Ext3/4 file systems

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Ext2 review

- Very reliable, "best-of-breed" traditional file system design
- Much like the JOS file system you are building now
  - Fixed location super blocks
  - A few direct blocks in the inode, followed by indirect blocks for large files
  - Directories are a special file type with a list of file names and inode numbers
  - Etc.

File systems and crashes

- What can go wrong?
  - Write a block pointer in an inode before marking block as allocated in allocation bitmap
  - Write a second block allocation before clearing the first – block in 2 files after reboot
  - Allocate an inode without putting it in a directory – "orphaned" after reboot
  - Etc.

Deeper issue

- Operations like creation and deletion span multiple on-disk data structures
  - Requires more than one disk write
- Think of disk writes as a series of updates
  - System crash can happen between any two updates
  - Crash between wrong two updates leaves on-disk data structures inconsistent!

Atomicity

- The property that something either happens or it doesn't
  - No partial results
- This is what you want for disk updates
  - Either the inode bitmap, inode, and directory are updated when a file is created, or none of them are
- But disks only give you atomic writes for a sector ☹
- Fundamentally hard problem to prevent disk corruptions if the system crashes

fsck

- Idea: When a file system is mounted, mark the on-disk super block as mounted
  - If the system is cleanly shut down, last disk write clears this bit
- Reboot: If the file system isn't cleanly unmounted, run fsck
- Basically, does a linear scan of all bookkeeping and checks for (and fixes) inconsistencies

fsck examples

- Walk directory tree: make sure each reachable inode is marked as allocated
- For each inode, check the reference count, make sure all referenced blocks are marked as allocated
- Double-check that all allocated blocks and inodes are reachable
- Summary: very expensive, slow scan of the entire file system

Journaling

- Idea: Keep a log of what you were doing
  - If the system crashes, just look at data structures that might have been involved
- Limits the scope of recovery; faster fsck!

Undo vs. redo logging

- Two main choices for a journaling scheme (same in databases, etc)
- Undo logging:

  1) Write what you are about to do (and how to undo it)
     - Synchronously

  2) Then make changes on disk

  3) Then write a commit record (synchronously)
- If system crashes before commit record, execute undo steps
  - Undo steps MUST be on disk before any other changes! Why?

Redo logging

- Before an operation (like create)

  1) Write everything that is going to be done to the log + a commit record
     - Sync

  2) Do the updates on disk

  3) When updates are complete, mark the log entry as obsolete
- If the system crashes during (2), re-execute all steps in the log during fsck

Which one?

- Ext3 uses redo logging
  - Tweedie says for delete
- Intuition: It is easier to defer taking something apart than to put it back together later
  - Hard case: I delete something and reuse a block for something else before journal entry commits
- Performance: This only makes sense if data comfortably fits into memory
  - Databases use undo logging to avoid loading and writing large data sets twice

Atomicity revisited

- The disk can only atomically write one sector
- Disk and I/O scheduler can reorder requests
- Need atomic journal "commit"

Atomicity strategy

- Write a journal log entry to disk, with a transaction number (sequence counter)
- Once that is on disk, write to a global counter that indicates log entry was completely written
  - This single write is the point at which a journal entry is atomically "committed" or not
    - Sometimes called a **linearization point**
- Atomic: either the sequence number is written or not; sequence number will not be written until log entry on disk

Batching

- This strategy requires a lot of synchronous writes
  - Synchronous writes are expensive
- Idea: let's batch multiple little transactions into one bigger one
  - Assuming no fsync()
  - For up to 5 seconds, or until we fill up a disk block in the journal
  - Then we only have to wait for one synchronous disk write!

Complications

- We can't write data to disk until the journal entry is committed to disk
  - Ok, since we buffer data in memory anyway
  - But we want to bound how long we have to keep dirty data (5s by default)
  - JBD adds some flags to buffer heads that transparently handles a lot of the complicated bookkeeping
    - Pins writes in memory until journal is written
    - Allows them to go to disk afterward

More complications

- We also can't write to the in-memory version until we've written a version to disk that is consistent with the journal
- Example:
  - I modify an inode and write to the journal
  - Journal commits, ready to write inode back
  - I want to make another inode change
    - Cannot safely change in-memory inode until I have either written it to the file system or created another journal entry

Another example

- Suppose journal transaction1 modifies a block, then transaction 2 modifies the same block.
- How to ensure consistency?
  - Option 1: stall transaction 2 until transaction 1 writes to fs
  - Option 2 (ext3): COW in the page cache + ordering of writes

Yet more complications

- Interaction with page reclaiming:
  - Page cache can pick a dirty page and tell fs to write it back
  - Fs can't write it until a transaction commits
  - PFRA chose this page assuming only one write-back; must potentially wait for several
- Advanced file systems need the ability to free another page, rather than wait until all prerequisites are met

Write ordering

- Issue, if I make file 1 then file 2, can I have a situation where file 2 is on disk but not file 1?
  - Yes, theoretically
- API doesn't guarantee this won't happen (journal transactions are independent)
  - Implementation happens to give this property by grouping transactions into a large, compound transactions (buffering)

Checkpointing

- We should "garbage collect" our log once in a while
  - Specifically, once operations are safely on disk, journal transaction is obviated
  - A very long journal wastes time in fsck
- Journal hooks associated buffer heads to track when they get written to disk
  - Advances logical start of the journal, allows reuse of those blocks

Journaling modes

- Full data + metadata in the journal
  - Lots of data written twice, batching less effective, safer
- Ordered writes
  - Only metadata in the journal, but data writes only allowed after metadata is in journal
  - Faster than full data, but constrains write orderings (slower)
- Metadata only – fastest, most dangerous
  - Can write data to a block before it is properly allocated to a file

Revoke records

- When replaying the journal, don't redo these operations
  - Mostly important for metadata-only modes
- Example: Once a file is deleted and the inode is reused, revoke the creation record in the log
  - Recreating and re-deleting could lose some data written to the file

ext3 summary

- A modest change: just tack on a journal
- Make crash recovery faster, less likely to lose data
- Surprising number of subtle issues
  - You should be able to describe them
  - And key design choices (like redo logging)

ext4

- ext3 has some limitations that prevent it from handling very large, modern data sets
  - Can't fix without breaking backwards compatibility
  - So fork the code
- General theme: several changes to better handle larger data
  - Plus a few other goodies

Example

- Ext3 fs limited to 16 TB max size
  - 32-bit block numbers (2^32 * 4k block size), or "address" of blocks on disk
  - Can't make bigger block numbers on disk without changing on-disk format
  - Can't fix without breaking backwards compatibility
- Ext4 – 48 bit block numbers

Indirect blocks vs. extents

- Instead of represent each block, represent large contiguous chunks of blocks with an extent
- More efficient for large files (both in space and disk scheduling)
- Ex: Disk sectors 50—300 represent blocks 0—250 of file
  - Vs.: Allocate and initialize 250 slots in an indirect block
  - Deletion requires marking 250 slots as free

Extents, cont.

- Worse for highly fragmented or sparse files
  - If no 2 blocks are contiguous, will have an extent for each block
    - Basically a more expensive indirect block scheme
  - Propose a block-mapped extent, which essentially reverts to a more streamlined indirect block

Static inode allocations

- When you create an ext3 or ext4 file system, you create all possible inodes
- Disk blocks can either be used for data or inodes, but can't change after creation
- If you need to create a lot of files, better make lots of inodes
- Why?

Why?

- Simplicity
  - Fixed location inodes means you can take inode number, total number of inodes, and find the right block using math
    - Dynamic inodes introduces another data structure to track this mapping, which can get corrupted on disk (losing all contained files!)
  - Bookkeeping gets a lot more complicated when blocks change type
- Downside: potentially wasted space if you guess wrong number of files

Directory scalability

- An ext3 directory can have a max of 32,000 sub-directories/files
  - Painfully slow to search – remember, this is just a simple array on disk (linear scan to lookup a file)
- Replace this in ext4 with an HTree
  - Hash-based custom BTree
  - Relatively flat tree to reduce risk of corruptions
  - Big performance wins on large directories – up to 100x

Other goodies

- Improvements to help with locality
  - Preallocation and hints keep blocks that are often accessed together close on the disk
- Checksumming of disk blocks is a good idea
  - Especially for journal blocks
- Fsck on a large fs gets expensive
  - Put used inodes at front if possible, skip large swaths of unused inodes if possible

Summary

- ext2 – Great implementation of a "classic" file system
- ext3 – Add a journal for faster crash recovery and less risk of data loss
- ext4 – Scale to bigger data sets, plus other features
  - Total FS size (48-bit block numbers)
  - File size/overheads (extents)
  - Directory size (HTree vs. a list)