Week 3 Exercises: Error handling, I/O, and traits

Great job making it so far in the quarter! It has only been two weeks, but we've covered a lot of ground. We hope you are staying healthy and enjoying yourself this quarter.

Purpose

In the first part of these exercises, you'll work through implementing a tool for inspecting file descriptors that you can use to debug your CS 110 assignments. This will give you more practice with structs and error handling.

The second part of the exercises will give you some experience with traits in Rust. Traits are most helpful in managing large codebases with many related types, and since we don't have the time to introduce a substantial codebase, we won't be having you design your own traits. However, these exercises will give you experience with implementing standard traits on your own data type.

By the end of this week, you will have learned what we consider to be the most crucial parts of the Rust language. There is plenty more to learn, but what you don't know yet you can quickly pick up through Googling and reading documentation. If you're still feeling shaky about any of the concepts we've talked about, that's okay! You'll internalize them as you write more code. As always, you're welcome to ask questions on the `#rust-questions` channel!

Due date: Wednesday, April 29, 11:59pm (Pacific time)

Ping us on Slack if you are having difficulty with this assignment. We would love to help clarify any misunderstandings, and we want you to sleep!

Getting the code

The starter code is available on GitHub here.

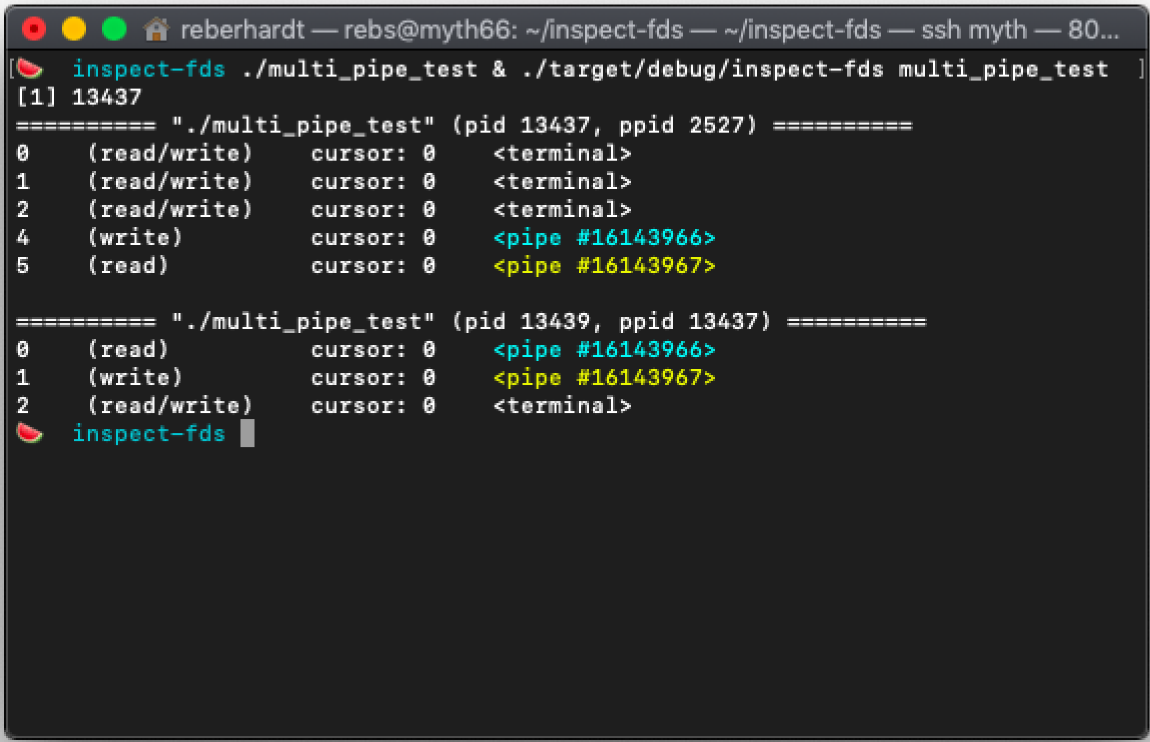
Part 1: Inspecting File Descriptors

In this part of the assignment, you will build a tool to inspect the open files of processes. This is based on a tool that was the precursor to C Playground's open files debugger; although it is a bit complicated to use and does not show a full representation of the open file table (the kernel doesn't expose much information to userspace, and we had to modify the kernel for C Playground), it is still very useful for debugging file descriptor issues in CS 110's assignments 3 (multiprocessing pset) and 4 (Stanford shell).

To use the tool to debug a file-descriptor-related problem, you would do the following:

- Add a `sleep(30)` call at the point in the program where you want to see the file descriptor table
- Run the buggy program in one terminal window
- In a second terminal window, `ssh` into the same myth machine (e.g. `myth65.stanford.edu` if that is where the first terminal window is logged in) and run `inspect-fds <name or PID of your program>`

`inspect-fds` then prints a representation of the file descriptor tables at that point in time. For example, here is the output where a parent process creates two pipes and forks, using the file descriptor 4 to write data to the child process's `stdin` and file descriptor 5 to read data from the child process's `stdout`:



The pipes are color coded so that it is easier to identify file descriptors that point to the same pipe (in this example, parent fd 4 writes to the pipe that child fd 0 reads from, and parent fd 5 reads from the pipe that child fd 1 writes to).

This tool is *especially* helpful for debugging mistakes in CS 110 assignment 4, in which you implement a shell. Shells do pretty complicated rewiring of the file descriptor table in order to create pipelines of processes of arbitrary length, and in order to read/write input from/to files on disk. Here is what the file descriptor tables should look like when the assignment 4 shell runs `sleep 100 < /tmp/testinput | sort | wc > /tmp/testoutput`. (This is a useless command, but we put `sleep 100` there in order to keep the pipeline running while we go to run `inspect-fds` in the other terminal.)

```
reberhardt — rebs@myth66: ~/inspect-fds — ~/inspect-fds — ssh myth — 80...
🍉 inspect-fds target/debug/inspect-fds stsh
========== "./stsh" (pid 19017, ppid 18850) ==========
0     (read/write)     cursor: 0     <terminal>
1     (read/write)     cursor: 0     <terminal>
2     (read/write)     cursor: 0     <terminal>

========== "sleep 100" (pid 21961, ppid 19017) ==========
0     (read)           cursor: 0     /tmp/testinput
1     (write)          cursor: 0     <pipe #16283287>
2     (read/write)     cursor: 0     <terminal>

========== "sort" (pid 21962, ppid 19017) ==========
0     (read)           cursor: 0     <pipe #16283287>
1     (write)          cursor: 0     <pipe #16283288>
2     (read/write)     cursor: 0     <terminal>

========== "wc" (pid 21963, ppid 19017) ==========
0     (read)           cursor: 0     <pipe #16283288>
1     (write)          cursor: 0     /tmp/testoutput
2     (read/write)     cursor: 0     <terminal>
🍉 inspect-fds
```

Here, you can see `sleep 100` is getting its input from `/tmp/testinput` and is writing output to a pipe, which is connected to stdin for `sort`, whose output goes to a second pipe, connected to `stdin` for `wc`, whose final output is written to `/tmp/testoutput`.

Implementing this tool involves a lot of file I/O, which will give you excellent practice with error handling. I think I/O is probably the absolute worst when it comes to error handling, so if you can put up with this, you can put up with anything. This exercise will also give you good practice working with structs. We hope that throughout the process, you have fun with it, learn a bit about how Linux works, and build yourself a tool that you can use in CS 110 in a week!

Word of warning

First, before you start working through the milestones below, you should run `make` in the `inspect-fds` directory. This will build some tiny C programs that you can use for testing.

Second, unfortunately, you need to run this tool on a Linux computer, because Mac and Windows don't use the same API for providing information about processes. If you aren't running Linux, you should do development on myth. If you're using an editor like Sublime or VSCode, you might want to check to see if there is an SSHFS plugin available to simplify this. In the worst case scenario, you can run your editor locally, then sync to `myth` and run `cargo` in one command:

```
rsync -avxh --exclude target inspect-fds myth: && ssh -t myth "cd inspect-fds &&
```

In order for this to not be a pain in the butt, you'll want to have set up an SSH config.

If you are working on myth, you may commonly see these errors:

```
warning: Hard linking files in the incremental compilation cache failed. Copying
```

You can ignore these errors. They indicate that the AFS filesystem doesn't support a feature that `cargo` uses for optimization, but it shouldn't be a problem for us.

Milestone 1: Getting the target process

A user specifies the process to inspect using a command line argument. For example, if you are running `bash`, you can inspect it like so:

```
cargo run bash
```

Our first order of business is to get information about the process the user wants to inspect.

Open `src/ps_utils.rs` and quicky skim the code that is provided to you. We have written some functions to call `ps` and `pgrep` to get information about processes by PID or by command name. There is a lot of semi-complicated error handling in this file (as there often is when dealing with I/O), so it may be helpful to read as an example. You won't need to modify anything in this file for this assignment, but you will need to call `get_target`.

Next, open `src/main.rs`. You'll see that we have declared a `target` variable containing the first argument in `argv`. Use the `ps_utils::get_target` function from the previous file to search for the target process.

- You're welcome to use `expect()` to handle the case where `get_target` returns an `Err`: just provide some error message about there being a problem calling `ps` or `pgrep`.
- If `get_target` returns `None`, you should print an error message about there not being any matching process and call `std::process::exit(1)`.
- Otherwise, print out the found process's PID.

Here is our output (which you are *not* required to match):

```
🍉  cargo run bash
    Finished dev [unoptimized + debuginfo] target(s) in 0.58s
     Running `target/debug/inspect-fds bash`
Found pid 18042
🍉  cargo run nonexistent
    Finished dev [unoptimized + debuginfo] target(s) in 0.72s
     Running `target/debug/inspect-fds nonexistent`
Target "nonexistent" did not match any running PIDs or executables
```

As a convenience, we have also provided tests that run your program, checking the exit code. (They don't verify that your program prints anything in particular!) You can run `cargo test exit_status -- --nocapture --test-threads=1`:

```
🍉  cargo test exit_status -- --nocapture --test-threads=1
    Finished dev [unoptimized + debuginfo] target(s) in 0.53s
     Running target/debug/deps/inspect_fds-41ab7dbb115eafda

running 2 tests
test test::test_exit_status_invalid_target ... Target "./nonexistent" did not mat
ok
test test::test_exit_status_valid_target ... Found pid 18306
ok

test result: ok. 2 passed; 0 failed; 0 ignored; 0 measured; 3 filtered out
```

Milestone 2: Printing process info

Let's start printing out some more information about these processes. First, in `src/process.rs`, let's add a `print()` method to the `Process` struct. This function will print details about this process. For now, print out the command name, pid, and ppid in a format that is something like this:

```
========== "bash" (pid 18042, ppid 17996) ==========
```

You are welcome to format your output however you like.

Note: You could implement this functionality as part of the `Display` trait for `Process`. However, the `Display` trait is typically supposed to generate a compact, general-purpose representation of a value that can be used anywhere in a codebase. Since this is generating detailed output for a high-level purpose of this program, we put our implementation in an ordinary `print()` method on `Process`.

Once you have implemented this method, go back to `main` and call your method on the `Process` object that you got in the previous milestone. Run your program (or use the `cargo test` command from the previous milestone) to ensure it is printing as you expect.

Milestone 3: Listing file descriptors

Let's get into the meat of this program! The Linux operating system exposes some information from the kernel through the `/proc` filesystem. Files and directories under `/proc` do not actually exist on disk; instead, they are generated by the kernel on demand whenever you read them. You can see a "directory" for each pid in `/proc`, and you can list each process's file descriptors by examining the directory `/proc/{pid}/fd`. For example, inspecting `zsh`'s file descriptors (you would see a different result if you are running `bash`):

```
🍉  ls /proc/$$/fd     # $$ is a shell variable containing the shell's pid
0  1  10  11  12  14  2
```

In this milestone, we will implement `Process::list_fds`, which lists the contents of `/proc/{pid}/fd` to get the file descriptor numbers that the process has open.

Open `src/process.rs` and have a look at the `list_fds` method. This function will return a list of file descriptor numbers (`Vec<usize>`) *if the file descriptor table is available*; otherwise, it will return `None`. It is important to handle the case of missing file descriptor tables for the purposes of handling *zombie processes,* which are processes that have exited but have not yet been reaped by their parents (i.e. their parents have not yet called `waitpid` on them). The processes still exist in the process table, but most of their resources have been freed, including the file descriptor table.

To implement this function, you should use `fs::read_dir(path)` to open the directory. Then, iterate over the directory entries, parse the file names as `usize`, and build a vector of file descriptor numbers. Here are some helpful hints:

- The `format!` macro will be useful for constructing the target path. `format!` is invoked exactly like `println!`, but instead of printing a formatted string, it returns it.
- Your function should not panic. That means you shouldn't call `unwrap()` or `expect()` anywhere. Errors are anticipated in this function, and if they occur, you should return `None`.
- When doing file I/O, you will encounter many functions that return a `Result`. If you encounter an `Err`, you should simply return `None`, as this indicates the file descriptor table is unavailable. Here is a nice syntactical shortcut to make this slightly more pleasant:

```
let some_var = something_that_returns_result().ok()?;
```

The `Result::ok()` function converts a `Result` to an `Option`, returning `Some(val)` if the `Result` was `Ok(val)`, or `None` if the `Result` was `Err(some_error)`. Then, the `?` operator unwraps the `Option`, making your function return `None` if the `Option` was `None`.

- The first example for [`fs::read_dir`] may be helpful for seeing how to read a directory. Note that their function returns `Result` and ours returns `Option`, so you will need to adopt the usage of `?` as explained in the previous bullet point.

When you have implemented this function, modify your `print()` function to call `list_fds()`, loop over each file descriptor, and print each one. Try running your program, and make sure it produces the output you expect. You can also run the provided tests:

```
cargo test list_fds
```

Milestone 4: Printing additional open file information

Let's take a closer look at `/proc/{pid}/fd`:

```
🍉  ls -l /proc/$$/fd
total 0
lrwx------ 1 rebs operator 64 Apr 22 15:13 0 -> /dev/pts/38
lrwx------ 1 rebs operator 64 Apr 22 15:13 1 -> /dev/pts/38
lrwx------ 1 rebs operator 64 Apr 22 15:13 10 -> /dev/pts/38
lr-x------ 1 rebs operator 64 Apr 22 15:13 11 -> /dev/urandom
lrwx------ 1 rebs operator 64 Apr 22 15:13 12 -> socket:[17099833]
lr-x------ 1 rebs operator 64 Apr 22 15:13 14 -> /usr/share/zsh/functions/Complet
lrwx------ 1 rebs operator 64 Apr 22 15:13 2 -> /dev/pts/38
```

Each file in this directory is a *symbolic link* pointing to whatever file the file descriptor points to in the vnode table. Here, you can see that file descriptors 0, 1, and 2 point to `/dev/pts/38`, which is the file that is mapped to the terminal I currently have open.

We can get additional information about each file descriptor from `/proc/{pid}/fdinfo/{fd}`:

```
🍉  cat /proc/$$/fdinfo/0
pos:    0
flags:  0100002
mnt_id: 22
```

This tells us the cursor, as well as flags set on the open file table entry (which includes flags like `O_RDONLY`, `O_WRONLY`, `O_WRONLY`).

Open `src/open_file.rs` and skim the code that is in this file. In this milestone, you will need to implement `OpenFile::from_fd`:

- First, use `fs::read_link` to read the destination path that the `/proc/{pid}/fd/{fd}` symbolic link points to. Similar to the previous milestone, you'll want to use `.ok()?` to return `None` if the file can't be read (presumably because the file descriptor table is no longer available – the process may have just exited). Pass the path (as a string – see `PathBuf::to_str()`) to `OpenFile::path_to_name` to get a human-friendly name for the file.
- Use `fs::read_to_string` to read the contents of `/proc/{pid}/fdinfo/{fd}`. (Be careful not to read `/proc/{pid}/**fd**/{fd}`! You should call `read_link` on `fd/` to see where the symbolic link points to, but if you call `read_to_string` on `fd/`, it will follow the symbolic link and try reading the file that the fd points to. When it tries to read `/proc/{pid}/fd/0`, that is going to attempt to read from `/dev/pts/38`, which is the terminal file, effectively trying to read from stdin, which will cause your program to hang. By contrast, `/proc/{pid}/fdinfo/0` is a *regular file* that you can read to get information about fd 0.)
    - Pass this to `OpenFile::parse_cursor` to extract the cursor from the file.
    - Pass this to `OpenFile::parse_access_mode` to extract the mode from the file.
- Return a new `OpenFile` struct with the name, cursor, and access mode you extracted.

You can use the supplied tests to check your work:

```
cargo test openfile_from_fd
```

Once you have implemented this function, open `process.rs` again and go to your `Process::print` function. Instead of iterating over `self.list_fds()`, use `self.list_open_files()` to get the file descriptors along with the corresponding `OpenFile`s. You can use the following code to print file descriptors, although you are welcome to write your own if you like:

```
match self.list_open_files() {
    None => println!(
        "Warning: could not inspect file descriptors for this process! \
            It might have exited just as we were about to look at its fd table, \
            or it might have exited a while ago and is waiting for the parent \
            to reap it."
    ),
    Some(open_files) => {
        for (fd, file) in open_files {
            println!(
                "{:<4} {:<15} cursor: {:<4} {}",
                fd,
```

```
                format!("({})", file.access_mode),
                file.cursor,
                file.colorized_name(),
            );
        }
    }
}
```

When this is done, your `inspect-fds` should be looking pretty good! Try it out:

```
🍉  cargo run bash
    Finished dev [unoptimized + debuginfo] target(s) in 1.16s
     Running `target/debug/inspect-fds bash`
========== "bash" (pid 19018, ppid 18803) ==========
0    (read/write)    cursor: 0    <terminal>
1    (read/write)    cursor: 0    <terminal>
2    (read/write)    cursor: 0    <terminal>
3    (read)          cursor: 0    /dev/urandom
4    (read/write)    cursor: 0    socket:[16103476]
255  (read/write)    cursor: 0    <terminal>

🍉  ./zombie_test & cargo run zombie_test
[1] 20630
    Finished dev [unoptimized + debuginfo] target(s) in 1.09s
     Running `target/debug/inspect-fds zombie_test`
========== "./zombie_test" (pid 20630, ppid 18509) ==========
0    (read/write)    cursor: 0    <terminal>
1    (read/write)    cursor: 0    <terminal>
2    (read/write)    cursor: 0    <terminal>
4    (write)         cursor: 0    <pipe #16102316>

========== "[zombie_test] <defunct>" (pid 20632, ppid 20630) ==========
Warning: could not inspect file descriptors for this process! It might have exite
```

Milestone 5: Inspecting child processes

For this tool to be most useful in debugging file descriptor issues (such as how pipes are wired up), we don't want to only show information about one process; we should also show information about other related processes. For our purposes, let's print the user-specified process along with all its child processes.

This involves a simple modification to your code in `main.rs`. After printing information about the user-specified process, call `ps_utils::get_child_processes` to get a list of child processes (again, it's acceptable to call `expect()` here). Iterate over these processes, and call your print function on each of them.

Your output should look something like this:

```
🍉  ./multi_pipe_test & cargo run multi_pipe_test
[1] 4060
    Finished dev [unoptimized + debuginfo] target(s) in 1.04s
     Running `target/debug/inspect-fds multi_pipe_test`
========== "./multi_pipe_test" (pid 4060, ppid 18509) ==========
0    (read/write)    cursor: 0    <terminal>
1    (read/write)    cursor: 0    <terminal>
2    (read/write)    cursor: 0    <terminal>
4    (write)         cursor: 0    <pipe #16301201>
5    (read)          cursor: 0    <pipe #16301202>

========== "./multi_pipe_test" (pid 4062, ppid 4060) ==========
0    (read)          cursor: 0    <pipe #16301201>
1    (write)         cursor: 0    <pipe #16301202>
2    (read/write)    cursor: 0    <terminal>
```

That's it! You're done! You'll be able to use this tool to debug your CS 110 assignment 3 and assignment 4 code.

Part 2: A Generic `LinkedList`

Let's get some practice with generics and traits! In this portion of the exercises, we will take the `LinkedList` lecture example from last Thursday and extend its implementation to make it more useful as a data structure.

You will find Thursday's code in `src/linked_list.rs`. You are invited to add code to `src/main.rs` to test your changes.

Make `LinkedList` generic

Our `LinkedList` implementation from last Thursday only stores `u32` values. Your first task is to modify `LinkedList` to support generic types, storing values of any type `T`. When you have done this, modify `src/main.rs` and try creating a list of `String`s!

Note: this may require you to modify the `impl fmt::Display` to incorporate a trait bound! You'll need to consider whether it makes sense to implement `Display` on `LinkedList` for *all* generic types. You should refer to Tuesday's lecture material for a discussion on trait bounds.

Implementing traits

There are four traits below that you may implement. Of them, **you only need to implement two.** The first three are the most straightforward, but if you have extra time and are feeling adventurous, try implementing `IntoIter`!

`Clone`

The Clone trait adds a `clone()` method to objects that creates a deep copy of the object. Your implementation should synthesize a freshly-allocated linked list copied from the original one. Similar to `Display`, you'll need to think about the trait bounds you want to impose on `T`.

Hint: Note that Box implements clone where T: Clone (it will allocate new heap memory and put the result of cloning T into that memory), Option implements clone where T: Clone, and you can implement Clone for your Node as well as a part of this! This results in self.head.clone() cloning all of your nodes! (think about why!)

`PartialEq`

The PartialEq trait makes it possible to compare values using the `==` operator. Two linked lists should be considered equal to one another if they are of the same length and corresponding nodes are equal. Again, you need to impose appropriate trait bounds here.

`ComputeNorm`

Implement the `ComputeNorm` trait from lecture for `LinkedList<f64>`. If you implement `Iterator`/`IntoIterator` (below), you should use that to implement `ComputeNorm`!

`Iterator` and `IntoIterator`

The IntoIterator trait allows you to iterate over a type using a `for` loop. Try implementing `IntoIter` for `LinkedList<T>` (i.e. an iterator that takes ownership of the list it is iterating over) and `&LinkedList<T>` (i.e. an iterator that only references elements in the list).

This article provides a great overview of what is going on and what is necessary to implement. I also highly recommend looking at Will Crichton's wonderful notes on traits under the "Associated Types" section for an example of how to implement the iterator trait. Note that he doesn't define his own struct and instead implements the trait on `&List<T>`. For your own implementation, you should implement your own struct that keeps track of the current node pointer and make that struct public i.e. with `pub struct LinkedListIterator`.

For `&LinkedList<T>`, implement the trait only on types `T` that implement `Clone`, so that the `next` function returns copies of the elements in your list. There is a way to implement this in a way that doesn't require cloning and we could also implement `IntoIterator` for `&mut T` – this would, however, lead to a more complex implementation. Feel free to try it though if you'd like an extra challenge!

Note that, in order to implement `IntoIterator` for `LinkedList<T>` (as in, an iterator that will take ownership of the `LinkedList<T>` it is iterating over), you can simply implement the `Iterator` trait for `LinkedList<T>`. Our implementation of `next` is only one line long since it makes a call to an already implemented function! (hint hint)

Implementing `IntoIterator` for `&LinkedList<T>` is a little more complicated, so we've scaffolded it for you. Here's what the implementation would look like for the original `LinkedList` that would only handle `u32`s:

```
pub struct LinkedListIter<'a> {
    current: &'a Option<Box<Node>>,
}


impl Iterator for LinkedListIter<'_> {
    type Item = u32;
    fn next(&mut self) -> Option<u32> {
        match self.current {
            Some(node) => {
                // YOU FILL THIS IN!
            },
            None => // YOU FILL THIS IN!
        }
    }
}

impl<'a> IntoIterator for &'a LinkedList {
    type Item = u32;
    type IntoIter = LinkedListIter<'a>;
    fn into_iter(self) -> LinkedListIter<'a> {
        LinkedListIter {current: &self.head}
    }
}
```

Here the `'a` syntax is labeling a lifetime. Let's zero in on the struct definition:

```
pub struct LinkedListIter<'a> {
    current: &'a Option<Box<Node>>,
}
```

This syntax essentially says that the struct lives as long as the reference it contains, so that we don't have issues with dangling pointers. In the code that you fill in, you won't have to deal with `'a` explicity. However, in order to make this generic, everywhere you see a `<'a>`, you will have to replace it with a `<'a, T>`.

You can read more about lifetimes here.

Part 3: Weekly survey

Please let us know how you're doing using this survey.

When you have submitted the survey, you should see a password. Put this code in `survey.txt` before submitting.

Submitting your work

As with last week, you can commit your progress using `git`:

```
git commit -am "Type some title here to identify this snapshot!"
```

In order to submit your work, commit it, then run `git push`. This will upload your commits (snapshots) to Github, where we can access them. You can verify that your code is submitted by visiting https://github.com/cs110l/week3-yourSunetid and browsing the code there. You can `git push` as many times as you'd like.

Grading

Part 1 (`inspect-fds`) will be worth 50% (with each milestone being worth 10%), Part 2 (linked list) will be worth 30%, and Part 3 (survey) will be worth 20%. You'll earn the full credit for each piece if we can see that you've made a good-faith effort to complete it.