CSCI 4500: Computer Science
Operating Systems
Fall 2023
Programming Assignment 1

Introduction

The purpose of this programming assignment is to give you some experience with simple input/output and processes. In the assignment you will employ a few of the most common system calls used for performing input/output and manipulating processes. In particular, you will need to use at least the **`access`**, **`fork`**, **`execve`**, **`dup`** (and/or **`dup2`**), **`pipe`**, **`read`**, **`write`** and **`exit`** system calls. Make certain you read and understand all of the material in the assignment.

The program you are to write is a simple command line interpreter, or shell. It will not have nearly as much functionality as a normal shell. Instead, it will deal only with creating processes, arranging for them to execute specified programs and connecting the standard input and output of the processes with a pipe.

Specifically, your program will repeatedly perform the steps shown below. Additional details on each of these steps are provided in the next section, and a significant part of the work (in particular, much of the string manipulation) is already done in the partial solution provided for you. For now, just make certain you understand the basic steps.

1. **`read`** a command line from the standard input. If the line contains only blanks and/or tab characters, ignore it and repeat this step. If the end of file is encountered, just terminate your program.
2. Identify the "words" on the command line read in step 1. Each word is a sequence of non-whitespace characters ("whitespace" means blanks or tabs here). In this shell we will assume at least one whitespace character is used to separate words from each other.
3. Determine if one of the words consists of just the single character **`'|'`** (that is, the "pipe symbol"). If no pipe symbol is present, then there is only a single command to be processed. For example, if the input line was

   ```
   echo  one  two  three
   ```

   there are four "words," none of which is the pipe symbol. In this case, your shell will create a new process to execute the command, as described below.

   But if the input line was

   ```
   echo  one  two  three  |  wc  -l
   ```

   then there are seven words, and one of them (the fifth, in particular) is the pipe symbol. Therefore there are two commands to be processed. The first command consists of the words to the left of the pipe symbol (specifically "**`echo one two three`**"), and the second command consists of the words to the right of the pipe symbol (specifically "**`wc -l`**"). The pipe symbol, of course, is not part of either command, but instead indicates (to the shell) that the output written to the standard output (associated with file descriptor 1) by the first (left) command is to be sent,

through a pipe, to the standard input (associated with file descriptor 0) of the second (right) command.

To achieve this task your shell will create a pipe before making the processes needed to execute the commands.

4. For each command, verify that there exists an appropriate program as evidenced by the existence of a suitable executable file. To verify this, first recognize that the word that identifies the command to be executed is the first word in the command. In the examples given in step 3, the two commands are identified by the words **`echo`** and **`wc`**. If the word corresponding to a command includes a slash (that is, **`'/'`**) then that word is an explicit *path* to the (presumably executable) file; your shell should then use the **`access`** system call to determine if that file exists and is executable (details are provided below).

   For example, in the command line

   `./mycommand data and moredata`

   we see that the first word includes a slash. As a result, it is to be interpreted as an explicit path to the file to be executed. In this case, we're given a relative path.

   If the word identifying the command does not include a slash, then the directory in which the (presumably executable) file exists must be located. Most systems (including Linux, Windows, and Mac OS X) specify the directories in which such executable files are sought as a list given by the value of the **`PATH`** environment variable. The first directory in the list that contains the specified file is the one to be used; details are provided below. Of course, if no directory specified in **`PATH`** contains the file, then the shell will report an error and read the next command (that is, return to step 1).

   To clarify some of the concepts, you might try some of these commands on Linux.

   `echo $PATH`

   This command will display the contents of the **`PATH`** environment variable. Note that it consists of the path specifications for several directories separated by colons. For example, it might display this (the font size was reduced here so the result would fit on a single line):

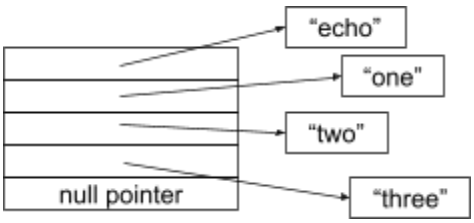
   `/usr/local/sbin:/usr/local/bin:/usr/sbin:/usr/bin:/sbin:/bin:/usr/games:/home/phuang/bin`

   `which echo`

   This command does basically the same thing your shell will do in this step if a command name does not include a slash. It searches through the directories specified in **`PATH`** to locate the first directory (if any) that contains the specified file. In this case, the output might be:

   `/bin/echo`

5. For each command, prepare the argument list from the words in the command. The argument list is just an array of pointers (**`char *`**) to the strings containing the words in the command, starting with the word that specifies the command and continuing through the last word in the command. A null pointer (that is a pointer whose value is zero) must follow the pointer to the last word in the command. For example, the argument list for the **`echo one two three`** command used in step 3 would look like this (the arrows are used to indicate the data items the pointers reference):



The array shown on the left has entries with subscripts 0 to 4 of type **`char *`** – that is, a pointer to a character; the top entry in the figure has subscript 0. Each entry (except the last) contains the address of the first character in the character string representing the corresponding word from the command line. For example, the element with subscript 0 contains the address of (that is, a pointer to) the **`'e'`** in **`"echo"`**. The last entry, containing the null pointer, marks the end of the argument list.

6. If there is only a single command, create a child process to execute it (using the **`fork`** system call, of course), and then (in the child process that was created) invoke the **`execve`** system call to replace the shell program (which is executing in the child process) with the desired program, and to supply the arguments to the program. The parent (executing the shell) waits (using the **`wait`** system call) for the child process to terminate before returning to step 1 to read and process the next command line.
7. If there are two commands, the process creation actions in step 6 must be done for each of the commands. In addition, you must arrange for the standard output of the first process (file descriptor 1) to be associated with the "write" end of the pipe created in step 3. Similarly, the standard input of the second process (file descriptor 0) must be associated with the "read" end of the pipe. The ends of the pipe not used in each process (the "read" end in the "left" process, the "write" end in the "right" process, and both ends in the shell/parent process) must be closed. The pipe to be used by the processes for the two commands will need to be created before the processes are created (that is, before the **`fork`** system call is executed to create either child). This is because we want the child processes to inherit the open file descriptors for the two ends of the pipe. The "redirection" of the standard input and output in the child processes must be done before the **`execve`** system calls are done. **`execve`** will be invoked twice, once in each child process, to execute the appropriate programs (as identified by the first "word" in each command) and to provide the appropriate arguments. The parent process (the one executing the shell program) will also need to execute the **`wait`** system call twice, to suspend its execution while waiting for each child process to terminate. Finally, the shell process will return to step 1 to obtain the next command line.

Details

Let's consider more detail about each of these actions. The codes should be run on the server instead of your computer.

In step 1 you must use the **`read`** system call. **Do not use any other system call for input!** And remember: don't use any language other than C! To avoid extra complexity, assume you are reading commands from a disk file (that is, assume your shell is run with the standard input redirected to a disk file), and read a single byte at a time – that is, the third argument to the **`read`** system call should always be **`1`**. The file descriptor to use is 0, which corresponds to the standard input (that is, the first argument to the **`read`** system call should always be 0). The **`read`** system call returns the number of characters successfully read or a negative error indication (-1). Since you are always reading a single character at a time, **`read`** should return **`1`** (if a single character was successfully read), **`0`** (if nothing was read, meaning you're at the end of file), or **`-1`** (which should normally not occur). When a single character is read and it is an end of line character (**`'\n'`**), then you have encountered the end of a line. You should echo the input you read (that is, write the characters read to the standard output, or file descriptor 1); when you are actually reading from the keyboard you will get an extra copy of the input, since the standard input mechanism echoes each character as it is typed. When reading from a disk file, you will get a display of the command you're about to process. You may assume that no input line contains more than 100 characters (including the end of line character). [It is advisable to display something like **`"# "`** (that is, a "sharp sign" and a space) before displaying the command being read. This will allow you to easily distinguish the command from any output it may produce.]

Step 2 is a simple parsing operation. We know words are separated by one or more blanks or tab characters (i.e. "whitespace"). Therefore can use the C library function **`strtok`** to identify the words (although you're certainly not required to do so). We will not worry about quoting arguments with single- or double-quotes or backslashes (as is done by more complete shells). Additionally, remember that the character used to specify a pipe connection between two commands (i.e. **`'|'`**) will be separated from other words by whitespace. You may assume there will be no more than 16 words in any input line, including the pipe character. You may also assume no word will be longer than 64 characters, including a null terminating character which is required for C-style string values.

At this point (step 3) you have a sequence of words corresponding to a command name, its arguments, and possibly a pipe symbol and another sequence of words corresponding to a second command name and its arguments. If the pipe symbol exists, and there is at least one word on each side of it, then the shell will need to create a pipe (using the **`pipe`** system call) to connect the output of the first ("left") command to the input of the second ("right") command. It may be appropriate to wait until after the next step to actually create the pipe, since you won't want to create it if step 4 discovers an error. If there is a pipe symbol, but no words before and/or no words after it, then there's obviously an error which you should diagnose just before ignoring the command line. Likewise, more than one pipe symbol is an error – at least in this shell!

In step 4 we will validate the name of the command (or commands) to be executed (the first word in each command). If this word includes **`'/'`**, then it is a relative or absolute path to a file that is expected to contain the executable code and data for the command. Otherwise it is assumed to be the name of a file that appears in one of the directories specified in the value of the **`PATH`** environment variable. The value of the **`PATH`** environment variable is character string containing a colon-separated list of the names of directories in which the shell is to search for an executable file.

So if I enter a command line like "**doit to it**", the shell will find that **doit** does not contain a '**/**', and search in the directories specified in **PATH**, in order, until the file doit is found, or each directory has been checked. If the file "**doit**" is not found in any of those directories, an error should be reported (something like "**doit not found**"), and the shell should repeat from step 1. Parsing the value of the **PATH** environment variable is easy using the **strtok** function.

The value of the **PATH** environment variable can be obtained using the **getenv** function. (The on-line description of this function can be found using the command "**man getenv**".) The **getenv** function expects a character string argument, and it returns a pointer to a character string containing the value of that environment variable (if it exists), or a **NULL** pointer (if there was no such environment variable). Since we're interested in the value of the **PATH** environment variable, an appropriate function invocation might be **getenv("PATH").** Recalling that the value is a colon-separated list of directory names, we can easily use the **strtok** function (again, use "**man strtok**" for details) to identify the individual directories. A small C program that determines if the file specified on the command line is found in a directory specified in the **PATH** environment variable can be found in **/prog1/path.c** . You may use any of this code in your program.

To determine if a file exists and is executable you should likely use the **access** system call. This call has two arguments. The first is the path to a file, and the second is the access mode to the file that is to be tested. In our case, we specifically want to test for executability, so the second argument should be **X_OK** (which is defined by including the header file **unistd.h**). If **access** returns 0, then the file exists and is executable (at least as far as the file's permissions indicate). Otherwise, the file does not exist, or is not executable. Notice that the first argument to **access** must be the path to the file, not just the file name. As a result, you'll need to concatenate a directory name from the **PATH** environment variable, a slash, and the file name to yield a suitable string for the first argument to **access**.

Of course, if there are two commands to be executed (connected by a pipe), this processing must be done for each of them. If either command is not executable, then neither should be executed, a suitable error message should be displayed, and the shell should return to step 1.

Step 5 is simple. We know that there will be no more than 16 words in a command (since there can be at most 16 words in a command line), and we need one additional entry in the array of pointers to arguments to store a terminating null pointer. Thus for each command, we need an array with 17 pointers to character strings for the argument list to a command. Since each word was identified (perhaps using **strtok**) in step 2, it should be a simple matter to store a pointer to each word of a command in the appropriate entry in the array.

In step 6, use the **fork** system call to create a process, being sure to save the value it returns. As is always the case, check to see if the returned value is –1. If it is, some error occurred (like you got stuck in a loop calling **fork**!), and you should abandon further execution (by printing an appropriate error message and calling **exit**.) Then, only in the child process, use the **execve** system call to execute the program and pass the array of command line arguments. In the shell (the parent process), you should execute the **wait** system call to delay execution until the child process terminates. Then return to step 1.

Step 7 is used only if there are two commands to be executed. The work of step 6 is done for each command, but there is a bit of additional effort required. Creating the pipe is done using the **pipe** system call, which expects a pointer to the first element of a two-element array of integers as its only

argument (you can just pass it the name of a two-element array of type **int**). It will return 0 if it succeeds in creating the pipe. In that case, the 0th element of the array passed to it will contain the file descriptor used to read from the pipe, and the 1st element of the array will contain the file descriptor used to write to the pipe.

In the child process for the first of the two commands, we want to replace the association of the standard output's file descriptor (which is 1) with whatever it was (possibly the keyboard, or a disk file – whatever the shell is using for standard input) with the "write" end of the pipe. This is a very simple task, but it's important to completely understand what is being done. First (again, only in the child process for the left command), **close** file descriptor 1. Then use the **dup** system call to create a duplicate of the file descriptor associated with the "write" end of the pipe. **dup** is guaranteed to use the lowest-numbered unused file descriptor. Since we know file descriptor 0 is in use (it's associated with the same thing as the shell's standard input), it won't be file descriptor 0. Instead, we know file descriptor 1 is not in use (we just closed it). So file descriptor 1 will be associated with the "write" end of the pipe (as will the other file descriptor already associated with it). You should **close** the "read" end of the pipe and the extra file descriptor for the "write" end of the pipe.

Similar steps are used in the process that's going to execute the "right" command, but we're naturally going to reassociate file descriptor 0 with the "read" end of the pipe created by the shell. So you'll want to **close** file descriptor 0, **dup** the file descriptor for the "read" end of the pipe, then **close** the "write" end of the pipe and the extra file descriptor for the "read" end of the pipe.

Using execve

The first argument to **execve** is the path to the file to be executed. If a relative or absolute path was explicitly provided in a command, then that's the path to be used. Otherwise, the path will be one of the entries from the **PATH** environment variable, a slash, and the name of the command to be executed (that is, the first word of the command). The second argument is a pointer to the array of argument pointers. The third and last argument to **execve** is a pointer to an array of strings representing the environment for the program about to be executed. This should usually be the value of the external variable **environ**. A simple program that illustrates these concepts can be found in the file **/prog1/echo_me.c** . That program uses the **execve** system call to execute the file **/bin/echo** to display "Hello, world!"

Using wait

The **wait** system call is used to delay execution of a process (in our case, the shell process) until one of its child processes terminates. The single argument to **wait** is a pointer to an integer which we'll call **status**. **status** will receive two pieces of information. In the low-order byte of **status** will be an indication of the reason for the termination of the child process. If the termination was normal (that is, by returning or executing the **exit** system call), this byte will contain 0. If the process was terminated abnormally (e.g. it divided by zero or tried to access memory that didn't belong to it), then this byte will be non-zero; we need not be concerned with the particular values at this time. In the event of a normal termination, the next higher byte (bits 15-8 of **status**) will contain the low-order eight bits of the value returned by the process, either with the return statement or the **exit** system call. The return value from **wait** is normally the process ID of the child process that terminated. If there was no child process on which to wait, then **wait** will return –1 (which you should not get!). If the process terminated

normally, display an appropriate message including its exit status (e.g. “process ### terminated normally with status ###”). If the process did not terminate normally, then display a different message (e.g. “process ### terminated abnormally for reason ###”). Of course, ### in the example messages represent the process ID, the exit status, or the termination status. In any case, return to step 1 to process the next command.

Here’s an example that shows how to use the **`wait`** system call. You should try changing the actions taken by the child process to illustrate different exit codes and termination statuses.

```
#include <stdlib.h>
#include <string.h>
#include <stdio.h>

extern char **environ;

int main(int argc, char *argv[])
{
    pid_t pid;
    int status, which;
    char msg[100];

    pid = fork();
    if (pid == -1) {
        write(1,"fork failed.\n",12);
        exit(1);
    }
    if (pid == 0) {             /* child process */
        int x, y, z;
        y = 12;
        z = 0;
        x = y / z;              /* divide by zero! */
        exit(1);
     }

     if (fork != 0) {           /* parent */
        which = wait(&status);
        if (which == -1) {
            write(1,"wait failed.\n",12);
            exit(1);
        }
        if (status & 0xff) {    /* abnormal termination */
      sprintf(msg,"process %d terminated abnormally for reason %d\n",
            which, status & 0xff);
        } else {                /* normal termination */
            sprintf(msg,"process %d terminated normally with status %d\n",
            which, (status >> 8) & 0xff);
        }
        write(1,msg,strlen(msg));
        exit(0);
    }
}
```

Template Source Code

A "template" for the solution to this assignment is provided in the file **`prog1/prog1_temp.c`**. You may use it if you wish, but you are not required to do so. The template code will compile, link and execute correctly, but it will only process a single command on each input line.

Notes and Restrictions

You may use **`sprintf`** (as illustrated in the last example) to prepare messages to be displayed, but no standard C library functions that perform actual input or output must be used in your solution. Instead, all input and output must be accomplished using the **`read`** and **`write`** system calls. You may also use the string functions for things like parsing the command line and computing the length of strings (for the **`write`** system call). Likewise, use no other standard C library functions related to creating processes. Your solution must be your own work only; do not work with others in developing your solution.)

Evaluation

Your program will be evaluated by testing with a variety of commands. To receive 100 percent, your program must process the entire set of commands correctly. Failure of your program to compile on Odin will result in a grade of no more than 50 percent. Failure to correctly handle a command line with a pipe will result in a grade of no more than 75 percent.

The instructor's solution to this problem is available in binary form (that is, as an executable) in the file **`prog1`**. Use it to determine acceptable results of processing a set of commands. A relatively simple set of commands, but very representative, can be found in **`prog1.pipe.input`**. The expected output can be determined by using the sample solution provided. Please execute the following command to get the expected output:

```
$ ./prog1 < prog1.pipe.input
```

If not an executable program and permission error, please execute the following command to become an executable program.

```
$ chmod u+x prog1
```

Note that the instructor's solution diagnoses most possible errors, but you may assume there will be no errors in the data used to evaluate your solution. However there will be an attempt to execute one or more commands that do not exist. This is not an error in the input; that is, the input syntax will be correct, but your program must identify that the command does not exist.

Requirements

You must write (and test) a **C program** that functions as a simple shell as just described. Your solution should be a single file of C source code named **`prog1.c`** and a **`Makefile`**. Please note that a 10 points grade penalty is assessed if you do not submit a **`Makefile`**. Please create a directory named **`FirstLastNAME-prog1`** (for example, **`Peggy Huang`**, named **`PeggyHuang-prog1`**), including the following two required files: **`prog1.c`** and **`Makefile`**, which the instructor can compile **`prog1.c`** as **`prog1`** (executable) by executing

```
$ make
```

where a failure to comply will deduct at least 10 points.

To submit your solution to the **Canvas**, please wrap the file **`FirstLastNAME-prog1`** by executing

```
$ tar zcf FirstLastNAME-prog1.tgz FirstLastNAME-prog1
```

where a failure to comply will deduct at least 10 points.

There should be no other files in that directory, and the files you place there should not be changed or removed until you have received a grade report for the assignment.

As always, please contact the instructor if you have questions, and periodically check the class web site for any additions or corrections to this assignment.