc_system.dts` file, which should include

```
vga_ball_0: vga@0x100000000 {  
    compatible = "csee4840,vga_ball-1.0";  
    reg = <0x00000001 0x00000000 0x00000008>;  
    clocks = <&clk_0>;  
}; //end vga@0x100000000 (vga_ball_0)
```

The entry itself comes from the `vga_ball_0` module instance in Qsys (`soc_system.qsys`). The `compatible` string is controlled by the `set_module_assignment` statements you should have added to the `vga_ball_hw.tcl` file.

As for the `.rbf` file, copy the `soc_system.dtb` file to the boot partition on your SD card.

## 4 Communicate with Your Peripheral Through Software

Connect a VGA monitor and a USB keyboard to your board. Boot Linux on your board from the SD card with your new `soc_system.rbf` and `soc_system.dtb` files (your SD card from lab2 is otherwise fine). If your board is already powered on, restart it by typing `reboot` (don't just power-cycle it).

Connect the console port (mini-USB cable) to your workstation and run `screen /dev/ttyUSB0 115200` as you did in lab 2.

Boot Linux on your board. It should go through the normal boot process and you should see a white box against a colored background on the VGA monitor.

Verify that the kernel sees the vga Ball device in the device tree:

```
# ls "/proc/device-tree/sopc@0/bridge@0xc0000000/"  
#address-cells clock-names compatible ranges reg-names  
#size-cells clocks name reg vga@0x100000000  
# more "/proc/device-tree/sopc@0/bridge@0xc0000000/vga@0x100000000/compatible"  
csee4840,vga_ball-1.0
```

### 4.1 Compile and Run the Sample Program

On your board, download and install `linux-headers-4.19.0.tar.gz`, which includes the `Makefile` for compiling kernel modules.

```
# wget http://www.cs.columbia.edu/~sedwards/classes/2019/4840-spring/linux-headers-4.19.0.tar.gz  
# tar Pzxf linux-headers-4.19.0.tar.gz  
# ls /usr/src/linux-headers-4.19.0  
Documentation arch drivers init mm scripts usr  
Kconfig block firmware ipc modules.order security virt  
Makefile certs fs kernel net sound  
Module.symvers crypto include lib samples tools
```

Install the kernel module management programs (e.g., `insmod`, `rmmod`).

```
# apt install -y kmod
```

Download *lab3-sw.tar.gz* from the class website to your board, unpack it, compile it, install the kernel module.

```
# wget http://www.cs.columbia.edu/~sedwards/classes/2019/4840-spring/lab3-sw.tar.gz
# tar xzf lab3-sw.tar.gz
# cd lab3-sw
```

Compile the device driver and user program, install the kernel module, and verify that it works. This should look like

```
# make
make -C /usr/src/linux-headers-4.19.0 SUBDIRS=/root/lab3 modules
make[1]: Entering directory '/usr/src/linux-headers-4.19.0'
CC [M] /root/lab3/vga_ball.o
Building modules, stage 2.
MODPOST 1 modules
CC /root/lab3/vga_ball.mod.o
LD [M] /root/lab3/vga_ball.ko
make[1]: Leaving directory '/usr/src/linux-headers-4.19.0'
cc hello.c -o hello
# insmod vga_ball.ko
# lsmod
Module                Size  Used by
vga_ball              16384  0
# ./hello
VGA ball Userspace program started
initial state: f9 e4 b7
ff 00 00
00 ff 00
00 00 ff
ff ff 00
...
ff 00 ff
VGA BALL Userspace program terminating
# rmmod vga_ball
rmmod: ERROR: ../libkmod/libkmod.c:514 lookup_builtin_file() could not open
builtin file '/lib/modules/4.19.0/modules.builtin.bin'
```

You may ignore the error from *rmmod*.

“make” compiles the kernel module (*vga\_ball.ko*) and the userspace program (*hello*).

“insmod” loads the generated kernel module. In the supplied device driver, doing this should change the display. “lsmod” lists installed modules.

The *hello* program is a userspace program that communicates with the *vga\_ball* device driver through the *ioctl* system call. It opens the device and reads and writes its state, which changes the color of the background.

“*rmmod*” removes the kernel module, which is necessary any time you modify and recompile the module.

## 5 What to Do

Modify the hardware and software in the skeleton you have been provided to display a bouncing ball. Change both the interface and contents of the hardware peripheral so that it displays a stationary ball at a software-controllable set of coordinates. Have your peripheral respond to writes to one or more addresses that control the location of the ball.

Adapt the provided device driver to communicate with your peripheral. E.g., create an *ioctl* that sets the coordinates of the ball.

Write a userspace program that bounces the ball by repeatedly communicating the new coordinates to your peripheral through your device driver.

## 6 What to turn in

Find an overworked TA or instructor, and show him/her your bouncing ball. Once s/he is satisfied, collect just the files *you wrote or modified* for this lab in a directory called “lab3,” make a tarball with *tar zcf lab3.tar.gz lab3*, and submit that via Courseworks. This should include the SystemVerilog for your peripheral and source for your device driver and userspace program.

*Do not submit everything in your lab3-hw directory: it is too big.*

## 7 Qsys Hints

### 7.1 Editing the Source of Your Qsys Component

If you modify the SystemVerilog for your hardware component **without changing its interface**, regenerate your system with Qsys then re-run Quartus. Do this by running `make qsys-clean ; make qsys` or open Qsys from Quartus (Tools→Qsys) and click on *Generate HDL...*

If you **modify the interface** your hardware component (e.g., to change the number of visible registers, add a read function, or change the signals passed through the conduit), edit the component. Start Qsys (e.g., run `qsys-edit`), open your `.qsys` file, select your component under “Project,” and click “Edit.” This should bring up the Component Editor window.

Re-analyze the synthesis files as you did in Section 2.1, make sure the interface signals are assigned correctly, and click *Finish*.

Every time you update the component, re-insert the `set_module_assignment` directives mentioned in Section 2.2.

In Qsys, select File→Refresh System (or just press F5). It should complete with a reassuring warning indicating the version of your component has changed. Hovering over the instance of your component should also indicate its version has changed. Save your project after doing this to update the `.qsys` file.

Now, select Generate→Generate... to instruct Qsys to regenerate your system so Quartus can recompile it. Alternately, run `make qsys-clean ; make qsys`, which does the same thing from the command line.

### 7.2 Don't Edit Copies

Do not edit the files in the `synthesis` directory (e.g., in `lab3-hw/synthesis/submodules`). These are copied by Qsys and will be overwritten the next time Qsys runs.

### 7.3 Viewing Components as Blocks

Select a component and then View→Block Symbol. This shows how Qsys interprets the interface to a component.

