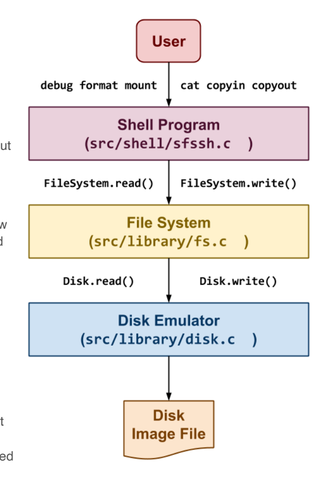
Simple File System

Overview



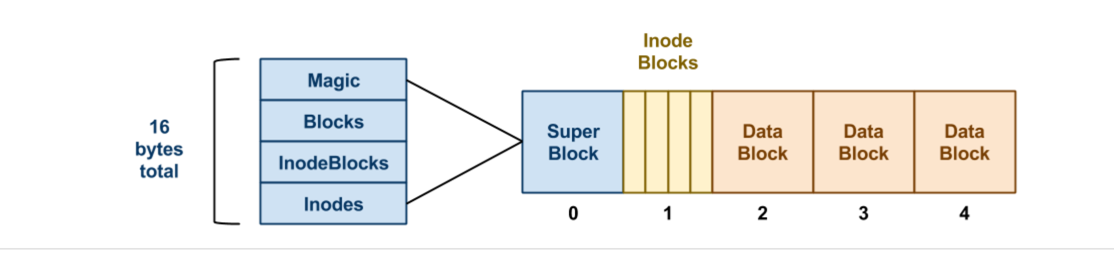
This lab is about create a *simplified* version of the Unix File System called **SimpleFS** as shown to the right. In this application, we have three components:

1. **Shell**: The first component is a simple shell application that allows the user to perform operations on the **SimpleFS** such as printing debugging information about the file system, formatting a new file system, mounting a file system, creating files, and copying data in or out of the file system. To do this, it will translate these user commands into **file system** operations such as `FileSystem.debug`, `FileSystem.format`, `FileSystem.debug`, `FileSystem.create`, `FileSystem.readInode` and `FileSystem.writeInode`.
2. **File System**: The second component takes the operations specified by the user through the **shell** and performs them on the **SimpleFS** disk image. This component is charged with organizing the on-disk data structures and performing all the bookkeeping necessary to allow for persistent storage of data. To store the data, it will need to interact with the **disk emulator** via methods such as `Disk.readDisk` and `Disk.writeDisk`, which allow the file system read and write to the disk image in `4096` byte blocks.
3. **Disk Emulator**: The third component emulates a disk by dividing a normal file (called a **disk image**) into `4096 byte` blocks and only allows the **File System** to read and write in terms of blocks. This emulator will persistently store the data to the disk image using the normal open, read, and write system calls.

The **shell** and **disk emulator** components are provided to you. You only have to complete the **file system** portion of the application for this lab.

Simple File System Design

To implement the **file system** component, you will first need to understand the **SimpleFS** disk layout. As noted previously, this lab assumes that disk blocks are the common size of `4KB`. The first block of the disk is the **superblock** that describes the layout of the rest of the filesystem. A certain number of blocks following the superblock contain inode data structures. Typically, **ten percent** of the total number of disk blocks are used as **inode** blocks. The remaining blocks in the filesystem are used as plain **data** blocks, and occasionally as **indirect** pointer blocks as shown in the example below:

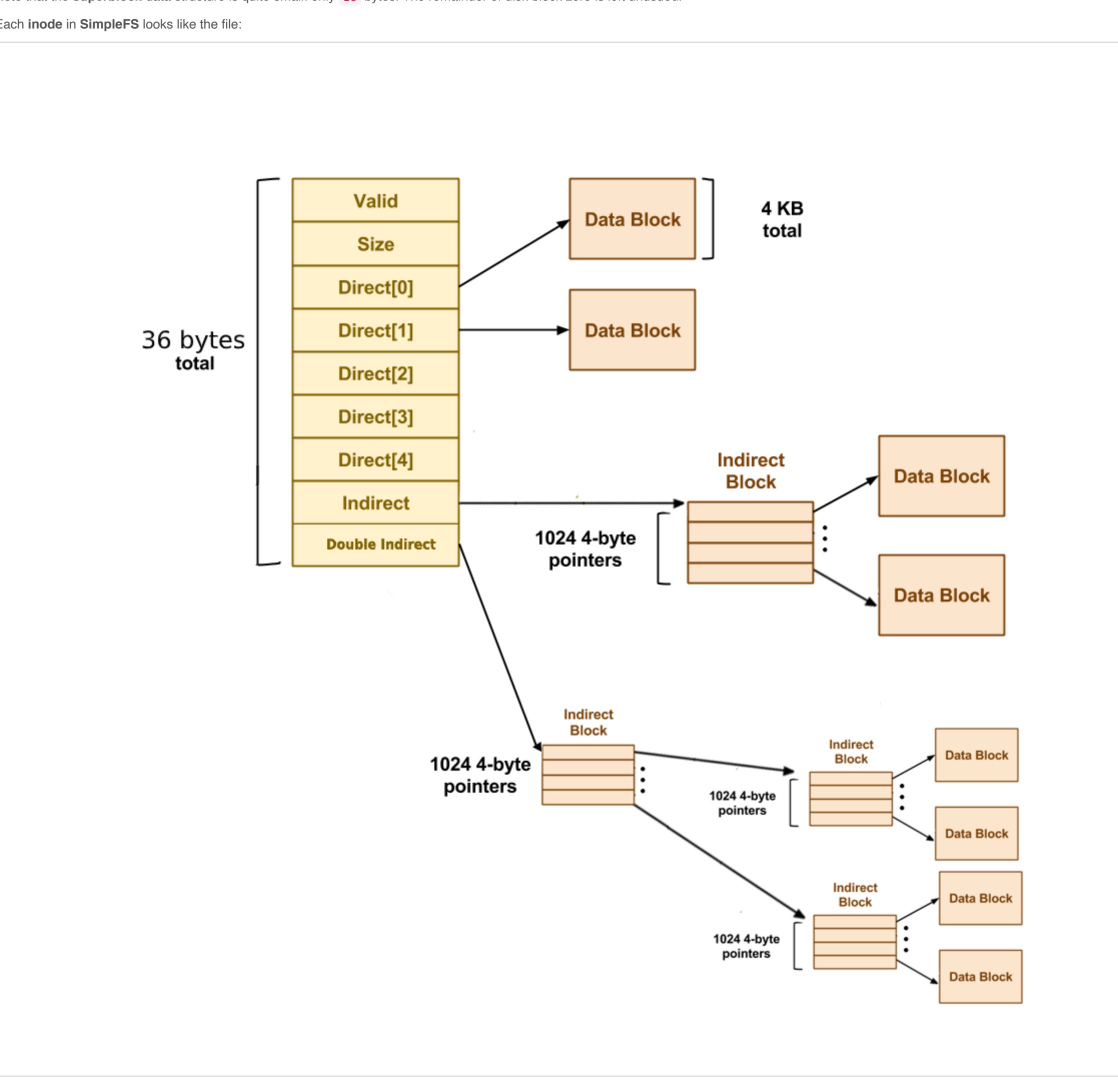


In this example, we have a **SimpleFS** disk image that begins with a **superblock**. This **superblock** consists of four fields:

1. **Magic**: The first field is always the `MAGIC_NUMBER` or `0xf0f03410`. The format routine places this number into the very first bytes of the **superblock** as a sort of filesystem "signature". When the filesystem is mounted, the OS looks for this magic number. If it is correct, then the disk is assumed to contain a valid filesystem. If some other number is present, then the mount fails, perhaps because the disk is not formatted or contains some other kind of data.
2. **Blocks**: The second field is the total number of blocks, which should be the same as the number of blocks on the disk.
3. **InodeBlocks**: The third field is the number of blocks set aside for storing **inodes**. The format routine is responsible for choosing this value, which should always be `10%` of the **Blocks**, rounding up.
4. **Inodes**: The fourth field is the total number of **inodes** in those **inode blocks**.

Note that the **superblock** data structure is quite small: only `16` bytes. The remainder of disk block zero is left unused.

Each **inode** in **SimpleFS** looks like the file:



Each field of the **inode** is a `4`-byte (`36`-bit) integer. The `Valid` field is `1` if the **inode** is valid (i.e. has been created) and is `0` otherwise. The `Size` field contains the logical size of the **inode** data in bytes. There are `5` direct pointers to data blocks, and one pointer to an **indirect** data block. In this context, "pointer" simply means the number of a block where data may be found. A value of `0` may be used to indicate a *null* block pointer. Each inode occupies `32` bytes, so there are `128` inodes in each `4KB` inode block.

Note that an **indirect** data block is just a big array of pointers to further data blocks. Each pointer is a `4`-byte int, and each block is `4KB`, so there are `1024` pointers per block. The data blocks are simply `4KB` of raw data.

One thing missing in **SimpleFS** is the free block bitmap. As discussed in class, a real filesystem would keep a free block bitmap on disk, recording one bit for each block that was available or in use. This bitmap would be consulted and updated every time the filesystem needed to add or remove a data block from an inode.

Because **SimpleFS** does not store this on-disk, you are required to keep a free block bitmap in memory. That is, there must be an array of integers, one for each block of the disk, noting whether the block is in use or available. When it is necessary to allocate a new block for a file, the system must scan through the array to locate an available block. When a block is freed, it must be likewise marked in the bitmap.

Suppose that the user makes some changes to a **SimpleFS** filesystem, and then reboots the system (ie. restarts the shell). Without a free block bitmap, **SimpleFS** cannot tell which blocks are in use and which are free. Fortunately, this information can be recovered by scanning the disk. Each time that an **SimpleFS** filesystem is mounted, the system must build a new free block bitmap from scratch by scanning through all of the inodes and recording which blocks are in use. (This is much like performing an fsck every time the system boots.)

SimpleFS looks much like the Unix file system. Each "file" is identified by an integer called an **inumber**. The **inumber** is simply an index into the array of inode structures that starts in block one. When a file is created, **SimpleFS** chooses the first available inumber and returns it to the user. All further references to that file are made using the **inumber**. Using **SimpleFS** as a foundation, you could easily add another layer of software that implements file and directory names. However, that will not be part of this assignment.

More details about this lab and your deliverables are described below.

File Systems

While it may seem that file systems are a solved problem with venerable examples such as Ext4, XFS, and NTFS, the growth in big data and the emergence of SSDs as the primary storage medium has once again made file systems a hot topic. Today, we have next-generation file systems in the form of ZFS, Btrfs, and AppleFS, which build upon the foundation set by previous file systems. In this assignment, you will explore the core principles about file systems and how they work.

Note: This assignment is based heavily on Project 6: File Systems by Doug Thain.

Deliverables

You must deliver in the corresponding moodle lab the file fs.c where all your implementation is located. In case you make changes to other files, you must explain the reason for your changes and add the code.

```
https://gitlab.com/CIIC4050/simple-file-system
```

Source Code

Folder hierarchy:

```
simple-file-system
    \_ Makefile            # This is the project Makefile
    \_ bin                 # This contains the application executables and scripts
    \_ include             # This contains the SimpleFS library header files
        \_ sfs
            \_ disk.h      # This contains the Disk Emulator header file
            \_ fs.h        # This contains the File System header file
    \_ src
        \_ library
            \_ disk.c    # This contains the Disk Emulator implementation code
            \_ fs.c      # This contains the File System implementation code
        \_ shell
            \_ sfssh.c   # This contains the Shell implementation code
    \_ tests               # This contains the test scripts
```

You must maintain this folder structure for your project and place files in their appropriate place.

Of the provided files, you are only required to modify the `include/sfs/fs.h` and `src/library/fs.c` files as described below.

To build the project, you can simply use `make clean and then make`:

```
$ make clean
rm -f src/library/disk.o src/library/fs.o lib/libsfs.a src/shell/sfssh.o bin/sfssh
$ make
gcc -Wall -Iinclude -fPIC -c -o src/library/disk.o src/library/disk.c
gcc -Wall -Iinclude -fPIC -c -o src/library/fs.o src/library/fs.c
ar rcs lib/libsfs.a src/library/disk.o src/library/fs.o
gcc -Wall -Iinclude -fPIC -c -o src/shell/sfssh.o src/shell/sfssh.c
gcc -Llib -o bin/sfssh src/shell/sfssh.o -lsfs
```

K.I.S.S.

While the exact organization of the lab code is up to you, keep in mind that you will be graded in part on coding style, cleaniness, and organization. This means your code should be consistently formatted, not contain any dead code, have reasonable comments, and appropriate naming among other things:

- Break long functions into smaller functions.
- Make sure each function does one thing and does it well.
- Abstract, but don't over do it.

Disk Emulator

As noted above, we provide you with a **disk emulator** on which to store your filesystem. This "disk" is actually stored as one big file in the file system, so that you can save data in a **disk image** and then retrieve it later. In addition, we will provide you with some sample disk images that you can experiment with to test your filesystem. Just like a real disk, the emulator only allows operations on entire disk blocks of `4 KB` (`BLOCK_SIZE`). You cannot read or write any smaller unit than than that. The primary challenge of building a filesystem is converting the user's requested operations on arbitrary amounts of data into operations on fixed block sizes.

The interface to the simulated disk is given in `include/sfs/disk.h`:

```c
const size_t BLOCK_SIZE = 4096;

typedef struct Disk {
    int     FileDescriptor;
    size_t  Blocks;
    size_t  Reads;
    size_t  Writes;
    size_t  Mounts;
    void (*sanity_check)(struct Disk * self,int blocknum, char *data);
    void (*DiskDestructor)(struct Disk * selft);
    void (*open)(struct Disk * self,const char *path, size_t nblocks);
    size_t (*size)(struct Disk * self);
    bool (*mounted)(struct Disk * self);
    void (*mount)(struct Disk * self);
    void (*unmount)(struct Disk * self);
    void (*readDisk)(struct Disk * self,int blocknum, char *data);
    void (*writeDisk)(struct Disk * self,int blocknum, char *data);
}Disk;
```

Before performing any sort of operation on the disk, you must call `Disk.open()` method and specify a (real) disk image for storing the disk data, and the number of blocks in the simulated disk. If this function is called on a disk image that already exists, the contained data will not be changed. When you are done using the disk, the destructor will automatcally release the file. Opening the disk image is already done for you in the shell, so you should not have to change this.

Once the disk is open, you may call `Disk.size()` to discover the number of blocks on the disk. As the names suggest, `Disk.readDisk(disk)` and `Disk.writeDisk(disk)` read and write one block of data on the disk. Notice that the first argument is a block number, so a call to `Disk.readDisk(disk,0, data)` reads the first `4KB` of data on the disk, and `Disk.readDisk(disk,1,data)` reads the next `4KB` block of data on the disk. Every time that you invoke a read or a write, you must ensure that data points to a full `4KB` of memory.

Additionally, you can register and unregister a disk as mounted by calling the `Disk.mount()` and `Disk.unmount()` methods respectively. The `Disk.mounted()` method returns whether or not the disk has been registerd as mounted.

Note that the disk has a few programming conveniences that a real disk would not. A real disk is rather finicky -- if you send it invalid commands, it will likely crash the system or behave in other strange ways. This simulated disk is more "helpful." If you send it an invalid command, it will halt the program with an error message. For example, if you attempt to read or write a disk block that does not exist, it will throw an exception.

File System

Using the existing **disk emulator** described above, you will build a working **file system**. Take note that we have already constructed the interface to the filesystem and provided some skeleton code. The interface is given in `include/sfs/fs.h`:

```c
typedef struct FileSystem {

    void (*debug)(Disk *disk);
    bool (*format)(Disk *disk);

    bool (*mount)(Disk *disk);

    size_t (*create)();
    bool    (*removeInode)(size_t inumber);
    size_t (*stat)(size_t inumber);

    size_t (*readInode)(size_t inumber, char *data, size_t length, size_t offset);
    size_t (*writeInode)(size_t inumber, char *data, size_t length, size_t offset);

}FileSystem;
```

The various methods must work as follows:

> A. `void (*debug)(Disk *disk)`

This method scans a mounted filesystem and reports on how the inodes and blocks are organized. Your output from this method should be similar to the following:

```
$ ./bin/sfssh data/image.5 5
sfs> debug
SuperBlock:
    magic number is valid
    5 blocks
    1 inode blocks
    128 inodes
Inode 1:
    size: 965 bytes
    direct blocks: 2
```

> B. `bool (*format)(Disk *disk)`

This method Creates a new filesystem on the disk, destroying any data already present. It should set aside ten percent of the blocks for inodes, clear the inode table, and write the superblock. It must return `true` on success, `false` otherwise.

Note: formatting a filesystem does not cause it to be mounted. Also, an attempt to format an already-mounted disk should do nothing and return failure.

> C. `bool (*mount)(Disk *disk)`

This method examines the disk for a filesystem. If one is present, read the superblock, build a free block bitmap, and prepare the filesystem for use. Return `true` on success, `false` otherwise.

Note: a successful mount is a pre-requisite for the remaining calls.

> D. `size_t (*create)()`

This method Creates a new **inode** of zero length. On success, return the `inumber`. On failure, return `-1`.

> E. `bool (*removeInode)(size_t inumber)`

This method removes the **inode** indicated by the `inumber`. It should release all data and indirect blocks assigned to this **inode** and return them to the free block map. On success, it returns `true`. On failure, it returns `false`.

> F. `size_t (*stat)(size_t inumber)`

This method returns the logical size of the given `inumber`, in bytes. Note that zero is a valid logical size for an **inode**. On failure, it returns `-1`.

> G. `size_t (*readInode)(size_t inumber, char *data, size_t length, size_t offset)`

This method reads data from a valid **inode**. It then copies `length` bytes from the data blocks of the **inode** into the `data` pointer, starting at `offset` in the **inode**. It should return the total number of bytes read. If the given `inumber` is invalid, or any other error is encountered, the method returns `-1`.

Note: the number of bytes actually read could be smaller than the number of bytes requested, perhaps if the end of the **inode** is reached.

> H. `size_t (*writeInode)(size_t inumber, char *data, size_t length, size_t offset)`

This method writes data to a valid **inode** by copying `length` bytes from the pointer `data` into the data blocks of the **inode** starting at `offset` bytes. It will allocate any necessary direct and indirect blocks in the process. Afterwards, it returns the number of bytes actually written. If the given `inumber` is invalid, or any other error is encountered, return `-1`.

Note: the number of bytes actually written could be smaller than the number of bytes request, perhaps if the disk becomes full.

It's quite likely that the **File System** will need additional internal member variables in order to keep track of the currently mounted filesystem. For example, you will certainly need a variable to keep track of the current free block bitmap, and perhaps other items as well. Feel free to modify the `include/sfs/fs.h` to include these additional bookkeeping items.

Implementation Notes

Your job is to implement **SimpleFS** as described above by filling in the implementation of `src/library/fs.c`. You do not need to change any other code modules. We have already created some sample data structures to get you started. These can be found in `include/sfs/fs.h`. To begin with, we have defined a number of common constants that you will use. Most of these should be self explanatory:

```c
const uint32_t MAGIC_NUMBER       = 0xf0f03410;
const uint32_tINODES_PER_BLOCK    = 128;
const uint32_t POINTERS_PER_INODE = 5;
const uint32_t POINTERS_PER_BLOCK = 1024;
```

Note that `POINTERS_PER_INODE` is the number of direct pointers in each inode structure, while `POINTERS_PER_BLOCK` is the number of pointers to be found in an indirect block.

The superblock and inode structures are easily translated from the pictures above:

```c
struct SuperBlock {         // Superblock structure
    uint32_t MagicNumber;   // File system magic number
    uint32_t Blocks;        // Number of blocks in file system
    uint32_t InodeBlocks;   // Number of blocks reserved for inodes
    uint32_t Inodes;        // Number of inodes in file system
};

struct Inode {              // Inode structure
    uint32_t Valid;         // Whether or not inode is valid
    uint32_t Size;          // Size of file
    uint32_t Direct[POINTERS_PER_INODE]; // Direct pointers
    uint32_t Indirect;      // Indirect pointer
    uint32_t DoubleIndirect;      // Double Indirect pointer
};
```

Note carefully that many inodes can fit in one disk block. A `4KB` chunk of memory containing `128` inodes would look like this:

```c
Inode       Inodes[INODES_PER_BLOCK];
```

Each indirect block is just a big array of `1024` integers, each pointing to another disk block. So, a `4KB` chunk of memory corresponding to an indirect block would look liks this:

```c
uint32_t    Pointers[POINTERS_PER_BLOCK];
```

Finally, each data block is just raw binary data used to store the partial contents of a file. A data block can be specified as simply an array for `4096` bytes:

```c
char        Data[BLOCK_SIZE];
```

Because a raw `4 KB` disk block can be used to represent four different kinds of data: a superblock, a block of `128` inodes, an indirect pointer block, or a plain data block, we can declare a union of each of our four different data types. A union looks like a struct, but forces all of its elements to share the same memory space. You can think of a union as several different types, all overlaid on top of each other:

```c
union Block {
    SuperBlock  Super;                        // Superblock
    Inode       Inodes[INODES_PER_BLOCK];     // Inode block
    uint32_t    Pointers[POINTERS_PER_BLOCK]; // Pointer block
    char        Data[BLOCK_SIZE];         // Data block
};
```

Note that the size of an `Block` union will be exactly `4KB`: the size of the largest members of the union. To declare a `Block` variable:

```c
Block block;
```

Now, we may use `Disk.readDisk(disk)` to load in the raw data from block zero. We give `Disk.readDisk(disk)` the variable block.data, which looks like an array of characters:

```c
Disk.readDisk(disk,0, block.Data);
```

But, we may interpret that data as if it were a struct superblock by accessing the super part of the union. For example, to extract the magic number of the super block, we might do this:

```c
x = block.Super.MagicNumber;
```

On the other hand, suppose that we wanted to load disk block `59`, assume that it is an indirect block, and then examine the `4th` pointer. Again, we would use `Disk.readDisk(disk)` to load the raw data:

```c
Disk.readDisk(Disk59, block.Data);
```

But then use the pointer part of the union like so:

```c
x = block.Pointers[4];
```

The union offers a convenient way of viewing the same data from multiple perspectives. When we load data from the disk, it is just a `4 KB` raw chunk of data (`block.Data`). But, once loaded, the filesystem layer knows that this data has some structure. The filesystem layer can view the same data from another perspective by choosing another field in the union.

General Advice

1. **Implement the functions roughly in order**. We have deliberately presented the functions of the filesystem interface in order to difficulty. Implement `debug`, `format`, and `mount` first. Make sure that you are able to access the sample disk images provided. Then, perform creation and deletion of inodes without worrying about data blocks. Implement reading and test again with disk images. If everything else is working, then attempt write.
2. **Divide and conquer**. Work hard to factor out common actions into simple functions. This will dramatically simplify your code. For example, you will often need to load and save individual inode structures by number. This involves a fiddly little computation to transform an inumber into a block number, and so forth. So, make two little methods to do just that:

   ```c
   bool    load_inode(size_t inumber, Inode *node);
   bool    save_inode(size_t inumber, Inode *node);
   ```

   Now, everywhere that you need to load or save an inode structure, call these functions. You may also wish to have functions that help you manage and search the free block map:

   ```c
   void    initialize_free_blocks();
   ssize_t allocate_free_block();
   ```

   Anytime that find yourself writing very similar code over and over again, factor it out into a smaller function.
3. **Test boundary conditions**. We will certainly test your code by probing its boundaries. Make sure that you test and fix boundary conditions before handing in. For example, what happens if `FileSystem.create` discovers that the inode table is full? It should cleanly return with an error code. It certainly should not crash the program or mangle the disk! Think critically about other possible boundary conditions such as the end of a file or a full disk.
4. **Don't worry about performance**. You will be graded on correctness, not performance. In fact, during the course of this assignment, you will discover that a simple file access can easily erupt into tens or hundreds of single disk accesses. Understand why this happens, but don't worry about optimization.

Shell

We have provided for you a simple shell that will be used to exercise your filesystem and the simulated disk. When grading your work, we will use the shell to test your code, so be sure to test extensively. To use the shell, simply run `bin/sfssh` with the name of a disk image, and the number of blocks in that image. For example, to use the `image.5` example given below, run:

```
$ ./bin/sfssh image.5 5
```

Or, to start with a fresh new disk image, just give a new filename and number of blocks:

```
$ ./bin/sfssh newdisk 25
```

Once the shell starts, you can use the `help` command to list the available commands:

```
sfs> help
Commands are:
    format
    mount
    debug
    create
    remove  <inode>
    cat     <inode>
    stat    <inode>
    copyin  <file> <inode>
    copyout <inode> <file>
    help
    quit
    exit
```

Most of the commands correspond closely to the filesystem interface. For example, `format`, `mount`, `debug`, `create` and `remove` call the corresponding methods in the `FileSystem`. Make sure that you call these functions in a sensible order. A filesystem must be formatted once before it can be used. Likewise, it must be mounted before being read or written.

The complex commands are `cat`, `copyin`, and `copyout`. `cat` reads an entire file out of the filesystem and displays it on the console, just like the Unix command of the same name. `copyin` and `copyout` copy a file from the local Unix filesystem into your emulated filesystem. For example, to copy the dictionary file into inode `10` in your filesystem, do the following:

```
sfs> copyin /usr/share/dict/words 10
```

Note that these three commands work by making a large number of calls to `FileSystem.readInode()` and `FileSystem.writeInode()` for each file to be copied.

Tests

To help you verify the correctness of your **SimpleFS** implementation, you are provided with the following disk images:

- image.5
- image.20
- image.200

Likewise, you are also provided a set of test scripts in the `tests` directory that will utilize these disk images to test your file system. You can run all the tests by simply doing `make test`:

```
$ make test
Testing cat on data/image.5 ... Success
Testing cat on data/image.20 ... Success
Testing copyin in /tmp/tmp.8mbVjt9XfO/image.5 ... Success
Testing copyin in /tmp/tmp.8mbVjt9XfO/image.20 ... Success
Testing copyin in /tmp/tmp.8mbVjt9XfO/image.200 ... Success
Testing copyout in data/image.5 ... Success
Testing copyout in data/image.20 ... Success
Testing copyout in data/image.200 ... Success
Testing create in data/image.5.create ... Success
Testing debug on data/image.5 ... Success
Testing debug on data/image.20 ... Success
Testing debug on data/image.200 ... Success
Testing format on data/image.5.formatted ... Success
Testing format on data/image.20.formatted ... Success
Testing format on data/image.200.formatted ... Success
Testing mount on data/image.5 ... Success
Testing mount-mount on data/image.5 ... Success
Testing mount-format on data/image.5 ... Success
Testing bad-mount on /tmp/tmp.BZoOChcGKj/image.5 ... Success
Testing bad-mount on /tmp/tmp.BZoOChcGKj/image.5 ... Success
Testing bad-mount on /tmp/tmp.BZoOChcGKj/image.5 ... Success
Testing bad-mount on /tmp/tmp.BZoOChcGKj/image.5 ... Success
Testing bad-mount on /tmp/tmp.BZoOChcGKj/image.5 ... Success
Testing remove in /tmp/tmp.p00nKXt3Ut/image.5 ... Success
Testing remove in /tmp/tmp.p00nKXt3Ut/image.5 ... Success
Testing remove in /tmp/tmp.p00nKXt3Ut/image.20 ... Success
Testing stat on data/image.5 ... Success
Testing stat on data/image.20 ... Success
Testing stat on data/image.200 ... Success
Testing valgrind on /tmp/tmp.Io2oaaqjD0/image.200 ... Success
```

Reads / Writes

Depending on how you implement the various functions, **the number of disk reads and writes may not match**. As long as you are not too far above the numbers in the test case, then you will be given credit.

Idempotent

The provided test scripts require that the provided disk images are in their original state. Therefore, if you make any modifications to them while developing and testing, you should make sure you restore them to their original state before attempting the tests. Since we are using [git], you can simply do the following to retrieve the original version of a disk image:

```
$ git checkout data/image.5
```

References

This lab is based on the online resources available from the Operating System Principles class at the University of Notre Dame.
Link