Lab 11: File System

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References:

- Silberschatz, et al. *Operating System Concepts* (10e), 2018
- Materials from OS courses offered at TCNJ (Dr. Jikai Li), Princeton, Rutgers, Columbia (Dr. Junfeng Yang), Stanford, MIT, UWisc, VT

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Agenda

- UNIX file system and inode exercise
- File System Example: xv6

Exercise 12.21

- Create two simple text files named file1.txt and file3.txt whose contents are unique sentences.
- Open file1.txt and examine its contents. Next, obtain the inode number of this file with the command

  ls -li file1.txt

- This will produce output similar to the following:

  16980 -rw-r--r-- 2 os os 22 Sep 14 16:13 file1.txt

- The inode number is boldfaced. The inode number of file1.txt is likely to be different on your system.

Exercise 12.21 (cont.)

- The UNIX ln command creates a link between a source and target file. This command works as follows: ln [-s] <source file> <target file>
- UNIX provides two types of links: (1) **hard links** and (2) **soft links**. A hard link creates a separate target file that has the same inode as the source file. Enter the following command to create a hard link between file1.txt and file2.txt: ln file1.txt file2.txt
- What are the inode values of file1.txt and file2.txt? Are they the same or different? Do the two files have the same—or different—contents?
- Next, edit file2.txt and change its contents. After you have done so, examine the contents of file1.txt. Are the contents of file1.txt and file2.txt the same or different?
- Next, enter the following command which removes file1.txt: rm file1.txt
- Does file2.txt still exist as well?

Exercise 12.21 (cont.)

- Now examine the man pages for both the rm and unlink commands. Afterwards, remove file2.txt by entering the command

  strace rm file2.txt

- The strace command traces the execution of system calls as the command rm file2.txt is run. What system call is used for removing file2.txt?

- A soft link (or symbolic link) creates a new file that “points” to the name of the file it is linking to. In the source code available with this text, create a soft link to file3.txt by entering the following command:

  ln -s file3.txt file4.txt

- After you have done so, obtain the inode numbers of file3.txt and file4.txt using the command:

  ls -li file*.txt

Exercise 12.21 (cont.)

- Are the inodes the same, or is each unique? Next, edit the contents of file4.txt. Have the contents of file3.txt been altered as well?
- Lastly, delete file3.txt. After you have done so, explain what happens when you attempt to edit file4.txt.

Indirect link and max file size

- For ease of debugging, we change Makefile so that CPUS option to 1 and add -snapshot switch at the end of QEMUOPTS as explained in above link.

- Let's think about the size of the file system that we are trying to make. We want to implement doubly-indirect system. How many blocks at maximum will one inode (i.e., one file) can access? That should be

  12 (direct) + 128 (single-indirect) + 128 * 128 (double-indirect) = 16,524

- That's the number of blocks that an inode file can access. This is equivalent to

  16,524 * 512 = 8,460,288 bytes = 8,262 KB = about 8.07 MB

- So, the maximum file size in this system will be about 8.07 MB.

fs.h and fs.c

- you need to read (and probably modify) following files, among others:
  - fs.h: Contains the inode definition, file system size, etc.
  - fs.c: Implementation of most of the file system features

- On the other hand, you may want to make change to mkfs.c file. This is **NOT** a user program in xv6. It is a Linux program to initialize xv6 disk image and file system. Consider this task as installing a new hard disk and formatting it. By default, it has following definition near the top:

```
int nblocks = 985;
int nlog = LOGSIZE;
int ninodes = 200;
int size = 1024;
```

fs.h and fs.c (cont.)

- The last number denotes the total size of the disk, i.e., total number of sectors. Thus, fs.img, our hard disk size should be 1024 * 512 = 524,288 bytes. You can check this number using ls.
- If size = 5,860,844 sectors as in the reference link above, that means the disk size will be about 2.8 GB.
- Let's try to create a 20 MB disk. To do this, change size to be 40,960. If you run [make clean] and [make], you will see an error:

```
./mkfs fs.img README _cat _echo _forktest _grep _init _kill _ln _ls _mkdir _rm _sh _stressfs _usertests _wc _zombie
used 39 (bit 11 ninode 26) free 39 log 10 total 1034
mkfs: mkfs.c:93: main: Assertion `nblocks + usedblocks + nlog == size' failed.
Makefile:169: recipe for target 'fs.img' failed
make: *** [fs.img] Aborted (core dumped)
make: *** Deleting file 'fs.img'
rm wc.o grep.o mkdir.o rm.o ln.o stressfs.o kill.o echo.o init.o usertests.o zombie.o cat.o sh.o ls.o
```

- Why?

fs.h and fs.c (cont.)

- As the assertion message shows, it should be **(number of usable blocks) + (number of blocks used by file system) + (number of blocks used by log/journal)**. The last part is defined in param.h as

```
#define LOGSIZE     10
```

- To understand the middle part, you need to read mkfs.c. You can find following lines:

```
bitblocks = size/(512*8) + 1;
usedblocks = ninodes / IPB + 3 + bitblocks;
freeblock = usedblocks;

printf("used %d (bit %d ninode %zu) free %u log %u total %d\n", usedblocks,
        bitblocks, ninodes/IPB + 1, freeblocks, nlog, nblocks+usedblocks+nlog);

assert(nblocks + usedblocks + nlog == size);
```

fs.h and fs.c (cont.)

```
bitblocks = size/(512*8) + 1;
usedblocks = ninodes / IPB + 3 + bitblocks;
freeblock = usedblocks;

printf("used %d (bit %d ninode %zu) free %u log %u total %d\n", usedblocks,
        bitblocks, ninodes/IPB + 1, freeblocks, nlog, nblocks+usedblocks+nlog);

assert(nblocks + usedblocks + nlog == size);
```

fs.h

```
// Inodes per block.
#define IPB           (BSIZE / sizeof(struct dinode))
```

512 B

Number of i-nodes contained in each block

In the original xv6, this is 8 since
sizeof (dinode) =
2 + 2 + 2 + 2 + 4 + 4 * 13 = 64
and
512 / 64 = 8

fs.h and fs.c (cont.)

- Comments at top of fs.h:

```
// Block 0 is unused
// Block 1 is super block
// Blocks 2 through sb.ninodes/IPB hold inodes
// Then free bitmap blocks holding sb.size bits
// Then sb.nblocks data blocks
// Then sb.nlog log blocks
```

- Here, important part is free bitmap blocks. They contain information whether each block in disk is in use of not, by using bitmap calculation. Each byte in the bitmap block can contain information for 8 blocks (8 bits = 1 byte), and each block is 512 bytes.
- Thus, given 40.960 total number of sectors (= potential blocks), we need 10 blocks to contain availability information. 1 additional block is for numerical remainders after division.

fs.h and fs.c (cont.)

- Comments at top of fs.h:

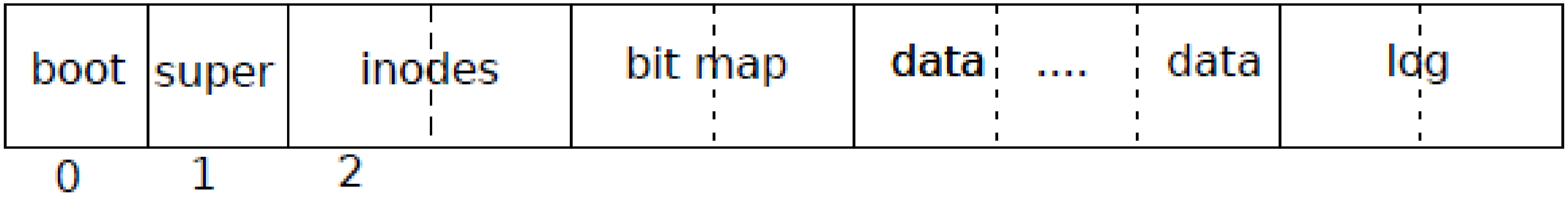
```
// Block 0 is unused
// Block 1 is super block
// Blocks 2 through sb.ninodes/IPB hold inodes
// Then free bitmap blocks holding sb.size bits
// Then sb.nblocks data blocks
// Then sb.nlog log blocks
```

- We need the additional bitblock to accommodate the remaining blocks. Total number of usedblocks in line 87 of mkfs.c, means the total number of blocks used by super block, inodes, and the bitmap.
- **3 additional blocks come from the fact that, as described in fs.h, we have 2 blocks (1 boot block + 1 super block) at the beginning, and another extra block for remainder of ninodes / IPB calculation.**

fs.h and fs.c (cont.)

- That explains every single portion of our disk structure. Since we did not change the maximum number of inodes, we need

1	boot block
1	super block
26	inode blocks (200 / 8 + 1)
11	bitblocks (40,960 / (512 * 8) + 1)
10	log/journal blocks



fs.h and fs.c (cont.)

- Therefore, we need total of 49 blocks used for the file system in 20 MB size of disk. Remainder can be allocated for data, i.e., data blocks, as defined as nblocks in line 14 of mkfs.c.
- In default xv6, since the disk size was 1024 blocks, only 1 bit block suffice the need. Thus, in that case, 39 blocks were needed for file system, thus 985 blocks can be used for data blocks. Therefore, in Project 4, nblocks should be 40,960 – 49 = 40,911 blocks.

```
14  int nblocks = 40911;
15  int nlog = LOGSIZE;
16  int ninodes = 200;
17  int size = 40960;
```

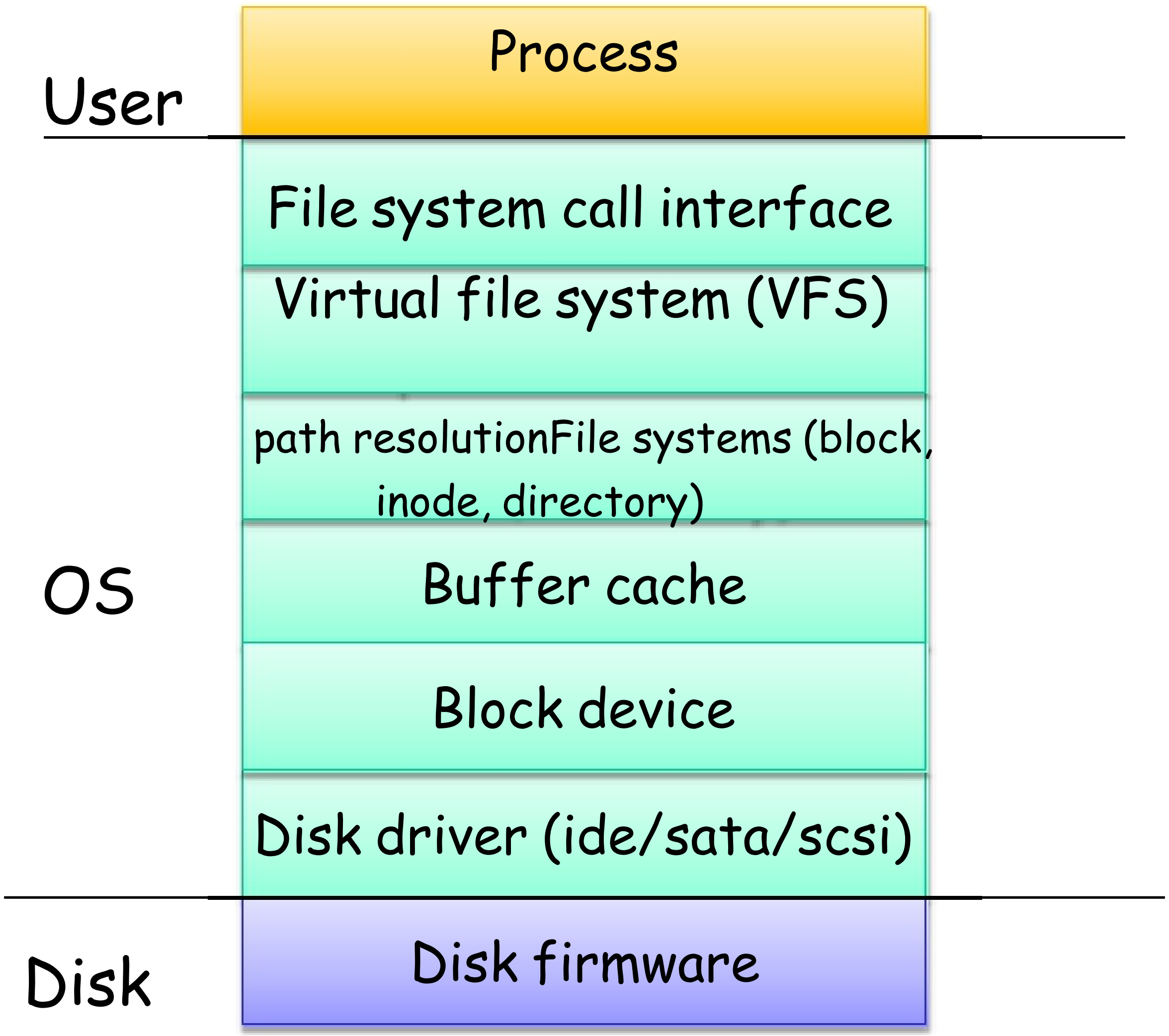
- Try to make changes accordingly in mkfs.c and recompile xv6

fs.h and fs.c (cont.)

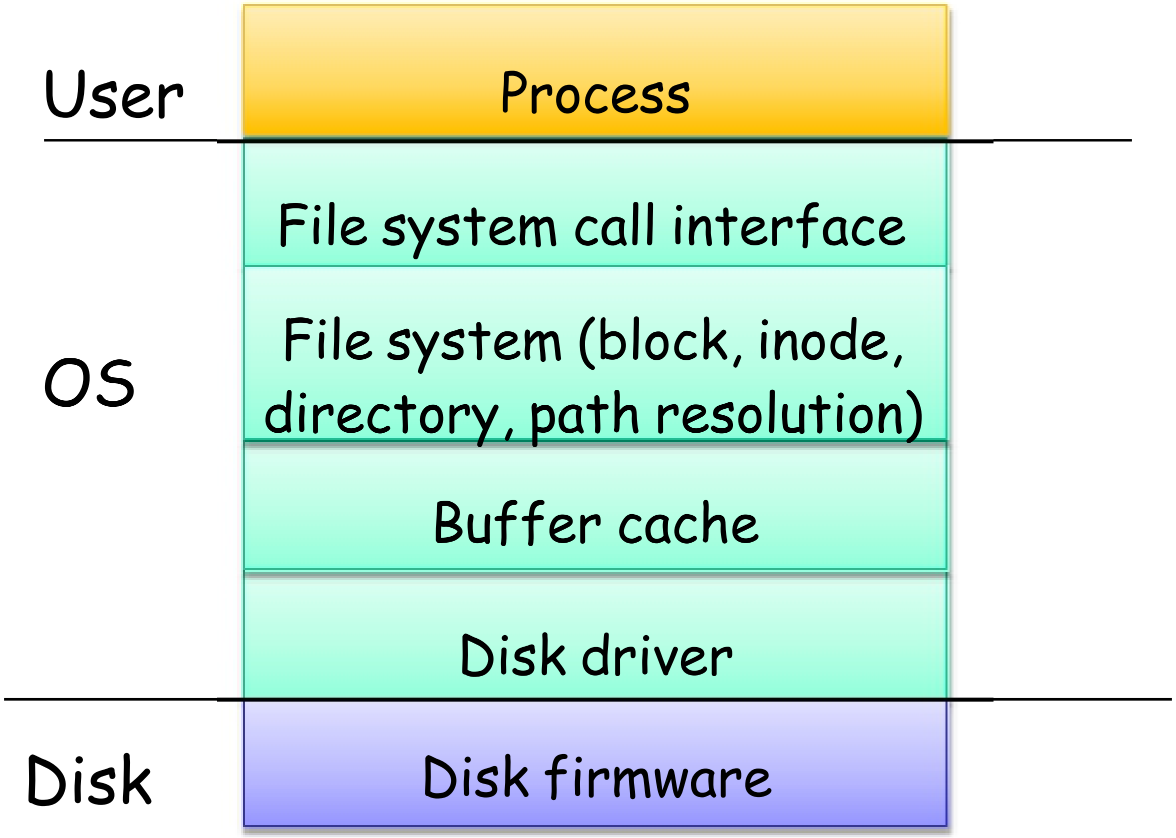
- fs.img file was created with correct size of 20,971,520 bytes = 20 MB.

```
oscreader@ubuntu:~/work/xv6$ ls -l fs*
-rw-rw-r-- 1 oscreader oscreader    14877 Nov 28 02:19 fs.c
-rw-rw-r-- 1 oscreader oscreader      113 Nov 28 03:21 fs.d
-rw-rw-r-- 1 oscreader oscreader     1516 Nov 27 20:03 fs.h
-rw-rw-r-- 1 oscreader oscreader 20971520 Nov 28 04:17 fs.img
-rw-rw-r-- 1 oscreader oscreader    17412 Nov 28 03:21 fs.o
oscreader@ubuntu:~/work/xv6$ ls -hl fs*
-rw-rw-r-- 1 oscreader oscreader  15K Nov 28 02:19 fs.c
-rw-rw-r-- 1 oscreader oscreader  113 Nov 28 03:21 fs.d
-rw-rw-r-- 1 oscreader oscreader 1.5K Nov 27 20:03 fs.h
-rw-rw-r-- 1 oscreader oscreader  20M Nov 28 04:17 fs.img
-rw-rw-r-- 1 oscreader oscreader  18K Nov 28 03:21 fs.o
oscreader@ubuntu:~/work/xv6$
```

Layered approach to storage systems



xv6 storage layers



xv6 disk driver

- ide.c
- iderw(struct buf *b): read or write disk sector
- idestart(struct buf *b): start request for b
- ideintr(): ide interrupt handler
- ideinit(): ide initializer

xv6 buffer cache

- bio.c
- struct buf
  - flags: B_BUSY, B_VALID, B_DIRTY
- struct bcache
  * head: LRU list of cached blocks
- bread(): read disk sector and return buffer
- bwrite(): write buffer to disk sector
- bget(): look up buffer cache for sector and set busy flag
- brelse(): clear busy flag and move buffer to head
- binit(): initialize buffer cache

xv6 buffer cache locking

- bcache.lock: lock for entire buffer cache

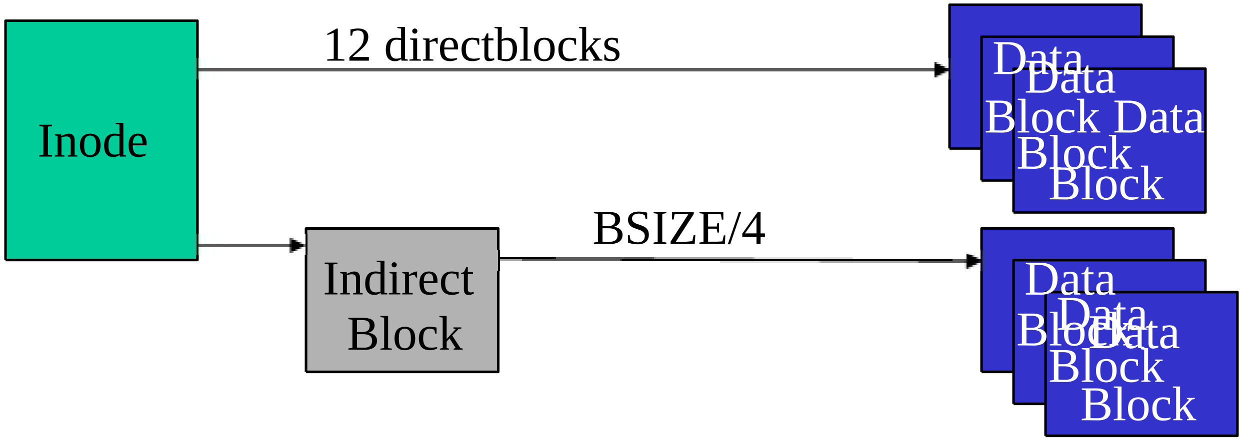
- b->flags & B_BUSY: busy bit for each buffer

- Ensures that only one process can be touching a struct buf at any time

xv6 file system layout

- fs.h, fs.c, mkfs.c
- struct superblock

xv6 file and directory layout



- NDIRECT = 12
- NINDIRECT = BSIZE/4 = 128
- struct dinode in fs.h, struct inode in file.h
- struct dirent in fs.h

xv6 block operations

- readsb(): read on-disk super block into in-mem super block

- bzero(): zero a block
- balloc(): allocate a block, set bitmap
- bfree(): free a block, clear bitmap

xv6 inode operations

- bmap(): map data block number to disk block number
- itrunc(): resize inode data
- ialloc(): allocate a new inode
- iupdate(): update information in inode

xv6 inode synchronization operations

- iget(): find in-memory inode from inode cache and bump reference count
- idup(): bump reference count
- iput(): decrement reference count and truncate inode if necessary
- ilock(): lock inode for read and write by setting I_BUSY flag
- iunlock(): unlock inode by clearing I_BUSY flag; must call iunlock() before iput()

xv6 file system calls

- file.c, sysfile.c

- Examples file system calls
  - sys_open()
  - sys_mkdir()

- Path resolution
  - namei()
  - nameiparent()

Exercise (no submission)

- Read Chapter 6 and write a report explaining, in your own words,
  - How xv6's buffer cache works
  - How xv6's journaling (log) works
  - How what is inode and how it is implemented in xv6

- Add the following line at the beginning of the log_write() function in log.c:

  cprintf("log_write %d\n", b->sector);

  - Try the commands '**$ echo > a**', '**$ echo x > a**', and '**$ rm a**'. Take a snapshot of each command result. Explain, in detail, what is happening, **line by line**, of the outcome. (It is very important that you understand why each line is printed!)