CSE 506: Lab 5: File System and Shell

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Due Friday, November 7, 2014, 11:59 PM

Introduction

In this lab, you will implement a simple disk-based file system. The file system itself will be implemented in micro-kernel fashion, outside the kernel but within its own user-space environment. Other environments access the file system by making IPC requests to this special file system environment.

You will implement `spawn`, a library call that loads and runs on-disk executables. You will then flesh out your kernel and library operating system enough to run a shell on the console.

Getting Started

Use Git to commit your Lab 4 source, fetch the latest version of the course repository, and then create a local branch called `lab5` based on our lab5 branch, `origin/lab5`:

```
kermit% cd ~/CSE506/lab
kermit% git commit -am 'my solution to lab4'

Created commit 734fab7: my solution to lab4
 4 files changed, 42 insertions(+), 9 deletions(-)
kermit% git pull
....
kermit% git checkout -b lab5 origin/lab5
Branch lab5 set up to track remote branch refs/remotes/origin/lab5.
Switched to a new branch "lab5"
kermit% git merge lab4
Merge made by recursive.
 kern/env.c |   42 +++++++++++++++++++
 1 files changed, 42 insertions(+), 0 deletions(-)
kermit%
```

The main new component for this part of the lab is the file system environment, located in the new `fs` directory. Scan through all the files in this directory to get a feel for what all is new. Also, there are some new file system-related source files in the `user` and `lib` directories. Be sure to scan through all of the files below.

`fs/fs.c`	Code that mainipulates the file system's on-disk structure.
`fs/bc.c`	A simple block cache built on top of our user-level page fault handling facility.
`fs/ide.c`	Minimal PIO-based (non-interrupt-driven) IDE driver code.
`fs/serv.c`	The file system server that interacts with client environments using file system IPCs.
`lib/fd.c`	Code that implements the general UNIX-like file descriptor interface.

`lib/file.c`	The driver for on-disk file type, implemented as a file system IPC client.
`lib/console.c`	The driver for console input/output file type.
`lib/spawn.c`	Code skeleton of the `spawn` library call.

You should run the pingpong, primes, and forktree test cases from lab 4 again after merging in the new lab 5 code. You will need to comment out the `ENV_CREATE(fs_fs)` line in `kern/init.c` because `fs/fs.c` tries to do some I/O, which JOS does allow yet. Similarly, temporarily comment out the call to `close_all()` in `lib/exit.c`; this function calls subroutines that you will implement later in the lab, and therefore will panic if called. If your lab 4 code doesn't contain any bugs, the test cases should run fine. Don't proceed until they work. Don't forget to un-comment these lines when you start Exercise 1.

If they don't work, use **`git diff lab4 | more`** to review all the changes, making sure there isn't any code you wrote for lab4 (or before) missing from lab 5. Make sure that lab 4 still works.

Lab Requirements

In this and all other labs, you may complete challenge problems for extra credit. If you do this, please create entries in challenge5.txt, which includes a short (e.g., one or two paragraph) description of what you did to solve your chosen challenge problem and how to test it. If you implement more than one challenge problem, you must describe each one. Be sure to list the challenge problem number. If you complete challenges from previous labs, please list them in this file (not a previous lab challenge file), with both the lab and problem number.

When you are ready to hand in your lab code and write-up, note in `slack.txt` how many late hours you have used for this assignment. (This is to help us agree on the number that you have used.) This file should contain a single line formatted as follows (where n is the number of late hours):

```
late hours taken: n
```

Commit your changes to the git repository using **`git commit -am "Your commit message"`**. Then run **`make handin`** in the lab directory. This will create a tag and push the tag and all committed changes to the course repository on scm.cs.stonybrook.edu, which the staff will use for grading. *If you submit multiple times, we will take the latest submission and count late hours accordingly.*

File system preliminaries

We have provided you with a simple, read-only, disk-based file system. You will need to slightly change your existing code in order to port the file system for your JOS, so that `spawn` can access on-disk executables using path names. Although you do not have to understand every detail of the file system, such as its on-disk structure. It is very important that you familiarize yourself with the design principles and its various interfaces.

The file system itself is implemented in micro-kernel fashion, outside the kernel but within its own user-space environment. Other environments access the file system by making IPC requests to this special file system environment.

On-Disk File System Structure

Most UNIX file systems divide available disk space into two main types of regions: *inode* regions and *data* regions. UNIX file systems assign one *inode* to each file in the file system; a file's inode holds critical meta-data about the file such as its `stat` attributes and pointers to its data blocks. The data regions are divided into much larger (typically 8KB or more) *data blocks*, within which the file system stores file data and directory meta-data. Directory entries contain file names and pointers to inodes; a file is said to be *hard-linked* if multiple directory entries in the file system refer to that file's inode. Since our file system will not support hard links, we do not need this level of indirection and therefore can make a convenient simplification: our file system will not use inodes at all and instead will simply store all of a file's (or sub-directory's) meta-data within the (one and only) directory entry describing that file.

Both files and directories logically consist of a series of data blocks, which may be scattered throughout the disk much like the pages of an environment's virtual address space can be scattered throughout physical memory. The file system environment hides the details of block layout, presenting interfaces for reading and writing sequences of bytes at arbitrary offsets within files. The file system environment handles all modifications to directories internally as a part of performing actions such as file creation and deletion. Our file system *does,* however, allow user environments to *read* directory meta-data directly (e.g., with `read` and `write`), which means that user environments can perform directory scanning operations themselves (e.g., to implement the `ls` program) rather than having to rely on additional special calls to the file system. The disadvantage of this approach to directory scanning, and the reason that most modern UNIX variants discourage it, is that it makes application programs dependent on the format of directory meta-data, making it difficult to change the file system's internal layout without changing or at least recompiling application programs as well.

Sectors and Blocks

Most disks cannot perform reads and writes at byte granularity and instead perform reads and writes in units of *sectors*, which today are almost universally 512 bytes each. File systems actually allocate and use disk storage in units of *blocks*. Be wary of the distinction between the two terms: *sector size* is a property of the disk hardware, whereas *block size* is an aspect of the operating system using the disk. A file system's block size must be a multiple of the sector size of the underlying disk.

Our file system will use a block size of 4096 bytes, conveniently matching the processor's page size.

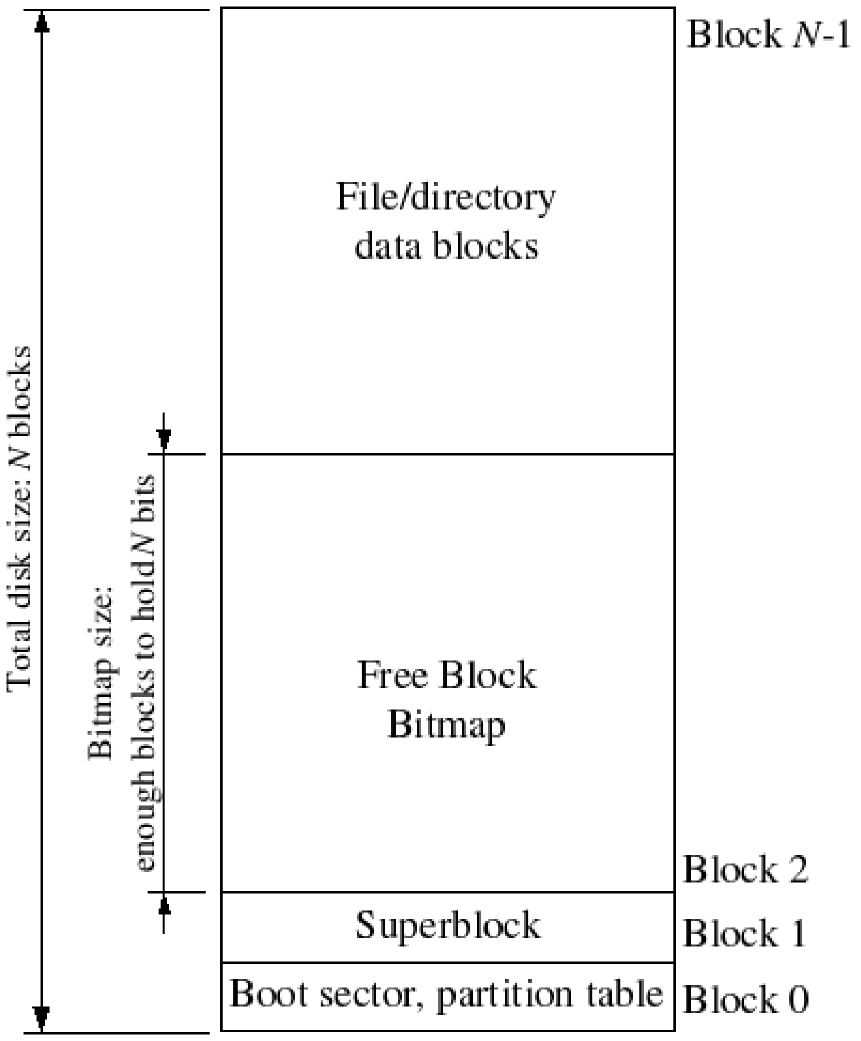
Superblocks

File systems typically reserve certain disk blocks at "easy-to-find" locations on the disk (such as the very start or the very end) to hold meta-data describing properties of the file system as a whole, such as the block size, disk size, any meta-data required to find the root directory, the time the file system was last mounted, the time the file system was last checked for errors, and so on. These special blocks are called *superblocks*.

Our file system will have exactly one superblock, which will always be at block 1 on the disk. Its layout is defined by `struct Super` in `inc/fs.h`. Block 0 is typically reserved to hold boot loaders and partition tables, so file systems generally do not use the very first disk block. Many "real" file systems maintain multiple superblocks, replicated throughout several widely-spaced regions of the disk, so that if one of them is corrupted or the disk develops a media error in that region, the other superblocks can still be found and used to access the file system.

The Block Bitmap: Managing Free Disk Blocks

In the same way that the kernel must manage the system's physical memory to ensure that a given physical page is used for only one purpose at a time, a file system must manage the blocks of storage on a disk to ensure that a given disk block is used for only one purpose at a time. In `pmap.c` you keep the `Page` structures for all free physical pages on a linked list, `page_free_list`, to keep track of the free physical pages. In file systems it is more common to keep track of free disk blocks using a *bitmap* rather than a linked list, because a bitmap is more storage-efficient than a linked list and easier to keep consistent. Searching for a free block in a bitmap can take more CPU time than simply removing the first element of a linked list, but for file systems this isn't a problem because the I/O cost of actually accessing the free block after we find it dominates for performance purposes.

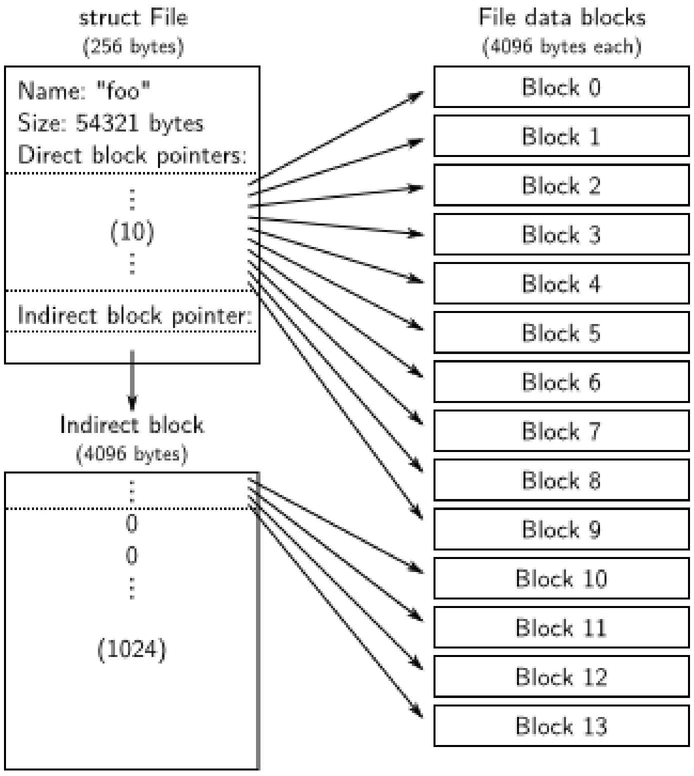

Block N-1
File/directory data blocks
Total disk size: N blocks
Bitmap size: enough blocks to hold N bits
Free Block Bitmap
Block 2
Superblock
Block 1
Boot sector, partition table
Block 0

To set up a free block bitmap, we reserve a contiguous region of space on the disk large enough to hold one bit for each disk block. For example, since our file system uses 4096-byte blocks, each bitmap block contains 4096*8=32768 bits, or enough bits to describe 32768 disk blocks. In other words, for every 32768 disk blocks the file system uses, we must reserve one disk block for the block bitmap. A given bit in the bitmap is set if the corresponding block is free, and clear if the corresponding block is in use. The block bitmap in our file system always starts at disk block 2, immediately after the superblock. For simplicity we will reserve enough bitmap blocks to hold one bit for each block in the entire disk, including the blocks containing the superblock and the bitmap itself. We will simply make sure that the bitmap bits corresponding to these special, "reserved" areas of the disk are always clear (marked in-use).

File Meta-data

The layout of the meta-data describing a file in our file system is described by `struct File` in `inc/fs.h`. This meta-data includes the file's name, size, type (regular file or directory), and pointers to the blocks comprising the file. As mentioned above, we do not have inodes, so this meta-data is stored in a directory entry on disk. Unlike in most "real" file systems, for simplicity we will use this one `File` structure to represent file meta-data as it appears *both on disk and in memory*.

The `f_direct` array in `struct File` contains space to store the block numbers of the first 10 (`NDIRECT`) blocks of the file, which we call the file's *direct* blocks. For small files up to 10*4096 = 40KB in size, this means that the block numbers of all of the file's blocks will fit directly within the `File` structure itself. For larger files, however, we need a place to hold the rest of the file's block numbers. For any file greater than 40KB in size, therefore, we allocate an additional disk block, called the file's *indirect block*, to hold up to 4096/4 = 1024 additional block numbers. Our file system therefore allows files to be up to 1034 blocks, or just over four megabytes, in size. To support larger files, "real" file systems typically support *double-* and *triple-indirect blocks* as well.



Directories versus Regular Files

A `File` structure in our file system can represent either a *regular* file or a directory; these two types of "files" are distinguished by the `type` field in the `File` structure. The file system manages regular files and directory-files in exactly the same way, except that it does not interpret the contents of the data blocks associated with regular files at all, whereas the file system interprets the contents of a directory-file as a series of `File` structures describing the files and subdirectories within the directory.

The superblock in our file system contains a `File` structure (the `root` field in `struct Super`) that holds the meta-data for the file system's root directory. The contents of this directory-file is a sequence of `File` structures describing the files and directories located within the root directory of the file system. Any subdirectories in the root directory may in turn contain more `File` structures representing sub-subdirectories, and so on.

The File System

The goal for this lab is not to have you implement the entire file system, but for you to implement only certain key components. In particular, you will be responsible for reading blocks into the block cache and flushing them back to disk; allocating disk blocks; mapping file offsets to disk blocks; and implementing read, write, and open in the IPC interface. Because you will not be implementing all of the file system yourself, it is very important that you familiarize yourself with the provided code and the various file system interfaces.

Much of the code for the file system has been rewritten for this year, so please let us know if you come across any bugs.

Disk Access

The file system environment in our operating system needs to be able to access the disk, but we have not yet implemented any disk access functionality in our kernel. Instead of taking the conventional "monolithic" operating system strategy of adding an IDE disk driver to the kernel along with the necessary system calls to allow the file system to access it, we will instead implement the IDE disk driver as part of the user-level file system environment. We will still need to modify the kernel slightly, in order to set things up so that the file system environment has the privileges it needs to implement disk access itself.

It is easy to implement disk access in user space this way as long as we rely on polling, "programmed I/O" (PIO)-based disk access and do not use disk interrupts. It is possible to implement interrupt-driven device drivers in user mode as well (the L3 and L4 kernels do this, for example), but it is more difficult since the kernel must field device interrupts and dispatch them to the correct user-mode environment.

The x86 processor uses the IOPL bits in the EFLAGS register to determine whether protected-mode code is allowed to perform special device I/O instructions such as the IN and OUT instructions. Since all of the IDE disk registers we need to access are located in the x86's I/O space rather than being memory-mapped, giving "I/O privilege" to the file system environment is the only thing we need to do in order to allow the file system to access these registers. In effect, the IOPL bits in the EFLAGS register provides the kernel with a simple "all-or-nothing" method of controlling whether user-mode code can access I/O space. In our case, we want the file system environment to be able to access I/O space, but we do not want any other environments to be able to access I/O space at all.

In the tests that follow, if you fail a test, `obj/fs/fs.img` is likely to be left inconsistent. Be sure to remove it before running **`make grade`** or **`make qemu`**.

Exercise 1. `i386_init` identifies the file system environment by passing the type `ENV_TYPE_FS` to your environment creation function, `env_create`. Modify `env_create` in `env.c`, so that it gives the file system environment I/O privilege, but never gives that privilege to any other environment.

Make sure you can start the file environment without causing a General Protection fault. You should pass the "fs i/o" test in **`make grade`**.

Do you have to do anything else to ensure that this I/O privilege setting is saved and restored properly when you subsequently switch from one environment to another? Make sure you understand how this environment state is handled.

Read through the files in the new `fs` directory in the source tree. The file `fs/ide.c` implements our minimal PIO-based disk driver. The file `fs/serv.c` contains the `umain` function for the file system environment.

Note that the `GNUmakefile` file in this lab sets up QEMU to use the file `obj/kern/kernel.img` as the image for disk 0 (typically "Drive C" under DOS/Windows) as before, and to use the (new) file `obj/fs/fs.img` as the image for disk 1 ("Drive D"). In this lab your file system should only ever touch disk 1; disk 0 is used only to boot the kernel. If you manage to corrupt either disk image in some way, you can reset both of them to their original, "pristine" versions simply by typing:

```
$ rm obj/kern/kernel.img obj/fs/fs.img
$ make
```

or by doing:

```
$ make clean
$ make
```

Challenge 1! (5 points) Implement interrupt-driven IDE disk access, with or without DMA. You can decide whether to move the device driver into the kernel, keep it in user space along with the file system, or even (if you really want to get into the micro-kernel spirit) move it into a separate environment of its own.

The Block Cache

In our file system, we will implement a simple "buffer cache" (really just a block cache) with the help of the processor's virtual memory system. The code for the block cache is in `fs/bc.c`.

Our file system will be limited to handling disks of size 3GB or less. We reserve a large, fixed 3GB region of the file system environment's address space, from 0x10000000 (`DISKMAP`) up to 0xD0000000 (`DISKMAP+DISKSIZE`), as a "memory mapped" version of the disk. For example, disk block 0 is mapped at virtual address 0x10000000, disk block 1 is mapped at virtual address 0x10001000, and so on. The `diskaddr` function in `fs/bc.c` implements this translation from disk block numbers to virtual addresses (along with some sanity checking).

Since our file system environment has its own virtual address space independent of the virtual address spaces of all other environments in the system, and the only thing the file system environment needs to do is to implement file access, it is reasonable to reserve most of the file system environment's address space in this way. It would be awkward for a real file system implementation on a 32-bit machine to do this since modern disks are larger than 3GB. Such a buffer cache management approach may still be reasonable on a machine with a 64-bit address space, such as Intel's Itanium or AMD's Athlon 64 processors.

Of course, it would be unreasonable to read the entire disk into memory, so instead we'll implement a form of *demand paging*, wherein we only allocate pages in the disk map region and read the corresponding block from the disk in response to a page fault in this region. This way, we can pretend that the entire disk is in memory.

Exercise 2. Implement the `bc_pgfault` function in `fs/bc.c`. `bc_pgfault` is a page fault handler, just like the one your wrote in the previous lab for copy-on-write fork, except that its job is to load pages in from the disk in response to a page fault. When writing this, keep in mind that (1) `addr` may not be aligned to a block boundary and (2) `ide_read` operates in sectors, not blocks.

Use **`make grade`** to test your code. Your code should pass check_super.

The `fs_init` function in `fs/fs.c` is a prime example of how to use the block cache. After initializing the block cache, it simply stores pointers into the disk map region in the `super` and `bitmap` global variables. After this point, we can simply read from these structures as if they were in memory and our page fault handler will read them from disk as necessary.

(5 points)

Challenge 2! The block cache has no eviction policy. Once a block gets faulted in to it, it never gets removed and will remain in memory forevermore. Add eviction to the buffer cache. Using the `PTE_A` "accessed" bits in the page tables, you can track approximate usage of disk blocks without the need to modify every place in the code that accesses the disk map region.

The Block Bitmap

After `fs_init` sets the `bitmap` pointer, we can treat `bitmap` as a packed array of bits, one for each block on the disk. See, for example, `block_is_free`, which simply checks whether a given block is marked free in the bitmap.

File Operations

We have provided a variety of functions in `fs/fs.c` to implement the basic facilities you will need to interpret and manage `File` structures, scan and manage the entries of directory-files, and walk the file system from the root to resolve an absolute pathname. Read through *all* of the code in `fs/fs.c` *carefully* and make sure you understand what each function does before proceeding.

Exercise 3. Implement `file_block_walk` and `file_get_block`. `file_block_walk` maps from a block offset within a file to the pointer for that block in the `struct File` or the indirect block, very much like what `pgdir_walk` did for page tables. `file_get_block` goes one step further and maps to the actual disk block, allocating a new one if necessary.

Use **`make grade`** to test your code. Your code should pass file_get_block.

`file_block_walk` and `file_get_block` are the workhorses of the file system. For example, `file_read` - and `file_write` are little more than the bookkeeping atop `file_get_block` necessary to copy bytes between scattered blocks and a sequential buffer.

The File System Interface

Now that we have implemented the necessary functionality within the file system environment itself, we must make it accessible to other environments that wish to use the file system. Since other environments can't directly call functions in the file system environment, we'll expose access to the file system environment via a *remote procedure call*, or RPC, abstraction, built atop JOS's IPC mechanism.

Graphically, here's what a call to the file system server (say, read) looks like

```
      Regular env           FS env
    +---------------+   +---------------+
    |      read     |   |   file_read   |
    |   (lib/fd.c)  |   |   (fs/fs.c)   |
 ...|.......|.......|...|.......^.......|...............
    |       v       |   |       |       | RPC mechanism
    |  devfile_read |   |  serve_read   |
    |  (lib/file.c) |   |  (fs/serv.c)  |
    |       |       |   |       ^       |
    |       v       |   |       |       |
    |     fsipc     |   |     serve     |
    |  (lib/file.c) |   |  (fs/serv.c)  |
    |       |       |   |       ^       |
    |       v       |   |       |       |
    |   ipc_send    |   |   ipc_recv    |
    |       |       |   |       ^       |
    +-------|-------+   +-------|-------+
            |                   |
            +-------------------+
```

Everything below the dotted line is simply the mechanics of getting a read request from the regular environment to the file system environment. Starting at the beginning, `read` (which we provide) works on any file descriptor and simply dispatches to the appropriate device read function, in this case `devfile_read` (we'll have more device types in future labs, like pipes and network sockets). `devfile_read` implements `read` specifically for on-disk files. This and the other `devfile_*` functions in `lib/file.c` implement the client side of the FS operations and all work in roughly the same way, bundling up arguments in a request structure, calling `fsipc` to send the IPC request, and unpacking and returning the results. The `fsipc` function simply handles the common details of sending a request to the server and receiving the reply.

The file system server code can be found in `fs/serv.c`. It loops in the `serve` function, endlessly receiving a request over IPC, dispatching that request to the appropriate handler function, and sending the result back via IPC. The corresponding client code can be found in `lib/file.c`. Here, the `fsipc` function handles the common details of sending some request to the server and receiving the reply. The remaining functions wrap the available RPC's as regular C functions that handle bundling up arguments in the request structure, calling `fsipc`, and unpacking and returning the results.

Recall that JOS's IPC mechanism lets an environment send a single 32-bit number and, optionally, share a page. To send a request from the client to the server, we use the 32-bit number for the request type (the file system server RPCs are numbered, just as how syscalls were numbered) and store the arguments to the request in a `union Fsreq` on the page shared via the IPC. On the client side, we always share the page at `fsipcbuf`; on the server side, we map the incoming request page at `fsreq` (`0x0ffff000`).

The server also sends the response back via IPC. We use the 32-bit number for the function's return code. For most RPCs, this is all they return. `FSREQ_READ` and `FSREQ_STAT` also return data, which they simply write to the page that the client sent its request on. There's no need to send this page in the response IPC, since the client shared it with the file system server in the first place. Also, in its response, `FSREQ_OPEN` shares with the client a new "Fd page". We'll return to this RPC shortly.

Exercise 4. Implement `serve_read` in `fs/serv.c` and `file_read` in `lib/file.c`.

`serve_read`'s heavy lifting will be done by the already-implemented `file_read` in `fs/fs.c` (which, in turn, is just a bunch of calls to `file_get_block`). `serve_read` just has to provide the RPC interface for file reading. Look at the comments and code in `serve_stat` to get a general idea of how the server functions should be structured.

Likewise, `file_read` should pack its arguments into `fsipcbuf` for `serve_read`, call `fsipc`, and handle the result.

Challenge 3! (20 points) Extend the file system to support write access. Here are a few points you need to consider:

1. Use the block bitmap starting at block 2 to keep track of which disk blocks are free and which are in use. Look at `fs/fsformat.c` to see how the bitmap is initialized.
2. Make use of the `alloc` argument in `file_block_walk`. In `file_get_block`, allocate new disk blocks as necessary.
3. In your block cache, use the VM hardware (the `PTE_D` "dirty" bit in the `uvpt` entry) to keep track of whether a cached disk block has been modified, and thus needs to be written back to the disk.
4. Handle `O_CREAT` and `O_TRUNC` open modes in `serve_open`.
5. Handle more file system IPC requests, such as `FSREQ_SET_SIZE`, `FSREQ_WRITE`, `FSREQ_FLUSH`, `FSREQ_REMOVE` and `FSREQ_SYNC`, in `fs/serv.c`. We have defined the argument for these calls for you in `inc/fs.h`. Also, write the corresponding service routines in `fs/fs.c` and hook them to client stubs in `lib/file.c`.
6. For more information about the file system's on-disk structure, read `inc/fs.h` and `fs/fsformat.c`. You may also refer to last year's lab 5 text.

Client-Side File Operations

The functions in `lib/file.c` are specific to on-disk files, but UNIX file descriptors are a more general notion that also encompasses pipes, console I/O, etc. In JOS, each of these device types has (or will have in later labs) a corresponding `struct Dev`, with pointers to the functions that implement read/write/etc. for that device type. `lib/fd.c` implements the general UNIX-like file descriptor interface on top of this. Each `struct Fd` indicates its device type, and most of the functions in `lib/fd.c` simply dispatch operations to functions in the appropriate `struct Dev`.

`lib/fd.c` also maintains the *file descriptor table* region in each application environment's address space, starting at `FDTABLE`. This area reserves one page's worth (4KB) of address space for each of the up to `MAXFD` (currently 32) file descriptors that the application can have open at once. At any given time, a particular file descriptor table page is mapped if and only if the corresponding file descriptor is in use. Each file descriptor also has an optional "data page" in the region starting at `FILEDATA`, though we won't use that until later labs.

For nearly all interactions with files, user code should go through the functions in `lib/fd.c`. The one "public" function in `lib/file.c` is `open`, which constructs a new file descriptor by opening a named on-disk file.

Exercise 5. Implement `open`. The `open` function must find an unused file descriptor using the `fd_alloc()` function we have provided, make an IPC request to the file system environment to open the file, and return the number of the allocated file descriptor. Be sure your code fails gracefully if the maximum number of files are already open, or if any of the IPC requests to the file system environment fails.

Use **`make grade`** to test your code. Your code should pass all file system tests at this point.

Challenge 4! (5 points) Change the file system to keep most file meta-data in Unix-style inodes rather than in directory entries, and add support for hard links.

Spawning Processes

We have given you the code for `spawn` which creates a new environment, loads a program image from the file system into it, and then starts the child environment running this program. The parent process then continues running independently of the child. The `spawn` function effectively acts like a `fork` in UNIX followed by an immediate `exec` in the child process.

We implemented `spawn` rather than a UNIX-style `exec` because `spawn` is easier to implement from user space in "exokernel fashion", without special help from the kernel. Think about what you would have to do in order to implement `exec` in user space, and be sure you understand why it is harder.

Exercise 6. `spawn` relies on the new syscall `sys_env_set_trapframe` to initialize the state of the newly created environment. Test your code by running the `user/spawnhello` program from `kern/init.c`, which will attempt to spawn `/bin/hello` from the file system.

Use **`make grade`** to test your code.

Challenge 5! (5 points) Implement Unix-style `exec`.

Challenge 6! (5 points) Implement `mmap`-style memory-mapped files and modify `spawn` to map pages directly from the ELF image when possible.

Sharing library state across fork and spawn

The UNIX file descriptors are a general notion that also encompasses pipes, console I/O, etc. In JOS, each of these device types has a corresponding `struct Dev`, with pointers to the functions that implement read/write/etc. for that device type. `lib/fd.c` implements the general UNIX-like file descriptor interface on top of this. Each `struct Fd` indicates its device type, and most of the functions in `lib/fd.c` simply dispatch operations to functions in the appropriate `struct Dev`.

`lib/fd.c` also maintains the *file descriptor table* region in each application environment's address space, starting at `FSTABLE`. This area reserves a page's worth (4KB) of address space for each of the up to `MAXFD` (currently 32) file descriptors the application can have open at once. At any given time, a particular file descriptor table page is mapped if and only if the corresponding file descriptor is in use. Each file descriptor also has an optional "data page" in the region starting at `FILEDATA`, which devices can use if they choose.

We would like to share file descriptor state across `fork` and `spawn`, but file descriptor state is kept in user-space memory. Right now, on `fork`, the memory will be marked copy-on-write, so the state will be duplicated rather than shared. (This means environments won't be able to seek in files they didn't open themselves and that pipes won't work across a fork.) On `spawn`, the memory will be left behind, not copied at all. (Effectively, the spawned environment starts with no open file descriptors.)

We will change `fork` to know that certain regions of memory are used by the "library operating system" and should always be shared. Rather than hard-code a list of regions somewhere, we will set an otherwise-unused bit in the page table entries (just like we did with the `PTE_COW` bit in `fork`).

We have defined a new `PTE_SHARE` bit in `inc/lib.h`. This bit is one of the three PTE bits that are marked "available for software use" in the Intel and AMD manuals. We will establish the convention that if a page table entry has this bit set, the PTE should be copied directly from parent to child in both `fork` and `spawn`. Note that this is different from marking it copy-on-write: as described in the first paragraph, we want to make sure to *share* updates to the page.

Exercise 7. Change `duppage` in `lib/fork.c` to follow the new convention. If the page table entry has the `PTE_SHARE` bit set, just copy the mapping directly. (You should use `PTE_SYSCALL`, not `0xfff`, to mask out the relevant bits from the page table entry. `0xfff` picks up the accessed and dirty bits as well.)

Likewise, implement `copy_shared_pages` in `lib/spawn.c`. It should loop through all page table entries in the current process (just like `fork` did), copying any page mappings that have the `PTE_SHARE` bit set into the child process.

Use **`make run-testpteshare`** to check that your code is behaving properly. You should see lines that say "`fork handles PTE_SHARE right`" and "`spawn handles PTE_SHARE right`".

Use **`make run-testfdsharing`** to check that file descriptors are shared properly. You should see lines that say "`read in child succeeded`" and "`read in parent succeeded`".

The keyboard interface

For the shell to work, we need a way to type at it. QEMU has been displaying output we write to the CGA display and the serial port, but so far we've only taken input while in the kernel monitor. In QEMU, input typed in the graphical window appear as input from the keyboard to JOS, while input typed to the console appear as characters on the serial port. `kern/console.c` already contains the keyboard and serial drivers that have been used by the kernel monitor since lab 1, but now you need to attach these to the rest of the system.

Exercise 8. In your `kern/trap.c`, call `kbd_intr` to handle trap `IRQ_OFFSET+IRQ_KBD` and `serial_intr` to handle trap `IRQ_OFFSET+IRQ_SERIAL`.

We implemented the console input/output file type for you, in `lib/console.c`.

Test your code by running **`make run-testkbd`** and type a few lines. The system should echo your lines back to you as you finish them. Try typing in both the console and the graphical window, if you have both available.

The Shell

Run **`make run-icode`** or **`make run-icode-nox`**. This will run your kernel and start `user/icode`. `icode` execs `init`, which will set up the console as file descriptors 0 and 1 (standard input and standard output). It will then spawn `sh`, the shell. You should be able to run the following commands:

```
	echo hello world | cat
	cat lorem |cat
	cat lorem |num
	cat lorem |num |num |num |num |num
	lsfd
	cat script
	sh <script
```

Note that the user library routine `cprintf` prints straight to the console, without using the file descriptor code. This is great for debugging but not great for piping into other programs. To print output to a particular file descriptor (for example, 1, standard output), use `fprintf(1, "...", ...)`. `printf("...", ...)` is a short-cut for printing to FD 1. See `user/lsfd.c` for examples.

Run **`make run-testshell`** to test your shell. `testshell` simply feeds the above commands (also found in `fs/testshell.sh`) into the shell and then checks that the output matches `fs/testshell.key`.

Your code should pass all tests at this point. As usual, you can grade your submission with **`make grade`** and hand it in with **`make handin`**.

This completes the lab.

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