Recall: Magnetic Disks

- **Cylinders**: all the tracks under the head at a given point on all surfaces
- Read/write data is a three-stage process:
  - **Seek time**: position the head/arm over the proper track
  - **Rotational latency**: wait for desired sector to rotate under r/w head
  - **Transfer time**: transfer a block of bits (sector) under r/w head

![Diagram of magnetic disk components](Image)

**Disk Latency** = Queueing Time + Controller time + Seek Time + Rotation Time + Xfer Time

1. **Software Queue (Device Driver)**
2. **Hardware Controller**
3. **Media Time (Seek+Rot+Xfer)**
4. **Result**
## Recall: Typical Numbers for Magnetic Disk

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Info/Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space/Density</td>
<td>Space: 18TB (Seagate), 9 platters, in 3½ inch form factor! Areal Density: ≥ 1 Terabit/square inch! (PMR, Helium, …)</td>
</tr>
<tr>
<td>Average Seek Time</td>
<td>Typically 4-6 milliseconds</td>
</tr>
<tr>
<td>Average Rotational Latency</td>
<td>Most laptop/desktop disks rotate at 3600-7200 RPM (16-8 ms/rotation). Server disks up to 15K RPM. Average latency is halfway around disk so 4-8 milliseconds</td>
</tr>
<tr>
<td>Controller Time</td>
<td>Depends on controller hardware</td>
</tr>
<tr>
<td>Transfer Time</td>
<td>Typically 50 to 250 MB/s. Depends on:</td>
</tr>
<tr>
<td></td>
<td>• Transfer size (usually a sector): 512B – 1KB per sector</td>
</tr>
<tr>
<td></td>
<td>• Rotation speed: 3600 RPM to 15000 RPM</td>
</tr>
<tr>
<td></td>
<td>• Recording density: bits per inch on a track</td>
</tr>
<tr>
<td></td>
<td>• Diameter: ranges from 1 in to 5.25 in</td>
</tr>
<tr>
<td>Cost</td>
<td>Used to drop by a factor of two every 1.5 years (or faster), now slowing down</td>
</tr>
</tbody>
</table>
Recall: Overall Performance for I/O Path

- Performance of I/O subsystem
  - Metrics: Response Time, Throughput
  - Effective BW = transfer size / response time
  - Contributing factors to latency:
    » Software paths (can be loosely modeled by a queue)
    » Hardware controller
    » I/O device service time

- Queuing behavior:
  - Can lead to big increases of latency as utilization increases
  - Solutions?

Response Time = Queue + I/O device service time

![Diagram showing the components and response time of the I/O path](image-url)
Recall: Optimize I/O Performance

Response Time = Queue + I/O device service time

- How to improve performance?
  - Make everything faster 😊
  - More Decoupled (Parallelism) systems
    - multiple independent buses or controllers
  - Optimize the bottleneck to increase service rate
    - Use the queue to optimize the service
  - Do other useful work while waiting
- Queues absorb bursts and smooth the flow
- Admissions control (finite queues)
  - Limits delays, but may introduce unfairness and livelock
When is Disk Performance Highest?

• When there are big sequential reads, or
• When there is so much work to do that they can be piggy backed (reordering queues—one moment)

• OK to be inefficient when things are mostly idle
• Bursts are both a threat and an opportunity
• <your idea for optimization goes here>
  – Waste space for speed?

• Other techniques:
  – Reduce overhead through user level drivers
  – Reduce the impact of I/O delays by doing other useful work in the meantime
Disk Scheduling (1/3)

- Disk can do only one request at a time; What order do you choose to do queued requests?

  - FIFO Order
    - Fair among requesters, but order of arrival may be to random spots on the disk ⇒ Very long seeks

  - SSTF: Shortest seek time first
    - Pick the request that’s closest on the disk
    - Although called SSTF, today must include rotational delay in calculation, since rotation can be as long as seek
    - Con: SSTF good at reducing seeks, but may lead to starvation
Disk Scheduling (2/3)

• Disk can do only one request at a time; What order do you choose to do queued requests?

  User Requests  →  Disk

  Head

• SCAN: Implements an Elevator Algorithm: take the closest request in the direction of travel
  – No starvation, but retains flavor of SSTF
Disk Scheduling (3/3)

- Disk can do only one request at a time; What order do you choose to do queued requests?
  - C-SCAN: Circular-Scan: only goes in one direction
    - Skips any requests on the way back
    - Fairer than SCAN, not biased towards pages in middle

![Diagram of disk scheduling](image-url)
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
Recall: I/O and Storage Layers

Application / Service

High Level I/O

Streams

File Descriptors

open(), read(), write(), close(), …

Open File Descriptions

Low Level I/O

Syscall

File System

Files/Directories/Indexes

I/O Driver

Commands and Data Transfers

Disks, Flash, Controllers, DMA

What we covered in Lecture 4

What we just covered…

What we will cover next…
From Storage to File Systems

I/O API and sy.calls

Variable-Size Buffer

Memory Address

Logical Index,
Typically 4 KB

File System

Block

HDD

SSD

Hardware Devices

Sector(s)

Physical Index,
512B or 4KB

Flash Trans. Layer

Phys. Block

Erasure Page

Phys Index., 4KB

HDD

SSD
Building a File System

- **File System**: Layer of OS that transforms block interface of disks (or other block devices) into Files, Directories, etc.

- Classic OS situation: Take limited hardware interface (array of blocks) and provide a more convenient/useful interface with:
  - Naming: Find file by name, not block numbers
  - Organize file names with directories
  - Organization: Map files to blocks
  - Protection: Enforce access restrictions
  - Reliability: Keep files intact despite crashes, hardware failures, 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
Translation 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 writing bytes 2 – 12?
  - Fetch block, modify relevant portion, write out block

- Everything inside file system is in terms of whole-size blocks
  - Actual disk I/O happens in blocks
  - read/write smaller than block size needs to translate and buffer
Disk Management

• Basic entities on a disk:
  – File: user-visible group of blocks arranged sequentially in logical space
  – Directory: user-visible index mapping names to files

• The disk is accessed as linear array of sectors

• How to identify a sector?
  – Physical position
    » Sectors is a vector [cylinder, surface, sector]
    » Not used anymore
    » OS/BIOS must deal with bad sectors
  – Logical Block Addressing (LBA)
    » Every sector has integer address
    » Controller translates from address ⇒ physical position
    » Shields OS from structure of disk
What Does the File System Need?

• Track free disk blocks
  – Need to know where to put newly written data
• Track which blocks contain data for which files
  – Need to know where to read a file from
• Track files in a directory
  – Find list of file's blocks given its name
• Where do we maintain all of this?
  – Somewhere on disk
Data Structures on Disk

• Bit different than data structures in memory
• Access a block at a time
  – Can't efficiently read/write a single word
  – Have to read/write full block containing it
  – Ideally want sequential access patterns

• Durability
  – Ideally, file system is in meaningful state upon shutdown
  – This obviously isn't always the case…
FILE SYSTEM DESIGN
Critical Factors in File System Design

- (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 carefully allocate / free blocks
  - Such that access remains efficient
Components of a File System

File path

Directory Structure

File number

“inode”

File Header Structure

Data blocks

One Block = multiple sectors
Ex: 512 sector, 4K block

“inumber”
Recall: Abstract Representation of a Process

Suppose that we execute open("foo.txt") and that the result is 3.

Next, suppose that we execute read(3, buf, 100) and that the result is 100.
Open file description is better described as remembering the inumber (file number) of the file, not its name.
Components of a File System

- Open performs *Name Resolution*
  - Translates path name into a “file number”
- Read and Write operate on the file number
  - Use file number as an “index” to locate the blocks

- 4 components:
  - directory, index structure, storage blocks, free space map
How to Get the File Number?

• Look up in directory structure

• A directory is a file containing <file_name : file_number> mappings
  – File number could be a file or another directory
  – Operating system stores the mapping in the directory in a format it interprets
  – Each <file_name : file_number> mapping is called a directory entry

• Process isn’t allowed to read the raw bytes of a directory
  – The read function doesn’t work on a directory
  – Instead, see readdir, which iterates over the map without revealing the raw bytes

• Why shouldn’t the OS let processes read/write the bytes of a directory?
Directories
Directory Abstraction

- Directories are specialized files
  - Contents: List of pairs <file name, file number>
- System calls to access directories
  - open / creat / readdir traverse the structure
  - mkdir / rmdir add/remove entries
  - link / unlink (rm)
- libc support
  - DIR * opendir (const char *dirname)
  - struct dirent * readdir (DIR *dirstream)
  - int readdir_r (DIR *dirstream, struct dirent *entry, struct dirent **result)
Directory Structure

• 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 used for resolving file names
  – Allows user to specify relative filename instead of absolute path
    (say CWD="/my/book" can resolve "count")
In-Memory File System Structures

- Open syscall: find inode on disk from pathname (traversing directories)
  - Create “in-memory inode” in system-wide open file table
  - One entry in this table no matter how many instances of the file are open
- Read/write syscalls look up in-memory inode using the file handle
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

Published in FAST 2007
Observation #1: Most Files Are Small

Fig. 2. Histograms of files by size.
Observation #2: Most Bytes are in Large Files

![Graph showing distribution of file sizes and usage](image)

Fig. 4. Histograms of bytes by containing file size.
CASE STUDY:
FAT: FILE ALLOCATION TABLE

• MS-DOS, 1977
• Still widely used!
FAT (File Allocation Table)

- 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 (File Allocation Table)

- File is a 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: block number and offset within block
- Follow list to get block number
- Unused blocks marked free
  - Could require scan to find
  - Or, could use a free list

File 31, Block 0
File 31, Block 1
File 31, Block 2

File number
memory
free

Disk Blocks
N-1:
N-1:
0:
0:
FAT (File Allocation Table)

- File is a 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: block number and offset within block
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- File offset: block number and offset within block
- Follow list to get block number
- Unused blocks marked free
  - Could require scan to find
  - Or, could use a free list
- Ex: `file_write(31, < 3, y >)`
  - Grab free block
  - Linking them into file
FAT (File Allocation Table)

- Where is FAT stored?
  - On disk
  - Usually 2 copies (to handle errors)
- How to format a disk?
  - Zero the blocks, mark FAT entries “free”
- How to quick format a disk?
  - Mark FAT entries “free”
- Simple: can implement in device firmware
FAT: Directories

- A directory is a file containing <file_name: file_number> mappings
- Free space for new/deleted entries
- In FAT: file attributes are kept in directory (!!!)
  - Not directly associated with the file itself
- Each directory a linked list of entries
  - Requires linear search of directory to find particular entry
- Where do you find root directory ("/")?
  - At well-defined place on disk
  - For FAT, this is at block 2 (there are no blocks 0 or 1)
  - Remaining directories
FAT Discussion

Suppose you start with the file number:
- Time to find block?
- Block layout for file?
- Sequential access?
- Random access?
- Fragmentation?
- Small files?
- Big files?
CASE STUDY: UNIX FILE SYSTEM (BERKELEY FFS)
Inodes in Unix (Including Berkeley FFS)

- File Number is index into set of inode arrays
- Index structure is an array of inodes
  - File Number (inumber) is an index into the array of inodes
  - Each inode corresponds to a file and contains its metadata
    - So, things like read/write permissions are stored with file, not in directory
    - Allows multiple names (directory entries) for a file
- Inode maintains a multi-level tree structure to find storage blocks for files
  - Great for little and large files
  - Asymmetric tree with fixed sized blocks

- Original inode format appeared in BSD 4.1 (more following)
  - Berkeley Standard Distribution Unix!
  - Part of your heritage!
  - Similar structure for Linux Ext 2/3
Inode Structure

Inode Array

- Inode
  - File Metadata
  - Direct Pointers
  - Indirect Pointer
  - Dbl. Indirect Ptr.
  - Tripl. Indirect Ptr.

Triple Indirect Blocks

Double Indirect Blocks

Indirect Blocks

Data Blocks
File Attributes

User
Group
9 basic access control bits
- UGO x RWX
SetUID bit
- execute at owner permissions rather than user
SetGID bit
- execute at group’s permissions
Small Files: 12 Pointers Direct to Data Blocks

Direct pointers

4kB blocks ⇒ sufficient for files up to 48KB

Fig. 2. Histogram of files by size.
Indirect pointers
- point to a disk block containing only pointers
- 4 kB blocks => 1024 ptrs
  => 4 MB @ level 2
  => 4 GB @ level 3
  => 4 TB @ level 4
Putting it All Together: On-Disk Index

- Sample file in multilevel indexed format:
  - 10 direct ptrs, 1K blocks
  - How many accesses for block #23? (assume file header accessed on open)?
    » Two: One for indirect block, one for data
  - How about block #5?
    » One: One for data
  - Block #340?
    » Three: double indirect block, indirect block, and data
Recall: Critical Factors in File System Design

- **(Hard) Disk 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

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  - What data structure (on disk) for that?

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\[
\text{Disk Latency} = \text{Queueing Time} + \text{Controller time} + \text{Seek Time} + \text{Rotation Time} + \text{Xfer Time}
\]
Fast File System (BSD 4.2, 1984)

• Same inode structure as in BSD 4.1
  – same file header and triply indirect blocks like we just studied
  – Some changes to block sizes from 1024 → 4096 bytes for performance

• Paper on FFS: “A Fast File System for UNIX”
  – Marshall McKusick, William Joy, Samuel Leffler and Robert Fabry
  – Off the “resources” page of course website – Take a look!

• Optimization for Performance and Reliability:
  – Distribute inodes among different tracks to be closer to data
  – Uses bitmap allocation in place of freelist
  – Attempt to allocate files contiguously
  – 10% reserved disk space
  – Skip-sector positioning (mentioned later)
FFS Changes in Inode Placement: Motivation

• In early UNIX and DOS/Windows’ FAT file system, headers stored in special array in outermost cylinders
  – Fixed size, set when disk is formatted
    » At formatting time, a fixed number of inodes are created
    » Each is given a unique number, called an “inumber”

• Problem #1: Inodes all in one place (outer tracks)
  – Head crash potentially destroys all files by destroying inodes
  – Inodes not close to the data that they point to
    » To read a small file, seek to get header, seek back to data

• Problem #2: When create a file, don’t know how big it will become (in UNIX, most writes are by appending)
  – How much contiguous space do you allocate for a file?
  – Makes it hard to optimize for performance
**FFS Locality: Block Groups**

- The UNIX BSD 4.2 (FFS) distributed the header information (inodes) closer to the data blocks
  - Often, inode for file stored in same “cylinder group” as parent directory of the file
  - Makes an “ls” of that directory run very fast
- File system volume divided into set of block groups
  - Close set of tracks
- Data blocks, metadata, and free space interleaved within block group
  - Avoid huge seeks between user data and system structure
- Put directory and its files in common block group
FFS Locality: Block Groups (Con’t)

• First-Free allocation of new file blocks
  – To expand file, first try successive blocks in bitmap, then choose new range of blocks
  – Few little holes at start, big sequential runs at end of group
  – Avoids fragmentation
  – Sequential layout for big files

• Important: keep 10% or more free!
  – Reserve space in the Block Group

• Summary: FFS Inode Layout Pros
  – For small directories, can fit all data, file headers, etc. in same cylinder ⇒ no seeks!
  – File headers much smaller than whole block (a few hundred bytes), so multiple headers fetched from disk at same time
  – Reliability: whatever happens to the disk, you can find many of the files (even if directories disconnected)
UNIX 4.2 BSD FFS First Fit Block Allocation

- Fills in the small holes at the start of block group
- Avoids fragmentation, leaves contiguous free space at end

**Start of Block**

**In-Use Block**

**Free Block**

**Start of Block Group**

**Write Two Block File**

**Start of Block Group**

**Write Large File**
**Attack of the Rotational Delay**

- Problem 3: Missing blocks due to rotational delay
  - Issue: Read one block, do processing, and read next block. In meantime, disk has continued turning: missed next block! Need 1 revolution/block!
  
  - Solution 1: Skip sector positioning (“interleaving”)
    - Place the blocks from one file on every other block of a track: give time for processing to overlap rotation
    - Can be done by OS or in modern drives by the disk controller
  
  - Solution 2: Read ahead: read next block right after first, even if application hasn’t asked for it yet
    - This can be done either by OS (read ahead)
    - By disk itself (track buffers) - many disk controllers have internal RAM that allows them to read a complete track

- Modern disks + controllers do many things “under the covers”
  - Track buffers, elevator algorithms, bad block filtering
UNIX 4.2 BSD FFS

• Pros
  – Efficient storage for both small and large files
  – Locality for both small and large files
  – Locality for metadata and data
  – No defragmentation necessary!

• Cons
  – Inefficient for tiny files (a 1-byte file requires both an inode and a data block)
  – Inefficient encoding when file is mostly contiguous on disk
  – Need to reserve 10-20% of free space to prevent fragmentation
Conclusion (1/2)

• Systems (e.g., file system) designed to optimize performance and reliability
  – Relative to performance characteristics of underlying device
• 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”
Conclusion (2/2)

• Naming: translating from user-visible names to actual system resources
  – Directories used for naming for local file systems
  – Linked or tree structure stored in files
• 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!
• 4.2 BSD Fast File System: Multi-level inode header to describe files
  – Inode contains ptrs to actual blocks, indirect blocks, double indirect blocks, etc.
  – Optimizations for sequential access: start new files in open ranges of free blocks, rotational optimization