CS111, Lecture 3
Unix V6 Filesystem

Announcements

- Lecture credit starts with today’s lecture – you can submit PollEV polls in person during live lecture, or complete the corresponding Canvas quiz by 30min prior to next lecture to get credit.
- Assign0 due Monday at 11:59PM, **no late submissions accepted** (except for OAE/Head TA extensions)
  - Check out our assignment Ed post for each assignment for pinned posts!
- Assignments preview: assign1 and assign3 are longer than 0 and 2, 4-6 similar to assign1 & 3
- Note: except for assign0 if needed, course staff cannot look at assignment code

CS111 Topic 1: Filesystems

Key Question: *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?*

Filesystems introduction and design → Case study: Unix V6 Filesystem → Crash Recovery → Filesystem System calls and file descriptors

Lecture 2 | **Today / Lecture 4** | **Lectures 5-6** | **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
- Assignment 1

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
- Assignment 1

Recap: Filesystems So Far

A **filesystem** is the portion of the OS that manages the disk (persistent storage). The disk only knows how to read a sector and write a sector.

- Blocks are the storage unit used by the filesystem, can be 1 or more sectors.

Designs we've discussed so far:

- *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* instead store all block numbers for a file together 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

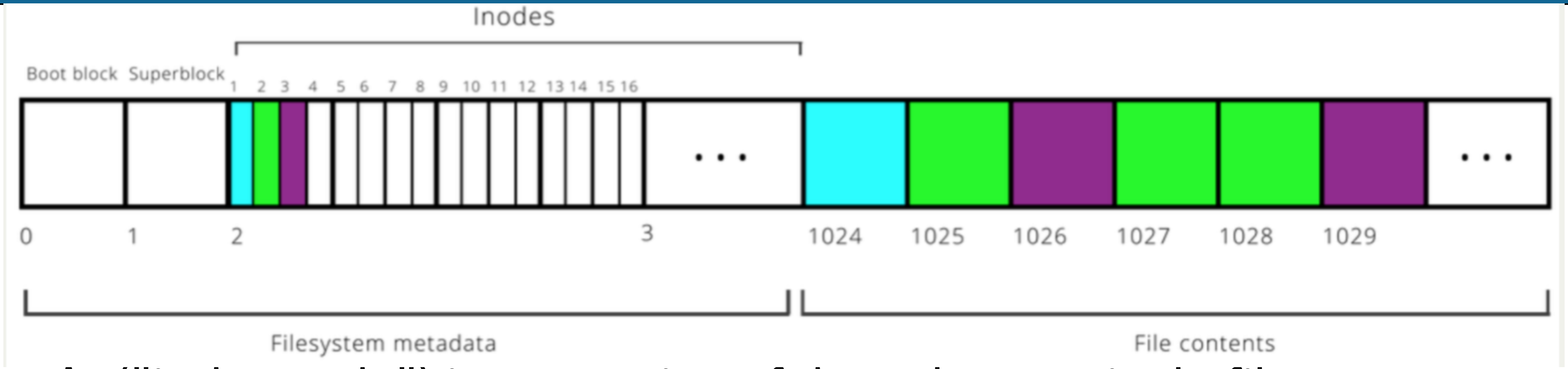
Filesystem Designs

- **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!)

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
- Assignment 1

Unix V6 Inodes



- An **inode** ("index node") is a grouping of data about a single file.
- The Unix v6 filesystem stores inodes on disk together in a fixed-size **inode table**. Each inode lives on disk, but we can read one into memory when a file is open.
- The inode table starts at block 2 (block 0 is "boot block" containing hard drive info, block 1 is "superblock" containing filesystem info). The inode table can span many blocks. 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

Each inode stores file information and has space for 8 block numbers.

```
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
};
```

Unix V6 Inodes

Each inode stores file information and has space for 8 block numbers.

```
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;** an array of 8 block numbers. **i_addr** entries are in file data order, not necessarily numerical order - the blocks could be scattered all over disk. E.g. a file could have i_addr = [12, 200, 56, …]. It uses only as many **i_addr** entries as needed to store file data.

Reading Second 16 Inodes From Disk

How do we access inodes on disk? E.g. how can we iterate over inodes 17-32?

```
for (int i = 17; i < 33; i++) {
     ...inodeTable[i]... // like this?
}
```

This won’t work – inodes (like file data) are stored on disk, not in memory. To access them, we must read them into memory first, sector by sector.

Reading Second 16 Inodes From Disk

Let's imagine that the hard disk creators provide software to let us interface with the disk. These can operate on 1 sector, regardless of what type of data it holds.

```
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*)

We also have our struct inode:

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

Reading Second 16 Inodes From Disk

```
int inodesPerBlock = DISKIMG_SECTOR_SIZE / sizeof(struct inode);
struct inode inodes[inodesPerBlock];
readSector(3, inodes);

// Loop over each inode in sector 3
for (size_t i = 0; i < inodesPerBlock; i++) {
    printf("%d\n", inodes[i].i_addr[0]); // print first block num
}
```

Reading Second 16 Inodes From Disk

We can pass in an array of any type to store the read-in data, but it’s easiest to use an array of the same type as the data being read in from disk.

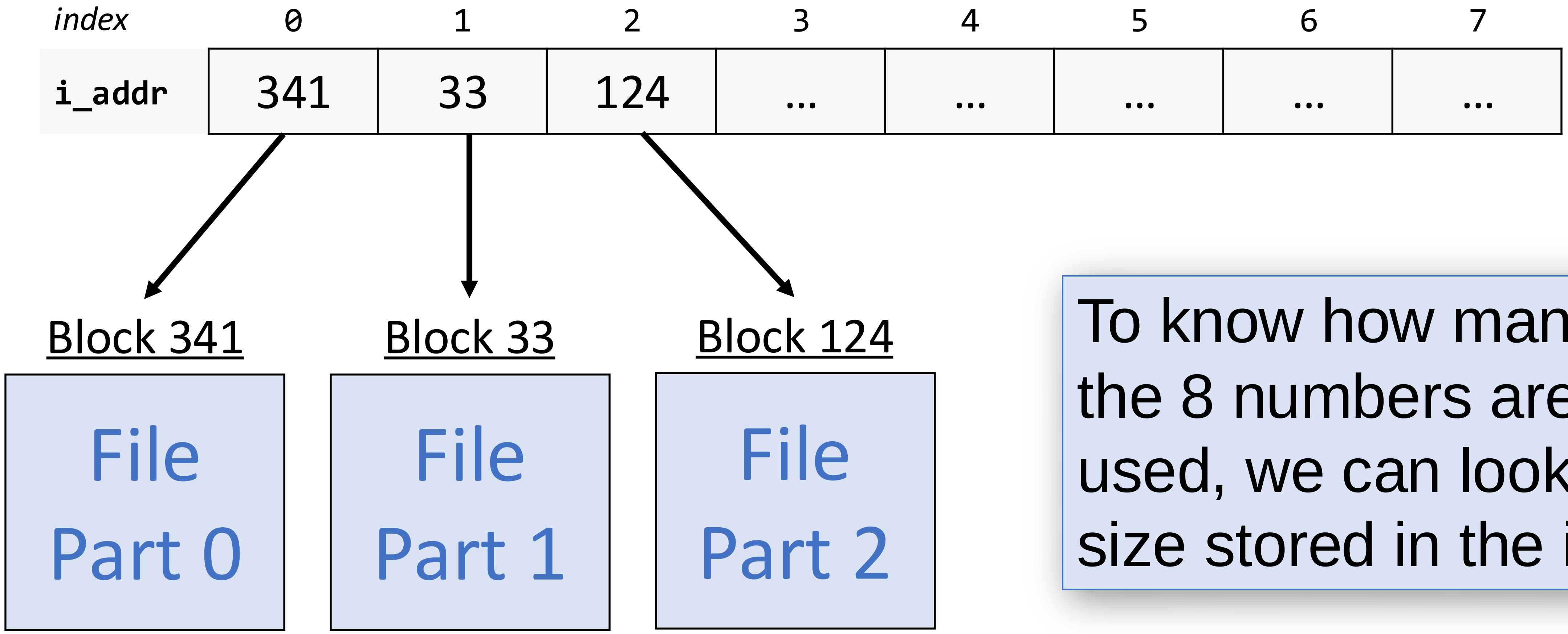
```
// use array of chars – harder to work with
char buf[DISKIMG_SECTOR_SIZE];
readSector(3, buf); // always reads in 512 bytes

// now buf is filled with 512 bytes from block 3
// but it’s an array of chars...must cast to access each inode
```

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

File Data

(For now) **i_addr** stores the numbers of blocks that contain payload data.



To know how many of the 8 numbers are used, we can look at the size stored in the inode.

Practice #1: File Data

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, ….]

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

Practice #1: File Data

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, ….]

- How many bytes of block 122 store file payload data? **512** (bytes 0-511)
- How many bytes of block 56 store file payload data? **88** (bytes 512-599)

Key Idea: we must read a full sector with readSector, but can ignore unused data

Practice #2: File Data

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

Inode:

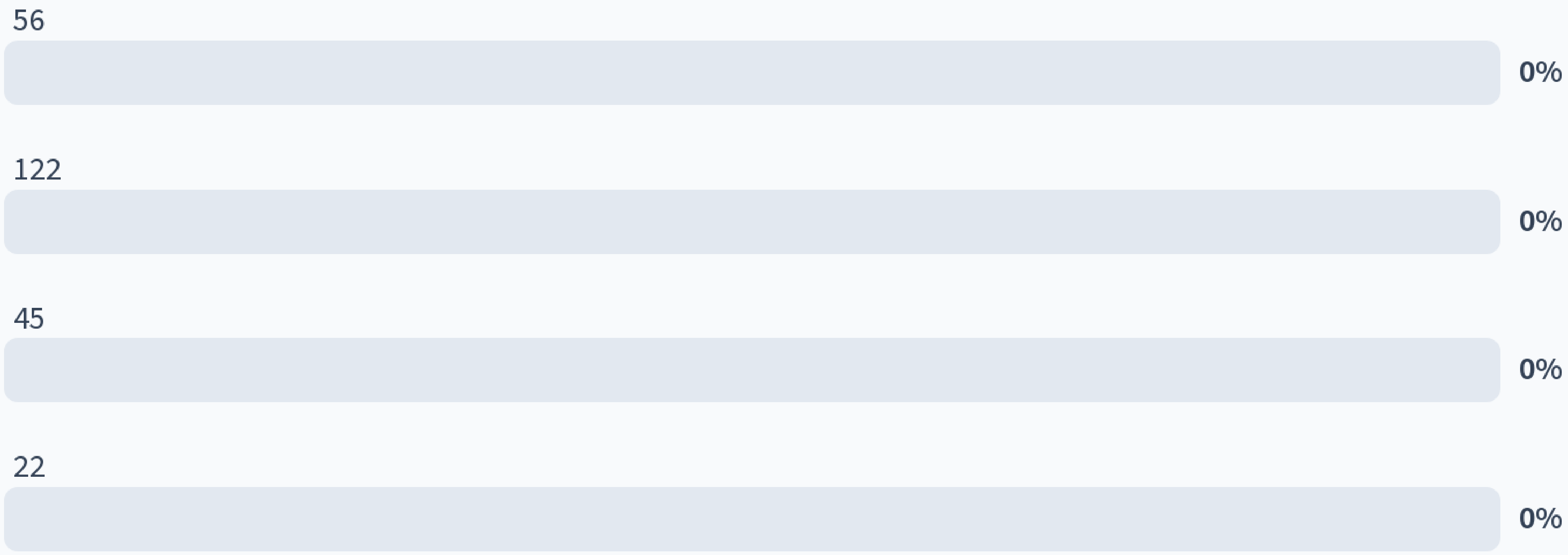
size = 2000 bytes

i_addr = [56, 122, 45, 22, …]

Which block number stores the index-1500th byte (0-indexed) of the file?

Respond on PollEv: pollev.com/cs111
or text CS111 to 22333 once to join.

With file size = 2000 bytes and block numbers = [56, 122, 45, 22], which block number stores the index-1500th (0-indexed) byte of the file?



56	0%
122	0%
45	0%
22	0%

Practice #2: File Data

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

Inode:

size = 2000 bytes

i_addr = [56, 122, 45, 22, …]

Which block number stores the index-1500th byte (0-indexed) 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.

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
- Assignment 1

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!

Assuming that the size of an inode is fixed, what can we do?

Solution: Unix V6 has two inode "modes": *small* and *large*, that dictate how it uses i_addr.

```
if ((inode.i_mode & ILARG) != 0) { // inode is “large mode”
```

A "small mode" inode is what we have seen already.   But what is a "large mode" inode?

“Large Mode” Inodes

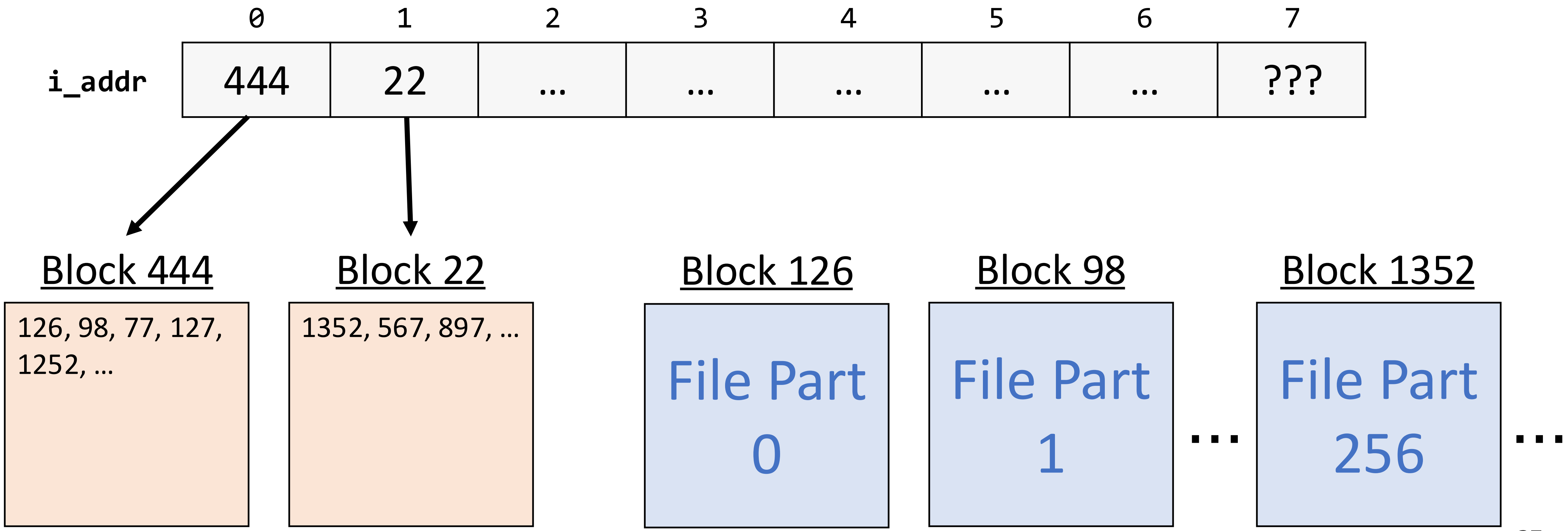
Let’s say a file’s data is stored across 300 blocks:

126, 98, 77, 127, 1252, *377, 81, 48, 198, 409, 150, 105, 110, 143, 338, 382, 173, 149, 178, 423…*

Key idea: the inode only fits 8. So let's store each group of 256 (512 / 2-byte-numbers) block numbers *in a block*, and then store *that* block's number in the inode! This approach is called *singly-indirect addressing*.

Singly-Indirect Addressing

If the inode is “large mode”, **i_addr** stores 7 numbers of blocks that contain block numbers, and those block numbers are of blocks that contain payload data. 8th block number? we'll get to that :)



“Large Mode” Inodes

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

- check flag in inode to know whether it is a “small mode” file (direct addressing) or “large mode” one (indirect addressing)
  - If **small**: all 8 block numbers are direct block numbers (block numbers of blocks that store file data)
  - If **large: first 7 block numbers** are singly-indirect block numbers (block numbers of blocks that store direct block numbers), and 8th is TBD ☺

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

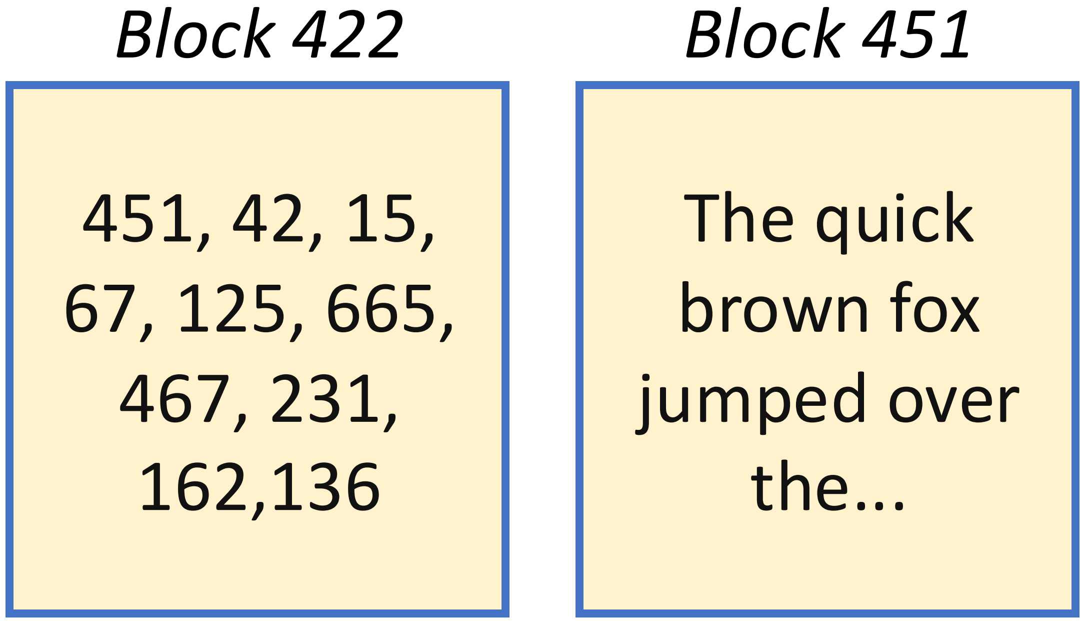
= ~1MB

Indirect Addressing: Design Decisions

We could use singly-indirect addressing in other ways, too – all design decisions!

- We could make *just some of* the block numbers in an inode use singly-indirect addressing, and others still be direct addressing
- We could have just one "mode" for files, instead of 2

One argument against indirect addressing: it takes more steps to get to the data and uses more blocks.



Practice: Indirect Addressing

Let's say we have a “large mode” 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, …]

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!

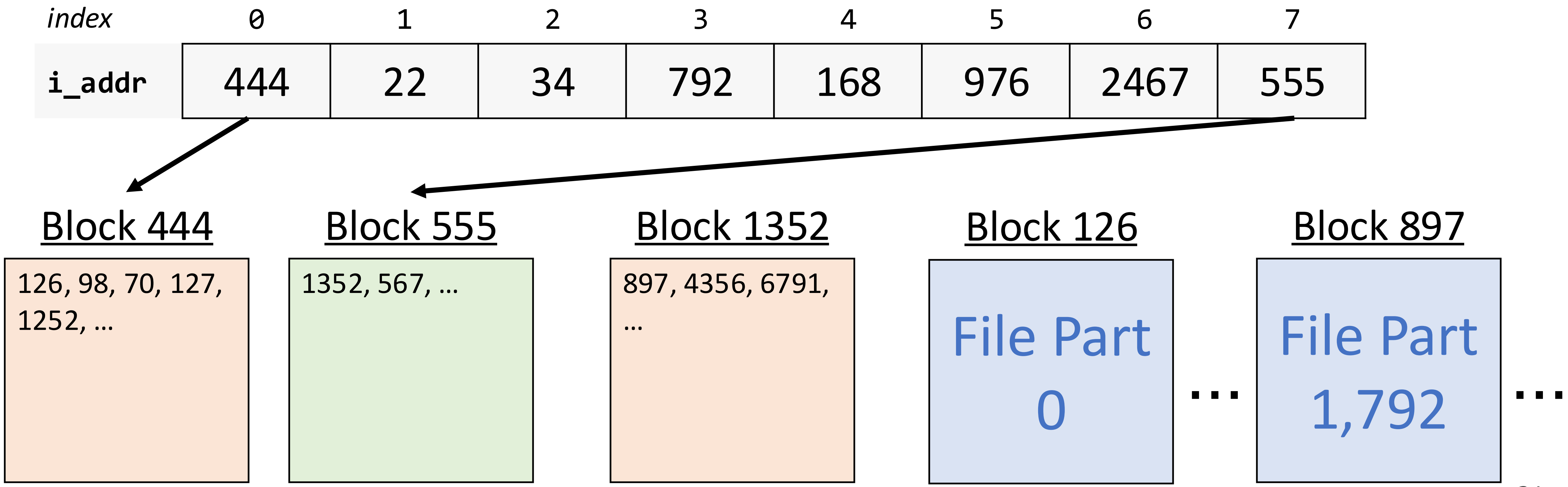
Solution: let’s have the 8th entry in **i_addr** use *doubly-indirect addressing*; store a block number for a block that contains *singly-indirect block numbers*.

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**
- Assignment 1

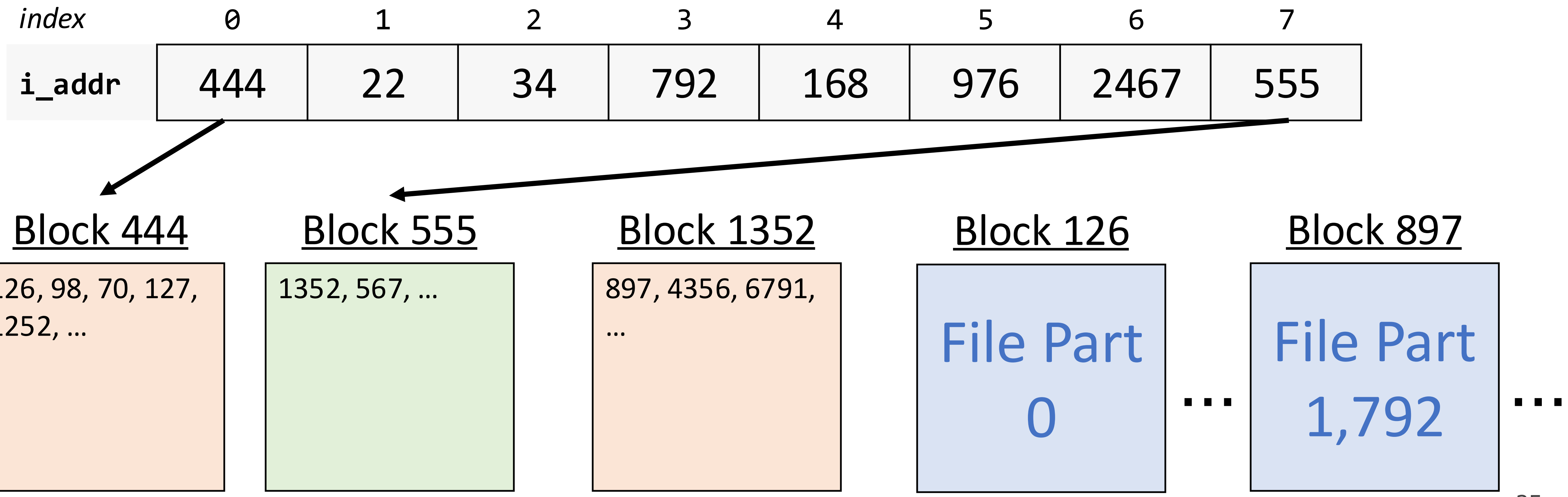
Large File Scheme

If the file is large, the first 7 entries in **i_addr** are *singly-indirect block numbers* (block numbers of blocks that contain direct block numbers). The 8th entry (if needed) is a *doubly-indirect block number* (the number of a block that contains singly-indirect block numbers).



Large File Scheme

Another way to think about it: a file can be represented using at most 7 + 256 = 263 singly-indirect blocks. The numbers of the first seven are stored in the inode. The numbers of the remaining 256 are stored in a block whose block number is stored in the inode.



Large File Scheme

An inode for a large file stores 7 singly-indirect block numbers and 1 doubly-indirect block number. What is the largest file size this supports? Each block number is 2 bytes big.

(7+256) singly-indirect block numbers total x

256 block numbers per singly-indirect block x

512 bytes per block

= ~34MB

Large File Scheme

An inode for a large file stores 7 singly-indirect block numbers and 1 doubly-indirect block number. What is the largest file size this supports? Each block number is 2 bytes big.

OR:

*(7 * 256 * 512) + (256 * 256 * 512) = ~34MB*

(singly indirect) + (doubly indirect)

Better! still not sufficient for today's standards, but perhaps in 1975. Moreover, since block numbers are 2 bytes, we can number at most 2^{16} = 65,536 blocks, meaning the entire filesystem can be at most 65,536 * 512 ~ 33MB.

“Large Mode” Inodes

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

- check flag in inode to know whether it is a “small mode” file (direct addressing) or “large mode” one (indirect addressing)
  - If **small**: all 8 block numbers are direct block numbers (block numbers of blocks that store file data)
  - If **large: first 7 block numbers** are singly-indirect block numbers (block numbers of blocks that store direct block numbers), 8th block number (if needed) is doubly-indirect (it refers to a block that stores singly-indirect block numbers)
- Files only use the block numbers they need (depending on their size)
- Note: doubly-indirect is useful (and there are many other possible designs!), but it means even more steps to access data.

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
- **Assignment 1**

Assignment 1

Implement core functions to read from a Unix v6 filesystem disk!

- **inode_iget** -> fetch a specific inode
- **inode_indexlookup** -> fetch a specific payload block number
- **file_getblock** -> fetch a specified payload block
- **directory_findname** -> fetch directory entry with the given name
- **pathname_lookup** -> fetch inumber for the file with the given path

Assignment 1

Implement core functions to read from a Unix v6 filesystem disk!

- **inode_iget** -> fetch a specific inode
- **inode_indexlookup** -> fetch a specific payload block number
- **file_getblock** -> fetch a specified payload block

can start immediately

- **directory_findname** -> fetch directory entry with the given name
- **pathname_lookup** -> fetch inumber for the file with the given path

will discuss next time!

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
- Assignment 1

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