CS162
Operating Systems and Systems Programming
Lecture 24

Filesystems 4: Buffering, Reliability, Transactions

April 18th, 2023
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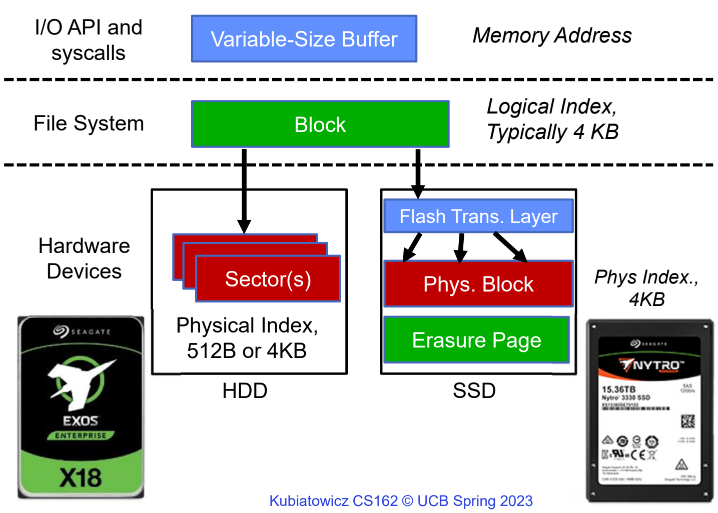
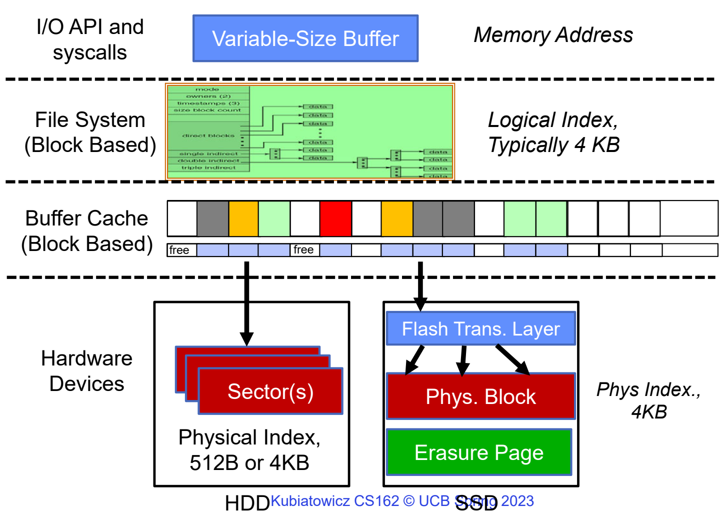
Recall: From Storage to File Systems



Need for Cache Between FileSystem and Devices



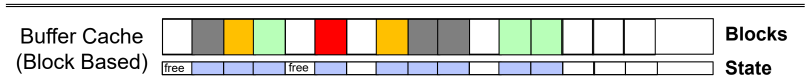
Not block-sized or block-aligned access

Reuse of inodes, indirect blocks, data blocks

Speed up access to file system path and data

Apparent speed and flexibility is greater because of Buffer Cache

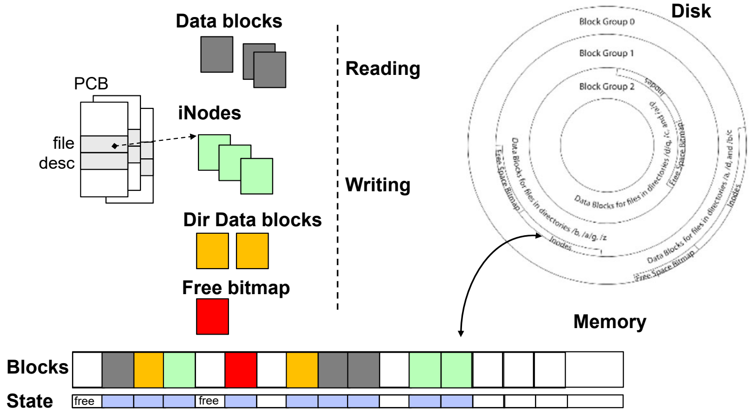
Buffer Cache: Motivation



- Kernel *must* copy disk blocks to memory (somewhere) to access their contents and write them back if modified
  - Could be data blocks, inodes, directory contents, etc.
  - Possibly dirty (modified and not yet written back)
- Key Idea: Exploit locality by caching disk data in memory
  - Name translations: Mapping from paths→inodes
  - Disk blocks: Mapping from block address→disk content
- Buffer Cache: Memory used to cache kernel resources, including disk blocks and name translations
  - Can contain "dirty" blocks (with modifications not on disk)

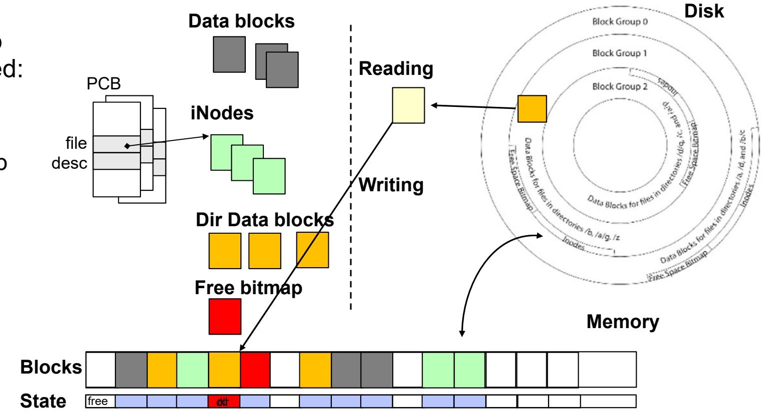
File System Buffer Cache

- OS implements a cache of disk blocks for efficient access to data, directories, inodes, freemap



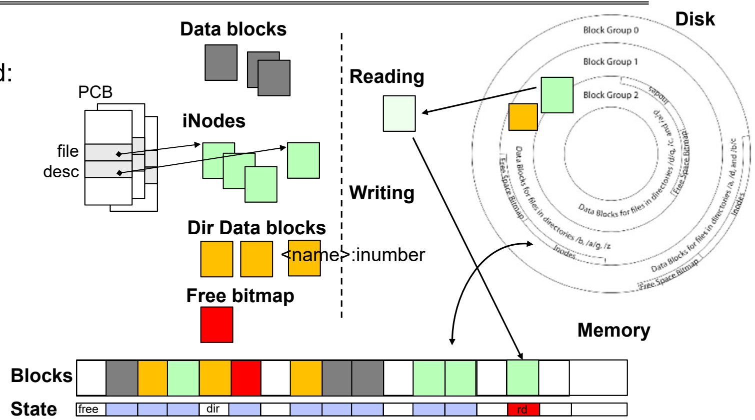
File System Buffer Cache: open

- Directory lookup repeat as needed:
  - load block of directory
  - search for map



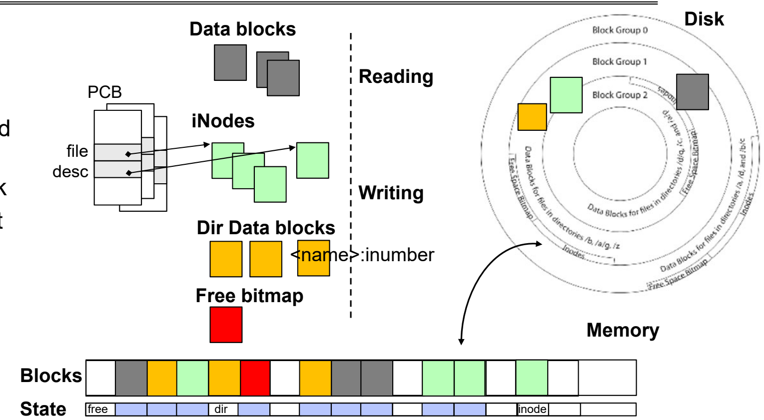
File System Buffer Cache: open

- Directory lookup repeat as needed:
  - load block of directory
  - search for map
- Create reference via open file descriptor



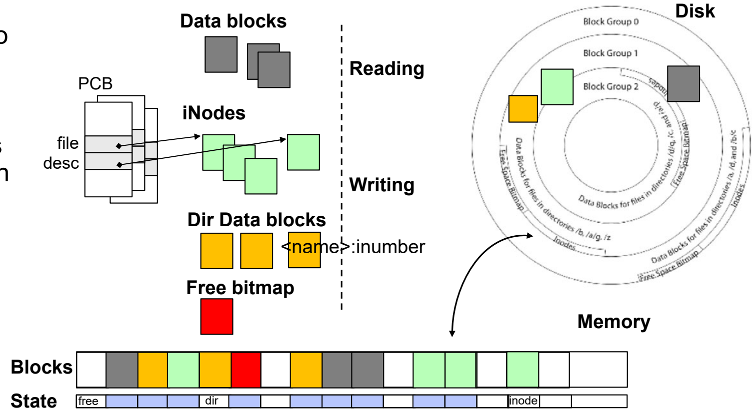
File System Buffer Cache: Read?

- Read Process
  - From inode, traverse index structure to find data block
  - load data block
  - copy all or part to read data buffer



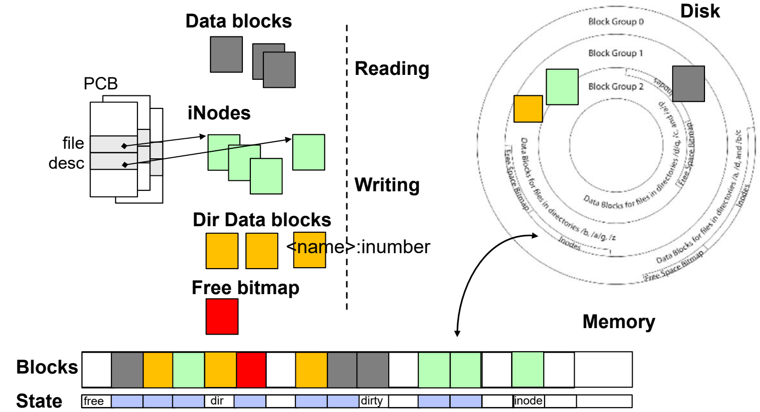
File System Buffer Cache: Write?

- Process similar to read, but may allocate new blocks (update free map), blocks need to be written back to disk; inode?



File System Buffer Cache: Eviction?

- Blocks being written back to disc go through a transient state



Buffer Cache Discussion

- Implemented entirely in OS software
  - Unlike memory caches and TLB
- Blocks go through transitional states between free and in-use
  - Being read from disk, being written to disk
  - Other processes can run, etc.
- Blocks are used for a variety of purposes
  - inodes, data for dirs and files, freemap
  - OS maintains pointers into them
- Termination – e.g., process exit – open, read, write
  - Data flushed to disk if necessary
- Replacement – what to do when it fills up?

File System Caching

- Replacement policy? LRU
  - Can afford overhead full LRU implementation
  - Advantages:
    - » Works very well for name translation
    - » Works well in general as long as memory is big enough to accommodate a host's working set of files.
  - Disadvantages:
    - » Fails when some application scans through file system, thereby flushing the cache with data used only once
    - » Example: `find . -exec grep foo {} \;`
- Other Replacement Policies?
  - Some systems allow applications to request other policies
  - Example, 'Use Once':
    - » File system can discard blocks as soon as they are used

File System Caching (con't)

- Cache Size: How much memory should the OS allocate to the buffer cache vs virtual memory?
  - Too much memory to the file system cache ⇒ won't be able to run many applications
  - Too little memory to file system cache ⇒ many applications may run slowly (disk caching not effective)
  - Solution: adjust boundary dynamically so that the disk access rates for paging and file access are balanced

Administrivia

- Midterm 3: Next Thursday!
  - No class on day of midterm
  - Three double-sided pages of notes
  - Watch for Ed post about where you should go: we have multiple exam rooms
  - Confict request form due Thursday!
- All material up to next Tuesday's lecture is fair game

File System Prefetching

- Read Ahead Prefetching: fetch sequential blocks early
  - Key Idea: exploit fact that most common file access is sequential by prefetching subsequent disk blocks ahead of current read request
  - Elevator algorithm can efficiently interleave prefetches from concurrent applications
- How much to prefetch?
  - Too much prefetching imposes delays on requests by other applications
  - Too little prefetching causes many seeks (and rotational delays) among concurrent file requests

Delayed Writes

- Buffer cache is a writeback cache (writes are termed "Delayed Writes")
- `write()` copies data from user space to kernel buffer cache
  - Quick return to user space
- `read()` is fulfilled by the cache, so `reads` see the results of `writes`
  - Even if the data has not reached disk
- When does data from a `write` syscall finally reach disk?
  - When the buffer cache is full (e.g., we need to evict something)
  - When the buffer cache is flushed periodically (in case we crash)

Delayed Writes (Advantages)

- Performance advantage: return to user quickly without writing to disk!
- Disk scheduler can efficiently order lots of requests
  - Elevator Algorithm can rearrange writes to avoid random seeks
- Delay block allocation:
  - May be able to allocate multiple blocks at same time for file, keep them contiguous
- Some files never actually make it all the way to disk
  - Many short-lived files!

Buffer Caching vs. Demand Paging

- Replacement Policy?
  - Demand Paging: LRU is infeasible; use approximation (like NRU/Clock)
  - Buffer Cache: LRU is OK
- Eviction Policy?
  - Demand Paging: evict not-recently-used pages when memory is close to full
  - Buffer Cache: write back dirty blocks periodically, even if used recently
    - » Why? To minimize data loss in case of a crash

Dealing with Persistent State

- Buffer Cache: write back dirty blocks periodically, even if used recently
  - Why? To minimize data loss in case of a crash
  - Linux does periodic flush every 30 seconds
- Not foolproof! Can still crash with dirty blocks in the cache
  - What if the dirty block was for a directory?
    - » Lose pointer to file's inode (leak space)
    - » **File system now in inconsistent state** ☹

Takeaway: File systems need recovery mechanisms

Important "ilities"

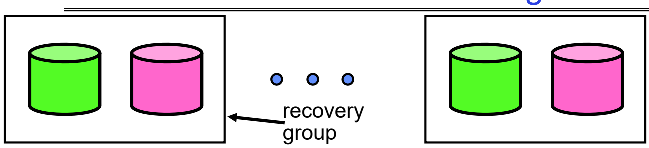
- Availability: the probability that the system can accept and process requests
  - Measured in "nines" of probability: e.g. 99.9% probability is "3-nines of availability"
  - Key idea here is independence of failures
- Durability: the ability of a system to recover data despite faults
  - This idea is fault tolerance applied to data
  - Doesn't necessarily imply availability: information on pyramids was very durable, but could not be accessed until discovery of Rosetta Stone
- Reliability: the ability of a system or component to perform its required functions under stated conditions for a specified period of time (IEEE definition)
  - Usually stronger than simply availability: means that the system is not only "up", but also working correctly
  - Includes availability, security, fault tolerance/durability
  - Must make sure data survives system crashes, disk crashes, other problems

HOW TO MAKE FILE SYSTEMS MORE *DURABLE*?

How to Make File Systems more Durable?

- Disk blocks contain Reed-Solomon error correcting codes (ECC) to deal with small defects in disk drive
  - Can allow recovery of data from small media defects
- Make sure writes survive in short term
  - Either abandon delayed writes or
  - Use special, battery-backed RAM (called non-volatile RAM or NVRAM) for dirty blocks in buffer cache
- Make sure that data survives in long term
  - Need to replicate! More than one copy of data!
  - Important element: independence of failure
    - » Could put copies on one disk, but if disk head fails…
    - » Could put copies on different disks, but if server fails…
    - » Could put copies on different servers, but if building is struck by lightning….
    - » Could put copies on servers in different continents…

RAID 1: Disk Mirroring/Shadowing

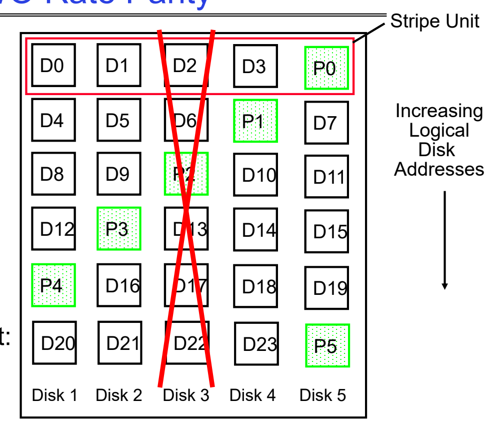


Redundant Array of Inexpensive D
(developed here at Berkeley!)

- Each disk is fully duplicated onto its “shadow”
  - For high I/O rate, high availability environments
  - Most expensive solution: 100% capacity overhead
- Bandwidth sacrificed on write:
  - Logical write = two physical writes
  - Highest bandwidth when disk heads and rotation synchronized (challenging)
- Reads may be optimized
  - Can have two independent reads to same data
- Recovery:
  - Disk failure ⇒ replace disk and copy data to new disk
  - Hot Spare: idle disk attached to system for immediate replacement

RAID 5+: High I/O Rate Parity

- Data stripped across multiple disks
  - Successive blocks stored on successive (non-parity) disks
  - Increased bandwidth over single disk
- Parity block (in green) constructed by XORing data blocks in stripe
  - $P0=D0\oplus D1\oplus D2\oplus D3$
  - Can destroy any one disk and still reconstruct data
- Suppose Disk 3 fails, then can reconstruct: $D2=D0\oplus D1\oplus D3\oplus P0$

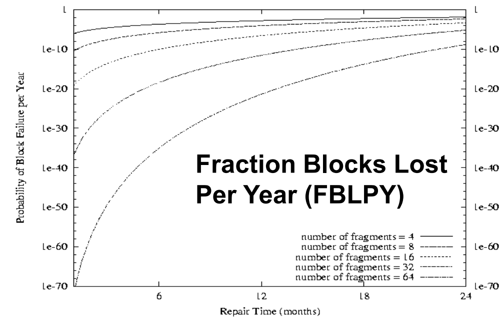


- Can spread information widely across internet for durability
  - RAID algorithms work over geographic scale

RAID 6 and other Erasure Codes

- In general: RAIDX is an "erasure code"
  - Must have ability to know which disks are bad
  - Treat missing disk as an "Erasure"
- Today, disks so big that: RAID 5 not sufficient!
  - Time to repair disk sooooo long, another disk might fail in process!
  - "RAID 6" – allow 2 disks in replication stripe to fail
  - Requires more complex erasure code, such as EVENODD code (see readings)
- More general option for general erasure code: Reed-Solomon codes
  - Based on polynomials in GF(2^k) (I.e. k-bit symbols)
  - m data points define a degree m polynomial; encoding is n points on the polynomial
  - Any m points can be used to recover the polynomial; $n - m$ failures tolerated
- Erasure codes not just for disk arrays. For example, geographic replication
  - E.g., split data into $m = 4$ chunks, generate $n = 16$ fragments and distribute across the Internet
  - Any 4 fragments can be used to recover the original data --- very durable!

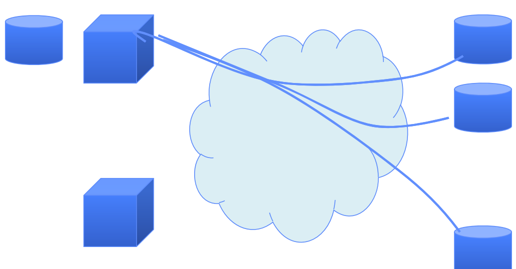
Use of Erasure Coding for High Durability/overhead ratio!



- Exploit law of large numbers for durability!
- 6 month repair, FBLPY with 4x increase in total size of data:
  - Replication (4 copies): 0.03
  - Fragmentation (16 of 64 fragments needed): 10^{-35}

Higher Durability through Geographic Replication

- Highly durable – hard to destroy all copies
- Highly available for reads
  - Simple replication: read any copy
  - Erasure coded: read m of n
- Low availability for writes
  - Can't write if any one replica is not up
  - Or – need relaxed consistency model
- Reliability? – availability, security, durability, fault-tolerance



HOW TO MAKE FILE SYSTEMS MORE *RELIABLE*?

File System Reliability: (Difference from Block-level reliability)

- What can happen if disk loses power or software crashes?
  – Some operations in progress may complete
  – Some operations in progress may be lost
  – Overwrite of a block may only partially complete
- Having RAID doesn't necessarily protect against all such failures
  – No protection against writing bad state
  – What if one disk of RAID group not written?
- File system needs durability (as a minimum!)
  – Data previously stored can be retrieved (maybe after some recovery step), regardless of failure
- But durability is not quite enough…!

Storage Reliability Problem

- Single logical file operation can involve updates to multiple physical disk blocks
  – inode, indirect block, data block, bitmap, …
  – With sector remapping, single update to physical disk block can require multiple (even lower level) updates to sectors
- At a physical level, operations complete one at a time
  – Want concurrent operations for performance
- How do we guarantee consistency regardless of when crash occurs?

Threats to Reliability

- Interrupted Operation
  – Crash or power failure in the middle of a series of related updates may leave stored data in an inconsistent state
  – Example: transfer funds from one bank account to another
  – What if transfer is interrupted after withdrawal and before deposit?
- Loss of stored data
  – Failure of non-volatile storage media may cause previously stored data to disappear or be corrupted

Two Reliability Approaches

Careful Ordering and Recovery
- FAT & FFS + (fsck)
- Each step builds structure,
- Data block ⇐ inode ⇐ free ⇐ directory
- Last step links it in to rest of FS
- Recover scans structure looking for incomplete actions

Versioning and Copy-on-Write
- ZFS, …
- Version files at some granularity
- Create new structure linking back to unchanged parts of old
- Last step is to declare that the new version is ready

Reliability Approach #1: Careful Ordering

- Sequence operations in a specific order
  - Careful design to allow sequence to be interrupted safely
- Post-crash recovery
  - Read data structures to see if there were any operations in progress
  - Clean up/finish as needed
- Approach taken by
  - FAT and FFS (fsck) to protect filesystem structure/metadata
  - Many app-level recovery schemes (e.g., Word, emacs autosaves)

Berkeley FFS: Create a File

Normal operation:

- Allocate data block
- Write data block
- Allocate inode
- Write inode block
- Update bitmap of free blocks and inodes
- Update directory with file name → inode number
- Update modify time for directory

Recovery:

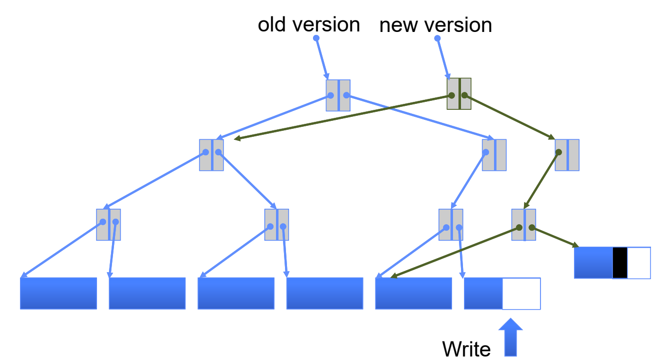
- Scan inode table
- If any unlinked files (not in any directory), delete or put in lost & found dir
- Compare free block bitmap against inode trees
- Scan directories for missing update/access times

Time proportional to disk size

Reliability Approach #2: Copy on Write File Layout

- Recall: multi-level index structure lets us find the data blocks of a file
- Instead of over-writing existing data blocks and updating the index structure:
  - Create a new version of the file with the updated data
  - Reuse blocks that don't change much of what is already in place
  - This is called: Copy On Write (COW)
- Seems expensive! But
  - Updates can be batched
  - Almost all disk writes can occur in parallel
- Approach taken in network file server appliances
  - NetApp's Write Anywhere File Layout (WAFL)
  - ZFS (Sun/Oracle) and OpenZFS

COW with Smaller-Radix Blocks



- If file represented as a tree of blocks, just need to update the leading fringe

Example: ZFS and OpenZFS

- Variable sized blocks: 512 B – 128 KB
- Symmetric tree
  – Know if it is large or small when we make the copy
- Store version number with pointers
  – Can create new version by adding blocks and new pointers
- Buffers a collection of writes before creating a new version with them
- Free space represented as tree of extents in each block group
  – Delay updates to freespace (in log) and do them all when block group is activated

More General Reliability Solutions

- Use Transactions for atomic updates
  – Ensure that multiple related updates are performed atomically
  – i.e., if a crash occurs in the middle, the state of the systems reflects either all or none of the updates
  – Most modern file systems use transactions internally to update filesystem structures and metadata
  – Many applications implement their own transactions
- Provide Redundancy for media failures
  – Redundant representation on media (Error Correcting Codes)
  – Replication across media (e.g., RAID disk array)

Transactions

- Closely related to critical sections for manipulating shared data structures
- They extend concept of atomic update from memory to stable storage
  – Atomically update multiple persistent data structures
- Many ad-hoc approaches
  – FFS carefully ordered the sequence of updates so that if a crash occurred while manipulating directory or inodes the disk scan on reboot would detect and recover the error (fsck)
  – Applications use temporary files and rename

Key Concept: Transaction

- A *transaction* is an atomic sequence of reads and writes that takes the system from consistent state to another.

- Recall: Code in a critical section appears atomic to other threads
- Transactions extend the concept of atomic updates from *memory* to *persistent storage*

Typical Structure

- Begin a transaction – get transaction id
- Do a bunch of updates
  - If any fail along the way, roll-back
  - Or, if any conflicts with other transactions, roll-back
- Commit the transaction

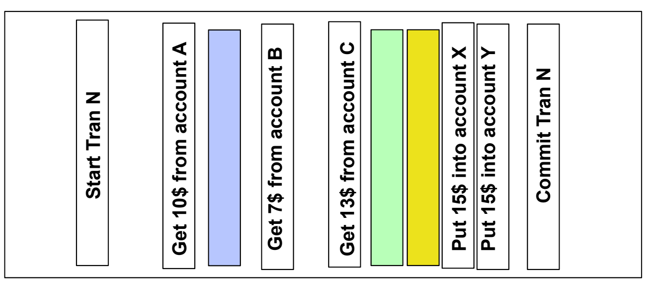
"Classic" Example: Transaction

```
BEGIN;    --BEGIN TRANSACTION
 UPDATE accounts SET balance = balance - 100.00 WHERE
   name = 'Alice';

 UPDATE branches SET balance = balance - 100.00 WHERE
   name = (SELECT branch_name FROM accounts WHERE name
   = 'Alice');

 UPDATE accounts SET balance = balance + 100.00 WHERE
   name = 'Bob';

 UPDATE branches SET balance = balance + 100.00 WHERE
   name = (SELECT branch_name FROM accounts WHERE name
   = 'Bob');
COMMIT;    --COMMIT WORK
```

Transfer $100 from Alice's account to Bob's account

Concept of a log

- One simple action is atomic – write/append a basic item
- Use that to seal the commitment to a whole series of actions



Transactional File Systems

- Better reliability through use of log
  - Changes are treated as transactions
  - A transaction is committed once it is written to the log
    - » Data forced to disk for reliability
    - » Process can be accelerated with NVRAM
  - Although File system may not be updated immediately, data preserved in the log
- Difference between "Log Structured" and "Journaled"
  - In a Log Structured filesystem, data stays in log form
  - In a Journaled filesystem, Log used for recovery

Journaling File Systems

- Don't modify data structures on disk directly
- Write each update as transaction recorded in a log
  – Commonly called a journal or intention list
  – Also maintained on disk (allocate blocks for it when formatting)
- Once changes are in the log, they can be safely applied to file system
  – e.g. modify inode pointers and directory mapping
- Garbage collection: once a change is applied, remove its entry from the log

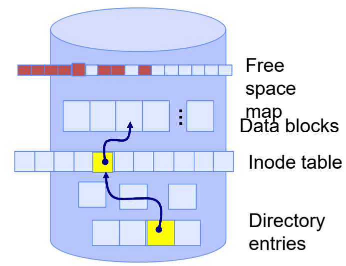
- Linux took original FFS-like file system (ext2) and added a journal to get ext3!
  – Some options: whether or not to write all data to journal or just metadata

- Other examples: NTFS, Apple HFS+/apfs, Linux XFS, JFS, ext4

Creating a File (No Journaling Yet)

- Find free data block(s)
- Find free inode entry
- Find dirent insertion point

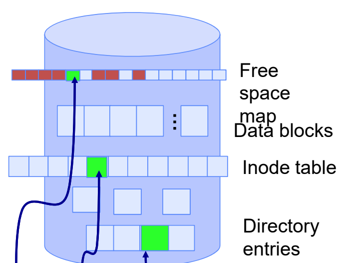
- Write map (i.e., mark used)
- Write inode entry to point to block(s)
- Write dirent to point to inode

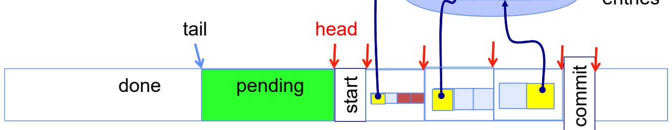


Creating a File (With Journaling)

- Find free data block(s)
- Find free inode entry
- Find dirent insertion point

- [log] Write map (i.e., mark used)
- [log] Write inode entry to point to block(s)
- [log] Write dirent to point to inode

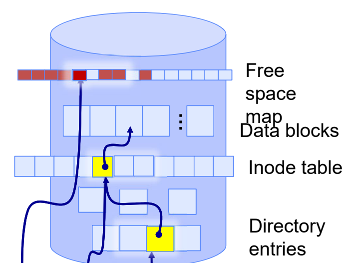


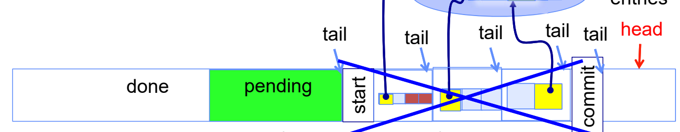


Log: in non-volatile storage (Flash or on Disk)

After Commit, Eventually Replay Transaction

- All accesses to the file system first looks in the log
  – Actual on-disk data structure might be stale
- Eventually, copy changes to disk and discard transaction from the log

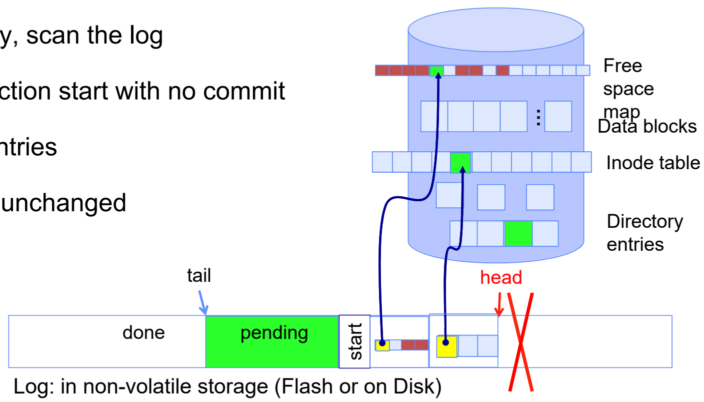




Log: in non-volatile storage (Flash or on Disk)

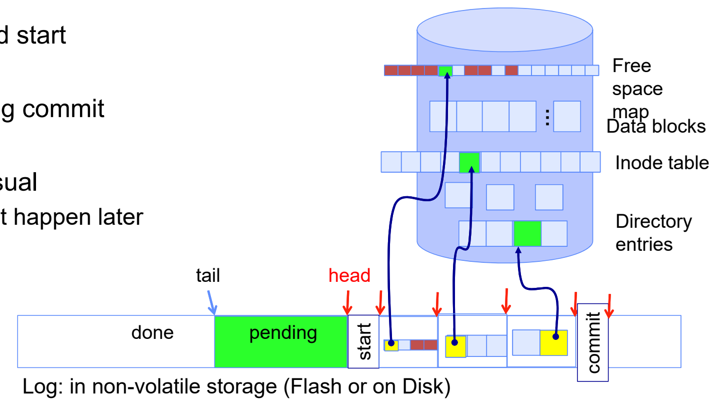
Crash Recovery: Discard Partial Transactions

- Upon recovery, scan the log
- Detect transaction start with no commit
- Discard log entries
- Disk remains unchanged



Crash Recovery: Keep Complete Transactions

- Scan log, find start
- Find matching commit
- Redo it as usual
  - Or just let it happen later



Journaling Summary

Why go through all this trouble?

- Updates atomic, even if we crash:
  - Update either gets fully applied or discarded
  - All physical operations *treated as a logical unit*

Isn't this expensive?

- Yes! We're now writing all data twice (once to log, once to actual data blocks in target file)
- Modern filesystems journal metadata updates only
  - Record modifications to file system data structures
  - But apply updates to a file's contents directly

Summary

- Buffer Cache: Memory used to cache kernel resources, including disk blocks and name translations
  - Can contain "dirty" blocks (blocks yet on disk)
- Important system properties
  - Availability: how often is the resource available?
  - Durability: how well is data preserved against faults?
  - Reliability: how often is resource performing correctly?
- RAID: Redundant Arrays of Inexpensive Disks
  - RAID1: mirroring, RAID5: Parity block
- Copy-on-write provides richer function (versions) with much simpler recovery
  - Little performance impact since sequential write to storage device is nearly free
- Use of Log to improve Reliability
  - Journaled file systems such as ext3, NTFS
- Transactions over a log provide a general solution
  - Commit sequence to durable log, then update the disk
  - Log takes precedence over disk
  - Replay committed transactions, discard partials