

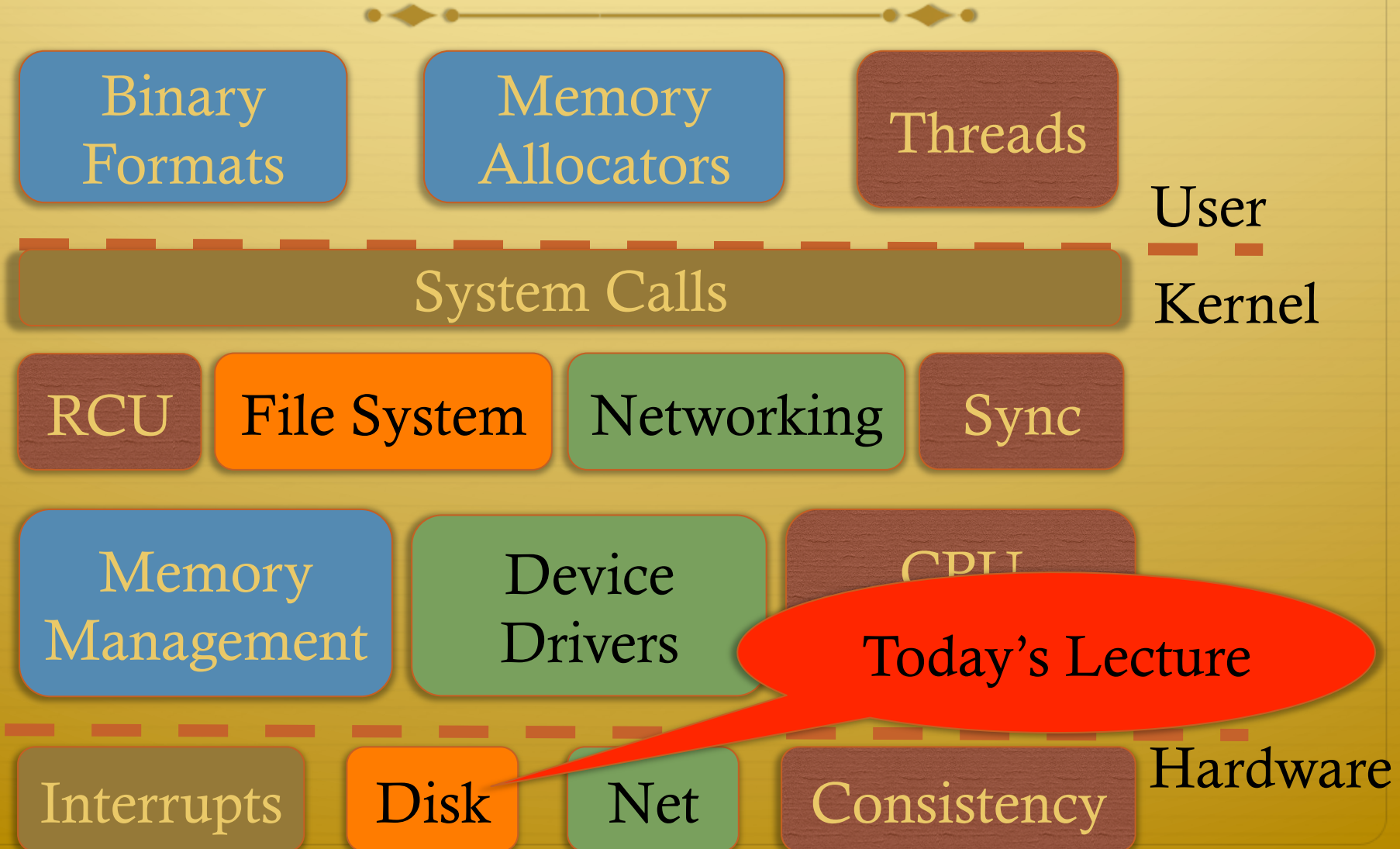
The background features a collage of various postage stamps from different countries, including Costa Rica, with visible text like 'PAR AVION', 'MADRID', and 'POSTAGE'.

# Block Device Scheduling

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CSE 506

# Logical Diagram



# 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

# 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

# Big Picture



VFS

Low-level FS (ext4, BTRFS, etc.)

Page Cache

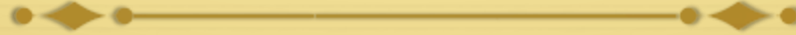
Block Device

IO Scheduler

Driver

Disk

# OS Model of a Block Dev.



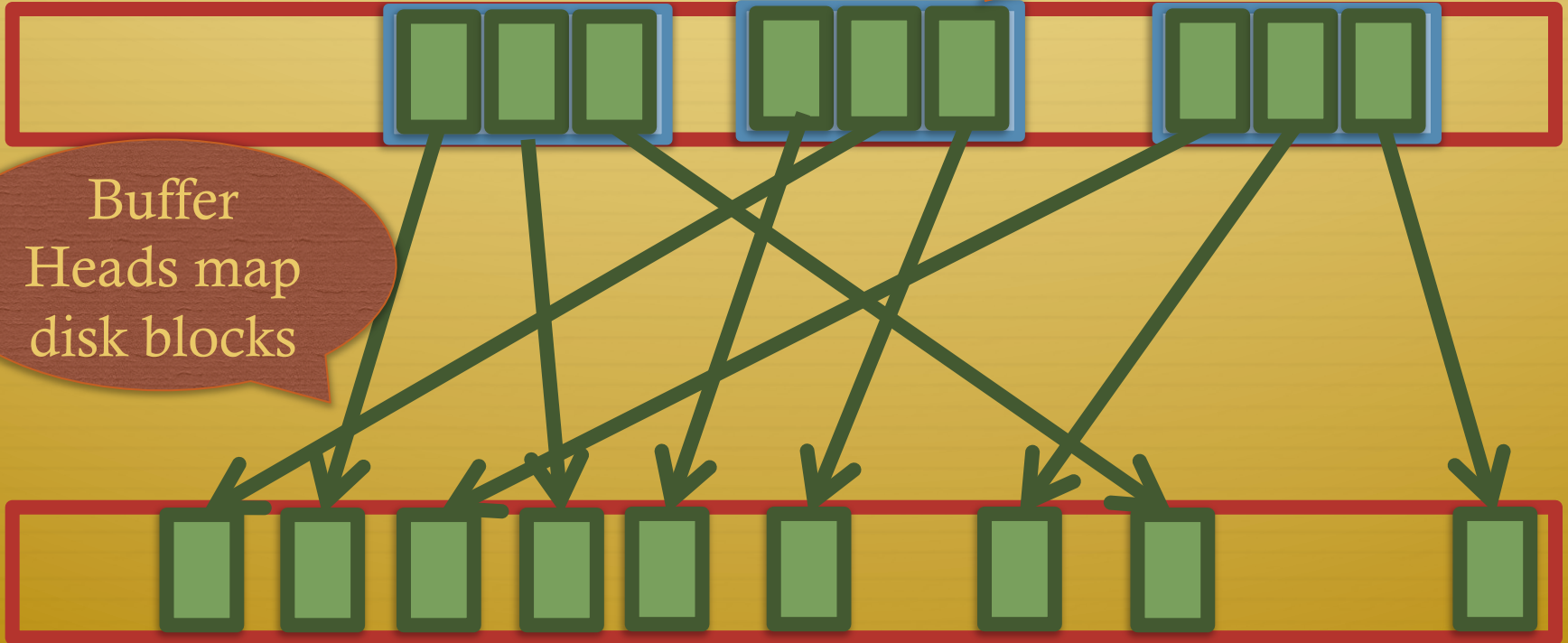
- ✦ Simple array of blocks
  - ✦ Blocks are usually 512 or 4k bytes

# Recall: Page Cache

Page Cache

Page (blue) w/ 3  
buffer heads (green)

Buffer  
Heads map  
disk blocks



Block Dev

# 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**

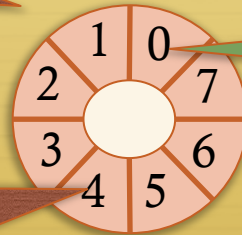
# A simple disk model



- ✦ Disks are slow. Why?
  - ✦ Moving parts  $\ll$  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

Each block  
on a sector

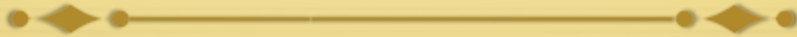


Disk  
Head

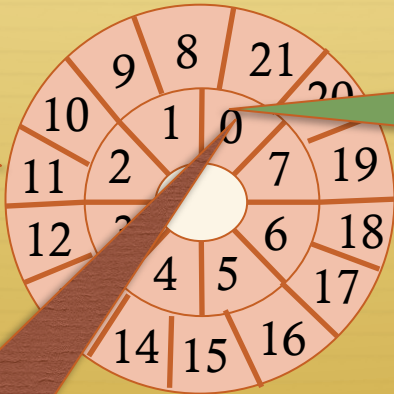
Disk spins at a  
constant speed.  
Sectors rotate  
underneath head.

Disk Head  
reads at  
granularity of  
entire sector

# Disk Model



Concentric tracks

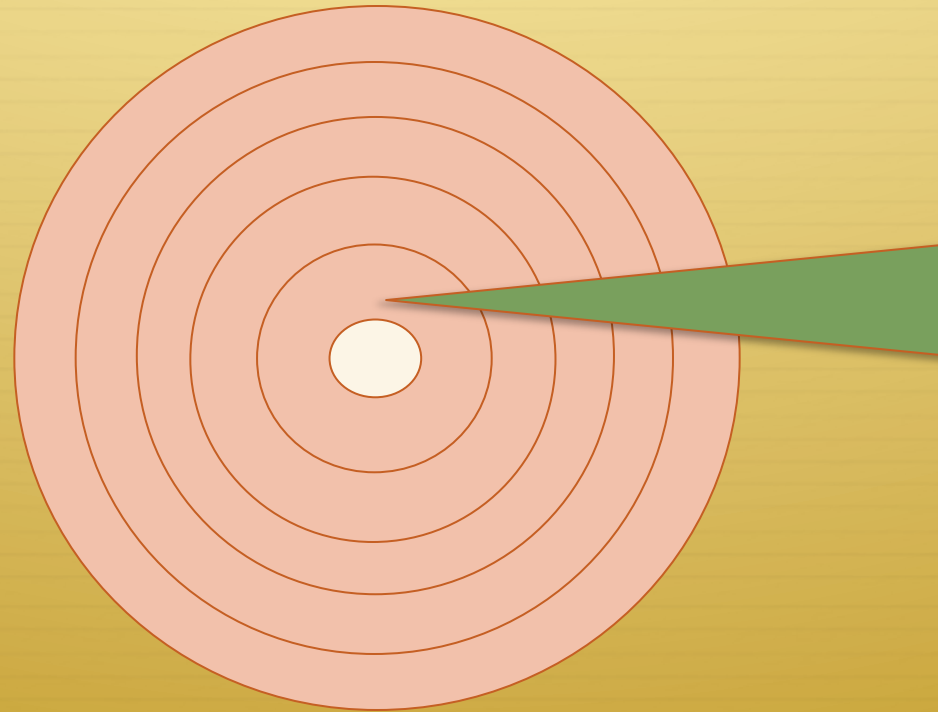


Disk Head

Gap between 7 and 8 accounts for seek time

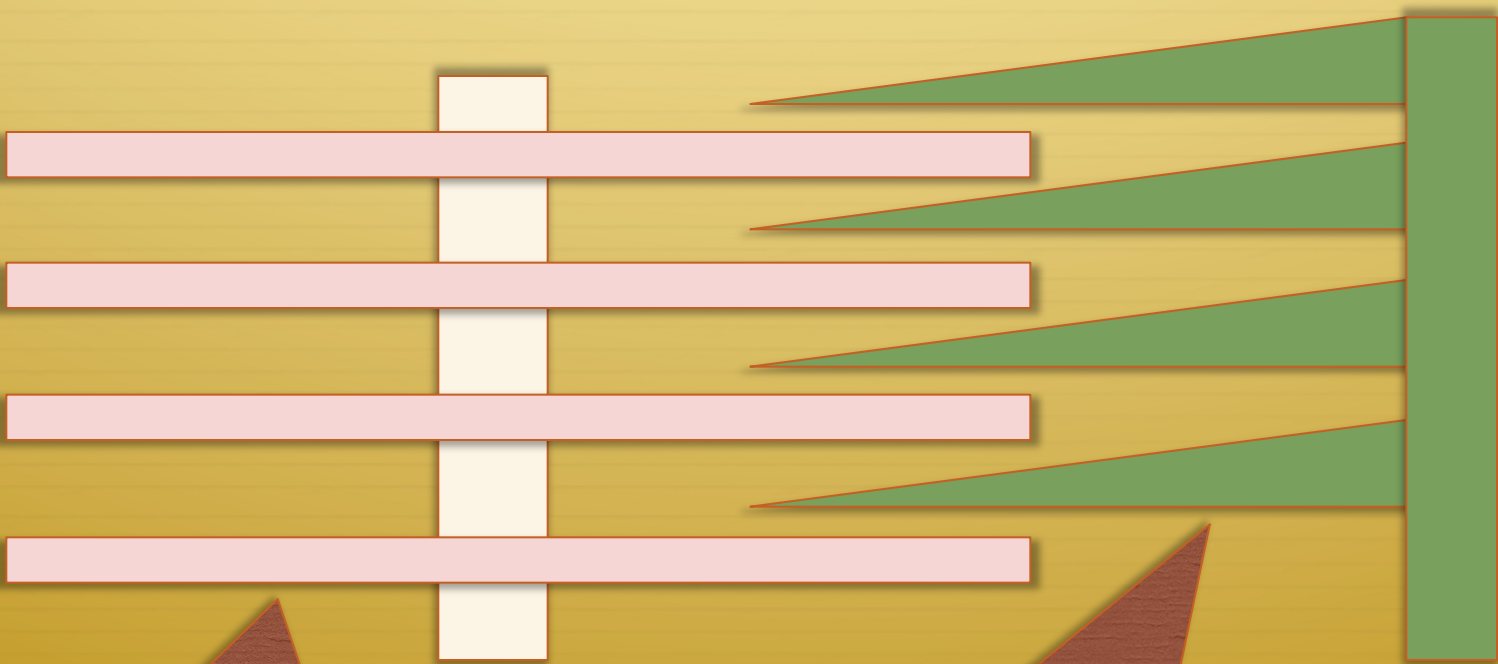
Disk head **seeks** to different tracks

# Many Tracks



Disk  
Head

# Several (~4) Platters



Platters spin together at same speed

Each platter has a head; All heads seek together

# 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
  
- ✦  $\text{Time} = (\Delta \text{ tracks} * s) + (\Delta \text{ sectors} * r) + I$
- ✦ Note:  $\Delta$  sectors 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

# Pluggable 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

# 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!!!

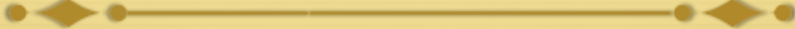
# 3 Simple Rules

(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)
  - ✦ 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)
- ✦ Still in the lab, but getting close

# 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