12: FFS,LFS and other file systems

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Building a file system

- To build a file system from an array of disk sectors we have to decide things like
  - Must files be allocated contiguously?
  - If not how will be find the pieces?
  - What information is stored about each file in the directory?
  - Where do we put new files that are created?
  - What do we do when files grow or shrink?
  - How do we recover the FS after a crash?

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Answers?

- We are going to look at two different file systems
  - Fast File System (FFS)
  - Log-Structured File Systems (LFS)

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How are they the same?

- Both allow files to be broken into multiple pieces
- Both use fixed sized blocks (for the most part)
- Both use the inode structure we discussed last time

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Fast File System

- Fast? Well faster than original UNIX file system (1970's)
  - Original system had poor disk bandwidth utilization
  - Remember why that is a problem? Too many seeks
- BSD UNIX folks redesigned in mid 1980's
  - Improved disk utilization by breaking files into larger pieces
  - Made FFS aware of disk structure (cylinder groups) and tried to keep related things together
  - Other semi-random improvements like support for long file names etc.

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Managing Free Space

- Break disk into cylinder groups and then into fixed size pieces called blocks (commonly 4 KB)
- Each cylinder group has a certain number of blocks
  - Cylinder group's free list maps which blocks free and which taken
  - Cylinder groups also store a copy of the superblock which contains special bootstrapping information like the location of the root directory (replicated)
  - Cylinder groups also contain a fixed number of I-nodes
  - Rest of blocks used to store file/directory data

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Inodes in FFS

- In FFS, fixed number of inodes at FS format time
  - When create file, pick an inode, will never move (so directory entry need not be updated)
  - Can run out of inodes and not be able to create file even though there is free space

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Creating a new file

- In the pre-FFS UNIX file system
  - Free list for the entire disk
  - Started out ordered nicely such that if ask for 3 free blocks likely to get 3 together
  - Randomized over time as files created and deleted such that pieces of a new file scattered over the disk
  - Also when create new file need a new inode too
    - All inodes at beginning of disk, far from the data
  - When read through a file likely to be seeks between each block – slow!

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FFS

- Divide the disk into cylinder groups
  - Try to put all blocks of file into same cylinder group
  - Inodes in each cylinder group so inodes near their files
  - Try to put files in the same directory into the same cylinder group
  - Big things forced into new cylinder group
- Is this fundamentally a new approach?
  - Not really…space within a cylinder group gets treated just like whole disk was
  - Space in cylinder group gets fragmented etc
  - Basically sort files into bins so reduce the frequent long seeks

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Cylinder Groups

- To keep things together must know when to keep things apart
  - Put large files into a different cylinder group
- FFS reserves 10% of the disk as free space
  - To be able to sort things into cylinder groups, must have free space in each cylinder group
  - 10% free space avoids worst allocation choice as approach full (ex. One block in each cylinder group)

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Other FFS Improvements

- Small or large blocks?
  - Orig UNIX FS had small blocks (1 KB)
  - ¼ less efficient BW utilization
- Larger blocks have problems too
  - For files < 4K , results in internal fragmentation
  - FFS uses 4K blocks but allows fragments within a block
  - Last < 4K of a file can be in fragments
- Exactly 4K?
  - FFS allows FS to be parameterized to the disk and CPU characteristics
  - Another cool example: when laying out logically sequential blocks skip a few blocks in between each to allow for CPU interrupt processing so don't just miss the blocks and force a whole rotation

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Update In Place

- Both the original UNIX FS and FFS were update-in-place
- When block X of a file is written then forever more, reads or writes to block X go to that location until file deleted or truncated
- As things get fragmented need “defragmenter” to reorganize things

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Another Problem with Update-in-place

Poor crash recovery performance

- Some operations take multiple disk requests so are impossible to do atomically
  - Ex. Write a new file (update directory, remove space from free list, write inode and data blocks, etc.)
- If system crashes (lose power or software failure), there may be file operations in progress
- When system comes back up, may need to find a fix these half done operations
- Where are they?
  - Could be anywhere?
  - How can we restore consistency to the file system?

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Fixed order

- Solution: Specify order in which FS ops are done
- Example to add a file
  - Update free list structures to show data block taken
  - Write the data block
  - Update free list structures to show an inode take
  - Write the inode
  - Add entry to the directory
- If crash occurs, on reboot scan disk looking for half done operations
  - Inodes that are marked taken but are not referred to by any directory
  - Data blocks that are maked taken but are not referred to by any inode

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Fixed order (con't)

- We've found a half done operation now what?
  - If data blocks not pointed to by any inode then release them
  - If inode not pointed to by any directory link into Lost and Found
- Fsck and similar FS recovery programs do these kinds of checks
  - Problems can be anywhere with update in place so must scan the whole FS!!
- Problems?
  - Recovery takes a long time! (System shutdown uncleanly..checking your FS.. For the next 10 minutes!)
  - Even worse(?) normal operation takes a long time because specific order = many small synchronous writes = slow!

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Write-Ahead Logging (Journaling)

- How can we solve problem of recovery in update in place systems?
- Borrow a technique from databases!
  - Logging or journaling
- Before perform a file system operation like create new file or move a file, make a note in the log
- If crash, can simply examine the log to find interrupted operations
  - Don't need to examine the whole disk

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Checkpoints

- Periodically write a checkpoint to a well known location
- Checkpoint establishes a consistent point in the file system
- Checkpoint also contains pointer to tail of the log (changes since checkpoint written)
- On recovery start at checkpoint and then "roll forward" through the log
- Checkpoint points to location system will use for first log write after checkpoint, then each log write has pointer to next location to be used
  - Eventually go to next location and find it empty or invalid
- When write a checkpoint can discard earlier portions of the log

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Problems with write-ahead logging

- Do writes twice
- Once to log and once to "real" data (still organized like FFS)
- Surprisingly can be more efficient than update-in-place!
  - Batched to log and then replayed to "real" in relaxed order (elevator scheduling on the disk)

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Recovery of the file system (not your data)

- Write-ahead logging or journaling techniques could be used to protect FS and user data
- Normally just used to protect the FS
- I look like a consistent FS but your data may be inconsistent
  - Even if some of the last files you were modifying are inconsistent still better than FS corrupted (insert bootable device please ☹)
- Still, why do we need a “real” data layout why couldn’t the log be the FS? Then user data would get same benefits?

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Log-Structured File System

- Treat the disk as an infinite append only log
  - Data blocks, inodes, directories everything written to the log
- Batch writes in large units called segments (~ 1 MB)
- Garbage collection process called cleaner reclaims holes in the log to regenerate large expanses of free space for log writes

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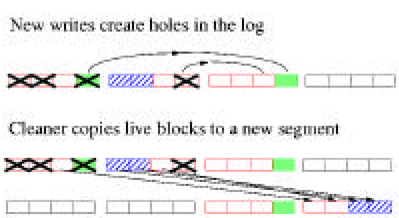
Log Writes and Cleaning



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Finding Data

- Inodes used to find data blocks
- Finding inodes?
  - Directories specify location of a file’s inode
- In an FSS, inodes are preallocated in each cylinder group and a given file’s inode never moves (update in place)
- In an LFS, inodes written to the log and so they move

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Chain Reaction

- LFS is not update in place when file block written its location changes
  - File location changes => entry in inode (and possibly also indirect blocks) changes => Inode (and indirect blocks) must be rewritten
- Parent directory contains location of inode – must directory be rewritten too?
  - If so then all directories to root must be rewritten?
- No! – introduce another level of indirection
  - Directory says inode *number* (rather than location)
  - Inode map to map inode number to current location

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Inode Map

- Inode map maps inode numbers to inode location
  - Map kept in a special file the ifile
- When a file’s inode is written, its parent directory does not change only the ifile does
- Caching inode map (ifile) in memory is pretty important for good performance
  - How big is this? Approx 2*4bytes(inode number and disk LBA) = 8 bytes for every file/directory in the file system
  - Can grow dynamically unlike FFS

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Checkpoint

- Like in Write Ahead Logging, write periodic checkpoints
  - Kind of like FFS superblocks
- Checkpoint region has a fixed location
  - Actually two fixed locations and alternate between them in case die in middle of writing and leave corrupt
  - Checksums to verify consistent; Timestamps say which is most recent
- Whats in checkpoint?
  - Location of inode for ifile and inode number of the root directory
  - Location of next segment will write log to
  - Basic FS parameters like segment size, block size, etc

LFS Pros and Cons

- What is good about this?
  - Leverage disk BW with large sequential writes
  - Near perfect write performance
  - Read performance? Good if read the same way as you write and many reads absorbed by caches
  - Cleaning can often be done in idle time
  - Fast efficient crash recovery
  - User data gets benefits of a log
- What's bad about this?
  - Cleaning overhead can be high – especially in the case of random updates to a full disk with little idle time
  - Reads may not follow write patterns (they may not follow directory structure either though!)
  - Additional metadata handling (inodes, indirect blocks and ifile rewritten frequently)

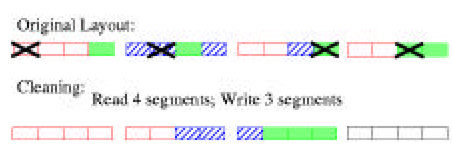
Cleaning Costs

- We are going to focus on talking about the problem of high cleaning costs
- Often cleaning is not a problem
  - If there is plenty of idle time (many workloads have this), cleaning costs hidden
  - Also if locality to writes, then easier to clean
  - If disk not very full then, segments clean themselves (overwrite everything in old segments before run out of free spaces for new writes)
- So when is cleaning a problem?
  - Cleaning expensive when random writes to full disk with no idle time

High Cleaning Costs

Random writes, full disk (little free space), no idle time = Sky-rocketting cleaning costs

For every 4 blocks written, also read 4 segments and write 3 segments!



Copy cleaning vs Hole-plugging

- Alternate cleaning method?
  - Hole-plugging = Take one segment break extract the live data and use it to plug holes in other segments
  - This will work well for full disk, random updates, little idle time!!
- Hole-plugging avoid problems with copy cleaning but transfers many small blocks which uses the disk less efficiently
- Could we get the best of both worlds?
  - First we have to talk about how to quantify the tradeoffs

Write Cost

- How do we quantify the benefits of large I/Os vs the penalty of copying data?
- Original LFS paper evaluated efficiency of cleaning algorithms according to the following metric
  - $(DataWritten_{NewData} + DataRead_{Cleaning} + DataWritten_{Cleaning}) / DataWritten_{NewData}$
  - Quantifies cleaning overhead in terms of the amount of data transferred while cleaning
  - What about the impact of large vs small transfers?

Cost of Small Transfers

- Quantify overhead due to using the disk inefficiently
  - $TransferTime_{Actual} / TransferTime_{Ideal}$
  - Where $TransferTime_{Actual}$ includes seek, rotational delay and transfer time and $TransferTime_{Ideal}$ only includes transfer time
- By factoring in the cost of small transfers, we see the cost of holeplugging

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Overall Write Cost

- Ratio of actual to ideal costs where
  - Actual includes cost of garbage collection and includes seek/rotational latency for each transfer
  - Ideal includes only cost of original writes to an infinite append only log – no seek/rotational delay and no garbage collection
- Now we have a metric that lets us compare hole-plugging to copy-cleaning
  - System can use this to choose which one to do!
  - Adaptive cleaning ☺

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Adaptive Cleaning

- When starting to run out of segments, do garbage collection
- Look in special file called the segmap that tells you how full each segment is
  - When rewrite a block in a segment, write in segmap file that segment is one block less full
- Estimate cost to do copy cleaning and cost to do hole-plugging
  - Compute overall write cost by seeing how full segments are
- Choose the most cost effective method this time
  - Can choose a different one next time ☺

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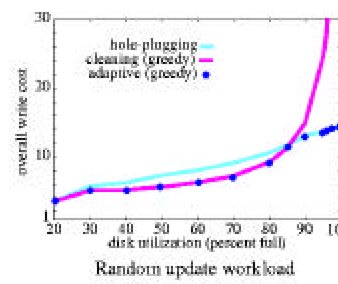
Adaptive Cleaning For Random Update Workload



Assume no idle time to clean

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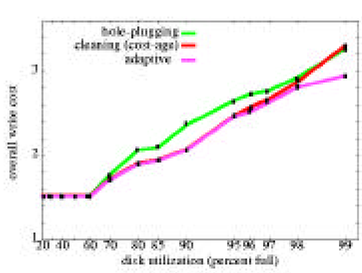
Adaptive Cleaning for Normal Usage Trace



Assume no idle time to clean

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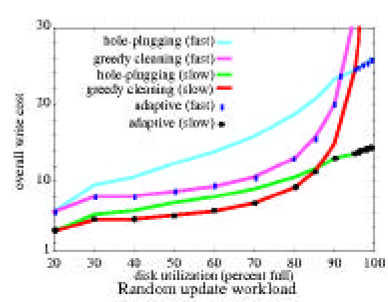
As Technology Changes



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Other factors?

- How does this layout work for reads?
  - Good if read in the same way you write
  - Well until start reorganizing during cleaning (hole-plugging is worse than copy cleaning here)
  - Special kind of hole-plugging that writes back on top of where it used to be?
- Accounting for additional metadata handling in the cache?
  - Modifying the write cost metric to account for "churn" in the metadata?
  - Model FFS in this same way

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Improving FFS also

- Extent like performance (McVoy)
- FFS-realloc (McKusick)
- FFS-frag and FFS-nochange(Smith)
- Colocating FFS (Ganger)
- Soft Updates (Ganger)

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Other FS?

- Update-in-place
  - FAT
  - ext2 (extent based rather than fixed size blocks)
- Write-ahead Logging (journaling)
  - NTFS
  - ReiserFS (B+ tree indices, optimizations for small files)
  - SGI's XFS (extent based and B+ trees)
  - Ext3 (journaling version of ext2)
  - Veritas VxFS
  - BeOS's BeFS
- No Update?
  - CD-ROM FS no update and often contiguous allocations (why does that make sense?)

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Network/Distributed FS

- Sun's NFS
- CMU's AFS and Coda
  - Transarc's (now IBM's) commercial AFS
  - Intermezzo (Linux Coda like system)
- Netware's NCP
- SMB

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Multiple FS?

- With all these choices, do we really have to choose just one FS for our OS?
- If we want to allow multiple FS in the same OS, what would be have to do?
  - Merge them into one directory hierarchy for the user
  - Make them obey a common interface for the rest of the OS

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Mount points

- Another kind of special file interpreted by the file system is a mount point
- Contains information about how to access the root of a separate FS tree (device information if local, server information if remote, type of FS, etc.)

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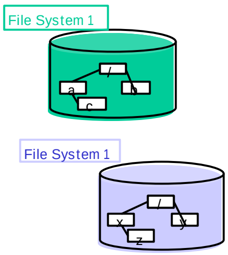
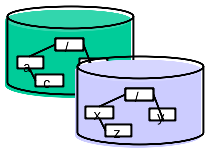
Mount Points





Mount file system 2 on /b then can refer
To z as /b/x/z

Common Interface?

- Different FS usually need the same "hooks" into the OS
  - Some need special things?
- Vnode interface
  - Proposed in 1986
  - Allow multiple FS in the same OS (without ugly case statements everywhere)
  - Allow FS to work on multiple OSes? (that's harder)

struct vnode

- One vnode structure for every opened (in-use) file
- Contains:
  - Array of pointers to procedures to implement basic operations on files
  - Pointer to parent FS
  - Pointer to FS that is mounted on top of this file (if any)
  - Reference count so know when to release the vnode

Vnode ops

- Open, close, create, remove, read, write
- Mkdir, rmdir, readdir
  - You don't know what that FS's directory format will be
- Symlink, Link, readlink (soft/hard links)
- Getattr, setattr, access (get/set/check attributes like permissions)
- Fsync
- Seek
- Map, getpage, putpage (memory map a file)
- Ioctl (misc I/O control ops)
- Rename
- ...

struct vfs

- One vfs structure in the OS for each mounted FS
- Contains:
  - Array of pointers to procedures that implement basic operations on file systems
  - FS type
  - Native block size
  - Pointer to vnode this FS is mounted on

vfsops

- Mount: procedure called to mount a FS of this type on a specified vnode
- Unmount: procedure to release this FS
- Root: return root vnode of this Fs
- Statvfs: return research usage status of the FS
- Sync: flush all dirty memory buffers to persistent storage managed by this FS
- Vget: turn a fileId into a a pointer to vnode for a specific file
- Mountroot: mount this FS as the root FS on this host
- Swapvp: return vnode of file in this FS to which the OS can swap

Evolving vnode interface?

- Kleiman86 => Rosenthal90

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Do we need FS interface?

- FS Interface
  - Giving things file names seems a bit arbitrary
- FS hierarchy vs directory search
- People like to find information both ways
  - I know exactly what I want don't bother looking for me I will get it myself
  - Give me everything matching these characteristics

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Outtakes

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