Lab 2: Shell and Bootloader

- **Handed out:** Tuesday, January 28, 2020
- **Due:** Monday, February 10, 2020

Introduction

In this assignment, you will write useful utilities, libraries, and a simple shell for your Raspberry Pi. You'll also write generic drivers for GPIO, UART, and the built-in timer. Finally, you'll write a "bootloader" using your new drivers that loads program binaries over UART using the XMODEM protocol and executes them.

Getting the Skeleton Code

To get the skeleton code for lab2, fetch the updates from our git repository to your development machine.

```
$ git fetch skeleton
$ git merge skeleton/lab2
```

This is the directory structure of our repository. The directories you will be working on this assignment are marked with *.

```
.
├── bin : common binaries/utilities
├── doc : reference documents
├── ext : external files (e.g., resources for testing)
├── tut : tutorial/practices
│    ├── 0-rustlings
│    ├── 1-blinky
│    └── 2-shell : questions for lab2 *
├── boot : bootloader *
├── kern : the main os kernel *
└── lib  : required libraries
     ├── pi *
     ├── shim
     ├── stack-vec *
     ├── ttywrite *
     ├── volatile *
     └── xmodem *
```

Please resolve conflict if you have and proceed to the next phase.

We recommend the following directory structure for your assignments. Confirm that your directories are properly laid out by running `make` inside the `kern` directory now. If all is well, the command will return successfully. If everything is good, feel free to explore the contents of the repository.

This and future assignments include *writing questions* that you must respond to. Here's an example of such question:

How do you set other GPIO pins? (1-blinky)

In assignment 1-blinky, you enabled GPIO pin 16 as an output and then repeatedly set and cleared it by writing to registers `GPFSEL1`, `GPSET0`, and `GPCLR0`. Which three registers would you write to to do the same for GPIO pin 27? Which physical pin on the Raspberry Pi maps to GPIO pin 27?

The word in a parenthesis of the question indicates the name of a file located inside `questions/` directory relative to the lab name in which the question is being asked. For instance, every questions in this `Lab2: Shell and Bootloader` should be answered in `tut/2-shell/questions/` subdirectory. Note that we have pre-generated empty files for every question.

Practice responding to questions now by answering the `1-blinky` question above.

Phase 1: Oxidation

In this phase, you will write two libraries, one command-line utility, and review one library. You will be working in the `stack-vec`, `volatile`, `ttywrite`, and `xmodem` skeleton subdirectories located in `lib` directory.

All projects are being managed with Cargo. You will find the following `cargo` commands useful:

- `cargo build` - build an application or library
- `cargo test` - test an application or library
- `cargo run` - run an application
- `cargo run -- $flags` - run an application and pass arbitrary flags to it

For more information on using Cargo and how Cargo works, see the Cargo Book.

Subphase A: `StackVec`

One important facility that operating systems provide is memory allocation. When a C, Rust, Java, Python, or just about *any* application calls `malloc()` and `malloc()` has run out of memory from the operating system, a system call is eventually made to request additional memory. The operating system determines if there is memory available, and if so, fulfills the request for memory.

Memory allocation is a complicated story.

In practice, modern operating systems like Linux have a complicated relationship with memory allocation. For instance, as an optimization, most requests for memory allocation are only “virtually” handled: no physical memory is actually allocated until the application tries to use the newly allocated memory. Nonetheless, most operating systems aim to provide the *illusion* that they are allocating memory in the simplistic manner we’ve described. Operating systems are master liars (🍰).

Heap-allocated structures like `Vec`, `String`, and `Box` internally call `malloc()` to allocate memory as necessary. This means that these structures require operating system support to function. In particular, they require the operating system to support memory allocation. We haven’t yet started writing our operating system, so clearly there’s no memory allocation support for our tiny bare-metal programs to make use of. As such, we can’t use heap-allocated structures like `Vec` until our operating system is further along.

This is a real shame because `Vec` is a nice abstraction! It allows us to think about `push`ing and `pop`ing elements without having to keep track of memory ourselves. *How we can get the benefits of the `Vec` abstraction without supporting memory allocation?*

One common technique is to *pre-allocate* memory and then hand that memory to a structure to abstract away. Some ways to pre-allocate memory include using `static` declarations to set apart memory in the static section of a binary or through stack allocations from local variable declarations. In any case, the allocations is of a fixed, predetermined size.

In this subphase, you will implement the `StackVec` structure, a structure that exposes a `Vec`-like API when given pre-allocated memory. You will use the `StackVec` type later in phase 2 when implementing a shell for your Raspberry Pi. You will work in the `lib/stack-vec` skeleton subdirectory. The subdirectory contains the following files:

- `Cargo.toml` - configuration file for Cargo
- `src/lib.rs` - where you will write your code
- `src/tests.rs` - tests that will run when `cargo test` is called

The `StackVec` Interface

A `StackVec<T>` is created by calling `StackVec::new()`, passing in a mutable slice to values of any type `T`. The `StackVec<T>` type implements many of the methods that Vec implements and is used in much the same way. Here’s an example of a `StackVec<u8>` being used:

```rust
let mut storage = [0u8; 10];
let mut vec = StackVec::new(&mut storage);

for i in 0..10 {
    vec.push(i * i).expect("can push 10 times");
}

for (i, v) in vec.iter().enumerate() {
    assert_eq!(*v, (i * i) as u8);
}

let last_element = vec.pop().expect("has elements");
assert_eq!(last_element, 9 * 9);
```

We've declared the `StackVec` structure for you already:

```rust
pub struct StackVec<'a, T: 'a> {
    storage: &'a mut [T],
    len: usize
}
```

Understanding `StackVec`

The following questions test your understanding about the `StackVec` interface:

❗ Why does `push` return a `Result`? (push-fails)

The `push` method from `Vec` in the standard library has no return value, but the `push` method from our `StackVec` does: it returns a `Result` indicating that it can fail. Why can `StackVec::push()` fail where `Vec::push()` does not?

❗ Why is the `'a` bound on `T` required? (lifetime)

```rust
struct StackVec<'a, T> { buffer: &'a mut [T], len: usize }
```

Rust automatically enforces the bound `T: 'a` and will complain if type `T` lives shorter than the lifetime `'a`. For instance, if `T` is `&'b str` and `'b` is strictly shorter than `'a`, Rust won't allow you to create the instance of `StackVec<'a, &'b str>`.

Why is the bound required? What could go wrong if the bound wasn't enforced by Rust?

❗ Why does `StackVec` require `T: Clone` to `pop()`? (clone-for-pop)

The `pop` method from `Vec<T>` in the standard library is implemented for all `T`, but the `pop` method from our `StackVec` is only implemented when `T` implements the `Clone` trait. Why might that be? What goes wrong when the bound is removed?

Implementing `StackVec`

Implement all of the `unimplemented!()` `StackVec` methods in `stack-vec/src/lib.rs`. Each method is documented in the source code. We have also provided tests in `src/tests.rs` that help ensure that your implementations are correct. You can run these tests with `cargo test`. You'll also need to implement the `Deref`, `DerefMut`, and `IntoIterator` traits for `StackVec` as well as the `IntoIterator` trait for `&StackVec` for all of the `cargo test` tests to pass. Once you feel confident that you implementation is correct and have answered this subphase's questions, proceed to the next subphase.

Which tests make use of the `Deref` implementations? (deref-in-tests)

Read through the tests we have provided in `src/tests.rs`. Which tests would fail to compile if the `Deref` implementation did not exist? What about the `DerefMut` implementation? Why?

Our unit tests are incomplete!

Our unit tests provide a *baseline* truth, but they are not complete! We will run additional tests when we grade your assignment. You may wish to find the gaps in our tests and add additional tests of your own to fill them.

Subphase B: `volatile`

In this subphase, you will learn about volatile memory accesses, read the source code in the `volatile` skeleton subdirectory, and answer questions related to the source code. You won't be writing any code in this subphase.

Like operating systems, compilers are masters at making things *appear* as if they're doing what you think they're doing when in reality, they're really doing something entirely different for the sake of optimization. One such optimization is dead-access elimination: compilers remove memory accesses (reads and writes) when they can prove doing so has no observable effect on the program's execution. For instance, consider the following program:

```rust
fn f() {
    let mut x = 0;
    let y = &mut x;
    *y = 10;
}
```

The compiler can completely eliminate the write to `*y` by reasoning that `*y` is never read after it's written. The compiler concludes that as a result, the write cannot possibly effect the program, and eliminates it in the compiled binary. For the same reason, it can then proceed to eliminate the declaration for `y`, the declaration for `x`, and calls to `f()` entirely.

These kinds of optimizations are almost exclusively beneficial: they speed up our programs without affecting their outcome. But sometimes these optimizations can have unintended consequences. Say, for example, that `y` was pointing to a write-only memory-mapped register. Then, writes to `*y` *will* have observable effects *without* having to read `*y` thereafter. If the compiler is not aware of this, it will optimize away these writes, and our program will not function correctly.

How can we force the compiler to keep around reads and writes that appear to have no effects at the source code level? This is where `volatile` memory accesses come in: the compiler promises *not* to optimize away volatile memory accesses. So if we want to ensure a read or write occurs at runtime, we must perform a volatile memory access.

Rusty `volatile`

In Rust, we use the read_volatile and write_volatile methods to perform volatile reads and writes to a raw pointer.

What's a *raw* pointer?

By now you're familiar with references (`&T` and `&mut T`). A raw pointer in Rust (`*const T` and `*mut T`) is a "reference" that isn't tracked with lifetimes by Rust's borrow checker. Because of this, read or writes to these pointers may be invalid, just as in C. Rust considers them `unsafe`, and code that reads or writes them must be annotated with `unsafe` to indicate this. You can read more about raw pointers in the rustdocs.

Calling read_volatile and write_volatile every time we want to perform a volatile read or write is error prone and frustrating. Thankfully Rust provides us the tools to make this easier and safer. Ideally we can simply declare a pointer as volatile (as in C) and ensure that every read or write thereafter is volatile. Even better, we should be able declare a pointer as read-only, write-only (unlike in C), or read/write and ensure only the appropriate memory accesses can be made.

Introducing `Volatile`, `ReadVolatile`, `WriteVolatile`, and `UniqueVolatile`

The `volatile` crate in the `volatile/` skeleton subdirectory implements these four types that allow us to do just this. Read the documentation for these types now by running `cargo doc --open` inside of the `volatile/` directory.

Why does `Unique<Volatile>` exist? (unique-volatile)

Both `Volatile` and `Unique<Volatile>` allow read/write volatile accesses to an underlying pointer. According to the documentation, what is the difference between these two types?

Now open the source code in `src/lib.rs`, `src/traits.rs`, and `src/macros.rs`. Read through the source code to the best of your abilities. When you're ready, answer the following questions. Once you have answered these questions, you're ready to move on to the next subphase.

What's with `#[repr(C)]`?

The `#[repr(C)]` annotation forces Rust to lay out the structure's fields in the same way that C would. In general, Rust optimizes the order and padding between fields of structures in an unspecified way. When we cast a raw address to a pointer to a structure, we typically have a very specific memory layout in mind. The `#[repr(C)]` annotation lets us confide that Rust will arrange the structure as we intend it to, not as it wishes.

How are read-only and write-only accesses enforced? (enforcing)

The `ReadVolatile` and `WriteVolatile` types make it impossible to write and read, respectively, the underlying pointer. How do they accomplish this?

What do the macros do? (macros)

What do the `readable!`, `writeable!`, and `readable_writeable!` macros do?

Subphase C: `xmodem`

In this subphase, you will implement the XMODEM file transfer protocol in the `xmodem` library in the `xmodem/` skeleton subdirectory. You will primarily be working in `xmodem/src/lib.rs`.

XMODEM is a simple file transfer protocol originally developed in 1977. It features packet checksums, cancellation, and automatic retries. It is widely implemented and used for transfers through serial interfaces. Its best feature, however, is its simplicity. For more about its history, see the XMODEM Wikipedia article.

We will use the XMODEM protocol to transfer files to the Raspberry Pi. While we could use existing implementations of the XMODEM protocol to *send* data to the Pi, we will still need to write our own receiver. So, while we're at it, we'll be implementing XMODEM transmission as well.

The Protocol

The XMODEM protocol is described in detail in the Understanding The X-Modem File Transfer Protocol txt file. We describe it again here, for posterity.

Do not base your implementation off of Wikipedia's explanation!

While Wikipedia's explanation is helpful at a high level, many of the details presented there are different from the protocol we'll be implementing here. As such, do not use the article as a reference for this subphase.

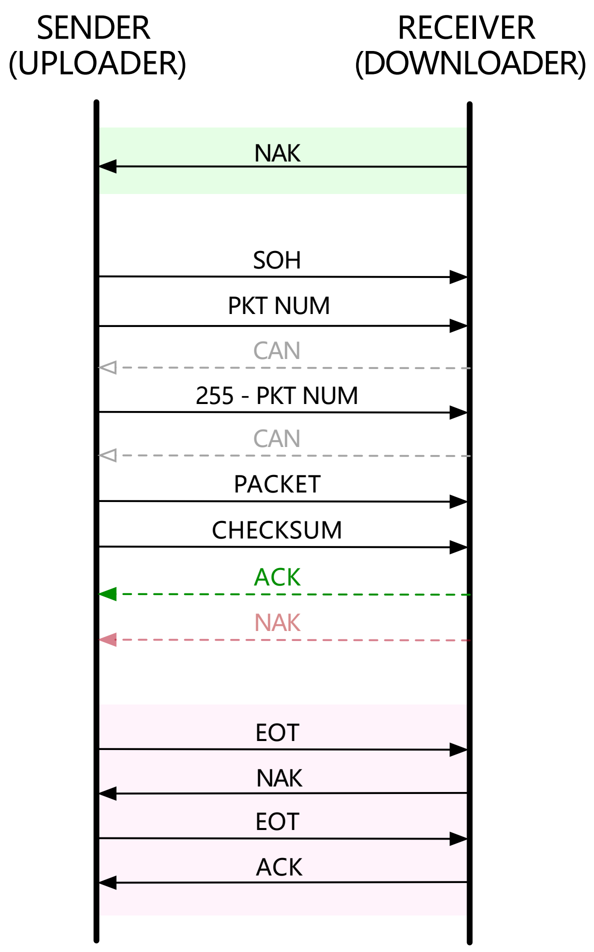
XMODEM is a binary protocol: bytes are sent and received in the raw. It is also "half duplex": at any point in time, either the sender or receiver is sending data, but never both. Finally it is packet-based: data is separated into 128 byte chunks known as packets. The protocol dictates which bytes are sent when, what they mean, and how they're interpreted.

First, we define a few constants:

```
const SOH: u8 = 0x01;
const EOT: u8 = 0x04;
const ACK: u8 = 0x06;
const NAK: u8 = 0x15;
const CAN: u8 = 0x18;
```

To start the file transfer, the receiver sends a `NAK` byte while the sender waits for a `NAK` byte. Once the sender has received the `NAK` byte, packet transmission begins. The receiver only sends a `NAK` byte to begin the file transfer, not once for every packet.

Once file transfer has begun, each packet's transmission and reception is identical. Packets are numbered in sequential order starting at `1` and wrap around to `0` after `255`.



XMODEM protocol diagram

To send a packet, the sender:

1. Sends an `SOH` byte.
2. Sends the packet number.
3. Sends the 1s complement of the packet number (`255 - $packet_number`).
4. Sends the packet itself.
5. Sends the packet checksum.
   - The checksum is the sum of all of the bytes in the packet mod 256.
6. Reads a byte from the receiver.
   - If the byte is `NAK`, transmission for the same packet is retried up to 10 times.
   - If the byte is `ACK`, the next packet is sent.

The receive a packet, the receiver performs the inverse:

1. Waits for an `SOH` or `EOT` byte from the sender.
    - If a different byte is received, the receiver cancels the transfer.
    - If an `EOT` byte is received, the receiver performs end of transmission.
2. Reads the next byte and compares it to the current packet number.
    - If the wrong packet number is received, the receiver cancels the transfer.
3. Reads the next byte and compares it to the 1s complement of the packet number.
    - If the wrong number is received, the receiver cancels the transfer.
4. Reads a packet (128 bytes) from the sender.
5. Computes the checksum for the packet.
    - The checksum is the sum of all of the bytes in the packet mod 256.
6. Reads the next byte and compares it to the computed checksum.
    - If the checksum differs, sends a `NAK` byte and retries reception for the same packet.
    - If the checksum is the same, sends an `ACK` byte and receives the next packet.

To cancel a transfer, a `CAN` byte is sent by either the receiver or sender. When either side receives a `CAN` byte, it errors out, aborting the connection.

To end the transmission, the sender:

1. Sends an `EOT` byte.
2. Waits for a `NAK` byte. If a different byte is received, the sender errors out.
3. Sends a second `EOT` byte.
4. Waits for an `ACK` byte. If a different byte is received, the sender errors out.

To end the transmission, the receiver performs the following after receiving the first `EOT`:

1. Sends a `NAK` byte.
2. Waits for a second `EOT` byte. If a different byte is received, the receiver cancels the transfer.
3. Sends an `ACK` byte.

Implementing XMODEM

We have provided an unfinished implementation of the XMODEM protocol in the `xmodem` skeleton subdirectory. Your task is to complete the implementation by writing the `expect_byte`, `expect_byte_or_cancel`, `read_packet`, and `write_packet` methods in `src/lib.rs`. Your implementations should make use of the internal state of the `Xmodem` type: `packet` and `started`. We recommend reading over the existing code before starting.

You should begin by implementing the `expect_byte` and `expect_byte_or_cancel` methods. You should then make use of all four of the helper methods (including `read_byte` and `write_byte`) to implement `read_packet` and `write_packet`. To see how these methods are used, read the `transmit` and `receive` implementations which transmit or receive a complete data stream using XMODEM via these methods. Be mindful of the specifications in the doc-comments. You can test your implementation using `cargo test`. Once you are confident that your implementation is correct, proceed to the next subphase.

Do not use any additional items from `std`.

Your implementation should only use items from `shim::io`. It should not use other items from `std` or any other libraries.

Hint

Our reference implementations for `{read,write}_packet` are roughly 43 lines of code each.

Hint

The io::Read and io::Write rustdocs will be useful.

Hint

Use the `?` operator generously.

Hint

The test source code can be a helpful guide.

Hint

You can use `ioerr!` macro to make and return a new `io::Error` easily. Please refer `shim/src/macros.rs` to find more macros which can be useful.

Subphase D: `ttywrite`

In this subphase, you will write a command line utility, `ttywrite`, that will allow you to send data to your Raspberry Pi in the raw or via the XMODEM protocol. You will use your `xmodem` library from the previous subphase in your implementation. You will write your code in `ttywrite/src/main.rs`. To test your `ttywrite` implementation, use the provided `test.sh` script.

What is a serial device?

A serial device is any device that accepts communication one bit at a time. This is known as *serial communication*. In contrast, in *parallel communication* multiple bits are being transferred at any point in time in parallel. We will be communicating with our Raspberry Pi via its UART device, a serial communication device.

What is a *TTY*?

A *TTY* is a "teletypewriter". It is a vestigial term that was adopted in computing to describe computer terminals. The term later become more general, coming to describe any device intended to be communicated with over serial. For this reason, your computer calls the device mapping to your Raspberry Pi a TTY.

Command-Line Interface

The skeleton code we have provided for `ttywrite` already parses and validates command-line arguments. To do so, it uses the structopt crate from crates.io which itself uses clap. You'll notice that we list it as a dependency in the `Cargo.toml` file. structopt works through code generation. We simply annotate a structure and its fields with a declaration of our command-line arguments and structopt generates the code to actually parse the command-line flags.

To see the interface that structopt generates, call the application with `--help`. Remember that you can pass arbitrary flags when using `cargo run`: `cargo run -- --help`. Take a look at the interface now. Then, take a look at the `Opt` structure in `main.rs` and compare the interface with its definition.

What happens when a flag's input is invalid? (invalid)

Try passing in some invalid values for flags. For instance, it should not be possible to set `-f` to `idk`. How does `structopt` know to reject invalid values?

You'll notice that there are plenty of options. All of these correspond to settings available on a serial device. For now it's not important to know exactly what these settings do.

Talking to a Serial Device

In `main`, you'll see a call to serial::open. This is calling the `open` function from the serial crate, also on crates.io. This `open` function returns a TTYPort which allows you to read and write to the serial device (via its `io::Read` and `io::Write` trait implementations) as well as read and set settings on a serial device (via its `SerialDevice` trait implementation).

Writing the Code

Implement the `ttywrite` utility. Your implementation should set all of the appropriate settings passed in via the command-line stored in the `opt` variable in `main`. It should read from `stdin` if no input file is passed in or from the input file if one is passed in. It should write the input data to the passed in serial device. If the `-r` flag is set, it should send the data as it is. Otherwise, you should use your `xmodem` implementation from the previous subphase to send the data using the XMODEM protocol. You should print the number of bytes sent on a successful transmission.

To transmit using the XMODEM protocol, your code should use either the `Xmodem::transmit` or `Xmodem::transmit_with_progress` methods from the `xmodem` library. We recommend using `transmit_with_progress` so that your utility indicates progress throughput the transmission. In its simplest form, this might look as follows:

```
fn progress_fn(progress: Progress) {
    println!("Progress: {:?}", progress);
}

Xmodem::transmit_with_progress(data, to, progress_fn)
```

You can test the baseline correctness of your implementation using the `test.sh` script in the `ttywrite` directory. When your implementation is at least somewhat correct, you will see the following when the script is run:

```
Opening PTYs...
Running test 1/10.
wrote 333 bytes to input
...
Running test 10/10.
wrote 232 bytes to input
SUCCESS
```

Hint

You can retrieve a handle to `stdin` with io::stdin().

Hint

You may find the io::copy() function useful.

Hint

The `main()` function in our reference implementation is roughly 35 lines of code.

Hint

Keep the TTYPort documentation open while writing your code.

Why does the `test.sh` script always set `-r`? (bad-tests)

The `test.sh` script that we have provided always uses the `-r` flag; it doesn't test that your utility uses the XMODEM protocol when it is asked to. Why might that be? What does the XMODEM protocol expect that sending data in the raw doesn't that makes testing its functionality difficult?

Installing `ttywrite` utility

After finish writing the `ttywrite` utility, install the tool with `cargo install --path .` command. This command will be used later to communicate with the bootloader.

Phase 2: *Not* a Seashell

In this phase, you will be implementing drivers for the built-in timer, GPIO, and UART devices. You'll use then these drivers to implement a simple shell. In the next phase, you'll use the same drivers to implement a bootloader.

What's a driver?

The term *driver*, or *device driver*, describes software that directly interacts with and controls a hardware device. Drivers expose a higher-level interface to the hardware they control. Operating systems may interact with device drivers to expose an even higher-level interface. For instance, the Linux kernel exposes ALSA (Advanced Linux Sound Architecture), an audio API, which interacts with device drivers that in-turn interact directly with sound cards.

Subphase A: Getting Started

Project Structure

Let's recall the repository structure we saw at the beginning of this lab.

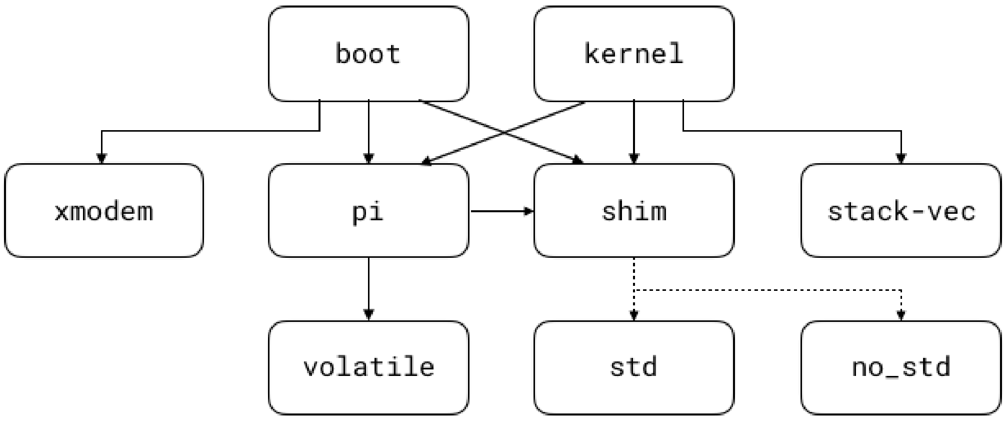
```
.
├── ...
├── boot : bootloader *
├── kern : the main os kernel *
└── lib  : required libraries
     ├── pi *
     ├── shim
     ├── stack-vec *
     ├── ttywrite *
     ├── volatile *
     └── xmodem *
```

All the libraries used by `boot` and `kernel` are located under the `lib` directory.

`shim` library selectively depends on either `std` or `no_std` library. With `#[cfg(feature = "no_std")]` specified, `shim` makes use of `core_io` and the custom `no_std` module which has minimum library we need such as `ffi`, `path` and `sync`. Otherwise, mostly in the test code, `shim` just uses `std` library.

`pi` subdirectory contains all of your driver code. The `pi` library makes use of the `volatile` library. It also depends on the `shim` library.

`boot` and `kernel` make use of the `pi` library to communicate with hardware. They also depend on `shim`. In addition to that, `boot` also depends on the `xmodem` library, and `kernel` depends on the `stack-vec` library. The `volatile` library has no dependencies. The diagram below illustrates these relationships:



Kernel

The `kern` directory contains the code for the operating system kernel: the core of your operating system. Calling `make` inside this directory builds the kernel. The build output is stored in the `build/` directory. To run the kernel, copy the `build/kernel.bin` file to the root of the MicroSD card as `kernel8.img`. You may wish to use a script to copy the kernel image to the sdcard with `make install` command. Please refer the Tools page to find details about our `Makefile`.

At present, the kernel does absolutely nothing. By the end of this phase, the kernel will start up a shell which you can communicate with.

As we saw above, the `kernel` crate depends on the `pi` library. As a result, you can use all of the types and items from the `pi` library in the kernel.

Documentation

While writing your device drivers, you'll want to keep the BCM2837 ARM Peripherals Manual open.

Subphase B: System Timer

In this subphase, you will write a device driver for the ARM system timer. You will primarily be working in `lib/pi/src/timer.rs` and `kern/src/main.rs`. The ARM system timer is documented on page 172 (section 12) of the BCM2837 ARM Peripherals Manual.

Start by looking at the existing code in `lib/pi/src/timer.rs`. In particular, note the relationship between the following sections:

```
const TIMER_REG_BASE: usize = IO_BASE + 0x3000;

  #[repr(C)]
  struct Registers {
      CS: Volatile<u32>,
      CLO: ReadVolatile<u32>,
      CHI: ReadVolatile<u32>,
      COMPARE: [Volatile<u32>; 4]
  }

  pub struct Timer {
      registers: &'static mut Registers
  }

  impl Timer {
      pub fn new() -> Timer {
          Timer {
              registers: unsafe { &mut *(TIMER_REG_BASE as *mut Registers) },
          }
      }
  }
```

The one line of `unsafe` in this program is very important: it casts the `TIMER_REG_BASE` address to a `*mut Registers` and then casts that to an `&'static mut Registers`. We are telling Rust that we have a static reference to a `Registers` structure at address `TIMER_REG_BASE`.

What is at the `TIMER_REG_BASE` address? On page 172 of the BCM2837 ARM Peripherals Manual, you'll find that `0x3000` is the peripheral offset for the ARM system timer. Thus, `TIMER_REG_BASE` is the address at which the ARM system timer registers start! After this one line of `unsafe`, we can use the `registers` field to access the timer's registers safely. We can read the `CLO` register with `self.registers.CLO.read()` and write the `CS` register with `self.registers.CS.write()`, then combine them together to represent the number of elapsed microseconds.

❗ Why can't you write to CLO or CHI? (restricted-reads)

The BCM2837 documentation states that the `CLO` and `CHI` registers are read-only. Our code enforces this property. How? What prevents us from writing to `CLO` or `CHI`?

What exactly is *unsafe*?

In short, `unsafe` is a marker for the Rust compiler that you're taking control of memory safety: the compiler won't protect you from memory issues. As a result, in `unsafe` sections, Rust lets you do anything you can do in C. In particular, you can cast between types with more freedom, dereference raw pointers, and fabricate lifetimes.

But note that `unsafe` is *very* unsafe. You must ensure that everything you do in an `unsafe` section is, in fact *safe*. This is more difficult than it sounds, especially when Rust's idea of *safe* is much stricter than in other languages. As such, you should try not to use `unsafe` at all. For operating systems, unfortunately, we *must* use `unsafe` so that we can directly speak to hardware, but we'll typically limit our use to **one** line per driver.

If you want to learn more about `unsafe`, read Chapter 1 of the Nomicon.

Implement the Driver

Implement the `Timer::read()`, `current_time()`, and `spin_sleep()` in `lib/pi/src/timer.rs`. The signatures on these items indicate their expected functionality. You'll need to read the timer's documentation in the BCM manual to implement `Timer::read()`. In particular, you should understand which registers to read to obtain the timer's current `u64` value. You can build the `pi` library with `cargo build`. You can also use `cargo check` to type-check the library without actually compiling it.

Hint

You'll find the core::time::Duration page useful.

Testing Your Driver

Let's test your driver by ensuring that `spin_sleep()` is accurate. We'll write the code to do this in `kern/src/main.rs`.

Copy your LED blinky code from phase 4 of lab 1 into `main.rs`. Instead of the `for` loop based sleep function, use your newly written `spin_sleep()` function with `Duration` to pause between blinks. Compile the kernel, load it onto the MicroSD card as `kernel8.img`, and then run it on the Raspberry Pi. Ensure that the LED blinks at the frequency that you intended it to. Try other pause times and ensure that they all work as expected. Until you write the bootloader in phase 3, you'll need to keep swapping the MicroSD card between the Pi and your computer to try out different binaries.

If your timer driver is working as expected, proceed to the next subphase.

Subphase C: GPIO

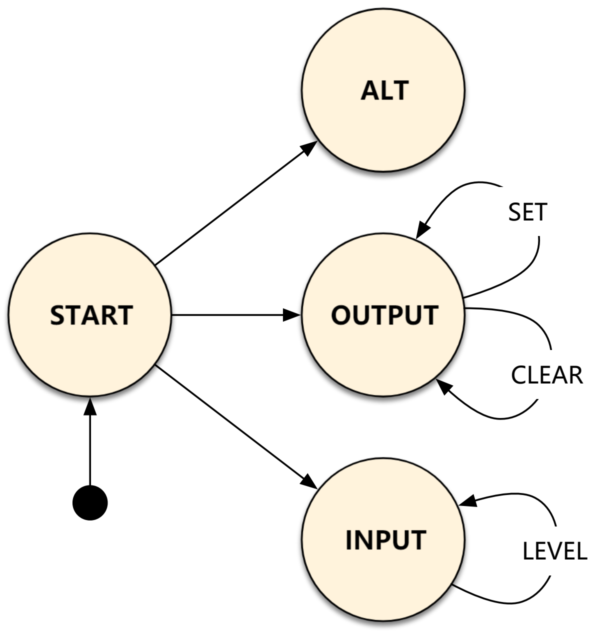
In this subphase, you will write a generic, pin-independent device driver for GPIO. You will primarily be working in `lib/pi/src/gpio.rs` and `kern/src/main.rs`. The GPIO subsystem is documented on page 89 (section 6) of the BCM2837 ARM Peripherals Manual.

State Machines

All hardware devices are state machines: they begin at a predetermined state and transition to different states based on explicit or implicit inputs. The device exposes different functionality depending on which state it is in. In other words, only *some* transitions are valid in *some* states. Importantly, this implies that some transitions are *invalid* when the device is in a given state.

Most programming languages make it impossible to faithfully encode the semantics of a state machine in hardware, but not Rust! Rust lets us *perfectly* encode state machine semantics, and we'll take advantage of this to implement a safer-than-safe device driver for the GPIO subsystem. Our driver will ensure that a GPIO pin is never misused, and it will do so at compile-time.

Below is the state diagram for a subset of the GPIO state machine for a single pin:



GPIO State Diagram

Our goal is to encode this state machine in Rust. Let's start by interpreting the diagram:

- The GPIO starts in the `START` state.
- From the `START` state it can transition to one of three states:

  1. `ALT` - no transitions are possible from this state
  2. `OUTPUT` - two "self" transitions are possible: `SET` and `CLEAR`
  3. `INPUT` - one "self" transition is possible: `LEVEL`

Which transitions did you follow in your lab 1 `blinky`? (blinky-states)

When you implementing the blinky code in phase 4 of lab 1, you implicitly implemented a subset of this state machine. Which transitions did your code implement?

We'll use Rust's type system to ensure that a pin can only be `SET` and `CLEAR`ed if it has been transitioned to the `OUTPUT` state and the `LEVEL` read if it is in the `INPUT` state. Take a look at the declaration for the `GPIO` structure in `lib/pi/src/gpio.rs`:

```
pub struct Gpio<State> {
  pin: u8,
  registers: &'static mut Registers,
  _state: PhantomData<State>
}
```

The structure has one generic argument, `State`. Except for `PhantomData`, nothing actually *uses* this argument. This is what PhantomData is there for: to convince Rust that the structure somehow uses the generic even though it otherwise wouldn't. We're going to use the `State` generic to encode which state the `Gpio` device is in. Unlike other generics, *we* must control this parameter and ensure that a client can never fabricate it.

The `state!` macro generates types that represent the states a `Gpio` can be in:

```
states! {
  Uninitialized, Input, Output, Alt
}

// Each parameter expands to an `enum` that looks like:
enum Input { }
```

This is *also* weird; why would we create an `enum` with no variants? `enum`'s with no variants have a nice property: they can *never* be instantiated. In this way, these types act purely as markers. No one can ever pass us a value of type `Input` because such a value can never be constructed. They exist purely at the type-level.

We can then implement methods corresponding to valid transitions given that a `Gpio` is in a certain state:

```
impl Gpio<Output> {
    /// Sets (turns on) the pin.
    pub fn set(&mut self) { ... }

    /// Clears (turns off) the pin.
    pub fn clear(&mut self) { ... }
}

impl Gpio<Input> {
    /// Reads the pin's value.
    pub fn level(&mut self) -> bool { ... }
}
```

This ensures that a `Gpio` can only be `set` and `clear`ed when it is a `Gpio<Output>` and its `level` read when it is a `Gpio<Input>`. Perfect! But how do we actually transition between states? Hello, `Gpio::transition()`!

```
impl<T> Gpio<T> {
    fn transition<S>(self) -> Gpio<S> {
        Gpio {
            pin: self.pin,
            registers: self.registers,
            _state: PhantomData
        }
    }
}
```

This method lets us transition a `Gpio` from any state to any other state. Given a `Gpio` in state `T`, this method returns a `Gpio` in state `S`. Note that it works for *all* `S` and `T`. We must be very careful when calling this method. When called, we are encoding the specification of a transition in the state diagram. If we get the specification or encoding wrong, our driver is wrong.

To use the `transition()` method, we need to tell Rust which type we want as an output `S` in `Gpio<S>`. We do this by giving Rust enough information so that it can infer the `S` type. For instance, consider the implementation of the `into_output` method:

```
pub fn into_output(self) -> Gpio<Output> {
    self.into_alt(Function::Output).transition()
}
```

This method requires its return type to be `Gpio<Output>`. When the Rust type system inspects the call to `transition()`, it will search for a `Gpio::transition()` method that returns a `Gpio<Output>` to satisfy the requirement. Since our `transition` method returns `Gpio<S>` for any `S`, Rust will replace `S` with `Output` and use that method. The result is that we've transformed our `Gpio<Alt>` (from the `into_alt()` call) into a `Gpio<Output>`.

What would go wrong if a client fabricates states? (fake-states)

Consider what would happen if we let the user choose the initial state for a `Gpio` structure. What could go wrong?

Why is this only possible with Rust?

Notice that the `into_` transition methods take a `Gpio` by move. This means that once a `Gpio` is transitioned into a another state, it can never be accessed in the previous state. Rust's move semantics make this possible. As long as a type doesn't implement `Clone`, `Copy`, or some other means of duplication, there is no coming back from a transition. No other language, not even C++, affords us this guarantee at compile-time.

Implement the Driver

Implement the `unimplemented!()` methods in `lib/pi/src/gpio.rs`. The signatures on these items indicate their expected functionality. You'll need to read the GPIO documentation (page 89, section 6 of the BCM2837 ARM Peripherals Manual) to implement your driver. Remember that you can use `cargo check` to type-check the library without actually compiling it.

Testing Your Driver

We'll again write code in `kern/src/main.rs` to ensure that our driver works as expected.

Instead of reading/writing to raw memory addresses, use your new GPIO driver to set and clear GPIO pin 16. Your code should get a lot cleaner. Compile the kernel, load it onto the MicroSD card as `kernel8.img`, run it on the Raspberry Pi, and ensure your LED blinks as before.

Now, connect more LEDs to your Raspberry Pi. Use GPIO pins 5, 6, 13, 19, and 26. Refer to the pin numbering diagram from assignment 0 to determine their physical location. Have your kernel blink all of the LEDs in a pattern of your choice.

Which pattern did you choose? (led-pattern)

What pattern did you have your LEDs blink in? If you haven't yet decided, one fun idea is to have them imitate a "loading spinner" by arranging the LEDs in a circle and turning them on/off in a sequential, circular pattern.

Once your GPIO driver is working as expected, proceed to the next subphase.

Subphase D: UART

In this subphase, you will write a device driver for the mini UART device on the Raspberry Pi. You will primarily be working in `lib/pi/src/uart.rs` and `kern/src/main.rs`. The mini UART is documented on page 8 and page 10 (sections 2.1 and 2.2) of the BCM2837 ARM Peripherals Manual.

UART: Universal Asynchronous RX/TX

A UART, or universal asynchronous receiver-transmitter, is a device and serial protocol for communicating over two wires. These are the two wires (rx/tx) that you used in phase 1 of lab 0 to connect the UART device on the CP2102 USB module to the UART device on the Pi. You can send any kind of data over UART: text, binaries, images, anything! As an example, in the next subphase, you'll implement a shell by reading from the UART device on the Pi and writing to the UART device on the CP2102 USB module. In phase 3, you'll read from the UART on the Pi to download a binary being sent via the UART on the CP2102 USB module.

The UART protocol has several configuration parameters, and both the receiver and transmitter need to be configured identically to communicate. These parameters are:

- **Data Size**: length of a single data frame (8 or 9 bits)
- **Parity Bit**: whether to send a parity (checksum) bit after the data
- **Stop Bits**: how many bits to use to signal the end of the data (1 or 2)
- **Baud Rate**: transmission rate in bits/second

The mini UART on the Pi does not support parity bits and only supports 1 stop bit. As such, only the baud rate and data frame length need to be configured. To learn more about UART, see the Basics of UART Communication article.

Implement the Driver

At this point, you have all of the tools to write a device driver without additional background information (congratulations! 🎉).

Implement the mini UART device driver in `lib/pi/src/uart.rs`. You'll need to complete the definition of the `Registers` structure. Ensure that you use the `Volatile` type with the *minimal set of capabilities* for each register: read-only registers should use `ReadVolatile`, write-only registers should use `WriteVolatile`, and reserved space should use `Reserved`. Then, initialize the device in `new()` by setting the baud rate to `115200` (a divider of `270`) and data length to `8` bits. Finally, implement the remaining `unimplemented!()` methods and the `fmt::Write`, `io::Read` and `io::Write` traits for `MiniUart`.

Hint

You'll need to write to the `LCR`, `BAUD`, and `CNTL` registers in `new`.

Hint

Use your GPIO driver from the previous subphase.

Testing Your Driver

Test your driver by writing a simple “echo” program in `kern/src/main.rs`: sit in a hot loop writing out every byte you read in. In pseudocode, this looks like:

```
loop {
  write_byte(read_byte())
}
```

Use `screen /dev/<your-path> 115200` to communicate over UART. `screen` sends every keypress over the TTY, so if your echo program works correctly, you’ll see every character you type. It might help to send an extra character or two each time you receive a byte to convince yourself things are working as you expect:

```
loop {
    write_byte(read_byte())
    write_str("<-")
}
```

Once your driver works as expected, proceed to the next subphase.

Subphase E: The Shell

In this subphase, you’ll use your new UART driver to implement a simple shell that will be the interface to your operating system. You will be working in `kern/src/console.rs`, `kern/src/shell.rs`, and `kernel/src/main.rs`.

The `Console`

To write our shell, we’ll need some notion of a global default input and output. Unix and friends typically refer to this is as `stdin` and `stdout`; we’ll be calling it `Console`. `Console` will allow us to implement the `kprint!` and `kprintln!` macros, our kernel-space versions of the familiar `print!` and `println!`, and give us a default source for reading user input. We’ll use `Console` and these macros to implement our shell.

Take a peek at `kernel/src/console.rs`. The file contains an unfinished implementation of the `Console` struct. `Console` is a *singleton* wrapper around a `MiniUart`: only one instance of `Console` will ever exist in our kernel. That instance will be globally available, for use anywhere and by anything. This will allow us to read and write to the mini UART without explicitly passing around an instance of `MiniUart` or `Console`.

Global Mutability

The notion of a globally mutable structure is a scary thought, especially in the face of Rust. After all, Rust doesn't allow more than one mutable reference to a value, so how can we possibly convince it to allow *as many as we want*? The trick, of course, relies on `unsafe`. The idea is as follows: we'll *tell* Rust that we're only going to read a value by using an immutable reference, but what we *actually* do is use `unsafe` to "cast" that immutable reference to a mutable reference. Because we can create as many immutable references as we want, Rust will be none the wiser, and we'll have all of the mutable references we desire!

Such a function might look like this:

```
// This function must never exist.
fn make_mut<T>(value: &T) -> &mut T {
    unsafe { /* magic */ }
}
```

Your alarm bells should be ringing: what we've proposed so far is wildly unsafe. Recall that we still need to ensure that everything we do in `unsafe` upholds Rust's rules. What we've proposed thus far clearly does not. As it stands, we're violating the "at most one mutable reference at a time" rule. The rule states that at any point in the program, a value should have at most one mutable reference to it.

The key insight to maintaining this rule while meeting our requirements is as follows: instead of the *compiler* checking the rule for us with its borrow and ownership checker, *we* will ensure that the rule is upheld *dynamically, at run-time*. As a result, we'll be able to share references to a structure as many times as we want (via an `&` reference) while also being able to safely retrieve a mutable reference when we need it (via our `&T -> &mut T` dynamic borrow checking function).

There are many concrete implementations of this idea. One such implementation ensures that only one mutable reference is returned at a time using a lock:

```
fn lock<T>(value: &T) -> Locked<&mut T> {
 unsafe { lock(value); cast value to Locked<&mut T> }
}

impl Drop for Locked<&mut T> {
 fn drop(&mut self) { unlock(self.value) }
}
```

This is known as Mutex in the standard library. Another way is to abort the program if more than one mutable reference is about to be created:

```
fn get_mut<T>(value: &T) -> Mut<&mut T> {
   unsafe {
      if ref_count(value) != 0 { panic!() }
      ref_count(value) += 1;
      cast value to Mut<&mut T>
   }
}

impl Drop for Mut<&mut T> {
   fn drop(&mut self) { ref_count(value) -= 1; }
}
```

This is RefCell::borrow_mut(). And yet another is to only return a mutable reference if it is known to be exclusive:

```
fn get_mut<T>(value: &T) -> Option<Mut<&mut T>> {
   unsafe {
      if ref_count(value) != 0 { None }
      else {
         ref_count(value) += 1;
         Some(cast value to Mut<&mut T>)
      }
   }
}

impl Drop for Mut<&mut T> {
   fn drop(&mut self) { ref_count(value) -= 1; }
}
```

This is RefCell::try_borrow_mut(). All of these examples implement some form of “interior mutability”: they allow a value to be mutated through an immutable reference. For our `Console`, we’ll be using `Mutex` to accomplish the same goal. Since the `std::Mutex` implementation requires operating system support, we’ve implemented our own `Mutex` in `kern/src/mutex.rs`. Our implementation is correct for now, but we’ll need to fix it when we introduce caching or concurrency to continue to uphold Rust’s rules. You don’t need to understand the `Mutex` implementation for now, but you should understand how to use one.

The global singleton is declared as `CONSOLE` in `kern/src/console.rs`. The global variable is used by the `kprint!` and `kprintln!` macros defined below below. Once you’ve implemented `Console`, you’ll be able to use `kprint!` and `kprintln!` to print to the console. You’ll also be able to use `CONSOLE` to globally access the console.

Rust also requires `static` globals to be `Sync`.

In order to store a value of type `T` in a `static` global, `T` must implement `Sync`. This is because Rust also guarantees data race safety at compile-time. Because global values can be accessed from any thread, Rust must ensure that those accesses are thread-safe. The `Send` and `Sync` traits, along with Rust's ownership system, ensure data race freedom.

❗ Why should we never return an `&mut T` directly? (drop-container)

You'll notice that every example we've provided wraps the mutable reference in a container and then implements `Drop` for that container. What would go wrong if we returned an `&mut T` directly instead?

❗ Where does the `write_fmt` call go? (write-fmt)

The `_print` helper function calls `write_fmt` on an instance of `MutexGuard<Console>`, the return value from `Mutex<Console>::lock()`. Which type will have its `write_fmt` method called, and where does the method implementation come from?

Implement and Test `Console`

implement all of the `unimplemented!()` methods in `kern/src/console.rs`. once you've implemented everything, use the `kprint!` and `kprintln!` macros in `kern/src/main.rs` to write to the console when you receive a character. you can use these macros exactly like `print!` and `println!`. use `screen /dev/<your-path> 115200` to communicate with your pi and ensure that your kernel works as expected.

❗ If this were C…

The fact that we get a `println!` implementation for free with zero effort is just another advantage to using Rust. If this were C, we'd need to implement `printf` ourselves. In Rust, the compiler provides a generic, abstracted, and safe OS-independent implementation. Whew!

❗ Hint

Your `Console` implementations should be very short: about a line each.

Implement the Shell

'Finished' Product

You're now ready to implement the shell in `kern/src/shell.rs`. We've provided a `Command` structure for your use. The `Command::parse()` method provides a simple command-line argument parser, returning a `Command` struct. The parse method splits the passed in string on spaces and stores all of the non-empty arguments in the `args` field as a `StackVec` using the passed in `buf` as storage. You must implement `Command::path()` yourself.

Use all of your available libraries (`Command`, `StackVec`, `Console` via `CONSOLE`, `kprint!`, `kprintln!`, and anything else!) to implement a shell in the `shell` function. Your shell should print the `prefix` string on each line it waits for input. In the GIF above, for instance, `"> "` is being used as the prefix. Your shell should then read a line of input from the user, parse the line into a command, and attempt to execute it. It should do this ad-infinitum. Since our operating system is only just beginning, we can't run any interesting commands just yet. We can, however, build known commands like `echo` into the shell.

To complete your implementation, your shell should…

- implement the `echo` built-in: `echo $a $b $c` should print `$a $b $c`
- accept both `\r` and `\n` as "enter", marking the end of a line
- accept both backspace and delete (ASCII `8` and `127`) to erase a single character
- ring the bell (ASCII `7`) if an unrecognized non-visible character is sent to it
- print `unknown command: $command` for an unknown command `$command`
- disallow backspacing through the prefix
- disallow typing more characters than allowed
- accept commands at most 512 bytes in length
- accept at most 64 arguments per command
- start a new line, without error, with the `prefix` if the user enters an empty command
- print `error: too many arguments` if the user passes in too many arguments

Test your implementation by calling your new `shell()` function in `kern/src/main.rs`. Minus the "SOS" banner, you should be able to replicate the GIF above. You should also be able to test all of the requirements we've set. Once your shell works as expected, revel in your accomplishments. Then, proceed to the next phase.

Hint

A byte literal, `b'a'` is the `u8` ASCII value for a character `'a'`.

Hint

Use `\u{b}` in a string literal to print any character with ASCII byte value `b`.

Hint

You must print both `\r` and `\n` to begin a new line at the line start.

Hint

To erase a character, backspace, print a space, then backspace again.

Hint

Use `StackVec` to buffer the user's input.

Hint

You'll find the core::str::from_utf8() function useful.

How does your shell tie the many pieces together? (shell-lookback)

Your shell makes use of much of the code you've written. Briefly explain: which pieces does it makes use of and in what way?

Phase 3: Boot 'em Up

In this phase, you'll use everything you've written thus far to implement a bootloader for your Raspberry Pi. You'll be working primarily in `boot/src/main.rs`.

You've likely become frustrated with the monotonous motions of swapping MicroSD cards to load a new binary onto your Pi. The bootloader you will write in this phase eliminates that process entirely. You'll replace the binary on the MicroSD *one more time*, this time with the bootloader. From then on, you can load new binaries remotely from your computer without ever touching the MicroSD card again.

The bootloader itself is a "kernel" of sorts that accepts XMODEM file transfers over UART. It writes the data received into memory at a known address and then executes it. We'll use our `ttywrite` utility to send it binaries. As a result, the process to load a new binary onto the Pi will be as simple as:

1. Resetting the Pi to start the bootloader.
2. Run `make transmit` command, which will build your kernel and transmit it with `ttywrite -i build/kern.bin /dev/ttyUSB0` command.

Loading Binaries

By default, the Raspberry Pi 3 loads files named `kernel8.img` at address `0x80000`. Said another way, the Pi will sequentially copy the contents of `kernel8.img` to `0x80000` and, after some initialization, set the ARM's program counter to `0x80000`. As a result, we must ensure that our binary expects to be loaded at this address. This means that all of the addresses in the binary should begin at `0x80000`.

Because the **linker** is what decides the addresses for all symbols in our binary, we must somehow inform the linker of this desire. To do this, we use a *linker script*: a file read by the linker that describes how we want it to assign addresses to symbols in our binary. Our kernel's linker script can be found in `kern/.cargo/layout.ld`. You'll notice the address `0x80000` on the second line. Indeed, this line instructs the linker to begin allocating addresses at `0x80000`.

To maintain compatibility with these defaults, our bootloader will *also* load binaries at address `0x80000`. But this raises an issue: if our bootloader's binary is at address `0x80000`, loading a different binary at the same address will result in overwriting our bootloader *as we're executing it!* To avoid this conflict, we **must** use different start addresses for the bootloader and the binaries it loads. We'd like to maintain compatibility with the Pi's defaults, so we'll need to change the start address of the bootloader. How?

Making Space

The first step is to choose a new address. As you can see in `boot/.cargo/layout.ld`, we've chosen `0x4000000` as the start address for our bootloader. While this fixes the addresses in the binary, the Pi will continue to load it at `0x80000`. Thankfully, we can ask the Pi to load our binary at a different address via a `kernel_address` parameter in the firmware's `config.txt`. Ensure you modify your `config.txt` in microSD to have `kernel_address=0x4000000` line.

As a result of this change, the memory between `0x80000` and `0x4000000` will be entirely unused by the bootloader, and we can load binaries up to `0x4000000 - 0x80000` bytes in size without conflict.

Is 63.5MiB really enough? (small-kernels)

You might be thinking that the free space we've set apart isn't enough. This is a fair concern. One way to answer the question is to look at the file size of kernels from successful operating systems. Would they fit?

Determine how large the kernel binary is for the operating system you're running now. On newer versions of macOS, the binary is `/System/Library/Kernels/kernel`. On older versions of macOS, the binary is `/mach_kernel`. On Linux, the binary is usually located in `/boot/` and is named either `vmlinuz`, `vmlinux`, or `bzImage`. How big is your kernel's binary? Would it fit in the 63.5MiB free space we've created?

Implement the Bootloader

Implement the bootloader in `boot/src/main.rs`. We've declared the bootloader's start address, the loaded binary's start address, and the maximum binary size in `const` declarations at the top of the file. We've also provided a `jump_to` function that unconditionally branches to the address `addr`. This has the effect of setting the program counter to that address. Your bootloader should use these declarations along with your existing code from the `pi` and `xmodem` libraries to receive a transmission over UART and write it to the memory address the binary expects to be loaded at. When the transmission is complete, your bootloader should execute the new binary.

Be aware that your bootloader should continuously attempt to initiate an XMODEM reception by setting a low timeout value (say, 750ms) and attempting a new reception if a timeout occurs. If a reception fails for any other reason, print an error message and try again. Once you've implemented the bootloader, test it by sending your kernel binary from `kern/build/kernel.bin` to your Pi using your `ttywrite` utility. If all is well, you should see your shell when you `screen` into your Pi.

Why is the timeout necessary? (bootloader-timeout)

Without the bootloader timing out and retrying a reception, it is possible for the transmitter to stall indefinitely under some conditions. What are those conditions, and why would the transmitter stall indefinitely?

`config.txt`

Remember to use the version of `config.txt` compatible with bootloader binaries!

Hint

Our reference `main()` function is 15 lines of code.

Hint

You'll find the core::slice::from_raw_parts_mut() function useful.

Hint

The `&mut [u8]` type implements `io::Write`.

Submission

Once you've completed the tasks above, you're done and ready to submit! Congratulations!

Ensure you've committed your changes. Any uncommitted changes *will not* be visible to us, thus unconsidered for grading.

Before submitting, check if you've answered every question and passed every unit tests for the libraries. Note that there are no unit tests for `pi` and `kernel`. You're responsible for ensuring that they work as expected.

When you're ready, push a commit to your GitHub repository with a tag named `lab2-done`.

```
# submit lab1
$ git tag lab2-done
$ git push --tags
```