Lab 3: FAT32 Filesystem

- **Handed out:** Tuesday, February 11, 2020
- **Due:** Monday, March 2, 2020

Introduction

In this assignment, you will enable the use of Rust's collections module (`Vec`, `String`, `HashMap`, and friends) by writing a memory allocator, implement the FAT32 file system, implement a Rust interface for a driver for the Raspberry Pi's EMMC (SD card controller), and extend your shell with `cd`, `ls`, `pwd`, and `cat`, commands.

Phase 0: Getting Started

Fetch the update for lab 3 from our git repository to your development machine.

```
$ git fetch skeleton
$ git merge skeleton/lab3
```

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
│    └── 3-fs : questions for lab3 *
├── boot : bootloader
├── kern : the main os kernel *
└── lib  : required libraries
     ├── fat32 *
     ├── pi *
     ├── shim
     ├── stack-vec
     ├── ttywrite
     ├── volatile
     └── xmodem
```

You may need to resolve conflicts before continuing. For example, if you see a message that looks like:

```
Auto-merging kern/src/main.rs
CONFLICT (content): Merge conflict in kern/src/main.rs
Automatic merge failed; fix conflicts and then commit the result.
```

You will need to manually modify the `main.rs` file to resolve the conflict. Ensure you keep all of your changes from lab 2. Once all conflicts are resolved, add the resolved files with `git add` and commit. For more information on resolving merge conflicts, see this tutorial on githowto.com.

`make transmit` command

Since you've finished writing the bootloader in the previous lab, you are ready to use the command `make transmit` that builds the kernel binary and calls `ttywrite` to send it to the Raspberry Pi for the bootloader to load. As a result, assuming the bootloader is installed as `kernel8.img`, you will be able to test new binaries simply by resetting your Raspberry Pi and running `make transmit`.

You should have installed `ttywrite` utility in the previous lab. If you didn't for some reason, install it now by running `cargo install --path .` in the `lib/ttywrite` directory. Ensure that the utility was properly installed by running `ttywrite --help`.

The `make transmit` target is configured to write to `/dev/ttyUSB0` by default. If your TTY device differs, modify the `TTY_PATH` declaration on line 7 of `kern/Makefile` appropriately.

Add your user to dialout group

If you are experiencing a permission issue when accessing the TTY, please try adding your user to the dialout group.

```
sudo usermod -a -G dialout $USER
sudo reboot
```

Compilation errors after merging lab3

We provide a template code for the final phase of lab3, which contains lots of uncompleted code. When you try to compile your code while working on this lab, you will see the compiler complains about some of the code you just merged. You can comment the offensive lines of the code until we fix them later. For instance, you may want to disable the file system component when working in phase 1. Make sure you only comment out minimum amount of the code!

The `ALLOCATOR.initialize()` call panics!

Your shell should continue to function as before. If you test the `make install` target now, however, you'll likely find that you shell appears to no longer work. The likely culprit is an `ALLOCATOR.initialize()` call preceding your `shell()` call. Because there is no memory allocator yet, the call will lead to a `panic!()`, halting your system without warning. We'll fix this soon. Feel free to comment out the line temporarily to ensure everything is working as expected.

Phase 1: Memory Lane

In this phase you will implement two memory allocators: a simple *bump* allocator and a more fully-featured *bin* allocator. These will immediately enable the use of heap allocating structures such as `Vec`, `Box`, and `String`. To determine the available memory on the system for allocation, you will read ARM tags (ATAGS). You will also implement the panic handler to properly handle `panic!` calls.

Subphase A: Panic!

In this subphase you will implement the panic handler. You will be working in `kern/src/init/panic.rs`.

Error Handling in Rust

Rust has two major categories of errors: *recoverable* and *unrecoverable*. Rust represents recoverable errors with `Result<T, E>` type. On the other hand, when a Rust program encounters an unrecoverable error, it stops the program execution altogether. This behavior is called `panic!` in Rust terminology.

When targeting standard operating systems, the Rust compiler will generate a program that prints the backtrace and sets the process exit code on panic. However, when the Rust compiler is instructed to compile a Rust program for a target without operating system support, such as we do for our Raspberry Pi, the compiler requires the manual implementation of the *panic handler*.

A panic handler is a function that is called when a `panic!` occurs. It has a type of `fn panic(info: PanicInfo) -> !`, which means it takes a PanicInfo as an argument and never returns. `PanicInfo` struct contains the information of the file name, line number, and column where the `panic!` occurred.

We’ve provided the panic handler that loops indefinitely in `kern/src/init/panic.rs`. You will extend this `panic` implementation so that it logs useful information to the console.

Implement the panic handler

Implement the `panic` function now. Your implementation should print the passed in information to the console and then allow the `loop` already in place to run. You’re free to implement the function as you like. As an example, our implementation takes inspiration from Linux kernel oops messages:

```
            (
       (      )     )
         )   (    (
        (          `
    .-""^"""^""^"""^""-.
  (//\\//\\//\\//\\//\\//)
   ~\^^^^^^^^^^^^^^^^^^^/~
     `================`

    The pi is overdone.

---------- PANIC ----------

FILE: src/kmain.rs
LINE: 40
COL: 5

index out of bounds: the len is 3 but the index is 4
```

Test your new `panic` implementation by having your kernel panic. Recall that you can use the new `make install` target to compile and send the kernel to your Raspberry Pi. Note that the `ALLOCATOR.initialize()` call already `panic!`s, so you shouldn’t need to make any changes. Ensure this function is called before your `shell()`.

Then, try making your kernel panic in other ways: a rogue `unwrap()`, an explicit `panic!()`, or an `unreachable!()`: ensure they all work as expected. When you’re satisfied with your implementation, continue to next the subphase.

Subphase B: ATAGS

In this subphase, you will implement an iterator over the ARM tags (ATAGS) loaded by the Raspberry Pi’s firmware. You will use your iterator to find the ATAG that specifies how much memory is available on the system. You will be working in the `lib/pi/src/atags` directory and `kern/src/allocator.rs`.

ARM Tags

ATAGS, or ARM tags, are a mechanism used by ARM bootloaders and firmware to pass information about the system to the kernel. Linux, for example, can use ATAGS when configured for the ARM architecture.

The Raspberry Pi places an array of ATAG structures at address 0x100. This is the structure of ATAGS, in Rust syntax:

```
#[repr(C)]
struct Atag {
    dwords: u32,
    tag: u32,
    kind: Kind
}
```

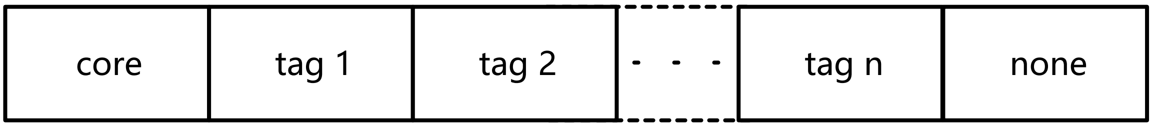
Each ATAG begins with an 8 byte header, `dwords` and `tag`. The `dwords` field specifies the size of the complete ATAG in *double words* (32-bit words) and includes the header. Thus the minimum size is `2`. The `tag` field specifies the *type* of the ATAG. There are 10 different types of specified tags, all documented in the ATAGS reference. The Raspberry Pi only makes use of four. These are documented below:

Name	Type (`tag`)	Size	Description
CORE	0x54410001	5 or 2 if empty	First tag used to start list
NONE	0x00000000	2	Empty tag used to end list
MEM	0x54410002	4	Describes a physical area of memory
CMDLINE	0x54410009	variable	Command line to pass to kernel

The type of tag determines how the data after the header should be interpreted. In our skeleton code, the data following the header is represented as a field named `kind` which is a union of different kind of tags. Clicking on the name of the tag in the table above directs you to the reference for that particular tag which includes the layout of the tag's data. The `MEM` tag data, for instance, is structured as below:

```
struct Mem {
    size: u32,
    start: u32
}
```

Tags are laid out sequentially in memory with zero padding between each tag. The first tag is specified to be a `CORE` tag while the final tag is indicated by the `NONE` tag. Other tags can appear in any order. The `dwords` field is used to determine the address of the adjacent ATAG. The diagram below depicts the general layout.



Unions & Safety

The raw ATAG data structures are declared in `lib/pi/src/atags/raw.rs`. The main declaration, copied below, makes use of a Rust `union`. Rust's unions are identical to C unions: they define a structure where all fields share common storage.

```
pub struct Atag {
    dwords: u32,
    tag: u32,
    kind: Kind
}

pub union Kind {
    core: Core,
    mem: Mem,
    cmd: Cmd
}
```

In effect, unions allow memory to be cast into arbitrary structures without regard for whether the cast is correct. As a result, accessing union fields in Rust is `unsafe`.

We've already handled most of the `unsafe` in the `atags` module for you, so you don't need to worry about handling unions yourself. Nonetheless, exposing unions to end-users of our `pi` library is a bad idea. Because of this, we've declared a *second* `Atag` structure in `lib/pi/src/atags/atag.rs`. This structure is entirely safe to use and access. This is the structure that the `pi` library will expose. When you finish the implementation of the `atag` module later in this subphase, you'll write conversions from the `raw` structures to the safe structures.

Why is it a bad idea to expose unions to end-users? (enduser-unsafe)

We're going through a lot of effort to expose a safe interface to unsafe data structures. You'll see this over and over again in Rust, with the standard library as a prime example. What benefit is there to exposing safe interfaces to unsafe structures or operations in Rust? Could we yield the same benefits in a language like C?

Command Line Arguments

The `CMDLINE` tag deserves special attention. Its declaration is:

```
struct Cmd {
    /// The first byte of the command line string.
    cmd: u8
}
```

As indicated by the comment, the `cmd` field holds the *first byte* of the command line string. In other words, `&cmd` is a pointer to a null-terminated, C-like string. The safe version of the `Cmd` tag is `Cmd(&'static str)`. When you write the conversion from the `raw` to safe version of the `Cmd` tag, you'll need to determine the size of the C-like string by searching for the null terminator in the string. You'll then need to cast the address and size into a slice using `slice::from_raw_parts()` and finally cast the slice into a string using `str::from_utf8()` or `str::from_utf8_unchecked()`. You used both of these functions before in lab 2.

Implement `atags`

You're ready to implement the `atags` module in `lib/pi/src/atags`. Start by implementing the `raw::Atag::next()` method in `atags/raw.rs`. The method determines the address of the ATAG following `self` and returns a reference to it. You'll need to use `unsafe` in your implementation. Then implement the helper methods and conversion traits from raw structures to safe structures in `atags/atag.rs`. You should only need to use `unsafe` when implementing `From<&'a raw::Cmd> for Atag`. Finally, finish the implementation of the `Iterator` trait for `Atags` in `atags/mod.rs`. This requires no `unsafe`.

Hint

You can convert from `x: &T` to `*const u32` using `x as *const T as *const u32`.

Hint

You can convert from `x: *const T` to `&T` using `&*x`. However, this conversion is **extremely** unsafe. Make sure that you don't violate the alias rule of Rust references.

Hint

You can perform pointer arithmetic with add(), sub(), or offset().

Testing `atags`

Test your implementation by running `cargo test` command in `lib/pi` directory. Then, test your ATAGS implementation with the RPi board by iterating over all of the ATAGS and debug printing them to your console in `kern/src/main.rs`. You should see at least one of each of the three non-`NONE` tags. Verify that the value of each ATAG matches your expectations. Once your implementation performs as expected, proceed to the next subphase.

Hint

The `{:#?}` format specifier prettifies the debug output of a structure.

What does the `CMDLINE` ATAG contain? (atag-cmdline)

What is the value of the command line string in the `CMDLINE` ATAG found on your Raspberry Pi? What do you think the parameters control?

How much memory is reported by the `MEM` tag? (atag-mem)

What is the exact start address and size of the available memory reported by the `MEM` ATAG? How close is this to the Raspberry Pi's purported 1GB of RAM?

Subphase C: Warming Up

In this subphase, we'll set the stage to write our two memory allocators in the next subphases. You'll implement two utility functions, `align_up` and `align_down`, that align addresses to a power of two. You'll also implement the `memory_map` function that returns the start and end address of the available memory on the system. Your `memory_map` function will be used by both memory allocators to determine the available memory for allocation.

Alignment

A memory address is *n-byte aligned* if it is a multiple of `n`. Said another way, a memory address `k` is *n-byte aligned* if `k % n == 0`. We don't *usually* need to be concerned about the alignment of our memory addresses, but as budding system's programmers, we do! This is because hardware, protocols, and other external forces enjoin alignment properties. For example, the ARM 32-bit architecture requires the stack pointer to be 8-byte aligned. The AArch64 architecture, our operating system's architecture of choice, requires the stack pointer to be 16-byte aligned; x86-64 requires the same alignment. Page addresses used for virtual memory typically need to be 4k-byte aligned. And there are many more examples, but it suffices to say that alignment of memory addresses is important.

In C, the alignment of a memory address returned from a libC allocator is guaranteed to be 8-byte aligned on 32-bit systems and 16-byte aligned on 64-bit systems. Beyond this, the caller has no control over the alignment of the returned memory address and must fend for themselves (POSIX functions like `posix_memalign` later corrected for this).

Why did C choose these alignments? (libc-align)

The choice to guarantee 8 or 16-byte alignment from libC's `malloc` is not without reason. Why did libC choose these particular alignment guarantees?

Recall the signatures for `malloc()` and `free()` in C:

```
void *malloc(size_t size);

void free(void *pointer);
```

In contrast, Rust's low-level, unsafe `alloc` and `dealloc` methods in `GlobalAlloc` trait have the following signatures:

```
// `layout.size()` is the requested size, `layout.align()` the requested alignment
unsafe fn alloc(&self, layout: Layout) -> *mut u8;

// `layout` should be the same as was used for the call that returned `ptr`
unsafe fn dealloc(&self, ptr: *mut u8, layout: Layout)
```

Note that the caller can specify the alignment with the layout argument, which is defined by two parameters, `size` and `align`. As a result, the onus is on the allocator, *not* the caller, to return a properly aligned memory address. When you implement memory allocators in the next phase, you'll need to ensure that the address you return satisfies the condition specified by the layout parameter.

The second thing to note is that the `dealloc` function, analogous to C's `free`, requires the caller to pass in the `Layout` used for the original call to `alloc`. As a result, the onus is on the caller, *not* the allocator, to remember the requested size and alignment of an allocation.

Size and alignment guarantee in Rust

In Rust, all layouts must have non-negative size and a power-of-two alignment; These conditions are checked when a layout is created.

Why do you think Rust split responsibilities in this way? (onus)

In C, the allocator has fewer restrictions on the alignment of memory addresses it returns but must record the size of an allocation for later use. The inverse is true in Rust. Why do you think Rust chose the opposite path here? What advantages does it have for the allocator and for the caller?

Utilities: `align_up` and `align_down`

When you implement your allocators in the next subphases, you'll find it useful to, given a memory address `u`, be able to determine the first address `>=` or `<=` `u` that is aligned to a power of two. The (unimplemented) `align_up` and `align_down` functions in `kernel/src/allocator/util.rs` do exactly this:

```
/// Align `addr` downwards to the nearest multiple of `align`.
/// Panics if `align` is not a power of 2.
fn align_down(addr: usize, align: usize) -> usize;

/// Align `addr` upwards to the nearest multiple of `align`.
/// Panics if `align` is not a power of 2
/// or aligning up overflows the address.
fn align_up(addr: usize, align: usize) -> usize;
```

Implement these functions now. You can unit test your implementations by calling `make test` or `cargo test` in the `kernel` directory. This will run the tests in `kern/src/allocator/tests.rs`. All of the `align_util` unit tests should pass.

Testing

During testing, calls to `kprint{ln}!` become calls to `print{ln}!`.

Thread Safety

Memory allocators like libC's `malloc()` and the two you will soon implement are *global*: they can be called by any thread at any point in time. As such, the allocator needs to be *thread safe*, and that's why `alloc()` and `dealloc()` method take shared (aliasable) reference `&self`, like other synchronization primitives such as Mutex and RwLock. Rust takes thread safety very seriously, and so it is difficult to implement an allocator that isn't thread-safe even if our system doesn't have any concurrency mechanisms like threads just yet.

The topic of thread-safe memory allocators is extensive, and many research papers have been published on exactly this topic. To avoid a deep tangent, we'll ignore the topic altogether and wrap our allocator in a `Mutex` ensuring that it is thread-safe by virtue of exclusion. We've provided the code that will wrap your allocators in `kern/src/allocator.rs`. Read through the code now. Notice how it implements Rust's GlobalAlloc trait; this is how Rust knows that it is a valid allocator. An implementation of this trait is required to register an instance of the struct as a `#[global_allocator]`, which we've done for you in `main.rs`. Once an instance is registered via the `#[global_allocator]` annotation, we can use structures like `Vec`, `String`, and `Box` via the alloc crate and Rust will forward the `alloc()` and `dealloc()` calls to our registered instance.

Utility: `memory_map`

The final item in the `kern/src/allocator.rs` file is the `memory_map` function. This function is called by the `Allocator::initialize()` method which in-turn is called in `kmain()`. The `initialize()` method constructs an instance of the internal `imp::Allocator` structure for use in later allocations and deallocations.

The `memory_map` function is responsible for returning the start and end address of all of the *free* memory on the system. Note that the amount of *free* memory is unlikely to be equal to the *total* amount of memory on the system, the latter of which is identified by ATAGS. This is because memory is already being used by data like the kernel's binary. `memory_map` should take care not to mark used memory as free. To assist you with this, we've declared the `binary_end` variable which holds the first address after the kernel's binary.

Implement the `memory_map` function now by using your `Atags` implementation from Subphase B and the `binary_end` variable. Ensure that the function returns the expected values. Then add a call to `String::from("Hi!")` (or any other allocating call) and ensure that a `panic!()` occurs because of an unimplemented bump allocator. If `memory_map()` returns what you expect and a call to `AllocatorImpl::new()` panics because the bump allocator hasn't been implemented yet, proceed to the next subphase.

Subphase D: Bump Allocator

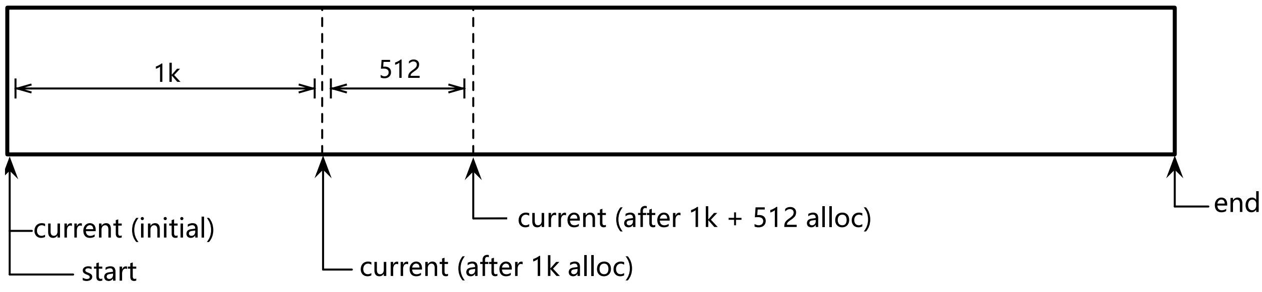
In this subphase, you will implement the simplest of allocators: the *bump* allocator. You will be working in `kern/src/allocator/bump.rs`.

Switching Implementations

The `GlobalAlloc` implementation for `Allocator` in `kernel/src/allocator.rs` simply forwards calls to an internal `AllocatorImpl` after taking a lock. We'll start with the `bump::Allocator` in `bump.rs` and later switch to the `bin::Allocator` in `bin.rs`.

A bump allocator works like this: on `alloc`, the allocator returns a `current` pointer, modified as necessary to guarantee the requested alignment, and *bumps* the `current` pointer up by the size of the requested allocation plus whatever was necessary to fulfill the alignment request. If the allocator runs out of memory, it returns an error. On `dealloc`, the allocator does nothing.

The diagram below depicts what happens to the `current` pointer after a `1k` byte allocation and a subsequent `512` byte allocation. Note that alignment concerns are absent in the diagram.



Your task is to implement a bump allocator in `kernel/src/allocator/bump.rs`. In particular, implement the `new()`, `alloc()`, and `dealloc()` methods of `bump::Allocator`. Use your `align_up` and `align_down` utility functions as necessary to guarantee the proper alignment of the returned addresses. We've provided unit tests that check the basic correctness of your implementation. You can run them with `make test` or `cargo test` in the `kernel` directory. You should pass all of the `allocator::bump_` unit tests.

Ensure that you don't perform any potentially overflowing operations!

Use the saturating_add and saturating_sub methods as necessary to prevent arithmetic overflow.

Once all of the unit tests pass, try allocating memory in `kmain()` to "see" your allocator in action. Here's a simple test:

```
use alloc::vec::Vec;

let mut v = Vec::new();
for i in 0..50 {
    v.push(i);
    kprintln!("{:?}", v);
}
```

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

What does the `alloc` call chain look like? (bump-chain)

If you paused execution when `bump::Allocator::alloc()` gets called, what would the backtrace look like? Asked another way: explain in detail how a call like `v.push(i)` leads to a call to your `bump::Allocator::alloc()` method.

Subphase E: Bin Allocator

In this subphase, you will implement a more complete allocator: the *bin* allocator. You will be working in `kern/src/allocator/bin.rs`.

A bin allocator segments memory allocations into size *classes*, or *bins*. The specific size classes are decided arbitrarily by the allocator. Each bin holds a linked-list of pointers to memory of the bin's size class. Allocations are rounded up to the nearest bin: if there is an item in the bin's linked list, it is popped and returned. If there is no free memory in that bin, new memory is allocated from the global pool and returned. Deallocation pushes an item to the linked list in the corresponding bin.

One popular approach is to divide bins into powers of two. For example, an allocator might choose to divide memory allocations into `k - 2` bins with sizes `2^n` for `n` from `3` to `k` (`2^3`, `2^4`, …, `2^k`). Any allocation or deallocation request for less than or equal to `2^3` bytes would be handled by the `2^3` bin, requests between `2^3` and `2^4` bytes from the `2^4` bin, and so on:

- bin 0 (`2^3` bytes): handles allocations in `(0, 2^3]`
- bin 1 (`2^4` bytes): handles allocations in `(2^3, 2^4]`
- …
- bin 29 (`2^32` bytes): handles allocations in `(2^31, 2^32]`

Linked List

We've provided an implementation of an *intrusive* linked list of memory addresses in `kern/src/allocator/linked_list.rs`. We've also imported the `LinkedList` struct in `kern/src/allocator/bin.rs`.

What's an *instrusive* linked list?

In an intrusive linked list, `next` and `previous` pointers, if any, are stored in the `push`ed items themselves. An intrusive linked list requires no additional memory, beyond the item, to manage an item. On the other hand, the user must provide valid storage in the item for these pointers.

A new, empty list is created using `LinkedList::new()`. A new address can be prepended to the list using `push()`. The first address in the list, if any, can be removed and returned using `pop()` or returned (but not removed) using `peek()`:

```
let mut list = LinkedList::new();
unsafe {
    list.push(address_1);
    list.push(address_2);
}

assert_eq!(list.peek(), Some(address_2));
assert_eq!(list.pop(), Some(address_2));
assert_eq!(list.pop(), Some(address_1));
assert_eq!(list.pop(), None);
```

`LinkedList` exposes two iterators. The first, obtained via `iter()`, iterates over all of the addresses in the list. The second, returned from `iter_mut()`, returns `Node`s that refer to each address in the list. The `value()` and `pop()` methods of `Node` can be used to read the value or pop the value from the list, respectively.

```
let mut list = LinkedList::new();
unsafe {
    list.push(address_1);
    list.push(address_2);
    list.push(address_3);
}

for node in list.iter_mut() {
    if node.value() == address_2 {
        node.pop();
    }
}

assert_eq!(list.pop(), Some(address_3));
assert_eq!(list.pop(), Some(address_1));
assert_eq!(list.pop(), None);
```

Read through the code for `LinkedList` now. Pay special attention to the safety properties required to call `push()` safely. You'll likely want to use `LinkedList` to manage the bins in your memory allocator.

❗ Why is it convenient to use an intrusive linked list? (ll-alloc)

Using an *intrusive* linked list for our memory allocators turns out to be a very convenient decision. What issues would arise if we had instead decided to use a regular, allocate-additional-memory-on-push, linked list?

Fragmentation

The concept of *fragmentation* refers to memory that is unused but unallocatable. An allocator incurs or creates *high fragmentation* if it creates a lot of unusable memory throughout the course of handling allocations. An *ideal* allocator has zero fragmentation: it never uses more memory than necessary to handle a request and it can always use available memory to handle new requests. In practice, this is neither desired nor achievable given other design constraints. But striving for low fragmentation is a key quality of good memory allocators.

We typically define two kinds of fragmentation:

- **internal fragmentation**

  The amount of memory wasted by an allocator to due to rounding up allocations. For a bin allocator, this is the difference between a request's allocation size and the size class of the bin it is handled from.

- **external fragmentation**

  The amount of memory wasted by an allocator due to being unable to use free memory for new allocations. For a bin allocator, this is equivalent to the amount of free space in every bin that can't be used to handle an allocation for a larger request even though the sum of all of the free space meets or exceeds the requested size.

Your allocator should try to keep fragmentation down within reason.

Implementation

Implement a bin allocator in `kern/src/allocator/bin.rs`. Besides being a bin-like allocator, the design of the allocator is entirely up to you. The allocator *must* be able to reuse freed memory. The allocator must also not incur excessive internal or external fragmentation. Our unit tests, which you can run with `make test` to check these properties. Remember to change `AllocatorImpl` to `bin::Allocator` in `kern/src/allocator.rs` so that your bin allocator is used for global allocations.

Once your allocator passes all tests and is set as the global allocator, proceed to the next phase.

❗ What does your allocator look like? (bin-about)

Briefly explain the design of your allocator. In particular answer the following questions:

- Which size classes did you choose and why?
- How does your allocator handle alignment?
- What are the bounds on internal and external fragmentation for your design choices?

❗ How could you decrease your allocator's fragmentation? (bin-frag)

Your allocator probably creates more fragmentation that it needs to, and that's okay! How could you do better? Sketch (only in writing) two brief design ideas for improving your allocator's fragmentation.

Phase 2: 32-bit Lipids

In this phase, you will implement a read-only FAT32 file system. You will be working primarily in the `lib/fat32` directory.

Disks and File Systems

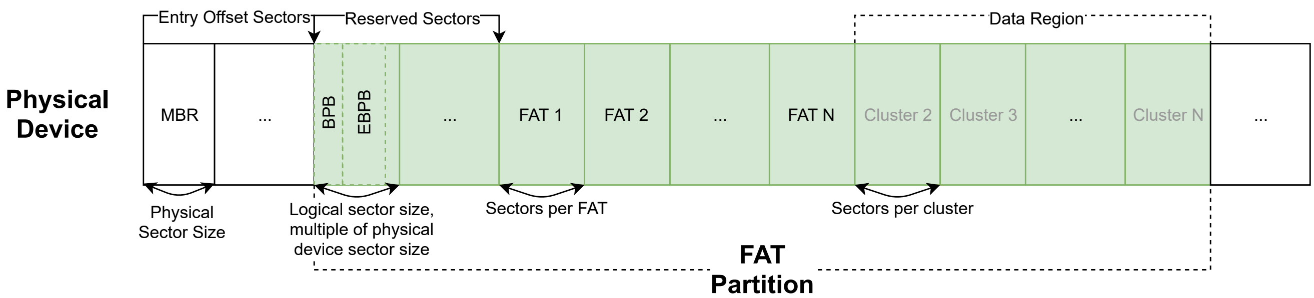
Data on a disk is managed by one or more file systems. Much like a memory allocator, a file system is responsible for managing, allocating, and deallocating free disk space. Unlike the memory managed by an allocator, the disk is *persistent*: barring disk failure, a write to allocated disk space is visible at any point in the future, including after machine reboots. Common file systems include EXT4 on Linux, HFS+ and APFS on macOS, and NTFS on Windows. FAT32 is another file system that is implemented by most operating systems, including Linux, macOS, and Windows, and was used in older versions of Windows and later versions of DOS. Its main advantage is its ubiquity: no other file system sees such cross-platform support.

To allow more than one file system to reside on a physical disk, a disk can be *partitioned*. Each partition can *formatted* for a different file system. To partition the disk, a table is written out to a known location on the disk that indicates where each partition begins and ends and the type of file system the partition uses. One commonly used partitioning scheme uses a master boot record, or MBR, that contains a table of four partition entries, each potentially unused, marking the start and size of a partition. GPT is a more modern partitioning scheme that, among other things, allows for more than four partitions.

In this assignment you will be writing the code to interpret an MBR partitioned disk that includes a FAT32 partition. This is the combination used by the Raspberry Pi: the SD card uses the MBR scheme with one partition formatted to FAT32.

Disk Layout

The following diagram shows the physical layout of an MBR-partitioned disk with a FAT32 file system:



The FAT structures PDF contains the specific details about all of these structures including their sizes, field locations, and field descriptions. You will be referring to this document when you implement your file system. You may also find the FAT32 design Wikipedia entry useful while implementing your file system.

Master Boot Record

The MBR is always located on sector 0 of the disk. The MBR contains four partition entries, each indicating the partition type (the file system on the partition), the offset in sectors of the partition from the start of the disk, and a boot/active indicator that dictates whether the partition is being used by a bootable system. Note that the CHS (cylinder, header, sector) fields are typically ignored by modern implementations; your should ignore these fields as well. FAT32 partitions have a partition type of `0xB` or `0xC`.

Extended Bios Parameter Block

The first sector of a FAT32 partition contains the extended BIOS parameter block, or EBPB. The EBPB itself starts with a BIOS parameter block, or BPB. Together, these structures define the layout of the FAT file system.

One particularly important field in the EBPB indicates the "number of reserved sectors". This is an offset from the start of the FAT32 partition, in sectors, where the FATs (described next) can be found. Immediately after the last FAT is the *data region* which holds the data for *clusters*. FATs, the data region, and clusters are explained next.

Clusters

All data stored in a FAT file system in separated into *clusters*. The size of a cluster is determined by the "number of sectors per cluster" field of the EBPB. Clusters are numbered starting at 2. As seen in the diagram, the data for cluster 2 is located at the start of the data region, the data for cluster 3 is located immediately after cluster 2, and so on.

File Allocation Table

FAT stands for "file allocation table". As the name implies, a FAT is a table (an array) of FAT entries. In FAT32, each entry is 32-bits wide; this is where the name comes from. The size of a complete FAT is determined by the "sectors per FAT" and "bytes per sectors" fields of the EBPB. For redundancy, there can be more than one FAT in a FAT32 file system. The number of FATs is determined by a field of the same name in the EBPB.

Besides entries 0 and 1, each entry in the FAT determines the *status* of a cluster. Entry 2 determines the status of cluster 2, entry 3 the status of cluster 3, and so on. Every cluster has an associated FAT entry in the FAT.

FAT entries 0 and 1 are special:

- **Entry 0**: `0xFFFFFFFN`, an ID.
- **Entry 1**: The *end of chain* marker.

Aside from these two entries, all other entries correspond to a cluster whose data is in the data region. While FAT entries are physically 32-bits wide, only 28-bits are actually used; the upper 4 bits are ignored. The value is one of:

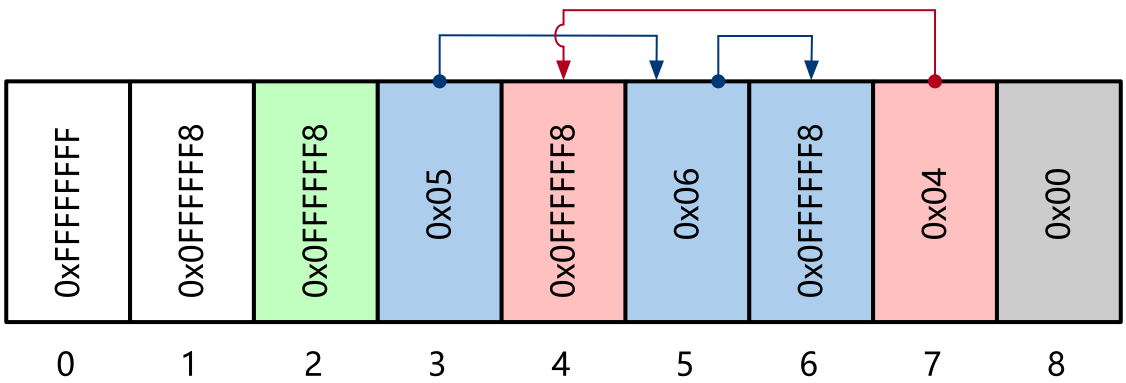
- `0x?0000000`: A free, unused cluster.
- `0x?0000001`: Reserved.

- `0x?0000002` - `0x?FFFFFEF` : A data cluster; value points to next cluster in chain.
- `0x?FFFFFF0` - `0x?FFFFFF6` : Reserved.
- `0x?FFFFFF7` : Bad sector in cluster or reserved cluster.
- `0x?FFFFFF8` - `0x?FFFFFFF` : Last cluster in chain. Should be, but may not be, the EOC marker.

Cluster Chains

Clusters form *chains*, or linked lists of clusters. If a cluster is being used for data, its corresponding FAT entry value either points to the next cluster in the chain or is the EOC marker indicating it is the final cluster in the chain.

As an example, consider the diagram below which depicts a FAT with 8 entries.



The clusters are color coded to indicate which chain they belong to. The first two entries are the ID and EOC marker, respectively. Entry 2 indicates that cluster 2 is a data cluster; its chain is 1 cluster long. Entry 3 indicates that cluster 3 is a data cluster; the next cluster in the chain is cluster 5 followed by the final cluster in the chain, cluster 6. Similarly, clusters 7 and 5 form a chain. Cluster 8 is free and unused.

Directories and Entries

A chain of clusters makes up the data for a file or directory. *Directories* are special files that map file names and associated metadata to the starting cluster for a file's date. Specifically, a directory is an array of directory entries. Each entry indicates, among other things, the name of the entry, whether the entry is a file or directory, and its starting cluster.

The root directory is the only file or directory that is not linked to via a directory entry. The starting cluster for the root directory is instead recorded in the EBPB. From there, the location of all other files can be determined.

For historical reasons, every physical directory entry can be interpreted in two different ways. The attributes field of an entry is overloaded to indicate which way an entry should be interpreted. An entry is either:

- A regular directory entry.

- A *long file name* entry.

Long file name (LFN) entries were added to FAT32 to allow for filenames greater than 11 characters in length. If an entry has a name greater than 11 characters in length, then its regular directory entry is preceded by as many LFN entries as needed to store the bytes for the entry's name. LFN entries are not ordered physically. Instead, they contain a field that indicates their sequence. As such, you cannot rely on the physical order of LFN entries to determine how the individual components are joined together.

Wrap Up

Before continuing, cross-reference your understanding with the FAT structures PDF. Then, answer the following questions:

How do you determine if the first sector is an MBR? (mbr-magic)

The first sector of a disk may not necessarily contain an MBR. How would you determine if the first sector contains a valid MBR?

What is the maximum number of FAT32 clusters? (max-clusters)

The FAT32 design enjoins several file limitations. What is the maximum number of clusters that a FAT32 file system can contain, and what dictates this limitation? Would you expect this limitation to be the same or different in a file system named FAT16?

What is the maximum size of one file? (max-file-size)

Is there a limit to the size of a file? If so, what is the maximum size, in bytes, of a file, and what determines it?

> **Hint**
>
> Take a close look at the structure of a directory entry.

How do you determine if an entry is an LFN? (lfn-identity)

Given the bytes for a directory entry, how, precisely, do you determine whether the entry is an LFN entry or a regular directory entry? Be specific about which bytes you read and what their values should be.

How would you lookup `/a/b/c.txt`? (manual-lookup)

Given an EBPB, describe the series of steps you would take to find the starting cluster for the file `/a/b/c.txt`.

Code Structure

Writing a file system of any kind is a serious undertaking, and a read-only FAT32 file system is no exception. The code that we've provided for you in the `lib/fat32` project provides a basic structure for implementation, but many of the design decisions and the majority of the implementation are up to you.

We'll describe this structure now. You should read the relevant code in the `fat32/src` directory as we describe the various components and how they fit together.

File System Traits

The `traits` module, rooted at `traits/mod.rs`, provides **7** trait declarations and **1** struct declaration. Your file system implementation will largely be centered on implementing these seven traits.

The single struct, `Dummy`, is a type that provides a dummy implementation of five of the seven traits. The type is useful as a place-holder. You'll see that we've used this type already in several places in the code. You may find this type useful while you work on the assignment as well.

You should read the code in the `traits/` directory in the following order:

- **Read the `BlockDevice` trait documentation in `traits/block_device.rs`.**

  The file system will be written generic to the physical or virtual backing storage. In other words, the file system will work on *any* device as long as the device implements the `BlockDevice` trait. When we test your file system, the `BlockDevice` will generally be backed by a file on your local file system. When your run the file system on the Raspberry Pi, the `BlockDevice` will be backed by a physical SD card and EMMC controller.

- **Read the `File`, `Dir`, and `Entry` traits in `traits/fs.rs`.**

  These traits define what it (minimally) means to be a file, directory, or directory entry in the file system. You'll notice that the associated types of the trait depend on each other. For example, the `Entry` trait requires its associated type `File` to implement the `File` trait.

- **Read the `FileSystem` traits in `traits/fs.rs`.**

  This trait defines what it means to be a file system and unifies the rest of the traits through its associated types. In particular, it requires a `File` that implements the `File` trait, a `Dir` that implements the `Dir` trait whose `Entry` associated type is the same as the associated type of file system's `Entry` associated type, and finally an

`Entry` associated type that implements `Entry` with the same `File` and `Dir` associated types as the file system. These constraints together ensure that there is only one concrete `File`, `Dir`, and `Entry` type.

- **Read the `Metadata` and `Timestamp` traits in `traits/metadata.rs`.**

  Every `Entry` must be associated with `Metadata` which allows access to details about a file or directory. The `Timestamp` trait defines the operations requires by a type that specifies a point in time.

Cached Partition

`CachedPartition` struct in `vfat/cache.rs` wraps `BlockDevice` and `Partition` and translates logical sectors, as specified by the EBPB, to physical sectors, as specified by the disk. We have provided an implementation of a method that does exactly this: `virtual_to_physical()`. You should use this method when determining which physical sectors to read from the disk. `CachedPartition` also provides a caching layer, which reduces the expensive cost of direct access to a physical disk. The `get()` and `get_mut()` methods of it allow for a sector to be referenced from the cache directly.

Actual disk cache implementations in commodity operating systems manage the disk cache very smartly. They predict the disk access pattern and preload disk contents, and they write the cache back to the disk if it is not accessed recently. For simplicity, our implementation will not implement such features. It will hold the disk content in the memory indefinitely.

Utilities

The `util.rs` file contains two declarations and implementations of *extension traits* for slices (`&[T]`) and vectors (`Vec<T>`). These traits can be used to cast a vector or slice of one type into a vector or slice of another type as long as certain conditions hold on the two types. For instance, to cast from an `&[u32]` to an `&[u8]`, you might write:

```
use util::SliceExt;

let x: &[u32] = &[1, 2, 3, 4];
assert_eq!(x.len(), 4);

let y: &[u8] = unsafe { x.cast() };
assert_eq!(y.len(), 16);
```

MBR and EBPB

The `MasterBootRecord` structure in `mbr.rs` is responsible for reading and parsing an MBR from a `BlockDevice`. Similarly, the `BiosParameterBlock` structure in `vfat/ebpb.rs` is responsible for reading and parsing the BPB and EBPB of a FAT32 partition.

Filesystem

The `vfat/vfat.rs` file contains the `VFat` structure, the file system itself. You'll note that the structure contains a `CachedPartition`: your implementation must wrap the provided `BlockDevice` in a `CachedPartition`.

> **What is VFAT?**
>
> VFAT is another file system from Microsoft that is a precursor to FAT32. The name has unfortunately become synonymous with FAT32, and we continue this poor tradition here.

The `vfat/vfat.rs` file also provides `VFatHandle` trait, which defines a way to share mutable access to `VFat` instance in a thread-safe way. When implementing your file system, you'll likely need to share mutable access to the file system itself among your file and directory structures. You'll rely on this trait to do so. Use `clone()` method for replicating the handle and `lock()` method for entering the critical section where the code can access `&mut VFat`.

`VFat` and a few other types in our file system such as `File` and `Dir` are generic over `HANDLE` type parameter that implements `VFatHandle` trait. This design allows the user of the library to *inject* lock implementation by implementing `VFatHandle` trait on their own type. Our kernel uses `PiVFatHandle` struct which internally uses its custom `Mutex` implementation, while the test code uses `StdVFatHandle` struct which is implemented with types in the standard library.

`VFat` is generic over `VFatHandle`, but `VFat` doesn't physically own `VFatHandle`. The relationship is reverse; implementors of `VFatHandle` will manage `VFat` as their field. To represent such relationship, zero-sized marker type PhantomData has been added to `VFat`.

We've started an implementation of the `FileSystem` trait for `&'a HANDLE` already. You'll also note that the `from()` method of `FileSystem` returns a `HANDLE`. Your main task will be to complete the implementation of the `from()` method and of the `FileSystem` trait for `&'a HANDLE`. This will require you to implement structures that implement the remainder of the file system traits.

We've provided the following code in `vfat/` to assist you with this:

- `error.rs`

  Contains an `Error` enum indicating the possible FAT32 initialization errors.

- `file.rs`

  Contains an incomplete `File` struct with an incomplete `traits::File` implementation.

- `dir.rs`

  Contains an incomplete `Dir` struct which you will implement `trait::Dir` for. Also contains incomplete definitions for raw, on-disk directory entry structures.

- `entry.rs`

  Contains an incomplete `Entry` struct which you will implement `traits::Entry` for.

- `metadata.rs`

  Contains structures (`Date`, `Time`, `Attributes`) that map to raw, on-disk entry metadata as well as incomplete structures (`Timestamp`, `Metadata`) which you should implement the appropriate file system traits for.

- `fat.rs`

  Contains the `FatEntry` structure which wraps a value for a FAT entry and which can be used to easily read the status of the cluster corresponding to the FAT entry.

- `cluster.rs`

  Contains the `Cluster` structure which wraps a raw cluster number and can be used to read the logical cluster number.

When you implement your file system, you should complete and use each of these structures and types. Don't be afraid to add extra helper methods to any of these structure. Do not, however, change any of the trait definitions or existing method signatures that we have provided for you.

Read through all of the code now, starting with `vfat.rs`, and ensure you understand how everything fits together.

Implementation

You're now ready to implement a read-only FAT32 file system. You may approach the implementation in any order you see fit.

We have provided a somewhat rigorous set of tests to check your implementation. Our tests use files in `ext/fat32-imgs`. In this directory you will find several real MBR, EBPB, and FAT32 file system images as well as hash values for file system traversals as run against our reference implementation. You may find it useful to analyze and check your understanding again the raw binaries by using a hex editor such as **Bless** (Linux), **Hex Fiend** (macOS), or **HxD** (Windows).

❗ Extract Fat32 test images first!

> The images we provided in `ext/fat32-imgs` are compressed. You need to un-archive them first before testing. You can use `bin/extract-fat.sh` to do that for you.

You can run the tests with `cargo test`. While debugging, you may wish to run the tests with `cargo test -- --nocapture` to prevent Cargo from capturing output to `stdout` or `stderr`. You may also find it useful to add new tests as you progress. To prevent future merge conflicts, you should add new tests in a file different from `tests.rs`.

Your implementation should adhere to the following guidelines:

- **Use meaningful types where you can.**

  For instance, instead of using a `u16` to represent a raw time field, use the `Time` struct.

- **Avoid `unsafe` code as much as possible.**

  Our implementation uses a total of four non-`union` lines of `unsafe`. Additionally, our implementation uses three lines of `unsafe` related to accessing unions. The number of `unsafe` code in your implementation should be comparable to this.

- **Avoid duplication by using helpers methods as necessary.**

  It's often useful to abstract common behavior into helper methods. You should do so when it makes sense.

- **Ensure your implementation is cluster size and sector size agnostic.**

  Do not hard-code or assume any particular values for sector sizes or cluster sizes. Your implementation *must* function with any cluster and sector sizes that are integer multiples of 512 as recorded in the EBPB.

- **Don't double buffer unnecessarily.**

  Ensure that you don't read a sector into memory that is already held in the sector cache to conserve memory.

Our recommended implementation approach is as follows:

1. **Implement MBR parsing in `mbr.rs`.**

   Your implementation will likely require the use of an `unsafe` method, but no more than one line. Possible candidates are slice::from_raw_parts_mut() or mem::transmute(). `mem::transmute()` is an incredibly powerful method. You should avoid it if you can. Otherwise, you should understand its implications thoroughly before using it.

When you implement `Debug`, use the debug_struct() method on `Formatter`. You can use the `Debug` implementation we have provided for `CachedPartition` as a reference.

> **Packed struct in Rust**
>
> Rust is very strict about the address alignment. All Rust references should respect the alignment of the underlying type. Because of this requirement, borrowing a field of a packed struct is sometimes illegal. You can workaround this limitation by copying the value to a temporary variable and borrowing the local variable with a syntax `&{ struct.field }`.

2. **Implement EBPB parsing in `vfat/ebpb.rs`.**

   As with the MBR, your implementation will likely require the use of an `unsafe` method, but no more than one line.

3. **Test your MBR and EBPB implementation.**

   Mock-up MBRs and EBPBs and ensure that you parse the values successfully. Note that we have provided an implementation of `BlockDevice` for `Cursor<&mut [u8]>`. Remember that you can pretty-print a structure using:

   ```
   println!("{:#?}", x);
   ```

4. **Implement `CachedPartition` in `vfat/cache.rs`.**

5. **Implement `VFat::from()` in `vfat/vfat.rs`.**

   Use your `MasterBootRecord`, `BiosParameterBlock`, and `CachedPartition` implementations to implement `VFat::from()`. Test your implementation as you did your MBR and EBPB implementations.

6. **Implement `FatEntry` in `vfat/fat.rs`.**

7. **Implement `VFat::fat_entry`, `VFat::read_cluster()`, and `VFat::read_chain()`.**

   These helpers methods abstract reading from a `Cluster` or a chain starting from a `Cluster` into a buffer. You'll likely need other helper methods, like one to calculate the disk sector from a cluster number, to implement these methods. You may wish to add helper methods to the `Cluster` type. You should use the `VFat::fat_entry()` method when implementing `read_cluster()` and `read_chain()`.

8. **Complete the `vfat/metadata.rs` file.**

The `Date`, `Time`, and `Attributes` types should map directly to fields in the on-disk directory entry. Refer to the FAT structures PDF when implementing them. The `Timestamp` and `Metadata` types do not have an analogous on-disk structure, but they serve as nicer abstractions over the raw, on-disk structures and will be useful when implementing the `Entry`, `File`, and `Dir` traits.

9. **Implement `Dir` in `vfat/dir.rs` and `Entry` in `vfat/entry.rs`.**

   Start by adding fields that store the directory's first `Cluster` and a file system handle to `Dir`. Then implement the `trait::Dir` trait for `Dir`. You may wish to provide dummy trait implementations for the `File` type in `vfat/file.rs` while implementing `Dir`. You'll want to create a secondary struct that implements `Iterator<Item = Entry>` and return this struct from your `entries()` method. You will likely need to use at-most one line of `unsafe` when implementing `entries()`; you may find the `VecExt` and `SliceExt` trait implementations we have provided particularly useful here. Note that you will frequently need to refer to the FAT structures PDF while implementing `Dir`.

   Parsing an Entry

   > Because the on-disk entry may be either an LFN entry or a regular entry, you must use a `union` to represent an on-disk entry. We have provided such a union for you: `VFatDirEntry`. You can read about unions in Rust in the Rust reference and about unions in general in the union type Wikipedia entry.
   >
   > You should first interpret a directory entry as an unknown entry, use that structure to determine whether there is an entry, and if so, the true kind of entry, and finally interpret the entry as that structure. Working with `union`s will require using `unsafe`. Do so sparingly. Our implementation uses one line of `unsafe` three times, one to access each variant.
   >
   > When parsing a directory entry's name, you must manually add a `.` to the non-LFN based directory entries to demarcate the file's extension. You should only add a `.` if the file's extension is non-empty.
   >
   > Finally, you'll need to decode UTF-16 characters when parsing LFN entries. Use the decode_utf16() function to do so. You will find it useful to store UTF-16 characters in one or more `Vec<u16>` while parsing a long filename.

   `Dir::find()`

   > You should implement `Dir::find()` *after* you implement the `traits::Dir` trait for `Dir`. Note that `Dir::find()` must be case-insensitive. Your implementation should be relatively short. You can use the eq_ignore_ascii_case() method to perform case-insensitive comparisons.

10. **Implement `File` in `vfat/file.rs`.**

Start by adding a fields that store the file's first `Cluster` and a file system handle to `File`. Then implement the `trait::File` trait and any required supertraits. Modify the iterator you return from `entries()` as necessary.

11. **Implement `VFat::open()` in `vfat/vfat.rs`.**

    Finally, implement the `VFat::open()` method. Use the components() method to iterate over a `Path`'s components. Note that the `Path` implementation we have provided for you in the `shim` library does not contain any of the methods that require a file system. These include `read_dir()`, `is_file()`, `is_dir()`, and others.

    Use your `Dir::find()` method in your implementation. You may find it useful to add a helper method to `Dir`.

Once your implementation passes all of the unit tests and works as you expect, you may once again revel; you have implemented a real file system! After sufficient reveling, proceed to the next phase.

Did you find any undefined behavior in the skeleton code? (undefined-behavior)

This is an optional extra credit question. While doing the assignment, did you notice any undefined behavior or unsound API in our skeleton code except those justified with comments? What type of Rust requirements do they violate? Why they seem to behave well in practice? How can we fix them?

Phase 3: Saddle Up

In this phase, you will interface with an existing SD card controller driver for the Raspberry Pi 3 using Rust's foreign function interface, or FFI. You can read more about Rust's FFI in TRPL. You will also create a global handle the file system for your operating system to use. You will be working primarily in `kernel/src/fs`.

Subphase A: SD Driver FFI

Rust's foreign function interface allows Rust code to interact with software written in other programming languages and vice-versa. Foreign items are declared in an `extern` block:

```
extern {
    static outside_global: u32;
    fn outside_function(param: i16) -> i32;
}
```

This declares an external `outside_function` as well as an `outside_global`. The function and global be used as follows:

```
unsafe {
    let y = outside_function(10);
    let global = outside_global;
}
```

Note the required use of unsafe. Rust requires the use of `unsafe` because it cannot ensure that the signatures you have specified are correct. The Rust compiler will blindly emit function calls and variable reads as requested. In other words, as with every other use of `unsafe`, the compiler assumes that what you've done is correct. At link-time, symbols named `outside_function` and `outside_global` must exist for the program to successfully link.

For a Rust function to be called from a foreign program, the function's location (its memory address) must be exported with a known symbol. Typically, Rust *mangles* function symbols for versioning and namespacing reasons in an unspecified manner. As such, by default, it is not possible to know the symbol that Rust will generate for a given function and thus not possible to call that function from an external program. To prevent Rust from mangling symbols, you can use the `#[no_mangle]` attribute:

```
#[no_mangle]
fn call_me_maybe(ptr: *mut u8) { .. }
```

A C program would then be able to call this function as follows:

```
void call_me_maybe(unsigned char *);

call_me_maybe(...);
```

❗ Why can't Rust ensure that using foreign code is safe? (foreign-safety)

Explain why Rust cannot ensure that using foreign code is safe. In particular, explain why Rust can ensure that *other* Rust code is safe, even when it lives outside of the current crate, but it cannot do the same for non-Rust code.

❗ Why does Rust mangle symbols? (mangling)

C does not mangle symbols. C++ and Rust, on the other hand, do. What's different about these languages that necessitates name mangling? Provide a concrete example of what would go wrong if Rust *didn't* name mangle.

SD Driver

We have provided a precompiled SD card driver library in `kern/.cargo/libsd.a`. We've also modified the build process so that the library is linked into the kernel. We've provided the definitions for the items exported from the library in an `extern` block in `kern/src/fs/sd.rs`.

The library depends on a `wait_micros` function which it expects to find in your kernel. The function should sleep for the number of microseconds passed in. You will need to create and export this function for your kernel to successfully link. The C signature for the function is:

```
/*
* Sleep for `us` microseconds.
*/
void wait_micros(unsigned int us);
```

Your task is to wrap the unsafe external API in a safe, Rusty API. Implement an `Sd` struct that initializes the SD card controller in its `new()` method. Then, implement the `BlockDevice` trait for `Sd`. You will need to use `unsafe` to interact with the foreign items. Test your implementation by manually reading the card's MBR in `kmain`. Ensure that the bytes read match what you expect. When everything works as expected, proceed to the next subphase.

Hint

On 64-bit ARM, an `unsigned int` in C is a `u32` in Rust.

Is your implementation thread-safe? (foreign-sync)

The precompiled SD driver we've provided you uses a global variable (`sd_err`) to keep track of error states without any kind of synchronization. As such, it has no hope of being thread-safe. How does this affect the correctness of your bindings? Recall that you must uphold Rust's data race guarantees in any `unsafe` code. Assuming your kernel called `sd_init` correctly, is your `BlockDevice` implementation for `Sd` thread-safe as required? Why or why not?

Subphase B: File System

In this subphase you will expose and initialize a global file system for use by your kernel. You will be working primarily in `kern/src/fs.rs`.

Like the memory allocator, the file system is a *global* resource: we want it to always be available so that we can access the data on the disk at any point. To enable this, we've created a global `static FILE_SYSTEM: FileSystem` in `main.rs`; it will serve as the global handle to your file system. Like the allocator, the file system begins uninitialized.

Tying the Knot

You've now implemented both a disk driver and a file system: it's time to tie them together. Finish the implementation of the `FileSystem` struct in `kernel/src/fs.rs` by using your FAT32 file-system and your Rusty bindings to the foreign SD card driver. You should initialize your file-system using the `Sd` `BlockDevice` in the `initialize()` function. Then, implement the `FileSystem` trait for the structure, deferring all calls to the internal `VFat`. Finally, ensure that you initialize the file system in `kmain`, just after the allocator.

Test your implementation by printing the files at the root (`"/"`) of your SD card in `kmain`. Once everything works as your expect, proceed to the next phase.

Phase 4: Mo'sh

In this phase, you will implement the `cd`, `ls`, `pwd`, and `cat` shell commands. You will be working primarily in `kern/src/shell.rs`.

'Finished' Product

Working Directory

You're likely familiar with the notion of a *working directory* already. The *current working directory* (or `cwd`) is the directory under which relative file accesses are rooted under. For example, if the `cwd` is `/a`, then accessing `hello` will result in accessing the file `/a/hello`. If the `cwd` is switched to `/a/b/c`, accessing `hello` will access `/a/b/c/hello`, and so on. The `/` character can be prepended to any path to make it *absolute* so that it is not relative to the current working directory. As such, `/hello` will always refer to the file named `hello` in the root directory regardless of the current working directory.

In a shell, the current working directory can be changed to `dir` with the `cd <dir>` command. For example, running `cd /hello/there` will change the `cwd` to `/hello/there`. Running `cd you` after this will result in the `cwd` being `/hello/there/you`.

Most operating systems provide a system call that changes a process's working directory. Because our operating system has neither processes nor system calls yet, you'll be keeping track of the `cwd` directly in the shell.

Commands

You will implement four commands that expose expose the file system through your operating system's primary interface: the shell. These are `cd`, `ls`, `pwd`, and `cat`. For the purposes of this assignment, they are specified as follows:

- **`pwd` - print the working directory**

  Prints the full path of the current working directory.

- **`cd <directory>` - change (working) directory**

  Changes the current working directory to `directory`. The `directory` argument is required.

- **`ls [-a] [directory]` - list the files in a directory**

  Lists the entries of a directory. Both `-a` and `directory` are optional arguments. If `-a` is passed in, hidden files are displayed. Otherwise, hidden files are not displayed. If `directory` is not passed in, the entries in the current working directory are displayed. Otherwise, the entries in `directory` are displayed. The arguments may be used together, but `-a` must be provided before `directory`.

  Invalid arguments results in an error. It is also an error if `directory` does not correspond to a valid, existing directory.

- **`cat <path..>` - concatenate files**

  Prints the contents of the files at the provided `path`s, one after the other. At least one `path` argument is required.

  It is an error if a `path` does not point to a valid, existing file. It is an error if an otherwise valid file contains invalid UTF-8.

All non-absolute paths must be must be treated as relative to the current working directory if they are not absolute. For an example of these commands in action, see the GIF above. When you implement these commands yourself, you are free to display directory entries and errors in any way that you'd like as long as all of the information is present.

Implementation

Extend your shell in `kern/src/shell.rs` with these four commands. Use a mutable PathBuf to keep track of the current working directory; this `PathBuf` should be modified by the `cd` command. You will find it useful to create functions with a common signature for each of your commands. For an extra level of type-safety, you can abstract the concept of an executable command into a trait that is implemented for each of your commands.

Once you have implemented, tested, and verified your four commands against the specifications above, you're ready to submit your assignment. Congratulations!

Ensure you're using your bin allocator!

Your file system is likely very memory intensive. To avoid running out of memory, ensure you're using your bin allocator.

Hint

Use the existing methods of `PathBuf` and `Path` to your advantage.

Hint

You'll need to handle `..` and `.` specially in `cd`.

Submission

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

You can call `make check` in `tut/3-fs` directory to check if you've answered every question and `cargo test` in `lib/fat32` directory to run the unit tests for your FAT32 implementation. Note that there are no unit tests for some tasks in `os`. You're responsible for ensuring that they work as expected.

Once you've completed the tasks above, you're done and ready to submit! Ensure you've committed your changes. Any uncommitted changes *will not* be visible to us, thus unconsidered for grading.

When you're ready, push a commit to your GitHub repository with a tag named `lab3-done`.

```
# submit lab3
$ git tag lab3-done
$ git push --tags
```