Spark Session: minishell

updated: 06/04/2021

Project description:

> Create a simple shell

Topics

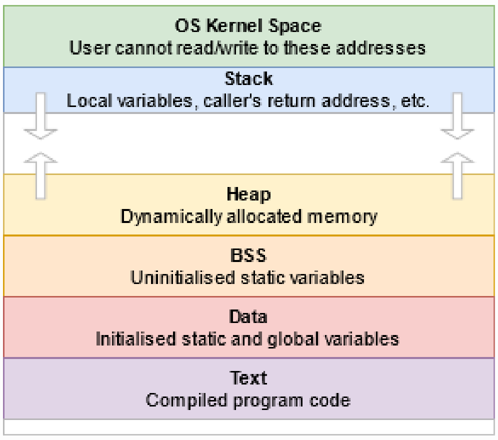
1. Processes
2. fork
3. wait
4. execve
5. dup & dup2
6. pipe

Processes

Before we get into how to work with processes, it's handy to understand what we actually mean by "process".

1. What is a process? (5 mins)
   > A process is a program in execution, an entity which implements a set of instructions (given by the program) in the system.
   > Processes are identified by their unique process ID (which is recycled after it terminates).
   > The `exec` family of functions implements the system call that creates a process.

A process is its own separate entity with its own defined **memory space**. This memory space is what is duplicated by `fork` and rewritten by `exec`, which we'll get to in a bit.
Here's a diagram showing how this memory is divided:



To put it in really simple terms, you can think of a process like a struct — a collection of information bound to an entity.

This information includes the process ID, open files, its status, etc. You can read more about that here later.

fork

`fork()` creates a new process — called the **child process** — by duplicating the calling process (**the parent process**).

1. What is the prototype of `fork()`? What does the function return? (10 mins)

   > `pid_t fork(void);`
   > On success, returns the PID of child process in the parent, and 0 in the child. On failure, -1 is returned in the parent, no child process is created.

   - How could you use the function return to identify if you are in the child or parent process?

     > By checking if the PID is 0, you can know if you're in the child process.

   - Is `fork`'s return the same as the child's PID?
     > Yes in the parent. Not in the child; child's actual PID can be seen by running `getpid`.

2. Which of the following is copied from the parent process to the child process? Which are not? (10 mins)

   - Data (the content of the process' memory space)
   - Location in memory
   - Process ID
   - Open file descriptors
     > Data: same data in their respective memory spaces (at time of fork)
     > Location in memory: not same - separate memory spaces
     > Process ID: not same - child has unique PID that doesn't match any of existing process group or session
     > Open FDs: same - child inherits copies of the parent's set of open file descriptors. Each FD in the child refers to the same open FD as the corresponding FD in the parent.

3. Let's see some of these characteristics in action. (20 mins)

   - Write a program that:
     - initialises an int `x` to **5**;
     - calls `fork()` and then prints its return value in a statement `"fork returned: %d\n"`;
     - checks for failed forks;
     - if in the **child** process: **decrements** `x` by 1, prints `"This line is from child, x is %d\n"`, and then **returns** 0;
     - else if in the **parent** process: **increments** `x` by 1 and then prints `"This line is from parent, x is %d\n"`.
   - You should see how the data (the variable `x` in this case) starts with the same initial value in both processes, but that changes to this variable in one process **does not affect** the variable in another process.

```
> ./fork_test
fork returned: 18895
This line is from parent, x is 6
fork returned: 0
This line is from child, x is 4
```

example output - your output order may vary

- Here we've specified that child should `return` when it's done. What happens if we comment that out? Try putting another `"x is %d"` statement at the **end of your main** to see.
  - You should see how the child and parent processes then both execute the code that follows, returning to a common point in the program. Whether or not you want that depends on the program's purpose.

In this case, the parent and the child process execute concurrently. The order of your output might also be jumbled between child and parent, depending on how your OS handles the processes.

Break (5 mins)

wait

It's also possible to have your parent process wait on its child processes to terminate. You do this by calling `wait()` in the parent process. This **synchronises** the parent and child process.

1. What is the prototype of `wait()`? What information is stored in the `int` whose address we pass as a parameter to the function? (5 mins)
   > `pid_t wait(int *wstatus);`
   > if not NULL, `wstatus` contains the child process' status information, which can be checked with macros like `WIFSIGNALED` and `WIFEXITED`.
2. Calling `wait()` (or `waitpid()`) in the parent process prevents what's called **"zombie processes"**. What does this mean? (10 mins)
   > Calling these functions collects the child's exit status from the kernel process table ("reaps" it), allowing the system to release the child's resources if it has terminated.
   > Not performing wait in the parent process leaves the terminated child in a zombie state. Because the kernel continues to keep info about the terminated child process and this takes up space. If you have too many of these, you could run out of space for new processes.
3. Let's add `wait()` to the code you wrote earlier. (10 mins)
   - Create an int variable, for example `w_status`, to be passed to `wait()`.
   - In the **parent process** code block, call `wait()` before anything else. *Remember to pass it the address of your `w_status` int.*
   - Make sure the **child process** is calling `return` when it's done.
   - Use one of the macros to check if the child process **terminated normally**. If so, print `"Child process exited with status: %d\n"`. Use one of the other macros to get the exit status.
     > if (WIFEXITED(w_status)) {
     > printf("Child process exited with status: %d\n", WEXITSTATUS(w_status));}
   - Try tweaking the argument you pass to the `return()` call in your child process. Does the output change accordingly?

```
> ./wait_test
fork returned: 17025
fork returned: 0
This line is from child, x is 4
This line is from parent, x is 6
Child process exited with status: 42
x is 6
```

example output

Here's a fun short explanation about zombie processes for later: understanding zombie processes

execve

The `exec()` family of functions allows us to **replace** the current process with a new program.
No new process is created; the PID remains the same. The functions simply have the existing process execute a new program.

1. What is the prototype of `execve()`? (10 mins)

   - Break down each of function parameters. What does each mean?
     > `int execve(const char *pathname, char *const argv[], char *const envp[]);`
     > pathname: binary executable, for example "/bin/ls"
     > argv: an array of pointers to strings to be passed to the program as its arguments.
     > envp: the environment variables you want to pass to the new program, which can differ from the env variables passed to the calling process
     > extra note: the 'v' in exec**v**e refers to the program args being passed as a vector (aka array). The 'e' in execv**e** refers to the ability to specify the environment.

2. What does `execve()` return? (5 mins)
   > On success, it doesn't return. Only returns on failure, giving -1 and setting erno appropriately.

3. To see how to execute a new program from within our child process, let's try using `execv()` (i.e. `execve` without the "e" environment option). (15 mins)

   - **Note**: for the purposes of keeping the exercise simple, we won't pass a specific environment. Also we'll hard-code our program arguments. You won't do this in your actual minishell of course.

   - At the beginning of your main, declare a `char *argv[3]`.

     - Initialize `argv[0]` to `"/bin/ls"`.
     - Initialize `argv[1]` to `"-l"`.
     - Initialize `argv[2]` to `NULL`.
     - *Do you know why these arguments are made in this order?*

     > By convention, argv[0] should contain the filename associated with the file being executed. The argv array must be terminated by a NULL pointer.

   - In your child process, below the `"This line is from child"` statement, **instead of return()** we'll call `execv()`, passing it `"/bin/ls"` and your `argv` array.

   - Below the `execv` call, place another print statement, `"This line is from child after execv"`.

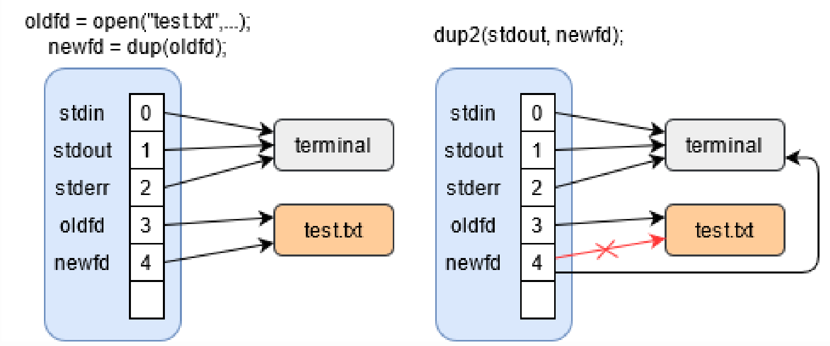
- Does your program execute `ls` with the `-l` list option when you run it? Does the "after execv" statement print?
  > Contents of folder should be outputted after "This line is from child", but the second print statement is never run because exec doesn't return if successful.

Break (5 mins)

dup & dup2

`dup()` and `dup2()` create a **copy** of a file descriptor.

1. What is the prototype for `dup()`? What about `dup2()`? What do both return? (5 mins)
   > `int dup(int oldfd);`
   > `int dup2(int oldfd, int newfd);`
   > on success, returns newfd. on failure, -1
2. What are some differences between `dup` and `dup2` with regards to the new file descriptor? (5 mins)
   - Here's a diagram to help you visualize the functions better:

     > `dup2` uses specified newfd, `dup` uses lowest-numbered unused fd.
     > `dup2`: If newfd was previously open, it is silently closed before being reused.
3. What do the new and old file descriptor share? (5 mins)
   > both refer to the same open file description and thus share file offset and file status flags. the two fds can therefore be used interchangeably.
4. Now let's write a program that: (15 mins)
   - opens a `test.txt` file with the following flags: `O_CREAT | O_TRUNC | O_RDWR, 0644`
     - Do you understand what these [flags]() do? Because this is one of the flag combinations you'll also use in minishell.
     - Here's a handy [permissions calculator]().
   - saves the `open` return in an int `fd`;
   - creates another int, for example `dup_fd`;
   - calls `dup()`, giving it `fd` as argument and saving its return in `dup_fd`;
   - passes `fd` as the 1st argument to `write()`, with the string `"This will be written to the test file\n"`.
   - passes `dup_fd` as the 1st argument to `write()`, with the string `"This will also be written to the test file\n"`.

     ```
     > cat test.txt
     This will be written to the test file.
     This will also be written to the test file.
     ```

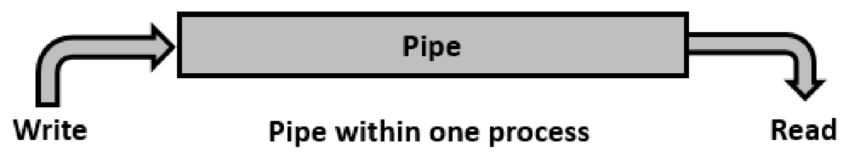
     > `write(fd, "This will be written to the test file\n", 38);`
     > `write(dup_fd, "This will also be written to the test file\n", 43);`

5. The real significance of `dup` and `dup2` to minishell is when we use them to **redirect** our output and/or input. For example, when the output of a command is redirected into a file or into a **pipe** (more on that later). (10 mins)
    - Now, using `dup2`, turn the fd `1` (that is, stdout) into a copy of our test.txt `fd`.
    - Call `write()` again, outputting `"This isn't being printed on stdout\n"` onto stdout (1).
    - Does anything get printed onto your terminal when you run the program?
      > `dup2(fd, 1);`
      > `write(1, "This isn't being printed on stdout\n", 35);`
      > string should be printed in test.txt instead of terminal

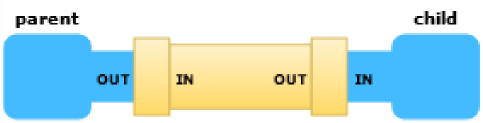
Bonus

pipe

`pipe()` allows data to be passed from one process to another.
This "pipeline" between processes is **unidirectional**, meaning data flows in one direction. Therefore, you have one end of the pipe that reads data and one end of the pipe that writes data.



1. What is the prototype of `pipe()`? What is being stored in the int array you're passing it? (10 mins)
   > `int pipe(int pipefd[2]);`
   > pipefd[0] refers to the read end of the pipe. pipefd[1] refers to the write end of the pipe.
2. If you're using a pipe to pass data from one process to a second process, which `pipefd` would the 1st process **write** to? Which would the 2nd process **read** from? (10 mins)

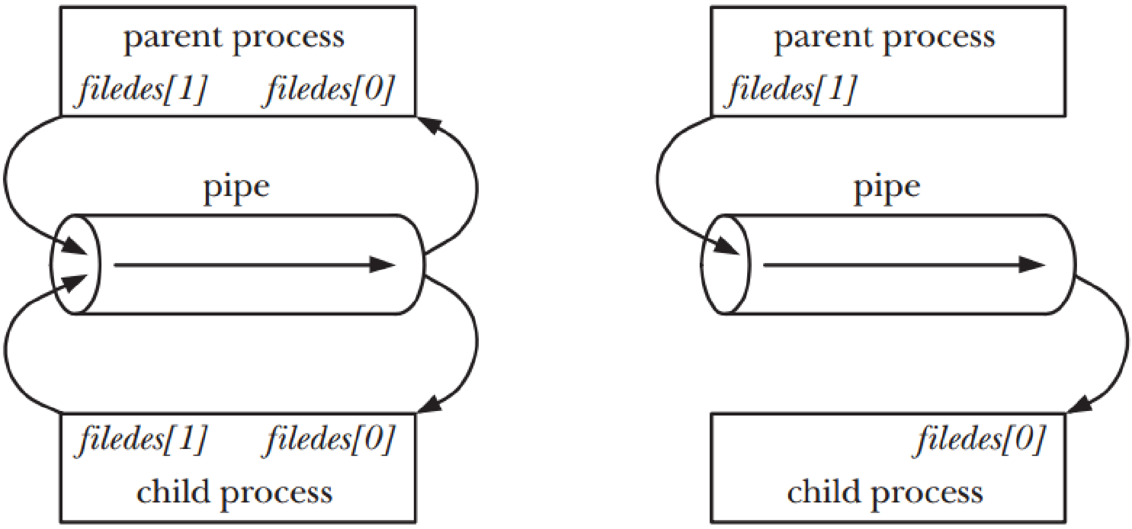
   

   > the read and write actions defined by a pipe() call are from the perspective of the two processes using the pipe, not the pipe itself.
   > therefore, the 1st process would write to `pipefd[1]` and the 2nd process would read from `pipefd[0]`.
3. Let's try using `pipe` in combination with `fork` and `wait`! Write a program that: (15 mins)
    - takes command-line arguments (i.e. `int argc, char **argv`);
    - creates a **pipe**;
    - then **forks** to create a child process;
    - the parent process:
        - should **close** the pipe end that it doesn't need;
        - **writes** argv[1] to the correct end of the pipe;
        - **closes** the remaining pipe end;
        - **waits** for its child processes to terminate and checks their status.
    - the child process:
        - should **close** the pipe end that it doesn't need;
        - in a loop, **reads** the string from the pipe, one byte at a time;

- calls `toupper()` (include `ctype.h`) on the read char;
- **writes** the converted char to stdout;
- writes a newline to stdout;
- **closes** the remaining pipe end.

```
./pipetest hello
HELLO
Child process exited with status: 0
```

4. Why do we close the **pipe ends we don't use** at the start? Why do we close the pipe end we used after we're done?



a) After *fork()* **b) After closing unused descriptors**

> If all fds referring to the write end of a pipe are closed, end-of-file is sent to `read`, which then knows to stop reading.
> If all fds referring to the read end of a pipe are closed, attempting `write` on the other end generates a SIGPIPE signal.
> Unnecessary duplicate fds should thus be closed, to ensure that EOF and SIGPIPE are delivered when appropriate, preventing a hanging state.

That was a simple exercise to show you how data can be passed through pipes and interacted with within child processes.

Things get even more mind-blowing when you throw `dup` / `dup2` into the mix.

Tips

Here's a more detailed explanation about data flows through pipes, with handy diagrams: pipes, forks, & dups

And here's a couple other things that could be helpful to look into for your project:

- abstract syntax tree
- finite state machines

```c
// example solution for pipe exercise
#include <stdio.h>
#include <sys/wait.h>
#include <unistd.h>
#include <string.h>
#include <ctype.h>

int main(int ac, char **av) {
    int pipefd[2];
    char buf;

    if (ac != 2){
        printf("incorrect number of args\n");
        return (1);
    }
    if (pipe(pipefd) < 0) {
        printf("pipe failed\n");
        return (1);
    }
    pid_t pid = fork();
    if (pid < 0)
        printf("fork failed\n");
    else if (pid == 0) {
        close(pipefd[1]);
        while (read(pipefd[0], &buf, 1) > 0) {
            char up = toupper(buf);
            write(STDOUT_FILENO, &up, 1);
        }
        write(STDOUT_FILENO, "\n", 1);
        close(pipefd[0]);
        return(0);
    }
    else {
        int w_status = 0;
        close(pipefd[0]);
        write(pipefd[1], av[1], strlen(av[1]));
        close(pipefd[1]);
        wait(&w_status);
        if (WIFEXITED(w_status))
            printf("Child process exited with status: %d\n", WEXITSTATUS(w_status));
    }
    return (0);
}
```