CS350: Operating Systems
Lecture 13: Advanced File Systems

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Outline

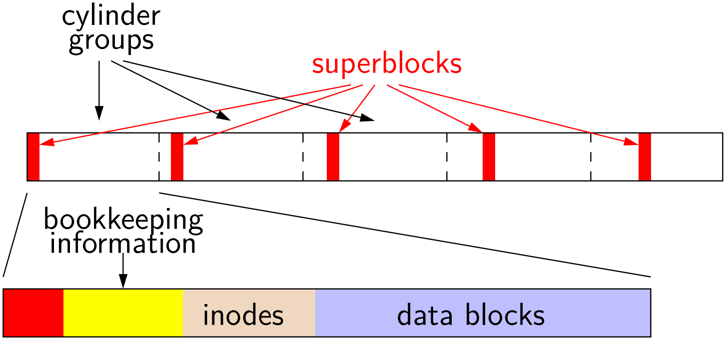
Review: FFS background

- 1980s improvement to original Unix FS, which had:
  - 512-byte blocks
  - Free blocks in linked list
  - All inodes at beginning of disk
  - Low throughput: 512 bytes per average seek time
- Unix FS performance problems:
  - Transfers only 512 bytes per disk access
  - Eventually random allocation $\rightarrow$ 512 bytes / disk seek
  - Inodes far from directory and file data
  - Within directory, inodes far from each other
- Also had some usability problems:
  - 14-character file names a pain
  - Can't atomically update file in crash-proof way

Review: FFS [McKusic] basics

- Change block size to at least 4K
  - To avoid wasting space, use “fragments” for ends of files
- Cylinder groups spread inodes around disk
- Bitmaps replace free list
- FS reserves space to improve allocation
  - Tunable parameter, default 10%
  - Only superuser can use space when over 90% full
- Usability improvements:
  - File names up to 255 characters
  - Atomic *rename* system call
  - Symbolic links assign one file name to another

Review: FFS disk layout



- Each cylinder group has its own:
  - Superblock
  - Bookkeeping information
  - Set of inodes
  - Data/directory blocks

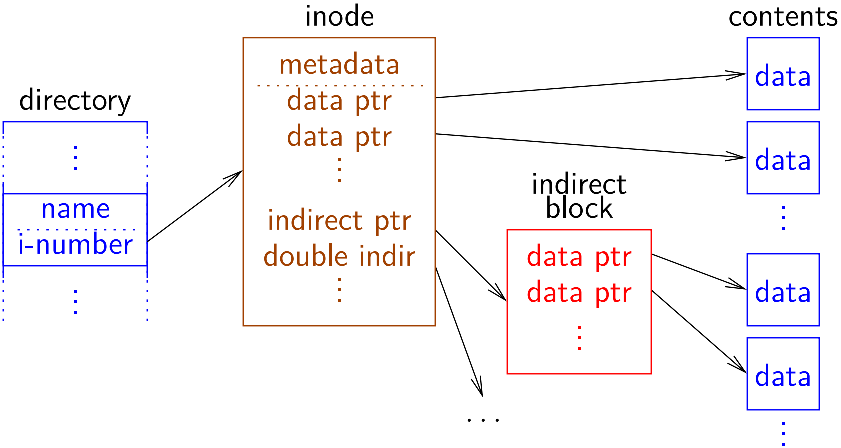
Superblock

- Contains file system parameters
  - Disk characteristics, block size, CG info
  - Information necessary to locate inode given i-number
- Replicated once per cylinder group
  - At shifting offsets, so as to span multiple platters
  - Contains magic number `0x011954` to find replicas if 1st superblock dies (Kirk McKusick's birthday?)
- Contains non-replicated "summary information"
  - # blocks, fragments, inodes, directories in FS
  - Flag stating if FS was cleanly unmounted

Bookkeeping information

- Block map
  - Bit map of available fragments
  - Used for allocating new blocks/fragments
- Summary info within CG
  - # free inodes, blocks/frags, files, directories
  - Used when picking cylinder group from which to allocate
- # free blocks by rotational position (8 positions)
  - Was reasonable in 1980s when disks weren't commonly zoned
  - Back then OS could do stuff to minimize rotational delay

Inodes and data blocks



- Each CG has fixed # of inodes (default one per 2K data)
- Each inode maps offset → disk block for one file
- An inode also contains metadata for its file
  - permissions, access/modification/change times, link count

Inode allocation

- Each file or directory created requires a new inode
- New file? Put inode in same CG as directory if possible
- New directory? Use different CG from parent
  - Consider CGs with greater than average # free inodes
  - Chose CG with smallest # directories
- Within CG, inodes allocated randomly (next free)
  - Would like related inodes as close as possible
  - OK, because one CG doesn't have that many inodes
  - All inodes in CG can be read and cached with small # of reads

Fragment allocation

- Allocate space when user writes beyond end of file
- Want last block to be a fragment if not full-size
  - If already a fragment, may contain space for write – done
  - Else, must deallocate any existing fragment, allocate new
- If no appropriate free fragments, break full block
- Problem: Slow for many small writes
  - May have to keep moving end of file around
- (Partial) soution: new `stat` struct field `st_blksize`
  - Tells applications file system block size
  - stdio library can buffer this much data

Block allocation

- Try to optimize for sequential access
  - If available, use rotationally close block in same cylinder (obsolete)
  - Otherwise, use block in same CG
  - If CG totally full, find other CG with quadratic hashing
    i.e., if CG $\#n$ is full, try $n + 1^2, n + 2^2, n + 3^2, \ldots \pmod{\#CGs}$
  - Otherwise, search all CGs for some free space
- Problem: Don't want one file filling up whole CG
  - Otherwise other inodes will have data far away
- Solution: Break big files over many CGs
  - But large extents in each CGs, so sequential access doesn't require many seeks
  - How big should extents be?

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  - How big should extents be?
  - Extent transfer time should be much greater than seek time

Directories

- Inodes like files, but with different type bits
- Contents considered as 512-byte *chunks*
- Each chunk has `direct` structure(s) with:
  - 32-bit inumber
  - 16-bit size of directory entry
  - 8-bit file type (added later)
  - 8-bit length of file name
- Coalesce when deleting
  - If first `direct` in chunk deleted, set inumber $= 0$
- Periodically compact directory chunks
  - But can never move directory entries across chunks
  - Recall only 512-byte sector writes atomic w. power failure

Updating FFS for the 90s

- No longer wanted to assume rotational delay
  - With disk caches, want data contiguously allocated
- Solution: Cluster writes
  - FS delays writing a block back to get more blocks
  - Accumulates blocks into 64K clusters, written at once
- Allocation of clusters similar to fragments/blocks
  - Summary info
  - Cluster map has one bit for each 64K if all free
- Also read in 64K chunks when doing read ahead

Outline

Fixing corruption – fsck

- Must run FS check (fsck) program after crash
- Summary info usually bad after crash
  - Scan to check free block map, block/inode counts
- System may have corrupt inodes (not simple crash)
  - Bad block numbers, cross-allocation, etc.
  - Do sanity check, clear inodes with garbage
- Fields in inodes may be wrong
  - Count number of directory entries to verify link count, if no entries but count $\neq 0$, move to `lost+found`
  - Make sure size and used data counts match blocks
- Directories may be bad
  - Holes illegal, `.` and `..` must be valid, file names must be unique
  - All directories must be reachable

Crash recovery permeates FS code

- Have to ensure fsck can recover file system
- Example: Suppose all data written asynchronously
  - Any subset of data structures may be updated before a crash
- Delete/truncate a file, append to other file, crash
  - New file may reuse block from old
  - Old inode may not be updated
  - Cross-allocation!
  - Often inode with older mtime wrong, but can't be sure
- Append to file, allocate indirect block, crash
  - Inode points to indirect block
  - But indirect block may contain garbage!

Ordering of updates

- Must be careful about order of updates
  - Write new inode to disk before directory entry
  - Remove directory name before deallocating inode
  - Write cleared inode to disk before updating CG free map
- Solution: Many metadata updates synchronous
  - Doing one write at a time ensures ordering
  - Of course, this hurts performance
  - E.g., untar much slower than disk bandwidth
- Note: Cannot update buffers on the disk queue
  - E.g., say you make two updates to same directory block
  - But crash recovery requires first to be synchronous
  - Must wait for first write to complete before doing second

Performance vs. consistency

- FFS crash recoverability comes at *huge* cost
  - Makes tasks such as untar easily 10-20 times slower
  - All because you *might* lose power or reboot at any time
- Even while slowing ordinary usage, recovery slow
  - If fsck takes one minute, then disks get $10\times$ bigger ...
- One solution: battery-backed RAM
  - Expensive (requires specialized hardware)
  - Often don't learn battery has died until too late
  - A pain if computer dies (can't just move disk)
  - If OS bug causes crash, RAM might be garbage
- Better solution: Advanced file system techniques
  - Topic of rest of lecture

Outline

First attempt: Ordered updates

- Want to avoid crashing after "bad" subset of writes
- Must follow 3 rules in ordering updates [Ganger]:
  1. Never write pointer before initializing the structure it points to
  2. Never reuse a resource before nullifying all pointers to it
  3. Never clear last pointer to live resource before setting new one
- If you do this, file system will be recoverable
- Moreover, can recover quickly
  - Might leak free disk space, but otherwise correct
  - So start running after reboot, scavenge for space in background
- How to achieve?
  - Keep a partial order on buffered blocks

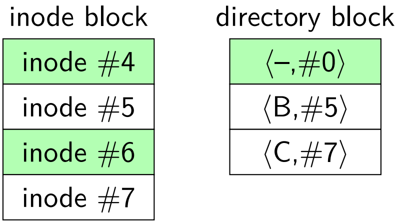
Ordered updates (continued)

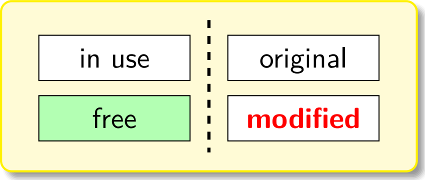
- Example: Create file A
  - Block X contains an inode
  - Block Y contains a directory block
  - Create file A in inode block X, dir block Y
- We say $Y \rightarrow X$, pronounced "Y *depends on* X"
  - Means Y cannot be written before X is written
  - X is called the *dependee*, Y the *depender*
- Can delay both writes, so long as order preserved
  - Say you create a second file B in blocks X and Y
  - Only have to write each out once for both creates

Problem: Cyclic dependencies

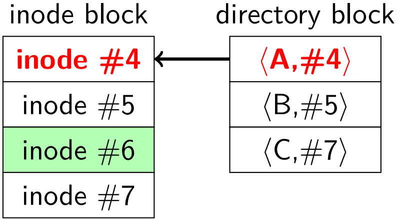
- Suppose you create file *A*, unlink file *B*
  - Both files in same directory block & inode block
- Can't write directory until *A*'s inode initialized
  - Otherwise, after crash directory will point to bogus inode
  - Worse yet, same inode # might be re-allocated
  - So could end up with file name *A* being an unrelated file
- Can't write inode block until *B*'s directory entry cleared
  - Otherwise, *B* could end up with too small a link count
  - File could be deleted while links to it still exist
- Otherwise, fsck has to be slow
  - Check every directory entry and inode link count

Cyclic dependencies illustrated

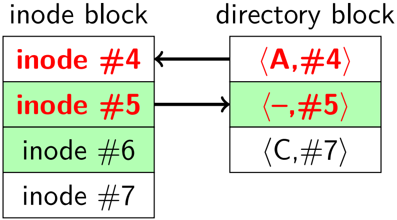




Original organization



Create file A

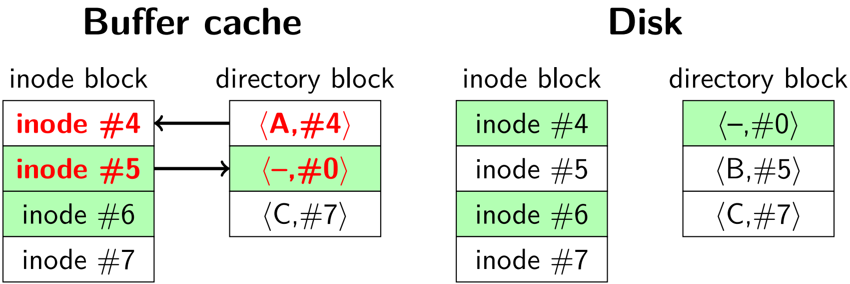


Remove file B

More problems

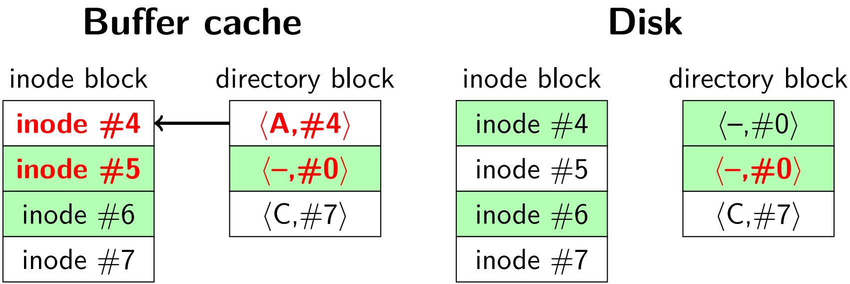
- Crash might occur between ordered but related writes
  - E.g., summary information wrong after block freed
- Block aging
  - Block that always has dependency will never get written back
- Solution: *Soft updates* [Ganger]
  - Write blocks in any order
  - But keep track of dependencies
  - When writing a block, temporarily roll back any changes you can't yet commit to disk
  - I.e., can't write block with any arrows pointing to dependees
    ...but can temporarily undo whatever change requires the arrow

Breaking dependencies with rollback



- Deleted Created file A and deleted file B
- Now say we decide to write directory block. . .
- Can't write file name *A* to disk—has dependee

Breaking dependencies with rollback



- Undo file *A* before writing dir block to disk
  - Even though we just wrote it, directory block still dirty
- But now inode block has no dependees
  - Can safely write inode block to disk as-is. . .

Breaking dependencies with rollback

Buffer cache

inode block
inode #4
inode #5
inode #6
inode #7

directory block
⟨A,#4⟩
⟨–,#0⟩
⟨C,#7⟩

Disk

inode block
inode #4
inode #5
inode #6
inode #7

directory block
⟨–,#0⟩
⟨–,#0⟩
⟨C,#7⟩

- Now inode block clean (same in memory as on disk)
- But have to write directory block a second time. . .

Breaking dependencies with rollback

Buffer cache

inode block
inode #4
inode #5
inode #6
inode #7

directory block
⟨A,#4⟩
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- All data stably on disk
- Crash at any point would have been safe

Soft updates

- Structure for each updated field or pointer, contains:
  - old value
  - new value
  - list of updates on which this update depends (*dependees*)
- Can write blocks in any order
  - But must temporarily undo updates with pending dependencies
  - Must lock rolled-back version so applications don't see it
  - Choose ordering based on disk arm scheduling
- Some dependencies better handled by postponing in-memory updates
  - E.g., when freeing block (e.g., because file truncated), just mark block free in bitmap after block pointer cleared on disk

Simple example

- Say you create a zero-length file A
- Depender: Directory entry for A
  - Can't be written untill dependees on disk
- Dependees:
  - Inode – must be initialized before dir entry written
  - Bitmap – must mark inode allocated before dir entry written
- Old value: empty directory entry
- New value: $\langle \text{filename } A, \text{inode \#} \rangle$
- Can write directory block to disk any time
  - Must substitute old value until inode & bitmap updated on disk
  - Once dir block on disk contains A, file fully created
  - Crash before A on disk, worst case might leak the inode

Operations requiring soft updates (1)

1. Block allocation
   - Must write the disk block, the free map, & a pointer
   - Disk block & free map must be written before pointer
   - Use Undo/redo on pointer (& possibly file size)
2. Block deallocation
   - Must write the cleared pointer & free map
   - Just update free map after pointer written to disk
   - Or just immediately update free map if pointer not on disk

- Say you quickly append block to file then truncate
  - You will know pointer to block not written because of the allocated dependency structure
  - So both operations together require no disk I/O!

Operations requiring soft updates (2)

3. Link addition (see simple example)
   - Must write the directory entry, inode, & free map (if new inode)
   - Inode and free map must be written before dir entry
   - Use undo/redo on i# in dir entry (ignore entries w. i# 0)
4. Link removal
   - Must write directory entry, inode & free map (if nlinks==0)
   - Must decrement nlinks only after pointer cleared
   - Clear directory entry immediately
   - Decrement in-memory nlinks once pointer written
   - If directory entry was never written, decrement immediately (again will know by presence of dependency structure)

- Note: Quick create/delete requires no disk I/O

Soft update issues

- *fsync* – sycall to flush file changes to disk
  - Must also flush directory entries, parent directories, etc.
- *unmount* – flush all changes to disk on shutdown
  - Some buffers must be flushed multiple times to get clean
- Deleting large directory trees frighteningly fast
  - *unlink* syscall returns even if inode/indir block not cached!
  - Dependencies allocated faster than blocks written
  - Cap # dependencies allocated to avoid exhausting memory
- Useless write-backs
  - Syncer flushes dirty buffers to disk every 30 seconds
  - Writing all at once means many dependencies unsatisfied
  - Fix syncer to write blocks one at a time
  - Fix LRU buffer eviction to know about dependencies

Soft updates fsck

- Split into foreground and background parts
- Foreground must be done before remounting FS
  - Need to make sure per-cylinder summary info makes sense
  - Recompute free block/inode counts from bitmaps – very fast
  - Will leave FS consistent, but might leak disk space
- Background does traditional fsck operations
  - Do after mounting to recuperate free space
  - Can be using the file system while this is happening
  - Must be done in forground after a media failure
- Difference from traditional FFS fsck:
  - May have many, many inodes with non-zero link counts
  - Don't stick them all in lost+found (unless media failure)

Outline

An alternative: Journaling

- Biggest crash-recovery challenge is inconsistency
  - Have one logical operation (e.g., create or delete file)
  - Requires multiple separate disk writes
  - If only some of them happen, end up with big problems
- Most of these problematic writes are to metadata
- Idea: Use a *write-ahead* log to *journal* metadata
  - Reserve a portion of disk for a log
  - Write any metadata operation first to log, then to disk
  - After crash/reboot, re-play the log (efficient)
  - May re-do already committed change, but won't miss anything

Journaling (continued)

- Group multiple operations into one log entry
  - E.g., clear directory entry, clear inode, update free map—either all three will happen after recovery, or none
- Performance advantage:
  - Log is consecutive portion of disk
  - Multiple operations can be logged at disk b/w
  - Safe to consider updates committed when written to log
- Example: delete directory tree
  - Record all freed blocks, changed directory entries in log
  - Return control to user
  - Write out changed directories, bitmaps, etc. in background (sort for good disk arm scheduling)

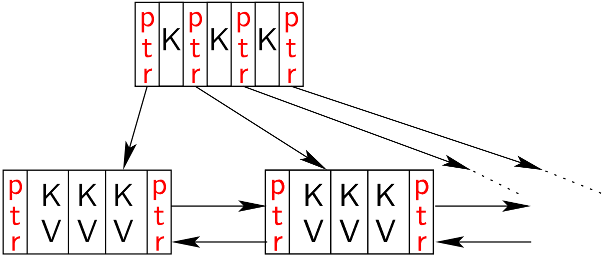
Journaling details

- Must find oldest relevant log entry
  - Otherwise, redundant and slow to replay whole log
- Use checkpoints
  - Once all records up to log entry N have been processed and affected blocks stably committed to disk...
  - Record N to disk either in reserved checkpoint location, or in checkpoint log record
  - Never need to go back before most recent checkpointed N
- Must also find end of log
  - Typically circular buffer; don't play old records out of order
  - Can include begin transaction/end transaction records
  - Also typically have checksum in case some sectors bad

Case study: XFS [Sweeney]

- Main idea: Think big
  - Big disks, files, large # of files, 64-bit everything
  - Yet maintain very good performance
- Break disk up into *Allocation Groups* (AGs)
  - 0.5 – 4 GB regions of disk
  - New directories go in new AGs
  - Within directory, inodes of files go in same AG
  - Unlike cylinder groups, AGs too large to minimize seek times
  - Unlike cylinder groups, no fixed # of inodes per AG
- Advantages of AGs:
  - Parallelize allocation of blocks/inodes on multiprocessor (independent locking of different free space structures)
  - Can use 32-bit block pointers within AGs (keeps data structures smaller)

B+-trees



- XFS makes extensive use of B+-trees
  - Indexed data structure stores ordered Keys & Values
  - Keys must have an ordering defined on them
  - Stored data in blocks for efficient disk access
- For B+-tree with n items, all operations $O(\log n)$:
  - Retrieve closest ⟨key, value⟩ to target key k
  - Insert a new ⟨key, value⟩ pair
  - Delete ⟨key, value⟩ pair

B+-trees continued

- See any algorithms book for details (e.g., [Cormen])
- Some operations on B-tree are complex:
  - E.g., insert item into completely full B+-tree
  - May require "splitting" nodes, adding new level to tree
  - Would be bad to crash & leave B+tree in inconsistent state
- Journal enables atomic complex operations
  - First write all changes to the log
  - If crash while writing log, incomplete log record will be discarded, and no change made
  - Otherwise, if crash while updating B+-tree, will replay entire log record and write everything

B+-trees in XFS

- B+-trees are complex to implement
  - But once you've done it, might as well use everywhere
- Use B+-trees for directories (keyed on filename hash)
  - Makes large directories efficient
- Use B+-trees for inodes
  - No more FFS-style fixed block pointers
  - Instead, B+-tree maps: file offset $\rightarrow$ $\langle$start block, # blocks$\rangle$
  - Ideally file is one or small number of contiguous extents
  - Allows small inodes & no indirect blocks even for huge files
- Use to find inode based on inumber
  - High bits of inumber specify AG
  - B+-tree in AG maps: starting i# $\rightarrow$ $\langle$block #, free-map$\rangle$
  - So free inodes tracked right in leaf of B+-tree

More B+-trees in XFS

- Free extents tracked by *two* B+-trees
  1. start block # → # free blocks
  2. # free blocks → start block #
- Use journal to update both atomically & consistently
- #1 allows you to coalesce adjacent free regions
- #1 allows you to allocate near some target
  - E.g., when extending file, put next block near previous one
  - When first writing to file, but data near inode
- #2 allows you to do best fit allocation
  - Leave large free extents for large files

Contiguous allocation

- Ideally want each file contiguous on disk
  - Sequential file I/O should be as fast as sequential disk I/O
- But how do you know how large a file will be?
- Idea: delayed allocation
  - *write* syscall only affects the buffer cache
  - Allow write into buffers before deciding where to place on disk
  - Assign disk space only when buffers are flushed
- Other advantages:
  - Short-lived files never need disk space allocated
  - *mmap*ed files often written in random order in memory, but will be written to disk mostly contiguously
  - Write clustering: find other nearby stuff to write to disk

Journaling vs. soft updates

- Both much better than FFS alone
- Some limitations of soft updates
  - Very specific to FFS data structures (E.g., couldn't easily add B-trees like XFS—even directory rename not quite right)
  - Metadata updates may proceed out of order (E.g., create A, create B, crash—maybe only B exists after reboot)
  - Still need slow background fsck to reclaim space
- Some limitations of journaling
  - Disk write required for every metadata operation (whereas create-then-delete might require no I/O with soft updates)
  - Possible contention for end of log on multi-processor
  - *fsync* must sync other operations' metadata to log, too