Lab # 1
Threads, Concurrency, and Operating System Device Drivers
COMP 421/ELEC 421, COMP 521/ELEC 552

Important Dates:
- Tuesday, January 24, 2017: Lab # 1 begins
- Wednesday, February 8, 2017: Lab # 1 due by 11:59 PM

1 Project Overview

Through this assignment, you will be able to gain practical experience in programming concurrent systems using threads with a monitor for synchronization. You will also gain experience with the design and operation of device drivers in operating systems. In particular, in this project you will implement a terminal device driver using a Mesa-style monitor for synchronization of interrupts and concurrent driver requests from different user threads that share an address space.

To simplify the project, we will use a software terminal emulation rather than working directly with real terminal hardware. This emulation is designed to give you the flavor of developing a real device driver, without as much complexity and frustration. We will also use a simplified threads library instead of the standard POSIX “Pthreads” library. We hope that by avoiding the overly large and complex Pthreads API, you will better be able to focus on the project itself.

This project must be done individually. The second and third projects in this class will be done in groups of 2 students, but you must do this first project by yourself.

2 Specifics

This section discusses a few pieces of important information related to the overall project.

2.1 Environment

- Your solution must be implemented in the C programming language (e.g., not in C++ or other languages).

- This project must be done on the CLEAR Linux systems at Rice. Specifically, all compiling, linking, and executing for the project will only work on CLEAR.

- For the terminal hardware simulation to work correctly, you must be running a local X Windows server program on your own local computer, and must log into CLEAR using ssh in a way that allows X Window operations to be forwarded back to your local X Windows server program through this ssh connection. This use of X Windows and ssh is explained more fully in Section 9.

- Your use of threads must be limited to the package provided for the project, and to only those features described in this document. You may not directly use Pthreads or any other threads package or other threads or synchronization mechanisms other than the threads package provided for this project.

- Your terminal device driver must support the simulated terminal hardware as described in this document.
You should create a new, separate directory to work in for this project. All work for the project should be done in this directory. Anything you want us to grade must be in this directory (or its subdirectories) when you turn in your project.

2.2 Form

- Your terminal device driver must compile into a single object file called montty.o. This name is short for “monitor” and “terminal” (“tty” is actually short for “teletypewriter,” a very old and still very common name for a terminal).
- You may use only a total of one monitor in your solution (e.g., not one monitor per terminal).
- All of the procedures defined in this project description in Section 6.1 (ReceiveInterrupt and TransmitInterrupt) and in Section 6.2 (WriteTerminal, ReadTerminal, InitTerminal, TerminalDriverStatistics, and InitTerminalDriver) must all be entry procedures of your monitor. Your monitor must have no other entry procedures.
- You may not create any threads that are simply a part of your terminal device driver. The only threads you may create should be the users of your terminal device driver (those that call procedures such as ReadTerminal and WriteTerminal that are part of the terminal device driver API described in Section 6.2). You may not call the ThreadCreate function anywhere within your terminal driver.
- Your terminal device driver must guarantee that no deadlock is possible and must generally also ensure that no starvation is possible as well. The one case in this project where starvation may be allowed is due simply to the use of Mesa monitor semantics rather than Hoare semantics. Specifically, before most condition variable waits, a Hoare monitor only requires an if whereas a Mesa monitor generally requires a while. This use of a while is generally required for correctness but may itself be the source of possible starvation, if every time the process is awoken from a signal, the process ends of going around the loop and waiting again on the same condition variable.
- For students taking COMP 521 or ELEC 552, the graduate student version of this course, you must also write and submit a report addressing issues including the factors affecting the performance of the design in your solution to the project and the issues involved in scaling the project to larger sizes in larger systems. This requirement for COMP 521/ELEC 552 students is defined more fully below in Section 11.

2.3 Grading

Grading for this project will consider the completeness, correctness, design, and implementation of your solution:

- Your submitted project must comply with the form requirements described above in Section 2.2.
- We will evaluate the correct operation of your terminal device driver, including through a series of private test programs. Since you will not know in advance what our private test programs do, you cannot write and test your code only to pass our private tests; you will need to focus on all aspects of correctness.
- Because of the nature of this assignment, design is important, and projects that do not correctly follow the required paradigms (particularly for structuring a Mesa monitor, as described in Section 8.2) will be severely penalized.
• Performance is also important in this project, and projects that perform badly due to synchronization issues will encounter design or implementation penalties, as appropriate.

• We will consider the design and implementation of your solution to help you improve. It is essential that you comment your code to the extent necessary to make it understandable for grading.

3 What is a Terminal Device Driver?

A device driver is a module within an operating system that manages some particular external device (or specific type of device) and encapsulates the messy details of interacting with the device’s hardware. Encapsulation is particularly necessary for devices, because there is a great variety of them and complexity in dealing with them. It is easier to provide many small modules that make all devices of a general type look the same, than to add support for each new device in many places within the operating system or within application programs that use these devices. I/O devices are also particularly messy because they operate at very different speeds. This makes the procedures of hardware interaction baroque as well as diverse, and exposes the OS device driver to some insidious possible concurrency problems.

Device drivers are generally structured into a “top half” and a “bottom half.” The top half deals with reacting to the application programs that request service from the I/O device, such as “read” and “write” calls that may be issued by the program. The bottom half deals with reacting to the hardware, such as servicing interrupts from the device hardware. The top and bottom halves coordinate their work by sharing data structures within the device driver.

To work correctly, this coordination must use some form of synchronization in controlling access to those shared data structures. Also, device drivers usually must implement some sort of synchronization with user programs in order to keep different concurrent requests from different programs from interfering with each other.

In a real operating system, interrupt synchronization for a device driver is typically provided largely by the interrupt priority levels supported by the hardware and occasionally also by disabling interrupts for a short time and then re-enabling them. To simplify the interrupt synchronization in this project, though, and to provide you experience using a monitor, the interrupt synchronization in this project will be provided solely through a monitor, rather than through hardware interrupt priorities and enabling and disabling interrupts. In particular, the entire terminal device driver must be structured as a single Mesa-style monitor. Each time an interrupt from the hardware occurs, this translates in this project into an entry procedure in the monitor being called. Likewise, each time a user thread makes some request of the terminal device driver, such as to write some output on the terminal or to read some input from the terminal, this translates in this project into the thread calling another entry procedure of the terminal driver monitor.

4 The Terminal Hardware

The terminals in this project are simulated on top of xterm windows running on your display using X11 window System. The terminals support both input and output, with all data being sent and/or received one character at a time. The hardware supports up to a maximum of NUM_TERMINALS terminals, a value defined in the hardware.h header file. Each terminal is identified by a unique terminal number, ranging from 0 to NUM_TERMINALS-1.

Each terminal’s hardware displays on that terminal’s screen each character written into the output data register for that terminal, but does not do so instantaneously. While the hardware is busy transmitting one character to the terminal for display, a new character must not be written by the driver into the output data register, as the output data register in the hardware can hold only a single character at a time. When the
transmission of the character from the output data register to the terminal is complete, the terminal hardware raises a transmit interrupt.

Each character typed on the keyboard of a terminal is deposited into the input data register for that terminal. When the hardware places a new character in this register, it raises a receive interrupt. Like the output data register, the input data register in the hardware can hold only a single character at a time. In real-life hardware, if another character is typed on the terminal keyboard, it is placed into the input data register for the terminal regardless of whether or not the previous character in the input data register has been read by the device driver. If the previous character has not yet been read by the driver, that is, if the driver failed to respond sufficiently quickly to the previous receive interrupt, that previous character would be lost without having ever been seen by the device driver, since, again, the input data register can hold only a single character. Our simulated terminal hardware behaves in the same way, except that our “hardware” will also print an error message when this happens, letting you know that the newly typed character has overwritten the previous character in the input data register.

It is in general not possible (even in a real device driver with real hardware) to guarantee that the device driver can always respond to one receive interrupt and read the character from the input data register, before the user could type another character on the terminal’s keyboard. But a well designed device driver should be able to complete handling each receive interrupt very quickly, making it very difficult for the user to type faster than the device driver can respond to each interrupt. With our simulated hardware, if you type very quickly, you may be able to generate this error message, but at normal typing speeds, this message should never occur if you have structured your device driver correctly.

5 The Hardware Emulation API

The API for the simulated terminal hardware is proved as part of the provided library and requires the inclusion of the include file hardware.h. You should include this file in your source file as:

```c
#include <hardware.h>
```

This file defines all of the function prototypes and other definitions for interacting with the hardware. The following functions are available:

- **void WriteDataRegister(int term, char c)**

  This hardware operation places the character `c` in the output data register of the terminal identified by the terminal number `term`. On any error, in this project, this function prints an error message on `stderr` and terminates the program.

- **char ReadDataRegister(int term)**

  This hardware operation reads (and returns) the current contents of the input data register of the terminal identified by `term`. On any error, in this project, this function prints an error message on `stderr` and terminates the program.

- **int InitHardware(int term)**

  This hardware operation initializes the terminal identified by `term`. It must be called once and only once before calling any of the other hardware procedures on that terminal. Returns 0 on success or -1 on any error.
• int HardwareInputSpeed(int term, int msecs)

This hardware operation may (optionally) be used to set the average delay associated with the reception of each character from the terminal identified by term. The parameter msecs specifies the average number of milliseconds of delay between the time at which a character is typed on the terminal and the time at which the character is available in the input data register (and a ReceiveInterrupt is generated). The actual delay is not predictable (it depends on many things in real life and in the simulated hardware). HardwareInputSpeed returns the previous value of this delay. On any error, in this project, this function prints an error message on stderr and terminates the program. If msecs is equal to the constant NO_CHANGE, this function returns the speed value without changing it. This function is not required for any reason, but you may find it useful in testing; by varying device speeds, you may be able to ferret out schedule-dependent bugs.

• int HardwareOutputSpeed(int term, int msecs)

This hardware operation may (optionally) be used to set the average delay associated with the transmission of each character to the terminal identified terminal. The parameter msecs specifies the average number of milliseconds of delay between the time at which a character is written to the output data register and the time at which the output data register again becomes available for writing another character (and a TransmitInterrupt is generated). HardwareOutputSpeed returns the previous value of this delay. On any error, in this project, this function prints an error message on stderr and terminates the program. If msecs is equal to the constant NO_CHANGE, this function returns the speed value without changing it. This function is not required for any reason, but you may find it useful in testing; by varying device speeds, you may be able to ferret out schedule-dependent bugs.

6 Required Terminal Device Driver Procedures

The device driver you write will need to service interrupts from the hardware as well as requests from the programs (threads) using the terminal. All of the procedures in this section must be written by you. These procedures are called either from the hardware as an interrupt handler or from a user thread requesting an operation on a terminal.

6.1 Interrupt Handlers

As mentioned above, when the transmission of a character to a terminal completes, the terminal hardware signals a transmit interrupt. Similarly, when the receipt of a new character from a keyboard completes, the terminal hardware signals a receive interrupt. In your terminal device driver, you must write a separate procedure to handle each of these two types of interrupts. In this project, these two interrupt handlers must have specific procedure names, whereas in a real (complete) operating system, the procedure name would be irrelevant, as each interrupt handler would be called simply by a pointer to that procedure being found at the right subscript within the interrupt vector table. Specifically, for this project, you must write the following two interrupt handler procedures as part of your terminal device driver:

• void ReceiveInterrupt(int term)

This procedure is called by the hardware once for each character typed on the keyboard of the terminal identified by terminal number term, after that character has been placed in the input data register for that terminal. The character that caused the interrupt should be read by your device driver from the input data register using the ReadDataRegister() operation. You must write your own
ReceiveInterrupt handler routine. Within your receive interrupt handler, you should not block
the current thread (i.e., wait on a condition variable), since further calls to the receive interrupt han-
dler for subsequent receive interrupts cannot be done until the current call to the receive interrupt
handler returns.

- void TransmitInterrupt(int term)

  This procedure is called by the hardware once for each character written to the output data register for
the terminal identified by terminal number term, after the character has been completely transmitted
to this terminal. After executing a WriteDataRegister() operation, you must assume that the
output data register for that terminal is “busy” with the transmission of that character until you receive
the corresponding transmit interrupt and your TransmitInterrupt() procedure is called with
this same terminal number. You must write your own TransmitInterrupt handler routine.

6.2 Device Driver API for User Threads

User threads in this project communicate with the terminal using procedures similar to the read() and
write() kernel calls in Unix/Linux. In addition to the two interrupt handler procedures defined above
in Section 6.1 that you must implement, this section describes the additional functions, which you must
implement for handling these user requests. You should #include the definitions of these functions from
the include file terminals.h as:

    #include <terminals.h>

All procedures below, unless otherwise noted, should return 0 for success or -1 in case of any error.

- int WriteTerminal(int term, char *buf, int buflen)

  This call should write to terminal number term, buflen characters from the buffer that starts at ad-
dress buf. The characters must be transmitted by your terminal device driver to the terminal one at a
time by calling WriteDataRegister() for each character. Other than as noted in Section 7.1, all
output characters should be sent to the terminal exactly as-is (e.g., without worrying if the character
is any special type of character such as a “control character”). Your driver must block the calling
thread until the transmission of the last character of the buffer is completed (including receiving a
TransmitInterrupt following the last character). This function should then return as its re-
sult the number of characters written (buflen), or -1 in case of any error. If buflen is 0, this
call should return immediately, and if there are no errors, the return value should be 0 in this case.
Your terminal device driver should not impose any limit on the maximum length of the user’s buffer
(buflen).

- int ReadTerminal(int term, char *buf, int buflen)

  This call should copy characters typed from terminal number term, placing each into the buffer
beginning at address buf. As you copy characters into this buffer, continue until either buflen
characters have been copied into buf or a newline (’\n’) has been copied into buf (whichever
occurs first), but note that, as described in Section 7.2, only characters from input lines that have been
terminated by a newline character in the input buffer can be returned. Your driver should block the
calling thread until this call can be completed.

Other than as noted in Section 7.1, all input characters should be returned to the calling thread ex-
actly as-is (e.g., without worrying if the character is any special type of character such as a “control
character” or if the user typed one of the cursor or “arrow” keys). This function should return as its
result the number of characters copied, or \(-1\) in case of any error. If \(\text{buflen} \) is 0, this call should return immediately, and if there are no errors, the return value should be 0 in this case. Note that the \text{ReadTerminal} \ procedure should not place a null character (‘\0’) at the end of the buffer.

- \text{int InitTerminal(int term)}

  This procedure should be called once and only once before any other call to the terminal device driver procedures defined above are called for terminal \(\text{term} \). Among other things, your \text{InitTerminal} \ procedure must initialize the terminal controller hardware for this terminal by calling the \text{InitHardware} \ operation for terminal number \(\text{term} \). Remember, you may not create any threads that are simply a part of your terminal device driver. The only threads you may create should be the users of your terminal device driver (those that call procedures such as \text{ReadTerminal} \ and \text{WriteTerminal} \ that are part of the terminal device driver API described in Section 6.2). This means that you may not create any new threads in your \text{InitTerminal} \ routine. Note that it is an error to initialize the same terminal more than once or to attempt to perform any other terminal device driver API calls on a terminal before that terminal has been initialized.

- \text{int TerminalDriverStatistics(struct termstat *stats)}

  This procedure returns a consistent snapshot of the I/O statistics for all terminals all at once. The description “consistent” here means “all taken at the same time, under the same mutual exclusion of the monitor.” Thus, none of the statistics can change within the device driver while you are copying out to the user’s buffer other of the terminal driver’s statistics. The argument \(\text{stats} \) must be a pointer to an array of \text{struct termstat} \ structures. The size of this array should be dimensioned at \text{NUM_TERMINALS} \ (that is, there should be space where this pointer points, for \text{NUM_TERMINALS} \ total \text{struct termstat} \ structures). The calling thread must have allocated/created the memory that this pointer points to before calling \text{TerminalDriverStatistics}. The definition of a \text{struct termstat} \ is given in the terminals.h include file for this project. For each terminal, this structure records the total number of characters received from and sent to the hardware for that terminal, and the total number of characters received from and returned to user programs for that terminal. The “in” and “out” counts in the \text{termstat} \ structure are defined from the point of view of the device driver. In particular:

  - Each time your driver does a successful \text{ReadDataRegister} \ call for some terminal, the \text{tty_in} \ count for that terminal should increase by 1.
  - Each time your driver does a successful \text{WriteDataRegister} \ call for some terminal, the \text{tty_out} \ count for that terminal should increase by 1.
  - Each time some user thread does a valid \text{WriteTerminal} \ call for some terminal (i.e., your driver does not initially return an error and not process the request), the \text{user_in} \ count for that terminal should increase by \(\text{len} \), the length of the buffer written by that request.
  - Each time some user thread does a successful \text{ReadTerminal} \ call for some terminal, the \text{user_out} \ count for that terminal should increase by the number of characters returned by that request.

  The I/O statistics for terminal number \(i\) are recorded in entry \(i\) in this array. If terminal number \(i\) has not yet been initialized with \text{InitTerminal}, all I/O statistics for this terminal should be recorded as \(-1\) in the results returned by \text{TerminalDriverStatistics}.  

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• int InitTerminalDriver()

This procedure must be called once and only once before any other calls to terminal driver procedures, even before any calls to InitTerminal are made. This procedure should perform any specific overall initialization that your terminal device driver needs. This overall initialization should include initializing the terminal device driver monitor itself. Remember you may not create any threads that are simply a part of your terminal device driver. The only threads you may create should be the users of your terminal device driver (those that call procedures such as ReadTerminal and WriteTerminal that are part of the terminal device driver API described in Section 6.2). This means that you may not create any new threads in your InitTerminalDriver routine.

7 Terminal Behavior

7.1 Character Processing

Terminal device drivers typically do much more than transfer characters between memory and the terminal hardware. They also process characters in a myriad of ways before (on reading) or after (on writing) the application program sees those characters (for example, try the command "man termios" if you want to get a taste of the many settable parameters for terminal character processing in Unix/Linux). In this project, you need not implement a complete set of these operations that Unix/Linux performs, but you must implement some of them. Specifically, you must carry out the character processing described in this section as part of your terminal device driver.

All characters input from the terminal must in general be “echoed” back to the terminal when they are typed (actually, when you get them from the input data register). This echoing allows the user typing on the keyboard to see each character as it is typed. In order for the terminal to appear responsive, the echoed characters should be transmitted back to the terminal at the earliest opportunity, regardless of what the user threads are doing or have done in the recent past. In particular no user application output characters from WriteTerminal should go to the terminal between the time a character is typed at the terminal (and you get a receive interrupt) and the time that input character is echoed to the terminal. Any characters being output for echoing should be given priority over any characters being output by user application thread calls to WriteTerminal. When echoing most typed characters, you simply output the character that was typed, but some typed characters require special processing and should result instead in echoing a multi-character sequence, rather than literally echoing the typed character itself, as described directly below; as described further in Section 7.3, such multi-character sequences resulting from this character processing must be echoed without other interleaved output characters on that terminal.

On input, the terminal hardware provides a “carriage return” (‘\r’ in C) character when you hit the “Enter” key on the keyboard. This carriage return should be converted on input to a single “newline” character (‘\n’) by your device driver (looking ultimately to user threads as if the user had typed ‘\n’ rather than ‘\r’). The echo for this typed single character should consist of the special two-character sequence ‘\r’ and ‘\n’, in that order. To the hardware, the ‘\r’ character is known as a “carriage return,” and when output moves the cursor to the beginning of the current displayed line; similarly, to the hardware, the ‘\n’ character is known as a “linefeed,” and when output moves the cursor down one line on the display.

Special processing is also required when you receive either a “backspace” character (‘\b’) or a “delete” character (‘\177’) from the terminal. When either of these two characters is typed, you should remove in memory (internal to your device driver) the last character (if any) from the current input line. The current input line consists of those characters you have received from the terminal that have not yet been terminated as a line of input by the receipt of a newline character (‘\n’), after the processing described...
If the current input line in memory is empty, you should ignore the backspace or delete character from the terminal. If the current input line in memory is nonempty, you should remove the last character in the line. In no case should you include the backspace or the delete character itself in the input line that is returned to a user thread calling the ReadTerminal function.

In the processing a backspace or delete character as described above, if you remove a character from the current input line in memory (because the current line was not empty), you should also then echo to the terminal the special three-character sequence of “backspace” (’\b’) followed by “space” (’ ’) followed by “backspace” (’\b’). In no case should you echo the delete or backspace character itself to the terminal. Echoing this three-character sequence is necessary because the effect of the user having typed backspace (’\b’) or delete (’\177’) should be to remove the previous character visibly from the screen, which the terminal hardware can do only with the sequence above: the first character (backspace) moves the cursor one space to the left, the second character (space) replaces on the screen the character that was there with a space (moving the cursor again one space to the right), and the third character (backspace) finally moves the cursor back one space to the left. This output 3-character sequence will result in the last character on the screen appearing to be “erased.” If, instead, the current input line was already empty when the backspace or delete character was typed, you should ignore the typed backspace or delete character and should not echo anything for this character (you optionally may want to ring the bell in this case, as some systems do; you can do this by sending ’\7’ to the terminal).

On output for characters from a call to WriteTerminal(), any newline (’\n’) character must be transmitted to the terminal hardware as the sequence of the two characters ’\r’ and ’\n’, in that order. As described above, to the terminal hardware, the ’\r’ character moves the cursor to the beginning of the line, and the ’\n’ character moves the cursor down one line. The C language, instead, defines the meaning of the single character ’\n’ on output to do both cursor movements in a single character, so a ’\n’ from a user program must be converted to ’\r’ followed by ’\n’ when sent to the hardware.

### 7.2 Line-Oriented Input

You will notice that the specification of ReadTerminal() considers the input as consisting of lines of text delimited with ’\n’, but that, at the same time, the terminal hardware lets your driver read you a single character every time it raises a receive interrupt. Something similar can be said for WriteTerminal() and the transmit interrupt.

This behavior implies that your terminal device driver must implement the illusion (abstraction) of a line-oriented terminal on top of a character-oriented hardware device. It is usually true, as it is in this case, that the diverse pieces of the operating system implement abstractions that are not directly or completely supported by the hardware.

Implementing this line-oriented behavior in the terminal device driver presents some complications that may not be obvious at first. Consider the following application code:

```c
int len1, len2, len3;
char buf1[2];
char buf2[10];
char buf3[10];
char buf4[10];

len1 = ReadTerminal(0, buf1, 2);
len2 = ReadTerminal(0, buf2, 10);
```
and suppose the user types the following on the keyboard of terminal number 0:

```
Hello\b\b\b\b\b\b\b\b\b.Universe\b\b\b\b\b\b\b\b\b.World\nGood bye
```

From the specification of `ReadTerminal` and the character processing that the driver must perform, after the application code executes, the variables have the following values (although note that the buffers are not terminated by a null character as suggested in the C notation used below):

```
len1 = 2
buf1 = "Hi"

len2 = 1
buf2 = "\n"

len3 = 6
buf3 = "World\n"
```

In addition, the calling thread will be blocked on the last `ReadTerminal()` call until the user types a ‘\n’ or ‘\r’. Think about why this is the case. You may come to realize that you need some buffering inside your terminal device driver.

As mentioned above, although the contents of `buf1`, `buf2`, and `buf3` are shown above as they would be written for typical C strings, in reality there is no null character at the end of each as would normally be the case in C. `ReadTerminal` should not put a null character at the end of the buffer when it returns.

### 7.3 Terminal Sharing Discipline

When used from different threads, the various terminal functions can be called concurrently. Furthermore, user program-driven output also occurs concurrently with the output from the echoing of input characters. You should decide what behavior is reasonable in the presence of concurrency, but here are some minimum standard requirements.

When a mix of two or more `WriteTerminal` calls occur concurrently to the same terminal, their output characters must not be interleaved on the screen. For example, if two `WriteTerminal` calls are made currently to terminal number 1, you must not output some of the characters from one `WriteTerminal` call, then some from the other `WriteTerminal` call, followed by more from the first `WriteTerminal` call, etc. Instead, you must finish outputting all of the characters from the first `WriteTerminal` call, and only then begin outputting the characters from the second `WriteTerminal` call, and must finish all of those characters before beginning the output of characters from some third `WriteTerminal` call, etc.

When, instead, a mix of two or more `WriteTerminal` calls occur concurrently to different terminals, the characters being output to each different terminal may be interleaved in time between the different terminals, as long as the characters from each individual `WriteTerminal` call are still output in the order they occur in the buffer that was an argument to that call. For example, if one `WriteTerminal` call is made to terminal number 1 and, concurrently, another `WriteTerminal` call is made to terminal number 2, one possible correct execution would be to output the first character from the first `WriteTerminal` call to terminal number 1, then output the first character from the second `WriteTerminal` call to terminal
number 2, and then the next character from the first WriteTerminal call to terminal number 1, followed by the next character from the second WriteTerminal call to terminal number 2, and so on.

The echoed input characters must be displayed at the earliest opportunity, as previously mentioned. They can (indeed, sometimes must) be mingled, on the screen, with the output from one or more WriteTerminal calls. For example, half-way through outputting the characters from one call to WriteTerminal, if the user types a key on the keyboard, that typed character must be echoed right away, before the rest of the characters from that call to WriteTerminal.

Multi-character sequences resulting from the input character processing described above, however, must be displayed without other interleaved output characters from WriteTerminal on that terminal. This restriction is to preserve the display effect of these sequences.

If there is more than one ReadTerminal call waiting to read characters from a terminal, the contents of each of their buffers, one at a time, must be filled by characters typed sequentially at the keyboard (after each input line has been terminated by a newline). That is, input characters (after the input line has been terminated by a newline) should go to a single ReadTerminal call until that ReadTerminal returns, and then on to the next ReadTerminal call, and so on. For example, two concurrent ReadTerminal calls reading from the same terminal should not alternate the characters read from that terminal.

Your terminal device driver should implement line-oriented terminals. For this project, this means that no data is returned for a ReadTerminal call until a newline has been received from that terminal to terminate this input line. This restriction does not imply that the whole line must be returned to the ReadTerminal call: only as many characters as requested should be returned, and the rest of those characters should remain available for the next ReadTerminal call to that terminal, even if this call is made by a different user thread. If a ReadTerminal call asks for fewer characters than the current length of the next input line, the ReadTerminal call must still be blocked until the input line ends with a newline.

### 7.4 Device Driver Implementation Constraints

Device drivers are critical parts of the code of the operating system: they are very stressed by concurrency and operate at a very low level inside the system. Notably, they are often invoked from hardware interrupts, which typically may preempt any other system activity, including other important OS functions. They are also restricted, for reasons that will become clear later in the course, to using only small portions of well-defined “pinned” memory. Because of this, your device driver must not block when running in an interrupt handler.

Furthermore, your device driver should allocate and use only a fixed amount of memory for its internal data structures and for each terminal device initialized. In the event that a sequence of terminal operations should require the driver to use more memory than this fixed amount, the last operation of the sequence should either not be carried out or should be blocked, depending on whether the operation is executed from within an interrupt handler or not. In particular, it is all right to drop input characters if you run out of buffer space to store them because characters are coming in faster, on the average, than they can be consumed by the applications calling ReadTerminal. However, it is unreasonable to require applications to have a pending ReadTerminal call at the time every single character arrives. You thus must use buffers inside your device driver to deal with bursts and temporarily “absent” applications, but such buffers must be of finite size.

When adding one input character to such a buffer would overflow the buffer, and the driver cannot block waiting for the buffer to drain (e.g., if called by a receive interrupt) you may choose a course of action. You may drop the character as stated above, and you might optionally in this case try to output a bell (‘\7’) to the terminal. The bell is not required, but you should implement some reasonable behavior for all cases.

You may not create any threads that are simply a part of your terminal device driver. The only
threads you may create should be the users of your terminal device driver (those that call procedures such as ReadTerminal and WriteTerminal that are part of the terminal device driver API described in Section 6.2.

8 Using Threads and Concurrency

8.1 The Threads Package

The threads package you will use in this project is simplified in order to be easy to use and to have only the procedures you may need in the project. In order to use the threads package, you must include the function prototypes and definitions for the library as:

```c
#include <threads.h>
```

You will also need to explicitly link in the threads library routines when you link your program. This is done automatically when you use the provided Makefile to link your code, as described in Section 10. (In case you are curious, the threads library routines, as well as the terminal hardware emulation routines, are part of the liblab1.a archive linked in by the provided Makefile.)

The threads package provides the following functions (you may not need all of these in the project, but they are provided for completeness):

- `thread_id_t ThreadCreate(void (*func)(void *), void *arg)`

  The `ThreadCreate()` function starts a new thread that begins executing the procedure `func`. The `func` procedure should have a prototype of

  ```c
  void func(void *arg)
  ```

  This means that `func` is a procedure that takes a generic pointer as an argument and does not return anything. The argument is specified via `ThreadCreate()`’s `arg` argument. This argument can be cast to the appropriate type, as needed. Upon success, `ThreadCreate()` returns the thread identifier of the new thread. Upon failure, `ThreadCreate()` prints an error message on `stderr` and terminates the program.

  Remember, you may not create any threads that are simply a part of your terminal device driver. The only threads you may create should be the users of your terminal device driver (those that call procedures such as ReadTerminal and WriteTerminal that are part of the terminal device driver API described in Section 6.2).

  Note that when the procedure `func` completes execution, that thread will exit immediately. And if this is the last of all the threads you have created, your entire program will then exit immediately.

- `void ThreadWait(thread_id_t th)`

  The `ThreadWait()` function waits for the thread identified by the thread identifier `th` to have exited; if that thread has not yet exited, the calling thread is blocked until that thread exits. On any failure, `ThreadWait()` prints an error message on `stderr` and terminates the program.

- `void ThreadWaitAll(void)`

  The `ThreadWaitAll()` function waits for all threads previously created by `ThreadCreate()` to have exited. On any failure, `ThreadWaitAll()` prints an error message on `stderr` and terminates the program. In all programs, before the `main()` thread ends, `ThreadWaitAll()` will automatically be called.
• void Declare_Monitor_Entry_Procedure(void)

Declarations of Monitor Entry Procedures

Declare_Monitor_Entry_Procedure() is used to declare that the current procedure is an entry procedure of the monitor. This call must be used only at the beginning of each C procedure that implements an entry procedure of the monitor. It acquires the mutual exclusion of the monitor, and when this entry procedure returns, the mutual exclusion for the monitor is then automatically released.

Note that the threads package for this project supports only a single monitor, so all entry procedures defined by Declare_Monitor_Entry_Procedure() are implicitly part of the same monitor. On any failure, Declare_Monitor_Entry_Procedure() prints an error message on stderr and terminates the program.

• cond_id_t CondCreate(void)

The CondCreate() call creates a new conditional variable and returns the condition variable id of the new condition variable. On any failure, CondCreate() prints an error message on stderr and terminates the program. Before calling any other operation on some condition variable, you must have created that condition variable by a call to CondCreate. In particular, CondCreate returns the condition variable id of the newly created condition variable, and this condition variable id must be used as the argument to any other condition variable operations for which you want to use that condition variable.

• void CondWait(cond_id_t cv)

The CondWait() call performs the condition variable wait operation on the condition variable identified by the condition variable identifier cv. In particular, this call blocks until the same condition variable is signaled using CondSignal(), but only one of possibly several waiting threads will be unblocked at that point. CondWait() releases the mutual exclusion of the monitor before blocking, to allow entry into other entry procedures protected of the monitor, and then reacquires this mutual exclusion before returning after being woken up by a signal operation. CondWait() may only be called while inside the monitor. On any failure, CondWait() prints an error message on stderr and terminates the program.

• void CondSignal(cond_id_t cv)

The CondSignal() call performs the condition variable signal operation on the condition variable identified by condition variable identifier cv. It causes one thread currently waiting for this condition variable to become unblocked, ready for execution. The waiting thread will not actually execute until later, after the calling thread has exited the monitor or itself become blocked by waiting on some other condition variable. CondSignal() may only be called while inside the monitor. On any failure, CondSignal() prints an error message on stderr and terminates the program.

• void CondDestroy(cond_id_t cv)

The CondDestroy() call deactivates the condition variable identified by cv. Any subsequent calls to CondSignal() or CondWait() on this condition variable will result in an error. On any failure, CondDestroy() prints an error message on stderr and terminates the program.

8.2 Using the Mesa Monitor Paradigm

As you know from the lectures, a monitor is a synchronization primitive that is similar to an “object” in the “object-oriented” sense, with “private” variables that can only be accessed through public “methods” known as entry procedures provided by the monitor. A monitor automatically provides mutual exclusion and also provides operations for concurrent threads to coordinate through condition variables.
Although the C programming language does not provide specific support for monitors, it is possible to create a monitor and to follow the monitor paradigm in C using the threads library procedures defined above. However, doing so requires a little self-disciplined in how the threads library calls are used.

An example of how to correctly write a monitor in C is provided on CLEAR in the directory

/clear/courses/comp421/lab1/philosophers/

This is an implementation of the classic Dining Philosophers problem, as described in class and in the textbook. In particular, the file philosopher.c in this directory contains all of the source code for the monitor itself. For convenience (and to encourage you to read this code to see how to write a monitor), the complete code for this implementation of the Dining Philosophers problem is reproduced in the Appendix to this handout.

In order to use the monitor paradigm to provide mutually exclusive access to a set of shared variables, you must use the threads library procedures in this project as shown in this Dining Philosophers example and as detailed below:

- A monitor is a collection of C procedures and all shared variables controlled by those procedures.

- You should put all of the code for a monitor into a single file of C source code. You should also put an initialization procedure for your monitor in that one source file. Nothing other than the monitor should be included in that same file. For example, as noted above, all of the source code for the example Dining Philosophers monitor is in the single file philosopher.c. The initialization procedure there is init_philosophers().

- You should create any condition variables to be used in the monitor in this initialization procedure.

- Some of the C procedures in this file will be entry procedures of the monitor, and some will be normal internal procedures called only from within the monitor. Each entry procedure should be defined as extern, and each internal procedure should be defined as static. The example monitor has two entry procedures, called pickup_forks() and putdown_forks(), and both are declared as extern. The example has one internal procedure, called test_forks(), and it is declared as static.

- At the beginning of each entry procedure, you should declare this procedure to be an entry procedure by calling Declare_Monitor_Entry_Procedure(). This procedure acquires the mutual exclusion of the monitor and arranges for the mutual exclusion to be automatically released when this entry procedure returns.

- Each condition variable should be used only from within the single monitor.

Please be sure to follow these rules in writing any monitor. The example monitor in philosopher.c shows clearly how to do this.

### 8.3 User Programs

In this project, each user program is composed of a set of threads that may call any of the procedures WriteTerminal(), ReadTerminal(), TerminalDriverStatistics(), HardwareInputSpeed(), and HardwareOutputSpeed() at will, but only after the procedure InitTerminal() has been called once (and only once) for each terminal used. In addition, some thread must call InitTerminalDriver() once before any other calls to any other terminal device driver procedures (including calls to InitTerminal()). The one call to InitTerminalDriver() and the
calls to InitTerminal() (one for each terminal you will use) should be done by your main() procedure, described next.

When a user program begins execution, only a single thread is executing. This thread begins executing at the normal main() routine of the C program; this thread is called the “boot” thread. When the boot thread begins execution, neither the terminal hardware nor your terminal device driver are active or initialized yet. The boot thread should call InitTerminalDriver() and InitTerminal(), as described above. The boot thread should also create any other threads you will use in your program.

The boot thread otherwise acts like any other thread, except that when it ends (e.g., by calling exit() or by “falling off” the bottom of main()), the ThreadWaitAll() routine (Section 8.1) is automatically called.

Please also note that your main() procedure is not part of the terminal device driver but is instead part of the user program that uses the terminal device driver. Thus, any code related to your device driver, including the initialization of any data structures you define in your driver, should not be part of or depend on any particular main() routine: your terminal device driver should be able to work with any main() routine and any mix of application threads started by that main() routine. In particular, when we test your terminal device driver, we will replace the main() routine with one of our own. Because of this, you should put the code for any main() you use in a source file separate from the file you use to hold the source code for your device driver itself. We will provide several sample test programs on CLEAR in the directory /clear/courses/comp421/lab1/samples. You should also write a number of your own test programs to test your device driver. The sample test programs we will provide are intended only as examples and will not test all features of your device driver (and we will use different test programs when grading your project).

9 Running Your Terminal Device Drivers

When you have a version of your terminal device driver compiled and you are ready to test it (for example, to test an initial version in which you have implemented some of the required functionality and want to test that before going on to implement and test further pieces of the project), you simply run your executable file that has been linked by the provided Makefile (Section 10).

This executable file, as linked with the provided library (done automatically by the provided Makefile), will try to open a new xterm window on your display whenever InitHardware is called for some new terminal. This xterm will emulate this terminal device, with which the hardware procedures (e.g., WriteDataRegister) interact.

Any output from your program (written to stdout and stderr via, e.g., printf or fprintf) will go to the Linux shell from which you invoked the executable file (in the same way as normal output from normal C programs).

When using the X11 Window System to support each xterm on CLEAR, you will need to log in to CLEAR using ssh; each xterm window will then display on your local screen (on the computer you are using locally, from which you logged on to CLEAR). For this to work correctly, you will need to tell your local ssh client program to allow X11 Window System operations to be forwarded through the ssh connection. However, different ssh client programs may do this in different ways; if you are using one of the common Unix/Linux/Cygwin command line-based ssh clients, you probably want to use the -X option on the ssh command line to do this (e.g., ssh -X ssh.clear.rice.edu).

Also, for this to work correctly, you will need to be running an X Windows server program on your local machine. Many systems already have this server available. However, Microsoft Windows does not come with such a server; many X Windows servers for Microsoft Windows are available, but I recommend the freely available Cygwin X server (directions on downloading and installing it are available on-line). Another
recommended Microsoft Windows X server is Xming, although I have not personally used it myself.

Remember that in all cases, you must be logged into a CLEAR machine before you can compile, link, or run your terminal device driver. And remember that for the terminal X windows to work correctly, you must be running a local X Windows server program on your own local computer, and must log into CLEAR using ssh in a way that allows X Window operations to be forwarded back to your local X Windows server program through this ssh connection.

## 10 Building Your Project

A template Makefile is available for your use, that will automatically compile your terminal device driver into montty.o. This template Makefile will also automatically make any user test programs that you want to test your terminal device driver with; these test programs will automatically be linked with montty.o and with the necessary libraries needed to make the terminal hardware emulation and the provided threads package work.

This template Makefile is available on CLEAR at

```
/clear/courses/comp421/lab1/samples/Makefile.template
```

You should make a copy of this file into your own directory that you use for the project. You should name your copy of this file just Makefile.

The only thing else you should need to modify in your Makefile is the line that begins “TEST =”. This line defines a list of test programs that will automatically be compiled and linked, that you want to test your terminal device driver with. You should edit this list to be a list of your own test programs (the example initially given in the Makefile is to make test programs named test1, test2, and test3).

For each user test program in this TEST list, the Makefile will make the program out of a single correspondingly named source file. In addition to this single source file for each test program, each program will also be linked with your device driver. For example, the Makefile will make test1 out of test1.c, if you have a file named test1.c in this directory.

Any #include files written by you and included by your programs should be located in your work directory and should be #included with double quotes; that is, you should include them using

```
#include "foobar.h"
```

Any include files that we provide that you use should be #included using

```
#include <foobar.h>
```

You should not copy any of our include files into your own directory. Using this form of #include with <...> will automatically get them (in their most recent version, in case any revisions become necessary) from the common comp421 directory for this project. Likewise, you should not copy any of our library files to your own directory.

## 11 For Students Enrolled in COMP 521 or ELEC 552

As noted previously, for students taking COMP 521 or ELEC 552, the graduate student version of this course, you must also write and submit a report addressing issues including the factors affecting the performance of the design in your solution to the project and the issues involved in scaling the project to larger sizes in larger systems. Students taking COMP 421 or ELEC 421, the undergraduate student version of this course, may ignore this section, as this project requirement does not apply to you.

For students taking the graduate version of this course, your report should address issues such as, but not necessarily limited to, the general points below:
• What design choices did you make in your solution to the project that you intended to improve the performance of your solution? Specifically explain these design choices and why they should improve performance.

• What design choices would you have made in your solution, if you’d had more time to implement them, that could have improved the performance of your solution? Specifically explain these design choices and why they should have improved performance.

• What are the biggest issues affecting the ability of your solution, and what your solution could have been if you’d had more time, to scale to larger sizes and larger systems? Specifically, think about things such as systems with more terminals, more users using the terminals, more output going to the terminals, more input being read from the terminals, etc. Think about factors including both execution time performance and memory consumption.

Your report must be limited to a maximum of 6 pages, although there is no minimum required length for your report; the report should otherwise be as long as you need to specifically and clearly address the issues above. Your report may be formatted in either single-column or double-column format and should use a font size no smaller than 10 points. Your report will be graded based on what you say in it, not on how many pages you fill. In writing your report, please try to think critically about what you want to say and to say it clearly.

In addition to the limit of a maximum report length of 6 pages, your report must be submitted only in PDF format (e.g., not in other strange formats such as Microsoft Word).

To submit your report for this project, please include it among the other files you want to turn in for grading for the project, as described below in Section 12. The file name for your report must be

`report.pdf`

Only reports named `report.pdf` that are turned in with the rest of your project, as described below, will be graded.

The grading of your report will be part of the overall grading for your project. In particular, your report will represent 15% of your grade for the project. The other aspects of the grading of the project will represent 85% of your grade for the project.

12 Turning in Your Project

Your project is due by 11:59 PM on Wednesday, February 8, 2017. Before turning in your project, please create a file named “README” in the same directory as the rest of your files for the project. In this file, please describe anything you think it would be helpful for the TAs to know in grading your project. This might, for example, mean describing unusual details of your algorithms or data structures, and/or describing the testing you have done and what parts of the project you think work (or don’t work).

To submit your project for grading when you are ready, please perform the following two steps:

• First, on CLEAR, change your current directory to the directory where your files for the project for grading are located. For example, use the “cd” command to change your current directory. When you run the submission program, it will submit everything in (and below) your current directory, including all files and all subdirectories (and everything in them, too).

• Second, on CLEAR, run the submission program

`/clear/courses/comp421/lab1/bin/lab1submit`
This program will check with you that you are in the correct directory that you want to submit for grading, and finally, will normally just print “SUCCESS” when your submission is complete. If you get any error messages in running lab1submit, please let me know.

You may (if you want to) submit your project multiple times or at any time. The lab1submit program will only remember the single most recent submission you make for this project.

13 Use of Piazza

As described previously in class and in the syllabus, this semester, we will be using Piazza for class discussion. Piazza is a web-based platform that will allow you to post questions about the course material, including Lab 1, and to quickly receive answers from me, from the TAs, and from your fellow classmates. With Piazza, you can also easily look to see if someone else has already posted a question about a problem that you may also be experiencing. Instead of sending questions by email to me and/or the TAs, we encourage you to post your questions on Piazza. You should also check Piazza regularly for new questions, answers, and announcements.

When posting questions or answers about the project on Piazza, please be careful about what you post, to avoid inadvertently violating the course’s Honor Code policy described in the course syllabus and below in Section 14. Specifically, please do not post details about your own project solution, such as portions of your source code or details of how your code works, in public questions or answers on Piazza. If you need to ask a question that includes such details, please make your question private on Piazza by selecting “Instructor(s)” (rather than “Entire Class”) for “Post to” at the top, so that only the course instructor and TAs can see your posting.

Most of you have already registered for the course’s forum on Piazza, but if not, you will need to do this before you can access this resource. To register for the course’s forum on Piazza, go to

https://piazza.com/rice/spring2017/comp421

Then select “Join as Student” and click on the “Join Classes” button. Note that Piazza requires a “rice.edu” email address to register; after registering, you can enter an alternate email address if you want to.

14 Honor Code Policy

The Honor Code is a special privilege and responsibility at Rice University. As stated in a January 20, 2016 editorial in The Rice Thresher: “As incoming students enter Rice, many are surprised by the degree to which the university’s Honor Code extends trust to the student body. ... The privileges of the Honor Code stem from the idea that Rice’s aim is not just to instill knowledge in its students, but [to] also help them develop moral character. This idea is fundamental to Rice’s identity: Students can and should be held to a high moral character standard.”

Specifically, all assignments in this course are conducted under the Rice Honor System, and you are expected to behave in all aspects of your work in this course according to the Rice Honor Code. When in doubt as to whether a specific behavior is acceptable, ask the instructor for a written clarification. Suspected Honor Code violations in this course will be reported in complete detail to the Rice Honor Council. For more information on the Rice Honor System, see http://honor.rice.edu/.

For this Lab 1 assignment, this project must be done individually. The second and third projects in this class should be done in groups of 2 students, but you must do this first project by yourself.

During the project, students are encouraged to talk to each other, to the TAs, to the instructor, or to anyone else about the assignment. This assistance, however, is limited to general discussion of the problem.
Each student must produce their own solution. Consulting or copying, in any manner, another student’s solution (even from a previous class or previous year) is prohibited, and submitted solutions may not be copied, even in part, from any source.

Also, for students taking COMP 521 or ELEC 552, each student must write their own report on performance and efficiency issues related to the project. Submitted reports must not be copied from any source, and you must fully cite any references you use in preparing your report.

15 A Suggested Plan of Attack

There is no need for you to do things in any order. However, some parts of this assignment will take longer than you think. This is not because you will have to write a lot of code but because some of the bugs you will encounter will be reluctant to show themselves. One of many reasonable plans to attack this project is as follows:

- While working on the project, remember to check the class web page regularly. Any announcements such as clarifications or corrections will be posted there.
- Also, please use Piazza, as described above in Section 13, if you have questions as you work on the project. Here, you can ask questions and find answers to your own questions and questions asked by other students that might be helpful to you too. Please check Piazza regularly.
- Read this complete handout. Read it again. Make sure you understand the bit about the top and bottom halves of device drivers. Think about how they should interact. Realize that the top and the bottom halves operate asynchronously, with the top half being called by user threads and the bottom half being called by a different thread for each type of interrupt. The granularity of the objects that the top and bottom half work on are also different (lines versus characters).
- Remember that you may not create any threads that are simply a part of your terminal device driver. The only threads you may create should be the users of your terminal device driver (those that call procedures such as ReadTerminal and WriteTerminal that are part of the terminal device driver API described in Section 6.2).
- Decide where buffers and other shared structures will be needed and which functions will interact with them. Perhaps draw out your design as a diagram on paper. Show the buffers and other data structures, as well as the procedures that will access them.
- Try to identify the synchronization problems. Think about the behavior of each terminal, both input and output. Also think about the behavior of the TerminalDriverStatistics call, which requires a consistent picture of the state of all terminals at once.
- Identify the critical section. Add notations indicating these to your diagram.
- Create an initial version of your terminal driver monitor that can successfully echo characters to the terminal, without having the ReceiveInterrupt handler block on the TransmitInterrupt handler (you will need to have at least some version of ReceiveInterrupt and TransmitInterrupt defined in your code in order to be able to link and run even this initial version of your device driver). Don’t worry yet about any input or output character processing; for now, just echo each character “as is.” Test and debug this version of your device driver using your own simple test programs before proceeding with the rest of the project. You should be able to type one character at a time and see it echo back onto the screen.
• Add support for \texttt{WriteTerminal} to your device driver. Make sure that the echo has priority over \texttt{WriteTerminal} output and that two or more concurrent \texttt{WriteTerminal} calls do not interfere with each other. Again, don’t worry yet about any input or output character processing; for now, just output each character “as is.” \textit{Test and debug} this version of your driver using your own simple test programs before proceeding with the rest of the project.

• Add support for \texttt{ReadTerminal} into your driver. Make sure that echoing of characters to the screen still works even if no application calls \texttt{ReadTerminal}. Again, \textit{test and debug} this version before proceeding with the rest of the project.

• Think about where best to introduce input and output character processing. Realize that the processing required for echo, output, and input, are different, but that they are not entirely dissimilar either.

• Add character processing.

• Thoroughly test what you have written so far. Try writing different test programs to exercise and stress different features of your terminal driver.

• Test everything some more.

• When you think you are ready, turn in your project by running the \texttt{lab1submit} program as described in Section 12.

• Relax. You are done with the project. Congratulations.
Appendix: Example of How to Write a Monitor (Dining Philosophers)

This appendix shows an example of how to use the threads package provided for this project, including how to create threads and how to write and use a monitor. In particular, this appendix shows a solution to the Dining Philosophers problem. The solution is divided into two files, as shown below.

File “philmain.c”

The file “philmain.c” contains the main() routine that creates one thread for each of the five philosophers, each executing the do_phil() routine (note that this Dining Philosophers program does not use the terminal hardware and so does not call InitTerminalDriver() or InitTerminal()). The do_phil routine in this file then executes the behavior of each philosopher, showing how the philosopher threads call the two entry procedures of the monitor: pickup_forks() and putdown_forks().

```c
#include <stdio.h>
#include <stdlib.h>
#include <threads.h> /* COMP 421 threads package definitions */

void pickup_forks(int);
void putdown_forks(int);
void init_philosophers(void);

void do_phil(void *arg)
{
    int i = (int)(long)arg;
    printf("do_phil %d\n", i);

    while (1) {
        pickup_forks(i);
        printf("eating %d\n", i);
        putdown_forks(i);
        printf("thinking %d\n", i);
    }
}

int main(int argc, char **argv)
{
    int i;

    init_philosophers();

    for (i = 0; i < 5; i++) {
        ThreadCreate(do_phil, (void *)(long)i);
    }

    ThreadWaitAll();

    exit(0);
}
```
The file “philosopher.c” contains the source code for the monitor itself. Each of the two entry procedures, pickup_forks() and putdown_forks(), is actually made into an entry procedure by the Declare_Monitor_Entry_Procedure() call at the beginning of that procedure.

#include <stdio.h>
#include <threads.h> /* COMP 421 threads package definitions */

/*
* The state of each of the 5 philosophers: either THINKING, HUNGRY,
* or EATING.
* This is declared ’static’ so it can’t be seen outside this .c file.
*/
static int state[5];
define THINKING 0
define HUNGRY 1
define EATING 2

/*
* A condition variable for each philosopher to wait on. Declared
* ’static’ as with all variables that should only be seen inside
* this monitor.
*/
static cond_id_t philcond[5];
define LEFTPHIL ((i+1) % 5) /* the philosopher to i’s left */
define RIGHTPHIL ((i+4) % 5) /* the philosopher to i’s right */

static void test_forks(int);

/*
* Pick up both of the forks for philosopher i. Waits until
* both forks are available.
* This is an entry procedure for the monitor, so:
* - it is an ’extern’ function (any function not defined ’static’
* is automatically extern, according to the C language; and
* - it acquires the mutual exclusion of the monitor at the top
* and releases it at the bottom.
*/
eextern void
pickup_forks(int i)
{
    /*
     * You MUST use Declare_Monitor_Entry_Procedure() at the
     * beginning of EACH and EVERY entry procedure of your monitor.
     * You MUST NOT use Declare_Monitor_Entry_Procedure() anywhere
     * else. This call acquires the mutual exclusion of the monitor
     * and arranges for the mutual exclusion to be automatically
     * released when this entry procedure returns.
     */
Declare_Monitor_Entry_Procedure();

state[i] = HUNGRY;
test_forks(i);
while (state[i] != EATING)
    CondWait(philcond[i]);
}

/*
* Put down both of the forks for philosopher i. If this allows either
* the philosopher to our left or to our right to begin eating, let them
* eat.
* As with pickup_forks, this is also an entry procedure of the monitor.
*/
extern void
putdown_forks(int i)
{
    /*
    * You MUST use Declare_Monitor_Entry_Procedure() at the
    * beginning of EACH and EVERY entry procedure of your monitor.
    * You MUST NOT use Declare_Monitor_Entry_Procedure() anywhere
    * else. This call acquires the mutual exclusion of the monitor
    * and arranges for the mutual exclusion to be automatically
    * released when this entry procedure returns.
    */
    Declare_Monitor_Entry_Procedure();

    state[i] = THINKING;
test_forks(LEFTPHIL);
test_forks(RIGHTPHIL);
}

/*
* Test whether philosopher i can begin eating. If so, move him
* to EATING state and signal him (in case he is waiting).
* This is an *internal* (non-entry) procedure of the monitor. Thus,
* it is a 'static' function, making this function name not known
* outside this .c file, so it can’t be called from outside the
* monitor. An internal procedure should be called only from a
* monitor entry procedure (or from another internal procedure of
* the monitor).
*/
static void
test_forks(int i)
{
    if (state[LEFTPHIL] != EATING &&
        state[i] == HUNGRY &&
        state[RIGHTPHIL] != EATING) {
        state[i] = EATING;
        CondSignal(philcond[i]);
    }
}
/ * Initialize the Dining Philosophers monitor.
 * This procedure should be called *once* when the whole program starts
 * running. It creates the condition variables and initializes the
 * shared variables used inside the monitor.
 */
void
init Philosophers()
{
    int i;

    for (i = 0; i < 5; i++) {
        state[i] = THINKING;
        philcond[i] = CondCreate();
    }
}