ECE391: Computer Systems Engineering — **Fall 2021**

Machine Problem 2

Midterm 1: Tuesday 28 September

Checkpoint 1: Tuesday 5 October

Checkpoint 2: Tuesday 12 October

Device, Data, and Timing Abstractions

Read the whole document before you begin, or you may miss points on some requirements, such as the bug log.

In this machine problem, you will extend a video game consisting of about 5,000 lines of code with additional graphical features and a serial port device. The code for the game is reasonably well-documented, and you will need to read and understand the code in order to succeed, thus building your ability to explore and comprehend existing software systems. Most code that you will encounter is neither as small nor as well documented—take a look at some of the Linux sources for comparison—but this assignment should help you start to build the skills necessary to extend more realistic systems. As your effort must span the kernel/user boundary, this assignment will also expose you to some of the mechanisms used to manage these interactions, many of which we will study in more detail later in the course. Before discussing the tasks for the assignment, let's discuss the skills and knowledge that we want you to gain:

- Learn to write code that interacts directly with devices.
- Learn to abstract devices with system software.
- Learn to manipulate bits and to transform data from one format into another.
- Learn the basic structure of an event loop.
- Learn to use a mutex with the pthread API.

Device protocols: We want you to have some experience writing software that interacts directly with devices and must adhere to the protocols specified by those devices. Similar problems arise when one must meet software interface specifications, but you need experience with both in order to recognize the similarities and differences. Unfortunately, most of the devices accessible from within QEMU have fully developed drivers within Linux. The video card, however, is usually managed directly from user-level so as to improve performance, thus most of the code is in other software packages (such as XFree86). We are also fortunate to have a second device designed by Kevin Bassett and Mark Murphy, two previous staff members. The device is a game controller called the Tux Controller (look at the back of the board) that attaches to a USB port. You can find one on each of the machines in the lab. On the Tux Controller board is an FTDI "Virtual Com Port" (VCP) chip, which together with driver software in Windows makes the USB port appear to as an RS232 serial port. QEMU is then configured to map a QEMU-emulated serial port on the virtual machine to the VCP-emulated serial port connected to the Tux Controller. In this assignment, you will write code that interacts directly with both the (emulated) video card and the game controller board.

Device abstraction: Most devices implement only part of the functionality that a typical user might associate with them. For example, disk drives provide only a simple interface through which bits can be stored and retrieved in fixed-size blocks of several kB. All other functionality, including everything from logical partitions and directories to variable-length files and file-sharing semantics, is supported by software, most of which resides in the operating system. In this machine problem, you will abstract some of the functionality provided by the Tux controller board.

Format interchange: This machine problem gives you several opportunities for working with data layout in memory and for transforming data from one form to another. Most of these tasks relate to graphics, and involve taking bit vectors or pixel data laid out in a form convenient to C programmers and changing it into a form easily used by the Video Graphics Array (VGA) operating in mode X. Although the details of the VGA mode X layout are not particularly relevant today, they do represent the end product of good engineers working to push the limits on video technology. If you work with cutting-edge systems, you are likely to encounter situations in which data formats have been contorted for performance or to meet standards, and you are likely to have to develop systems to transform from one format to another.

Event loops: The idea of an event loop is central to a wide range of software systems, ranging from video games and discrete event simulators to graphical user interfaces and web servers. An event loop is not much different than a state machine implemented in software, and structuring a software system around an event loop can help you to structure your thoughts and the design of the system. In this machine problem, the event loop is already defined for you, but be sure to read it and understand how the implementation enables the integration of various activities and inputs in the game.

Threading: Multiple threads of execution allow logically separate tasks to be executed using synchronous operations. If one thread blocks waiting for an operation to complete, other threads are still free to work. In this machine problem, we illustrate the basic concepts by using a separate thread to clear away status messages after a fixed time has passed. You will need to synchronize your code in the main thread with this helper thread using a Posix mutex. You may want to read the class notes on Posix threads to help you understand these interactions. Later classes will assume knowledge of this material.

Software examples and test strategies: In addition to the five learning objectives for the assignment, this machine problem provides you with examples of software structure as well as testing strategies for software components.

When you design software interfaces, you should do so in a way that allows you to test components separately in this manner and thus to deal with bugs as soon as possible and in as small a body of code as possible. Individual function tests and walking through each function in a debugger are also worthwhile, but hard to justify in an academic setting.

The `modex.c` file is compiled by the Makefile to create a separate executable that returns your system to text mode. We also made use of a technique known as a memory fence to check some of the more error-prone activities in the file; read the code to understand what a memory fence is and what it does for you.

The Pieces Provided

You are given a working but not fully-functional copy of the source tree for an adventure game along with a skeletal kernel module for the Tux controller. The Tux controller boards are attached to each machine in the lab.

The table below explains the contents of the source files.

`adventure.c`	Game logic, including the main event loop, helper thread, timing logic, display control logic (motion and scrolling), and a simple command interpreter (command execution code is in `world.c`).
`assert.c`	Support for assertions and cleanups as design and debugging aids.
`input.c`	Input control. Provides for initialization and shutdown of the input controller. The version provided to you supports keyboard control. You must write the support for the Tux controller. Can be compiled stand-alone to test the input device.
`modex.c`	Functions to support use of VGA mode X. Includes things like switching from text mode to mode X and back, and clearing the screens. Provides a logical view window abstraction that is drawn in normal memory and copied into video memory using a double-buffering strategy. When the logical view is shifted, data still on the screen are retained, thus only those portions of the logical view that were not previously visible must be drawn. Finally, supports mapping from pixelized graphics in formats convenient to C into drawing a screen at a certain logical position. Relies on `photo.c` to provide vertical and horizontal lines from the photo images. Is also compiled stand-alone to create the `tr` text mode restoration program.
`photo.c`	Support for reading photo and object image data and mapping them into VGA colors. Also draws vertical and horizontal lines into graphics buffers for use with scrolling.
`text.c`	Text font data and conversion from ASCII strings to pixelized graphic images of text (you must write the latter).
`world.c`	Populates game world by setting up virtual rooms, placing objects, and executing commands issued by the player.

We have also included two stripped binaries to illustrate your end goal. The `adventure-demo` program is a fully working version of the game that allows both keyboard and Tux controller input. The `input-demo` program is a stand-alone compilation of `input.c`, again allowing both forms of input. Finally, the `mp2photo.c` program can be used to transform 24-bit BMP files into photos for the game, and the `mp2object.c` program can be used for object images. Neither tool is needed for your assignment.

The `tr` Program

The make file provided to you builds both the adventure game and a text-mode-restoration program called `tr`. The latter program is provided to help you with debugging. One difficulty involved with debugging code that makes use of the video hardware is that the display may be left in an unusable (that is, non-text-mode) state when the program crashes, hangs, or hits a breakpoint. In order to force the display back into text mode for debugging purposes (or, if you are not running the program in a debugger, to regain control of your shell), you can run the `tr` program. Unless you are fairly confident in your ability to type without visual feedback, we recommend that you keep a second virtual console (CTRL-ALT-F1 through F6) logged in with the command to execute the text restoration program pre-typed, allowing you to simply switch into that console and press Enter. Using this program is substantially easier than rebooting your machine to put it back into text mode.

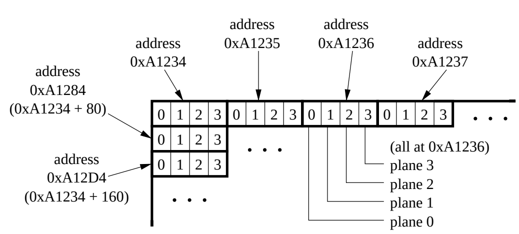
You should also look at the cleanup handlers provided by the `assert` module (`assert.h` and `assert.c`). These cleanup handlers provide support for fatal exceptions, putting the machine back into a usable state when your program crashes. However, there may be instances and problems not covered by the handlers, and GDB can stop the program before the handlers are invoked, leaving the machine in an unusable state until you restore text mode with `tr`.

Mode X and Graphic Images

Mode X is a 256-color graphics mode with 320x200 resolution. It was not supported by the standard graphics routines that came with the original VGAs, but was supported by the VGA hardware itself, and was quickly adopted as the standard for video games at the time because of certain technical advantages over the documented 256-color mode (mode 13h, where the 'h' stands for hexadecimal). In particular, mode X supports multiple video pages, allowing a program to switch the display between two screens, drawing only to the screen not currently displayed, and thereby avoiding the annoying flicker effects associated with showing a partially-drawn image. This technique is called **double-buffering**.

Each pixel in mode X is represented by a one-byte color value. Although only 256 colors are available in mode X, the actual color space is 18-bit, with 6-bit depth for red, green, and blue saturation. A level of indirection is used to map one-byte pixel color values into this space. The table used in this mapping is called a **palette**, as it is analogous to a painter's palette, which in theory holds an infinite range of colors, but can only hold a few at any one time. Palettes are often used to reduce the amount of memory necessary to describe an image, and are thus useful on embedded devices even today. For your final projects, some of you may want to play with graphic techniques such as palette color selection to best represent a more detailed image and dithering to map a more detailed image into a given palette.

The mapping between screen pixels and video memory in mode X is a little contorted, but is not as bad as some of the older modes. The screen is first separated into blocks four pixels wide and one pixel high. Each block corresponds to a single memory address from the processor's point of view. You may at this point wonder how four bytes of data get crammed into a single memory address (one byte in a byte-addressable memory). The answer, of course, is that they don't. For performance reasons, the VGA memory was 32-bit, and the interface between the processor and the VGA is used to determine how the processor's 8-bit reads and writes are mapped into the VGA's 32-bit words. For example, when the processor writes to a memory address, four bits of a specific VGA register are used to enable (1 bits) or disable (0 bits) writes to 8-bit groups of the corresponding word in VGA memory. When drawing rectangles of one color, this mask reduces the work for the processor by a factor of four. When drawing images, however, it poses a problem in that adjacent pixels must be written using different mask register settings. As changing a VGA register value is relatively slow, the right way to use mode X is to split the image data into four groups of interleaved pixels, set the mask for each group, and write each group as a whole using the x86 string instructions (you won't need to write any of these, although you may want to look at how it is done in the existing code or in the x86 manual).



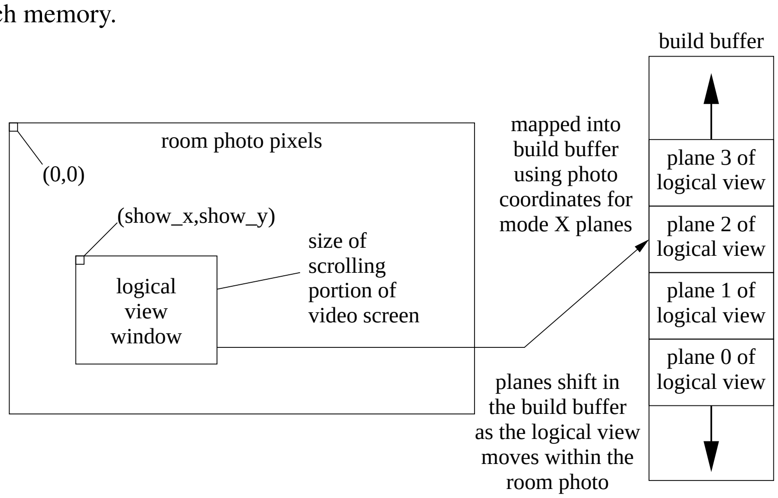
Mode X video memory is memory-mapped and runs from (physical) memory address 0xA0000 to 0xAFFFF, for a total of 2^{16} addresses and 256 kB of addressable memory (counting all four planes). The addresses used in your program are virtual rather than physical addresses, a concept to be discussed later in the course; don't be surprised if they are not the same as the physical addresses, though. A full screen occupies $320 \times 200/4 = 16,000$ addresses, so four fit into the full memory, with a little extra room. The VGA can be directed to start the display from any address in its memory; addresses wrap around if necessary. In the figure shown above, for example, the screen starts at address 0xA1234.

Due to the timing behavior of emulated interactions with video memory, the code provided to you does not use a traditional double-buffering model in which the off-screen image is drawn directly within video memory. As with double-buffering, we do maintain two regions within the video memory for screen images. However, we use regular memory to maintain an image of the screen and to update that image in place. When a new image is ready for display, we copy it into one of two regions of the video memory (the one not being displayed) and then change the VGA registers to display the new image. Copying an entire screen into video memory using one x86 string instruction seems to take about as long as writing a small number of bytes to video memory under QEMU, thus our image display is actually faster than trying to draw a vertical line in video memory, which requires one MOV instruction per vertical pixel.

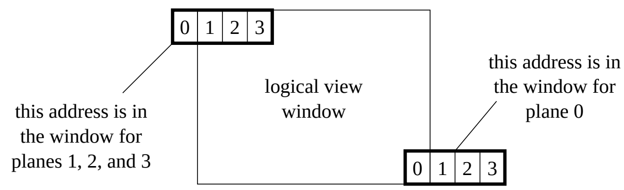
Only the `modex.c` file relies on mode X. The rest of the code should use a graphics format more convenient to C. In particular, an image that is X pixels wide and Y pixels high should be placed in an array of dimensions $[Y][X]$. The type of the array depends on the color depth of the image, and in our case is an `unsigned char` to store the 8-bit color index for a pixel. When you write code to generate graphic images from text, as described in a later section, you should use the same format.

Graphical Mapping in the Game

The game shows a two-dimensional photo for each virtual room in the simulated world, and the screen at any time shows a region of the current photo. The photo is fully resident in memory, but could in theory be constructed dynamically as necessary to fill the screen. This facet is useful for games in which drawing the entire virtual world at once requires too much memory.

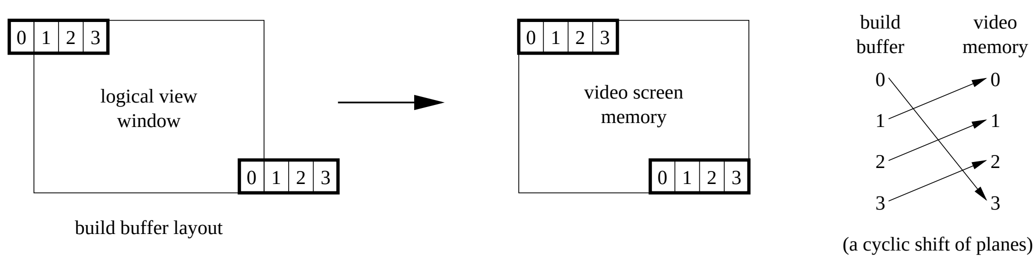


We use a build buffer to keep the pixel data relevant to the screen organized in a form convenient for moving into video memory in mode X. However, in order to avoid having to move the data around a lot in the build buffer (or redraw the whole screen each time we move the logical view window by one pixel), we break the room photo into 4x1 pixel chunks using the mode X mapping illustrated in the previous section. The address of the logical view window in the room photo is used to decide where to place the image planes within the build buffer, and moves around within the build buffer as the logical window moves in the room photo, as shown in the figure below.



The mapping that we have described has a subtle detail: the address range used for the different planes within the logical view window may not be the same. Consider the case shown above, in which `show_x & 3 == 1`. As we move the logical view window around in the room photo, we need to keep each address block at a fixed plane in the build buffer (again to avoid having to copy data around). If we were to keep the planes in the order 0 to 3 and not put any extra space between them, the image of plane 0 would in this case overlap with the image of plane 1 in the build buffer. By reversing the order, we can avoid this problem (alternatively, we could have used a one-byte buffer zone between consecutive planes).

The next problem is mapping the build buffer into the video memory. We use two buffers in video memory and map into the non-displayed buffer, then change the VGA register to show the new screen. You can read about this double-buffering technique in the code and see how it works. The complexity with regard to the plane mapping is that we must map the build buffer planes, which are defined in terms of the room photo coordinates, into the video planes, which are defined in terms of the screen coordinates. The picture below illustrates this problem. In general, a cyclic shift of the planes suffices for the mapping.

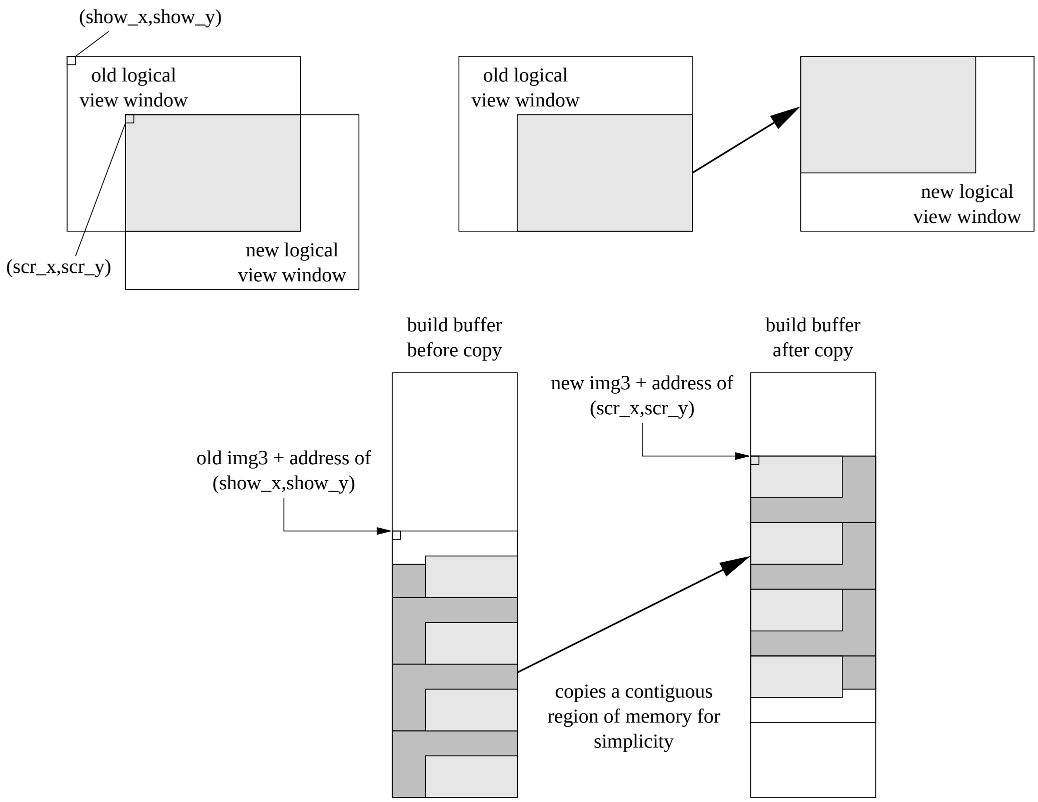


The next question is the size of the build buffer. If we can limit the size of the room photo, we can allocate a build buffer large enough to hold any logical view window. If the window starts at pixel (0,0) in the room photo, plane 3 is placed at the beginning of the build buffer. If the window occupies the lower right corner of the room photo, plane 0 is placed at the end of the build buffer. Such calculations are not particularly hard.

However, we do not want to restrict the size of the room photo, so we add a level of indirection and move the relative offset of the logical view window within the build buffer as the logical view shifts within the room photo. The room photo can thus be of almost arbitrary size, and is limited only by the size of the coordinate types (32-bit indices).

The `img3` and `img3_off` variables provide the additional level of indirection. At any point in time, adding the address calculated from the logical view window coordinates (show_x,show_y) to the `img3` pointer produces a pointer to the start of plane 3 in the build buffer. However, the actual position of that plane in the build buffer may change over time. Whenever a new logical view window setting is requested, the code checks whether all four planes of the new window fall within the build buffer boundaries. If they do not, the window is repositioned within the build buffer in order to make it fit. To minimize copying, the planes of the new window are centered within the build buffer. The figure at the bottom of the previous page illustrates the process.

Finally, we add a memory fence to the build buffer to ensure that we didn't screw up the copying calculations. Read about it in the code.



A Few Preliminaries

Obtain a copy of the MP2 starting code. As with MP1, you will be given access to your Git repository shortly after the MP is released. Watch your @illinois.edu email for an invitation from Gitlab. Refer to MP1 documents for the proper `git` commands. We suggest that you check out the files in the work directory (Z drive or /workdir): when working with the Tux controller code, both of your virtual machines will need access to the files, and keeping them on the work directory server means that you don't have to copy them around as often.

Read the code and understand it. We will ask you questions about the code as part of the demo, and will also test your conceptual understanding of the techniques used in the code during examinations. Don't be shy about asking questions on Piazza, but do be careful so as not to give away MP answers. For example, it's ok to ask **and answer** questions about memory fences or other code given to you, but it's not ok to give code or pseudo-code for writing a vertical line to the mode X build buffer (one of the tasks below).

We expect you to follow good software engineering practices in your code. Variables should almost never be global. On the other hand, don't go parameter-happy: file scope variables are fine. The code given to you has one global variable, which contains the font data for restoring text mode and for drawing text as graphic images while in graphics mode. Buffers passed to functions should either be fixed-size, or the available space should be passed and checked. Everything should be clearly thought out and well-commented. Functions should have function headers. Prototypes and variables should be organized, not scattered about the files. Indentation must be done correctly.

Keep a log of your debugging experiences with this MP. Include all bugs that do not generate compiler errors (if you are foolhardy enough to ignore a warning and later find that the warning pointed you about a bug, report it). Describe the type of problem, the symptom that drew your attention to the problem (*e.g.*, the screen looked wrong), the difficulty (rough time: ten minutes, an hour, a day) of finding the bug, and the difficulty (one-line change, one-hundred-line change, complete redesign) of fixing it. The error taxonomy from ECE 220 may help you describe types of bugs. Briefly, syntactic errors are the trivial typos that generally result in compiler errors and that we don't want to hear about. Semantic errors are also often typos, but manage to pass the compiler and separate what the computer does from what you meant for it to do. You may have used less-or-equal instead of less-than, for example. Algorithmic errors occur when your thinking about a problem is just wrong in some way; for example, you forget about a certain case or a boundary condition. Finally, specification ambiguity errors occur when behavior in certain cases is unspecified or undocumented, and incompatible assumptions are made (explicitly or implicitly) to resolve the ambiguity.

We won't believe you if you claim that you had no bugs. Keeping the bug log will help you both to identify and to remember how you encountered problems. Debugging is not unlike integration: a big part of it is memorization, mapping symptoms back into bugs (with integration, you memorized how derivatives could be mapped back into the original functions). It will also help us to figure out how much time students spend on the assignments and which parts give you the most trouble.

Checkpoint 1 Requirements

The order presented here is only a suggestion, but we do strongly recommend that you read the code first, that you tackle the parts one at a time rather than working on them all at once, that you commit working versions to your repository as you get each part working, and that you start with the easier parts. You must do all of these things for the first checkpoint. Other parts of the final MP are optional at the first checkpoint, and will not serve to make up points for missing required functionality.

Write the vertical line drawing routine in `modex.c`. Everything but the function body is already in place for you (even the function header!), and you can look at the horizontal line drawing routine right next to it, so this part should be an easy place to start. The main difficulty is for you to understand both how mode X maps pixels and how the abstractions in `modex.c` work, so try to read the code and documentation to the point that you feel you understand these things, then try to write the function with the help of the examples.

Find the VGA documentation for the status bar. Doing so was part of PS2, and you can work together and discuss how it should be done, but not trade code to do it.

Add the status bar to the game. It should be big enough to allow you to write a line of text with **an extra pixel above and below**. How big is that? Read the code. Defined constants have been cleverly included to reduce the amount of work for you (see IMAGE versus SCROLL dimensions in the code), but you will have to shift a couple of bits of the existing code around here and there because of VGA constraints.

Write a text to graphics image generation routine in `text.c`. Given a string, it should produce a buffer that holds a graphical image of the ASCII characters in the string. The height of the buffer is fixed. You may either (a) figure out how much text fits on the status bar and produce a buffer of fixed-size, or (b) return the resulting image width. In either case, the text must be centered on the bar, in case (a) by this routine, and in case (b) by the next routine. Don't forget to put a prototype and explanation into `text.h`.

Write a routine to put a graphic image, and in particular, the output of routine described in the previous paragraph, on to the status bar.

Use your routine to fill the status bar with text. Synchronize with the helper thread, then check for a non-empty status message. If one exists, show it on the bar. Otherwise, put the room name and current typing on the bar. Arrange these things as you see fit to make them attractive.

Be sure to look ahead at the rest of the assignment. You may want to get an early start.

Checkpoint 2: Tux Controller Serial Port Device

This portion of the MP is due on the final due date. A subsequent document will be released with the tux controller requirements. Your requirements in the game are:

- Display the elapsed time (minutes.seconds) on the 7-segment displays.
- Up/down/left/right on the tux controller have the same affect as the keyboard's keys.
- A/B/C on the tux controller should have the same affect as Ins/Home/PgUp.
- Enable the device driver to control the LEDs on the Tux controller
- Enable the device driver to report when buttons are pressed and released
- Handle device resets correctly
- Enable control of the game using the Tux controller (support keyboard input simultaneously).
- In the game, enable the up/down/left/right buttons on the Tux controller to do what the arrow keys do on the keyboard.

Remember, the Tux driver is expected to work with ANY user-level program. This means you will not receive full credit if you do not implement all `ioctl`s described in this document even if the game does not make use of them.

Set up instructions:

1. Remember to use Git or save a current version of your code as a backup.
2. You no longer need to compile the entire linux kernel, so you no longer need to boot your compiled kernel. To prevent your compiled kernel from running, right click on "test_debug.lnk" shortcut, go to properties and remove the -kernel ...
   bzImage from the target line.
3. Enable your test machine to make use of the serial port (named COM#) corresponding to the Tux controller. To check which COM number the Tux controller is currently connected on: Go to Start -> Devices and Printers -> right-click on FT232R USB UART -> Hardware tab -> USB Serial Port (COM#) where # should be less than 10. If it is higher, call a TA because it will not work with QEMU. Right click on "test_debug.lnk" shortcut, go to properties and add `-serial COM#` to the end of the target line. This connects the Windows COM# port to the Linux ttyS0 serial port. Note: Only your test machine will be able to communicate with the Tux controller with this setup. Although you can also add this option to your devel machine, you can only have one virtual machine use the Tux at a time. Therefore, we recommend you use the devel machine to compile your code and the test machine to load the kernel module and run the game.
4. Also remove the `-s` option from the end of the target line This option told `qemu` to wait until `gdb` was attached. In this assignment we don't need to start gdb until after the kernel is up and running.
5. When you first start your debug machine, a dialog will appear asking you for COM# Properties. The default values (Bits per second should be = 9600, Data bits = 8, Parity = None, Stop bits = 1, Flow control = None) will be correct. Click OK to continue booting your debug machine.
6. If there is no activity for approximately 2 hours, the Tux controllers will enter a low-power state and turn off the LEDs. This is intended to prolong the life of the LEDs. Pressing the RESET button will return it to a responsive state. Be aware of this if you sit down at a new machine or do not use the controller for more than two hours.
7. There is a bug in QEMU that may cause the test machine to freeze occasionally while using the Tux controllers. When it is frozen, you will be unable to connect to or interact with it from GDB. If that happens, go to the QEMU console (ctrl+alt+2), type `i 0x3f8` (this will pull bytes from UART like `in`), press the up arrow to get the command again and repeatedly enter it several times. Go back to the virtual terminal you were in (ctrl+alt+1). If it is still locked, repeat the steps above until it becomes responsive.

Building the driver: The `mp2/module` directory contains a framework for the driver you will be implementing for the Tux controller. A module is similar to a dynamically-loaded user-level library but instead of being used by an application it is used by the kernel to extend functionality. Modules allow for drivers to be loaded without having to recompile (or even reboot) the whole kernel. This simplifies the process of debugging as well. Modules can also be unloaded and a new version loaded into the kernel assuming that nothing catastrophic happened that would crash the kernel. Your driver code, of course, is running in the kernel, and bugs that are severe enough to crash the kernel are not impossible to produce.

The `module` directory uses a separate Makefile to compile a device driver module for use with Tux controller, thus building a module is similar to building a user level program: Change directories into the `module` directory and type `make`.

To **load** the module into the kernel, type `sudo /sbin/insmod ./tuxctl.ko` while in the module directory. A line should print out saying the tuxctl line discipline has been registered. You can safely ignore the "`module license 'unspecified' taints the kernel`" message. [1]

If you want to **remove** the module, issue the `sudo /sbin/rmmod tuxctl` command. This removes the module from kernel space and should print a line stating the tuxctl line discipline was removed. You can use these commands to install and remove the kernel module repeatedly during your development. If your module corrupts the kernel, however, you may eventually crash the system and have to reboot. If all else fails, try rebooting the test machine and then loading your module to see if it is really your latest code that is failing.

The module we have given you implements a tty line discipline. A line discipline is a driver that receives commands from the tty or serial port driver. In other words, it acts as a middle man between the serial port and the code you will implement to actually interpret the Tux controller commands. The code you will be implementing is in the `tuxctl-ioctl.c` file. You may add anything you deem necessary to the header files to make your implementation work. We also recommend you look at the mtcp.h file for a description of how the Tux controller works and some predefined constants, and at the appendix at the end of this document.

Writing your driver: You will write portions of both the device driver which communicates with the Tux controller and the user-level application code to make use of the driver. On the driver side, you will need to add constants and definitions for the abstracted bit format to the header file. These constants (located in tuxctl-ioctl.h) will shared by the kernel and user-level code, ensuring that no inconsistencies arise. *There is no user-level test harness for MP2.* We advise you to write a simple test program to test your driver outside the game. We suggest that you write a test program to test the basic functionality (open, close, ioctls) before trying to make the game use the driver. We have provided input.c as a starting point for your user-level testing. To compile input.c type `make input`. We will test your driver with our own testing code, so be sure to test your driver's functionality thoroughly and adhering strictly to the spec. For the checkpoint, you must add the Tux controller functions (open, ioctls, close) to the input control in `input.c` and test it by compiling the file by itself. You will need to include `tuxctl-ioctl.h`. Only once you have debugged your input control completely as a stand alone program should you try it with the full game. *To interface with the game you will need to create a new thread to take input from the Tux controller (you must support keyboard input simultaneously.* Opening the Tux controller is fairly simple. You may use the following code as an example to open the serial port and set the Tux controller line discipline:

```
fd = open("/dev/ttyS0", O_RDWR | O_NOCTTY);
int ldisc_num = N_MOUSE;
ioctl(fd, TIOCSETD, &ldisc_num);
```

This code simply opens the tty port and sets the line discipline. You will want to add some error checking and whatever else you see fit to make this work with your code.

[1] This simply indicates that the module you have loaded has not been designated as GPL and therefore taints the kernel so don't try to submit any bug reports to Linus.

What your driver has to do: Your device driver transforms the protocol supported by the Tux controller into a simpler abstraction for use by user-level programs such as the game. You must implement the following `ioctl`s for your device abstraction:

`TUX_INIT` Takes no arguments. Initializes any variables associated with the driver and returns 0. Assume that any user-level code that interacts with your device will call this `ioctl` before any others.

`TUX_SET_LED` The argument is a 32-bit integer of the following form: The low 16-bits specify a number whose hexadecimal value is to be displayed on the 7-segment displays. The low 4 bits of the third byte specifies which LED's should be turned on. The low 4 bits of the highest byte (bits 27:24) specify whether the corresponding decimal points should be turned on. This `ioctl` should return 0.

`TUX_BUTTONS` Takes a pointer to a 32-bit integer. Returns -EINVAL error if this pointer is not valid. Otherwise, sets the bits of the low byte corresponding to the currently pressed buttons, as shown:

7							0
right	left	down	up	c	b	a	start

For full credit, use an interrupt-driven approach rather than polling.

Your changes to the device driver should be limited to the files `tuxctl-ioctl.h` and `tuxctl-ioctl.c`. The function `tuxctl_handle_packet` handles all packets received by the computer from the Tux controller. The function `tuxctl_ioctl` handles calls from user code (the game) to `ioctl`. You may add more `ioctl` calls, however the required `ioctl`s above must work as intended.

Tux Controller communication protocol: The Tux controller protocol for interacting with the PC is described in `mtcp.h`, as you saw in PS2. Messages sent to the Tux controller are of variable length, while messages sent to the computer are always three bytes in length of the following general form:

Responses from the controller to the PC are always sent as three-byte packets of the following general form:

7							0	
0	1	R4	R3	0	R2	R1	R0	0
1	7 data bits							1
1	7 data bits							2

The 5-bit vector `R[4:0]` in byte 0 represents an opcode. All possible opcodes are defined in `mtcp.h` The other three bits in byte zero are fixed as indicated. Notice that bit 7 of each byte is fixed and used to frame the packets. This is a feature of the packet format because the COM port emulation in the old Microsoft Virtual PC software that we used to use was unreliable and occasionally lost bytes sent through it. The provided kernel patch includes code to detect this behavior and avoids providing you with broken packets. See the code in `tuxctl-ld.c` for details.

The Tux controller supports many different commands, each of which is defined in `mtcp.h`. You are only required to use a couple of them for this MP.

We recommend that you make use of `MTCP_BIOC_ON` and `MTCP_LED_SET`, in which case you must handle `MTCP_ACK` and `MTCP_BIOC_EVENT`. You must also handle `MTCP_RESET` packets sent to the computer by attempting to restore the controller state (value displayed on LEDs, button interrupt generation, *etc.*).

`MTCP_POLL` This command consists of a single `MTCP_POLL` byte (0xC2) sent to the controller: The response is a three-byte packet with the following format:

7							0	
0	1	0	0	0	1	0	0	0
1	X	X	X	C	B	A	S	1
1	X	X	X	R	D	L	U	2

That is, the first byte will have the value `MTCP_POLL_OK`, the second and third will contain active-low bit masks of which buttons are pressed; that is, a bit will be '0' when the corresponding button is pressed. The `C`, `B`, `A`, and `START` (S) buttons are in the second byte, and the `right` (R), `down` (D), `left` (L), and `up` (U) bits are in the third. Bits marked as 'X' in the diagram are unused.

`MTCP_LED_SET` See mtcp.h for the definition of the LED_SET bytes

Finally, a few important notes about the Tux controller:

For debugging purposes, when the controller receives an erroneous command, it locks up and displays `00P5` on the seven-segment display. Pressing the `reset` button returns it to a usable state. This behavior can be disabled by sending an `MTCP_DBG_OFF` command; after this is sent, an erroneous command will elicit an `MTCP_ERROR` response.

Additionally, when the controller is reset, for example by pressing the `reset` button, it asynchronously sends an `MTCP_RESET` packet to the PC. **Your code must detect this condition and re-initialize the controller to the same state it was in before the reset.** In order to accomplish this your code must internally keep track of the state of the device.

Debugging the Tux Controller: Debugging in kernel space is not as simple as debugging in user space. You made find it helpful to use `printk()` from your driver module. `printk()` is like `printf()` for kernel mode.

For when the kernel loads the tuxctl module, it may load it anywhere it pleases in its address space. This means GDB needs to know where the module was loaded before it can start debugging it. The object file for the tuxctl also needs to be loaded into GDB so that the proper symbols can be resolved.

Once your debug machine loads, load the tuxctl module (see above). You now need to find out where in memory the kernel loaded the module. Issue the command `cat /proc/modules` to print out the location of all modules currently loaded in the kernel. You should see a line such as

```
tuxctl 6792 0 - Live 0xd0813000 (P)
```

at the top. `0xd0813000` is the address the module was loaded at. (It will probably be different for you). Back in your devel machine, in the `module` directory, launch gdb with no arguments. Once in GDB, type `add-symbol-file ./tuxctl.o ADDRESS` where ADDRESS is the address that was printed out in for the module in your debug machine, 0xd0813000 in my case. GDB will then ask you to confirm. Type `y` and hit `enter`. Now you will need to connect GDB to the remote machine by typing `target remote 10.0.2.2:1234`. You may now define breakpoints for your driver and continue as normal.

Again, make use of the stand-alone input program in `input.c` before tackling the full game.

Checkpoint 2: Color Clustering and VGA Palette Manipulations

The rest of the MP, which is also only due at the final due date, consists primarily of manipulating VGA palette colors and making use of the event loop to control timing.

Find the VGA documentation for setting palette colors. As with the status bar, doing so was part of PS2. Write a function that sets a palette color. Put the function in `modex.c`.

Notice the difference in color quality between the demo version of the adventure game and the distribution provided to you. The version provided to you maps each photograph into 6-bit color, using only 64 of the 256 colors available in mode X. The same 64 colors are used for objects and the status bar.

To improve the visual quality of the game, you must optimize the remaining 192 colors for the photo being displayed and adjust these colors whenever the player moves to a new room. Color optimization requires that you implement an algorithm based on octrees.

The Task: The graphics mode used in MP2 provides a 320×200 display in which each pixel color is specified using one byte. The 8-bit value for a given pixel is used as an index into a palette of 256 colors, each of which is selected from one of 2^{18} possible colors. These palette colors, as you should know from the pre-lab, are stored in VGA memory by writing three bytes corresponding to the red, green, and blue components of a color. The two most significant bits in each byte are ignored, leaving six bits (0 to 63) for red (R), six bits for green (G), and six bits for blue (B).

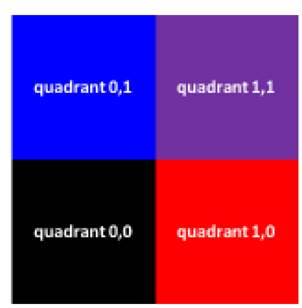
In contrast, many image formats provide 24-bit RGB color for each pixel. The `.photo` files in the distribution have been transformed into a smaller format in which each pixel is represented with a 16-bit value in which the five most significant bits form a red component, the middle six bits form a green component, and the five least significant bits form a blue component. Visually, you have bits as shown here: RRRRRGGGGGGBBBBB.

The code that we distributed to you maps these 16-bit values into the first 64 VGA palette colors, which have been set up for you (in `modex.c`) to provide 6-bit RGB colors (two bits each). These colors are also used for objects in the game, and you must not change them. The other 192 colors are free for your use in selecting colors that best represent the content of an individual room photo.

Your task, then, is to implement an algorithm that examines the 16-bit pixels for a single room photo, selects 192 colors that enhance the visual quality of the photo, transform the image data stored in the file into a C array containing appropriate bytes (one-byte VGA colors), and set the VGA palette registers to the colors that you have selected whenever that particular photo is displayed by the game.

Octrees: The most common algorithms for mapping the multitude of colors that comprise a typical image into a smaller number for display on a computer screen make use of octrees, or degree eight trees. Each level of such a tree categorizes pixels based on one bit of red, one bit of green, and one bit of blue. The eight possible children for a node correspond to the eight possible values of these bits.

An example using two colors (one level of a quadtree) is shown to the right. Here, pixels corresponding to colors with the most significant bit of both their red and blue components equal to 0 are added into the lower left quadrant of the tree. Those with blue MSB equal to 1 and red MSB equal to 0 are added to the upper left quadrant. And so forth. Each quadrant can then be subdivided into four parts based on the second MSB of red and the second MSB of blue. And the process can continue as long as we have bits of colors left.



In the first level of an octree, we also make use of the green component's MSB, resulting in eight octants. Each of these octants can then be subdivided into eight octants based on the second MSB, and so forth. With 5:6:5 RGB, we could in theory build a tree six levels deep, but our algorithm will make use of only four levels.

An octree need not be built as a pointer-based data structure. In fact, we strongly recommend that you not try to follow such an approach. Since each level contains exactly eight children for each node, each level fits easily into an array. For example, the first level is an array of eight elements indexed by a concatenation of the RGB MSBs. The second level is an array of 64 elements that you can index by any interleaving of the two MSBs of each color—we suggest RRGGBB, but just be sure to use the same interleaving of bits for all uses. Other levels are equally straightforward.

The Algorithm: This section outlines the algorithm that you must use. The text here is simply a rewriting of Section 2.2 from `http://www.leptonica.org/papers/colorquant.pdf`, which is in turn mostly a practical overview of earlier work along with some useful implementation details. The paper does provide enough references for you to trace back to much of that earlier work (most of which you can find free online or by leveraging UIUC's online library subscriptions). The paper also provides a number of more sophisticated algorithms, which you are welcome to attempt or extend. As usual, we strongly recommend that you first get this version working and save a copy to avoid unhappiness at handin time.

The basic idea behind the algorithm is to set aside 64 colors for the 64 nodes of the second level of an octree, and then to use the remaining colors (in this case, 128 of them) to represent those nodes in the fourth level of an octree that contain the most pixels from the image. In other words, you choose the 128 colors that comprise as much of the image as possible and assign color values for them, then fill in the rest of the image with what's left.

The first step in the algorithm requires that you count the number of pixels in each node at level four of an octree. Define a structure for all relevant data for a level-four octree node, then create an array of that structure for your algorithm. Go through the pixels in the image file, map them into the appropriate octree node, and count them up. Once you're done, you must sort the octree nodes based on the number of pixels appearing in each and select the most frequent 128 for specific palette colors. The C library `qsort` routine will help here, provided that you have recorded some sort of color identifier in your node structure for use after the sort completes. If you're not already familiar with the C library implementation of quicksort, you may want to read the man page (`man 3 qsort`) to avoid implementing your own sorting routine.

What 18-bit color should you use for the palette? The average of the 5:6:5 RGB values for those pixels that make use of the color. Note that you must calculate the averages for red, green, and blue separately. Calculating the average of the 16-bit pixels directly may be amusing, but will not earn many points. Rather than going through the pixels in the file again, of course, you should keep track of the necessary data during the first pass and calculate averages only for those 128 nodes for which you plan to assign palette colors. Eventually, you also need a way to map these 5:6:5 RGB color values into the 8-bit VGA colors that you assign, so be sure to keep track of the mapping implied by your octree node selection.

Every pixel in the image must be assigned a color, of course. The next step in the algorithm is to assign the remaining 64 palette colors to the 64 level-two octree nodes. You may find that in some images, some of these nodes contain no pixels—*you need not bother to optimize this case by reassigning the palette colors to level-four nodes*.

What 18-bit color should be used for the palette for the level-two octree nodes? As before, the average of the 5:6:5 RGB values for those pixels that make use of the color. Here there's a twist, however: any pixels that have been assigned to one of the level-four octree nodes *do not make use of the level-two palette color*. So you must remove their contribution before calculating the average color for the level-two node.

Your code should write the palette values that it selects for an image in the `photo_t` structure along with the final image data. Once your code has finished selecting colors and palette values, it must go through the file data again and map 5:6:5 RGB values into VGA colors. Don't forget that your colors are indexed from 0 to 191 in the arrays, but must occupy colors 64 to 255 in the VGA palette. The first 64 colors in the palette are used for objects and the status bar. You may want to review `fseek` (`man 3 fseek`) to help you go over the file data again.

Finally, don't forget to make use of the palette that you define (probably in `prep_room`) via your `set_palette` function.

Lumetta's implementation, including all structures, variables, and code, required a little over 150 lines.

Handin

Both the checkpoint and the final handin will require you to sit down with a TA in the lab to demonstrate your code and to answer a few questions.

Important Things to Note:

- Demos will be done over two days, as with MP1. Day assignments may be different, so please take note and let us know quickly if you have a conflict. You are strongly encouraged to print the gradesheet for your own record keeping.
- The workload for the two checkpoints is NOT equal. The exam date normally falls in the middle of checkpoint 1, which may give you the illusion of extra time. We strongly suggest that you use this time to get ahead for the final checkpoint, but make sure that you do not break the work that you did earlier, particularly for your first checkpoint demo.
- As with MP1, your demo will be based on the last version of your code in your repository **before the deadline—NO EXCEPTIONS.** Be ABSOLUTELY SURE that that version compiles. You are free to develop your own system of code organization, but we will **STRICTLY** use only the `master` branch for grading. All files to be graded must be in the root directory as initialized for you.
- We expect you to be very familiar with Git at this point, so we will be even less forgiving if you find yourself having Git issues right before the deadline, especially if that is your first commit/push for the whole assignment.
- The "correct" behavior of certain routines includes interfaces that allow one to prevent buffer overflows (that is, the interfaces do not leave the size of a buffer as an unknown) and other such behavior. While the TAs will probably not have time to sift through all of your code in detail, they will read parts of it and look at your overall design.
- If you miss functionality points at the checkpoint, you will be able to regain **half** of those points by completing the functionality by the final due date.