CS162
Operating Systems and Systems Programming
Lecture 18

File Systems

October 30th, 2017
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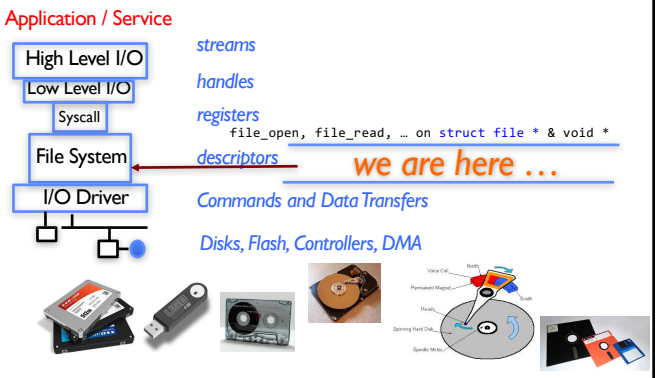
Recall: How do we Hide I/O Latency?

- Blocking Interface: "Wait"
  - When request data (*e.g.*, read() system call), put process to sleep until data is ready
  - When write data (*e.g.*, write() system call), put process to sleep until device is ready for data
- Non-blocking Interface: "Don't Wait"
  - Returns quickly from read or write request with count of bytes successfully transferred to kernel
  - Read may return nothing, write may write nothing
- Asynchronous Interface: "Tell Me Later"
  - When requesting data, take pointer to user's buffer, return immediately; later kernel fills buffer and notifies user
  - When sending data, take pointer to user's buffer, return immediately; later kernel takes data and notifies user

I/O & Storage Layers

Operations, Entities and Interface



Recall: C Low level I/O

- Operations on File Descriptors – as OS object representing the state of a file
  - User has a "handle" on the descriptor

```
#include <fcntl.h>
#include <unistd.h>
#include <sys/types.h>

int open (const char *filename, int flags [, mode_t mode])
int create (const char *filename, mode_t mode)
int close (int filedes)
```

Bit vector of:
- Access modes (Rd,Wr, …)
- Open Flags (Create, …)
- Operating modes (Appends, …)

Bit vector of Permission Bits:
- User|Group|Other X R|W|X

http://www.gnu.org/software/libc/manual/html_node/Opening-and-Closing-Files.html

Recall: C Low Level Operations

```
ssize_t read (int filedes, void *buffer, size_t maxsize)
 - returns bytes read, 0 => EOF, -1 => error
ssize_t write (int filedes, const void *buffer, size_t size)
 - returns bytes written
off_t lseek (int filedes, off_t offset, int whence)
 - set the file offset
   * if whence == SEEK_SET: set file offset to "offset"
   * if whence == SEEK_CRT: set file offset to crt location + "offset"
   * if whence == SEEK_END: set file offset to file size + "offset"
int fsync (int fildes)
 - wait for i/o of filedes to finish and commit to disk
void sync (void) - wait for ALL to finish and commit to disk
```

- When write returns, data is on its way to disk and can be read, but it may not actually be permanent!

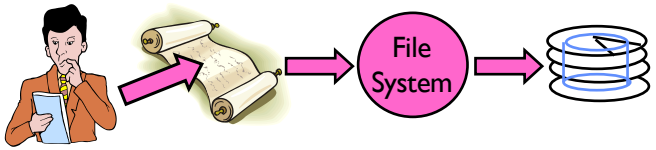
Building a File System

- File System: Layer of OS that transforms block interface of disks (or other block devices) into Files, Directories, etc.
- File System Components
  - **Naming**: Interface to find files by name, not by blocks
  - **Disk Management**: collecting disk blocks into files
  - **Protection**: Layers to keep data secure
  - **Reliability/Durability**: Keeping of files durable despite crashes, media failures, attacks, etc.

Recall: User vs. System View of a File

- User's view:
  - Durable Data Structures
- System's view (system call interface):
  - Collection of Bytes (UNIX)
  - Doesn't matter to system what kind of data structures you want to store on disk!
- System's view (inside OS):
  - Collection of blocks (a block is a logical transfer unit, while a sector is the physical transfer unit)
  - Block size ≥ sector size; in UNIX, block size is 4KB

Recall: Translating from User to System View



- What happens if user says: give me bytes 2—12?
  - Fetch block corresponding to those bytes
  - Return just the correct portion of the block
- What about: write bytes 2—12?
  - Fetch block
  - Modify portion
  - Write out Block
- Everything inside File System is in whole size blocks
  - For example, `getc()`, `putc()` ⇒ buffers something like 4096 bytes, even if interface is one byte at a time
- From now on, file is a collection of blocks

Disk Management Policies (1/2)

- Basic entities on a disk:
  - File: user-visible group of blocks arranged sequentially in logical space
  - Directory: user-visible index mapping names to files
- Access disk as linear array of sectors. Two Options:
  - Identify sectors as vectors [cylinder, surface, sector], sort in cylinder-major order, not used anymore
  - Logical Block Addressing (LBA): Every sector has integer address from zero up to max number of sectors
  - Controller translates from address ⇒ physical position
    - » First case: OS/BIOS must deal with bad sectors
    - » Second case: hardware shields OS from structure of disk

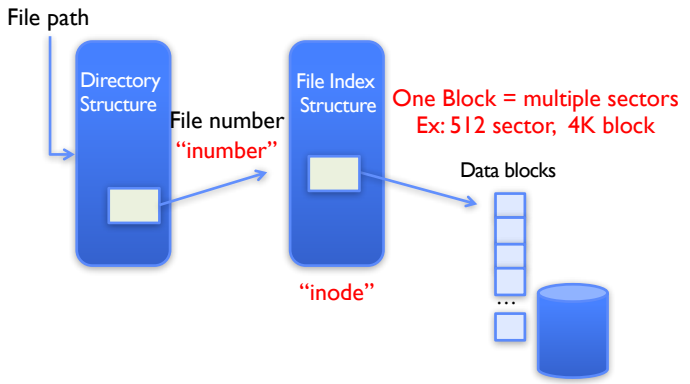
Recall: Disk Management Policies (2/2)

- Need way to track free disk blocks
  - Link free blocks together ⇒ too slow today
  - Use bitmap to represent free space on disk
- Need way to structure files: File Header
  - Track which blocks belong at which offsets within the logical file structure
  - Optimize placement of files' disk blocks to match access and usage patterns

Designing a File System …

- What factors are critical to the design choices?
- Durable data store => it's all on disk
- (Hard) Disks Performance !!!
  - Maximize sequential access, minimize seeks
- Open before Read/Write
  - Can perform protection checks and look up where the actual file resource are, in advance
- Size is determined as they are used !!!
  - Can write (or read zeros) to expand the file
  - Start small and grow, need to make room
- Organized into directories
  - What data structure (on disk) for that?
- Need to allocate / free blocks
  - Such that access remains efficient

Components of a File System



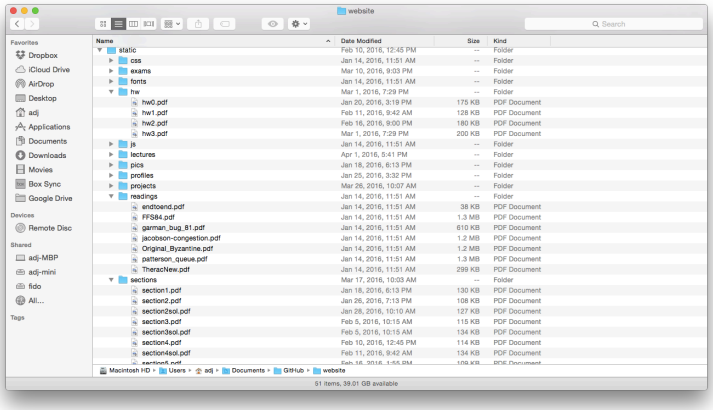
Components of a file system

file name → *file number* → *Storage block*

offset directory *offset* index structure

- Open performs *Name Resolution*
  - Translates pathname into a "file number"
    - » Used as an "index" to locate the blocks
  - Creates a file descriptor in PCB within kernel
  - Returns a "handle" (another integer) to user process
- Read, Write, Seek, and Sync operate on handle
  - Mapped to file descriptor and to blocks

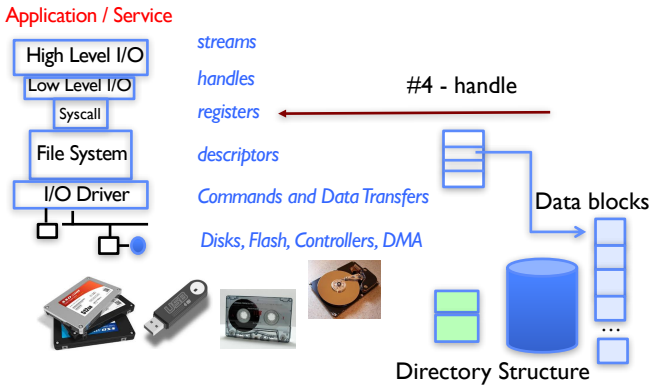
Directories



Directory

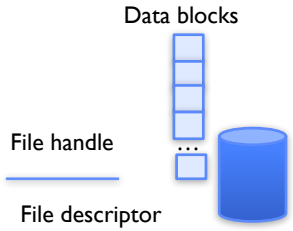
- Basically a hierarchical structure
- Each directory entry is a collection of
  - Files
  - Directories
    - » A link to another entries
- Each has a name and attributes
  - Files have data
- Links (hard links) make it a DAG, not just a tree
  - Softlinks (aliases) are another name for an entry

I/O & Storage Layers

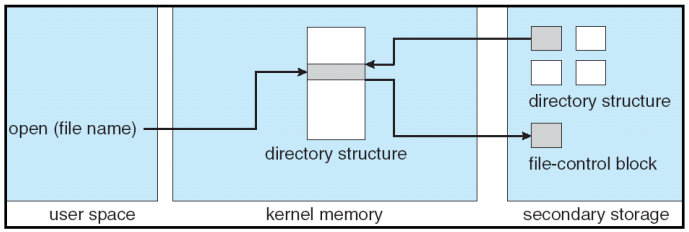


File

- Named permanent storage
- Contains
  - Data
    - » Blocks on disk somewhere
  - Metadata (Attributes)
    - » Owner, size, last opened, …
    - » Access rights
      - R, W, X
      - Owner, Group, Other (in Unix systems)
      - Access control list in Windows system

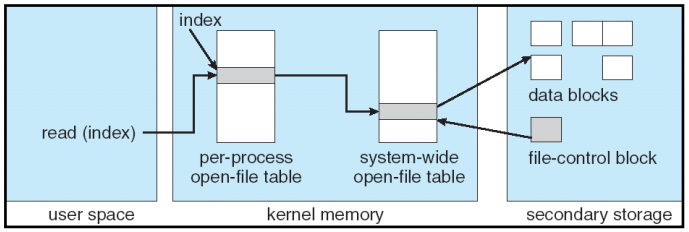


In-Memory File System Structures



- Open system call:
  - Resolves file name, finds file control block (inode)
  - Makes entries in per-process and system-wide tables
  - Returns index (called "file handle") in open-file table

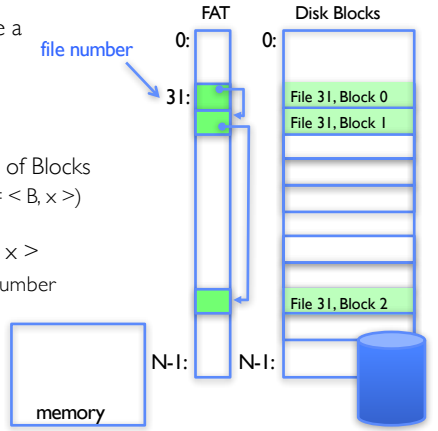
In-Memory File System Structures



- Read/write system calls:
  - Use file handle to locate inode
  - Perform appropriate reads or writes

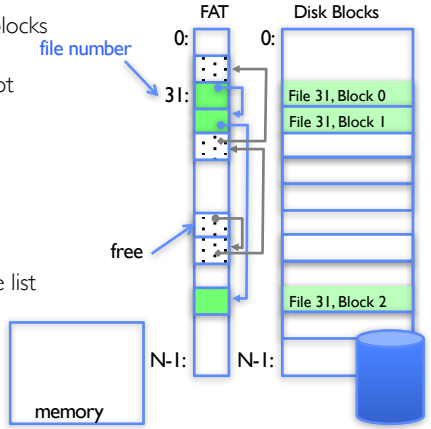
Our first filesystem: FAT (File Allocation Table)

- The most commonly used filesystem in the world!
- Assume (for now) we have a way to translate a path to a "file number"
  - i.e., a directory structure
- Disk Storage is a collection of Blocks
  - Just hold file data (offset o = < B, x >)
- Example: file_read 31, < 2, x >
  - Index into FAT with file number
  - Follow linked list to block
  - Read the block from disk into memory



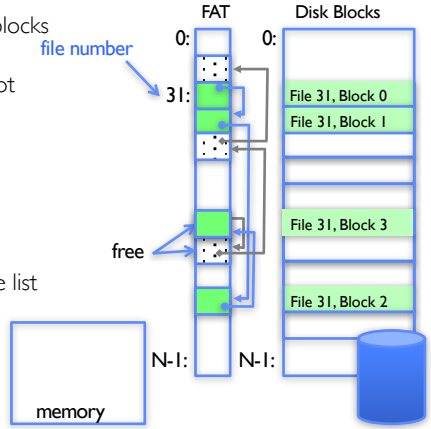
FAT Properties

- File is collection of disk blocks
- FAT is linked list 1-1 with blocks
- File Number is index of root of block list for the file
- File offset (o = < B, x >)
- Follow list to get block #
- Unused blocks ⇔ FAT free list



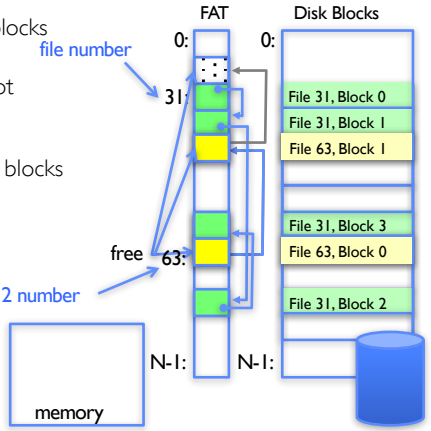
FAT Properties

- File is collection of disk blocks
- FAT is linked list 1-1 with blocks
- File Number is index of root of block list for the file
- File offset (o = < B, x >)
- Follow list to get block #
- Unused blocks ⇔ FAT free list
- Ex: file_write(31, < 3, y >)
  - Grab blocks from free list
  - Linking them into file



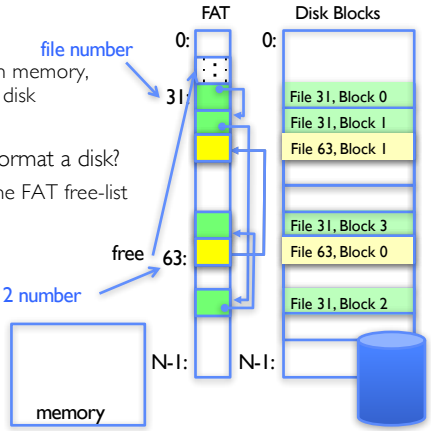
FAT Properties

- File is collection of disk blocks
- FAT is linked list 1-1 with blocks
- File Number is index of root of block list for the file
- Grow file by allocating free blocks and linking them in
- Ex: Create file, write, write



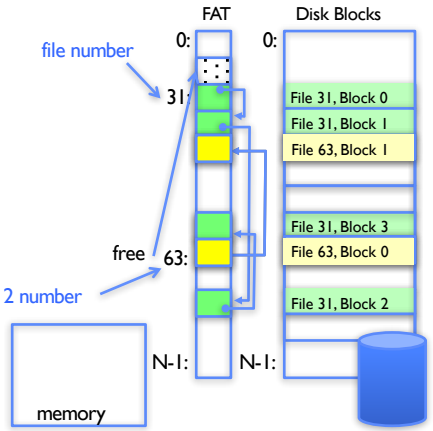
FAT Assessment

- *FAT32 (32 instead of 12 bits) used in Windows, USB drives, SD cards, …*
- Where is FAT stored?
  - On Disk, on boot cache in memory, second (backup) copy on disk
- What happens when you format a disk?
  - Zero the blocks, link up the FAT free-list
- What happens when you quick format a disk?
  - Link up the FAT free-list
- *Simple*
  - Can implement in device firmware



FAT Assessment – Issues

- Time to find block (large files) ??
- Block layout for file ???
- Sequential Access ???
- Random Access ???
- Fragmentation ???
  - MSDOS defrag tool
- Small files ???
- Big files ???

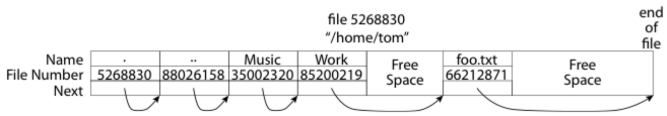


Administrivia

- Project 2 code due tonight at 11:59PM
  - Final report and student test report due Wed Nov 1 at 11:59 PM
- Midterm 2 regrade requests deadline is tomorrow Tue Oct 31 at 11:59PM
- Homework 3 is due Mon Nov 6 at 11:59PM

BREAK

What about the Directory?



- Essentially a file containing
  <file_name: file_number> mappings
- Free space for new entries
- In FAT: file attributes are kept in directory (!!!)
- Each directory a linked list of entries
- Where do you find root directory ("/")?

Directory Structure (cont'd)

- How many disk accesses to resolve "/my/book/count"?
  - Read in file header for root (fixed spot on disk)
  - Read in first data block for root
    - » Table of file name/index pairs. Search linearly – ok since directories typically very small
  - Read in file header for "my"
  - Read in first data block for "my"; search for "book"
  - Read in file header for "book"
  - Read in first data block for "book"; search for "count"
  - Read in file header for "count"
- Current working directory: Per-address-space pointer to a directory (inode) used for resolving file names
  - Allows user to specify relative filename instead of absolute path (say CWD="/my/book" can resolve "count")

Many Huge FAT Security Holes!

- FAT has no access rights
- FAT has no header in the file blocks
- Just gives an index into the FAT
  - (file number = block number)

Characteristics of Files

A Five-Year Study of File-System Metadata

NITIN AGRAWAL
University of Wisconsin, Madison
and
WILLIAM J. BOLOSKY, JOHN R. DOUCEUR, and JACOB R. LORCH
Microsoft Research

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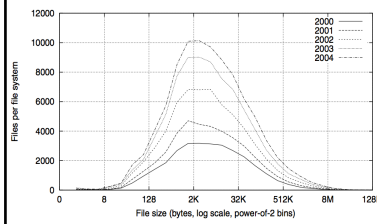


Fig. 2. Histograms of files by size.

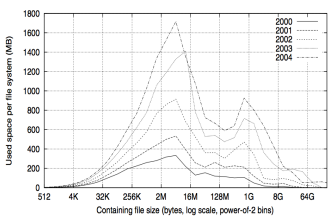


Fig. 4. Histograms of bytes by containing file size.

Characteristics of Files

- Most files are small, growing numbers of files over time

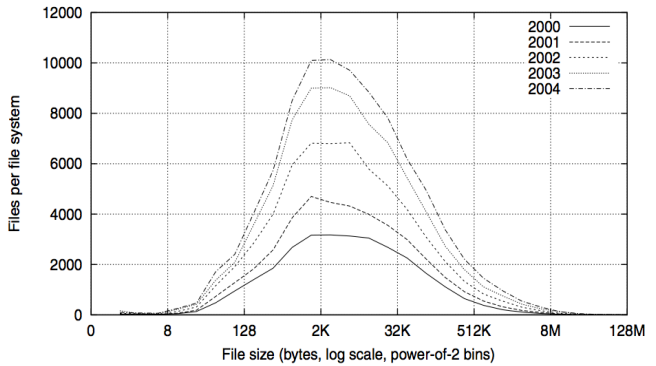


Fig. 2. Histograms of files by size.

Characteristics of Files

- Most of the space is occupied by the rare big ones

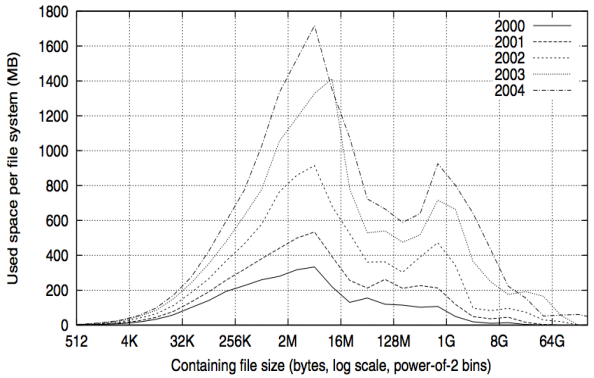
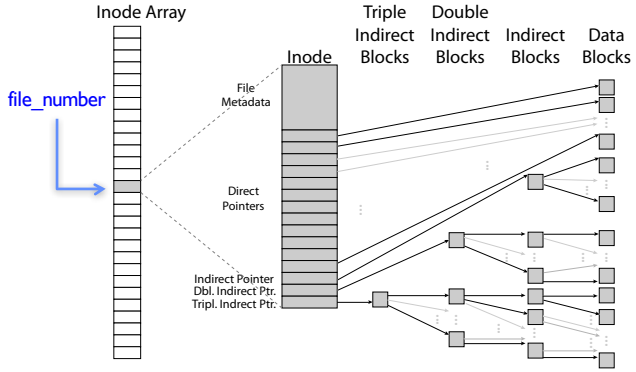


Fig. 4. Histograms of bytes by containing file size.

So What About a "Real" File System?

- Meet the inode:



An "Almost Real" File System

- Pintos: `src/filesys/file.c`, `inode.c`

```
/* An open file. */
struct file
  {
    struct inode *inode;        /* File's inode. */
    off_t pos;                  /* Current position. */
    bool deny_write;            /* Has file_deny_write() been called? */
  };
```

```
/* In-memory inode. */
struct inode
  {
    struct list_elem elem;              /* Element in inode list. */
    block_sector_t sector;              /* Sector number of disk location. */
    int open_cnt;                       /* Number of openers. */
    bool removed;                       /* True if deleted, false otherwise. */
    int deny_write_cnt;                 /* 0: writes ok, >0: deny writes. */
    struct inode_disk data;             /* Inode content. */
  };
```

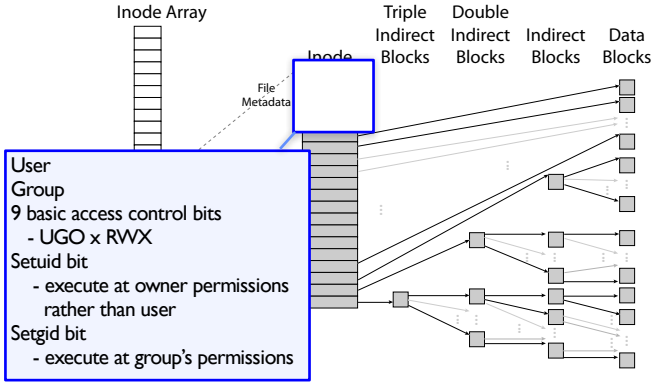
```
/* On-disk inode.
   Must be exactly BLOCK_SECTOR_SIZE bytes long. */
struct inode_disk
  {
    block_sector_t start;               /* First data sector. */
    off_t length;                       /* File size in bytes. */
    unsigned magic;                     /* Magic number. */
    uint32_t unused[125];               /* Not used. */
  };
```


Unix File System

- Original inode format appeared in BSD 4.1
  - Berkeley Standard Distribution Unix
  - Part of your heritage!
  - Similar structure for Linux Ext2/3
- File Number is index into inode arrays
- Multi-level index structure
  - Great for little and large files
  - Asymmetric tree with fixed sized blocks
- Metadata associated with the file
  - Rather than in the directory that points to it
- UNIX Fast File System (FFS) BSD 4.2 Locality Heuristics:
  - Block group placement
  - Reserve space
- Scalable directory structure

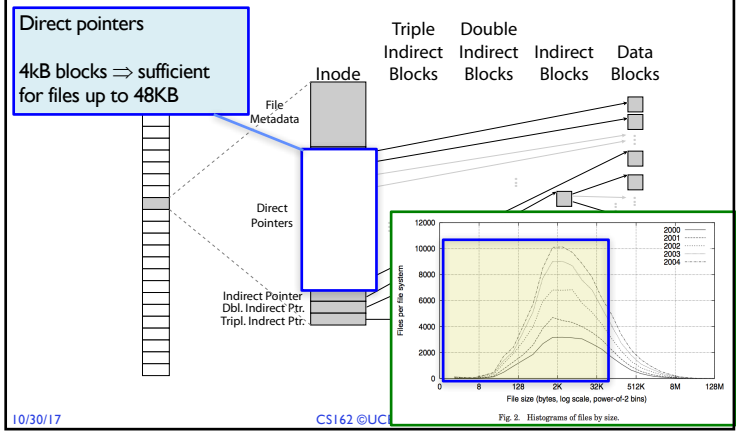
File Attributes

- inode metadata



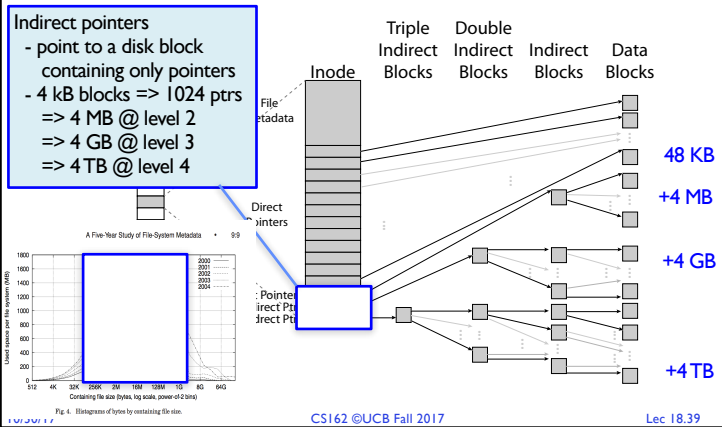
Data Storage

- Small files: 12 pointers direct to data blocks



Data Storage

- Large files: 1,2,3 level indirect pointers



Summary

- File System:
  - Transforms blocks into Files and Directories
  - Optimize for access and usage patterns
  - Maximize sequential access, allow efficient random access
- File (and directory) defined by header, called "inode"
- File Allocation Table (FAT) Scheme
  - Linked-list approach
  - Very widely used: Cameras, USB drives, SD cards
  - Simple to implement, but poor performance and no security
- Look at actual file access patterns – many small files, but large files take up all the space!