CSE 120
Principles of Operating Systems

Fall 2014

Lecture 12: File Systems

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File Systems

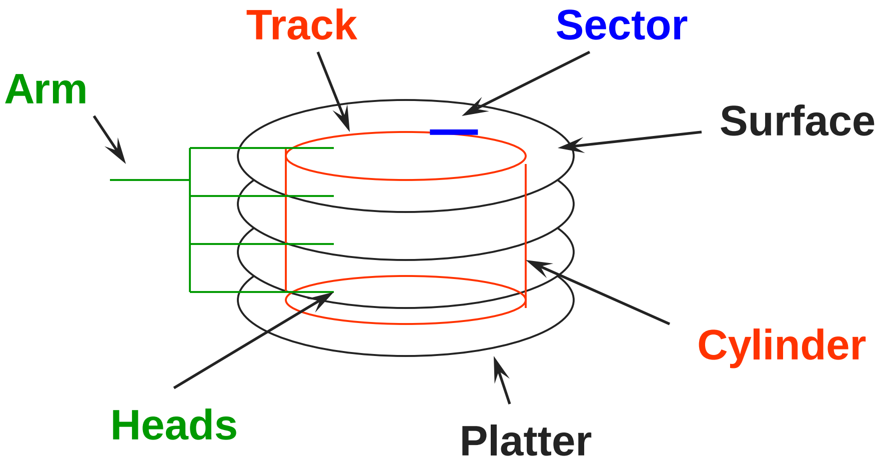
- First we’ll discuss properties of physical disks
  - Structure
  - Performance
  - Scheduling
- Then we’ll discuss how we build file systems on them
  - Files
  - Directories
  - Sharing
  - Protection
  - File System Layouts
  - File Buffer Cache
  - Read Ahead

Disks and the OS

- Disks are messy physical devices:
  - Errors, bad blocks, missed seeks, etc.
- The job of the OS is to hide this mess from higher level software
  - Low-level device control (initiate a disk read, etc.)
  - Higher-level abstractions (files, databases, etc.)
- The OS may provide different levels of disk access to different clients
  - Physical disk (surface, cylinder, sector)
  - Logical disk (disk block #)
  - Logical file (file block, record, or byte #)

Physical Disk Structure

- Disk components
  - Platters
  - Surfaces
  - Tracks
  - Sectors
  - Cylinders
  - Arm
  - Heads



Disk Interaction

- Specifying disk requests requires a lot of info:
  - Cylinder #, surface #, track #, sector #, transfer size…
- Older disks required the OS to specify all of this
  - The OS needed to know all disk parameters
- Modern disks are more complicated
  - Not all sectors are the same size, sectors are remapped, etc.
- Current disks provide a higher-level interface (SCSI)
  - The disk exports its data as a logical array of blocks [0…N]
    - » Disk maps logical blocks to cylinder/surface/track/sector
  - Only need to specify the logical block # to read/write
  - But now the disk parameters are hidden from the OS

Disks: 2014

- Seagate Enterprise Performance 3.5" (server)
  - capacity: 600 GB
  - rotational speed: 15,000 RPM
  - sequential read performance: 233 MB/s (outer) – 160 MB/s (inner)
  - seek time (average): 2.0 ms
- Seagate Barracuda 3.5" (workstation)
  - capacity: 3000 GB
  - rotational speed: 7,200 RPM
  - sequential read performance: 210 MB/s - 156 MB/s (inner)
  - seek time (average): 8.5 ms
- Seagate Savvio 2.5" (smaller form factor)
  - capacity: 2000 GB
  - rotational speed: 7,200 RPM
  - sequential read performance: 135 MB/s (outer) - ? MB/s (inner)
  - seek time (average): 11 ms

Disk Performance

- Disk request performance depends upon three steps
  - Seek – moving the disk arm to the correct cylinder
    - » Depends on how fast disk arm can move (increasing very slowly)
  - Rotation – waiting for the sector to rotate under the head
    - » Depends on rotation rate of disk (increasing, but slowly)
  - Transfer – transferring data from surface into disk controller electronics, sending it back to the host
    - » Depends on density (increasing quickly)
- When the OS uses the disk, it tries to minimize the cost of all of these steps
  - Particularly seeks and rotation

Solid State Disks

- SSDs are a relatively new storage technology
  - Memory that does not require power to remember state
- No physical moving parts → faster than hard disks
  - No seek and no rotation overhead
  - But…more expensive, not as much capacity
- Generally speaking, file systems have remained unchanged when using SSDs
  - Some optimizations no longer necessary (e.g., layout policies, disk head scheduling), but basically leave FS code as is
  - Most commonly, SSDs have the same disk interface (SATA)
  - But can be faster to use directly over the I/O bus (PCIe)

Disk Scheduling

- Because seeks are so expensive (milliseconds!), the OS tries to schedule disk requests that are queued waiting for the disk
  - FCFS (do nothing)
    - » Reasonable when load is low
    - » Long waiting times for long request queues
  - SSTF (shortest seek time first)
    - » Minimize arm movement (seek time), maximize request rate
    - » Favors middle blocks
  - SCAN (elevator)
    - » Service requests in one direction until done, then reverse
  - C-SCAN
    - » Like SCAN, but only go in one direction (typewriter)

Disk Scheduling (2)

- In general, unless there are request queues, disk scheduling does not have much impact
  - Important for servers, less so for PCs
- Modern disks often do the disk scheduling themselves
  - Disks know their layout better than OS, can optimize better
  - Ignores, undoes any scheduling done by OS

File Systems

- File systems
  - Implement an abstraction (files) for secondary storage
  - Organize files logically (directories)
  - Permit sharing of data between processes, people, and machines
  - Protect data from unwanted access (security)

Files

- A file is data with some properties
  - Contents, size, owner, last read/write time, protection, etc.
- A file can also have a type
  - Understood by the file system
    - » Block, character, device, portal, link, etc.
  - Understood by other parts of the OS or runtime libraries
    - » Executable, dll, souce, object, text, etc.
- A file's type can be encoded in its name or contents
  - Windows encodes type in name
    - » .com, .exe, .bat, .dll, .jpg, etc.
  - Unix encodes type in contents
    - » Magic numbers, initial characters (e.g., #! for shell scripts)

Basic File Operations

Unix

- creat(name)
- open(name, how)
- read(fd, buf, len)
- write(fd, buf, len)
- sync(fd)
- seek(fd, pos)
- close(fd)
- unlink(name)

NT

- CreateFile(name, CREATE)
- CreateFile(name, OPEN)
- ReadFile(handle, …)
- WriteFile(handle, …)
- FlushFileBuffers(handle, …)
- SetFilePointer(handle, …)
- CloseHandle(handle, …)
- DeleteFile(name)
- CopyFile(name)
- MoveFile(name)

File Access Methods

- Some file systems provide different access methods that specify different ways for accessing data in a file
  - Sequential access – read bytes one at a time, in order
  - Direct access – random access given block/byte number
  - Record access – file is array of fixed- or variable-length records, read/written sequentially or randomly by record #
  - Indexed access – file system contains an index to a particular field of each record in a file, reads specify a value for that field and the system finds the record via the index (DBs)
- What file access method does Unix, NT provide?
- Older systems provide the more complicated methods

Directories

- Directories serve two purposes
  - For users, they provide a structured way to organize files
  - For the file system, they provide a convenient naming interface that allows the implementation to separate logical file organization from physical file placement on the disk
- Most file systems support multi-level directories
  - Naming hierarchies (/, /usr, /usr/local/, …)
- Most file systems support the notion of a current directory
  - Relative names specified with respect to current directory
  - Absolute names start from the root of directory tree

Directory Internals

- A directory is a list of entries
  - <name, location>
  - Name is just the name of the file or directory
  - Location depends upon how file is represented on disk
- List is usually unordered (effectively random)
  - Entries usually sorted by program that reads directory
- Directories typically stored in files
  - Only need to manage one kind of secondary storage unit

Basic Directory Operations

Unix

- Directories implemented in files
  - Use file ops to create dirs
- C runtime library provides a higher-level abstraction for reading directories
  - opendir(name)
  - readdir(DIR)
  - seekdir(DIR)
  - closedir(DIR)

NT

- Explicit dir operations
  - CreateDirectory(name)
  - RemoveDirectory(name)
- Very different method for reading directory entries
  - FindFirstFile(pattern)
  - FindNextFile()

Path Name Translation

- Let's say you want to open "/one/two/three"
- What does the file system do?
  - Open directory "/" (well known, can always find)
  - Search for the entry "one", get location of "one" (in dir entry)
  - Open directory "one", search for "two", get location of "two"
  - Open directory "two", search for "three", get location of "three"
  - Open file "three"
- Systems spend a lot of time walking directory paths
  - This is why open is separate from read/write
  - OS will cache prefix lookups for performance
    - » /a/b, /a/bb, /a/bbb, etc., all share "/a" prefix

File Sharing

- File sharing has been around since timesharing
  - Easy to do on a single machine
  - PCs, workstations, and networks get us there (mostly)
- File sharing is incredibly important for getting work done
  - Basis for communication and synchronization
- Two key issues when sharing files
  - Semantics of concurrent access
    - » What happens when one process reads while another writes?
    - » What happens when two processes open a file for writing?
    - » What are we going to use to coordinate?
  - Protection

Protection

- File systems implement some kind of protection system
  - Who can access a file
  - How they can access it
- More generally…
  - Objects are “what”, subjects are “who”, actions are “how”
- A protection system dictates whether a given action performed by a given subject on a given object should be allowed
  - You can read and/or write your files, but others cannot
  - You can read “/etc/motd”, but you cannot write it

Representing Protection

Access Control Lists (ACL)

- For each object, maintain a list of subjects and their permitted actions

Capabilities

- For each subject, maintain a list of objects and their permitted actions

Objects

Subjects

	/one	/two	/three
Alice	rw	-	rw
Bob	w	-	r
Charlie	w	r	rw

Capability

ACL

ACLs and Capabilities

- The approaches differ only in how the table is represented
  - What approach does Unix use in the FS?
- Capabilities are easier to transfer
  - They are like keys, can handoff, does not depend on subject
- In practice, ACLs are easier to manage
  - Object-centric, easy to grant, revoke
  - To revoke capabilities, have to keep track of all subjects that have the capability – a challenging problem
- ACLs have a problem when objects are heavily shared
  - The ACLs become very large
  - Use groups (e.g., Unix)

File System Layout

How do file systems use the disk to store files?

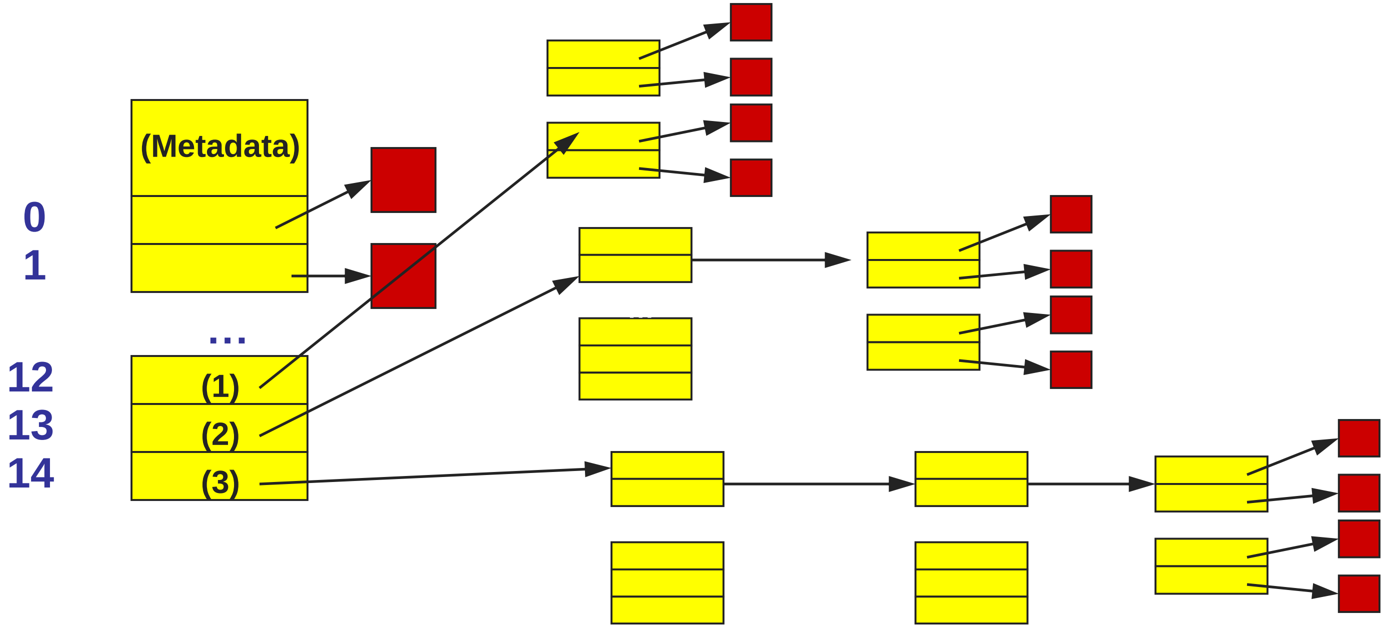
- File systems define a block size (e.g., 4KB)
  - Disk space is allocated in granularity of blocks
- A “Master Block” determines location of root directory
  - Always at a well-known disk location
  - Often replicated across disk for reliability
- A free map determines which blocks are free, allocated
  - Usually a bitmap, one bit per block on the disk
  - Also stored on disk, cached in memory for performance
- Remaining disk blocks used to store files (and dirs)
  - There are many ways to do this

Disk Layout Strategies

- Files span multiple disk blocks
- How do you find all of the blocks for a file?
  1. Contiguous allocation
     » Like memory
     » Fast, simplifies directory access
     » Inflexible, causes fragmentation, needs compaction
  2. Linked structure
     » Each block points to the next, directory points to the first
     » Good for sequential access, bad for all others
  3. Indexed structure (indirection, hierarchy)
     » An “index block” contains pointers to many other blocks
     » Handles random better, still good for sequential
     » May need multiple index blocks (linked together)

Unix Inodes

- Unix inodes implement an indexed structure for files
  - Also store metadata info (protection, timestamps, length, ref count…)
- Each inode contains 15 block pointers
  - First 12 are direct blocks (e.g., 4 KB blocks)
  - Then single, double, and triple indirect



Unix Inodes and Path Search

- Unix inodes are not directories
- Inodes describe where on the disk the blocks for a file are placed
  - Directories are files, so inodes also describe where the blocks for directories are placed on the disk
- Directory entries map file names to inodes
  - To open "/one", use Master Block to find inode for "/" on disk
  - Open "/", look for entry for "one"
  - This entry gives the disk block number for the inode for "one"
  - Read the inode for "one" into memory
  - The inode says where first data block is on disk
  - Read that block into memory to access the data in the file

File Buffer Cache

- Applications exhibit significant locality for reading and writing files
- Idea: Cache file blocks in memory to capture locality
  - Called the file buffer cache
  - Cache is system wide, used and shared by all processes
  - Reading from the cache makes a disk perform like memory
  - Even a small cache can be very effective
- Issues
  - The file buffer cache competes with VM (tradeoff here)
  - Like VM, it has limited size
  - Need replacement algorithms again (LRU usually used)

Caching Writes

- On a write, some applications assume that data makes it through the buffer cache and onto the disk
  - As a result, writes are often slow even with caching
- OSes typically do write back caching
  - Maintain a queue of uncommitted blocks
  - Periodically flush the queue to disk (30 second threshold)
  - If blocks changed many times in 30 secs, only need one I/O
  - If blocks deleted before 30 secs (e.g., /tmp), no I/Os needed
- Unreliable, but practical
  - On a crash, all writes within last 30 secs are lost
  - Modern OSes do this by default; too slow otherwise
  - System calls (Unix: fsync) enable apps to force data to disk

Read Ahead

- Many file systems implement "read ahead"
  - FS predicts that the process will request next block
  - FS goes ahead and requests it from the disk
  - This can happen while the process is computing on previous block
    - » Overlap I/O with execution
  - When the process requests block, it will be in cache
  - Compliments the disk cache, which also is doing read ahead
- For sequentially accessed files can be a big win
  - Unless blocks for the file are scattered across the disk
  - File systems try to prevent that, though (during allocation)

Summary

- Files
  - Operations, access methods
- Directories
  - Operations, using directories to do path searches
- Sharing
- Protection
  - ACLs vs. capabilities
- File System Layouts
  - Unix inodes
- File Buffer Cache
  - Strategies for handling writes
- Read Ahead