COMP 790: OS Implementation

Block Device Scheduling

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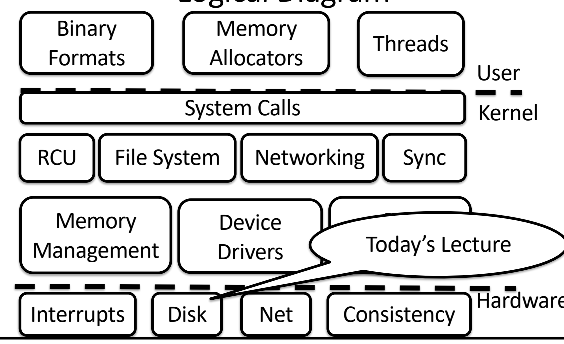
COMP 790: OS Implementation

Logical Diagram



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Quick Recap

- CPU Scheduling
  - Balance competing concerns with heuristics
    - What were some goals?
  - No perfect solution
- Today: Block device scheduling
  - How different from the CPU?
  - Focus primarily on a traditional hard drive
  - Extend to new storage media

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Block device goals

- Throughput
- Latency
- Safety – file system can be recovered after a crash
- Fairness – surprisingly, very little attention is given to storage access fairness
  - Hard problem – solutions usually just prevent starvation
  - Disk quotas for space fairness

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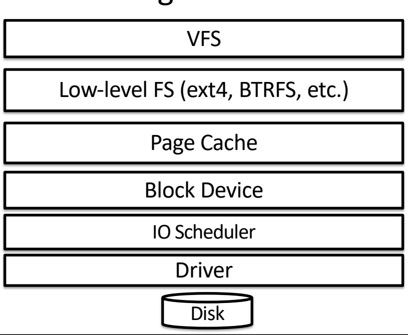
Big Picture



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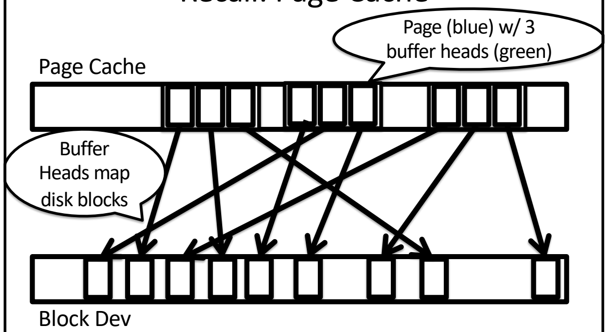
OS Model of a Block Dev.

- Simple array of sectors
  - Sectors are usually 512 or 4k bytes

Recall: Page Cache



Caching

- Obviously, the number 1 trick in the OS designer's toolbox is caching disk contents in RAM
  – Remember the page cache?
- Latency – can be hidden by pre-reading data into RAM
  – And keeping any free RAM full of disk contents
  – Doesn't help synchronous reads (that miss in RAM cache) or synchronous writes

Caching + throughput

- Assume that most reads and writes to disk are asynchronous
  – Dirty data can be buffered and written at OS's leisure
  – Most reads hit in RAM cache – most disk reads are read-ahead optimizations
- Key problem: How to optimally order pending disk I/O requests?
  – Hint: it isn't first-come, first-served

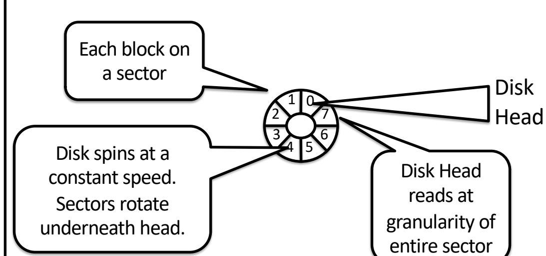
Another view of the problem

- Between page cache and disk, you have a queue of pending requests
- Requests are a tuple of (block #, read/write, buffer addr)
- You can reorder these as you like to improve throughput
- What reordering heuristic to use? If any?
- Heuristic is called the **IO Scheduler**

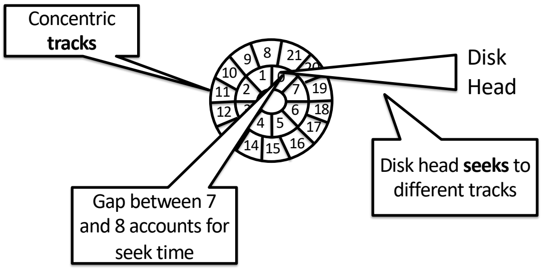
A simple disk model

- Disks are slow. Why?
  – Moving parts << circuits
- Programming interface: simple array of sectors (blocks)
- Physical layout:
  – Concentric circular "tracks" of blocks on a platter
  – E.g., sectors 0-9 on innermost track, 10-19 on next track, etc.
  – Disk arm moves between tracks
  – Platter rotates under disk head to align w/ requested sector

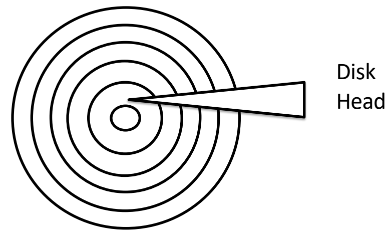
Disk Model



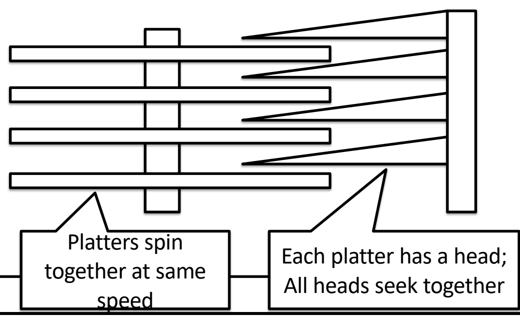
Disk Model



Many Tracks



Several (~4) Platters



Implications of multiple platters

- Blocks actually striped across platters
- Example:
  - Sector 0 on platter 0
  - Sector 1 on platter 1 at same position
  - Sector 2 on platter 2, Sec. 3 on Plat. 3 also at same position
  - 4 heads can read all 4 sectors simultaneously

3 key latencies

- I/O delay: time it takes to read/write a sector
- Rotational delay: time the disk head waits for the platter to rotate desired sector under it
  - Note: disk rotates continuously at constant speed
- Seek delay: time the disk arm takes to move to a different track

Observations

- Latency of a given operation is a function of current disk arm and platter position
- Each request changes these values
- Idea: build a model of the disk
  - Maybe use delay values from measurement or manuals
  - Use simple math to evaluate latency of each pending request
  - Greedy algorithm: always select lowest latency

Example formula

- s = seek latency, in time/track
- r = rotational latency, in time/sector
- i = I/O latency, in seconds

- Time = (Δtracks * s) + (Δsectors * r) + I
- Note: Δsectors must factor in position after seek is finished. Why?

Problem with greedy?

- "Far" requests will starve
- Disk head may just hover around the "middle" tracks

Elevator Algorithm

- Require disk arm to move in continuous "sweeps" in and out
- Reorder requests within a sweep
  - Ex: If disk arm is moving "out," reorder requests between the current track and the outside of disk in ascending order (by block number)
  - A request for a sector the arm has already passed must be ordered after the outermost request, in descending order

Elevator Algo, pt. 2

- This approach prevents starvation
  - Sectors at "inside" or "outside" get service after a bounded time
- Reasonably good throughput
  - Sort requests to minimize seek latency
  - Can get hit with rotational latency pathologies (How?)
- Simple to code up!
  - Programming model hides low-level details; difficult to do fine-grained optimizations in practice

Modular Schedulers

- Linux allows the disk scheduler to be replaced
  - Just like the CPU scheduler
- Can choose a different heuristic that favors:
  - Fairness
  - Real-time constraints
  - Performance

Complete Fairness Queue (CFQ)

- Idea: Add a second layer of queues (one per process)
  - Round-robin promote them to the "real" queue
- Goal: Fairly distribute disk bandwidth among tasks
- Problems?
  - Overall throughput likely reduced
  - Ping-pong disk head around

Deadline Scheduler

- Associate expiration times with requests
- As requests get close to expiration, make sure they are deployed
  - Constrains reordering to ensure some forward progress
- Good for real-time applications

Anticipatory Scheduler

- Idea: Try to anticipate locality of requests
  - If process P tends to issue bursts of requests for close disk blocks,
  - When you see a request from P, hold the request in the disk queue for a while
    - See if more "nearby" requests come in
    - Then schedule all the requests at once
      - And coalesce adjacent requests

Optimizations at Cross-purposes

- The disk itself does some optimizations:
  - Caching
    - Write requests can sit in a volatile cache for longer than expected
  - Reordering requests internally
    - Can't assume that requests are serviced in-order
    - Dependent operations must wait until first finishes
  - Bad sectors can be remapped to "spares"
    - Problem: disk arm flailing on an old disk

A note on safety

- In Linux, and other OSes, the I/O scheduler can reorder requests arbitrarily
- It is the file system's job to keep unsafe I/O requests out of the scheduling queues
  - Or issue barriers in the queue

Dangerous I/Os

- What can make an I/O request unsafe?
  - File system bookkeeping has invariants on disk
    - Example: Inodes point to file data blocks; data blocks are also marked as free in a bitmap
  - Updates must uphold these invariants
    - Ex: Write an update to the inode, then the bitmap
    - What if the system crashes between writes?
    - Block can end up in two files!!!

3 Simple Rules

(Courtesy of Ganger and McKusick, "Soft Updates" paper)

- Never write a pointer to a structure until it has been initialized
  - Ex: Don't write a directory entry to disk until the inode has been written to disk
- Never reuse a resource before nullifying all pointers to it
  - Ex: Before re-allocating a block to a file, write an update to the inode that references it
- Never reset the last pointer to a live resource before a new pointer has been set
  - Ex: Renaming a file – write the new directory entry before the old one (better 2 links than none)

A note on safety

- It is the file system's job to keep unsafe I/O requests out of the scheduling queues
- While these constraints are simple, enforcing them in the average file system is surprisingly difficult
  - Journaling helps by creating a log of what you are in the middle of doing, which can be replayed
  - (Simpler) Constraint: Journal updates must go to disk before FS updates

Disks aren't everything

- Flash is increasing in popularity
  - Different types with slight variations (NAND, NOR, etc)
- No moving parts – who cares about block ordering anymore?
- Can only write to a block of flash ~100k times
  - Can read as much as you want

More in a Flash

- Flash reads are generally fast, writes are more expensive
- Prefetching has little benefit
- Queuing optimizations can take longer than a read
- New issue: wear leveling – need to evenly distribute writes
  - Flash devices usually have a custom, log-structured FS
  - Group random writes

Even newer hotness

- Byte-addressible, persistent RAMs (BPRAM)
  - Optane, Phase-Change Memory (PCM), Memristors, etc.
- Splits the difference between RAM and flash:
  - Byte-granularity writes (vs. blocks)
  - Fast reads, slower, high-energy writes
  - Doesn't need energy to hold state (DRAM refresh)
  - Wear an issue (bytes get stuck at last value)
- Intel shipping first Optane prototypes, more to come…

Important research topic

- Most work on optimizing storage accessed is tailored to hard drives
- These heuristics are not easily adapted to new media
- Future systems will have a mix of disks, flash, PRAM, DRAM
- Does it even make sense to treat them all the same?

Summary

- Performance characteristics of disks, flash, BPRAM
- Disk scheduling heuristics
- Safety constraints for file systems