

Lab 8:

The Serial I/O Device Driver

Due date: April 11, 2019, Thursday. Your solutions should be submitted by **11:59 p.m.** Late submissions will not be accepted beyond 8 hours after the submission deadline. Within the eight-hour grace period, a mark penalty of 10% will be applied.

Overview and Goal

In this lab, you will implement a device driver for the serial terminal interface, and will modify the syscall interface to allow user-level programs to access this device. The goals include learning how the kernel makes the connection between syscalls and device drivers, and gaining additional experience in concurrent programming in the context of an OS kernel.

Files for this Lab

All the files for this lab are available at the following directory on the ECF workstations:

`/share/copy/ece353s/lab8` (after logging into your account in the ECF UNIX lab)

The following files are new to this lab:

```
TestProgram5.h
TestProgram5.c
fileA
fileB
fileC
fileD
script
help
```

The following files have been modified from the last lab:

```
makefile
DISK
```

The `makefile` has been modified to compile the new programs. The `DISK` file has been enlarged, since the previous version was too small to accommodate all these new files.

All remaining files are unchanged from Lab 7.

Required changes to the syscall interface

In this lab, you will make changes to several syscalls to allow the user program to access the serial device. The serial device is an ASCII "dumb" terminal; individual characters can be sent and received asynchronously, one-by-one. Characters sent as output to the BLITZ serial device will appear directly on the screen (in the terminal or docker container where the emulator is being run), and characters typed at the keyboard will appear as input to the BLITZ serial device.

UNIX divides all I/O devices into two classes, called "character" and "block." In UNIX, user programs can operate character devices (like the keyboard) using the same syscalls as block devices (like the disk). Your kernel will also use the same syscalls, so in this lab you will not add any new syscalls.

To send or receive characters to/from the serial terminal device, the user program will first invoke the **Open** syscall to get a file descriptor. Then the user program will invoke **Read** to get several characters or **Write** to put several characters to the terminal.

In the last lab, the **Open** syscall was passed a filename. In this lab, the behavior of **Open** will be modified slightly: if the filename argument happens to be the special string "**terminal**", your kernel will not search the disk for a file with that name; instead your kernel will return a file descriptor that refers to the serial terminal device.

The **Close** syscall is passed a file descriptor. When **Close** is passed a file descriptor referring to the terminal, it will function very similarly (from the user-level view) as with a disk file. The file descriptor will be marked as unused and free, and any further attempt to read or write with that file descriptor will cause errors.

When the **Read** syscall is applied to the terminal, it will return characters up to either the **sizeInBytes** of the buffer or to the next newline character (**\n**), whichever occurs first. **Read** will return the number of characters gotten, including the newline character. **Read** will wait for characters to be typed, if necessary.

When the **Write** syscall is applied to the terminal file, it will send the characters in the buffer to the serial terminal device, so they will appear on the screen.

Resources

The following sections from the document titled "The BLITZ Emulator" are relevant:

- Emulating the BLITZ Input/Output Devices (near page 25)

- Memory-Mapped I/O (near page 25)

- The Serial I/O Device (near page 27)

- Echoing and Buffering of Raw and Cooked Serial Input (near page 28)

You may wish to consult these sections as needed when working on this lab.

Implementation hints

In this section, we will make some suggestions about how you may implement the required functionality.

Here are the changes our design would require you to make to **Kernel.h**. These will be discussed below as we describe our suggested approach, but all the changes are given here, for your reference.

The following should already be present in your **Kernel.h** file:

```
const
    SERIAL_GET_BUFFER_SIZE = 10
    SERIAL_PUT_BUFFER_SIZE = 10

enum FILE, TERMINAL, PIPE
```

The following should also be there; uncomment it.

```
var
    serialDriver: SerialDriver
```

Add a new global variable:

```
var
    serialHasBeenInitialized: bool
```

Add a new class called SerialDriver:

```
----- SerialDriver -----
--
--  There is only one instance of this class.
--
const
    SERIAL_CHARACTER_AVAILABLE_BIT          = 0x00000001
    SERIAL_OUTPUT_READY_BIT                = 0x00000002
    SERIAL_STATUS_WORD_ADDRESS             = 0x00FFFF00
    SERIAL_DATA_WORD_ADDRESS               = 0x00FFFF04

class SerialDriver
    superclass Object
    fields
        serial_status_word_address: ptr to int
        serial_data_word_address: ptr to int
        serialLock: Mutex
        getBuffer: array [SERIAL_GET_BUFFER_SIZE] of char
        getBufferSize: int
        getBufferNextIn: int
        getBufferNextOut: int
        getCharacterAvail: Condition
        putBuffer: array [SERIAL_PUT_BUFFER_SIZE] of char
        putBufferSize: int
        putBufferNextIn: int
        putBufferNextOut: int
        putBufferSem: Semaphore
        serialNeedsAttention: Semaphore
        serialHandlerThread: Thread
    methods
        Init ()
        PutChar (value: char)
        GetChar () returns char
        SerialHandler ()
endClass
```

The following field should already be present in class FileManager:

```
serialTerminalFile: OpenFile
```

The following field should already be present in class `OpenFile`:

```
kind: int                -- FILE, TERMINAL, or PIPE
```

The serial device driver code will go into the class **SerialDriver**, of which there will be exactly one instance called **serialDriver**. In analogy to the disk driver, the single **SerialDriver** object should be created in **Main** at startup time and the **Init** method should be called during startup to initialize it. The provided **Main.c** has been modified for you accordingly.

The **SerialDriver** has many fields, but basically it maintains two FIFO queues called **putBuffer** and **getBuffer**. The **putBuffer** contains all the characters that are waiting to be printed and the **getBuffer** contains all the characters that have been typed but not yet requested by a user program. The **getBuffer** allows users to type ahead.

There will be only two methods that users of the serial device will invoke: **PutChar** and **GetChar**. **PutChar** is passed a character, which it will add to the **putBuffer** queue. If the **putBuffer** is full, the **PutChar** method will block; otherwise it will return immediately after buffering the character. **PutChar** will not wait for the I/O to complete.

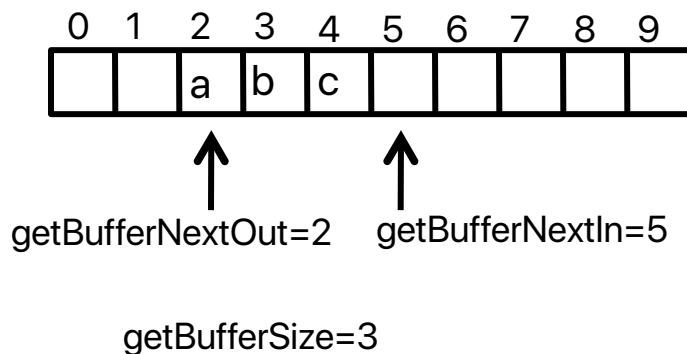
The **GetChar** method will get a character from the **getBuffer** queue and return it. If the **getBuffer** queue is empty (i.e., there is no type-ahead), **GetChar** will block and wait for the user to type a character before returning.

The **Read** syscall handler should invoke the **GetChar** method and the **Write** syscall handler should invoke the **PutChar** method.

Each of these buffers is a shared resource and the **SerialDevice** class is a monitor, regulating concurrent access by several threads. The buffers will be read and updated in the **GetChar**, **PutChar** and **SerialHandler** methods, so the data must be protected from getting corrupted. To regulate access to the shared data in the **SerialDriver**, the field **serialLock** is a mutex lock which must be acquired before accessing either of the buffers. (Our design uses only one lock for both buffers, but using two locks would allow more concurrency.)

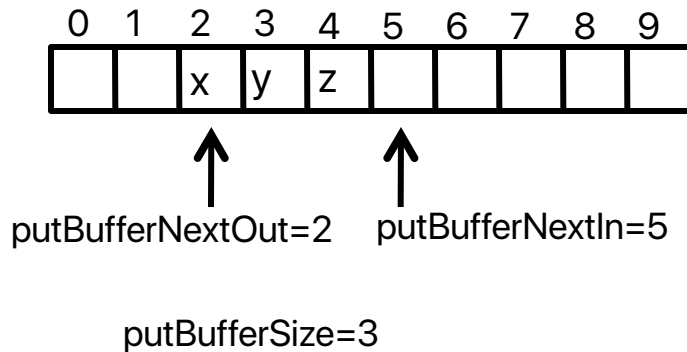
Look at **getBuffer** first. The **GetChar** routine is an entry method of the **SerialDevice** monitor. As such, it must acquire the **serialLock** as its first operation. The variables **getBufferSize**, **getBufferIn**, and **getBufferOut** describe the status of the buffer.

Here is a **getBuffer** containing "abc". The next character to be fetched by **GetChar** is "a". The most recently typed character is "c".



If the **getBufferSize** is zero, then **GetChar** must wait on the condition **getCharacterAvail**, which will be signaled with a **Down()** operation after a new character is received from the device and added to the buffer. After getting a character, **GetChar** must adjust **getBufferNextOut** and **getBufferSize** before releasing **serialLock** and returning the character.

Next look at **PutChar**. There is a similar buffer called **putBuffer**. Here is an example containing "xyz".



The **PutChar** method must first wait until there is space in the buffer. To handle this, You can use the semaphore called **putBufferSem**. This semaphore is initialized with

```
putBufferSem.Init (SERIAL_PUT_BUFFER_SIZE)
```

which starts the semaphore with one excess signal per available buffer entry. Each time a character is removed from the buffer, it will create an additional space, so every time a character is removed (by the **SerialHandler** method, discussed later), the semaphore will be signaled with an **Up** operation. By waiting on the semaphore with **Down**, **PutChar** ensures that there is at least one free space. Then it acquires the **serialLock**. (Note that even though other threads may sneak in and run between the completion of the **Down** and the acquisition of the **serialLock**, there will always be at least one free space.)

PutChar will then add its character to the next "in" spot in the buffer and adjust **putBufferNextIn** and **putBufferSize**. Then it will release the lock. Finally, before returning, it will signal another semaphore, called **serialNeedsAttention**, which will wake up the **SerialHandler** thread.

In our design, the serial device will be controlled by a kernel thread called "SerialHandler." Every time the serial device interrupts the CPU, this thread will be awakened. Also, every time **PutChar** adds a character to the **putBuffer**, this thread will be awakened.

The **SerialHandler** thread has two tasks. (1) If a new character has been received (i.e., the user has pressed a new key), the new character must be fetched from the device and moved into the **getBuffer**. (2) If the serial transmission channel is free (i.e., done transmitting the previous character) and there are more characters waiting in **putBuffer** to be printed, the outputting of the next character must be started. The thread must also wake up any other threads waiting on the **getBuffer** (becoming non-empty) and the **putBuffer** (becoming non-full).

We just mentioned that, in the **SerialDriver** class there is a semaphore called **serialNeedsAttention**, which will be signaled (with **Up**) to wake up the **SerialHandler** thread. The code for **SerialHandler** is

an infinite loop that waits on the semaphore, then checks things, and then repeats (going to sleep until the next time the semaphore is signaled).

The **SerialInterruptHandler** routine should be modified to signal the **serialNeedsAttention** semaphore and thereby wake up the serial handler thread. Unfortunately, this semaphore will not be initialized when the OS first begins. Although the semaphore will be initialized as part of the OS startup, serial interrupts may occur from the very beginning. An attempt to signal a semaphore that has not yet been initialized will result in an “uninitialized object” error. You don’t want that!

To deal with serial interrupts that might occur before the semaphore has been initialized, You can add a new global variable

```
serialHasBeenInitialized: bool
```

In KPL, global variables are always initialized to their zero values; for a boolean this is “false”. The code in **SerialDriver.Init** should create the semaphore and initialize it. As the last thing it does, **Init** should set

```
serialHasBeenInitialized = true
```

Here is the code for the **SerialInterruptHandler** function:

```
currentInterruptStatus = DISABLED
if serialHasBeenInitialized
    serialDriver.serialNeedsAttention.Up()
endif
```

Next let’s look at **SerialDriver.Init**. First it might want to print the message “Initializing Serial Driver...” The two fields called **serial_status_word_address** and **serial_data_word_address** are pointers to the memory-mapped addresses of the two serial device registers. They should be initialized here and will never change. (KPL cannot handle “const” values that are pointers, so instead, you can make them fields of **SerialDriver**.)

Next, **Init** must initialize the **serialLock**, and then the fields associated with the input buffer. They are: **getBuffer**, **getBufferSize**, **getBufferNextIn**, **getBufferNextOut**, and the **GetCharacterAvail** condition. Next, **Init** must initialize the fields associated with the output buffer: **putBuffer**, **putBufferNextIn**, **putBufferNextOut**, and the **putBufferSem** semaphore. As mentioned above, the argument to **putBufferSem.Init** indicates one initial signal per buffer slot. Next, **Init** must initialize the **serialNeedsAttention** semaphore.

Then **Init** must create a new thread (a kernel thread) which will monitor the serial terminal device. This is the **serialHandlerThread** field in **SerialDriver**. As you know, the **Thread.Fork** function requires a pointer to a function and a single integer argument. You should create a function (called **SerialHandlerFunction**) that ignores the integer argument and immediately invokes the **serialDriver.SerialHandler** method. This method contains all the code and it never returns.

Finally, the **Init** method should set **serialHasBeenInitialized** to true and return.

As mentioned before, the **SerialHandler** method contains an infinite loop. The first thing in the loop is a wait on the **serialNeedsAttention** semaphore. This semaphore can be signaled by either the **PutChar** method (when a new character is added to the output queue) or when a serial interrupt

occurs. In either case, the thread will wake up, check things, and then go back to sleep, waiting for the next signal.

When awakened, the **SerialHandler** thread will need to look at the serial device to see if a character has arrived at the device (i.e., a key has been pressed). So it must query the serial device status register and check the "character available" bit. If set to 1, it must get the character from the serial device data register. Then the **SerialHandler** must add it to the input buffer. This requires first acquiring the **serialLock**.

It is possible that the input buffer is full and this must be checked for. If the **getBuffer** is full, we have a case of the user typing too many characters ahead, before the program has asked for them. In our design, the character is simply dropped (i.e., do not add it to the buffer). Instead, you should print out a message containing the character. This will be very helpful in debugging.

```
print ("\nSerial input buffer overrun - character '")
printChar (inChar)
print ("' was ingored\n")
```

After adding the character to the buffer, the **SerialHandler** needs to signal the **getCharacterAvail** condition, then release the **serialLock**.

After dealing with the input stream, the **SerialHandler** needs to look at the output stream. (It would also be correct to handle the output before the input.)

First, you need to query the status register and check the "output ready" bit. A 1 bit indicates the device is ready to transmit another character, so next you need to check to see if there are any characters queued for output. Before you check **putBufferSize**, You will need to acquire the **serialLock**. If there is at least one character in the queue, you can remove it (adjusting **putBufferSize** and **putBufferNextOut**) and move it into the serial device data register. Finally, You will need to signal **putBufferSem**, to wake up any **PutChar** threads waiting to add characters to a full buffer. And don't forget to release the **serialLock** no matter what the code does, or the BLITZ OS will freeze up.

Regarding buffers and pointers, here is a little trick. Assume you have the following code (not part of this lab):

```
var buffer: array [MAX_SIZE] of char = ...
    nextPos: int
```

To add an element to the buffer, You will need to increment the **nextPos** index variable. The following code uses the **mod** operator when it adds 1, which cause the buffer to be a "circular" buffer.

```
buffer[nextPos] = x
nextPos = (nextPos + 1) % MAX_SIZE
```

If **MAX_SIZE** = 100, then this code will add 1, going from 99 back to 0. The same trick works when decrementing index values:

```
nextPos = (nextPos - 1) % MAX_SIZE
```

The specification says that a user program can open "terminal" just like any other file. The file descriptor array associated with each process points to **OpenFiles**, with a null value indicating that the given file descriptor is not an open file.

Since the **Open** syscall must assign a new file descriptor when called for "terminal" and the new file descriptor must point to an **OpenFile**, you will need two kinds of **OpenFile**. One kind is for files and one is for the terminal. We will ignore pipes, which can be implemented but is out of the scope of this lab.

The **kind** field in **OpenFile** will have one of the following values:

```
enum FILE, TERMINAL, PIPE
```

Since there is only one terminal, there will only be one **OpenFile** whose **kind** is **TERMINAL**. Since there is exactly one **OpenFile** for the terminal, you can pre-allocate this **OpenFile** object. The logical place to do this is in **FileManager.Init**. You can use the field called **serialTerminalFile** in the **fileManager** object. In **Init**, you can create this unique **OpenFile** object, set its **kind** to **TERMINAL**, and make **serialTerminalFile** point to it.

The **serialTerminalFile** is pretty much a dummy place holder. None of its other fields (**currentPos**, **fc**, **numberOfUsers**) will be needed.

The **Open** syscall handler requires very few changes. Presumably in the previous lab, you began by copying the String argument (**filename**) from the virtual address space to a kernel buffer (and aborting if problems). Then you found the next free entry in the **fileDescriptors** array (and aborting if none).

At that point, you can check to see if the **filename** is equal to "terminal" (see the **StrEqual** function from the **System** package). If so, you can just make the **fileDescriptor** entry point to the **OpenFile** called **serialTerminalFile** and return.

The syscall handler for **Close** is straightforward. You will need to reclaim the entry in the **fileDescriptors** array, but that is all. In particular, **FileManager.Close** should not do anything if called on **serialTerminalFile**. Or perhaps you simply avoid ever invoking **FileManager.Close** on the **serialTerminalFile**.

Modifying the **Read** syscall handler will require a little more effort. Presumably in the last lab your **Handle_Sys_Read** function began by checking the **fileDesc** argument and locating the **OpenFile** in question (and aborting if problems). After possibly dealing with a **sizeInBytes** of zero or less, you can insert code to see if you are dealing with the **serialTerminalFile** object, instead of a regular disk file.

If so, You will need to call **SerialDriver.GetChar** once to get each character from the device. We will leave the details to you, but perhaps you can use a single loop that calls **GetChar** once per iteration. You will need to keep track of the virtual address in which to store the next incoming character.

You will need to perform the virtual-to-physical translation, and check to make sure that (1) the virtual page number is between 0 and the top legal page in the address space; (2) the page is valid (In this lab all pages should be valid, since we haven't yet implemented paging to disk); and (3) the page is writable.

You will also need to set the page to dirty and referenced, under the assumption that this would be needed if we were swapping out pages. The **Read** syscall must return the number of characters

gotten from the input stream and moved into the user-space buffer. The reading will stop just after a newline (**\n**) character, but the user program will always get at least one character unless there is an error with the arguments to the syscall, or the end-of-file (EOF) character (control-D, ASCII value 0x04) is typed as a first character on a read. When EOF is typed, the read buffer should not be modified any further and the number of characters read until before EOF was pressed should be returned. In particular, if EOF is the first character on a read, the **Read** syscall should return 0 without modifying its buffer.

The modifications to the **Write** syscall handler are quite similar. A single loop can call **SerialDriver.PutChar** once per iteration. You will need to have the same checks on the arguments and the same checks on the virtual address pointer. Of course the code should not set the page to dirty for a write operation.

The **KEYBOARD_WAIT_TIME** Simulation Constant

One of the simulation constants used by the emulator is **KEYBOARD_WAIT_TIME**. The value of this number tells the emulator how fast the serial terminal device is. In particular, it tells it about how many instructions are to be executed between serial interrupts.

If, for some reason, your kernel does not retrieve an incoming character from the terminal device fast enough, the character might get lost when the next character comes in. If this happens, the emulator (which checks for various program errors) will notice that your OS is failing to get incoming characters fast enough and will print out a message such as:

```
ERROR: The serial input character "g" was not fetched in a timely way
and has been lost!
```

If you see this message, it indicates that your kernel has an error. It is not getting the incoming characters when it should.

The default value for **KEYBOARD_WAIT_TIME** (30,000) should be more than enough to give your device driver time to process each character and add it to the type-ahead buffer. If you run into this error, the solution is to fix your kernel, not modify the simulation constant!

Of course the user program may fail to call **Write** fast enough to prevent the type-ahead buffer from overflowing, but that is a different problem.

Raw and Cooked Input

Review the material in the document "The BLITZ Emulator" regarding "raw" and "cooked" input. You should play around with your program using both "raw" and "cooked" mode. See the **raw** and **cooked** commands or the **-raw** command line option.

In cooked mode, which is the default, the host UNIX system will echo all characters as you type them. Only after you hit the "enter" key will any characters get delivered to the emulator and hence to the BLITZ serial device and to your BLITZ kernel code.

In general, cooked mode is very nice because it lets the user edit his/her input (using the backspace key) and relieves most UNIX programs from the burden of echoing keystrokes and dealing with the backspace character.

But be aware that with cooked mode, the BLITZ emulator may get frozen, waiting for you to hit the enter key. Or it may not. Since this may be rather confusing, the BLITZ emulator will print a message whenever it stops executing BLITZ code and is just waiting for user input.

The emulator takes a command line parameter **-wait** that tells it what to do when there is nothing more to do. If you go back and look at the code in the thread scheduler, You will see that when a thread goes to sleep and there are no remaining threads on the ready list, the "idle thread" will execute the "wait" instruction, which suspends CPU execution and waits on an interrupt.

In the past labs, we did not use the **-wait** option, so when a "wait" instructions was executed, the emulator would print out the familiar message:

```
A 'wait' instruction was executed and no more interrupts are scheduled...
halting emulation!
```

With this lab, the user is now able to type input so we don't want the emulator to just quit. We want the kernel to wait for incoming events—keystrokes, in particular—wake up, service the interrupts, and possibly resume execution in some user-level thread.

So in this lab You will need to use **-wait** on the command line. For example:

```
% blitz -g os -wait
```

or

```
% blitz -g os -wait -raw
```

Now, You will might see a different message:

```
Execution suspended on 'wait' instruction; waiting for additional user input
```

When you see this message, the emulator has stopped executing instructions and is waiting for you to enter something. This message only appears when the emulator is running in cooked mode; in raw mode the emulator will just quietly wait for the next keystroke.

But now there is another problem: How can you stop the emulator? The answer is by hitting **control-C**. Hitting control-C once will suspend BLITZ instruction emulation and put you back in the debugging command line loop. You might see something like this:

```
Beginning execution...
===== KPL PROGRAM STARTING =====
Initializing Thread Scheduler...
Initializing Process Manager...
Initializing Thread Manager...
Initializing Frame Manager...

***** Control-C *****
Done! The next instruction to execute will be:
026C5C: A3FFFFFF8    bne    0xFFFFF8    ! targetAddr = _Label_168_2
>
```

Control-C behaves a little funny when in “cooked” mode. You may need to hit the ENTER/RETURN key one or two times after hitting control-C before you see the “>” prompt.

Hitting control-C twice in a row will terminate the BLITZ emulator, which could be useful if the emulator has a bug.

Dealing With \n and \r

In the **Read** syscall handler, you should replace any incoming **\r** characters by **\n** and treat the character just like the **\n** character (i.e., return from the **Read** syscall immediately without waiting for additional characters).

Why? Because if you are running the emulator in “raw” mode, some terminals will send a **\r** character whenever the key marked “enter” or “return” is struck. By substituting **\n** for **\r**, the BLITZ user-level program will never see a **\r** character and can work only with **\n** characters.

In the **Write** syscall handler, whenever the user-level program tries to send the **\n** character to the serial device, you should insert an additional call to send a **\r** as well. Perhaps this code will work:

```
if ch == '\n'
    serialDriver.PutChar ('\r')
endif
serialDriver.PutChar (ch)
```

This may be helpful in raw mode and should not have any effect in cooked mode. You might enjoy experimenting to see what your terminal does if this additional **\r** is left out. (Try hitting control-J which will send a **\n** to your program. Try hitting control-M which will send **\r** to your program.)

Ideally, an OS would perform character editing and everything associated with cooked mode in the terminal driver code. Ideally, you would run your kernel using the **-raw** option in the emulator and your driver would perform all echoing and character editing. You might wish to experiment with such modifications, but they are not part of the assignment.

The “Print” Functions

Up to now, you have been using functions such as **print**, **println**, **printlnVar**, and **printHex** to assist in debugging your kernel code. These functions do not work like normal I/O on any real computer. Instead, these functions all make use of a BLITZ instruction called “debug2” which would not be found on any real computer. This magic little instruction will cause some string or number to be immediately printed out. There are no devices to interface with, no delays, and no interrupts. The output occurs “atomically” (i.e., all at once, with no intervening instructions) which turns out to be very, very useful in being able to read output from concurrent programs.

In a real kernel, there is a similar mechanism for printing to facilitate debugging. However, the output is written to an in-memory buffer (rather than displayed), where it can be examined (after the kernel has crashed) by some simpler program that copies the “output” sitting in memory to somewhere where it can be read by a human. A real nuisance, but debugging kernel code is only for the strongest of programmers!

In order for user-level programs to print, they should call **Write** on the serial terminal file. Technically, any use of the “debug2” instruction ought to be removed, but we have left it in. The **print**, **println**, **printlnVar**, etc. functions are for debugging use only; they are not like anything found in a real kernel.

To print, a user-level program needs to call a function (such as **printf** in C) which in turn will invoke the **Write** syscall.

In our test programs, we will dispense with library functions like **printf** which call **Write** and just invoke **Write** directly. Likewise, we will not get around to implementing input functions like **scanf**, but will just invoke the **Read** syscall directly.

Grading

The `/share/copy/ece353s/lab8` directory contains a new user-level program called `TestProgram5`. Please modify your code to load `TestProgram5` as the initial process.

`TestProgram5` is structured like the previous test programs, but in addition to the individual test functions, it also contains a menu-driven interface. Once you get the serial device code functioning, you can change the `main` function in `TestProgram5` to invoke the `Menu` function. Then you can run the various tests interactively from a menu, instead of recompiling each time. This should make your life easier when debugging and playing with raw and cooked modes.

During your testing, it may be convenient to modify the tests as you try to see what is going on and get things to work. However, the original version of `TestProgram5.c` will be used for marking.

After the submission deadline closes, your solution will be marked manually by the TAs using the provided test cases. The maximum possible mark for this lab assignment is 8. The TAs will run the following 4 test methods in `TestProgram5.c`:

`BasicSerialTest`

`EOFTest`

`OpenCloseTerminalTest`

`TerminalErrorTest`

Each test case is worth 2 marks, for a total of 8 marks.

Sample Output

Refer to `/share/copy/ece353s/lab8/DesiredOutput.txt` for examples of the correct output with each of the four test cases given.