

**Lab Assignment 2**  
**Released: September 10, 2024**  
**Due date: Sep 24, 2024, 11:59pm**  
**Total points: 150**

**Assignment Description**

In this lab project, you will learn –

- (1) How to change OS/161 kernel and compile.
- (2) How to add system calls to operating system kernel.
- (3) How to make the system level functions available to the user program.

This project requires you to implement new system calls in OS/161. You will also develop user programs (either one for each new system call or just one program that tests all new system calls) to test the new system calls. **You should use the ASST0 kernel to test your programs (same as Lab1).**

**(20 points) Part A**

This part is to get yourself familiarized with the OS/161 source code. Your job is to identify and revise the proper module(s) to customize your OS/161 greeting message that is displayed on the menu screen. Print your name during the boot process.

**What to submit for part A:**

- Please include a screenshot of the boot screen (same as Lab1) with your message and include in the report.
- Please specify the name of the file that you changed.
- Please submit the source code.

**Hints:**

1. Look inside **os161-1.11/kern/main directory (for VirtualBox based setup)** or **os161-1.99/kern/startup directory (for Docker based setup)**
2. You will need to compile kernel and execute/run the kernel. You should already know how to compile/run the kernel (assuming you have already installed OS/161).

### **(30 point) Part B**

Implement a simplified system call named ***void \_exit(int exitCode)***

In OS161, you can end user programs by calling the “\_exit( )” system call. **Without an Implementation of \_exit( ), the threads created to handle user programs will hang around forever, executing an infinite loop in the user space and taking up a lot of CPU time.**

#### **Hints:**

1. You should find an existing function that is almost an ideal handler for the \_exit( ) system call – and modify that function to receive the exitCode as a parameter (you will also have to modify all the other uses of that function in order to pass the exitCode).
2. In this part, you have to print out the exitCode that is passed.

**Once you implement the \_exit() system call, you will find that useful for the next part to prevent infinite loop.**

### **(30 point) Part C**

Implement a simplified system call named ***int printint(int c)***

This system call should accept an integer and print it using the internal **kprintf( )** function. The return value should be 0 if the integer is divisible by 2 or 1 otherwise.

### **(40 point) Part D**

Implement a simplified system call named ***int reversestring(const char \*str, int len)***

This system call should accept a string and length of the string as input and print the reverse of the string using the internal **kprintf( )** function. The return value should be 1 if the length of the string is multiple of 5 or 0 otherwise.

## Test Functions for the System Calls

Write **user level programs** to test Part B, C, and D respectively. You can write one program to test all three or write individual programs as well.

**(15 point) Part E.** Create a test program, named *testprint*, to test the **printint( )** system call developed in Part C. Pass 5 integers (any) in a for loop and see if these are printed or not.

**(15 point) Part F.** Create another test program, named *testreverse* to use the **reversestring( )** system call developed in Part D. Pass any string as argument.

**Please note that you will need to use the `_exit` system call in the above programs to avoid infinite loop.**

Note that the system calls given here are user-level functions, i.e. these are the functions that user programs will call to invoke the system calls. You will need to use different names for the handlers of these functions in the kernel as shown in the following example.

- **`sys_reboot( )` (in the kernel) is called to handle the `reboot( )` (in the test program) system call.**

As a reference, the Appendix contains a list of OS/161 system calls, along with some literature to help make understanding these systems calls a little easier. You are highly encouraged to study and discuss the Appendix among yourselves while working on this assignment.

## Optional part for extra credit: Implement system calls in Linux kernel

**(130 point) Part G (optional).** Add a system call `my_info` in linux kernel tree 5.14.4, which printk your NetID, email and name.

**(20 point) Part H (optional).** Write a test program, named `get_my_info` to test the `my_info` system call in Part G. Use `dmesg` to get the screen shot about your info.

**You should submit the patch which the code you change based on kernel tree 5.14.4, test code and screen shot about the test output for Part G and Part H.**

## Include the following in your report:

1. Add a cover page describing what parts are completed.
2. Include the list of the files you changed for each part, the change itself, along with your new source code and test programs. You must explain the reasons/purpose behind your changes briefly.
3. Include the sample outputs of your test programs for **parts E, F and H**.

**You may add the above items in a single word file and upload that to HuskyCT.**

### Important Points:

- The system calls given here are user-level function names (e.g., `printchar`), that the user programs will call to invoke these system calls. You will need to use different names for the handlers of these functions in the kernel (e.g., `sys_printchar( )`), which will be called to handle the `printchar( )` system call.
- You should look at the following files (the first four is for implementing the syscalls in kern directory):
  - **syscall.h**
  - **syscall.c**
  - **callno.h** (only if you are using the VirtualBox based setup from Lab1. If you used the docker based installation, look for multiple versions of the syscall.h instead)
  - **conf.kern**
  - **unistd.h** (this is not a kernel level header and the correct one that you need to change is outside of the kern directory)
- **Caution 1:** One or more files in this list (e.g., `unistd.h`) may have multiple copies in separate directories. You need to change the right file.
- **Caution 2:** Read the comments in `syscall.c` to figure out how to pass multiple parameters.
- You may add a new file (e.g., `simple_syscalls.c`) that will implement your newly added system calls.
- After you finish adding each system call, you will need to compile the new kernel and user programs to see the effect of your change. Please refer to the first assignment to see how to compile a kernel.

### Writing, compiling and running Test Programs

- Your **test programs need to be saved under /testbin directory**. Create a folder called `/testA` and save your test program in the `/testbin` directory along with the other test programs.
- You will need to modify the makefile that you can copy from another directory within testbin folder (e.g., `/palin`).
- You will also need to edit the makefile under `/testbin` directory. **Hint: look at the content of the makefile and see how other test programs are included. You will need to add one line per test program.**
- To compile your user program, just type **“make” from /os161-1.11** (VirtualBox) OR **“bmake” from /os161-1.99** (Docker) directory.
- You can run your user program as follows (see next page):

- First, execute the following from command prompt:

- **sys161 kernel-ASST0**

- Next, execute the following from your new kernel command prompt

- **p testbin/testA** (assuming testA.c is your test program name for Part E and F and it is saved under testbin/testA directory)

You will need to modify the code in **syscall.c** to detect your new system calls and dispatch appropriate system call handlers. Although these system calls are simple enough to implement fully within **syscall.c**, it is suggested that you place the handlers in a separate function in a file in the **kern/userprog (VirtualBox)** or **kern/syscall (Docker)** subdirectory. You should name this file **simple\_syscalls.c**. You will also need to add an entry for this new file in **conf.kern** file, and reconfigure your kernel so that it is included in the build. Because you will call functions from **syscall.c**, which are defined elsewhere, you should add prototypes for these functions to the **syscall.h** header file, similar to what is done for the **sys\_reboot( )** function.

## Understanding System Calls

In this document, we walk through the functions and steps that are involved in (1) starting a user-level program, (2) handling system calls in the OS, and (3) invoking system calls at the user-level. You should read this document together with the OS/161 source code files that it refers to.

### User-Level Programs

The System/161 simulator can run normal programs compiled from C. These programs are compiled with the cross-compiler `cs161-gcc`. This compiler runs on the host machine and produces MIPS executables. It is the same compiler used to compile your OS/161 kernel. To create new user programs, you will need to edit the Makefile in `bin`, `sbin`, or `testbin` (depending on where you put your programs), and then create a directory similar to those that already exist. Use an existing program and its Makefile as a template. You should create new user-level test programs that use the system calls you are adding.

### Getting to User-Mode (i.e. Starting a User-Level Program).

Examine `menu.c` to see how the “p” menu command is handled. This command allows us to load and execute a single user-level program. We will describe this in great detail, most of which is not of critical importance for this Project. But you will need to understand this eventually, however, and the sooner the better.

The `menu()` function loops forever, printing the menu prompt, getting a string from the console, and calling `menu_execute()` to handle the input. Looking at `menu_execute()`, we see that it separates the input into individual commands (indicated by a semi-colon) and then calls `cmd_dispatch()` for each command. In `cmd_dispatch()`, the name of the command is separated from its arguments, and the name is looked up in the `cmdtable` data structure. This table stores the string name of each menu command and a function pointer to the function that should handle that command.

Looking at the `cmdtable` declaration, we find that the “p” command is handled by calling the `cmd_prog()` function. This function simply strips off the “p” part and passes the rest of the input to the `common_prog()` function. Looking at `common_prog()` we see that it calls `thread_fork()`, creating a new thread to run the specified user-level program. Following this call to `thread_fork()`, our system has 2 threads: the initial boot thread that runs the `menu()` loop, and the new thread that runs the requested user-level program.

You can look `thread.c` to see what `thread_fork()` does, but the important thing right now is that the fourth argument to `thread_fork()` specifies the function that the new thread should start executing (in this case, `cmd_progthread()`), and the second and third arguments to `thread_fork()` are the arguments to pass to that function (in this case, the name of the program to load). The `cmd_progthread()` function calls `runprogram()`, passing it the name of the program to load and execute. Note that if `runprogram()` is successful, the thread will continue with the execution of the user-level program and will never return to `cmd_progthread()`.

Now let's consider how `runprogram()` operates. The source files that are responsible for the loading and running of user-level programs include `loadelf.c`, `uio.c`, and `runprogram.c`.

`runprogram.c`: This file contains only one function, `runprogram()`, which is responsible for running a program from the kernel menu. It uses the virtual file system operations to open the file containing the program we want to load, creates an address space for the thread, and loads the program into that address space, using the `load_elf()` function. If loading the program is successful, `runprogram()` then sets up the user stack area in the address space, and switches to user mode and start running the user program.

`loadelf.c` : This file contains the functions responsible for loading an ELF executable from the file system into the virtual memory space. (ELF is the name of the executable format produced by `cs161-gcc`.) Of course, at this point this virtual memory space does not provide what is normally meant by virtual memory – although there is translation between the addresses that the executables “believe” they are using and physical addresses, there is no mechanism for providing more memory than exists physically.

`uio.c`: This file contains functions for moving data between kernel and user spaces. Knowing when and how to cross this boundary is critical to properly implementing user level programs, so this is a good file to carefully study.

Once a user program starts running, it requests service from the OS by way of system calls. We now take a look at these.

### **Getting to System Mode: Traps and Syscalls**

Exceptions are the key to operating systems; they are the mechanism that enables the OS to regain control of execution and therefore do its job. You can think of exceptions as the interface between the processor and the operating system. When OS boots, it installs an “exception handler” (essentially carefully crafted assembly code) at a specific address in memory. When the processor raises an exception, it invokes this, which sets up a “trap frame” and calls into the OS. Initializing the trap frame and returning from an exception is all done in assembly code, and is found in `exception.S`.

You need not be able to read MIPS assembly code, but the comments in this `.S` file are reasonably good. You can see how all the registers are saved (“`sw`” == `!store word`”), followed by a “`jal`” call to the `mips_trap` function (“`jal`” == `!jump and link`”). On return from `mips_trap`, all of the saved state is restored (“`lw`” == `!load word`”) and execution resumes at the point where the exception occurred.

Looking at `struct trapframe` in `trapframe.h`, we can see that a trap frame includes space to save all the processor registers that the user program might have been using, as well as some additional state that identifies the cause of the exception (the “`tf_cause`” field), and the



instruction that was being executed when the exception occurred (the "T\_epc" field, where epc == "Exception PC" == contents of the program counter register when the exception occurred). Note that since "exception" is such an overloaded term in computer science, OS lingo for an exception is a "trap" – when the OS traps `execuBng`. Interrupts are exceptions, and more significantly for this Project, so are system calls. Specifically, `syscall.c` handles traps that happen to be system calls.

`mips_trap( )` in `trap.c` is the key function for returning control to the operating system. This is the C function that gets called by the assembly language exception handler. It includes code to determine what type of exception occurred, and to dispatch an appropriate handler. If the exception code is `EX_SYS`, then `mips_syscall( )` is called to handle the system call, passing it the trap frame. `mips_syscall( )` in `syscall.c` is the function that delegates the actual work of a system call to the kernel function that implements it. Read the comments at the top of this file (second block of comments) carefully! In `mips_syscall( )`, we begin by extracting the system call number from the trapframe's `T_v0` field. This means that the system call number was stored in register `v0` prior to `execuBng` the `syscall( )` instruction. Then we simply switch on the system call number, with a separate "case" to handle each possible system call. Notice that `reboot( )` is the only case currently handled. You will need to add your stuffs here to handle your newly added system calls.

Following the switch statement, we prepare to return from the system call. The user-level side of the system call expects to find the result of the system call in register `v0`, with register `a3` indicating whether or not an error occurred. We accomplish this by setting the appropriate fields in the trap frame, which will be loaded into the machine registers before returning control to the user program. Finally, we have to advance the program counter to the next instruction, so that the `mips_syscall( )` instruction will not be repeated. This is done by incrementing the `T_epc` field of the trap frame.

### User Side of a System Call

That is what happens on the OS side when a system call occurs. Now let's look at the user-level interface to system calls. Most of this is encapsulated in C library functions. `/lib/libc/`: This is where the user-level C library is. There's obviously a lot of code here. We don't expect you to read it all, although it may be instructive in the long run to do so. Job interviewers have an uncanny habit of asking people to implement standard C library functions on the whiteboard. For present purposes you need only look at the code that implements the user-level side of system calls, which we detail below.

`errno.c`: This is where the global variable "errno" is defined. Note that this variable is a global within a user-level C program. Therefore, you **cannot** set `errno` for a user-level program by setting a variable named "errno" in the kernel.

`syscalls-mips.S`: This file contains the machine-dependent code necessary for implementing the user-level side of MIPS system calls. It consists of a C pre-processor (i.e. `#define`) that declares the body of each system call. The body of each system call is identical, except that a different system call number "num" is used. This body simply loads the system call number (as defined in `syscall.h`) into register `v0` and then jumps to the code common to all system calls. (Compare this with what's on the OS side, where the system call number is extracted from the `T_v0` field of the trap frame).

You may notice that it looks like the code jumps to the `__syscall` label *before* setting the system call number. This is just a peculiarity of the MIPS architecture – the instruction immediately following a branch is called a “delay slot”. This means that an instruction can be scheduled and executed *during* a branch. Such instructions appear immediately after the branch instruction itself. Therefore, the “`addiu v0, $0, SYS_###sym`” instruction happens before we get to the common syscall code at the label `__syscall`.

Now, let’s take a look at the assembly code at the `__syscall` label. The common system call code begins with the `syscall` instruction, which causes a “system call exception”, and transfers control to the OS as outlined above. The `T_epc` field in the trap frame (on the OS side) points to this instruction, and we finish our system call handler by setting `T_epc` to the next instruction. Thus, on return from the system call, we execute the `beq` instruction. This instruction tests if the system call failed or succeeded (recall that the OS side sets `T_a3` to 1 on error, and 0 on success). If an error occurs, we take the error code from the `v0` register and store it into the global variable `errno`, and set the return value of the system call (the `v0` register) to -1. If no error occurred, then the OS puts the result of the system call into `T_v0`, and we can just return.

`syscalls.S`: This file is created from `syscalls-mips.S` at compile time, and is the actual file assembled into the C library. Adding new entries to `syscall.h` automatically causes new user-level system call procedures to be defined when you rebuild the user-level code. Every “`SYSCALL(sym, num)`” macro statement in `syscalls.S` is expanded by the C preprocessor into a declaration of the appropriate system call function.

`/include/unistd.h`: This file contains the user-level interface definition of the system calls for OS/161 (including the ones you will implement). The only thing you need to do to complete the user-level system call interface is to declare prototypes for your new system calls in `unistd.h`. Everything else on the user side happens automatically when you rebuild the kernel after updating `syscall.h`. Note that the user-level interface defined in `unistd.h` differs from that of the kernel functions you will define to implement the calls. You will need to declare these kernel functions in `syscall.h` (note the name will be different from your user side definition).

## APPENDIX

### A List (Not Exhaustive) of OS/161 Systems Calls

`errno` - error code reporting  
`_exit` - terminate process  
`chdir` - change current directory  
`close` - close file  
`dup2` - clone file handles  
`execv` - execute a program  
`fork` - copy the current process  
`fstat` - get file state information  
`fsync` - flush file system data for a specific file to disk  
`truncate` - set size of a file  
`__getcwd` - get name of current working directory (backend)  
`getdirent` - read filename from directory  
`getpid` - get process id  
`ioctl` - miscellaneous device I/O operations  
`link` - create hard link to a file  
`lseek` - change current position in file  
`lstat` - get file state information  
`mkdir` - create directory  
`open` - open a file  
`pipe` - create pipe object  
`read` - read data from file  
`readlink` - fetch symbolic link contents  
`reboot` - reboot or halt system  
`remove` - delete (unlink) a file  
`rename` - rename or move a file  
`rmdir` - remove directory  
`sbrk` - set process break (allocate memory)  
`stat` - get file state information  
`symlink` - create symbolic link  
`sync` - flush file system data to disk  
`__time` - get time of day  
`waitpid` - wait for a process to exit  
`write` - write data to file