CSE 120
Principles of Operating Systems

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Lecture 12: File Systems

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File Systems

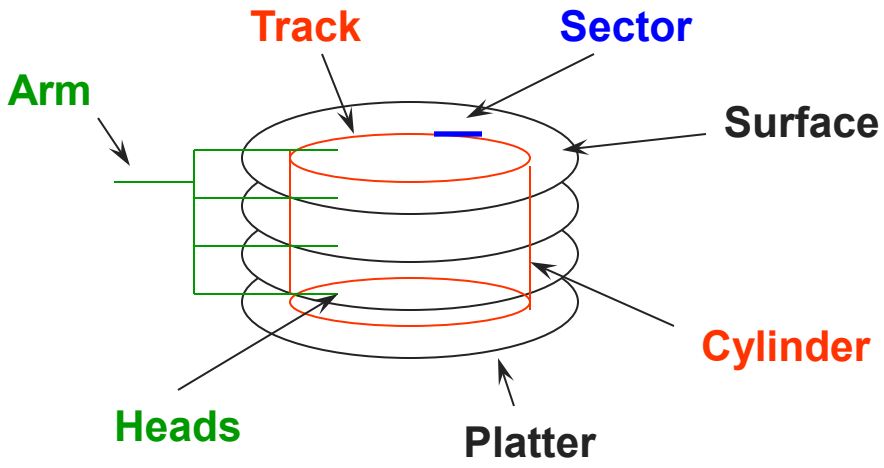
- First we'll discuss properties of physical disks
  - Structure
  - Performance
- Then how file systems support users and programs
  - Files + Directories
  - Sharing
  - File buffer cache
- Then how file systems are implemented
  - File system data structures and layouts
  - Name resolution
- End with protection

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 tracks are the same size, sectors are remapped, etc.
- Current disks provide a higher-level interface
  - The disk exports its data as a logical array of blocks [0…N]
    - Disk maps logical blocks to cylinder/surface/track/sector
    - Block size can be configured via low-level formatting
  - Only need to specify the logical block # to read/write
  - But now the disk parameters are hidden from the OS

Disk Specifications

- 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/track
    - 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 (plateaued)
  - Transfer – transferring data from surface into disk controller electronics, sending it back to the host
    - Depends on density (increasing slowly)
- 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 now standard in personal devices
  - 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, lower 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
  - Initially, SSDs have the same disk interface (SATA)
  - Increasingly, SSDs used directly over the I/O bus (PCIe M.2/3)
    - » Much higher performance

Non-Volatile Memory (NVM)

- Under development are new technologies that provide non-volatile memory
  - Phase change (PCM), spin-torque transfer (STTM), resistive
- Performance close to DRAM…but persistent!
- Byte-addressable
  - SSD is in units of a page
- Unlike SSDs, NVM will have a dramatic effect on both operating systems and applications
  - See Steve Swanson's and Jishen Zhao's research!
- Intel/Micron Optane first commercially available product
  - Although then cancelled…

File Systems

- File systems
  - Implement an abstraction (files) for secondary storage
  - Organize files logically (directories)
  - Permit sharing of data among processes, people, and machines
  - Protect data from unwanted access (protection)
- OSes abstract file systems behind an interface
  - Unix: virtual file system (VFS)
  - Windows: installable file system (IFS)
- Interface defines set of methods and data types
  - OS implemented to use any file system through this interface
  - Linux (ext3, ext4, xfs, btrfs), Windows (FAT16, FAT32, NTFS)
  - Another example of level-of-indirection in systems design

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, source, 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)
- rename(old,new)

Windows

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

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
- File systems support multi-level directories
  - Naming hierarchies (/, /usr, /usr/local/, …)
- OSes support the notion of a current directory
  - Relative names specified with respect to current directory
  - Absolute names start from the root of directory tree
  - Maintained on a per-process basis

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
  - Try “ls –U /bin”
- 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)

Windows

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

Path Name Translation (v1)

- 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
  - 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

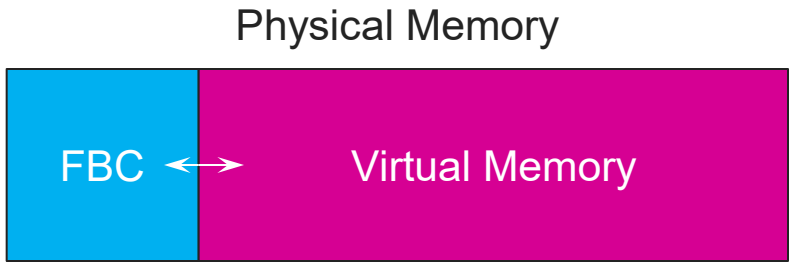
- File sharing has been around since timesharing
  - Easy to do on a single machine
  - Networks give us remote sharing
- File sharing is important for getting work done
  - Basis for communication and synchronization
- Two key issues when sharing files
  - Semantics of concurrent access
    - What happens 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

File Buffer Cache

- Applications exhibit significant locality for reading and writing files → exploit this locality for performance
- 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: More physical memory for file cache, less for VM
  - Like VM, it has limited size
  - Need replacement algorithm (form of LRU usually used)

Physical Memory Split

- VM and buffer cache dynamically compete over time




```
top - 10:55:28 up 55 days, 21:52,  3 users,  load average: 2.05, 1.67, 0.95
Tasks: 213 total,   1 running, 135 sleeping,   1 stopped,   0 zombie
%Cpu(s): 24.9 us,  2.2 sy,  0.0 ni, 72.7 id,  0.1 wa,  0.0 hi,  0.1 si,  0.0
KiB Mem : 98967440 total, 86684056 free,  1098808 used, 11184572 buff/cache
KiB Swap:  2097148 total,  2097148 free,        0 used. 96879200 avail Mem

  PID USER      PR  NI    VIRT    RES    SHR S  %CPU %MEM     TIME+ COMMAND
 8558 ubachira  20   0 28.067g  44056  17960 S  16.6  0.0   0:00.50 java
 4436 voelker   20   0   33532   3704   3164 R   0.7  0.0   0:00.31 top
    9 root      20   0       0      0      0 I   0.3  0.0  40:02.62 rcu_sch+
  279 root       0 -20       0      0      0 I   0.3  0.0   7:44.40 kworker+
30948 root      20   0  584532  22712  10016 S   0.3  0.0  62:47.92 fail2ba+
    1 root      20   0  225532   9640   7036 S   0.0  0.0   1:40.59 systemd
    2 root      20   0       0      0      0 S   0.0  0.0   0:01.07 kthreadd
    4 root       0 -20       0      0      0 I   0.0  0.0   0:00.00 kworker+
    6 root      20   0       0      0      0 I   0.0  0.0   0:05.14 kworker+
    7 root       0 -20       0      0      0 I   0.0  0.0   0:00.00 mm_perc+
    8 root      20   0       0      0      0 S   0.0  0.0   0:05.45 ksoftir+
   10 root      20   0       0      0      0 I   0.0  0.0   0:00.00 rcu_bh
   11 root      rt   0       0      0      0 S   0.0  0.0   0:00.31 migrati+
```

Caching Writes

- On a write, some applications assume that data makes it through the buffer cache and onto the disk
  - Writes become 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

- File systems implement a “read ahead” optimization
  - FS predicts that the process will request next block
  - FS goes ahead and requests it from the disk
  - 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)

Next time…

- Chapter 40