CS111, Lecture 3

Filesystem Design

😷 masks strongly recommended

Reminder: PollEverywhere

- Visit pollev.stanford.edu to log in (or use the PollEverywhere app) and sign in with your **@stanford.edu email – NOT your personal email!**

Announcements

- Remember to input your section preferences by 5PM Sat! Link is on the course website (under "Sections").
- Assign0 due Tues. 1/17 at 11:59PM PDT
  - **Clarification 1:** for debugging question "which line in the file causes the crash", we are looking for the most specific line in that program that causes the crash.
  - **Clarification 2:** fix should be changing 1 line (e.g., add 1 new line or change 1 line to be something else). Don't introduce any other issues like memory leaks!

Topic 1: Filesystems - How can we design filesystems to manage files on disk, and what are the tradeoffs inherent in designing them? How can we interact with the filesystem in our programs?

CS111 Topic 1: Filesystems

1. Filesystems introduction and design — **Lecture 1**
2. Case study: Unix V6 Filesystem — **Lecture 2 / Today / Lecture 4**
3. Filesystem System calls and file descriptors — **Lecture 5**
4. Crash recovery — **Lectures 6-7**

assign1: implement portions of the Unix v6 filesystem!

Learning Goals

- Explore the design of the Unix V6 filesystem
- Understand how we can use inodes to store and access file data
- Learn about how inodes can accommodate small and large files

Plan For Today

- **Recap**: filesystems so far
- The Unix V6 Filesystem and Inodes
- **Practice**: reading file data
- Large files and Singly-Indirect Addressing
- **Practice**: singly-indirect addressing
- Large files and Doubly-Indirect Addressing

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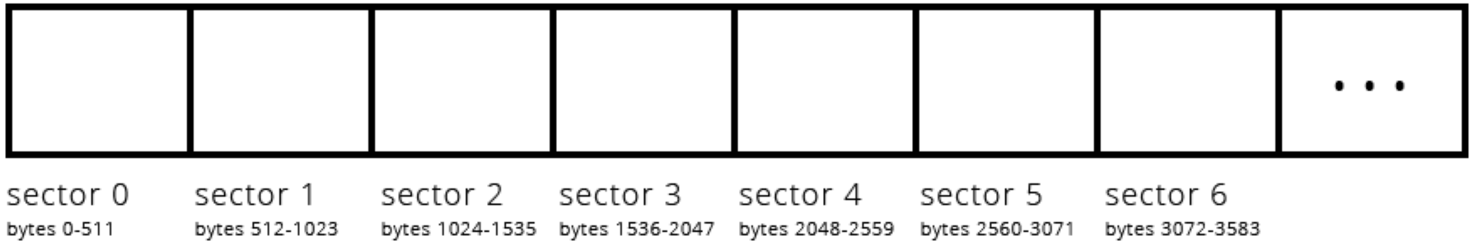
Recap: Filesystems

We are imagining that we are filesystem implementers. A **filesystem** is the portion of the OS that manages the disk.

- A hard drive (or, more commonly these days, flash storage) is persistent storage – it can store data between power-offs.
- We have a hard disk that supports only two operations (reading a sector and writing a sector), and need to layer complex filesystem operations (like reading/writing/locating entire files) on top.
- A “block” is a filesystem storage unit (1 or more sectors)
- Both file payload data and metadata must be stored on disk



Some Possible Filesystem Designs

- *Contiguous allocation* allocates a file in one contiguous space
- *Linked files* allocates files by splitting them into blocks and having each block store the location of the next block.
- *Windows FAT* is like linked files but stores the links in a "file allocation table" in memory for faster access.
- *Multi-level indexes* store all block numbers for a file so we can quickly jump to any point in the file (but how?). Example: Unix v6 Filesystem
- Many other designs possible – many use a tree-like structure

Filesystem Designs

- **Internal Fragmentation**: space allocated for a file is larger than what is needed. A file may not take up all the space in the blocks it's using. E.g. block = 512 bytes, but file is only 300 bytes. (you could share blocks between multiple files, but this gets complex)
- **External Fragmentation (issue with contiguous allocation)**: no single space is large enough to satisfy an allocation request, even though enough aggregate free disk space is available
- Wait, how do we look up / find files? (we'll talk more about this!)

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Unix V6 Inodes

The Unix v6 filesystem stores inodes on disk together in the **inode table** for quick access. An **inode** ("index node") is a grouping of data about a single file. It’s stored on disk, but we can read it into memory when the file is open.

- inodes are stored in a reserved region starting at block 2 (block 0 is "boot block" containing hard drive info, block 1 is "superblock" containing filesystem info). Typically, at most 10% of the drive stores metadata.
- Inodes are 32 bytes big, and 1 block = 1 sector = 512 bytes, so 16 inodes/block.
- Filesystem goes from **filename** to **inode number** ("inumber") to **file data**.

Unix V6 Inodes

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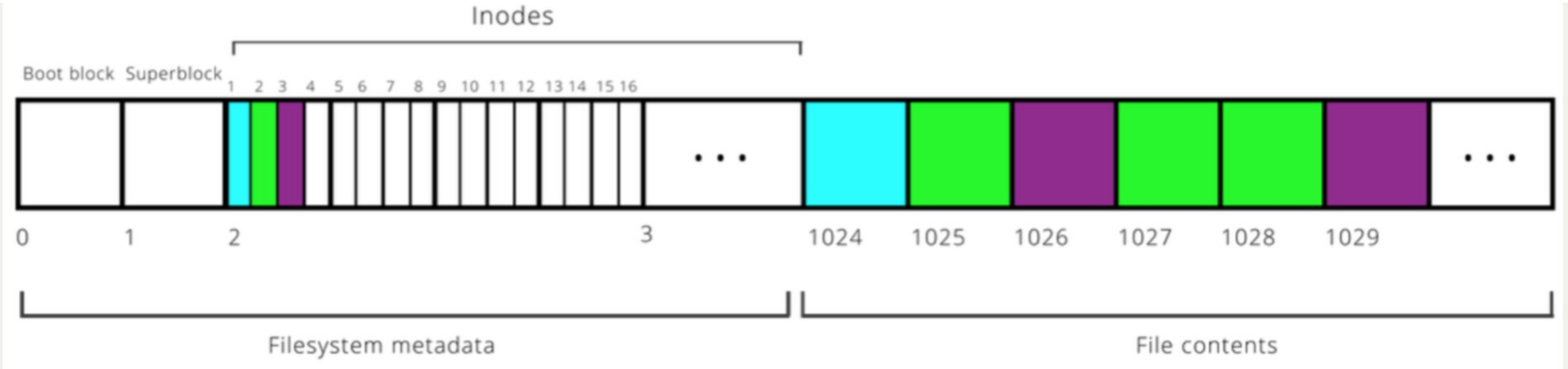
- Each Unix v6 inode has space for 8 block numbers



Unix V6 Inodes

```
struct inode {
  uint16_t  i_mode;     // bit vector of file
                        //   type and permissions
  uint8_t   i_nlink;    // number of references
                        //   to file
  uint8_t   i_uid;      // owner
  uint8_t   i_gid;      // group of owner
  uint8_t   i_size0;    // most significant byte
                        //  of size
  uint16_t  i_size1;    // lower two bytes of size
                        //  (size is encoded in a
                        //  three-byte number)
  uint16_t  i_addr[8];  // device addresses
                        //   constituting file
  uint16_t  i_atime[2]; // access time
  uint16_t  i_mtime[2]; // modify time
};
```

For now, we just need **i_addr**; that is an array of 8 block numbers, stored in the inode. **i_addr entries** are in order of file data, but the blocks could be scattered all over disk. E.g. a file could have i_addr = [12, 200, 56, …].

Unix V6 Inodes

Let's imagine that the hard disk creators provide software to let us interface with the disk.

```
void readSector(size_t sectorNumber, void *data);
void writeSector(size_t sectorNumber, const void *data);
```

*(Refresher: size_t is an unsigned number, void * is a generic pointer)*

Let’s look at how we might access inodes in filesystem code.

Unix V6 Inodes

```
char buf[DISKIMG_SECTOR_SIZE];
readSector(2, buf); // always reads in 512 bytes

// now buf is filled with 512 bytes from block 2
```

Unix V6 Inodes

```
struct inode {
  uint16_t  i_addr[8];  // block numbers
  ...
};

struct inode inodes[512 / sizeof(struct inode)];
readSector(2, inodes);

// Loop over each inode in sector 2
for (size_t i = 0; i < sizeof(inodes) /
    sizeof(inodes[0]); i++) {
    printf("%\n", inodes[i].i_addr[0]); // first block num
}
```

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Practice #1: Inodes

Let's say we have an inode that looks like the following (remember 1 block = 1 sector = 512 bytes):

Inode:

size = 600 bytes

i_addr = [122, 56, X, X, X, X, X, X]

- How many bytes of block 122 store file payload data?
- How many bytes of block 56 store file payload data?

Bytes 0-511 (512 bytes) reside within block 122, bytes 512-599 (88 bytes) within block 56.

Practice #2: Inodes

Let's say we have an inode that looks like the following (remember 1 block = 1 sector = 512 bytes):

<u>Inode:</u>

size = 2000 bytes

i_addr = [56, 122, 45, 22, X, X, X, X]

- Which block number stores the index-1500th byte of the file?

Bytes 0-511 reside within block 56, bytes 512-1023 within block 122, bytes 1024-1535 within block 45, and bytes 1536-1999 at the front of block 22.

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File Size

Problem: with 8 block numbers per inode, the largest a file can be is 512 * 8 = 4096 bytes (~4KB). That definitely isn't realistic!

Let's say a file's payload is stored across 10 blocks:

45, 42, 15, 67, 125, 665, 467, 231, 162, 136

<u>Assuming that the size of an inode is fixed, where can we put these block numbers?</u>

Solution: let's store them *in a block*, and then store *that* block's number in the inode!

File Size

Let's say a file's payload is stored across 10 blocks:

451, 42, 15, 67, 125, 665, 467, 231, 162, 136

Solution: let's store them *in a block*, and then store *that* block's number in the inode! This approach is called *indirect addressing*.

Block 450	*Block 451*
451, 42, 15, 67, 125, 665, 467, 231, 162,136	The quick brown fox jumped over the...

Indirect Addressing

Design questions:

- Should we make *all* the block numbers in an inode use indirect addressing?
- Should we use this approach for all files, or just large ones?

Indirect addressing is useful but means that it takes more steps to get to the data, and uses more blocks.

Block 450	*Block 451*
451, 42, 15, 67, 125, 665, 467, 231, 162,136	The quick brown fox jumped over the...

Indirect Addressing

The Unix V6 filesystem uses *singly-indirect addressing* (blocks that store payload block numbers) just for large files.

- check flag or size in inode to know whether it is a small file (direct addressing) or large one (indirect addressing)
  - If small, each block number in the inode stores payload data
  - If large, **first 7 block numbers** in the inode stores block numbers for payload data
  - 8th block number? we'll get to that :)
- Let's assume for now that an inode for a large file uses all 8 block numbers for singly-indirect addressing. What is the largest file size this supports? Each block number is 2 bytes big.

Indirect Addressing

Let's assume for now that an inode for a large file uses all 8 block numbers for singly-indirect addressing. What is the largest file size this supports? Each block number is 2 bytes big.

8 block numbers in an inode x

256 block numbers per singly-indirect block x

512 bytes per block

= ~1MB

Practice: Indirect Addressing

Let's say we have an inode with the following information (remember 1 block = 1 sector = 512 bytes, and block numbers are 2 bytes big):

Inode:

size = 200,000 bytes

i_addr = [56, 122, X, X, X, X, X, X]

Which singly-indirect block stores the block number holding the index-150,000th byte of the file?

*Bytes 0-131,071 reside within blocks whose block numbers are in block 56. Bytes 131,072 (256*512) - 199,999 reside within blocks whose block numbers are in block 122.*

Even Larger Files

Problem: even with singly-indirect addressing, the largest a file can be is 8 * 256 * 512 = 1,048,576 bytes (~1MB). That still isn't realistic!

Solution: let's use *doubly-indirect addressing*; store a block number for a block that contains *singly-indirect block numbers*.

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Lecture 3 takeaway: The Unix v6 filesystem represents small files by storing direct block numbers, and larger files by using indirect addressing - storing 7 singly-indirect and 1 doubly-indirect block number.

Next time: directories, file lookup and links