A Brief History
of the
BSD Fast Filesystem

Brought to you by

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1979 − Early Filesystem Work

- Improved reliability
  - staged modifications to critical filesystem information
  - modifications could be either completed or repaired cleanly by **fsck** after a crash
- Increased the block size of the filesystem from 512 to 1K bytes
  - doubled performance because each disk transfer accessed twice as much data
  - eliminated the need for indirect blocks for many files
  - still utilized only about 4% of disk bandwidth

1982 − Birth of the Fast Filesystem

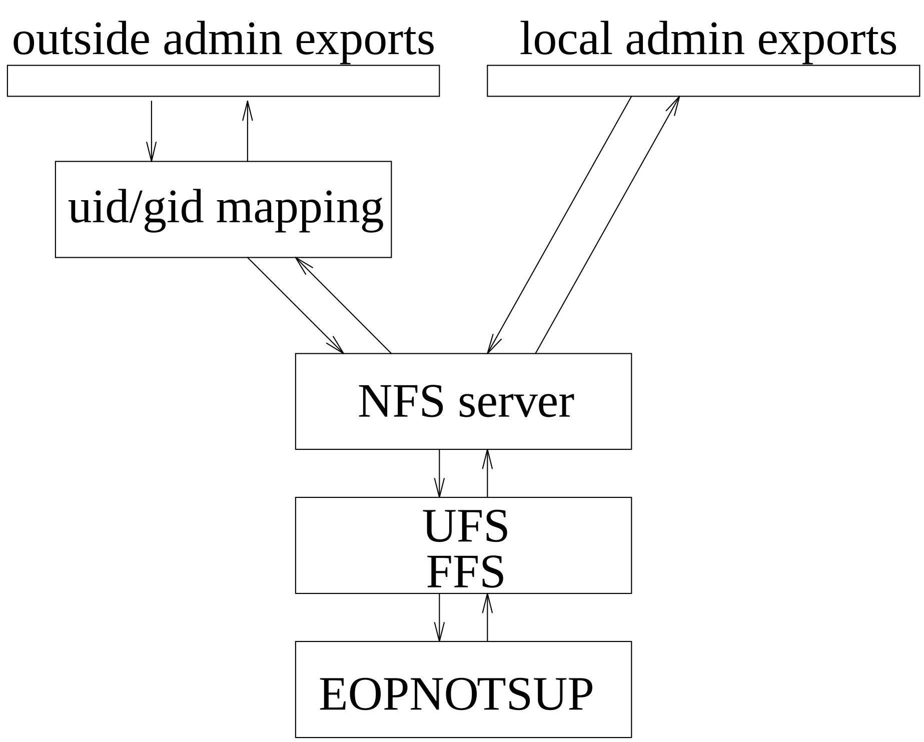
- Designed with a hybrid blocksize in which large blocks could be broken up into as many as eight fragments
- Large files used large blocks
- Small files could use as little as a single fragment
- First deployed with default blocksize 4K/512
- Still in use today

1986 − Dropping Disk-geometry Calculations

- Originally a cylinder group comprised one or more consecutive cylinders on a disk
- The filesystem could get an accurate view of the disk geometry and could compute the rotational location of every sector
- By 1986, disks were hiding this information and it was too complex to compute it
- All the rotational layout code was deprecated in favor of laying out files using numerically close block numbers (sequential being viewed as optimal)
- Cylinder group structure was retained only as a convenient way to manage logically-close groups of blocks

1987 − Filesystem Stacking

- Allows filesystem modules to be stacked
- When a request is not implemented by a layer it is passed down to the next lower layer.
- Requests that reach the bottom of the stack without being serviced return with EOPNOTSUPP
- Requests may be modified and then passed on to a lower layer



1988 − Raising the Blocksize

- Default blocksize raised to 8K/1K
- Small files use a minimum of two disk sectors
- Nearly doubled throughput at a cost of only 1.4% additional wasted disk space

1990 − Dynamic Block Reallocation

- With the advent of disk caches and tag queueing it became desirable to begin laying files out contiguously

- Size of file unknown when first opened

  - If always assume big and place in biggest available space, then soon have only small areas of contiguous space available

  - If always assume small and place in areas of fragmented space, then beginning of large files will be poorly laid out

Implementation of Dynamic Block Reallocation

- Dynamic block reallocation places file in small areas of free space, then moves them to larger areas of free space if file grows
    - small files use the small chunks of free space
    - large files get laid out contiguously in the large areas of free space
- Little increase in I/O load as the buffer cache generally holds the file until its final location is known
- Free space remains largely unfragmented even after years of use (15% versus 40% degredation after three years)

1996 − Soft Updates

- Speed up file and directory creation, deletion, and renaming
- Keep filesystem consistent enough that **fsck** need not be run after a system crash
- Ensure that unwritten data blocks never show up in files
- Minimize need to do synchronous disk writes

Keeping Metadata Consistent 1

- Synchronous writes
  - Benefits: simple and effective
  - Drawbacks: create/delete intensive applications run slowly, slow recovery after a crash
- Non-Volatile RAM
  - Benefits: usually runs all operations at memory speed, quick recovery after a crash
  - Drawbacks: expensive hardware unavailable on many machines, somewhat complex recovery
- Atomic Updates (journaling and logging)
  - Benefits: create/remove do not slow down under under heavy load, quick recovery after a crash
  - Drawbacks: extra I/O generated, little speed-up for light loads

Keeping Metadata Consistent 2

- Copy-on-write Filesystem (LFS, ZFS, WAFL, etc)
  - Benefits: write throughput, cheap snapshots, always consistent
  - Drawbacks: disk fragmentation, memory overhead

- Soft updates
  - Benefits: most operations run at memory speed, reduced system I/O, instant recovery after a crash
  - Drawbacks: complex code, background fsck, and increased memory loading

1999 − Snapshots

- Create a read-only frozen-in-time copy of a filesystem
- Minimize time that the filesystem is unavailable while taking the snapshot
- Minimize amount of disk space overhead to hold the snapshot
- Allow multiple snapshots to be concurrently maintained

2001 − Raising the Blocksize, Again

- Default blocksize raised to 16K/2K
  - Small files use a minimum of four disk sectors
  - Nearly doubled throughput at a cost of only 2.9% additional wasted disk space

2002 − Background Fsck

- Disk state is always valid but behind in-memory state
- Only inconsistencies:
  - Blocks marked in use that are free
  - Inodes marked in use that are free
- It is safe to run immediately after a crash though eventually lost space must be reclaimed

Background Block Recovery

- Block recovery on an active system:

  1) Snapshot the filesystem

  2) Run standard filesystem check program on the snapshot

  3) Add a system call to add lost blocks and inodes to the filesystem map

2003 − Multi-terabyte support

- Original fast filesystem used 32-bit pointers to reference a file’s blocks
- The 32-bit block pointers of the original filesystem run out of space in the 1 to 4 terabyte range
- Considered other alternatives but chose to extend the original filesystem
  - Allowed reuse of most of existing code base which allowed quick development and deployment
  - Became stable and reliable rapidly
  - Same code base supported both 32-bit block and 64-bit block filesystem formats so bug fixes and feature or performance enhancements usually applied to both filesystem formats

2003 − Extended Attributes

- Extended attributes added at the same time as multi-terabyte support
- Extended attributes are a piece of auxiliary data storage associated with an inode that can be used to store auxiliary data that is separate from the contents of the file
- By integrating the extended attributes into the inode itself, **fsync**( ) can provide the same integrity guarantees as are made for the contents of the file itself

2004 − Access-control Lists

- Extended attributes were first used to support an access control list (ACL)
    - specific list of the users and groups that are permitted to access the file
    - a list of the permissions that each user or group is granted

Implementation of Access-control Lists

- Replaced an earlier implementation using a single auxiliary file per filesystem indexed by inode number which had two problems:
  - fixed size of the space per inode meant only short user lists
  - difficult to atomically commit changes to the ACL
- Both problems fixed by using extended attributes:
  - extended attribute can be 64K, so long list of users possible
  - atomic update is easy since it can be updated with one write of inode

2005 − Mandatory-access Controls

- Extended attributes next used for mandatory access control (MAC)
- MAC framework permits dynamically introduced system-security modules to modify system security functionality
  - MAC framework provides control over kernel entry points affecting access control and object creation
  - When hit, MAC framework then calls out to security modules to offer them the opportunity to modify security behavior
- Filesystem does not codify how the labels are used or enforced; it just stores the labels associated and produces them when a security modules needs to do a permission check

2006 − Symmetric Multi-processing

- In the late 1990’s, the FreeBSD Project began the long hard task of converting their kernel to support symmetric multi-processing

- Start with giant lock around kernel

- Piece-by-piece add multi-threaded locking and remove from giant lock

  2004 − Vnode interface

  2005 − Disk subsystem

  2006 − Fast filesystem

2009 − Journaled Soft Updates

Only need to journal operations that orphan resources

Journal needs only 16Mb independent of filesystem size

Filesystem operations that require journaling

- free operations in maps tracking blocks and inodes
- Link count changes
- Unlink while referenced

2011 − Raising the Blocksize, Yet Again

- Default blocksize raised to 32K/4K
    - Driven by the change of disk technology to 4K sectors
    - Small files once again use a minimum of one disk sector
    - Nearly doubled throughput with no additional wasted disk space

2013 − Optimized Metadata Layout

Based on Ao Ma, etal. FAST ’13 ffsck paper

The first 4% of the data area of each cylinder group is held for metadata

Directory contents placed in metadata area of cylinder group holding its inode

First indirect block placed inline with data, but all other indirect blocks placed in metadata area of its inode’s cylinder group

Benefits:

- speeds file tree traversal
- speeds random access to file
- speeds sequential access because metadata tends to be in disk track cache
- speeds fsck because less seeking needed to get directories and file metadata

Metadata area is advisory

- if it runs out, metadata can go in data area
- if data area runs out, data can go in metadata area
- handled on per cylinder group basis

Future Directions for UFS2

- Collapse trims to GEOM layer
- Enable snapshots when using jounalled soft updates
  - always
  - don’t carry snapshots across crashes
- SMR drives
  - split bitmap into fragmented and contiguous areas to match zones
  - stage soft-update completions to batch cache flush
- Filesystem Hardening
  - Turn unrecoverable write errors into downgrade to read-only
  - Turn panics into forcible unmount

Future Directions for UFS3

- 64-bit inodes
- 32-bit link count
- Dynamic block size
- Endian independence

Questions

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May the Source Be With You!