The Shell, Processes and Basic Inter Process Communication (IPC) with System Calls

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The Shell

- Shell is a program that lets users communicate with the Operating System
- Typically, in a shell, users are given access to a command line interface (CLI) through which users can input textual commands
- The shell accepts the command, interprets it and executes it
  - The command will be an executable program that either comes with the OS or is created by the user
  - The shell usually looks for the program from the entries in the system's PATH environment variable (you can check using: 'echo $PATH' on your terminal)
  - If the program is not in any of the directories of the PATH variable, then we have to input the command using its full path
    - If the command is in the current directory, we can use './<command>'

Processes

- Processes are nothing but programs that are being executed

- Processes are created in the following ways

  - When we execute a program, a process is created

  - A child process can be created from within another process using fork() system call (more on this later)

IPC at a Glance

- Operating Systems provide mechanisms for processes to cooperate and communicate with one another through Inter Process Communication (IPC)

- Pipes are one such mechanism to provide unidirectional communication channel between two processes

- We will work with pipes in today's lab

A Few System Calls

- System calls are special functions that are invoked through the kernel space
- We will use the following system calls for today's lab

  - fork - used to create child processes
  - waitpid - used when a parent process blocks itself until a specific child process exits

  - pipe - used to create a pipe for IPC
  - dup2 - used to duplicate a file descriptor into another file descriptor

  - execl - used to execute a specific program with arguments just like we would do on a shell

  - read - used to read from a file
  - write - used to write to a file

fork

- fork is a system call that creates a child process
  - Declaration: *pid_t fork(void);*[1]
  - Invocation: *pid_val = fork();*
- The process that calls fork is the parent process
- The child process is created by duplicating the parent process
- Starting from the line after the fork call, all the remaining lines of code are executed for both the parent and child processes

1) https://www.man7.org/linux/man-pages/man2/fork.2.html

fork (continued)

- Since the remaining lines of code are executed for both parent and child processes, we can use the return value from fork to identify the code sections that we want to run for either the parent or child process
  - Return value (pid_val == 0): child process section
    - When the child process looks at the pid_val, it finds 0
  - Return value (pid_val > 0): parent process section
    - When the parent process looks at the pid_val, it finds the unique process id of the child process (useful to keep track of the child processes)
  - Return value (pid_val == -1): error
    - When an error occurs, the *errno*[1] value is set and can be used by *perror*[2] to print error message
- The parent and child processes run in separate memory spaces
- The child inherits “copies” of parent’s attributes (e.g. *file descriptors*)

1) https://man7.org/linux/man-pages/man3/errno.3.html
2) https://linux.die.net/man/3/perror

waitpid

- waitpid is a system call that lets a parent process wait for the completion of a child process
  - Declaration: *pid_t waitpid(pid_t pid, int *status, int options);*[1]
  - Invocation (for this lab): *waitpid(pid_val, NULL, 0);*

- Waiting for the child process prevents "orphan" and "zombie" processes (both waste system resources)
  - Orphan process:
    - When parent process finishes execution before child, the child becomes orphan process
    - Orphan process is adopted by the init or system daemon process
  - Zombie process:
    - When child process finishes execution before parent, the child becomes zombie process
    - If the parent process "waits" to read the exit status of the child, the child process is reaped from the process entry table and prevents the child from remaining a zombie process
    - The waitpid system call lets a parent process read the exit status of finished child processes and reaps off zombie processes

1) https://linux.die.net/man/2/waitpid

File Descriptors

- A file descriptor is a unique, non-negative integer used to identify an open file
- File descriptors can be used with open, close, read and write system calls
- Some special file descriptors:
  - [1]STDIN_FILENO – a file descriptor for the standard input (keyboard)
  - [2]STDOUT_FILENO – a file descriptor for the standard output (computer display)
  - Pipe file descriptors – two file descriptors for a pipe's read and write end (more on these later)
- Inside the PCB of a process, there is a file descriptor table which:
  - Keeps a mapping of file descriptors (used by the process) to actual files on the system
  - Is inherited by the children of the process

1, 2) https://stackoverflow.com/questions/12902627/the-difference-between-stdout-and-stdout-fileno/12902707#12902707

pipe

- Pipe is a “unidirectional” data channel that can be used by a process to communicate with other processes
  - Declaration: *int pipe(int pipefd[2]);*[1]
  - Invocation:

    int fd[2];
    pipe(fd);

- fd[0] is the read end of the pipe
- fd[1] is the write end of the pipe
- Close pipe ends when they are no longer needed (very important):

  close(fd[0]);
  close(fd[1]);

1) https://man7.org/linux/man-pages/man2/pipe.2.html

dup2

- dup2 is a system call that copies one file descriptor into another
  - Declaration: *int dup2(int oldfd, int newfd);*[1]
  - Invocation: *dup2(fd_one, fd_two);*

- Can be used for I/O redirection
  - Input redirection:
    - dup2(pipe_read_end, STDIN_FILENO);
    - Input of the process is taken from the pipe
  - Output redirection:
    - dup2(pipe_write_end, STDOUT_FILENO);
    - Output of the process is sent to the pipe

1) https://man7.org/linux/man-pages/man2/dup.2.html

exec

- exec represents a group of system calls that can be used to execute external programs just like we would from a terminal
- We will use *execl* for today's lab
  - Declaration: *int execl(const char* pathname, const char* arg, …, (char*)NULL);*[1]
  - Invocation: *execl(program_path, variable_number_of_args, (char*)NULL);*
- *exec* system calls replace the calling process's image by a new image
- So, lines of code after a successful exec call inside a "specific process" will not be executed

1) https://man7.org/linux/man-pages/man3/exec.3.html

read

- read is a system call that is used to read from a file descriptor
  - Declaration: *ssize_t read(int fd, void *buf, size_t count);*[1]
  - Invocation:

```
char buf[n];
int numOfBytesRead = read(fd, buf, sizeof(buf));
```

- Reading from pipes:
  - Reading from a pipe will block the caller and read as long as any process has open write descriptors for that pipe
  - If all processes close the write end of a specific pipe, reading from that pipe will no longer block and instead return 0

1) https://www.man7.org/linux/man-pages/man2/read.2.html

write

- Write is a system call that is used to write to a file descriptor
  - Declaration: *ssize_t write(int fd, void *buf, size_t count);*[1]
  - Invocation:

    char buf[n];

    int numOfBytesWritten = write(fd, buf, sizeof(buf));

- Writing to pipes:
  - If the read end of a pipe has been closed by all processes, writing to that pipe will result in SIGPIPE signal and the process trying to write to that pipe will be terminated

1) https://www.man7.org/linux/man-pages/man2/write.2.html

Understanding Processes and IPC through the Shell

Example Shell Commands (Redirections)

- Some common bash operators:

  - *foo* < in.txt – redirect standard input of program *foo* to in.txt.
  - *foo* > out.txt – redirect standard output of program *foo* to out.txt.
  - *foo* >> out.txt – redirect standard output of program *foo* to be appended to the file out.txt.
  - *foo* | *bar* – redirect standard output of program *foo* to be the standard input to program *bar.*

- Bash is also a scripting programming language (complete with variables and if and while statements) that can be used to script the OS.

Utility Programs

- Any Unix distribution comes with several utility programs for interacting with the OS.
  - grep – search for strings in a file
  - find – find a particular file
  - du – Determine the disk usage of files and directories
  - ls – List files and their permissions
- Many, many more. Proficiency with these basic tools will make you a much more effective developer on your platform.
- Unix provides a manual (accessible from the shell) that documents the use and syntax of each core utility. e.g:

– man grep

finder.sh

```
find $1 -name '*'.[ch] | xargs grep -c $2 | sort -t : +1.0 -2.0
        --numeric --reverse | head --lines=$3
```

- find $1 -name '*'.[ch] – Find files with .c and .h extensions under the directory given by the first argument.
- xargs grep -c $2 – Search the set of files on standard input for the string given by the second argument. -c says that instead of printing out each usage in each file, give me the number of times $2 is used in each file.
- sort – Sort standard input and print the sorted order to standard output. -t : +1.0 -2.0 says sort using the second column on each line (delimited by the ':' character) as a key. --numeric says to sort numerically (as opposed to alphabetically). --reverse says sort in reverse order.
- head – print only the first *n* lines of standard input. --lines=$3 lets us set the number of lines with the third argument.

How finder.sh Works in the Shell

- When the user types this command at a shell, the shell parses the input, and issues system calls to create the processes and set up the pipes between these processes.
- In this lab, we will implement what the shell would typically perform when given a command like this.

– Although to save time, our implementation will only work for pipelines of length 4 as opposed to arbitrarily long pipelines (as a shell would handle).

Getting Started

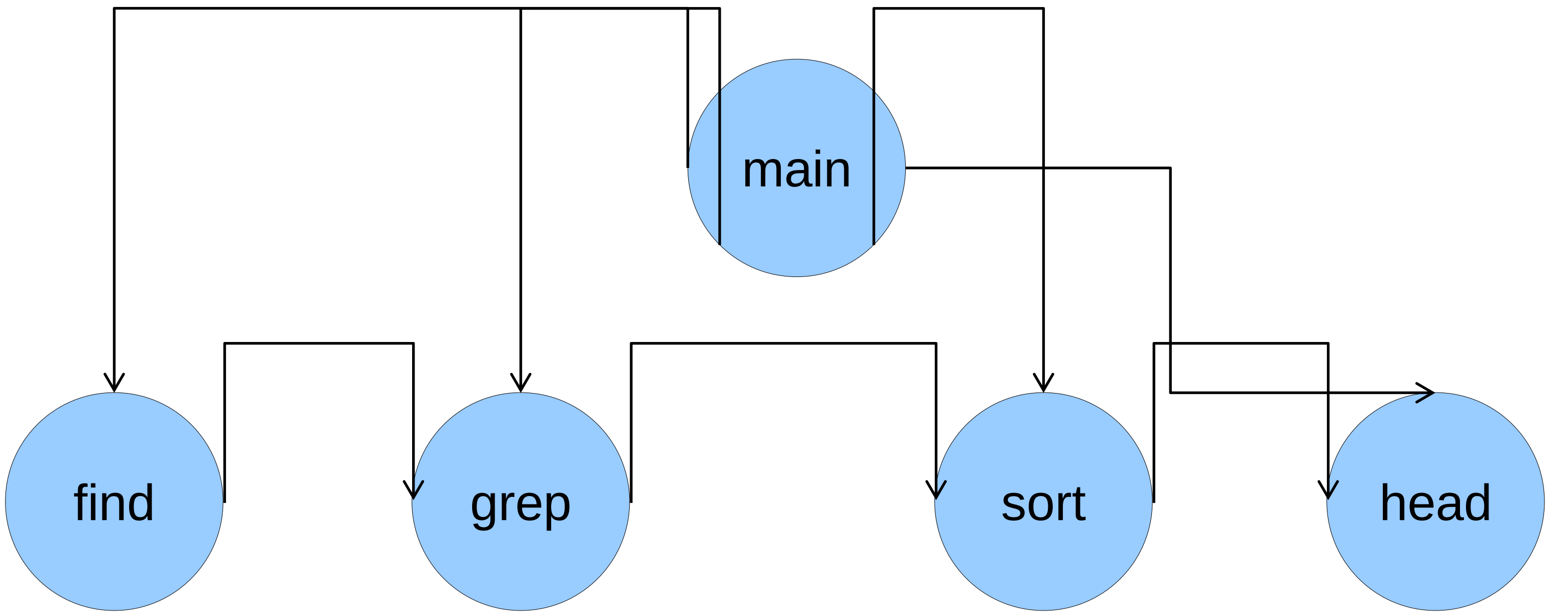
- The first thing to notice after untarring the tar file is the Makefile:
  - Notice the variables DIR, STR, and NUM_FILES and the command under the 'find' target.
  - Test the command. In this lab's directory, do:
    - bash> make find
- Should see the output as described two slides back.
- The goal of this lab is to write a program – finder.c – that produces the same output as the finder.sh command.

finder.c

- As it is given, this program is a skeleton for a four stage pipeline.
- All it currently does is start a process, which forks off four children (which do nothing), waits for them to finish, and exits.

finder.c (cont.)

- We want a program that forks off four children, sets up pipes between these children, and executes the appropriate command with each child:



Step 1 - Constructing the Pipeline

- Go ahead and try to setup the pipeline using the pipe() and dup2() system calls.
- Remember to close() unused file descriptors for each process.
- You may want to experiment with pipes using the pipe.c program first.
- Try to connect the processes in pipe.c so that the file read in the first process is written down a pipe which is read from in the second process.

Step 2 - Adding exec

- When you are confident your pipeline is working correctly, all that is left is to tell each process to exec the appropriate binary (e.g. find, grep, sort etc.)

- exec replaces the current process image with a new process image specified by a binary file name and arguments.

- Once the image is replaced, you have no control over what the process does (which is why it is recommended that you test the pipeline well before this step).

Example

```
if (pid_1 == 0) {
   /* First Child */
   char cmdbuf[BSIZE];
   bzero(cmdbuf, BSIZE);
   sprintf(cmdbuf, "%s %s -name \'*\'.[ch]", FIND_EXEC, argv[1]);

   /* set up pipes */
   …

   if ( (execl(BASH_EXEC, BASH_EXEC, "-c", cmdbuf, (char *) 0)) < 0) {
     fprintf(stderr, "\nError execing find. ERROR#%d\n", errno);
     return EXIT_FAILURE;
   }
}
```

Finishing Up

- After you have each completed your implementation, compile the finder program and run the test code:
    - bash> make test
- If the diff line does not produce an error, your implementation is correct.